

<sup>1</sup> **Searches for Supersymmetry using the  $\alpha_T$**   
<sup>2</sup> **variable with the CMS detector at the LHC**

<sup>3</sup> Darren Burton

<sup>4</sup> Imperial College London  
<sup>5</sup> Department of Physics

<sup>6</sup> A thesis submitted to Imperial College London  
<sup>7</sup> for the degree of Doctor of Philosophy

## Abstract

10

## Declaration

11

I, the author of this thesis, declare that the work presented within this  
12 document to be my own. The work presented in Chapters 3.4.1, 4 and 5  
13 is a result of the authors own work or that of which I have been a major  
14 contributor unless explicitly stated otherwise, and is carried out within the  
15 context of the Imperial College London and CERN SUSY groups, itself a  
16 subsection of the greater CMS collaboration. All figures and studies taken  
17 from external sources are referenced appropriately throughout this document.

18

Darren Burton

19

## Acknowledgements

20

Of the many people who deserve thanks, some are particularly prominent....

# Preface

# **Contents**

23	<b>List of Figures</b>	ix
24	<b>List of Tables</b>	xii
25	<b>1. Introduction</b>	2
26	<b>2. A Theoretical Overview</b>	5
27	2.1. The Standard Model . . . . .	5
28	2.1.1. Gauge Symmetries of the SM . . . . .	7
29	2.1.2. The Electroweak Sector and Electroweak Symmetry Breaking . . . . .	9
30	2.2. Motivation for Physics Beyond the Standard Model . . . . .	13
31	2.3. Supersymmetry Overview . . . . .	15
32	2.3.1. R-Parity . . . . .	16
33	2.4. Experimental signatures of SUSY at the LHC . . . . .	17
34	2.4.1. Simplified Models . . . . .	18
35	<b>3. The LHC and the CMS Detector</b>	20
36	3.1. The LHC . . . . .	20
37	3.2. The CMS detector . . . . .	23
38	3.2.1. Detector Subsystems . . . . .	23
39	3.2.2. Tracker . . . . .	24
40	3.2.3. Electromagnetic Calorimeter . . . . .	25
41	3.2.4. Hadronic Calorimeter . . . . .	26
42	3.2.5. Muon Systems . . . . .	28
43	3.3. Event Reconstruction and Object Definition . . . . .	28
44	3.3.1. Jets . . . . .	28
45	3.3.2. B-tagging . . . . .	30
46	3.4. Triggering System . . . . .	32
47	3.4.1. The Level-1 Trigger . . . . .	34

48	3.4.2. L1 Trigger Jet Algorithm . . . . .	35
49	3.4.3. Measuring L1 Jet Trigger Efficiencies . . . . .	36
50	3.4.4. Effects of the L1 Jet Seed . . . . .	38
51	3.4.5. Robustness of L1 Jet Performance against Pile-up . . . . .	41
52	3.4.6. Summary . . . . .	43
53	<b>4. SUSY searches in Hadronic Final States</b>	<b>45</b>
54	4.1. An introduction to the $\alpha_T$ search . . . . .	46
55	4.1.1. The $\alpha_T$ variable . . . . .	48
56	4.2. Search Strategy . . . . .	50
57	4.2.1. Physics Objects . . . . .	53
58	4.2.2. Event Selection . . . . .	55
59	4.2.3. Control Sample Definition . . . . .	58
60	4.2.4. Estimating the QCD background multi-jet background . . . . .	65
61	4.3. Trigger Strategy . . . . .	67
62	4.4. Measuring MC normalisation factors via $H_T$ sidebands . . . . .	68
63	4.5. Determining MC yields with higher statistical precision . . . . .	69
64	4.5.1. The formula method . . . . .	70
65	4.5.2. Establishing proof of principle . . . . .	71
66	4.5.3. Correcting measured efficiencies in simulation to data . . . . .	71
67	4.6. Systematic Uncertainties on Transfer Factors . . . . .	72
68	4.7. Searches for Natural SUSY with B-tag templates. . . . .	72
69	<b>5. Results</b>	<b>73</b>
70	5.1. Statistical Interpretation . . . . .	73
71	5.2. Interpretation in Simplified Signal Models . . . . .	73
72	<b>A. Miscellaneous</b>	<b>74</b>
73	A.1. Noise Filters . . . . .	74
74	A.2. Primary Vertices . . . . .	75
75	<b>B. L1 Jets</b>	<b>76</b>
76	B.1. Jet matching efficiencies . . . . .	76
77	B.2. Leading Jet Energy Resolution . . . . .	77
78	B.3. Resolution for Energy Sum Quantities . . . . .	80
79	<b>C. Additional material on background estimation methods</b>	<b>85</b>
80	C.1. Determination of $k_{QCD}$ . . . . .	85

81	<b>Bibliography</b>	<b>87</b>
----	---------------------	-----------

## <sup>82</sup> List of Figures

<sup>83</sup> 2.1.	One loop quantum corrections to the Higgs squared mass parameter $m_h^2$ due to a fermion. . . . .	<sup>84</sup> 14
<sup>85</sup> 2.2.	Two example simplified model decay chains. . . . .	<sup>85</sup> 19
<sup>86</sup> 3.1.	A top down layout of the LHC, with the position of the four main detectors labelled. . . . .	<sup>87</sup> 21
<sup>88</sup> 3.2.	The total integrated luminosity delivered to and collected by Compact Muon Solenoid (CMS) during the 2012 8 TeV $pp$ runs . . . . .	<sup>89</sup> 22
<sup>90</sup> 3.3.	A pictorial depiction of the CMS detector. . . . .	<sup>91</sup> 24
<sup>91</sup> 3.4.	Illustration of the CMS Electromagnetic CALorimeter (ECAL). . . . .	<sup>92</sup> 26
<sup>92</sup> 3.5.	Schematic of the CMS Hadronic CALorimeter (HCAL). . . . .	<sup>93</sup> 27
<sup>93</sup> 3.6.	Combined Secondary Vertex (CSV) algorithm discriminator values in enriched $t\bar{t}$ and inclusive multi jet samples . . . . .	<sup>94</sup> 31
<sup>95</sup> 3.7.	Data/MC b-tag scale factors derived using the Combined Secondary Vertex Medium Working Point (CSVM) tagger. . . . .	<sup>96</sup> 32
<sup>97</sup> 3.8.	Data/MC mis-tag scale factors derived using the CSVM tagger. . . . .	<sup>98</sup> 33
<sup>98</sup> 3.9.	The CMS Level 1 Trigger (L1) Trigger system. . . . .	<sup>99</sup> 34
<sup>99</sup> 3.10.	Illustration of the Level-1 jet finding algorithm. . . . .	<sup>100</sup> 36
<sup>100</sup> 3.11.	L1 jet efficiency turn-on curves as a function of the offline CaloJet and PFJet $E_T$ . . . . .	<sup>101</sup> 38
<sup>102</sup> 3.12.	L1 jet efficiency turn-on curves as a function of the offline CaloJet $E_T$ for the 2012 run period B and C. . . . .	<sup>103</sup> 39

---

104	3.13. Trigger cross section for the L1HTT150 trigger path. . . . .	40
105	3.14. L1 $H_T$ efficiency turn-on curves as a function of the offline CaloJet $H_T$ . . . . .	41
106	3.15. L1 jet efficiency turn-on curves as a function of the leading offline $E_T$ Calo	
107	(left) and PF (right) jet, for low, medium and high pile-up conditions. . . . .	42
108	3.16. Fit values from an Exponentially Modified Gaussian (EMG) function fitted	
109	to the resolution plots of leading Calo jet $E_T$ measured as a function of	
110	$\frac{(L1\ E_T - \text{Offline}\ E_T)}{\text{Offline}\ E_T}$ for low, medium and high pile-up conditions. . . . .	43
111	3.17. Fit values from an EMG function fitted to the resolution plots of leading	
112	PF jet $E_T$ measured as a function of $\frac{(L1\ E_T - \text{Offline}\ E_T)}{\text{Offline}\ E_T}$ for low, medium and	
113	high pile-up conditions. . . . .	44
114	4.1. Reconstructed offline $H_T$ for $11.7\text{fb}^{-1}$ of data after a basic pre-selection. . . . .	48
115	4.2. The event topologies of background QCD dijet events (right) and a generic	
116	SUPERSYmmetry (SUSY) signature with genuine $Z_T$ (left). . . . .	48
117	4.3. The $\alpha_T$ distributions for the low 2-3 (left) and high $\geq 4$ (right) jet	
118	multiplicities after a full analysis selection and shown for $H_T > 375$ . . . . .	50
119	4.4. Pictorial depiction of the analysis strategy employed by the $\alpha_T$ search to	
120	increase sensitivity to a wide spectra of SUSY models. . . . .	52
121	4.5. Data/MC comparisons of key variables for the hadronic signal region. . . . .	58
122	4.6. Data/MC comparisons of key variables for the $\mu + \text{jets}$ selection. . . . .	61
123	4.7. Data/MC comparisons of key variables for the $\mu\mu + \text{jets}$ selection. . . . .	63
124	4.8. Data/MC comparisons of key variables for the $\gamma + \text{jets}$ selection. . . . .	64
125	4.9. QCD sideband regions, used for determination of $k_{QCD}$ . . . . .	66
126	B.1. Leading jet matching efficiency as a function of the offline CaloJet $E_T$ . . . . .	76
127	B.2. Resolution plots of the leading offline Calo $E_T$ measured as a function of	
128	$\frac{(L1\ E_T - \text{Offline}\ E_T)}{\text{Offline}\ E_T}$ for low (a), medium (b) and high (c) pile-up conditions. . . . .	78
129	B.3. Resolution plots of the leading off-line PF $E_T$ measured as a function of	
130	$\frac{(L1\ E_T - \text{Offline}\ E_T)}{\text{Offline}\ E_T}$ for low (a), medium (b) and high (c) pile-up conditions. . . . .	80

131	B.4. $\sum E_T$ resolution parameters in bins of Calo $\sum E_T$ measured for the defined low, medium and high pile up conditions. . . . .	81
132		
133	B.5. $\sum E_T$ resolution parameters in bins of PF $\sum E_T$ measured for the defined low, medium and high pile up conditions. . . . .	81
134		
135	B.6. $\cancel{E}_T$ resolution parameters in bins of Calo $\cancel{E}_T$ measured for the defined low, medium and high pile up conditions. . . . .	82
136		
137	B.7. $\cancel{E}_T$ resolution parameters in bins of PF $\cancel{E}_T$ measured for the defined low, medium and high pile up conditions. . . . .	82
138		
139	B.8. $H_T$ resolution parameters in bins of Calo $H_T$ measured for the defined low, medium and high pile up conditions. . . . .	83
140		
141	B.9. $H_T$ resolution parameters in bins of PF $H_T$ measured for the defined low, medium and high pile up conditions. . . . .	83
142		
143	B.10. $\cancel{H}_T$ resolution parameters in bins of $\cancel{H}_T$ measured for the defined low, medium and high pile up conditions. . . . .	84
144		
145	B.11. $\cancel{H}_T$ resolution parameters in bins of PF $\cancel{H}_T$ measured for the defined low, medium and high pile up conditions. . . . .	84
146		
147	C.1. $R_{\alpha_T}(H_T)$ and exponential fits for each of the data sideband regions. Fit is conducted between the $H_T$ region $275 < H_T < 575$ . . . . .	85
148		

# <sup>149</sup> List of Tables

150	2.1. The fundamental particles of the Standard Model (SM), with spin, charge and mass displayed. . . . .	6
152	3.1. Results of a cumulative EMG function fit to the turn-on curves for L1 single jet triggers in 2012 Run Period C. . . . .	38
154	3.2. Results of a cumulative EMG function fit to the turn-on curves for L1 single jet triggers in the 2012 run period B and C. . . . .	39
156	3.3. Results of a cumulative EMG function fit to the turn-on curves for $H_T$ in 2012 run period B and C. . . . .	40
158	3.4. Results of a cumulative EMG function fit to the efficiency turn-on curves for L1 single jet triggers in the 2012 run period C, for low,medium and high pile-up conditions. . . . .	41
161	3.5. Results of a cumulative EMG function fit to the efficiency turn-on curves for Level-1 single jet triggers in the 2012 run period C, for low,medium and high pile-up conditions. . . . .	42
164	4.1. A summary of the Simplified Model Spectra (SMS) models interpreted in this analysis, involving both direct (D) and gluino-induced (G) production of squarks and their decays. . . . .	46
167	4.2. Jet Identification criteria for the “loose” CaloJet ID used with the analysis.	53
168	4.3. Muon Identification criteria used within the analysis for selection/veto purposes in the muon control/signal selections. . . . .	54
170	4.4. Photon Identification criteria used within the analysis for selection/veto purposes in the $\gamma +$ jets control/signal selections. . . . .	54

172	4.5. Electron Identification criteria used within the analysis for veto purposes.	55
173	4.6. Jet thresholds used in the three $H_T$ regions of the analysis. . . . .	56
174	4.7. Best fit values for the parameters $k_{QCD}$ obtained from sideband regions	
175	B,C <sub>1</sub> ,C <sub>2</sub> ,C <sub>3</sub> . . . . .	67
176	4.8. Measured efficiencies of the $H_T$ and $\alpha_T$ legs of the HT and $HT\_alphaT$	
177	triggers in independent analysis bins. . . . .	68
178	4.9. k-factors calculated for different Electroweak Sector (EWK) processes. .	69
179	4.10. place holder . . . . .	71
180	B.1. Results of a cumulative EMG function fit to the turn-on curves for the	
181	matching efficiency of the leading jet in an event to a Level-1 jet in run	
182	2012C and 2012B data. . . . .	77

<sup>183</sup> **Acronyms**

<sup>184</sup> <b>ALICE</b>	A Large Ion Collider Experiment
<sup>185</sup> <b>ATLAS</b>	A Toroidal LHC ApparatuS
<sup>186</sup> <b>APD</b>	Avalanche Photo-Diodes
<sup>187</sup> <b>BSM</b>	Beyond Standard Model
<sup>188</sup> <b>CERN</b>	European Organization for Nuclear Research
<sup>189</sup> <b>CMS</b>	Compact Muon Solenoid
<sup>190</sup> <b>CMSSM</b>	Compressed Minimal SuperSymmetric Model
<sup>191</sup> <b>CSC</b>	Cathode Stripe Chamber
<sup>192</sup> <b>CSV</b>	Combined Secondary Vertex
<sup>193</sup> <b>CSVM</b>	Combined Secondary Vertex Medium Working Point
<sup>194</sup> <b>DT</b>	Drift Tube
<sup>195</sup> <b>ECAL</b>	Electromagnetic CALorimeter
<sup>196</sup> <b>EB</b>	Electromagnetic CALorimeter Barrel
<sup>197</sup> <b>EE</b>	Electromagnetic CALorimeter Endcap
<sup>198</sup> <b>ES</b>	Electromagnetic CALorimeter pre-Shower
<sup>199</sup> <b>EMG</b>	Exponentially Modified Gaussian
<sup>200</sup> <b>EPJC</b>	European Physical Journal C
<sup>201</sup> <b>EWK</b>	Electroweak Sector
<sup>202</sup> <b>GCT</b>	Global Calorimeter Trigger
<sup>203</sup> <b>GMT</b>	Global MuonTrigger
<sup>204</sup> <b>GT</b>	Global Trigger
<sup>205</sup> <b>HB</b>	Hadron Barrel
<sup>206</sup> <b>HCAL</b>	Hadronic CALorimeter

207	<b>HE</b>	Hadron Endcaps
208	<b>HF</b>	Hadron Forward
209	<b>HLT</b>	Higher Level Trigger
210	<b>HO</b>	Hadron Outer
211	<b>HPD</b>	Hybrid Photo Diode
212	<b>LUT</b>	Look Up Table
213	<b>L1</b>	Level 1 Trigger
214	<b>LHC</b>	Large Hadron Collider
215	<b>LHCb</b>	Large Hadron Collider Beauty
216	<b>LSP</b>	Lightest Supersymmetric Partner
217	<b>NNLO</b>	Next to Next Leading Order
218	<b>POGs</b>	Physics Object Groups
219	<b>PS</b>	Proton Synchrotron
220	<b>QED</b>	Quantum Electro-Dynamics
221	<b>QCD</b>	Quantum Chromo-Dynamics
222	<b>QFT</b>	Quantum Field Theory
223	<b>RPC</b>	Resistive Plate Chamber
224	<b>RCT</b>	Regional Calorimeter Trigger
225	<b>RMT</b>	Regional Muon Trigger
226	<b>SUSY</b>	SUperSYmmetry
227	<b>SM</b>	Standard Model
228	<b>SMS</b>	Simplified Model Spectra
229	<b>SPS</b>	Super Proton Synchrotron
230	<b>TF</b>	Transfer Factor
231	<b>VEV</b>	Vacuum Expectation Value

<sup>232</sup> **VPT** Vacuum Photo-Triodes

<sup>233</sup> **WIMP** Weakly Interacting Massive Particle

<sup>234</sup>

*“The Universe is about 1,000,000 years old.”*

— Matthew Kenzie, 1987-present : Discoverer of the Higgs Boson.

<sup>235</sup>

# Chapter 1.

## <sup>236</sup> Introduction

<sup>237</sup> During the 20th century great advances have been made in our understanding of the  
<sup>238</sup> universe, where it comes from, where it is going and what it is made of. The Standard  
<sup>239</sup> Model (**SM**) first formulated in the 1960's is one of the crowning achievements in science's  
<sup>240</sup> quest to explain the most fundamental processes and interactions that make up our  
<sup>241</sup> universe. It has provided a highly successful explanation of a wide range of phenomena  
<sup>242</sup> in Particle Physics and has stood up to extensive experimental scrutiny [1].

<sup>243</sup> Despite it's successes it is not a complete theory, with significant questions remaining  
<sup>244</sup> unanswered. It describes only three of the four known forces with gravity not incorpo-  
<sup>245</sup> rated within the framework of the **SM**. Cosmological experiments infer that just  $\sim 4\%$   
<sup>246</sup> of the observable universe exists as matter, with elusive "Dark Matter" accounting for a  
<sup>247</sup> further  $\sim 23\%$  [2]. However no particle predicted by the **SM** is able to account for it. At  
<sup>248</sup> higher energy scales and small distances the (non-)unification of the fundamental forces  
<sup>249</sup> point to problems with the **SM** at least at higher energies not yet probed experimentally.

<sup>250</sup> Many theories exist as extensions to the **SM** and predict a range of observables  
<sup>251</sup> that can be detected at the Large Hadron Collider (**LHC**) of which SUperSYmmetry  
<sup>252</sup> (**SUSY**) is one such example. It predicts a new symmetry of nature in which all current  
<sup>253</sup> particles in the **SM** would have a corresponding supersymmetric partner. Common to  
<sup>254</sup> most Supersymmetric theories is a stable, weakly interacting Lightest Supersymmetric  
<sup>255</sup> Partner (**LSP**), which has the properties of a possible dark matter candidate. The **SM**  
<sup>256</sup> and the main principles of Supersymmetric theories are outlined in Chapter 2, with  
<sup>257</sup> emphasis on placed on how experimental signatures of **SUSY** may reveal themselves at  
<sup>258</sup> the **LHC**.

259     The experimental goal of the **LHC** is to further test the framework of the **SM**,  
260   exploring the TeV mass scale for the first time, and to seek a connection between the  
261   particles produced in proton collisions and dark matter. The first new discovery by  
262   this extraordinary machine was announced on the 4th of July 2012. The long-awaited  
263   discovery was the culmination decades of experimental endeavours in the search for the  
264   Higgs boson, providing an answer to the mechanism of electroweak symmetry breaking  
265   within the **SM** [3][4].

266     This discovery was made possible through data taken by the two multi purpose  
267   detectors (**CMS** and A Toroidal LHC ApparatuS (**ATLAS**)) located on the **LHC** ring.  
268   An experimental description of the **CMS** detector and the **LHC** is described in Chapter 3,  
269   including some of the object reconstruction used by **CMS** in searches for **SUSY** signatures.  
270   The performance of the **CMS** Level-1 calorimeter trigger, benchmarked by the author is  
271   also included within this chapter.

272     The analysis conducted by the author is detailed within Chapter 4. This chapter  
273   contains a description of the search for evidence of the production of Supersymmetric  
274   particles at the **LHC**. The main basis of the search centres around the kinematic  
275   dimensionless  $\alpha_T$  variable, which provides strong rejection of backgrounds with fake  
276   missing energy signatures whilst maintaining good sensitivity to a variety of **SUSY**  
277   topologies. The author's work as an integral part of the analysis group is documented in  
278   detail, which has culminated in numerous publications over the past two years. The latest  
279   of which was published in the European Physical Journal C (**EPJC**) [5] and contains the  
280   results which are discussed within this and the sequential Chapter.

281     The author in particular has played a major role in the extension of the  $\alpha_T$  analysis into  
282   the additional b-tagged and jet multiplicity dimensions increasing the sensitivity of the  
283   analysis to a range of **SUSY** topologies. Additionally the author has worked extensively  
284   in both increasing the statistical precision of electroweak predictions measured from  
285   simulation through analytical techniques, and the derivation of a data driven systematic  
286   uncertainty through the establishment of closure tests within the control samples of the  
287   analysis.

288     Also included within this Chapter is a method to search for **SUSY** signatures which  
289   are rich in top and bottom flavoured jet final states. A parametrisation of the b-tagging  
290   distribution for different Electroweak processes is used to establish templates, which  
291   are then used to estimate the expected number of 3 or 4 b-tagged jet events from **SM**

292 processes. The  $\alpha_T$  search is used as a cross check for this template method to establish  
293 it's functionality.

294 Finally the interpretation of such results within the framework of a variety of Simplified  
295 Model Spectra (**SMS**), which describe an array of possible **SUSY** event topologies is  
296 documented in Chapter 5. A description of the statistical model used to derive these  
297 interpretations and the possible implications of the results presented in this thesis is  
298 discussed within this Chapter. Natural units are used throughout this thesis in which  $\hbar$   
299  $= c = 1$ .

# Chapter 2.

## <sup>300</sup> A Theoretical Overview

<sup>301</sup> Within this chapter, a brief introduction and background to the **SM** is given. Its success  
<sup>302</sup> as a rigorously tested and widely accepted theory is discussed as well as the deficiencies  
<sup>303</sup> with this theory that hint there this theory is not a complete description of our universe.  
<sup>304</sup> The motivations for new physics at the TeV scale and in particular Supersymmetric  
<sup>305</sup> theories are outlined within Section (2.3), with the chapter concluding with how an  
<sup>306</sup> experimental signature of such theories can be produced and observed at the **LHC**,  
<sup>307</sup> Section (2.4).

### <sup>308</sup> 2.1. The Standard Model

<sup>309</sup> The **SM** is the name given to the relativistic Quantum Field Theory (**QFT**), where  
<sup>310</sup> particles are represented as excitations of fields, which describes the interactions and  
<sup>311</sup> properties of all the known elementary particles [6][7][8][9]. It is a renormalisable field  
<sup>312</sup> theory which contains three symmetries:  $SU(3)$  for colour charge,  $SU(2)$  for weak isospin  
<sup>313</sup> and  $U(1)$  relating to weak hyper charge, which require its Lagrangian  $\mathcal{L}_{SM}$  to be invariant  
<sup>314</sup> under local gauge transformation.

<sup>315</sup> Within the **SM** theory, matter is composed of spin  $\frac{1}{2}$  fermions, which interact with each  
<sup>316</sup> other via the exchange of spin-1 gauge bosons. A summary of the known fundamental  
<sup>317</sup> fermions and bosons is given in Table 2.1.

<sup>318</sup> Fermions are separated into quarks and leptons of which only quarks interact with  
<sup>319</sup> the strong nuclear force. Quarks unlike leptons are not seen as free particles in nature,  
<sup>320</sup> but rather exist only within baryons, composed of three quarks with an overall integer

Particle	Symbol	Spin	Charge	Mass (GeV)
<b>First Generation Fermions</b>				
Electron Neutrino	$\nu_e$	$\frac{1}{2}$	0	$< 2.2 \times 10^{-6}$
Electron	e	$\frac{1}{2}$	-1	$0.51 \times 10^{-3}$
Up Quark	u	$\frac{1}{2}$	$\frac{2}{3}$	$2.3^{+0.7}_{-0.5} \times 10^{-3}$
Down Quark	d	$\frac{1}{2}$	$-\frac{1}{3}$	$4.8^{+0.7}_{-0.3} \times 10^{-3}$
<b>Second Generation Fermions</b>				
Muon Neutrino	$\nu_\mu$	$\frac{1}{2}$	0	-
Muon	$\mu$	$\frac{1}{2}$	-1	$1.05 \times 10^{-3}$
Charm Quark	c	$\frac{1}{2}$	$\frac{2}{3}$	$1.275 \pm 0.025$
Strange Quark	s	$\frac{1}{2}$	$-\frac{1}{3}$	$95 \pm 5 \times 10^{-3}$
<b>Third Generation Fermions</b>				
Tau Neutrino	$\nu_\tau$	$\frac{1}{2}$	0	-
Tau	$\tau$	$\frac{1}{2}$	-1	1.77
Top Quark	t	$\frac{1}{2}$	$\frac{2}{3}$	$173.5 \pm 0.8$
Bottom Quark	b	$\frac{1}{2}$	$-\frac{1}{3}$	$4.65 \pm 0.03$
<b>Gauge Bosons</b>				
Photon	$\gamma$	1	0	0
W Boson	$W^\pm$	1	$\pm 1$	$80.385 \pm 0.015$
Z Boson	Z	1	0	$91.187 \pm 0.002$
Gluons	g	1	0	0
Higgs Boson	H	0	0	$125.3 \pm 0.5$ [4]

**Table 2.1.:** The fundamental particles of the SM, with spin, charge and mass displayed. Latest mass measurements taken from [1].

charge, and quark-anti-quark pairs called mesons. Both leptons and quarks are grouped into three generations which have the same properties, but with ascending mass in each subsequent generation.

The gauge bosons mediate the interactions between fermions. The field theories of Quantum Electro-Dynamics (QED) and Quantum Chromo-Dynamics (QCD), yield massless mediator bosons, the photon and eight coloured gluons which are consequences of the gauge invariance of those theories, detailed in Section (2.1.1).

The unification of the electromagnetic and weak-nuclear forces into the current Electroweak theory yield the weak gauge bosons,  $W^\pm$  and Z through the mixing of the associated gauge fields. The force carriers of this theory were experimentally detected by

<sup>331</sup> the observation of weak neutral current, discovered in 1973 in the Gargamelle bubble  
<sup>332</sup> chamber located at European Organization for Nuclear Research (**CERN**) [10], with the  
<sup>333</sup> masses of and the weak gauge bosons measured by the UA1 and U2 experiments at the  
<sup>334</sup> Super Proton Synchrotron (**SPS**) collider in 1983 [11][12].

### <sup>335</sup> 2.1.1. Gauge Symmetries of the SM

<sup>336</sup> Symmetries are of fundamental importance in the description of physical phenomena.  
<sup>337</sup> Noether's theorem states that for a dynamical system, the consequence of any symmetry  
<sup>338</sup> is an associated conserved quantity [13]. Invariance under translations, rotations, and  
<sup>339</sup> Lorentz transformations in physical systems lead to conservation of momentum, energy  
<sup>340</sup> and angular momentum.

<sup>341</sup> In the **SM**, a quantum theory described by Lagrangian formalism, the weak, strong and  
<sup>342</sup> electromagnetic interactions are described in terms of “gauge theories”. A gauge theory  
<sup>343</sup> possesses invariance under a set of “local transformations”, which are transformations  
<sup>344</sup> whose parameters are space-time dependent. The requirement of gauge invariance within  
<sup>345</sup> the **SM** necessitates the introduction of force-mediating gauge bosons and interactions  
<sup>346</sup> between fermions and the bosons themselves. Given the nature of the topics covered by  
<sup>347</sup> this thesis, the formulation of **EWK** within the **SM** Lagrangian is reviewed within this  
<sup>348</sup> section.

<sup>349</sup> The simplest example of the application of the principle of local gauge invariance  
<sup>350</sup> within the **SM** is in Quantum Electro-Dynamics (**QED**), the consequences of which  
<sup>351</sup> require a massless photon field [14][15].

<sup>352</sup> Starting from the free Dirac Lagrangian written as

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi, \quad (2.1)$$

<sup>353</sup> where  $\psi$  represents a free non interacting fermionic field, with the matrices  $\gamma^\mu, \mu \in$   
<sup>354</sup>  $0, 1, 2, 3$  defined by the anti commutator relationship  $\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2\eta^{\mu\nu} I_4$  where  $\eta^{\mu\nu}$  is  
<sup>355</sup> the flat space-time metric  $(+, -, -, -)$  and  $I_4$  is the  $4 \times 4$  identity matrix.

<sup>356</sup> Under a local U(1) abelian gauge transformation in which  $\psi$  transforms as:

$$\psi(x) \rightarrow \psi'(x) = e^{i\theta(x)}\psi(x) \quad \bar{\psi}(x) \rightarrow \bar{\psi}'(x) = e^{i\theta(x)}\bar{\psi}(x) \quad (2.2)$$

357 the kinetic term of the Lagrangian does not remain invariant, due to the partial  
358 derivative interposed between the  $\bar{\psi}$  and  $\psi$  yielding,

$$\partial_\mu \psi \rightarrow e^{i\theta(x)} \partial_\mu \psi + i e^{i\theta(x)} \psi \partial_\mu \theta. \quad (2.3)$$

359 To ensure that  $\mathcal{L}$  remains invariant, a modified derivative,  $D_\mu$ , that transforms  
360 covariantly under phase transformations is introduced. In doing this a vector field  $A_\mu$   
361 with transformation properties that cancel out the unwanted term in (2.3) must also be  
362 included,

$$D_\mu \equiv \partial_\mu - ieA_\mu, \quad A_\mu \rightarrow A_\mu + \frac{1}{e} \partial_\mu \theta. \quad (2.4)$$

363 Invariance of the Lagrangian is then achieved by replacing  $\partial_\mu$  by  $D_\mu$ :

$$\begin{aligned} \mathcal{L} &= i\bar{\psi}\gamma^\mu D_\mu \psi - m\bar{\psi}\psi \\ &= \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi + e\bar{\psi}\gamma^\mu \psi A_\mu \end{aligned} \quad (2.5)$$

364 An additional interaction term is now present in the Lagrangian, coupling the Dirac  
365 particle to this vector field, which is interpreted as the photon in QED. To regard this  
366 new field as the physical photon field, a term corresponding to its kinetic energy must be  
367 added to the Lagrangian from Equation (2.5). Since this term must also be invariant  
368 under the conditions of Equation (2.4), it is defined in the form  $F_{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ .

369 This then leads to the Lagrangian of QED:

$$\mathcal{L}_{QED} = \underbrace{i\bar{\psi}\gamma^\mu\partial_\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{kinetic term}} + \underbrace{m\bar{\psi}\psi}_{\text{mass term}} + \underbrace{e\bar{\psi}\gamma^\mu\psi A_\mu}_{\text{interaction term}} \quad (2.6)$$

Within the Lagrangian there remains no mass term of the form  $m^2A_\mu A^\mu$ , which is prohibited by gauge invariance. This implies that the gauge particle, the photon, must be massless.

### 2.1.2. The Electroweak Sector and Electroweak Symmetry Breaking

The same application of gauge symmetry and the requirement of local gauge invariance can be used to unify QED and the Weak force in the Electroweak Sector (EWK). The nature of EWK interactions is encompassed within a Lagrangian invariant under transformations of the group  $SU(2)_L \times U(1)_Y$ .

The weak interactions from experimental observation [16], are known to violate parity and are therefore not symmetric under interchange of left and right helicity fermions. Thus within the SM the left and right handed parts of these fermion fields are treated separately. A fermion field is then split into two left and right handed chiral components,  $\psi = \psi_L + \psi_R$ , where  $\psi_{L/R} = (1 \pm \gamma^5)\psi$ .

The  $SU(2)_L$  group is the special unitary group of  $2 \times 2$  matrices  $U$  satisfying  $UU^\dagger = I$  and  $\det(U) = 1$ . It may be written in the form  $U = e^{-i\omega_i T_i}$ , with the generators of the group  $T_i = \frac{1}{2}\tau_i$  where  $\tau_i$ ,  $i \in 1,2,3$  being the  $2 \times 2$  Pauli matrices

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad (2.7)$$

which form a non Abelian group obeying the commutation relation  $[T^a, T^b] \equiv if^{abc}T^c \neq 0$ . The gauge fields that accompany this group are represented by  $\hat{W}_\mu = (\hat{W}_\mu^1, \hat{W}_\mu^2, \hat{W}_\mu^3)$  and act only on the left handed component of the fermion field  $\psi_L$ .

390 One additional generator  $Y$  which represents the hypercharge of the particle under  
 391 consideration is introduced through the  $U(1)_Y$  group acting on both components of the  
 392 fermion field, with an associated vector boson field  $\hat{B}_\mu$ .

393 The  $SU(2)_L \times U(1)_Y$  transformations of the left and right handed components of  $\psi$   
 394 are summarised by,

$$\begin{aligned}\chi_L &\rightarrow \chi'_L = e^{i\theta(x) \cdot T + i\theta(x)Y} \chi_L, \\ \psi_R &\rightarrow \psi'_R = e^{i\theta(x)Y} \psi_R,\end{aligned}\tag{2.8}$$

395 where the left handed fermions form isospin doubles  $\chi_L$  and the right handed fermions  
 396 are isosinglets  $\psi_R$ . For the first generation of leptons and quarks this represents

$$\begin{aligned}\chi_L &= \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, & \begin{pmatrix} u \\ d \end{pmatrix}_L \\ \psi_R &= e_R, & u_R, d_R\end{aligned}\tag{2.9}$$

397 Imposing local gauge invariance within  $\mathcal{L}_{EWK}$  is once again achieved by modifying  
 398 the covariant derivative

$$D_\mu = \partial_\mu - \frac{ig}{2}\tau^i W_\mu^i - \frac{ig'}{2}Y B_\mu,\tag{2.10}$$

399 where  $g$  and  $g'$  are the coupling constant of the  $SU(2)_L$  and  $U(1)_Y$  groups respectively.  
 400 Taking the example of the first generation of fermions defined in Equation.(2.9), with input  
 401 hypercharge values of -1 and -2 for  $\chi_L$  and  $e_R$  respectively, would lead to a Lagrangian  
 402  $\mathcal{L}_1$  of the form,

$$\begin{aligned}\mathcal{L}_1 = &\bar{\chi}_L \gamma^\mu [i\partial_\mu - g \frac{1}{2} \tau \cdot W_\mu - g' (-\frac{1}{2}) B_\mu] \chi_L \\ &+ \bar{e}_R \gamma^\mu [i\partial_\mu - g' (-1) B_\mu] e_R - \frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}.\end{aligned}\tag{2.11}$$

<sup>403</sup> As in **QED**, these additional gauge fields introduce field strength tensors  $B_{\mu\nu}$  and  
<sup>404</sup>  $W_{\mu\nu}$ ,

$$\hat{B}_{\mu\nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu \quad (2.12)$$

$$\hat{W}_{\mu\nu} = \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu - g \hat{W}_\mu \times \hat{W}_\nu \quad (2.13)$$

<sup>405</sup> corresponding to the kinetic energy and self coupling of the  $W_\mu$  fields and the kinetic  
<sup>406</sup> energy term of the  $B_\mu$  field.

<sup>407</sup> None of these gauge bosons are physical particles, and instead linear combinations of  
<sup>408</sup> these gauge bosons make up  $\gamma$  and the W and Z bosons, defined as

$$W^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \quad (2.14)$$

<sup>409</sup> where the mixing angle,  $\theta_w = \tan^{-1} \frac{g'}{g}$ , relates the coupling of the neutral weak and  
<sup>410</sup> electromagnetic interactions.

<sup>411</sup> As in the case of the formulation of the **QED** Lagrangian there remains no mass term  
<sup>412</sup> for the photon. However this is also the case for the W, Z and fermions in the Lagrangian,  
<sup>413</sup> contrary to experimental measurement. Any explicit introduction of mass terms would  
<sup>414</sup> break the symmetry of the Lagrangian and instead mass terms can be introduced through  
<sup>415</sup> spontaneous breaking of the **EWK** symmetry via the Higgs mechanism.

<sup>416</sup> The Higgs mechanism induces spontaneous symmetry breaking through the introduc-  
<sup>417</sup> tion of a complex scalar SU(2) doublet field  $\phi$  which attains a non-zero Vacuum  
<sup>418</sup> Expectation Value (**VEV**) [17][18][19][20].

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \text{with} \quad \begin{aligned} \phi^+ &\equiv (\phi_1 + i\phi_2)/\sqrt{2} \\ \phi^0 &\equiv (\phi_3 + i\phi_4)/\sqrt{2} \end{aligned} \quad (2.15)$$

419 The Lagrangian defined in Equation (2.11) attains an additional term  $\mathcal{L}_{Higgs}$  of the  
420 form

$$\mathcal{L}_{Higgs} = \overbrace{(D_\mu \phi)^\dagger (D^\mu \phi)}^{\text{kinetic}} - \overbrace{\mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2}^{\text{potential } V(\phi)} \quad (\mu^2, \lambda) > 0 \in \mathbb{R},$$

$$\mathcal{L}_{SM} = \mathcal{L}_{EWK} + \mathcal{L}_{Higgs}, \quad (2.16)$$

421 where the covariant derivative  $D_\mu$  is that defined in Equation (2.10). The last two  
422 terms of  $\mathcal{L}_{Higgs}$  correspond to the Higgs potential, in which positive real positive values  
423 of  $\mu^2$  and  $\lambda$  are required to ensure the generation of masses for the bosons and leptons.  
424 The minimum of this potential is found at  $\phi^\dagger \phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = \mu^2/\lambda = v^2$ ,  
425 where  $v$  represents the **VEV**.

426 Defining the ground state of the  $\phi$  field to be consistent with the  $V(\phi)$  minimum, and  
427 then expanding around a ground state chosen to maintain an unbroken electromagnetic  
428 symmetry thus preserving a zero photon mass [21] leads to

$$\phi_0 = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \phi(x) = e^{i\tau \cdot \theta(x)/v} \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad (2.17)$$

429 where the fluctuations from the vacuum  $\phi_0$  are parametrized in terms of four real  
430 fields,  $\theta_1, \theta_2, \theta_3$  and  $h(x)$ .

431 Choosing to gauge away the three massless Goldstone boson fields by setting  $\theta(x)$  to  
432 zero and substituting  $\phi(x)$  back into kinetic term of  $\mathcal{L}_{Higgs}$  from Equation (2.16) leads to  
433 mass terms for the  $W^\pm$  and  $Z$  bosons

$$(D_\mu \phi)^\dagger (D^\mu \phi) = \frac{1}{2}(\partial_\mu h)^2 + \frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \frac{v^2 g^2}{8 \cos^2 \theta_w} Z_\mu Z^\mu + 0 A_\mu A^\mu, \quad (2.18)$$

434 where the relations between the physical and electroweak gauge fields from Equation  
435 (2.14) are used. The  $W^\pm$  and  $Z$  bosons can then be determined to be

$$M_W = \frac{1}{2}gv \quad M_Z = \frac{1}{2} \frac{gv}{\cos \theta_w}. \quad (2.19)$$

436 This mechanism is also used to generate fermion masses by introducing a Yukawa  
 437 coupling between the fermions and the  $\phi$  field [22], with the coupling strength of a particle  
 438 to the  $\phi$  field governing its mass. Additionally a scalar boson  $h$  with mass  $m_h = v\sqrt{\frac{\lambda}{2}}$ , is  
 439 also predicted as a result of this spontaneous symmetry breaking and became known as  
 440 the Higgs boson. Its discovery by the CMS and ATLAS experiments in 2012 is concrete  
 441 evidence to support this method of mass generation within the SM.

## 442 2.2. Motivation for Physics Beyond the Standard 443 Model

444 As has been described, the SM has proved to be a very successful theory, predicting the  
 445 existence of the  $W^\pm$  and  $Z$  bosons and the top quark long before they were experimentally  
 446 observed. However the theory does not accurately describe all observed phenomena and  
 447 has some fundamental theoretical flaws that hint at the need for additional extensions to  
 448 the current theory.

449 On a theoretical level, the SM is unable to incorporate the gravitational interactions  
 450 of fundamental particles within the theory. Whilst at the electroweak energy scales the  
 451 relative strength of gravity is negligible compared to the other three fundamental forces,  
 452 at much higher energy scales  $M_{planck} \sim 10^{18} GeV$  quantum gravitational effects become  
 453 increasingly dominant. The failure to reconcile gravity within the SM, demonstrates that  
 454 the SM must become invalid at some higher energy scale.

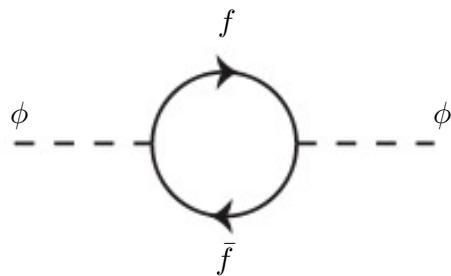
455 Some other deficiencies with the SM include the fact that the predicted rate of  
 456 Charge-Parity violation does not account for the matter dominated universe which we  
 457 inhabit, and the SM prediction of zero neutrino mass conflicts with the observation of  
 458 neutrino flavour mixing, attributed to mixing between neutrino mass eigenstates [23][24].

459 Perhaps one of the most glaring gaps in the predictive power of the SM is that there  
 460 exists no candidate to explain the cosmic dark matter observed in galactic structures  
 461 through indirect techniques including gravitational lensing and measurement of the  
 462 orbital velocity of stars in galactic edges. Any such candidate must be very weakly

463 interacting which must also be stable, owing to the lack of direct detection of the decay  
464 products of such an process. Providing a dark matter candidate is of the prime goals  
465 which be tackled by any Beyond Standard Model (**BSM**) physics model.

466 The recent discovery of the Higgs boson whilst a significant victory for the predictive  
467 power of the **SM**, brings with it still unresolved questions. This issue is commonly  
468 described as the “hierarchy problem”.

469 In the absence of new physics between the TeV and Planck scale, calculating beyond  
470 tree-level contributions to the Higgs mass term given by its self interaction, result in  
471 divergent terms that push the Higgs mass up to the planck mass  $M_{planck}$ .



**Figure 2.1.:** One loop quantum corrections to the Higgs squared mass parameter  $m_h^2$  due to a fermion.

472 This can be demonstrated by considering the one loop quantum correction to the  
473 Higgs mass with a fermion  $f$ , shown in Figure 2.1 with mass  $m_f$ . The Higgs field couples  
474 to  $f$  with a term in the Lagrangian  $-\lambda_f h \bar{f} f$ , yielding a correction of the form [25],

$$\delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda^2 + \dots, \quad (2.20)$$

475 where  $\lambda_f$  represents the coupling strength for each type of fermion  $\propto m_f$ , and  $\Lambda$  the  
476 cutoff energy scale at which the **SM** ceases to be a valid theory.

477 To recover the mass of the now discovered Higgs boson would require a fine-tuning of  
478 the parameters to cancel out these mass corrections the the Higgs mass to the scale of  
479 30 orders of magnitude. This appears as an unnatural solution to physicists and it is  
480 this hierarchy problem that provides one of the strongest motivations for the theory of  
481 SUperSYmmetry (**SUSY**).

## <sup>482</sup> 2.3. Supersymmetry Overview

<sup>483</sup> Supersymmetry provides potential solutions to many of the issues raised in the previous  
<sup>484</sup> section. It provides a dark matter candidate, can explain baryogenesis in the early  
<sup>485</sup> universe and also provides an elegant solution to the hierarchy problem [26][27][28][29].  
<sup>486</sup> At its heart it represents a new space-time symmetry that relates fermions and bosons.  
<sup>487</sup> This symmetry converts bosonic states into fermionic states, and vice versa, see Equation  
<sup>488</sup> (2.21) ,

$$Q|Boson\rangle = |Fermion\rangle \quad Q|Fermion\rangle = |Boson\rangle, \quad (2.21)$$

<sup>489</sup> where the operator  $Q$  is the generator of these transformations. Quantum field theories  
<sup>490</sup> which are invariant under such transformations are called supersymmetric.

<sup>491</sup> This symmetry operator therefore acts upon a particles spin altering it by a half integer  
<sup>492</sup> value. The consequences of the introduction of this additional space-time symmetry  
<sup>493</sup> introduce a new rich phenomenology. For example in supersymmetric theories, both  
<sup>494</sup> the left handed  $SU(2)$  doublet and right handed singlet of fermions will have a spin-0  
<sup>495</sup> superpartner, containing the same electric charge, weak isospin, and colour as its **SM**  
<sup>496</sup> partner. In the case of the leptons  $(\nu_l, l)_L$  will have two superpartners, a sneutrino  $\tilde{\nu}_l{}_L$   
<sup>497</sup> and a slepton  $\tilde{l}_L$ , whilst the singlet  $l_R$  also has a superpartner slepton  $\tilde{l}_R$ .

<sup>498</sup> Each particle in a supersymmetric theory is paired together with their superpartners  
<sup>499</sup> as a result of this supersymmetric transformations in a so called supermultiplet. These  
<sup>500</sup> superpartners will then consequently also contribute to the corrections to the Higgs mass.  
<sup>501</sup> Bosonic and fermionic loops contributing to the correction appear with opposite signs,  
<sup>502</sup> and therefore cancellation of these divergent terms will stabilise the Higgs mass, solving  
<sup>503</sup> the hierarchy problem [30][31].

<sup>504</sup> One of the simplest forms of **SUSY** would predict a whole set of supersymmetric  
<sup>505</sup> partners to their **SM** counterparts with the same mass and interactions. However the  
<sup>506</sup> currently lack of any experimental evidence for the predicted sparticle spectrum implies  
<sup>507</sup> **SUSY** must be a broken symmetry in which any sparticle masses must be greater than  
<sup>508</sup> their SM counterparts.

<sup>509</sup> There exist many techniques which can induce supersymmetric breaking [32][33][34].  
<sup>510</sup> Of particular interest to experimental physicists are those at which the breaking scale

511 is of an order that is experimentally accessible to the **LHC** i.e.  $\sim$  TeV scale. Whilst  
512 there is no requirement for supersymmetric breaking to occur at this energy scale, for  
513 supersymmetry to provide a solution to the hierarchy problem, it is necessary for this  
514 scale to not differ too drastically from the **EWK** scale [35][36].

### 515 2.3.1. R-Parity

516 Some supersymmetric theories also present a solution to the dark matter problem. Such  
517 theories can contain a Lightest Supersymmetric Partner (**LSP**), which matches the criteria  
518 of a Weakly Interacting Massive Particle (**WIMP**) required by cosmological observation  
519 if R-parity is conserved.

520 Baryon (B) and Lepton (L) number conservation is forbidden in the **SM** by renor-  
521 malisability requirements. The violation of Baryon or Lepton number would result in  
522 the proton lifetime much shorter than those set by experimental limits [37]. Another  
523 symmetry called R-parity is then often introduced to **SUSY** theories to maintain baryon  
524 and lepton conservation.

525 R-parity is described by the equation

$$R_P = (-1)^{3(B-L)+2s}, \quad (2.22)$$

526 where s represents the spin of the particles.  $B = \pm \frac{1}{3}$  for quarks/antiquarks and  $B = 0$   
527 for all others,  $L = \pm 1$  for leptons/antileptons,  $L = 0$  for all others.

528 R-parity ensures the stability of the proton in **SUSY** models, and also has other  
529 consequences for the production and decay of supersymmetric particles. At particle  
530 colliders supersymmetric particles can only be pair produced, and similarly the decay  
531 of any produced supersymmetric particle is restricted to a **SM** particle and a lighter  
532 supersymmetric particle as allowed by conservation laws. A further implication of R-  
533 parity is that once a supersymmetric particle has decayed to the **LSP** it remains stable,  
534 unable to decay into a **SM** particle.

535 A **LSP** would not interact in a detector at a particle collider, leaving behind a missing  
536 energy  $\cancel{E}_T$  signature. The assumption of R-parity and its consequences are used to  
537 determine the physical motivation and search strategies for **SUSY** model at the **LHC**.

## 538 2.4. Experimental signatures of SUSY at the LHC

539 Should strongly interacting sparticles be within the experimental reach of the LHC, then  
540 it is expected that they can be produced in a variety of ways.

- 541 • squark/anti-squark and gluino pairs can be produced via both gluon fusion and  
542 quark/anti-quark scattering.
- 543 • a gluino and squark produced together via quark-gluon scattering
- 544 • squark pairs produced via quark-quark scattering

545 Whilst most SUSY searches invoke the requirement of R-parity to explore parameter  
546 phase space, there still exist a whole plethora of possible SUSY model topologies which  
547 could be discovered at the LHC.

548 During the 2011 run period at a  $\sqrt{s} = 7$  TeV particular models were used to benchmark  
549 performance and experimental reach of both CMS searches and previous experiments.  
550 The Compressed Minimal SuperSymmetric Model (CMSSM) was initially chosen for a  
551 number of reasons [38]. One of the most compelling being the reduction from the up to  
552 105 new parameters introduced by SUSY in addition to the existing 19 of the SM to that  
553 of just 5 free extra free parameters. It was this simplicity, combined with the theory not  
554 requiring any fine tuning of particle masses to produce the experimentally verified SM  
555 that made it an attractive model to interpret physics results.

556 However recent results from the LHC now strongly disfavour large swathes of CMSSM  
557 parameter space [39][40][41]. In the face of such results a more pragmatic model indepen-  
558 dent search strategy is now applied across most SUSY searches at the LHC, see Section  
559 (2.4.1).

560 As previously stated, a stable LSP that exhibits the properties of a dark matter would  
561 be weakly interacting and therefore will not be directly detected in a detector environment.  
562 Additionally the cascade decays of supersymmetric particles to the LSP would also result  
563 in significant hadronic activity. These signatures can then be characterised through  
564 large amounts of hadronic jets (see Section (3.3.1)), leptons and a significant amount of  
565 missing energy dependent upon the size of the mass splitting between the LSP and the  
566 supersymmetric particle it has decayed from.

567 Whilst the SM contains processes which can exhibit a similar event topology to that  
568 described above. The largest contribution of which comes in from the general QCD

569 environment of a hadron collider. A multitude of different analytical techniques are used  
570 by experimental physicists to reduce or estimate any reducible or irreducible backgrounds,  
571 allowing a possible **SUSY** signature to be extracted. The techniques employed within  
572 this thesis are described in great detail within Section (4.1).

### 573 2.4.1. Simplified Models

574 With such a variety of different ways for a **SUSY** signal to manifest itself, it is necessary  
575 to be able to interpret experimental reach through the masses of gluinos and squarks  
576 which can excluded by experimental searches rather than on a model specific basis.

577 This is accomplished through **SMS** models, which are defined by a set of hypothetical  
578 particles and a sequence of their production and decay [42][43]. In the **SMS** models  
579 considered within this thesis, only the production process for the two primary particles  
580 are considered. Each primary particle can undergo a direct or a cascade decay through  
581 an intermediate new particle. At the end of each decay chain there remains a neutral,  
582 undetected **LSP** particle, denoted  $\tilde{\chi}_{LSP}$  which can represent a neutralino or gravitino.  
583 Essentially it is easier to consider each **SMS** with branching ratios set to 100% The  
584 masses of the primary particle and the **LSP** remain as free parameters, in which the  
585 absolute value and relative difference between the primary and **LSP** particle alter the  
586 kinematics of the event.

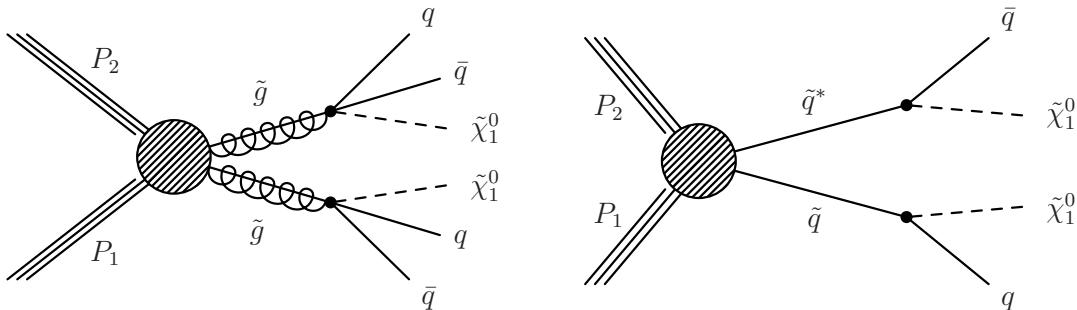
587 Different **SMS** models are denoted with a T-prefix, with a summary of the types  
588 interpreted within this thesis listed below [44].

- 589 • **T1,T1xxxx**, models represent a simplified version of gluino pair production with  
590 each gluino (superpartner to the gluon) undergoing a three-body decay to a quark-  
591 antiquark pair and the **LSP** (i.e.  $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{LSP}$ ). The resultant final state from this  
592 decay is typically 4 jets +  $\cancel{E}_T$  in the absence of initial/final state radiation and  
593 detector effects. xxxx denotes models in which the quarks are of a specific flavour,  
594 typically t or b quark-antiquarks.
- 595 • **T2,T2xx**, models represent a simplified version of squark anti-squark production  
596 with each squark undergoing a two-body decay into a light-flavour quark and **LSP**  
597 (i.e.  $\tilde{q} \rightarrow q\tilde{\chi}_{LSP}$ ). This results in final states with less jets than gluino mediated  
598 production, typically 2 jets +  $\cancel{E}_T$  when again ignoring the effect of initial/final state  
599 radiation and detector effects. xx models again represent decays in which both the  
600 quark and the squark within the decay is of a specific flavour, typically  $\tilde{t}/t$  or  $\tilde{b}/b$ .

Models rich in b and t quarks are interpreted within this thesis as they remain of particular interest within “Natural SUSY” scenarios [45][46]. The largest contribution to the quadratic divergence in the Higgs mass parameter comes from a loop of top quarks via the Yukawa coupling. Cancellation of these divergences can be achieved in supersymmetric theories by requiring a light right handed top squark,  $\tilde{t}_R$ , and left-handed double  $SU(2)_L$  doublet containing top and bottom squarks,  $(\tilde{\frac{t}{b}})_L$  [47].

These theories therefore solve the hierarchy problem by predicting light  $\sim$  EWK scale third generation sleptons, to be accessible at the LHC. Search strategies involving the requirement of b-tagging (see Section (3.3.2)) are used to give sensitivity to these type of SUSY scenarios and are discussed in greater detail within Chapter 5.

Two example decay chains are shown in Figure 2.2; the pair production of gluinos (T1) and the pair production of squarks (T2) decaying into SM particles and LSP’s.



**Figure 2.2.:** Two example SMS model decays (T1 (left), T2 (right)), which are used in interpretations of physics reach by CMS.

# Chapter 3.

## <sup>613</sup> The LHC and the CMS Detector

<sup>614</sup> Probing the SM for signs of new physics would not be possible without the immensely  
<sup>615</sup> complex electronics and machinery that makes the TeV energy scale accessible for the  
<sup>616</sup> first time. This chapter will cover the LHC based at European Organization for Nuclear  
<sup>617</sup> Research (CERN) and the Compact Muon Solenoid (CMS) detector, being the experiment  
<sup>618</sup> the author is a member of. Section (3.2) serves to introduce an overview of the different  
<sup>619</sup> components of the CMS detector, with more detail spent on those that are relevant in  
<sup>620</sup> the search for Supersymmetric particles. Section (3.3) will focus on event and object  
<sup>621</sup> reconstruction again with more emphasis on jet level quantities which are most relevant  
<sup>622</sup> to the author's analysis research. Finally Section (3.4) will cover work performed by  
<sup>623</sup> the author, as service to the CMS Collaboration, in measuring the performance of the  
<sup>624</sup> Global Calorimeter Trigger (GCT) component of the L1 trigger during the 2012-2013  
<sup>625</sup> run period.

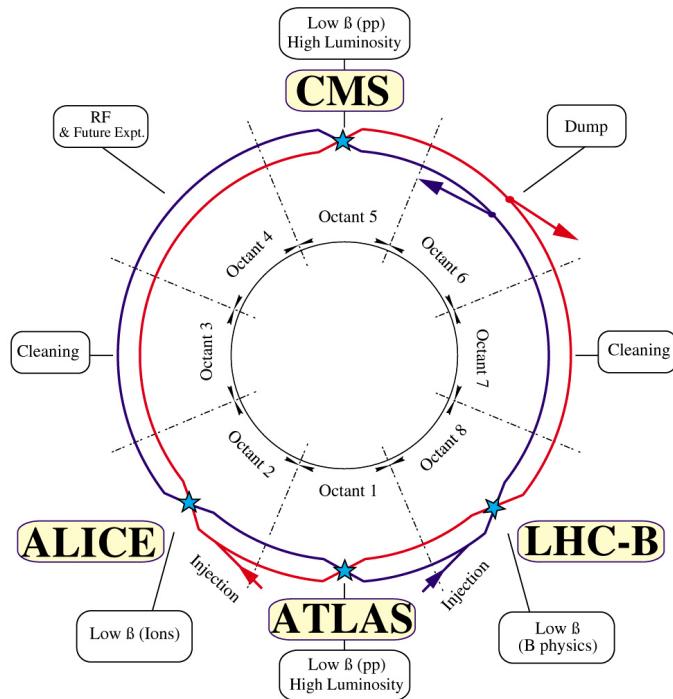
### <sup>626</sup> 3.1. The LHC

<sup>627</sup> The LHC is a storage ring, accelerator, and collider of circulating beams of protons or  
<sup>628</sup> ions. Housed in the tunnel dug for the Large Electron-Positron collider (LEP), it is  
<sup>629</sup> approximately 27 km in circumference, 100 m underground, and straddles the border  
<sup>630</sup> between France and Switzerland outside of Geneva. It is currently the only collider  
<sup>631</sup> in operation that is able to study physics at the TeV scale. A double-ring circular  
<sup>632</sup> synchrotron, it was designed to collide both proton-proton (pp) and heavy ion (PbPb)  
<sup>633</sup> with a centre of mass energy  $\sqrt{s} = 14$  TeV at a final design luminosity of  $10^{34}\text{cm}^{-2}\text{s}^{-1}$ .

<sup>634</sup>

These counter-circulating beams of protons/Pb ions are merged in four sections around the ring to enable collisions of the beams, with each interaction point being home to one of the four major experiments; A Large Ion Collider Experiment (**ALICE**) [48], A Toroidal LHC ApparatuS (**ATLAS**) [49], Compact Muon Solenoid (**CMS**) [50] and Large Hadron Collider Beauty (**LHC-B**) [51] which record the resultant collisions. The layout of the **LHC** ring is shown in Figure 3.1. The remaining four sections contain acceleration, collimation and beam dump systems. In the eight arc sections, the beams are steered by magnetic fields of up to 8 T provided by super conduction dipole magnets, which are maintained at temperatures of 2 K using superfluid helium. Additional magnets for focusing and corrections are also present in straight sections within the arcs and near the interaction regions where the detectors are situated.

646



**Figure 3.1.:** A top down layout of the LHC. [52], with the position of the four main detectors labelled.

Proton beams are formed inside the Proton Synchrotron (**PS**) from bunches of protons 50 ns apart with an energy of 26 GeV. The protons are then accelerated in the Super Proton Synchrotron (**SPS**) to 450 GeV before being injected into the **LHC**. These **LHC** proton beams consists of many “bunches” i.e. approximately  $1.1 \times 10^{11}$  protons localized into less than 1 ns in the direction of motion. Before collision the beams are ramped to 4

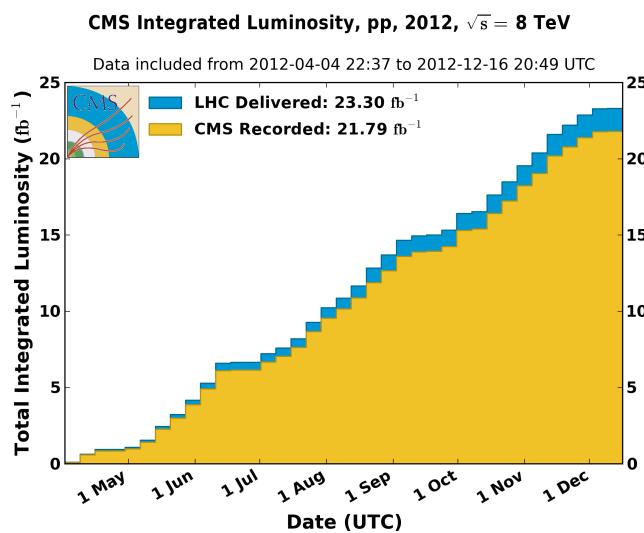
651

652 TeV (2012) per beam in a process involving increasing the current passing through the  
 653 dipole magnets. Once the desired  $\sqrt{s}$  energy is reached then the beams are allowed to  
 654 collide at the interaction points. The luminosity falls regularly as the run progresses as  
 655 protons are lost in collisions, and eventually the beam is dumped before repeating the  
 656 process again.

657

658 Colliding the beams produced an instantaneous luminosity of approximately  $5 \times$   
 659  $10^{33} \text{ cm}^{-2}\text{s}^{-1}$  during the 2012 run. The high number of protons in each bunch increases  
 660 the likelihood of multiple interactions with each crossing of the counter-circulating  
 661 beams. This leads to isotropic energy depositions within the detectors positioned at these  
 662 interaction points, increasing the energy scale of the underlying event. This is known as  
 663 pile-up and the counteracting of it's effects are important to the many measurements  
 664 performed at the LHC.

