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A search for sparticles in zero lepton final states

2

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ABSTRACT

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A search for sparticles in zero lepton final states

14

Russell W. Smith

15 TODO : Here's where your abstract will eventually go. The above text is all in the

16 center, but the abstract itself should be written as a regular paragraph on the page,

17 and it should not have indentation. Just replace this text.

Acknowledgements

Chapter 1

Introduction

Particle physics is a remarkably successful field of scientific inquiry. The ability to precisely predict the properties of a exceedingly wide range of physical phenomena, such as the description of the cosmic microwave background [**Perdereau:2016akt**, **Aghanim:2016sns**], the understanding of the anomalous magnetic dipole moment of the electron [**Schwinger:1948iu**, **Laporta:1996mq**], and the measurement of the number of weakly-interacting neutrino flavors [**ALEPH:2005ab**] is truly amazing.

The theory that has allowed this range of predictions is the *Standard Model* of particle physics (SM). The Standard Model combines the electroweak theory of Glashow, Weinberg, and Salam [**Glashow:1961tr**, **Weinberg:1967tq**, **Salam:1968rm**] with the theory of the strong interactions, as first envisioned by Gell-Mann and Zweig [**GellMann:1964nj**, **Zweig:1964jf**]. This quantum field theory (QFT) contains a tiny number of particles, whose interactions describe phenomena up to at least the TeV scale. These particles are manifestations of the fields of the Standard Model, after application of the Higgs Mechanism. The particle content of the SM consists only of the six quarks, the six leptons, the four gauge bosons, and the scalar Higgs boson.

Despite its impressive range of described phenomena, the Standard Model has some theoretical and experimental deficiencies. The SM contains 26 free parameters ¹. It would be more theoretically pleasing to understand

¹This is the Standard Model corrected to include neutrino masses. These parameters are the fermion masses (6 leptons, 6 quarks), CKM and PMNS mixing angles (8 angles, 2 CP-violating phases), W/Z/Higgs masses (3), the Higgs field expectation value, and the couplings of the strong,

42 these free parameters in terms of a more fundamental theory. The major
 43 theoretical concern of the Standard Model, as it pertains to this thesis, is
 44 the *hierachy problem*[**Weinberg:1975gm**, **Weinberg:1979bn**, **Gildener:1976ai**,
 45 **Susskind:1978ms**, **susyPrimer**]. The light mass of the Higgs boson (125 GeV)
 46 should be quadratically dependent on the scale of UV physics, due to the quan-
 47 tum corrections from high-energy physics processes. The most perplexing exper-
 48 imental issue is the existence of *dark matter*, as demonstrated by galactic rota-
 49 tion curves [**Rubin:1970zza**, **Roberts:1970zza**, **Rubin:1980zd**, **Rubin:1985ze**,
 50 **Bosma:1981zz**, **Persic:1995ru**, **darkMatterPrimer**]. This data has shown that
 51 there exists additional matter which has not yet been seen interacting with the par-
 52 ticles of the Standard Model. There is no particle in the SM which can act as a
 53 candidate for dark matter.

54 Both of these major issues, as well as numerous others, can be solved by the in-
 55 troduction of *supersymmetry* (SUSY) [**Miyazawa:1966mfa**, **Gervais:1971xj**,
 56 **Gervais:1971ji**, **Golfand:1971iw**, **Neveu:1971rx**, **Neveu:1971iv**,
 57 **Volkov:1973ix**, **Wess:1973kz**, **Salam:1974ig**, **Ferrara:1974ac**, **Wess:1974tw**,
 58 **susyPrimer**]. In supersymmetric theories, each SM particles has a so-called *super-*
 59 *partner*, or sparticle partner, differing from given SM particle by 1/2 in spin. These
 60 theories solve the hierachy problem, since the quantum corrections induced from the
 61 superpartners exactly cancel those induced by the SM particles. In addition, these
 62 theories are usually constructed assuming R -parity, which can be thought of as the
 63 “charge” of supersymmetry, with SM particles having $R = 1$ and sparticles having
 64 $R = -1$. In collider experiments, since the incoming SM particles have total $R = 1$,
 65 the resulting sparticles are produced in pairs. This produces a rich phenomenology,
 66 which is characterized by significant hadronic activity and large missing transverse
 67 energy (E_T^{miss}), which provide significant discrimination against SM backgrounds

weak, and electromagnetic forces ($3 \alpha_{force}$) .

