Abstract

We propose a model of Electroweak Symmetry Breaking (EWSB) that includes a technicolor sector and a Higgs-like boson. The model includes a bound state of technifermions held together by a new strong interaction, denoted π^0_{TC}, which decays like a Standard Model (SM) higgs boson. By observing an excess in diphoton final states, the ATLAS and CMS collaborations have recently discovered a Higgs-like boson at 125 GeV. For $m_{\pi^0_{TC}} < 200$ GeV, we determine bounds on our model from the Large Hadron Collider (LHC) search for new scalar bosons decaying to $\gamma\gamma$. For $m_{\pi^0_{TC}} > 200$ GeV, we consider the dominant decay mode $\pi^0_{TC} \to Z\sigma$, where σ is a scalar boson of the model. An excess in this channel could provide evidence of the new pseudoscalar.

Contents

1 Introduction

1.1 The Need for Electroweak Symmetry Breaking

The gauge invariance of the Standard Model lagrangian predicts that all ordinary particles are massless. Massive particles like the W and Z bosons are inconsistent with this unbroken gauge symmetry. By introducing electroweak symmetry breaking (EWSB), particles such as the W and Z are able to acquire masses consistent with observation.

EWSB can be achieved through the Higgs mechanism. We will consider a simplified version of the Higgs Mechanism with the following toy lagrangian:

$$L = (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\phi), \tag{1}$$

where

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2, \tag{2}$$

$$D_\mu = \partial_\mu + ieA_\mu, \tag{3}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{4}$$

and ϕ is a complex scalar field. This lagrangian is invariant under the transformation $\phi \to \phi e^{i\alpha(x)}$ and $A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \alpha(x)$. It has no mass terms.

If μ^2 is a positive parameter, the minimum potential energy, or vacuum expectation value (vev), occurs at $\phi = 0$. However, if we allow μ^2 to be negative and minimize the lagrangian, we find a new vev at $\phi = \sqrt{\frac{-\mu^2}{2\lambda}}$. Let us expand about the new minumum by letting $\phi \to \frac{1}{\sqrt{2}}\left(\sigma + i\eta + \sqrt{\frac{-\mu^2}{\lambda}}\right)$, so that now $\sigma = \eta = 0$ corresponds to the new minimum. The lagrangian becomes

$$\frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma + \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - \frac{1}{2}(2\mu^2)\sigma^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\frac{e^2\mu^2}{\lambda}A_\mu A^\mu e\sqrt{\frac{-\mu^2}{\lambda}}A_\mu \partial^\mu \eta \tag{5}$$

The η terms represent unphysical fields (they can be gauged away), but the σ and A_μ terms represent real fields; σ is a new scalar boson with mass $\sqrt{2\mu^2}$ and A_μ is a new vector field with a mass $\sqrt{-\frac{e^2\mu^2}{\lambda}}$. The W and Z bosons are analagous to A_μ, so we have indirectly generated mass for the W and Z particles by breaking the symmetry of the Lagrangian. Fermion masses can also be generated in a similar way.

1.2 Technicolor Models

There are other, non-SM ways to break electroweak symmetry. Simple Technicolor Models (TM) achieve EWSB through an unobservably broad, spinless composite of non-SM fermions (technifermions). The technifermions can condense under a new, very strong gauge interaction, i.e., a scalar combination of the fermion fields develop a vev. Due to this vev, TM can generate mass terms in the same way as the Higgs Mechanism. The advantage of these models is that they relate the weak scale to the scale at which the new gauge interaction becomes strong, and this allows the weak scale to naturally be much smaller than the Planck scale. However, TM do not include a Higgs-like boson and are now conclusively excluded since ATLAS and CMS observed a Higgs-like boson at 125 GeV.

1.3 Bosonic Technicolor

Simple TM are now conclusively excluded after the ATLAS and CMS collaborations observed a Higgs-like boson at 125 GeV. Hybrid TM that include a Higgs-like boson are still valid. Bosonic Technicolor models (BTC) include both a Higgs-like boson and a technicolor sector so that new strong dynamics still contribute to EWSB. The technicolor sector induces EWSB when the technifermions condense and produce a linear term in the Higgs potential. The Higgs potential then has a minimum away from the origin and the Higgs field develops a vev [3].

2 The Model

All SM particles are included in BTC. However, there are additional techniparticles that behave differently than their SM counterparts. We propose two flavors of technifermions (see Fig 1), which can form a condensate

$$\langle p\bar{p} + m\overline{m}\rangle. \tag{6}$$

One of the fluctuations about this vev is the neutral technipion, π^0_{TC}. Because the technipion is bound by Technicolor's additional gauge interaction, it behaves very differently than a SM pion. There are additional technipions (see Fig 2), but we are not as interested in their decays as in those of the neutral pion.

Figure 1: The Techniquarks

Name	Charge	Spin
p	$\frac{1}{2}$	$\frac{1}{2}$
m	-$\frac{1}{2}$	$\frac{1}{2}$

Figure 2: Properties of Techniquarks

Symbol	Composition	Spin	Charge
π^+_{TC}	$p\bar{m}$	0	1
π^-_{TC}	$m\bar{p}$	0	-1
π^0_{TC}	$\frac{1}{\sqrt{2}}(m\bar{m} - p\bar{p})$	0	0

From now on, all TC subscripts will be dropped to simplify notation.

We define

$$\Pi = \begin{pmatrix} \frac{\pi^0}{2} & \frac{\pi^+}{\sqrt{2}} \\ \frac{\pi^-}{\sqrt{2}} & -\frac{\pi^0}{2} \end{pmatrix}, \tag{7}$$

$$\Sigma = e^{2i\Pi/f}, \tag{8}$$

$$\Pi' = \begin{pmatrix} \frac{\pi^{0'}}{2} & \frac{\pi^{+'}}{\sqrt{2}} \\ \frac{\pi^{-'}}{\sqrt{2}} & -\frac{\pi^{0'}}{2} \end{pmatrix}, \tag{9}$$

$$\Sigma^{'} = e^{2i\Pi/f^{'}}, \tag{10}$$

where $f^{'}$ and f are parameters of the model; f represents the new vacuum expectation value of the technifermion condensate, i.e., $\langle p\bar{p} + m\bar{m}\rangle \approx 4\pi f^3$, and $f^{'}$ is the vev of the fundamental higgs boson in the theory. Therefore, if v is the electroweak scale,

$$\begin{aligned}\sqrt{f^2 + f^{'2}} &= v \\ &= 246 \text{ GeV}.\end{aligned} \tag{11}$$

In addition, note that the Π matrix does not represent physical technipions. Instead, the physical technipions are a linear combination of Π and $\Pi^{'}$:

$$\Pi_p = \frac{-f^{'}\Pi + f\Pi^{'}}{v}. \tag{12}$$

The unphysical pions,

$$\Pi_a = \frac{f^{'}\Pi^{'} + f\Pi}{v}, \tag{13}$$

can be gauged away.