665 In the early phase of prolonged operation after the initial shutdown the machine  
 666 operated in 2010-2011 at 3.5 TeV per beam,  $\sqrt{s} = 7 \text{ TeV}$ , delivering  $6.13 \text{ fb}^{-1}$  of data  
 667 [53]. During the 2012-2013 run period, data was collected at an increased  $\sqrt{s} = 8 \text{ TeV}$   
 668 improving the sensitivity of searches for new physics. Over the whole run period  $23.3$   
 669  $\text{fb}^{-1}$  of data was delivered of which  $21.8 \text{ fb}^{-1}$  was recorded by the CMS detector as shown  
 670 in Figure 3.2 [53]. A total of  $12 \text{ fb}^{-1}$  of 8 TeV certified data was collected by October  
 671 2012, and it is this data which forms the basis of the results discussed within this thesis.



**Figure 3.2.:** The total integrated luminosity delivered to and collected by CMS during the 2012 8 TeV  $pp$  runs.

## 672 3.2. The CMS detector

673 The Compact Muon Solenoid (**CMS**) detector is one of two general purpose detectors  
 674 at the **LHC** designed to search for new physics. The detector is designed to provide  
 675 efficient identification and measurement of many physics objects including photons,  
 676 electrons, muons, taus, and hadronic showers over wide ranges of transverse momentum  
 677 and direction. Its nearly  $4\pi$  coverage in solid angle allows for accurate measurement of  
 678 global transverse momentum imbalance. These design factors give **CMS** the ability to  
 679 search for direct production of **SUSY** particles at the TeV scale, making the search for  
 680 Supersymmetric particles one of the highest priorities among the wide range of physics  
 681 programmes at **CMS**.

682

683 **CMS** uses a right-handed Cartesian coordinate system with the origin at the interaction  
 684 point and the z-axis pointing along the beam axis, the x-axis points radially inwards to  
 685 the centre of the collider ring, with the y-axis points vertically upward. The azimuthal  
 686 angle,  $\phi$  ranging between  $[-\pi, \pi]$  is defined in the x-y plane starting from the x-axis. The  
 687 polar angle  $\theta$  is measured from the z axis. The common convention in particle physics is  
 688 to express an out going particle in terms of  $\phi$  and its pseudorapidity defined as

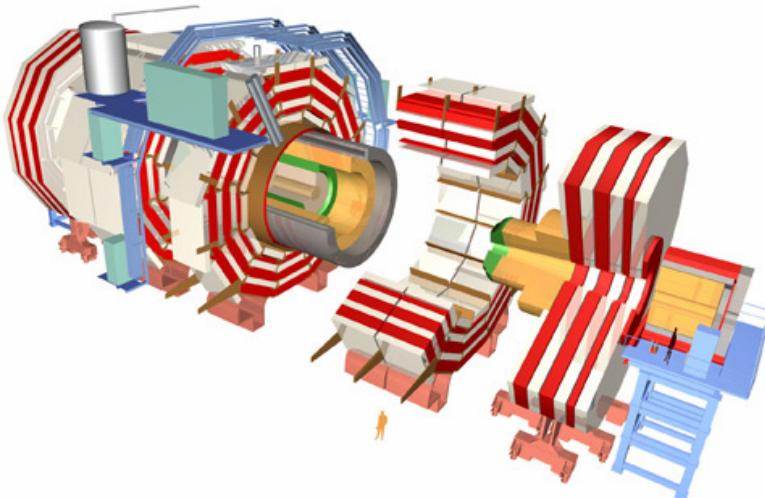
$$\eta = -\log \tan \left( \frac{\theta}{2} \right). \quad (3.1)$$

689 The variable  $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$  is commonly used to define angular distance  
 690 between objects within the detector and additionally energy and momentum is typically  
 691 measured in the transverse plane perpendicular to the beam line. These values are  
 692 calculated from the x and y components of the object and are denoted as  $E_T = E \sin \theta$   
 693 and  $p_T = \sqrt{p_x^2 + p_y^2}$ .

### 694 3.2.1. Detector Subsystems

695 As the range of particles produced in  $pp$  collisions interact in different ways with mat-  
 696 ter, **CMS** is divided into subdetector systems, which perform complementary roles to  
 697 identify the identity, mass and momentum of the different physics objects present in  
 698 each event. These detector sub-systems contained inside **CMS** are wrapped in layers

699 around a central 13 m long 4 T super conducting solenoid as shown in Figure 3.3. With  
 700 the endcaps closed , CMS is a cylinder of length 22 m, diameter 15 m, and mass 12.5  
 701 kilotons. A more detailed complete description of the detector can be found elsewhere [50].  
 702



**Figure 3.3.:** A pictorial depiction of the CMS detector with the main detector subsystems labelled. [54]

### 703 3.2.2. Tracker

704 The inner-most subdetector of the barrel is the multi-layer silicon tracker, formed of a  
 705 pixel detector component encased by layers of silicon strip detectors. The pixel detector  
 706 consists of three layers of silicon pixel sensors providing measurements of the momentum,  
 707 position coordinates of the charged particles as they pass, and the location of primary  
 708 and secondary vertices between 4cm and 10cm transverse to the beam. Outside the pixel  
 709 detector, ten cylindrical layers of silicon strip detectors extend the tracking system out to  
 710 a radius of 1.20m from the beam line. The tracking system provides efficient and precise  
 711 determination of the charges, momenta, and impact parameters of charged particles with  
 712 the geometry of the tracker extending to cover a rapidity range up to  $|\eta| < 2.5$ .  
 713

714 The tracking system also plays a crucial part in the identification of jets originating  
 715 from b-quarks through measurement of displaced secondary vertices, which is covered in  
 716 more detail in Section (3.3.2). The identification of b-jets is important in many searches

717 for natural SUSY models and forms an important part of the inclusive search strategy  
718 described within Section (4.2).

719 **3.2.3. Electromagnetic Calorimeter**

720 Immediately outside of the tracker, but still within the magnet core, sits the Electromag-  
721 netic CALorimeter (**ECAL**). Covering a pseudorapidity up to  $|\eta| < 3$  and comprising  
722 of over 75,000 PbWO<sub>4</sub> (lead tungstate) crystals that scintillate as particles deposit energy,  
723 the **ECAL** provides high resolution measurements of the electromagnetic showers from  
724 photons, electrons in the detector.

725

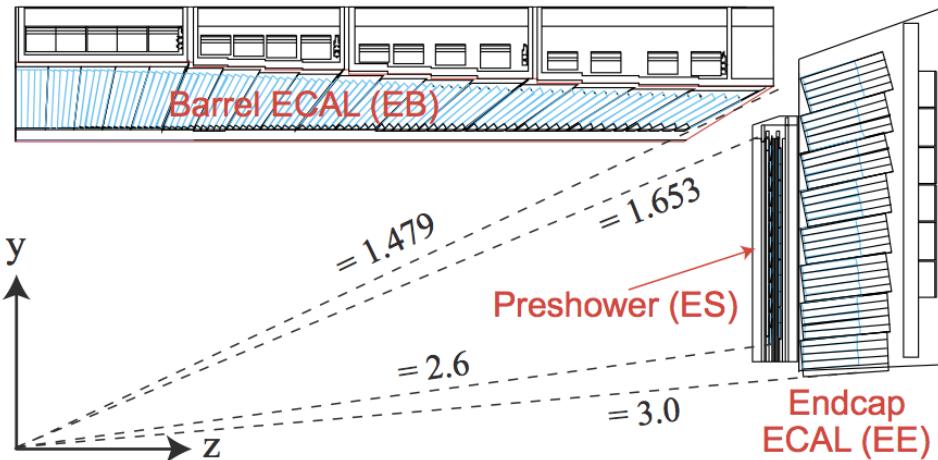
726 Lead tungstate is used because of its short radiation length ( $X_0 \sim 0.9\text{cm}$ ) and small  
727 Molieré radius ( $\sim 2.1\text{cm}$ ) leading to high granularity and resolution. It's fast scintillation  
728 time ( $\sim 25\text{ns}$ ) reduces the effects of pile-up due to energy from previous collisions still  
729 being read out, and its radiation hardness gives it longevity. The crystals are arranged  
730 in modules which surround the beam line in a non-projective geometry, angled at  $3^\circ$   
731 with respect to the interaction point to minimise the risk of particles escaping down the  
732 cracks between the crystals.

733

734 The **ECAL** is primarily composed of two sections, the Electromagnetic CALorime-  
735 ter Barrel (**EB**) which extends in pseudo-rapidity to  $|\eta| < 1.479$  with a crystal front  
736 cross section of  $22 \times 22 \text{ mm}^2$  and a length of 230 mm corresponding to 25.8 radia-  
737 tion lengths, and the Electromagnetic CALorimeter Endcap (**EE**) covering a rapidity  
738 range of  $1.479 < |\eta| < 3.0$ , which consists of two identical detectors on either side of  
739 the **EB**. A lead-silicon sampling ‘pre-shower’ detector Electromagnetic CALorimeter  
740 pre-Shower (**ES**) is placed before the endcaps to aid in the identification of neutral pions.  
741 Their arrangement are shown in Figure 3.4.

742

743 Scintillation photons from the lead tungstate crystals are instrumented with Avalanche  
744 Photo-Diodes (**APD**) and Vacuum Photo-Triodes (**VPT**) located in the **EB** and **EE**  
745 respectively, converting the scintillating light into an electric signal which is consequently  
746 used to determine the amount of energy deposited within the crystal . These instruments  
747 are chosen for their resistance under operation to the strong magnetic field of **CMS**. The  
748 scintillation of the **ECAL** crystals as well as the response of the **APDs** varies as a function



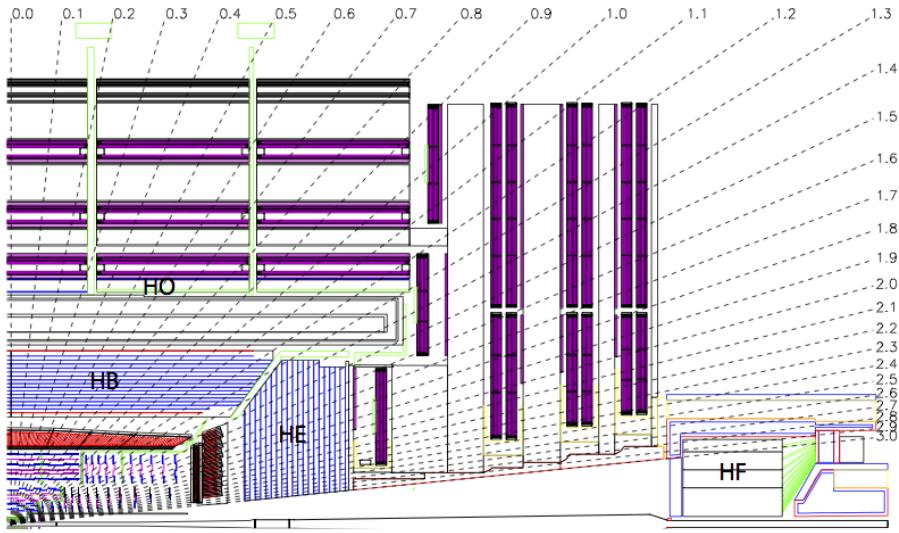
**Figure 3.4.:** Illustration of the CMS ECAL showing the arrangement of the lead tungstate crystals in the EB and EE. The ES is also shown and is located in front of the EE [55].

749 of temperature and so cooling systems continually maintain an overall constant ECAL  
 750 temperature  $\pm 0.05^\circ C$ .

### 751 3.2.4. Hadronic Calorimeter

752 Beyond the ECAL lies the Hadronic CALorimeter (HCAL) which is responsible for  
 753 the accurate measurement of hadronic showers, crucial for analyses involving jets or  
 754 missing energy signatures. The HCAL is a sampling calorimeter which consists of al-  
 755 ternating layers of brass absorber and plastic scintillator, except in the hadron forward  
 756 ( $3.0 < |\eta| < 5.0$ ) region in which steel absorbers and quartz fibre scintillators are used  
 757 because of their increased radiation tolerance. Hadron showers are initiated in the  
 758 absorber layers inducing scintillation in the plastic scintillator tiles. These scintillation  
 759 photons are converted by wavelength shifting fibres for read-out by hybrid photodiodes.  
 760

761 The HCAL's size is constrained to a compact size by the presence of the solenoid,  
 762 requiring the placement of an additional outer calorimeter on the outside of the solenoid  
 763 to increase the sampling depth of the HCAL. A schematic of the HCAL can be seen in  
 764 Figure 3.5.



**Figure 3.5.:** Schematic of the hadron calorimeters in the  $r$ - $z$  plane, showing the locations of the **HCAL** components and the **HF**. [50].

766     The **HCAL** covers the range  $|\eta| < 5$  and consists of four subdetectors: the Hadron  
 767     Barrel (**HB**)  $|\eta| < 1.3$ , the Hadron Outer (**HO**), the Hadron Endcaps (**HE**)  $1.3 < |\eta| < 3.0$   
 768     and the Hadron Forward (**HF**). The **HB** is contained between the outer edge of the **ECAL**  
 769     and the inner edge of the solenoid, formed of 36 azimuthal wedges it is split between  
 770     two half-barrel segments. Each wedge is segmented into four azimuthal angle ( $\phi$ ) sectors,  
 771     and each half-barrel is further segmented into 16  $\eta$  towers. The electronic readout chain,  
 772     channels the light from the active scintillator layers from one  $\phi$ -segment and all  $\eta$ -towers  
 773     of a half-barrel to a Hybrid Photo Diode (**HPD**).

774     The relatively short number of interaction lengths ( $\lambda_l$ , the distance a hadron will  
 775     travel through the absorber material before it has lost  $\frac{1}{e}$  of its energy) within the **HB**,  
 776     the lowest being  $\lambda_l = 5.82$  for  $|\eta| = 0$ , facilitates the need for the ‘tail catching’ **HO**  
 777     to increase the sampling depth in the central barrel rapidity region  $|\eta| < 1.3$  to 11  
 778     interaction lengths . Significant fractions of the hadrons energy will be deposited in the  
 779     **ECAL** as it passed through the detector. Therefore measurements of hadron energies  
 780     in the central regions  $|\eta| < 3.0$  use both the **ECAL** and **HCAL** to reconstruct the true  
 781     energy from showering hadrons.

782 **3.2.5. Muon Systems**

783 Muons being too massive to radiate away energy via Bremsstrahlung, interact little in  
784 the calorimeters and mostly pass through the detector until they reach the system of  
785 muon detectors which forms the outer most part of the **CMS** detector.

786 Outside of the superconducting solenoid are four muon detection layers interleaved  
787 with the iron return yokes which measure the muons energy via ionisation of gas within  
788 detector elements. Three types of gaseous chamber are used. The Drift Tube (**DT**),  
789 Cathode Stripe Chamber (**CSC**), and Resistive Plate Chamber (**RPC**) systems provide  
790 efficient detection of muons with pseudo-rapidity  $|\eta| < 2.4$ . The best reconstruction  
791 performance is obtained when the muon chamber is combined with the inner tracking  
792 information to determine muon trajectories and their momenta [56].

793

794 **3.3. Event Reconstruction and Object Definition**

795 The goal of event reconstruction is to take the raw information recorded by the detector  
796 and to compute from it higher-level quantities which can be used at an analysis level.  
797 These typically correspond to an individual particle’s energy and momenta, or groups of  
798 particles which shower in a narrow cone and the overall global energy and momentum  
799 balance of the event. The reconstruction of these objects are described in great detail in  
800 [57], however covered below are brief descriptions of those which are most relevant to the  
801 analysis detailed in Chapter 4.

802 **3.3.1. Jets**

803 Quarks and gluons are produced copiously at the LHC in the hard scattering of partons.  
804 As these quarks and gluons fragment, they hadronise and decay into a group of strongly  
805 interactive particles and their decay products. These streams of particles travel in the  
806 same direction, as they have been “boosted” by the momentum of the primary hadron.  
807 These collections of decay products are reconstructed and identified together as a “jet”.

808 At **CMS** jets are reconstructed from energy deposits in the detector using the anti-kt  
809 algorithm [58] with size parameter  $\Delta R = 0.5$ . The anti-kt jet algorithm clusters jets by  
810 defining a distance between hard (high  $p_T$ ) and soft (low  $p_T$ ) particles such that soft

811 particles are preferentially clustered with hard particles before being clustered between  
812 themselves. This produces jets which are robust to soft particle radiation from the pile-up  
813 conditions experienced at the **LHC**.

814

815 There are two main type of jet reconstruction used at **CMS**, Calorimeter (Calo) and  
816 Particle Flow (PF) jets [59]. Calorimeter jets are reconstructed using both the **ECAL**  
817 and **HCAL** cells, combined into calorimeter towers . These calorimeter towers consist of  
818 geometrically matched **HCAL** cells and **ECAL** crystals. Electronics noise is suppressed by  
819 applying a threshold to the calorimeter cells, with pile-up effects reduced by a requirement  
820 placed on the tower energy [60]. Calorimter jets are the jets used within the analyses  
821 described in this thesis.

822 PF jets are formed from combining information from all of the **CMS** subdetectors  
823 systems to determine which final state particles are present in the event. Generally,  
824 any particle is expected to produce some combination of a track in the silicon tracker,  
825 a deposit in the calorimeters, or a track in the muon system. The PF jet momentum  
826 and spatial resolutions are greatly improved with respect to calorimeter jets, as the use  
827 of the tracking detectors and of the high granularity of **ECAL** allows resolution and  
828 measurement of charged hadrons and photons inside a jet, which together constitute  $\sim$   
829 85% of the jet energy [61].

830 The jets reconstructed by the clustering algorithm in **CMS** typically have an energy  
831 that differs to the ‘true’ energy measured by a perfect detector. This stems from the  
832 non-linear and nonuniform response of the calorimeters as well as other residual effects  
833 including pile-up and underlying events, and therefore additional corrections are applied  
834 to recover a uniform relative response as a function of pseudo-rapidity. These are applied  
835 as separate sub corrections [62].

- 836 • A PU correction is first applied to the jet. It subtracts the average extra energy  
837 deposited in the jet that comes from other vertices present in the event and is  
838 therefore not part of the hard jet itself.
- 839 •  $p_T$  and  $\eta$  dependant corrections derived from Monte Carlo simulations are used to  
840 account for the non-uniform response of the detector.
- 841 •  $p_T$  and  $\eta$  residual corrections are applied to data only to correct for difference  
842 between data and Monte Carlo. The residual is derived from QCD dijet samples  
843 and the  $p_T$  residual from  $\gamma+$  jet and  $Z+$  jets samples in data.

<sup>844</sup> **3.3.2. B-tagging**

<sup>845</sup> The decays of b quarks are suppressed by small CKM matrix elements. As a result, the  
<sup>846</sup> lifetimes of b-flavoured hadrons, produced in the fragmentation of b quarks, are relatively  
<sup>847</sup> long;  $\mathcal{O}$  1ps. The identification of jets origination from b quarks is very important for  
<sup>848</sup> searches for new physics and for measurements of standard model processes.

<sup>849</sup>

<sup>850</sup> Many different algorithms developed by CMS select b-quark jets based on variables  
<sup>851</sup> such as the impact parameters of the charged-particle tracks, the properties of recon-  
<sup>852</sup> structed decay vertices, and the presence or absence of a lepton, or combinations thereof  
<sup>853</sup> [63]. One of the most efficient of which is the Combined Secondary Vertex (CSV) which  
<sup>854</sup> operates based on secondary vertex and track-based lifetime information, benchmarked  
<sup>855</sup> in ‘Loose’, ‘Medium’ and ‘Tight’ working points, of which the medium point is the tagger  
<sup>856</sup> used within the  $\alpha_T$  search detailed in Section (4.1).

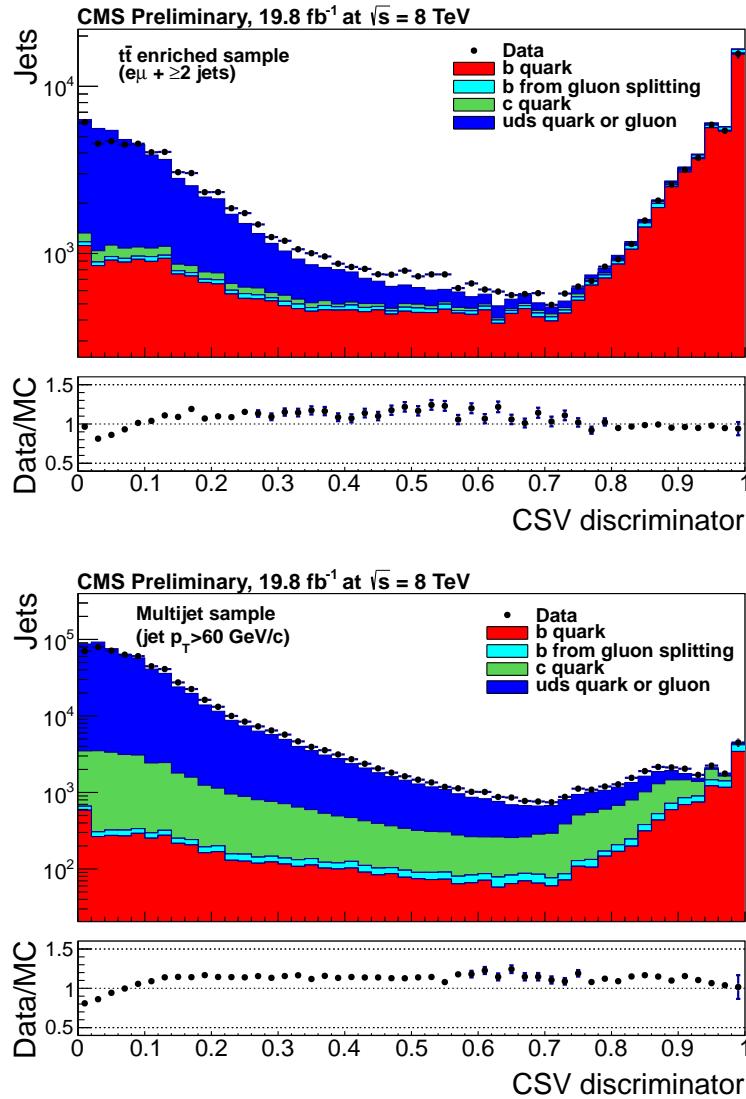
<sup>857</sup> Using the CSV tagger, a likelihood-based discriminator distinguishes between jets  
<sup>858</sup> from b-quarks, and those from charm or light quarks and gluons, which is shown in Figure  
<sup>859</sup> 3.6. The minimum thresholds on the discriminator for each working point correspond to  
<sup>860</sup> the misidentification probability for light-parton jets of 10%, 1%, and 0.1%, respectively,  
<sup>861</sup> in jets with an average  $p_T$  of about 80 GeV.

<sup>862</sup> The b-tagging performance is evaluated to measure the b-jet tagging efficiency  $\epsilon_b$ ,  
<sup>863</sup> and the misidentification probability of charm  $\epsilon_c$  and light-parton jets  $\epsilon_s$ . The tagging  
<sup>864</sup> efficiencies for each of these three jet flavours are compared between data and MC  
<sup>865</sup> simulation, from which a series of  $p_T$  and  $|\eta|$  binned jet corrections are determined,

$$SF_{b,c,s} = \frac{\epsilon_{b,c,s}^{data}}{\epsilon_{b,c,s}^{MC}}. \quad (3.2)$$

<sup>866</sup> These are collectively named ‘Btag Scale Factors’ and allow MC simulation to accu-  
<sup>867</sup> rately reflect the running conditions and performance of the tagging algorithm in data.  
<sup>868</sup> Understanding of the b-tagging efficiency is essential in order to minimise systematic  
<sup>869</sup> uncertainties in physics analyses that employ b-tagging.

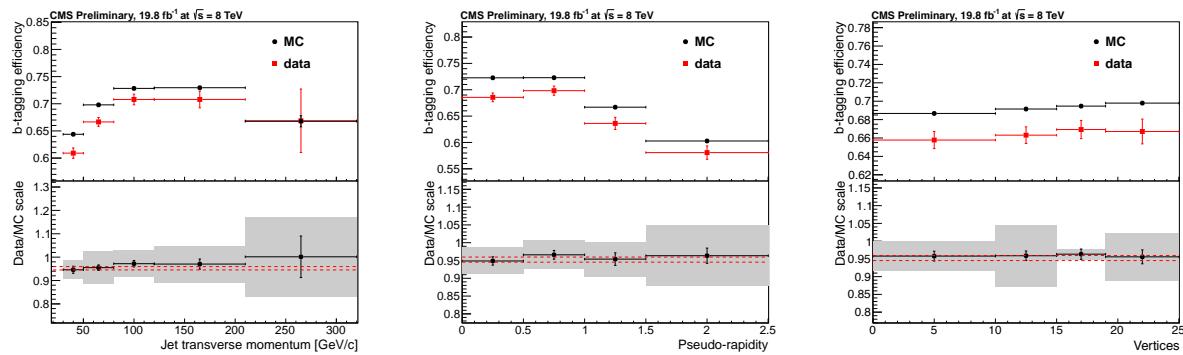
<sup>870</sup>



**Figure 3.6.:** CSV algorithm discriminator values in enriched  $t\bar{t}$  (top) and inclusive multi-jet samples (bottom) for b,c and light flavoured jets [64]. Working points are determined from the misidentification probability for light-parton jets to be tagged as a b-jet and are given as 0.244, 0.679 and 0.898 for L,M and T working points respectively.

871        The b-tagging efficiency is measured in data using several methods applied to multi  
 872        jet events, primarily based on a sample of jets enriched in heavy flavour content. One  
 873        method requires the collection of events with a soft muon within a cone  $\Delta R < 0.4$  around  
 874        the jet axis. Because the semileptonic branching fraction of b hadrons is significantly  
 875        larger than that for other hadrons, these jets are more likely to arise from b quarks than  
 876        from another flavour, with the resultant momentum component of the muon transverse  
 877        to the jet axis larger for muons from b-hadron decays than from light or charm jets.

878 Additionally the performance of the tagger can also be benchmarked in  $t\bar{t}$  events where  
 879 in the SM, the top quark is expected to decay to a W boson and a b quark about 99.8%  
 880 of the time [1]. Further selection criteria is applied to these events to further enrich the  
 881 b quark content of these events. The methods to identify b-jets in data are discussed  
 882 in great detail at [65]. The jet flavours are determined in simulation using truth level  
 883 information and are compared to data to determine the correction scale factors ( $SF_b$ ),  
 884 which are displayed for the CSVM tagger in Figure 3.7.

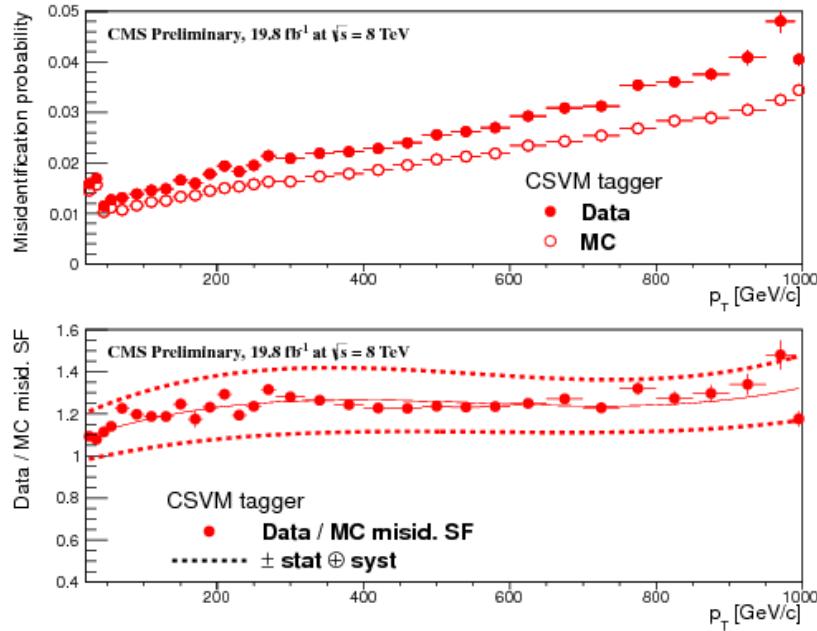


**Figure 3.7.:** Measured in  $t\bar{t} \rightarrow$  di-lepton events using the CSVM tagger: (upper panels) b-tagging efficiencies and (lower panels) data/MC scale factor  $SF_b$  as a function of (left) jet  $p_T$ , (middle) jet  $|\eta|$  and (right) number of primary vertices. In the lower panels, the grey filled areas represent the total statistical and systematic uncertainties, whereas the dotted lines are the average  $SF_b$  values within statistical uncertainties.

885 The measurement of the misidentification probability for light-parton jets relies on  
 886 the inversion of tagging algorithms, selecting non-b jets using the same variables and  
 887 techniques used in benchmarking the b-tagging efficiency. The scale factors ( $SF_s$ ) to be  
 888 applied to MC are shown in Figure 3.8 for the CSVM tagger.

### 889 3.4. Triggering System

890 With bunch crossings separated by just 25 ns, the rate at which data from all collisions  
 891 would have to be written out and processed would be unfeasible. A two-tiered triggering  
 892 system is applied at CMS in order to cope with the high collision rate of protons. The  
 893 CMS trigger is designed to use limited information from each event to determine whether  
 894 to record the event, reducing the rate of data taking to manageable levels whilst ensuring  
 895 a high efficiency of interesting physics object events are selected.



**Figure 3.8.:** For the **CSVM** tagging criterion: (top) misidentification probability in data (filled circles) and simulation (open circles); (bottom) scale factor for the misidentification probability. The last  $p_T$  bin in each plot includes all jets with  $p_T > 1000$  GeV. The solid curve is the result of a polynomial fit to the data points. The dashed curves represent the overall statistical and systematic uncertainties on the measurements.

896        The **L1** is a pipelined, dead-timeless system based on custom-built electronics [66],  
 897        and is a combination of several sub systems which is shown pictorially in Figure 3.9. The  
 898        L1 system is covered in more detail within the following section along with a description  
 899        of the service work undertaken by the author to benchmark the performance of the L1  
 900        calorimeter trigger during the 2012 8 TeV run period.

901        The Higher Level Trigger (**HLT**) is a large farm of commercial computers [67]. The  
 902        **HLT** processes events with software reconstruction algorithms that are more detailed,  
 903        giving performance more similar to the reconstruction used offline. The **HLT** reduces  
 904        the event rate written to disk by a factor of  $\sim 500$  ( $\sim 200$ Hz). The recorded events are  
 905        transferred from **CMS** to the **CERN** computing centre, where event reconstruction is  
 906        performed, and then distributed to **CMS** computing sites around the globe for storage  
 907        and analysis.

