



Profiling Z' bosons with top pair asymmetries

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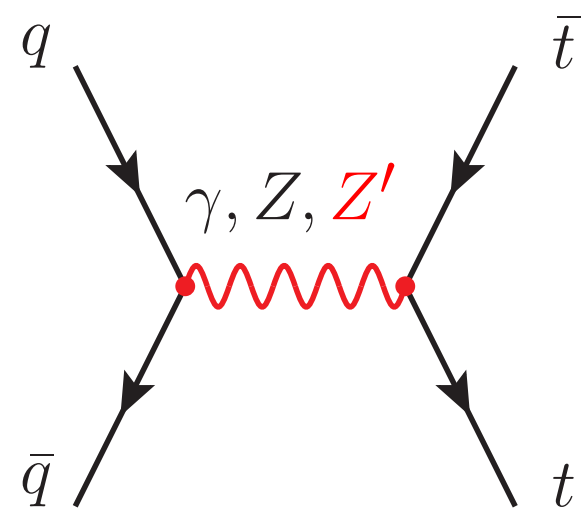
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1. Introduction

- ▶ New fundamental, massive, neutral, spin-1 gauge bosons (Z') are ubiquitous in BSM.
- ▶ E.g. due to residual gauge symmetries after the spontaneous symmetry breaking of a GUT:

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

- ▶ $Z' \rightarrow t\bar{t}$ search alternative to $Z' \rightarrow l^+l^-$.



- ▶ $Z't$ coupling significant in many BSM.
- ▶ E.g. Composite Higgs Models.
- ▶ Top quarks decay prior to hadronisation.
- ▶ Spin info transmitted to decay products.
- ▶ Can define unique **Asymmetry Observables**.

4. Charge asymmetry

- ▶ Forward-backward Asymmetry is defined

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

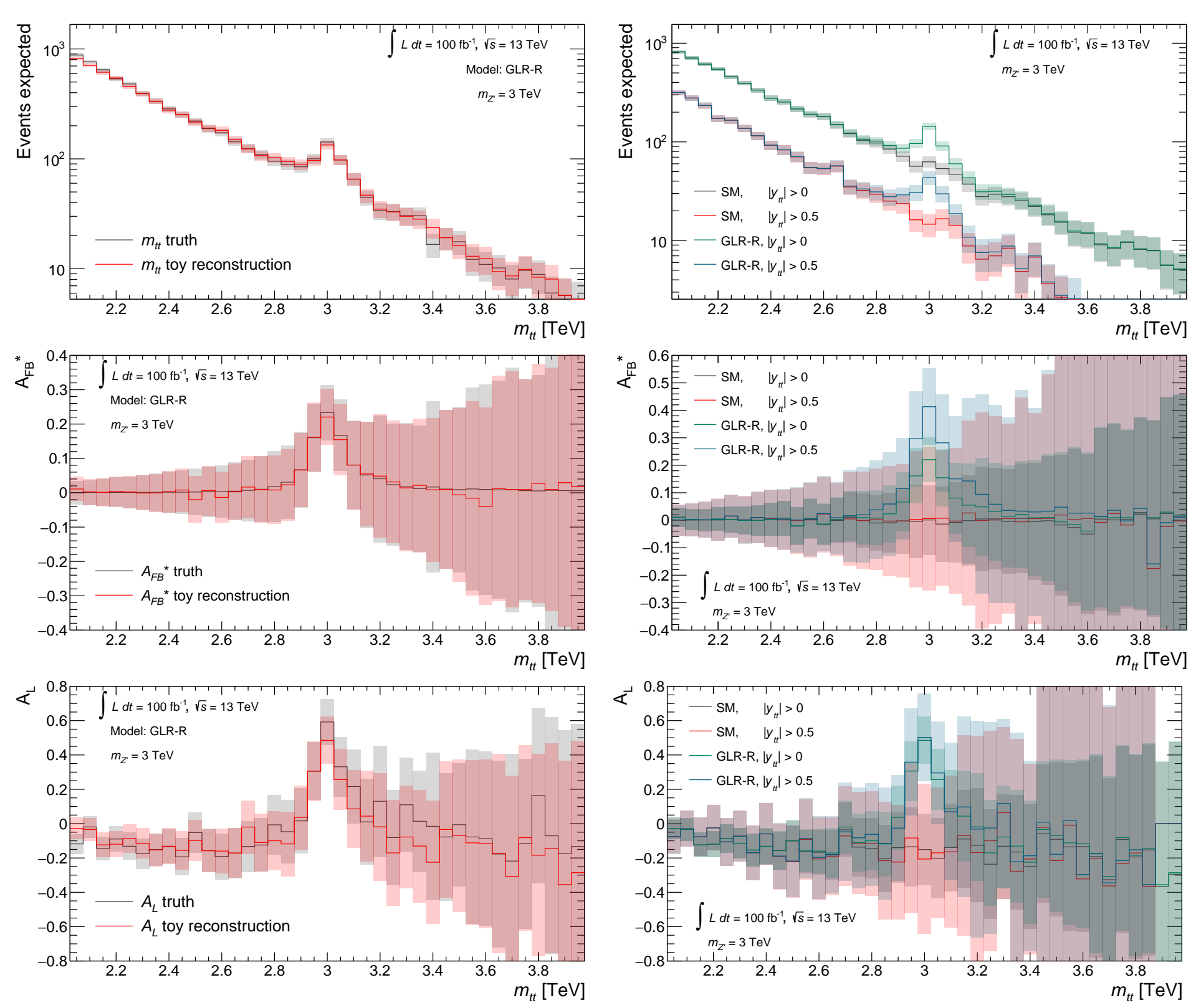
- ▶ Unique couplings to Z' :