The lagrangian of our model is

$$\begin{aligned}\mathcal{L} = &\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{f^2}{4}Tr\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right) + \frac{(\sigma + f^{'})^2}{4}Tr\left(D_\mu\Sigma^{'\dagger} D^\mu\Sigma^{'}\right) \\ &- \left(\frac{\sigma + f^{'}}{\sqrt{2}}\bar{\psi}_L\Sigma^{'}\begin{pmatrix} h_U & 0 \\ 0 & V_{CKM}h_D\end{pmatrix}\psi_R + h.c.\right),\end{aligned} \tag{14}$$

where $\psi_L = (U_L, V_{CKM}D_L)$, $\psi_R = (U_R, D_R)$, and σ is the SM-like h. In the limit that f goes to zero, i.e., the technicolor sector does not contribute to EWSB, σ will become the SM Higgs. The covariant derivative can be expressed

$$D^\mu\Sigma = \partial^\mu\Sigma - \frac{ig}{2}W_a^\mu\tau^a\Sigma + \frac{ig^{'}}{2}B^\mu\Sigma\tau^3. \tag{15}$$

The lagrangian in a field theory model contains information about how particles decay and interact. Each term in the (fully expanded) lagrangian represents a vertex. For example, a term of the form $c_0\phi_1\phi_2\phi_3$ represents three fields $\phi_1\phi_2\phi_3$ participating in a vertex, with c_0 as their coupling constant. The coupling constant is related to how strongly the fields interact.

We expand Σ to second order in Π and find the following π^0 decay terms:

$$\mathcal{L}_{q\bar{q},Z\sigma} = -\frac{ef}{v\sin\theta_W\cos\theta_W}\sigma Z_\mu \partial^\mu \pi^0 + \left[-\frac{if}{v}\left(\frac{\pi^0}{\sqrt{2}}\right)\left(h_t\bar{t}\gamma^5 t - h_b\bar{b}\gamma^5 b\right)\right]. \tag{16}$$

where γ^5 is the usual dirac matrix.

Now it is possible to analyze these decay terms to determine whether collaborations like ATLAS and CMS would be able to detect the technipion.

3 Analysis of the Model

3.1 Sample Calculation of Decay Rate

Define

$$\Gamma(x \to yz) \equiv \text{ the probability per unit time that x decays to y and z}$$

This is the decay rate, also called the decay width, which can be calculated using Feynman's Golden Rules [6].[1]

[1] We include only the rules that apply to the diagram $\pi^0 \to t\bar{t}$. For different types of interactions, the vertices, internal lines, and outgoing and incoming lines can have different factors than the ones we discuss here. The approach is still the same: calculate the squared amplitude $|\mathcal{M}|^2$ and from that, the decay width. For a more thorough discussion, see [6] Chapters 6,7, and 8.

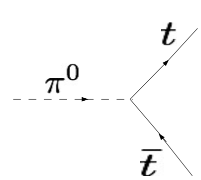
Feynman's Golden Rules

1. Draw the Feynman diagram.
2. Label the incoming and outgoing momenta $(p_1, p_2, p_3, \ldots, p_n)$.
3. Each vertex gets a factor $-ig$, where g is the coupling constant.
4. Each outgoing particle of spin $\frac{1}{2}$ gets a factor $u^{(s_i)}(p_i)$, where u is a spinor.
5. Each outgoing antiparticle of spin $\frac{1}{2}$ gets a factor $\bar{v}^{(s_i)}(p_i)$, where v is also a spinor.
6. Multiply all these factors together; this is equal to $-i\mathcal{M}$. Calculate $|\mathcal{M}|^2$.
7. Sum over the spins and color charge of all outgoing particles.
8. For a two body decay, $\Gamma = \frac{|\boldsymbol{p}|}{8\pi m_1^2}|\mathcal{M}|^2$, where $\boldsymbol{p}$ is the momentum of either of the outgoing particles.

We provide a sample calculation of the decay rate.

1. The feynman diagram in Fig 3 shows the process $\pi^0 \to t\bar{t}$.

Figure 3: Feynman diagram for $\pi^0 \to t\bar{t}$



2. Let π^0 have four-momentum p_1, t have four-momentum p_2, and $\bar{t}$ have four-momentum p_3.

3. From Eq. (16), the Lagrangian term for this decay is

$$\mathcal{L}_{t\bar{t}} = \frac{-ifh_t}{\sqrt{2}v}\pi^0\bar{t}\gamma^5 t. \tag{17}$$

   Therefore the vertex is given by

$$\frac{fh_t}{\sqrt{2}v}\gamma^5. \tag{18}$$

4. The outgoing top quark t gets a spinor $\bar{u}^{(s_2)}(p_2)$.

5. The outgoing $\bar{t}$ gets a spinor $v^{(s_3)}(p_3)$.

6. Putting all of these factors together, we have

$$-i\mathcal{M} = \bar{u}^{(s_2)}(p_2)\frac{fh_t}{\sqrt{2}v}\gamma^5 v^{(s_3)}(p_3), \tag{19}$$

   and

$$|\mathcal{M}|^2 = \frac{f^2h_t^2}{2v^2}\left[\bar{u}^{(s_2)}(p_2)\gamma^5 v^{(s_3)}(p_3)\right]\left[\bar{u}^{(s_2)}(p_2)\gamma^5 v^{(s_3)}(p_3)\right]^*. \tag{20}$$

