

SEARCH FOR  $t\bar{t}Z' \rightarrow t\bar{t}t\bar{t}$  PRODUCTION IN THE MULTILEPTON FINAL STATE IN  
 $pp$  COLLISIONS AT  $\sqrt{s} = 13$  AND 13.6 TEV WITH THE ATLAS DETECTOR

By

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A DISSERTATION

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in partial fulfillment of the requirements  
for the degree of

Physics — Doctor of Philosophy

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## ABSTRACT

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ATLAS in general & funding agencies

## PREFACE

This is my preface. remarks remarks remarks

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## KEY TO ABBREVIATIONS

Physical & mathematical quantities

$\chi^2$  chi-squared

$\Delta R$  angular distance

$\eta$  pseudorapidity

$E_T$  transverse energy

$E_T^{\text{miss}}$  missing transverse momentum

$\hat{H}$  Higgs oblique parameter

$I$  weak isospin

$L$  instantaneous luminosity

$\mu$  signal strength

$p_T$  transverse momentum

Particles

$b$  bottom quark

$pp$  proton-proton

$t\bar{t}$  top/anti-top quark

$t\bar{t}t\bar{t}$  four-top-quark

$tW$  single-top

Acronyms

**1LOS** one lepton, or two leptons of opposite charges

**ATLAS** A Toroidal LHC ApparatuS

**BDT** boosted decision tree

**BSM** Beyond the Standard Model

**CERN** European Organization for Nuclear Research

**CMS** Compact Muon Solenoid

**CR** control region

**ECIDS** Electron Charge ID Selector  
**GNN** graph neural network  
**HLT** High-Level Trigger  
**ID** inner detector  
**JER** jet energy resolution  
**JES** jet energy scale  
**JVT** Jet Vertex Tagger  
**L1** Level 1  
**LH** likelihood  
**LLH** log-likelihood  
**LO** leading order  
**LAr** liquid argon  
**LHC** Large Hadron Collider  
**MET** missing transverse energy  
**NF** normalization factor  
**NLO** next-to-leading order  
**NNLO** next-to-next-to-leading order  
**NP** nuisance parameter  
**OP** operating point  
**PS** parton shower  
**PDF** parton distribution function  
**PCBT** pseudo-continuous  $b$ -tagging  
**QED** quantum electrodynamics  
**QCD** quantum chromodynamics  
**QFT** quantum field theory  
**QmisID** charge mis-identification  
**SF** scale factor

**SM** Standard Model

**SR** signal region

**SSML** two leptons of the same charge, or more than two leptons (multilepton)

**TDAQ** Trigger and Data Acquisition

# Roadmap

1. Finish adding bullets for all sections ..... 05/16  
    Remaining
  - introduction
  - higgs-top yukawa coupling, SMEFT & Higgs oblique parameter
  - collider physics
  - mc background samples
  - ttbar/ptrel/high pT calibration & results
2. Fill in details ..... 05/23
  - Add missing figures
  - Add missing bib
3. Finalize analysis ..... 05/30
4. String everything together
5. Miscellaneous/logistics (proofreading, review, ATLAS approval, etc.) .....
6. Submission to the graduate school ..... 06/15
7. Defense ..... 06/30

# Chapter 1. Introduction

# Chapter 2. Theoretical Overview

## 2.1 The Standard Model

- SM describes fundamental forces & elementary particles
- more descriptions (a bit of history + recent developments - higgs & neutrino masses) -
- limitations: gravity & general relativity, arbitrary free parameters

### 2.1.1 Elementary particles

- Bosons (Bose-Einstein statistics, integer spin) & fermions (Fermi-Dirac statistics, half-integer spin)
- Fermions - building blocks: quarks & leptons [protons/neutrons constituents?]
- Bosons - force carriers & interaction mediators (elementary bosons == gauge bosons  
(chart of elementary particles here))

#### Fermions

- elementary particles
- half-integer spin

#### Quarks

- building blocks for hadrons & bosons
- up down — charm strange — bottom top [by order of discovery and mass]
- charge doublets:  $+2/3$  and  $-1/3$  charge
- color charge & color confinement in hadrons
- interacts with all 4 fundamental forces

## Leptons

- electron — muon — tau + neutrino [by order of mass]
- charge -1, neutrinos charge neutral
- interacts with all forces except strong, neutrinos only weak and gravitational

## Bosons

- force mediators
- integer spin

### Scalar

- spin 0
- Higgs massive, charge neutral, provides rest mass for all elementary particles,

### Vector

- spin 1
- W/Z (weak), photon (QED/electrodynamic), gluons (QCD/strong)
- photon/gluon massless, charge neutral, gluon carries color charge out of 8 combinations of quark colors (color octet)
- W/Z massive, charged/neutral

## 2.1.2 Mathematical formalism

- QFT: treats particles as excitations of corresponding quantum fields: fermion field  $\psi$ , electroweak boson fields  $W_{1/2/3}$  &  $B$ , gluon field  $G_\alpha$ , Higgs field  $\phi$
- Lagrangian: gauge QFT containing local gauge symmetries of  $SU(3)_C \times SU(2)_L \times U(1)_Y$  and global Poincar symmetry: translational symmetry, rotational symmetry & special relativity frame invariance

- Noether's theorem: local symmetries  $\rightarrow$  strong/weak/EM, Poincar  $\rightarrow$  momentum, angular momentum & energy conservation
- unexpanded Lagrangian with description of each part: kinetic terms, coupling terms, mass/Higgs terms)

## Quantum chromodynamics

- strong interaction,  $SU(3)_C$  gauge group under Yang-Mills theory
- C = color charge conservation
- QCD Lagrangian, expansion & brief explanation

## Electroweak

- unified weak & electromagnetic interactions,  $SU(2)_L \times U(1)_Y$  gauge group
- L = left-handed chirality  $\rightarrow$  weak isospin (I) conservation
- Y = weak hyper charge conservation
- Q = charge conservation =  $I_3 + 1/2Y$
- QED Lagrangian, expansion & brief explanation

## Higgs mechanism

fermions & bosons still massless from previous section, resolved by introduction of the Higgs mechanism

(show Higgs field, potential & Lagrangian)

(show minimum of Higgs potential aka VEV)

—————[continue later]—————



### 2.1.3 Beyond the Standard Model

## 2.2 Four-top quark production

- Top: heaviest particle, strong coupling to many BSM particles in BSM models.
- 4top: xsec relevant to and enhanced by many BSM models
- Predicted by SM and observed [observation paper]
- Predicted xsec and observed xsec
- (insert Feynman diagrams)
- Decay products & final state topologies

### Top-philic vector resonance

- (briefly introduce composite pseudo-nambu-Goldstone boson and motivation)
- hypothesis: top quark large mass results from high mixing between a "true" top quark and a colored, fermionic composite state
- composite vector resonance can be modeled as a top-philic  $Z'$  boson (without QCD color) or top-philic KK-gluon (with QCD color)
- color singlet vector boson ( $Z'$ ) model coupling strongly to top and weakly or not at all to others
- (show Lagrangian for interaction)
- two body decay  $Z'$  into  $t\bar{t}$  with  $m_{Z'}$  in TeV range  $\rightarrow$  top mass
- decay channels:  $t\bar{t}Z'$  s & t channels,  $tWZ'$ ,  $tjZ'$
- (show decay width at LO)
- (Feynman diagrams here)

## Higgs-top Yukawa coupling

(show Lagrangian of Higgs-top Yukawa coupling)

(show dependence of  $t\bar{t}t\bar{t}$  xsec on Yukawa coupling at LO)

## Effective field theory

SMEFT expanding on SM Lagrangian using higher order operators

(show EFT Lagrangian)

quick overview on SMEFT dimension-6 four-fermion operators for BSM interpretation

and Higgs oblique parameter

## 2.3 Collider physics

[pp collision, pdf, cross section, luminosity]

### Luminosity

### Proton-proton collisions

jets, parton shower, hadronization

### Parton distribution function

### Cross section

# Chapter 3. LHC & ATLAS Experiment

## 3.1 The Large Hadron Collider

theoretical predictions are tested with experimental data obtained from particle accelerators world's largest accelerator built by CERN situated on the border of Switzerland and France has been operating since xxxx lifetime divided into 3 runs, currently on Run 3 with planned upgrades on the horizon responsible for a number of discoveries aka Higgs, etc.

### 3.1.1 Overview

[Basic info: location, size, main working mechanism, main detectors, main physics done]

- 27 km circumference, reusing LEP tunnels 175 m below ground level
- 7-13-13.6 TeV center of mass energies for pp collisions
- other than pp, also collides pPb, PbPb at 4 points with 4 main detectors: ATLAS, CMS (general purpose detectors), ALICE (heavy ion physics, ion collisions), LHCb (*b*-physics)

### 3.1.2 LHC operations

- focuses mainly on pp collisions for this thesis - beams split into bunches of  $1.1 \times 10^{11}$  protons with instantaneous luminosity of up to  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- beam energies ramp up in other accelerators before injection, full ramp up to 6.5 GeV about 20 minutes

(insert full diagram of accelerator chain)

Linac 4: hydrogen atoms, accelerated up to 160 MeV

PSB: H atoms stripped of electrons before injection, accelerated to 2 GeV

PS: 26 GeV, SPS: 450 GeV

LHC: injection in opposite directions, 6.5 TeV per beam

Run 1: 2010-2012, Run 2: 2015-2018, Run 3: 2022-2025, HL-LHC: 2029-?

