Global Trigger firmware Specification for MP7 platform for Upgrade Phase I

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Revision History

Doc Rev	Description of Change	Revision Date
5.7	Fixed typo in section "Invariant mass calculation for three objects" 3.4.9.1.6.	2020/12/03
5.6	Updated text in section "VHDL-Templates for VHDL-Producer" 3.5.	2020/09/31
5.5	Inserted links to VHDL modules.	2020/09/18
5.4	Updated text in section "Correlation conditions" 3.4.9. Description is for v1.10.0 of Global Trigger Logic.	2020/09/17
5.3	Inserted description of "Invariant mass divided by delta R calculation" (see 3.4.9.1.5).	2020/09/10
5.2	Fixed typo (unconstrained pt).	2020/09/09
5.1	Inserted text for new muon structure in sections 3.2.2, 3.4.8.1 and 3.4.9.2. Added subsections in section 3.5	2020/08/04
5.0	Additional text in section 3.4.9.2.3.	2020/05/25
4.9	Inserted text in section 3.4.3.2.2 for Calorimeter Overlap Remover conditions and 3.4.9.2.3 for Calo Calo Overlap Remover Correlation conditions.	2020/04/16
4.8	Updated text in sections 3.4.3, 3.4.8 and 3.4.9 for changes which have been done for GTL VHDL version 1.8.0 (module names without version number, "five eta cuts").	2019/08/13
4.7	Inserted "Asymmetry" and "Centrality" of "Energy sums" (GTL VHDL version 1.6.0). Therefore updated sections 3.1, 3.2.1, 3.4.4 added section "Centrality condition" 3.4.7 and updated Table 2	2018/08/13
4.6	Updated text in section "Global Trigger Logic" (3) according to firmware version v1.5.0 of gtl_module.vhd	2018/02/21
4.5	Updated text in section "Framework" (2) according to firmware version v1.2.3 of frame.vhd	2018/01/19
4.4	New "icons" ET^{HF}_{miss} and HT^{HF}_{miss} in Table 2 and Section 3. Updated glossary (see Section 6)	2016/11/11
4.3	Updated table "μFDL register map" (36) and section "Register map" (4.4.1.1). Moved "List of Tables" and "List of Figures" to the end of document. Inserted link to "Scales for inputs to μGT" (3.3). Moved section "Software reset" to section "Framework" as subsection (2.7). Removed empty sections "IPBus", "Firmware Configuration" and "Bibliography"	2016/11/03
4.2	Updated sections "Calo-Layer2 optical interfaces" (3.2.1) and "Energy sum quantities conditions" (3.4.4) for towercount trigger bits. Inserted section "Towercount condition" (3.4.6)	2016/10/25

Doc Rev	Description of Change	Revision Date
4.1	Updated section "Calo-Layer2 optical interfaces" (3.2.1) for new energy sum quantities and minimum bias trigger bits. Updated sections "Firmware" (1), "Framework" (2) and "Final Desicion Logic" (4).	2016/06/09
4.0	Updated Text in section "Muon Muon Correlation condition module" (3.4.9.2.8).	2016/01/15
3.9	Removed "Double objects requirements condition with spatial correlation", because not used anymore in the future, replaced by Correlation conditions (see sections 3.4.3.2 and 3.4.8.3.	2016/01/08
3.8	Minor changes in text and updated Figure 11.	2016/01/08
3.7	Changed colour in Figure 12 and updated text for correlation conditions (see section 3.4.9.	2016/01/07
3.6	Updated Figures 11 and 10 and text 3.4.9.2.2.	2015/12/21
3.5	Inserted drawing of VHDL structure of cuts for correlation conditions (see Figure 13).	2015/11/18
3.4	Updated muon η ranges (Table 14) and inserted correlation conditions (see section 3.4.9). Created scheme for conversion of calorimeter η and φ to muon scale for calo-muon-correlation conditions (see Figure 14).	2015/11/17
3.3	Added Text in sections (3.4.3.2.4) and (3.4.8.3.3).	2015/10/08
3.2	Updated Text in section "Final Desicion Logic" (4).	2015/10/06
3.1	Updated Figure 15 and Tables 36, 12 and 24. Remaned section "Calorimeter conditions module - version 2" to "Calorimeter conditions module - version 3" (see 3.4.3.2), section "Muon conditions module" to "Muon conditions module - version 2" and section "Muon comparators module" to "Muon comparators module - version 2" (see 3.4.8.3)	2015/10/02
3.0	Updated text and tables of η ranges for Calorimeter objects (see 3.4.3.1).	2015/09/22
2.9	Renewed Figures in GTL and FDL (see Figure 9, 10 and 11) and FDL(see Figure 15 and 16). Added register bits description of FDL Register map (see section 4.4.1.1).	2015/09/16
2.8	Updated text, tables and listings of section "VHDL-Templates for VHDL-Producer" (see 3.5).	2015/09/15
2.7	Corrected calculation of muon η step width (see 3.4.8.1).	2015/09/10
2.6	Edited text in Tables 12, 23 and 24.	2015/08/28
2.5	Updated definition of η ranges for Calorimeter objects and Muon objects (3.4.3.1 and 3.4.8.1).	2015/08/20
2.4	Added section Calo Muon Correlation condition (3.4.9.2.7).	2015/08/19
2.3	Added section "Register map" (4.4.1.1) for μFDL.	2015/06/26

Doc Rev	Description of Change	Revision Date
2.2	Updated figures (9, 10 and 11) for GTL and edited section "Correlation conditions" (see 3.4.9).	2015/05/08
2.1	Added tables for calorimeter isolation-bits and for muon quality- and isolation-bits definition (10, 16 and 18). Edited section glossary (6) and acronyms.	2015/05/07
2.0	Added text for "Energy sum conditions" (3.4.4) and updated chapters for "Calorimeter conditions" for version 2. Inserted isolation bits for electron/γ and tau objects (3.4.3.1).	2015/05/06
1.9	Minor changes "Demux Lane Data" (see 2.2) and "Muon data" (see 3.4.8.1).	2014/11/06
1.8	Edited Section "Energy sum quantities conditions" (see 3.4.4).	2014/10/08
1.7	Added sections "Configuration of optical connections" (2.1), "Demux Lane Data" (2.2) and "Lane Mapping Process" (2.3) to framework. Removed tables of optical interfaces from gtl and referenced to tables in framework.	2014/10/07
1.6	Minor changes in "Calorimeter conditions" (3.4.3) and "Muon conditions" (3.4.8)	2014/07/01
1.5	Updated with minor changes in "Muon conditions" (3.4.8)	2014/06/17
1.4	Fixed bug in Figure 12	2014/04/30
1.3	Updated section "Muon conditions" (3.4.8)	2014/04/22
1.2	Removed section "Muon charge module" and added new section "Muon charge correlation module" (see 3.4.8.2). Edited text in section and subsections "Muon conditions definition" (see 3.4.8.3)	2014/04/15
1.1	Changed Figure 12 and minor changes in text for anti-clockwise behaviour in φ	2014/04/04
1.0	Added definition for "calorimeter conditions over bx", see section **??**.	2014/03/12
0.9	Changed text of condition description in subsections 3.4.3.2 and 3.4.8.3	2014/02/12
0.8	Updated calorimeter data structure in 3.2.1	2013/12/03
0.7	Updated muon data structure in 3.2.2	2013/12/02
0.6	Moved decription of VHDL templates for TME to 3.5	2013/11/18
0.5	Subsection 3.2 added to section 3	2013/11/11
0.4	GTL and FDL firmware implemented for new data structure (GTL firmware version v1.0.0 [fix part of GTL], FDL firmware version v1.0.0)	2013/11/06
0.3	New framework implementation based on new object types definition. Additionally, the ROP is implemented based on production requirements	2013/10/13

Doc Rev	Description of Change	Revision Date
0.2	First framework implementation + ROP	2012/07/01
0.1	Document created	2012/02/22

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1 Firmware overview

The figure 1 shows the architecture of μGT payload. It consists of framework, IPBus, output mux and the ALGORITHM LOGIC, which it consists of the following modules:

1. μGTL
2. μFDL

The output mux collects data for read-out record which are send via MP7 read-out to AMC13.

The IPBus system allows the control of hardware via a 'virtual bus', using a standard IP-over-gigabit-Ethernet network connection (section [??]).

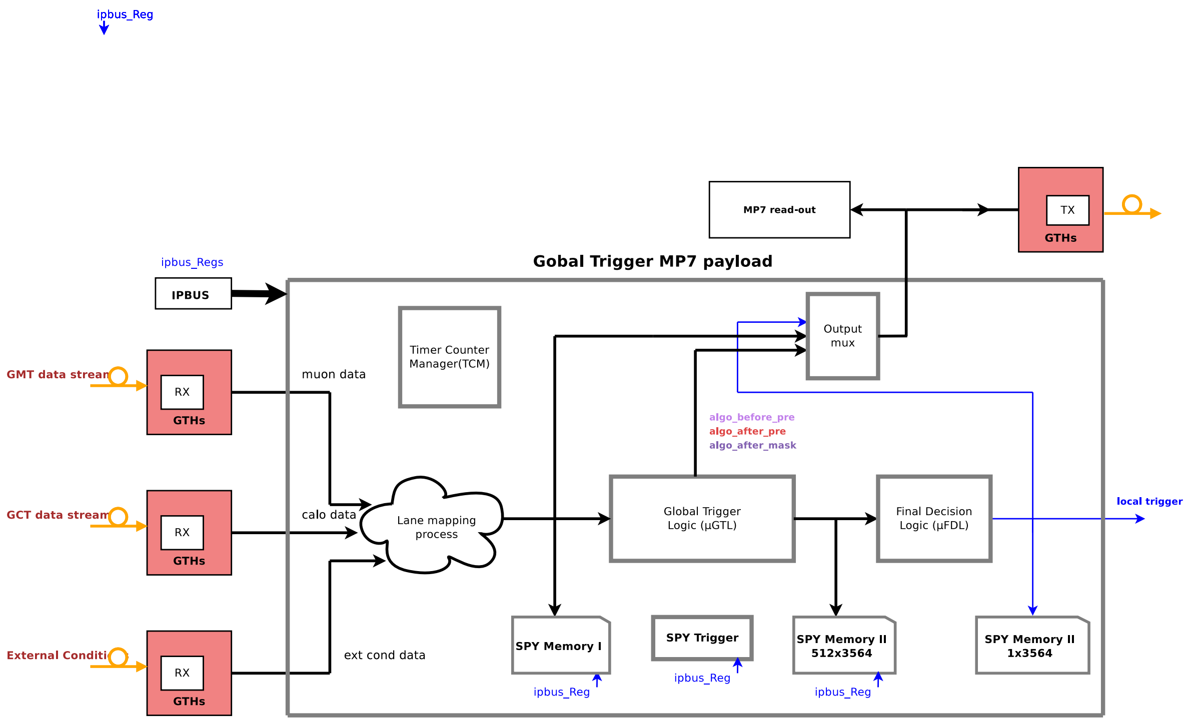


Figure 1: μGT payload

Moreover the `Tx_AMC13` should be instanitate for sending the readout-record to AMC13. This part is outside of framework functionality.

1.1 Package: lhc_data_pkg

The VHDL record lhc_data_t (shown in Listing 1) is used as a container for all object streams processed by the system. It is declared in the VHDL package lhc_data_pkg. For debugging and simulation purposes a second package (lhc_data_debug_util_pkg) is created which contains functions to convert the lhc_data_t to a hexadecimal string representation and vice versa. The testbench of the design uses this functions to load the contents of the SIM memory from a file.

Listing 1: lhc_data_t record specification

```
type lhc_data_t is record
        muon : muon_array_t;
        eg : eg_array_t;
        tau : tau_array_t;
        jet : jet_array_t;
        ett : std_logic_vector(ETT_DATA_WIDTH-1 downto 0);
        ht : std_logic_vector(HT_DATA_WIDTH-1 downto 0);
        etm : std_logic_vector(ETM_DATA_WIDTH-1 downto 0);
        htm : std_logic_vector(HTM_DATA_WIDTH-1 downto 0);
        etmhf : std_logic_vector(ETMHF_DATA_WIDTH-1 downto 0);
        htmhf : std_logic_vector(HTMHF_DATA_WIDTH-1 downto 0);
        link_11_fr_0_data : std_logic_vector(LINK_11_FR_0_WIDTH-1 downto
            0);
        link_11_fr_1_data : std_logic_vector(LINK_11_FR_1_WIDTH-1 downto
            0);
        link_11_fr_2_data : std_logic_vector(LINK_11_FR_2_WIDTH-1 downto
            0);
        link_11_fr_3_data : std_logic_vector(LINK_11_FR_3_WIDTH-1 downto
            0);
        link_11_fr_4_data : std_logic_vector(LINK_11_FR_4_WIDTH-1 downto
            0);
        link_11_fr_5_data : std_logic_vector(LINK_11_FR_5_WIDTH-1 downto
            0);
        external_conditions : std_logic_vector(
            EXTERNAL_CONDITIONS_DATA_WIDTH-1 downto 0);
end record;
```

2 Framework

Remark:
with frame v1.2.3 "Delay Manager" (dm.vhd) and "Data Source Multiplexer" (dsmux.vhd) are removed because these features were never used in production system, only for tests. Simmem data not useable anymore, because of removed dsmux. The reason of removing is to get more available resources.

Figure 2 shows the basic components the framework together with Readout-Process.

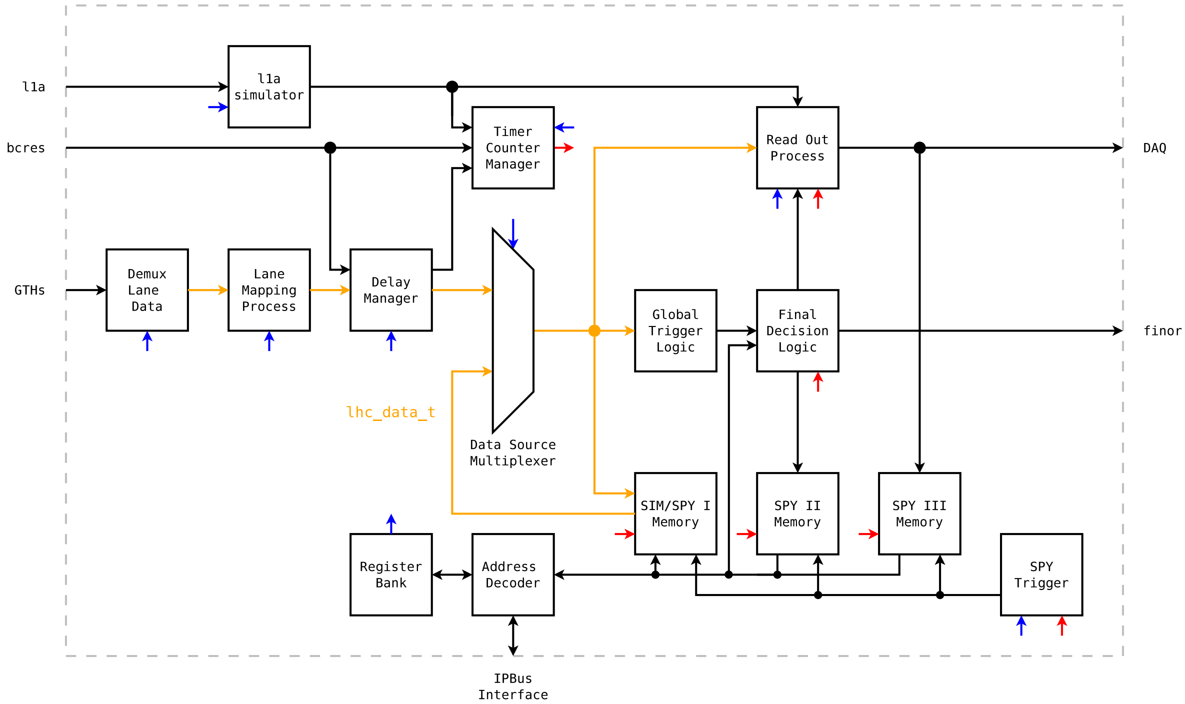


Figure 2: System architecture overview

The central data type of the framework is shown in Listing 1 (see Section 1.1 for details). In the current configuration it comprises 2304 bits (288 Bytes). Data from the GTH interfaces is demultiplexed (from 240 MHz clock domain to LHC clock domain, see Demux Lane Data 2.2) and mapped to this data type in the LMP (Lane Mapping Process). It is also used as input and output type for the SIM/SPY I memory. The DM (Delay Manager) takes the output of the LMP and applies software configurable delays to the the different object streams (e.g. muon data, jet, tau etc.) in the `lhc_data_t` to produce a consistent output (also regarding to the bcres signal). The software configurable multiplexer DSMUX (Data Source Multiplexer) is used to select which data stream is used as input for the processing elements (trigger logic). The output of the DSMUX is routed to the GTL (Global Trigger Logic) and ROP (Read Out Process) and can optionally be stored in the SPY I memory.

2.1 Configuration of optical connections

The configuration of the optical connections to Calo-Layer2 is (currently) done as described in Table 2, where frame means the 32 bits data (240 MHz) within a LHC clock period.

2.2 Demux Lane Data

Data from GTH interfaces is in the 240 MHz clock domain. The demultiplexing to the LHC clock domain (about 40 MHz) is done in demux_lane_data.vhd, which is instantiated in frame.vhd as often as lanes are used (currently 16 lanes are used).

2.3 Lane Mapping Process

In the Lane Mapping Process module data from the lanes are mapped to objects structure defined in lhc_data_pkg.vhd.

2.3.1 Implementation

Currently lane mapping is "fixed" in lmp.vhd module, see Table 3

2.4 Delay Manager

Remark:
with frame v1.2.3 "Delay Manager" (dm.vhd) and "Data Source Multiplexer" (dsmux.vhd) is removed because these features were never used in production system, only for tests. The reason of removing is to get more available resources.

The Delay Manager is responsible for creating a delayed version of the `lhc_data` and the bcres signal on its input. For this purpose it uses an internal memory to record the history of the input signals.

2.4.1 Implementation

The DM is basically a reimplementation of the concept of the last design. The reimplementation was necessary because the new framework version uses the register bank for software registers and the old DM was not flexible enough to handle the `lhc_data_t` introduced in the new framework.

The DM instantiates one `delay_element` for every object type defined in the `lhc_data_t` (e.g. muon, eg, etc.). The `delay_element` uses RAM blocks to implement the delay line. However, for the delays 0 and 1 this memory can not be used (write latency) and must be bypassed (Figure 3).

Table 2: Configuration of optical connections

	frame					
link	**0**	**1**	**2**	**3**	**4**	**5**
0	reserved	reserved	muon obj. 0 [0..31]	muon obj. 0 [32..63]	muon obj. 1 [0..31]	muon obj. 1 [32..63]
1	reserved	reserved	muon obj. 2 [0..31]	muon obj. 2 [32..63]	muon obj. 3 [0..31]	muon obj. 3 [32..63]
2	reserved	reserved	muon obj. 4 [0..31]	muon obj. 4 [32..63]	muon obj. 5 [0..31]	muon obj. 5 [32..63]
3	reserved	reserved	muon obj. 6 [0..31]	muon obj. 6 [32..63]	muon obj. 7 [0..31]	muon obj. 7 [32..63]
4	electron/γ obj. 0	electron/γ obj. 1	electron/γ obj. 2	electron/γ obj. 3	electron/γ obj. 4	electron/γ obj. 5
5	electron/γ obj. 6	electron/γ obj. 7	electron/γ obj. 8	electron/γ obj. 9	electron/γ obj. 10	electron/γ obj. 11
6	jet obj. 0	jet obj. 1	jet obj. 2	jet obj. 3	jet obj. 4	jet obj. 5
7	jet obj. 6	jet obj. 7	jet obj. 8	jet obj. 9	jet obj. 10	jet obj. 11
8	tau obj. 0	tau obj. 1	tau obj. 2	tau obj. 3	tau obj. 4	tau obj. 5
9	tau obj. 6	tau obj. 7	tau obj. 8	tau obj. 9	tau obj. 10	tau obj. 11
10	ET ETTEM MBT0HFP	HT TOWER-COUNT MBT0HFM	ET_{miss} ASYMET MBT1HFP	HT_{miss} ASYMHT MBT1HFM	ET_{miss}^{HF} ASYM-ETHF CENT[3:0]	HT_{miss}^{HF} ASYM-HTHF CENT[7:4]
11	free	free	free	free	free	free
12	external-conditions [0..31]	external-conditions [32..63]	reserved	reserved	reserved	reserved
13	external-conditions [64..95]	external-conditions [96..127]	reserved	reserved	reserved	reserved
14	external-conditions [128..159]	external-conditions [160..191]	reserved	reserved	reserved	reserved
15	external-conditions [192..223]	external-conditions [224..255]	reserved	reserved	reserved	reserved

Table 3: Current lane mapping

lane	**objects**
0	muon objects 0..1
1	muon objects 2..3
2	muon objects 4..5
3	muon objects 6..7
4	electron/γ objects 0..5
5	electron/γ objects 6..11
6	jet object 0..5
7	jet object 6..11
8	tau object 0..5
9	tau object 6..11
10	energy sum quantities (incl. minimum bias trigger bits and towercounts)
11	n/a (currently not used)
12	external-conditions [0..63]
13	external-conditions [64..127]
14	external-conditions [128..191]
15	external-conditions [192..255]

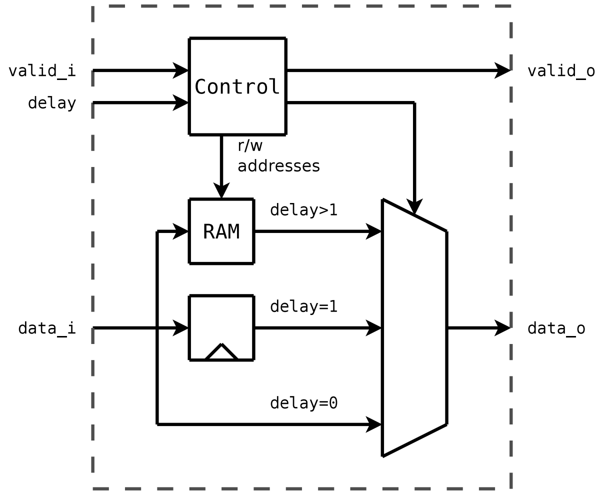


Figure 3: Delay Manager: delay_element

The Implementation of the DM is very generic because it makes extensive use of the constants provided by the `lhc_data_pkg`. The *lhc_data_i* input signal is converted into a `std_logic_vector`. The constants `LHC_DATA_SLV_START_INDICES` and `LHC_DATA_SLV_OBJECT_WIDTH` provide the start index of each object in this vector and their width respectively. The number of objects is given by the `LHC_DATA_OBJECT_COUNT` constant. This information is used by a for-generate statement to instantiate the required `delay_element` components.

For the *bcres_o* and the *bcres_FDL_o* signals two additional `delay_element` components are instantiated.

If only the data width or the array size of an object in the `lhc_data_t` is changed the DM does not need any modification. If, however, a new object is added a new delay register must be added, as described in the register bank section.

The registers for all delays have the same layout (see Register 2.1). The names for the individual (per object) delay registers are given in Table 4. For the software addresses of these registers refer to the `xml/gt_amc514_dm.xml` file.

Register 2.1: Delay Manager Registers

reserved	delay
31 … 12	11 … 0
0	0

delay The delay in lhc clock cycles (40 MHz) used for the specific object data.

Table 4: delay manager registers

object description	register name
bcres for TCM	bcres_tcm_delay
bcres for FDL	bcres_fdl_delay
muon data	muons_delay
e/g	eg_delay
tau	tau_delay
jet	jet_delay
ett	ett_delay
ht	ht_delay
etm	etm_delay
htm	htm_delay
external conditions	ex_con_delay

2.5 SIM and SPY Memory

Remark:
with frame v1.2.3 Simmem data not useable anymore, because of removed "Data Source Multiplexer". The reason of removing "Data Source Multiplexer" is to get more available resources.

Under construction!!!

Figure 4 shows the SIM/SPY memory subsystem of the framework. It is used to calibrate the system, i.e. to set the correct delays in the Delay Manager, to record results of the GTL/FDL and output packages of the ROP and to provide simulation data for the system. All source files for the memory subsystem are located in `src/mem` directory.

2.5.1 Implementation

The memory subsystem consists of four main parts, which will be discussed in more detail in the following sections

- SPY Trigger
- SIM/SPY Memory
- SPY Memory II
- SPY Memory III

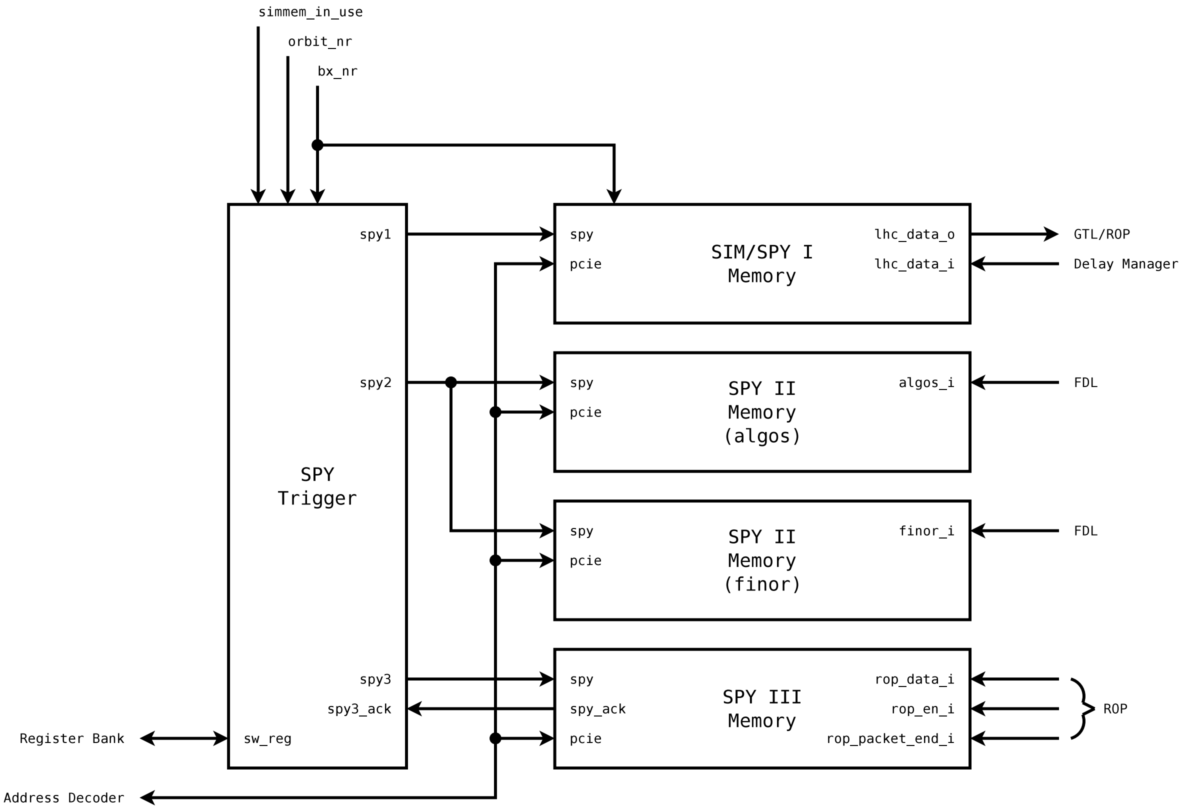


Figure 4: Memory subsystem

2.5.1.1 SPY Trigger

The SPY trigger controls the SPY memories and decides when data is recorded. It can be configured and controlled using software registers 2.2 and 2.3 provided by the register bank.

When the SPY trigger receives a spy12 command (next or once) over the software register interface it asserts the *spy*1 and *spy*2 signals for the appropriate orbit. This means that the *spy* signals go high with the bunch crossing counter reaching the value zero and stay high until it reaches zero again (overflow). Note that when the SIM memory is being used (indicated by the *simem_in_use_i* input provided by the DSMUX component) the *spy*1 output will not be asserted.

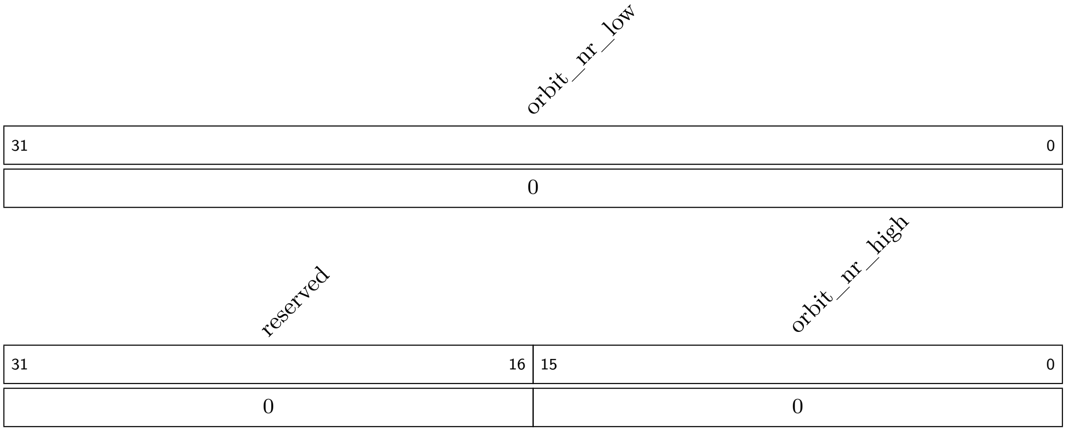
When a spy3 command is received the SPY trigger asserts the *spy*3 signal and waits until the *spy*3*_ack* signal is asserted.

2.5.1.2 SIM/SPY memory

This component combines the SIM memory and the SPY memory I. This optimization is possible because these two memories are never used at the same time. There are basically two use cases for this memory.

- SIM memory: Data is read form the memory and provided to GTL and ROP to test these components.

Register 2.2: SPY TRIGGER ORBIT NUMBER REGISTERS



orbit_nr_low The 32 low bits of the 48 bit orbit number, used for the spy once trigger.

orbit_nr_high The 16 high bits of the 48 bit orbit number, used for the spy once trigger.

- SPY memory: External data is received by the GTX and stored in the memory to check the alignment of the data.

It is very important to guarantee that the spy input signal is not asserted, as long as the memory is used as SIM memory. Note that this functionality is implemented in the SPY trigger component.

The SIM/SPY memory converts the *lhc_data_i* input signal to a `std_logic_vector` using the converter function provided by the `lhc_data_pkg`. This vector is then divided into chunks of 32 bits (the PCIe data width). For each of these chunks a 32 bit true-dual-port memory (2 read ports, 2 write ports, 2 clock domains) is instanciated. Thus, every memory has a read/write port in both clock domain, the 125MHz PCIe clock domain and the 40MHz LHC clock domain, which can be used simultaneously. The PCIe data-in signal (*sw_i.data*) is connected to PCIe-clock domain write port of the memories. A memory select signal is generated form the LSBs of the software address (*sw_i.addr*). The memory select signal also controls the multiplexer on the output of the memories to generate the *sw_o.data* signal.

Depending on whether the SIM/SPY memory is used to provide simulation data or to store/spy data the address on the LHC-clock domain port of the internal memories is adjusted. If data is recorded (SPY) the bunch crossing counter is used as memory address directly. When the memory is read the read latency (two clock cycles) must be taken into account. This is achieved by subtracting 2 form the bunch crossing number before using it as address. To generate the *lhc_data_o* signal the LHC-clock domain data out ports of the internal memories are concatenated and converted back to the `lhc_data_t`.

If the `lhc_data_t` is changed (e.g. new objects added) no modifications in the SIM/SPY memory are required. The SIM/SPY memory only depends on the (auto-generated) functions

Register 2.3: SPY TRIGGER CONFIGURATION REGISTER

	31	30	29	28	27	26 … 6	5	4	3	2	1	0
	spy12__bsy	spy3__bsy	spy12__rdy	spy3__rdy	spy12__err	reserved	clr__spy12__err	clr__spy3__rdy	clr__spy12__rdy	spy3	spy12__next	spy12__once
Reset	0	0	0	0	0	0	0	0	0	0	0	0

spy12__once Triggers the recording of the selected orbit to SPY memories I and II, when written with 1.

spy12__next Triggers the recording of the next whole orbit to SPY memories I and II, when written with 1.

spy3 Triggers the recording of the next package that will be sent by the ROP to SPY memory III, when written with 1.

clr__spy12__rdy Clears the ready flag of the SPY trigger for SPY memories I and II, when written with 1.

clr__spy3__rdy Clears the ready flag of the SPY trigger for SPY memory III, when written with 1.

clr__spy12__err Clears the error flag, when written with 1.

spy12__bsy Indicates that the SPY trigger for SPY memories I and II is busy.

spy3__bsy Indicates that the SPY trigger for SPY memory III is busy.

spy12__rdy Indicates that one orbit has been recorded in SPY memories I and II and that the SPY trigger is ready for new commands.

spy3__rdy Indicates that packet has been recorded in SPY memory III and that the SPY trigger is ready for new commands.

spy12__err Indicates an error condition (Set only when the selected orbit number for the spy once trigger lies in the past and can therefore not be recorded).

used to convert a `lhc_data_t` signal to `std_logic_vector` and vice versa (see Section 1.1 for details).

In the current implementation the size every object in the `lhc_data_t` is a multiple of 32 bit. This is also expected by the SIM/SPY memory. If objects with 16 bit sizes are added the SIM/SPY memory must be modified to support this situation (e.g. zero pad the `lhc_data_t`). Furthermore take into account that the PCIe memory bus is 32 bits wide. So 16 bit objects should be added to the end of the `lhc_data_t` (as last entry) to keep software memory access simple.

2.5.1.3 SPY memory II

The SPY memory II is divided into two subcomponents, to store the *algos* and *finor* outputs of the FDL. Both memory can only be read over the SW interface. A write access has no effect. The algos memory uses the same architecture as the SIM memory. The finor memory uses a true-dual-port memory with asymmetric ports. This memory can be written with a data width of one bit and read with a data width of 32 bit.

2.5.1.4 SPY memory III

The SPY memory III stores the output of the ROP, which is sent to the DAQ. The input data width is configurable to bus widths of 16, 32 or 64 bits. Depending on the input data width the memory uses different architectures.

- 16 Bit
  A true-dual-port memory with asymmetric ports (16 and 32 bits) is used.
- 32 Bit
  A true-dual-port memory with 32 Bit data width is used.
- 64 Bit
  Two true-dual-port memories with 32 Bit data width are used.

2.5.2 Interface Specification

Listing 2: SPY trigger interface specification

```
entity spytrig is
        port
        (
                lhc_clk     : in  std_logic;
                lhc_rst     : in  std_logic;
                orbit_nr    : in  orbit_nr_t;
                bx_nr       : in bx_nr_t;
                sw_reg_i    : in  sw_reg_spytrigger_in_t;
                sw_reg_o    : out sw_reg_spytrigger_out_t;

                spy1_o      : out std_logic;
                spy2_o      : out std_logic;
                spy3_o      : out std_logic;
                spy3_ack_i  : in  std_logic;

                simmem_in_use_i : in std_logic
        );
end;
```

2.6 TCM

Under construction!!!