7. Now we must average over the spins. We use Casmir's Identity. If Γ is an arbitrary 4×4 matrix, $\bar{\Gamma} = \gamma^0\Gamma^\dagger\gamma^0$, and $\not{p} = \gamma^\mu p_\mu$, then

$$\begin{aligned} &\sum_{\text{all spins}}\left[\bar{u}^{(s_2)}(p_2)\Gamma v^{(s_3)}(p_3)\right]\left[\bar{u}^{(s_2)}(p_2)\Gamma v^{(s_3)}(p_3)\right]^\dagger \\ &= \text{Tr}\left[\Gamma(\not{p}_3 - m_3)\overline{\Gamma}(\not{p}_2 + m_2)\right]. \end{aligned} \tag{21}$$

   In our case, $\Gamma = \gamma^5$ and $m_2 = m_3 = m_t$, where m_t is the mass of the top quark. Therefore we have

$$\sum_{\text{all spins}}|\mathcal{M}|^2 = \frac{f^2h_t^2}{2v^2}\,\text{Tr}\left[\gamma^5(\not{p}_3 - m_t)\gamma^0\gamma^{5\dagger}\gamma^0(\not{p}_2 + m_t)\right]. \tag{22}$$

   Because the trace of the product of an odd number of gamma matrices is zero, the cross terms are zero. Then

$$\sum_{\text{all spins}}|\mathcal{M}|^2 = \frac{f^2h_t^2}{2v^2}\,\text{Tr}\left[\gamma^5\not{p}_3\gamma^0\gamma^{5\dagger}\gamma^0\not{p}_2 - m_t^2\gamma^5\gamma^0\gamma^{5\dagger}\gamma^0\right]. \tag{23}$$

We can reduce this expression dramatically using identities and commutation relationships of gamma matrices to rearrange the matrices and find

$$\sum_{\text{all spins}} |\mathcal{M}|^2 = \frac{f^2 h_t^2}{2v^2} \text{ Tr } \left[\not{p}_3 \not{p}_2 + m_t^2\right]. \tag{24}$$

However, Tr $(\not{a}\not{b}) = 4a \cdot b$, so

$$\sum_{\text{all spins}} |\mathcal{M}|^2 = \frac{2f^2 h_t^2}{v^2} \left[p_3 \cdot p_2 + m_t^2\right] = \frac{f^2 h_t^2 m_{\pi^0}^2}{v^2}. \tag{25}$$

We also have to consider the quark's color, which contributes a factor of three:

$$\sum_{\text{color}} \sum_{\text{all spins}} |\mathcal{M}|^2 = 3\frac{f^2 h_t^2 m_{\pi^0}^2}{v^2}. \tag{26}$$

8. We next solve for the decay width. In this case, the outgoing momentum is

$$\begin{aligned} |\boldsymbol{p}| &= \frac{\sqrt{m_{\pi^0}^4 + 2m_t^4 - 2 \cdot (2m_{\pi^0}^2 m_t^2 + m_t^4)}}{2m_{\pi^0}} \\ &= \frac{1}{2}\sqrt{m_\pi^2 - 4m_t^2} \end{aligned} \tag{27}$$

Finally, we have the full width:

$$\Gamma\left(\pi^0 \to t\bar{t}\right) = 3\left(\frac{f h_t}{v}\right)^2 \frac{\sqrt{m_{\pi^0}^2 - 4m_t^2}}{16\pi}, \tag{28}$$

We simply list the decay rates for the $Z\sigma$ and $b\bar{b}$ channels. They were calculated similarly to the $t\bar{t}$ channel.

$$\Gamma\left(\pi^0 \to b\bar{b}\right) = 3\left(\frac{f h_b}{v}\right)^2 \frac{\sqrt{m_{\pi^0}^2 - 4m_b^2}}{16\pi}, \tag{29}$$

$$\begin{aligned} &\Gamma\left(\pi^0 \to Z\sigma\right) = \\ &\quad \left(\frac{ef}{v \sin\theta_W \cos\theta_W}\right)^2 \left(\frac{\left(m_{\pi^0}^2 + m_Z^2 - m_\sigma^2\right)^2}{4m_Z^2} \right. \\ &\quad \left. - m_{\pi^0}^2\right) \frac{\sqrt{m_{\pi^0}^4 + m_Z^4 + m_\sigma^4 - 2\left(m_{\pi^0}^2 m_\sigma^2 + m_{\pi^0}^2 m_Z^2 + m_\sigma^2 m_Z^2\right)}}{16\pi\ m_{\pi^0}^3}. \end{aligned} \tag{30}$$

The $\pi^0 \to \gamma\gamma$ decay is more complicated and involves loop diagrams. Instead of calculating the rate directly, we use The Higgs Hunter's Guide, which provides an appendix on diphoton decays in type-I Two-Doublet Models [7]. Our model is of this type, provided we use $\cot\beta = \frac{f}{f'}$.

$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2}{36\pi^3 m_{\pi^0}} \left(\frac{f}{f'v}\right)^2 \left| \sum_{i=d,s,b} m_i^2 F(\tau_i) - 4 \sum_{i=t,u,c} m_i^2 F(\tau_i) \right|^2 \tag{31}$$

where

$$F(\tau) = \begin{cases} \left[\sin^{-1}\left(\sqrt{\frac{1}{\tau}}\right)\right]^2 & \text{if } \tau \geq 1 \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \text{if } \tau < 1 \end{cases} \tag{32}$$

and

$$\tau_i = \frac{4m_i^2}{m_{\pi^0}^2}. \tag{33}$$

3.2 Branching Fractions

Define the branching fraction for a decay channel to be

$$\text{BF} = \frac{\Gamma_i}{\sum_i \Gamma_i}.$$

We plot the predicted branching fractions for the decays of the π^0 (see Fig 4), choosing $m_\sigma = 125$ GeV, to be consistent with the LHC Higgs discovery, and $f'/v = 0.95$, which is an allowed value in the model's parameter space (see discussion in [4]). Note that the branching ratios for $t\bar{t}$ and $Z\sigma$ go to zero when those decays are no longer kinematically possible.