COM energies: 7 & 8 TeV, 13 TeV, 13.6 TeV, 13.6 & 14 TeV

inbetween periods: long shutdowns (LS1, LS2, LS3)

(add HL-LHC timeline graph)

(insert LHC SM processes cross sections chart)

## **Top quark production at the LHC**

history (CDF/D0)

LHC as a top factory: show luminosity and cross section for top processes

couples to Higgs as heaviest elementary particle

Higgs produced mainly from ggH (90%) via top loop and from ttH

(Feynman diagram of related processes)

## **3.2 The ATLAS detector**

multipurpose particle detector with a symmetric cylindrical geometry and a solid angle

coverage of almost  $4\pi$

44m long, 25m diameter

inner detector, solenoid/toroid magnet, EM & hadronic calorimeters, muon spectrometer

(insert figure)

right-handed cylindrical system, z-axis follows beamline, azimuthal and polar (0 in the beam direction) angles measured with respect to beam axis.

pseudorapidity  $\eta = -\ln \tan(\theta/2)$ , approaches  $\pm \infty$  along and 0 orthogonal to the beamline

distance  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

transverse energy  $E_T = \sqrt{p_T^2 + m^2}$

transverse momentum  $p_T$  component of momentum orthogonal to the beam axis  $p_T = \sqrt{p_x^2 + p_y^2}$

### 3.2.1 Inner detector

- measures tracks of charged particles with high momentum resolution ( $\sigma_{p_T}/p_T = 0.05\% \pm 1\%$ )
- covers particles with  $p_T > 0.5 \text{ GeV}$ ,  $|\eta| < 2.5$   
 pixel detector -> semiconductor tracker -> transition radiation tracker, innermost to outermost
- pixel detector:
  - innermost, 250  $\mu\text{m}$  silicon pixel layers
  - detects charged particles from electron-hole pair production in silicon
  - measures impact parameter resolution & vertex identification for reconstruction of short-lived particles
  - spatial resolution of 10  $\mu\text{m}$  in the  $R - \phi$  plane and 115  $\mu\text{m}$  in the z-direction
  - 80.4m readout channels
- sct:

- surrounds pixel detector, silicon microstrip layers with 80  $\mu\text{m}$  strip pitch
  - particle tracks cross 8 strip layers
  - measures particle momentum, impact parameters, vertex position
  - spatial resolution of 17  $\mu\text{m}$  in the  $R - \phi$  plane and 580  $\mu\text{m}$  in the z-direction
  - 6.3m readout channels.
- trt:
    - outermost, layers of 4 mm diameter gaseous straw tubes with transition radiation material (70%  $Xe + 27\% CO_2 + 3\% O_2$ ) & 30  $\mu\text{m}$  gold-plated wire in the center
    - tubes 144 cm length in barrel region ( $|\eta| < 1$ ), 37 cm in the endcap region ( $1 < |\eta| < 2$ ), arranged in wheels instead of parallel to beamline)
    - gas mixture produces transition radiation when ionized for electron identification
    - resolution/accuracy of 130  $\mu\text{m}$  for each straw tube in the  $R - \phi$  plane
    - 351k readout channels

### 3.2.2 Calorimeter systems

surrounds the inner detector & solenoid magnet, covers  $|\eta| < 4.9$  and full  $\phi$  range. Alternates passive and active material layers. Incoming particles passing through calorimeter produce EM cascades or hadronic showers in passive layer. Energies deposited and convert to electric signals in active layers for readout.

EM calorimeter:

- innermost, lead-LAr detector (passive-

active)

- measures EM cascades (bremsstrahlung & pair production) produced by electrons/photons
- divided into barrel region ( $|\eta| < 1.475$ ) & endcap regions ( $1.375 < |\eta| < 3.2$ ) with transition region ( $1.372 < |\eta| < 1.52$ ) containing extra cooling materials for inner detector
- end-cap divided into outer wheel ( $1.372 < |\eta| < 2.5$ ) & inner wheel ( $2.5 < |\eta| < 3.2$ )
- higher granularity in ID ( $|\eta| < 2.5$ ) range for electrons/photons & precision physics, coarser elsewhere for jet reconstruction & MET measurements

hadronic calorimeter:

- outermost
- measures hadronic showers from inelastic QCD collisions

- thick enough to prevent most particles showers from reaching muon spectrometer
- split into tile calorimeter in barrel region ( $|\eta| < 1.0$ ) & extended barrel region ( $0.8 < |\eta| < 1.7$ ), LAr hadronic end-cap calorimeter (HEC) in end-cap regions ( $1.5 < |\eta| < 3.2$ ) & LAr forward calorimeters (FCal) in  $3.1 < |\eta| < 4.9$  range.
  - tile calorimeters: steel-plastic scintillating tiles, readout via photomultiplier tubes
  - hec: behind tile calorimeters, 2 wheels per end-cap. copper plates-LAr. overlap with other calorimeter systems to cover for gaps between subsystems
  - fcal: 1 copper module & 2 tungsten modules-LAr. copper optimized for EM measurements, tungsten for hadronic.

### 3.2.3 Muon spectrometer

- ATLAS outermost layer. measures muon momenta & charge in range  $|\eta| < 2.7$
- momentum measured by deflection in track from toroid magnets producing magnetic field orthogonal to muon trajectory
  - large barrel toroids in  $|\eta| < 1.4$ , strength 0.5 T
  - 2 smaller end-cap toroids in  $1.6 < |\eta| < 2.7$ , strength 1 T
  - transition region  $1.4 < |\eta| < 1.6$ , deflection provided by a combination of barrel and end-cap magnets
- chambers installed in 3 cylindrical layers, around the beam axis in barrel region & in planes perpendicular to beam axis in the transition and end-cap regions
- split into high-precision tracking chambers (monitored drift tubes & cathode strip chambers) & trigger chambers (resistive plate chambers & thin gap chambers)
- trigger chambers provide fast muon multiplicity & approximate energy range information with L1 trigger logic
  - mdt:
 

<ul style="list-style-type: none"> <li>* range <math> \eta  &lt; 2.7</math>, innermost layer <math> \eta  &lt; 2.0</math></li> <li>* precision momentum measurement</li> <li>* layers of 30 mm drift tubes filled</li> </ul>	<ul style="list-style-type: none"> <li>with 93% <i>Ar</i> &amp; 7% <i>CO</i><sub>2</sub>, with a 50 <math>\mu</math>m gold-plated tungsten-rhenium wire at the center</li> <li>* muons pass through tube, ionizing gas and providing signals.</li> <li>Combining signals from tubes</li> </ul>
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- forms track
- \* maximum drift time from wall to wire 700 ns
- \* resolution: 35  $\mu\text{m}$  per chamber, 80  $\mu\text{m}$  per tube
- csc:
  - \* forward region  $2.0 < |\eta| < 2.7$ , highest particle flux and density region
  - \* multiwire proportional chambers with higher granularity, filled with 80% *Ar* & 20% *CO*<sub>2</sub>
  - \* shorter drift time than MDT, plus other features making CSC suitable for high particle densities and consequently able to handle background conditions
  - \* resolution: 40  $\mu\text{m}$  in bending  $\eta$ -plane, 5 mm in nonbending  $\phi$ -plane due to coarser cathode segmentation, per CSC plane
- rpc:
  - \* range  $|\eta| < 1.05$
  - \* provide fast meas
- tgc:
  - \* range  $1.05 < |\eta| < 2.7$

### 3.2.4 Forward detectors

- LUCID (Luminosity measurement using Cherenkov Integrating Detector):  $\pm 17$  m from interaction point, measures luminosity using  $pp$  scattering in the forward region
- ALFA (Absolute Luminosity for ATLAS):  $\pm 240$  m, measures  $pp$  scattering at small angles
- ZDC (Zero-Degree Calorimeter):  $\pm 140$  m, measures centrality in heavy-ion collisions

### 3.2.5 Magnetic systems

superconducting solenoid & toroid magnets cooled to 4.5 K with liquid helium

solenoid: 2.56 m diameter, 5.8 m length, 2 T strength axial magnetic field, encloses inner detector

toroid = barrel + endcap toroid x2

barrel toroid: 9.2/20.1 m inner/outer diameter, 25.3 m length, 0.5 T strength

endcap toroid: 1.65/10.7 m inner/outer diameter, 5 m length, 1 T strength

(show magnet system diagram)

### 3.2.6 Trigger & data acquisition

LHC produces large amount of data (40 MHz with 25 ns bunch crossing), necessitates a way to filter out trash from interesting events

handles online processing, selecting and recording interesting events for further offline processing and more in-depth analyses

- Level-1 (L1) trigger: online, fast hardware-based trigger, reduces to 100 kHz
  - L1 calorimeter triggers (L1Calo): selects high energy objects & MET
  - L1 muon triggers (L1Muon): selects using hit information from RPC & TGC
  - L1 topological trigger (L1Topo): select based on topological selection synthesized using information from L1Calo & L1Muon
  - Central Trigger Processor (CTP): uses L1Calo/Muon/Topo for final L1 trigger decision within  $2.5 \mu\text{s}$  latency. Also identify regions of interest in  $\eta$  and  $\phi$  to be processed directly by HLT
- L1 trigger information read out by Front-End (FE) detector electronics then sent to ReadOut Drivers (ROD) for preprocessing and subsequently to ReadOut System (ROS) to buffer
- High-Level Trigger (HLT): offline, software-based trigger, using dedicated algorithms and L1 output as input, reduces to 1 kHz
- Send to storage for analyses after HLT

overall trigger process reduces original collision data rate by a factor of about 10000 after HLT

(show TDAQ diagram)

# Chapter 4. Data & Simulated Samples

## 4.1 Data samples

LHC Run 2 data collected at  $\sqrt{s} = 13$  TeV between 2015-2018

luminosity  $140 \text{ fb}^{-1}$

(include uncertainty for Run 2 only)

## 4.2 Monte Carlo samples

Monte Carlo simulated samples are used to estimate signal acceptance before unblinding, profile the physics background for the analysis and to study object optimizations.

Simulated samples for this analysis use are generated from ATLAS' generalized MC20a/d/e samples for Run 2, using full detector simulation (FS) based on Geant4.

### 4.2.1 $t\bar{t}Z'$ signal samples

Run 2  $t\bar{t}Z'$  sample

samples: 6 samples for each mass point from  $[1, 1.25, 1.5, 2, 2.5, 3]$  TeV

generator: MADGRAPH5\_AMC@NLO v.2.8.1p3.atlas9 at LO with NNPDF3.1LO pdf

event: PYTHIA8 [v.244p3.rangefix] using A14 tune & NNPDF2.3LO pdf

parameters:

- chirality  $\theta$ : does not affect the strong production mode for  $t\bar{t}Z'$ , therefore picking default value  $\pi/4$  to suppress loop-production of the  $Z'$  resonance
- top- $Z'$  coupling  $c_t = 1$

resonance width computed with MADGRAPH5\_AMC@NLO to be 4% of model configuration  
with these parameters

### **4.2.2 Background samples**

Run 2 mc20 samples (2015-2018)

(show MC sample table)

(go in depth into each sample? briefly explain different generator, pdf and ps?)

