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

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Z' bosons in $t\bar{t}$

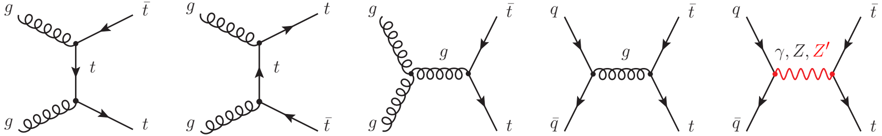
- Z' bosons are generically any new, heavy, neutral spin-1 bosons.
- Embedded due to residual $\mathrm{U}(1)'$ symmetries after Grand Unified Theory (GUT) breaking:

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)'.$$

- Multiple Z' may also arise in extra-dimensional/composite Higgs theories.
- Leads to additional term in low-energy neutral current Lagrangian:

$$\mathcal{L} \supset g' Z'_\mu \bar{f} \gamma^\mu (c_V^f - c_A^f \gamma_5) f = g' Z'_\mu \bar{f} \gamma^\mu Q_{Z'} f.$$

- May appear in $Z' \to \ell^+\ell^-$, $Z' \to q\bar{q}$, $Z' \to t\bar{t}$.



GUT motivated benchmark Z' models

- Generalised Sequential Models (GSMs):

$$Q_{GSM} = \cos\alpha\, T^3_L + \sin\alpha\, Q,$$

- General Left-Right symmetric models (GLRs):

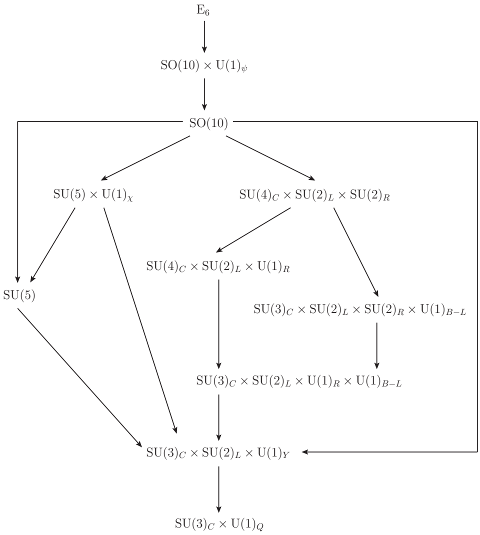
$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \rightarrow \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

$$Q_{GLR} = \cos\phi\, T^3_R + \sin\phi\, T_{B-L},$$

- E_6 inspired models:

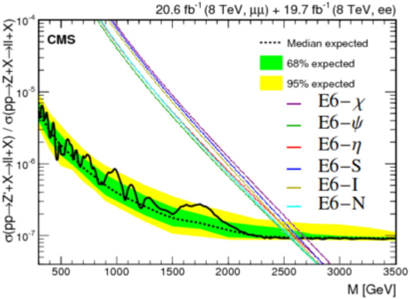
$$\mathrm{E}_6 \rightarrow \mathrm{SO}(10) \times \mathrm{U}(1)\psi$$
$$\mathrm{SO}(10) \rightarrow \mathrm{SU}(5) \times \mathrm{U}(1)_\chi$$

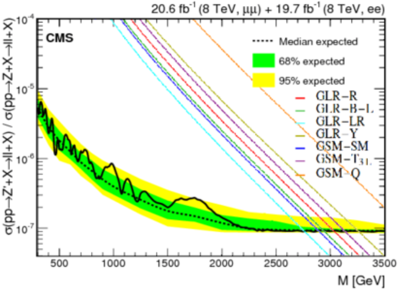
$$Q_{E_6} = \cos\theta\, T_\chi + \sin\theta\, T_\psi.$$



Experimental bounds on benchmark model Z' masses

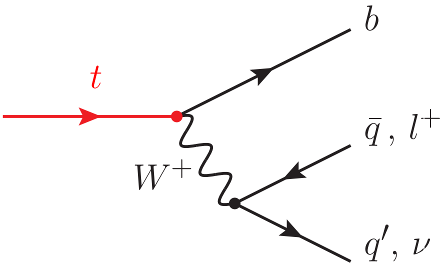
- Lower mass bound in GeV extracted by Accomando et al. based on CMS Drell-Yan results. [arXiv:1503.02672]





