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A search for sparticles in zero lepton final states

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ABSTRACT

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A search for sparticles in zero lepton final states

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Russell W. Smith

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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.

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Acknowledgements

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 [1, 2], the understanding of the anomalous magnetic dipole moment of the electron [3, 4], and the measurement of the number of weakly-interacting neutrino flavors [5] 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 [6–8] with the theory of the strong interactions, as first envisioned by Gell-Mann and Zweig [9, 10]. 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 parameters¹. It would be more theoretically pleasing to understand these free parameters in terms of a more fundamental theory. The major theoretical concern of the Standard Model, as it pertains to this thesis, is the *hierachy problem*[11–15]. The light mass

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, weak, and electromagnetic forces (3 α_{force}).

84 of the Higgs boson (125 GeV) should be quadratically dependent on the scale of UV
 85 physics, due to the quantum corrections from high-energy physics processes. The
 86 most perplexing experimental issue is the existence of *dark matter*, as demonstrated
 87 by galactic rotation curves [16–22]. This data has shown that there exists additional
 88 matter which has not yet been seen interacting with the particles of the Standard
 89 Model. There is no particle in the SM which can act as a candidate for dark matter.

90 Both of these major issues, as well as numerous others, can be solved by the
 91 introduction of *supersymmetry* (SUSY) [15, 23–33]. In supersymmetric theories, each
 92 SM particles has a so-called *superpartner*, or sparticle partner, differing from given SM
 93 particle by 1/2 in spin. These theories solve the hierarchy problem, since the quantum
 94 corrections induced from the superpartners exactly cancel those induced by the SM
 95 particles. In addition, these theories are usually constructed assuming R -parity,
 96 which can be thought of as the “charge” of supersymmetry, with SM particles having
 97 $R = 1$ and sparticles having $R = -1$. In collider experiments, since the incoming
 98 SM particles have total $R = 1$, the resulting sparticles are produced in pairs. This
 99 produces a rich phenomenology, which is characterized by significant hadronic activity
 100 and large missing transverse energy (E_T^{miss}), which provide significant discrimination
 101 against SM backgrounds [34].

102 Despite the power of searches for supersymmetry where E_T^{miss} is a primary dis-
 103 criminating variable, there has been significant interest in the use of other variables
 104 to discriminate against SM backgrounds. These include searches employing variables
 105 such as αT , $M_{T,2}$, and the razor variables (M_R, R^2) [35–45]. In this thesis, we will
 106 present the first search for supersymmetry using the novel Recursive Jigsaw Recon-
 107 struction (RJR) technique. RJR can be considered the conceptual successor of the
 108 razor variables. We impose a particular final state “decay tree” on an events, which
 109 roughly corresponds to a simplified Feynmann diagram in decays containing weakly-
 110 interacting particles. We account for the missing degrees of freedom associated to

111 the weakly-interacting particles by a series of simplifying assumptions, which allow
112 us to calculate our variables of interest at each step in the decay tree. This allows an
113 unprecedented understanding of the internal structure of the decay and the ability to
114 construct additional variables to reject Standard Model backgrounds.

115 This thesis details a search for the superpartners of the gluon and quarks, the
116 gluino and squarks, in final states with zero leptons, with 13.3 fb^{-1} of data using the
117 ATLAS detector. We organize the thesis as follows. The theoretical foundations of
118 the Standard Model and supersymmetry are described in Chapters 2 and 3. The
119 Large Hadron Collider and the ATLAS detector are presented in Chapters 4 and 5.
120 Chapter 5 provides a detailed description of Recursive Jigsaw Reconstruction and a
121 description of the variables used for the particular search presented in this thesis.
122 Chapter 6 presents the details of the analysis, including details of the dataset, object
123 reconstruction, and selections used. In Chapter 7, the final results are presented;
124 since there is no evidence of a supersymmetric signal in the analysis, we present the
125 final exclusion curves in simplified supersymmetric models.