Process	ME Generator	ME Order	ME PDF	PS	Tune	Sim.
<b>Signals</b>						
$t\bar{t}H/A$	MADGRAPH5_AMC@NLO	LO	NNPDF30 LO	PYTHIA8	A14	AF3
$t\bar{t}Z'/tjZ'/tWZ'$	MADGRAPH5_AMC@NLO	LO	NNPDF3.1LO	PYTHIA8	A14	FS
<b><math>t\bar{t}t\bar{t}</math> and <math>t\bar{t}t</math></b>						
$t\bar{t}t\bar{t}$	MADGRAPH5_AMC@NLO	NLO	NNPDF3.0nlo	PYTHIA8	A14	AF3
	MADGRAPH5_AMC@NLO	NLO	MMHT2014LO	HERWIG7 H7-UE- MMHT		AF3
	SHERPA	NLO	NNPDF3.0 NNLO	HERWIG7 SHERPA		FS
$t\bar{t}t$	MADGRAPH5_AMC@NLO	LO	NNPDF2.31o	PYTHIA8	A14	AF3
<b><math>t\bar{t}V</math></b>						
$t\bar{t}H$	POWHEGBOX v2	NLO	NNPDF3.0nlo (mc20)	PYTHIA8	A14	FS
			PDF4LHC21 (mc23)			AF3
	POWHEGBOX v2	NLO	NNPDF3.0nlo	HERWIG7 H7.2- Default		FS
$t\bar{t}Z$	MADGRAPH5_AMC@NLO	NLO	NNPDF3.0 NNLO	PYTHIA8	A14	FS
$t\bar{t}W$	SHERPA	NLO	NNPDF3.0 NNLO	SHERPA	SHERPA	FS
	SHERPA	LO	NNPDF3.0 NNLO	SHERPA	SHERPA	FS
<b><math>t\bar{t}</math> and Single-Top</b>						
$t\bar{t}$	POWHEGBOX v2	NLO	NNPDF3.0nlo	PYTHIA8	A14	FS
$tW$	POWHEGBOX v2	NLO	NNPDF3.0nlo	PYTHIA8	A14	FS
$t(q)b$	POWHEGBOX v2	NLO	NNPDF3.0nlo (s)	PYTHIA8	A14	FS
			NNPDF3.0nlo 4f (t)			FS
$tWZ$	MADGRAPH5_AMC@NLO	NLO	NNPDF3.0nlo	PYTHIA8	A14	FS
$tZ$	MADGRAPH5_AMC@NLO	LO	NNPDF3.0nlo 4f	PYTHIA8	A14	FS
<b><math>t\bar{t}VV</math></b>						
$t\bar{t}WW$	MADGRAPH5_AMC@NLO	LO	NNPDF3.0nlo	PYTHIA8	A14	FS
	(mc20)					
	MADGRAPH (mc23)					FS
$t\bar{t}WZ$	MADGRAPH	LO	NNPDF3.0nlo	PYTHIA8	A14	AF3
$t\bar{t}HH$	MADGRAPH	LO	NNPDF3.0nlo	PYTHIA8	A14	AF3
$t\bar{t}WH$	MADGRAPH	LO	NNPDF3.0nlo	PYTHIA8	A14	AF3
$t\bar{t}ZZ$	MADGRAPH	LO	NNPDF3.0nlo	PYTHIA8	A14	AF3
<b><math>V(VV)+\text{jets}</math> and <math>VH</math></b>						
$V+\text{jets}$	SHERPA	NLO	NNPDF3.0 NNLO	SHERPA	SHERPA	FS
$VV+\text{jets}$	SHERPA	NLO	NNPDF3.0 NNLO	SHERPA	SHERPA	FS
		LO ( $gg \rightarrow VV$ )				FS
$VVV+\text{jets}$	SHERPA	NLO	NNPDF3.0 NNLO	SHERPA	SHERPA	FS
$VH$	POWHEGBOX v2	NLO	NNPDF3.0 AZNLO	PYTHIA8	A14	FS

Table 4.1: Summary of all Monte-Carlo samples used in this analysis.

# Chapter 5. Particle Reconstruction & Identification

Reconstruction software reconstructs basic objects from signals collected from the event: interaction vertices, tracks, topological clusters of energy deposits

These quantities then used to reconstruct physics objects i.e. particles (electron, muon), jets, MET

## 5.1 Primary reconstruction

### 5.1.1 Topological clusters

[16][21]

Topological cluster (topo-cluster): Clusters of topologically connected cell signals in the calorimeter at the EM scale. This scale does not consider loss of signal from hadrons. Singular hits without hits from neighboring cells are considered noise.

Done in an effort to extract signal while minimizing electronic effects and physical fluctuations. Used to reconstruct hadronic objects and particles decaying hadronically i.e.  $\tau$  leptons

Signal hits with significance above a cell signal significance level  $\varsigma_{\text{cell}}^{\text{EM}}$  are seeded in as part of a proto-cluster. Neighboring cells satisfying a cluster growth threshold are collected into the cluster.

Two clusters are merged if a cell is matched to both

If a cluster has two or more local signal maxima satisfying  $E_{\text{cell}}^{\text{EM}} > 500 \text{ MeV}$ , the cluster is split accordingly.

The process continues iteratively until all cells with significant signal efficiency have been matched to a cluster.

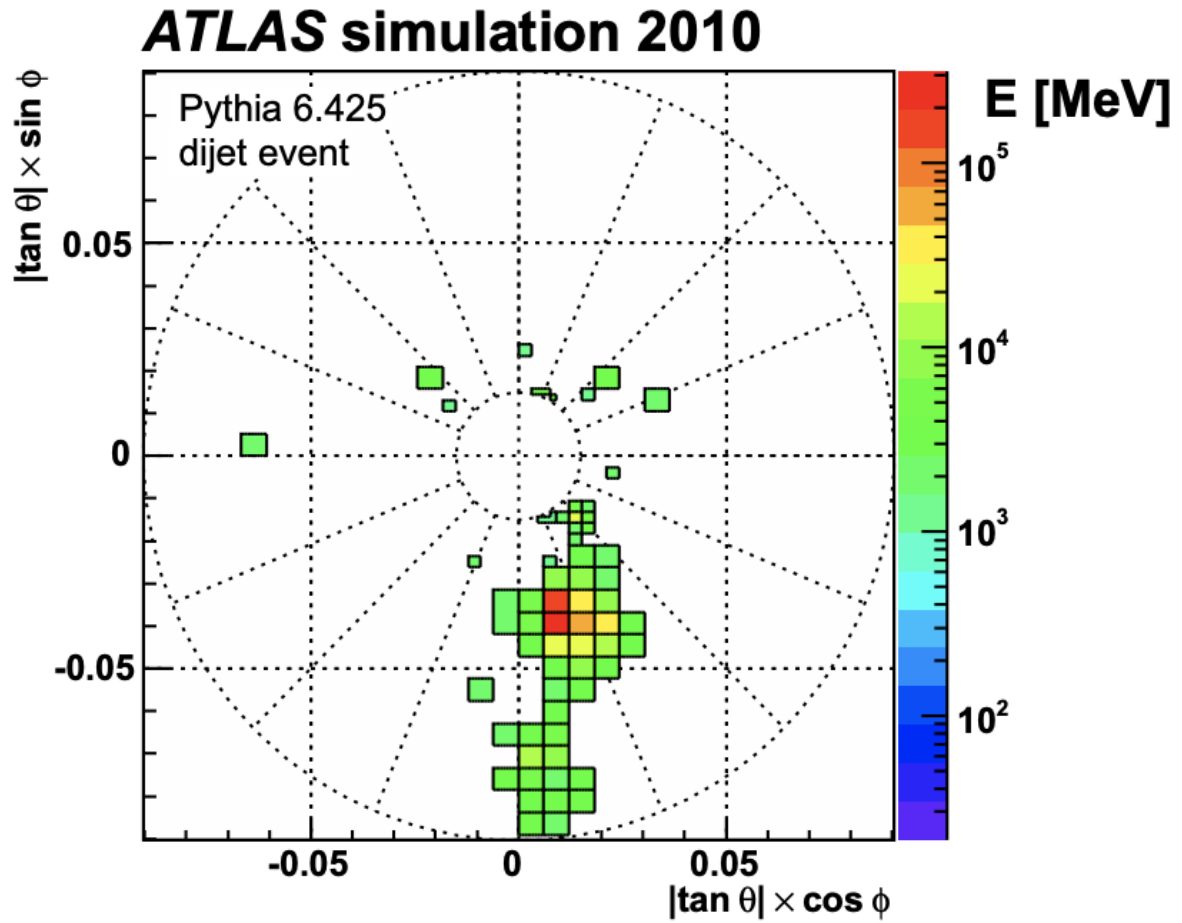


Figure 5.1

### 5.1.2 Tracks

[15]

Charged particles deposit energy in different layers of the inner detector and muon spectrometer



ID reco software: inside-out and outside-in algorithms

- Inside-out: [17]

Starts with seeded hits in the silicon detector in pixel & SCT

Loosely matched to an EM cluster to form a track candidate

Hits are added to form a track candidate using a pattern recognition algorithm based on a Kalman filter formalism [20]

Track candidates are then fitted with a  $\chi^2$  filter [18] and loosely matched to a fixed-sized EM cluster. Successfully matched track candidates are re-fitted with a Gaussian-sum filter (GSF) [8]

This is followed by a track scoring strategy to resolve fake tracks & hit ambiguity between different tracks [25]

Extend to TRT to form final tracks, filtered by threshold  $p_T > 400$  MeV.

