Z' physics through $t\bar{t}$ asymmetries

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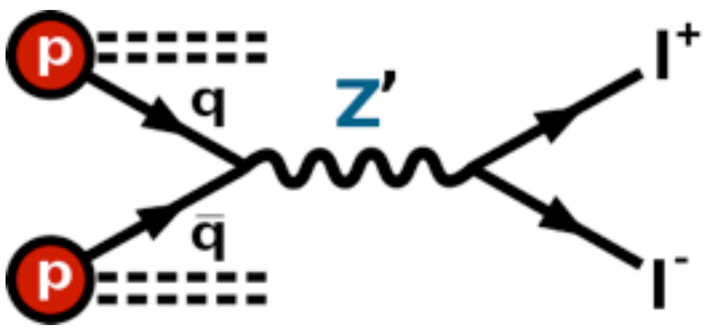
Overview

- Introduction
  - Extra neutral gauge bosons
  - $t\bar{t}$ channel
  - Asymmetries at the LHC
- Study of asymmetry variables for a generic B-L Z' model
  - $t\bar{t}$ as a complementary channel to di-leptons
  - Sensitivity to chiral couplings & distinguishability
- Accessing Z' couplings
  - Asymmetries as a handle on extracting parameters of Z' models
- Asymmetries with Multiple Z's
  - Quasi-degeneracy
- Summary

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
  - ~100% reconstruction efficiency



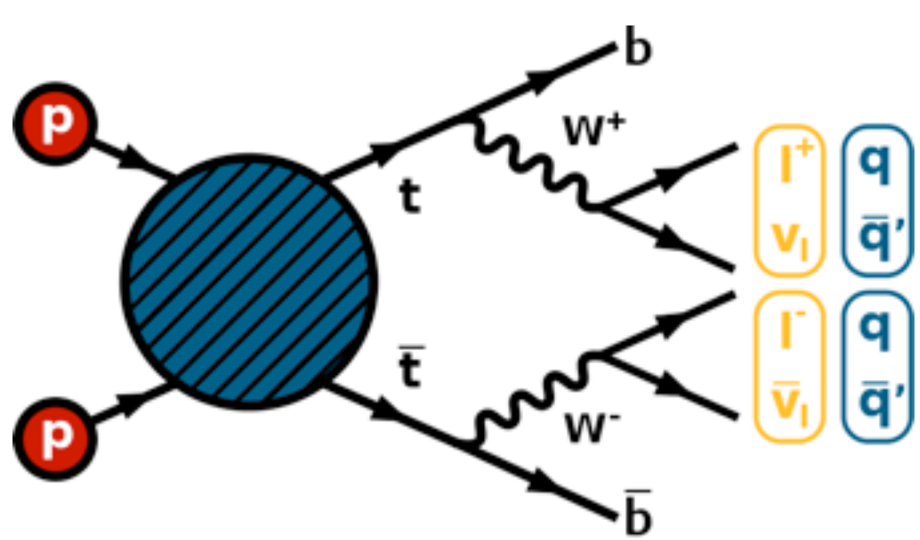
- $Z' \rightarrow t\bar{t}$ also has a role to play being another significant channel at the LHC
  - Access to up-type quark coupling of new physics
  - New asymmetry observables