126

Chapter 2

127

The Standard Model

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

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

131 **2.1 Quantum Field Theory**

132

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

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

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

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

- 142 1. Translational invariance - The Lagrangian is only a function of the fields ϕ and
 143 their derivatives $\partial_\mu \phi$
- 144 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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- 145 3. Reality condition - The Lagrangian is real to conserve probability.
- 146 4. Lorentz invariance - The Lagrangian is invariant under the Poincaré group of
147 spacetime.
- 148 5. Analyticity - The Lagrangian is an analytical function of the fields; this is to
149 allow the use of perturbation theory.
- 150 6. Invariance and Naturalness - The Lagrangian is invariant under some internal
151 symmetry groups; in fact, the Lagrangian will have *all* terms allowed by the
152 imposed symmetry groups.
153 7. Renormalizability - The Lagrangian will be renormalizable - in practice, this
154 means there will not be terms with more than power 4 in the fields.

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

158 2.2 Symmetries

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

163 \mathbb{Z}_2 symmetry

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

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

Now we *impose* the symmetry

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

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

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

170 The effect of this symmetry is that the total number of ϕ particles can only change
 171 by even numbers, since the only interaction term $\lambda\phi^4$ is an even power of the field.
 172 This symmetry is often imposed in supersymmetric theories, as we will see in Chapter
 173 3.

174 **$U(1)$ symmetry**

175 $U(1)$ is the simplest example of a continuous (or *Lie*) group. Now consider a theory
 176 with a single complex scalar field $\phi = \text{Re } \phi + i \text{Im } \phi$

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

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

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

2.3 Local symmetries

The two examples considered above are “global” symmetries in the sense that the symmetry transformation does not depend on the spacetime coordinate x_μ . We know look at local symmetries; in this case, for example with a local $U(1)$ symmetry, the transformation has the form $\phi(x_\mu) \rightarrow e^{i\theta(x_\mu)}\phi(x_\mu)$. These symmetries are also known 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 2.2 are *not* invariant under a local symmetry transformation

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

GET THIS

RIGHT

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

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

$$\begin{aligned} D^\mu \phi &\rightarrow e^{iq\theta(x^\mu)} D^\mu \phi \\ D^\mu \phi^* &\rightarrow e^{-iq\theta(x^\mu)} D^\mu \phi \end{aligned} \quad (2.8)$$

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

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

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

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

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

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

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

199 and then we must also add the kinetic term :

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

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

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

202 Symmetry breaking and the Higgs mechanism

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

207 There are two ideas of symmetry breaking

- 208 • Explicit symmetry breaking by a small parameter - in this case, we have a small
 209 parameter which breaks an “approximate” symmetry of our Lagrangian. An
 210 example would be the theory of the single scalar field [2.2](#), when $\mu \ll m^2$ and
 211 $\mu \ll \lambda$. In this case, we can often ignore the small term when considering
 212 low-energy processes.

213 • Spontaneous symmetry breaking (SSB) - spontaneous symmetry breaking oc-
 214 curs when the Lagrangian is symmetric with respect to a given symmetry trans-
 215 formation, but the ground state of the theory is *not* symmetric with respect to
 216 that transformation. This can have some fascinating consequences, as we will
 217 see in the following examples

