

Z' signals in polarised top-antitop final states

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[arXiv:1203.2542](https://arxiv.org/abs/1203.2542)



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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

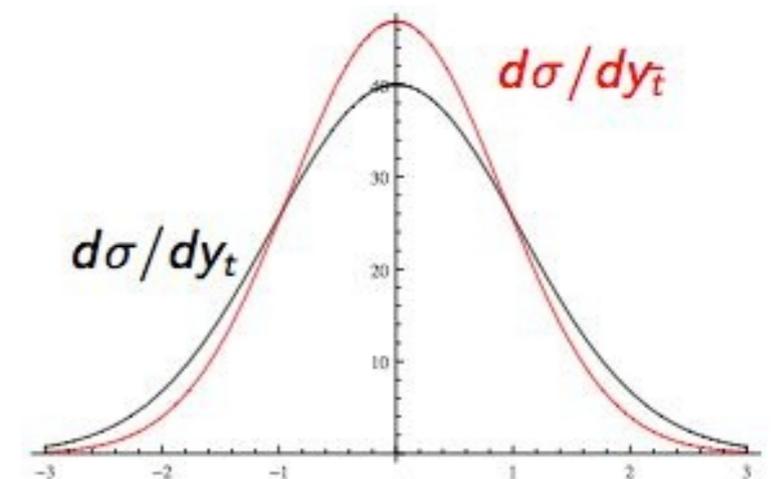
- Z' : massive neutral s-channel resonance
 - Extra gauge boson from an extension of the SM symmetry group
 - KK excitation of SM gauge fields in extra dimensions
 - Many more...
- Drell-Yan: $pp(\bar{p}) \rightarrow Z' \rightarrow l^+l^-$
 - Discovery channel
 - Low background $\sim 100\%$ reconstruction 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 ($q\bar{q} \rightarrow f^+f^-$) \rightarrow 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



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

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

$$A_{OFB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \Bigg|_{|p_{t\bar{t}}^z| > p_{cut}^z}$$

$$A_{RFB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \Bigg|_{|y_{t\bar{t}}| > |y_{t\bar{t}}^{cut}|}$$

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
[Stelzer, Willenbrock '96; Bernreuther; Godbole et al.]

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

- $N(h_t, h_{tbar})$ obtained by calculating polarised matrix elements using helicity amplitude methods
[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 (ν_R decoupled)
- Parametrise interaction in vector-axial basis
- Split models into two classes
 - 'E₆ type': E₆ + G_{LR}(B-L) - only one non-zero up-type coupling
 - 'Generalised': G_{LR} + G_{SM} - both non-zero

Benchmarks: E₆, G_{LR}, G_{SM}

U(1)'	Parameter	g_V^u	g_A^u	g_V^d	g_A^d
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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
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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	-0.354	-0.118	0.354
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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
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[Accomando, Belyaev, Fedeli, King, Shepherd-Themistocleous. arXiv:1010.6058]

Z': asymmetries

$$\mathcal{L}_{Z'} = \frac{g'}{2} Z'_\mu \bar{\psi}^i \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi^i$$

- 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 σ_{total}
- A_L only non-zero if both $g_V^t g_A^t$ non-zero, sensitive to relative sign in these couplings

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

$$A_L^i \propto g_A^t g_V^t \beta \left((g_V^i)^2 + (g_A^i)^2 \right); \quad \beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$$

Phenomenological study

- Developed a tool based on HELAS/MADGRAPH that can output observables in $t\bar{t}$ final state
 - $M_{Z'}=2.0$ and 2.5 TeV,
 - LHC at $8[14]$ TeV assuming $L_{int} = 15[100]$ fb $^{-1}$
- Focus around Z' peak: $|M_{t\bar{t}}-M_{Z'}| < 500$ GeV
 - Invariant mass distributions/profiles of asymmetries
 - Tree-level SM and interference
 - Folded in $t\bar{t}$ reconstruction efficiency $\epsilon=10\%$