68 [Farrar:1978xj].

69 Despite the power of searches for supersymmetry where E_T^{miss} is a primary discrim-
70 inating variable, there has been significant interest in the use of other variables to dis-
71 criminate against SM backgrounds. These include searches employing variables such
72 as αT , $M_{T,2}$, and the razor variables (M_R, R^2) [SUSY-2014-05, SUSY-2014-06,
73 SUSY-2014-07, CMS-SUS-12-005, CMS-SUS-11-024, CMS-SUS-12-005,
74 CMS-SUS-10-003, CMS-SUS-11-003, CMS-SUS-12-002, CMS-SUS-13-019,
75 CMS-SUS-15-003, SUSY-2011-22]. In this thesis, we will present the first search
76 for supersymmetry using the novel Recursive Jigsaw Reconstruction (RJR) technique.
77 RJR can be considered the conceptual successor of the razor variables. We impose
78 a particular final state “decay tree” on an events, which roughly corresponds to a
79 simplified Feynmann diagram in decays containing weakly-interacting particles. We
80 account for the missing degrees of freedom associated to the weakly-interacting parti-
81 cles by a series of simplifying assumptions, which allow us to calculate our variables of
82 interest at each step in the decay tree. This allows an unprecedented understanding
83 of the internal structure of the decay and the ability to construct additional variables
84 to reject Standard Model backgrounds.

85 This thesis details a search for the superpartners of the gluon and quarks, the
86 gluino and squarks, in final states with zero leptons, with 13.3 fb^{-1} of data using the
87 ATLAS detector. We organize the thesis as follows. The theoretical foundations of
88 the Standard Model and supersymmetry are described in Chapters 2 and 3. The
89 Large Hadron Collider and the ATLAS detector are presented in Chapters 4 and 5.
90 Chapter 5 provides a detailed description of Recursive Jigsaw Reconstruction and a
91 description of the variables used for the particular search presented in this thesis.
92 Chapter 6 presents the details of the analysis, including details of the dataset, object
93 reconstruction, and selections used. In Chapter 7, the final results are presented;
94 since there is no evidence of a supersymmetric signal in the analysis, we present the

95 final exclusion curves in simplified supersymmetric models.

The Standard Model

98 Here you can write some introductory remarks about your chapter. I like to give each
99 sentence its own line.

100 When you need a new paragraph, just skip an extra line.

101 **2.1 Quantum Field Theory**

102

103 In this section, we provide a brief overview of the necessary concepts from Quan-
104 tum Field Theory (QFT).

105 In modern physics, the laws of nature are described by the “action” S , with the
106 imposition of the principle of minimum action. The action is the integral over the
107 spacetime coordinates of the “Lagrangian density” \mathcal{L} , or Lagrangian for short. The
108 Lagrangian is a function of “fields”; general fields will be called $\phi(x^\mu)$, where the
109 indices μ run over the space-time coordinates. We can then write the action S as

$$S = \int d^4x \mathcal{L}[\phi_i(x^\mu), \partial_\mu \phi_i(x^\mu)] \quad (2.1)$$

110 where we have an additional summation over i (of the different fields). Generally,
111 we impose the following constraints on the Lagrangian :

- 112 1. Translational invariance - The Lagrangian is only a function of the fields ϕ and
113 their derivatives $\partial_\mu \phi$
- 114 2. Locality - The Lagrangian is only a function of one point x_μ in spacetime.

cite Yuval's
lectures and
notes some-
how

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- 115 3. Reality condition - The Lagrangian is real to conserve probability.
- 116 4. Lorentz invariance - The Lagrangian is invariant under the Poincaré group of
117 spacetime.
- 118 5. Analyticity - The Lagrangian is an analytical function of the fields; this is to
119 allow the use of perturbation theory.
- 120 6. Invariance and Naturalness - The Lagrangian is invariant under some internal
121 symmetry groups; in fact, the Lagrangian will have *all* terms allowed by the
122 imposed symmetry groups.
- 123 7. Renormalizability - The Lagrangian will be renormalizable - in practice, this
124 means there will not be terms with more than power 4 in the fields.

