Phenomenology of distinguishing Z' bosons using asymmetry observables in dileptonic top pair production with the ATLAS detector

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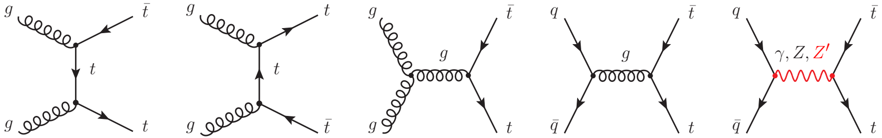
Z' bosons in $t\bar{t}$

- Z' bosons are generically any new, heavy, neutral spin-1 bosons.
- May appear in $Z' \to \ell^+\ell^-$, $Z' \to q\bar{q}$, $Z' \to t\bar{t}$.
- 

- Can be embedded by residual $\mathrm{U}(1)'$ symmetries after the spontaneous symmetry breaking of a Grand Unified Theory (GUT):

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

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

$$\mathcal{L} \supset g' Z'_\mu \bar{\psi} \gamma^\mu Q_{Z'} \psi = g' Z'_\mu \bar{\psi} \gamma^\mu (f_V - f_A \gamma_5) \psi.$$

encoded using vector (V) and axial-vector couplings (A).
- Multiple Z' also arise in extra-dimensional/composite Higgs theories.
- $Z' \to t\bar{t}$ can be dominant discovery channel for non-universal theories.

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GUT motivated benchmark Z' models

- E_6 inspired models:

$$E_6 \to SO(10) \times U(1)_\psi$$
$$SO(10) \to SU(5) \times U(1)_\chi$$

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

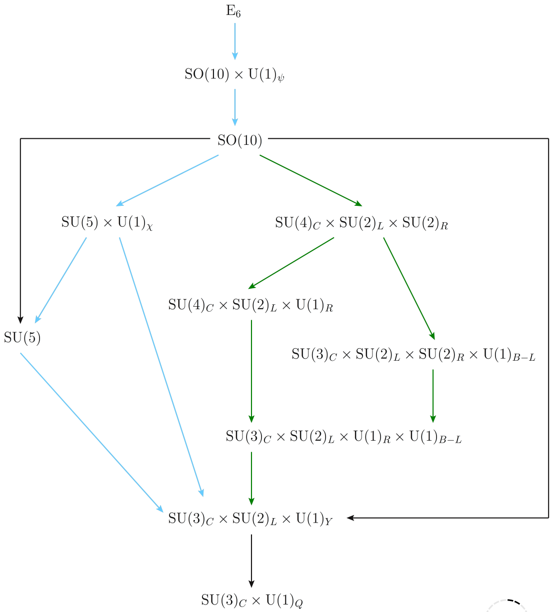
- General Left-Right symmetric models (GLR):

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

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

- Generalised Sequential Models (GSM):

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



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Benchmark model Z' parameters and couplings

U(1)′	Angle	g_V^u	g_A^u	g_V^d	g_A^d	$\Gamma_{Z'}/m_{Z'}$
E$_6$ ($g' = 0.462$)	θ					
U(1)$_\chi$ (∗)	0	0	−0.316	−0.632	0.316	1.2
U(1)$_\psi$ (∗)	0.5π	0	0.408	0	0.408	0.5
U(1)$_\eta$	−0.29π	0	−0.516	−0.387	0.129	0.6
U(1)$_S$	0.129π	0	−0.129	−0.581	0.452	1.2
U(1)$_I$	0.21π	0	0	0.5	−0.5	1.1
U(1)$_N$	0.42π	0	−0.316	−0.158	0.474	0.6
GLR ($g' = 0.595$)	ϕ					
U(1)$_R$ (∗)	0	0.5	−0.5	−0.5	0.5	2.5
U(1)$_{B-L}$ (∗)	0.5π	0.333	0	−0.333	0	1.5
U(1)$_{LR}$	−0.128π	0.329	−0.46	−0.591	0.46	2.1
U(1)$_Y$	0.25π	0.589	−0.353	−0.118	0.354	2.4
GSM ($g' = 0.760$)	α					
U(1)$_{SM}$ (∗)	−0.072π	0.193	0.5	−0.347	−0.5	3.2
U(1)$_{T^3_L}$	0	0.5	0.5	−0.5	−0.5	4.7
U(1)$_Q$	0.5π	1.333	0	−0.666	0	12.5

- (∗) Investigated in ATL-COM-PHYS-2017-052.