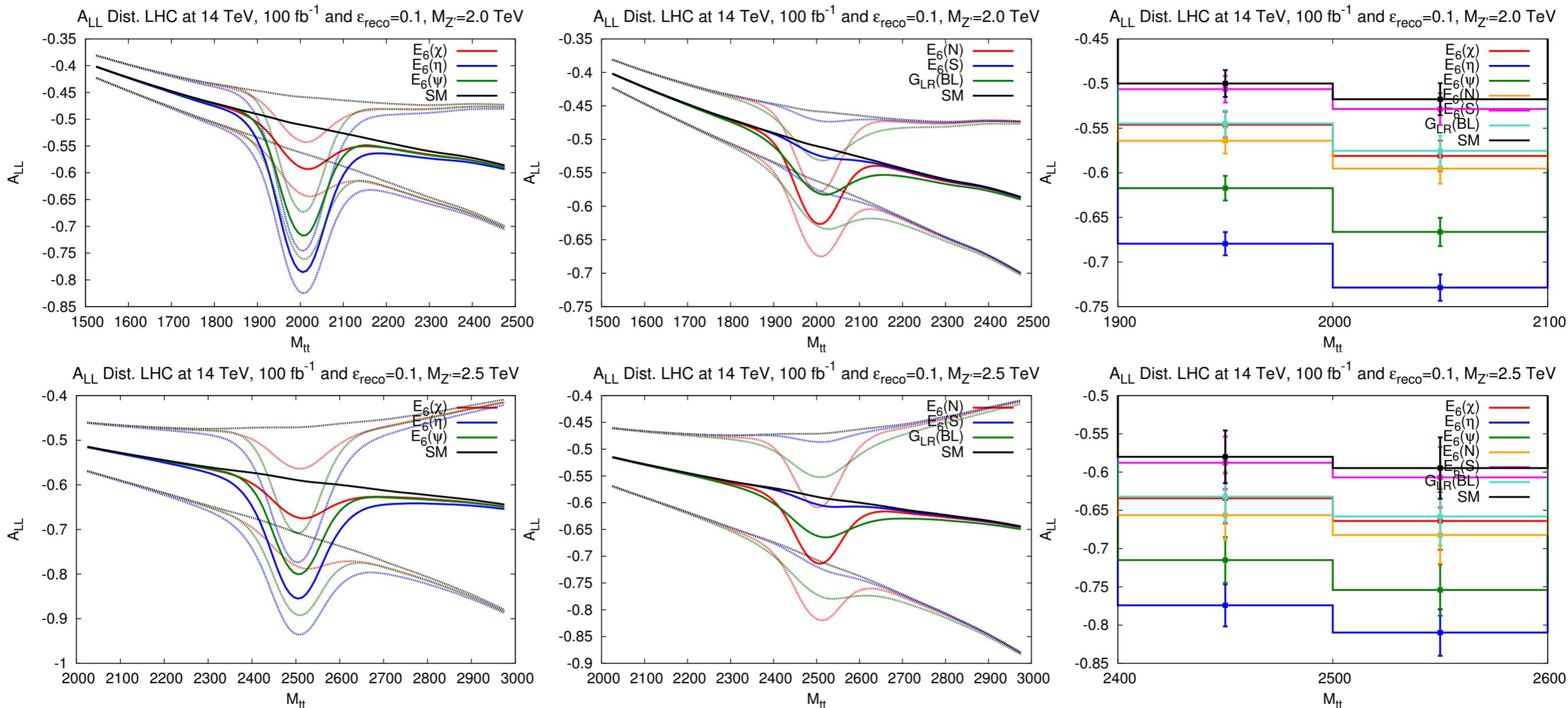
Statistical error on generic asymmetry δA based on invariant mass bins of 50 GeV