Two decay channels are of interest. Because our π^0 decays like the SM Higgs and the Higgs was observed through an excess of diphoton final states, there is current data available about $\gamma\gamma$ decays around 125 GeV. Therefore we consider the process $pp \to \pi^0 \to \gamma\gamma$ at low π^0 energies ($m_{\pi^0} < 200$ GeV) to determine whether the diphoton signal could be due to the technipion instead of the SM Higgs. At higher

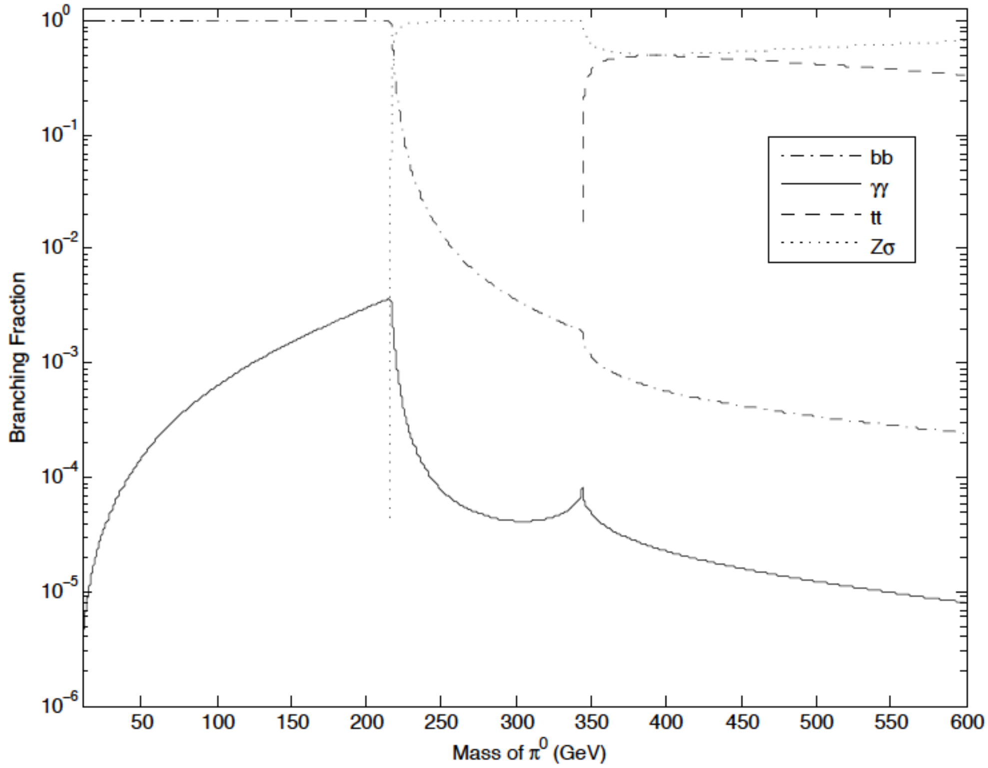


Figure 4: Branching ratios for the π^0, for $f^{'}/v = 0.95$. Note that the branching ratios for $t\bar{t}$ and $Z\sigma$ go to zero when those decays are no longer kinematically possible.

m_{π^0}, $\pi^0 \to Z\sigma$ dominates. Since Z decays to muons, which are easily observed in colliders, we next consider the process $\pi^0 \to Z\sigma \to \mu^+\mu^-\sigma$.

3.3 $\gamma\gamma$ Channel

ATLAS has data on the $\gamma\gamma$ cross section, so we calculate $\sigma_{\pi^0} \times \mathrm{BR}(gg \to \pi^0 \to \gamma\gamma)$ and compare this to the observed production cross section. The SM cross section for $gg \to \pi^0$ is given by [2]

$$\sigma_{\pi^0} = \frac{9}{4}\frac{\left|\cot\beta I_A(\tau_t) - \cot\beta I_A(\tau_b)\right|^2}{\left|I_S(\tau_t)\right|^2}\sigma_{SM} \tag{34}$$

where σ_{SM} is the SM $gg \to h$ production cross section and $\cot\beta = \frac{f}{f'}$. The functions I_A and I_S are given by

$$I_A(\tau) = \tau F\left(\frac{1}{\tau}\right), \tag{35}$$

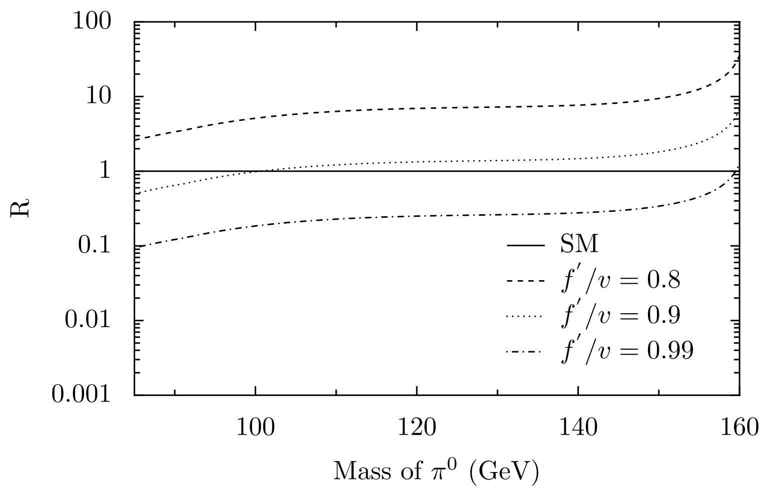
and

$$I_S(\tau) = \frac{3}{2}\tau^2 \left[\frac{1}{\tau} + \left(\frac{1}{\tau} - 1\right) F\left(\frac{1}{\tau}\right)\right]. \tag{36}$$

where F is the F of Eq. (31) and τ is given by Eq. (32).

We are now ready to plot $R = \frac{\sigma_{\pi^0} \times \mathrm{BF}(gg \to \pi^0 \to \gamma\gamma)}{\sigma_{SM} \times \mathrm{BF}(gg \to h \to \gamma\gamma)}$. The different curves correspond to different choices of the parameter $f^{'}$ (see Fig 5).

Figure 5: The ratio R vs m_{π^0} for different values of $f^{'}$



The graph of R constrains the parameter space of $f^{'}/v$ for part of the range of the π^0. If $f^{'}/v$ is too small in the region $\sim 120 - 160$ GeV, the excess in $\gamma\gamma$ decays would have already been observed at the LHC, since ATLAS provides bounds on $\gamma\gamma$ decay in this region.

BTC is still a viable theory for large values of $f^{'}$ in the region 120-160GeV. In other regions, $f^{'}$ could be any value consistent with our model, but the LHC is not sensitive enough to $\gamma\gamma$ decay outside this range. Therefore we consider the other decay mode, $pp \to Z\sigma$.

