Z’ signals in polarised top-antitop final states

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Overview

- **Introduction**
  - Extra neutral gauge bosons
  - $t\bar{t}$ channel: Asymmetries at the LHC

- **Benchmark $Z'$ models and asymmetries**

- **Study of asymmetry variables in $t\bar{t}$ from broad classes of $Z'$ models being searched for at the LHC**
  - Sensitivity to up quark chiral couplings
  - Distinguishability from SM and amongst themselves

- **Results**
  - Differential distributions; significance and luminosity analysis

- **Summary & outlook**
Introduction

• **Z’**: massive neutral s-channel resonance
  - Extra gauge boson from an extension of the SM symmetry group
  - KK excitation of SM gauge fields in extra dimensions
  - Many more...

• **Drell-Yan**: \( pp(\bar{p}) \rightarrow Z' \rightarrow l^+l^- \)
  - Discovery channel
  - Low background \( \sim 100\% \) reconstruction efficiency

• **Z’ \rightarrow t\bar{t}** also has a role to play being another significant channel at the LHC
  - Access to up-type quark coupling
  - Asymmetries
Charge asymmetry

• Measure of the symmetry of a process under charge conjugation ($qq\rightarrow f^+f^-$) → angular asymmetry
  - Tevatron $t\bar{t}$ forward backward asymmetry

• LHC: symmetric pp collider
  - Cannot define an absolute ‘forward’ direction
  - Boost of CM frame correlated with incoming quark direction
  - Top rapidity distribution broadened w.r.t antitop

\[
A_C = \frac{N_t(|y| < y_{cut}^C) - N_{\bar{t}}(|y| < y_{cut}^C)}{N_t(|y| < y_{cut}^C) + N_{\bar{t}}(|y| < y_{cut}^C)}
\]

\[
A_F = \frac{N_t(|y| > y_{cut}^F) - N_{\bar{t}}(|y| > y_{cut}^F)}{N_t(|y| > y_{cut}^F) + N_{\bar{t}}(|y| > y_{cut}^F)}
\]

\[
A_{OBF} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}|p_{t\bar{t}}^z| > p_{cut}^z
\]

\[
A_{RFB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}|y_{t\bar{t}}| > y_{cut}^t
\]
Spin asymmetry

- Single (L) and double (LL) spin asymmetries: defined in terms of the helicity of the outgoing top/antitop
  - Can be extracted from kinematical properties of top decay products
    \[ A_{LL} = \frac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N_{Total}} \]
    \[ A_L = \frac{N(-,-) + N(-,+) - N(+,+) - N(+,-)}{N_{Total}} \]

- \( N(h_t, h_{t\bar{t}}) \) obtained by calculating polarised matrix elements using helicity amplitude methods
  \[ \text{[Hagiwara, Zeppenfeld '85; Mangano, Parke '90; Arai et al. '08]} \]

- Asymmetries are an independent probe of chiral couplings of new physics to tops
Z’: models

- **TeV scale extra U(1)’**:
  - Universal couplings to generations
  - Fields in the same SM representations will have the same charge under new U(1)
  - 5 independent couplings $Q_L, L_L, u_R, d_R, e_R$ ($\nu_R$ decoupled)

- **Parametrise interaction in vector-axial basis**

- **Split models into two classes**
  - ‘E6 type’: $E_6 + G_{LR}(B-L)$ - only one non-zero up-type coupling
  - ‘Generalised’: $G_{LR} + G_{SM}$ - both non-zero

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### Benchmarks: $E_6, G_{LR}, G_{SM}$

| $U(1)'$ | Parameter | $g'_U$ | $g'_A$ | $g'_L$ | $g'_D$ |
|---------|-----------|--------|--------|--------|--------|
| $E_6$ ($g' = 0.462$) | $\theta$ | 0 | -0.316 | -0.632 | 0.316 |
| $U(1)_x$ | 0 | 0 | -0.316 | -0.632 | 0.316 |
| $U(1)_\psi$ | $0.5\pi$ | 0 | 0.408 | 0 | 0.408 |
| $U(1)_\eta$ | $-0.29\pi$ | 0 | -0.516 | -0.387 | -0.129 |
| $U(1)_S$ | $0.129\pi$ | 0 | -0.129 | -0.581 | 0.452 |
| $U(1)_N$ | $0.42\pi$ | 0 | 0.316 | -0.158 | 0.474 |