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

'Significance' measure, s , of distinguishability between models

$$s \equiv \frac{|A(1) - A(2)|}{\sqrt{\delta A(1)^2 + \delta A(2)^2}}$$

E_6 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

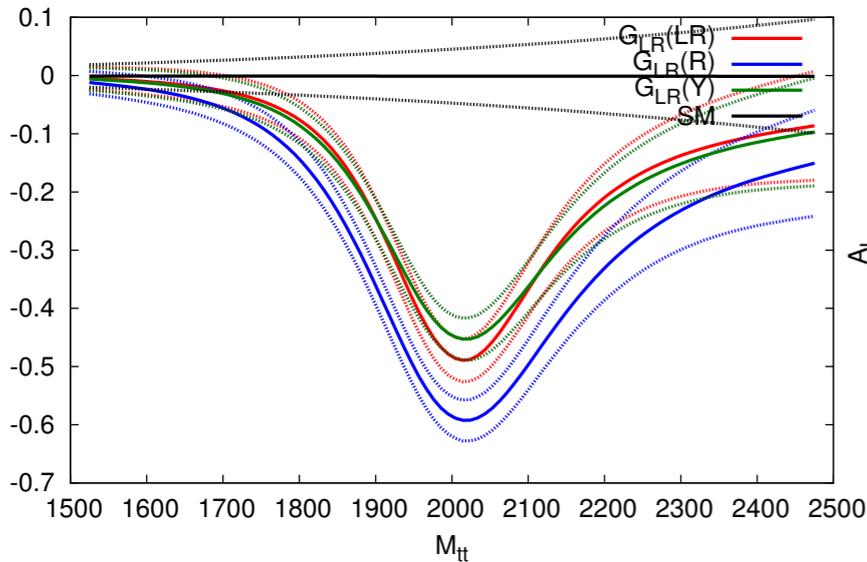
E_6 type models: ALL

- Integrating over narrow mass window around the peak increases significances

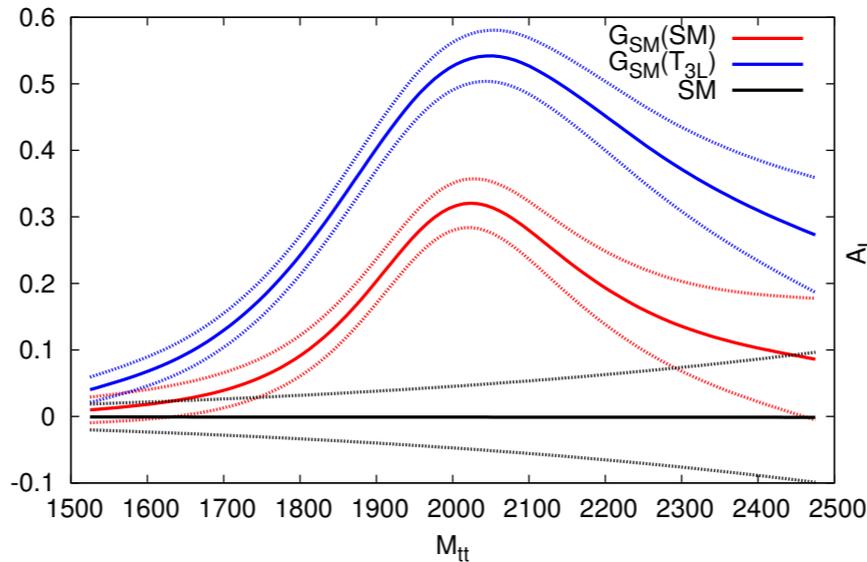
$A_{LL}(\times 10)$	$\sqrt{s} = 14 \text{ TeV}$	$\mathcal{L}_{int} = 100 \text{ fb}^{-1}$	$\sqrt{s} = 8 \text{ TeV}$	$\mathcal{L}_{int} = 15 \text{ fb}^{-1}$
$M_{Z'} = 2.0 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.5 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.1 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.5 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.1 \text{ TeV}$
SM	-4.55 ± 0.09	-5.07 ± 0.11	-5.60 ± 0.84	-6.26 ± 1.24
$E_6(\chi)$	-4.65 ± 0.09	-5.61 ± 0.11	-5.72 ± 0.84	-6.95 ± 1.15
$E_6(\eta)$	-5.01 ± 0.09	-7.01 ± 0.10	-6.18 ± 0.81	-8.40 ± 0.90
$E_6(\psi)$	-4.81 ± 0.09	-6.39 ± 0.10	-5.92 ± 0.83	-7.84 ± 1.01
$E_6(N)$	-4.68 ± 0.09	-5.77 ± 0.11	-5.76 ± 0.84	-7.16 ± 1.12
$E_6(S)$	-4.56 ± 0.09	-5.16 ± 0.11	-5.62 ± 0.84	-6.37 ± 1.23
$G_{LR}(BL)$	-4.66 ± 0.09	-5.58 ± 0.11	-5.74 ± 0.84	-6.94 ± 1.14
$M_{Z'} = 2.5 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.5 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.1 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.5 \text{ TeV}$	$\Delta M_{t\bar{t}} < 0.1 \text{ TeV}$
SM	-5.54 ± 0.21	-5.86 ± 0.26	-6.69 ± 2.64	-7.11 ± 3.62
$E_6(\chi)$	-5.68 ± 0.21	-6.47 ± 0.25	-6.83 ± 2.60	-7.76 ± 3.29
$E_6(\eta)$	-6.16 ± 0.20	-7.91 ± 0.20	-7.37 ± 2.43	-9.03 ± 2.31
$E_6(\psi)$	-5.90 ± 0.21	-7.33 ± 0.22	-7.08 ± 2.52	-8.61 ± 2.71
$E_6(N)$	-5.72 ± 0.21	-6.68 ± 0.24	-6.88 ± 2.58	-7.99 ± 3.15
$E_6(S)$	-5.56 ± 0.21	-5.96 ± 0.26	-6.71 ± 2.63	-7.22 ± 3.58
$G_{LR}(BL)$	-5.69 ± 0.21	-6.43 ± 0.25	-6.86 ± 2.59	-7.78 ± 3.24