3.4 Z h Channel

Recalling that in the limit $f \to 0$, the σ of our model becomes the SM Higgs boson, we approximate the $pp \to Z\sigma$ channel as $pp \to Zh$ where h is the SM Higgs. Results from the LHC Higgs boson searches do not directly provide constraints on $pp \to \pi^0 \to Zh$, so we must study this process directly. Three programs, FeynRules, Madgraph, and MadAnalysis allow us to simulate events at the LHC for the process $pp \to \pi^0 \to Zh \to \mu^+\mu^- h$.

3.4.1 FeynRules

FeynRules is a Mathematica package that calculates the Feynman rules for any new field theory. In other words, we can specify new particles, coupling constants, and lagrangian terms for non-SM theories, and FeynRules will calculate all the decay amplitudes ($|\mathcal{M}|^2$) for the new theory.

The relevant Lagrangian terms for $pp \to \pi^0 \to Zh$ are:

$$\mathcal{L} = c_1 \pi^0 \epsilon^{\alpha\beta\mu\nu} G^a_{\mu\nu} G^a_{\alpha\beta} - c_2 h Z_\mu \partial^\mu \pi^0 \tag{37}$$

where $G^a_{\mu\nu}$ is the gluon field strength tensor, and c_1 and c_2 are coupling constants. c_2 is simply defined by Eq. (16):

$$\begin{aligned} c_2 &= \frac{ef}{v \sin\theta_W \cos\theta_W} \\ &= 0.105, \end{aligned} \tag{38}$$

for $v = 246$ GeV, $\sin^2\theta_W = 0.2312$, $\frac{e^2}{4\pi} = \frac{1}{137}$, and $\frac{f'}{v} = 0.99$. In models that include a pseudoscalar Higgs A^0, (similar to our π^0), the effective lagrangians for fermion and gluon interactions are[2]

$$\mathcal{L}_{ff} = -i g_A \frac{A^0}{v} m_i \bar{\psi} \gamma^5 \psi \tag{39}$$

$$\begin{aligned} \mathcal{L}_{gg} &= g_A \frac{A^0}{v} \left[\frac{\alpha_S(m_Z)}{16\pi} \right] \epsilon^{\alpha\beta\mu\nu} G^a_{\mu\nu} G^a_{\alpha\beta} \\ &\approx g_A \frac{A^0}{v} \left[\frac{m_Z}{16\pi} \right] \epsilon^{\alpha\beta\mu\nu} G^a_{\mu\nu} G^a_{\alpha\beta} \end{aligned} \tag{40}$$

where A^0 is the pseudoscalar identified here with π^0 [5]. Since Eq. (38) is of the same form as Eq. (16), we can sove for g_A:

$$-\frac{i f h_t}{\sqrt{2} v} = -\frac{i g_A}{v} m_t \tag{41}$$

[2] In this equation we assume that the mass of the top quark is much greater than the other mass scales.

Given that $f' = \frac{\sqrt{2}m_t}{h_t}$, we have

$$\begin{aligned} g_A &= \frac{f}{f'} \\ &= \cot\beta. \end{aligned} \tag{42}$$

Now that g_A is known, we can find c_1 from Eqs. (36) and (39):

$$\begin{aligned} c_1 &= \frac{\cot\beta\ m_Z}{16\pi v} \\ &= 1.1 \times 10^{-5}\ \mathrm{GeV}^{-1} \end{aligned} \tag{43}$$

Now that we have coupling constants and lagrangian terms, we are ready to run FeynRules. The package already has all the SM lagrangian terms in a supplementary file; those terms are imported along with the new Bosonic Technicolor terms.

```
LoadModel["SM.fr", "Bosonic_Technicolor.fr"];
```

Then we specify the lagrangian.

```
LBTC = c0 piZero Eps[μ, ν, α, β]
FS[G, μ, ν, a] FS[G, α, β, a]
-c1 H Z[μ].del[piZero, μ]
```

and FeynRules calculates the vertices and decay amplitudes for all processes.

```
vertsDM = FeynmanRules[LBTC];
WriteUFO[LBTC, LGauge, LFermions, LHiggs, LYukawa];
```

FeynRules generates a Universal FeynRules Output folder which can be read by the Monte Carlo event generator MadGraph. Monte Carlo refers to the fact that scattering events are randomly generated, following probability distributions given by the underlying field theory.

3.4.2 MadGraph

Let us begin with a tutorial process in MadGraph. If we generate the $pp \to Zh$ (the Z does not decay) and plot the invariant mass of the outgoing Z and h, we should see a peak near the mass of π^0, which we have set to 300 GeV.

We begin by importing the new model:

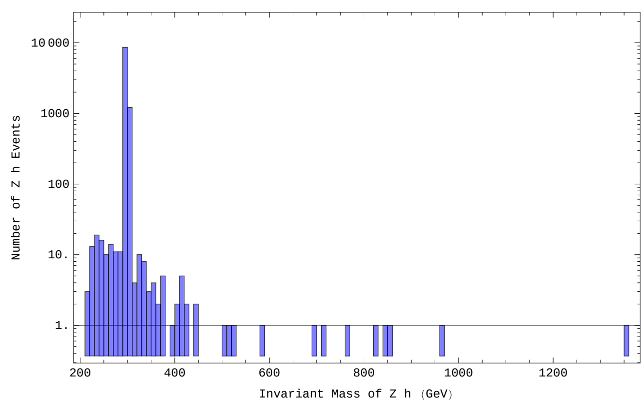
```
mg5> import model Bosonic_Technicolor_UFO
```

then generate 10,000 events at 7 TeV for the process $pp \to Zh$.

```
mg5> generate p p > z h
mg5> output
mg5> launch
```

MadGraph outputs an “event” file, which contains all the information about a given run in the standard Les Houches format (filename.lhe). We will not analyze the file in MadAnalysis because it is simple enough to be handled by Mathematica. Maxim Perelstein provides a tutorial on using Mathematica to analyze MadGraph files at the International School of Cargese 2012 website [8]. He includes a Mathematica notebook that extracts energy and momentum from the lhe file. We use his notebook (see Appendix C) to generate a plot of the Zh invariant mass. See Fig 6. There is a

Figure 6: Invariant Mass of Z h in Bosonic Technicolor Decay $pp \to Zh$
$m_{\pi^0} = 300$ **GeV**



clear peak at 300 GeV, as expected.