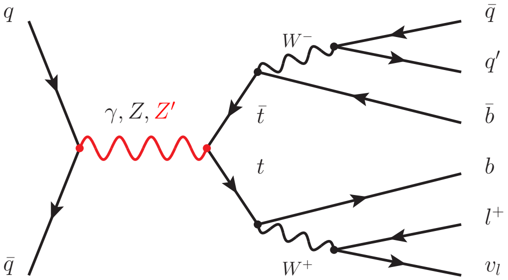
Class	E_6						GLR				GSM		
$U(1)'$	χ	ψ	η	S	I	N	R	BL	LR	Y	SM	T_L^3	Q
$M_{Z'}$	2700	2560	2620	2640	2600	2570	3040	2950	2765	3260	2900	3135	3720

Top quark pair production



- $Z' \to t\bar{t}$ can provide additional information to $Z' \to \ell^+\ell^-$.
- Top mass of 173 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.

Generation tools



- We generate the parton level 6 fermion final state and include full tree-level Standard Model $t\bar{t}$ interference, with all intermediate particles allowed off-shell.
- Helicity amplitude calculations based on HELAS subroutines.
- $m_t = 173$ GeV, $m_b = 4.18$ GeV, all other fermions massless.
- Can optionally enforce the narrow width approximation.
- PDFs used are by CTEQ6L1 at a scale of $Q = \mu = 2m_t$.
- VEGAS for multi-dimensional numerical phase-space integration.

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 (σ):

$$\sigma \propto \left(({c_V}^i)^2 + ({c_A}^i)^2\right)\left(({c_A}^t)^2 + ({c_V}^t)^2(4-\beta^2)\right),$$

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

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

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

$$\cos\theta \rightarrow \cos\theta^* = \frac{y_{tt}}{|y_{tt}|}\cos\theta \quad \Rightarrow \quad A_{FB} \rightarrow A^*_{FB}.$$

Top polarisation Asymmetry

- Top polarisation Asymmetry is defined

$$A_L = \frac{N(+,+) + N(+,-) - N(-,+) - N(-,-)}{N(+,+) + N(+,-) + N(-,+) + N(-,-)}$$

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

$$\sigma \propto \left(({c_V}^i)^2 + ({c_A}^i)^2\right)\left(({c_A}^t)^2 + ({c_V}^t)^2(4-\beta^2)\right),$$

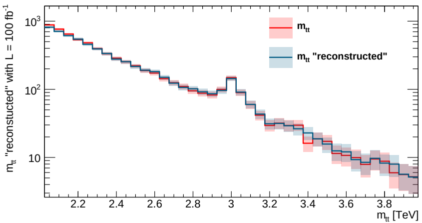
$$A_L \propto \left(({c_V}^i)^2 + ({c_A}^i)^2\right){c_V}^t{c_A}^t\beta.$$

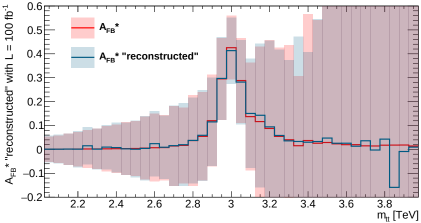
- Information about the top quark polarization is preserved in:

$$\frac{1}{\Gamma_f}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}(1 + \kappa_f A_L cos\theta_f)$$

- θ_f is the angle between the top quark momentum in the partonic rest frame and the decay fermion in the top rest frame.
- Create a 2D distribution in m_{tt} and $\cos\theta_\ell$
- Fit a straight line to the $\cos\theta_\ell$ distribution for each mass slice.
- Extract A_L as the fitted gradient.

Toy top pair reconstruction for lepton-plus jets





- 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.
- Assume $p_T^\nu = p_T^{miss}$ and on-shell W:

$$p_T^{e\,2} p_Z^{\nu\,2} - 2kp_z^e p_z^\nu + p_T^{\nu\,2}|p^e|^2 - k^2 = 0,$$

- Select solution that minimises:

$$\chi^2 = \left(\frac{m_{bl\nu} - m_t}{\Gamma_t}\right)^2 + \left(\frac{m_{bqq} - m_t}{\Gamma_t}\right)^2$$

Uncertainty and significance

- Propagate error:

$$\delta A^*_{FB} = \sqrt{\frac{1 - A^{*2}_{FB}}{N}}$$

(shown as colored bands).

