Search for Higgs Decay to Dark Matter and Trigger Studies

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A dissertation submitted to Imperial College London
for the degree of Doctor of Philosophy

Abstract

Here the abstract of the thesis

Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee.

João Pela

Acknowledgements

TODO:

- Family
- Friends
- Work colleagues (include CMS collaboration)
- more

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Preface

Thesis structure and so on...

"To my grand mother"

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Chapter 1

Theory

TODO: Something

1.1 Standard Model of Particle Physics

TODO: Very brief summary of the Standard Model.

1.2 Higgs Mechanism

Summary of the Higgs Mechanism. Should include

- Motivations
- Explanation of the mechanism itself
- Consequences
- Possible decays

1.3 Higgs Invisible decays

TODO: Explain what are SM Higgs invisible decays. Go over the possibility of BSM invisible decays.

Chapter 2

Experimental Apparatus

The LHC Machine article [?].

2.1 The Large Hadron Collider

TODO:

- CERN basics location etc
- Basics of machine and operation
- New to include Instantaneous luminosity equation

The Large Hadron Collider [?] is a 27 km synchrotron machine located in Geneva Switzerland.

Luminosity Equation

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F, \tag{2.1}$$

2.2 The Compact Muon Solenoid Experiment

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2.2.2 Electromagnetic Calorimeter

2.2.3 Hadronic Calorimeter

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Chapter 3

Physics Objects and Monte Carlo simulation

3.1 Physics objects definition

3.1.1 Electron

3.1.2 Muon

3.1.3 Tau

3.1.4 Jets

3.1.5 Missing Transverse Energy

3.2 Monte Carlo simulation

3.3 Introduction

The search for an invisible decay of a vector boson produced Higgs boson was first made public with CMS Physics Analysis Summary (PAS) HIG-13-013 which was further improved and combined with other Higgs boson production channel in the CMS paper HIG-13-30. Additional support material can be found at the CMS Analysis Notes (AN) AN-2012/403[?] and AN-2013/205.

During the 2012 data taking run two main streams of data were recorded. The main stream with an event rate of the order of 300 Hz to be promptly reconstructed and made available for analysis in a few days after being recorded, this dataset is referred to as the prompt data. The secondary stream with lower trigger thresholds with an event rate of the order of 1kHz which would only be reconstructed when the computing resources would be available outside of the data taking period, dataset is referred to as parked data. Our previous results were produced using the prompt data only and this work now extends on previous work by using the now available parked data. Since this dataset has been recorded with lower trigger thresholds the analysis was re-optimised to take advantage of this new available phase space. The details of the newly developed analysis can be found in CMS AN-14-243[?].

It is normally a requirement for many CMS publications to have a cross check analysis implemented independently from the main result in order to be able to ensure accuracy of the final results due to possible errors with the software implementation. For this purpose the previous prompt data VBF Higgs to Invisible results and publication were produced by two different and independent code frameworks and before publication a good level of synchronization were obtained. Due to lack of man power and time it was decide for the 2012 parked data analysis to only proceed with a single framework. At a later stage of the analysis it was thought that at least some level of cross check would be a good measure to limit the possibility of implementation errors and to allow extra confidence on the final results.

This cross check analysis starts from the same ntuples produced by the main analysis which were produced over all the relevant datasets and are recorded with data formats also used by other analysis at Imperial College London, e.g. both the SM and MSSM Higgs to $\tau\bar{\tau}$, the Higgs to $\tau\bar{\tau}b\bar{b}$ and prompt Higgs to invisible analyses. No cuts are applied at ntuple production except the official CMS selection for good usable data using the appropriate golden JSON file.

From those initial ntuple an independent code framework was developed in order to replicate all relevant numbers and plots from the main analysis.

3.4 Data samples

For this analysis we used the proton-proton collision parked data collected by the CMS experiment during 2012-13. An analysis purposely constructed trigger was used to collect this data.