Generalised models: A_L

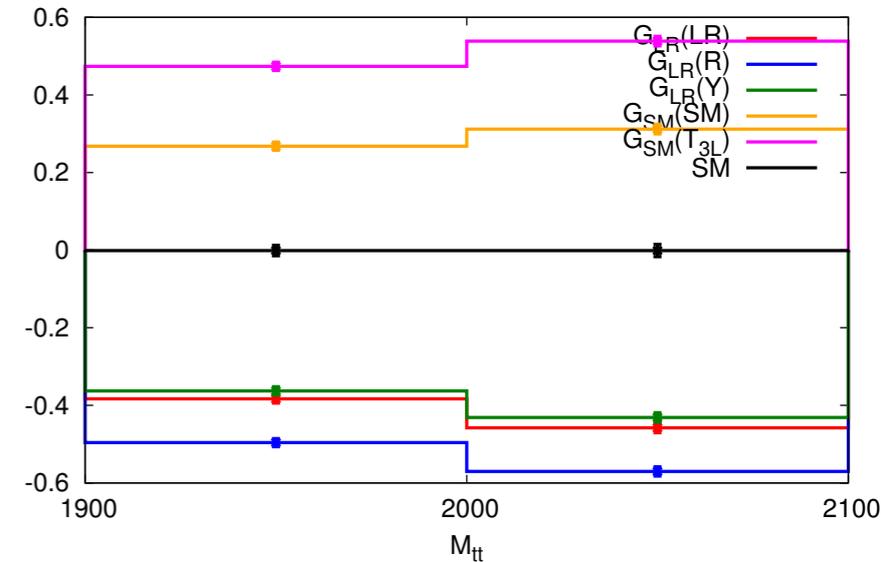
A_L Dist. LHC at 14 TeV, 100 fb^{-1} and $\epsilon_{\text{reco}}=0.1$, $M_Z=2.0 \text{ TeV}$