218 Symmetry breaking a

219 U(1) global symmetry breaking

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

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

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

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

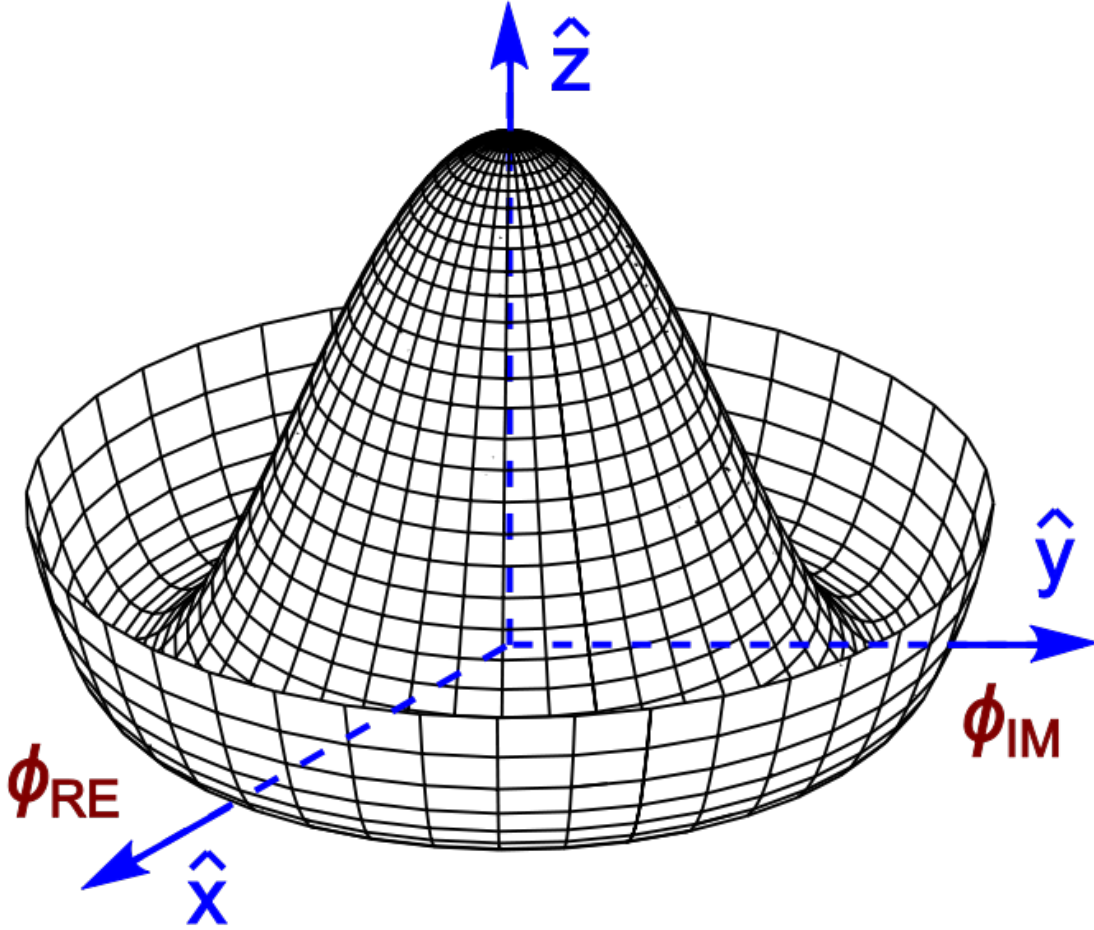
First, note that the theory is only stable when $\lambda > 0$. To understand the effect of SSB, we now enforce that $\mu^2 < 0$, and define $v^2 = -\mu^2/\lambda$. We can then write the scalar potential of this theory as :

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

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

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

Figure 2.1: Sombrero potential



220 We now reach the “breaking” point of this procedure. In the (h, ξ) plane, the
 221 minima form a circle of radius v . We are free to choose any of these minima to expand
 222 our Lagrangian around; the physics is not affected by this choice. For convenience,
 223 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

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

225 U(1) local symmetry breaking

226 2.4 The Standard Model

227 Overview

228 The Standard Model is another name for the theory of the internal symmetry group

CHECK 229 $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. This quantum field theory is the culmination of years

cite 230 of work in both theoretical and particle physics.

CITE THIS 231

PICTURE

232 Field Content

The SM field content is

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

$$\text{Vector Fields } G^\mu(8, 1)_0 W^\mu(1, 3)_0 B^\mu(1, 1)_0$$

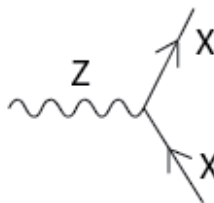
233 where the $(A, B)_Y$ notation represents the irreducible representation under $SU(3)$
234 and $SU(2)$, with Y being the electroweak hypercharge. Each of these fields has an
235 additional index, representing the three generation of fermions.

236 We observed that Q_L, U_R , and D_R are triplets under $SU(3)_C$; these are the *quark*
237 fields. The “color” group, $SU(3)_C$ is mediated by the “gluon” field $G^\mu(8, 1)_0$, which
238 has 8 degrees of freedom; we say there are 8 gluons. The fermion fields $L_L(1, 2)_{-1}$
239 and $E_R(1, 1)_{-2}$ are singlets under $SU(3)_C$; we call them *leptons*.