The Timer Counter Manager (TCM) provides different counters, listed in table 5.

2.6.1 Counter Overview

Table 5: counters of the timer counter manager

Counter	range	increase condition	reset condition	Comments
bx_nr	$0to3563$	rising_edge(lhc_clk)	overflow	
event_nr	$0to2^{32}-1$	l1a=1 and rising_edge(lhc_clk)	BGOS: event counter reset	
trigger_nr	$0to2^{48}-1$	l1a=1 and rising_edge(lhc_clk)	BGOS: start run	
orbit_nr	$0to2^{48}-1$	overflow of bx_nr	BGOS: orbit counter reset	
luminosity_seg_nr	$0to2^{32}-1$	rising_edge(orbit_nr(18))	BGOS: orbit counter reset	
start_lumisection	$0to1$	luminosity_seg_nr increases	after 25ns	'1' for 25ns
bx_nr_d_fdl	$0to3563$	rising_edge(lhc_clk)	overflow	

2.6.2 Bunch Crossing Number and counters derived from it

All counters except for event_nr and the trigger_nr (which are trivial because they are increased with l1a) are dependent on the bunch crossing counter bx_nr as stated in table 5. The bx_nr is zero at startup, then waits for the the first bcres_d (bunch crossing reset delayed) and starts counting as depicted in figure 5. It's maximal value is 3563 (0xdeb), then it automatically overflows and starts at zero again (see figure 6). Exactly when bx_nr = 0, bcres_d has to be asserted. Otherwise the counter is out of synchronization. If this happens, the software register err_det is set and the counter waits for the next bcres_d to synchronize again. Note that the value of the counter is invalid until it has synchronized again.

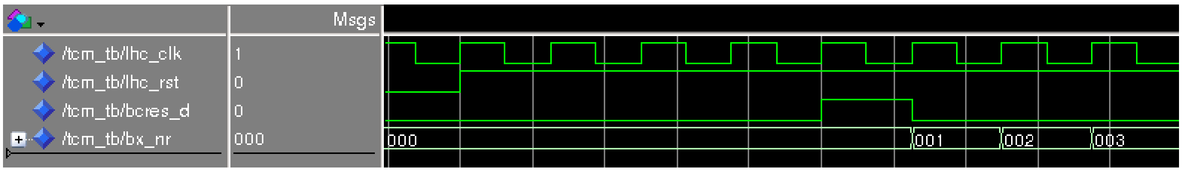


Figure 5: start of the bunch crossing number with the first bcres_d

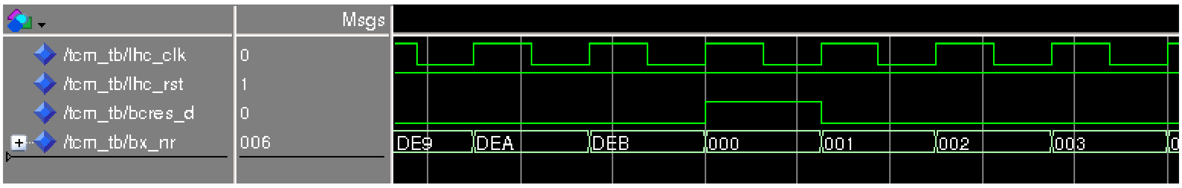


Figure 6: normal operation of the bunch crossing number

2.6.3 Special counter: bx_nr_d_fdl

The bx_nr_d_fdl is derived from bcres_d_fdl in the same manner as bx_nr is derived from bcres_d. bx_nr_d_fdl will automatically resync if the logic described in subsection 2.6.5 detects a synchronization error for bx_nr.

2.6.4 Counters derived from l1a

The counters event_nr and trigger_nr are increased with l1a, i.e. they are increased twice if l1a is high for 2 clock cycles, etc. They differ only in their value range and the condition that resets the counters, see table 5.

2.6.5 Errors

As stated above, bcres_d has to be asserted exactly when bx_nr = 0, otherwise the counter is out of sync. Then the software register err_det is set as depicted in figure 7. err_det can be reset via the software event register err_det_reset_event as depicted in figure 8. Furthermore err_det is set if bgos = Resync-0x1 and the counter value is not 3563.

The TCM implements two additional counters (bx_nr_chk and bx_nr_max) for debugging purposes. These counters are not visible by any other module but readable via software. bx_nr_chk is a 32bit Counter that increases with every LHC clock cycle and resets with bcres_d. bx_r_max holds the highest value bx_nr_chk ever reached (should be 3563 if the link is aligned).

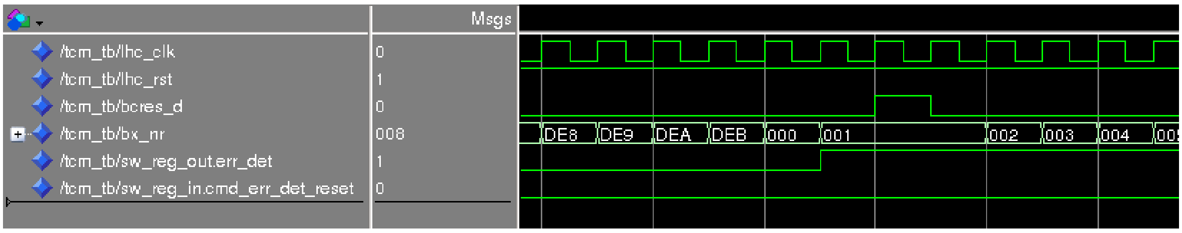


Figure 7: set of the software register err_det when bc_res_d is not asserted correctly

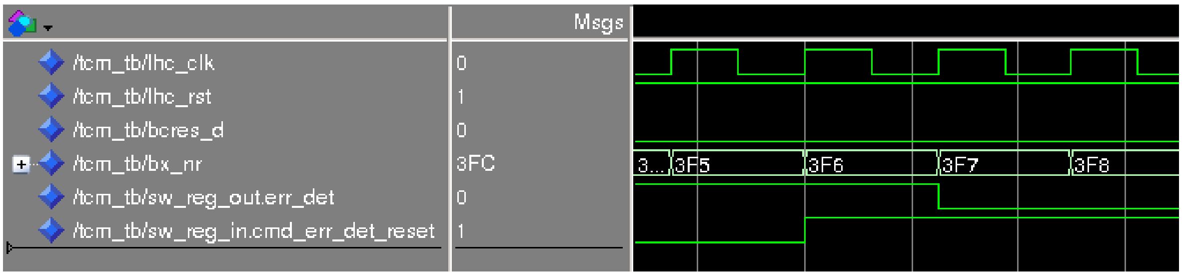


Figure 8: reset of the software register err_det when err_det_reset_event toggles

2.6.6 SW-Registers

All counters except for the start_lumisection described in table 5 can be read by software via the following sw registers:

Register 2.4: TCM Bunch Crossing Number Register

reserved	bx_nr
31 … 12	11 … 0
0	0

Register 2.5: TCM Event Number Register

event_nr
31 … 0
0

Register 2.6: TCM Trigger Number Registers

trigger_nr_l
31 … 0
0

reserved	trigger_nr_h
31 … 16	15 … 0
0	0

trigger_nr_l The 32 low bits of the 48 bit trigger number.

trigger_nr_h The 16 high bits of the 48 bit trigger number.

Register 2.7: TCM Orbit Number Registers

orbit_nr_l
31 … 0
0

reserved	orbit_nr_h
31 … 16	15 … 0
0	0

orbit_nr_l The 32 low bits of the 48 bit orbit number.

orbit_nr_h The 16 high bits of the 48 bit orbit number.

Register 2.8: TCM Luminosity Segment Number Register

luminosity_seg_nr
31 … 0
0

Register 2.9: TCM Bunch Crossing Number FDL Register

reserved	bx__nr__d__fdl
31 … 12	11 … 0
0	0

Register 2.10: TCM Bunch Crossing Number Check Register

bx__nr__chk
31 … 0
0

Register 2.11: TCM Bunch Crossing Number Max Register

bx__nr__max
31 … 0
0

Some additional control register can be used to check and reset err__det, disable the check of bcres__d and bcres__d__fdl (bx__nr and bx__nr__d__fdl automatically reset when they overflow if cmd__ign__bcres is set, bcres__d is ignored) and simulate the bgos signal. To do this, a value of the orbit signal has to be written to sw-register bgos. The value of the input signal bgos is replaced by the value of the sw-register for exactly one clock cycle, when "1" is written to the event register bgos__event.

Register 2.12: TCM cmd__ign__bcres

reserved	cmd__ign__bcres	
31 … 1	0	
0	0	Reset

cmd__ign__bcres bcres is ignored (not checked) when this is set.

Register 2.13: TCM ERR_DET

	reserved	err_det
Bits	31 … 1	0
Reset	0	0

err_det Set when out of synchronization.

Register 2.14: TCM ERR_DET_RESET_EVENT

	reserved	err_det_reset_event
Bits	31 … 1	0
Reset	0	0

err_det_reset_event Event register: resets err_det.

Register 2.15: TCM BGOS

	reserved	bgos
Bits	34 … 4	3 … 0
Reset	0	0

bgos For simulation of the bgos signal.

Register 2.16: TCM BGOS_EVENT

	reserved	bgos_event
Bits	31 … 1	0
Reset	0	0

bgos_event Event register: replaces the input signal bgos by the sw-register bgos for exactly one clock cycle.

Register 2.17: TCM LUMINOSITY_SEG_PERIOD_MSK

luminosity_seg_period_msk							
31						0	
0	x	4	0	0	0	0	Reset

luminosity_seg_period_msk luminosity_seg_nr is increased when the orbit_nr mod lum_seg_period_mask = 0.

2.6.7 Hardware Test

There are various python scripts located in the software/GtControl/branches/fpga-design-2013/python/GtControl directory for testing the tcm module. Please refer to the output of the scripts for information how the tests are performed in detail. See table 6.

Table 6: scripts for testing the tcm

script	purpose
`tcm_counter_values.py`	outputs the values of all counters defined above
`tcm_produce_err_det`	produces an err_det by manipulating bgos
`tcm_err_det_reset`	resets the err_det software register
`tcm_trigger_test`	tests trigger_nr and event_nr by generating l1a signals using l1asim
`tcm_lum_seg_nr_test`	checks the period of two successive increases of the luminositiy_seg_nr

2.7 Software Reset

The software reset module (sw_reset) provides the possiblity for a software reset via the software event register sw_reset_event.

Register 2.18: SOFTWARE RESET REGISTER

reserved	sw_reset_event	
31 … 1	0	
0	0	Reset

sw_reset_event Event register: Generates a reset signal for exactly one clock cycle.

3 Global Trigger Logic

Remark:
This description is for version 1.10.0 of Global Trigger Logic.

The Global Trigger Logic (μGTL) firmware contains conditions and Algorithms for trigger decision.

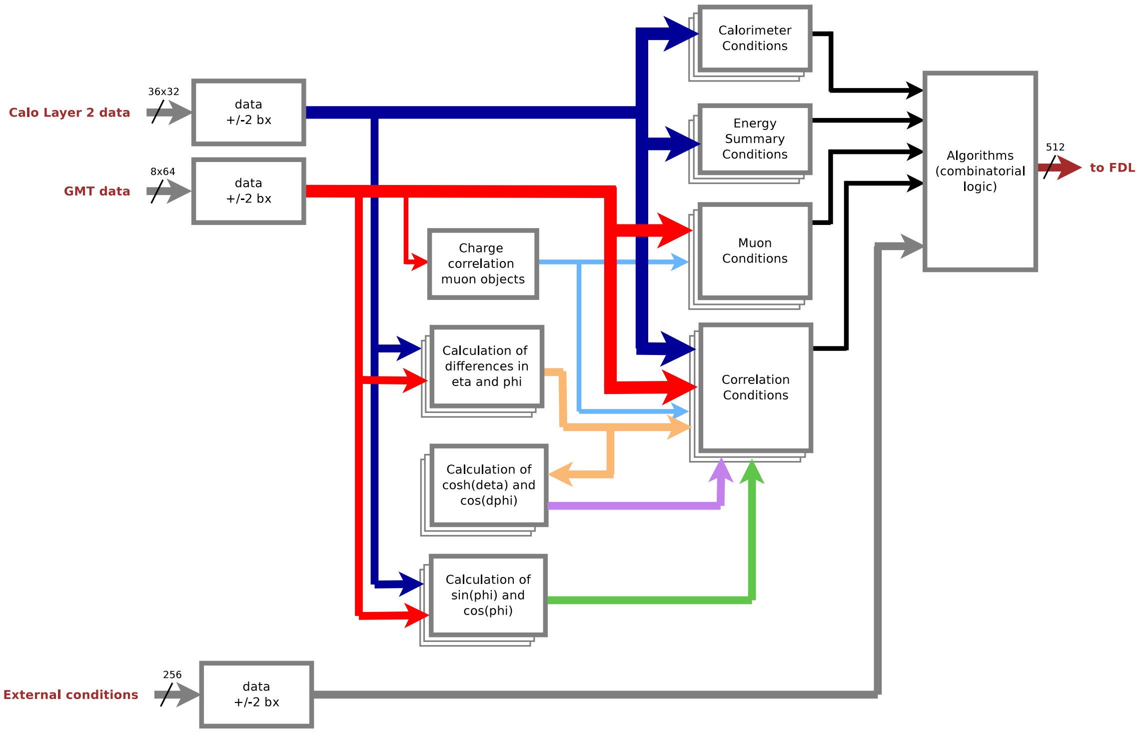


Figure 9: μGTL firmware

3.1 μGTL Interface

Inputs:

- Calo-Layer2 data
  - Electron/γ objects
  - Jet objects
  - Tau objects
  - Energy summary information: Total Et (ET), total Et from ECAL only (ETTEM), total calibrated Et in jets (HT), missing Et (ET_{miss}), missing Et including HF (ET_{miss}^{HF}), missing Ht objects (HT_{miss}), missing Ht including HF (HT_{miss}^{HF}) and "Asymmetry" information (ASYMET, ASYMHT, ASYMETHF, ASYMHTHF)

  - Minimum bias HF bits (included in energy summary information data structure)
  - Towercount bits (number of firing HCAL towers, included in energy summary information data structure)
  - "Centrality" bits
- Global Muon Trigger data
- External conditions
- LHC-clock

Outputs:

- Algorithms

3.2 Definition of optical interfaces

Remark:
All definitions for scales in the following chapters are from a CMS Detector Note: "Scales for inputs to μGT" (see actual version in https://raw.githubusercontent.com/cms-l1-globaltrigger/mp7_ugt_legacy/master/doc/scales_inputs_2_ugt/pdf/scales_inputs_2_ugt.pdf).

3.2.1 Calo-Layer2 optical interfaces

The configuration of optical connections from Calo-Layer2 to μGT is shown in Table 2.

The data structure of an electron/γ object (bits 27..31 are not defined yet, reserved for quality, ...):

31 27	26 25	24 17	16 9	8 0
qual/spare	iso	φ	η	E_T

The data structure of a jet object (bits 27..31 are not defined yet, reserved for quality, ...):

31 27	26 19	18 11	10 0
iso/qu/sp	φ	η	E_T

The data structure of a tau object (bits 27..31 are not defined yet, reserved for quality, ...):

31 27	26 25	24 17	16 9	8 0
qual/spare	iso	φ	η	E_T

The data structure of "total Et" (ET) quantity [including "total Et from ECAL only" (ET-TEM) and "minimum bias HF+ threshold 0" bits]:

31 28	27 24	23 12	11 0
MBT0HFP	spare	E_{T} [ETTEM]	E_{T} [ET]

The data structure of "total calibrated Et in jets" (HT) quantity [including "towercount" and "minimum bias HF- threshold 0" bits]:

31 28	27 25	24 12	11 0
MBT0HFM	spare	TOWERCOUNT	E_{T}

The data structure of "missing Et" (ET_{miss}) quantity [including "Asymmetry" ASYMET and "minimum bias HF+ threshold 1" bits]:

31 28	27 20	19 12	11 0
MBT1HFP	ASYMET	φ	E_{T}

The data structure of "missing Ht" (HT_{miss}) quantity [including "Asymmetry" ASYMHT and "minimum bias HF- threshold 1" bits]:

31 28	27 20	19 12	11 0
MBT1HFM	ASYMHT	φ	E_{T}

The data structure of "missing Et including HF" (ET^{HF}_{miss}) quantity [including "Asymmetry" ASYMETHF and "Centrality" bits (3:0)]:

31 28	27 20	19 12	11 0
[CENT3:0]	ASYMETHF	φ	E_{T}

The data structure of "missing Ht including HF" (HT^{HF}_{miss}) quantity [including "Asymmetry" ASYMHTHF and "Centrality" bits (7:4)]:

31 28	27 20	19 12	11 0
CENT[7:4]	ASYMHTHF	φ	E_{T}

3.2.2 Global Muon Trigger optical interfaces

The data structure of a muon object (64 bits - bit 34 = charge sign, bit 35 = charge valid, bit 61 is a spare bit, bit 63..62 = impact parameter):

63 62	61	60 53	52 43	42 36	35 34	33 32
imp para	*r*	*unconst.*p_{T}	φ *(out)*	*index bits*	*ch*	*iso*

31 23	22 19	18 10	9 0
η *(extrapol.)*	*qual*	p_{T}	φ *(extrapol.)*

3.3 Implementation in firmware

The firmware of μGTL consists of two main parts:

- A top-of-hierarchy file (`gtl_module.vhd`), which contains the pipeline for ±2bx data, the instantiations of calculators for differences in η and φ, the instantiations of conditions, the instantiations of charge correlation logic of muons and the Algorithms logic for 512 Algorithms, as well as a package file (`gtl_pkg.vhd`) for declarations. Actually 6 AMC board are used to contain 512 Algorithms. Therefore the 512 Algorithms are **partitioned by VHDL Producer**. The VHDL Producer for every Trigger Menu creates VHDL snippets files (`algo_index.vhd`, `gtl_module_instances.vhd`, `gtl_module_signals.vhd`, `ugt_constants.vhd`), these snippets are inserted into templates for `gtl_module.vhd` (`gtl_module_tpl.vhd`) and `gtl_pkg.vhd` (`gtl_pkg_tpl.vhd`) during simulation and synthesis.
- A set of VHDL-files exists for all the modules instantiated in top-of-hierarchy and the modules in the hierarchy. These files, called the "fixed part", are not influenced by VHDL Producer.

The latency of μGTL is fixed to 5 bunch-crossings, 2 bunch-crossings for the pipeline of ±2bx data (for data with +2bx and +1bx), 2 bunch-crossings for conditions (fixed), also for the conditions requested in the future, 1 bunch-crossing for the logic of Algorithms (See Figure 11).

3.3.1 Top-of-hierarchy module

The top-of-hierarchy module (`gtl_module.vhd`) contains

- the pipeline for ±2bx data
- the instantiations of charge correlation logic of muons (generated by VHDL Producer)
- the instantiations of calculators for differences in η and φ (generated by VHDL Producer)
- the instantiations of conditions (generated by VHDL Producer)
- a boolean logic for Algorithms (generated by VHDL Producer)

Listing 3 contains the entity-declaration of the top-of-hierarchy file (`gtl_module.vhd`).

Listing 3: Entity declaration of `gtl_module.vhd`

```
entity gtl_module is
    port(
        lhc_clk : in std_logic;
        eg_data : in calo_objects_array(0 to NR_EG_OBJECTS-1);
        jet_data : in calo_objects_array(0 to NR_JET_OBJECTS-1);
        tau_data : in calo_objects_array(0 to NR_TAU_OBJECTS-1);
```

```
        ett_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        ht_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        etm_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        htm_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
--
    ************************************************************************************
-- HB 2016-04-18: updates for "min bias trigger" objects (quantities) for Low-
    pileup-run May 2016
        mbt1hfp_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        mbt1hfm_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        mbt0hfp_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        mbt0hfm_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
-- HB 2016-06-07: inserted new esums quantities (ETTEM and ETMHF).
        ettem_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        etmhf_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
-- HB 2016-09-16: inserted HTMHF and TOWERCNT
        htmhf_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        towercount_data : in std_logic_vector(MAX_TOWERCOUNT_BITS-1 downto 0);
-- HB 2018-08-06: inserted signals for "Asymmetry" and "Centrality" (included in
    esums data structure).
        asymet_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        asymht_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        asymethf_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        asymhthf_data : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        centrality_data : in std_logic_vector(NR_CENTRALITY_BITS-1 downto 0);
--
    ************************************************************************************

        muon_data : in muon_objects_array(0 to NR_MUON_OBJECTS-1);
        external_conditions : in std_logic_vector(NR_EXTERNAL_CONDITIONS-1 downto
            0);
        algo_o : out std_logic_vector(NR_ALGOS-1 downto 0));
end gtl_module;
```

3.3.2 Package module

All the declarations for arrays ('type'), parameters ('constant') and look-up-tables ('constant') used in modules are available in `gtl_pkg.vhd` package-file.

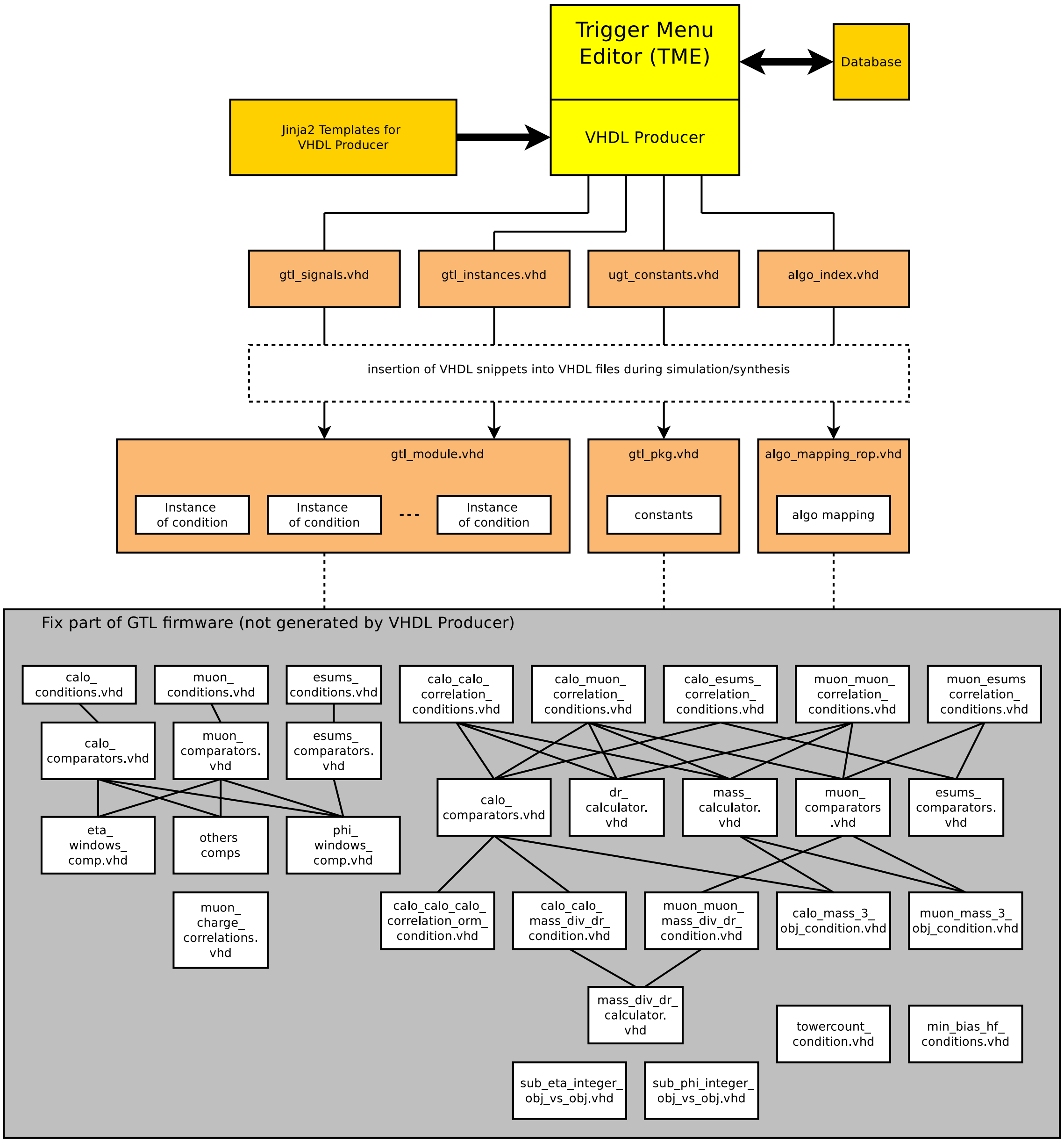


Figure 10: VHDL file generation by VHDL Producer

3.4 μGTL structure

3.4.1 Data ±2bx

The μGTL input data flow through a register pipeline of four stages. With those data it is possible to have conditions with objects from different bunch-crossings (within ±2 bunch-crossings), e.g. for Correlation conditions.
See Figure 11 for a scheme of μGTL pipeline structure. The data "data_p_1bx" and "data_-p_2bx" occur 1 respectively 2 bunch-crossings after data for a certain bunch-crossing, therefore we got 2 bunch-crossings of latency from those data. The data "data_m_1bx" and "data_m_2bx" have no influence on latency, because coming before data for a certain bunch-crossing.

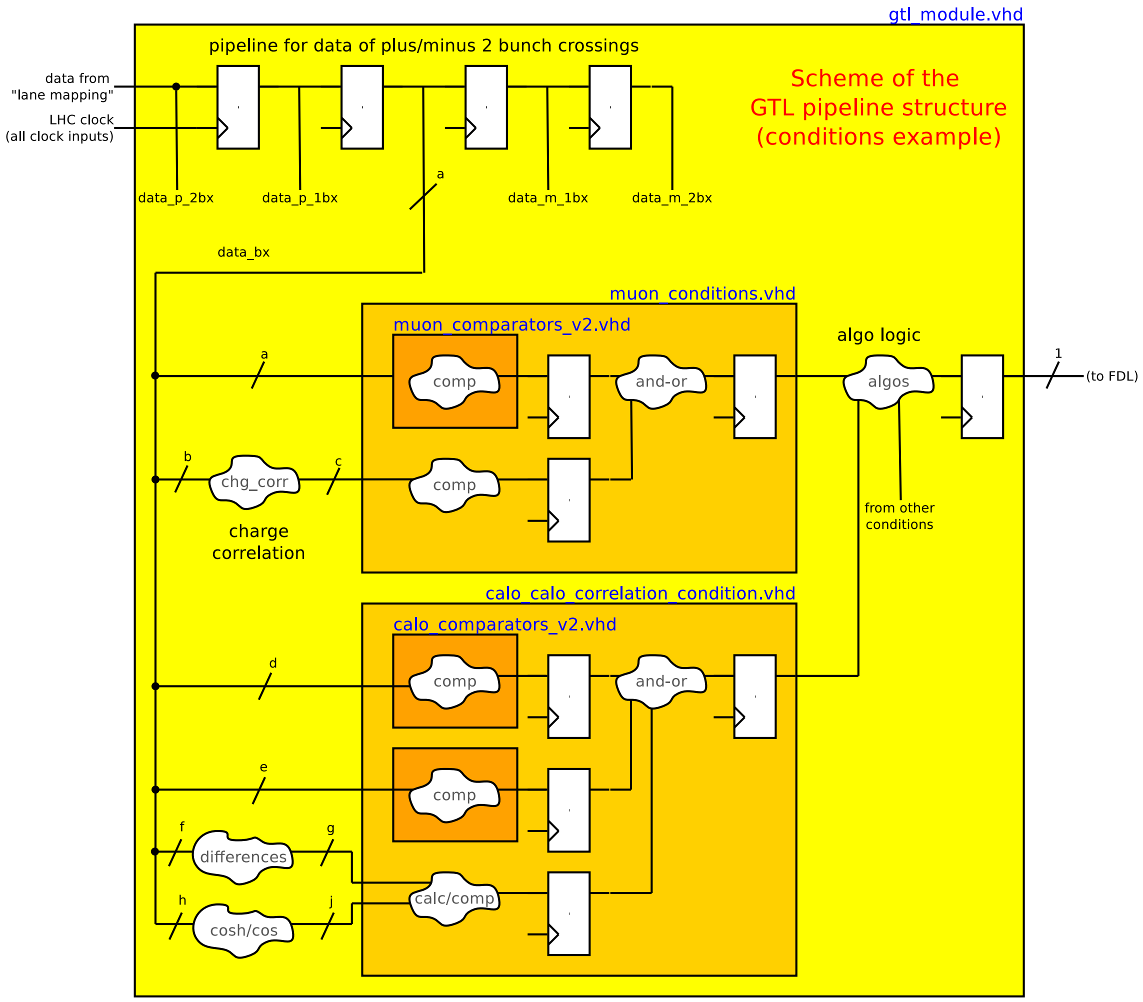


Figure 11: Scheme of μGTL pipeline structure

3.4.2 Calculation of differences in η and φ

Some condition types namely correlation conditions uses differences in η and φ to make the decision. Therefore these differences are calculated out of these conditions, because the differences can be used several times in different condition types. The differences in η and φ are calculated in bins. These differences in bins are converted to numbers (by LUTs), which represents values of differences (multiples of units in η and φ). Differences in φ are provided by module `sub_phi_integer_obj_vs_obj.vhd`, which instantiates the module `sub_unsigned_phi.vhd` as many times as the numbers of both objects determine.
In the module `sub_unsigned_phi.vhd` a calculation of a difference of two objects is done, both objects must have the same resolution, namely the higher one. The result is the absolute value of the difference. There are two differences in φ, one "clockwise" and one "anti-clockwise". For the final result the smaller difference is taken.
Differences in η are provided by module `sub_eta_integer_obj_vs_obj.vhd`, which instantiates the module `sub_unsigned_eta.vhd` as many times as the numbers of both objects determine.
In the module `sub_unsigned_eta.vhd` a calculation of a difference of two objects is done with a signed subtraction, because of the Two's Complement notation of η values. The result is the absolute value of the difference.

3.4.3 Calorimeter conditions

3.4.3.1 Calorimeter data

The calorimeter trigger processing identifies **electron/γ, jet and tau** objects and **energy sum quantities**.

electron/γ:
Twelve objects are passed to the μGT for each event.
For each selected object, the Calo-Layer2 sends parameters for E_{T} and for position and quality information - encoded in 32 bits:

- 9 bits E_{T}, range = 0..255 GeV (HW index = 0..0x1FF), step = 0.5, the highest bin will mark an overflow (HW index 0x1FF): meaning has to be defined
- 8 (7+1 sign) bits pseudo-rapidity (η) position, range = -3.0 to 3.0, step = 0.087/2, linear scale, 138 bins (HW index = 0xBC..0x44)
- 8 bits azimuth angle (φ) position, range = 2π, step $\approx 2\pi/144$ ($\widehat{=}2.5°$), 144 bins (HW index = 0..0x8F), HW index starting at 0° (anti-clockwise)
- 2 bits isolation (meaning not defined yet!)
- 5 bits quality and spare (not defined yet!)

The data structure of an electron/γ object (bits 27..31 are not defined yet, reserved for quality, ...):

31 27	26 25	24 17	16 9	8 0
qual/spare	iso	φ	η	E_{T}

jet:
Twelve objects are passed to the μGT for each event.
For each selected object, the Calo-Layer2 sends parameters: E_{T}, for position and quality information - encoded in 32 bits:

- 11 bits E_{T}, range = 0..1023 GeV (HW index = 0..0x7FF), step = 0.5, the highest bin will mark an overflow (HW index 0x7FF): meaning has to be defined
- 8 (7+1 sign) bits pseudo-rapidity (η) position, range = -5.0 to 5.0, step = 0.087/2, linear scale, 230 bins (HW index = 0x8E..0x72)
- 8 bits azimuth angle (φ) position, range = 2π, step $\approx 2\pi/144$ ($\widehat{=}2.5°$), 144 bins (HW index = 0..0x8F), HW index starting at 0° (anti-clockwise)
- 5 bits quality and spare (not defined yet!)

The data structure of a jet object (bits 27..31 are not defined yet, reserved for quality, ...):

31 27	26 19	18 11	10 0
iso/qu/sp	φ	η	E_{T}

tau:
Twelve objects are passed to the μGT for each event.
For each selected object, the Calo-Layer2 sends parameters for E_{T} and for position and quality information - encoded in 32 bits:

- 9 bits E_{T}, range = 0..255 GeV (HW index = 0..0x1FF), step = 0.5, the highest bin will mark an overflow (HW index 0x1FF): meaning has to be defined
- 8 (7+1 sign) bits pseudo-rapidity (η) position, range = -3.0 to 3.0, step = 0.087/2, linear scale, 138 bins (HW index = 0xBC..0x44)
- 8 bits azimuth angle (φ) position, range = 2π, step $\approx 2\pi/144$ ($\widehat{=}2.5°$), 144 bins (HW index = 0..0x8F), HW index starting at 0° (anti-clockwise)
- 2 bits isolation (meaning not defined yet!)
- 5 bits quality and spare (not defined yet!)

The data structure of a tau object (bits 27..31 are not defined yet, reserved for quality, ...):

31 27	26 25	24 17	16 9	8 0
qual/spare	iso	φ	η	E_{T}

Table 7: η scale of electron/γ and tau

HW index	**η range**	**η bin**
0x44	68∗0.087/2 to 69∗0.087/2	68
...	...	...
0x01	0.087/2 to 2∗0.087/2	1
0x00	0 to 0.087/2	0
0xFF	0 to -0.087/2	-1
0xFE	-0.087/2 to -2∗0.087/2	-2
...	...	...
0xBC	-68∗0.087/2 to -69∗0.087/2	-69

Table 8: η scale of jet

HW index	**η range**	**η bin**
0x72	114∗0.087/2 to 115∗0.087/2	114
...	...	...
0x01	0.087/2 to 2∗0.087/2	1
0x00	0 to 0.087/2	0
0xFF	0 to -0.087/2	-1
0xFE	-0.087/2 to -2∗0.087/2	-2
...	...	...
0x8E	-114∗0.087/2 to -115∗0.087/2	-115

The representation of the 8 bits (called "hardware index [HW index]") in η is expected as Two's Complement notation as shown in Table 8.

The representation of the 8 bits in φ is expected as shown in Table 9.

Table 9: φ scale of calorimeter objects

HW index	φ range	φ range [degrees]	φ bin
0x00	0 to $2\pi/144$	0 to 2.5	0
0x01	$2\pi/144$ to $2*2\pi/144$	2.5 to 5.0	1
...	...	...	...
0x8F	$143*2\pi/144$ to 2π	357.5 to 360	143

The representation of the 2 bits for isolation (e/γ and tau) is expected as shown in Table 10.