$$A_{FB} \propto q_V q_A t_V t_A$$

- ▶ pp collisions have no preferred Z direction.
- ▶ But, parton momentum fraction: $x_q > x_{\bar{q}}$.
- ▶ Use the boost direction to define the Z axis.

$$\cos\theta^* = \frac{y_{t\bar{t}}}{|y_{t\bar{t}}|} \cos\theta \Rightarrow A_{FB}^*$$

7. Reconstruction and cuts



10. Expected significance

- ▶ Construct profile likelihood ratio from

$$L(\mathbf{x}|\mu, \theta) = \prod_i e^{(\mu s_i + b_i)} \frac{(\mu s_i + b_i)^{n_i}}{n_i!}$$

- ▶ Statistic for test of $\mu = 0$, assuming $\mu = 1$.
- ▶ Determine using asymptotic formulae.
- ▶ General enough for **n-dimensional histograms**.

$U(1)'$	Significance (Z)		
	m_{tt}	m_{tt} & $\cos\theta^*$	m_{tt} & $\cos\theta_l$
$U(1)_R$	7.7	8.5	8.6
$U(1)_{LR}$	5.1	5.6	5.8
$U(1)_Y$	6.3	6.8	7.0
$U(1)_{T^3}$	12.1	13.0	14.0
$U(1)_{SM}$	7.1	7.3	7.6

2. Models

- ▶ Generalised Sequential Models (GSMs):

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

- ▶ General Left-Right (GLR) symmetric models:

$$\begin{aligned} &SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\rightarrow SU(2)_L \times U(1)_R \times U(1)_{B-L}, \\ &\rightarrow SU(2)_L \times U(1)_Y. \end{aligned}$$

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

- ▶ E_6 inspired models:

$$\begin{aligned} E_6 &\rightarrow SO(10) \times U(1)_\psi, \\ SO(10) &\rightarrow SU(5) \times U(1)_\chi, \\ SU(5) &\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y. \end{aligned}$$