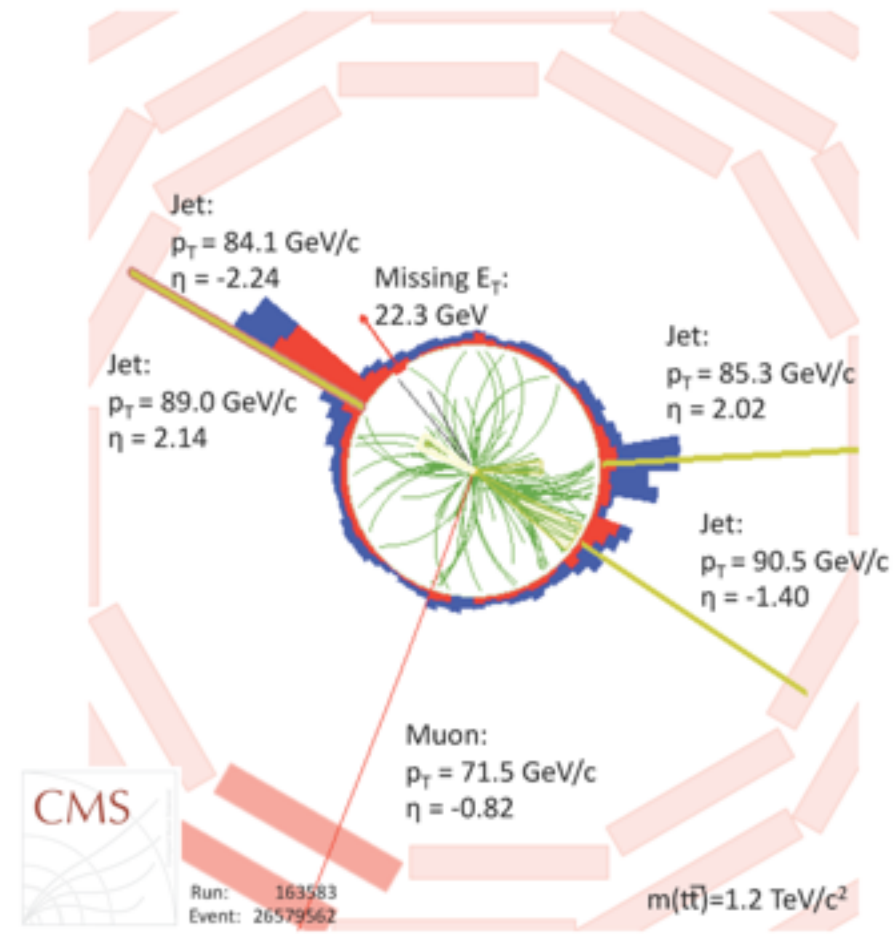
The top quark

- Discovered at the Tevatron in 1995: heaviest fundamental particle
  - M_t=173.2±0.6(stat.)±0.8(syst.) GeV (Tevatron combination)
  - M_t=173.3±0.5(stat.)±1.3(syst.) GeV (LHC combination)
- Mass near the EW scale
  - Strongly coupled to EWSB dynamics, important component of BSM theories
- Theoretical QCD cross sections well known to N(N)LO/NNLL, NLO EW corrections are known
- Top quark decays before hadronisation
  - Behaves like 'free' parton
  - Charge, spin information propagated to decay products

$t\bar{t}$ at the LHC

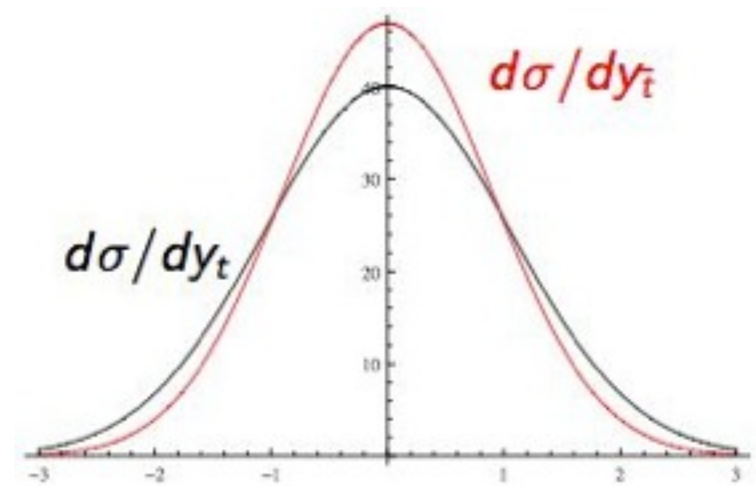
- Large production cross section at the LHC
  - BSM searches: irreducible QCD background (~800 pb @ 14 TeV)
  - More involved 6 body final state
  - Lower reconstruction efficiency ~ 10%
- Top quark events characterised by their decay modes
  - ~100% t → b + W(→ hadronic/leptonic)
  - $t\bar{t}$ → hadronic/semi-leptonic/dileptonic