Table 10: Definition of e/γ and tau isolation bits

bits [26..25]	definition
00	not isolated
01	isolated
10	TBD
11	TBD

3.4.3.2 Calorimeter conditions definition

A condition consists of calorimeter objects as input data and a set of requirements, which contain the requirements to be complied.

The requirement for calorimeter conditions contains:
one threshold for E_{T}, ranges for η, φ LUTs for isolation and differences in η and φ. In addition the selection of the "relative bx" of objects is done in the requirement.
The condition is complied, if every comparison between object parameters and requirements is valid for the following equation:

- E_{T} greater-equal (or equal) threshold
- η in range
- φ in range
- isolation as requested (for electron/γ and tau)

Additional comparisons for "quality information" could be part of the equation - but not defined yet.

There are different types of calorimeter conditions implemented, depending of how many objects have to comply the requirements.

- "Quad objects requirements condition": this condition type consists of requirements for 4 different trigger objects of the same object type. For each object the requirements can be different. To fulfill this condition, there must exist at least one set of 4 different objects, each of which fulfills at least one of the requirements.
- "Triple objects requirements condition": this condition type consists of requirements for 3 different trigger objects of the same object type. For each object the requirements can be different. To fulfill this condition, there must exist at least one set of 3 different objects, each of which fulfills at least one of the requirements.
- "Double objects requirements condition": this condition type consists of requirements for 2 different trigger objects of the same object type. For each object the requirements can be different. To fulfill this condition, there must exist at least one set of 2 different objects, each of which fulfills at least one of the requirements.[1]
- "Single object requirement condition": this condition type consists of one requirement for one trigger object of a given object type. To fulfill this condition, there must exist at least one object which fulfills the requirement.

The selection of the mode of E_{T}-comparator (greater/equal or equal), the E_{T}-threshold-value, ranges for η and φ set with thresholds, LUTs for isolation and ranges for differences in η and φ set with thresholds are fixed values given by VHDL Producer for every Trigger Menu. The objects have to be of same type and same bunch-crossing.

[1] "Double objects requirements condition with spatial correlation" not used anymore, replaced by Correlation conditions

3.4.3.2.1 Calorimeter conditions module

The module for conditions with calorimeter objects (`calo_conditions.vhd`) instantiates the calorimeter comparators module (`calo_comparators.vhd`) as many times as the numbers of objects and requirements determine. Depending on the condition-type, different and-or-structures of object vs. requirement are selected. The selection of condition-type and the number of objects is done by parameters in the generic interface list of the module (see Listing 4, see also the explanations below).
For comparison in η, φ and the differences in η and φ, "window"-comparators are used.
In the calorimeter conditions module a cut for two-body pt calculation can be selected (see 3.4.9.1.4). Therefore a threshold value for two-body pt is required.

Listing 4: Entity declaration of `calo_conditions.vhd`

```
entity calo_conditions is
     generic(
        calo_object_slice_1_low: natural;
        calo_object_slice_1_high: natural;
        calo_object_slice_2_low: natural;
        calo_object_slice_2_high: natural;
        calo_object_slice_3_low: natural;
        calo_object_slice_3_high: natural;
        calo_object_slice_4_low: natural;
        calo_object_slice_4_high: natural;
        nr_templates: positive;
        et_ge_mode: boolean;
        obj_type : natural := EG_TYPE;
        et_thresholds: calo_templates_array;
        nr_eta_windows : calo_templates_natural_array;
        eta_w1_upper_limits: calo_templates_array;
        eta_w1_lower_limits: calo_templates_array;
        eta_w2_upper_limits: calo_templates_array;
        eta_w2_lower_limits: calo_templates_array;
        eta_w3_upper_limits: calo_templates_array;
        eta_w3_lower_limits: calo_templates_array;
        eta_w4_upper_limits: calo_templates_array;
        eta_w4_lower_limits: calo_templates_array;
        eta_w5_upper_limits: calo_templates_array;
        eta_w5_lower_limits: calo_templates_array;
        phi_full_range : calo_templates_boolean_array;
        phi_w1_upper_limits: calo_templates_array;
        phi_w1_lower_limits: calo_templates_array;
        phi_w2_ignore : calo_templates_boolean_array;
        phi_w2_upper_limits: calo_templates_array;
        phi_w2_lower_limits: calo_templates_array;
        iso_luts: calo_templates_iso_array;

        twobody_pt_cut: boolean := false;
        pt_width: positive := 1;
        pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
            downto 0) := (others => '0');
        sin_cos_width: positive := 1;
        pt_sq_sin_cos_precision : positive := 1
    );
```

```
    port(
        clk: in std_logic;
        data_i: in calo_objects_array;
        condition_o: out std_logic;
        pt : in diff_inputs_array(0 to MAX_CALO_OBJECTS-1) := (others => (others
            => '0'));
        cos_phi_integer : in sin_cos_integer_array(0 to MAX_CALO_OBJECTS-1) := (
            others => 0);
        sin_phi_integer : in sin_cos_integer_array(0 to MAX_CALO_OBJECTS-1) := (
            others => 0)
    );
end calo_conditions;
```

Table 11: Explanation of Listing 4

Item	Explanation
calo_object_slice_1_low	low value of slice for object 1.
calo_object_slice_1_high	high value of slice for object 1.
calo_object_slice_2_low	low value of slice for object 2.
calo_object_slice_2_high	high value of slice for object 2.
calo_object_slice_3_low	low value of slice for object 3.
calo_object_slice_3_high	high value of slice for object 3.
calo_object_slice_4_low	low value of slice for object 4.
calo_object_slice_4_high	high value of slice for object 4.
nr_templates	valid values are 1 (for single), 2 (double), 3 (triple) and 4 (quad) - depending on condition type.
et_ge_mode	'mode-selection' for the E_T comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
obj_type	valid strings are 'EG_TYPE', 'JET_TYPE', and 'TAU_TYPE'.
et_thresholds	array of four threshold values for comparison in E_T (four thresholds, because of max. 4 requirements).
nr_eta_windows	array of four integer values for number of η cuts.
eta_w1_upper_limits	array of four "upper limits" of "window"-comparator 1 for η.
eta_w1_lower_limits	array of four "lower limits" of "window"-comparator 1 for η.
eta_w2_upper_limits	array of four "upper limits" of "window"-comparator 2 for η.
eta_w2_lower_limits	array of four "lower limits" of "window"-comparator 2 for η.
eta_w3_upper_limits	array of four "upper limits" of "window"-comparator 3 for η.
eta_w3_lower_limits	array of four "lower limits" of "window"-comparator 3 for η.
eta_w4_upper_limits	array of four "upper limits" of "window"-comparator 4 for η.
eta_w4_lower_limits	array of four "lower limits" of "window"-comparator 4 for η.
eta_w5_upper_limits	array of four "upper limits" of "window"-comparator 5 for η.
eta_w5_lower_limits	array of four "lower limits" of "window"-comparator 5 for η.
phi_full_range	array of four boolean to set full range of φ.
phi_w1_upper_limits	array of four "upper limits" of "window"-comparator 1 for φ.
phi_w1_lower_limits	array of four "lower limits" of "window"-comparator 1 for φ.
phi_w2_ignore	array of four boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limits	array of four "upper limits" of "window"-comparator 2 for φ.
phi_w2_lower_limits	array of four "lower limits" of "window"-comparator 2 for φ.
iso_luts	array of four LUTs for comparison of isolation.
twobody_pt_cut	valid strings are 'true' and 'false' (type is boolean).
pt_width	vector length of pt value for two-body pt.
pt_sq_threshold_vector	hex value for threshold of two-body pt comparison (value for pt square).
sin_cos_width	vector length of sine and cosine.
pt_sq_sin_cos_precision	precision of sine and cosine calculation in LUTs.
clk	clock input (LHC clock).
data_i	data, structure defined in `obj_type`.
condition_o	output of condition (routed to Algorithms logic, see 3.4.11).
pt	pt value for two-body pt.
cos_phi_integer	interger value of cosine for two-body pt.
sin_phi_integer	interger value of sine for two-body pt.

3.4.3.2.2 Calorimeter Overlap Remover conditions module

The Calorimeter Overlap Remover conditions consits of a Calorimeter condition (3.4.3.2.1) and a single condition for a different calo object type. One or more correlation cut(s) ($\Delta\eta$, $\Delta\varphi$ and ΔR - 3.4.9) for overlap removal is required between different calo object types. Overlap Remover conditions `calo_conditions_orm.vhd` are implemented only for calo object types.

3.4.3.2.3 Calorimeter conditions module - template for VHDL-Producer

See in Chapter 3.5.4 and in Listing 13 for a VHDL-template for VHDL-Producer of instantiating a calorimeter condition (`calo_conditions.vhd`).

3.4.3.2.4 Calorimeter comparators module

A comparator between the energy (E_{T}) and a threshold (et_threshold) and a comparison in η with five "window"-comparators and φ with two "window"-comparators is done in this basic module. The values for E_{T} threshold, the 'mode-selection' for the E_{T} comparator and the "limits" of the "window"-comparators is given in the generic interface list of the module. Additionally the data-structure of input data (data_i in port interface list) is provided as a record in this list. The output signal of the module is in high state, if all comparisons are true.
The comparison in η is done with five "window"-comparators, so one gets max. five ranges for η. The η value (HW index) has a Two's Complement notation, the comparisons is done signed. Number of windows is given for η.
The comparison in φ is done with two "window"-comparators, so one gets two ranges for φ. The comparisons is done unsigned. There are two flags, one for "full-range" and one for "ignore-second-window" for the selection of the ranges.
There are two cases how the limits of one "window"-comparator could be set (see also Figure 12 and Listing 5):

- Upper limit is less than lower limit => φ range between the limits, including the φ bin with value = 0 (HW index).
- Upper limit is greater/equal than lower limit => φ range between the limits, not including the φ bin with value = 0 (HW index).

The comparison of isolation (for electron/γ and tau) is done with LUTs.

The values of η and φ have to be inside of only one of the required ranges ("or").

The comparison of isolation (for electron/γ and tau) is done with LUTs (see Table 12). Only the least significant 4 bits of LUT are used, because currently 2 isolation bits are defined.

Table 12: LUT contents for isolation comparison of electron/γ and tau objects

LUT content (16 bits)	isolation bits [26..25]	trigger
X"0"	xx	no trigger
X"1"	00	trigger on isolation bits = 00
X"2"	01	trigger on isolation bits = 01
X"3"	00 or 01	trigger on isolation bits = 00 or 01
X"4"	10	trigger on isolation bits = 10
X"5"	00 or 10	trigger on isolation bits = 00 or 10
X"6"	01 or 10	trigger on isolation bits = 01 or 10
X"7"	00 or 01 or 10	trigger on isolation bits = 00 or 01 or 10
X"8"	11	trigger on isolation bits = 11
X"9"	00 or 11	trigger on isolation bits = 00 or 11
X"A"	01 or 11	trigger on isolation bits = 01 or 11
X"B"	00 or 01 or 11	trigger on isolation bits = 00 or 01 or 11
X"C"	10 or 11	trigger on isolation bits = 10 or 11
X"D"	00 or 10 or 11	trigger on isolation bits = 00 or 10 or 11
X"E"	01 or 10 or 11	trigger on isolation bits = 01 or 10 or 11
X"F"	00 or 01 or 10 or 11	trigger on isolation bits = 00 or 01 or 10 or 11 (= "ignore" isolation)

Listing 5: VHDL code of "window"-comparator in φ

```
phi_comp_w1 <= '1' when phi_w1_upper_limit < phi_w1_lower_limit and
                (phi <= phi_w1_upper_limit or phi >= phi_w1_lower_limit) else
               '1' when phi_w1_upper_limit >= phi_w1_lower_limit and
                (phi <= phi_w1_upper_limit and phi >= phi_w1_lower_limit)
                else '0';
```

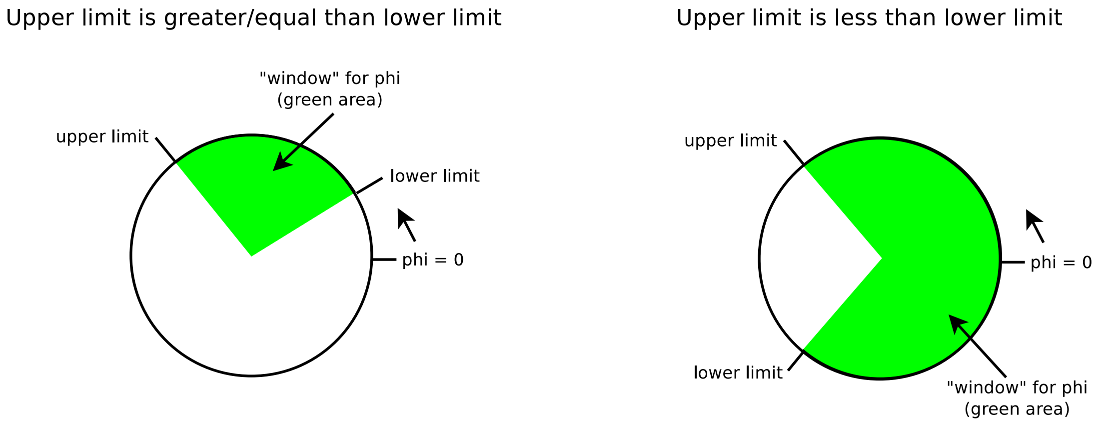


Figure 12: Setting the limits for "window"-comparators for φ

3.4.4 Energy sum quantities conditions

energy sum quantities:
Consists of following quantities (naming convention see 6):

- **ET**
- **HT**
- ET_{miss}
- HT_{miss}
- **ETTEM**
- $\mathbf{ET}^{HF}_{miss}$
- $\mathbf{HT}^{HF}_{miss}$
- **ASYMET**
- **ASYMHT**
- **ASYMETHF**
- **ASYMHTHF**
- **CENT0**
- ..
- **CENT7**

3.4.4.1 Energy sum quantities data

Calo-Layer2 sends 6 frames (each 32 bits) with Energy sum quantities containing the following information:

- E_{T}, 12 bits, range = 0..2047 GeV (HW index = 0..0xFFF), step = 0.5, the highest bin will mark an overflow (HW index 0xFFF): meaning has to be defined
- azimuth angle (φ) position, 8 bits, range = 2π, step $\approx 2\pi/144$ ($\hat{=}$2.5°), 144 bins (HW index = 0..0x8F), HW index starting at 0° (anti-clockwise)
- "Towercount", 13 bits, range = 0..8191
- "Minimum bias", 4 bits, range = 0..15
- "Asymmetry", 8 bits, range = 0..255 (used 0..100)
- "Centrality", 8 bits, used as signals

Frame0: The data structure of "total Et" (ET) quantity [including "total Et from ECAL only" (ETTEM) and "minimum bias HF+ threshold 0" bits]:

31 – 28	27 – 24	23 – 12	11 – 0
MBT0HFP	*spare*	E_{T} *[ETTEM]*	E_{T} *[ET]*

Frame1: The data structure of "total calibrated Et in jets" (HT) quantity [including "tower-count" and "minimum bias HF- threshold 0" bits]:

31 – 28	27 – 25	24 – 12	11 – 0
MBT0HFM	*spare*	*TOWERCOUNT*	E_{T}

Frame2: The data structure of "missing Et" (ET_{miss}) quantity [including "Asymmetry" ASYMET and "minimum bias HF+ threshold 1" bits]:

31 – 28	27 – 20	19 – 12	11 – 0
MBT1HFP	*ASYMET*	φ	E_{T}

Frame3: The data structure of "missing Ht" (HT_{miss}) quantity [including "Asymmetry" ASYMHT and "minimum bias HF- threshold 1" bits]:

31 – 28	27 – 20	19 – 12	11 – 0
MBT1HFM	*ASYMHT*	φ	E_{T}

Frame4: The data structure of "missing Et including HF" (ET_{miss}^{HF}) quantity [including "Asymmetry" ASYMETHF and "Centrality" bits (3:0)]:

31 – 28	27 – 20	19 – 12	11 – 0
CENT[3:0]	*ASYMETHF*	φ	E_{T}

Frame5: The data structure of "missing Ht including HF" (HT_{miss}^{HF}) quantity [including "Asymmetry" ASYMHTHF and "Centrality" bits (7:4)]:

31 – 28	27 – 20	19 – 12	11 – 0
CENT[7:4]	*ASYMHTHF*	φ	E_{T}

3.4.4.2 Energy sum quantities conditions module (including Asymmetry conditions)

For the entity-declaration of `esums_conditions.vhd`, see Listing 6.

Listing 6: Entity declaration of esums_conditions.vhd

```
entity esums_conditions is
    generic     (
        et_ge_mode : boolean;
        obj_type : natural := ETT_TYPE; -- ett=0, ht=1, etm=2, htm=3
        et_threshold: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0);
        phi_full_range : boolean;
        phi_w1_upper_limit: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0)
            ;
        phi_w1_lower_limit: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0)
            ;
        phi_w2_ignore : boolean;
        phi_w2_upper_limit: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0)
            ;
        phi_w2_lower_limit: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0)
   );
    port(
        clk : in std_logic;
        data_i : in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        condition_o : out std_logic
    );
end esums_conditions;
```

Table 13: Explanation of Listing 6

Item	Explanation
et_ge_mode	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
obj_type	valid strings are 'ETT_TYPE', 'HTT_TYPE', 'ETM_TYPE', 'HTM_-TYPE' and 'ETMHF_TYPE'.
et_threshold	threshold value for comparison in E_{T}. The size of the std_logic_vector depends on the number of E_{T} bits.
phi_full_range	boolean to set full range of φ.
phi_w1_upper_limits	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limits	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limits	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limits	"lower limit" of "window"-comparator 2 for φ.
clk	clock input (LHC clock).
data_i	input data, structure defined in obj_type.
condition_o	output of condition (routed to Algorithms logic, see 3.4.11).

A comparator between E_{T} and a threshold (et_threshold) and, depending on object type, a comparison in φ with two "window"-comparators is done in this module. The value for E_{T} threshold, the 'mode-selection' for the E_{T} comparator and the limits for the "window"-comparators are given in the generic interface list of the module. The selection whether a comparison in φ is part of the condition is done with the value of the generic parameter 'obj_type' ('ETM_TYPE', 'ETMHF_TYPE', 'HTM_TYPE' and 'HTMHF_TYPE' force a comparison). The comparison in φ is done in the same way as for calorimeter conditions (see 3.4.3.2.4). Additionally the data-structure of input data (data_i in port interface list)

is provided as a record in this list. The output signal of the module is in high state, if all comparisons are true.
Data for Asymmetry trigger are received on 4 frames on bits 27..20 (8 bits). For every type a comparision with an 8-bit threshold (greater-equal [or equal]) is done. Asymmetry data are interpreted as counts.

3.4.4.3 Energy sum quantities conditions module - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `esums_conditions.vhd` is given below (see Listing 14).

3.4.5 Minimum bias trigger conditions

Data for Minimum bias trigger are received on the 4 MSBs of 4 frames used for Energy sum quantities (see 3.4.4).

- MBT0HFP: "minimum bias HF+ threshold 0" bits
- MBT0HFM: "minimum bias HF- threshold 0" bits
- MBT1HFP: "minimum bias HF+ threshold 1" bits
- MBT1HFM: "minimum bias HF- threshold 1" bits

In minimum bias trigger conditions module (`min_bias_hf_conditions.vhd`) there is a comparision with a 4-bit threshold (greater-equal [or equal]).

3.4.6 Towercount condition

Data for Towercount trigger (number of firing HCAL towers) are received on frame HT (see 3.4.4) on bits 24..12 (13 bits) of HT data structure.
In towercount condition module (`towercount_condition.vhd`) there is a comparision with a 13-bit threshold (greater-equal [or equal]).

3.4.7 Centrality condition

Centrality bits used as a signals for triggers (similar to external signals).

3.4.8 Muon conditions

3.4.8.1 Muon data

Eight Muon objects are provided by Global Muon Trigger. One Muon object has a 64 bits data structure with parameters for p_T, for position, charge, quality and isolation information:

- 10 bits azimuth angle (φ) position, range = 2π, step $\approx 2\pi/576$ ($\hat{=}0.625°$), 576 bins (HW index = 0..0x23F), HW index starting at 0° (anti-clockwise)
- 9 bits p_{T}, range = 0..255 GeV (HW index = 0..0x1FF), step = 0.5, the highest bin will mark an overflow (HW index 0x1FF): meaning has to be defined
- 4 bits quality, 16 types for quality (meaning not defined yet!)
- 9 (8+1 sign) bits pseudo-rapidity (η) position, range = -2.45 to 2.45, step = 0.087/8, linear scale, 452 bins (-225..225, HW index = 0x11F..0x0E1)
- 2 bits isolation, 4 types for isolation (meaning not defined yet!)
- 1 bit charge sign, charge sign = '0' means "positive" charge, charge sign = '1' means "negative" charge
- 1 bit charge valid (='1' means "valid")
- 7 index bits
- 10 bits azimuth angle (φ) position, raw data
- 8 bits unconstrained p_{T}, range = 0..255 GeV (HW index = 0..0xFF), step = 1.0, the highest bin will mark an overflow (HW index 0xFF)
- 1 spare bit
- 2 bits impact parameter

The data structure of a muon object (64 bits - bit 34 = charge sign, bit 35 = charge valid, bit 61 is a spare bit, bit 63..62 = impact parameter):

63 62	61	60 53	52 43	42 36	35 34	33 32
imp para	r	unconst.p_{T}	φ (out)	index bits	ch	iso

31 23	22 19	18 10	9 0
η (extrapol.)	qual	p_{T}	φ (extrapol.)

The representation of the 9 bits (called "hardware index [HW index]") in η is expected as Two's Complement notation as shown in Table 14.
The central value of the bin 0 (-0.010875/2 to +0.010875/2) = 0.0, the left edge of the bins will range from $-255 \times 0.010875 - 0.010875/2 = -2.7785625$ to $+255 \times 0.010875 - 0.010875/2 = 2.7676875$. The central value of the bins will range between ± 2.773125 . The physical η range of the muon detectors is about ± 2.45, so that not all possible η bins will be used.

The representation of the 10 bits in φ is expected as shown in Table 15.

The representation of the 4 bits for quality is expected as shown in Table 16.

Table 14: η scale of muon objects

HW index	η range	η bin
0x0E1	224.5∗0.087/8 to 225.5∗0.087/8	225
0x0E0	223.5∗0.087/8 to 224.5∗0.087/8	224
...	...	...
0x001	0.5∗0.087/8 to 1.5∗0.087/8	1
0x000	0.5∗-0.087/8 to 0.5∗0.087/8	0
0x1FF	0.5∗-0.087/8 to 1.5∗-0.087/8	-1
0x1FE	1.5∗-0.087/8 to -2.5∗0.087/8	-2
...	...	...
0x11F	-224.5∗0.087/8 to -225.5∗0.087/8	-225

Table 15: φ scale of muon objects

HW index	φ range	φ range [degrees]	φ bin
0x000	0 to $2\pi/576$	0 to 0.625	0
0x001	$2\pi/576$ to $2*2\pi/576$	0.625 to 1.250	1
...	...	...	...
0x23F	$575*2\pi/576$ to 2π	359.375 to 360	575

The representation of the 2 bits for isolation is expected as shown in Table 18.

The representation of the 2 bits for impact parameter is expected as shown in Table 18.

Table 16: Definition of muon quality bits

bits [22..19]	definition
0000	quality "level 0"
0001	quality "level 1"
0010	quality "level 2"
0011	quality "level 3"
0100	quality "level 4"
0101	quality "level 5"
0110	quality "level 6"
0111	quality "level 7"
1000	quality "level 8"
1001	quality "level 9"
1010	quality "level 10"
1011	quality "level 11"
1100	quality "level 12"
1101	quality "level 13"
1110	quality "level 14"
1111	quality "level 15"

Table 17: Definition of muon isolation bits

bits [33..32]	definition
00	not isolated
01	isolated
10	TBD
11	TBD

Table 18: Definition of muon impact parameter bits

bits [63..62]	definition
00	TBD
01	TBD
10	TBD
11	TBD

3.4.8.2 Muon charge correlation module

For definition of muon charge, see 3.4.8.
In the muon charge correlation module (`muon_charge_correlations.vhd`), the charge correlations are made for different muon conditions-types. The module is instantiated in the top-of-hierarchy module (`gtl_module.vhd`) and not inside of a muon conditions module. The charges of objects (number of objects depends on muon condition type) are compared to get "like sign charge" ("LS") or "opposite sign charge" ("0S"), "LS" means that the charges (charge sign) of objects are the same, "0S" means that at least one object has different charge than the others. This information is used in all instatiated muon conditions. There is no charge correlation for single type conditions.
In all cases the "charge valid" bit of the objects must be set.
In TME one can select "LS", "0S" or ignore for charge correlation in muon conditions.

Table 19: Muon charge correlation - Double Muon

x x	I ignore (charge x = +, -, I)
+ +	LS both positive muons
− −	LS both negative muons
I I	LS both muons with the same sign, positive or negative
+ −	OS two muons of opposite sign
− +	OS idem
I I	OS idem

Table 20: Muon charge correlation - Triple Muon

x x x	I ignore (charge x = +, -, I)
+ + +	LS three muons of positive charge
− − −	LS three muons of negative charge
I I I	LS three muons of the same sign (positive or negative)
+ + −	OS a pair plus a positive muon
+ − −	OS a pair plus a negative muon
+ − I	OS a pair plus a negative or positive muon

Table 21: Muon charge correlation - Quad Muon

x x x x	I ignore (charge x = +, -, I)
+ + + +	LS four muons of positive charge
− − − −	LS four muons of negative charge
I I I I	LS four muons of the same sign (positive or negative)
+ + + −	OS a pair plus two positive muons
+ + − −	OS two pairs
+ − − −	OS a pair plus two negative muons
+ − I I	OS a pair plus two negative or positive muons

3.4.8.3 Muon conditions definition

A condition consists of input-data and a set of requirements, which contain the requirements to be complied.

The requirement for muon conditions contains:
a threshold for p_{T}, a threshold for unconstrained p_{T}, ranges for η and φ, a LUT for quality, a LUT for isolation, a requsted charge, a LUT for impact parameter. The condition is complied, if every comparison between object parameters and requirements is valid for the following object cuts (only for requested cuts):

- p_{T} greater-equal (or equal) threshold
- unconstrained p_{T} greater-equal (or equal) threshold
- η in range
- φ in range
- requested charge
- quality LUT
- iso LUT
- impact parameter LUT

There are different types of calorimeter conditions implemented, depending of how many objects have to comply the requirements.

- "Quad objects requirements condition": this condition type consists of requirements for 4 different trigger objects of the same object type. For each object the requirements can be different. To fulfill this condition, there must exist at least one set of 4 different objects, each of which fulfills at least one of the requirements.
- "Triple objects requirements condition": this condition type consists of requirements for 3 different trigger objects of the same object type. For each object the requirements can be different. To fulfill this condition, there must exist at least one set of 3 different objects, each of which fulfills at least one of the requirements.
- "Double objects requirements condition": this condition type consists of requirements for 2 different trigger objects of the same object type. For each object the requirements can be different. To fulfill this condition, there must exist at least one set of 2 different objects, each of which fulfills at least one of the requirements.[2]
- "Single object requirement condition": this condition type consists of one requirement for one trigger object of a given object type. To fulfill this condition, there must exist at least one object which fulfills the requirement.

[2] "Double objects requirements condition with spatial correlation" not used anymore, replaced by Correlation conditions

In addition requested charge correlation must be matched (except for "Single object requirement condition", there is no charge correlation). The calculation of charge correlations is done in an own module in the top-of-hierarchy module (`gtl_module.vhd`).

3.4.8.3.1 Muon conditions module

A module for conditions with muon objects (`muon_conditions.vhd`) instantiates the muon comparators module (`muon_comparators.vhd`) as many times as the numbers of objects and requirements determine. Depending on the condition-type different and-or-structures of object vs. requirement are selected. The selection of condition-type and the number of objects is done by parameters in the generic interface list of the module (see the following VHDL entity definition in Listing 7).

Listing 7: Entity declaration of `muon_conditions.vhd`

```vhdl
entity muon_conditions is
    generic (
        muon_object_slice_1_low: natural;
        muon_object_slice_1_high: natural;
        muon_object_slice_2_low: natural;
        muon_object_slice_2_high: natural;
        muon_object_slice_3_low: natural;
        muon_object_slice_3_high: natural;
        muon_object_slice_4_low: natural;
        muon_object_slice_4_high: natural;
        nr_templates: positive;
        pt_ge_mode : boolean;
        pt_thresholds: muon_templates_array;
        nr_eta_windows : muon_templates_natural_array;
        eta_w1_upper_limits: muon_templates_array;
        eta_w1_lower_limits: muon_templates_array;
        eta_w2_upper_limits: muon_templates_array;
        eta_w2_lower_limits: muon_templates_array;
        eta_w3_upper_limits: muon_templates_array;
        eta_w3_lower_limits: muon_templates_array;
        eta_w4_upper_limits: muon_templates_array;
        eta_w4_lower_limits: muon_templates_array;
        eta_w5_upper_limits: muon_templates_array;
        eta_w5_lower_limits: muon_templates_array;
        phi_full_range : muon_templates_boolean_array;
        phi_w1_upper_limits: muon_templates_array;
        phi_w1_lower_limits: muon_templates_array;
        phi_w2_ignore : muon_templates_boolean_array;
        phi_w2_upper_limits: muon_templates_array;
        phi_w2_lower_limits: muon_templates_array;
        requested_charges: muon_templates_string_array;
        qual_luts: muon_templates_quality_array;
        iso_luts: muon_templates_iso_array;
        upt_cuts: muon_templates_boolean_array;
        upt_upper_limits: muon_templates_array;
        upt_lower_limits: muon_templates_array;
        ip_luts: muon_templates_ip_array;
        requested_charge_correlation: string(1 to 2);

        twobody_pt_cut: boolean := false;
        pt_width: positive := 1;
        pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
            downto 0) := (others => '0');
        sin_cos_width: positive := 1;
        pt_sq_sin_cos_precision : positive := 1

    );
    port(
        lhc_clk : in std_logic;
        data_i : in muon_objects_array;
        condition_o : out std_logic;
        ls_charcorr_double: in muon_charcorr_double_array := (others => (others
            => '0'));
        os_charcorr_double: in muon_charcorr_double_array := (others => (others
            => '0'));
```

```
        ls_charcorr_triple: in muon_charcorr_triple_array := (others => (others
            => (others => '0')));
        os_charcorr_triple: in muon_charcorr_triple_array := (others => (others
            => (others => '0')));
        ls_charcorr_quad: in muon_charcorr_quad_array := (others => (others => (
            others => (others => '0'))));
        os_charcorr_quad: in muon_charcorr_quad_array := (others => (others => (
            others => (others => '0'))));
        pt : in diff_inputs_array(0 to NR_MUON_OBJECTS-1) := (others => (others
            => '0'));
        cos_phi_integer : in sin_cos_integer_array(0 to NR_MUON_OBJECTS-1) := (
            others => 0);
        sin_phi_integer : in sin_cos_integer_array(0 to NR_MUON_OBJECTS-1) := (
            others => 0)
    );
end muon_conditions;
```

Table 22: Explanation of Listing 7

Item	Explanation
`muon_object_slice_1_low`	low value of slice for object 1.
`muon_object_slice_1_high`	high value of slice for object 1.
`muon_object_slice_2_low`	low value of slice for object 2.
`muon_object_slice_2_high`	high value of slice for object 2.
`muon_object_slice_3_low`	low value of slice for object 3.
`muon_object_slice_3_high`	high value of slice for object 3.
`muon_object_slice_4_low`	low value of slice for object 4.
`muon_object_slice_4_high`	high value of slice for object 4.
`nr_templates`	number of requirements, selector of condition-type. Valid values are 1, 2, 3 and 4.
`pt_ge_mode`	'mode-selection' for the p_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
`pt_thresholds`	array of four threshold values for comparison in pt (four threshold, because of max. 4 requirements).
`nr_eta_windows`	array of four integer values for number of η cuts.
`eta_w1_upper_limits`	array of four "upper limits" of "window"-comparator 1 for η.
`eta_w1_lower_limits`	array of four "lower limits" of "window"-comparator 1 for η.
`eta_w2_upper_limits`	array of four "upper limits" of "window"-comparator 2 for η.
`eta_w2_lower_limits`	array of four "lower limits" of "window"-comparator 2 for η.
`eta_w3_upper_limits`	array of four "upper limits" of "window"-comparator 3 for η.
`eta_w3_lower_limits`	array of four "lower limits" of "window"-comparator 3 for η.
`eta_w4_upper_limits`	array of four "upper limits" of "window"-comparator 4 for η.
`eta_w4_lower_limits`	array of four "lower limits" of "window"-comparator 4 for η.
`eta_w5_upper_limits`	array of four "upper limits" of "window"-comparator 5 for η.
`eta_w5_lower_limits`	array of four "lower limits" of "window"-comparator 5 for η.
`phi_full_range`	array of four boolean to set full range of φ.
`phi_w1_upper_limits`	array of four "upper limits" of "window"-comparator 1 for φ.
`phi_w1_lower_limits`	array of four "lower limits" of "window"-comparator 1 for φ.
`phi_w2_ignore`	array of four boolean to ignore "window"-comparator 2 for φ.
`phi_w2_upper_limits`	array of four "upper limits" of "window"-comparator 2 for φ.
`phi_w2_lower_limits`	array of four "lower limits" of "window"-comparator 2 for φ.
`requested_charges`	array of four strings for requested charge ("pos" means "positive charge", "neg" means "negative charge" and "ign" means "ignore charge").
`qual_luts`	array of four LUTs (16 bits) for quality.
`iso_luts`	array of four LUTs (4 bits) for isolation.
`upt_cuts`	array of four boolean for using unconstrained p_{T} cuts.
`upt_upper_limits`	array of four "upper limits" of unconstrained p_{T}.

Table 22: Explanation of Listing 7

Item	Explanation
upt_lower_limits	array of four "lower limits" of unconstrained p_{T}.
ip_luts	array of four LUTs (4 bits) for impact parameter.
requested_charge_correlation	string (2 characters) for requested charge correlation ("ls" means "like sign", "os" means "opposite sign" or "ig" means "ignore").
twobody_pt_cut	valid strings are 'true' and 'false' (type is boolean).
pt_width	vector length of pt value for two-body pt.
pt_sq_threshold_vector	hex value for threshold of two-body pt comparison (value for pt square).
sin_cos_width	vector length of sine and cosine.
pt_sq_sin_cos_precision	precision of sine and cosine calculation in LUTs.
lhc_clk	clock input (LHC clock).
data_i	input data, structure defined in d_s_i.
condition_o	output of condition (routed to Algorithms logic, see 3.4.11).
ls_charcorr_double	array of "like sign" charge correlation for double condition.
os_charcorr_double	array of "opposite sign" charge correlation for double condition.
ls_charcorr_triple	array of "like sign" charge correlation for triple condition.
os_charcorr_triple	array of "opposite sign" charge correlation for triple condition.
ls_charcorr_quad	array of "like sign" charge correlation for quad condition.
os_charcorr_quad	array of "opposite sign" charge correlation for quad condition.
pt	pt value for two-body pt.
cos_phi_integer	interger value of cosine for two-body pt.
sin_phi_integer	interger value of sine for two-body pt.