125 The key item from the point of view of this thesis is that of “Invariance and
126 Natural”. We impose a set of “symmetries” and then our Lagrangian is the most
127 general which is allowed by those symmetries.

128 2.2 Symmetries

129 Symmetries can be seen as the fundamental guiding concept of modern physics. Sym-
130 metries are described by “groups”. . To illustrate the importance of symmetries and
131 their mathematical description, groups, we start here with two of the simplest and
132 most useful examples : \mathbb{Z}_2 and $U(1)$.

133 \mathbb{Z}_2 symmetry

134 \mathbb{Z}_2 symmetry is the simplest example of a “discrete” symmetry. Consider the most
135 general Lagrangian of a single real scalar field $\phi(x_\mu)$

$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m^2}{2}\phi^2 - \frac{\mu}{2\sqrt{2}}\phi^3 - \lambda\phi^4 \quad (2.2)$$

Now we *impose* the symmetry

$$\mathcal{L}(\phi) = \mathcal{L}(-\phi) \quad (2.3)$$

136 This has the effect of restricting the allowed terms of the Lagrangian. In particular,
 137 we can see the term $\phi^3 \rightarrow -\phi^3$ under the symmetry transformation, and thus must
 138 be disallowed by this symmetry. This means under the imposition of this particular
 139 symmetry, our Lagrangian should be rewritten as

$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m^2}{2}\phi^2 - \lambda\phi^4 \quad (2.4)$$

140 The effect of this symmetry is that the total number of ϕ particles can only change
 141 by even numbers, since the only interaction term $\lambda\phi^4$ is an even power of the field.
 142 This symmetry is often imposed in supersymmetric theories, as we will see in Chapter
 143 3.

144 **$U(1)$ symmetry**

145 $U(1)$ is the simplest example of a “continuous” (or Lie) group. Now consider a theory
 146 with a single complex scalar field $\phi = \text{Re } \phi + i \text{Im } \phi$

$$\mathcal{L}_\phi = \delta_{i,j} \frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_j - \frac{m^2}{2}\phi_i\phi_j - \frac{\mu}{2\sqrt{2}}\phi_i\phi_j\phi_k - \lambda\phi_i\phi_j\phi_k\phi_l \quad (2.5)$$

147 where $i, j, k, l = \text{Re}, \text{Im}$. In this case, we impose the following $U(1)$ symmetry
 148 : $\phi \rightarrow e^{i\theta}\phi, \phi^* \rightarrow e^{-i\theta}\phi^*$. We see immediately that this again disallows the third-order
 149 terms, and we can write a theory of a complex scalar field with $U(1)$ symmetry as

$$\mathcal{L}_\phi = \partial_\mu\phi\partial^\mu\phi^* - \frac{m^2}{2}\phi\phi^* - \lambda(\phi\phi^*)^2 \quad (2.6)$$

150 2.3 Local symmetries

151 The two examples considered above are “global” symmetries in the sense that the
 152 symmetry transformation does not depend on the spacetime coordinate x_μ . We know
 153 look at local symmetries; in this case, for example with a local $U(1)$ symmetry, the
 154 transformation has the form $\phi(x_\mu) \rightarrow e^{i\theta(x_\mu)}\phi(x_\mu)$. These symmetries are also known
 155 as “gauge” symmetries; all symmetries of the Standard Model are gauge symmetries.

There are wide-ranging consequences to the imposition of local symmetries. To begin, we note that the derivative terms of the Lagrangian ?? are *not* invariant under a local symmetry transformation

$$\partial_\mu \phi(x_\mu) \rightarrow \partial_\mu (e^{i\theta(x_\mu)} \phi(x_\mu)) = (1 + i\theta(x_\mu)) e^{i\theta(x_\mu)} \phi(x_\mu) \quad (2.7)$$

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156 This leads us to note that the kinetic terms of the Lagrangian are also not invariant
 158 under a gauge symmetry. This would lead to a model with no dynamics, which is
 159 clearly unsatisfactory.