- Outside-in: [22]

Reverse, starts with segments in TRT extending inward to silicon hits in pixel & SCT

Targeting secondary tracks (decays/interactions of primary particles) or long-lived particles

### 5.1.3 Vertices

Vertices: interaction or decay point

Primary vertex: pp interaction point

Important for reconstruction of the hard scattering pp interaction, resulting trajectories and

kinematic information of the event

- Vertex finding:

Uses the z-position of a track as input

Vertices require to have at least 2 tracks

Iterative  $\chi^2$  algorithm evaluate track-vertex compatibility, using the track as new seed for another vertex if large discrepancy

- Vertex fitting:

Adaptive multi-vertex fitter (AVF) algorithm assigns weights that depend on the track-vertex compatibility to each track to measure the probability of the track being an outlier vs inlier.

Vertex is then estimated by iteratively minimizing an objective function of these weights

## 5.2 Jets

- Quarks, gluons & other non-color-neutral hadrons cannot be observed individually due to QCD color confinement

- A non-color-neutral hadron will almost immediately undergo hadronization producing a cone of color-neutral hadrons also known as a jet

- Jet signals can be used to reconstruct and consequently indirectly observe the original quarks/gluons the jets originated from

- Jet reconstruction:

- PFlow: energy deposited in the calorimeter systems by charged particles is removed and replaced by particle objects created with the remaining energy in the calorimeter and tracks matched to the topo-clusters. (include PFlow graphics)
- anti- $k_t$  algorithms: sequential recombination jet algorithms
- pile-up jets: multiple interactions associated with one bunch crossing in addition to the hard scattering of interest and reconstructed as jets in the final states. Reconstructed pile-up jets can result from Pile-up jets are usually from soft interactions and can be distinguished with JVT algorithm using tracking information from the ID.
- JES/JER calibration: Jet reconstruction at EM scale does not accurately account for energy from QCD interactions and needs to be calibrated to jets reconstructed at particle level. This is done via a MC-based JES calibration sequence and additional JER calibration to match jet resolution in simulation to data using dijet events.

### 5.2.1 Flavor tagging

- Classification of hadronic jets is an important task for many LHC analyses especially ones studying final states (Higgs decay/4top)
- Flavor tagging is namely interested in identifying jets containing  $b$ -hadrons,  $c$ -hadrons,  $uds$ -hadrons (light-jets), and hadronic decays from  $\tau$ .
- Of these, identifying  $b$ -jets is of particular interest due to their characteristically long lifetime ( $\approx 1.5$  ps) from decay suppression by CKM factor, with a displaced secondary decay vertex and usually a tertiary vertex from  $c$ -hadron decays.

## Efficiency calibration

- [9]

- Performance of  $b$ -taggers are studied on MC simulated samples. However, the  $b$ -tagging efficiency predicted by simulation  $\varepsilon_b^{\text{sim}}$  is usually not the same as the efficiency measured in data  $\varepsilon_b^{\text{data}}$ .

- The correction for the rate of events after applying a  $b$ -tagging requirement is calibrated and applied jet by jet in the form of data-to-simulation scale factors  $\text{SF} = \varepsilon_b^{\text{data}}/\varepsilon_b^{\text{sim}}$ .

- Usage of  $b$ -tagger in this analysis is done via five operating points (OPs), corresponding to 60%, 70%, 77%, 85% and 90%  $b$ -jet tagging efficiency  $\varepsilon_b$  in simulated  $t\bar{t}$  events in order from loosest to tightest discriminant cut points. - OPs are defined by selection on the tagger output to provide a pre-defined level of  $\varepsilon_b$ , and act as a variable trade-off between  $b$ -tagging efficiency and  $c$ -/light-jet rejection i.e.  $b$ -jet purity

- A jet is considered  $b$ -tagged if it passes the efficiency criteria for a given OP. A pseudo-continuous  $b$ -tagging (PCBT) score is defined to summarize the OP criteria a jet passes into a variable. The PCBT score can take integer values between 1 and 6, where a score of 6 means a jet passes all four OP thresholds (passing 65% OP), a score of 2 for jets that pass only the 90% OP, and a score of 1 for jets that don't pass any OP. Additionally, PCBT defines a value of -1 for any jet that does not satisfy  $b$ -tagging criteria.

- (insert TPR/FPR discriminant trade-off figure)

-  $t\bar{t}$ bar calibration [1]

- ptrel and high pT calibration [24][10][2]
- impact parameter  $\rightarrow$  signed transverse impact parameter significance
- calibration results

## GN2 $b$ -tagging algorithm

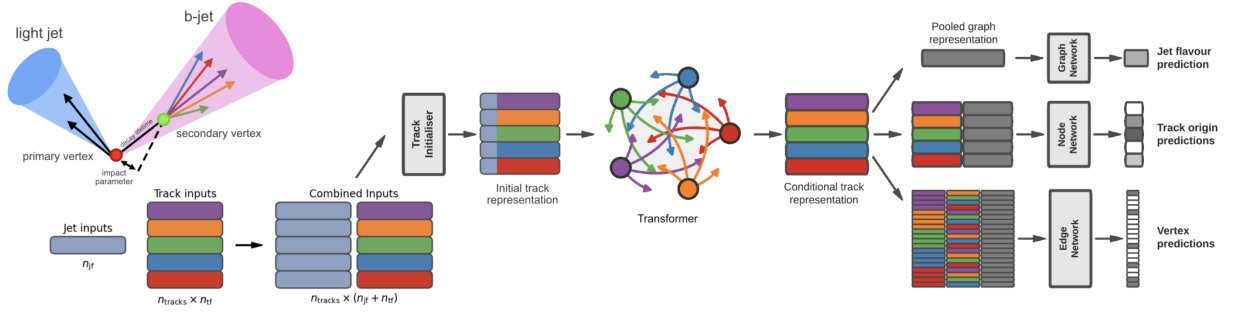


Figure 5.2: [7][19][23]

- GN2 transformer-based  $b$ -tagging algorithm, utilized for analysis of Run 2 and Run 3 data
- GN2 gives a factor of 1.5-4 improvement in experimental applications compared to the previous convolutional neural network-based standard  $b$ -tagging algorithm, DL1d, without dependence on the choice of MC event generator.
- Attention-based architecture, modified to incorporate domain knowledge and additional auxiliary physics objectives: grouping tracks originating from common vertices and prediction of the underlying process for each track
- MC simulated SM  $t\bar{t}$  and BSM  $Z'$  events from  $pp$  collisions were used as training and evaluation samples. In order to minimize bias, both  $b$ - and light-jet samples are re-sampled to match  $c$ -jet distributions.
- GN2 concatenates 2 jet and 19 track reconstruction variables of up to 40 tracks to form

the input feature vector, normalized to zero mean and unit variance.

- The output consists of a jet classification layer of size 4 consisting of  $p_b$ ,  $p_c$ ,  $p_u$  and  $p_\tau$  for the probability of each jet being a  $b$ -,  $c$ -, light- or  $\tau$ -jet respectively; a track-pairing output layer of size 2, and a track origin classification layer of 7 output categories.

## 5.3 Leptons

- Lepton reconstruction is concerned mainly with electron and muon construction, since tau decays quickly and can either be reconstructed using jets or light leptons. From here on out lepton will be used mostly to refer to electrons and muons

- Leptons can be classified into two categories: prompt leptons resulting from heavy particle decays, or non-prompt leptons resulting from detector or reconstruction effects, or from  $b$ - or  $c$ - hadron decays

- Reconstruction of leptons is therefore important to study the underlying physics and suppressing background

### 5.3.1 Electrons

- [\[5\]](#)[\[3\]](#)

- Electrons lose energy interacting with the detector materials via bremsstrahlung. The bremsstrahlung photon can then produce an electron-positron pair which can itself leaves signals in the detector, creating a collimated object that can leave multiple tracks in the ID or EM showers in the calorimeter, all considered part of the same EM topo-cluster.

- Electron signal signature has three characteristic components: localized energy deposits in the calorimeter, multiple tracks in the ID and compatibility between the above tracks and

energy clusters in the  $\eta \times \phi$  plane. Electron reconstruction in ATLAS follows these steps accordingly - Seed-cluster reconstruction and track reconstruction are performed sequentially

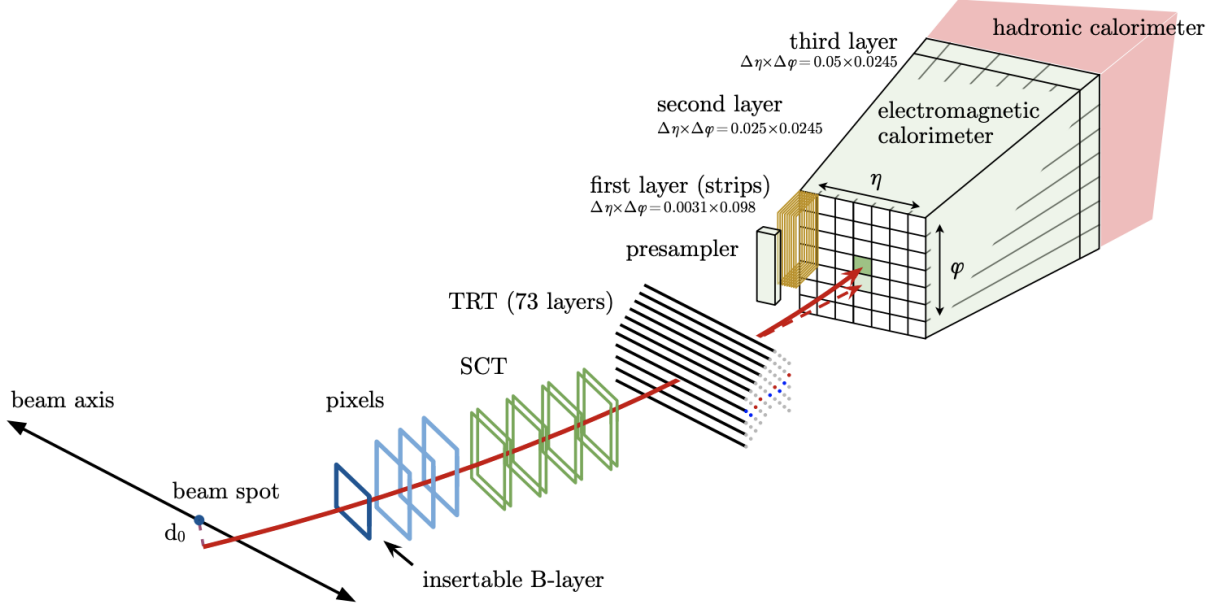


Figure 5.3: [5]

in accordance with the iterative clustering algorithm and track reconstruction method respectively, described in section 5.1

- The seed-cluster and track candidate associated with a conversion vertex are then matched to form an electron candidate.
- A reconstructed cluster is expanded from the seed-cluster in either  $\phi$  or  $\eta$  in the barrel or endcap region respectively
- The cluster energy is then calibrated to compute the original electron energy.