Now we can run MadGraph in the same manner for $pp \to Zh \to \mu^+\mu^- h$ in BTC and in the SM. We use MadAnalysis to analyze this process because it allows us to more accurately simulate events at the LHC.

3.4.3 MadAnalysis

MadAnalysis is a user-friendly python interface for ROOT, the C++ data analysis and plotting software used by CERN. We import the lhe file for $pp \to Zh \to \mu^+\mu^- h$:

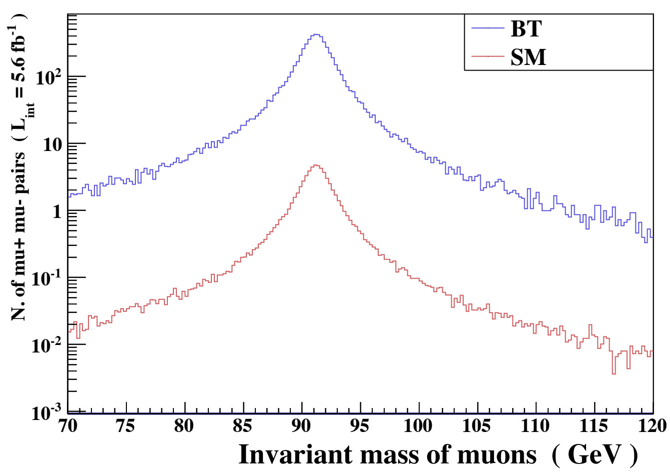
```
ma5>import /Users/Jennifer/PROC_Bosonic_Technicolor_UFO_0/
Events/run_01/unweighted_events.lhe.gz as BTC
```

Next we set the integrated luminosity to 5.6 fb^{-1}, which was the luminosity for the ATLAS 2011 run at 7 TeV [1].

```
ma5>set main.lumi = 5.6
```

Now MadAnlaysis can plot the invariant mass of dimuon events (see Fig 7). This

Figure 7: Invariant mass of dimuon events.



plot shows that the signal is very large; the SM expects to see less than five dimuon events at the mass of the Z, while BTC expects to see over 100 (see Appendix D for the full MadAnalysis Report). This may be a promising decay mode for the LHC.

In practice, the LHC background would be more complicated than simply $pp \to Zh \to \mu + \mu - h$. The LHC would need to reconstruct Zh events from $\mu^+\mu^- b\bar{b}$ or $\mu^+\mu^-\gamma\gamma$, not $\mu^+\mu^- h$, since the Higgs cannot be observed directly, but decays to other particles. The background for $\mu^+\mu^- b\bar{b}$ and $\mu^+\mu^-\gamma\gamma$ may be high, in which case technipion may be more difficult to observe.

4 Conclusions

More data from LHC on $\gamma\gamma$ decays would be necessary to rule out bosonic technicolor. It is still a viable theory for large values of $f^{'}$ in the region 120-160 GeV. In other regions, $f^{'}$ could be any value consistent with our model, but the LHC is not sensitive enough to $\gamma\gamma$ decay outside this range.

The technipion may be observable around $m_{\pi^0} = 300$ GeV through an excess in dimuon events from the Z. The simulator software FeynRules, Madgraph, and MadAnalysis show a nearly 100-fold excess in dimuon events in the channel $pp \rightarrow Zh \rightarrow \mu^+\mu^- h$. However, more analysis would be required to determine whether the dimuon signal could be observed over the true standard model background.

Because the Z can decay to e^+e^- as well, this channel may offer another way to detect the technipion. Further work could include analysis of Z and h decays through $e^+e^-\gamma\gamma$ and $\mu^+\mu^- b\bar{b}$. MadAnalysis also provides ways to cut event data so that it more accurately reflects what would be seen at the LHC. This may allow us to put further constraints on the model, rule it out completely, or, if the technipion is discovered, provide important evidence in favor of the Bosonic Technicolor Model.

Appendices

A FeynRules .fr file

```
M$ModelName = "Bosonic_Technicolor";

M$Parameters = {
zhiggs == {
Value -> 0.1048397274353207
InteractionOrder-> {BT,1},
Description -> "Z Higgs Coupling"},

lSH == {
Value -> 1.1*10^(-5),
InteractionOrder-> {BT,1},
Description -> "Temporary Constant"}
}

M$ClassesDescription = {
S[4] == {
ClassName -> piZero,
SelfConjugate -> True,
Mass -> {Msc, 300},
Width -> 0.04713756815012967,
ParticleName -> "piZero"}
}
```