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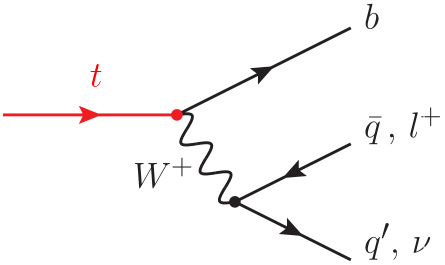
Top quark pair production



- $Z' \to t\bar{t}$ can provide additional information to $Z' \to \ell^+\ell^-$.
- Top mass of 172.5 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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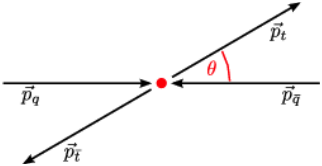
Forward-Backward Asymmetry

- Forward-backward Asymmetry is defined

$$A^t_{FB} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$



- This asymmetry demonstrates different couplings between Z', initial quarks (q_V, q_A) and tops (t_V, t_A) to the cross section (σ):

$$\sigma \propto \left({q_V}^2 + {q_A}^2\right)\left({t_A}^2 + {t_V}^2(4 - \beta^2)\right),$$

$$A^t_{FB} \propto q_V q_A t_V t_A.$$

where $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$ and $\hat{s}$ the energy is $q\bar{q}$ CoM frame.

- A^t_{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:

$$\cos\theta_t \rightarrow \cos\theta^*_t = \frac{y_{tt}}{|y_{tt}|}\cos\theta_t \quad \rightarrow \quad A^t_{FB} \rightarrow A^t_{FB^*}$$

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Charge Asymmetry with dilepton final state

- The Reconstructed Forward-backward Asymmetry

$$A^{t}_{FB^*} = \frac{N(\cos\theta^*_t > 0) - N(\cos\theta^*_t < 0)}{N(\cos\theta^*_t > 0) + N(\cos\theta^*_t < 0)}$$

  is functionally equivalent to

$$A^{tt}_{C} = \frac{N(\Delta|y_{tt}| > 0) - N(\Delta|y_{tt}| < 0)}{N(\Delta|y_{tt}| > 0) + N(\Delta|y_{tt}| < 0)}$$

  where $\Delta|y_{tt}| = |y_t| - |y_{\bar{t}}|$.
- Naturally these both require a full reconstruction of the top quarks.
- However, an analogue may be constructed with the decay leptons:

$$A^{\ell\ell}_{C} = \frac{N(\Delta|\eta_{\ell\ell}| > 0) - N(\Delta|\eta_{\ell\ell}| < 0)}{N(\Delta|\eta_{\ell\ell}| > 0) + N(\Delta|\eta_{\ell\ell}| < 0)}$$

  where $\Delta|\eta_{\ell\ell}| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$
- Likewise

$$A^{\ell}_{FB^*} = \frac{N(\cos\theta^*_\ell > 0) - N(\cos\theta^*_\ell < 0)}{N(\cos\theta^*_\ell > 0) + N(\cos\theta^*_\ell < 0)}.$$

  where $\cos\theta^*_\ell = \frac{\eta_{\ell\ell}}{|\eta_{\ell\ell}|}\cos\theta_\ell$

Top polarisation Asymmetry

- Top polarisation Asymmetry is defined

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

- $N(\lambda_t, \lambda_{\bar{t}})$: number of events with helicity eigenvalues $\lambda_{t(\bar{t})} = \pm$.
- Again, different couplings to $Z's$ when compared to the cross section:

$$A_L \propto \left({q_V}^2 + {q_A}^2\right) t_V t_A.$$

- Information about the top quark polarization is preserved in:

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

- 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 $\cos\theta_\ell$ (ℓ = final state lepton).