- Construct likelihood:

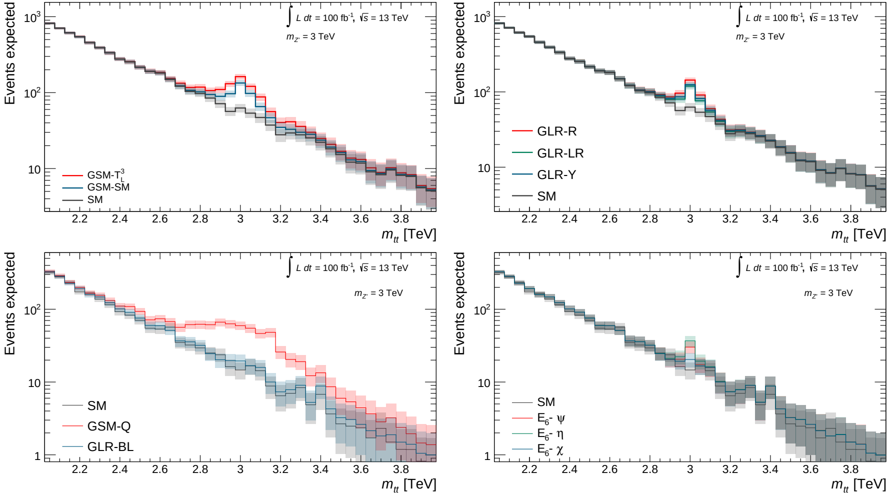
$$L(\mu, \theta) = \sum_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j} e^{-(\mu s_j + b_j)}.$$

- Find profile likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}.$$

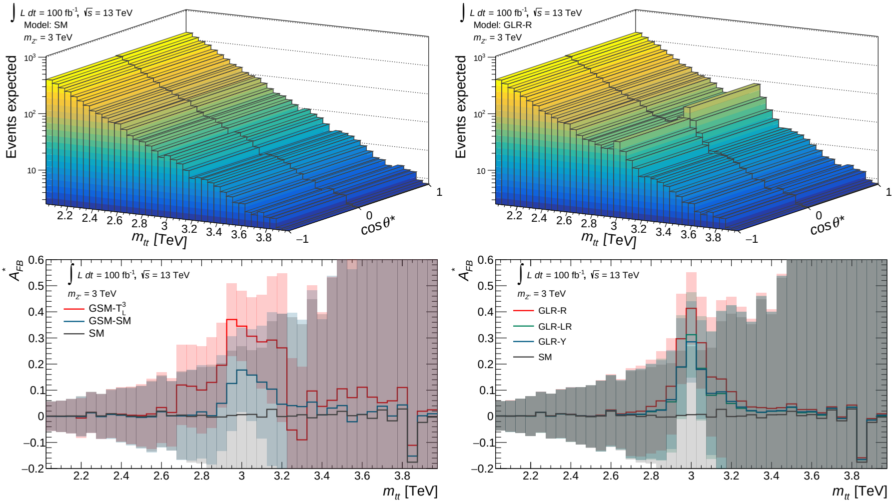
- Set $\mu = 0$ hypothesis - set $\mu = 0$, i.e. assume that there is no new physics contribution, derive distribution with toys/asymptotic
- Code is available in RootStats [arXiv:1007.1727v3].
- General method applicable to any n-dimensional histogram.