160 Let us take inspiration from the case of global symmetries. We need to define a
 161 so-called “covariant” derivative D^μ such that

$$D^\mu \phi \rightarrow e^{iq\theta(x^\mu)} D^\mu \phi \rightarrow e^{-iq\theta(x^\mu)} D^\mu \phi \quad (2.8)$$

162 Since ϕ and ϕ^* transforms with the opposite phase, this will lead the invariance
 163 of the Lagrangian under our local gauge transformation. This D^μ is of the following
 164 form

$$D^\mu = \partial_\mu - igqA^\mu \quad (2.9)$$

165 where A^μ is a vector field we introduce with the transformation law

$$A^\mu \rightarrow A^\mu - \frac{1}{g} \partial_\mu \theta \quad (2.10)$$

166 and g is the coupling constant associated to vector field. This vector field A^μ is
 167 also known as a “gauge” field.

168 Since we need to add all allowed terms to the Lagrangian, we define

$$F^{\mu\nu} = A^\mu A^\nu - A^\nu A^\mu \quad (2.11)$$

169 and then we must also add the kinetic term :

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \quad (2.12)$$

170 The most general renormalizable Lagrangian with fermion and scalar fields can
 171 be written in the following form

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_\phi + \mathcal{L}_\psi + \mathcal{L}_{Yukawa} \quad (2.13)$$

172 Symmetry breaking and the Higgs mechanism

173 Here we view some examples of symmetry breaking. We investigate breaking of a
 174 global $U(1)$ symmetry and a local $U(1)$ symmetry. The SM will break the electroweak
 175 symmetry $SU(2) \times U(1)$, and in Chapter 3 we will see how supersymmetry must also
 176 be broken.

177 There are two ideas of symmetry breaking

178 • Explicit symmetry breaking by a small parameter - in this case, we have a small
 179 parameter which breaks an “approximate” symmetry of our Lagrangian. An
 180 example would be the theory of the single scalar field ϕ , when $\mu \ll m^2$ and
 181 $\mu \ll \lambda$. In this case, we can often ignore the small term when considering
 182 low-energy processes.

183 • Spontaneous symmetry breaking (SSB) - spontaneous symmetry breaking oc-
 184 curs when the Lagrangian is symmetric with respect to a given symmetry trans-

185 formation, but the ground state of the theory is *not* symmetric with respect to
 186 that transformation. This can have some fascinating consequences, as we will
 187 see in the following examples

188 Symmetry breaking a

189 **U(1) global symmetry breaking**

Consider the theory of a complex scalar field under the $U(1)$ symmetry, or the transformation

$$\phi \rightarrow e^{i\theta} \phi \quad (2.14)$$

The Lagrangian for this theory is

$$\mathcal{L} = \partial^\mu \phi^\dagger \partial_\mu \phi + \frac{\mu^2}{2} \phi^\dagger \phi + \frac{\lambda}{4} (\phi^\dagger \phi)^2 \quad (2.15)$$

Let us write this theory in terms of two scalar fields, h and ξ : $\phi = (h + i\xi)/\sqrt{2}$.

The Lagrangian can then be written as

$$\mathcal{L} = \partial^\mu h \partial_\mu h + \partial^\mu \xi \partial_\mu \xi - \frac{\mu^2}{2} (h^2 + \xi^2) - \frac{\lambda}{4} (h^2 + \xi^2)^2 \quad (2.16)$$

First, note that the theory is only stable when $\lambda > 0$. To understand the effect of SSB, we now enforce that $\mu^2 < 0$, and define $v^2 = -\mu^2/\lambda$. We can then write the scalar potential of this theory as :

$$V(\phi) = \lambda(\phi^\dagger \phi - v^2/2)^2 \quad (2.17)$$

Minimizing this equation with respect to ϕ , we can see that the “vacuum expectation value” of the theory is

$$2 \langle \phi^\dagger \phi \rangle = \langle h^2 + \xi^2 \rangle = v^2 \quad (2.18)$$

190 We now reach the “breaking” point of this procedure. In the (h, ξ) plane, the
 191 minima form a circle of radius v . We are free to choose any of these minima to expand

our Lagrangian around; the physics is not affected by this choice. For convenience, choose $\langle h \rangle = v, \langle \xi^2 \rangle = 0$.