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

5. Polarisation asymmetry

- ▶ Top polarisation Asymmetry is defined

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

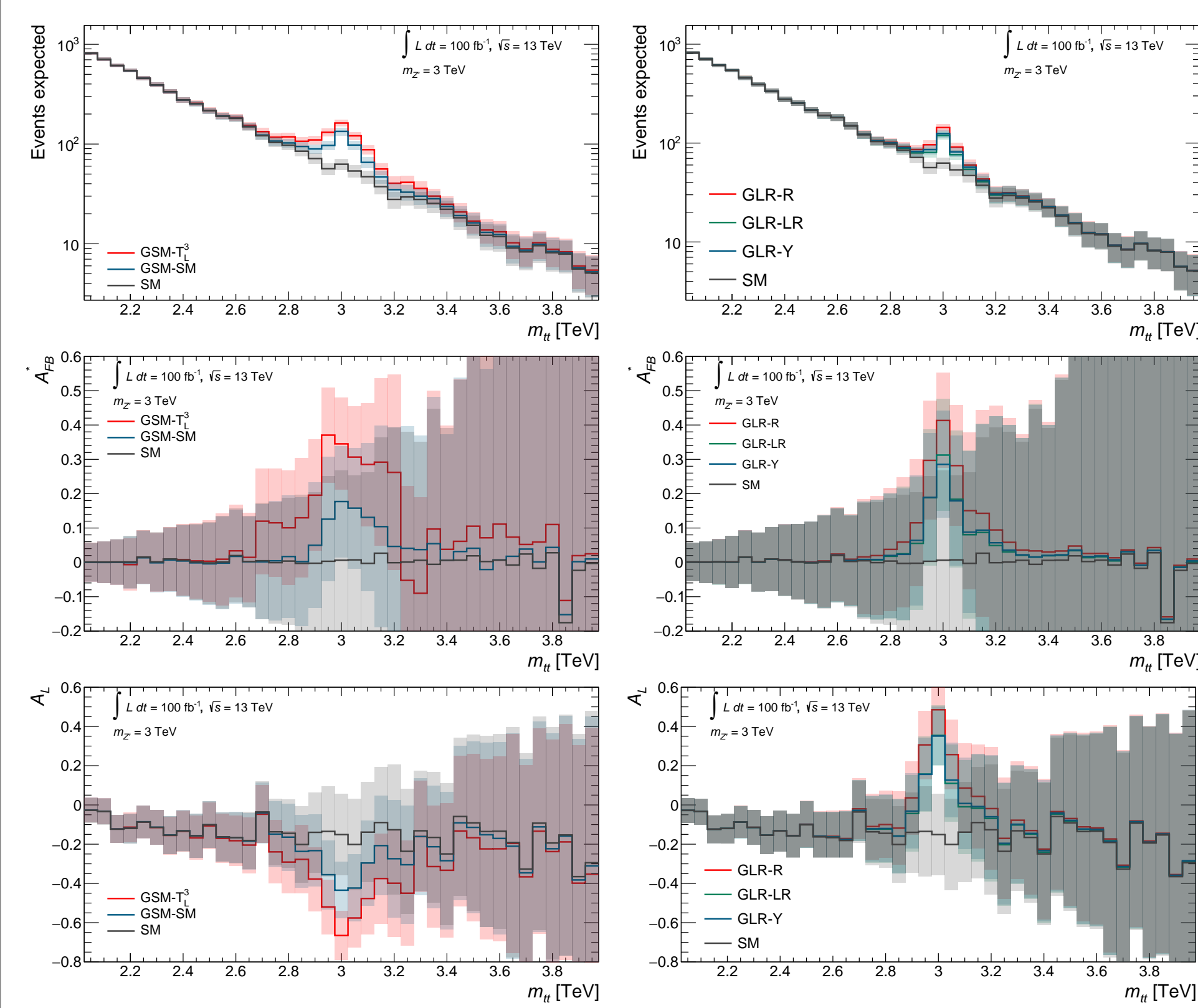
- ▶ Unique couplings to Z' :

$$A_L \propto (q_V^2 + q_A^2) t_V t_A$$

- ▶ θ_f : angle between the \mathbf{p}_t in the partonic rest frame and \mathbf{p}_f in the top rest frame.
- ▶ Top quark polarization information preserved:

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

8. Distinguishing Z' models



11. Conclusions

- ▶ We characterise the sensitivity of the LHC to a variety of benchmark models for $Z' \rightarrow t\bar{t}$.
- ▶ A combination of the cross section, A_{FB} and A_L can be used to **distinguish** between different classes of Z' models.
- ▶ These asymmetries also consistently increase the significance of Z' observation, demonstrating their potential as **complementary discovery channels**.
- ▶ E_6 inspired models universally feature negligible A_{FB}^* and A_L in $Z' \rightarrow t\bar{t}$.
- ▶ The top polarisation asymmetry demonstrates particularly promising distinguishing power, and boosts to significance.
- ▶ A_{FB}^* and A_L survive a simplified reconstruction.

3. Calculation

- ▶ Residual $U(1)'$ gauge symmetry is broken around the TeV scale: massive Z' boson.
- ▶ Additional low-energy Lagrangian neutral term:

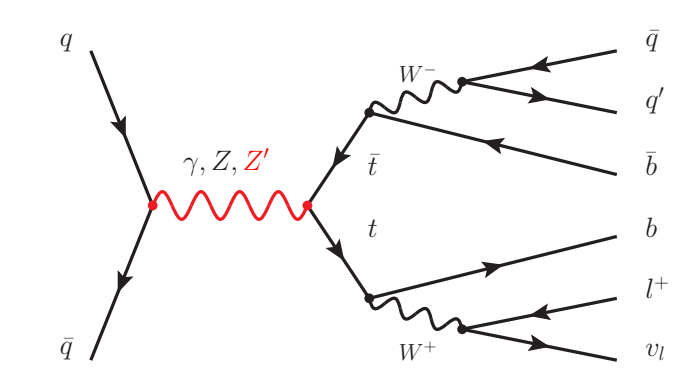
$$\mathcal{L} \supset g' Z'_\mu \bar{\psi} \gamma^\mu (f_V - f_A \gamma_5) \psi = g' Z'_\mu \bar{\psi} \gamma^\mu Q_{Z'} \psi$$

- ▶ The **cross section** demonstrates Z' coupling:

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

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

- ▶ Generate the parton-level 6 fermion final state.



- ▶ Include full tree-level SM $t\bar{t}$ interference, with all intermediate particles allowed off-shell.

6. Toy reconstruction of $l+j$

- ▶ Parton level, but mimic specific experimental constraints in lepton + jets final state.
- ▶ Reconstruct p_Z^ν in presence of E_T^{miss} :