Dataset	$\int$ *Luminosity* $[pb^{-1}]$
/MET/Run2012A-22Jan2013-v1/AOD	889
/VBF1Parked/Run2012B-22Jan2013-v1/AOD	3871
/VBF1Parked/Run2012C-22Jan2013-v1/AOD	7152
/VBF1Parked/Run2012D-22Jan2013-v1/AOD	7317
Total analysed	19229
Total certified luminosity	19789

Table 3.1: Used datasets and their respective integrated luminosities after applying certified for physics filtering. Each dataset corresponds to a recording period/era of the 2012-13 data acquisition run.

3.5 Event Filters and object definitions

3.5.1 Vertex

The interaction point is normally assumed to be the reconstructed primary vertex, defined as the vertex with highest sum of associated tracks p_{T} squared, or if that cannot be determined the beam spot position is assumed. Knowing precisely the interaction point will allow to determine object quantities relative to it which allow for better object identification and pile-up control. At least one good vertex implicitly required by tracking failure event quality filter. And Additionally we require explicitly that a good vertex is reconstructed with the following characteristics.

- NOT(isFake): We require a real reconstructed vertex from tracks, not the beam spot.

- Number of degrees of freedom: $n_{dof} > 4$
- Longitudinal distance: $|z| <= 24$
- Radial distance to beam line: $d_{xy} < 2$

3.5.2 Event quality filters

During data recording issues may happen with the detector or acquisition which may render some of the events unusable. The groups responsible for each part of the detector and physics object check the data after and was taken and if they find such problems software event filters are made available for analysis to be able to remove this problematic events. This event filters will address issues like detector know problems, miss firing of calibration sequences or failure to reconstruct physics objects. The Jet-MET Particle Object Group (POG) recommends the usage of the following filters which are used in this analysis[**?**].

- CSCTightHaloFilter
- HBHENoiseFilter
- EcalDeadCellTriggerPrimitiveFilter
- trackingFailureFilter
- eeBadScFilter
- ECAL Laser filter (via event list)
- HCAL Laser filter (via event list)

In turn the JetMET group recommend the usage of the following Tracking POG Filter[**?**]:

- logErrorTooManyClusters
- manystripclus53X
- toomanystripclus53X

The event rejection efficiencies from the all filters except ECAL and HCAL laser event filters can be found at table 3.3. This values are measured the vertex requirements.

The values for the ECAL and HCAL laser event filters are present in table 3.5. This value are calculated after vertex requirement and the filters in table 3.3.

Filter	Prompt A	Parked B	Parked C	Parked D
ECAL Laser Filter	0.928521	0.008659	0.000000	0.000000
HCAL Laser Filter	0.007258	0.000000	0.000270	0.000000
ECAL+ HCAL Laser Filter	0.935704	0.008659	0.000270	0.000000

Table 3.2: Event rejection efficiency for the ECAL and HCAL Laser Filters. This events have to be removed due to the untimely firing of the calibration laser for this systems.

Filter	Prompt A	Parked B	Parked C	Parked D
HBHENoiseFilter	22.900905	0.190670	0.187739	0.170753
EcalDeadCellTriggerPrimitiveFilter	0.375381	0.009300	0.010206	0.012526
eeBadScFilter	0.007852	0.000001	0.000000	0.000009
trackingFailureFilter	3.073876	0.000328	0.007464	0.000290
manystripclus53X	0.001829	0.001319	0.002335	0.001327
toomanystripclus53X	0.000484	0.001149	0.002006	0.001173
logErrorTooManyClusters	0.000027	0.000009	0.000021	0.000016
CSCTightHaloFilter	10.263068	0.398497	0.402936	0.508025
Total	28.501208	0.598417	0.601999	0.689380

Table 3.3: Percentage of events in data failing each of the event quality filters after requesting on good vertex. For the parked analysis we use prompt A and parked B, C and D datasets.

