Phenomenology of minimal \(Z'\) models: \textit{from the LHC to high energy scales}

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Outline

1. The minimal $Z'$ model
2. EWPTs and LHC constraints
3. RG and high energy behaviour
4. LHC phenomenology
The minimal Z’ model

• Z’ naturally arises from many GUT scenarios such as SO(10), E₆, L-R, string-theory constructions, KK theories, etc.

• Interesting phenomenology potentially accessible at colliders: Z’ usually accompanied by extra degrees of freedom (seesaw can be implemented)

• Possibility to explain baryogenesis through resonant leptogenesis

➢ Gauge sector

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)' \]

➢ Fermion sector

SM-singlet right-handed neutrinos \( \nu_R \)
required by anomaly cancellation

➢ Scalar sector

SM-singlet scalar \( \chi \)
required by SSB of \( U(1)' \)
provides Majorana masses for \( \nu_R \)

➢ New states: \( Z' \) gauge boson, 3 heavy neutrinos, 1 real scalar

➢ New parameters:

\[ g'_1, \tilde{g}, M_{Z'}, \alpha, m_{H2}, m_{\nu_h} \]
The minimal $Z'$ model: *a comment on the kinetic mixing*

- The most general Lagrangian allowed by gauge invariance admits a *kinetic mixing* between the two abelian field strengths

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\kappa}{2} F^{\mu\nu} F'_{\mu\nu}$$

even if absent at tree-level it can be reintroduced by radiative corrections

- The kinetic Lagrangian can be recast into a diagonal form thus introducing a non-diagonal covariant derivative

$$\mathcal{D}_{\mu} = \partial_{\mu} + i g_1 Y B_{\mu} + i (\tilde{g} Y + g_1' Y_{B-L}) B'_{\mu} + \ldots$$

*an additional abelian gauge factor can always be described by a linear combination of the hypercharge and of the B-L quantum number*

- We can explore an entire class of minimal Abelian models through the ratio of the gauge couplings $\tilde{g}/g_1'$

- Typical benchmark models:
  - $g_1' = 0$ : sequential SM
  - $\tilde{g} = 0$ : pure B-L
  - $\tilde{g} = -2 g_1'$ : $U(1)_R$
  - $\tilde{g} = -4/5 g_1'$ : $U(1)_X$ from SO(10)
Constraints from EWPTs and LHC searches

2σ significance contour levels in the $\tilde{g} - g'_1$ space

- $M_{Z'} = 2.5$ TeV
- $M_{Z'} = 3$ TeV

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Leptophobc direction $g'_1/\tilde{g} \sim -3/4$

EWPTs from LEP2 data

Di-lepton channel at LHC 8 TeV $L = 20$ fb$^{-1}$

LHC studies represent a strong improvement with respect to the EW ones
The extended scalar sector is strongly constrained by Higgs searches at the LHC

- **full leptonic decay of two Z**
- **full leptonic decay of two W**
- **full and semi leptonic decay of ZZ and WW**
- **combined search in γγ, ZZ, WW, ττ, bb**

\[\chi^2\] compatibility fit with the Higgs signal measurements
establish a direct connection between accessible EW scale spectra and a potential underlying GUT structure

along the RG evolution we require:

- perturbativity of the couplings
- stability of the vacuum
- unification (work in progress)

- delineate the viable parameter space from both a phenomenological perspective and its theoretical consistency

- ultimately direct experimental investigations towards key analyses enabling one to make an assessment of the high energy structure of the model
High energy behaviour

Perturbativity of the couplings and stability of the vacuum and in the $\tilde{g} - g'_1$ space

$M_Z = 3\text{TeV}, \alpha = 0, m_{H_2} = 200\text{GeV}, m_{\nu_\alpha} = 95\text{GeV}$

$M_Z = 3\text{TeV}, \alpha = 0.2, m_{H_2} = 200\text{GeV}, m_{\nu_\alpha} = 95\text{GeV}$

$M_Z = 3\text{TeV}, \alpha = 0.3, m_{H_2} = 200\text{GeV}, m_{\nu_\alpha} = 95\text{GeV}$

- $10^5 \text{GeV} < Q_{\text{max}} < 10^8 \text{GeV}$
- $10^8 \text{GeV} < Q_{\text{max}} < 10^{10} \text{GeV}$
- $10^{10} \text{GeV} < Q_{\text{max}} < 10^{15} \text{GeV}$
- $Q_{\text{max}} > 10^{15} \text{GeV}$

Black dots represent some benchmark models $(U(1)_R, U(1)_X, U(1)_{B-L})$

usually addressed in the literature

- The destabilising effect of heavy neutrinos is suppressed
- Stability improves as $\alpha$ moves away from zero
High energy behaviour

Perturbativity of the couplings and stability of the vacuum and in the $m_{H2} - \alpha$ space

Comparison between NLO (yellow region) and LO (region in dashed line) results

- $10^5$ GeV < $Q_{\text{max}}$ < $10^8$ GeV
- $10^8$ GeV < $Q_{\text{max}}$ < $10^{10}$ GeV
- $10^{10}$ GeV < $Q_{\text{max}}$ < $10^{15}$ GeV
- $Q_{\text{max}}$ > $10^{15}$ GeV