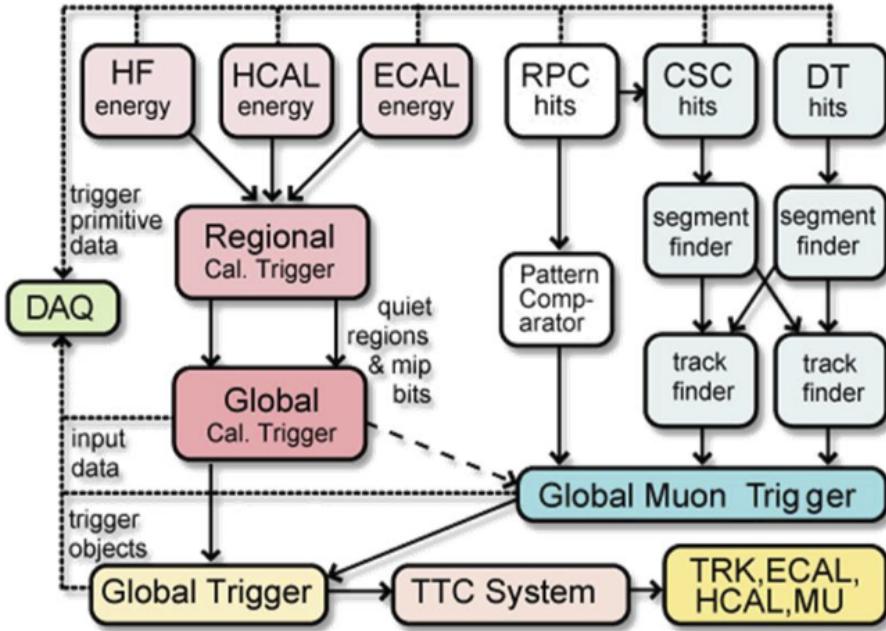


Figure 3.9.: The CMS L1 Trigger system.

### 3.4.1. The Level-1 Trigger

The L1 trigger reduces the rate of events collected from 40 MHz to  $\sim 100$  kHz using information from the calorimeters and muon chambers, but not the tracker. A tree system of triggers is used to decide whether to pass on an event to the HLT for further reconstruction. Firstly the calorimeter and muon event information is kept separate, with local reconstruction of objects ( $\mu, e, \gamma, \text{jets}$ ) performed by the Regional Calorimeter Trigger (RCT) and Regional Muon Trigger (RMT) respectively. The RCT generates up to 72 isolated and non-isolated electromagnetic objects. These are sorted by rank, which is equivalent to transverse energy  $E_T$ , with the four highest ranked electromagnetic objects being passed via the Global Calorimeter Trigger (GCT) and Global MuonTrigger (GMT) to the Global Trigger (GT).

In the L1 GCT, coarse measurements of the energy deposited in the electromagnetic and hadronic calorimeters are combined and by using sophisticated algorithms the following physics objects are formed:

- isolated and non-isolated electromagnetic objects ( $e$  and  $\gamma$ );
- hadronic jets in the central and forward sections of the hadronic calorimeters;

- hadronically decaying tau leptons;
- total transverse energy ( $E_T$ ), the scalar sum of the energy measured at L1, and missing transverse energy ( $\cancel{E}_T$ ), defined as the vector sum of the energy of L1 objects;
- total transverse jet energy ( $H_T$ ), the scalar sum of the energy of all L1 jet objects, and missing transverse jet energy ( $\cancel{H}_T$ ), defined as the vector sum of the energy of L1 jets, are calculated from uncorrected L1 jets.

In addition quantities suitable for triggering minimum bias events, forward physics and beam background events are calculated. Additionally relevant muon isolation information is also passed on to the **GMT** for decisions involving the muon triggers where it is combined with information from across the three muon sub-systems. The resultant final accept/reject decision at **L1** is then performed by the **GT** based on the objects received from the **GCT** and **GMT** ( $e/\gamma$ ,  $\mu$ , jets,  $E_T$ ,  $\cancel{E}_T$ ,  $H_T$ ).

The L1 trigger is therefore of upmost importance to the functioning of the detector. Without a high-performing trigger and a good understanding of its performance, there would be no data to analyse. Observations of how the L1 trigger performance is affected by changing **LHC** running conditions over the 2012 run period and also the introduction of a jet seed threshold to the L1 jet trigger algorithm is presented in the following Sections (3.4.2 - 3.4.6).

### 3.4.2. L1 Trigger Jet Algorithm

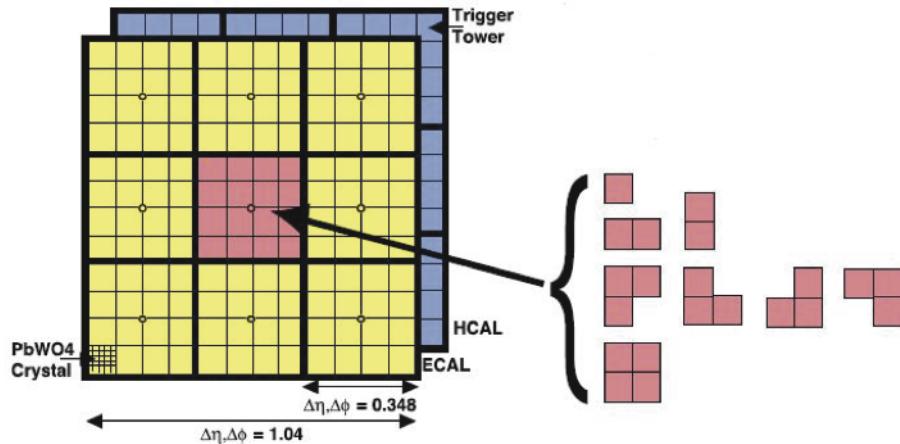
The L1 jet trigger uses the transverse energy sums computed in the calorimeter (both hadronic and electromagnetic) trigger regions. Each region consists of  $4 \times 4$  trigger tower windows, spanning a region of  $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$  in pseudorapidity-azimuth. The jet trigger uses a  $3 \times 3$  calorimeter region (112 trigger towers) sliding window technique which spans the full  $(\eta, \phi)$  coverage of the **CMS** calorimeter as shown in Figure 3.10.

In forming a L1 jet is it required that the central region to be higher than the eight neighbouring regions  $E_{T\text{central}} > E_{T\text{surround}}$ . Additionally a minimum threshold of 5 GeV on  $E_{T\text{central}}$  was introduced during the 2012 run period to suppress noise from pile-up, the effects of which are shown in Section (3.4.4).

The L1 jets are characterised by the  $E_T$ , summed over the  $3 \times 3$  calorimeter regions, which corresponds to  $12 \times 12$  trigger towers in barrel and endcap or  $3 \times 3$  larger **HF**

955 towers in the **HF**. The  $\phi$  size of the jet window is the same everywhere, whilst the  $\eta$   
956 binning gets somewhat larger at high  $\eta$  due to calorimeter and trigger tower segmentation.  
957 The jets are labelled by  $(\eta, \phi)$  indexes of the central calorimeter region.

958 Jets with  $|\eta| > 3.0$  are classified as forward jets, whereas those with  $|\eta| < 3.0$  are  
959 classified as central. The four highest energy central, forward and  $\tau$  jets in the calorimeter  
960 are passed through Look Up Table (**LUT**)'s, which apply a programmable  $\eta$ -dependent  
961 jet energy scale correction. These are then used to make L1 trigger decisions.



**Figure 3.10.:** Illustration of the Level-1 jet finding algorithm.

962 The performance of the L1 jets is evaluated with respect to offline jets, which are  
963 taken from the standard Calo jet and the PF jet reconstruction algorithms of **CMS**.  
964 Jets are corrected for pile-up and detector effects as described in [3.3.1](#). A moderate  
965 level of noise rejection is applied to the offline jets by selecting jets passing the “loose”  
966 identification criteria for both Calo and PF. These criteria are summarised in Appendix  
967 ([A.1](#)).

### 968 3.4.3. Measuring L1 Jet Trigger Efficiencies

969 The L1 jet efficiency is defined as the fraction of leading offline jets which were matched  
970 with a L1 tau or central jet above a certain trigger threshold, divided by all the leading  
971 offline jets in the event. This quantity is then plotted as a function of the offline jet  $E_T$ ,  
972  $\eta$  and  $\phi$ .

973 The efficiency is determined by matching the L1 and reconstructed offline jets spatially  
974 in  $\eta - \phi$  space. This is done by calculating the minimum separation in  $\Delta R$  between the

highest offline reconstructed jet in  $E_T$  ( $E_T > 10$  GeV,  $|\eta| < 3$ ) and any L1 jet. A jet will be matched if this value is found to be  $< 0.5$ . Should more than one jet satisfy this, the jet closest in  $\Delta R$  is taken as the matched jet. The matching efficiency is close to 100%, above ? 30(45) GeV for run 2012B(C) data (see Appendix (??)).

Each efficiency curve is fitted with a function which is the cumulative distribution function of an Exponentially Modified Gaussian (EMG) distribution:

$$f(x; \mu, \sigma, \lambda) = \frac{\lambda}{2} \cdot e^{\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2x)} \cdot \text{erfc}\left(\frac{\mu + \lambda\sigma^2 - x}{\sqrt{2}\sigma}\right) \quad (3.3)$$

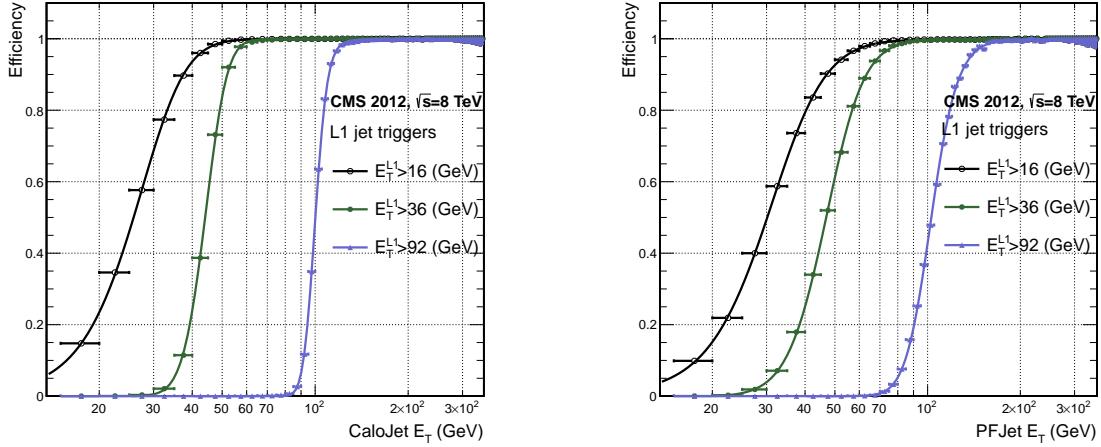
where erfc is the complementary error function defined as:

$$\text{erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt.$$

In this functional form, the parameter  $\mu$  determines the point of 50% of the plateau efficiency and the  $\sigma$  gives the resolution. This parametrisation is used to benchmark the efficiency at the plateau, the turn-on points and resolution for each L1 Jet trigger. The choice of function is purely empirical. Previous studies used the error function alone, which described the data well at high threshold values but could not describe the efficiencies well at lower thresholds [68].

The efficiency turn-on curves for various L1 jet thresholds are evaluated as a function of the offline reconstructed jet  $E_T$  for central jets with  $|\eta| < 3$ . These are measured using single isolated  $\mu$  triggers which have high statistics, and are orthogonal and therefore unbiased to the hadronic triggers under study. The efficiency is calculated with respect to offline Calo and PF Jets in Figure 3.11. Table 3.1 shows the values of these parameters, calculated for three example L1 single jet triggers taken from 2012 8 TeV data.

The results from the L1 single jet triggers shows good performance for both Calo and PF jets. A better resolution for Calo jets with respect to L1 jets quantities is observed. This effect is due to Calo jet reconstruction using the same detector systems as in L1 jets, whereas with PF jet construction using tracker and muon information, a more smeared resolution when compared to L1 is expected.



**Figure 3.11.:** L1 jet efficiency turn-on curves as a function of the offline CaloJet  $E_T$  (left) and PFJet  $E_T$  (right), measured in 2012 Run Period C data and collected with an isolated single  $\mu$  data sample.

Trigger	Calo		PF	
	$\mu$	$\sigma$	$\mu$	$\sigma$
L1_SingleJet16	$21.09 \pm 0.03$	$7.01 \pm 0.02$	$22.17 \pm 0.04$	$7.83 \pm 0.03$
L1_SingleJet36	$41.15 \pm 0.05$	$5.11 \pm 0.02$	$39.16 \pm 0.06$	$8.04 \pm 0.03$
L1_SingleJet92	$95.36 \pm 0.13$	$5.62 \pm 0.03$	$90.85 \pm 0.19$	$11.30 \pm 0.10$

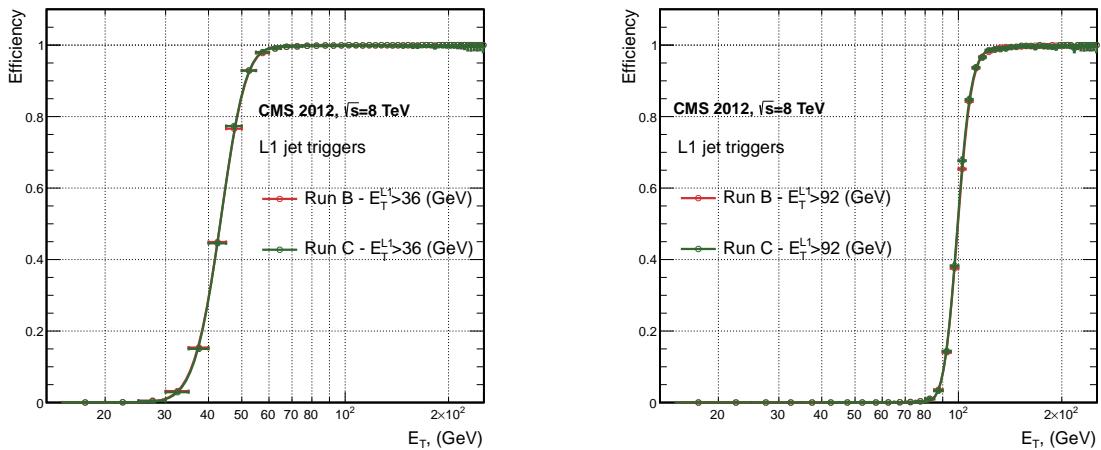
**Table 3.1.:** Results of a cumulative EMG function fit to the turn-on curves for L1 single jet triggers in run 2012 Run Period C, measured in an isolated  $\mu$  data sample. The turn-on point,  $\mu$ , and resolution,  $\sigma$ , of the L1 jet triggers are measured with respect to offline Calo Jets (left) and PF Jets (right).

#### 3.4.4. Effects of the L1 Jet Seed

Between run period B and C of the 2012 data taking period, a jet seed threshold was introduced into the L1 trigger jet algorithm. There was previously no direct requirement made on the energy deposited in the central region. The introduction of a jet seed threshold required that the central region have  $E_T \geq 5\text{GeV}$ , and was introduced to counteract the effects of high pile up running conditions which create a large number of soft non-collimated jets, that are then added to the jets from the primary interaction or other soft jets from other secondary interactions [69]. This in turn causes a large increase in trigger rate due to the increase in the likelihood that the event causes the L1 trigger to fire. This was implemented to maintain trigger thresholds by cutting the rate of events recorded without significant reduction in the efficiency of physics events of interest.

1010 The effect of the introduction of this jet seed threshold between these two run periods  
 1011 is benchmarked through a comparison of the efficiency of the L1 jet triggers with respect  
 1012 to offline Calo jets shown in Figure 3.12, and the L1  $H_T$  trigger efficiency in Figure 3.14  
 1013 which is compared to offline  $H_T$  constructed from Calo jets with  $E_T \geq 40\text{GeV}$ .

1014 To negate any effects from different pile-up conditions in the run periods, the efficiencies  
 1015 are measured in events which contain between 15 and 20 primary vertices as defined in  
 1016 Appendix (A.2).



**Figure 3.12.:** L1 jet efficiency turn-on curves as a function of the offline CaloJet  $E_T$ , measured for the L1 SingleJet 36 and 92 trigger in 2012 run period B and C collected with an isolated single  $\mu'$  sample.

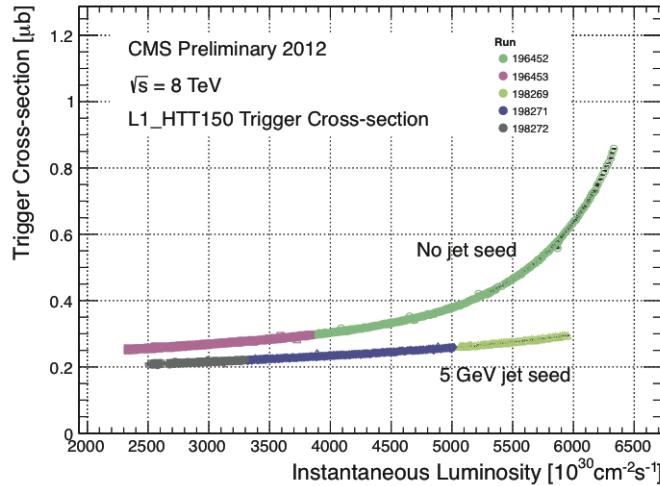
1017 It can be seen that the performance of the  $E_T > 36, 92$  single jet are almost identical,  
 1018 with the jet seed having no measurable effect on these triggers as shown in Table 3.2 .

Trigger	2012B		2012C	
	$\mu$	$\sigma$	$\mu$	$\sigma$
L1_SingleJet36	$40.29 \pm 0.04$	$5.34 \pm 0.02$	$40.29 \pm 0.11$	$5.21 \pm 0.05$
L1_SingleJet92	$94.99 \pm 0.09$	$5.93 \pm 0.06$	$94.82 \pm 0.29$	$5.74 \pm 0.18$

**Table 3.2.:** Results of a cumulative EMG function fit to the turn-on curves for L1 single jet triggers in the 2012 run period B and C, preselected on an isolated muon trigger. The turn-on point  $\mu$  and resolution  $\sigma$  of the L1 jet triggers are measured with respect to offline Calo Jets in run B (left) and run C (right).

1019 For the  $H_T$  triggers, a large increase in rate during high pile-up conditions is expected.  
 1020 This is due to the low energy threshold required for a jet to be added to the L1  $H_T$  sum,

1021 which is compiled from all uncorrected L1 jets formed in the RCT. The introduction  
 1022 of the jet seed threshold removes the creation of many of these soft low  $E_T$  jets, thus  
 1023 lowering the  $H_T$  calculation at L1. The effect on the trigger cross section for L1  $H_T$  150  
 1024 trigger can be seen in Figure 3.13.

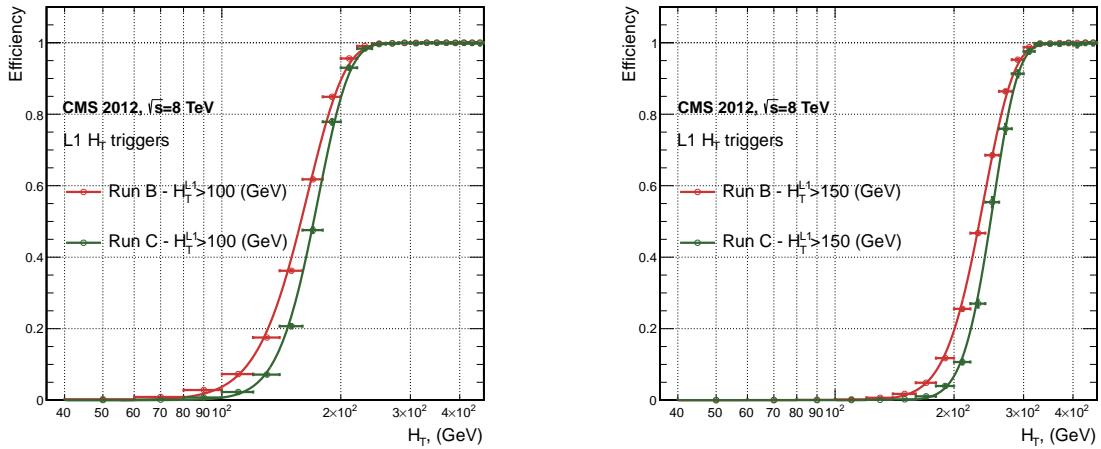


**Figure 3.13.:** Trigger cross section for the L1HTT150 trigger path. Showing that a 5 GeV jet seed threshold dramatically reduces the dependance of cross section on the instantaneous luminosity for L1  $H_T$  triggers [70].

1025 Different behaviours for the trigger turn ons between these run periods are therefore  
 1026 expected. The turn on point is observed to shift to higher  $H_T$  values after the introduction  
 1027 of the jet seed threshold, whilst having a sharper resolution due to less pile-up jets being  
 1028 included the  $H_T$  sum, the results are shown in Table 3.3.

Trigger	2012B		2012C	
	$\mu$	$\sigma$	$\mu$	$\sigma$
L1 HT-100	$157.5 \pm 0.08$	$32.9 \pm 0.08$	$169.8 \pm 0.08$	$28.7 \pm 0.03$
L1 H1-150	$230.9 \pm 0.02$	$37.3 \pm 0.01$	$246.4 \pm 0.16$	$31.8 \pm 0.05$

**Table 3.3.:** Results of a cumulative EMG function fit to the turn-on curves for  $H_T$  in run 2012 B and C, preselected on an isolated single  $\mu$  trigger. The turn-on point  $\mu$ , resolution  $\sigma$  of the L1  $H_T$  triggers are measured with respect to offline  $H_T$  formed from CaloJets with a  $E_T \geq 40$  in run period B (left) and C (right).



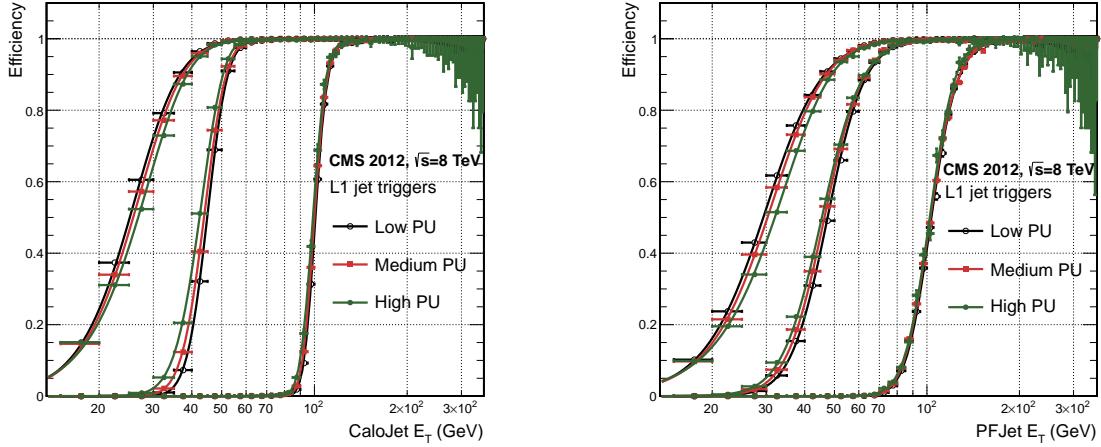
**Figure 3.14.:** L1  $H_T$  efficiency turn-on curves as a function of the offline CaloJet  $H_T$ , measured for the L1  $H_T$  100 and 150 trigger during the run 2012 B and C collected using an isolated single  $\mu$  triggered sample.

### 3.4.5. Robustness of L1 Jet Performance against Pile-up

The performance of the L1 single jet triggers is evaluated in different pile-up conditions to benchmark any dependence on pile-up. Three different pile-up bins of 0-10, 10-20 and  $>20$  vertices are defined, reflecting the low, medium and high pile-up running conditions at CMS in 2012. This is benchmarked relative to Calo and PF jets for the run 2012 C period where the jet seed threshold is applied, with L1 single jet thresholds of 16, 36 and 92 GeV, shown in Figure 3.15. The results of fits to these efficiency turn-on curves are given in Table 3.4 and Table 3.5 for Calo and PF jets respectively.

Vertices	0-10		11-20		> 20	
	$\mu$	$\sigma$	$\mu$	$\sigma$	$\mu$	$\sigma$
L1_SingleJet16	$19.9 \pm 0.1$	$6.1 \pm 0.3$	$20.8 \pm 0.1$	$6.5 \pm 0.1$	$22.3 \pm 0.2$	$7.5 \pm 0.1$
L1_SingleJet36	$41.8 \pm 0.1$	$4.6 \pm 0.1$	$40.9 \pm 0.1$	$5.1 \pm 0.1$	$40.6 \pm 0.6$	$5.9 \pm 0.2$
L1_SingleJet92	$95.9 \pm 0.2$	$5.4 \pm 0.1$	$95.2 \pm 0.2$	$5.6 \pm 0.1$	$94.5 \pm 0.6$	$6.2 \pm 0.3$

**Table 3.4.:** Results of a cumulative EMG function fit to the efficiency turn-on curves for L1 single jet triggers in the 2012 run period C, measured from isolated  $\mu$  triggered data. The turn-on point,  $\mu$ , and resolution,  $\sigma$ , of the L1 jet triggers are measured with respect to offline Calo jets in low (left), medium (middle) and high (right) pile-up conditions.



**Figure 3.15.:** L1 jet efficiency turn-on curves as a function of the leading offline  $E_T$ Calo (left) and PF (right) jet, for low, medium and high pile-up conditions.

Vertices	0-10		11-20		> 20	
	$\mu$	$\sigma$	$\mu$	$\sigma$	$\mu$	$\sigma$
L1_SingleJet16	$21.1 \pm 0.1$	$7.16 \pm 0.05$	$22.34 \pm 0.1$	$7.9 \pm 0.1$	$24.6 \pm 0.2$	$9.5 \pm 0.1$
L1_SingleJet36	$39.6 \pm 0.1$	$7.4 \pm 0.1$	$38.4 \pm 0.1$	$7.4 \pm 0.1$	$37.1 \pm 0.2$	$7.5 \pm 0.1$
L1_SingleJet92	$91.6 \pm 0.3$	$11.3 \pm 0.2$	$90.4 \pm 0.3$	$11.2 \pm 0.1$	$92.0 \pm 0.9$	$12.1 \pm 0.4$

**Table 3.5.:** Results of a cumulative EMG function fit to the efficiency turn-on curves for Level-1 single jet triggers in the 2012 run period C, measured from isolated  $\mu$  triggered data. The turn-on point,  $\mu$ , and resolution,  $\sigma$ , of the L1 jet triggers are measured with respect to offline PF jets in low (left), medium (middle) and high (right) pile-up conditions.

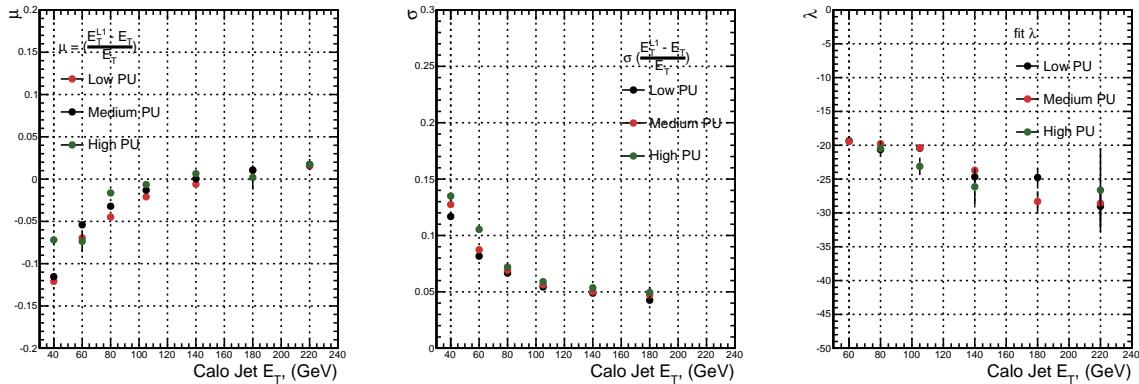
1037 No significant drop in efficiency is observed in the presence of a high number of  
 1038 primary vertices. The increase in hadronic activity in higher pile-up conditions, combined  
 1039 with the absence of pile-up subtraction for L1 jets, results in the expected observation of  
 1040 a decrease in the  $\mu$  value of the efficiency turn-ons as a function of pile-up, while the  
 1041 resolution,  $\sigma$  of the turn-ons are found to gradually worsen as expected with increasing  
 1042 pile-up.

1043 These features are further emphasised when shown as a function of

$$\frac{(L1 E_T - Offline E_T)}{Offline E_T} \quad (3.4)$$

in bins of matched leading offline jet  $E_T$ , of which the individual fits can be found in Appendix (B.2). Each of these distributions are fitted with an EMG function as defined in Equation (3.3).

The  $\mu$ ,  $\sigma$  and  $\lambda$  values extracted for the low, medium and high pile-up conditions are shown for Calo and PF jets in Figure 3.16 and Figure 3.17 respectively. The central value of  $\frac{(L1 E_T - \text{Offline } E_T)}{\text{Offline } E_T}$  is observed to increases as a function of jet  $E_T$ , whilst the resolution is also observed to improve at higher offline jet  $E_T$ .

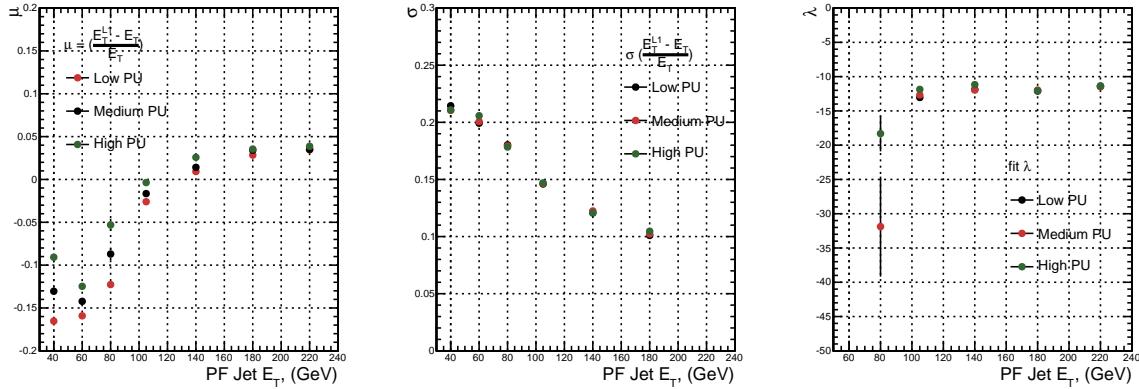


**Figure 3.16.:** Fit values from an EMG function fitted to the resolution plots of leading Calo jet  $E_T$  measured as a function of  $\frac{(L1 E_T - \text{Offline } E_T)}{\text{Offline } E_T}$  for low, medium and high pile-up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (middle) of the Gaussian as well as the decay term  $\lambda$  (right) of the exponential.