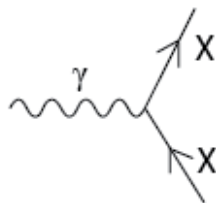
240 Next, we note the “left-handed” (“right-handed”) fermion fields, denoted by L (R)
241 subscript, The left-handed fields form doublets under $SU(2)_L$. These are mediated
242 by the three degrees of freedom of the “W” fields $W^\mu(1, 3)_0$. These fields only act
243 on the left-handed particles of the Standard Model. This is the reflection of the
244 “chirality” of the Standard Model; the left-handed and right-handed particles are

Figure 2.2: The interactions of the Standard Model

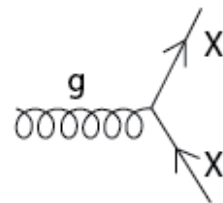
Standard Model Interactions (Forces Mediated by Gauge Bosons)



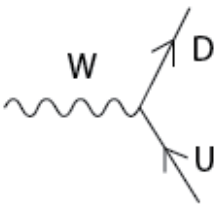
X is any fermion in the Standard Model.



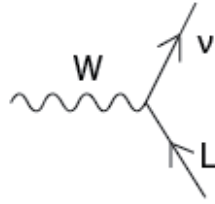
X is electrically charged.



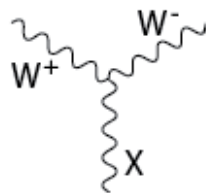
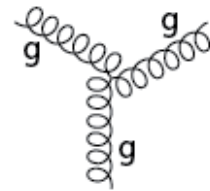
X is any quark.



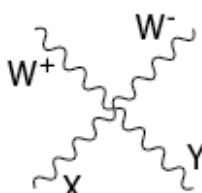
U is a up-type quark;
D is a down-type quark.



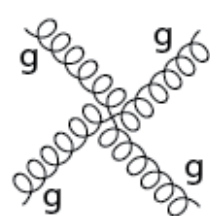
L is a lepton and ν is the corresponding neutrino.



X is a photon or Z-boson.



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



245 treated differently by the electroweak forces. The right-handed fields, U_R, D_R , and
 246 E_R , are singlets under $SU(2)_L$.

247 The $U(1)_Y$ symmetry is associated to the $B^\mu(1,1)_0$ boson with one degree of
 248 freedom. The charge Y is known as the electroweak hypercharge.

249 \mathcal{L}_{kin}

250 For each of the vector boson fields, we have the follow field strenghts :

$$\begin{aligned} G_a^{\mu\nu} &= \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f_{abc} G_b^\mu G_c^\nu \\ W_a^{\mu\nu} &= \partial^\mu W_a^\nu - \partial^\nu W_a^\mu - g \epsilon_{abc} W_b^\mu W_c^\nu \\ B^{\mu\nu} &= \partial^\mu B^\nu - \partial^\nu B^\mu \end{aligned} \quad (2.21)$$

251 where g and g_s are the electroweak and strong coupling constant.

We can write the covariant derivative for the Standard Model as

$$D^\mu = \partial^\mu + ig_s G_a^\mu L_a + ig W_a^\mu T_a + ig' Y B^\mu \quad (2.22)$$

252 where L_a and T_a are the generators of $SU(3)_C$ and $SU(2)_L$ respectively for each of
 253 the representations. Explicitly, for the $SU(3)_C$ triplets, $L_a = \frac{1}{2}\lambda_a$ and for the $SU(3)_C$
 254 singlets, $L_a = 0$. For $SU(2)_L$ doublets, $T_a = \frac{1}{2}\sigma_a$ and for $SU(2)_L$ singlets, $T_a = 0$.

GELLMANN
and Pauli
matrices

The combination of these terms allows us to write the kinetic terms of the La-
 grangian as

$$\begin{aligned} \mathcal{L}_{kin} &= G^{\mu\nu} G_{\mu\nu} + W^{\mu\nu} W_{\mu\nu} + B^{\mu\nu} B_{\mu\nu} \\ &+ D^\mu Q_L D_\mu Q_L + D^\mu U_R D_\mu U_R + D^\mu D_R D_\mu D_R + D^\mu L_L D_\mu L_L + D^\mu E_R D_\mu E_R \end{aligned} \quad (2.23)$$

255 \mathcal{L}_ψ

256 We cannot write down any mass terms for fermions in the Standard Model. Dirac
 257 mass terms are forbidden since they are all assigned to “chiral” representations of the
 258 gauge symmetry. Majorana mass terms are disallowed since there are no fields with
 259 $Y \neq 0$.

