Profiling $Z'$ bosons using asymmetry observables in top pair production with the lepton-plus-jets final state at the LHC

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PASCOS, Quy Nhon, Vietnam
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Z' bosons

• Generally any new, heavy, neutral spin-one bosons.

• Arise from residual $U(1)'$ symmetries after GUT breaking:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

• Leads to additional term in low-energy neutral current Lagrangian:

$$L \supset g' Z' \mu \bar{f} \gamma \mu (c_f V - c_f A_{\gamma/5}) f / g' Z' \mu \bar{f} \gamma \mu Q_{Z'} f.$$
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Benchmark $Z'$ models

- Generalised Sequential Models (GSMs):
  \[ \text{GSM} / \text{equal.osf cos} \alpha \text{L} / \text{three.osf} \text{R} / \text{plus.osf sin} \alpha \text{Q} \]

- General Left-Right symmetric models (GLRs):
  \[ \text{SU}(2) \times \text{SU}(2) \times \text{U}(1) \rightarrow \text{SU}(2) \times \text{U}(1) \text{Y} \]

- E/six.osf inspired models:
  \[ \text{E/six.osf} \rightarrow \text{SO}(1/0) \times \text{U}(1) \psi \rightarrow \text{SU}(5) \times \text{U}(1) \chi \rightarrow \text{SU}(3) \times \text{SU}(2) \times \text{U}(1) \text{Y} \]
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- $E_6$ inspired models:
  \[ E_6 \rightarrow \text{SO}(10) \times U(1)_\psi \]
  \[ \text{SO}(10) \rightarrow \text{SU}(5) \times U(1)_\chi \]
  \[ \text{SU}(5) \rightarrow \text{SU}(3)_C \times \text{SU}(2)_L \times U(1)_Y. \]
  \[ Q_{E_6} = \cos \theta T^\chi + \sin \theta T^\psi. \]
Experimental bounds on benchmark model $Z'$ masses

• Lower mass bound in GeV extracted by Accomando et al. based on CMS Drell-Yan results. [arXiv:/one/osf/five/zero/three/zero/two/six/seven/two]
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<table>
<thead>
<tr>
<th>Class</th>
<th>$E_6$</th>
<th>GLR</th>
<th>GSM</th>
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<tbody>
<tr>
<td>$U(1)'$</td>
<td>$\chi$</td>
<td>$\psi$</td>
<td>$\eta$</td>
</tr>
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<td>$M_{Z'}$</td>
<td>2700</td>
<td>2560</td>
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</tr>
</tbody>
</table>

![Graph showing experimental bounds on $Z'$ masses](image)
Top quark pair production

- $t\bar{t} + q, l + q', \nu W +$ is an alternative search channel to $Z' \to l/\pm osf l$.

- Top mass of $/one.osf/seven.osf/three.osf$ GeV is close to EW symmetry breaking scale.

- $Z' - t$ couplings significant in many BSMs, e.g. composite Higgs.

- Extremely short lifetime: top quarks decay prior to hadronisation.

- Top spin information is transmitted to decay products.

- Allows definition of unique Asymmetry observables.
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Generation tools

We generate the parton level final state and include full tree-level Standard Model interference, with all intermediate particles allowed off-shell.

Helicity amplitude calculations based on HELAS subroutines.

Can optionally enforce the narrow width approximation.

PDFs used are by CTEQ at a scale of $Q^2/m_t$.

VEGAS for multi-dimensional numerical phase-space integration.
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Matrix element Calculation and interference

\[|M_{pp \rightarrow t\bar{t}}| \approx \frac{\gamma, Z, Z^{'}}{2},\]

\[|M_{QCD}| \approx \frac{M_{\gamma, Z, Z^{'}}}{2},\]

\[D_{ij} \approx \frac{\hat{s} - m_{i}}{2} \frac{\hat{s} - m_{j}}{2} \Gamma_{i} \Gamma_{j} \left( \frac{\hat{s} - m_{j}}{2} + m_{i} \right) \right( \frac{\hat{s} - m_{i}}{2} + m_{j} \right).\]
Matrix element Calculation and interference