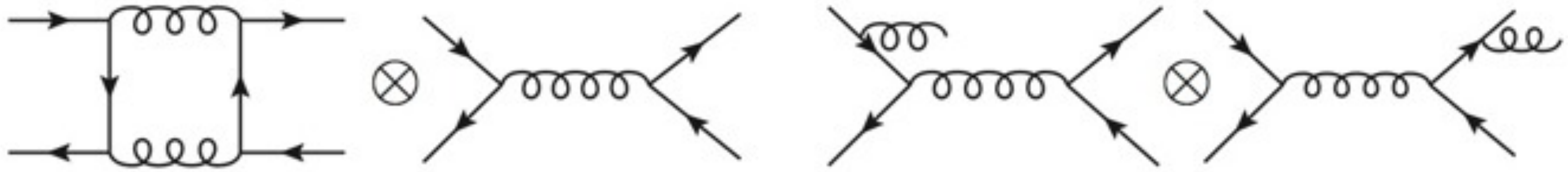
Charge asymmetry

- Measure of the symmetry of a process under charge conjugation ($q\bar{q} \rightarrow f^+ f^-$)
  - CP invariance → angular asymmetry of matrix element
  - 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



- Define variables accordingly:
  - Define z direction as that of $t\bar{t}$ system boost *[Krohn et al. '11]*
  - Rapidity difference + kinematical cuts to enhance qqbar *[Zhou et al. '11]*

Charge asymmetry



- Dominant SM contribution: O(α_S^3) NLOQCD
  [Halzen '87; Kuhn, Rodrigo '99]
  - gg is C-symmetric
  - Interference of ISR and FSR
  - Box diagram with tree level
  - Other contributions: LO EW O(α^2) and NLOEW x QCD O($\alpha_S^2\alpha$)
    [Moretti; Ross & Nolten, 2006; Kuhn, Scharf and Uwer (CERN), 2006; Bernreuther, Fücker & Si, 2008]

$$A^*_{FB} = \left.\frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) + N(\cos\theta^* < 0)}\right|_{\hat{z}=\hat{p}^z_{t\bar{t}}}$$

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

Spin asymmetry

- Single (L) and double (LL) spin asymmetries: defined in terms of the helicity of the outgoing top/antitop
  - AKA spin polarisation/correlation
  - 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]
- Can be measured for any decaying final state (taus)

Reconstruction

- $t\bar{t}$ invariant mass is difficult to reconstruct: how much more information is needed to extract asymmetries?
  - Charge asymmetry relies only on angular information of $t\bar{t}$ system, relatively ‘cheap’
- Spin asymmetries rely on angular information of decay products of one or both tops
  - lepton(b-jet) angle has 100(40)% spin analysing power
- As the scale of new physics is pushed up, $t\bar{t}$ system becomes more boosted: collimated decay products
  - Angular resolution, b-tagging, lepton isolation deteriorate
  - Experimental analyses on efficiencies in different channels ongoing
  - Several suggestions on ways to measure certain asymmetries without fully reconstructing invariant mass: energy fractions, p_T spectra

Z′: asymmetries

$$\mathcal{L}_{Z'} = Z'_\mu \bar{\psi}^i \gamma^\mu (C_V^i - C_A^i \gamma^5) \psi^i$$

$$\begin{aligned}\sigma_{tot} &\propto \Big((C_V^i)^2 + (C_A^i)^2\Big)\Big((C_V^f)^2(\beta^2 - 4) - 3(C_A^f)^2\beta^2\Big); \quad \beta = \sqrt{1 - \frac{4m_f^2}{\hat{s}}} \\ &\propto \Big((C_L^i)^2 + (C_R^i)^2\Big)\Big(2(C_L^f + C_R^f) + ((C_L^f)^2 - 4C_L^f C_R^f + (C_R^f)^2)\beta^2\Big) \\ &\Rightarrow \Big((C_{V,L}^i)^2 + (C_{A,R}^i)^2\Big)\Big((C_{V,L}^f)^2 + (C_{A,R}^f)^2\Big); \quad \beta \to 1\end{aligned}$$

- Charge asymmetry
  - Asymmetric part of the matrix element (cos θ term)
  - Requires all non-zero couplings to generate at tree-level
  - Purely vector/axial models only generate via interference with SM (EW)
  - Interaction to initial and final state must be chiral

$$\begin{aligned}\mathcal{A} &\propto C_V^i C_A^i C_V^f C_A^f \\ &\propto \Big((C_R^i)^2 - (C_L^i)^2\Big)\Big((C_R^f)^2 - (C_L^f)^2\Big)\end{aligned}$$