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Spin Correlation Asymmetry

- The Spin Correlation Asymmetry is defined

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

- $N(\lambda_t, \lambda_{\bar{t}})$: number of events with helicity eigenvalues $\lambda_{t(\bar{t})} = \pm$.
- This has a similar coupling structure to the cross section:

$$A_{LL} \propto \left({q_V}^2 + {q_A}^2\right)\left((2+\beta^2){t_V}^2 + 3{t_A}^2\right).$$

- A number of decay-level variables are sensitive to this asymmetry.
- After reconstruction, one may use $\cos\theta_{\ell^+}\cos\theta_{\ell^-}$ and $\cos\varphi$.
- Without reconstruction one may use $\Delta\phi_{\ell^+\ell^-}$.

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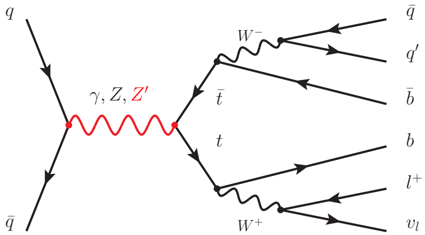
Generating $pp \to t\bar{t}$ (Z' + SM $t\bar{t}$ + interference)



- We generate the partonic final state using a custom Monte Carlo:
- $2 \to 6$ all intermediate particles allowed off-shell.
- Includes full tree-level $t\bar{t}$ interference with SM.
- Helicity amplitude calculations based on HELAS subroutines.
- PDFs used are by CT14(LL) at a scale of $Q = \mu = 2m_t$.
- VEGAS Amplified (VAMP) for multi-dimensional numerical integration and event generation.
- LHEF output is interpreted by Delphes and Pythia 8.2 for parton-shower, hadronisation, detector reconstruction.

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Object reconstruction and selection

q	Efficiency [%]
u, d, s	0.746
c	16.6
b	77.0

Table: Modified Delphes configuration for b-tagging efficiencies for each quark species (q).

- Pythia8 showered events are analysed using a custom modified version of the default ATLAS detector card.
- Modifications:
  - Include altering the b-tagging efficiencies (Tab. 1), in addition to using $R = 0.4$ for jet construction.
  - Electron, muon and photon isolation is disabled (we perform this ourselves).
  - Scalar H_{T} calculation is disabled.
  - Unique object selection for muons is disabled (see next slide).

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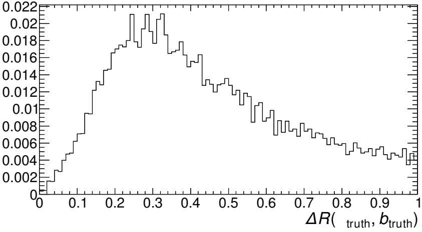
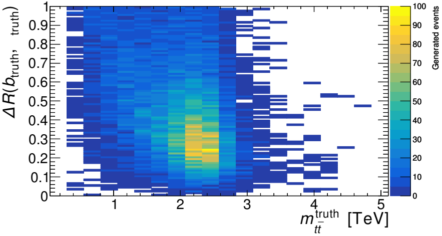
Object Overlap Removal



True $\Delta R(\ell, b)$ (Normalised).



True $m_{t\bar{t}}$ vs true $\Delta R(\ell, b)$.

- Events mediated by $\gamma + Z + Z'$ including a 2.5 TeV mass Z' boson.
- Observe that $\Delta R(\ell, b)$ has peak events lower than 0.4, such that the lepton falls inside the jet radius.
- This results in the loss of signal objects during overlap removal.
- To see this, reconstructed objects are truth-tagged and impact on this population was observed following selection requirements.
- Little can be done for electrons as their energy deposits are inseparable from jets without a dedicated treatment; however, for muons overlap removal is disabled.