It is observed that the HBHENoiseFilter vetos around 22% of the event for prompt run A but this behaviour is not observed in any of the parked datasets. This specific filter removed events with noise in the HCAL. An example of noise would be a "hot tower" reading very high energy values, some times for several events. Since this energy will not be balance in each event this will greatly increase $E_{\mathrm{T}}^{\mathrm{miss}}$. On the prompt dataset there are $E_{\mathrm{T}}^{\mathrm{miss}}$ only triggers which were fired in such events which then get removed by this filter, those triggers are not present in parked dataset. This can clearly be seen if we apply first our trigger selection (Jets+$E_{\mathrm{T}}^{\mathrm{miss}}$) and then recalculate the event rejection efficiencies, this values can be found in table 3.4.

Both tables 3.3 and 3.5 can be directly compared with the values produced by the main analysis and presented in AN-14-243[**?**]. No differences are observed.

Filter	Prompt A	Parked B	Parked C	Parked D
HBHENoiseFilter	1.264571	0.186895	0.178422	0.154080
EcalDeadCellTriggerPrimitiveFilter	0.572468	0.010081	0.010338	0.010725
eeBadScFilter	0.000989	0.000001	0.000000	0.000000
trackingFailureFilter	0.062289	0.000401	0.009729	0.000231
manystripclus53X	0.002966	0.001264	0.002304	0.001255
toomanystripclus53X	0.002966	0.001093	0.001955	0.001103
logErrorTooManyClusters	0.000000	0.000000	0.000000	0.000000
CSCTightHaloFilter	0.400431	0.397531	0.403156	0.506917
Total	2.201877	0.594332	0.592977	0.671026

Table 3.4: Percentage of events in data failing each of the event quality filters after requesting on good vertex and trigger conditions. For the parked analysis we use prompt A and parked B, C and D datasets.

3.5.3 Jets

In this analysis we use particle flow jets clustered with the $anti-k_T$ algorithm with a cone size of 0.5.

The correction L1FastJet, L2Relative and L3Absolute are applied to both data and monte carlo (MC) and additionally we apply L2L3Residual to data.

The to correct Jet Energy Scale we apply global tag FT53_V21A_AN6::All for data and START53_V27::All for monte carlo.

The jets with this characteristics and corrections are available in the ntuples produced by the main analysis as the "standard" jets collection. We further require that our selected jets pass PFJet ID and pileup ID. And we clean the jet collection by removing all jets that closer then $\Delta R < 0.5$ to any veto electron or loose muon (relevant for control regions).

3.5.4 Missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$)

3.5.5 Electrons

For this analysis we use two categories of electrons "veto electrons" and "tight electrons". Both this categories of particles are based on standard EGamma POG cut based object definition which can be found at (TODO:CITATION). Additionally, we require some additional cuts to each category (TODO:WHY).

Veto electrons

The "veto electrons" are defined by the base requirements of the cut based electron ID veto working point of the EGamma POG with some additional cuts on top.

Requirements of the cut based electron ID veto working point:

Barrel Cuts ($|\eta_{supercluster}| <= 1.479$)

- $|\Delta\eta(track, supercluster)| < 0.007$
- $|\Delta\phi(track, supercluster)| < 0.8$
- $\sigma(i\eta, i\eta) < 0.01$
- $H/E < 0.15$
- $|d_0(vertex)| < 0.04$
- $|d_Z(vertex)| < 0.2$
- $\frac{PF_{isolation}}{p_\perp} < 0.15$ for $\Delta R_{cone} = 0.3$

Endcap Cuts ($1.479 < |\eta_{supercluster}| < 2.5$)

- $|\Delta\eta(track, supercluster)| < 0.1$
- $|\Delta\phi(track, supercluster)| < 0.7$
- $\sigma(i\eta, i\eta) < 0.03$
- $|d_0(vertex)| < 0.04$
- $|d_Z(vertex)| < 0.2$
- $\frac{PF_{isolation}}{p_\perp} < 0.15$ for $\Delta R_{cone} = 0.3$

Additional requirements for this analysis

- $p_\perp > 10$ GeV
- $|\eta| < 2.4$
- $Effective-Area-Corrected-Isolation < 0.15$ (is stated in the note as additional requirement but does not look like it is)

- $d_{xy} < 0.04$ cm (is stated in the note as additional requirement but does not look like it is)
- $d_z < 0.2$ cm (is stated in the note as additional requirement but does not look like it is)

Tight electrons

The "tight electrons" are defined by using the base requirements of the cut based electron ID tight working point (similar to 2011 very tight WP70) of the EGamma POG with some additional cuts on top.