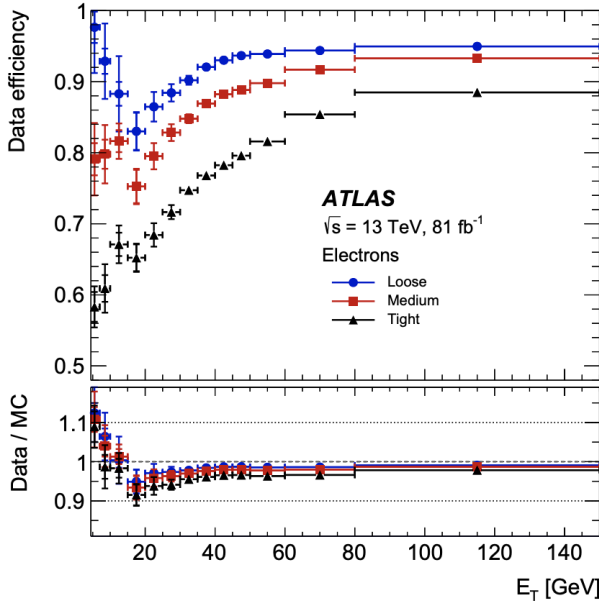
## Electron identification

- Additional likelihood-based identification selections using ID and EM calorimeter information are implemented to further improve the purity of the reconstructed electrons and

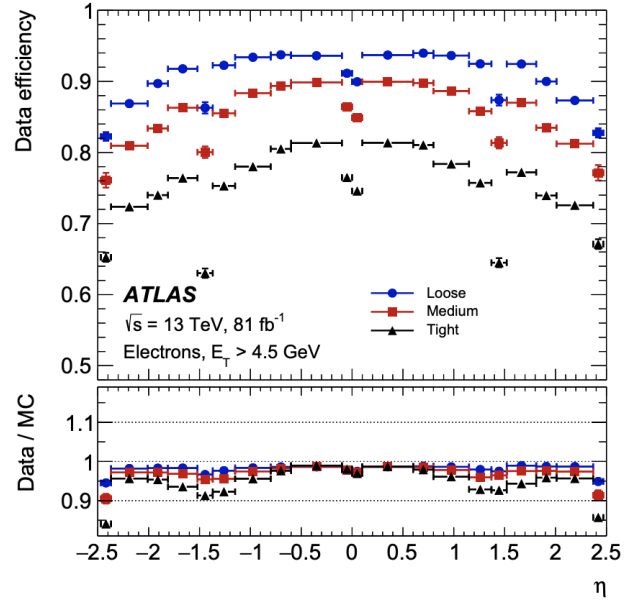
photons. These selections also help suppress background from hadronic jet deposits, photon conversions or electrons from heavy-flavor decays.

- Three operating points are defined for physics analyses: Loose, Medium and Tight, optimized for 9 bins in  $|\eta|$  and 12 bins in  $E_T$  with each corresponding to a fixed efficiency requirement for each bin. The target efficiencies for Loose, Medium and Tight start at 93%, 88% and 80% respectively for typical EW processes and increases with  $E_T$

Similar to  $b$ -tagging OPs, the electron OPs represent a trade-off in signal efficiency and background rejection. The electron efficiency are estimated using tag-and-probe method [5] on samples of  $J/\Psi \rightarrow ee$  and  $Z \rightarrow ee$ .



(a) Figure A



(b) Figure B

Figure 5.4: [3]

## Electron isolation

- A characteristic distinction between prompt electrons and electrons from background processes is the relative lack of activity in both the ID and calorimeter within an area of  $\Delta\eta \times \Delta\phi$



surrounding the reconstruction candidate

- Electron isolation variables are needed to quantify the amount of activity around the electron candidate.
- Calorimeter-based isolation variables  $E_T^{\text{cone}XX}$  is calculated by first summing the energy of topological clusters with barycenters falling within a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = XX/100$  around the direction of the electron candidate.
- The final isolation variable is then obtained by subtracting energy at the core of the cone belonging to the candidate electron from the sum, then applying corrections for energy leakage outside of the core and pile-up effects.
- Similar to calorimeter-based variables, track-based isolation variables  $p_T^{\text{varcone}XX}$  are calculated by summing all track  $p_T$  within a cone of variable radius  $\Delta R$  around the electron candidate, minus the candidate's contribution. The cone radius is variable as a function of  $p_T$

$$\Delta R = \min \left( \frac{10}{p_T[\text{GeV}]}, \Delta R_{\text{max}} \right)$$

with  $\Delta R_{\text{max}}$  being the maximum cone size, to account for the closer proximity of decay products to the electron in high-momentum heavy particle decays.

- Four isolation operating points are implemented to satisfy specific needs by physics analyses: Loose, Tight, HighPtCaloOnly and Gradient. The first three OPs are fixed in isolation variables, while the Gradient OP fixes the isolation efficiency to a  $p_T$  dependent function defined as  $\varepsilon = 0.1143 \times p_T + 92.14\%$  with  $p_T$  in GeV, using  $\Delta R = 0.2$  for calorimeter isolation and  $\Delta R_{\text{max}} = 0.2$  for track isolation.

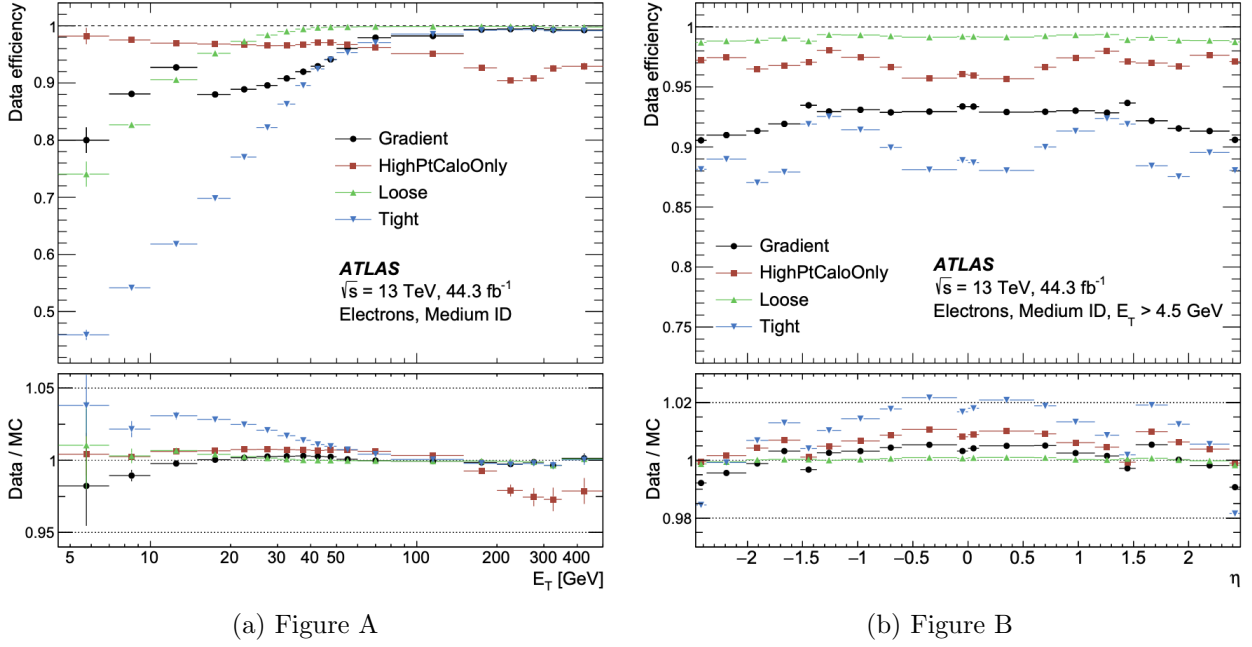


Figure 5.5: [3]

## Electron charge misidentification

[5][4]

Electron charge is determined by the curvature of the associated track. Misidentification of charge can then occur via either an incorrect curvature measurement, or an incorrectly matched track.

The former is more likely for electrons with high  $p_T$  due to the small curvature in track trajectories at such scale, while the latter usually results from bremsstrahlung pair-production, creating additional secondary tracks in the vicinity.

Charge misidentification is a crucial irreducible background for analyses with charge selection criteria, and suppression of this background is assisted via a boosted decision tree discriminant known as the Electron Charge ID Selector (ECIDS) [5]. The addition of ECIDS removed 90% of electrons with incorrect charge while selecting 98% of electrons with correct

charge from electrons in  $Z \rightarrow ee$  events satisfying Medium/Tight identification and Tight isolation criteria.