260 \mathcal{L}_{Yuk}

261 We write the Yukawa portion of the Standard Model Lagrangian

$$\mathcal{L}_{Yuk} = Y_{ij} L_{Li} \bar{E}_{Rj} \phi + h.c. \quad (2.24)$$

262 The Yukawa matrix Y is a general complex 3×3 matrix of dimensionless cou-
263 plings which can be diagonalized, leading to a diagonal matrix with only three real
264 parameters (y_e, y_μ, y_τ) . This reflects the fact that for the electron, muon, and tau
265 lepton, the interaction basis is the same as the mass basis; this is the same as saying
266 an electron has a well-defined mass.

267 2.5 \mathcal{L}_ϕ , Electroweak Symmetry breaking and the 268 Higgs Boson

269 Let us now recall that local gauge invariance means that the vector fields in this
270 theory are *massless*. Naïvely, it seems this combined with the chirality of the Standard
271 Model, that *none* of the fields have masses. The solution to this seeming conundrum
272 is of course the well-known “Higgs” mechanism, described in Sec. 2.3.

In the Standard Model, the Higgs potential is given by

$$\mathcal{L}_\phi = -\mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (2.25)$$

Since λ is dimensionless and real, to have a potential bounded from below, we
require $\lambda > 0$. To break the gauge symmetry, we require $\mu^2 < 0$, leading again to the
sombbrero potential ???. We define

$$v^2 = -\frac{\mu^2}{\lambda}. \quad (2.26)$$

This allows us to write 2.25 as

$$\mathcal{L}_\phi = -\lambda \left(\phi^\dagger \phi - \frac{v^2}{2} \right)^2 \quad (2.27)$$

273 after dropping the constant term.

This means the ϕ field acquires a VEV $|\langle \phi \rangle| = v/\sqrt{2}$. Choosing the convenient gauge

$$\phi = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad (2.28)$$

The VEV breaks the $SU(2)_L \otimes U(1)_Y$ symmetry to a $U(1)_{EM}$ subgroup. We can identify the unbroken generator of this $U(1)_{EM}$ subgroup as $Q_{EM} = T_3 + Y/2$, since this vanishes in the down component

$$Q_\gamma \phi = (T_3 + Y/2)\phi = \left(\frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{1}{2} I\right) \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}. \quad (2.29)$$

274 Here we see the indicative γ for the photon, as this unbroken $U(1)_{EM}$ symmetry is of
 275 course the symmetry associated to the electromagnetic force mediated by the gauge
 276 boson known as the photon.

There are three broken generators : $T_1, T_2, T_3 - Y/2$. These are each associated to one of the massive gauge bosons induced by the symmetry breaking. Choosing a gauge which rotates away the “eaten” Goldstone boson degrees of freedom, we can write the Higgs field as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \quad (2.30)$$

277 **2.6 Particle Spectrum : Standard Model**

278 **Lagrangian after Electroweak Symmetry**

279 **Breaking**

280 We can now return to the Standard Model Lagrangian and use the equation for the
 281 Higgs field after EWSB [2.30](#). This will show us the “physical” particle content of the
 282 Standard Model.

283 Particle content associated to \mathcal{L}_ϕ

Setting ϕ as in Eq.2.30, we quickly see that we can rewrite Eq.2.27 as

$$\mathcal{L}_\phi = -\lambda(\phi^\dagger\phi - \frac{v^2}{2})^2 = -\lambda(\frac{1}{2}(v+h(x))^2 - \frac{v^2}{2})^2 = -\lambda(h(x)^2 + vh(x))^2 = -\lambda(h(x)^4 + vh(x)^3 + \frac{v^2}{2}h(x)^2). \quad (2.31)$$

CHECK

FACTORS
OF TWO

284 Interpreting the Higgs field squared term as the mass term of the Higgs boson,
285 we see that $m_H = \sqrt{2\lambda}v$.