Requirements of the cut based electron ID tight working point (similar to 2011 very tight WP70):

Barrel Cuts ($|\eta_{supercluster}| <= 1.479$)

- $|\Delta\eta(track, supercluster)| < 0.004$
- $|\Delta\phi(track, supercluster)| < 0.3$
- $\sigma(i\eta, i\eta) < 0.01$
- $H/E < 0.12$
- $|d_0(vertex)| < 0.02$
- $|d_Z(vertex)| < 0.1$
- $|\frac{1}{E} - \frac{1}{p}| < 0.05$
- $\frac{PF_{isolation}}{p_\perp} < 0.10$ for $\Delta R_{cone} = 0.3$
- Conversion rejection: vertex fit probability: 1e-6
- Conversion rejection: missing hits <= 0

Endcap Cuts ($1.479 < |\eta_{supercluster}| < 2.5$)

- $|\Delta\eta(track, supercluster)| < 0.005$
- $|\Delta\phi(track, supercluster)| < 0.2$
- $\sigma(i\eta, i\eta) < 0.03$
- $H/E < 0.10$

- $|d_0(vertex)| < 0.02$
- $|d_Z(vertex)| < 0.1$
- $|\frac{1}{E} - \frac{1}{p}| < 0.05$
- $\frac{PF_{isolation}}{p_\perp} < 0.10(0.07)$ for $p_\perp > 20(p_\perp <= 20)$ and $\Delta R_{cone} = 0.3$
- Conversion rejection: vertex fit probability: 1e-6
- Conversion rejection: missing hits <= 0

Additional requirements for this analysis:

- $p_\perp > 20$ GeV
- $|\eta| < 2.4$
- $Effective - Area - Corrected - Isolation < 0.10$
- $d_{xy} < 0.02$ cm
- $d_z < 0.1$ cm

3.5.6 Muons

3.5.7 Taus

3.6 Signal selection

3.6.1 Pre-selection

Filter	Prompt A	Parked B	Parked C	Parked D
ECAL Laser Filter	0.928521	0.008659	0.000000	0.000000
HCAL Laser Filter	0.007258	0.000000	0.000270	0.000000
ECAL+ HCAL Laser Filter	0.935704	0.008659	0.000270	0.000000

Table 3.5: Event rejection efficiency for the ECAL and HCAL Laser Filters. This events have to be removed due to the untimely firing of the calibration laser for this systems.

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 0$	96600	74947192	137241812	151725585	364011189
$N(Muon_{loose}) = 0$	94864	74913002	137179173	151652654	363839693
Dijet cut	28164	23666926	43292391	42218637	109206118
MET cut	6252	57929	102384	120600	287165
$MET_{Significance}$ cut	3828	24179	42683	41620	112310
$Min(\Delta\phi(MET, jets))$ cut	405	1824	3452	3374	9055

Table 3.6: Event Yield for the Pre-Selection Region.

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt A	405	405	0.00%
Parked B	1824	1824	0.00%
Parked C	3453	3452	-0.03 %
Parked D	3374	3374	0.0%
Total	9056	9055	-0.01%

Table 3.7: Comparison between main and cross check analysis for the event yield of the event pre-selection. There is a difference of a single event between both analysis which is a difference in total yield around 0.01%.

3.6.2 Signal region

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 0$	96600	74947192	137241812	151725585	364011189
$N(Muon_{loose}) = 0$	94864	74913002	137179173	151652654	363839693
Dijet cut	18338	13678405	25090291	24082304	62869338
MET cut	4167	38178	68047	79723	190115
$MET_{Significance}$ cut	786	3396	5988	5567	15737
$Min(\Delta\phi(MET, jets))$ cut	34	91	205	178	508

Table 3.8: Event Yield for the Signal Region.

