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

Lucio Cerrito, **Declan Millar**, Stefano Moretti, Francesco Spanò

UNIVERSITY OF Southampton Queen Mary University of London

PASCOS, Quy Nhon, Vietnam
12th July 2016

Z' bosons

- Z' bosons are generally any new, heavy, neutral spin-1 bosons.

- Arise from residual $\mathrm{U}(1)'$ symmetries after GUT breaking:

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

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

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

Benchmark Z' models

- Generalised Sequential Models (GSMs):

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

- General Left-Right symmetric models (GLRs):

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

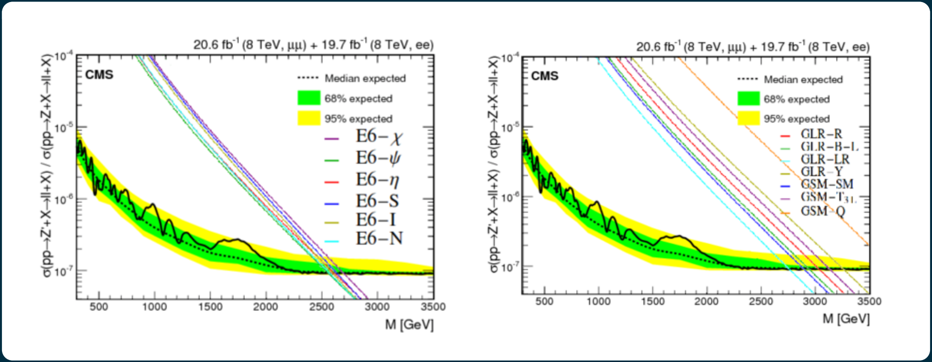
$$Q_{GLR} = \cos\phi T_R^3 + \sin\phi T_{B-L},$$

- E_6 inspired models:

$$\begin{aligned} \mathrm{E}_6 &\to \mathrm{SO}(10) \times \mathrm{U}(1)\psi \\ \mathrm{SO}(10) &\to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi \\ \mathrm{SU}(5) &\to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times U(1)_Y. \end{aligned}$$

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

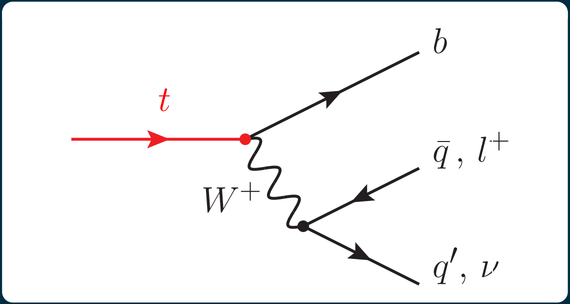
Experimental bounds on benchmark model Z' masses



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

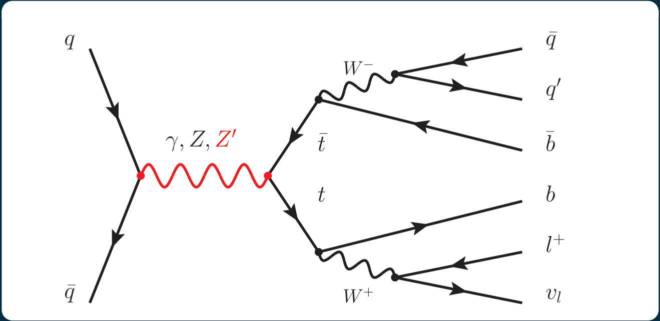
- Lower mass bound in GeV extracted by Accomando et al. based on CMS Drell-Yan results. [arXiv:1503.02672]

Top quark pair production



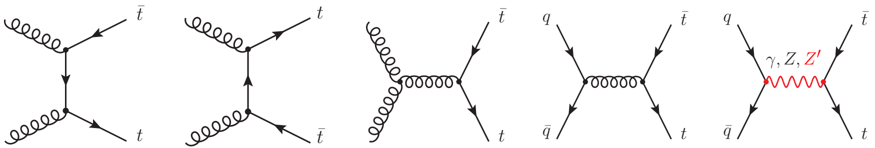
- $Z' \rightarrow t\bar{t}$ is an alternative search channel to $Z' \rightarrow l^+ l^-$.
- Top mass of 173 GeV is close to EW symmetry breaking scale.
- Z'-t couplings significant in many BSMs, e.g. composite Higgs.
- Extremely short lifetime: top quarks decay prior to hadronisation.
- Top spin information 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.

Matrix element Calculation and interference



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

$$|\mathcal{M}(\gamma, Z, Z')|^2 = \frac{\hat{s}^2}{6} \frac{D_{ij}}{1 + \delta_{ij}} \left\{ C^q_{ij} \left[C^t_{ij}(1 + \beta^2 \cos^2\theta) + B^t_{ij}(1 - \beta^2) \right] + 2A^q_{ij}A^t_{ij}\beta\cos\theta \right\}.$$

$$A^f = g^i_L g^j_L - g^i_R g^j_R, \qquad B^f = g^i_L g^j_R + g^i_R g^j_L, \qquad C^f = g^i_L g^j_L + g^i_R g^j_R,$$

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

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.