Now, let us define $h' = h - v, \xi' = \xi$ with VEVs $\langle h' \rangle = 0, \langle \xi' \rangle = 0$. We can then write our spontaneously broken Lagrangian in the form

$$\mathcal{L} = \frac{1}{2} \partial_\mu h' \partial^\mu h' + \frac{1}{2} \partial_\mu \xi' \partial^\mu \xi' - \lambda v^2 h'^2 - \lambda v h' (h'^2 + \xi'^2) - \lambda (h'^2 + \xi'^2)^2 \quad (2.19)$$

194

195 **U(1) local symmetry breaking**

Add a picture of the potential

196 **2.4 The Standard Model**

197 **Overview**

198 The Standard Model is another name for the theory of the internal symmetry group
199 $SU(3)_C \times SU(2)_L \times U(1)_Y$. This quantum field theory is the culmination of years of
200 work in both theoretical and particle physics.

201

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CITE THIS
PICTURE

202 **Field Content**

The SM field content is

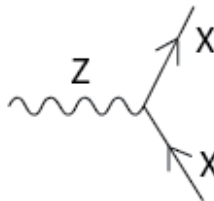
$$\text{Fermions } Q_L(3, 2)_{+1/3}, U_R(3, 1)_{+4/3}, D_R(3, 1)_{-2/3}, L_L(1, 2)_{-1}, E_R(1, 1)_{-2} \text{ Scalar (Higgs) } \phi(1, 2)_{+1/2} \text{ Vector } \dots \quad (2.20)$$

203 where the $(A, B)_Y$ notation represents the irreducible representation under $SU(3)$
204 and $SU(2)$, with Y being the electroweak hypercharge. Each of these fields has an
205 additional index, representing the three generation of fermions.

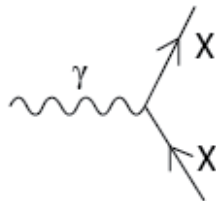
206 We observed that Q_L, U_R , and D_R are triplets under $SU(3)$; these are the *quark*
207 fields. They are mediated by the “gluon” field $G^\mu(8, 1)_0$. The fermion fields $L_L(1, 2)_{-1}$
208 and $E_R(1, 1)_{-2}$ are singlets under $SU(3)$; we call them *leptons*.

Figure 2.1: The interactions of the Standard Model

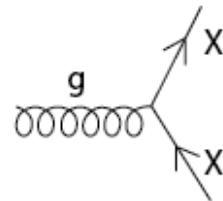
Standard Model Interactions (Forces Mediated by Gauge Bosons)



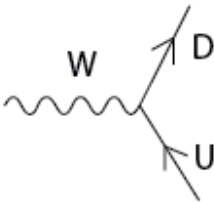
X is any fermion in the Standard Model.



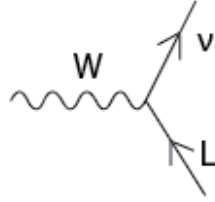
X is electrically charged.



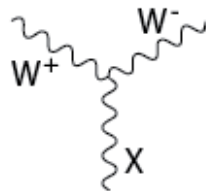
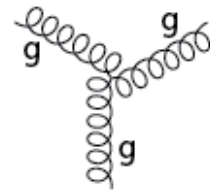
X is any quark.



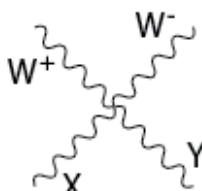
U is a up-type quark;
D is a down-type quark.



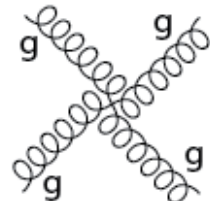
L is a lepton and ν is the
corresponding neutrino.



X is a photon or Z-boson.



X and Y are any two
electroweak bosons such
that charge is conserved.



209 Next, we note the “left-handed” particles, denoted by L , which are doublets under
210 $SU(2)$. This is mediated by the unification of the This is the reflection of the “chi-
211 rality” of the Standard Model; the left-handed and right-handed particles are treated
212 differently by the electroweak forces.

213 **2.5 Electroweak Symmetry breaking and the** 214 **Higgs Boson**

215 By using the asterisk to start a new section, I keep the section from appearing in the
216 table of contents. If you want your sections to be numbered and to appear in the
217 table of contents, remove the asterisk.

218 **2.6 Deficiencies of the Standard Model**

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220 table of contents. If you want your sections to be numbered and to appear in the
221 table of contents, remove the asterisk.