| $G_{LR}$ ($g' = 0.595$) | $\phi$ | 0 | 0.5 | -0.5 | -0.5 | 0.5 |
| $U(1)_R$ | 0 | 0.5 | -0.5 | -0.5 | 0.5 |
| $U(1)_{B-L}$ | $0.5\pi$ | 0.333 | 0 | 0.333 | 0 |
| $U(1)_{LR}$ | $-0.128\pi$ | 0.329 | -0.46 | -0.591 | 0.46 |
| $U(1)_Y$ | $0.25\pi$ | 0.589 | -0.354 | -0.118 | 0.354 |

| $G_{SM}$ ($g' = 0.760$) | $\alpha$ | $-0.072\pi$ | 0.193 | 0.5 | -0.347 | -0.5 |
| $U(1)_{SM}$ | 0 | 0.5 | 0.5 | -0.5 | -0.5 |
| $U(1)_{T3L}$ | $0.5\pi$ | 1.333 | 0 | -0.666 | 0 |

[Accomando, Belyaev, Fedeli, King, Shepherd-Themistocleous. arXiv:1010.6058]
Z′: asymmetries

- **Charge asymmetry**
  - Asymmetric part of the matrix element (cos θ term) \( \propto g_V^i g_A^i g_V^t g_A^t \)
  - Requires all non-zero couplings to generate at tree-level
  - Purely vector/axial models only generate via interference with SM (EW)

- **Spin asymmetries**
  - Calculated using helicity amplitudes
  - \( A_{LL} \) depends on square of top couplings like \( \sigma_{\text{total}} \)
  - \( A_L \) only non-zero if both \( g_V^t g_A^t \) non-zero, sensitive to relative sign in these couplings

\[
A_{LL}^i \propto \left(3(g_A^t)^2 \beta^2 + (g_V^t)^2 (2 + \beta^2)\right) \left((g_V^i)^2 + (g_A^i)^2\right)
\]

\[
A_L^i \propto g_A^t g_V^t \beta \left((g_V^i)^2 + (g_A^i)^2\right); \quad \beta = \sqrt{1 - \frac{4m_t^2}{s}}
\]
Developed a tool based on HELAS/MADGRAPH that can output observables in $t\bar{t}$ final state
- $M_{Z'}=2.0$ and $2.5 \text{ TeV}$,
- LHC at $8[14] \text{ TeV}$ assuming $L_{\text{int}} = 15[100] \text{ fb}^{-1}$

Focus around $Z'$ peak: $|M_{t\bar{t}}-M_{Z'}| < 500 \text{ GeV}$
- Invariant mass distributions/profiles of asymmetries
- Tree-level SM and interference
- Folded in $t\bar{t}$ reconstruction efficiency $\varepsilon = 10\%$

Statistical error on generic asymmetry $\delta A$ based on invariant mass bins of 50 GeV

$$\delta A \equiv \delta \left( \frac{N_F - N_B}{N_F + N_B} \right) = \sqrt{\frac{2}{L\varepsilon} \left( \frac{\sigma_F^2 + \sigma_B^2}{\sigma_{Total}^3} \right)}$$

‘Significance’ measure, $s$, of distinguishability between models

$$s \equiv \frac{|A(1) - A(2)|}{\sqrt{\delta A(1)^2 + \delta A(2)^2}}$$
E₆ type models: $A_{LL}$

- Clear signatures with distinction between most models and the SM when up-type coupling is large enough
- Set of overlapping models have similar magnitude v/a couplings
- Neither $A_{LL}$ nor cross section measurements can distinguish these
**E\textsubscript{6} type models: A\textsubscript{LL}**

- Integrating over narrow mass window around the peak increases significances

| A\textsubscript{LL}(\times 10) | \(\sqrt{s} = 14\text{\ TeV}\) | \(\mathcal{L}_{\text{int}} = 100\text{\ fb}^{-1}\) | \(\sqrt{s} = 8\text{\ TeV}\) | \(\mathcal{L}_{\text{int}} = 15\text{\ fb}^{-1}\) |
|-----------------------------|----------------|----------------|----------------|----------------|
| \(M_{Z'} = 2.0\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.5\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.1\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.5\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.1\text{\ TeV}\) |
| \(S\text{\ M}\) | \(-4.55 \pm 0.09\) | \(-5.07 \pm 0.11\) | \(-5.60 \pm 0.84\) | \(-6.26 \pm 1.24\) |
| \(E_6(\chi)\) | \(-4.65 \pm 0.09\) | \(-5.61 \pm 0.11\) | \(-5.72 \pm 0.84\) | \(-6.95 \pm 1.15\) |
| \(E_6(\eta)\) | \(-5.01 \pm 0.09\) | \(-7.01 \pm 0.10\) | \(-6.18 \pm 0.81\) | \(-8.40 \pm 0.90\) |
| \(E_6(\psi)\) | \(-4.81 \pm 0.09\) | \(-6.39 \pm 0.10\) | \(-5.92 \pm 0.83\) | \(-7.84 \pm 1.01\) |
| \(E_6(N)\) | \(-4.68 \pm 0.09\) | \(-5.77 \pm 0.11\) | \(-5.76 \pm 0.84\) | \(-7.16 \pm 1.12\) |
| \(E_6(S)\) | \(-4.56 \pm 0.09\) | \(-5.16 \pm 0.11\) | \(-5.62 \pm 0.84\) | \(-6.37 \pm 1.23\) |
| \(G_{LR}(BL)\) | \(-4.66 \pm 0.09\) | \(-5.58 \pm 0.11\) | \(-5.74 \pm 0.84\) | \(-6.94 \pm 1.14\) |