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

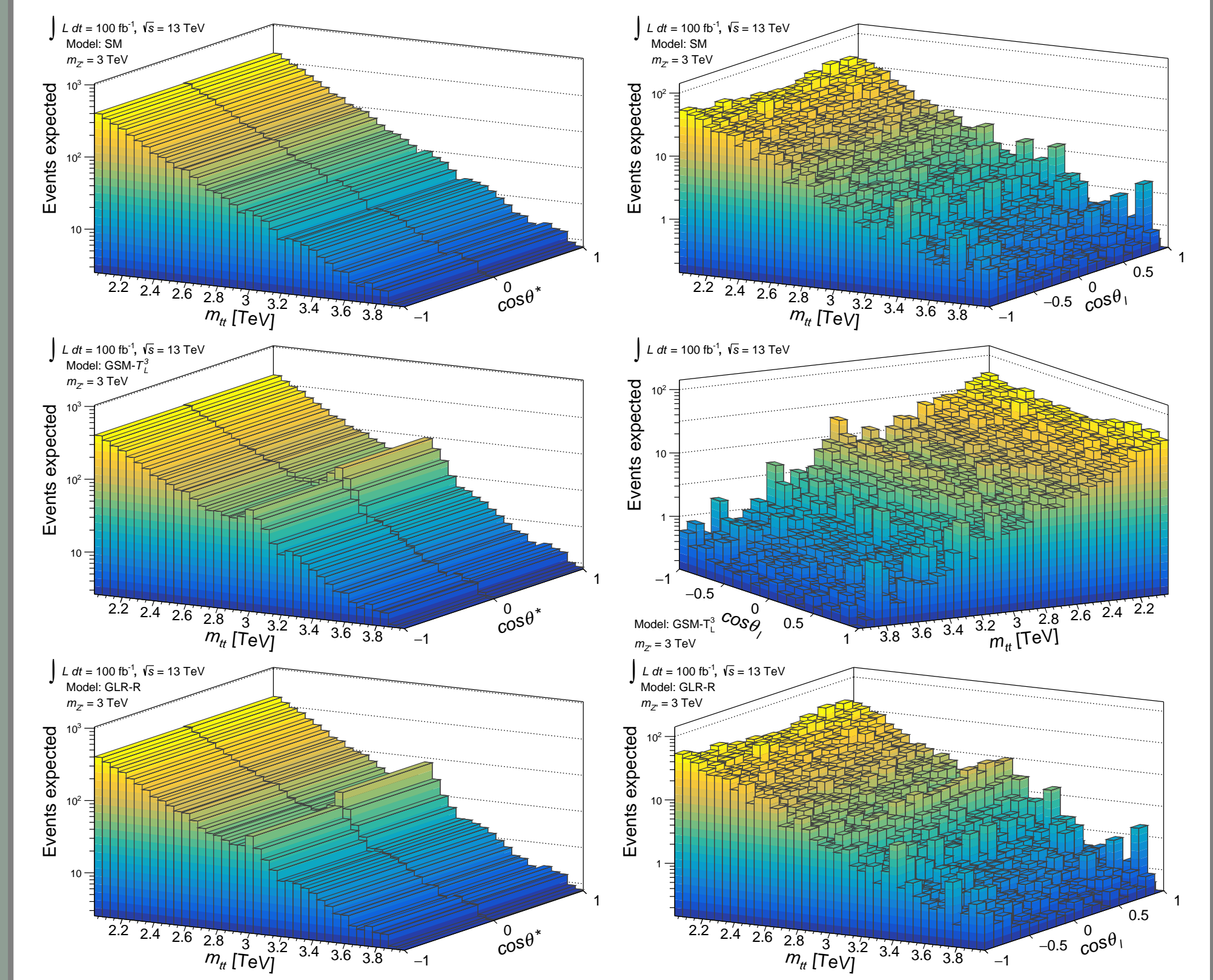
where

$$k = \frac{m_W^2}{2} + \mathbf{p}_T^l \mathbf{p}_T^\nu$$

- ▶ Resolve ambiguity in jet-top assignment.
- ▶ Select the combination for reconstruction by minimising:

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

9. Complementary discovery



12. Future work

- ▶ Investigate other angular variables, focusing on **dilepton $t\bar{t}$ events**: $\Delta\phi_l, \cos\theta_l, \cos\theta_{l^+} \cos\theta_{l^-}$.
- ▶ Extend to include parton-shower, fragmentation/hadronisation, heavy flavour decay and **detector reconstruction**.
- ▶ Perform an appropriate **boosted reconstruction** that preserves high signal efficiency with increasing momentum and maintains control over associated systematic uncertainties.
- ▶ Investigate models featuring **multiple interfering Z'** : Composite Higgs, Extra-Dimensions.
- ▶ These models may feature generationally non-universal couplings to Z' 's, therefore, **$Z' \rightarrow t\bar{t}$ can be the dominant discovery mode**.