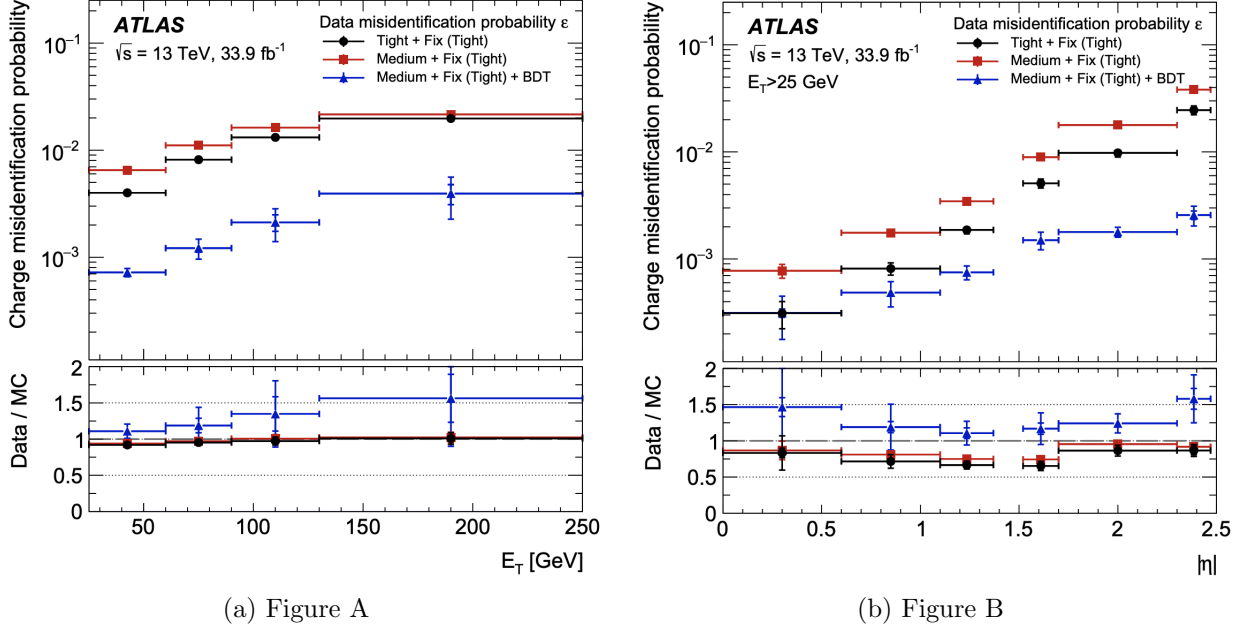


Figure 5.6: [3]

### 5.3.2 Muons

Signature: minimum-ionizing particle leaves tracks in the MS or characteristics energy deposits in the calorimeter

Muons can be reconstructed globally using information from the ID, MS and calorimeters.

Five reconstruction strategies, each corresponding to a muon type:

- Combined (CB): primary ATLAS muon reconstruction method. Muons first reconstructed using MS tracks then extrapolated to include ID tracks (outside-in strategy).

A global combined fit is then performed on both MS and ID tracks

- Inside-out combined (IO): Complementary to CB algorithm. Muon tracks are extrap-

olated from ID to MS, then fitted together with a combined track fit. Useful for muons without good MS information.

- MS extrapolated (ME): ME muons are defined as muons with a MS track that cannot be matched to an ID track using CB method. ME muons allow extension of muon reconstruction acceptance to regions not covered by the ID ( $2.5 < |\eta| < 2.7$ )
- Segment-tagged (ST): ST muons are ID tracks satisfying tight angular matching criteria to at least one reconstructed local segment in the MDT or CSC chambers when extrapolated to the MS. Used primarily when muons only crossed one layer of MS chambers.
- Calorimeter-tagged (CT): CT muons are ID tracks that when extrapolated through the calorimeter, can be matched to energy deposits consistent with those of a minimum-ionizing particle. Extends acceptance range to regions in the MS with sparse instrumentation ( $|\eta| < 0.1$ ), with a higher  $p_T$  threshold of 5 GeV compared to 2 GeV threshold used by other muon reconstruction algorithms due to large background contamination at the low  $p_T$  range of  $15 < p_T < 100$  GeV

## Muon identification

[\[11\]](#)[\[12\]](#)

Reconstructed muons are further filtered by identification criteria to select for high-quality prompt muons for physics analyses. Requirements include number of hits in the MS/ID, track fit properties and compatibility between measurements of the two systems.

Three standard WPs (Loose, Medium, Tight) are defined to better match the needs of different physics analyses concerning prompt muon ID efficiency,  $p_T$  resolution and non-prompt

muon rejection. Of the three, Medium WP is the default ID WP for ATLAS, by virtue of being optimized in efficiency and purity for a wide range of analyses while minimizing non-prompt rejection and systematic uncertainties.

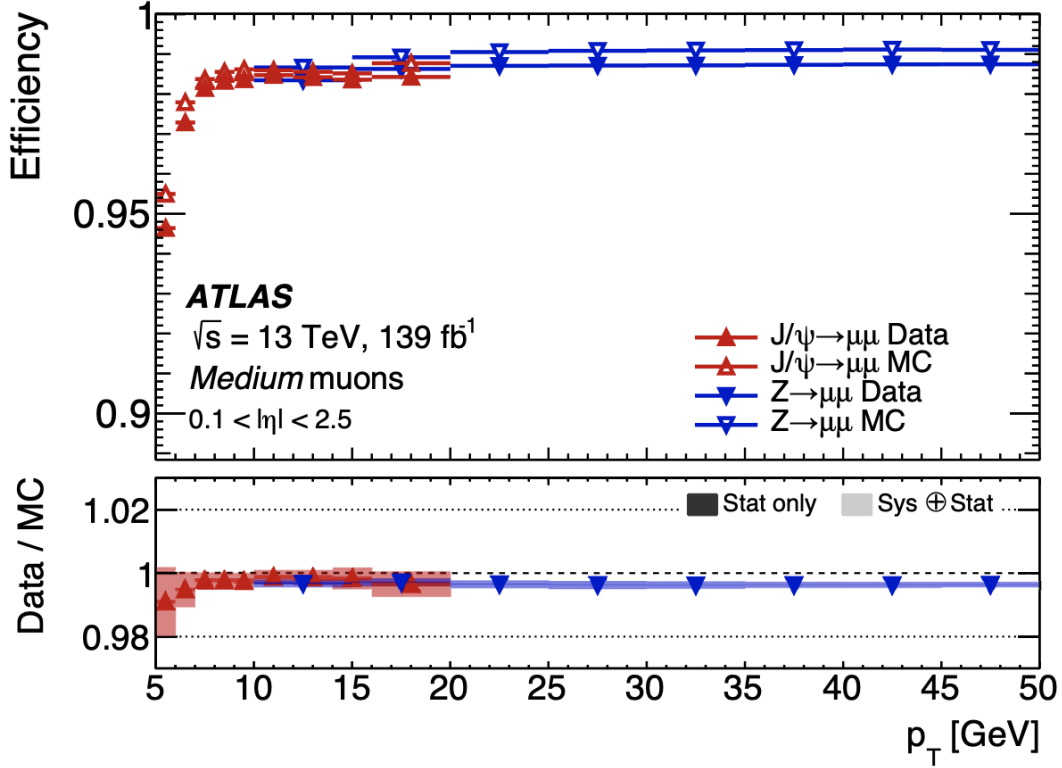


Figure 5.7: [11]

## Muon isolation

Muons from heavy particle decays are often produced in an isolated manner compared to muons from semileptonic decays. Muon isolation is therefore an important tool for background rejection in physics analyses

Muon isolation strategies are similar to that of electron in Figure 5.3.1, with track-based and calorimeter-based isolation variables.

Seven isolation WPs are defined to satisfy analyses' needs.

## 5.4 Missing transverse momentum

[14]

Collisions at the LHC happen along the z-axis of the ATLAS coordination system between two particle beam of equal center-of-mass energy. By conservation of momentum, the sum of transverse momenta of outgoing particles should be zero. A discrepancy between measured momentum and zero would then suggest the presence of undetectable particles, which would consist of either SM neutrinos or some unknown BSM particles. This makes missing transverse momentum ( $E_{\text{T}}^{\text{miss}}$ ) an important observable to reconstruct.

Reconstructing  $E_{\text{T}}^{\text{miss}}$  utilizes information from fully reconstructed leptons, photons, jets and other matched track-vertex objects not associated with a prompt object (soft signals), defined with respect to the  $x(y)$ -axis as

$$E_{x(y)}^{\text{miss}} = - \sum_{i \in \{\text{hard objects}\}} p_{x(y),i} - \sum_{j \in \{\text{soft signals}\}} p_{x(y),j}, \quad (5.1)$$

where  $p_{x(y)}$  is the  $x(y)$ -component of  $p_{\text{T}}$  for each particle. The following observables can then be defined:

$$\mathbf{E}_{\text{T}}^{\text{miss}} = (E_x^{\text{miss}}, E_y^{\text{miss}}), \quad (5.2)$$

$$E_{\text{T}}^{\text{miss}} = |\mathbf{E}_{\text{T}}^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad (5.3)$$

$$\phi^{\text{miss}} = \tan^{-1}(E_y^{\text{miss}}/E_x^{\text{miss}}), \quad (5.4)$$

where  $E_T^{\text{miss}}$  represents the magnitude of the missing transverse energy vector  $\mathbf{E}_T^{\text{miss}}$ , and  $\phi^{\text{miss}}$  its direction in the transverse plane. Since physics analyses have differing requirements for object selection, the vectorial sum  $\mathbf{E}_T^{\text{miss}}$  can be broken down into

$$\mathbf{E}_T^{\text{miss}} = - \underbrace{\sum_{\text{selected electrons}} \mathbf{p}_T^e - \sum_{\text{selected muons}} \mathbf{p}_T^\mu - \sum_{\text{accepted photons}} \mathbf{p}_T^\gamma - \sum_{\text{accepted } \tau\text{-leptons}} \mathbf{p}_T^\tau - \sum_{\text{accepted jets}} \mathbf{p}_T^{\text{jet}}}_{\text{hard term}} - \underbrace{\sum_{\text{unused tracks}} \mathbf{p}_T^{\text{track}}}_{\text{soft term}}. \quad (5.5)$$

Two WPs are defined for  $E_T^{\text{miss}}$ , Loose and Tight [6], with selections on jet  $p_T$  and JVT criteria. The Tight WP reduces pileup dependence of  $E_T^{\text{miss}}$  by removing the phase space region with more pileup jets than hard-scatter jets, at the expense of resolution at low pileup and scale of the reconstructed  $E_T^{\text{miss}}$ .

## 5.5 Overlap removal

Since the reconstruction processes for different objects are performed independently, it is possible for the same detector signals to be used to reconstruct multiple objects. An overlap removal strategy to resolve ambiguities; the overlap removal process for this analysis applies selections listed in Table 5.1 sequentially, from top to bottom.