| \(M_{Z'} = 2.5\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.5\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.1\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.5\text{\ TeV}\) | \(\Delta M_{\tilde{t}\tilde{t}} < 0.1\text{\ TeV}\) |
|-----------------------------|----------------|----------------|----------------|----------------|
| \(S\text{\ M}\) | \(-5.54 \pm 0.21\) | \(-5.86 \pm 0.26\) | \(-6.69 \pm 2.64\) | \(-7.11 \pm 3.62\) |
| \(E_6(\chi)\) | \(-5.68 \pm 0.21\) | \(-6.47 \pm 0.25\) | \(-6.83 \pm 2.60\) | \(-7.76 \pm 3.29\) |
| \(E_6(\eta)\) | \(-6.16 \pm 0.20\) | \(-7.91 \pm 0.20\) | \(-7.37 \pm 2.43\) | \(-9.03 \pm 2.31\) |
| \(E_6(\psi)\) | \(-5.90 \pm 0.21\) | \(-7.33 \pm 0.22\) | \(-7.08 \pm 2.52\) | \(-8.61 \pm 2.71\) |
| \(E_6(N)\) | \(-5.72 \pm 0.21\) | \(-6.68 \pm 0.24\) | \(-6.88 \pm 2.58\) | \(-7.99 \pm 3.15\) |
| \(E_6(S)\) | \(-5.56 \pm 0.21\) | \(-5.96 \pm 0.26\) | \(-6.71 \pm 2.63\) | \(-7.22 \pm 3.58\) |
| \(G_{LR}(BL)\) | \(-5.69 \pm 0.21\) | \(-6.43 \pm 0.25\) | \(-6.86 \pm 2.59\) | \(-7.78 \pm 3.24\) |
Generalised models: $A_L$

- Larger couplings contribute to more visible effects, increased width
- Good discrimination among models, sensitivity to relative sign of vector and axial couplings: $G_{LR}$ and $G_{SM}$ can be separated
**Generalised models: $$A_L$$**

- $$G_{LR}(LR)$$ and $$G_{LR}(Y)$$ are not visibly distinguishable in the invariant mass distributions due to similar magnitude of couplings but can be disentangled by the narrow mass window.

| $$A_L(\times 10)$$ | $$\sqrt{s} = 14\text{ TeV}$$ | $$\mathcal{L}_{int} = 100\text{ fb}^{-1}$$ | $$\sqrt{s} = 8\text{ TeV}$$ | $$\mathcal{L}_{int} = 15\text{ fb}^{-1}$$ |
|---------------------|-------------------------------|---------------------------------|-------------------------------|---------------------------------|
| $$M_{Z'} = 2.0\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.5\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.1\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.5\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.1\text{ TeV}$$ |
| $$SM$$ | $-0.01 \pm 0.08$ | $-0.01 \pm 0.10$ | $-0.02 \pm 0.7$ | $-0.02 \pm 1.05$ |
| $$G_{LR}(LR)$$ | $-1.27 \pm 0.08$ | $-4.17 \pm 0.08$ | $-1.86 \pm 0.67$ | $-5.73 \pm 0.76$ |
| $$G_{LR}(R)$$ | $-1.97 \pm 0.07$ | $-5.30 \pm 0.08$ | $-2.85 \pm 0.65$ | $-6.92 \pm 0.70$ |
| $$G_{LR}(Y)$$ | $-1.28 \pm 0.08$ | $-3.94 \pm 0.08$ | $-1.97 \pm 0.66$ | $-5.51 \pm 0.72$ |
| $$G_{SM}(SM)$$ | $1.04 \pm 0.07$ | $2.87 \pm 0.08$ | $1.56 \pm 0.66$ | $4.02 \pm 0.72$ |
| $$G_{SM}(T_3L)$$ | $2.40 \pm 0.07$ | $5.03 \pm 0.08$ | $3.47 \pm 0.63$ | $6.68 \pm 0.72$ |