286 Particle content associated to \mathcal{L}_{kin}

Again using Eq.2.30 and $D^\mu = \partial^\mu + ig_s G_a^\mu L_a + ig W_a^\mu T_a + ig' Y B^\mu$, we can see how the mass terms associated to the three massive gauge bosons, and also see how the photon stays massless. The mass terms for the gauge boson fields come from the kinetic term of the Higgs field :

$$\begin{aligned} \mathcal{L}_{M_V} = D^\mu \phi D_\mu \phi &= (ig W_a^\mu T_a + ig' Y B^\mu) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} (ig W_{\mu,a} T_a + ig' Y B_\mu) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} = \\ &= \frac{1}{8} \left| \begin{pmatrix} gW_3 + g'B & g(W_1 - iW_2) \\ g(W_1 + iW_2) & -gW_3 + g'B \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2 \end{aligned} \quad (2.32)$$

where we have noted that ∂_μ and L_a both disappear when acting on ϕ . Defining the *Weinberg* angle $\tan(\theta_W) = g'/g$ and the following physical fields :

$$\begin{aligned} W^\pm &= \frac{1}{\sqrt{2}}(W_1 \mp iW_2) \\ Z^0 &= \cos \theta_W W_3 - \sin \theta_W B \\ A^0 &= \sin \theta_W W_3 + \cos \theta_W B \end{aligned} \quad (2.33)$$

we see that we can write the piece of the Lagrangian associated to the vector boson masses as

$$\mathcal{L}_{M_V} = \frac{1}{4}g^2 v^2 W^+ W^- + \frac{1}{8}(g^2 + g'^2)v^2 Z^0 Z^0. \quad (2.34)$$

and we have the following values of the masses for the vector bosons :

$$\begin{aligned}m_W^2 &= \frac{1}{4}g^2v^2 \\m_Z^2 &= \frac{1}{4}(g^2 + g'^2)v^2 \\m_A^2 &= 0\end{aligned}\tag{2.35}$$