3.4.8.3.2 Muon conditions module - template for VHDL-Producer

See in Chapter 3.5 and in Listing 15 for a VHDL-template for VHDL-Producer of instantiating a muon condition (`muon_conditions.vhd`).

3.4.8.3.3 Muon comparators module

A comparator between p_{T} and a threshold (pt_threshold), a comparator between unconstrained p_{T} and a threshold (upt_threshold), a comparison in η with five "window"-comparators and φ with two "window"-comparators, a comparison of quality with LUT, a comparison of isolation with LUT and a comparison of the requested charge is done in this basic module. The values for p_{T} threshold, unconstrained p_{T} threshold, the 'mode-selection' for the p_{T} comparator, the "limits" of the "window"-comparators, the quality LUTs, the isolation LUTs and the requested charge is given in the generic interface list of the module. Additionally the data-structure of input data (data_i in port interface list) is provided as a record in this list. The output signal of the module is in high state, if all comparisons are true.
The comparison in η is done with five "window"-comparators, so one gets max. five ranges for η. The η value (HW index) has a Two's Complement notation, the comparisons is done signed. Number of windows is given for η.
The comparison in φ is done with two "window"-comparators, so one gets two ranges for φ. The comparisons is done unsigned. There are two flags, one for "full-range" and one for "ignore-second-window" for the selection of the ranges.
There are two cases how the limits of one "window"-comparator could be set (see also Figure 12 and Listing 5):

- Upper limit is less than lower limit => φ range between the limits, including the φ bin with value = 0 (HW index).
- Upper limit is greater/equal than lower limit => φ range between the limits, not including the φ bin with value = 0 (HW index).

The values of η and φ have to be inside of only one of the two required ranges ("or").

Charge valid and charge sign bits must be equal to the requested charge.
The comparison of quality is done with LUT. To ignore quality comparison, all bits in the LUT have to be '1'.

The comparison of isolation is done with LUT. To ignore isolation comparison, all bits in the LUT have to be '1' (see Table 24).

Table 23: LUT contents for quality comparison of muon objects

LUT content (16 bits)	quality bits [22..19]	trigger
X"0000"	xxxx	no trigger
X"0001"	0000	trigger on quality "level 0"
X"0002"	0001	trigger on quality "level 1"
X"0003"	0001 or 0000	trigger on quality "level 1" or "level 0"
X"0004"	0010	trigger on quality "level 2"
...	...	...
X"8000"	1111	trigger on quality "level 15"
X"C000"	1111 or 1110	trigger on quality "level 15" or "level 14"
...	...	...
X"FFFF"	xx	trigger on all quality "levels" (= "ignore")

Table 24: LUT contents for isolation comparison of muon objects

LUT content (4 bits)	isolation bits [33..32]	trigger
X"0"	xx	no trigger
X"1"	00	trigger on isolation bits = 00
X"2"	01	trigger on isolation bits = 01
X"3"	00 or 01	trigger on isolation bits = 00 or 01
X"4"	10	trigger on isolation bits = 10
X"5"	00 or 10	trigger on isolation bits = 00 or 10
X"6"	01 or 10	trigger on isolation bits = 01 or 10
X"7"	00 or 01 or 10	trigger on isolation bits = 00 or 01 or 10
X"8"	11	trigger on isolation bits = 11
X"9"	00 or 11	trigger on isolation bits = 00 or 11
X"A"	01 or 11	trigger on isolation bits = 01 or 11
X"B"	00 or 01 or 11	trigger on isolation bits = 00 or 01 or 11
X"C"	10 or 11	trigger on isolation bits = 10 or 11
X"D"	00 or 10 or 11	trigger on isolation bits = 00 or 10 or 11
X"E"	01 or 10 or 11	trigger on isolation bits = 01 or 10 or 11
X"F"	00 or 01 or 10 or 11	trigger on isolation bits = 00 or 01 or 10 or 11 (= "ignore" isolation)

3.4.9 Correlation conditions

The correlation conditions contain a combination of two "Single object requirement conditions" of two object types or one "Double objects requirement condition" of objects of the same type. In addition with "object requirements" there are cuts for $\Delta\eta$, $\Delta\varphi$, ΔR, mass and "two-body pt".

The following cuts can be used:

- Cut for $\Delta\eta$ (DETA).
- Cut for $\Delta\varphi$ (DPHI).
- Cut for ΔR (DR).
- Cuts for mass (MASS) of following mass types:
  - Cut for Invariant mass.
  - Cut for Invariant mass with unconstrained pt (only for muons).
  - Cut for Invariant mass divided by ΔR.
  - Cut for Transverse mass.
- Cut for Two-body pt.

There is one correlation condition type for a mass cut with three objects:

- Cut for invariant mass for three objects (MASS).

3.4.9.1 Calculation of cuts

Calculation of $\Delta\eta$ and $\Delta\varphi$ see section "Calculation of differences in η and φ" (3.4.2).

3.4.9.1.1 ΔR calculation

The calculation of ΔR of two objects is done with formula:

$$\Delta R = \sqrt{(\eta_1 - \eta_2)^2 + (\varphi_1 - \varphi_2)^2}.$$

In the TME there are two thresholds for ΔR: "greater/equal lower limit" and "less/equal upper limit", given in floating point notation with one position after decimal point. The comparison in VHDL is done with ΔR^2 (no square root in VHDL), thresholds for ΔR^2 are provided by VHDL-Producer.

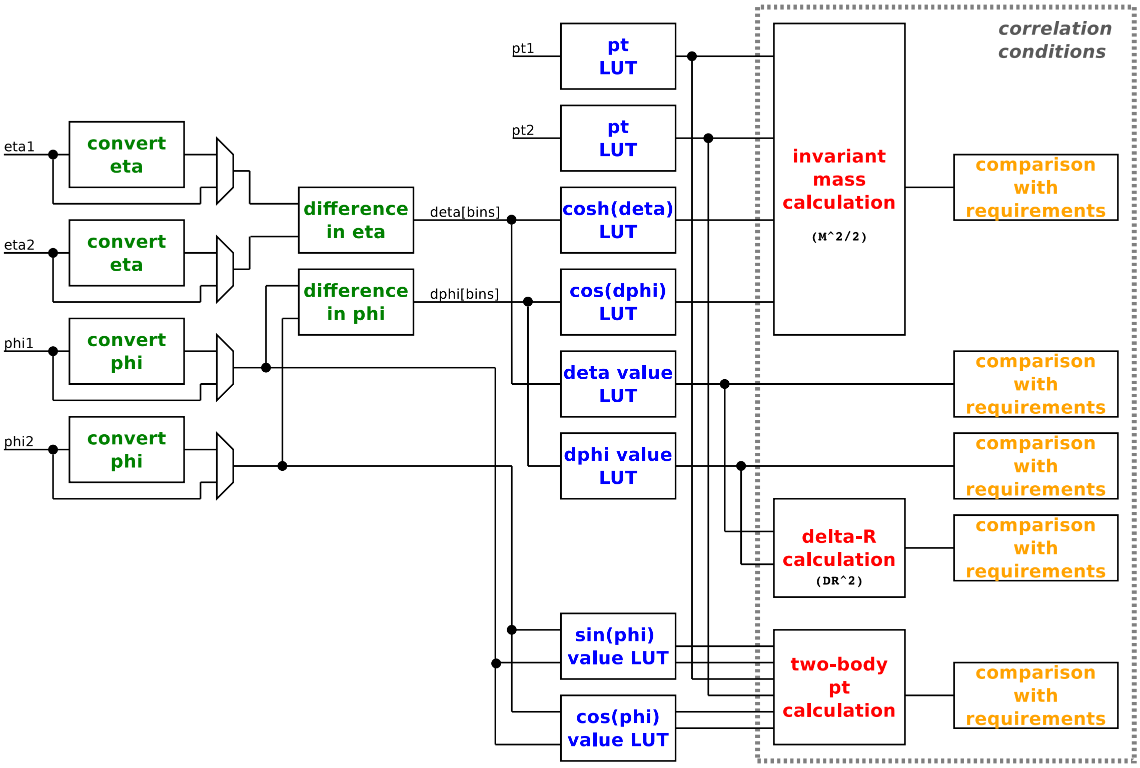


Figure 13: VHDL structure of cuts for correlation conditions

3.4.9.1.2 Invariant mass calculation

The calculation of *invariant mass of two objects* is done with formula:

M=$\sqrt{2pt_1pt_2(\cosh(\eta_1-\eta_2)-\cos(\varphi_1-\varphi_2))}$.

In the TME there are two thresholds for M: "greater/equal lower limit" and "less/equal upper limit", given in GeV (floating point notation) with one position after decimal point in even numbers.[3] The comparison in VHDL is done with $\frac{M^2}{2}$ (no square root in VHDL), thresholds for $\frac{M^2}{2}$ are provided by VHDL-Producer.

3.4.9.1.3 Transverse mass calculation

The calculation of *transverse mass of two objects* is done with formula:

M=$\sqrt{2pt_1pt_2(1-\cos(\varphi_1-\varphi_2))}$.

In the TME there are two thresholds for M: "greater/equal lower limit" and "less/equal upper limit", given in GeV (floating point notation) with one position after decimal point in even

[3] even numbers to get a precision of one position after decimal point after dividion by 2, because VHDL-Producer calculates thresholds for $\frac{M^2}{2}$, which includes a division by 2.

numbers.
The comparison in VHDL is done with $\frac{M^2}{2}$ (no square root in VHDL), thresholds for $\frac{M^2}{2}$ are provided by VHDL-Producer.

3.4.9.1.4 Two-body pt calculation

The calculation of *two-body pt* is done with formula:

pt=$\sqrt{pt_1^2 + pt_2^2 + 2pt_1pt_2(\cos(\varphi_1)\cos(\varphi_2) + \sin(\varphi_1)\sin(\varphi_2))}$

In the TME there is one threshold for pt, given in GeV (floating point notation) with one position after decimal point. The comparison in VHDL is done with pt^2 (no square root in VHDL), threshold for pt^2 is provided by VHDL-Producer.

3.4.9.1.5 Invariant mass divided by ΔR calculation

The formulas for *invariant mass divided by* ΔR *of two objects* are:

M=$\sqrt{2pt_1pt_2(\cosh(\eta_1 - \eta_2) - \cos(\varphi_1 - \varphi_2))}$.

$\Delta R = \sqrt{(\eta_1 - \eta_2)^2 + (\varphi_1 - \varphi_2)^2}$.

In the TME there is one threshold for M/ΔR, given in GeV (floating point notation) with one position after decimal point. The calculation of *invariant mass divided by* ΔR *of two objects* is done in an own module outside of the condition (`mass_div_dr_calculator.vhd`) with $\frac{M^2}{2}\times(1/\Delta R^2)$ (no square root in VHDL). This module is instantiated once for every object type bunch-crossing combination.
The values of $1/\Delta R^2$ in VHDL are given by LUTs stored in BRAMs (as ROMs). The addresses of the BRAMs are given by $\Delta\eta$ and $\Delta\varphi$. The contents of the LUTs are created by calculating $1/\Delta R^2$, rounding-up at the 5^{th} position after decimal point and multiplying by 100000 to get integer values.

3.4.9.1.6 Invariant mass calculation for three objects

The calculation of *invariant mass calculation for three objects* is done by calculating the invariant mass for all two-object combinations and take the sum of the three invariant masses of the two-object combinations.
In the TME there are two thresholds for M: "greater/equal lower limit" and "less/equal upper limit", given in GeV (floating point notation) with one position after decimal point in even numbers.

3.4.9.2 Correlation condition modules

As described in section Correlation conditions (3.4.9), correlations of two object types are available. Therefore several modules are provided with possible correlations (objects 1-objects 2):

- Correlation condition with calorimeter objects (calo_calo_correlation_condition.vhd: electron/γ-electron/γ, electron/γ-jet, electron/γ-tau, jet-jet, jet-tau and tau-tau are possible.)
- Correlation condition for mass divided by ΔR with calorimeter objects (calo_calo_mass_div_dr_condition.vhd: electron/γ-electron/γ, electron/γ-jet, electron/γ-tau, jet-jet, jet-tau and tau-tau are possible.)
- Correlation condition with calorimeter objects and energy sum quantities (ET_{miss}, ET^{HF}_{miss} and HT_{miss} only) (calo_esums_correlation_condition.vhd: electron/γ-etm, jet-etm, tau-etm, electron/γ-htm, jet-htm, tau-htm, electron/γ-etmhf, jet-etmhf and tau-etmhf are possible.)
- Correlation condition with calorimeter objects and muons objects (calo_muon_correlation_condition.vhd: electron/γ-muon, jet-muon and tau-muon are possible.)
- Correlation condition with muon objects (muon_muon_correlation_condition.vhd)
- Correlation condition for mass divided by ΔR with muon objects (muon_muon_mass_div_dr_condition.vhd)
- Correlation condition with muon objects and energy sum quantities (ET_{miss}, ET^{HF}_{miss} and HT_{miss} only) (muon_esums_correlation_condition.vhd: muon-etm, muon-etmhf and muon-htm are possible.)

There are two modules for mass with three objects:

- Correlation condition for mass with three objects with calorimeter objects (same type, same bunch-crossing) (calo_mass_3_obj_condition.vhd
- Correlation condition for mass with three objects with muon objects (muon_mass_3_obj_condition.vhd)

3.4.9.2.1 Overview of possible correlation cuts in conditions

The following list gives an overview of possible correlation cuts in conditions:

- Calo conditions:

  - two-body pt (for double condition)

- Calo conditions overlap removal:
  - $\Delta\eta$ overlap removal
  - $\Delta\varphi$ overlap removal
  - ΔR overlap removal
  - two-body pt (for double condition)

- Muon conditions:
  - charge correlation
  - two-body pt (for double condition)

- Calo calo correlation condition with calo overlap removal:
  - $\Delta\eta$ overlap removal
  - $\Delta\varphi$ overlap removal
  - ΔR overlap removal
  - $\Delta\eta$
  - $\Delta\varphi$
  - ΔR
  - invariant mass
  - two-body pt

- Calo calo correlation condition:
  - $\Delta\eta$
  - $\Delta\varphi$
  - ΔR
  - invariant mass
  - two-body pt

- Calo calo correlation condition for invariant mass divided by ΔR:
  - invariant mass divided by ΔR

- Calo calo correlation condition mass with three objects:
  - invariant mass with three objects

- Calo muon correlation condition:
  - $\Delta\eta$
  - $\Delta\varphi$
  - ΔR
  - invariant mass

- two-body pt

- Calo esums correlation condition:
  - $\Delta\varphi$
  - transverse mass
  - two-body pt
- Muon muon correlation condition:
  - charge correlation
  - $\Delta\eta$
  - $\Delta\varphi$
  - ΔR
  - invariant mass or invariant mass unconstraint pt
  - two-body pt
- Muon muon correlation condition for invariant mass divided by ΔR:
  - charge correlation
  - invariant mass divided by ΔR
- Muon muon correlation condition mass with three objects:
  - charge correlation
  - invariant mass with three objects
- Muon esums correlation condition:
  - $\Delta\varphi$
  - transverse mass
  - two-body pt

3.4.9.2.2 Calo Calo Correlation condition module

The calo calo correlation condition module contains two "Single object requirement conditions" for different types of calo objects (electron/γ, jet or tau) or same type with data from different bunch-crossings as one possible mode and a "Double objects requirement condition" for calo objects of same type and same bunch-crossing as a second mode (selection is done by a parameter in the generic list of `calo_calo_correlation_condition.vhd` named "same_bx").
In addition there are "Cuts" for differences in η ($\Delta\eta$) and φ ($\Delta\varphi$), a calculation of ΔR (DR), a calculation of invariant mass (MASS) and a calculation of two-body pt, see Figure 13.
The differences in η and φ are calculated in bins. These differences in bins are converted to numbers (by LUTs, e.g. EG_EG_DIFF_ETA_LUT, EG_EG_DIFF_PHI_LUT, ...), which represents values of differences (multiples of units in η and φ). These values given in the LUTs are calculated as floating-point values (based on the scales of η and φ), which are multiplied

by a factor and truncated to an integer value. So, in the LUTs we have integer values, the factor is $10^{\text{precision}}$. This "precision" is a parameter given for certain LUTs.

Remark: Definitions of scales (see Tables 8, 9, 14 and 15):

- Calorimeter objects:
- η bin width $= \frac{0.087}{2}$ (bin 0 from 0.0 to $\frac{0.087}{2}$)
- ϕ bin width $= \frac{2\pi}{144}$ (bin 0 from 0.0 to $\frac{2\pi}{144}$)

The contents of the LUTs for $\cosh(\Delta\eta)$ (EG_EG_COSH_DETA_LUT, ...) and $\cos(\Delta\varphi)$ (EG_EG_COS_DPHI_LUT, ...) for invariant mass (formular see 3.4.9.1.2) are created by calculating hyperbolic cosine and cosine, rounding-up at the 3rd position after decimal point, and multiplying by 1000 to get integer values.[4]
The contents of the LUTs for $\cos(\varphi)$ (CALO_COS_PHI_LUT) and $\sin(\varphi)$ (CALO_SIN_PHI_LUT) for two-body pt (formular see 3.4.9.1.4) are created by calculating cosine and sine, rounding-up at the 3rd position after decimal point and multiplying by 1000 to get integer values.
The condition is complied, if at least one comparison between object parameters and requirements is valid for the both "Single object requirement condition" or the "Double objects requirement condition" and the results of selected "Cuts" are inside of a range (upper and lower limit) or greater/eual a threshold (e.g. for two-body pt). This limits are parts of the "generic" list of the entity declaration of the module and are expressed in hex notation. The limits for $\Delta\eta$ and $\Delta\varphi$ are expressed with a precision of 3rd position after decimal point, for DR, MASS and two-body pt with 1st position after decimal point.

For the VHDL entity declaration of calo calo correlation condition module in `calo_calo_correlation_condition.vhd`, see Listing 8.

[4] Definition of "`constant CALO_INV_MASS_COSH_COS_PRECISION...`" in file `gtl_pkg.vhd`. Value 1000 from $10^{\text{CALO\_INV\_MASS\_COSH\_COS\_PRECISION}}$.

Listing 8: Entity declaration of calo_calo_correlation_condition.vhd

```
entity calo_calo_correlation_condition is
    generic(
        same_bx: boolean;

        deta_cut: boolean;
        dphi_cut: boolean;
        dr_cut: boolean;
        mass_cut: boolean;
        mass_type : natural;
        twobody_pt_cut: boolean;

        calo1_object_low: natural;
        calo1_object_high: natural;
        et_ge_mode_calo1: boolean;
        obj_type_calo1: natural := EG_TYPE;
        et_threshold_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_calo1 : natural;
        eta_w1_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w1_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w2_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w2_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w3_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w3_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w4_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w4_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w5_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w5_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_full_range_calo1: boolean;
        phi_w1_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_calo1: boolean;
        phi_w2_upper_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_calo1: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        iso_lut_calo1: std_logic_vector(2**MAX_CALO_ISO_BITS-1 downto 0);

        calo2_object_low: natural;
        calo2_object_high: natural;
        et_ge_mode_calo2: boolean;
        obj_type_calo2: natural := JET_TYPE;
        et_threshold_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_calo2 : natural;
        eta_w1_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
```

```
        downto 0);
    eta_w1_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w2_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w2_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w3_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w3_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w4_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w4_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w5_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    eta_w5_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    phi_full_range_calo2: boolean;
    phi_w1_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    phi_w1_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    phi_w2_ignore_calo2: boolean;
    phi_w2_upper_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    phi_w2_lower_limit_calo2: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
        downto 0);
    iso_lut_calo2: std_logic_vector(2**MAX_CALO_ISO_BITS-1 downto 0);

    diff_eta_upper_limit_vector: std_logic_vector(
        MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
    diff_eta_lower_limit_vector: std_logic_vector(
        MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

    diff_phi_upper_limit_vector: std_logic_vector(
        MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
    diff_phi_lower_limit_vector: std_logic_vector(
        MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

    dr_upper_limit_vector: std_logic_vector(MAX_WIDTH_DR_LIMIT_VECTOR-1
        downto 0);
    dr_lower_limit_vector: std_logic_vector(MAX_WIDTH_DR_LIMIT_VECTOR-1
        downto 0);

    mass_upper_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
        downto 0);
    mass_lower_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
        downto 0);

    pt1_width: positive;
    pt2_width: positive;
    mass_cosh_cos_precision : positive;
    cosh_cos_width: positive;

    pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
```

```
            downto 0);
        sin_cos_width: positive;
        pt_sq_sin_cos_precision : positive

    );
    port(
        lhc_clk: in std_logic;
        calo1_data_i: in calo_objects_array;
        calo2_data_i: in calo_objects_array;
        diff_eta: in deta_dphi_vector_array;
        diff_phi: in deta_dphi_vector_array;
        pt1 : in diff_inputs_array;
        pt2 : in diff_inputs_array;
        cosh_deta : in calo_cosh_cos_vector_array;
        cos_dphi : in calo_cosh_cos_vector_array;
        cos_phi_1_integer : in sin_cos_integer_array;
        cos_phi_2_integer : in sin_cos_integer_array;
        sin_phi_1_integer : in sin_cos_integer_array;
        sin_phi_2_integer : in sin_cos_integer_array;
        condition_o: out std_logic
    );
end calo_calo_correlation_condition;
```

Table 25: Explanation of Listing 8

Item	Explanation
`same_bx`	boolean indicating whether data are from same Bx - 'true' for same Bx.
`deta_cut`	boolean for using $\Delta\eta$ cut.
`dphi_cut`	boolean for using $\Delta\varphi$ cut.
`dr_cut`	boolean for using DR cut.
`mass_cut`	boolean for using MASS cut.
`mass_type`	selection of mass type (INVARIANT_MASS_TYPE, INVARIANT_MASS_PT_TYPE, TRANSVERSE_MASS_TYPE or TRANSVERSE_MASS_PT_TYPE are allowed).
`calo1_object_low`	low index of object range (valid numbers: 0..11).
`calo1_object_high`	high index of object range (valid numbers: 0..11, but greater or equal calo1_object_low).
`et_ge_mode_calo1`	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only).
`obj_type_calo1`	selection of calo1 object type (EG_TYPE, JET_TYPE or TAU_TYPE are allowed)
`et_threshold_calo1`	threshold value for comparison in E_{T}.
`nr_eta_windows_calo1`	integer value for number of η cuts.
`eta_w1_upper_limit_calo1`	"upper limit" of "window"-comparator 1 for η.
`eta_w1_lower_limit_calo1`	"lower limit" of "window"-comparator 1 for η.
`eta_w2_upper_limit_calo1`	"upper limit" of "window"-comparator 2 for η.
`eta_w2_lower_limit_calo1`	"lower limit" of "window"-comparator 2 for η.

Table 25: Explanation of Listing 8

Item	Explanation
eta_w3_upper_limit_calo1	"upper limit" of "window"-comparator 3 for η.
eta_w3_lower_limit_calo1	"lower limit" of "window"-comparator 3 for η.
eta_w4_upper_limit_calo1	"upper limit" of "window"-comparator 4 for η.
eta_w4_lower_limit_calo1	"lower limit" of "window"-comparator 4 for η.
eta_w5_upper_limit_calo1	"upper limit" of "window"-comparator 5 for η.
eta_w5_lower_limit_calo1	"lower limit" of "window"-comparator 5 for η.
phi_full_range_calo1	boolean to set full range of φ.
phi_w1_upper_limit_calo1	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limit_calo1	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_calo1	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limit_calo1	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_calo1	"lower limit" of "window"-comparator 2 for φ.
iso_lut_calo1	content of LUT (4 bits) for isolation comparison.
calo2_object_low	low index of object range (valid numbers: 0..11).
calo2_object_high	high index of object range (valid numbers: 0..11, but greater or equal calo2_object_low).
et_ge_mode_calo2	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
obj_type_calo2	selection of calo2 object type (EG_TYPE, JET_TYPE or TAU_TYPE are allowed)
et_threshold_calo2	threshold value for comparison in E_{T}.
nr_eta_windows_calo2	integer value for number of η cuts.
eta_w1_upper_limit_calo2	"upper limit" of "window"-comparator 1 for η.
eta_w1_lower_limit_calo2	"lower limit" of "window"-comparator 1 for η.
eta_w2_upper_limit_calo2	"upper limit" of "window"-comparator 2 for η.
eta_w2_lower_limit_calo2	"lower limit" of "window"-comparator 2 for η.
eta_w3_upper_limit_calo2	"upper limit" of "window"-comparator 3 for η.
eta_w3_lower_limit_calo2	"lower limit" of "window"-comparator 3 for η.
eta_w4_upper_limit_calo2	"upper limit" of "window"-comparator 4 for η.
eta_w4_lower_limit_calo2	"lower limit" of "window"-comparator 4 for η.
eta_w5_upper_limit_calo2	"upper limit" of "window"-comparator 5 for η.
eta_w5_lower_limit_calo2	"lower limit" of "window"-comparator 5 for η.
phi_full_range_calo2	boolean to set full range of φ.
phi_w1_upper_limit_calo2	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limit_calo2	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_calo2	boolean to ignore "window"-comparator 2 for φ.

Table 25: Explanation of Listing 8

Item	Explanation
phi_w2_upper_limit_calo2	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_calo2	"lower limits" of "window"-comparator 2 for φ.
iso_lut_calo2	content of LUT (4 bits) for isolation comparison.
diff_eta_upper_limit	"upper limit" of "window"-comparator for comparison of differences in η (hex value).
diff_eta_lower_limit	"lower limit" of "window"-comparator for comparison of differences in η (hex value).
diff_phi_upper_limit	"upper limit" of "window"-comparator for comparison of differences in φ (hex value).
diff_phi_lower_limit	"lower limit" of "window"-comparator for comparison of differences in φ (hex value).
dr_upper_limit	"upper limit" of "window"-comparator for comparison of ΔR^2 (hex value).
dr_lower_limit	"lower limit" of "window"-comparator for comparison of ΔR^2 (hex value).
DETA_DPHI_VECTOR_WIDTH	vector width of $\Delta\eta$ and $\Delta\varphi$ for calculation of ΔR^2.
DETA_DPHI_PRECISION	position after decimal point for $\Delta\eta$ and $\Delta\varphi$.
mass_upper_limit	"upper limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
mass_lower_limit	"lower limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
MASS_PRECISION	position after decimal point for $\frac{M^2}{2}$.
pt1_width	number of bits of pt1.
pt2_width	number of bits of pt2.
MASS_COSH_COS_PRECISION	position after decimal point for $\cosh(\Delta\eta)$ and $\cos(\Delta\varphi)$.
cosh_cos_width	number of bits for the maximum value in the LUT for $\cosh(\Delta\eta)$.
pt_sq_threshold	threshold value for comparison in two-body pt (pt^2).
sin_cos_width	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$.
PT_PRECISION	position after decimal point for pt^2.
PT_SQ_SIN_COS_PRECISION	position after decimal point for $\cos(\varphi)$ and $\sin(\varphi)$.
lhc_clk	clock input (LHC clock).
calo1_data_i	calorimeter input data, structure defined with obj_type_calo1.
calo2_data_i	calorimeter input data, structure defined with obj_type_calo2.
diff_eta	differences in η, calculated in an instance of module sub_eta_integer_obj_vs_obj.vhd in top-of-hierarchy module (gtl_module.vhd), see 3.4.2.
diff_phi	differences in φ, calculated in an instance of module sub_phi_integer_obj_vs_obj.vhd in top-of-hierarchy module (gtl_module.vhd).
pt1	calo1 E_T values [from LUT, in $GeV \times 10$].[5]

[5] value 10 from $10^{\mathrm{CALO\_INV\_MASS\_PT\_PRECISION}}$

Table 25: Explanation of Listing 8

Item	Explanation
`pt2`	calo2 E_{T} values [from LUT, in $GeV \times 10$].
`cosh_deta`	$\cosh(\Delta\eta)$ values [from LUT, $\cosh(\Delta\eta)\times 1000$].[6]
`cos_dphi`	$\cos(\Delta\varphi)$ values [from LUT, $\cosh(\Delta\varphi)\times 1000$].
`cos_phi_1`	$\cos(\varphi)$ values from LUT for calo1.
`cos_phi_2`	$\cos(\varphi)$ values from LUT for calo2.
`sin_phi_1`	$\sin(\varphi)$ values from LUT for calo1.
`sin_phi_2`	$\sin(\varphi)$ values from LUT for calo2.
`condition_o`	output of condition (routed to Algorithms logic, see 3.4.11).

3.4.9.2.3 Calo Calo Overlap Remover Correlation condition module

The Calo Calo Overlap Remover Correlation conditions consits of two modes. One with a Calo Calo Correlation condition with "Double objects requirement condition" for calo objects of same type and same bunch-crossing (3.4.9.2.2) and a single condition for a different calo object type (can have different bunch-crossing too). There has to be at least one correlation cut for the objects of "Double objects requirement condition" and a correlation cut for overlap removal between objects (one or more cut(s) of $\Delta\eta$, $\Delta\varphi$ and ΔR) of different object types ("2plus1"). A second mode ("1plus1") with a Calo Calo Correlation condition with a single condition and a different calo object type (can have different bunch-crossing too) also with a single condition. There has to be at least one correlation cut for the different objects (e.g. invariant mass) and a correlation cut for overlap removal between the objects (one or more cut(s) of $\Delta\eta$, $\Delta\varphi$ and ΔR).

Overlap Remover Correlation conditions `calo_calo_calo_correlation_orm_condition.vhd` are implemented only for calo object types.

3.4.9.2.4 Calo Calo Correlation condition module for Invariant Mass Divided by ΔR

The calo calo correlation condition module for invariant mass divided by ΔR contains two "Single object requirement conditions" for different types of calo objects (electron/γ, jet or tau) or same type with data from different bunch-crossings as one possible mode and a "Double objects requirement condition" for calo objects of same type and same bunch-crossing as a second mode (selection is done by a parameter in the generic list of `calo_calo_mass_div_dr_condition.vhd` named "same_bx").
The calculation of *invariant mass divided by ΔR of two objects* is done in an own module outside of the condition (`mass_div_dr_calculator.vhd`), see 3.4.9.1.5. This module is instantiated once for every object type bunch-crossing combination.

[6] value 1000 from $10^{\text{CALO\_INV\_MASS\_COSH\_COS\_PRECISION}}$

The comparison of calculated values and threshold is done inside the module (calo_calo_-mass_div_dr_condition.vhd).
In the TME there is one threshold for M/ΔR: "greater/equal threshold", given in GeV (floating point notation).
The threshold for comparison with $\frac{M^2}{2} \times (1/\Delta R^2)$ (no square root in VHDL) is provided by VHDL-Producer.
No other correlation cuts available in this condition type.

3.4.9.2.5 Calo Correlation condition module for Invariant Mass with Three Objects

The calo correlation condition module for invariant mass with three objects (calo_mass_-3_obj_condition.vhd) contains a "Triple objects requirement condition" for calo objects of same type and same bunch-crossing.
In addition a "Cut" for calculation of *invariant mass with three objects* (see 3.4.9.1.6) is mandatory.
No other correlation cuts available in this condition type.

3.4.9.2.6 Calo Esums Correlation condition module

The calo esums correlation condition module (calo_esums_correlation_condition.vhd) contains two "Single object requirement conditions", one of calo objects (electron/γ, jet or tau) and one of esums (ET_{miss}, ET^{HF}_{miss} or HT_{miss}).
In addition there are "Cuts" for differences in φ ($\Delta\varphi$) or a calculation of mass (MASS) for Transverse mass or Transverse mass with two-body pt.
The differences in φ are calculated in bins. These differences in bins are converted to numbers (by LUTs, e.g. EG_ETM_DIFF_PHI_LUT, ...), which represents values of differences (multiples of units in φ). These values given in the LUTs are calculated as floating-point values (based on the scales of φ), which are multiplied by a factor and truncated to an integer value. So, in the LUTs we have integer values, the factor is $10^{\mathrm{precision}}$.

The contents of the LUTs $\cos(\Delta\varphi)$ (EG_ETM_COS_DPHI_LUT, ...) for Transverse mass (formular see 3.4.9.1.3) are created by calculating cosine, rounding-up at the 3^{rd} position after decimal point and multiplying by 1000 to get integer values.[7]
The contents of the LUTs for $\cos(\varphi)$ (CALO_COS_PHI_LUT) and $\sin(\varphi)$ (CALO_SIN_PHI_-LUT) for two-body pt (formular see 3.4.9.1.4) are created by calculating cosine and sine, rounding-up at the 3^{rd} position after decimal point and multiplying by 1000 to get integer values.
The condition is complied, if at least one comparison between object parameters and requirements is valid for the both "Single object requirement condition" and the results of selected "Cuts" are inside of a range (upper and lower limit). This limits are parts of the "generic" list of the entity declaration of the module and are expressed in hex notation. The limits for $\Delta\varphi$

[7]Definition of "constant CALO_INV_MASS_COSH_COS_PRECISION..." in file gtl_pkg.vhd. 1000 from $10^{\mathrm{CALO\_INV\_MASS\_COSH\_COS\_PRECISION}}$.

are expressed with a precision of 3rd position after decimal point, for MASS with 1st position after decimal point.

For VHDL entity declaration for calo esums correlation condition module in calo_esums_correlation_condition.vhd, see Listing 9.