| $$M_{Z'} = 2.5\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.5\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.1\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.5\text{ TeV}$$ | $$\Delta M_{t\bar{t}} < 0.1\text{ TeV}$$ |
|---------------------|-------------------------------|---------------------------------|-------------------------------|---------------------------------|
| $$SM$$ | $-0.01 \pm 0.18$ | $-0.01 \pm 0.22$ | $-0.02 \pm 2.19$ | $-0.03 \pm 2.95$ |
| $$G_{LR}(LR)$$ | $-1.97 \pm 0.17$ | $-4.87 \pm 0.18$ | $-4.00 \pm 1.83$ | $-7.46 \pm 1.85$ |
| $$G_{LR}(R)$$ | $-2.93 \pm 0.17$ | $-6.01 \pm 0.17$ | $-4.00 \pm 1.83$ | $-7.46 \pm 1.85$ |
| $$G_{LR}(Y)$$ | $-2.00 \pm 0.17$ | $-4.62 \pm 0.17$ | $-2.95 \pm 1.86$ | $-6.14 \pm 1.89$ |
| $$G_{SM}(SM)$$ | $1.58 \pm 0.17$ | $3.32 \pm 0.17$ | $2.22 \pm 1.84$ | $4.38 \pm 1.91$ |
| $$G_{SM}(T_3L)$$ | $3.41 \pm 0.16$ | $5.65 \pm 0.17$ | $4.63 \pm 1.76$ | $7.16 \pm 1.92$ |
Significance

- Significance $s$ of $A_L$ and $A_{RFB}$ between models, $M_{Z'}=2[2.5]$ TeV in upper[lower] triangles, invariant mass window $\Delta M_{tt}=100(500)$ GeV, LHC at 14 TeV $L=100\text{fb}^{-1}$

| $A_L$ | $SM$ | $GLR(LR)$ | $GLR(R)$ | $GLR(Y)$ | $GSM(SM)$ | $GSM(T_3L)$ |
|------|------|-----------|----------|----------|-----------|-------------|
| $SM$ | –    | 31.9(11.1)| 40.6(18.3)| 30.1(11.2)| 22.1(9.8) | 38.7(22.5) |
| $GLR(LR)$ | 16.9(7.7) | –         | 10.0(6.6) | 2.0(0.1) | 62.2(21.7) | 81.3(34.5) |
| $GLR(R)$ | 21.3(11.5) | 4.6(4.0)  | –         | 12.0(6.5) | 72.2(30.4) | 91.3(44.1) |
| $GLR(Y)$ | 16.3(7.8) | 1.0(0.1)  | 5.8(3.9)  | –         | 60.2(21.8) | 79.3(34.6) |
| $GSM(SM)$ | 11.8(6.3) | 33.1(14.8)| 38.8(18.8)| 33.0(14.9)| 9.7(7.8)   | 19.1(13.7) |
| $GSM(T_3L)$ | 20.1(13.9) | 42.5(23.0)| 48.5(27.2)| 42.7(23.2)| –         | –           |

| $A_{RFB}$ | $SM$ | $GLR(LR)$ | $GLR(R)$ | $GLR(Y)$ | $GSM(SM)$ | $GSM(T_3L)$ |
|-----------|------|-----------|----------|----------|-----------|-------------|
| $SM$ | –    | 9.2(3.3)  | 12.8(5.7)| 8.6(3.4) | 5.2(2.2) | 12.2(7.2) |
| $GLR(LR)$ | 4.8(2.2) | –         | 4.1(2.5) | 0.8(0.1) | 4.9(1.2) | 3.4(3.9) |
| $GLR(R)$ | 6.4(3.6) | 1.9(1.5)  | –         | 4.9(2.4) | 9.2(3.7) | 0.8(1.4) |
| $GLR(Y)$ | 4.4(2.2) | 0.6($\ll 1$) | 2.5(1.5) | –         | 4.1(1.3) | 4.1(3.9) |
| $GSM(SM)$ | 2.6(1.4) | 2.7(0.8)  | 4.7(2.4) | 2.2(0.9) | –         | 8.4(5.2) |
| $GSM(T_3L)$ | 5.9(4.2) | 1.4(2.1)  | 0.4(0.7) | 2.0(2.2) | 4.2(3.0) | –           |
Luminosity dependence

- Required integrated luminosity to achieve \( s=3 \) between models
  - Measure of the power of an asymmetry variable