MadEvent analysis routines

```
(* Based on the Chameleon package by Philip Shuster, Jesse Thaler, Natalia Toro *)
(* Modified by Maxim Perelstein and Andi Weiler, 2008-09 *)

(*format of the compulsory event vector*)
eventInfo = {_, _, _, _, _, _};

ClearAll[particle, finout];

(*PDG numbers see e.g. http://
 home.fnal.gov/~maeshima/alignment/ORCA/PYTHIA_particle_codes.ps*)

particle[2] = u;
particle[-2] = uBar;

particle[1] = d;
particle[-1] = dBar;

particle[3] = "s";
particle[-3] = "sBar";

particle[4] = "c";
particle[-4] = "cBar";

particle[5] = b;
particle[-5] = bBar;

particle[6] = t;
particle[-6] = tBar;

particle[11] = e⁻;
particle[-11] = e⁺;

particle[12] = "νe";
particle[-12] = "νe^c";

particle[13] = "μ⁻";
particle[-13] = "μ⁺";

particle[14] = "νμ";
particle[-14] = "νμ^c";

particle[16] = "ντ";
particle[-16] = "ντ^c";

particle[21] = gluon;

particle[23] = Z;

particle[24] = W⁺;
particle[-24] = W⁻;

particle[1 000 006] = OverTilde[t]1;
particle[-1 000 006] = OverTilde[t]1*;
particle[1 000 022] = OverTilde[χ]0;

finout[-1] = in;
finout[1] = out;
finout[2] = decayed;
```

```
ReadME[rawInput_] :=
  (
   (*Search for beginning of events*)
   pos = Position[rawInput, {"</init>"}][[1, 1]];
   (*Throw away crap at start of file,
   combine events in {} array and remove the XML commands and compulsory
    eventinfo *)
   DeleteCases[Split[Drop[ rawInput, pos], # =!= {"</event>"} &],
    {"<event>"} | {"</LesHouchesEvents>"} | {"</event>"} | eventInfo, 2]
  );

EventPrint[ event_ ] :=
  ( Print[
    Join[{{pid, in / out, mother1, mother2, color1, color2, px, py, pz, p0,
        mass, 6, hel}},
      event /. {x1_, x2_, x3_, x4_, x5_, x6_, x7_, x8_, x9_, x10_, x11_, x12_, x13_} ->
        {particle[x1], finout[x2], x3, x4, x5, x6, x7, x8, x9, x10, x11, x12, x13}] //
     MatrixForm]);

(* those are input or decayed particles*)
decayedOrIn = {_, -1, _, _, _, _, _, _, _, _, _, _, _} |
   {_, 2, _, _, _, _, _, _, _, _, _, _, _};

EventOut[ event_ ] := (DeleteCases[event, decayedOrIn]);

SetOut[ event_ ] := (DeleteCases[event, decayedOrIn, 2]);

(* EffMassAll[objList_]  :=Plus @@ Map[ptOf,objList//Transpose,{2}]; *)

EffMass[event_] := Plus @@ Map[ptOf, event, {1}];

pT[event_] := Map[ptOf, event, {1}] // Flatten;
eta[event_] := Map[etaOf, event, {1}] // Flatten;
theta[event_] := Map[thetaOf, event, {1}] // Flatten;
threeVector[event_] := Map[ThreeVectorFrom, event, {1}];


ptOf[{_, _, _, _, _, _, px_, py_, ___}] := Sqrt[px^2 + py^2];
enOf[{_, _, _, _, _, _, _, _, _, En_, ___}] := En;
thetaOf[{_, _, _, _, _, _, px_, py_, pz_, ___}] := ArcCos[pz / Sqrt[px^2 + py^2 + pz^2]];
etaOf[{_, _, _, _, _, _, px_, py_, pz_, ___}] :=
  - Log[ Abs[Tan[ ArcCos[pz / Sqrt[px^2 + py^2 + pz^2]] / 2]]];
FourVectorFrom[{_, _, _, _, _, _, px_, py_, pz_, En_, ___}] := {En, px, py, pz };

FourLength[{pe_, pz_, px_, py_}] := Sqrt[Max[pe^2 - pz^2 - px^2 - py^2, 0.0]];

ThreeVectorFrom[{_, _, _, _, _, _, px_, py_, pz_, ___}] := { px, py, pz };

CosthetaTwoJet[{jet1_, jet2_}] :=
  (a = ThreeVectorFrom[jet1]; b = ThreeVectorFrom[jet2]; a.b / Sqrt[a.a b.b]);

GetAll[evt_] := evt;
all[evt_] := True;

Freq[evtList_, crit_, objsel_, plotfunc_, {min_, max_, nbins_}] :=
  BinCounts[ Flatten[ plotfunc /@ Flatten4[objsel /@ Select[evtList, crit]]],
```

The LaTeX report

Generated by Jennifer on 15 April 2013, 18:56:12

This report has been generated automatically by MadAnalysis 5.

Please cite:

> **E. Conte, B. Fuks and G. Serret**,
> *MadAnalysis 5, A User-Friendly Framework for Collider Phenomenology*,
> Comput. Phys. Commun. **184** (2013) 222-256,
> arXiv:1206.1599 [hep-ph].

To contact us:

> **http://madanalysis.irmp.ucl.ac.be**
> **ma5team@iphc.cnrs.fr**

Contents

1 Setup

1.1 Command history

```
ma5>import /Users/Jennifer/PROC_Bosonic_Technicolor_UFO_0/Events/run_01/unweighted_events.
as BT
ma5>import /Users/Jennifer/PROC_Standard_Model_UFO_0/Events/run_01/unweighted_events.lhe.gz
as SM
ma5>set main.lumi = 5.6
ma5>set BT.type = signal
ma5>set SM.type = background
ma5>plot M(mu+ mu-) 200 70 120 [superimpose]
ma5>plot M(mu+ mu-) 200 70 120 [logY superimpose]
ma5>set selection[1].titleX = "Invariant mass of muons (GeV)"
ma5>set selection[2].titleX = "Invariant mass of muons (GeV)"
ma5>set main.SBratio = "(S-B)/sqrt(B)"
ma5>reject ETA(mu+ mu-) > 100
ma5>submit MAD_ANALYSIS_MUONS
```

1.2 Configuration

- MadAnalysis version 1.1.5 (2012/11/28).
- Histograms given for an integrated luminosity of 5.6fb^{-1}.

2 Datasets

2.1 bt

- Sample consisting of: signal events.
- Generated events: 100000 events.
- Normalization to the luminosity: 6589+/- 4 events.
- Ratio (event weight): 0.066 .

Path to the event file	Nr. of events	Cross section (pb)	Negative wgts (%)
PROC_Bosonic_Technicolor_U Events/run_01/-unweighted_events.lhe.gz	100000	1.18 @ 0.052%	0.0

2.2 sm

- Sample consisting of: background events.
- Generated events: 100000 events.
- Normalization to the luminosity: 72+/- 1 events.
- Ratio (event weight): 0.00072 .

Path to the event file	Nr. of events	Cross section (pb)	Negative wgts (%)
PROC_Standard_Model_UFC Events/run_01/-unweighted_events.lhe.gz	100000	0.013 @ 0.089%	0.0

3 Histos and cuts

3.1 Histogram 1

*** Plot: M (mu+ mu-)**

Table 1. Statistics table

Dataset	Integral	Entries / events	Mean	RMS	Underflow	Overflow
bt	6589	1.0	90.865	5.005	1.084	0.006
sm	72.7	1.0	91.1161	4.574	0.913	0.011