\[ |M(\text{pp} \rightarrow t\bar{t})|/two.osf = |M(\text{QCD})|/two.osf + |M(\gamma, Z, Z')|/two.osf,
\]

\[ |M(\gamma, Z, Z')|/two.osf = \hat{s}/two.osf \times D_{ij}/one.osf + \delta_{ij} \{ C_{qij} [ C_{tij} \cos \theta + B_{tij} (1 - \beta/2) ] + A_{qij} A_{tij} \beta \cos \theta \}.
\]

\[ A_f = g_i L g_j L - g_i R g_j R,
\]

\[ B_f = g_i L g_j R + g_i R g_j L,
\]

\[ C_f = g_i L g_j L + g_i R g_j R.
\]

\[ D_{ij} = (\hat{s} - m_i/2)(\hat{s} - m_j/2)/m_i m_j \Gamma_i \Gamma_j (\hat{s} - m_j/2)^2/\Gamma_j^2 + (\hat{s} - m_i/2)^2/\Gamma_i^2).
\]
Matrix element Calculation and interference

\begin{align*}
|\mathcal{M}(pp \to t \bar{t})| &= \frac{1}{\text{two.osf}} |\mathcal{M}(QCD)| + \frac{1}{\text{two.osf}} |\mathcal{M}(\gamma, Z, Z')|,
\end{align*}

\begin{align*}
A_{ij} &= \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij} \frac{1}{\text{six.osf}} \left( \hat{s} - \frac{m}{2} \right)_{ij}.
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Matrix element Calculation and interference

\[ |M(\gamma, Z, Z')| \sim \frac{1}{\text{six}} |D_{ij}| + \delta_{ij} \left\{ C_{q_{ij}} + C_{t_{ij}} (\beta \cos \theta) \right\} + B_{t_{ij}} (\beta) \sim \frac{1}{\text{six}} \left\{ A_{q_{ij}} + A_{t_{ij}} (\beta \cos \theta) \right\} \]
Matrix element Calculation and interference

\[ |M(\gamma, Z, Z')|_{\text{QCD}} + |M(\gamma, Z, Z')|_{\text{QCD}} \]

\[ D_{ij} = \delta_{ij} \{ C_{qij} + C_{tij}(1 - \beta \cos \theta) + B_{tij} \} \]

\[ A_{f} = g_{iL} g_{jL} - g_{iR} g_{jR}, \quad B_{f} = g_{iL} g_{jR} + g_{iR} g_{jL}, \quad C_{f} = g_{iL} g_{jL} + g_{iR} g_{jR} \]

\[ D_{ij} = (\hat{s} - m_i/2)(\hat{s} - m_j/2) \Gamma_i \Gamma_j \]

\[ \Gamma_i = (\hat{s} - m_j/2)/(\hat{s} + m_i/2), \quad \Gamma_j = (\hat{s} - m_i/2)/(\hat{s} + m_j/2) \]
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|M_{pp \rightarrow t\bar{t}}|/two.osf = |M_{QCD}|/two.osf + |M_{\gamma, Z, Z'}|/two.osf
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D_{ij} = (\hat{s} - m^2_i)(\hat{s} - m^2_j)/m_i m_j \Gamma_i \Gamma_j \left( (\hat{s} - m^2_j)/two.osf + m^2_i/\Gamma_i \right) \left( (\hat{s} - m^2_j)/two.osf + m^2_j/\Gamma_j \right)
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|\mathcal{M}(pp \to t\bar{t})|^2 = |\mathcal{M}(QCD)|^2 + |\mathcal{M}(\gamma, Z, Z')|^2,
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|M(pp \to t\bar{t})|^2 = |M(QCD)|^2 + |M(\gamma, Z, Z')|^2,
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\[
|M(\gamma, Z, Z')|^2 = \frac{\hat{s}^2}{6} \frac{D_{ij}}{1 + \delta_{ij}} \left\{ C^q_{ij} \left[ C^t_{ij}(1 + \beta^2 \cos^2 \theta) + B^t_{ij}(1 - \beta^2) \right] + 2A^q_{ij}A^t_{ij} \beta \cos \theta \right\}.
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\[ A^f = g^i_L g^i_L - g^i_R g^i_R. \]
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\[ A^f = g^i_L g^j_L - g^i_R g^j_R, \quad B^f = g^i_L g^j_R + g^i_R g^j_L, \]
|\mathcal{M}(pp \rightarrow t\bar{t})|^2 = |\mathcal{M}(\text{QCD})|^2 + |\mathcal{M}(\gamma, Z, Z')|^2,