The resolution of other L1 energy sum quantities,  $H_T$ ,  $\not{E}_T$  and  $\sum E_T$  parameterised as in Equation (3.4), can be found in Appendix (B.3). The same behaviour observed for the single jet triggers is also found for these quantities, where in the presence of higher pile-up the  $\mu$  values are shifted to higher values, with a worsening resolution,  $\sigma$  again due to the increase in soft pile-up jets and the absence of pile-up subtraction at L1.

### 3.4.6. Summary

The performance of the CMS Level-1 Trigger has been studied and evaluated for jets and energy sum quantities using data collected during the 2012 LHC 8TeV run. These studies include the effect of introduction of a 5 GeV jet seed threshold into the jet algorithm configuration, the purpose of which is to mitigate the effects of pile-up on the rate of L1 triggers whilst not adversely affecting the efficiency of these triggers. No significant



**Figure 3.17.:** Fit values from an **EMG** function fitted to the resolution plots of leading PF jet  $E_T$  measured as a function of  $\frac{(L1\ E_T - \text{Offline}\ E_T)}{\text{Offline}\ E_T}$  for low and medium pile-up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (middle) of the Gaussian as well as the decay term  $\lambda$  (right) of the exponential.

1062 change in performance is observed with this change and good performance is observed  
 1063 for a range of L1 quantities.

# Chapter 4.

## <sup>1064</sup> SUSY searches in Hadronic Final

### <sup>1065</sup> States

<sup>1066</sup> In this chapter a model independent search for **SUSY** in hadronic final states with  $\cancel{E}_T$   
<sup>1067</sup> using the  $\alpha_T$  variable and b-quark multiplicity is introduced and described in detail. The  
<sup>1068</sup> results presented are based on a data sample of pp collisions collected in 2012 at  $\sqrt{s} = 8$   
<sup>1069</sup> TeV, corresponding to an integrate luminosity of  $11.7 \pm 0.5 \text{ fb}^{-1}$ .

<sup>1070</sup> The kinematic variable  $\alpha_T$  is motivated as a variable to provide strong rejections  
<sup>1071</sup> of QCD backgrounds, whilst maintaining sensitivity to possible a **SUSY** signal within  
<sup>1072</sup> Section (4.1). The search and trigger strategy in addition to the event reconstruction  
<sup>1073</sup> and selection are outlined within Sections (4.2-4.2.2).

<sup>1074</sup> The method in which the **SM** background is estimated using an analytical technique  
<sup>1075</sup> to improve statistical precision at higher b-tag multiplicities is detailed within Section  
<sup>1076</sup> (4.5), with a discussion on the impact of b-tagging and mis-tagging scale factors between  
<sup>1077</sup> data and MC on any background predictions. Finally a description of the formulation of  
<sup>1078</sup> appropriate systematic uncertainties applied to the background predictions to account for  
<sup>1079</sup> theoretical uncertainties and limitations in the simulation modelling of event kinematics  
<sup>1080</sup> and instrumental effects is covered in Section (4.6).

<sup>1081</sup> In addition to the  $\alpha_T$  search, a complimentary technique is discussed as a means to  
<sup>1082</sup> predict the distribution of 3 and 4 reconstructed b-quark jets in an event in Section  
<sup>1083</sup> (4.7). The recent discovery of the Higgs boson has made third-generation “Natural **SUSY**”  
<sup>1084</sup> models attractive, given that light top and bottom squarks are a candidate to stabilise  
<sup>1085</sup> divergent loop corrections to the Higgs boson mass.

1086 Using the  $\alpha_T$  search as a base, a simple templated fit is employed to estimate the  
 1087 **SM** background in higher b-tag multiplicities (3-4) from a region of a low number  
 1088 of reconstructed b-jets (0-2). The predictions using this technique are first tested in  
 1089 simulation before being compared to the **SM** background predictions obtained from the  
 1090  $\alpha_T$  search.

1091 The experimental reach of the analysis discussed within this thesis is interpreted in  
 1092 two classes of **SMS** models, the topologies of which are detailed in Section (2.4.1). The  
 1093 **SMS** models considered in this analysis are summaries in Table 4.1. For each model, the  
 1094 **LSP** is assumed to be the lightest neutralino.

1095 Within Table 4.1 is also defined reference points, parameterised in terms of parent  
 1096 gluino/squark and **LSP** sparticle masses,  $m_{parent}$  and  $m_{LSP}$ , respectively, which are used  
 1097 within the following two chapters to demonstrate potential yields within the signal region  
 1098 of the search. The masses are chosen to reflect parameter space which is within the  
 1099 expect sensitivity reach of the search.

Model	Production/decay mode	Reference model	
		$m_{parent}$	$m_{LSP}$
G1 (T1)	$pp \rightarrow \tilde{g}\tilde{g}^* \rightarrow q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$	700	300
G2 (T1bb)	$pp \rightarrow \tilde{g}\tilde{g}^* \rightarrow b\bar{b}\tilde{\chi}_1^0 b\bar{b}\tilde{\chi}_1^0$	900	500
G3 (T1tt)	$pp \rightarrow \tilde{g}\tilde{g}^* \rightarrow t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$	850	250
D1 (T2)	$pp \rightarrow \tilde{q}\tilde{q}^* \rightarrow q\tilde{\chi}_1^0 \bar{q}\tilde{\chi}_1^0$	600	250
D2 (T2bb)	$pp \rightarrow \tilde{b}\tilde{b}^* \rightarrow b\tilde{\chi}_1^0 \bar{b}\tilde{\chi}_1^0$	500	150
D3 (T2tt)	$pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 \bar{t}\tilde{\chi}_1^0$	400	0

**Table 4.1.:** A summary of the **SMS** models interpreted in this analysis, involving both direct (D) and gluino-induced (G) production of squarks and their decays. Reference models are also defined in terms of parent and **LSP** sparticle mass

## 1100 4.1. An introduction to the $\alpha_T$ search

1101 The experimental signature of **SUSY** signal in the hadronic channel would manifest as a  
 1102 final state containing energetic jets and  $\cancel{E}_T$ . The search focuses on topologies where new  
 1103 heavy supersymmetric, R-parity conserving particles are pair-produced in pp collisions.  
 1104 These particles decaying to a **LSP** escape the detector undetected, leading to significant  
 1105 missing energy and missing hadronic transverse energy,

$$\mathcal{H}_T = \left| \sum_{i=1}^n p_T^{jet_i} \right|, \quad (4.1)$$

1106 defined as the vector sum of the transverse energies of jets selected in an event.  
1107 Energetic jets produced in the decay of these supersymmetric particles also can produce  
1108 significant visible transverse energy,

$$H_T = \sum_{i=1}^n E_T^{jet_i}, \quad (4.2)$$

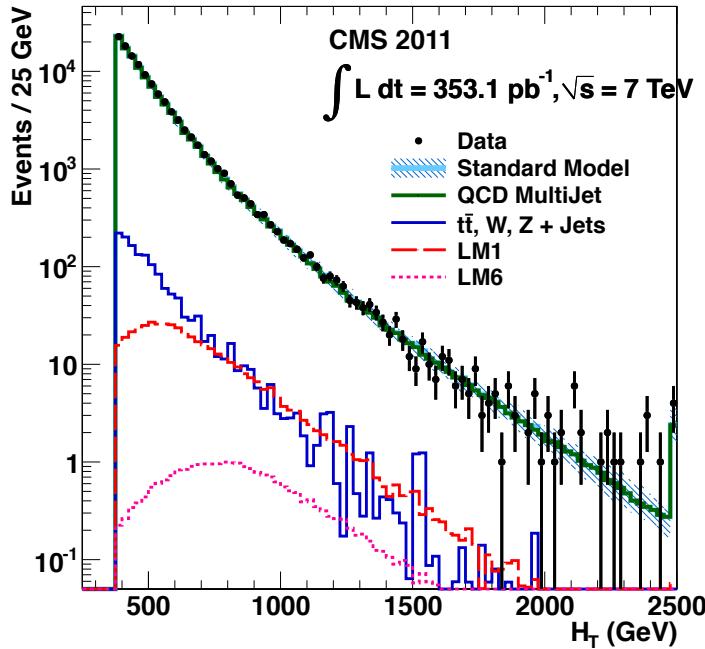
1109 defined as the scalar sum of the transverse energies of jets selected in an event.

1110 A search within this channel is greatly complicated in a hadron collider environment,  
1111 where the overwhelming background comes from inherently balanced multi-jet (“QCD”)  
1112 events which are produced with an extremely large cross section as demonstrated within  
1113 Figure 4.1.  $\cancel{E}_T$  can appear in such events with a substantial mis-measurement of jet  
1114 energy or missed objects due to detector miscalibration or noise effects.

1115 Additional **SM** background from **EWK** processes with genuine  $\cancel{E}_T$  from escaping  
1116 neutrinos comprise the irreducible background within this search and come mainly from:

- 1117 •  $Z \rightarrow \nu\bar{\nu}$  + jets,
- 1118 •  $W \rightarrow l\nu$  + jets in which a lepton falls outside of detector acceptance, or the lepton  
1119 decays hadronically  $\tau \rightarrow \text{had}$ ,
- 1120 •  $t\bar{t}$  with at least one leptonic W decay,
- 1121 • small background contributions from DY, single top and Diboson (WW,ZZ,WZ)  
1122 processes.

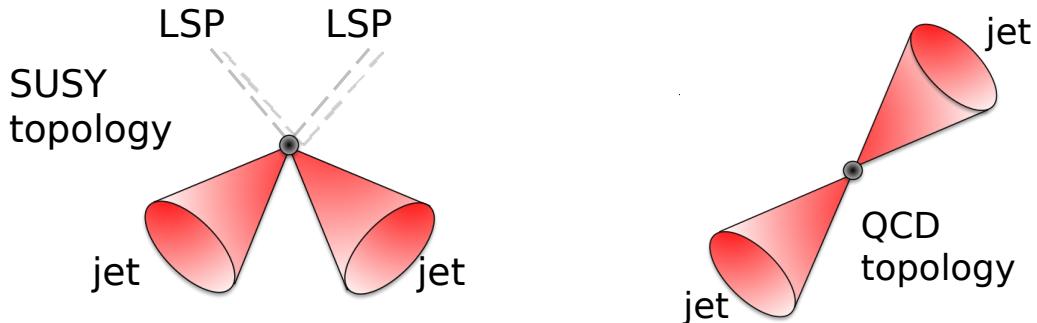
1123 The search is designed to have a strong separation between events with genuine and  
1124 “fake”  $\cancel{E}_T$  which is achieved primarily through the dimensionless kinematic variable,  $\alpha_T$   
1125 [71][72].



**Figure 4.1.:** Reconstructed offline  $H_T$  for  $11.7\text{fb}^{-1}$  of data after a basic pre-selection. Sample is collected from prescaled  $H_T$  triggers. Overlaid are expectations from MC simulation of EWK processes as well as a reference signal model (labelled D2 from Table 4.1).

### <sub>1126</sub> 4.1.1. The $\alpha_T$ variable

<sub>1127</sub> For a perfectly measured di-jet QCD event, conservation laws dictate that they must be  
<sub>1128</sub> produced back-to-back and of equal magnitude. However in di-jet events with real  $\cancel{E}_T$ , both of these jets are produced independently of one another, depicted in Figure 4.2.



**Figure 4.2.:** The event topologies of background QCD diet events (right) and a generic SUSY signature with genuine  $\cancel{E}_T$  (left).

1130 Exploiting this feature leads to the formulation of  $\alpha_T$  in di-jet systems defined as,

$$\alpha_T = \frac{E_T^{j2}}{M_T}, \quad (4.3)$$

1131 where  $E_T^{j2}$  is the transverse energy of the least energetic of the two jets and  $M_T$   
1132 defined as:

$$M_T = \sqrt{\left(\sum_{i=1}^2 E_T^{ji}\right)^2 - \left(\sum_{i=1}^2 p_x^{ji}\right)^2 - \left(\sum_{i=1}^2 p_y^{ji}\right)^2} \equiv \sqrt{H_T^2 - \cancel{H}_T^2}. \quad (4.4)$$

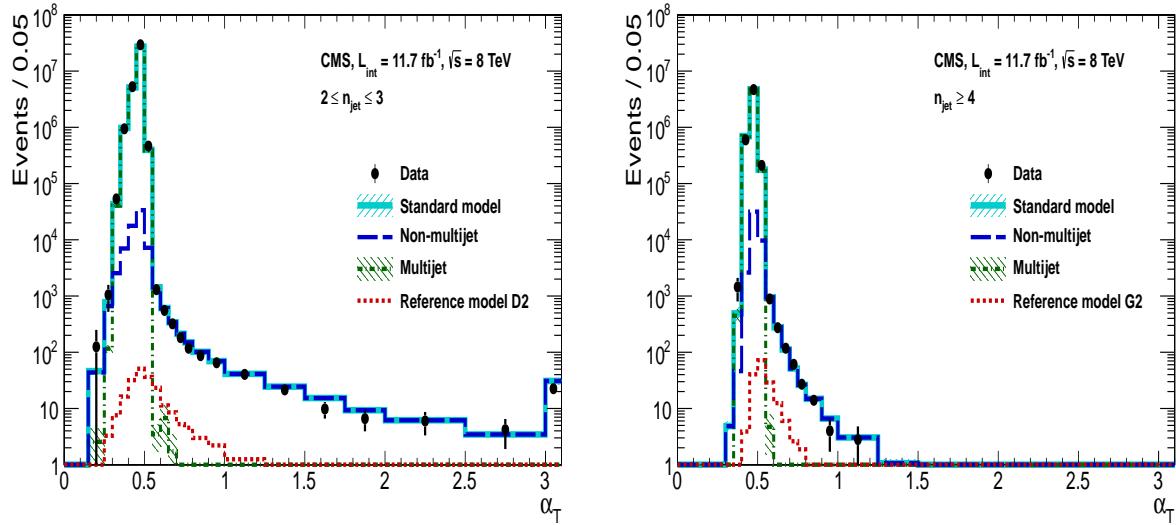
1133 A perfectly balanced di-jet event i.e.  $E_T^{j1} = E_T^{j2}$  would give an  $\alpha_T = 0.5$ , where as  
1134 events with jets which are not back-to-back, for example in events in which a W or Z  
1135 recoils off a system of jets,  $\alpha_T$  can achieve values in excess of 0.5.

1136  $\alpha_T$  can be extended to apply to any arbitrary number of jets, undertaken by modelling  
1137 a system of  $n$  jets as a di-jet system, through the formation of two pseudo-jets [73].  
1138 The two pseudo-jets are built by merging the jets present in the event such that the 2  
1139 pseudo-jets are chosen to be as balanced as possible, i.e the  $\Delta H_T \equiv |E_T^{pj1} - E_T^{pj2}|$  is  
1140 minimised between the two pseudo jets. Using Equation (4.4),  $\alpha_T$  can be rewritten as,

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \cancel{H}_T^2}} = \frac{1}{2} \frac{1 - \Delta H_T/H_T}{\sqrt{1 - (\cancel{H}_T/H_T)^2}}. \quad (4.5)$$

1141 The distribution of  $\alpha_T$  for the two jet categories used within this analysis, 2,3 and  
1142  $\geq 4$  jets, is shown in the Figure 4.3, demonstrating the ability of the  $\alpha_T$  variable to  
1143 discriminate between multi jet events and EWK processes with genuine  $\cancel{E}_T$  in the final  
1144 state.

1145 The  $\alpha_T$  requirement used within the search is chosen to be  $\alpha_T > 0.55$  to ensure  
1146 that the QCD multijet background is negligible even in the presence of moderate jet  
1147 mis-measurement. There still remains other effects which can cause multijet events to  
1148 artificially have a large  $\alpha_T$  value, which are discussed in detail in Section (4.2.2).



**Figure 4.3.:** The  $\alpha_T$  distributions for the low 2-3 (left) and high  $\geq 4$  (right) jet multiplicities after a full analysis selection and shown for  $H_T > 375$ . Data is collected using both prescaled  $H_T$  triggers and dedicated  $\alpha_T$  triggers for below and above  $\alpha_T = 0.55$  respectively. . Expected yields as given by simulation are also shown for multijet events (green dash-dotted line), EWK backgrounds with genuine  $\cancel{E}_T$  (blue long-dashed line), the sum of all SM processes (cyan solid line) and the reference signal model D2 (left, red dotted line) or G2 (right, red dotted line).

## 1149 4.2. Search Strategy

1150 The aim of the analysis presented in this thesis is to identify an excess of events in data  
1151 over the SM background expectation in multi-jet final states and significant  $\cancel{E}_T$ . The  
1152 essential suppression of the dominant QCD background for such a search is addressed by  
1153 the  $\alpha_T$  variable described in the previous section. For estimation of the remaining EWK  
1154 backgrounds, three independent data control samples are used to predict the different  
1155 processes that compose the background :

- 1156 •  $\mu + \text{jets}$  to determine  $W + \text{jets}$ ,  $t\bar{t}$  and single top backgrounds,
- 1157 •  $\gamma + \text{jets}$  to determine the irreducible  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  background,
- 1158 •  $\mu\mu + \text{jets}$  to determine the irreducible  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  background.

1159 These control samples are chosen to both be rich in specific EWK processes, be free of  
1160 QCD multi-jet events and to also be kinematically similar to the hadronic signal region  
1161 that they are estimating the backgrounds of, see Section (4.2.3).

1162 To remain inclusive to a large range of possible **SUSY** models, the signal region is  
1163 binned in the following categories to allow for increased sensitivity in the interpretation  
1164 of results for different **SUSY** topologies:

1165 **Sensitivity to a range of SUSY mass splittings**

1166 The hadronic signal region is defined by  $H_T > 275$ , divided into eight bins in  $H_T$ .

- 1167 – Two bins of width 50 GeV in the range  $275 < H_T < 375$  GeV,
- 1168 – five bins of width 100 GeV in the range  $375 < H_T < 875$  GeV,
- 1169 – and a final open bin,  $H_T > 875$  GeV.

1170 The choice at low  $H_T$  is driven primarily by trigger constraints. The mass difference  
1171 between the **LSP** and the particle that it decays from is an important factor in the  
1172 amount of hadronic activity in the event.

1173 A large mass splitting will lead to hard high  $p_T$  jets which contribute to the  $H_T$   
1174 sum. From Figure 4.1 it can be seen that the **SM** background falls sharply at high  
1175  $H_T$  values, therefore a large number of  $H_T$  bins will lead to easier identification  
1176 of such signals. Conversely smaller mass splittings lead to softer jet  $p_T$ 's which will  
1177 subsequently fall into the lower  $H_T$  range.

1178 **Sensitivity to production method of SUSY particles**

1179 The production mechanism of any potential **SUSY** signal can lead to different event  
1180 topologies. One such way to discriminate between gluino ( $g\tilde{g}$  - “high multiplicity”),  
1181 and direct squark ( $q\tilde{q}$  - “low multiplicity”) induced production of **SUSY** particles is  
1182 realised through the number of reconstructed jets in the final state.

1183 The analysis is thus split into two jet categories : 2-3 jets ,  $\geq 4$  jets to give sensitivity  
1184 to both of these mechanisms.

1185 **Sensitivity to “Natural SUSY” via tagging jets from b-quarks**

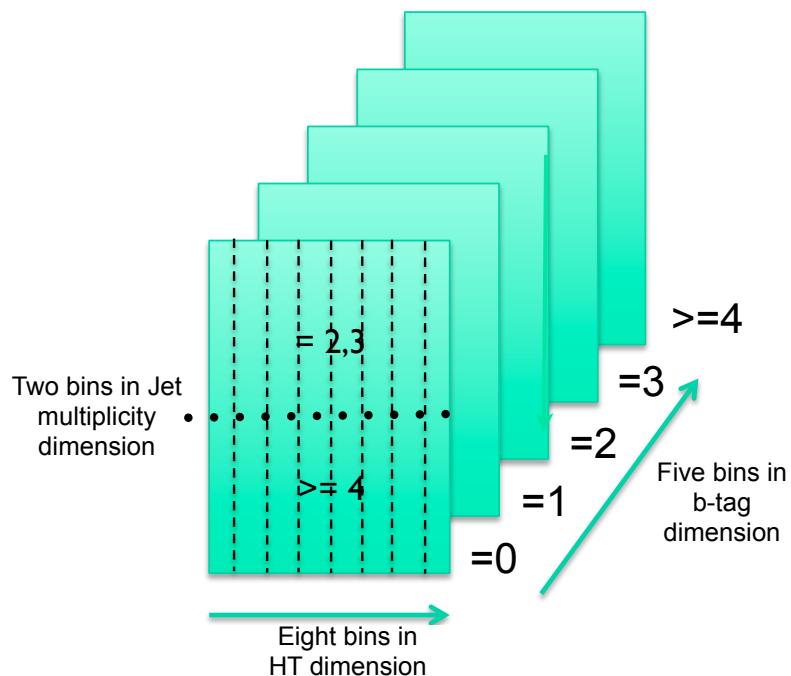
1186 Jets originating from bottom quarks (b-jets) are identified through vertices that  
1187 are displaced with respect to the primary interaction. The algorithm used to tag  
1188 b-jets is the Combined Secondary Vertex Medium Working Point (**CSV**) tagger,  
1189 described within Section (3.3.2). A cut is placed on the discriminator variable of  
1190  $> 0.679$ , leading to a gluon/light-quark mis-tag rate of 1% and a jet  $p_T$  dependant  
1191 b-tagging efficiency of 60-70% [64].

Natural SUSY models would be characterised through final-state signatures rich in bottom quarks. A search relying on methods to identify jets originating from bottom quarks through b-tagging, will significantly improve the sensitivity to this class of signature.

This is achieved via the binning of events in the signal region according to the number of b-tagged jets reconstructed in each event, in the following: 0,1,2,3, $\geq 4$  b-tag categories . In the highest  $\geq 4$  b-tag category due to a limited number of expected signal and background, just three  $H_T$  bins are employed: 275-325 GeV, 325-375 GeV,  $\geq 375$  GeV.

This characterisation is identically mirrored in all control samples, with the information from all samples and b-tag categories used simultaneously in the likelihood model (see Chapter 5) in order to interpret the results in a coherent and powerful way.

The combination of the  $H_T$ , jet multiplicity and b-tag categorisation of the signal region as described above, resultantly leads to 67 different bins in which the analysis is interpreted in, which is depicted in Figure 4.4.



**Figure 4.4.:** Pictorial depiction of the analysis strategy employed by the  $\alpha_T$  search to increase sensitivity to a wide spectra of SUSY models.

---

<sub>1208</sub> **4.2.1. Physics Objects**

<sub>1209</sub> The physics objects used in the analysis defined below, follow the recommendation of  
<sub>1210</sub> the various CMS Physics Object Groups ([POGs](#)).

<sub>1211</sub> • **Jets**

<sub>1212</sub> The jets used in this analysis are CaloJets, reconstructed as described in Section  
<sub>1213</sub> ([3.3.1](#)) using the anti- $k_T$  jet clustering algorithm.

<sub>1214</sub> To ensure the jet object falls within the calorimeter systems a pseudo-rapidity  
<sub>1215</sub> requirement of  $|\eta| < 3$  is applied. Each jet must pass a “loose” identification criteria  
<sub>1216</sub> to reject jets resulting from unphysical energy, the criteria of which are detailed in  
<sub>1217</sub> Table [4.2](#) [[74](#)].

Variable	Definition
$f_{HPD} < 0.98$	Fraction of jet energy contributed from “hottest” <b>HPD</b> , which rejects <b>HCAL</b> noise.
$f_{EM} > 0.01$	Noise from the <b>HCAL</b> is further suppressed by requiring a minimal electromagnetic component to the jet $f_{EM}$ .
$N_{hits}^{90} \geq 2$	Jets that have $> 90\%$ of its energy from a single channel are rejected, to serve as a safety net that catches jets arising from undiagnosed noisy channels.

**Table 4.2.:** Jet Identification criteria for the “loose” CaloJet ID, used to reject reconstructed jets resulting from fake calorimeter deposits representing unphysical energy.

<sub>1218</sub> • **Muons**

<sub>1219</sub> Muons are selected in the  $\mu +$  jets and  $\mu\mu +$  jets control samples, and vetoed in  
<sub>1220</sub> the signal region. The same cut based identification criteria is applied to muons in  
<sub>1221</sub> both search regions and is summarised in Table [4.3](#) [[75](#)].

<sub>1222</sub> Additionally muons are required to be within the acceptance of the muon tracking  
<sub>1223</sub> systems. For the muon control samples, trigger requirements necessitate a  $|\eta| <$   
<sub>1224</sub> 2.1 for the selection of muons. In the signal region where muons are vetoed these  
<sub>1225</sub> conditions are relaxed to  $|\eta| < 2.5$  and a minimum threshold of  $p_T > 10$  GeV is  
<sub>1226</sub> required of muon objects.

<sub>1227</sub> • **Photons**

Categories	Criteria
Global Muon	True
PFMuon	True
$\chi^2$	< 10
Muon chamber hits	> 0
Muon station hits	> 1
Transvere impact $d_{xy}$	< 0.2mm
Longitudinal distance $d_z$	< 0.5mm
Pixel hits	> 0
Track layer hits	> 5
PF Isolation (DeltaB corrected)	<0.12

**Table 4.3.:** Muon Identification criteria used within the analysis for selection/veto purposes in the muon control/signal selections.

1228 Photons are selected within the  $\gamma +$  jets control sample and vetoed in all other  
1229 selections. Photons are identified in both cases according to the cut based criteria  
1230 listed in Table 4.4 [76].

Variable	Definition
$H/E < 0.05$	The ratio of hadronic energy in the <b>HCAL</b> tower directly behind the <b>ECAL</b> super-cluster and the <b>ECAL</b> super-cluster itself.
$\sigma_{in\eta} < 0.011$	The log energy weighted width ( $\sigma$ ), of the extent of the shower in the $\eta$ dimension.
$R9 < 1.0$	The ratio of the energy of the $3 \times 3$ crystal core of the super-cluster compared to the total energy stored in the $5 \times 5$ super-cluster.
Combined Isolation $< 6$ GeV	The photons are required to be isolated with no electromagnetic or hadronic activity within a radius $\Delta R = 0.3$ of the photon object. A combination of the pileup subtracted [77], <b>ECAL</b> , <b>HCAL</b> and tracking isolation sums are used to determine the combined total isolation value.

**Table 4.4.:** Photon Identification criteria used within the analysis for selection/veto purposes in the  $\gamma +$  jets control/signal selections.

1231 Photon objects are also required to have a minimum momentum of  $p_T > 25$  GeV.

1232 • **Electrons**

1233 Electron identification is defined for veto purposes. They are selected according to  
1234 the following cut-based criteria listed in Table 4.5, utilising PF-based isolation.

Categories	Barrel	EndCap
$\Delta\eta_{In}$	0.007	0.009
$\Delta\phi_{In}$	0.15	0.10
$\sigma_{inj\eta}$	0.01	0.03
H/E	0.12	0.10
d0 (vtx)	0.02	0.02
dZ (vtx)	0.20	0.20
$ (1/E_{ECAL} - 1/p_{track}) $	0.05	0.05
PF Combined isolation/ $p_T$	0.15	0.15
Vertex fit probability	$10^{-6}$	$10^{-6}$

**Table 4.5.:** Electron Identification criteria used within the analysis for veto purposes.

1235 Electrons are required to be identified at  $|\eta| < 2.5$ , with a minimum  $p_T > 10$  GeV  
1236 threshold to ensure that the electron falls within the tracking system of the detector.

1237 • **Noise and  $E_T$  Filters**

1238 A series of Noise filters are applied to veto events which contain spurious non-physical  
1239 jets that are not picked up by the jet id, and events which give large unphysical  $E_T$   
1240 values. These filters are listed within Appendix (A.1).

1241 **4.2.2. Event Selection**

1242 The selection criteria for events within the analysis are detailed below. A set of common  
1243 cuts are applied to both signal (maximise acceptance to a range of SUSY signatures), and  
1244 control samples (retain similar jet kinematics for background predictions), with additional  
1245 selection cuts applied to each control sample to enrich the sample in a particular EWK  
1246 processes, see Section (4.2.3).

1247 The jets considered in the analysis are required to have a transverse momentum  $p_T >$   
1248 50 GeV, with a minimum of two jets required in the event. The highest  $E_T$  jet is required  
1249 to lie within the central tracker acceptance  $|\eta| < 2.5$ , and the two leading  $p_T$  jets must

1250 each have  $p_T > 100\text{GeV}$ . Any event which has a jet with  $p_T > 50\text{ GeV}$  that either fails  
1251 the “loose” identification criteria described in Section(4.2.1) or has  $|\eta| > 3.0$ , is rejected.  
1252 Similarly events in which an electron, muon or photon fails object identification but pass  
1253  $\eta$  and  $p_T$  restrictions are identified as an “odd” lepton/photon and the event is vetoed.

1254 At low  $H_T$ , the jet threshold requirements applied to be considered as part of the  
1255 analysis and enter the  $H_T$  sum are scaled downwards. These are scaled down in order to  
1256 not restrict phase space, preserving jet multiplicities and background admixture in the  
1257 lower  $H_T$  bins, as listed in Table 4.6.

$H_T$ bin	minimum jet $p_T$	second leading jet $p_T$
$275 < H_T < 325$	36.7	73.3
$325 < H_T < 375$	43.3	86.6
$375 < H_T$	50.0	100.0

**Table 4.6.:** Jet thresholds used in the three  $H_T$  regions of the analysis.

1258 Within the signal region to suppress **SM** processes with genuine  $\cancel{E}_T$  from neutrinos,  
1259 events containing isolated electrons or muons are vetoed. Furthermore to ensure a pure  
1260 multi-jet topology, events are vetoed if an isolated photon is found with  $p_T > 25\text{ GeV}$ .