Listing 9: Entity declaration of calo_esums_correlation_condition.vhd

```
entity calo_esums_correlation_condition is
     generic(

        dphi_cut: boolean;
        mass_cut: boolean;
        mass_type : natural;
        twobody_pt_cut: boolean;

        calo_object_low: natural;
        calo_object_high: natural;
        et_ge_mode_calo: boolean;
        obj_type_calo: natural := EG_TYPE;
        et_threshold_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_calo : natural;
        eta_w1_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w1_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w2_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w2_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w3_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w3_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w4_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w4_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w5_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w5_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_full_range_calo: boolean;
        phi_w1_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_calo: boolean;
        phi_w2_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        iso_lut_calo: std_logic_vector(2**MAX_CALO_ISO_BITS-1 downto 0);

        et_ge_mode_esums: boolean;
        obj_type_esums: natural := ETM_TYPE;
```

```
        et_threshold_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0)
            ;
        phi_full_range_esums: boolean;
        phi_w1_upper_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_esums: boolean;
        phi_w2_upper_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);

        diff_phi_upper_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
        diff_phi_lower_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

        mass_upper_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);
        mass_lower_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);

        pt1_width: positive;
        pt2_width: positive;
        mass_cosh_cos_precision : positive;
        cosh_cos_width: positive;

        pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
            downto 0);
        sin_cos_width: positive;
        pt_sq_sin_cos_precision : positive

    );
    port(
        lhc_clk: in std_logic;
        calo_data_i: in calo_objects_array;
        esums_data_i: in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        diff_phi: in deta_dphi_vector_array;
        pt1 : in diff_inputs_array;
        pt2 : in diff_inputs_array;
        cos_dphi : in calo_cosh_cos_vector_array;
        cos_phi_1_integer : in sin_cos_integer_array;
        cos_phi_2_integer : in sin_cos_integer_array;
        sin_phi_1_integer : in sin_cos_integer_array;
        sin_phi_2_integer : in sin_cos_integer_array;
        condition_o: out std_logic
    );
end calo_esums_correlation_condition;
```

Table 26: Explanation of Listing 9

Item	Explanation
`dphi_cut`	boolean for using $\Delta\varphi$ cut.
`mass_cut`	boolean for using MASS cut.
`mass_type`	selection of mass type (TRANSVERSE_MASS_TYPE or TRANSVERSE_MASS_PT_TYPE are allowed).
`calo_object_low`	low index of object range (valid numbers: 0..11).
`calo_object_high`	high index of object range (valid numbers: 0..11, but greater or equal calo_object_low).
`et_ge_mode_calo`	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only).
`obj_type_calo`	selection of calo1 object type (EG_TYPE, JET_TYPE or TAU_TYPE are allowed)
`et_threshold_calo`	threshold value for comparison in E_{T}.
`nr_eta_windows_calo`	integer value for number of η cuts.
`eta_w1_upper_limit_calo`	"upper limit" of "window"-comparator 1 for η.
`eta_w1_lower_limit_calo`	"lower limit" of "window"-comparator 1 for η.
`eta_w2_upper_limit_calo`	"upper limit" of "window"-comparator 2 for η.
`eta_w2_lower_limit_calo`	"lower limit" of "window"-comparator 2 for η.
`eta_w3_upper_limit_calo`	"upper limit" of "window"-comparator 3 for η.
`eta_w3_lower_limit_calo`	"lower limit" of "window"-comparator 3 for η.
`eta_w4_upper_limit_calo`	"upper limit" of "window"-comparator 4 for η.
`eta_w4_lower_limit_calo`	"lower limit" of "window"-comparator 4 for η.
`eta_w5_upper_limit_calo`	"upper limit" of "window"-comparator 5 for η.
`eta_w5_lower_limit_calo`	"lower limit" of "window"-comparator 5 for η.
`phi_full_range_calo`	boolean to set full range of φ.
`phi_w1_upper_limit_calo`	"upper limit" of "window"-comparator 1 for φ.
`phi_w1_lower_limit_calo`	"lower limit" of "window"-comparator 1 for φ.
`phi_w2_ignore_calo`	boolean to ignore "window"-comparator 2 for φ.
`phi_w2_upper_limit_calo`	"upper limit" of "window"-comparator 2 for φ.
`phi_w2_lower_limit_calo`	"lower limit" of "window"-comparator 2 for φ.
`iso_lut_calo`	content of LUT (4 bits) for isolation comparison.
`et_ge_mode_esums`	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
`obj_type_esums`	selection of esums type (ETM_TYPE, ETMHF_TYPE or HTM_TYPE are allowed)
`et_threshold_esums`	threshold value for comparison in E_{T}.
`phi_full_range_esums`	boolean to set full range of φ.
`phi_w1_upper_limit_esums`	"upper limit" of "window"-comparator 1 for φ.

Table 26: Explanation of Listing 9

Item	Explanation
phi_w1_lower_limit_esums	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_esums	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limit_esums	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_esums	"lower limits" of "window"-comparator 2 for φ.
diff_phi_upper_limit	"upper limit" of "window"-comparator for comparison of differences in φ (hex value).
diff_phi_lower_limit	"lower limit" of "window"-comparator for comparison of differences in φ (hex value).
DETA_DPHI_VECTOR_WIDTH	vector width of $\Delta\varphi$.
DETA_DPHI_PRECISION	position after decimal point for $\Delta\varphi$.
mass_upper_limit	"upper limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
mass_lower_limit	"lower limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
MASS_PRECISION	position after decimal point for $\frac{M^2}{2}$.
pt1_width	number of bits of pt1.
pt2_width	number of bits of pt2.
MASS_COSH_COS_PRECISION	position after decimal point for $\cos(\Delta\varphi)$.
cosh_cos_width	number of bits for the maximum value in the LUT for $\cos(\Delta\varphi)$.
pt_sq_threshold	threshold value for comparison in two-body pt (pt^2).
sin_cos_width	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$.
PT_PRECISION	position after decimal point for pt^2.
PT_SQ_SIN_COS_PRECISION	position after decimal point for $\cos(\varphi)$ and $\sin(\varphi)$.
lhc_clk	clock input (LHC clock).
calo_data_i	calorimeter input data, structure defined with `obj_type_calo1`.
esums_data_i	esums input data, structure defined with `obj_type_esums`.
diff_phi	differences in φ, calculated in an instance of module `sub_phi_integer_obj_vs_obj.vhd` in top-of-hierarchy module (`gtl_module.vhd`).
pt1	calo1 E_{T} values [from LUT, in $GeV\times 10$].[8]
pt2	esums E_{T} values [from LUT, in $GeV\times 10$].
cos_dphi	$\cos(\Delta\varphi)$ values from LUT.
cos_phi_1	$\cos(\varphi)$ values from LUT for calo1.
cos_phi_2	$\cos(\varphi)$ values from LUT for esums.
sin_phi_1	$\sin(\varphi)$ values from LUT for calo1.
sin_phi_2	$\sin(\varphi)$ values from LUT for esums.
condition_o	output of condition (routed to Algorithms logic, see 3.4.11).

[8] value 10 from $10^{\text{CALO\_INV\_MASS\_PT\_PRECISION}}$

3.4.9.2.7 Calo Muon Correlation condition module

The calo muon correlation condition module (`calo_muon_correlation_condition.vhd`) contains a "Single object requirement condition" for one type of calo objects (electron/γ, jet or tau) and a "Single object requirement condition" for muon objects. In addition there are "Cuts" for differences in η ($\Delta\eta$) and φ ($\Delta\varphi$), a calculation of ΔR (DR), a calculation of invariant mass (MASS) and a calculation of two-body pt, see Figure 13.
The differences in η and φ are calculated in bins. These differences in bins are converted to numbers (by LUTs, e.g. EG_MU_DIFF_ETA_LUT, EG_MU_DIFF_PHI_LUT, ...), which represents values of differences (multiples of units in η and φ). These values given in the LUTs are calculated as floating-point values (based on the scales of η and φ), which are multiplied by a factor and truncated to an integer value. So, in the LUTs we have integer values, the factor is $10^{\text{precision}}$. This "precision" is a parameter given for certain LUTs.
Because of the different scales of calorimeter and muon objects in η and φ, there are LUTs for conversion the calorimeter bins to muon bins (in `gtl_pkg.vhd`: e.g. EG_ETA_CONV_2_MUON_ETA_LUTand EG_PHI_CONV_2_MUON_PHI_LUT).

Remark:
The center value of bins are used as reference value for conversion. The content of EG_ETA_CONV_2_MUON_ETA_LUTis calculated with formular:
"converted-calo-eta[bin] = calo-eta[bin] × 4 + 2",
of EG_PHI_CONV_2_MUON_PHI_LUTwith formular:
"converted-calo-phi[bin] = calo-phi[bin] × 4 + 2".
The conversion calculations are preliminary, others may be proposed.

Definitions of scales (see Tables 8, 9, 14 and 15):

- Calorimeter objects:
  - η bin width = $\frac{0.087}{2}$ (bin 0 from 0.0 to $\frac{0.087}{2}$)
  - ϕ bin width = $\frac{2\pi}{144}$ (bin 0 from 0.0 to $\frac{2\pi}{144}$)
- Muon objects:
  - η bin width = $\frac{0.087}{8}$ (bin 0 from $0.5\times\frac{-0.087}{8}$ to $0.5\times\frac{+0.087}{8}$)
  - ϕ bin width = $\frac{2\pi}{576}$ (bin 0 from 0.0 to $\frac{2\pi}{576}$)

The contents of the LUTs for cosh($\Delta\eta$) (EG_MUON_COSH_DETA_LUT, ...) and cos($\Delta\varphi$) (EG_MUON_COS_DPHI_LUT, ...) for invariant mass (formular see 3.4.9.1.2) are created by calculating hyperbolic cosine and cosine, rounding-up at the 4^{th} position after decimal point, and multiplying by 10000($10^{\text{CALO\_MUON\_INV\_MASS\_COSH\_COS\_PRECISION}}$) to get integer values.[9]
The contents of the LUTs for cos(φ) (CALO_COS_PHI_LUT and MUON_COS_PHI_LUT) and sin(φ) (CALO_SIN_PHI_LUT and MUON_SIN_PHI_LUT) for two-body pt (formular see 3.4.9.1.4) are created by calculating cosine and sine, rounding-up at the 3^{rd} position after

[9] Definition of "`constant CALO_MUON_INV_MASS_COSH_COS_PRECISION` ...", "`constant EG_ETA_CONV_2_MUON_ETA_LUT` ..." and "`constant EG_PHI_CONV_2_MUON_PHI_LUT` ..." in file `gtl_pkg.vhd`.

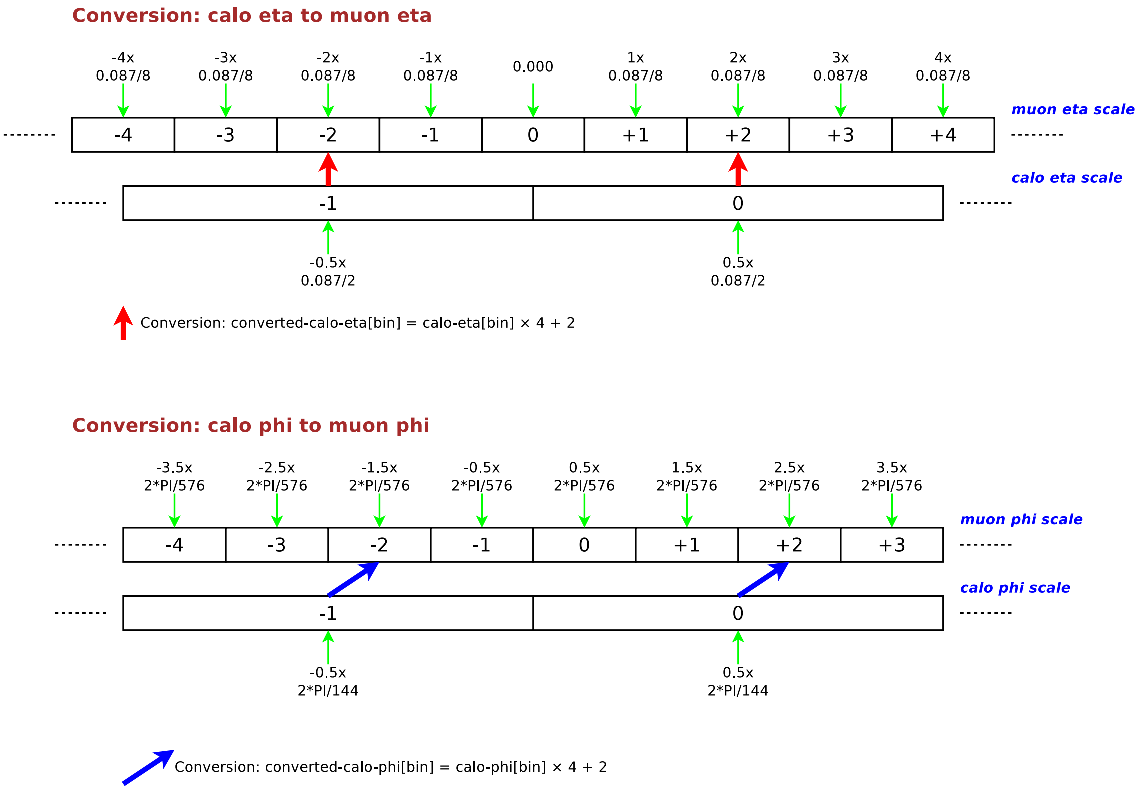


Figure 14: Conversion of calorimeter η and φ to muon scales

decimal point, and multiplying by 1000 to get integer values.
The condition is complied, if at least one comparison between object parameters and requirements is valid for the both "Single object requirement condition" and the results of selected "Cuts" are inside of a range (upper and lower limit) or greater/eual a threshold (e.g. for two-body pt). This limits are parts of the "generic" list of the entity declaration of the module and are expressed in hex notation. The limits for $\Delta\eta$ and $\Delta\varphi$ are expressed with a precision of 3rd position after decimal point, for DR, MASS and two-body pt with 1st position after decimal point.

For the VHDL entity declaration of calo muon correlation condition module in `calo_muon_correlation_condition.vhd`, see Listing 10.

Listing 10: Entity declaration of calo_muon_correlation_condition.vhd

```
entity calo_muon_correlation_condition is
    generic(
        deta_cut: boolean;
        dphi_cut: boolean;
        dr_cut: boolean;
        mass_cut: boolean;
        mass_type : natural;
        twobody_pt_cut: boolean;

        calo_object_low: natural;
        calo_object_high: natural;
        et_ge_mode_calo: boolean;
        obj_type_calo: natural := EG_TYPE;
        et_threshold_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_calo : natural;
        eta_w1_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w1_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w2_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w2_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w3_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w3_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w4_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w4_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w5_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        eta_w5_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_full_range_calo: boolean;
        phi_w1_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_calo: boolean;
        phi_w2_upper_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_calo: std_logic_vector(MAX_CALO_TEMPLATES_BITS-1
            downto 0);
        iso_lut_calo: std_logic_vector(2**MAX_CALO_ISO_BITS-1 downto 0);

        muon_object_low: natural;
        muon_object_high: natural;
        pt_ge_mode_muon: boolean;
        pt_threshold_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_muon : natural;
        eta_w1_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w1_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
```

```
eta_w2_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w2_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w3_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w3_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w4_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w4_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w5_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
eta_w5_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
phi_full_range_muon : boolean;
phi_w1_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
phi_w1_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
phi_w2_ignore_muon : boolean;
phi_w2_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
phi_w2_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
    downto 0);
requested_charge_muon: string(1 to 3);
qual_lut_muon: std_logic_vector(2**(D_S_I_MUON_V2.qual_high-D_S_I_MUON_V2
    .qual_low+1)-1 downto 0);
iso_lut_muon: std_logic_vector(2**(D_S_I_MUON_V2.iso_high-D_S_I_MUON_V2.
    iso_low+1)-1 downto 0);
upt_cut_muon : boolean;
upt_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
    0);
upt_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
    0);
ip_lut_muon: std_logic_vector(2**(D_S_I_MUON_V2.ip_high-D_S_I_MUON_V2.
    ip_low+1)-1 downto 0);

diff_eta_upper_limit_vector: std_logic_vector(
    MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
diff_eta_lower_limit_vector: std_logic_vector(
    MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

diff_phi_upper_limit_vector: std_logic_vector(
    MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
diff_phi_lower_limit_vector: std_logic_vector(
    MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

dr_upper_limit_vector: std_logic_vector(MAX_WIDTH_DR_LIMIT_VECTOR-1
    downto 0);
dr_lower_limit_vector: std_logic_vector(MAX_WIDTH_DR_LIMIT_VECTOR-1
    downto 0);

mass_upper_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
    downto 0);
```

```
        mass_lower_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);

        pt1_width: positive;
        pt2_width: positive;
        mass_cosh_cos_precision : positive;
        cosh_cos_width: positive;

        pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
            downto 0);
        sin_cos_width: positive;
        pt_sq_sin_cos_precision : positive

    );
    port(
        lhc_clk: in std_logic;
        calo_data_i: in calo_objects_array;
        muon_data_i: in muon_objects_array;
        diff_eta: in deta_dphi_vector_array;
        diff_phi: in deta_dphi_vector_array;
        pt1 : in diff_inputs_array;
        pt2 : in diff_inputs_array;
        cosh_deta : in calo_muon_cosh_cos_vector_array;
        cos_dphi : in calo_muon_cosh_cos_vector_array;
        cos_phi_1_integer : in sin_cos_integer_array;
        cos_phi_2_integer : in sin_cos_integer_array;
        sin_phi_1_integer : in sin_cos_integer_array;
        sin_phi_2_integer : in sin_cos_integer_array;
        condition_o: out std_logic
    );
end calo_muon_correlation_condition;
```

Table 27: Explanation of Listing 10

Item	Explanation
deta_cut	boolean for using $\Delta\eta$ cut.
dphi_cut	boolean for using $\Delta\varphi$ cut.
dr_cut	boolean for using DR cut.
mass_cut	boolean for using MASS cut.
mass_type	selection of mass type (INVARIANT_MASS_TYPE, INVARIANT_MASS_PT_TYPE, TRANSVERSE_MASS_TYPE or TRANSVERSE_MASS_PT_TYPE are allowed).
calo_object_low	low index of object range (valid numbers: 0..11).
calo_object_high	high index of object range (valid numbers: 0..11, but greater or equal calo_object_low).
calo_et_ge_mode_calo	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only).
obj_type_calo	selection of calo object type (EG_TYPE, JET_TYPE or TAU_TYPE are allowed)
et_threshold_calo	threshold value for comparison in E_{T}.

Table 27: Explanation of Listing 10

Item	Explanation
nr_eta_windows_calo	integer value for number of η cuts.
eta_w1_upper_limit_calo	"upper limit" of "window"-comparator 1 for η.
eta_w1_lower_limit_calo	"lower limit" of "window"-comparator 1 for η.
eta_w2_upper_limit_calo	"upper limit" of "window"-comparator 2 for η.
eta_w2_lower_limit_calo	"lower limit" of "window"-comparator 2 for η.
eta_w3_upper_limit_calo	"upper limit" of "window"-comparator 3 for η.
eta_w3_lower_limit_calo	"lower limit" of "window"-comparator 3 for η.
eta_w4_upper_limit_calo	"upper limit" of "window"-comparator 4 for η.
eta_w4_lower_limit_calo	"lower limit" of "window"-comparator 4 for η.
eta_w5_upper_limit_calo	"upper limit" of "window"-comparator 5 for η.
eta_w5_lower_limit_calo	"lower limit" of "window"-comparator 5 for η.
phi_full_range_calo	boolean to set full range of φ.
phi_w1_upper_limit_calo	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limit_calo	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_calo	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limit_calo	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_calo	"lower limit" of "window"-comparator 2 for φ.
iso_lut_calo	content of LUT (4 bits) for isolation comparison.
muon_object_low	low index of object range (valid numbers: 0..7).
muon_object_high	high index of object range (valid numbers: 0..7, but greater or equal muon_object_low).
pt_ge_mode_muon	'mode-selection' for the p_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
pt_threshold_muon	threshold value for comparison in p_{T}.
nr_eta_windows_muon	integer value for number of η cuts.
eta_w1_upper_limit_muon	"upper limit" of "window"-comparator 1 for η.
eta_w1_lower_limit_muon	"lower limit" of "window"-comparator 1 for η.
eta_w2_upper_limit_muon	"upper limit" of "window"-comparator 2 for η.
eta_w2_lower_limit_muon	"lower limit" of "window"-comparator 2 for η.
eta_w3_upper_limit_muon	"upper limit" of "window"-comparator 3 for η.
eta_w3_lower_limit_muon	"lower limit" of "window"-comparator 3 for η.
eta_w4_upper_limit_muon	"upper limit" of "window"-comparator 4 for η.
eta_w4_lower_limit_muon	"lower limit" of "window"-comparator 4 for η.
eta_w5_upper_limit_muon	"upper limit" of "window"-comparator 5 for η.
eta_w5_lower_limit_muon	"lower limit" of "window"-comparator 5 for η.
phi_full_range_muon	boolean to set full range of φ.

Table 27: Explanation of Listing 10

Item	Explanation
phi_w1_upper_limit_muon	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limit_muon	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_muon	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limit_muon	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_muon	"lower limits" of "window"-comparator 2 for φ.
requested_charge_muon	string for requested charge ("pos" means "positive charge", "neg" means "negative charge" and "ign" means "ignore charge").
qual_lut_muon	content of LUT (16 bits) for quality comparison.
iso_lut_muon	content of LUT (4 bits) for isolation comparison.
upt_cut_muon	boolean for using unconstrained p_T cuts.
upt_upper_limit_muon	"upper limit" of unconstrained p_T.
upt_lower_limit_muon	"lower limit" of unconstrained p_T.
ip_lut_muon	content of LUTs (4 bits) for impact parameter.
diff_eta_upper_limit	"upper limit" of "window"-comparator for comparison of differences in η (hex value).
diff_eta_lower_limit	"lower limit" of "window"-comparator for comparison of differences in η (hex value).
diff_phi_upper_limit	"upper limit" of "window"-comparator for comparison of differences in φ (hex value).
diff_phi_lower_limit	"lower limit" of "window"-comparator for comparison of differences in φ (hex value).
dr_upper_limit	"upper limit" of "window"-comparator for comparison of ΔR^2 (hex value).
dr_lower_limit	"lower limit" of "window"-comparator for comparison of ΔR^2 (hex value).
DETA_DPHI_VECTOR_WIDTH	vector width of $\Delta\eta$ and $\Delta\varphi$ for calculation of ΔR^2.
DETA_DPHI_PRECISION	position after decimal point for $\Delta\eta$ and $\Delta\varphi$.
mass_upper_limit	"upper limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
mass_lower_limit	"lower limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
MASS_PRECISION	position after decimal point for $\frac{M^2}{2}$.
pt1_width	number of bits of pt1.
pt2_width	number of bits of pt2.
MASS_COSH_COS_PRECISION	position after decimal point for $\cosh(\Delta\eta)$ and $\cos(\Delta\varphi)$.
cosh_cos_width	number of bits for the maximum value in the LUT for $\cosh(\Delta\eta)$.
pt_sq_threshold	threshold value for comparison in two-body pt (pt^2).
sin_cos_width_1	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$ of calos.
sin_cos_width_2	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$ of muon.

Table 27: Explanation of Listing 10

Item	Explanation
PT_PRECISION	position after decimal point for pt^2.
PT_SQ_SIN_COS_PRECISION	position after decimal point for $\cos(\varphi)$ and $\sin(\varphi)$.
lhc_clk	clock input (LHC clock).
calo_data_i	calorimeter input data, structure defined with obj_type_calo.
muon_data_i	muon input data.
diff_eta	differences in η, calculated in an instance of module sub_-eta_integer_obj_vs_obj.vhd in top-of-hierarchy module (gtl_-module.vhd), see 3.4.2.
diff_phi	differences in φ, calculated in an instance of module sub_-phi_integer_obj_vs_obj.vhd in top-of-hierarchy module (gtl_-module.vhd).
pt1	calo E_{T} values [from LUT, in $GeV \times 10$].[10]
pt2	muon p_{T} values [from LUT, in $GeV \times 10$].
cosh_deta	$\cosh(\Delta\eta)$ values [from LUT, $\cosh(\Delta\eta) \times 10000$].[11]
cos_dphi	$\cos(\Delta\varphi)$ values [from LUT, $\cosh(\Delta\varphi) \times 10000$].
cos_phi_1	$\cos(\varphi)$ values from LUT for calo.
cos_phi_2	$\cos(\varphi)$ values from LUT for muon.
sin_phi_1	$\sin(\varphi)$ values from LUT for calo.
sin_phi_2	$\sin(\varphi)$ values from LUT for muon.
condition_o	output of condition (routed to Algorithms logic, see 3.4.11).

3.4.9.2.8 Muon Muon Correlation condition module

The muon muon correlation condition module contains two "Single object requirement conditions" for data from different bunch-crossings as one possible mode and a "Double objects requirement condition" for muon objects at same bunch-crossing as a second mode (selection is done by a parameter in the generic list of muon_muon_correlation_condition.vhd named "same_bx"). In the case of a "Double objects requirement condition", requirements for "requested charge correlations" are used and a muon charge correlation module (see 3.4.8.2) is required.
In addition there are "Cuts" for differences in η ($\Delta\eta$) and φ ($\Delta\varphi$), a calculation of ΔR (DR), a calculation of invariant mass with pt or of invariant mass with unconstrained pt (MASS), a calculation of two-body pt.
The differences in η and φ are calculated in bins. These differences in bins are converted to numbers (by LUTs, e.g. MUON_MUON_DIFF_ETA_LUT, MUON_MUON_DIFF_PHI_-LUT), which represents values of differences (multiples of units in η and φ). These values

[10] value 10 from $10^{\mathrm{CALO\_MUON\_INV\_MASS\_PT\_PRECISION}}$
[11] value 10000 from $10^{\mathrm{CALO\_MUON\_INV\_MASS\_COSH\_COS\_PRECISION}}$

given in the LUTs are calculated as floating-point values (based on the scales of η and φ), which are multiplied by a factor and truncated to an integer value. So, in the LUTs we have integer values, the factor is $10^{\text{precision}}$. This "precision" is a parameter given for certain LUTs.

Remark: Definitions of scales (see Tables 14 and 15):

- Muon objects:
- η bin width $= \frac{0.087}{8}$ (bin 0 from $0.5 \times \frac{-0.087}{8}$ to $0.5 \times \frac{+0.087}{8}$)
- ϕ bin width $= \frac{2\pi}{576}$ (bin 0 from 0.0 to $\frac{2\pi}{576}$)

The contents of the LUTs for $\cosh(\Delta\eta)$ (MUON_MUON_COSH_DETA_LUT) and $\cos(\Delta\varphi)$ (MUON_MUON_COS_DPHI_LUT) for invariant mass (formular see 3.4.9.1.2) are created by calculating hyperbolic cosine and cosine, rounding-up at the 4^{th} position after decimal point, and multiplying by 10000 to get integer values.[12]
The contents of the LUTs for $\cos(\varphi)$ (MUON_COS_PHI_LUT) and $\sin(\varphi)$ (MUON_SIN_-PHI_LUT) for two-body pt (formular see 3.4.9.1.4) are created by calculating cosine and sine, rounding-up at the 3^{rd} position after decimal point, and multiplying by 1000 to get integer values.
The condition is complied, if at least one comparison between object parameters and requirements is valid for the both "Single object requirement condition" or the "Double objects requirement condition" and the results of selected "Cuts" are inside of a range (upper and lower limit) or greater/eual a threshold (e.g. for two-body pt). This limits are parts of the "generic" list of the entity declaration of the module and are expressed in hex notation. The limits for $\Delta\eta$ and $\Delta\varphi$ are expressed with a precision of 3^{rd} position after decimal point, for DR and MASS with 1^{st} position after decimal point.

For the VHDL entity declaration of muon muon correlation condition module in `muon_-muon_correlation_condition.vhd`, see Listing 11.

[12] Definition of "`constant MUON_INV_MASS_COSH_COS_PRECISION`" in file `gtl_pkg.vhd`. Value 10000 from $10^{\text{MUON\_INV\_MASS\_COSH\_COS\_PRECISION}}$.

Listing 11: Entity declaration of muon_muon_correlation_condition.vhd

```
entity muon_muon_correlation_condition is
    generic(
        same_bx: boolean;

        deta_cut: boolean;
        dphi_cut: boolean;
        dr_cut: boolean;
        mass_cut: boolean;
        mass_type : natural;
        twobody_pt_cut: boolean;

        muon1_object_low: natural;
        muon1_object_high: natural;
        pt_ge_mode_muon1: boolean;
        pt_threshold_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_muon1: natural;
        eta_w1_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w1_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w2_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w2_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w3_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w3_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w4_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w4_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w5_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w5_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_full_range_muon1: boolean;
        phi_w1_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_muon1: boolean;
        phi_w2_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        requested_charge_muon1: string(1 to 3);
        qual_lut_muon1: std_logic_vector(2**(D_S_I_MUON_V2.qual_high-
            D_S_I_MUON_V2.qual_low+1)-1 downto 0);
        iso_lut_muon1: std_logic_vector(2**(D_S_I_MUON_V2.iso_high-D_S_I_MUON_V2.
            iso_low+1)-1 downto 0);
        upt_cut_muon1 : boolean;
        upt_upper_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
            0);
        upt_lower_limit_muon1: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
            0);
```

```
        ip_lut_muon1: std_logic_vector(2**(D_S_I_MUON_V2.ip_high-D_S_I_MUON_V2.
            ip_low+1)-1 downto 0);

        muon2_object_low: natural;
        muon2_object_high: natural;
        pt_ge_mode_muon2: boolean;
        pt_threshold_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto 0);
        nr_eta_windows_muon2: natural;
        eta_w1_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w1_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w2_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w2_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w3_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w3_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w4_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w4_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w5_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        eta_w5_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_full_range_muon2: boolean;
        phi_w1_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_muon2: boolean;
        phi_w2_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
            downto 0);
        requested_charge_muon2: string(1 to 3);
        qual_lut_muon2: std_logic_vector(2**(D_S_I_MUON_V2.qual_high-
            D_S_I_MUON_V2.qual_low+1)-1 downto 0);
        iso_lut_muon2: std_logic_vector(2**(D_S_I_MUON_V2.iso_high-D_S_I_MUON_V2.
            iso_low+1)-1 downto 0);
        upt_cut_muon2 : boolean;
        upt_upper_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
            0);
        upt_lower_limit_muon2: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
            0);
        ip_lut_muon2: std_logic_vector(2**(D_S_I_MUON_V2.ip_high-D_S_I_MUON_V2.
            ip_low+1)-1 downto 0);

        requested_charge_correlation: string(1 to 2);

        diff_eta_upper_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
        diff_eta_lower_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
```

```
        diff_phi_upper_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
        diff_phi_lower_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

        dr_upper_limit_vector: std_logic_vector(MAX_WIDTH_DR_LIMIT_VECTOR-1
            downto 0);
        dr_lower_limit_vector: std_logic_vector(MAX_WIDTH_DR_LIMIT_VECTOR-1
            downto 0);

        mass_upper_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);
        mass_lower_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);

        pt_width: positive;
        upt_width: positive;
        mass_cosh_cos_precision : positive;
        cosh_cos_width: positive;

        pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
            downto 0);
        sin_cos_width: positive;
        pt_sq_sin_cos_precision : positive

    );
    port(
        lhc_clk: in std_logic;
        muon1_data_i: in muon_objects_array;
        muon2_data_i: in muon_objects_array;
        ls_charcorr_double: in muon_charcorr_double_array;
        os_charcorr_double: in muon_charcorr_double_array;
        diff_eta: in deta_dphi_vector_array;
        diff_phi: in deta_dphi_vector_array;
        pt1 : in diff_inputs_array;
        pt2 : in diff_inputs_array;
        upt1 : in diff_inputs_array;
        upt2 : in diff_inputs_array;
        cosh_deta : in muon_cosh_cos_vector_array;
        cos_dphi : in muon_cosh_cos_vector_array;
        cos_phi_1_integer : in sin_cos_integer_array;
        cos_phi_2_integer : in sin_cos_integer_array;
        sin_phi_1_integer : in sin_cos_integer_array;
        sin_phi_2_integer : in sin_cos_integer_array;
        condition_o: out std_logic
    );
end muon_muon_correlation_condition;
```

Table 28: Explanation of Listing 11

Item	Explanation
same_bx	boolean indicating whether data are from same Bx - 'true' for same Bx.
deta_cut	boolean for using $\Delta\eta$ cut.
dphi_cut	boolean for using $\Delta\varphi$ cut.

Table 28: Explanation of Listing 11

Item	Explanation
dr_cut	boolean for using DR cut.
mass_cut	boolean for using MASS cut.
mass_type	selection of mass type (INVARIANT_MASS_TYPE, INVARIANT_MASS_PT_TYPE, TRANSVERSE_MASS_TYPE or TRANSVERSE_MASS_PT_TYPE are allowed).
muon_object_low	low index of object range (valid numbers: 0..7).
muon_object_high	high index of object range (valid numbers: 0..7, but greater or equal muon_object_low).
pt_ge_mode_muon1	'mode-selection' for the p_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
pt_threshold_muon1	threshold value for comparison in p_{T}.
nr_eta_windows_muon1	integer value for number of η cuts.
eta_w1_upper_limit_muon1	"upper limit" of "window"-comparator 1 for η.
eta_w1_lower_limit_muon1	"lower limit" of "window"-comparator 1 for η.
eta_w2_upper_limit_muon1	"upper limit" of "window"-comparator 2 for η.
eta_w2_lower_limit_muon1	"lower limit" of "window"-comparator 2 for η.
eta_w3_upper_limit_muon1	"upper limit" of "window"-comparator 3 for η.
eta_w3_lower_limit_muon1	"lower limit" of "window"-comparator 3 for η.
eta_w4_upper_limit_muon1	"upper limit" of "window"-comparator 4 for η.
eta_w4_lower_limit_muon1	"lower limit" of "window"-comparator 4 for η.
eta_w5_upper_limit_muon1	"upper limit" of "window"-comparator 5 for η.
eta_w5_lower_limit_muon1	"lower limit" of "window"-comparator 5 for η.
phi_full_range_muon1	boolean to set full range of φ.
phi_w1_upper_limit_muon1	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limit_muon1	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_muon1	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limit_muon1	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_muon1	"lower limits" of "window"-comparator 2 for φ.
requested_charge_muon1	string for requested charge ("pos" means "positive charge", "neg" means "negative charge" and "ign" means "ignore charge").
qual_lut_muon1	content of LUT (16 bits) for quality comparison.
iso_lut_muon1	content of LUT (4 bits) for isolation comparison.
upt_cut_muon1	boolean for using unconstrained p_{T} cuts.
upt_upper_limit_muon1	"upper limit" of unconstrained p_{T}.
upt_lower_limit_muon1	"lower limit" of unconstrained p_{T}.
ip_lut_muon1	content of LUTs (4 bits) for impact parameter.