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

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 $\boldsymbol{Z's}$ when compared to the cross section (σ):

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

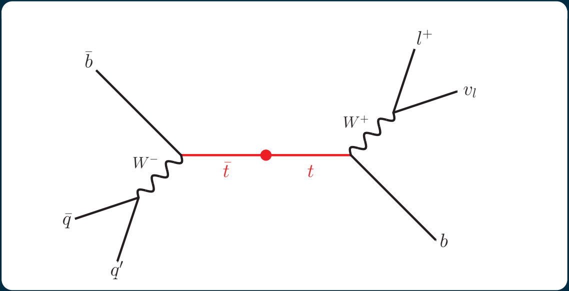
$$A_L \propto \left(({c_V}^i)^2 + ({c_A}^i)^2\right) {c_V}^t {c_A}^t \beta.$$

- Information about the top quark polarization is preserved in:

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

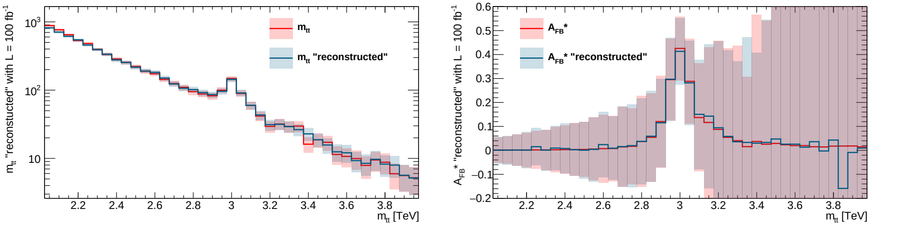
- θ_f is the angle between the top quark momentum in the partonic rest frame and the decay fermion in the top rest frame.

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_{FB}^* and A_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.

Solving for the neutrino momentum



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

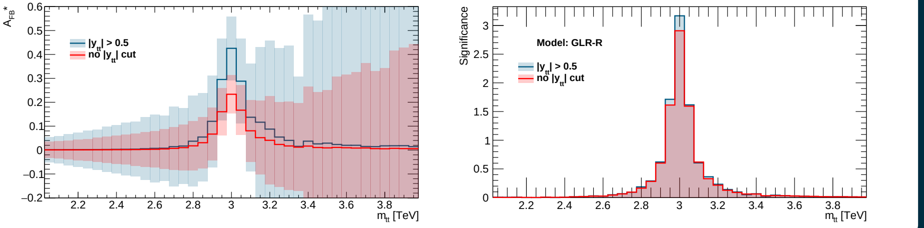
$$p_T^{e2} p_Z^{\nu 2} - 2k p_z^e p_z^\nu + p_T^{\nu 2} |p^e|^2 - k^2 = 0,$$

where $k = \frac{m_W^2}{2} + \mathbf{p}_T^e \mathbf{p}_T^\nu$.

- Select solution by minimising chi-square:

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

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:

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

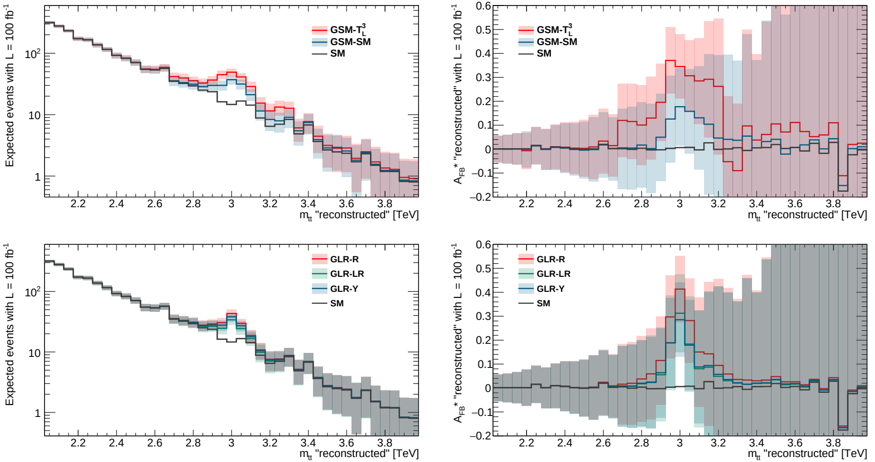
(Shown as colored bands)

- Therefore, define Significance for observable as:

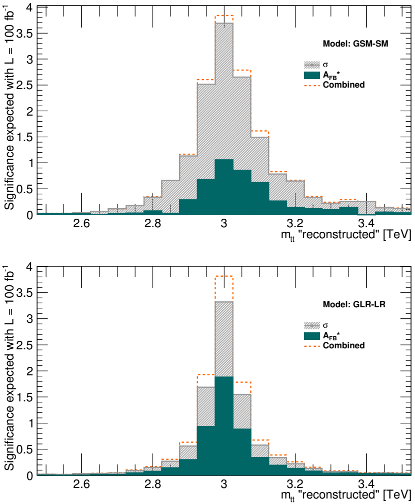
$$S = \frac{O_{SM+BSM} - O_{SM}}{\delta O^{stat}_{SM+BSM}} \qquad (2)$$

- Combine significance by adding in quadrature (ad-hoc).