Events expected m_{tt} distributions with $L = 100\ \text{fb}^{-1}$



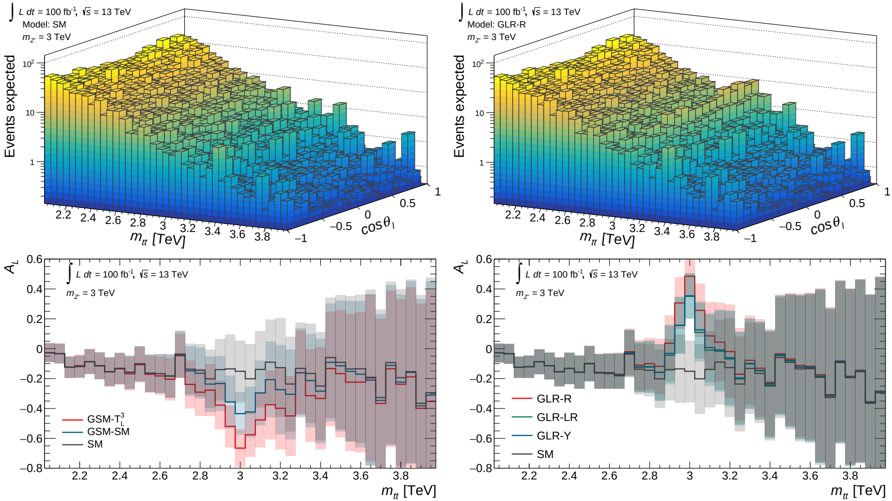
- m_{tt} offers good distinguishing power between SM and BSM.
- Not easy to profile a discovered Z' as similar BSM response.

Expected A^*_{FB} binned in m_{tt} with $L = 100\ \text{fb}^{-1}$



- A^*_{FB} distinguishes different BSM models more strongly.
- Negligible for E_6; universally feature $c_V^u = 0$.
- Can be used to distinguish BSM models for a discovered Z'.

Expected A_L with $L = 100\ \text{fb}^{-1}$



- A_L clearly distinguishes between GSM and GLR model Z'.
- Negligible for E_6; universally feature $c_V^u = 0$.
- Can be used to profile a discovered Z'.

Results - 1D and 2D significances

Class	U(1)′	Significance (Z)		
		m_{tt}	m_{tt} & $\cos\theta^*$	m_{tt} & $\cos\theta_l$
E_6	$U(1)_\chi$	3.7	-	-
	$U(1)_\psi$	5.0	-	-
	$U(1)_\eta$	6.1	-	-
	$U(1)_S$	3.4	-	-
	$U(1)_I$	3.4	-	-
	$U(1)_N$	3.5	-	-
GLR	$U(1)_R$	7.7	8.5	8.6
	$U(1)_{B-L}$	3.6	-	-
	$U(1)_{LR}$	5.1	5.6	5.8
	$U(1)_Y$	6.3	6.8	7.0
GSM	$U(1)_{T^3_L}$	12.1	13.0	14.0
	$U(1)_{SM}$	7.1	7.3	7.6
	$U(1)_Q$	24.8	-	-

Summary

- Written tool to generate top pair production 6 fermion final state 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:
  - Leptons embedded in jets.
  - We can not resolve individual jets.

Future work

- Investigate other angularly dependent variables that may be constructed for di-leptonic $t\bar{t}$ events (in progress).
- Interface with parton-shower, hadronisation, detector reconstruction tools, e.g. Pythia+Delphes (in progress).
- Assess the performance of a boosted reconstruction of these variables.
- Investigate models featuring multiple interfering, non-universal, top-philic Z's, e.g. Composite Higgs.
- Include full irreducible background.

Thanks for your attention!

Backup slides

Matrix element Calculation and interference

$$|\mathcal{M}(pp \to t\bar{t})|^2 = |\mathcal{M}(QCD)|^2 + |\mathcal{M}(\gamma, Z, Z')|^2,$$

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

$$A^f = g_L^i g_L^j - g_R^i g_R^j, \qquad B^f = g_L^i g_R^j + g_R^i g_L^j, \qquad C^f = g_L^i g_L^j + g_R^i g_R^j,$$

$$D^{ij} = \frac{(\hat{s} - m_i^2)(\hat{s} - m_j^2) + m_i m_j \Gamma_i \Gamma_j}{\left((\hat{s} - m_j^2)^2 + m_i^2 \Gamma_i^2\right)\left((\hat{s} - m_j^2)^2 + m_j^2 \Gamma_j^2\right)}.$$