1261 An  $\alpha_T$  requirement of  $> 0.55$  is required to reduce the QCD multi-jet background  
1262 to a negligible amount. Finally additional cleaning cuts are applied to protect against  
1263 pathological deficiencies such as reconstruction failures or severe energy mis-measurements  
1264 due to detector inefficiencies:

- Significant  $\cancel{H}_T$  can arise in events with no real  $\cancel{E}_T$  due to multiple jets falling below the  $p_T$  threshold used for selecting jets. This in turn leads to events which can then incorrectly pass the  $\alpha_T$  requirements of the analysis. This effect can be negated by requiring that the missing transverse momentum reconstructed from jets alone does not greatly exceed the missing transverse momentum reconstructed from all of the detector’s calorimeter towers,

$$R_{miss} = \cancel{H}_T / \cancel{E}_T < 1.25.$$

- 1265 • Fake  $\cancel{E}_T$  and  $\cancel{H}_T$  can arise due to significant jet mis-measurements cause by a small  
1266 number of non-functioning **ECAL** regions. These regions absorb electromagnetic  
1267 showers which are subsequently not added to the jet energy sum. To circumvent

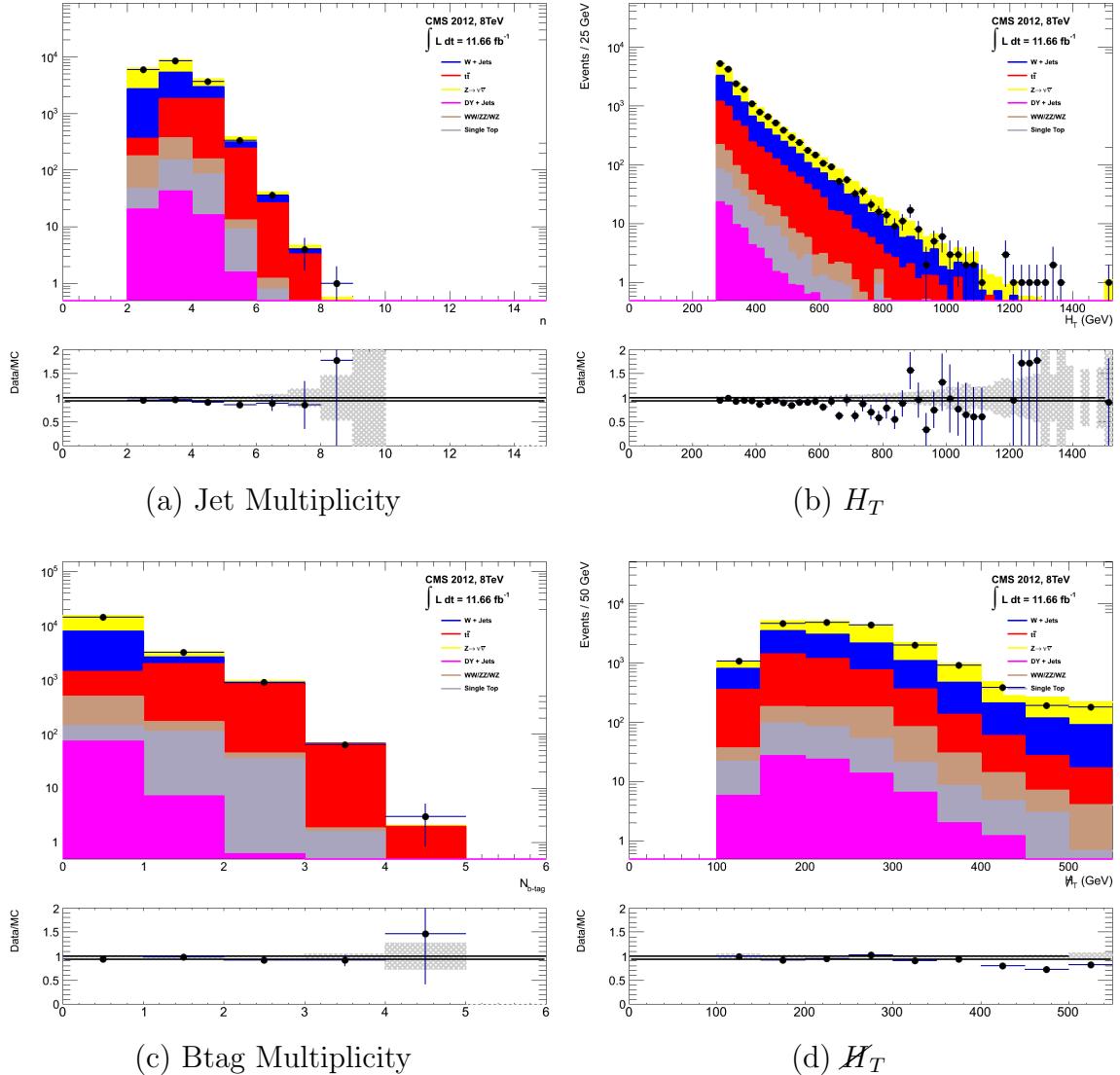
1268 this problem the following procedure is employed : For each jet in the event, the  
1269 angular separation

$$\Delta\phi_j^* \equiv \Delta\phi(\vec{p_j} - \sum_{i \neq j} \vec{p_i}), \quad (4.6)$$

1270 is calculated where that jet is itself removed from the event. Here  $\Delta\phi^*$  is a measure  
1271 of how aligned the  $H_T$  of an event is with a jet, a small value is compatible with the  
1272 hypothesis of an inherently balanced event in which a jet has been mis-measured.  
1273 For every jet in a event with  $\Delta\phi^* < 0.5$ , if the  $\Delta R$  distance between the selected jet  
1274 and the closest dead **ECAL** region is also  $< 0.3$ , then the event is rejected. Similarly  
1275 events are rejected if the jet points within  $\Delta R < 0.3$  of the **ECAL** barrel-endcap  
1276 gap at  $|\eta| = 1.5$ .

1277 Some of the key distributions of the data used in this analysis compared to MC  
1278 simulation are shown in Figure 4.5. The MC samples are normalised to a luminosity of  
1279  $11.7 \text{ fb}^{-1}$ , with no requirement placed upon the number of b-tagged jets or number of  
1280 jets in the events.

1281 The distributions shown are presented for purely illustrative purposes, with the MC  
1282 simulation itself not used in absolute term to estimate the yields from background  
1283 processes, see Sections (4.2.3,4.5). However it is nevertheless important to demonstrate  
1284 that good agreement exists between simulation and observation in data.



**Figure 4.5.:** Data/MC comparisons of key variables for the hadronic signal region, following the application of the hadronic selection criteria and the requirements of  $H_T > 275$  GeV and  $\alpha_T > 0.55$ . Bands represent the uncertainties due to the statistical size of the MC samples. No requirement is made upon the number of b-tagged jets or jet multiplicity in these distributions.

### 4.2.3. Control Sample Definition

The method used to estimate the background contributions in the hadronic signal region relies on the use of a Transfer Factor (TF). This is determined from MC simulation in both the control,  $N_{MC}^{\text{control}}$ , and signal,  $N_{MC}^{\text{signal}}$ , region to transform the observed yield measured in data for a control sample,  $N_{\text{obs}}^{\text{control}}$ , into a background prediction,  $N_{\text{pred}}^{\text{signal}}$ , via Equation (4.7),

$$N_{\text{pred}}^{\text{signal}} = \frac{N_{\text{MC}}^{\text{signal}}}{N_{\text{MC}}^{\text{control}}} \times N_{\text{obs}}^{\text{control}}. \quad (4.7)$$

1292 All MC samples are normalised to the luminosity of the data samples,  $11.7 \text{ fb}^{-1}$ .  
 1293 Through this method, “vanilla” predictions for the **SM** background in the signal region  
 1294 can be made by considering separately the sum of the prediction from either the  $\mu + \text{jets}$   
 1295 and  $\gamma + \text{jets}$  or  $\mu + \text{jets}$  and  $\mu\mu + \text{jets}$  samples. However the final background estimation  
 1296 from which results are interpreted, is calculated via a fitting procedure defined formally  
 1297 by the likelihood model described in Chapter 5.

1298 The sum of the expected yields from all MC processes, in each control sample enter  
 1299 the denominator,  $N_{\text{MC}}^{\text{control}}$ , of the **TF** defined in Eq (4.7). However for the numerator  
 1300 ,  $N_{\text{MC}}^{\text{signal}}$ , only the relevant processes that the control sample is used in estimating a  
 1301 background for, enter into the **TF**.

1302 For the  $\mu + \text{jets}$  sample the simulated MC processes which enter the numerator of  
 1303 the **TF** are,

$$N_{\text{MC}}^{\text{signal}}(H_T, n_{\text{jet}}) = N_W + N_{t\bar{t}} + N_{DY} + N_t + N_{di-boson}, \quad (4.8)$$

1304 whilst for both the  $\mu\mu + \text{jets}$  and  $\gamma + \text{jets}$  samples the only MC process used in the  
 1305 numerator is,

$$N_{\text{MC}}^{\text{signal}}(H_T, n_{\text{jet}}) = N_{Z \rightarrow \nu\bar{\nu}}. \quad (4.9)$$

1306 The control samples and the **EWK** processes they are specifically tuned to select  
 1307 are defined below, with distributions of key variables for each of the control samples  
 1308 shown for illustrative purposes in Figures 4.6, 4.7 and 4.8. No requirement is placed  
 1309 upon the number of b-tagged jets or jet multiplicity in the distributions shown. The  
 1310 MC distributions highlight the background compositions of each control sample, where  
 1311 in general, good agreement is observed between data and simulation, giving confidence

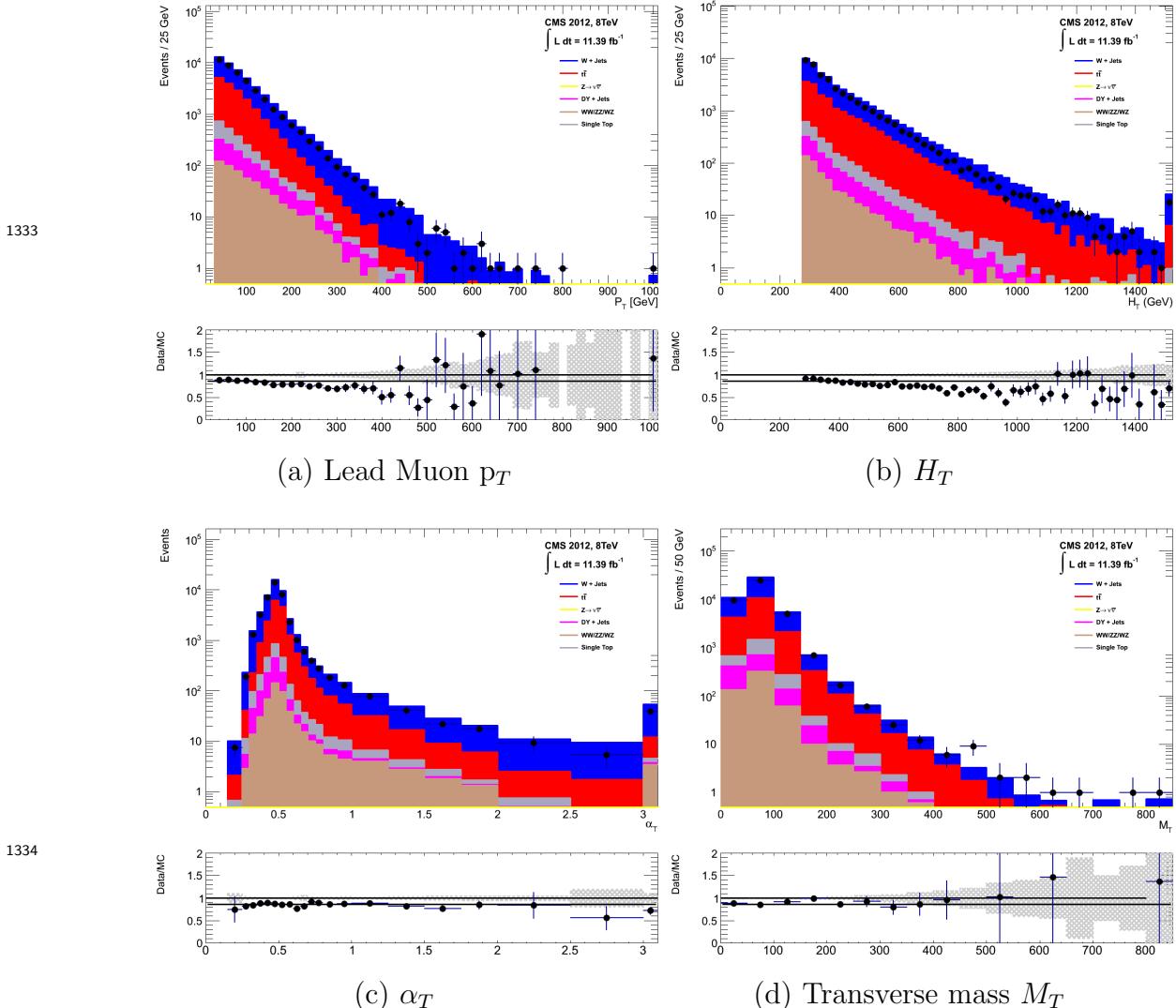
1312 that the samples are well understood. The contribution from QCD multi-jet events is  
1313 expected to be negligible :

1314 **The  $\mu +$  jets control sample**

1315 Events from  $W +$  jets and  $t\bar{t}$  processes enter into the hadronic signal sample due to  
1316 unidentified leptons from acceptance or threshold effects and hadronic tau decays.  
1317 These leptons originate from the decay of high  $p_T$   $W$  bosons.

1318 The control samples specifically identifies  $W \rightarrow \mu\bar{\nu}$  decays within the same phase-  
1319 space of the signal region, where the muon is subsequently ignored in the calculation  
1320 of event level variables, i.e.  $H_T$ ,  $\mathcal{H}_T$ ,  $\alpha_T$ . All kinematic jet-based cuts are identical  
1321 to those applied in the hadronic search region detailed in Section (4.2.2), with the  
1322 same  $H_T$ , jet multiplicity and b-jet multiplicity binning described above.

- 1323 – Muons originating from  $W$  boson decays are selected by requiring one tightly  
1324 isolated muon defined in Table 4.3, with a  $p_T > 30$  GeV and  $|\eta| < 2.1$ . Both of  
1325 these threshold arise from trigger restrictions.
- 1326 – The transverse mass of the  $W$  candidate must satisfy  $M_T(\mu, \cancel{E}_T) < 30$  GeV (   
1327 to suppress QCD multi-jet events).
- 1328 – Events which contain a jet overlapping with a muon  $\Delta R(\mu, \text{jet}) < 0.5$  are vetoed  
1329 to remove events from muons produced as part of a jet’s hadronisation process.
- 1330 – Events containing a second muon candidate which has failed id, but passed  $p_T$   
1331 and  $|\eta|$  requirements, are checked to have an invariant mass that satisfies  $m_Z -$   
1332  $25 < M_{\mu_1\mu_2} > m_Z + 25$ , thus removing  $Z \rightarrow \mu\mu$  contamination.



**Figure 4.6.:** Data/MC comparisons of key variables for the  $\mu + \text{jets}$  selection, following the application of selection criteria and the requirements that  $H_T > 275$  GeV. Bands represent the uncertainties due to the statistical size of the MC samples. No requirement is made upon the number of b-tagged jets or jet multiplicity in these distributions.

### The $\mu\mu + \text{jets}$ control sample

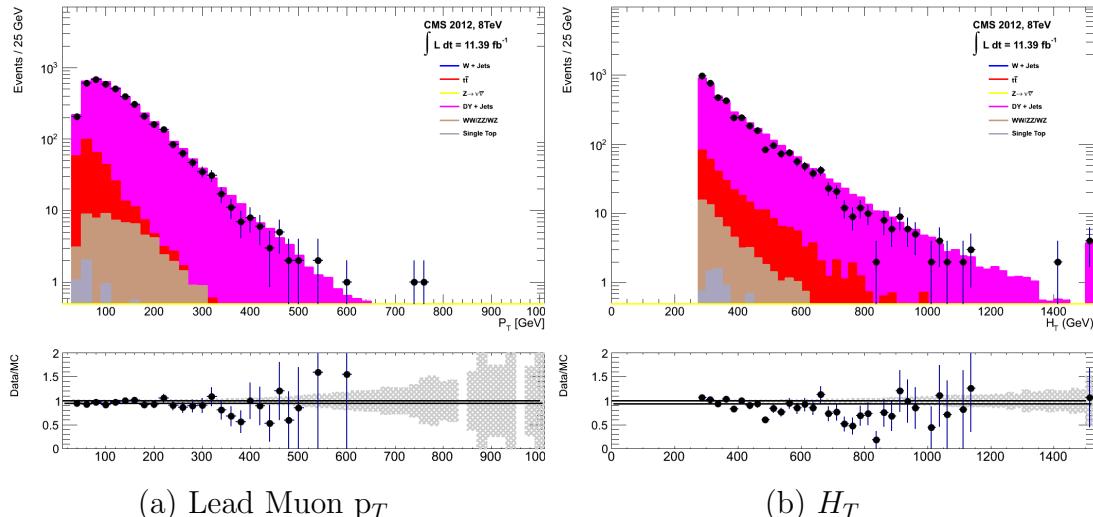
The  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  background enters into the signal region from genuine  $\cancel{E}_T$  from the escaping neutrinos. This background is estimated using two control samples, the first of which is the  $Z \rightarrow \mu\bar{\mu} + \text{jets}$  process, which posses identical kinematic properties, but with different acceptance and branching ratio [1].

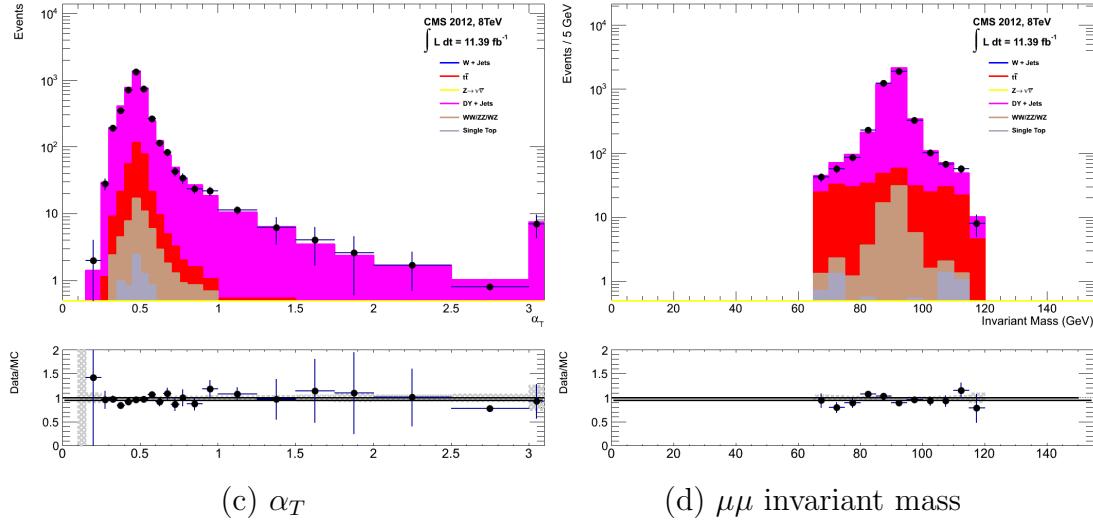
The same acceptance requirements as the  $\mu + \text{jets}$  selection for muons is applied, as defined in Table 4.3. Muons in the event are ignored for the purpose of the

calculation of event level variables. Kinematic jet-based cuts and phase space binning identical to the hadronic search region are also applied.

- Muons origination from a Z boson decay are selected requiring exactly two tightly isolated muons. Due to trigger requirements the leading muon is required to have  $p_T > 30$  GeV and  $|\eta| < 2.1$ . The requirement of the  $p_T$  on the second muon is relaxed to 10 GeV.
- Events are vetoed if containing a jet overlapping with a muon  $\Delta R(\mu, \text{jet}) < 0.5$ .
- In order to specifically select two muons both originating from a single Z boson decay, the invariant mass of the two muons must satisfy  $m_Z - 25 > M_{\mu_1\mu_2} < m_Z + 25$ .

The  $\mu\mu + \text{jets}$  sample is used to make predictions in the signal region in the two lowest  $H_T$  bins, providing coverage where the  $\gamma + \text{jets}$  sample is unable to, due to trigger requirements. In higher  $H_T$  bins, the higher statistics of the  $\gamma + \text{jets}$  sample is instead used to determine the  $Z \rightarrow \nu\bar{\nu}$  estimation.



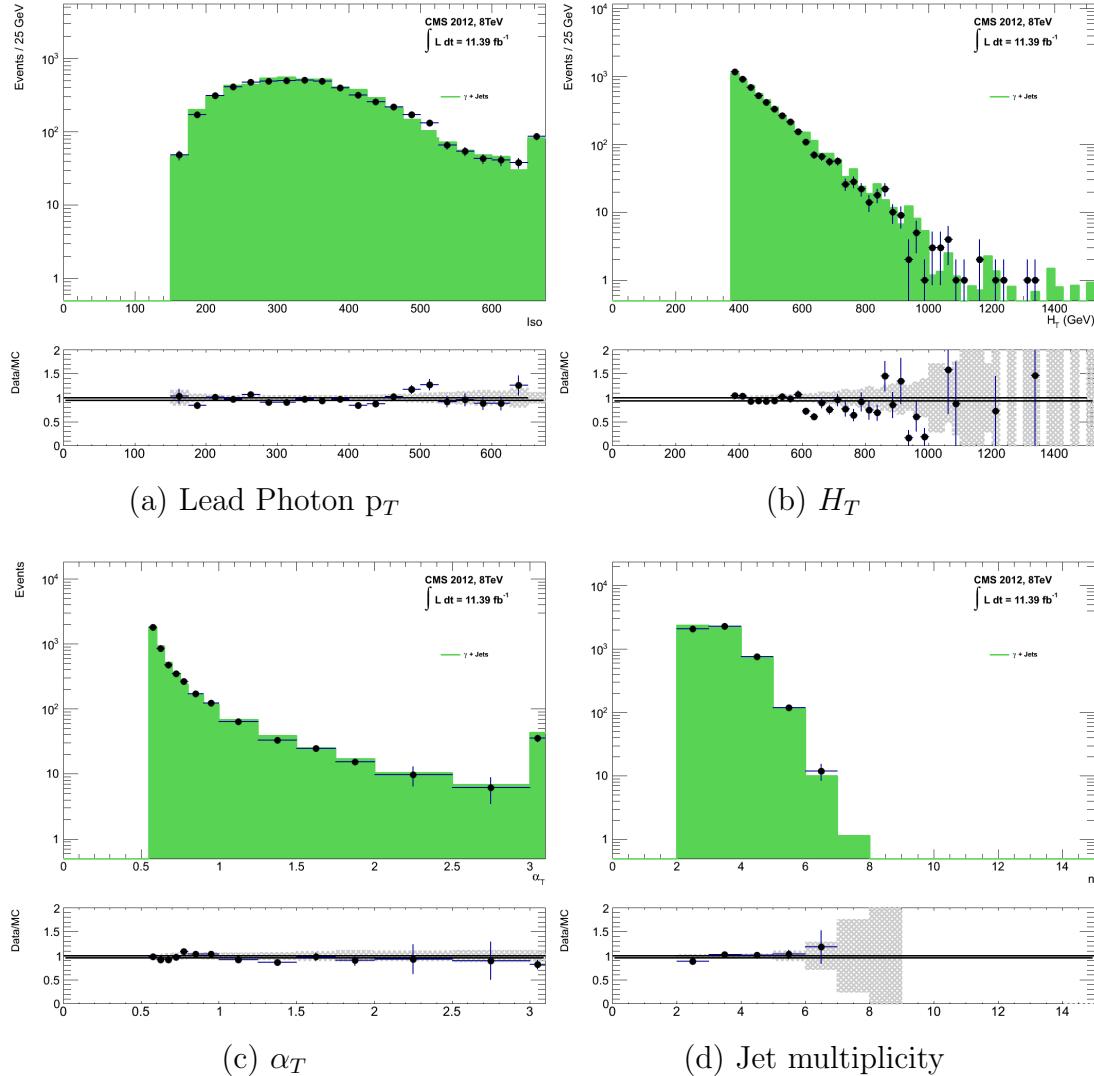


**Figure 4.7.:** Data/MC comparisons of key variables for the  $\mu\mu + \text{jets}$  selection, following the application of selection criteria and the requirements that  $H_T > 275$  GeV. Bands represent the uncertainties due to the statistical size of the MC samples. No requirement is made upon the number of b-tagged jets or jet multiplicity in these distributions.

### The $\gamma + \text{jets}$ control sample

The  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  background is also estimated from a  $\gamma + \text{jets}$  control sample, which possesses a larger cross section and kinematic properties similar to those of  $Z \rightarrow \mu\bar{\mu}$  events where the photon is ignored [78][79]. The photon is ignored for the purpose of the calculation of event level variables, and identical selection cuts to the hadronic signal region are applied.

- Exactly one photon is selected, satisfying identification criteria as detailed in Table 4.4, with a minimum  $p_T > 165$  GeV to satisfy trigger thresholds and  $|\eta| < 1.45$  to ensure the photon remains in the barrel of the detector.
- A selection criteria of  $\Delta R(\gamma, \text{jet}) < 1.0$ , between the photon and all jets is applied to ensure the acceptance of only well isolated  $\gamma + \text{jets}$  events.
- Given that the photon is ignored, this control sample can only be applied in the  $H_T$  region  $> 375$  GeV, due to the trigger thresholds on the minimum  $p_T$  of the photon, and the  $H_T$  requirement of an  $\alpha_T > 0.55$  cut from Equation (4.5).



**Figure 4.8.:** Data/MC comparisons of key variables for the  $\gamma + \text{jets}$  selection, following the application of selection criteria and the requirements that  $H_T > 375 \text{ GeV}$  and  $\alpha_T > 0.55$ . Bands represent the uncertainties due to the statistical size of the MC samples. No requirement is made upon the number of b-tagged jets or jet multiplicity in these distributions.

The selection criteria of the three control samples are defined to ensure background composition and event kinematics mirror closely the signal region. This is done in order to minimise the reliance on MC simulation to model correctly the backgrounds and event kinematics in the control and signal samples.

However in the case of the  $\mu + \text{jets}$  and  $\mu\mu + \text{jets}$  samples, the  $\alpha_T$  requirement is relaxed in the selection criteria of these samples. This is made possible as contamination from QCD multi-jet events is suppressed to a negligible level by the other kinematic selection criteria within the two control samples, to select pure EWK processes. Thus in

1381 this way, the acceptance of the two muon control samples can be significantly increased,  
1382 which simultaneously improves their predictive power and further reduces the effect of  
1383 any potential signal contamination.

1384 The modelling of the  $\alpha_T$  variable is probed through a dedicated set of closure tests,  
1385 described in Section (4.6), which demonstrate that the different  $\alpha_T$  acceptances for the  
1386 control and signal samples have no significant systematic bias on the prediction.

#### 1387 4.2.4. Estimating the QCD background multi-jet background

1388 A negligible background from QCD multi-jet events within the hadronic signal region  
1389 is expected due to the selection requirement, and additional cleaning filters applied.  
1390 However a conservative approach is still adopted and the likelihood model (see Section  
1391 (5.1)), is given the freedom to estimate any potential QCD multi-jet contamination.

1392 Any potential contamination can be identified through the variable  $R_{\alpha_T}$ , defined as  
1393 the ratio of events above and below the  $\alpha_T$  threshold value used in the analysis. This is  
1394 modelled by a  $H_T$  dependant falling exponential function which takes the form,

$$R_{\alpha_T}(H_T) = A \exp^{-k_{QCD} H_T}, \quad (4.10)$$

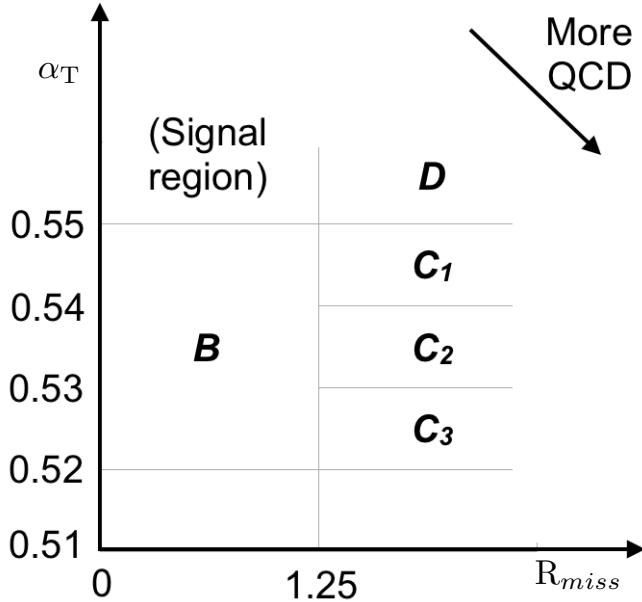
1395 where the parameters  $A$  and  $k_{QCD}$  are the normalisation and exponential decay  
1396 constants respectively.

1397 For QCD event topologies this exponential behaviour is expected as a function of  $H_T$   
1398 for several reasons. The improvement of jet energy resolution at higher  $H_T$  due to higher  
1399  $p_T$  jets leads to a narrower peaked distribution, causing  $R_{\alpha_T}$  to fall. Similarly at higher  
1400  $H_T$  values  $> 375$  GeV, the jet multiplicity rises slowly with  $H_T$ . As shown in Figure 4.3,  
1401 at higher jet multiplicities, the result of the combinatorics used in the determination of  
1402  $\alpha_T$ , also lead to a narrower  $\alpha_T$  distribution.

1403 The value of the decay constant  $k_{QCD}$  is constrained via measurements within data  
1404 sidebands to the signal region. This is also done to validate the falling exponential  
1405 assumption for QCD multi-jet topologies. The sidebands are enriched in QCD multi-jet  
1406 background and defined as regions where  $\alpha_T$  is relaxed or that the  $R_{miss}$  cut is inverted.

1407 Figure 4.9 depicts the definition of these data sidebands used to constrain the value of  
1408  $k_{QCD}$ .

1409



**Figure 4.9.:** QCD sideband regions, used for determination of  $k_{QCD}$ .

1410 The fits to determine the value of  $k_{QCD}$  are shown in Appendix (C.1), for which the best  
1411 fit value obtained from sideband region B is determined to be  $k_{QCD} = 2.96 \pm 0.64 \times 10^{-2}$   
1412  $\text{GeV}^{-1}$ .

1413 The best fit values of the remaining three C sideband regions are used to estimate  
1414 the systematic uncertainty on the central value obtained from sideband region B. The  
1415 variation of these measured values is used to determine the error on the determined  
1416 central value, and is calculated to be  $1.31 \pm 0.26 \times 10^{-2} \text{GeV}^{-1}$ . This relative error of  $\sim$   
1417 20% gives an estimate of the systematic uncertainty of the measurement to be applied to  
1418  $k_{QCD}$ .

1419 Finally the same procedure is performed for sideband region D to establish that the  
1420 value of  $k_{QCD}$  extracted from a lower  $\alpha_T$  slice can be applied to the signal region  $\alpha_T >$   
1421 0.55. The likelihood fit is performed across all  $H_T$  bins within the QCD enriched region  
1422 with no constraint applied to  $k_{QCD}$ . The resulting best fit value for  $k_{QCD}$  shows good  
1423 agreement between that and the weighted mean determined from the three C sidebands  
1424 regions. This demonstrates that the assumption of using the central value determined  
1425 from sideband region B, to provide an unbiased estimator for  $k_{QCD}$  in the signal region  
1426 ( $\alpha_T > 0.55$ ) is valid.

1427 Table 4.7, summarises the best fit  $k_{QCD}$  values determined for each of the sideband  
1428 regions to the signal region.