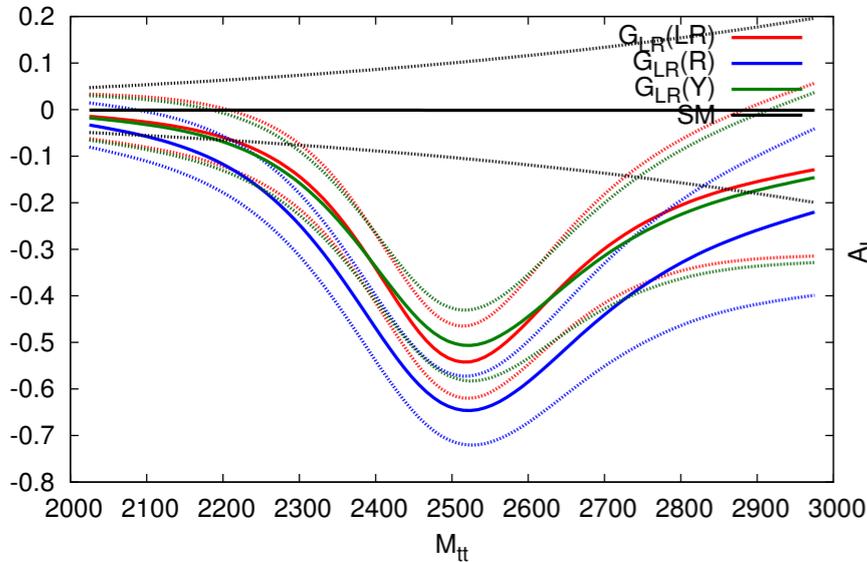
A_L Dist. LHC at 14 TeV, 100 fb^{-1} and $\epsilon_{\text{reco}}=0.1$, $M_Z=2.0 \text{ TeV}$



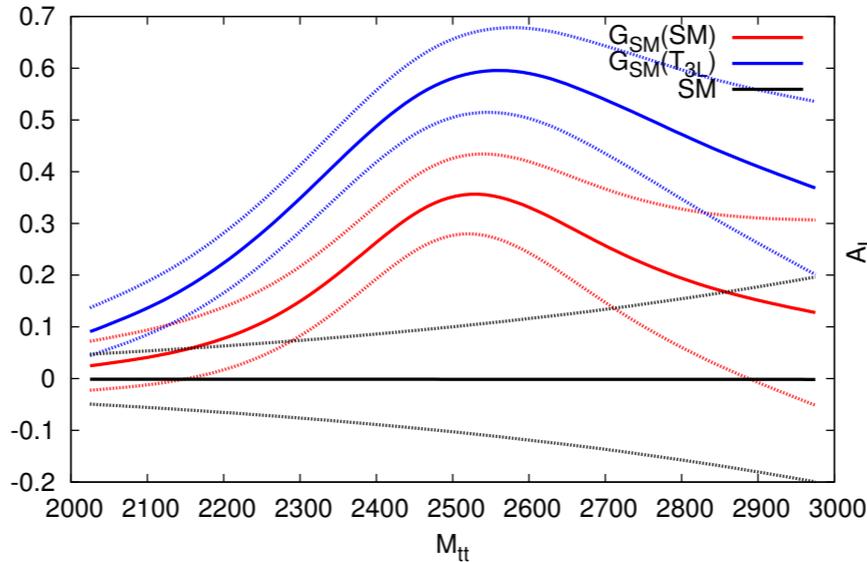
A_L Dist. LHC at 14 TeV, 100 fb^{-1} and $\epsilon_{\text{reco}}=0.1$, $M_Z=2.0 \text{ TeV}$



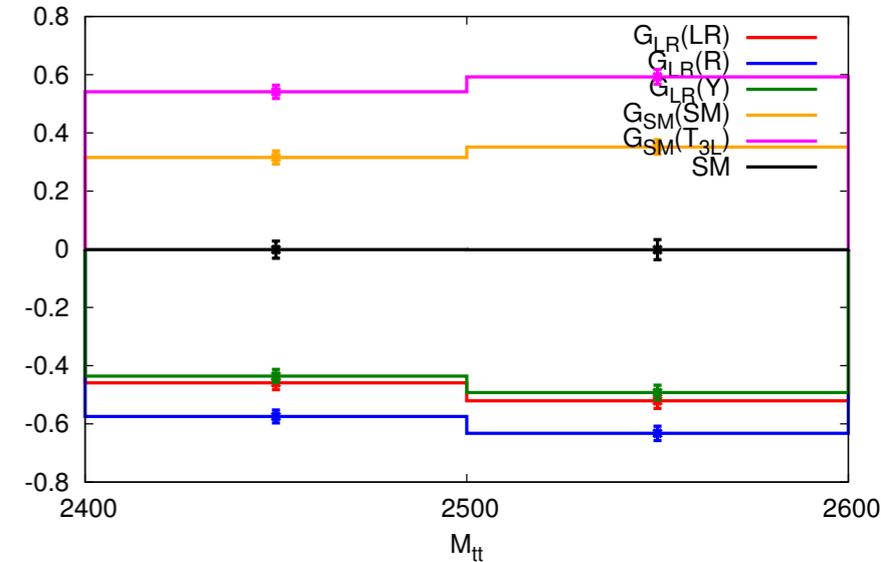
A_L Dist. LHC at 14 TeV, 100 fb^{-1} and $\epsilon_{\text{reco}}=0.1$, $M_Z=2.5 \text{ TeV}$