|\mathcal{M}(\gamma, Z, Z')|^2 = \frac{\hat{s}^2}{6} \frac{D_{ij}}{1 + \delta_{ij}} \left\{ C_{ij}^q \left[ C_{ij}^t (1 + \beta^2 \cos^2 \theta) + B_{ij}^t (1 - \beta^2) \right] + 2A_{ij}^q A_{ij}^t \beta \cos \theta \right\}.

A^f = g_L^i g_L^j - g_R^i g_R^j, \quad B^f = g_L^i g_R^j + g_R^i g_L^j, \quad C^f = g_L^i g_L^j + g_R^i g_R^j,
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\[ D^{ij}_{ij} = \frac{(\hat{s} - m_i^2)(\hat{s} - m_j^2) + m_i m_j \Gamma_i \Gamma_j}{(\hat{s} - m_i^2)^2 + m_i^2 \Gamma_i^2} \frac{(\hat{s} - m_j^2)^2 + m_j^2 \Gamma_j^2}{(\hat{s} - m_j^2)^2 + m_j^2 \Gamma_j^2}. \]
Forward-Backward Asymmetry

Forward-backward Asymmetry is defined as:

\[
N_t(\cos \theta > \text{zero}) - N_t(\cos \theta < \text{zero})
\]

This asymmetry demonstrates a different coupling to the cross section \(\sigma\):

\[
\sigma \propto \left( \frac{c_V}{2} + \frac{c_A}{2} \right) \left( \frac{c_A}{2} + \frac{c_V}{2} \left( \frac{1}{4} - \beta/2 \right) \right),
\]

where \(\beta = \sqrt{1 - \frac{4m_t}{\hat{s}}}\).

\(A_{FB}\) is sensitive to the sign of the couplings.

\(pp\) collisions have no preferred \(z\) direction.

However, typically parton momentum fraction:

\[x(q) > x(\bar{q})\]

Use the boost direction to define the \(z\) axis.

\[
\cos \theta \rightarrow \cos \theta^* = y_{tt} |y_{tt}| \cos \theta \Rightarrow A_{FB} \rightarrow A^*_{FB}.
\]
• Forward-backward Asymmetry is defined

\[ \frac{N_t(\cos \theta > 0) - N_t(\cos \theta < 0)}{N_t(\cos \theta > 0) + N_t(\cos \theta < 0)} \]

• This asymmetry demonstrates a different couplings to \( Z' \) when compared to the cross section \( \sigma \):

\[ \sigma \propto (c_{V_i}^2 + c_{A_i}^2)(c_{V_t}^2 + c_{A_t}^2) \]

\[ A_{FB} \propto c_{V_i} c_{A_i} c_{V_t} c_{A_t}. \]

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\[ \sigma \propto \left( (c_V^i)^2 + (c_A^i)^2 \right) \left( (c_A^t)^2 + (c_V^t)^2(4 - \beta^2) \right) \]

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A_{FB} \propto c_V^i c_A^i c_V^t c_A^t.
\]

where \(\beta = \sqrt{1 - 4m_t^2/\hat{s}}\)

- \(A_{FB}\) is sensitive to the sign of the couplings.
- \(pp\) collisions have no preferred \(z\) direction.
- However, typically parton momentum fraction: \(x(q) > x(\bar{q})\).
- Use the boost direction to define the \(z\) axis.
Forward-Backward Asymmetry

- Forward-backward Asymmetry is defined

\[ A_{FB} = \frac{N_t(\cos \theta > 0) - N_t(\cos \theta < 0)}{N_t(\cos \theta > 0) + N_t(\cos \theta < 0)} \]