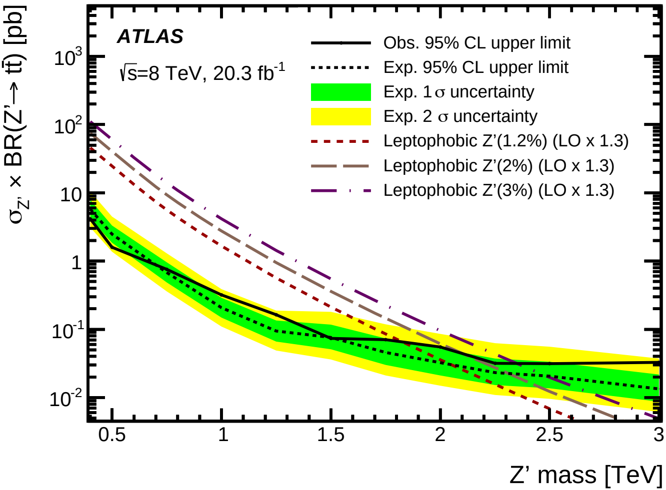
- Width determined by

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

- where

$$\beta = \sqrt{1 - 4\frac{m_f^2}{m_{Z'}^2}}.$$

Experimental bounds from ATLAS - lepton-plus-jets



Benchmark model Z' parameters and couplings

$U(1)'$	Angle	g_V^u	g_A^u	g_V^d	g_A^d
E_6 ($g' = 0.462$)	θ				
$U(1)_\chi$	0	0	−0.316	−0.632	0.316
$U(1)_\psi$	0.5π	0	0.408	0	0.408
$U(1)_\eta$	-0.29π	0	−0.516	−0.387	0.129
$U(1)_S$	0.129π	0	−0.129	−0.581	0.452
$U(1)_I$	0.21π	0	0	0.5	−0.5
$U(1)_N$	0.42π	0	−0.316	−0.158	0.474
GLR ($g' = 0.595$)	ϕ				
$U(1)_R$	0	0.5	−0.5	−0.5	0.5
$U(1)_{B-L}$	0.5π	0.333	0	−0.333	0
$U(1)_{LR}$	-0.128π	0.329	−0.46	−0.591	0.46
$U(1)_Y$	0.25π	0.589	−0.353	−0.118	0.354
GSM ($g' = 0.760$)	α				
$U(1)_{SM}$	-0.072π	0.193	0.5	−0.347	−0.5
$U(1)_{T_{3L}}$	0	0.5	0.5	−0.5	−0.5
$U(1)_Q$	0.5π	1.333	0	−0.666	0

Asymmetries with polarized stable tops

- Spatial/spin asymmetries categorize events:

$$A = \frac{N_A - N_B}{N_A + N_B}$$

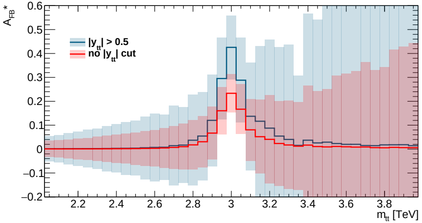
- At the polarised top level we can define a number of variables, e.g.

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

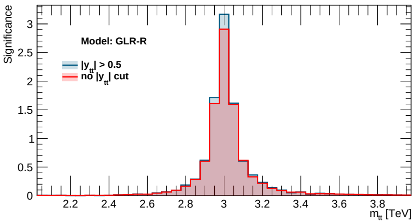
$$A_{LL} = \frac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N(+,+) + N(-,-) + N(+,-) + N(-,+)},$$

$$A_{L} = \frac{N(+,+) + N(+,-) - N(-,+) - N(-,-)}{N(+,+) + N(+,-) + N(-,+) + N(-,-)},$$

$|y_{tt}|$ cut



A_{FB}^*
|y_tt| > 0.5
no |y_tt| cut
m_tt [TeV]



Significance
Model: GLR-R
|y_tt| > 0.5
no |y_tt| cut
m_tt [TeV]

Likelihood for asymmetry and m_{tt}

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

$$\nu(i,j)(\mu,\sigma_{t\bar{t}},\sigma_{Z'},\theta) = L[\epsilon_{t\bar{t}}(i,j,\theta)\sigma_{t\bar{t}}+\alpha_{Z',t\bar{t}}(i,j,\theta)\mu(\sigma_{Z'}+\sigma_{int(Z',t\bar{t})})] \quad (1)$$

- L for the above is the luminosity. ϵ and α represent the efficiencies for SM background and for signal to fall in the given bin: asymmetry*detector.
- Observed number of events

$$\mathcal{L}(N(i,j)|\mu,\sigma_{t\bar{t}},\sigma_{Z'}) = \sum_{i,j} e^{\nu(i,j)} \frac{\nu^{N(i,j)}}{N(i,j)!} \quad (2)$$

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