287 **2.7 Deficiencies of the Standard Model**

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

291

Chapter 3

292

Supersymmetry

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

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

296 **3.1 Motivation**

297 **Only Additional allowed Lorentz invariant symmetry**

298 **Dark Matter**

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

300 **Higgs Mass**

301 **3.2 Supersymmetry**

302 **3.3 Additional particle content**

303 **3.4 Phenomenology**

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

305

Chapter 4

306

The Large Hadron Collider

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

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

310 **4.1 Magnets**

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

314

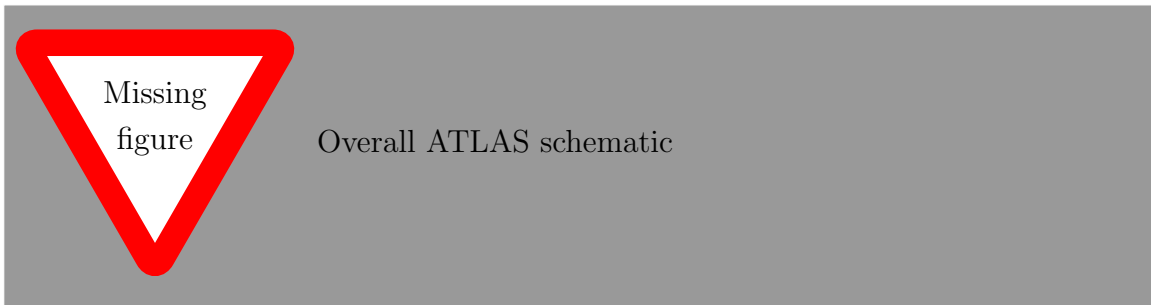
Chapter 5

315

The ATLAS detector

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

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



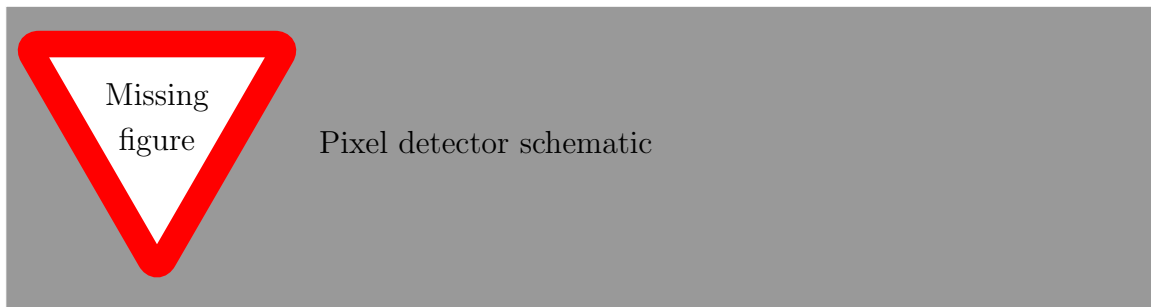
319

320

321 **5.1 Inner Detector**

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

325 **Pixel Detector**

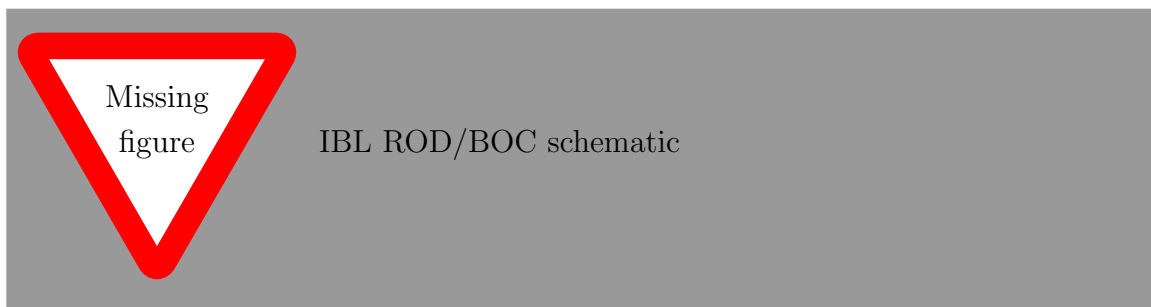


326

327

328 **Insertable B-Layer**

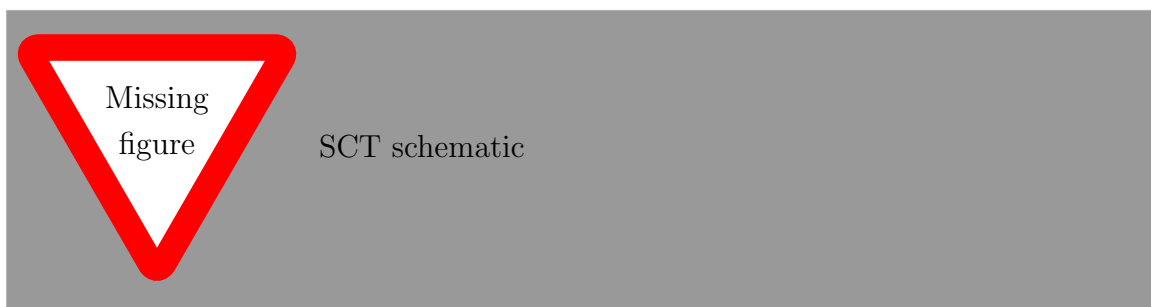
329 Qualification task, so add a bit more.