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Event selection

- Event-level selection intended to suppress the hadronic background (e.g. J/Ψ) and events attributable to jet-accompanied Drell-Yan production

Requirements	$e^+e^-/\mu^+\mu^-$	$e^\pm\mu^\mp$
Leptons	2	2
Jets	≥ 2	≥ 2
$m_{\ell\ell}$	> 15 GeV	> 15 GeV
$\|m_{\ell\ell} - m_Z\|$	> 10 GeV	-
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 60 GeV	-
b-tagged jets	$\geq 2^*$	$\geq 2^*$
H_{T}	-	> 130 GeV

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Dilepton top reconstruction

- The dileptonic $t\bar{t}$ channel features two neutrinos in the final state.
- Cannot calculate invariant mass m for all particles i in the system:

$$m = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2}.$$

- Presence in the final state inferred from momentum conservation.
- Longitudinal momentum of the colliding partons is also an unknown.
- Therefore, the only handle is $E_{\mathrm{T}}^{\mathrm{miss}} = -\sum_i p_{\mathrm{T}}^i$.
- $E_{\mathrm{T}}^{\mathrm{miss}}$ may also be attributed to additional sources, e.g. mis-measurement at the detector level.
- Can attempt to reconstruct the system or use transverse variables as a replacement for m_{tt}.

$$H_{\mathrm{T}} = E_{\mathrm{T}}^{b} + E_{\mathrm{T}}^{\bar{b}} + E_{\mathrm{T}}^{\ell^+} + E_{\mathrm{T}}^{\ell^-}$$
$$K_{\mathrm{T}} = E_{\mathrm{T}}^{\mathrm{vis}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

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Neutrino Weighting Method

- By making 6 assumptions the system may be fully constrained.
- These are by fixing E_x^{miss}, E_y^{miss}, m_{W^+}, m_{W^-}, m_t, and $m_{\bar{t}}$.
- In Neutrino Weighting (NW) we put aside $E_{\text{T}}^{\text{miss}}$ constraints and scan over neutrino η's.
- Weighted average of all possible solutions is then taken in order to reconstruct the system

$$\omega = \exp\left(-\frac{E_x^{\text{miss}} - p_x^{\nu} - p_x^{\bar{\nu}}}{2\sigma_x^2}\right) \exp\left(-\frac{E_y^{\text{miss}} - p_y^{\nu} - p_y^{\bar{\nu}}}{2\sigma_y^2}\right)$$

- The reconstruction of a given event is tried several times (N_{smear}).
- Takes into account the resolution of the measured objects.
- The jet p_T, E_x^{miss}, E_y^{miss}, m_{W^+}, m_{W^-}, m_t, and $m_{\bar{t}}$ are smeared.
- To construct the jet resolution functions, the variable $(p_{\text{T}}^{truth} - p_{\text{T}}^{reco})/p_{\text{T}}^{truth}$ is plotted per bin of p_T.
- These distributions are then fitted with a combination of two Gaussian functions.

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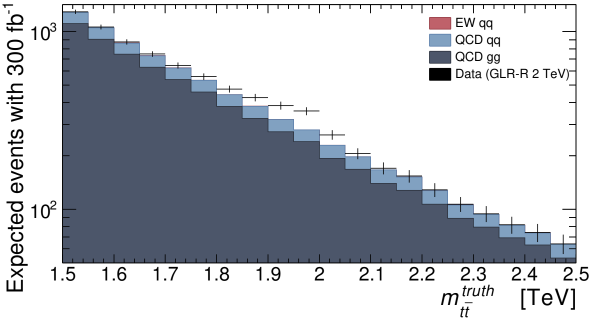
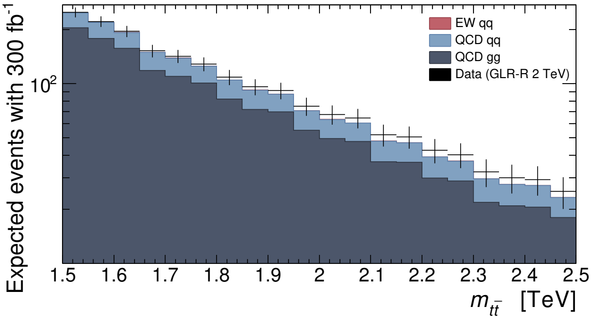
Results for dimuon channel with a 2 TeV Z' boson