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The decay mode hierarchy is drastically changed when $\tilde{g} \neq 0$

- $g'_1 = 0$ recovers the SSM limit
- $\tilde{g} \neq 0$ opens new $Z'$ decay channels
  \[ \begin{align*}
  Z' &\to WW \\
  Z' &\to Z H_1 \\
  Z' &\to Z H_2 
  \end{align*} \]

BR $\sim 2\%$ each
Z’ production

Z’ on-shell production cross section at the LHC

$M_Z' = 2 \text{ TeV}, \sqrt{s} = 13 \text{ TeV}$

$M_Z' = 3 \text{ TeV}, \sqrt{s} = 13 \text{ TeV}$

dashed lines are excluded by LHC Run 1

$\sigma$ up to $\sim 10 \text{ fb}$

$\sigma$ up to $\sim 100 \text{ fb}$
Z' signatures

\[ Z' \rightarrow \nu_h \nu_h \rightarrow 3l + 2j + E_{T\text{miss}} \ (1 \nu_l) \]

Backgrounds

- \( WZjj \)
- \( t\bar{t} \) (with 3\(^{rd}\) lepton from b quark)
- \( t\bar{t}l\nu \)

Cuts

- momenta, angular acceptance, isolation
- \( |M_{jj} - M_W| < 20 \text{ GeV} \)
- \( |M_{l^+l^-} - M_Z| > 10 \text{ GeV} \)
- \( |M_{all} - M_{Z'}| < 250 \text{ GeV} \)

The longitudinal momentum of the \( \nu_l \) is reconstructed from the W mass and

\[ \text{minimising } X = |M_{l_1l_2\nu_l}^2 - M_{l_3j_1j_2}^2| \]
$Z'$ signatures

$Z' \to \nu_h \nu_h \to 3l + 2j + E_{T\text{miss}} \ (1 \nu_l)$

The heavy neutrino mass can be identified

- $|M_{jj} - M_W| < 20 \text{ GeV}$
- $|M_{l+} - M_Z| > 10 \text{ GeV}$
- $|M_{all} - M_{Z'}| < 250 \text{ GeV}$

The longitudinal momentum of the $\nu_l$ is reconstructed from the $W$ mass and minimising $X = |M_{l_1 l_2 \nu_l}^2 - M_{l_3 j_1 j_2}^2|$
Heavy Higgs production and decay

Standard production mechanisms

$q\bar{q} \rightarrow Z^* \rightarrow Z' H_2$
low $\sigma$ but it is the only accessible channel for $\alpha = 0$

- $H_2$ couplings to SM particles are rescaled by $\sin \alpha$ with respect to the SM Higgs
- Gluon fusion is the main production mode: $\sigma(M_{H_2}, \alpha) \sim (\sin \alpha)^2 \sigma_{SM}(M_{H_2})$
- New decay channels: $H_2 \rightarrow \nu_h \nu_h, \ H_2 \rightarrow H_1 H_1$
Heavy Higgs production and decay

- Favoured discovery channels
  \[
  \begin{align*}
  pp &\rightarrow H_2 \rightarrow WW & \sigma \text{ up to } \sim 200 \text{ fb} - 1 \text{ pb} \\
  pp &\rightarrow H_2 \rightarrow ZZ & \sigma \text{ up to } \sim 200 \text{ fb} \\
  pp &\rightarrow H_2 \rightarrow t\bar{t} & \sigma \text{ up to } \sim 50 \text{ fb}
  \end{align*}
  \]
  (LHC 13 TeV)

- \( \sigma \times \text{BR} \) contour level in the \( m_{H2} - \alpha \) space

  \[
  pp \rightarrow H_2 \rightarrow \nu_h \nu_h \\
  M_{Z'} = 2 \text{TeV}, m_{\nu_h} = 95 \text{GeV}
  \]

  \[
  pp \rightarrow H_2 \rightarrow H_1 H_1 \\
  M_{Z'} = 2 \text{TeV}, m_{\nu_h} = 95 \text{GeV}
  \]

  this channel represents a peculiar feature of this minimal class of \( Z' \) models

interesting cross section

\( \mu = 0.5 \text{ fb} \)

\( \mu = 0.2 \text{ fb} \)

\( \mu = 0.1 \text{ fb} \)
SM-like Higgs new decay channel

When $m_{H_1} > 2m_{\nu_h}$ a new decay channel becomes accessible: $H_1 \rightarrow \nu_h \nu_h$

$BR(H_1) \approx (\sin \alpha) \frac{m_{\nu_h}}{x} \sim (\sin \alpha) \frac{m_{\nu_h}}{M_{Z'}} g'_1$

BR spans from 0.1% to 1%

$\sigma_{pp \rightarrow H_1} \times BR(H_1 \rightarrow \nu_h \nu_h) \approx (\sin \alpha) \frac{m_{\nu_h}}{x} \sim (\sin \alpha) \frac{m_{\nu_h}}{M_{Z'}} g'_1$