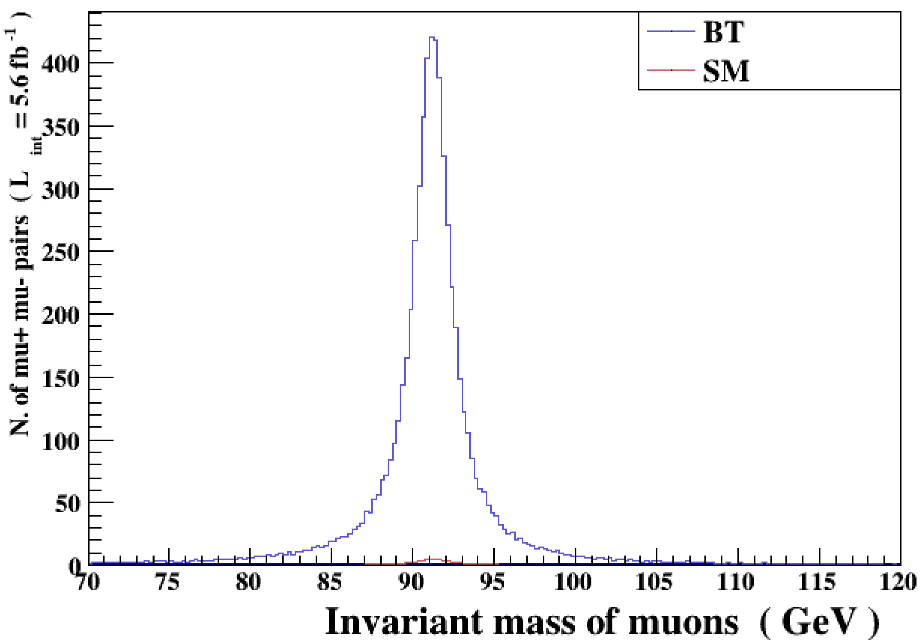


Figure 1.

3.2 Histogram 2

*** Plot: M (mu+ mu-)**

Table 2. Statistics table

Dataset	Integral	Entries / events	Mean	RMS	Underflow	Overflow
bt	6589	1.0	90.865	5.005	1.084	0.006
sm	72.7	1.0	91.1161	4.574	0.913	0.011

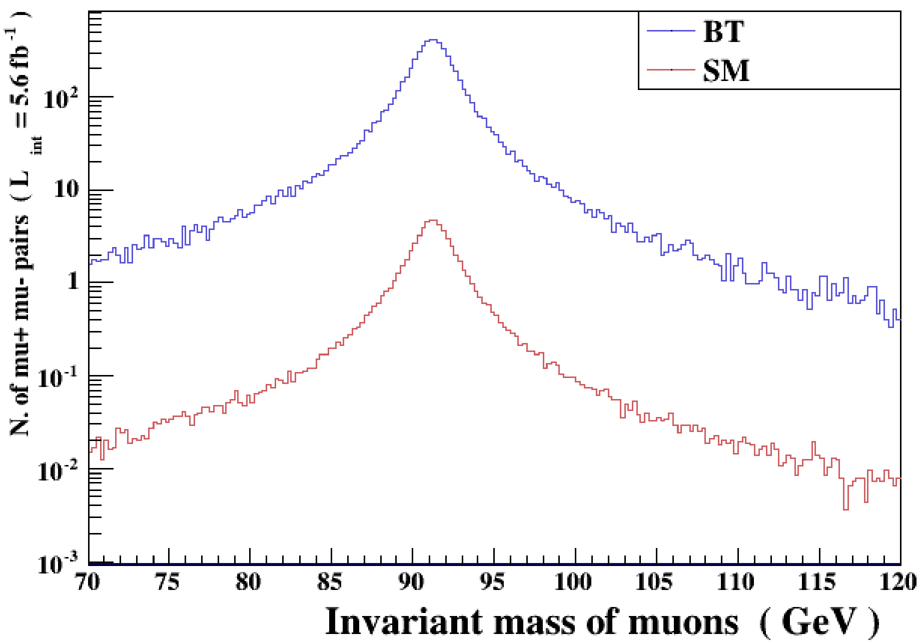


Figure 2.

3.3 Cut 1

Cut: reject ETA (mu+ mu-) > 100.0

Dataset	Events kept: K	Rejected events: R	Efficiency: K / (K + R)	Cumul. efficiency: K / Initial
bt	6589.90 +/- 3.42	0.0 +/- 0.0	1.0	1.0
sm	72.6828 +/- 0.0645	0.0 +/- 0.0	1.0	1.0

4 Summary

4.1 Cut-flow chart

- How to compare signal (S) and background (B): (S-B) /sqrt (B) .
- Associated uncertainty: 1./(B**2)*sqrt(B**2*ES**2+S**2*EB**2) .

Table 3. Signal and Background comparison

Cuts	Signal (S)	Background (B)	S vs B
Initial (no cut)	6589.90 +/- 3.42	72.6828 +/- 0.0645	764.4454 +/- 0.0932
Cut 1	6589.90 +/- 3.42	72.6828 +/- 0.0645	764.4454 +/- 0.0932

References

[1] Georges Aad et al. "Improved luminosity determination in pp collisions at sqrt(s) = 7 TeV using the ATLAS detector at the LHC". In: (2013). arXiv:1302.4393 [hep-ex].

[2] Gustavo Burdman, Carlos E.F. Haluch, and Ricardo D. Matheus. "Is the LHC Observing the Pseudo-scalar State of a Two-Higgs Doublet Model ?" In: *Phys.Rev.* D85 (2012), p. 095016. DOI: 10.1103/PhysRevD.85.095016. arXiv:1112.3961 [hep-ph].

[3] Christopher D. Carone. "Technicolor with a 125 GeV Higgs Boson". In: *Phys.Rev.* D86 (2012), p. 055011. DOI: 10.1103/PhysRevD.86.055011. arXiv:1206.4324 [hep-ph].

[4] Christopher D. Carone and Reinard Primulando. "Combined Constraints on Holographic Bosonic Technicolor". In: *Phys.Rev.* D82 (2010), p. 015003. DOI: 10.1103/PhysRevD.82.015003. arXiv:1003.4720 [hep-ph].

[5] B. Field, S. Dawson, and J. Smith. "Scalar and pseudoscalar Higgs boson plus one jet production at the CERN LHC and Tevatron". In: *Phys.Rev.* D69 (2004), p. 074013. DOI: 10.1103/PhysRevD.69.074013. arXiv:hep-ph/0311199 [hep-ph].

[6] David Griffiths. *Introduction to Elementary Particles.* John Wiley & Sons, 1987.

[7] John F. Gunion et al. "THE HIGGS HUNTER'S GUIDE". In: *Front.Phys.* 80 (2000), pp. 1–448.

[8] Maxim Perelstein. *International School Cargese 2012: Across the TeV frontier with the LHC.* Aug. 2012. URL: http://indico.cern.ch/internalPage.py?pageId=1&confId=162087.