Remove	Keep	Matching criteria
Electron	Electron	Shared ID track, $p_{T,1}^e < p_{T,2}^e$
Muon	Electron	Shared ID track, CT muon
Electron	Muon	Shared ID track
Jet	Electron	$\Delta R < 0.2$
Electron	Jet	$\Delta R < 0.4$
Jet	Muon	$(\Delta R < 0.2 \text{ or ghost-associated}) \ \& \ N_{\text{track}} < 3$
Muon	Jet	$\Delta R < \min(0.4, 0.04 + 10\text{GeV}/p_T^\mu)$

Table 5.1: [13]

# Chapter 6. Analysis Strategy

## 6.1 Event selection

Events for the analysis first are preselected following a list of criteria to optimize for event quality and background rejection.

The criteria are applied sequentially, from top to bottom

1. **Good Run List (GRL):** data events must be part of a predefined list of suitable runs and luminosity blocks.
2. **Calorimeter cleaning:** events containing signal hits indicating an error in the calorimeter are removed.
3. **Primary vertex:** events must have at least one reconstructed vertex matched to 2 or more associated tracks with  $p_T > 500$  MeV.
4. **Trigger:** events must be selected by at least one trigger documented in subsection 6.1.2.
5. **Jet cleaning:** events must pass the LooseBad WP for jet cleaning using jets passing preselection criteria in subsection 6.1.1. This is done to remove events with significant number of calorimeter hits from non-prompt sources (e.g. instrumental effects, cosmic ray background, non-collision particles)
6. **Bad muon veto:** events are removed if they contain at least one muon before overlap removal with insufficient  $p_T$  resolution.



**7. Kinematic selection:** events must have exactly two Tight leptons with the same electric charge, or at least three Tight leptons of any charge. The leading lepton must have  $p_T > 28$  GeV, and all leptons must satisfy  $p_T > 15$  GeV.

Events are separated into two channels based on the number of leptons: same-sign dilepton (SS2L) for events with exactly two leptons of the same charge, or multilepton (ML) for events with three or more leptons.

Further selections are applied based on the lepton flavors present. In the SS2L channel, if both leptons are electrons, the invariant mass  $m_{ll}$  must satisfy  $m_{ll} < 81$  GeV and  $m_{ll} > 101$  GeV to suppress background involving  $Z$ -bosons. In the ML channel, the same criteria must be satisfied for every opposite-sign same-flavor pair of leptons in an event.

### 6.1.1 Object definition

(electrons, muons, jets)

Jets are reconstructed using particle-flow method with anti- $k_t$  algorithm, using radius parameter  $\Delta R = 0.4$ .

Each selection comes with associated calibration scale factors to account for discrepancies between data and MC simulation, and are applied multiplicatively to the MC event weights.

Jets containing  $b$ -hadrons are identified and tagged with the **GN2v01** algorithm, described in subsection 5.2.1. For this analysis, a jet is considered  $b$ -tagged if it passes the 85% WP; this gives the best sensitivity to the signal as shown in Table 6.1.1. A PCBT score is used to quantify the complete output of the  $b$ -tagging process for a qualifying jet, with values ranging from 1 to 6 corresponding respectively to the jet not passing any WP, to the jet passing all five WPs.

Selection	Electrons	Muons	Jets
$p_T$ [GeV]	$> 15$ $p_T(l_0) > 28$	$> 15$	$> 20$
$ \eta $	$1.52 \leq  \eta  < 2.47$ $< 1.37$	$< 2.5$	$< 2.5$
Identification	TightLH pass ECIDS ( $ee/e\mu$ )	Medium	NNJvt FixedEffPt ( $p_T < 60$ , $ \eta  < 2.4$ )
Isolation	Tight_VarRad	PflowTight_VarRad	
Track-vertex assoc.			
$ d_0^{\text{BL}}(\sigma) $	$< 5$	$< 3$	
$ \Delta z_0^{\text{BL}} \sin \theta $ [mm]	$< 0.5$	$< 0.5$	

Table 6.1: Caption

The  $E_T^{\text{miss}}$  reconstruction also applies the NNJvt algorithm to jets, and uses the Tight WP for this analysis.

### Lepton $p_T$ cut

(lepton  $p_T$  cut study: 7 GeV vs 15 GeV)

### $b$ -tagging optimization

(WP optimization study)

Trigger	Data period			
	2015	2016	2017	2018
Single electron triggers				
HLT_e24_lhmedium_L1EM20VH	✓	-	-	-
HLT_e60_lhmedium	✓	-	-	-
HLT_e120_lhloose	✓	-	-	-
HLT_e26_lhtight_nod0_ivarloose	-	✓	✓	✓
HLT_e60_lhmedium_nod0	-	✓	✓	✓
HLT_e140_lhloose_nod0	-	✓	✓	✓
Di-electron triggers				
HLT_2e12_lhloose_L12EM10VH	✓	-	-	-
HLT_2e17_lhvloose_nod0	-	✓	-	-
HLT_2e24_lhvloose_nod0	-	-	✓	✓
HLT_2e17_lhvloose_nod0_L12EM15VHI	-	-	-	✓
Single muon trigger				
HLT_mu20_iloose_L1MU15	✓	-	-	-
HLT_mu40	✓	-	-	-
HLT_mu26_ivarmedium	-	✓	✓	✓
HLT_mu50	-	✓	✓	✓

Table 6.2: Caption

### 6.1.2 Trigger selection

### 6.1.3 Event categorization

Simulated events are categorized using truth information of leptons ( $e/\mu$ ) and their originating MC particle (mother-particle).

Each lepton can be classified as either prompt or non-prompt, with non-prompt leptons further categorized for background estimation purposes.

If an event contains only prompt leptons, the event is classified as its corresponding process.

If the event contains one non-prompt lepton, the event is classified as the corresponding type of the non-prompt lepton. If the event contains more than one non-prompt lepton, the event

is classified as other.

- **Prompt:** if the lepton originates from  $W/Z/H$  boson decays, or from a mother-particle created by a final state photon.
- **Non-prompt:**
  - **Charge-flip ( $e$  only):** if the reconstructed charge of the lepton differs from that of the first mother-particle.
  - **Material conversion ( $e$  only):** if the lepton originated from a photon conversion and the mother-particle is an isolated prompt photon, non-isolated final state photon, or heavy boson.
  - **$\gamma$ -conversion ( $e$  only):** if the lepton originated from a photon conversion and the mother-particle is a background electron.
  - **Heavy flavor decay:** if the lepton originated from a  $b$ - or  $c$ -hadron.
  - **Fake:** if the lepton originated from a light- or  $s$ -hadron, or if the truth type of the lepton is hadron.
  - **Other:** any lepton that does not belong to one of the above categories.

## 6.2 Analysis regions

Events are selected and categorized into analysis regions belonging to one of two types: control regions (CRs) enriched in background events, and signal regions (SRs) enriched in signal events. This allows for the examination and control of backgrounds and systematic uncertainties, as well as study of signal sensitivities.

The signal is then extracted from the SRs with a profile LH fit using all regions.

### 6.2.1 Signal regions

[include blinding strategy]

- All events selected for SS2L and 3L signal regions must satisfy the following criteria:

- Contains 6 or more jets, with at least 2 jets  $b$ -tagged at the 85% WP
- Scalar sum of the transverse momenta of all leptons and jets  $H_T > 500$  GeV
- Dilepton invariant mass  $m_{\ell\ell}$  does not coincide with the  $Z$ -boson mass range of  $81 - 101$  GeV

- The SR is further granularized by the number of  $b$ -jets and leptons to further study and improve signal sensitivity

SR	Selection criteria	
	$b$ -jets	leptons
2b2l	$N_b = 2$	$N_l = 2$
2b3l4l	$N_b = 2$	$N_l \geq 3$
3b2l	$N_b = 3$	$N_l = 2$
3b3l4l	$N_b = 3$	$N_l \geq 3$
4b	$N_b = 4$	

Table 6.3: Caption

(4L study)

### 6.2.2 Control regions

Control regions are defined for each background to be enriched in the targeted background events, in order to maximize the targeted background's purity and minimize contamination

from other sources within the region.

This helps to constrain and reduce correlation between background normalization factors.

Fit variables and selection criteria are determined via optimization studies on CRs to achieve the largest discriminating power possible between the target background and other event types.

### **$t\bar{t}W$ background CRs**

Four CRs are defined to estimate the flavor composition and normalization of  $t\bar{t}W$  +jets background.

Selections on  $H_T$  and  $N_{\text{jets}}$  to ensure orthogonality to SR

Selections on total charge for each charged  $W^\pm$  boson

Two types of CRs for  $t\bar{t}W$  +jets background: CR  $t\bar{t}W^\pm$  +jets to constrain flavor composition, and CR 1b( $\pm$ ) to constrain jet multiplicity spectrum.

### **Fake/non-prompt background CRs**

Selection for fake/non-prompt CRs are determined using the `DFCommonAddAmbiguity` (DFCAA) variable for reconstructed leptons.

DFCAA	Description
-1	No 2nd track found
0	2nd track found, no conversion found
1	Virtual photon conversion candidate
2	Material conversion candidate

Table 6.4: Caption

Four CRs for three main types of fake/non-prompt backgrounds: virtual photon ( $\gamma^*$ ) conversion, photon conversion in detector material (Mat. Conv.) and heavy flavor decays

(HF).

- Low  $m_\gamma^*$ : events with an  $e^+e^-$  pair produced from a virtual photon

Selects two same-sign leptons with at least one electron reconstructed as an internal conversion candidate and neither as with a material conversion candidate ( $\text{DFCAA}_{\ell_1(\ell_2)} = 1$  and  $\neq 2$ )

NF constrained using yield count only.

- Mat. Conv.: events with an electron originating from photon conversion within the detector material.

Selects two same-sign leptons with at least one electron reconstructed as a material conversion candidate ( $\text{DFCAA}_{\ell_1(\ell_2)} = 2$ ).

NF constrained using yield count only.

- HF  $e/\mu$ : events with a reconstructed non-prompt lepton from semi-leptonic decays of  $b$ - and  $c$ -hadrons (heavy flavor decays)

Selects three leptons with at least two electrons/muons, with no lepton reconstructed as a conversion candidate ( $\text{DFCAA} < 0$ ).

NFs constrained by fitting with  $p_T$  of the third leading lepton  $\ell_3$ .

### 6.2.3 Validation regions

In addition, validation regions are also defined to validate the normalization and modeling of  $t\bar{t}Z$  and  $t\bar{t}W$  background without being used in the fit.