$\sigma$ spans from 10 fb to 100 fb
SM-like Higgs new decay channel

When $m_{H_1} > 2m_{\nu_h}$ a new decay channel becomes accessible: $H_1 \rightarrow \nu_h \nu_h$

**signals**

1. $H \rightarrow \nu_h \nu_h \rightarrow 3l + 2j + E_{T\text{miss}} \quad (1 \nu_l)$

2. $H \rightarrow \nu_h \nu_h \rightarrow 4l + E_{T\text{miss}} \quad (2 \nu_l)$

**main backgrounds**

- $WZjj, t\bar{t}, t\bar{t}l\nu$
- $WWZ$

Heavy neutrinos are very long-lived particles: displaced vertices

example: $m_{\nu_h} = 50 \text{ GeV}$

$v_h$ decay length (lab frame) distribution extracted from process (2)
Conclusions

- Minimal Z' extensions of the SM
  neutral gauge boson, scalar and RH neutrinos

- LHC Run-I significantly constrains the parameter space

- RG methods can be effectively used to establish a connection between EW scale parameters and the underlying GUT structure

- Peculiar signatures:
  \[ pp \to Z' \to \nu_h \nu_h \]  (heavy neutrinos are long-lived particles: displaced vertices)
  \[ pp \to Z'^* \to Z' H_2 \]
  \[ pp \to H_2 \to \nu_h \nu_h, \ pp \to H_2 \to H_1 H_1 \]
  \[ pp \to H_1 \to \nu_h \nu_h \]
Backup slides
Renormalisation group evolution

Some technical details:

<table>
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<th>Order</th>
<th>β functions</th>
<th>matching conditions</th>
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<td>LO</td>
<td>one loop</td>
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<td>NLO</td>
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<tr>
<td>NNLO</td>
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<td>two loop</td>
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</tbody>
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- A complete NNLO analysis is only available for the SM
- NLO analysis can be implemented for a general QFT
  - 2L β functions are known
  - 1L matching conditions must be computed for each model

*Matching conditions* provide the initial value of the running couplings computed in the $\overline{\text{MS}}$ renormalisation scheme as a function of the physical on-shell parameters

$$\alpha_{\overline{\text{MS}}} = \alpha_{OS} + \delta \alpha_{OS} \bigg|_{\text{fin}}$$
Heavy neutrinos production from $Z'$

$\sigma \times \text{BR}$ contour level in the $\tilde{g} - g'$ space (LHC 13 TeV)

For $m_{vh}$ fixed:

$$\mu = \sigma_{pp\rightarrow Z'} \times \text{BR}(Z'\rightarrow \Sigma_{h} h), \quad m_{vh} = 95 \text{ GeV}$$

Solid, dashed and dotted lines refer to $M_{Z'} = 2, 2.5, 3$ TeV, respectively.

For $M_{Z'}$ fixed:

$$\mu = \sigma_{pp\rightarrow Z'} \times \text{BR}(Z'\rightarrow \Sigma_{h} h), \quad M_{Z'} = 2 \text{ TeV}$$

Solid, dashed and dotted lines refer to $m_{vh} = 95, 300, 500$ GeV, respectively.
Heavy Higgs branching ratios

$m_{H1} = 125.09$ GeV, $m_{H2} = 200$ GeV, $m_{vh} = 95$ GeV

$m_{H1} = 125.09$ GeV, $m_{H2} = 500$ GeV, $m_{vh} = 95$ GeV

- The BR into heavy neutrinos drops as $\alpha$ increases $H_2 \nu_h \nu_h \sim \cos \alpha$
- The BR into light higges shows a non-trivial $\alpha$ dependence
- The regions on the right of the vertical dashed lines are excluded by Higgs searches
Heavy Higgs production and decay

Favoured discovery channels: \( \sigma \times \text{BR} \) contour level in the \( m_{H2} - \alpha \) space (LHC 13 TeV)

\[
\begin{align*}
pp & \rightarrow H_2 \rightarrow WW \\
pp & \rightarrow H_2 \rightarrow ZZ \\
pp & \rightarrow H_2 \rightarrow t\bar{t}
\end{align*}
\]
The impact of the top mass in an extended scalar sector

The dashed line corresponds to the central value of the top mass $M_t = 173.34 \pm 0.76$ GeV extracted through MC modelling of production and decay of the top quark in hadronic collisions: *MC mass*

*MC mass does not represent neither the pole mass nor the $\overline{MS}$ mass!*

One usually assumes that the MC mass is sufficiently close to the pole mass with differences of the order of 1 GeV

![Diagram](image)

it would be better to define MC generators directly in terms of the $\overline{MS}$ Yukawa

- the mixing angle $\alpha$ weakens the destabilising effect of the top and eventually completely overcomes it for $\alpha > 0.4$
- the effect of $m_{H2}$ is softened and only shifts the instability induced by the top quark to higher values of its mass