Sideband region	$k_{QCD} (\times 10^{-2} \text{GeV}^{-1})$	p-value
B	$2.96 \pm 0.64$	0.24
C <sub>1</sub>	$1.19 \pm 0.45$	0.93
C <sub>2</sub>	$1.47 \pm 0.37$	0.42
C <sub>3</sub>	$1.17 \pm 0.55$	0.98
C(weighted mean)	$1.31 \pm 0.26$	-
D(likelihood fit)	$1.31 \pm 0.09$	0.57

**Table 4.7.:** Best fit values for the parameters  $k_{QCD}$  obtained from sideband regions B,C<sub>1</sub>,C<sub>2</sub>,C<sub>3</sub>. The weighted mean is determined from the three measurements made within sideband region C. The maximum likelihood value of  $k_{QCD}$  given by the simultaneous fit using sideband region D. Quotes errors are statistical only.

### 1429 4.3. Trigger Strategy

1430 A cross trigger based on the quantities  $H_T$  and  $\alpha_T$ , labelled is used with varying thresholds  
1431 across  $H_T$  bins to record the events used in the hadronic signal region. The  $\alpha_T$  legs of the  
1432  $HT\_alphaT$  triggers used in the analysis are chosen to fully suppress QCD multi-jet events,  
1433 whilst maintaining a sustainable trigger rate. To further maintain an acceptable rate for  
1434 these analysis specific triggers, only calorimeter information is used in the reconstruction  
1435 of the  $H_T$  sum, leading to the necessity for Calo jets to be used within the analysis.

1436 A single object prescaled  $H_T$  trigger is used to collect events for the hadronic control  
1437 region described above in Section (4.2.4).

1438 The performance of the  $\alpha_T$  and  $H_T$  triggers used to collect data for the signal and  
1439 hadronic control region is measured with respect to a reference sample collected using the  
1440 muon system. This allows measurement of both the Level 1 seed and higher level triggers  
1441 simultaneously, as the reference sample is collected independent of any jet requirements.

1442 The selection for the trigger efficiency measurement is identical to that described in  
1443 Section (4.2.2), with the requirement of exactly one well identified muon with  $p_T > 30$   
1444 GeV which is subsequently ignored.

1445 The efficiencies measure for the  $HT\_alphaT$  triggers in bins individual  $H_T$  and  $\alpha_T$  legs,  
1446 is summarised in Table 4.8.

$H_T$ range (GeV)	$\epsilon$ on $H_T$ leg (%)	$\epsilon$ on $\alpha_T$ leg (%)
275-325	$87.7^{+1.9}_{-1.9}$	$82.8^{+1.0}_{-1.1}$
325-375	$90.6^{+2.9}_{-2.9}$	$95.9^{+0.7}_{-0.9}$
375-475	$95.7^{+0.1}_{-0.1}$	$98.5^{+0.5}_{-0.9}$
475- $\infty$	$100.0^{+0.0}_{-0.0}$	$100.0^{+0.0}_{-4.8}$

**Table 4.8.:** Measured efficiencies of the  $H_T$  and  $\alpha_T$  legs of the HT and  $HT\_alphaT$  triggers in independent analysis bins. The product of the two legs gives the total efficiency of the trigger in a given offline  $H_T$  bin.

1447 Data for the control samples of the analysis, detailed in Section (4.2.3), are collected  
1448 using single object photon trigger for the  $\gamma +$  jets sample, and a single object muon  
1449 trigger for both the  $\mu +$  jets and  $\mu\mu +$  jets control samples. The photon trigger is  
1450 measured to be full efficient for the threshold  $p_T^{photon} > 150 GeV$ , whilst the single muon  
1451 efficiency satisfying  $p_T^{muon} > 30 GeV$  is measured to have an efficiency of  $(88 \pm 2)\%$  that  
1452 is independent of  $H_T$ . In the case of the  $\mu\mu +$  jets control sample, the efficiency is  
1453 measured to be  $(95 \pm 2)\%$  for the lowest  $H_T$  bin, rising to  $(98 \pm 2)\%$  for the highest  $H_T$   
1454 bin.

## 1455 4.4. Measuring MC normalisation factors via $H_T$ 1456 sidebands

1457 The theoretical cross sections of different **SM** processes at Next to Next Leading Order  
1458 (**NNLO**) and the number of MC simulated events generated for that particular process,  
1459 is typically used to determine the appropriate normalisation for a MC sample. However  
1460 within the particular high- $H_T$  and high- $\mathcal{E}_T$  corners of kinematic phase space probed  
1461 within this search, the theoretical cross sections for various processes are far less well  
1462 understood.

1463 To mitigate the problem of theoretical uncertainties and arbitrary choices of cross  
1464 sections, the normalisation of MC samples used in the analysis are determined through  
1465 the use data sidebands. The sidebands are used to calculate sample specific correct  
1466 factors (k-factors) that are appropriate for the  $H_T$ - $\mathcal{E}_T$  phase space covered by this analysis.

<sup>1467</sup> They are defined within the  $\mu + \text{jets}$  and  $\mu\mu + \text{jets}$  control sample, by the region  $200 < H_T < 275$ , using the same jet  $p_T$  thresholds as the adjacent first analysis bin. Individual <sup>1468</sup> **EWK** processes are isolated within each of these control samples via requirements on <sup>1469</sup> jet multiplicity and the requirement on b-tags, summarised in Table 4.9. The purity of <sup>1470</sup> the samples are typically  $> 90\%$  with any residual contamination corrected for. The <sup>1471</sup> resultant k-factor for each process is determined by then taking ratio of the data yield <sup>1472</sup> over the MC expectation in the sideband. Subsequently these k-factors are then applied <sup>1473</sup> to the processes within the phase space of the analysis. <sup>1474</sup>

Process	Selection	Observation	MC expectation	k-factor
W + jets	$\mu + \text{jets}$ , $n_b=0$ , $n_{jet} = 2,3$	26950	$29993.2 \pm 650.1$	$0.90 \pm 0.02$
$Z \rightarrow \mu\mu + \text{jets}$	$\mu\mu + \text{jets}$ , $n_b=0$ , $n_{jet} = 2,3$	3141	$3402.0 \pm 43.9$	$0.92 \pm 0.02$
$t\bar{t}$	$\mu + \text{jets}$ , $n_b=2$ , $n_{jet} = \geq 4$	2190	$1967.8 \pm 25.1$	$1.11 \pm 0.02$

**Table 4.9.:** k-factors calculated for different **EWK** processes. All k-factors are derived relative to theoretical cross sections calculated in **NNLO**. The k-factors measured for the  $Z \rightarrow \mu\mu + \text{jets}$  processes, are also applied to the  $Z \rightarrow \nu\bar{\nu} + \text{jets}$  and  $\gamma + \text{jets}$  MC samples.

## <sup>1475</sup> 4.5. Determining MC yields with higher statistical <sup>1476</sup> precision

<sup>1477</sup> Reconstructing events from **EWK** processes with many b-tagged jets ( $\geq 3$ ),  $n_b^{reco}$ , is largely <sup>1478</sup> driven by the mis-tagging of light jets within the event. This is clear when considering <sup>1479</sup> the main **EWK** backgrounds in the analysis, such as  $t\bar{t} + \text{jets}$  events, which typically <sup>1480</sup> contain two b-flavoured jets from the decay of the top quarks, whilst W + jets and <sup>1481</sup> Z  $\rightarrow \mu\mu + \text{jets}$  events will typically contain no b-flavoured jets.

<sup>1482</sup> When the expectation for the number of  $n_b^{reco}$  is taken directly from simulation, the <sup>1483</sup> statistical uncertainty at large b-tag multiplicities becomes relatively large. In order to <sup>1484</sup> reduce this uncertainty one approach is to use the information encoded throughout all <sup>1485</sup> events in the simulation sample, to measure each of the four ingredients:

- <sup>1486</sup> 1. the b-tagging efficiency in the event selection,
- <sup>1487</sup> 2. the charm-tagging efficiency in the event selection

1488 3. the mis-tagging rate in the event selection,

1489 4. the underlying flavour distribution of the jets in the events,

1490 that determine the  $n_b^{reco}$  distribution of the process being measured. This method  
1491 allows the determination of higher b-tag multiplicities to a higher degree of accuracy  
1492 reducing the statical uncertainties of the MC which enter into the TF's. For the discussion  
1493 that follows, these predictions are determined on average (i.e not on an event-by-event  
1494 basis), and is known as the formula method.

#### 1495 4.5.1. The formula method

1496 The assigning of jet flavours to reconstruction level jets in simulation is achieved via an  
1497 algorithmic method defined as:

- 1498 • Try to find the parton that most likely determines the properties of the jet and  
1499 assign that flavour as true flavour,
- 1500 • Here, the “final state” partons (after showering, radiation) are analysed (also within  
1501  $\Delta R < 0.3$  of reconstructed jet cone),
- 1502 • Jets from radiation are matched with full efficiency,
- 1503 • If there is a b/c flavoured parton within the jet cone: label as b/c flavoured jet,
- 1504 • Otherwise: assign flavour of the hardest parton.

1505 Within each individual MC process and each  $H_T$ - $n_{jet}$  bin in the analysis, the  $n_b^{reco}$

1506 distribution is constructed in the following way:

1507 Let  $N(n_b^{gen}, n_c^{gen}, n_q^{gen})$  represent the yield in simulation of events with  $b$  underlying  
1508 b-quarks,  $c$  underlying c-quarks and  $q$  underlying light quarks which are matched to  
1509 reconstructed jets. Light quarks are defined as those which originate from a  $u,d,s,g$  and  
1510  $\tau$  jets which are grouped together having similar mis-tagging rates. Similarly defining  $\epsilon$ ,  
1511  $\beta$  and  $m$ , which represent the measured b-tagging,c-tagging and mis-tagging efficiency  
1512 averaged over all the jets within that particular analysis bin.

1513 Using this information the expected number of jets which have been b-tagged can be

1514 analytically calculated using the formula :

$$N(n_b) = \sum_{n_b^{gen} + n_c^{gen} + n_q^{gen} = n_{jet}} \sum_{n_b^{tag} + n_c^{tag} + n_q^{tag} = n_b} N(n_b^{gen}, n_c^{gen}, n_q^{gen}) \times P(n_b^{tag}, n_b^{gen}, \epsilon) \times \\ P(n_c^{tag}, n_c^{gen}, \beta) \times P(n_q^{tag}, n_q^{gen}, m), \quad (4.11)$$

where  $N(n_b)$  represents the event yield where  $n_b$  jets have been tagged as originating from a b jet,  $n_b^{tag}$ ,  $n_c^{tag}$  and  $n_q^{tag}$  represent the number of times that a particular jet flavour results in a b-tagged jet, and  $P(n_b^{tag}, n_b^{gen}, \epsilon)$ ,  $P(n_c^{tag}, n_c^{gen}, \beta)$  and  $P(n_q^{tag}, n_q^{gen}, m)$  represent the binomial probabilities for that to happen.

This approach ultimately results in a more precise  $n_b^{reco}$  distribution prediction as information from throughout the entire MC sample is used to estimate the high  $n_b^{reco}$  bins.

### 4.5.2. Establishing proof of principle

In order to validate the procedure, the predictions obtained from the formula method summarised in Eq (4.11), are compared directly to those obtained directly from simulation. These results for the  $\mu +$  jets control sample are summarised in Table 4.10, for the 0,1,2 and 3  $n_b^{reco}$  bins.

Process	Selection	Observation	MC expectation	k-factor
---------	-----------	-------------	----------------	----------

**Table 4.10.:** place holder

### 4.5.3. Correcting measured efficiencies in simulation to data

As detailed in Section (3.3.2), it is necessary for certain  $p_T$  and  $\eta$  dependant corrections, to be applied to both the b-tagging efficiency and mis-tagging rates in order correct the efficiencies from simulation to the distributions seen in data. These corrections are factored in.

Show plot of before and after correction to btag/mistag rate.

These corrections come with uncertainties..

1534 show plot of effect of scaling correction factor up and down.

## 1535 4.6. Systematic Uncertainties on Transfer Factors

1536 Since the TF's used to establish the background prediction are obtained from simulation,  
1537 an appropriate systematic uncertainty is assigned to each factor to account for theoretical  
1538 uncertainties [80] and limitations in the simulation modelling of event kinematics and  
1539 instrumental effects.

## 1540 4.7. Searches for Natural SUSY with B-tag 1541 templates.

1542 Btag Templates blah blah

# Chapter 5.

## <sup>1543</sup> Results

<sup>1544</sup> Results at 12fb 8TeV

### <sup>1545</sup> 5.1. Statistical Interpretation

<sup>1546</sup> Likelihood stuff

### <sup>1547</sup> 5.2. Interpretation in Simplified Signal Models

<sup>1548</sup> Result interpretation

<sup>1549</sup>

# Appendix A.

## <sup>1550</sup> Miscellaneous

### <sup>1551</sup> A.1. Noise Filters

<sup>1552</sup> For Calo jets the following criteria were applied:

<sup>1553</sup> • N90 hits  $> 1$ ,

<sup>1554</sup> • HBHE  $> 0.01$ ,

<sup>1555</sup> • fHPD  $< 0.98$ ,

<sup>1556</sup> For PF jets the following criteria were applied:

<sup>1557</sup> • Neutral hadron fraction  $< 0.99$ ,

<sup>1558</sup> • Neutral EM fraction  $< 0.99$ ,

<sup>1559</sup> • Number of constituents  $> 1$ ,

<sup>1560</sup> • Charged hadron fraction  $> 0$ ,

<sup>1561</sup> • Charged multiplicity  $> 0$ ,

<sup>1562</sup> • Charged EM fraction  $< 0.99$ .

<sup>1563</sup> The following noise filters are applied, to remove events with spurious, non-physical  
<sup>1564</sup> jets or missing transverse energy.

<sup>1565</sup> • CSC tight beam halo filter,

<sup>1566</sup> • HBHE noise filter with isolated noise rejection,

- 1567     • HCAL laser filter,
- 1568     • ECAL dead cell trigger primitive (TP) filter,
- 1569     • Tracking failure filter,
- 1570     • Bad EE Supercrystal filter,
- 1571     • ECAL Laser correction filter.

## 1572   A.2. Primary Vertices

1573   The pileup per event is defined by the number of 'good' reconstructed primary vertices  
1574   in the event, with each vertex satisfying the following requirements

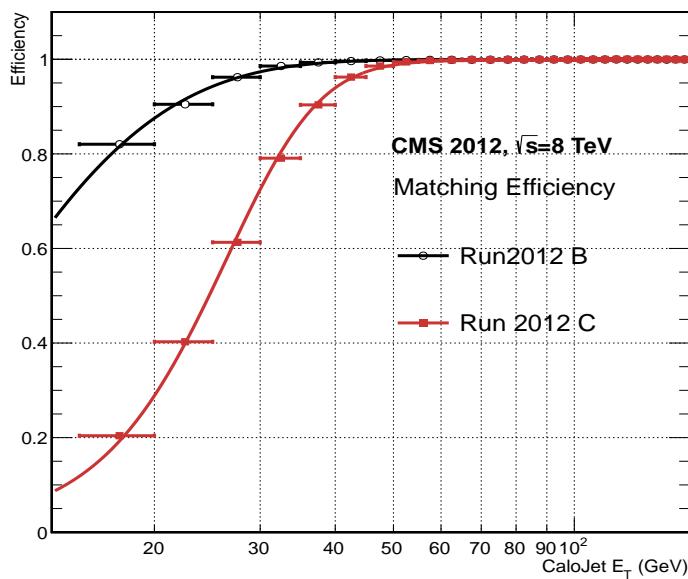
- 1575     •  $N_{dof} > 4$ ;
- 1576     • vertex position along the bead direction of  $|z_{vtx}| < 24\text{cm}$ ;
- 1577     • vertex position perpendicular to the beam of  $\rho < 2\text{cm}$ .

# Appendix B.

## <sup>1578</sup> L1 Jets

### <sup>1579</sup> B.1. Jet matching efficiencies

<sup>1580</sup> The single jet turn-on curves are derived from events independent of whether the leading  
<sup>1581</sup> jet in an event is matched to a Level 1 jet using  $\Delta R$  matching detailed in Section (3.4.3)  
<sup>1582</sup> or not. These turn-ons are produced from events which are not triggered on jet quantities  
<sup>1583</sup> and therefore it is not guaranteed that the lead jet of an event will be seeded by a Level  
<sup>1584</sup> 1 jet. Figure B.1 shows the particular matching efficiency of a lead jet to a L1 jet.



**Figure B.1.:** Leading jet matching efficiency as a function of the offline CaloJet  $E_T$ , measured in an isolated muon triggered dataset in the 2012B and 2012C run periods.

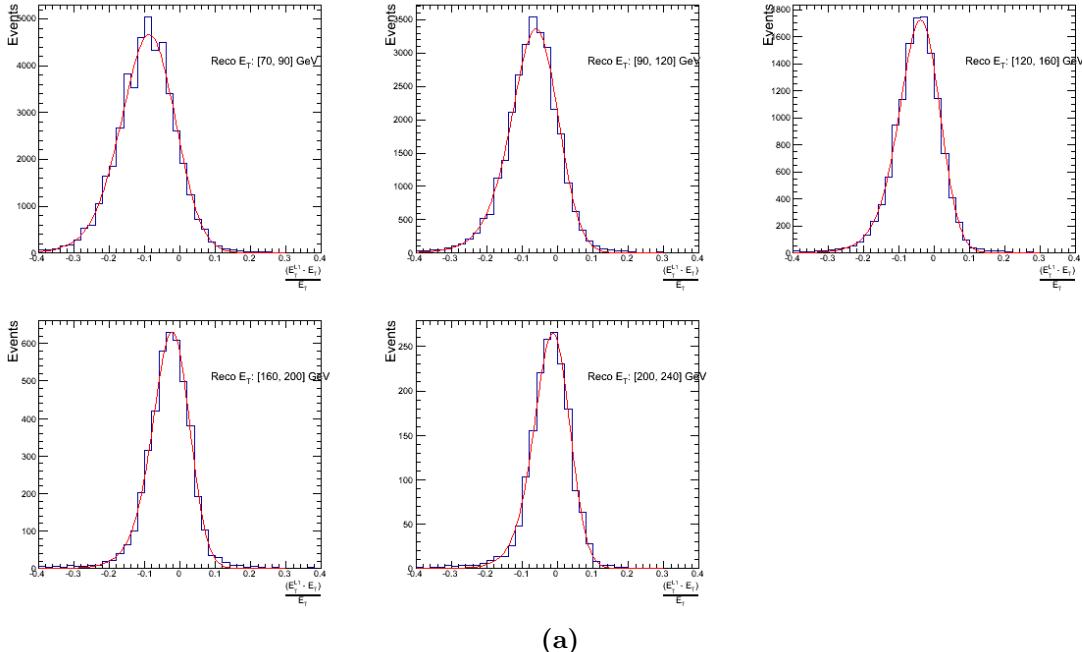
Run Period	$\mu$	$\sigma$
2012B	$6.62 \pm 0.01$	$0.79 \pm 0.03$
2012C	$19.51 \pm 0.03$	$7.14 \pm 0.02$

**Table B.1.:** Results of a cumulative EMG function fit to the turn-on curves for the matching efficiency of the leading jet in an event to a Level-1 jet in run 2012C and 2012B data, measured in an isolated muon triggered sample. The turn-on point,  $\mu$ , and resolution,  $\sigma$ , are measured with respect to offline Calo Jet  $E_T$ .

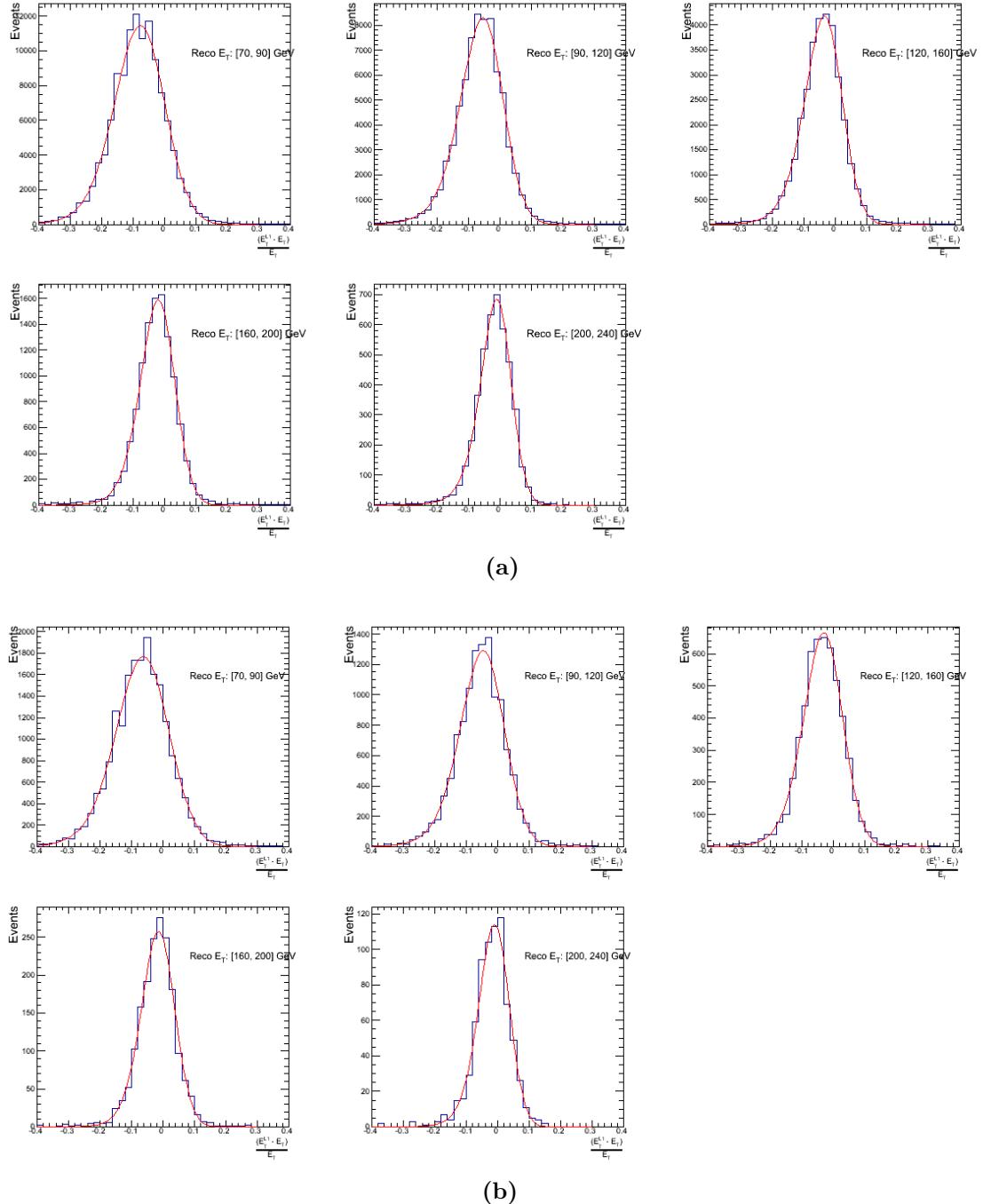
It can be seen that the turn on is sharper during the 2012B run period. The seed threshold requirement of a 5 GeV jet seed in run 2012C results in more events in which even the lead offline jet does not have an associated L1 jet. For larger jet  $E_T$  thresholds, typical of thresholds used in physics analyses, 100% efficiency is observed.

The matching efficiencies have a  $\mu$  values of 6.62 GeV and 19.51 GeV for Run 2012B and 2012C respectively and is shown in Table B.1.

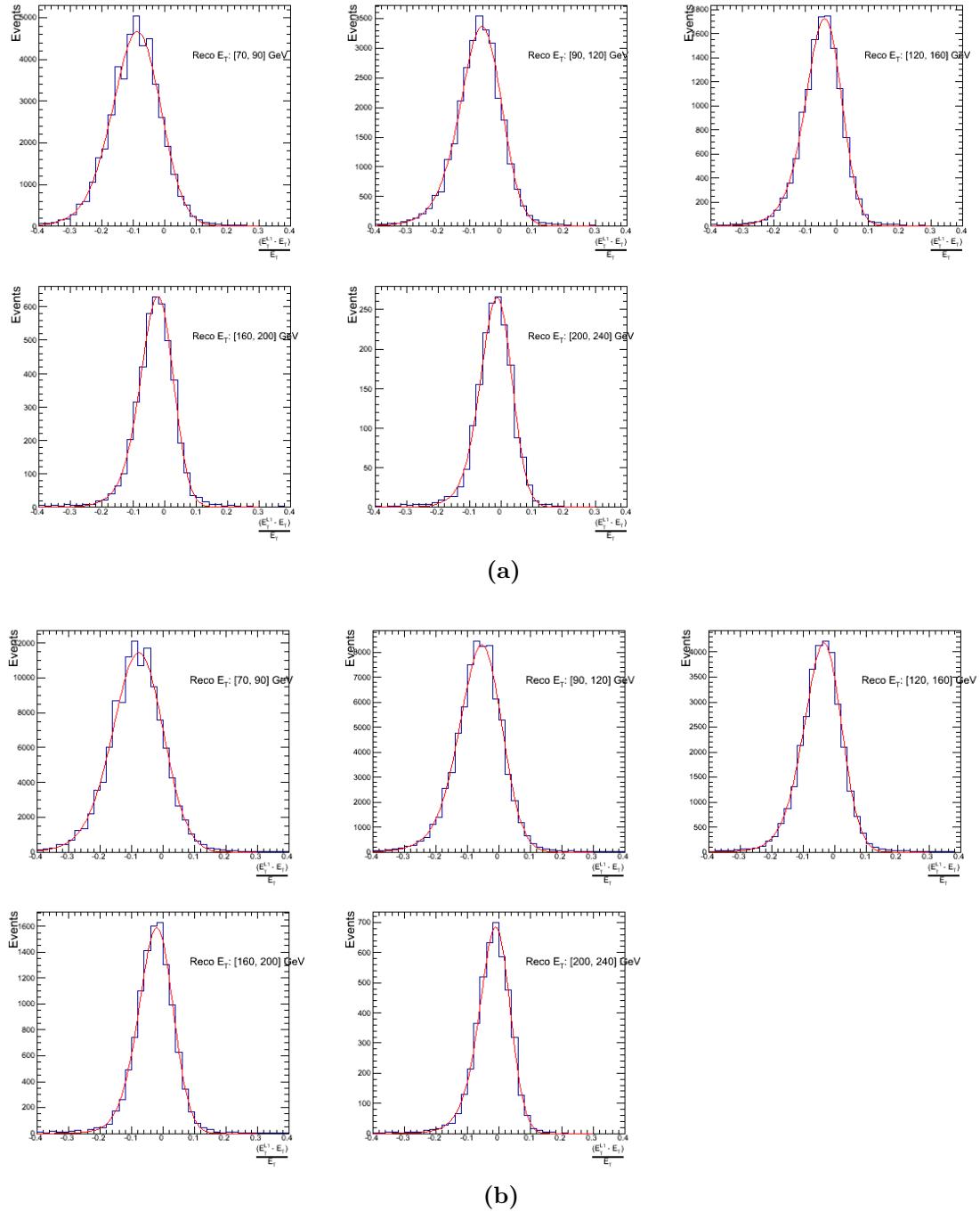
## B.2. Leading Jet Energy Resolution

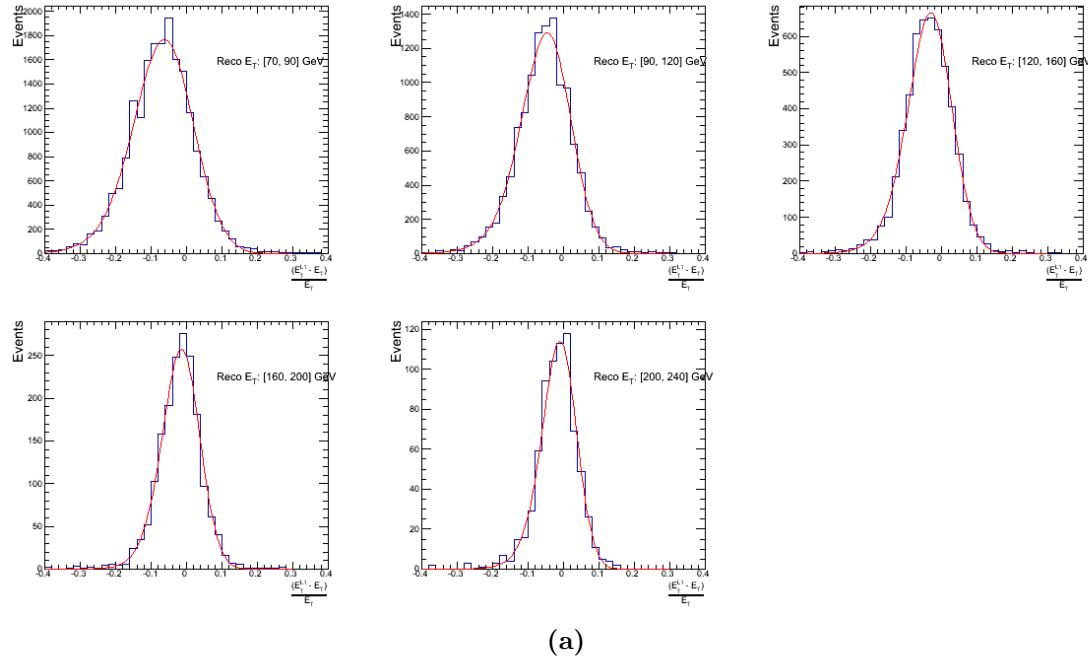


(a)



**Figure B.2.:** Resolution plots of the leading offline jet Calo  $E_T$  measured as a function of  $\frac{(\text{L1 } E_T - \text{Offline } E_T)}{\text{Offline } E_T}$  for low (a), medium (b) and high (c) pile-up conditions.