330

331

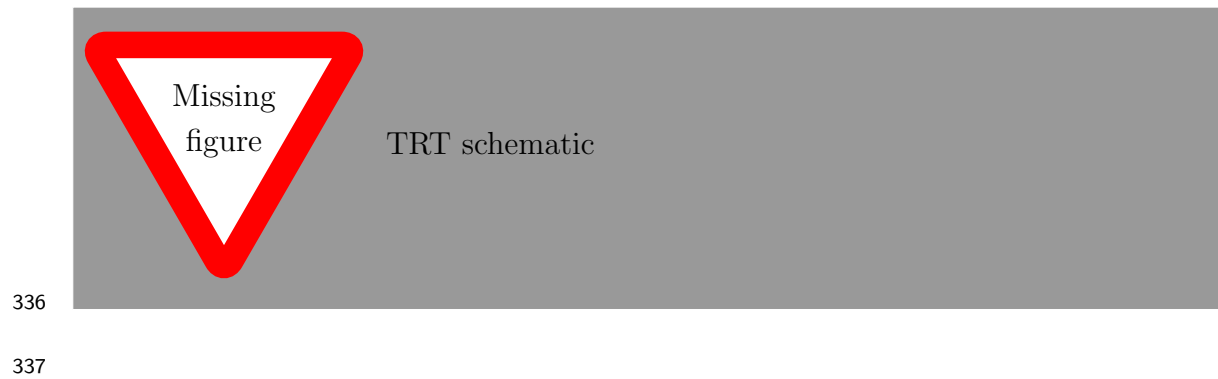
332 **Semiconductor Tracker**



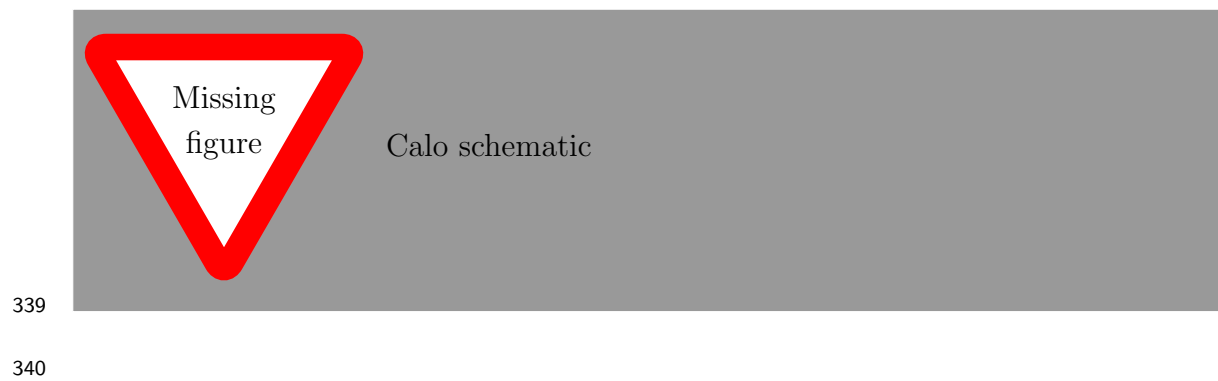
333

334

335 **Transition Radiation Tracker**



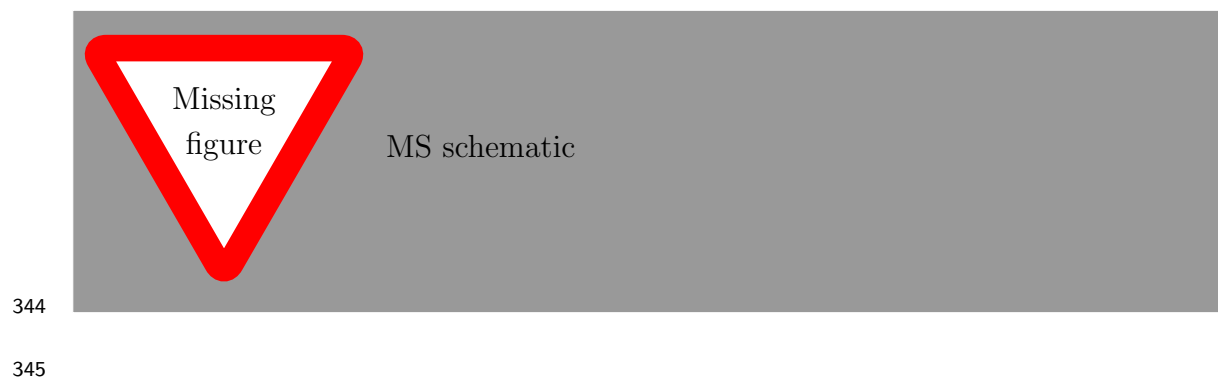
338 **5.2 Calorimeter**



341 **Electromagnetic Calorimeter**

342 **Hadronic Calorimeter**

343 **5.3 Muon Spectrometer**



The Recursive Jigsaw Technique

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

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

351 **6.1 Razor variables**

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

355 **6.2 SuperRazor variables**

356 **6.3 The Recursive Jigsaw Technique**

357 **6.4 Variables used in the search for zero lepton**

358 **SUSY**

Title of Chapter 1

361

Chapter 8

362

Title of Chapter 1

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

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

366 **8.1 Object reconstruction**

367 **Photons, Muons, and Electrons**

368 **Jets**

369 **Missing transverse momentum**

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

371 **8.2 Signal regions**

372 **Gluino signal regions**

373 **Squark signal regions**

374 **Compressed signal regions**

375 **8.3 Background estimation**

376 **Z $\nu\nu$**

377 **W $e\nu$**

378 **$t\bar{t}$**

379

Chapter 9

380

Title of Chapter 1

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

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

384 **9.1 Statistical Analysis**

385 maybe to be moved to an appendix

386 **9.2 Signal Region distributions**

387 **9.3 Pull Plots**

388 **9.4 Systematic Uncertainties**

389 **9.5 Exclusion plots**

390

Conclusion

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

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

394 **9.6 New Section**

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

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