Table 28: Explanation of Listing 11

Item	Explanation
pt_ge_mode_muon2	'mode-selection' for the p_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
pt_threshold_muon2	threshold value for comparison in p_{T}.
nr_eta_windows_muon2	integer value for number of η cuts.
eta_w1_upper_limit_muon2	"upper limit" of "window"-comparator 1 for η.
eta_w1_lower_limit_muon2	"lower limit" of "window"-comparator 1 for η.
eta_w2_upper_limit_muon2	"upper limit" of "window"-comparator 2 for η.
eta_w2_lower_limit_muon2	"lower limit" of "window"-comparator 2 for η.
eta_w3_upper_limit_muon2	"upper limit" of "window"-comparator 3 for η.
eta_w3_lower_limit_muon2	"lower limit" of "window"-comparator 3 for η.
eta_w4_upper_limit_muon2	"upper limit" of "window"-comparator 4 for η.
eta_w4_lower_limit_muon2	"lower limit" of "window"-comparator 4 for η.
eta_w5_upper_limit_muon2	"upper limit" of "window"-comparator 5 for η.
eta_w5_lower_limit_muon2	"lower limit" of "window"-comparator 5 for η.
phi_full_range_muon2	boolean to set full range of φ.
phi_w1_upper_limit_muon2	"upper limit" of "window"-comparator 1 for φ.
phi_w1_lower_limit_muon2	"lower limit" of "window"-comparator 1 for φ.
phi_w2_ignore_muon2	boolean to ignore "window"-comparator 2 for φ.
phi_w2_upper_limit_muon2	"upper limit" of "window"-comparator 2 for φ.
phi_w2_lower_limit_muon2	"lower limits" of "window"-comparator 2 for φ.
requested_charge_muon2	string for requested charge ("pos" means "positive charge", "neg" means "negative charge" and "ign" means "ignore charge").
qual_lut_muon2	content of LUT (16 bits) for quality comparison.
iso_lut_muon2	content of LUT (4 bits) for isolation comparison.
upt_cut_muon2	boolean for using unconstrained p_{T} cuts.
upt_upper_limit_muon2	"upper limit" of unconstrained p_{T}.
upt_lower_limit_muon2	"lower limit" of unconstrained p_{T}.
ip_lut_muon2	content of LUTs (4 bits) for impact parameter.
requested_charge_correlation	string (2 characters) for requested charge correlation ("ls" means "like sign", "os" means "opposite sign" or "ig" means "ignore").
diff_eta_upper_limit	"upper limit" of "window"-comparator for comparison of differences in η (hex value).
diff_eta_lower_limit	"lower limit" of "window"-comparator for comparison of differences in η (hex value).
diff_phi_upper_limit	"upper limit" of "window"-comparator for comparison of differences in φ (hex value).
diff_phi_lower_limit	"lower limit" of "window"-comparator for comparison of differences in φ (hex value).

Table 28: Explanation of Listing 11

Item	Explanation
`dr_upper_limit`	"upper limit" of "window"-comparator for comparison of ΔR^2 (hex value).
`dr_lower_limit`	"lower limit" of "window"-comparator for comparison of ΔR^2 (hex value).
`DETA_DPHI_VECTOR_WIDTH`	vector width of $\Delta\eta$ and $\Delta\varphi$ for calculation of ΔR^2.
`DETA_DPHI_PRECISION`	position after decimal point for $\Delta\eta$ and $\Delta\varphi$.
`mass_upper_limit`	"upper limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
`mass_lower_limit`	"lower limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
`MASS_PRECISION`	position after decimal point for $\frac{M^2}{2}$.
`pt_width`	number of bits of pt.
`MASS_COSH_COS_PRECISION`	position after decimal point for $\cosh(\Delta\eta)$ and $\cos(\Delta\varphi)$.
`cosh_cos_width`	number of bits for the maximum value in the LUT for $\cosh(\Delta\eta)$.
`pt_sq_threshold`	threshold value for comparison in two-body pt (pt^2).
`sin_cos_width`	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$.
`PT_PRECISION`	position after decimal point for pt^2.
`PT_SQ_SIN_COS_PRECISION`	position after decimal point for $\cos(\varphi)$ and $\sin(\varphi)$.
`lhc_clk`	clock input (LHC clock).
`muon1_data_i`	muon1 input data.
`muon2_data_i`	muon2 input data.
`ls_charcorr_double`	array of "like sign" charge correlation for double condition.
`os_charcorr_double`	array of "opposite sign" charge correlation for double condition.
`diff_eta`	differences in η, calculated in an instance of module `sub_eta_integer_obj_vs_obj.vhd` in top-of-hierarchy module (`gtl_module.vhd`), see 3.4.2.
`diff_phi`	differences in φ, calculated in an instance of module `sub_phi_integer_obj_vs_obj.vhd` in top-of-hierarchy module (`gtl_module.vhd`).
`pt1`	muon1 p_T values [from LUT, in $GeV \times 10$].[13]
`pt2`	muon2 p_T values [from LUT, in $GeV \times 10$].
`upt1`	muon1 unconstrained p_T values [from LUT, in $GeV \times 10$].[14]
`upt2`	muon2 unconstrained p_T values [from LUT, in $GeV \times 10$].
`cosh_deta`	$\cosh(\Delta\eta)$ values [from LUT, $\cosh(\Delta\eta)\times 10000$].[15]
`cos_dphi`	$\cos(\Delta\varphi)$ values [from LUT, $\cosh(\Delta\varphi)\times 10000$].
`cos_phi_1`	$\cos(\varphi)$ values from LUT for muon.
`cos_phi_2`	$\cos(\varphi)$ values from LUT for muon (different to cos_phi_1, when data from different bunch-crossings).

[13] value 10 from $10^{\mathrm{MUON\_MUON\_INV\_MASS\_PT\_PRECISION}}$

[14] value 10 from $10^{\mathrm{MUON\_MUON\_INV\_MASS\_PT\_PRECISION}}$

[15] value 10000 from $10^{\mathrm{MUON\_MUON\_INV\_MASS\_COSH\_COS\_PRECISION}}$

Table 28: Explanation of Listing 11

Item	Explanation
`sin_phi_1`	$\sin(\varphi)$ values from LUT for muon.
`sin_phi_2`	$\sin(\varphi)$ values from LUT for muon (different to sin_phi_1, when data from different bunch-crossings).
`condition_o`	output of condition (routed to Algorithms logic, see 3.4.11).

3.4.9.2.9 Muon Muon Correlation condition module for Invariant Mass Divided by ΔR

The muon muon correlation condition module for invariant mass divided by ΔR contains two "Single object requirement conditions" from different bunch-crossings as one possible mode and a "Double objects requirement condition" for objects of same bunch-crossing as a second mode (selection is done by a parameter in the generic list of `muon_muon_mass_div_dr_-condition.vhd` named "same_bx").
The calculation of *invariant mass divided by* ΔR *of two objects* is done in an own module outside of the condition (`mass_div_dr_calculator.vhd`), see 3.4.9.1.5. This module is instantiated once for every object type bunch-crossing combination.
The comparison of calculated values and threshold is done inside the module (texttttmuon_-muon_mass_div_dr_condition.vhd).
In the TME there is one threshold for M/ΔR: "greater/equal threshold", given in GeV (floating point notation).
The threshold for comparison with $\frac{M^2}{2} \times (1/\Delta R^2)$ (no square root in VHDL) is provided by VHDL-Producer.
No other correlation cuts, except "charge correlation", available in this condition type.

3.4.9.2.10 Muon Correlation condition module for Invariant Mass with Three Objects

The muon correlation condition module for invariant mass with three objects (`muon_mass_-3_obj_condition.vhd`) contains a "Triple objects requirement condition" for objects of same type and same bunch-crossing.
In addition a "Cut" for calculation of *invariant mass with three objects* (see 3.4.9.1.6) is mandatory.
No other correlation cuts, except "charge correlation", available in this condition type.

3.4.9.2.11 Muon Esums Correlation condition module

The muon esums correlation condition module (`muon_esums_correlation_condition.vhd`) contains two "Single object requirement conditions", one of muon objects and one of esums (ET_{miss}, ET^{HF}_{miss} or HT_{miss}).
In addition there are "Cuts" for differences in φ ($\Delta\varphi$) or a calculation of mass (MASS) for Transverse mass or Transverse mass with two-body pt.

The differences in φ are calculated in bins. These differences in bins are converted to numbers (by LUTs, e.g. MUON_ETM_DIFF_PHI_LUT, ...), which represents values of differences (multiples of units in φ). These values given in the LUTs are calculated as floating-point values (based on the scales of φ), which are multiplied by a factor and truncated to an integer value. So, in the LUTs we have integer values, the factor is $10^{\text{precision}}$.
Because of the different scales of muon objects and esums in φ, there are LUTs for conversion the esums bins to muon bins (in `gtl_pkg.vhd`: e.g. ETM_PHI_CONV_2_MUON_PHI_-LUT).

Remark:
The center value of bins are used as reference value for conversion. The content of LUT is calculated with formular:
"converted-esums-phi[bin] = esums-phi[bin] $\times$ 4 + 2"
(see Figure 14). The conversion calculations are preliminary, others may be proposed.

Definitions of scales:

- ET_{miss}, ET^{HF}_{miss} or HT_{miss}:
  - ϕ bin width = $\frac{2\pi}{144}$ (bin 0 from 0.0 to $\frac{2\pi}{144}$)
- Muon objects:
  - ϕ bin width = $\frac{2\pi}{576}$ (bin 0 from 0.0 to $\frac{2\pi}{576}$)

The contents of the LUTs for $\cos(\Delta\varphi)$ (MU_ETM_COS_DPHI_LUT, ...) for Transverse mass (formular see 3.4.9.1.3) are created by calculating cosine, rounding-up at the 4$^{\text{th}}$ position after decimal point and multiplying by 10000 ($10^{\text{MU\_ETM\_COSH\_COS\_PRECISION}}$) to get integer values.[16]
The contents of the LUTs for $\cos(\varphi)$ (CALO_COS_PHI_LUT and MUON_COS_PHI_LUT) and $\sin(\varphi)$ (CALO_SIN_PHI_LUT and MUON_SIN_PHI_LUT) for two-body pt (formular see 3.4.9.1.4) are created by calculating cosine and sine, rounding-up at the 3$^{\text{rd}}$ position after decimal point and multiplying by 1000 to get integer values.
The condition is complied, if at least one comparison between object parameters and requirements is valid for the both "Single object requirement condition" and the results of selected "Cuts" are inside of a range (upper and lower limit). This limits are parts of the "generic" list of the entity declaration of the module and are expressed in hex notation. The limits for $\Delta\varphi$ are expressed with a precision of 3$^{\text{rd}}$ position after decimal point, for MASS with 1$^{\text{st}}$ position after decimal point.

For VHDL entity declaration for muon esums correlation condition module in `muon_esums_-correlation_condition.vhd`, see Listing 12.

Listing 12: Entity declaration of `muon_esums_correlation_condition.vhd`

```
entity muon_esums_correlation_condition is
```

[16]Definition of "`constant MU_ETM_COSH_COS_PRECISION` ..." and "`constant CALO_PHI_-CONV_2_MUON_PHI_LUT` ..." in file `gtl_pkg.vhd`.

```
generic(

    dphi_cut: boolean;
    mass_cut: boolean;
    mass_type : natural;
    twobody_pt_cut: boolean;

    muon_object_low: natural;
    muon_object_high: natural;
    pt_ge_mode_muon: boolean;
    pt_threshold_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto 0);
    nr_eta_windows_muon : natural;
    eta_w1_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w1_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w2_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w2_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w3_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w3_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w4_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w4_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w5_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    eta_w5_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    phi_full_range_muon : boolean;
    phi_w1_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    phi_w1_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    phi_w2_ignore_muon : boolean;
    phi_w2_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    phi_w2_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1
        downto 0);
    requested_charge_muon: string(1 to 3);
    qual_lut_muon: std_logic_vector(2**(D_S_I_MUON_V2.qual_high-D_S_I_MUON_V2
        .qual_low+1)-1 downto 0);
    iso_lut_muon: std_logic_vector(2**(D_S_I_MUON_V2.iso_high-D_S_I_MUON_V2.
        iso_low+1)-1 downto 0);
    upt_cut_muon : boolean;
    upt_upper_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
        0);
    upt_lower_limit_muon: std_logic_vector(MAX_MUON_TEMPLATES_BITS-1 downto
        0);
    ip_lut_muon: std_logic_vector(2**(D_S_I_MUON_V2.ip_high-D_S_I_MUON_V2.
        ip_low+1)-1 downto 0);

    et_ge_mode_esums: boolean;
    obj_type_esums: natural := ETM_TYPE;
```

```
        et_threshold_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1 downto 0)
            ;
        phi_full_range_esums: boolean;
        phi_w1_upper_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);
        phi_w1_lower_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);
        phi_w2_ignore_esums: boolean;
        phi_w2_upper_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);
        phi_w2_lower_limit_esums: std_logic_vector(MAX_ESUMS_TEMPLATES_BITS-1
            downto 0);

        diff_phi_upper_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);
        diff_phi_lower_limit_vector: std_logic_vector(
            MAX_WIDTH_DETA_DPHI_LIMIT_VECTOR-1 downto 0);

        mass_upper_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);
        mass_lower_limit_vector: std_logic_vector(MAX_WIDTH_MASS_LIMIT_VECTOR-1
            downto 0);

        pt1_width: positive;
        pt2_width: positive;
        mass_cosh_cos_precision : positive;
        cosh_cos_width: positive;

        pt_sq_threshold_vector: std_logic_vector(MAX_WIDTH_TBPT_LIMIT_VECTOR-1
            downto 0);
        sin_cos_width: positive;
        pt_sq_sin_cos_precision : positive

    );
    port(
        lhc_clk: in std_logic;
        muon_data_i: in muon_objects_array;
        esums_data_i: in std_logic_vector(MAX_ESUMS_BITS-1 downto 0);
        diff_phi: in deta_dphi_vector_array;
        pt1 : in diff_inputs_array;
        pt2 : in diff_inputs_array;
        cos_dphi : in calo_muon_cosh_cos_vector_array;
        cos_phi_1_integer : in sin_cos_integer_array;
        cos_phi_2_integer : in sin_cos_integer_array;
        sin_phi_1_integer : in sin_cos_integer_array;
        sin_phi_2_integer : in sin_cos_integer_array;
        condition_o: out std_logic
    );
end muon_esums_correlation_condition;
```

Table 29: Explanation of Listing 11

Item	Explanation
`dphi_cut`	boolean for using $\Delta\varphi$ cut.
`mass_cut`	boolean for using MASS cut.
`mass_type`	selection of mass type (TRANSVERSE_MASS_TYPE or TRANSVERSE_MASS_PT_TYPE are allowed).
`muon_object_low`	low index of object range (valid numbers: 0..7).
`muon_object_high`	high index of object range (valid numbers: 0..7, but greater or equal muon_object_low).
`pt_ge_mode_muon`	'mode-selection' for the p_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
`pt_threshold_muon`	threshold value for comparison in p_{T}.
`nr_eta_windows_muon`	integer value for number of η cuts.
`eta_w1_upper_limit_muon`	"upper limit" of "window"-comparator 1 for η.
`eta_w1_lower_limit_muon`	"lower limit" of "window"-comparator 1 for η.
`eta_w2_upper_limit_muon`	"upper limit" of "window"-comparator 2 for η.
`eta_w2_lower_limit_muon`	"lower limit" of "window"-comparator 2 for η.
`eta_w3_upper_limit_muon`	"upper limit" of "window"-comparator 3 for η.
`eta_w3_lower_limit_muon`	"lower limit" of "window"-comparator 3 for η.
`eta_w4_upper_limit_muon`	"upper limit" of "window"-comparator 4 for η.
`eta_w4_lower_limit_muon`	"lower limit" of "window"-comparator 4 for η.
`eta_w5_upper_limit_muon`	"upper limit" of "window"-comparator 5 for η.
`eta_w5_lower_limit_muon`	"lower limit" of "window"-comparator 5 for η.
`phi_full_range_muon`	boolean to set full range of φ.
`phi_w1_upper_limit_muon`	"upper limit" of "window"-comparator 1 for φ.
`phi_w1_lower_limit_muon`	"lower limit" of "window"-comparator 1 for φ.
`phi_w2_ignore_muon`	boolean to ignore "window"-comparator 2 for φ.
`phi_w2_upper_limit_muon`	"upper limit" of "window"-comparator 2 for φ.
`phi_w2_lower_limit_muon`	"lower limits" of "window"-comparator 2 for φ.
`requested_charge_muon`	string for requested charge ("pos" means "positive charge", "neg" means "negative charge" and "ign" means "ignore charge").
`qual_lut_muon`	content of LUT (16 bits) for quality comparison.
`iso_lut_muon`	content of LUT (4 bits) for isolation comparison.
`upt_cut_muon`	boolean for using unconstrained p_{T} cuts.
`upt_upper_limit_muon`	"upper limit" of unconstrained p_{T}.
`upt_lower_limit_muon`	"lower limit" of unconstrained p_{T}.
`ip_lut_muon`	content of LUTs (4 bits) for impact parameter.

Table 29: Explanation of Listing 11

Item	Explanation
`et_ge_mode_esums`	'mode-selection' for the E_{T} comparator. Valid strings are 'true' and 'false' (type is boolean), 'true' means comparator works on greater/equal, 'false' means equal (for tests only)
`obj_type_esums`	selection of esums type (ETM_TYPE or HTM_TYPE are allowed)
`et_threshold_esums`	threshold value for comparison in E_{T}.
`phi_full_range_esums`	boolean to set full range of φ.
`phi_w1_upper_limit_esums`	"upper limit" of "window"-comparator 1 for φ.
`phi_w1_lower_limit_esums`	"lower limit" of "window"-comparator 1 for φ.
`phi_w2_ignore_esums`	boolean to ignore "window"-comparator 2 for φ.
`phi_w2_upper_limit_esums`	"upper limit" of "window"-comparator 2 for φ.
`phi_w2_lower_limit_esums`	"lower limits" of "window"-comparator 2 for φ.
`diff_phi_upper_limit`	"upper limit" of "window"-comparator for comparison of differences in φ (hex value).
`diff_phi_lower_limit`	"lower limit" of "window"-comparator for comparison of differences in φ (hex value).
`DETA_DPHI_VECTOR_WIDTH`	vector width of $\Delta\varphi$.
`DETA_DPHI_PRECISION`	position after decimal point for $\Delta\varphi$.
`mass_upper_limit`	"upper limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
`mass_lower_limit`	"lower limit" of "window"-comparator for comparison of $\frac{M^2}{2}$ (hex value).
`MASS_PRECISION`	position after decimal point for $\frac{M^2}{2}$.
`pt1_width`	number of bits of pt1.
`pt2_width`	number of bits of pt2.
`MASS_COSH_COS_PRECISION`	position after decimal point for $\cos(\Delta\varphi)$.
`cosh_cos_width`	number of bits for the maximum value in the LUT for $\cos(\Delta\varphi)$.
`pt_sq_threshold`	threshold value for comparison in two-body pt (pt^2).
`sin_cos_width_1`	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$ of muon.
`sin_cos_width_2`	number of bits for the maximum value in the LUT for $\cos(\varphi)$ and $\sin(\varphi)$ of esums.
`PT_PRECISION`	position after decimal point for pt^2.
`PT_SQ_SIN_COS_PRECISION`	position after decimal point for $\cos(\varphi)$ and $\sin(\varphi)$.
`lhc_clk`	clock input (LHC clock).
`muon_data_i`	muon input data.
`esums_data_i`	esums input data, structure defined with `obj_type_esums`.
`diff_phi`	differences in φ, calculated in an instance of module `sub_phi_integer_obj_vs_obj.vhd` in top-of-hierarchy module (`gtl_module.vhd`).
`pt1`	muon E_{T} values [from LUT, in $GeV \times 10$].
`pt2`	esums E_{T} values [from LUT, in $GeV \times 10$].

Table 29: Explanation of Listing 11

Item	Explanation
`cos_dphi`	$\cos(\Delta\varphi)$ values from LUT.
`cos_phi_1`	$\cos(\varphi)$ values from LUT for muon.
`cos_phi_2`	$\cos(\varphi)$ values from LUT for esums.
`sin_phi_1`	$\sin(\varphi)$ values from LUT for muon.
`sin_phi_2`	$\sin(\varphi)$ values from LUT for esums.
`condition_o`	output of condition (routed to Algorithms logic, see 3.4.11).

3.4.10 External Conditions

Maximal 256 External Conditions are possible in Global Trigger. They are provided as inputs in the Algorithms logic of μGTL. External Conditions will include the "Technical Trigger" of the legacy system.

3.4.11 Algorithms logic

The outputs of all the instantiated conditions are combined in the Algorithms logic with boolean algebra given by TME for every single Algorithm. These Algorithms are registered and provided as inputs for Final Decision Logic.

3.5 VHDL-Templates for VHDL-Producer

The VHDL-Producer software generates a set of VHDL files (`gtl_module_instances.vhd`, `gtl_module_signals.vhd`, `ugt_constants.vhd and algo_index.vhd`) which contain the requirements of a certain L1Menu, set in the TME. The templates are created in "Jinja2" (a template engine for python). All the templates described in this section, are located in https://github.com/cms-l1-globaltrigger/tm-vhdlproducer/tree/master/tmVhdlProducer/templates/vhdl.

3.5.1 Global Trigger Logic module - template for VHDL-Producer

In the Trigger Menu Editor one can generate a set of conditions, which are instantiated in the top-of-hierarchy module (`gtl_module.vhd`). This is done by reading a VHDL-template of a condition module and replacing substitution parameters with values given in VHDL Producer.
In the template of Global Trigger Logic module (`gtl_module_instances.vhd`), the inserting of instances is specified by Jinja2 substitution parameters.

3.5.1.1 Instances

- *%- include "instances/instance_correlation_conditions_pt_eta_phi.vhd.j2"%* => replace with strings defined in template:
  `instance_correlation_conditions_pt_eta_phi.vhd.j2`.
  Instantiations of loops for pt, eta and phi signals for correlation conditions (used for DETA, DPHI and DR) - once for every object type in certain bunch-crossing used in correlation conditions.
  - Parameters in template
    `instance_correlation_conditions_pt_eta_phi.vhd.j2`:
    {{o.type}} => object type used in a correlation condition.
    {{o.bx}} => bunch-crossing within ± 2 of object type used in a correlation condition.

- *%- include "instances/instance_correlation_conditions_eta_phi_conversion.vhd.j2"%* => replace with strings defined in template:
  `instance_correlation_conditions_eta_phi_conversion.vhd.j2`.
  Instantiations of loops for eta and phi converted signals (to muon scale) for calo-muon correlation conditions - once for every calo object type in certain bunch-crossing used in calo-muon correlation conditions
  - Parameters in template
    `instance_correlation_conditions_eta_phi_conversion.vhd.j2`:
    {{o.type}} => object type used in a correlation condition.
    {{o.bx}} => bunch-crossing within ± 2 of object type used in a correlation condition.

- *%- include "instances/instances/instance_correlation_conditions_differences.vhd.j2"%* => replace with strings defined in template:
  `instance_correlation_conditions_differences.vhd.j2`.
  Instantiations of differences for correlation conditions (used for DETA, DPHI and DR) - once for correlation conditions with two object types in certain bunch-crossings
  - Parameters in template
    `instance_correlation_conditions_differences.vhd.j2`:
    {{o1.type}} => object type of object 1 of correlation condition.
    {{o2.type}} => object type of object 2 of correlation condition.
    {{o1.bx}} => bunch-crossing within ±2 of object 1.
    {{o2.bx}} => bunch-crossing within ±2 of object 2.

- *%- include "instances/instance_correlation_conditions_inv_mass.vhd.j2"%* => replace with strings defined in template:
  `instance_correlation_conditions_inv_mass.vhd.j2`.
  Instantiations of cosh-deta and cos-dphi LUTs for correlation conditions (used for invariant mass) - once for correlation conditions with two object types in certain bunch-crossings
  - Parameters in template
    `instance_correlation_conditions_inv_mass.vhd.j2`:
    {{o1.type}} => object type of object 1 of correlation condition.
    {{o2.type}} => object type of object 2 of correlation condition.
    {{o1.bx}} => bunch-crossing within ±2 of object 1.
    {{o2.bx}} => bunch-crossing within ±2 of object 2.

- *%- include "instances/instance_muon_charge_correlation.vhd.j2"%* => replace with string defined in template:
  `instance_muon_charge_correlations.vhd.j2` only once in a certain bunch-crossing, if there is at least one DoubleMuon, TripleMuon or QuadMuon condition. Instantiations of muon charge correlations.
  - Parameters in template
    `instance_muon_charge_correlations.vhd`:
    {{o.bx}} => bunch-crossing within ±2.

- *%- include "instances/instance_calo_condition.vhd.j2"%* => replace with strings defined in template:
  `instance_calo_condition.vhd.j2`.

- *%- include "instances/instance_muon_condition.vhd.j2"%* => replace with strings defined in template:
  `instance_muon_condition.vhd.j2`.

- *%- include "instances/instance_esums_condition.vhd.j2"%* => replace with strings defined in template:
  `instance_esums_condition.vhd.j2`.

- *%- include "instances/instance_calo_calo_correlation_condition.vhd.j2"%* => replace with strings defined in template:
  `instance_calo_calo_correlation_condition.vhd.j2`.

- *%- include "instances/instance_calo_muon_correlation_condition.vhd.j2"%* => replace with strings defined in template:
  `instance_calo_muon_correlation_condition.vhd.j2`.

- *%- include "instances/instance_muon_muon_correlation_condition.vhd.j2"%* => replace with strings defined in template:
  `instance_muon_muon_correlation_condition.vhd.j2`.

- *%- include "instances/instance_algorithm.vhd.j2"%* => replace with strings defined in template:
  `instance_algorithm.vhd.j2`.

3.5.1.2 Signal declarations

In the template of Global Trigger Logic module (`gtl_module_signals.vhd`), the inserting of signal declarations is specified by Jinja2 substitution parameters.

- *%- include "signals/correlation_conditions_pt_eta_phi_cos_sin_phi.vhd.j2"%* => replace with string defined in template:
  `signal_correlation_conditions_pt_eta_phi_cos_sin_phi.vhd.j2`.
  Insert template as often as an object type at a certain bunch-crossing is used in a correlation condition.
  - Parameters in template
    `signal_correlation_conditions_pt_eta_phi_cos_sin_phi.vhd.j2`:
    {{o.type}} => object type used in a correlation condition.
    {{o.bx}} => bunch-crossing within ±2 of object type used in a correlation condition.

- *%- include "signals/signal_correlation_conditions_differences.vhd.j2"%* => replace with string defined in template:
  `signal_correlation_conditions_differences.vhd.j2`.
  Insert template once for correlation conditions of different object types and Bx combinations.

- Parameters in template
  `signal_correlation_conditions_differences.vhd.j2`:
  {{o1.type}} => object type of objects 1 used in a correlation condition.
  {{o2.type}} => object type of objects 2 used in a correlation condition.
  {{o1.bx}} => bunch-crossing within ±2 of objects 1.
  {{o2.bx}} => bunch-crossing within ±2 of objects 2.

- *%- include "signals/signal_muon_charge_correlations.vhd.j2"%* => replace with string defined in template:
  `signal_muon_charge_correlations.vhd` for at least one occurance of a DoubleMuon, TripleMuon or QuadMuon condition in a certain bunch-crossing.
  - Parameters in template
    `signal_muon_charge_correlations.vhd.j2`:
    {{bx1}} => bunch-crossing within ±2 of objects 1.
    {{bx2}} => bunch-crossing within ±2 of objects 2.

- Parameters in template
  `gtl_module_signals.vhd`:
  {{ConditionName}} => unique condition name given by physicist to TME.
  {{AlgoName}} => unique algorithm name given by physicist to TME.

3.5.2 Global Trigger Logic package module - template for VHDL-Producer

The Global Trigger Logic package module VHDL template (`gtl_pkg_tpl.vhd`) has parts which are replaced by the content of (`ugt_constants.vhd`), the inserting of constants is done by Jinja2 substitution parameters.

3.5.3 Algorithms mapping module - template for VHDL-Producer

The template of Algorithms mapping module VHDL template (`instances/algo_mapping_rop_tpl.vhd`) has parts which are replaced by the content of (`algo_index.vhd`), the inserting is done by Jinja2 substitution parameters.

3.5.4 Calorimeter conditions - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating
`calo_conditions.vhd` is given below (see Listing 13).

Listing 13: Template of `calo_conditions.vhd` for VHDL-Producer

```
{%- block instantiate_calo_condition %}
  {%- set o1 = condition.objects[0] %}
```

```
  {%- set o2 = condition.objects[1] %}
  {%- set o3 = condition.objects[2] %}
  {%- set o4 = condition.objects[3] %}

{{ condition.vhdl_signal }}_i: entity work.calo_conditions
    generic map({{ o1.sliceLow }}, {{ o1.sliceHigh }}, {{ o2.sliceLow }}, {{ o2.
        sliceHigh }}, {{ o3.sliceLow }}, {{ o3.sliceHigh }}, {{ o4.sliceLow }}, {{
         o4.sliceHigh }},
        {{ condition.nr_objects }}, {{ o1.operator }}, {{ o1.type }}_TYPE,
        (X"{{ o1.threshold|X04 }}", X"{{ o2.threshold|X04 }}", X"{{ o3.threshold|
            X04 }}", X"{{ o4.threshold|X04 }}"),
        ({{ o1.etaNrCuts }}, {{ o2.etaNrCuts }}, {{ o3.etaNrCuts }}, {{ o4.
            etaNrCuts }}),
        (X"{{ o1.etaW1UpperLimit|X04 }}", X"{{ o2.etaW1UpperLimit|X04 }}", X"{{
            o3.etaW1UpperLimit|X04 }}", X"{{ o4.etaW1UpperLimit|X04 }}"), (X"{{ o1
            .etaW1LowerLimit|X04 }}", X"{{ o2.etaW1LowerLimit|X04 }}", X"{{ o3.
            etaW1LowerLimit|X04 }}", X"{{ o4.etaW1LowerLimit|X04 }}"),
        (X"{{ o1.etaW2UpperLimit|X04 }}", X"{{ o2.etaW2UpperLimit|X04 }}", X"{{
            o3.etaW2UpperLimit|X04 }}", X"{{ o4.etaW2UpperLimit|X04 }}"), (X"{{ o1
            .etaW2LowerLimit|X04 }}", X"{{ o2.etaW2LowerLimit|X04 }}", X"{{ o3.
            etaW2LowerLimit|X04 }}", X"{{ o4.etaW2LowerLimit|X04 }}"),
        (X"{{ o1.etaW3UpperLimit|X04 }}", X"{{ o2.etaW3UpperLimit|X04 }}", X"{{
            o3.etaW3UpperLimit|X04 }}", X"{{ o4.etaW3UpperLimit|X04 }}"), (X"{{ o1
            .etaW3LowerLimit|X04 }}", X"{{ o2.etaW3LowerLimit|X04 }}", X"{{ o3.
            etaW3LowerLimit|X04 }}", X"{{ o4.etaW3LowerLimit|X04 }}"),
        (X"{{ o1.etaW4UpperLimit|X04 }}", X"{{ o2.etaW4UpperLimit|X04 }}", X"{{
            o3.etaW4UpperLimit|X04 }}", X"{{ o4.etaW4UpperLimit|X04 }}"), (X"{{ o1
            .etaW4LowerLimit|X04 }}", X"{{ o2.etaW4LowerLimit|X04 }}", X"{{ o3.
            etaW4LowerLimit|X04 }}", X"{{ o4.etaW4LowerLimit|X04 }}"),
        (X"{{ o1.etaW5UpperLimit|X04 }}", X"{{ o2.etaW5UpperLimit|X04 }}", X"{{
            o3.etaW5UpperLimit|X04 }}", X"{{ o4.etaW5UpperLimit|X04 }}"), (X"{{ o1
            .etaW5LowerLimit|X04 }}", X"{{ o2.etaW5LowerLimit|X04 }}", X"{{ o3.
            etaW5LowerLimit|X04 }}", X"{{ o4.etaW5LowerLimit|X04 }}"),
        ({{ o1.phiFullRange }}, {{ o2.phiFullRange }}, {{ o3.phiFullRange }}, {{
            o4.phiFullRange }}),
        (X"{{ o1.phiW1UpperLimit|X04 }}", X"{{ o2.phiW1UpperLimit|X04 }}", X"{{
            o3.phiW1UpperLimit|X04 }}", X"{{ o4.phiW1UpperLimit|X04 }}"), (X"{{ o1
            .phiW1LowerLimit|X04 }}", X"{{ o2.phiW1LowerLimit|X04 }}", X"{{ o3.
            phiW1LowerLimit|X04 }}", X"{{ o4.phiW1LowerLimit|X04 }}"),
        ({{ o1.phiW2Ignore }}, {{ o2.phiW2Ignore }}, {{ o3.phiW2Ignore }}, {{ o4.
            phiW2Ignore }}),
        (X"{{ o1.phiW2UpperLimit|X04 }}", X"{{ o2.phiW2UpperLimit|X04 }}", X"{{
            o3.phiW2UpperLimit|X04 }}", X"{{ o4.phiW2UpperLimit|X04 }}"), (X"{{ o1
            .phiW2LowerLimit|X04 }}", X"{{ o2.phiW2LowerLimit|X04 }}", X"{{ o3.
            phiW2LowerLimit|X04 }}", X"{{ o4.phiW2LowerLimit|X04 }}"),
        (X"{{ o1.isolationLUT|X01 }}", X"{{ o2.isolationLUT|X01 }}", X"{{ o3.
            isolationLUT|X01 }}", X"{{ o4.isolationLUT|X01 }}"),
    {%- if condition.twoBodyPt.enabled == "true" %}
        true, {{ o1.type|upper }}_PT_VECTOR_WIDTH, X"{{ condition.twoBodyPt.
            threshold|X16 }}",
        CALO_SIN_COS_VECTOR_WIDTH, {{ o1.type|upper }}_{{ o1.type|upper }}
            _SIN_COS_PRECISION
    {%- else %}
        false
    {%- endif %}
    )
    port map(lhc_clk, {{ o1.type|lower }}_bx_{{ o1.bx }},
```

```
    {%- if condition.twoBodyPt.enabled == "true" %}
        {{ condition.vhdl_signal }},
        {{ o1.type|lower }}_pt_vector_bx_{{ o1.bx }}, {{ o1.type|lower }}
            _cos_phi_bx_{{ o1.bx }}, {{ o1.type|lower }}_sin_phi_bx_{{ o1.bx }});
    {%- else %}
        {{ condition.vhdl_signal }});
    {%- endif %}

{% endblock instantiate_calo_condition %}
{# eof #}
```

Table 30: Explanation of Listing 13

Item	Explanation
`vhdl_signal`	condition name.
`sliceLow`	low value of an object slice.
`sliceHigh`	high value of an object slice.
`nr_objects`	valid values are 1 (for single), 2 (double), 3 (triple) and 4 (quad) - depending on condition type.
`operator`	valid strings are 'true' and 'false' - 'true' for greater/equal-, 'false' for equal-mode of E_{T} comparator.
`type`	valid strings are 'EG', 'JET', and 'TAU'.
`threshold`	array with requirements for et_thresholds (4x 16-bit values, hex notation). Valid values depending on the scales of E_{T}.
`nrEtaWindows`	array to set number of η cuts.
`etaW1UpperLimit, ...`	arrays of limits for "window"-comparators for η (4x 16-bit values, hex notation). Valid values depending on the scales for η.
`phiFullRange`	array to set full range of φ (4x boolean).
`phiW1UpperLimit, ...`	arrays of limits for "window"-comparators for φ (4x 16-bit values, hex notation). Valid values depending on the scales for φ.
`[phiW2Ignore`	array to ignore "window"-comparator 2 of φ (4x boolean).
`isolationLUT`	array for LUTs (4 bits) of isolation).
`twoBodyPt.threshold`	value of threshold for two-body pt comparison.
`bx`	valid strings are 'p2', 'p1', '0', 'm1' and 'm2'. This indicates which data in a range of plus/minus 2 bunch-crossing is used in the condition.

3.5.5 Energy sum quantities conditions - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `esums_conditions.vhd` is given below (see Listing 14).