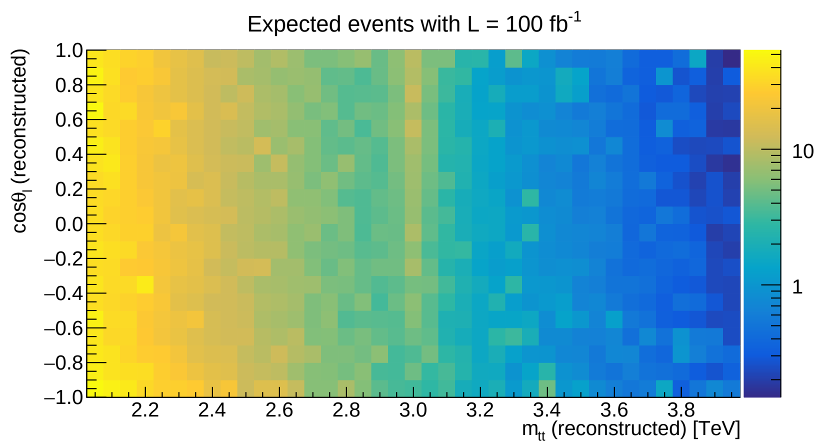
Expected m_{tt} distribution and A^{*}_{FB} with L = 100 fb^{-1}



Expected significance with $L = 100\ \mathrm{fb}^{-1}$

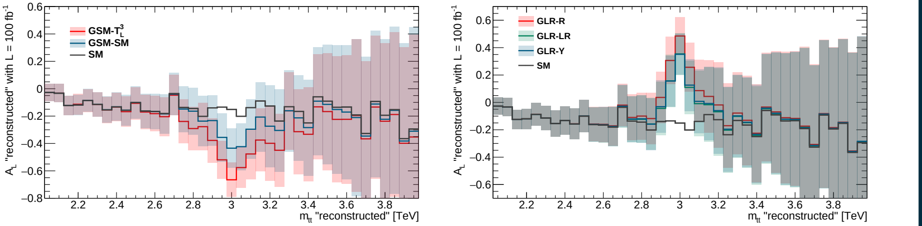


Calculating A_L in m_{tt} bins using decay products



- Create a 2D distribution in m_{tt} and $\cos\theta_l$
- Bin the expected number of events with $L = 100$ fb^{-1}.
- Normalise each mass slice by the integral of the slice.
- Fit a straight line to the $\cos\theta_l$ distribution for each mass slice.
- Extract A_L as the fitted gradient.

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



- A_L clearly distinguishes between GSM and GLR model Z'.
- E_6 Z's universally feature $c_V^u = 0$.
- Asymmetries only manifest through interference term: are negligible for these models.
- Can be used to profile a discovered Z'.

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: we could not resolve individual jets.

Future work

- Use more rigorous assessment of significance and combination (in progress).
- Interface with parton-shower, hadronisation, detector reconstruction tools, e.g. Pythia+Delphes (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.

Thanks for listening!

Backup slides

Z' boson parameters

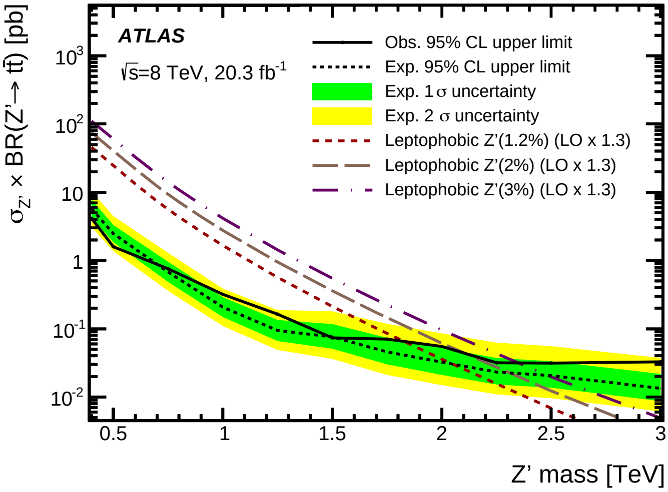
- Width determined by

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

- 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

$U(1)'$	Parameter	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
$U(1)_N$	0.42π	0	-0.316	-0.158	0.474
G_{LR} (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
G_{SM} (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.

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

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

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

Significance

- Construct likelihood:

$$L(\mu,\theta) = \sum_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j} e^{-(\mu s_j + b_j)} \sum_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} \tag{3}$$

- Find profile likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})} \tag{4}$$

- 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.
- See arXiv:1007.1727v3.

Liklihood for asymmetry and m_{tt}

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

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

- 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

$$\mathcal{L}(N(i,j)|\mu,\sigma_{t\bar{t}},\sigma_{Z'}) = \sum_{i,j} e^{\nu(i,j)} \frac{\nu^{N(i,j)}}{N(i,j)!} \quad (6)$$

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