- $t\bar{t}Z$ : Selects events with at least two  $b$ -tagged jets, at least four total jets and three

leptons with at least one same-flavor opposite-sign lepton pair possessing invariant mass  $m_{\ell\ell}$  within the  $Z$ -boson mass window of  $81 - 101$  GeV

- $t\bar{t}W$ : Main charge asymmetric background leaning  $t\bar{t}W^+$ , validated using the difference in number of positively and negatively charged events  $N_+ - N_-$  instead of total number of events.

Selects using CR  $t\bar{t}W$  and CR 1b criteria, with one VR not orthogonal to SR and one orthogonal VR with more limited statistics.

## 6.2.4 Unblinding strategy

Run 2 data has already been unblinded, but general unblinding strategy is still carried out.

- Plain Asimov fit
- Real CRs-only fit
- Real SR-blinded fit
- Real SR-unblinded fit

## 6.3 Background estimation

Background events in this analysis consist of SM processes that can result in a  $t\bar{t}t\bar{t}$  SSML final state.

Can be divided into two types: reducible and irreducible.

Reducible background consists of processes that do not result in SSML final state physically, but are reconstructed as such due to erroneous detector and reconstruction effects.



Region	Channel	$N_{\text{jets}}$	$N_b$	Other selections	Fitted variable
CR Low $m_{\gamma^*}$	SS $e\ell$	[4, 6)	$\geq 1$	$\ell_1/\ell_2$ is from virtual photon decay $\ell_1 + \ell_2$ not from material conversion	event yield
CR Mat. Conv.	SS $e\ell$	[4, 6)	$\geq 1$	$\ell_1/\ell_2$ is from material conversion	event yield
CR HF $\mu$	$\ell\mu\mu$	$\geq 1$	1	$\ell_1 + \ell_2$ not conversion candidates $100 < H_T < 300$ GeV $E_T^{\text{miss}} > 35$ GeV total charge = $\pm 1$	$p_T(\ell_3)$
CR HF $e$	$e\ell\ell$	$\geq 1$	1	$\ell_1 + \ell_2$ not conversion candidates $100 < H_T < 275$ GeV $E_T^{\text{miss}} > 35$ GeV total charge = $\pm 1$	$p_T(\ell_3)$
CR $t\bar{t}W^+$	SS $\ell\mu$	$\geq 4$	$\geq 2$	$ \eta(e)  < 1.5$ for $N_b = 2$ : $H_T < 500$ GeV or $N_{\text{jets}} < 6$ for $N_b \geq 3$ : $H_T < 500$ GeV total charge $> 0$	$N_{\text{jets}}$
CR $t\bar{t}W^-$	SS $\ell\mu$	$\geq 4$	$\geq 2$	$ \eta(e)  < 1.5$ for $N_b = 2$ : $H_T < 500$ GeV or $N_{\text{jets}} < 6$ for $N_b \geq 3$ : $H_T < 500$ GeV total charge $< 0$	$N_{\text{jets}}$
CR 1b(+)	SS2L+3L	$\geq 4$	1	$\ell_1 + \ell_2$ not from material conversion $H_T < 500$ GeV total charge $> 0$	$N_{\text{jets}}$
CR 1b(-)	SS2L+3L	$\geq 4$	1	$\ell_1 + \ell_2$ not from material conversion $H_T < 500$ GeV total charge $< 0$	$N_{\text{jets}}$
VR $t\bar{t}Z$	3L $\ell^\pm\ell^\mp$	$\geq 4$	$\geq 2$	$m_{\ell\ell} \in [81, 101]$ GeV	$N_{\text{jets}}, m_{\ell\ell}$
VR $t\bar{t}W + 1b$	SS2L+3L			CR $t\bar{t}W^\pm$    CR 1b( $\pm$ )	$N_{\text{jets}}$
VR $t\bar{t}W + 1b + \text{SR}$	SS2L+3L			CR $t\bar{t}W^\pm$    CR 1b( $\pm$ )    SR	$N_{\text{jets}}$
SR	SS2L+3L	$\geq 6$	$\geq 2$	$H_T < 500$ GeV $m_{\ell\ell} \notin [81, 101]$ GeV	$H_T$

Table 6.5: Caption

Three main types: charge misidentification (QmisID), fake leptons and non-prompt leptons. Estimated using template fitting method to adjust MC predictions via floating normalization factors constrained in the CRs.

Irreducible background consists of SM processes that result in SSML final states physically, with all leptons being prompt.

Main irreducible background considered in this analysis:  $t\bar{t}t\bar{t}$ ,  $t\bar{t}W$ ,  $t\bar{t}Z$ , and  $t\bar{t}H$  with smaller contributions from  $VV$ ,  $VVV$ ,  $VH$  and rarer processes like  $t\bar{t}VV$ ,  $tWZ$ ,  $tZq$  and  $t\bar{t}t$ .

Most irreducible backgrounds are estimated using MC simulations normalized to their theoretical SM cross sections, with the exception of  $t\bar{t}W$  background due to MC mismodeling of the process at high jet multiplicities.

The  $t\bar{t}W$  is instead given four dedicated CRs, and estimated using a data-driven method with a fitted function parameterized in  $N_{\text{jets}}$

### 6.3.1 Template fitting for fake/non-prompt estimation

Template fit method is a semi-data-driven approach that estimates background distributions by fitting the corresponding MC kinematic profiles to data via free-floating normalization factors.

There are four NFs for fake/non-prompt backgrounds, one for each corresponding background and CR used to constrain them:  $\text{NF}_{\text{HF } e(\mu)}$  for events with one non-prompt electron (muon) from heavy flavor decays,  $\text{NF}_{\text{Mat. Conv.}}$  for events with non-prompt electrons from material conversion, and  $\text{NF}_{\text{Low } m_{\gamma^*}}$  for events with non-prompt electrons from virtual photon conversion.

The free-floating NFs are calibrated using a fit to data within each CR, then applied to the MC background estimates in the final SR fit as a correction factor.

### 6.3.2 Charge misidentification data-driven estimation

The same-sign di-lepton channel in the analysis gives rise to a major background contamination in opposite-sign di-lepton events with one misidentified charge.

Charge misidentification occurs via incorrect track curvature measurements or trident electron contamination from bremsstrahlung, and therefore mainly concerns electrons due to muons' low bremsstrahlung rate and precise curvature information using the ID and MS.

The charge misidentification rates is significant at higher  $p_T$  and varies with  $|\eta|$  as a proxy for the amount of detector material the electron interacted with, and is consequently estimated in this analysis using a data-driven method with assistance from ECIDS.

The charge flip probability  $\epsilon$  is estimated using a sample of  $Z \rightarrow e^+e^-$  events with additional constraints on the invariant mass  $m_{ee}$  to be within 10 GeV of the  $Z$ -boson mass.

The  $Z$ -boson mass window is defined to be within  $4\sigma$  to include most events within the peak, and is determined by fitting the  $m_{ee}$  spectrum of the two leading electrons to a Breit-Wigner function, resulting in a range of  $[65.57, 113.49]$  for SS events and  $[71.81, 109.89]$  for OS events. Background contamination near the peak is assumed to be uniform and subtracted using a sideband method.

Since the  $Z$ -boson decay products consist of a pair of opposite-sign electrons, all same-sign electron pairs are considered to be affected by charge misidentification.

Assuming the charge flip probabilities of electrons in an event are uncorrelated, the number of events with same-sign electrons  $N_{ij}^{\text{SS}}$  with the leading electron in the  $i^{\text{th}}$  2D bin in  $(p_T, |\eta|)$  and the sub-leading electron in the  $j^{\text{th}}$  bin can be estimated as

$$N_{ij}^{\text{SS}} = N_{ij}^{\text{tot}}(\epsilon_i(1 - \epsilon_j) + \epsilon_j(1 - \epsilon_i)), \quad (6.1)$$

where  $N_{ij}^{\text{tot}}$  is the total number of events in the  $i^{\text{th}}$  and  $j^{\text{th}}$  bin regardless of charge, and  $\epsilon_{i(j)}$  is the charge flip rate in the  $i^{\text{th}}(j^{\text{th}})$  bin.

Assuming  $N_{ij}^{\text{SS}}$  follows a Poisson distribution around the expectation value  $\bar{N}_{ij}^{\text{SS}}$ , the charge flip rate  $\epsilon$  can be estimated by minimizing a negative-LLH function parameterized in  $p_{\text{T}}$  and  $|\eta|$ ,

$$-\ln(\mathcal{L}(\epsilon|N_{\text{SS}})) = -\ln \prod_{ij} \frac{(N_{ij}^{\text{tot}})^{N_{ij}^{\text{SS}}} \cdot e^{-N_{ij}^{\text{tot}}}}{N_{ij}^{\text{SS}}!} \quad (6.2)$$

$$= -\sum_{ij} \left[ N_{ij}^{\text{SS}} \ln(N_{ij}^{\text{tot}}(\epsilon_i(1-\epsilon_j) + \epsilon_j(1-\epsilon_i))) - N_{ij}^{\text{tot}}(\epsilon_i(1-\epsilon_j) + \epsilon_j(1-\epsilon_i)) \right]. \quad (6.3)$$

The charge flip rate is then calculated separately for SR and CRs with different electron definitions (CR Low  $m_{\gamma^*}$ , CR Mat. Conv., CR  $t\bar{t}W$ ) using events satisfying 2LSS kinematic selections but with OS electrons, after applying region-specific lepton selections and ECIDS. The following weight is applied to OS events to correct for misidentified SS events within the region:

$$w = \frac{\epsilon_i + \epsilon_j - 2\epsilon_i\epsilon_j}{1 - \epsilon_i - \epsilon_j + 2\epsilon_i\epsilon_j}. \quad (6.4)$$

### 6.3.3 $t\bar{t}W$ data-driven estimation

## 6.4 Signal extraction

# Chapter 7. Systematic Uncertainties

## 7.1 Experimental uncertainties

## 7.2 Modeling uncertainties

### 7.2.1 Signal modeling uncertainties

### 7.2.2 Background modeling uncertainties

# Chapter 8. Results

## 8.1 Likelihood fit

## 8.2 Limits

## 8.3 Interpretation

## Chapter 9. Summary

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