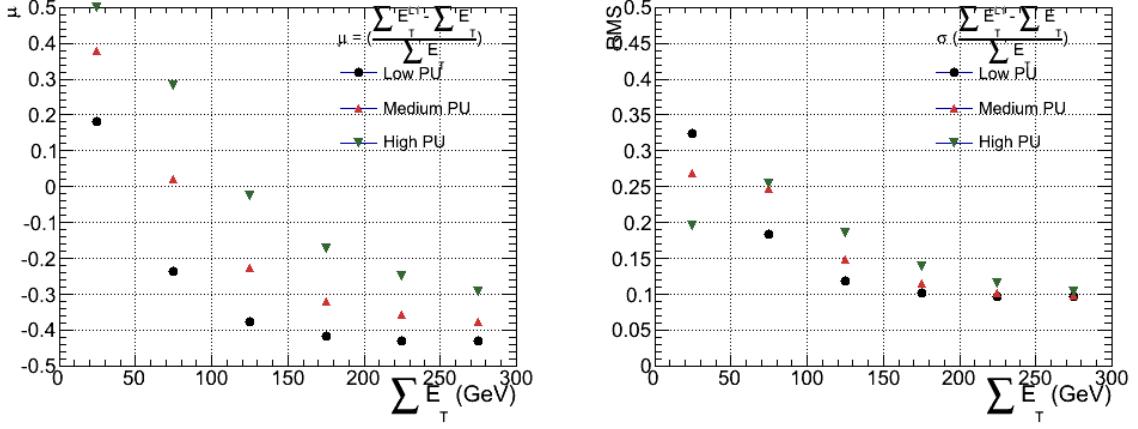


(a)

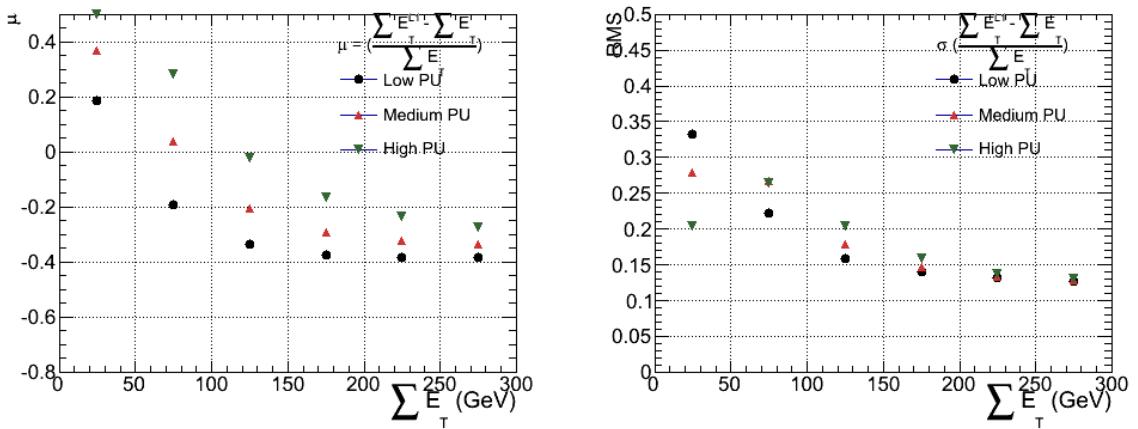
**Figure B.3.:** Resolution plots of the leading offline jet PF  $E_T$  measured as a function of  $\frac{(L1 E_T - Offline E_T)}{Offline E_T}$  for low (a), medium (b) and high (c) pile-up conditions.

### 1592 B.3. Resolution for Energy Sum Quantities

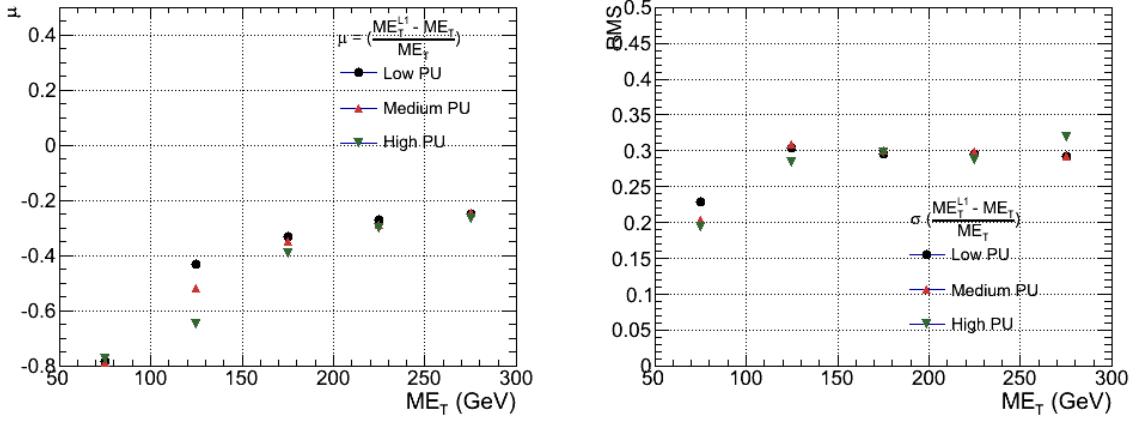
1593 The following plots show the resolution parameters for the four energy sum quantities as  
 1594 a function of the quantity ( $q$ ) itself. In this case, The mean and RMS of the individual  
 1595  $\frac{(L1 q - Offline q)}{Offline q}$  distributions, in bins of the quantity  $q$  is displayed.



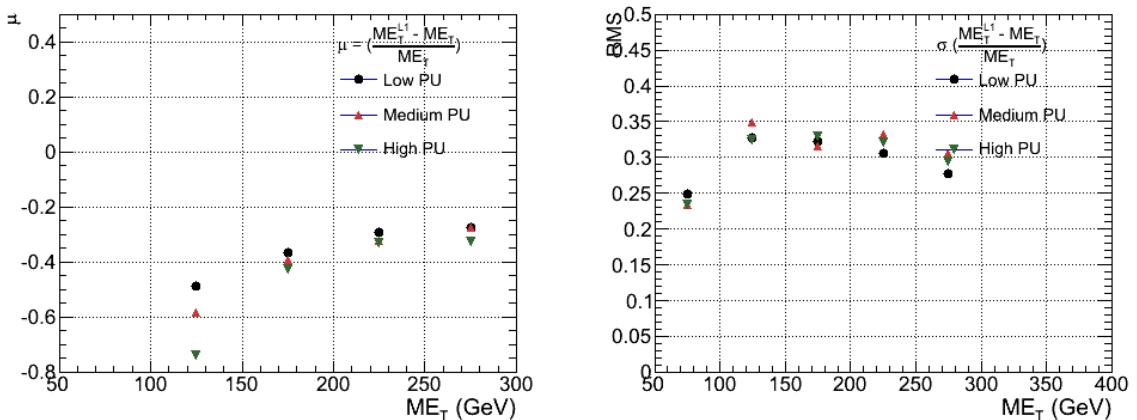
**Figure B.4.:**  $\sum E_T$  resolution parameters in bins of Calo  $\sum E_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



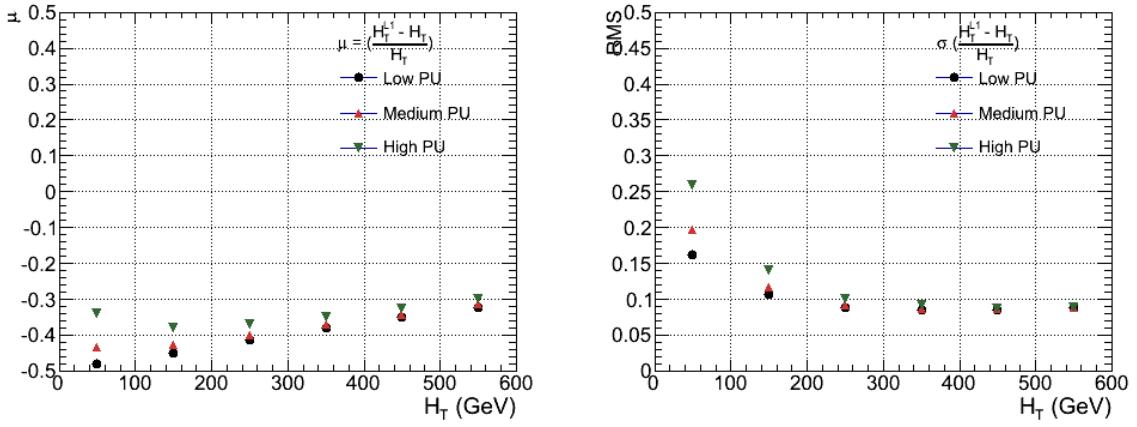
**Figure B.5.:**  $\sum E_T$  resolution parameters in bins of PF  $\sum E_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



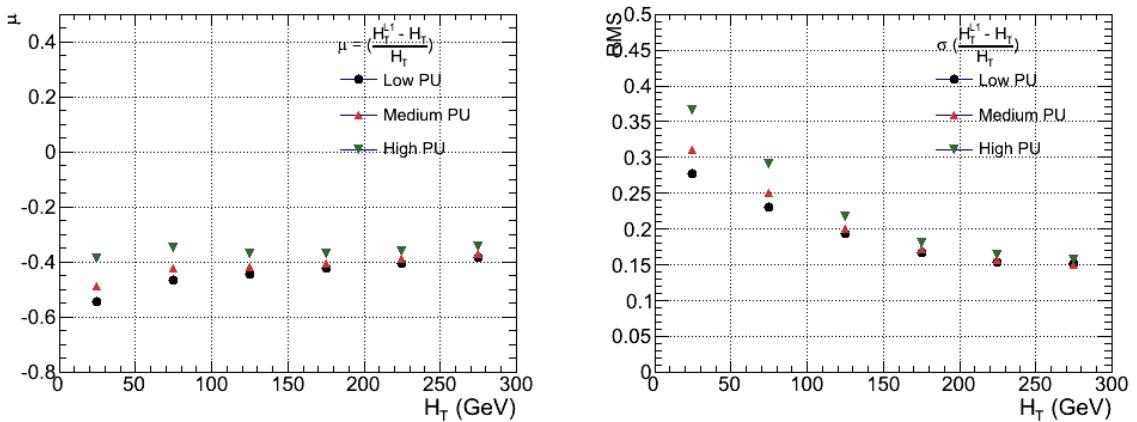
**Figure B.6.:**  $\mathcal{E}_T$  resolution parameters in bins of Calo  $\mathcal{E}_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



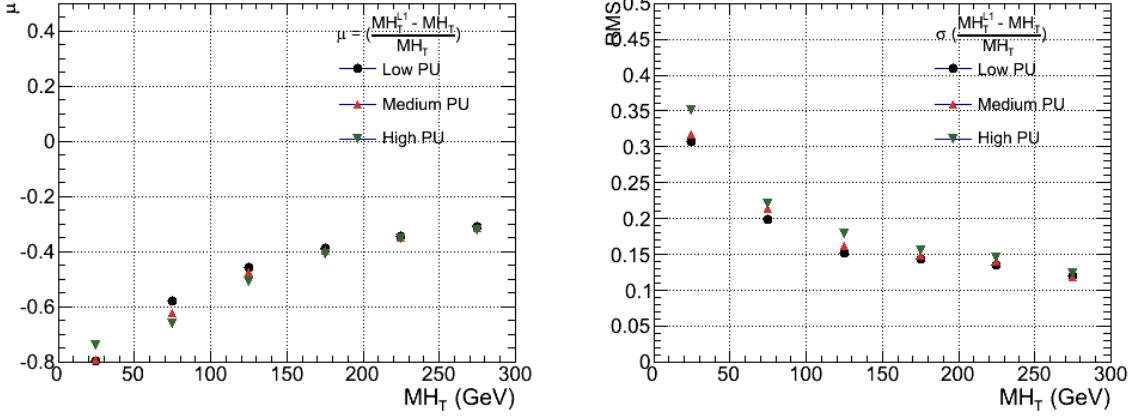
**Figure B.7.:**  $\mathcal{E}_T$  resolution parameters in bins of PF  $\mathcal{E}_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



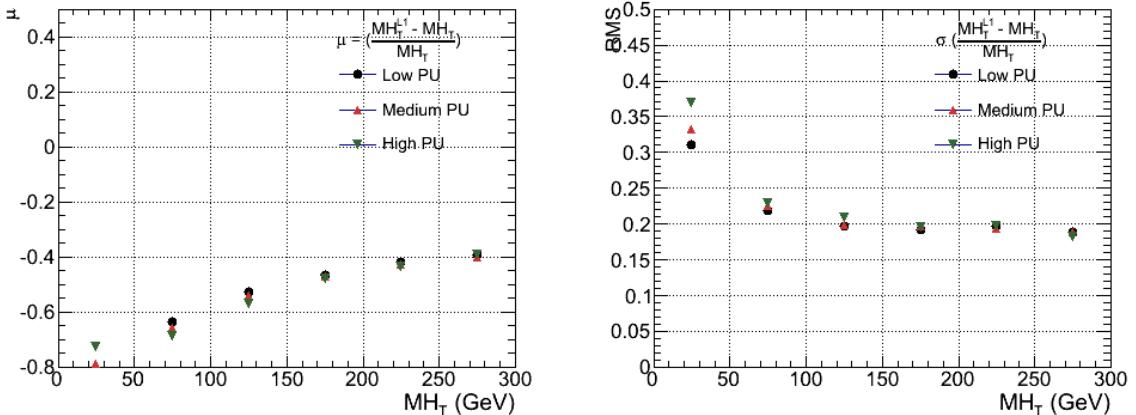
**Figure B.8.:**  $H_T$  resolution parameters in bins of Calo  $H_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



**Figure B.9.:**  $H_T$  resolution parameters in bins of PF  $H_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



**Figure B.10.:**  $H_T$  resolution parameters in bins of  $H_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.



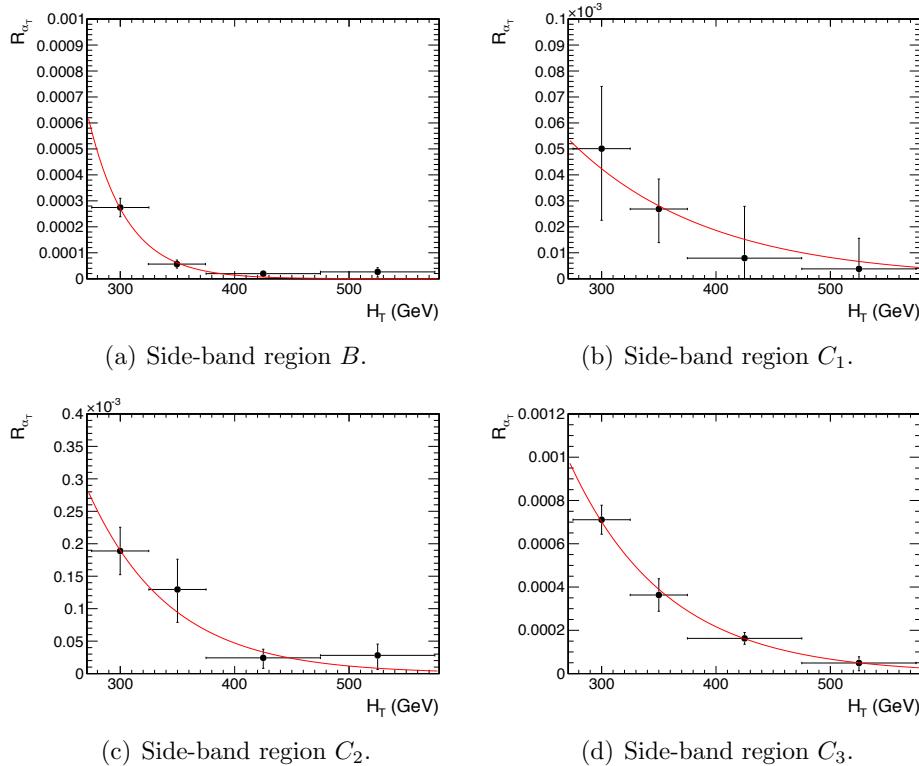
**Figure B.11.:**  $H_T$  resolution parameters in bins of PF  $H_T$  measured for the defined low, medium and high pile up conditions. The plots show the mean  $\mu$  (left), resolution  $\sigma$  (RMS) of the  $\frac{\Delta q}{q}$  distributions.

## Appendix C.

<sup>1596</sup> **Additional material on background  
estimation methods**

<sup>1597</sup>

<sup>1598</sup> **C.1. Determination of  $k_{QCD}$**



**Figure C.1.:**  $R_{\alpha_T}(H_T)$  and exponential fits for each of the data sideband regions. Fit is conducted between the  $H_T$  region  $275 < H_T < 575$ .



# <sup>1601</sup> Bibliography

- <sup>1602</sup> [1] J. Beringer *et al.*, “Review of Particle Physics (RPP),” *Phys.Rev.*, vol. D86, p. 010001, 2012.
- <sup>1604</sup> [2] G. H. et al., “Nine-year wilkinson microwave anisotropy probe (wmap) observations: Cosmological parameter results,” *The Astrophysical Journal Supplement Series*, vol. 208, no. 2, p. 19, 2013.
- <sup>1607</sup> [3] G. Aad *et al.*, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” *Phys.Lett.*, vol. B716, pp. 1–29, 2012.
- <sup>1610</sup> [4] S. Chatrchyan *et al.*, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Phys.Lett.*, vol. B716, pp. 30–61, 2012.
- <sup>1612</sup> [5] S. Chatrchyan *et al.*, “Search for supersymmetry in hadronic final states with missing transverse energy using the variables AlphaT and b-quark multiplicity in pp collisions at 8 TeV,” *Eur.Phys.J.*, vol. C73, p. 2568, 2013.
- <sup>1615</sup> [6] S. Weinberg, “A model of leptons,” *Phys. Rev. Lett.*, vol. 19, pp. 1264–1266, Nov 1967.
- <sup>1617</sup> [7] S. Glashow, “Partial Symmetries of Weak Interactions,” *Nucl.Phys.*, vol. 22, pp. 579–588, 1961.
- <sup>1619</sup> [8] A. Salam, “Weak and Electromagnetic Interactions,” *Conf.Proc.*, vol. C680519, pp. 367–377, 1968.
- <sup>1621</sup> [9] G. Hooft, “Renormalizable lagrangians for massive yang-mills fields,” *Nuclear Physics B*, vol. 35, no. 1, pp. 167 – 188, 1971.
- <sup>1623</sup> [10] F. Hasert *et al.*, “Observation of Neutrino Like Interactions Without Muon Or Electron in the Gargamelle Neutrino Experiment,” *Phys.Lett.*, vol. B46, pp. 138–140, 1973.

- [1626] [11] G. Arnison *et al.*, “Experimental Observation of Lepton Pairs of Invariant Mass Around 95-GeV/c\*\*2 at the CERN SPS Collider,” *Phys.Lett.*, vol. B126, pp. 398–410, 1983.
- [1629] [12] M. Banner *et al.*, “Observation of Single Isolated Electrons of High Transverse Momentum in Events with Missing Transverse Energy at the CERN anti-p p Collider,” *Phys.Lett.*, vol. B122, pp. 476–485, 1983.
- [1632] [13] E. Noether, “Invariante variationsprobleme,” *Nachrichten von der Gesellschaft der Wissenschaften zu Gttingen, Mathematisch-Physikalische Klasse*, vol. 1918, pp. 235–257, 1918.
- [1635] [14] F. Halzen and A. D. Martin, “Quarks and leptons.” Wiley, 1985.
- [1636] [15] *Introduction to Elementary Particles*. Wiley-VCH, 2nd ed., Oct. 2008.
- [1637] [16] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, “Experimental Test of Parity Conservation in Beta Decay,” *Physical Review*, vol. 105, pp. 1413–1415, Feb. 1957.
- [1640] [17] P. Higgs, “Broken symmetries, massless particles and gauge fields,” *Physics Letters*, vol. 12, no. 2, pp. 132 – 133, 1964.
- [1642] [18] F. Englert and R. Brout, “Broken symmetry and the mass of gauge vector mesons,” *Phys. Rev. Lett.*, vol. 13, pp. 321–323, Aug 1964.
- [1644] [19] P. W. Higgs, “Broken symmetries and the masses of gauge bosons,” *Phys. Rev. Lett.*, vol. 13, pp. 508–509, Oct 1964.
- [1646] [20] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, “Global conservation laws and massless particles,” *Phys. Rev. Lett.*, vol. 13, pp. 585–587, Nov 1964.
- [1648] [21] S. Weinberg, “A model of leptons,” *Phys. Rev. Lett.*, vol. 19, pp. 1264–1266, Nov 1967.
- [1650] [22] H. Yukawa, “On the interaction of elementary particles. i,” *Progress of Theoretical Physics Supplement*, vol. 1, pp. 1–10, 1955.
- [1652] [23] Y. e. a. Fukuda, “Evidence for oscillation of atmospheric neutrinos,” *Phys. Rev. Lett.*, vol. 81, pp. 1562–1567, Aug 1998.
- [1654] [24] R. Becker-Szendy, C. Bratton, D. Casper, S. Dye, W. Gajewski, *et al.*, “A Search for muon-neutrino oscillations with the IMB detector,” *Phys.Rev.Lett.*, vol. 69,

- 1656 pp. 1010–1013, 1992.
- 1657 [25] S. P. Martin, “A Supersymmetry primer,” 1997.
- 1658 [26] H. Nilles, *Supersymmetry, Supergravity and Particle Physics*. Physics reports, North-Holland Physics Publ., 1984.
- 1660 [27] H. E. Haber and G. L. Kane, “The Search for Supersymmetry: Probing Physics Beyond the Standard Model,” *Phys.Rept.*, vol. 117, pp. 75–263, 1985.
- 1662 [28] E. Witten, “Dynamical Breaking of Supersymmetry,” *Nucl.Phys.*, vol. B188, p. 513, 1981.
- 1664 [29] J. Wess and B. Zumino, “Supergauge transformations in four dimensions,” *Nuclear Physics B*, vol. 70, no. 1, pp. 39 – 50, 1974.
- 1666 [30] H. Muller-Kirsten and A. Wiedemann, *Introduction to Supersymmetry*. World Scientific lecture notes in physics, World Scientific, 2010.
- 1668 [31] I. Aitchison, *Supersymmetry in Particle Physics: An Elementary Introduction*. Cambridge University Press, 2007.
- 1670 [32] K. A. Intriligator and N. Seiberg, “Lectures on Supersymmetry Breaking,” *Class.Quant.Grav.*, vol. 24, pp. S741–S772, 2007.
- 1672 [33] Y. Shadmi, “Supersymmetry breaking,” pp. 147–180, 2006.
- 1673 [34] C. Burgess, P. G. Camara, S. de Alwis, S. Giddings, A. Maharana, *et al.*, “Warped Supersymmetry Breaking,” *JHEP*, vol. 0804, p. 053, 2008.
- 1675 [35] H. Murayama, “Supersymmetry breaking made easy, viable, and generic,” 2007.
- 1676 [36] H. Baer and X. Tata, *Weak Scale Supersymmetry: From Superfields to Scattering Events*. Cambridge University Press, 2006.
- 1678 [37] S. P. Martin, “Implications of supersymmetric models with natural r-parity conservation,” 1996.
- 1680 [38] G. L. Kane, C. F. Kolda, L. Roszkowski, and J. D. Wells, “Study of constrained minimal supersymmetry,” *Phys.Rev.*, vol. D49, pp. 6173–6210, 1994.
- 1682 [39] C. Stlege, G. Bertone, D. Cerdeno, M. Fornasa, R. Ruiz de Austri, *et al.*, “Updated global fits of the cmSSM including the latest LHC SUSY and Higgs searches and XENON100 data,” *JCAP*, vol. 1203, p. 030, 2012.

- 1685 [40] M. Citron, J. Ellis, F. Luo, J. Marrouche, K. Olive, *et al.*, “The End of the CMSSM  
1686 Coannihilation Strip is Nigh,” *Phys.Rev.*, vol. D87, p. 036012, 2013.
- 1687 [41] D. Ghosh, M. Guchait, S. Raychaudhuri, and D. Sengupta, “How Constrained is  
1688 the cMSSM?,” *Phys.Rev.*, vol. D86, p. 055007, 2012.
- 1689 [42] D. Alves *et al.*, “Simplified Models for LHC New Physics Searches,” *J.Phys.*, vol. G39,  
1690 p. 105005, 2012.
- 1691 [43] J. Alwall, P. Schuster, and N. Toro, “Simplified Models for a First Characterization  
1692 of New Physics at the LHC,” *Phys.Rev.*, vol. D79, p. 075020, 2009.
- 1693 [44] S. Chatrchyan *et al.*, “Interpretation of Searches for Supersymmetry with simplified  
1694 Models,” *Phys.Rev.*, vol. D88, p. 052017, 2013.
- 1695 [45] J. Hisano, K. Kurosawa, and Y. Nomura, “Natural effective supersymmetry,”  
1696 *Nucl.Phys.*, vol. B584, pp. 3–45, 2000.
- 1697 [46] M. Papucci, J. T. Ruderman, and A. Weiler, “Natural SUSY Endures,” *JHEP*,  
1698 vol. 1209, p. 035, 2012.
- 1699 [47] B. Allanach and B. Gripaios, “Hide and Seek With Natural Supersymmetry at the  
1700 LHC,” *JHEP*, vol. 1205, p. 062, 2012.
- 1701 [48] K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC,” *JINST*, vol. 3,  
1702 p. S08002, 2008.
- 1703 [49] G. Aad *et al.*, “The ATLAS Experiment at the CERN Large Hadron Collider,”  
1704 *JINST*, vol. 3, 2008.
- 1705 [50] R. Adolphi *et al.*, “The cms experiment at the cern lhc,” *JINST*, vol. 0803, p. S08004,  
1706 2008.
- 1707 [51] A. A. Alves *et al.*, “The LHCb Detector at the LHC,” *JINST*, vol. 3, p. S08005,  
1708 2008.
- 1709 [52] J.-L. Caron, “Lhc layout.. schema general du lhc..” Sep 1997.
- 1710 [53] C. Collaboration, “Cms luminosity - public results.”  
1711 twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults., 2011.
- 1712 [54] CERN, “Cms compact muon solenoid..” <http://public.web.cern.ch/public/Objects/LHC/CMSnc.jpg>  
1713 Feb 2010.

- <sub>1714</sub> [55] *The CMS electromagnetic calorimeter project: Technical Design Report*. Technical Design Report CMS, Geneva: CERN, 1997.
- <sub>1715</sub>
- <sub>1716</sub> [56] *The CMS muon project: Technical Design Report*. Technical Design Report CMS, Geneva: CERN, 1997.
- <sub>1717</sub>
- <sub>1718</sub> [57] CMS Collaboration, “The cms physics technical design report, volume 1,” *CERN/LHCC*, vol. 2006-001, 2006.
- <sub>1719</sub>
- <sub>1720</sub> [58] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-  $k_t$  jet clustering algorithm,” *Journal of High Energy Physics*, vol. 2008, no. 04, p. 063, 2008.
- <sub>1721</sub>
- <sub>1722</sub> [59] “Jet performance in pp collisions at 7 tev,” Tech. Rep. CMS-PAS-JME-10-003, CERN, Geneva, 2010.
- <sub>1723</sub>
- <sub>1724</sub> [60] X. Janssen, “Underlying event and jet reconstruction in cms,” Tech. Rep. CMS-CR-2011-012, CERN, Geneva, Jan 2011.
- <sub>1725</sub>
- <sub>1726</sub> [61] T. C. collaboration, “Determination of jet energy calibration and transverse momentum resolution in cms,” *Journal of Instrumentation*, vol. 6, no. 11, p. P11002, 2011.
- <sub>1727</sub>
- <sub>1728</sub>
- <sub>1729</sub> [62] R. Eusebi and on behalf of the CMS collaboration), “Jet energy corrections and uncertainties in cms: reducing their impact on physics measurements,” *Journal of Physics: Conference Series*, vol. 404, no. 1, p. 012014, 2012.
- <sub>1730</sub>
- <sub>1731</sub>
- <sub>1732</sub> [63] “Algorithms for b Jet identification in CMS,” Tech. Rep. CMS-PAS-BTV-09-001, CERN, 2009. Geneva, Jul 2009.
- <sub>1733</sub>
- <sub>1734</sub> [64] “Performance of b tagging at  $\sqrt{s}=8$  tev in multijet, ttbar and boosted topology events,” no. CMS-PAS-BTV-13-001, 2013.
- <sub>1735</sub>
- <sub>1736</sub> [65] T. C. collaboration, “Identification of b-quark jets with the cms experiment,” *Journal of Instrumentation*, vol. 8, no. 04, p. P04013, 2013.
- <sub>1737</sub>
- <sub>1738</sub> [66] S. Dasu *et al.*, “CMS. The TriDAS project. Technical design report, vol. 1: The trigger systems,” 2000.
- <sub>1739</sub>
- <sub>1740</sub> [67] P. Sphicas, “CMS: The TriDAS project. Technical design report, Vol. 2: Data acquisition and high-level trigger,” 2002.
- <sub>1741</sub>
- <sub>1742</sub> [68] J. B. et al., “Calibration and Performance of the Jets and Energy Sums in the Level-1 Trigger ,” no. CMS IN 2013/006 (2013), 2013.
- <sub>1743</sub>

- <sub>1744</sub> [69] B. et al., “Study of Level-1 Trigger Jet Performance in High Pile-up Running  
<sub>1745</sub> Conditions,” no. CMS IN 2013/007 (2013), 2013.
- <sub>1746</sub> [70] J. J. Brooke, “Performance of the cms level-1 trigger,” Tech. Rep. CMS-CR-2012-322.  
<sub>1747</sub> CERN-CMS-CR-2012-322, CERN, Geneva, Nov 2012.
- <sub>1748</sub> [71] L. Randall and D. Tucker-Smith, “Dijet searches for supersymmetry at the large  
<sub>1749</sub> hadron collider,” *Phys. Rev. Lett.*, vol. 101, p. 221803, Nov 2008.
- <sub>1750</sub> [72] “SUSY searches with dijet events,” 2008.
- <sub>1751</sub> [73] “Search strategy for exclusive multi-jet events from supersymmetry at CMS,” Tech.  
<sub>1752</sub> Rep. CMS-PAS-SUS-09-001, CERN, 2009. Geneva, Jul 2009.
- <sub>1753</sub> [74] “Calorimeter Jet Quality Criteria for the First CMS Collision Data,” Tech. Rep.  
<sub>1754</sub> CMS-PAS-JME-09-008, CERN, 2010. Geneva, Apr 2010.
- <sub>1755</sub> [75] T. C. collaboration, “Performance of cms muon reconstruction in pp collision events  
<sub>1756</sub> at  $\sqrt{s} = 7$  tev,” *Journal of Instrumentation*, vol. 7, no. 10, p. P10002, 2012.
- <sub>1757</sub> [76] “Search for supersymmetry in events with photons and missing energy,” Tech. Rep.  
<sub>1758</sub> CMS-PAS-SUS-12-018, CERN, Geneva, 2012.
- <sub>1759</sub> [77] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas,” *Phys.Lett.*,  
<sub>1760</sub> vol. B659, pp. 119–126, 2008.
- <sub>1761</sub> [78] Z. Bern, G. Diana, L. J. Dixon, F. Febres Cordero, S. Hoche, H. Ita, D. A. Kosower,  
<sub>1762</sub> D. Maitre, and K. J. Ozeren, “Driving missing data at next-to-leading order,” *Phys.  
Rev. D*, vol. 84, p. 114002, Dec 2011.
- <sub>1764</sub> [79] “Data-Driven Estimation of the Invisible Z Background to the SUSY MET Plus  
<sub>1765</sub> Jets Search,” Tech. Rep. CMS-PAS-SUS-08-002, CERN, 2009. Geneva, Jan 2009.
- <sub>1766</sub> [80] Z. Bern, G. Diana, L. Dixon, F. Febres Cordero, S. Hoche, *et al.*, “Driving Missing  
<sub>1767</sub> Data at Next-to-Leading Order,” *Phys.Rev.*, vol. D84, p. 114002, 2011.