Listing 14: Template of `esums_conditions.vhd` for VHDL-Producer

```
{%- block instantiate_esums_condition %}
  {%- set o = condition.objects[0] %}
    {%- if o.is_esums_type  %}
{{ condition.vhdl_signal }}_i: entity work.esums_conditions
    generic map({{ o.operator }}, {{ o.type|upper }}_TYPE,
    {%- if o.hasCount  %}
        X"{{ o.count|X04 }}",
    {%- else %}
        X"{{ o.threshold|X04 }}",
    {%- endif %}
        {{ o.phiFullRange }}, X"{{ o.phiW1UpperLimit|X04 }}", X"{{ o.
            phiW1LowerLimit|X04 }}",
        {{ o.phiW2Ignore }}, X"{{ o.phiW2UpperLimit|X04 }}", X"{{ o.
            phiW2LowerLimit|X04 }}"
        )
    port map(lhc_clk, {{ o.type|lower }}_bx_{{ o.bx }}, {{ condition.vhdl_signal
        }});
    {%- endif %}
{% endblock instantiate_esums_condition %}
{# eof #}
```

Table 31: Explanation of Listing 14

Item	Explanation
`vhdl_signal`	condition name.
`operator`	valid strings are 'true' and 'false' - 'true' for greater/equal-, 'false' for equal-mode of E_{T} comparator.
`type`	valid strings are 'EG', 'JET', and 'TAU'.
`threshold`	array with requirements for et_thresholds (4x 16-bit values, hex notation). Valid values depending on the scales of E_{T}.
`phiFullRange`	array to set full range of φ (4x boolean).
`phiW1UpperLimit, ...`	arrays of limits for "window"-comparators for φ (4x 16-bit values, hex notation). Valid values depending on the scales for φ.
`phiW2Ignore`	array to ignore "window"-comparator 2 of φ (4x boolean).
`bx`	valid strings are 'p2', 'p1', '0', 'm1' and 'm2'. This indicates which data in a range of plus/minus 2 bunch-crossing is used in the condition.

3.5.6 Muon conditions - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `muon_conditions.vhd` is given below (see Listing 15).

Listing 15: Template of `muon_conditions.vhd` for VHDL-Producer

```
{%- block instantiate_muon_condition %}
  {%- set o1 = condition.objects[0] %}
  {%- set o2 = condition.objects[1] %}
  {%- set o3 = condition.objects[2] %}
  {%- set o4 = condition.objects[3] %}
  {%- set bx = o1.bx %}
{{ condition.vhdl_signal }}_i: entity work.muon_conditions
    generic map({{ o1.sliceLow }}, {{ o1.sliceHigh }}, {{ o2.sliceLow }}, {{ o2.
        sliceHigh }}, {{ o3.sliceLow }}, {{ o3.sliceHigh }}, {{ o4.sliceLow }}, {{
         o4.sliceHigh }},
        {{ condition.nr_objects }}, {{ o1.operator }},
        (X"{{ o1.threshold|X04 }}", X"{{ o2.threshold|X04 }}", X"{{ o3.threshold|
            X04 }}", X"{{ o4.threshold|X04 }}"),
        ({{ o1.etaNrCuts }}, {{ o2.etaNrCuts }}, {{ o3.etaNrCuts }}, {{ o4.
            etaNrCuts }}),
        (X"{{ o1.etaW1UpperLimit|X04 }}", X"{{ o2.etaW1UpperLimit|X04 }}", X"{{
            o3.etaW1UpperLimit|X04 }}", X"{{ o4.etaW1UpperLimit|X04 }}"), (X"{{ o1
            .etaW1LowerLimit|X04 }}", X"{{ o2.etaW1LowerLimit|X04 }}", X"{{ o3.
            etaW1LowerLimit|X04 }}", X"{{ o4.etaW1LowerLimit|X04 }}"),
        (X"{{ o1.etaW2UpperLimit|X04 }}", X"{{ o2.etaW2UpperLimit|X04 }}", X"{{
            o3.etaW2UpperLimit|X04 }}", X"{{ o4.etaW2UpperLimit|X04 }}"), (X"{{ o1
            .etaW2LowerLimit|X04 }}", X"{{ o2.etaW2LowerLimit|X04 }}", X"{{ o3.
            etaW2LowerLimit|X04 }}", X"{{ o4.etaW2LowerLimit|X04 }}"),
        (X"{{ o1.etaW3UpperLimit|X04 }}", X"{{ o2.etaW3UpperLimit|X04 }}", X"{{
            o3.etaW3UpperLimit|X04 }}", X"{{ o4.etaW3UpperLimit|X04 }}"), (X"{{ o1
            .etaW3LowerLimit|X04 }}", X"{{ o2.etaW3LowerLimit|X04 }}", X"{{ o3.
            etaW3LowerLimit|X04 }}", X"{{ o4.etaW3LowerLimit|X04 }}"),
        (X"{{ o1.etaW4UpperLimit|X04 }}", X"{{ o2.etaW4UpperLimit|X04 }}", X"{{
            o3.etaW4UpperLimit|X04 }}", X"{{ o4.etaW4UpperLimit|X04 }}"), (X"{{ o1
            .etaW4LowerLimit|X04 }}", X"{{ o2.etaW4LowerLimit|X04 }}", X"{{ o3.
            etaW4LowerLimit|X04 }}", X"{{ o4.etaW4LowerLimit|X04 }}"),
        (X"{{ o1.etaW5UpperLimit|X04 }}", X"{{ o2.etaW5UpperLimit|X04 }}", X"{{
            o3.etaW5UpperLimit|X04 }}", X"{{ o4.etaW5UpperLimit|X04 }}"), (X"{{ o1
            .etaW5LowerLimit|X04 }}", X"{{ o2.etaW5LowerLimit|X04 }}", X"{{ o3.
            etaW5LowerLimit|X04 }}", X"{{ o4.etaW5LowerLimit|X04 }}"),
        ({{ o1.phiFullRange }}, {{ o2.phiFullRange }}, {{ o3.phiFullRange }}, {{
            o4.phiFullRange }}),
        (X"{{ o1.phiW1UpperLimit|X04 }}", X"{{ o2.phiW1UpperLimit|X04 }}", X"{{
            o3.phiW1UpperLimit|X04 }}", X"{{ o4.phiW1UpperLimit|X04 }}"), (X"{{ o1
            .phiW1LowerLimit|X04 }}", X"{{ o2.phiW1LowerLimit|X04 }}", X"{{ o3.
            phiW1LowerLimit|X04 }}", X"{{ o4.phiW1LowerLimit|X04 }}"),
        ({{ o1.phiW2Ignore }}, {{ o2.phiW2Ignore }}, {{ o3.phiW2Ignore }}, {{ o4.
            phiW2Ignore }}),
        (X"{{ o1.phiW2UpperLimit|X04 }}", X"{{ o2.phiW2UpperLimit|X04 }}", X"{{
            o3.phiW2UpperLimit|X04 }}", X"{{ o4.phiW2UpperLimit|X04 }}"), (X"{{ o1
            .phiW2LowerLimit|X04 }}", X"{{ o2.phiW2LowerLimit|X04 }}", X"{{ o3.
            phiW2LowerLimit|X04 }}", X"{{ o4.phiW2LowerLimit|X04 }}"),
        ("{{ o1.charge }}", "{{ o2.charge }}", "{{ o3.charge }}", "{{ o4.charge
            }}"),
```

```
        (X"{{ o1.qualityLUT|X04 }}", X"{{ o2.qualityLUT|X04 }}", X"{{ o3.
            qualityLUT|X04 }}", X"{{ o4.qualityLUT|X04 }}"),
        (X"{{ o1.isolationLUT|X01 }}", X"{{ o2.isolationLUT|X01 }}", X"{{ o3.
            isolationLUT|X01 }}", X"{{ o4.isolationLUT|X01 }}"),
        ({{ o1.uptCutSel }}, {{ o2.uptCutSel }}, {{ o3.uptCutSel }}, {{ o4.
            uptCutSel }}),
        (X"{{ o1.uptUpperLimit|X04 }}", X"{{ o2.uptUpperLimit|X04 }}", X"{{ o3.
            uptUpperLimit|X04 }}", X"{{ o4.uptUpperLimit|X04 }}"), (X"{{ o1.
            uptLowerLimit|X04 }}", X"{{ o2.uptLowerLimit|X04 }}", X"{{ o3.
            uptLowerLimit|X04 }}", X"{{ o4.uptLowerLimit|X04 }}"),
        (X"{{ o1.impactParameterLUT|X01 }}", X"{{ o2.impactParameterLUT|X01 }}",
            X"{{ o3.impactParameterLUT|X01 }}", X"{{ o4.impactParameterLUT|X01 }}"
            ),
        "{{ condition.chargeCorrelation }}",
  {%- if condition.twoBodyPt.enabled == "true" %}
        true, {{ o1.type|upper }}_PT_VECTOR_WIDTH, X"{{ condition.twoBodyPt.
            threshold|X16 }}",
        MUON_SIN_COS_VECTOR_WIDTH, {{ o1.type|upper }}_{{ o1.type|upper }}
            _SIN_COS_PRECISION
  {%- else %}
        false
  {%- endif %}
    )
    port map(lhc_clk, mu_bx_{{ bx }},
  {%- if condition.nr_objects >= 2 and condition.twoBodyPt.enabled == "true" %}
        {{ condition.vhdl_signal }},
        ls_charcorr_double_bx_{{ bx }}_bx_{{ bx }}, os_charcorr_double_bx_{{ bx
            }}_bx_{{ bx }},
        ls_charcorr_triple_bx_{{ bx }}_bx_{{ bx }}, os_charcorr_triple_bx_{{ bx
            }}_bx_{{ bx }},
        ls_charcorr_quad_bx_{{ bx }}_bx_{{ bx }}, os_charcorr_quad_bx_{{ bx }}
            _bx_{{ bx }},
        {{ o1.type|lower }}_pt_vector_bx_{{ o1.bx }}, {{ o1.type|lower }}
            _cos_phi_bx_{{ o1.bx }}, {{ o1.type|lower }}_sin_phi_bx_{{ o1.bx }});
  {%- elif condition.nr_objects >= 2 and condition.twoBodyPt.enabled == "false"
      %}
        {{ condition.vhdl_signal }},
        ls_charcorr_double_bx_{{ bx }}_bx_{{ bx }}, os_charcorr_double_bx_{{ bx
            }}_bx_{{ bx }},
        ls_charcorr_triple_bx_{{ bx }}_bx_{{ bx }}, os_charcorr_triple_bx_{{ bx
            }}_bx_{{ bx }},
        ls_charcorr_quad_bx_{{ bx }}_bx_{{ bx }}, os_charcorr_quad_bx_{{ bx }}
            _bx_{{ bx }});
  {%- elif condition.nr_objects == 1 and condition.twoBodyPt.enabled == "true" %}
        {{ condition.vhdl_signal }},
        {{ o1.type|lower }}_pt_vector_bx_{{ o1.bx }}, {{ o1.type|lower }}
            _cos_phi_bx_{{ o1.bx }}, {{ o1.type|lower }}_sin_phi_bx_{{ o1.bx }});
  {%- else %}
        {{ condition.vhdl_signal }});
  {%- endif %}
{% endblock instantiate_muon_condition %}
{# eof #}
```

Table 32: Explanation of Listing 15

Item	Explanation
`vhdl_signal`	condition name.
`sliceLow`	low value of an object slice.
`sliceHigh`	high value of an object slice.
`nr_objects`	valid values are 1 (for single), 2 (double), 3 (triple) and 4 (quad) - depending on condition type.
`operator`	valid strings are 'true' and 'false' - 'true' for greater/equal-, 'false' for equal-mode of E_T comparator.
`type`	valid strings are 'EG', 'JET', and 'TAU'.
`threshold`	array with requirements for et_thresholds (4x 16-bit values, hex notation). Valid values depending on the scales of E_T.
`nrEtaWindows`	array to set number of η cuts.
`etaW1UpperLimit, ...`	arrays of limits for "window"-comparators for η (4x 16-bit values, hex notation). Valid values depending on the scales for η.
`phiFullRange`	array to set full range of φ (4x boolean).
`phiW1UpperLimit, ...`	arrays of limits for "window"-comparators for φ (4x 16-bit values, hex notation). Valid values depending on the scales for φ.
`[phiW2Ignore`	array to ignore "window"-comparator 2 of φ (4x boolean).
`charge`	array for requested charge (4x strings). Valid strings are 'pos' ("positive charge") and 'neg' ("negative charge") and 'ign' ("ignore").
`qualityLUT`	array for LUTs (16 bits) of quality.
`isolationLUT`	array for LUTs (4 bits) of isolation).
`twoBodyPt.threshold`	value of threshold for two-body pt comparison.
`bx`	valid strings are 'p2', 'p1', '0', 'm1' and 'm2'. This indicates which data in a range of plus/minus 2 bunch-crossing is used in the condition.

3.5.7 Calo Calo Correlation condition - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `calo_calo_correlation_condition.vhd` is given below (see Listing 16).

Listing 16: Template of `calo_calo_correlation_condition.vhd` for VHDL-Producer

```
{%- block instantiate_calo_calo_correlation_condition %}
  {%- set o1 = condition.objects[0] %}
  {%- set o2 = condition.objects[1] %}
{{ condition.vhdl_signal }}_i: entity work.calo_calo_correlation_condition
    generic map(
        {{ condition.objectsInSameBx }},
        {{ condition.deltaEta.enabled }}, {{ condition.deltaPhi.enabled }}, {{
            condition.deltaR.enabled }}, {{ condition.mass.enabled }}, {{
            condition.mass.type }}, {{ condition.twoBodyPt.enabled }},
        {{ o1.sliceLow }}, {{ o1.sliceHigh }}, {{ o1.operator }}, {{ o1.type|
            upper }}_TYPE,
        X"{{ o1.threshold|X04 }}",
        {{ o1.etaNrCuts }},
        X"{{ o1.etaW1UpperLimit|X04 }}", X"{{ o1.etaW1LowerLimit|X04 }}",
        X"{{ o1.etaW2UpperLimit|X04 }}", X"{{ o1.etaW2LowerLimit|X04 }}",
        X"{{ o1.etaW3UpperLimit|X04 }}", X"{{ o1.etaW3LowerLimit|X04 }}",
        X"{{ o1.etaW4UpperLimit|X04 }}", X"{{ o1.etaW4LowerLimit|X04 }}",
        X"{{ o1.etaW5UpperLimit|X04 }}", X"{{ o1.etaW5LowerLimit|X04 }}",
        {{ o1.phiFullRange }}, X"{{ o1.phiW1UpperLimit|X04 }}", X"{{ o1.
            phiW1LowerLimit|X04 }}",
        {{ o1.phiW2Ignore }}, X"{{ o1.phiW2UpperLimit|X04 }}", X"{{ o1.
            phiW2LowerLimit|X04 }}",
        X"{{ o1.isolationLUT|X01 }}",
        {{ o2.sliceLow }}, {{ o2.sliceHigh }}, {{ o2.operator }}, {{ o2.type|
            upper }}_TYPE,
        X"{{ o2.threshold|X04 }}",
        {{ o2.etaNrCuts }},
        X"{{ o2.etaW1UpperLimit|X04 }}", X"{{ o2.etaW1LowerLimit|X04 }}",
        X"{{ o2.etaW2UpperLimit|X04 }}", X"{{ o2.etaW2LowerLimit|X04 }}",
        X"{{ o2.etaW3UpperLimit|X04 }}", X"{{ o2.etaW3LowerLimit|X04 }}",
        X"{{ o2.etaW4UpperLimit|X04 }}", X"{{ o2.etaW4LowerLimit|X04 }}",
        X"{{ o2.etaW5UpperLimit|X04 }}", X"{{ o2.etaW5LowerLimit|X04 }}",
        {{ o2.phiFullRange }}, X"{{ o2.phiW1UpperLimit|X04 }}", X"{{ o2.
            phiW1LowerLimit|X04 }}",
        {{ o2.phiW2Ignore }}, X"{{ o2.phiW2UpperLimit|X04 }}", X"{{ o2.
            phiW2LowerLimit|X04 }}",
        X"{{ o2.isolationLUT|X01 }}",
        X"{{ condition.deltaEta.upper|X08 }}", X"{{ condition.deltaEta.lower|X08
            }}",
        X"{{ condition.deltaPhi.upper|X08 }}", X"{{ condition.deltaPhi.lower|X08
            }}",
        X"{{ condition.deltaR.upper|X16 }}", X"{{ condition.deltaR.lower|X16 }}",
        X"{{ condition.mass.upper|X16 }}", X"{{ condition.mass.lower|X16 }}",
        {{ o1.type|upper }}_PT_VECTOR_WIDTH, {{ o2.type|upper }}_PT_VECTOR_WIDTH,
             {{ o1.type|upper }}_{{ o2.type|upper }}_COSH_COS_PRECISION, {{ o1.
            type|upper }}_{{ o2.type|upper }}_COSH_COS_VECTOR_WIDTH,
        X"{{ condition.twoBodyPt.threshold|X16 }}", CALO_SIN_COS_VECTOR_WIDTH, {{
             o1.type|upper }}_{{ o2.type|upper }}_SIN_COS_PRECISION
    )
```

```
    port map(lhc_clk, {{ o1.type|lower }}_bx_{{ o1.bx }}, {{ o2.type|lower }}_bx_
        {{ o2.bx }},
        diff_{{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.bx }}_bx_{{ o2.bx
            }}_eta_vector, diff_{{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.
            bx }}_bx_{{ o2.bx }}_phi_vector,
        {{ o1.type|lower }}_pt_vector_bx_{{ o1.bx }}, {{ o2.type|lower }}
            _pt_vector_bx_{{ o2.bx }},
        {{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.bx }}_bx_{{ o2.bx }}
            _cosh_deta_vector, {{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.bx
             }}_bx_{{ o2.bx }}_cos_dphi_vector,
        {{ o1.type|lower }}_cos_phi_bx_{{ o1.bx }}, {{ o2.type|lower }}
            _cos_phi_bx_{{ o2.bx }}, {{ o1.type|lower }}_sin_phi_bx_{{ o1.bx }},
            {{ o2.type|lower }}_sin_phi_bx_{{ o2.bx }},
        {{ condition.vhdl_signal }});
{%- endblock instantiate_calo_calo_correlation_condition %}
{# eof #}
```

Table 33: Explanation of Listing 16

Item	Explanation
`vhdl_signal`	condition name.
`objectsInSameBx`	valid strings are 'true' and 'false' - 'true' for data with same Bx.
`deltaEta.enabled`	valid strings are 'true' and 'false' - 'true' for use of $\Delta\eta$.
`deltaPhi.enabled`	valid strings are 'true' and 'false' - 'true' for use of $\Delta\varphi$.
`deltaR.enabled`	valid strings are 'true' and 'false' - 'true' for use of DR.
`mass.enabled`	valid strings are 'true' and 'false' - 'true' for use of MASS.
`mass.type`	valid strings are 'INVARIANT_MASS_TYPE' and 'TRANSVERSE_-MASS_TYPE'.
`twoBodyPt.enabled`	valid strings are 'true' and 'false' - 'true' for use of two-body pt.
`sliceLow`	low value of an object slice.
`sliceHigh`	high value of an object slice.
`operator`	valid strings are 'true' and 'false' - 'true' for greater/equal-, 'false' for equal-mode of E_{T} comparator.
`threshold`	requirements for et_thresholds (16-bit values, hex notation). Valid values depending on the scales of E_{T}.
`nrEtaWindows`	number of η cuts.
`etaW1UpperLimit, ...`	limits for "window"-comparators for η (4x 16-bit values, hex notation). Valid values depending on the scales for η.
`phiFullRange`	set full range of φ (boolean).
`phiW1UpperLimit, ...`	limits for "window"-comparators for φ (16-bit values, hex notation). Valid values depending on the scales for φ.
`[phiW2Ignore`	ignore "window"-comparator 2 of φ (boolean).
`isolationLUT`	LUT (4 bits) of isolation).
`deltaEta.upper, ...`	limits for "window"-comparator for comparison of differences in η (hex notation). Valid values depending on the scales for η.
`deltaPhi.upper, ...`	limits for "window"-comparator for comparison of differences in φ (hex notation). Valid values depending on the scales for φ.

Table 33: Explanation of Listing 16

Item	Explanation
`deltaR.upper, ...`	limits for "window"-comparator for comparison of ΔR^2 (hex notation).
`mass.upper, ...`	limits for "window"-comparator for comparison of $\frac{M^2}{2}$ (hex notation).
`twoBodyPt.threshold`	value of threshold for two-body pt comparison.
`bx`	valid strings are 'p2', 'p1', '0', 'm1' and 'm2'. This indicates which data in a range of plus/minus 2 bunch-crossing is used in the condition.

3.5.8 Calo Muon Correlation condition - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `calo_muon_correlation_condition.vhd` is given below (see Listing 17).

Listing 17: Template of `calo_muon_correlation_condition.vhd` for VHDL-Producer

```
{%- block instantiate_calo_muon_correlation_condition %}
  {%- set o1 = condition.objects[0] %}
  {%- set o2 = condition.objects[1] %}
{{ condition.vhdl_signal }}_i: entity work.calo_muon_correlation_condition
    generic map(
        {{ condition.deltaEta.enabled }}, {{ condition.deltaPhi.enabled }}, {{
            condition.deltaR.enabled }}, {{ condition.mass.enabled }}, {{
            condition.mass.type }}, {{ condition.twoBodyPt.enabled }},
        {{ o1.sliceLow }}, {{ o1.sliceHigh }}, {{ o1.operator }}, {{ o1.type|
            upper }}_TYPE,
        X"{{ o1.threshold|X04 }}",
        {{ o1.etaNrCuts }},
        X"{{ o1.etaW1UpperLimit|X04 }}", X"{{ o1.etaW1LowerLimit|X04 }}",
        X"{{ o1.etaW2UpperLimit|X04 }}", X"{{ o1.etaW2LowerLimit|X04 }}",
        X"{{ o1.etaW3UpperLimit|X04 }}", X"{{ o1.etaW3LowerLimit|X04 }}",
        X"{{ o1.etaW4UpperLimit|X04 }}", X"{{ o1.etaW4LowerLimit|X04 }}",
        X"{{ o1.etaW5UpperLimit|X04 }}", X"{{ o1.etaW5LowerLimit|X04 }}",
        {{ o1.phiFullRange }}, X"{{ o1.phiW1UpperLimit|X04 }}", X"{{ o1.
            phiW1LowerLimit|X04 }}",
        {{ o1.phiW2Ignore }}, X"{{ o1.phiW2UpperLimit|X04 }}", X"{{ o1.
            phiW2LowerLimit|X04 }}",
        X"{{ o1.isolationLUT|X01 }}",
        {{ o2.sliceLow }}, {{ o2.sliceHigh }}, {{ o2.operator }},
        X"{{ o2.threshold|X04 }}",
        {{ o2.etaNrCuts }},
        X"{{ o2.etaW1UpperLimit|X04 }}", X"{{ o2.etaW1LowerLimit|X04 }}",
        X"{{ o2.etaW2UpperLimit|X04 }}", X"{{ o2.etaW2LowerLimit|X04 }}",
        X"{{ o2.etaW3UpperLimit|X04 }}", X"{{ o2.etaW3LowerLimit|X04 }}",
        X"{{ o2.etaW4UpperLimit|X04 }}", X"{{ o2.etaW4LowerLimit|X04 }}",
        X"{{ o2.etaW5UpperLimit|X04 }}", X"{{ o2.etaW5LowerLimit|X04 }}",
        {{ o2.phiFullRange }}, X"{{ o2.phiW1UpperLimit|X04 }}", X"{{ o2.
            phiW1LowerLimit|X04 }}",
        {{ o2.phiW2Ignore }}, X"{{ o2.phiW2UpperLimit|X04 }}", X"{{ o2.
            phiW2LowerLimit|X04 }}",
        "{{ o2.charge }}", X"{{ o2.qualityLUT|X04 }}", X"{{ o2.isolationLUT|X01
            }}",
        {{ o2.uptCutSel }}, X"{{ o2.uptUpperLimit|X04 }}", X"{{ o2.uptLowerLimit|
            X04 }}", X"{{ o2.impactParameterLUT|X01 }}",
        X"{{ condition.deltaEta.upper|X08 }}", X"{{ condition.deltaEta.lower|X08
            }}",
        X"{{ condition.deltaPhi.upper|X08 }}", X"{{ condition.deltaPhi.lower|X08
            }}",
        X"{{ condition.deltaR.upper|X16 }}", X"{{ condition.deltaR.lower|X16 }}",
        X"{{ condition.mass.upper|X16 }}", X"{{ condition.mass.lower|X16 }}",
        {{ o1.type|upper }}_PT_VECTOR_WIDTH, {{ o2.type|upper }}_PT_VECTOR_WIDTH,
             {{ o1.type|upper }}_{{ o2.type|upper }}_COSH_COS_PRECISION, {{ o1.
            type|upper }}_{{ o2.type|upper }}_COSH_COS_VECTOR_WIDTH,
        X"{{ condition.twoBodyPt.threshold|X16 }}", MUON_SIN_COS_VECTOR_WIDTH, {{
             o1.type|upper }}_{{ o2.type|upper }}_SIN_COS_PRECISION
```

```
    )
    port map(lhc_clk, {{ o1.type|lower }}_bx_{{ o1.bx }}({{ o1.sliceLow }} to {{
        o1.sliceHigh }}), {{ o2.type|lower }}_bx_{{ o2.bx }}({{ o2.sliceLow }} to
        {{ o2.sliceHigh }}),
        diff_{{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.bx }}_bx_{{ o2.bx
            }}_eta_vector, diff_{{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.
            bx }}_bx_{{ o2.bx }}_phi_vector,
        {{ o1.type|lower }}_pt_vector_bx_{{ o1.bx }}, {{ o2.type|lower }}
            _pt_vector_bx_{{ o2.bx }},
        {{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.bx }}_bx_{{ o2.bx }}
            _cosh_deta_vector, {{ o1.type|lower }}_{{ o2.type|lower }}_bx_{{ o1.bx
             }}_bx_{{ o2.bx }}_cos_dphi_vector,
        conv_{{ o1.type|lower }}_cos_phi_bx_{{ o1.bx }}, {{ o2.type|lower }}
            _cos_phi_bx_{{ o2.bx }}, conv_{{ o1.type|lower }}_sin_phi_bx_{{ o1.bx
            }}, {{ o2.type|lower }}_sin_phi_bx_{{ o2.bx }},
        {{ condition.vhdl_signal }});
{%- endblock instantiate_calo_muon_correlation_condition %}
{# eof #}
```

Table 34: Explanation of Listing 17

Item	Explanation
`vhdl_signal`	condition name.
`deltaEta.enabled`	valid strings are 'true' and 'false' - 'true' for use of $\Delta\eta$.
`deltaPhi.enabled`	valid strings are 'true' and 'false' - 'true' for use of $\Delta\varphi$.
`deltaR.enabled`	valid strings are 'true' and 'false' - 'true' for use of DR.
`mass.enabled`	valid strings are 'true' and 'false' - 'true' for use of MASS.
`mass.type`	valid strings are 'INVARIANT_MASS_TYPE' and 'TRANSVERSE_-MASS_TYPE'.
`twoBodyPt.enabled`	valid strings are 'true' and 'false' - 'true' for use of two-body pt.
`sliceLow`	low value of an object slice.
`sliceHigh`	high value of an object slice.
`operator`	valid strings are 'true' and 'false' - 'true' for greater/equal-, 'false' for equal-mode of E_{T} comparator.
`threshold`	requirements for et_thresholds and pt_thresholds (16-bit values, hex notation). Valid values depending on the scales of E_{T}.
`nrEtaWindows`	number of η cuts.
`etaW1UpperLimit, ...`	limits for "window"-comparators for η (4x 16-bit values, hex notation). Valid values depending on the scales for η.
`phiFullRange`	set full range of φ (boolean).
`phiW1UpperLimit, ...`	limits for "window"-comparators for φ (16-bit values, hex notation). Valid values depending on the scales for φ.
`[phiW2Ignore`	ignore "window"-comparator 2 of φ (boolean).
`charge`	requested charge. Valid strings are 'pos' ("positive charge") and 'neg' ("negative charge") and 'ign' ("ignore").
`qualityLUT`	LUT (16 bits) of quality.
`isolationLUT`	LUT (4 bits) of isolation).

Table 34: Explanation of Listing 17

Item	Explanation
`uptCutSel`	set use of unconstrained p_{T}.
`uptUpperLimit, ...`	limits for unconstrained p_{T}.
`impactParameterLUT`	LUT (4 bits) of impact parameter).
`deltaEta.upper, ...`	limits for "window"-comparator for comparison of differences in η (hex notation). Valid values depending on the scales for η.
`deltaPhi.upper, ...`	limits for "window"-comparator for comparison of differences in φ (hex notation). Valid values depending on the scales for φ.
`deltaR.upper, ...`	limits for "window"-comparator for comparison of ΔR^2 (hex notation).
`mass.upper, ...`	limits for "window"-comparator for comparison of $\frac{M^2}{2}$ (hex notation).
`twoBodyPt.threshold`	value of threshold for two-body pt comparison.
`bx`	valid strings are 'p2', 'p1', '0', 'm1' and 'm2'. This indicates which data in a range of plus/minus 2 bunch-crossing is used in the condition.

3.5.9 Muon Muon Correlation condition - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `muon_muon_correlation_condition.vhd` is given below (see Listing 18).

Listing 18: Template of `muon_muon_correlation_condition.vhd` for VHDL-Producer

```
{%- block instantiate_muon_muon_correlation_condition %}
  {%- set o1 = condition.objects[0] %}
  {%- set o2 = condition.objects[1] %}
{{ condition.vhdl_signal }}_i: entity work.muon_muon_correlation_condition
    generic map(
        {{ condition.objectsInSameBx }},
        {{ condition.deltaEta.enabled }}, {{ condition.deltaPhi.enabled }}, {{
            condition.deltaR.enabled }}, {{ condition.mass.enabled }}, {{
            condition.mass.type }}, {{ condition.twoBodyPt.enabled }},
        {{ o1.sliceLow }}, {{ o1.sliceHigh }}, {{ o1.operator }},
        X"{{ o1.threshold|X04 }}",
        {{ o1.etaNrCuts }},
        X"{{ o1.etaW1UpperLimit|X04 }}", X"{{ o1.etaW1LowerLimit|X04 }}",
        X"{{ o1.etaW2UpperLimit|X04 }}", X"{{ o1.etaW2LowerLimit|X04 }}",
        X"{{ o1.etaW3UpperLimit|X04 }}", X"{{ o1.etaW3LowerLimit|X04 }}",
        X"{{ o1.etaW4UpperLimit|X04 }}", X"{{ o1.etaW4LowerLimit|X04 }}",
        X"{{ o1.etaW5UpperLimit|X04 }}", X"{{ o1.etaW5LowerLimit|X04 }}",
        {{ o1.phiFullRange }}, X"{{ o1.phiW1UpperLimit|X04 }}", X"{{ o1.
            phiW1LowerLimit|X04 }}",
        {{ o1.phiW2Ignore }}, X"{{ o1.phiW2UpperLimit|X04 }}", X"{{ o1.
            phiW2LowerLimit|X04 }}",
        "{{ o1.charge }}", X"{{ o1.qualityLUT|X04 }}", X"{{ o1.isolationLUT|X01
            }}",
        {{ o1.uptCutSel }}, X"{{ o1.uptUpperLimit|X04 }}", X"{{ o1.uptLowerLimit|
            X04 }}", X"{{ o1.impactParameterLUT|X01 }}",
        {{ o2.sliceLow }}, {{ o2.sliceHigh }}, {{ o2.operator }},
        X"{{ o2.threshold|X04 }}",
        {{ o2.etaNrCuts }},
        X"{{ o2.etaW1UpperLimit|X04 }}", X"{{ o2.etaW1LowerLimit|X04 }}",
        X"{{ o2.etaW2UpperLimit|X04 }}", X"{{ o2.etaW2LowerLimit|X04 }}",
        X"{{ o2.etaW3UpperLimit|X04 }}", X"{{ o2.etaW3LowerLimit|X04 }}",
        X"{{ o2.etaW4UpperLimit|X04 }}", X"{{ o2.etaW4LowerLimit|X04 }}",
        X"{{ o2.etaW5UpperLimit|X04 }}", X"{{ o2.etaW5LowerLimit|X04 }}",
        {{ o2.phiFullRange }}, X"{{ o2.phiW1UpperLimit|X04 }}", X"{{ o2.
            phiW1LowerLimit|X04 }}",
        {{ o2.phiW2Ignore }}, X"{{ o2.phiW2UpperLimit|X04 }}", X"{{ o2.
            phiW2LowerLimit|X04 }}",
        "{{ o2.charge }}", X"{{ o2.qualityLUT|X04 }}", X"{{ o2.isolationLUT|X01
            }}",
        {{ o2.uptCutSel }}, X"{{ o2.uptUpperLimit|X04 }}", X"{{ o2.uptLowerLimit|
            X04 }}", X"{{ o2.impactParameterLUT|X01 }}",
         "{{ condition.chargeCorrelation }}",
        X"{{ condition.deltaEta.upper|X08 }}", X"{{ condition.deltaEta.lower|X08
            }}",
        X"{{ condition.deltaPhi.upper|X08 }}", X"{{ condition.deltaPhi.lower|X08
            }}",
        X"{{ condition.deltaR.upper|X16 }}", X"{{ condition.deltaR.lower|X16 }}",
        X"{{ condition.mass.upper|X16 }}", X"{{ condition.mass.lower|X16 }}",
```

```
        {{ o1.type|upper }}_PT_VECTOR_WIDTH, {{ o1.type|upper }}_UPT_VECTOR_WIDTH
            , {{ o1.type|upper }}_{{ o2.type|upper }}_COSH_COS_PRECISION, {{ o1.
            type|upper }}_{{ o2.type|upper }}_COSH_COS_VECTOR_WIDTH,
        X"{{ condition.twoBodyPt.threshold|X16 }}", MUON_SIN_COS_VECTOR_WIDTH, {{
             o1.type|upper }}_{{ o2.type|upper }}_SIN_COS_PRECISION
    )
    port map(lhc_clk, {{ o1.type|lower }}_bx_{{ o1.bx }}, {{ o2.type|lower }}_bx_
        {{ o2.bx }},
        ls_charcorr_double_bx_{{ o1.bx }}_bx_{{ o2.bx }}, os_charcorr_double_bx_
            {{ o1.bx }}_bx_{{ o2.bx }},
        diff_{{ o1.type|lower }}_{{ o1.type|lower }}_bx_{{ o1.bx }}_bx_{{ o2.bx
            }}_eta_vector, diff_{{ o1.type|lower }}_{{ o1.type|lower }}_bx_{{ o1.
            bx }}_bx_{{ o2.bx }}_phi_vector,
        {{ o1.type|lower }}_pt_vector_bx_{{ o1.bx }}, {{ o1.type|lower }}
            _pt_vector_bx_{{ o2.bx }},
        {{ o1.type|lower }}_upt_vector_bx_{{ o1.bx }}, {{ o1.type|lower }}
            _upt_vector_bx_{{ o2.bx }},
        {{ o1.type|lower }}_{{ o1.type|lower }}_bx_{{ o1.bx }}_bx_{{ o2.bx }}
            _cosh_deta_vector, {{ o1.type|lower }}_{{ o1.type|lower }}_bx_{{ o1.bx
             }}_bx_{{ o2.bx }}_cos_dphi_vector,
        {{ o1.type|lower }}_cos_phi_bx_{{ o1.bx }}, {{ o1.type|lower }}
            _cos_phi_bx_{{ o2.bx }}, {{ o1.type|lower }}_sin_phi_bx_{{ o1.bx }},
            {{ o1.type|lower }}_sin_phi_bx_{{ o2.bx }},
        {{ condition.vhdl_signal }});
{%- endblock instantiate_muon_muon_correlation_condition %}
{# eof #}
```

Table 35: Explanation of Listing 18

Item	Explanation
vhdl_signal	condition name.
objectsInSameBx	valid strings are 'true' and 'false' - 'true' for data with same Bx.
deltaEta.enabled	valid strings are 'true' and 'false' - 'true' for use of $\Delta\eta$.
deltaPhi.enabled	valid strings are 'true' and 'false' - 'true' for use of $\Delta\varphi$.
deltaR.enabled	valid strings are 'true' and 'false' - 'true' for use of DR.
mass.enabled	valid strings are 'true' and 'false' - 'true' for use of MASS.
mass.type	valid strings are 'INVARIANT_MASS_TYPE' and 'TRANSVERSE_-MASS_TYPE'.
twoBodyPt.enabled	valid strings are 'true' and 'false' - 'true' for use of two-body pt.
sliceLow	low value of an object slice.
sliceHigh	high value of an object slice.
operator	valid strings are 'true' and 'false' - 'true' for greater/equal-, 'false' for equal-mode of E_T comparator.
threshold	requirements for pt_thresholds (16-bit values, hex notation). Valid values depending on the scales of E_T.
nrEtaWindows	number of η cuts.
etaW1UpperLimit, ...	limits for "window"-comparators for η (4x 16-bit values, hex notation). Valid values depending on the scales for η.
phiFullRange	set full range of φ (boolean).