A_L Dist. LHC at 14 TeV, 100 fb^{-1} and $\epsilon_{\text{reco}}=0.1$, $M_Z=2.5 \text{ TeV}$



A_L Dist. LHC at 14 TeV, 100 fb^{-1} and $\epsilon_{\text{reco}}=0.1$, $M_Z=2.5 \text{ TeV}$



- 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 ± 0.08	-0.01 ± 0.10	-0.02 ± 0.7	-0.02 ± 1.05
$G_{LR}(LR)$	-1.27 ± 0.08	-4.17 ± 0.08	-1.86 ± 0.67	-5.73 ± 0.76
$G_{LR}(R)$	-1.97 ± 0.07	-5.30 ± 0.08	-2.85 ± 0.65	-6.92 ± 0.70
$G_{LR}(Y)$	-1.28 ± 0.08	-3.94 ± 0.08	-1.97 ± 0.66	-5.51 ± 0.72
$G_{SM}(SM)$	1.04 ± 0.07	2.87 ± 0.08	1.56 ± 0.66	4.02 ± 0.72
$G_{SM}(T_{3L})$	2.40 ± 0.07	5.03 ± 0.08	3.47 ± 0.63	6.68 ± 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 ± 0.18	-0.01 ± 0.22	-0.02 ± 2.19	-0.03 ± 2.95
$G_{LR}(LR)$	-1.97 ± 0.17	-4.87 ± 0.18	-2.69 ± 1.92	-6.28 ± 2.02
$G_{LR}(R)$	-2.93 ± 0.17	-6.01 ± 0.17	-4.00 ± 1.83	-7.46 ± 1.85
$G_{LR}(Y)$	-2.00 ± 0.17	-4.62 ± 0.17	-2.95 ± 1.86	-6.14 ± 1.89
$G_{SM}(SM)$	1.58 ± 0.17	3.32 ± 0.17	2.22 ± 1.84	4.38 ± 1.91
$G_{SM}(T_{3L})$	3.41 ± 0.16	5.65 ± 0.17	4.63 ± 1.76	7.16 ± 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 $\Delta M_{t\bar{t}}=100(500)$ 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)	–	19.1(13.7)
$GSM(T_{3L})$	20.1(13.9)	42.5(23.0)	48.5(27.2)	42.7(23.2)	9.7(7.8)	–

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

$M_{Z'}=2.5 \text{ TeV}$												
$A_L \searrow A_{LL}$	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	46.4	31.1
$E_6(\eta)$			-	236.5	58.1	25.5	42.1	>300	>300	>300	>300	>300
$E_6(\psi)$				-	225.8	55.6	123.2	200.5	77.3	188.3	263.0	110.4
$E_6(N)$					-	217.4	>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
$GLR(B-L)$							-	39.4	24.4	38.4	43.9	29.7
$GLR(LR)$	3.2							-	>300	>300	>300	>300
$GLR(R)$	2.0							42.5	-	>300	369.4	>300
$GLR(Y)$	3.4							>300	26.9	-	>300	>300
$GSM(SM)$	6.4							0.8	0.6	0.8	-	>300
$GSM(T_{3L})$	2.2							0.5	0.4	0.5	9.6	-

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

Outlook

- 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 EWSB / 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

BACKUP

Z': Models

- **E₆ models**

- Two additional U(1)'s from GUT group breaking pattern
- $E_6 \rightarrow SO(10) \otimes U(1)_\Psi \rightarrow SU(5) \otimes U(1)_\Psi \otimes U(1)_X \rightarrow SM \otimes U(1)_\Psi \otimes U(1)_X$
- Linear combination survives down to TeV scale
- $Q(E_6) = \cos\theta T_X + \sin\theta T_\Psi$

- **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