Extracting signal significance

- Define signal (s) and background (b):

$$\sigma_s = \sigma_{(Z'+t\bar{t})} - \sigma_{t\bar{t}} = \sigma_{Z'} + \sigma_{int(Z',t\bar{t})},$$

$$\sigma_b = \sigma_{t\bar{t}}.$$

- 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:

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

- Assume $\mu = 0$ hypothesis, i.e. assume that there is no new physics contribution, derive $\lambda(0)$ distribution with asymptotic approach, extract p-value and convert to significance [Eur.Phys.J.C71:1554,2011].
- Code is available in RooStats.
- General method applicable to any nD histogram.
- For each 1D and 2D distribution, construct likelihood.

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Results for dimuon channel with a 2 TeV Z' boson

	Observable	Expected Significance (σ)
Truth-level	$m_{t\bar{t}}$	5.8
	$H_\mathrm{T} + E_\mathrm{T}^\mathrm{miss}$	4.5
	K_T	4.6
Detector level	$H_\mathrm{T} + E_\mathrm{T}^\mathrm{miss}$	3.6
	K_T	3.5
	$\Delta\phi_{\ell\ell}$	0.5
	$\Delta\|\eta_{\ell\ell}\|$	0.5
	$\cos\theta_\ell^*$	0.5
	$H_\mathrm{T} \times \Delta\phi_{\ell\ell}$	3.5
	$K_\mathrm{T} \times \Delta\phi_{\ell\ell}$	3.5
	$H_\mathrm{T} \times \cos\theta_\ell^*$	3.6
	$K_\mathrm{T} \times \cos\theta_\ell^*$	3.6
	$H_\mathrm{T} \times \Delta\|\eta_{\ell\ell}\|$	3.6
	$K_\mathrm{T} \times \Delta\|\eta_{\ell\ell}\|$	3.6
Detector level and NW reconstruction	$m_{t\bar{t}}$	2.0
	$\Delta\|y_{tt}\|$	0.3
	$\cos\theta_t^*$	0.3
	$\cos\theta_{\ell+}^t$	0.3
	$\cos\theta_{\ell-}^t$	0.3
	$\cos\theta_{\ell+}^t \cos\theta_{\ell-}^t$	0.3
	$m_{t\bar{t}} \times \cos\theta_t^*$	2.3
	$m_{t\bar{t}} \times \cos\theta_{\ell+}^t$	2.6
	$m_{t\bar{t}} \times \cos\theta_{\ell-}^t$	2.6
	$m_{t\bar{t}} \times \cos\theta_{\ell+}^t \cos\theta_{\ell-}^{\bar{t}}$	2.3
	$m_{t\bar{t}} \times \cos\varphi_{\ell\ell}$	2.1

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Summary

- Written an MC program to generate top pair production six fermion final state with all intermediate bosons allowed off-shell.
- Final state fully treated with parton-shower, hadronisation, detector reconstruction.
- Analysis conducted including full reconstruction of the top pair system with the Neutrino Weighting method.
- Shown that observables sensitive to the Z' couplings survive object reconstruction/selection and top reconstruction.
- Found that kinematic observables out-perform reconstructed in 1D and 2D analyses.
- Found that asymmetry observables can be used to increase the significance in a 2D analysis following reconstruction.