222

Chapter 3

223

Supersymmetry

224 Here you can write some introductory remarks about your chapter. I like to give each
225 sentence its own line.

226 When you need a new paragraph, just skip an extra line.

227 **3.1 Motivation**

228 **Only Additional allowed Lorentz invariant symmetry**

229 **Dark Matter**

230 **Cancellation of quadratic divergences in corrections to the**

231 **Higgs Mass**

232 **3.2 Supersymmetry**

233 **3.3 Additional particle content**

234 **3.4 Phenomenology**

235 **R parity Consequences for sq/gl decays**

The Large Hadron Collider

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239 sentence its own line.

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241 **4.1 Magnets**

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243 table of contents. If you want your sections to be numbered and to appear in the
244 table of contents, remove the asterisk.

245

Chapter 5

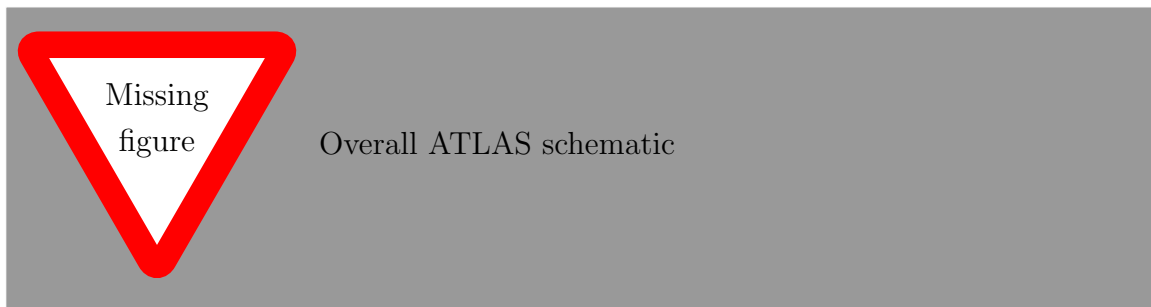
246

The ATLAS detector

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248 sentence its own line.

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250

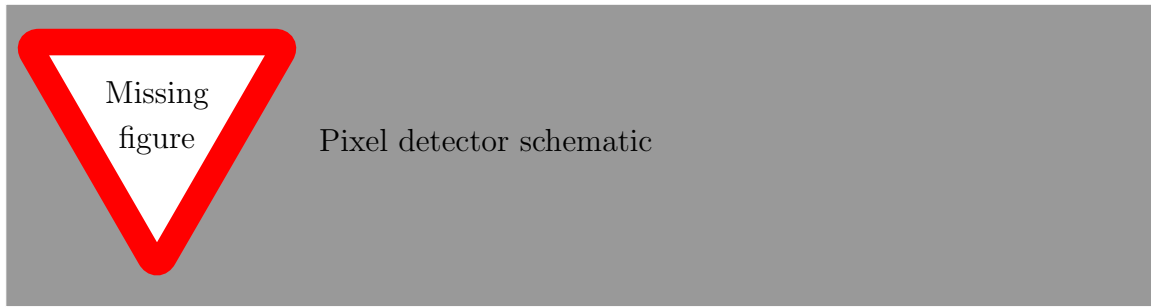


251

252 **5.1 Inner Detector**

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254 table of contents. If you want your sections to be numbered and to appear in the
255 table of contents, remove the asterisk.