- This asymmetry demonstrates a different couplings to $Z'$s when compared to the cross section ($\sigma$):

\[ \sigma \propto \left( (c_V^i)^2 + (c_A^i)^2 \right) \left( (c_A^t)^2 + (c_V^t)^2(4 - \beta^2) \right), \]

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\[ \cos \theta \rightarrow \cos \theta^* = \frac{Y_{tt}}{|Y_{tt}|} \cos \theta \quad \Rightarrow \quad A_{FB} \rightarrow A_{FB}^*. \]
Top polarisation Asymmetry

Top polarisation Asymmetry is defined as:

\[ A_L = \frac{N(\uparrow, \uparrow) - N(\downarrow, \downarrow)}{N(\uparrow, \downarrow) + N(\downarrow, \uparrow)} \]

This asymmetry demonstrates different couplings to \( Z' \)s compared to the cross section (\( \sigma \)):

\[ \sigma \propto (c_V \alpha) (c_A \beta) \]

Information about the top quark polarization is preserved in:

\[ \Gamma_f \propto \Gamma_f \cos \theta_f \]

\( \theta_f \) is the angle between the top quark momentum in the partonic rest frame and the decay fermion in the top rest frame.
Top polarisation Asymmetry

- Top polarisation Asymmetry is defined

\[ \text{Top polarisation Asymmetry} = \frac{\sigma_{+N}(I_+)}{\sigma_{-N}(I_-)} \]

- This asymmetry demonstrates a different couplings to $Z'$s when compared to the cross section ($\sigma$):

\[ \sigma \propto \left( c_{Vt} c_{At} \right) \left( c_{Vi} c_{Ai} \right) \]

\[ A_L \propto \left( c_{Vi} c_{Ai} \right) c_{Vt} c_{At} \beta. \]

- Information about the top quark polarization is preserved in:

\[ \Gamma_f d \Gamma_f d \cos \theta_f = \kappa_f A_L \cos \theta_f \]

- $\theta_f$ is the angle between the top quark momentum in the partonic rest frame and the decay fermion in the top rest frame.
Top polarisation Asymmetry

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\[ A_L = \frac{N(+, +) + N(+, -) - N(-, +) - N(-, -)}{N(+, +) + N(+, -) + N(-, +) + N(-, -)} \]
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Toy top pair reconstruction for lepton-plus jets

• We presently focus on semileptonic decay.
• Allows reasonable reconstruction of $t \bar{t}$ system.
• Enables reconstruction of $A^\ast_{FB}$ and $A^\ast_{L}$.
• Presently limited to the parton-level.
• Wish to mimic experimental conditions.
• Must resolve combinatorial ambiguity in jet-top assignment.
• Must also reconstruct the longitudinal neutrino momentum in the presence of missing transverse energy.
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Toy top pair reconstruction for lepton-plus jets

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![Diagram showing the reconstruction of a top quark pair in a semileptonic decay](image)
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Solving for the neutrino momentum

\[ p_{\nu} \]

\[ p_{\text{miss}} \]

\[ W \]

\[ p_e \]

\[ p_{\nu} Z \]

\[ k \]

\[ m_W \]

\[ \chi^2 \]

\[ m_{b\nu} - m_t \Gamma_t \]

\[ m_{bq} - m_t \Gamma_t \]

\[ \chi^2 = \left( m_{b\nu} - m_t \Gamma_t \right)^2 + \left( m_{bq} - m_t \Gamma_t \right)^2 \]
Solving for the neutrino momentum

- Assume \( p_T^\nu = p_T^{miss} \) and on-shell \( W \):

\[
p_T^{e2} p_Z^\nu{}^2 - 2kp_Z^e p_Z^\nu + p_T^\nu{}^2 |p_e|^2 - k^2 = 0,
\]

where \( k = \frac{m_w^2}{2} + p_T^e p_T^\nu \).
Solving for the neutrino momentum

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where $k = \frac{m_W^2}{2} + p_T^e p_T^\nu$.