- Even for the higher mass, there is scope for disentanglement (where possible) at relatively early stages of 14 TeV run

| \( A_L \) \( A_{LL} \) | SM | \( E_6(\chi) \) | \( E_6(\eta) \) | \( E_6(\psi) \) | \( E_6(N) \) | \( E_6(S) \) | GLR(\( B-L \)) | GLR(LR) | GLR(R) | GLR(Y) | GSM(SM) | GSM(\( T_{3L} \)) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SM | - | 314.7 | 23.0 | 48.3 | 167.6 | >300 | 360.4 | 22.0 | 15.1 | 21.5 | 23.7 | 17.6 |
| \( E_6(\chi) \) | - | 44.5 | 135.0 | >300 | >300 | >300 | 41.6 | 25.5 | 40.5 | >300 | >300 |
| \( E_6(\eta) \) | - | 236.5 | 58.1 | 25.5 | 42.1 | >300 | >300 | >300 | >300 | >300 |
| \( E_6(\psi) \) | - | 225.8 | 55.6 | 123.2 | >300 | >300 | 200.5 | 77.3 | 188.3 | 263.0 | 110.4 |
| \( E_6(N) \) | - | - | 217.4 | >300 | >300 | 53.6 | 30.9 | 52.0 | 61.0 | 38.5 |
| \( E_6(S) \) | - | - | - | >300 | 24.2 | 16.4 | 23.7 | 26.3 | 19.3 |
| GLR(\( B-L \)) | 3.2 | - | - | - | 39.4 | 24.4 | 38.4 | 43.9 | 29.7 |
| GLR(LR) | 2.0 | - | - | - | - | >300 | >300 | >300 | >300 |
| GLR(R) | 3.4 | - | - | - | >300 | 26.9 | - | >300 | >300 |
| GLR(Y) | 6.4 | - | - | - | >300 | >300 | >300 | >300 | >300 |
| GSM(SM) | 2.2 | 0.8 | 0.6 | 0.8 | 0.5 | 0.4 | 0.5 | 9.6 | - |
| GSM(\( T_{3L} \)) | - | - | - | - | - | - | - | - | - |
Conclusion

- Overview of a phenomenological study of spin and spatial asymmetries from a set of benchmark $Z'$ models in $t\bar{t}$ channel.

- Quantified the ability to distinguish these models from the SM and among themselves.

- Clear that such models will be visible/distinguishable in the relatively early stages of LHC running.

- Spin asymmetries depend strongly on the chiral couplings of the $Z'$ and in some cases can disentangle models which would not be by cross section measurements.
The set of benchmark models considered lend themselves to di-lepton searches
- $t\bar{t}$ can complement but not compete

Other BSM scenarios with Z’s naturally have preferential couplings to the top or are leptophobic
- Dynamical EWSP / composite Higgs
- Extra dimensions
- etc.

Apply this kind of study to such models in which the $t\bar{t}$ channel is a competitive discovery mode

Investigate the complementarity of asymmetries in $t\bar{t}$, $b\bar{b}$ and $l^+l^-$ channels to fully probe parameter space of $Z'$ models
Z’: Models

• **E₆ models**
  - Two additional U(1)’s from GUT group breaking pattern
  - \( E₆ \rightarrow SO(10) \otimes U(1) \psi \rightarrow SU(5) \otimes U(1) \psi \otimes U(1) \chi \rightarrow SM \otimes U(1) \psi \otimes U(1) \chi \)
  - Linear combination survives down to TeV scale
  - \( Q(E₆) = \cos \theta \ T_\chi + \sin \theta \ T_\psi \)

• **Left-Right symmetric**
  - \( SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \rightarrow SU(2)_L \otimes U(1)_Y \)
  - \( U(1)_R \otimes U(1)_{B-L} \rightarrow U(1)_Y \)
  - \( Q(G_{LR}) = \cos \phi \ T_{3R} + \sin \phi \ T_{B-L} \)

• **Generalised sequential SM**
  - Sequential = SM couplings: Standard candle in experimental searches
  - \( Q(G_{SM}) = \cos \alpha \ T_{3L} + \sin \alpha \ Q_{EM} \)
Invariant Mass

$M_{tt}$ Dist. LHC at 14 TeV, 100 fb$^{-1}$ and $\epsilon_{\text{reco}}=0.1$, $M_{Z'}=2.0$ TeV

$M_{tt}$ Dist. LHC at 14 TeV, 100 fb$^{-1}$ and $\epsilon_{\text{reco}}=0.1$, $M_{Z'}=2.0$ TeV