256 **Pixel Detector**

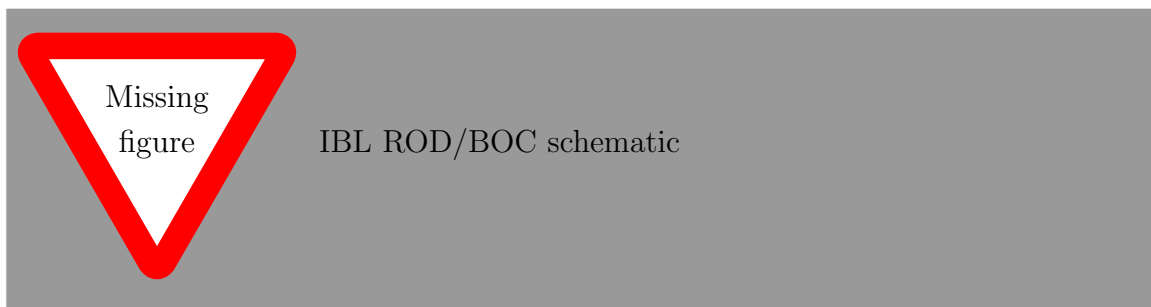


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258

259 **Insertable B-Layer**

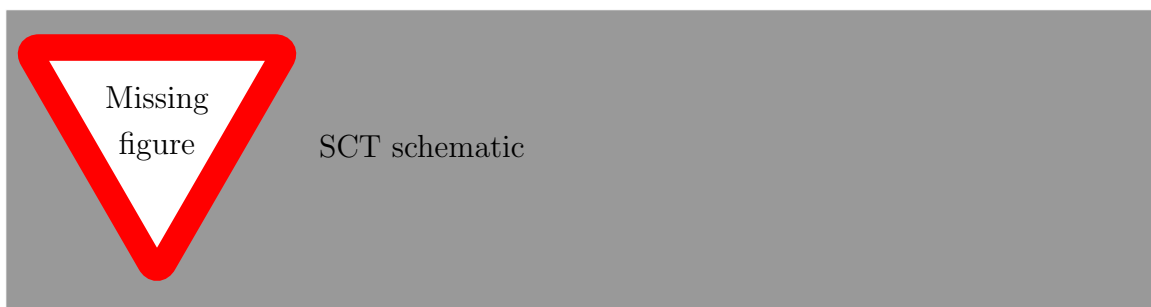
260 Qualification task, so add a bit more.



261

262

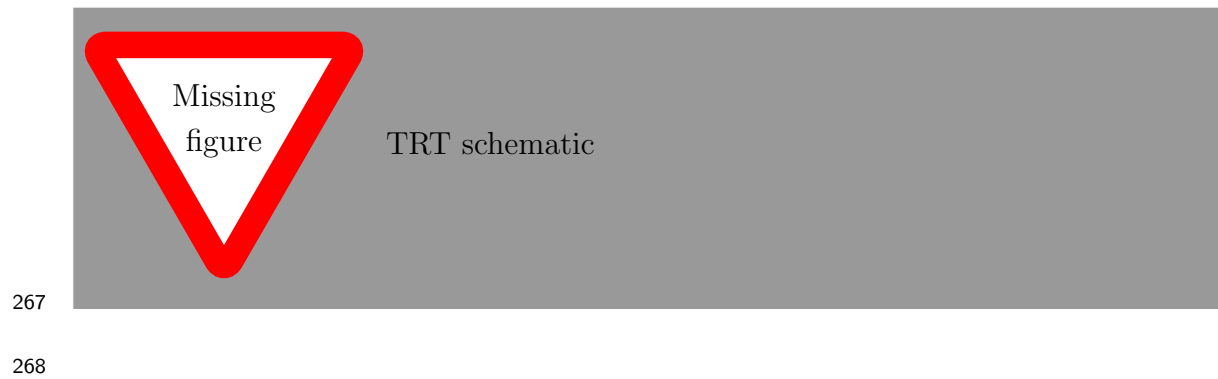
263 **Semiconductor Tracker**



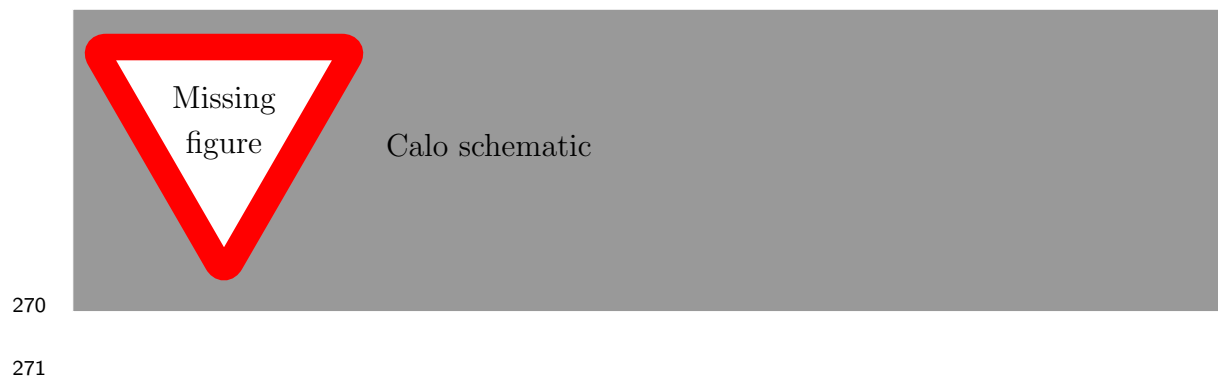
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265