Table 35: Explanation of Listing 18

Item	Explanation
`phiW1UpperLimit, ...`	limits for "window"-comparators for φ (16-bit values, hex notation). Valid values depending on the scales for φ.
`[phiW2Ignore`	ignore "window"-comparator 2 of φ (boolean).
`charge`	requested charge. Valid strings are 'pos' ("positive charge") and 'neg' ("negative charge") and 'ign' ("ignore").
`qualityLUT`	LUT (16 bits) of quality.
`isolationLUT`	LUT (4 bits) of isolation).
`uptCutSel`	set use of unconstrained p_{T}.
`uptUpperLimit, ...`	limits for unconstrained p_{T}.
`impactParameterLUT`	LUT (4 bits) of impact parameter).
`deltaEta.upper, ...`	limits for "window"-comparator for comparison of differences in η (hex notation). Valid values depending on the scales for η.
`deltaPhi.upper, ...`	limits for "window"-comparator for comparison of differences in φ (hex notation). Valid values depending on the scales for φ.
`deltaR.upper, ...`	limits for "window"-comparator for comparison of ΔR^2 (hex notation).
`mass.upper, ...`	limits for "window"-comparator for comparison of $\frac{M^2}{2}$ (hex notation).
`twoBodyPt.threshold`	value of threshold for two-body pt comparison.
`bx`	valid strings are 'p2', 'p1', '0', 'm1' and 'm2'. This indicates which data in a range of plus/minus 2 bunch-crossing is used in the condition.

3.5.10 Calo Esums Correlation condition - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `calo_esums_correlation_condition.vhd` is given below (see Listing 16).

3.5.11 Muon Esums Correlation condition - template for VHDL-Producer

A VHDL-template for VHDL-Producer of instantiating `muon_esums_correlation_condition.vhd` is given below (see Listing **??**).

4 Final Desicion Logic

The Final Desicion Logic (μFDL) firmware contains algo-bx-masks, suppression of algos caused by calibration trigger, prescalers, veto-masks and rate-counters ("before prescalers", "after prescalers" and "post dead time") for each Algorithm and the local Final-OR- and veto-logic.

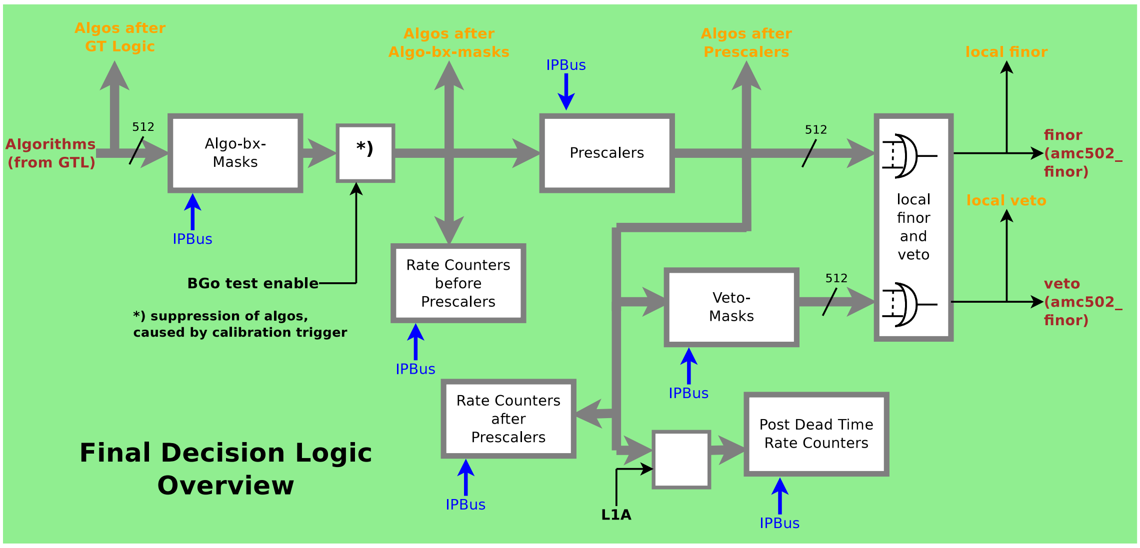


Figure 15: μFDL firmware v1.0.1

4.1 μFDL Interface

Inputs:

- Algorithms from μGTL
- IPBus interface (for registers, counters and memories)
- LHC-clock
- Reset signal
- BC0, BGo test-enable, L1A
- Begin of lumi-section

Outputs:

- Prescale factor set index to Readout-Process
- Algorithms after GTLogic to Readout-Process
- Algorithms after algo-bx-masks to Readout-Process

- Algorithms after prescalers to Readout-Process
- Algorithms after Final-OR-masks to Readout-Process
- Local Final-OR to Readout-Process
- Local veto to Readout-Process
- Local Final-OR with veto to Readout-Process
- Local Final-OR to mezzanine
- Local veto to mezzanine
- Local Final-OR with veto to mezzanine

4.2 MP7 Final-OR hardware solution

The firmware of μFDL in this document is based on a hardware configuration with maximum 6 μGT modules.

4.3 Data flow

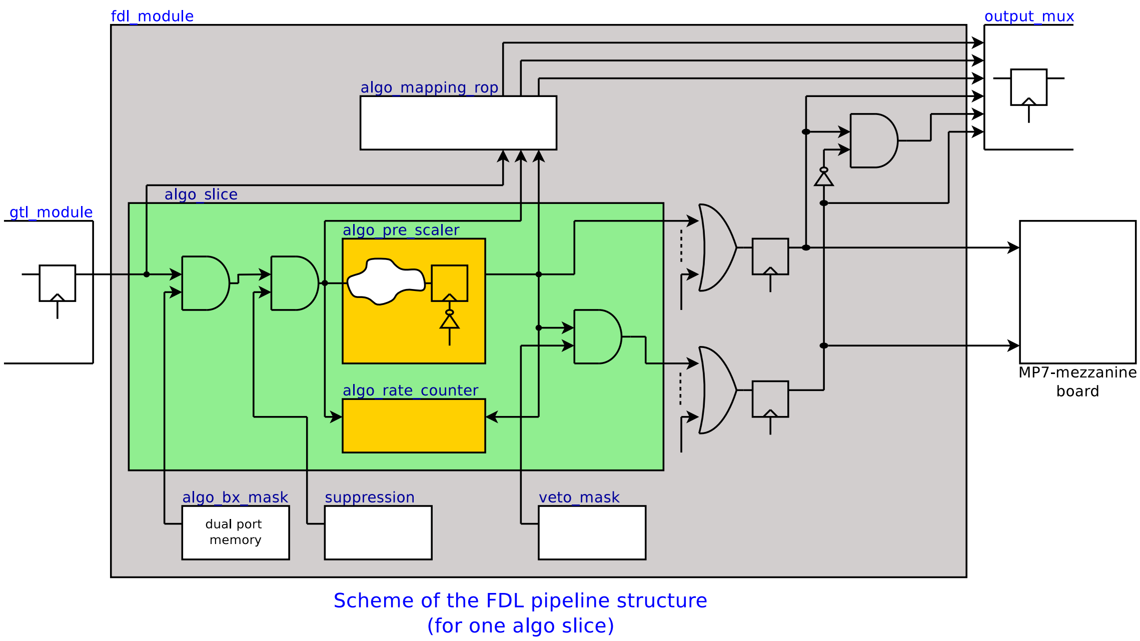


Figure 16: μFDL pipeline v1.0.1

Every Algorithm, in total 512 coming from μGTL, passes a algo-bx-mask, the logic for suppression of algos caused by calibration trigger and a prescaler, which reduces the trigger rate by a given factor. Prescaled Algorithms signals are combined to a local final-or-signal (Final-OR). For every Algorithm there is a rate-counter before prescaler and after prescaler, which

are incremented by LHC-clock if the Algorithm is true. In addition there are post-dead-time counters, one for each Algorithm, which are incremented, if the Algorithm and the L1A-signal are true at the same bunch-crossing. Algorithms after GTLogic, after algo-bx-masks, after prescalers, the local Final-OR- and local veto-signal are provided for read-out-record.
If there are not enough firmware resources in one μGT board, more boards could be used. Therefore the 512 Algorithms are partitioned by TME. TME will set the number of Algorithms as constant in the package module `gtl_pkg.vhd`. This means μGTL and μFDL firmware considered as a unit for synthesis. In the case of more μGT boards, the local Final-OR and local veto are routed via a mezzanine board on MP7 (located on "General Purpose I/O connector") to the FINOR-AMC502 module, where the total Final-OR is created and send to TCDS.
A mapping for Algorithms is provided, to give flexibility for setting the index of Algorithms:

- creating a mapping instance (algo_mapping_rop.vhd) over TME (see 3.5.3), this component will be instantiated in fix part of FDL, and new calculation will done each time over TME.
- TME delivers just the number of Algorithms, which will be built on each card.
- from FDL point of view, FDL see incremented number of Algorithms indexes, e.g. 0, 1, 2, which is e.g. 69, 200, 300.
- TME should take care of assignment of each Algorithm to a number, that means if in card 1 algo_59 is defined, nobody allows to produce the same number again.

4.4 Main parts

The top-of-hierarchy module (`fdl_module.vhd`) contains

- version registers
- a command pulse register
- prescalers for all Algorithms
- registers for prescale factors
- register for prescale factor set index
- rate-counters for all Algorithms, finor, veto, L1A and post-dead-time
- read only registers for rate-counter values
- algo-bx-masks for all Algorithms
- Final-OR-masks for all Algorithms
- veto-masks for all Algorithms
- the Final-OR-logic

4.4.1 Registers and memories

All registers and memories are 32 bits wide. (A first draft of the definition of the relative addresses is shown in Table 36.)

- Dual-port memories for the algo-bx-masks are implemented. For each Algorithm there is a mask bit at every bunch crossing of one orbit. Therefore in total memories of 4096 x 512 bits are implemented. Because of the 32 bit data interface, 16 memories each with a size of 4096 x 32 bits are instantiated.
- Read-only registers for the value of rate-counters (before and after prescalers, post-dead-time counters) are implemented, 512 registers, one for every Algorithm. Rate-counter value has 32 bits.
- Registers for prescale factor of the prescalers are implemented, 512 registers, one for every Algorithm. A prescale factor value has 24 bits.
- Registers for masks (finor- and veto-masks) are implemented, 512 registers.
- One register for prescale factors set index is implemented. This register contains a value, which is unique for a given set of prescale factors. The content of this register is part of Readout-record.
- One register for command pulses is implemented. One bit of this register (bit 0) is used for "setting the request signal for updating prescale factors high", which enables, that the prescale factors and the prescale factor set index are loaded at the begin of a luminosity segment period. (Other bits are not defined yet.)
- One control register is implemented (the content has to be defined).
- 32 register for L1 Trigger Menu name for μGTL is implemented.
- 4 register for L1 Trigger Menu UUID for μGTL is implemented.
- One register for L1 Trigger Menu compiler version is implemented.
- One register for μFDL firmware version is implemented.
- One register for μGTL firmware (fixed code) version is implemented.

4.4.1.1 Register map

The register map for μFDL has a base address of `0x90000000`.

Table 36: μFDL register map

Offset	Register name	Access	Description
0x90000000	`Algo BX masks(0)`	r/w	4096 memory addresses of algo-bx-masks for Algorithms 0-31.

Table 36: μFDL register map

Offset	Register name	Access	Description
0x90001000	`Algo BX masks(1)`	r/w	4096 memory addresses of algo-bx-masks for Algorithms 32-63.
...	...	...	...
0x9000F000	`Algo BX masks(15)`	r/w	4096 memory addresses of algo-bx-masks for Algorithms 480-511.
0x90010000	`Rate counter before prescaler`	r	512 read-only registers for rate-counter values before prescalers.
0x90010200	`Prescale factors`	r/w	512 registers for prescale factors.
0x90010400	`Rate counter after prescaler`	r	512 read-only registers for rate-counter values after prescalers.
0x90010600	`Rate counter post-dead-time`	r	512 read-only registers for post-dead-time rate-counter values.
0x90010800	`Masks`	r/w	512 registers for finor-masks and veto-masks. Bit 0 = finor-mask, bit 1 = veto-mask.
0x90091880	`Prescale factors set index`	r/w	Register for prescale factors set index.
0x900918C0	`L1tm name`	r	32 registers for L1 Trigger Menu name for μGTL.
0x900918E0	`L1tm uuid`	r	4 registers for L1 Trigger Menu UUID for μGTL.
0x900918E4	`L1tm compiler version`	r	Register for L1 Trigger Menu compiler version.
0x900918E5	`GTL FW version`	r	Register for firmware version of μGTL VHDL code.
0x900918E6	`FDL FW version`	r	Register for firmware version of μFDL VHDL code.
0x900918E7	`L1tm FW uuid`	r	4 registers for L1 Trigger Menu FW UUID for μGTL.
0x900918EB	`SVN revision number`	r	Register for SVN revision number.
0x900918EC	`L1tm uuid hash`	r	Register for L1 Trigger Menu UUID hash for μGTL.

Table 36: μFDL register map

Offset	Register name	Access	Description
0x900918ED	`L1tm FW uuid hash`	r	Register for L1 Trigger Menu FW UUID hash for μGTL.
0x900918EE	`Module ID`	r	Register for Module ID of L1 Trigger Menu.
0x90091900	`Command Pulses`	r/w	Register for command pulses.
0x90091980	`Rate counter finor`	r	One read-only registers for finor rate-counter value.
0x90092200	`L1A latency delay`	r/w	Register for L1A latency delay value (used for post-dead-time counter).
0x90093000	`Rate counter L1A`	r	One read-only registers for L1A rate-counter value.
0x90094000	`Rate counter veto`	r	One read-only registers for veto rate-counter value.
0x90095000	`Current prescale set index`	r	Read-only register for prescale factors set index, which was "updated" with begin of current lumi-section ("prescale_factors_set_index_reg_updated(0)" in VHDL).
0x90095001	`Previous prescale set index`	r	Read-only register for prescale factors set index, which was "updated" with begin of previous lumi-section for monitoring "prescale_factors_set_index_reg_updated(1)" in VHDL).
0x90096000	`Calibration trigger gap`	r/w	Register for begin and end (in Bx) of calibration trigger gap.

Register 4.1: Rate counter before prescaler

rate_counter_before_prescaler	
31 … 0	
0	Reset

rate__counter__before__prescaler Rate counter before prescaler. Counts the occurancy of an algo (given by register address) in one luminosity segment.

Register 4.2: Prescale factor

reserved	prescale_factor	
31 … 24	23 … 0	
0	1	Reset

prescale__factor Prescale factor of an algo (given by register address). Prescale factor = 0 means disable algo.

Register 4.3: Rate counter after prescaler

rate_counter_after_prescaler	
31 … 0	
0	Reset

rate__counter__after__prescaler Rate counter after prescaler. Counts the occurancy of an algo (given by register address) in one luminosity segment.

Register 4.4: Rate counter post-dead-time

rate_counter_postdeadtime	
31 … 0	
0	Reset

rate_counter_postdeadtime Rate counter post-dead-time. Counts the occurancy of an algo (given by register address) and L1A at the same bx in one luminosity segment.

Register 4.5: Masks

reserved	veto_mask	finor_mask	
31 … 2	1	0	
0	0	1	Reset

veto_mask Selection of a veto (by an algo, given by register address) for veto-or.

finor_mask Selection of an algo (given by register address) for final-or.

Register 4.6: Prescale factors set index

reserved	prescale_factor_set_index	
31 … 8	7 … 0	
0	0	Reset

prescale_factor_set_index Index for a certain set of prescale factors.

Register 4.7: L1tm compiler version

reserved	major	minor	revision	
31 24	23 16	15 8	7 0	
0	0	0	0	Reset

major Major version of L1tm compiler.

minor Minor version of L1tm compiler.

revision Revision version of L1tm compiler.

Register 4.8: GTL FW version

reserved	major	minor	revision	
31 24	23 16	15 8	7 0	
0	0	0	0	Reset

major Major version of GTL firmware.

minor Minor version of GTL firmware.

revision Revision version of GTL firmware.

Register 4.9: FDL FW version

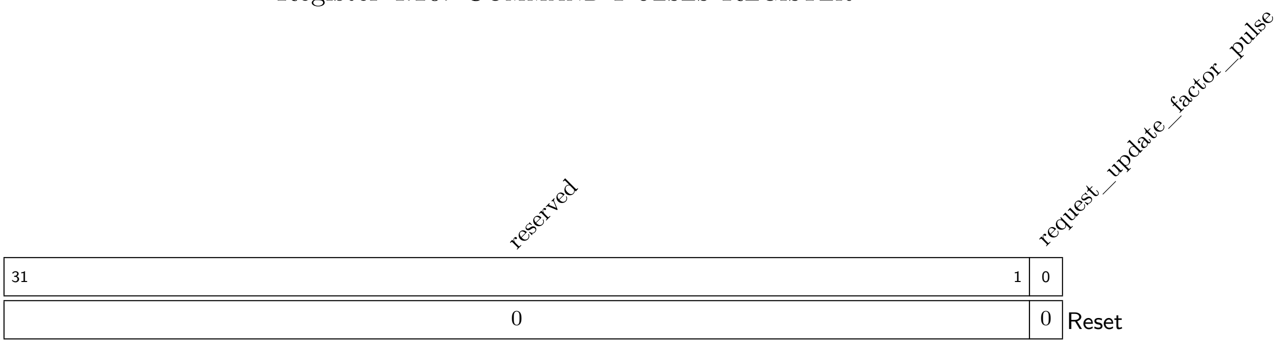
reserved	major	minor	revision	
31 24	23 16	15 8	7 0	
0	0	0	0	Reset

major Major version of FDL firmware.

minor Minor version of FDL firmware.

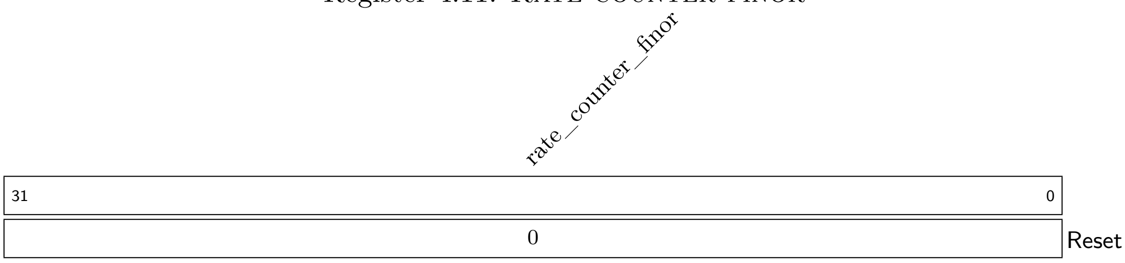
revision Revision version of FDL firmware.

Register 4.10: Command Pulses Register



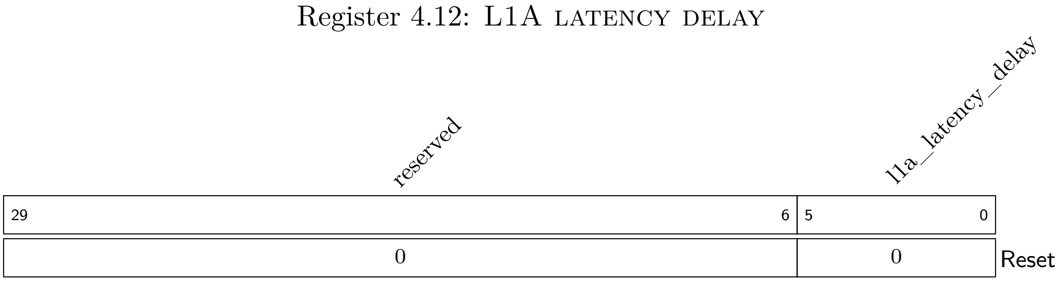
request_update_factor_pulse Sets the request signal for updating prescale factors high. Updating is done at the next "begin of luminosity segment".

Register 4.11: Rate counter finor



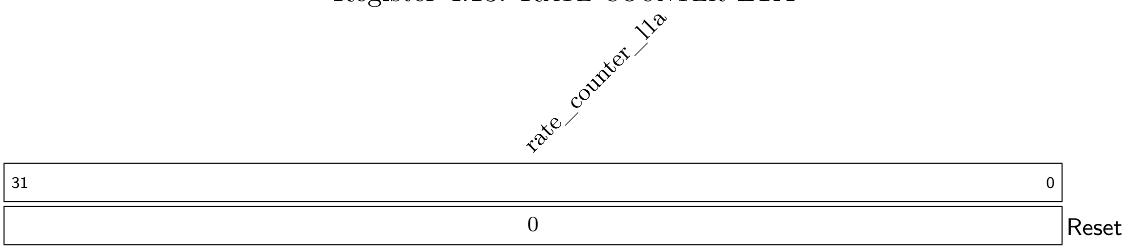
rate_counter_finor Rate counter finor. Counts the occurancy of finor in one luminosity segment.

Register 4.12: L1A latency delay



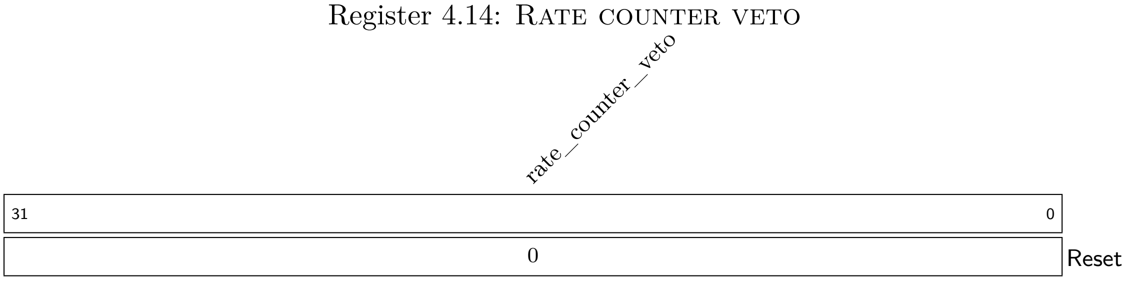
l1a_latency_delay L1A latency delay value (used for post-dead-time counter).

Register 4.13: Rate counter L1A



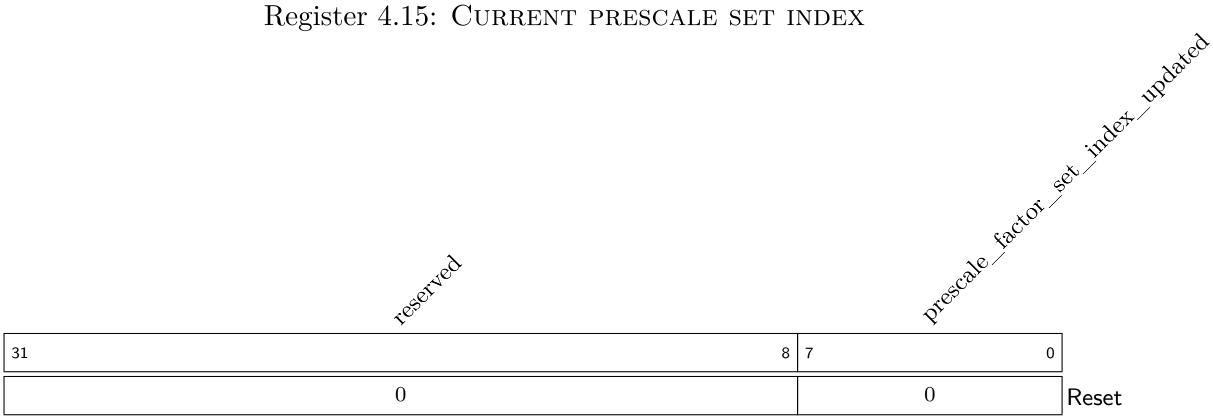
rate_counter_l1a Rate counter L1A. Counts the occurancy of L1A in one luminosity segment.

Register 4.14: Rate counter veto



rate_counter_veto Rate counter veto. Counts the occurancy of veto in one luminosity segment.

Register 4.15: Current prescale set index



prescale_factor_set_index_updated Index for a certain set of prescale factors, which was "updated" with begin of current lumi-section.

Register 4.16: Previous prescale set index

reserved	prescale_factor_set_index_updated	
31 8	7 0	
0	0	Reset

prescale_factor_set_index_updated Index for a certain set of prescale factors, which was "updated" with begin of previous lumi-section.

Register 4.17: Calibration trigger gap

reserved	end_calibration_trigger_gap	reserved	begin_calibration_trigger_gap	
31 28	27 16	15 12	11 0	
0	0	0	0	Reset

begin_calibration_trigger_gap Begin of calibration trigger gap (in Bx).

end_calibration_trigger_gap End of calibration trigger gap (in Bx).

4.4.2 Algo-bx-masks

Every Algorithm passes a logic where at every bunch-crossing of the orbit the Algorithm is enabled (or not). The algo-bx-masks are implemented as dual-port memories and loaded at the begin of run. The size of the algo-bx-masks memory is number of bunch-crossings per orbit for address length and number of Algorithms for data-depth (3564 [4096] x 512 bits).
The address (bx-number) of the memory for masking the Algorithm is delivered by an address-counter for algo-bx-masks memory, which is reseted with a delay-able bcres signal, to get the correct relations between Algorithms and masks from memory.

4.4.3 Rate-counters

Every Algorithm has a rate-counters with 32 bits, because of the length of one luminosity segment period. There are counters before and after prescalers and post-dead-time counters. The counters before and after prescalers are incremented, if the Algorithm signal is in high state and a positive edge of LHC-clock occur. The post-dead-time counters are incremented, if the Algorithm signal is in high state (delayed by L1A latency delay), a L1A signal and a positive edge of LHC-clock occur. The content of a counter is updated into a register (for reading the counter value) and is reseted at the begin of a luminosity segment period. So there is one luminosity segment period time to read the registers with the counter values by software.

4.4.4 Prescalers

Every Algorithm has a prescaler with a prescale factor of 24 bits. The prescaler reduces the trigger-rate per Algorithm with a factor, so e.g. a factor of 2 passes through every second trigger. A prescale factor of 0 inhibits all triggers of the certain Algorithm. The factor is loaded into a register by software and updated at begin of a new luminosity segment period, if the update was enabled by software ('request_update_factor_pulse' was set in "command_-pulses" register). The prescaler works with the new factor. A register for "prescale factor set index" contains a value which represents a certain set of prescale factors. The content of this register is seen in the Readout-record too. The "prescale factor set index" is loaded into the register by software and updated at begin of a new luminosity segment period.

4.4.5 Finor-masks

Every Algorithm passes a Final-OR-mask, which enables the Algorithm for Final-OR. The Final-OR-masks are implemented as registers and loaded at the begin of a run.

4.4.6 Veto-masks

Every Algorithm passes a veto-mask, if at least one Algorithm, which is enabled by veto-mask, becomes high state, then Final-OR is disabled as long as the Algorithm is in high state. The veto-masks are implemented as registers and loaded at the begin of a run.

4.4.7 Finor

The Final-OR-signal is a disjunction of all Algorithms passed the Final-OR-bx-masks. An Algorithm enabled by veto-mask, disables the Final-OR. This is done on the FINOR-AMC502 module.

4.5 Implementation in firmware

The entity-declaration of `fdl_module.vhd` is shown in 4.3.

Listing 19 contains the entity-declaration of the `fdl_module.vhd`.

Listing 19: Entity declaration of `fdl_module.vhd`

```
entity fdl_module is
    generic(
        SIM_MODE : boolean := false; -- if SIM_MODE = true, "algo_bx_mask" is
            given by "algo_bx_mask_sim".
        PRESCALE_FACTOR_INIT : ipb_regs_array(0 to MAX_NR_ALGOS-1);
        MASKS_INIT : ipb_regs_array(0 to MAX_NR_ALGOS-1);
        PRESCALE_FACTOR_SET_INDEX_WIDTH : positive := 8;
        PRESCALE_FACTOR_SET_INDEX_REG_INIT : ipb_regs_array(0 to 1) := (others =>
             X"00000000");
        L1A_LATENCY_DELAY_INIT : ipb_regs_array(0 to 1) := (others => X"00000000"
            );
        CNTRL_REG_INIT : ipb_regs_array(0 to 1) := (others => X"00000000");
-- Input flip-flops for algorithms of fdl_module.vhd - used for tests of
    fdl_module.vhd only
        ALGO_INPUTS_FF: boolean := false
    );
    port(
        ipb_clk             : in std_logic;
        ipb_rst             : in std_logic;
        ipb_in              : in ipb_wbus;
        ipb_out             : out ipb_rbus;
-- ==========================================================================
        lhc_clk             : in std_logic;
        lhc_rst             : in std_logic;
        bcres               : in std_logic;
        test_en             : in std_logic;
        l1a                 : in std_logic;
        begin_lumi_section  : in std_logic;
        algo_i              : in std_logic_vector(NR_ALGOS-1 downto 0);
        bx_nr_out : out std_logic_vector(11 downto 0);
        prescale_factor_set_index_rop : out std_logic_vector(
            PRESCALE_FACTOR_SET_INDEX_WIDTH-1 downto 0);
        algo_after_gtLogic_rop   : out std_logic_vector(MAX_NR_ALGOS-1 downto 0);
        algo_after_bxomask_rop      : out std_logic_vector(MAX_NR_ALGOS-1 downto
            0);
        algo_after_prescaler_rop       : out std_logic_vector(MAX_NR_ALGOS-1
            downto 0);
        local_finor_rop     : out std_logic;
        local_veto_rop      : out std_logic;
```

```
        finor_2_mezz_lemo      : out std_logic; -- to LEMO
        finor_preview_2_mezz_lemo      : out std_logic; -- to LEMO
        veto_2_mezz_lemo      : out std_logic; -- to LEMO
        finor_w_veto_2_mezz_lemo      : out std_logic; -- to tp_mux.vhd
        local_finor_with_veto_o       : out std_logic; -- to SPY2_FINOR
-- HB 2016-03-02: v0.0.21 - algo_bx_mask_sim input for simulation use with
    MAX_NR_ALGOS (because of global index).
        algo_bx_mask_sim    : in std_logic_vector(MAX_NR_ALGOS-1 downto 0)
    );
end fdl_module;
```

5 Readout-Process

The readout is done via TX-links of MP7 to AMC13.

6 Glossary

electron/γ = electron/gamma objects over Calo-Layer2 (VHDL: eg)

jet = jet objects over Calo-Layer2 (VHDL: jet)

tau = tau objects over Calo-Layer2 (VHDL: tau)

muon = muon objects over μGMT (VHDL: muon)

ET = Scalar sum of transverse energy components over Calo-Layer2 (VHDL: ett)

ETTEM = Scalar sum of transverse energy components from ECAL only over Calo-Layer2 (VHDL: ettem)

MBTxHFy = Minimum bias HF bits (VHDL: MBT0HFP, MBT0HFM, MBT1HFP, MBT1HFM)

HT = Magnitude of the vectorial sum of transverse energy of jets (hadronic) over Calo-Layer2 (VHDL: htt)

TOWERCOUNT = tower counts (VHDL: towercount)

ET_{miss} = 2-vector sum of transverse energy over Calo-Layer2 (VHDL: etm)

HT_{miss} = Missing Total transverse energy of jets over Calo-Layer2 (VHDL: htm)

$\mathbf{ET}_{miss}^{HF}$ = 2-vector sum of transverse energy including HF over Calo-Layer2 (VHDL: etmhf)

$\mathbf{HT}_{miss}^{HF}$ = Missing Total transverse energy of jets including HF over Calo-Layer2 (VHDL: htmhf)

ASYMET = Asymmetry of ET over Calo-Layer2 (VHDL: asymet)

ASYMHT = Asymmetry of HT over Calo-Layer2 (VHDL: asymht)

ASYMETHF = Asymmetry of ET including HF over Calo-Layer2 (VHDL: asymethf)

ASYMHTHF = Asymmetry of HT including HF over Calo-Layer2 (VHDL: asymhthf)

CENTx = Centrality bits [7:0] over Calo-Layer2 (VHDL: cent7, cent6, ...)

p_{T} = transverse momentum of muon objects(VHDL: pt)

E_{T} = energy of calorimeter objects (VHDL: et)

η = pseudo-rapidity position (VHDL: eta)

φ = azimuth angle position (VHDL: phi)

isolation = isolation information (VHDL: iso)

quality = quality information (VHDL: qual)

Acronyms

DAQ Data Acquisition

DM Delay Manager Module

FDL Final Decision Logic Module

GTL Global Trigger Logic Module

ROP Readout-Process Module

TCM Timing Counter Manager Module

TCS Trigger Control System

GCT Calorimeter Trigger Layer-2

GMT Global Muon Trigger

GT Global Trigger

References