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Future work

- Investigate all remaining benchmark models.
- Demonstrate the capacity for these observables to distinguish Z' embedded by different benchmarks.
- Investigate models featuring wide resonances, e.g. Benchmarks with arbitary high widths, or NUSU(2) etc.
- Investigate models featuring multiple interfering, generationally non-universal Z's, e.g. Composite Higgs.
- Include the effects of pile-up simulation.
- Include theoretical and detector-based systematic uncertainties.
- Assess the performance of a boosted reconstruction of these asymmetries with the lepton-plus-jets final state (large R jets, top-taggers, non-isolated leptons).

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Thanks for your attention!

Backup slides

Matrix element calculation and interference

- Square matrix element:

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

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

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

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

- Decay width:

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

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

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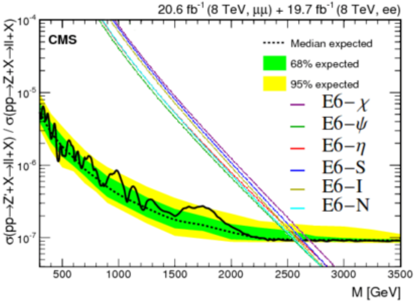
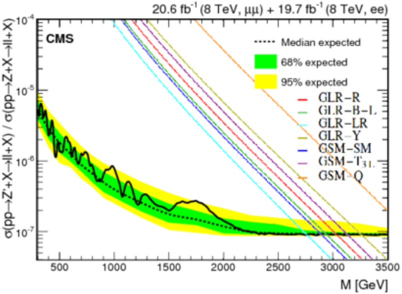
Experimental bounds on benchmark model Z' masses





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

- Dominant bounds on generationally universal Z' come from Drell-Yan
- Lower mass bound extracted based on CMS results in JHEP01(2016)127.
- 4 TeV bounds on SSM Z' in ATLAS-CONF-2016-045 & CMS-PAS-EXO-16-031.

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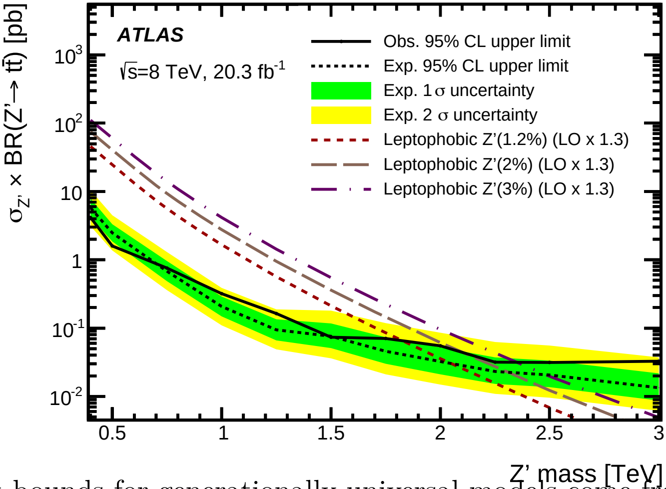
Experimental bounds from ATLAS - lepton-plus-jets



- Dominant bounds for generationally universal models come from Drell-Yan.
- Non-universal models (CHM) bounds come only from $t\bar{t}$.
- Lower bound on $m_{Z'_{SSM}}$ currently 2.4 TeV from JHEP08(2015)148.

Asymmetries with polarized stable tops

- Asymmetry observables: number of events (N) in two categories (A,B):

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

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

$$\begin{aligned} A_{FB} =& \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \\ A_{LL} =& \frac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N(+,+) + N(-,-) + N(+,-) + N(-,+)}, \\ A_{L} =& \frac{N(+,+) + N(+,-) - N(-,+) - N(-,-)}{N(+,+) + N(+,-) + N(-,+) + N(-,-)}, \end{aligned}$$

- $N(\lambda_t, \lambda_{\bar{t}})$: number of events with helicity eigenvalues $\lambda_{t(\bar{t})} = \pm$.