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt A	34	34	0.00%
Parked B	91	91	0.00%
Parked C	205	205	0.00 %
Parked D	178	178	0.00%
Total	508	508	0.00%

Table 3.9: Comparison between main and cross check analysis for the event yield of signal region. No difference in yields is observed either in total or by acquisition era.

3.7 Background estimation

3.7.1 W to electron+$E_{\mathrm{T}}^{\mathrm{miss}}$

The selection consists of the following cuts:

- Vertex cut
- Event quality filters (MET Filters)
- ECAL+HCAL Laser filters
- L1T ETM Filter (L1T_ETM40 emulation)
  - $L1T\_ETM >= 40$
- HLT path filter
  - From run 190456 to 193621 (Run 2012 A) use HLT_DiPFJet40_PFMETnoMu65_MJJ800VBF_Al
  - From run 193833 to 196531 (Run 2012 B) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 198022 to 203742 (Run 2012 C) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 203777 to 208686 (Run 2012 D) use HLT_DiJet30_MJJ700_AllJets_DEta3p5_VBF*
- Exactly one $Electron_{Veto}$
  - Using veto electron defined on this page
- Exactly one $Electron_{Tight}$
  - Using tight electron defined on this page
- Muon Veto
  - Using veto muons defined on this page (to be done)
- $MET > 90$ GeV
- $MET_{significance} > 4.0$
- Dijet cut (leading dijet requirements):
  - Lead dijet $p_{\perp} > 50$ GeV
  - Sub-lead dijet $p_{\perp} > 45$ GeV
  - Jets $|\eta| < 4.7$

- Dijet $\Delta\eta < 3.6$
- Dijet $m_{jj} > 1200$ GeV

- $Min(\Delta\phi(MET, Jet_{p_\perp>30}))) > 2.3$

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 1$	899	151621	282481	312807	747808
$N(Muon_{loose}) = 0$	852	151249	281801	312033	745935
$N(Electrons_{tight}) = 1$	398	23751	44323	50279	118751
Dijet cut	64	1607	3145	3077	7893
MET cut	55	281	543	525	1404
$MET_{Significance}$ cut	31	123	242	197	593
$Min(\Delta\phi(MET, jets))$ cut	4	16	24	24	68

Table 3.10: Electron+MET Yields

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt Run A	4	4	0.00%
Parked Run B	16	16	0.00%
Parked Run C	24	24	0.00%
Parked Run D	24	24	0.00%
Total	68	68	0.00%

Table 3.11: Comparison between main and cross check analysis for the event yield of Electron+MET event selection. No difference in yields is observed either in total or by acquisition era.

3.7.2 W to μ+$E_{\mathrm{T}}^{\mathrm{miss}}$

The selection consists of the following cuts

- Vertex cut
- Event quality filters (MET Filters)
- ECAL+HCAL Laser filters
- L1T ETM Filter (L1T_ETM40 emulation)
  - $L1T\_ETM >= 40$
- HLT path filter
  - From run 190456 to 193621 (Run 2012 A) use HLT_DiPFJet40_PFMETnoMu65_MJJ800VBF_Al
  - From run 193833 to 196531 (Run 2012 B) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 198022 to 203742 (Run 2012 C) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 203777 to 208686 (Run 2012 D) use HLT_DiJet30_MJJ700_AllJets_DEta3p5_VBF*
- Electron Veto
  - Using veto electron defined on this page
- Exactly one $Muon_{loose}$
  - Using veto muons defined on this page (to be done)
- Exactly one $Muon_{tight}$
  - Using veto muons defined on this page (to be done)
- $MET > 90$ GeV
- $MET_{significance} > 4.0$
- Dijet cut (leading dijet requirements):
  - Lead dijet $p_{\perp} > 50$ GeV
  - Sub-lead dijet $p_{\perp} > 45$ GeV
  - Jets $|\eta| < 4.7$
  - Dijet $\Delta\eta < 3.6$