266 **Transition Radiation Tracker**



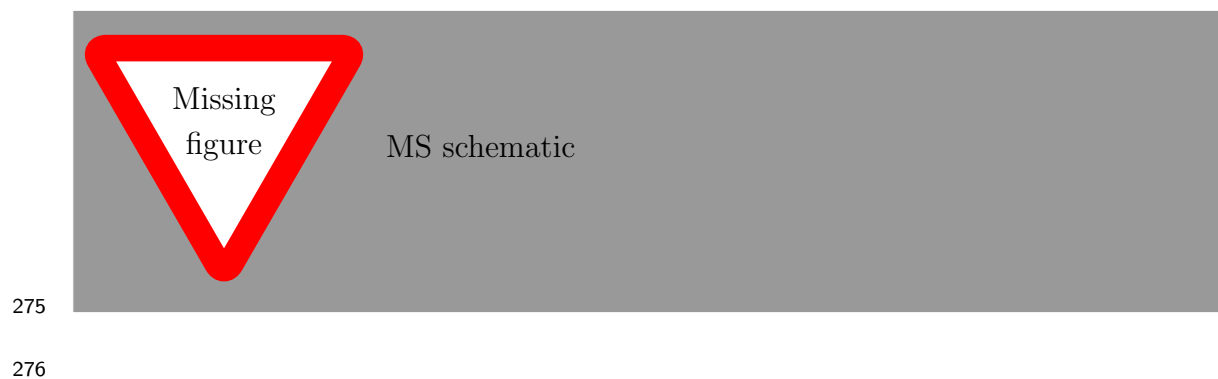
269 **5.2 Calorimeter**



272 **Electromagnetic Calorimeter**

273 **Hadronic Calorimeter**

274 **5.3 Muon Spectrometer**



The Recursive Jigsaw Technique

279 Here you can write some introductory remarks about your chapter. I like to give each
280 sentence its own line.

281 When you need a new paragraph, just skip an extra line.

282 **6.1 Razor variables**

283 By using the asterisk to start a new section, I keep the section from appearing in the
284 table of contents. If you want your sections to be numbered and to appear in the
285 table of contents, remove the asterisk.

286 **6.2 SuperRazor variables**

287 **6.3 The Recursive Jigsaw Technique**

288 **6.4 Variables used in the search for zero lepton** 289 **SUSY**

Title of Chapter 1

292

Chapter 8

293

Title of Chapter 1

294 Here you can write some introductory remarks about your chapter. I like to give each
295 sentence its own line.

296 When you need a new paragraph, just skip an extra line.

297 **8.1 Object reconstruction**

298 **Photons, Muons, and Electrons**

299 **Jets**

300 **Missing transverse momentum**

301 Probably longer, show some plots from the PUB note that we worked on

302 **8.2 Signal regions**

303 **Gluino signal regions**

304 **Squark signal regions**

305 **Compressed signal regions**

306 **8.3 Background estimation**

307 **Z $\nu\nu$**

308 **W $e\nu$**

309 **$t\bar{t}$ bar**

310

Chapter 9

311

Title of Chapter 1

312 Here you can write some introductory remarks about your chapter. I like to give each
313 sentence its own line.

314 When you need a new paragraph, just skip an extra line.

315 **9.1 Statistical Analysis**

316 maybe to be moved to an appendix

317 **9.2 Signal Region distributions**

318 **9.3 Pull Plots**

319 **9.4 Systematic Uncertainties**

320 **9.5 Exclusion plots**

321

Conclusion

322 Here you can write some introductory remarks about your chapter. I like to give each
323 sentence its own line.

324 When you need a new paragraph, just skip an extra line.

325 **9.6 New Section**

326 By using the asterisk to start a new section, I keep the section from appearing in the
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