• Select solution by minimising chi-square:

$$\chi^2 = \left( \frac{m_{bl\nu} - m_t}{\Gamma_t} \right)^2 + \left( \frac{m_{bqq} - m_t}{\Gamma_t} \right)^2$$
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Uncertainty, significance and cuts on $|y_{tt}|$

- Account only for dominant statistical uncertainty of the expected events in data and assume $\delta N/\sqrt{N}$.
- Propagate error: $\delta A^*FB/\sqrt{\delta A^*/\text{one.osf} - \delta A^*/\text{two.osf}}$.
- Therefore, define Significance for observable as:
  $$S^*/\text{one.osf}O_{SM}^{\text{BSM}} - O_{SM}^{\text{BSM}}\delta O_{stat}/\text{two.osf}$$
- Combine significance by adding in quadrature (ad-hoc).
Uncertainty, significance and cuts on $|ytt|$

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$$\delta A_{FB}^* = \frac{1 - A_{FB}^2}{N}$$

(Shown as colored bands)
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  (Shown as colored bands)

- Therefore, define Significance for observable as:

  $$S = \frac{O_{SM+BSM} - O_{SM}}{\delta O_{SM+BSM}^{stat}}$$  \hspace{1cm} (2)

- Combine significance by adding in quadrature (ad-hoc).
Uncertainty, significance and cuts on $|y_{tt}|$

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Expected $m_{tt}$ distribution and $A^*_FB$ with $L = 100 \text{ fb}^{-1}$
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- **Model: GSM-SM**
  - Significance expected with $L = 100$ fb$^{-1}$
  - $m_{\text{reconstructed}}$ [TeV]

- **Model: GSM-T3L**
  - Significance expected with $L = 100$ fb$^{-1}$
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Expected significance with $L = 100 \text{ fb}^{-1}$

Model: GSM-SM

Model: GS-M-T3L

Model: GLR-LR

Model: GLR-R
Expected significance with $L = 100 \text{ fb}^{-1}$
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- Extract $A_L$ as the fitted gradient.
Expected $A_L$ with $L = 100 \text{ fb}^{-1}$
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- $A_L$ clearly distinguishes between GSM and GLR model $Z'$.
- $E_{\text{six.osf}}Z'$ universally feature $c_uV$.
- Asymmetries only manifest through interference term: are negligible for these models.
- Can be used to profile a discovered $Z'$.
Expected $A_L$ with $L = 100 \text{ fb}^{-1}$

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Summary

• Written tool to generate top pair production with all intermediates bosons allowed off-shell.
• We have simulated event reconstruction for the semi-leptonic channel, at parton-level.
• Reconstructed $A^*_{FB}$ and $A_L$ retain sensitivity to new gauge bosons.
• These asymmetries can be used to profile $Z'$ in top quark pair production.
• Additionally the asymmetry can be used as a complementary discovery observable to a standard bump hunt.
• In reality this process would fall in the boosted regime: we could not resolve individual jets.
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· Written tool to generate top pair production fermion final state with all intermediates bosons allowed off-shell.

· We have simulated event reconstruction for the semi-leptonic channel, at parton-level.
Summary

- Written tool to generate top pair production 6 fermion final state with all intermediates bosons allowed off-shell.

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Future work

• Use more rigorous assessment of significance and combination (in progress).
• Interface with parton-shower, hadronisation, detector reconstruction tools, e.g. Pythia/plus.osfDelphes (in progress).
• Investigate models featuring multiple interfering, non-universal, top-philic $Z'$s, e.g. Composite Higgs.
• Include full irreducible background.
• Investigate other angularly dependent variables that may be constructed for di-leptonic $t\bar{t}$ events.
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Thanks for listening!
Backup slides
Z' boson parameters

- Width determined by

\[
\Gamma(Z' \rightarrow f\bar{f}) = N_c \frac{g^2_Z m_{Z'}}{48\pi} \beta \left[ \frac{3 - \beta^2}{2} c_V^2 + \beta^2 c_A^2 \right],
\]

- where

\[
\beta = \sqrt{1 - 4 \frac{m_f^2}{m_{Z'}^2}}.
\]
Experimental bounds from ATLAS - lepton plus jets