  - Dijet $m_{jj} > 1200$ GeV

- $Min(\Delta\phi(MET, Jet_{p_\perp > 30}))) > 2.3$

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 0$	96600	74947192	137241812	151725585	364011189
$N(Muon_{loose}) = 1$	1625	33505	61325	71449	167904
$N(Muon_{tight}) = 1$	1223	9662	17873	20088	48846
Dijet cut	176	1493	2740	2684	7093
MET cut	157	809	1545	1493	4004
$MET_{Significance}$ cut	86	487	910	825	2308
$Min(\Delta\phi(MET, jets))$ cut	10	60	124	106	300

Table 3.12: Muon+MET Region

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt Run A	10	10	0.00%
Parked Run B	60	60	0.00%
Parked Run C	124	124	0.00%
Parked Run D	106	106	0.00%
Total	300	300	0.00%

Table 3.13: Comparison between main and cross check analysis for the event yield of Muon+MET event selection. No difference in yields is observed either in total or by acquisition era.

3.7.3 W to τ+$E_{\mathrm{T}}^{\mathrm{miss}}$

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 0$	96600	74947192	137241812	151725585	364011189
$N(Muon_{loose}) = 0$	94864	74913002	137179173	151652654	363839693
Dijet cut	18338	13678405	25090291	24082304	62869338
MET cut	4167	38178	68047	79723	190115
$MET_{Significance}$ cut	786	3396	5988	5567	15737
$N(Tau) = 1$	12	47	63	59	181
$M_{perp}(MET, \tau)$ cut	5	35	46	38	124
$Min(\Delta\phi(MET, Dijet))$ cut	2	22	25	27	76

Table 3.14: Event Yield for the Tau+MET Region.

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt Run A	2	2	0.00%
Parked Run B	22	22	0.00%
Parked Run C	25	25	0.00%
Parked Run D	27	27	0.00%
Total	76	76	0.00%

Table 3.15: Comparison between main and cross check analysis for the event yield of Tau+MET event selection. No difference in yields is observed either in total or by acquisition era.

3.7.4 Z to $\mu\mu$

The selection consists of the following cuts:

- Vertex cut
- Event quality filters (MET Filters)
- ECAL+HCAL Laser filters
- !L1T ETM Filter (L1T_ETM40 emulation)
  - $L1T\_ETM >= 40$
- HLT path filter
  - From run 190456 to 193621 (Run 2012 A) use HLT_DiPFJet40_PFMETnoMu65_MJJ800VBF_Al
  - From run 193833 to 196531 (Run 2012 B) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 198022 to 203742 (Run 2012 C) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 203777 to 208686 (Run 2012 D) use HLT_DiJet30_MJJ700_AllJets_DEta3p5_VBF*
- Electron Veto
  - Using veto electron defined on this page
- Exactly two $Muon_{loose}$
  - Using veto muons defined on this page (to be done)
- Exactly two $Muon_{tight}$
  - Using veto muons defined on this page (to be done)
- Dimuon with $60 < mass < 120$ GeV
- $MET > 90$ GeV
- $MET_{significance} > 4.0$
- Dijet cut (leading dijet requirements):
  - Lead dijet $p_{\perp} > 50$ GeV
  - Sub-lead dijet $p_{\perp} > 45$ GeV
  - Jets $|\eta| < 4.7$

- Dijet $\Delta\eta < 3.6$
- Dijet $m_{jj} > 1200$ GeV

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 0$	96600	74947192	137241812	151725585	364011189
selTwoMuonsLoose	111	683	1312	1480	3586
selTwoMuonsTight	73	450	822	935	2280
Z Mass cut	62	379	686	768	1895
Dijet cut	11	58	98	96	263
MET cut	9	41	74	70	194
$MET_{Significance}$ cut	7	18	55	44	124
$Min(\Delta\phi(MET, jets))$ cut	2	4	5	7	18

Table 3.16: Event Yield for the Z to $\mu\mu$ Region.