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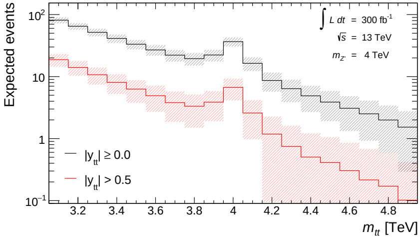
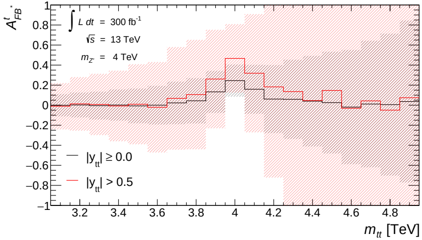
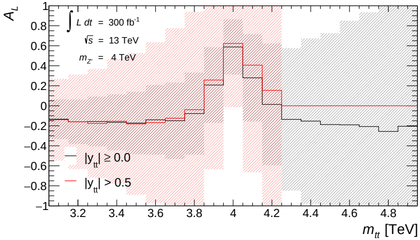
Impact of $|y_{tt}| > 0.5$ requirement

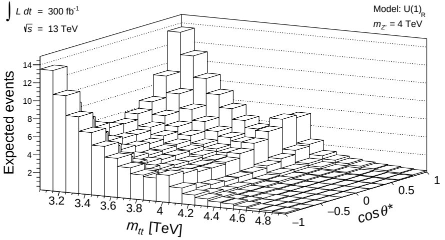


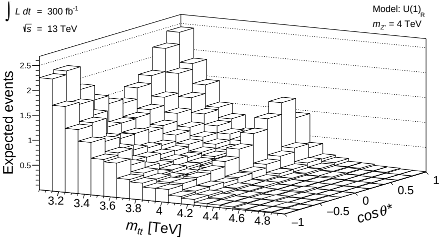


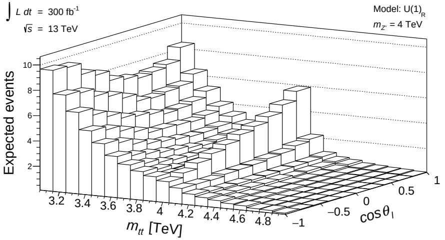


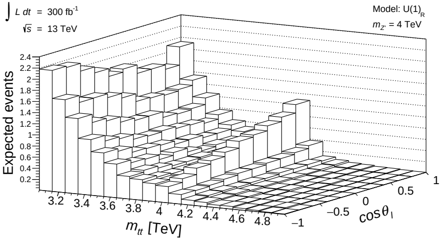
- Enhances signal containing qq contribution over gg background.
- Overall significance lowered by reduced events.
- Not applied.

Impact of $|y_{tt}| > 0.5$ requirement - 2D distributions









Left: m_{tt} vs $\cos\theta^*$ Right: m_{tt} vs $\cos\theta_\ell$.

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Likelihood for asymmetry and m_{tt}

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

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

- 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

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

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

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Parton Level Lepton-plus-jets Results - 1D and 2D expected significances - 300 fb^{-1}

Class	U(1)′	Significance (Z)		
		m_{tt}	m_{tt} & $\cos\theta^*$	m_{tt} & $\cos\theta_l$
E_6	$U(1)_\chi$	1.0	1.1	1.0
	$U(1)_\psi$	3.5	3.6	3.5
	$U(1)_\eta$	6.0	6.2	6.1
	$U(1)_S$	0.1	0.1	0.1
	$U(1)_I$	0.0	0.0	0.0
	$U(1)_N$	1.5	1.6	1.5
GLR	$U(1)_R$	7.1	7.6	7.9
	$U(1)_{B-L}$	1.3	1.3	1.3
	$U(1)_{LR}$	4.7	5.0	5.2
	$U(1)_Y$	6.0	6.2	6.4
GSM	$U(1)_{T^3_L}$	15.3	15.9	15.6
	$U(1)_{SM}$	9.0	9.4	9.2
	$U(1)_Q$	26.9	27.4	26.9

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