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

- Obs. 95% CL upper limit
- Exp. 95% CL upper limit
- Exp. 1 \( \sigma \) uncertainty
- Exp. 2 \( \sigma \) uncertainty
- Leptophobic Z' (1.2%) (LO x 1.3)
- Leptophobic Z' (2%) (LO x 1.3)
- Leptophobic Z' (3%) (LO x 1.3)
## Benchmark model $Z'$ parameters and couplings

<table>
<thead>
<tr>
<th>$U(1)'$ Parameters</th>
<th>$E_6$ ($g'=0.462$)</th>
<th>$U(1)_\chi$</th>
<th>$0$</th>
<th>$0$</th>
<th>$-0.316$</th>
<th>$-0.632$</th>
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<td>$U(1)_\psi$</td>
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<td>$U(1)_\eta$</td>
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<td>$G_{LR}$ ($g'=0.595$)</td>
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<td>$U(1)_R$</td>
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<td>$U(1)_{B-L}$</td>
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<td>$0$</td>
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<td></td>
<td>$U(1)_{LR}$</td>
<td>$-0.128\pi$</td>
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<td>$U(1)_Y$</td>
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<td>$0.589$</td>
<td>$-0.353$</td>
<td>$-0.118$</td>
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<tr>
<td>$G_{SM}$ ($g'=0.760$)</td>
<td>$\alpha$</td>
<td>$U(1)_{SM}$</td>
<td>$-0.072\pi$</td>
<td>$0.193$</td>
<td>$0.5$</td>
<td>$-0.347$</td>
<td>$-0.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$U(1)<em>{T</em>{3L}}$</td>
<td>$0$</td>
<td>$0.5$</td>
<td>$0.5$</td>
<td>$-0.5$</td>
<td>$-0.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$U(1)_{Q}$</td>
<td>$0.5\pi$</td>
<td>$1.333$</td>
<td>$0$</td>
<td>$-0.666$</td>
<td>$0$</td>
</tr>
</tbody>
</table>
Asymmetries with polarized stable tops

- Spatial/spin asymmetries categorize events:

  \[ A = \frac{N_A - N_B}{N_A + N_B} \]

- At the polarised top level we can define a number of variables, e.g.

  \[ A_{FB} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)} \]

  \[ A_{LL} = \frac{N(+, +) + N(-, -) - N(+, -) - N(-, +)}{N(+, +) + N(-, -) + N(+, -) + N(-, +)} \]

  \[ A_L = \frac{N(+, +) + N(+, -) - N(-, +) - N(-, -)}{N(+, +) + N(+, -) + N(-, +) + N(-, -)} \]
Significance

- Construct likelihood:

\[
L(\mu, \theta) = \sum_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j} e^{-(\mu s_j + b_j)} \sum_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k}
\]  

- Find profile likelihood ratio:

\[
\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}
\]  

- Set \( \mu = 0 \) hypothesis - set \( \mu = 0 \), i.e. assume that there is no new physics contribution, derive distribution with toys/asymptotic

- Code is available in RootStats.

Likelihood for asymmetry and $m_{tt}$

- Mean expected number of events in a given $m_{tt}$ ($i$) and $\cos \theta^* (j)$ bin.

$$\nu(i, j)(\mu, \sigma_{tt}, \sigma_{Z'}, \theta) = L[\epsilon_{tt}(i, j, \theta)\sigma_{tt} + \alpha_{Z',\bar{t}t}(i, j, \theta)\mu(\sigma_{Z'} + \sigma_{int(Z',\bar{t}t)})]$$ (5)

- $L$ for the above is the luminosity. $\epsilon$ and $\alpha$ represent the efficiencies for SM background and for signal to fall in the given bin: asymmetry*detector.

- Observed number of events

$$\mathcal{L}(N(i, j)|\mu, \sigma_{tt}, \sigma_{Z'}) = \sum_{i,j} e^{\nu(i, j)} \frac{\nu N(i, j)}{N(i, j)!}$$ (6)

- We only use statistical uncertainty.
- We can possibly add theoretical uncertainties.