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt A	2	2	0.00%
Parked B	4	4	0.00%
Parked C	5	5	0.00%
Parked D	7	7	0.00%
Total	18	18	0.00%

Table 3.17: Comparison between main and cross check analysis for the event yield of Z to $\mu\mu$ event selection. No difference in yields is observed either in total or by acquisition era.

3.7.5 Top

The selection consists of the following cuts:

- Vertex cut
- Event quality filters (MET Filters)
- ECAL+HCAL Laser filters
- L1T ETM Filter (L1T_ETM40 emulation)
  - $L1T\_ETM >= 40$
- HLT path filter
  - From run 190456 to 193621 (Run 2012 A) use HLT_DiPFJet40_PFMETnoMu65_MJJ800VBF_Al
  - From run 193833 to 196531 (Run 2012 B) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 198022 to 203742 (Run 2012 C) use HLT_DiJet35_MJJ700_AllJets_DEta3p5_VBF*
  - From run 203777 to 208686 (Run 2012 D) use HLT_DiJet30_MJJ700_AllJets_DEta3p5_VBF*
- Exactly one $Electron_{Veto}$
  - Using veto electron defined on this page
- Exactly one $Electron_{Tight}$
  - Using tight electron defined on this page
- Exactly one $Muon_{loose}$
  - Using veto muons defined on this page (to be done)
- Exactly one $Muon_{tight}$
  - Using veto muons defined on this page (to be done)
- $MET > 90$ GeV
- $MET_{significance} > 4.0$
- Dijet cut (leading dijet requirements):
  - Lead dijet $p_{\perp} > 50$ GeV
  - Sub-lead dijet $p_{\perp} > 45$ GeV

- Jets $|\eta| < 4.7$
- Dijet $\Delta\eta < 3.6$
- Dijet $m_{jj} > 1200$ GeV

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Muon_{loose}) = 1$	1674	33877	61994	72215	169760
$N(Muon_{tight}) = 1$	1259	9913	18322	20585	50079
$N(Electrons_{veto}) = 1$	35	247	444	492	1218
$N(Electrons_{tight}) = 1$	23	150	273	300	746
Dijet cut	0	15	21	17	53
MET cut	0	10	14	12	36
$MET_{Significance}$ cut	0	4	9	8	21

Table 3.18: Event Yield for the Top Region.

Dataset	Main Analysis	Cross Check Analysis	$\frac{CC}{Main} - 1$
Prompt A	0	0	0.00%
Parked B	4	4	0.00%
Parked C	9	9	0.00%
Parked D	8	8	0.00%
Total	21	21	0.00%

Table 3.19: Comparison between main and cross check analysis for the event yield of top event selection. No difference in yields is observed either in total or by acquisition era.

3.7.6 QCD

	Prompt Run A	Parked Run B	Parked Run C	Parked Run D	Total Data
Vertex Filter	3606391	132346320	228049748	308041846	672044305
Event Quality Filters	2658960	131554431	226680352	305918529	666812272
ECAL Laser Filter	2634271	131543040	226680352	305918529	666776192
HCAL Laser Filter	2634080	131543040	226679741	305918529	666775390
L1T ETM Filter	2461217	88174347	160560859	227801622	478998045
HLT Filter	97522	75100422	137527238	152041761	364766943
$N(Electrons_{veto}) = 0$	96600	74947192	137241812	151725585	364011189
$N(Muon_{loose}) = 0$	94864	74913002	137179173	151652654	363839693
Dijet cut	18338	13678405	25090291	24082304	62869338
MET cut	4167	38178	68047	79723	190115
$MET_{Significance}$ cut	2532	15594	27623	27068	72817
$Min(\Delta\phi(MET, jets))$ cut	2314	14691	25826	25326	68157

Table 3.20: Event Yield for the QCD Region.

Chapter 4

Technical work

4.1 Level 1 Trigger Data Quality Monitoring System

Hello

Chapter 5

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Chapter 6

Conclusions

Summary of relevant results and their impact on Particle Physics

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