Z': asymmetries

- Spin asymmetries
  - Calculated using helicity amplitudes
  - A_{LL} depends on square of top couplings like σ_{total}
  - Becomes maximal in the massless limit
  - A_L only non-zero if both $g_V^t\, g_A^t$ non-zero, sensitive to relative sign

$$\mathcal{A}^i_{LL} \propto \Big((C^i_V)^2 + (C^i_A)^2\Big)\Big(3\,(C^f_A)^2\beta^2 + (C^f_V)^2(2+\beta^2)\Big)$$
$$\propto \Big((C^i_L)^2 + (C^i_R)^2\Big)\Big((C^f_L + C^f_R)^2 + 2\Big((C^f_L)^2 - C^f_L C^f_R + (C^f_R)^2\Big)\beta^2\Big)$$
$$\mathcal{A}^i_L \propto \beta\Big((C^i_V)^2 + (C^i_A)^2\Big)C^f_A C^f_V$$
$$\propto \Big((C^i_R)^2 + (C^i_L)^2\Big)\Big((C^f_R)^2 - (C^f_L)^2\Big)$$

- Charge/spin asymmetries probe the chiral structure of Z’ couplings

Minimal Z′ model

- 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)
- Gauged $U(1)_{B-L}$
  - Extensively studied in literature
  - Possible low energy limit of GUT/Gauge group extension scenarios

$$D_\mu \equiv \partial_\mu + ig_S T^\alpha G_\mu{}^\alpha + igT^a W_\mu{}^a + ig_1 Y B_\mu + i(\widetilde{g}Y + g_1' Y_{B-L})B_\mu'$$

- No requirements on gauge unification:
  - g_1’, $\tilde{g}$ free parameters
  - effective gauge coupling: $g_E Y^E \equiv \widetilde{g}Y + g_1' Y_{B-L}$

Z' Couplings

$$C_V^u(g_1', \tilde{g}) = \frac{-C' C_W (4g_1' + 5\tilde{g}) S_W + e S' (3 - 8 S_W^2)}{12 C_W S_W},$$

$$C_A^u(g_1', \tilde{g}) = -\frac{e S' + C' C_W \tilde{g} S_W}{4 C_W S_W},$$

$$C_V^d(g_1', \tilde{g}) = \frac{C' C_W (-4g_1' + \tilde{g}) S_W + e S' (-3 + 4 S_W^2)}{12 C_W S_W},$$

$$C_A^d(g_1', \tilde{g}) = \frac{C' \tilde{g} C_W S_W + e S'}{4 C_W S_W},$$

$$C_V^\ell(g_1', \tilde{g}) = \frac{-C' C_W (4g_1' + 3\tilde{g}) S_W + e S' (1 - 4 S_W^2)}{4 C_W S_W},$$

$$C_A^\ell(g_1', \tilde{g}) = -\frac{e S' + C' C_W \tilde{g} S_W}{4 C_W S_W},$$

$$U(1)_{B-L} : \tilde{g} = 0$$
$$\to C_A^{u,d,l} \sim 0$$
$$U(1)_R : \tilde{g} = -2g_1'$$
$$\to C_V^{u,d,l} = C_A^{u,d,l}$$
$$U(1)_\chi : \tilde{g} = -\frac{4}{5} g_1'$$
$$\to C_V^u \sim 0$$
$$\not{L} : \tilde{g} = 4g_1'$$
$$\to C_V^l \sim 0$$
$$\not{B} : \tilde{g} = -\frac{4}{3} g_1'$$
$$\to C_V^d \sim 0$$

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

- Mass mixing with SM (S') Z heavily constrained, neglected
- Recover familiar benchmarks by enforcing relations between the two couplings, define two new benchmarks with vanishing d,l couplings
- Model also requires right handed neutrinos for anomaly cancellation

Z' Study

- Performed a parameter scan on $(g_1', \tilde{g})$ computing parton-level asymmetries at the LHC in lepton, $t\bar{t}$, ll and $(b\bar{b})$ final states
  - Estimate associated reconstruction efficiencies from experimental publications
  - For $t\bar{t}$, BR weighted efficiencies per channel
- Assess the ability to fully access the parameter space and demonstrate the complementarity of the various channels
  - Show that in some cases, multiple final states are necessary to disentangle benchmark models
- Bear in mind the possibility of extracting Z' couplings from a set of independent observables including asymmetries in multiple final states

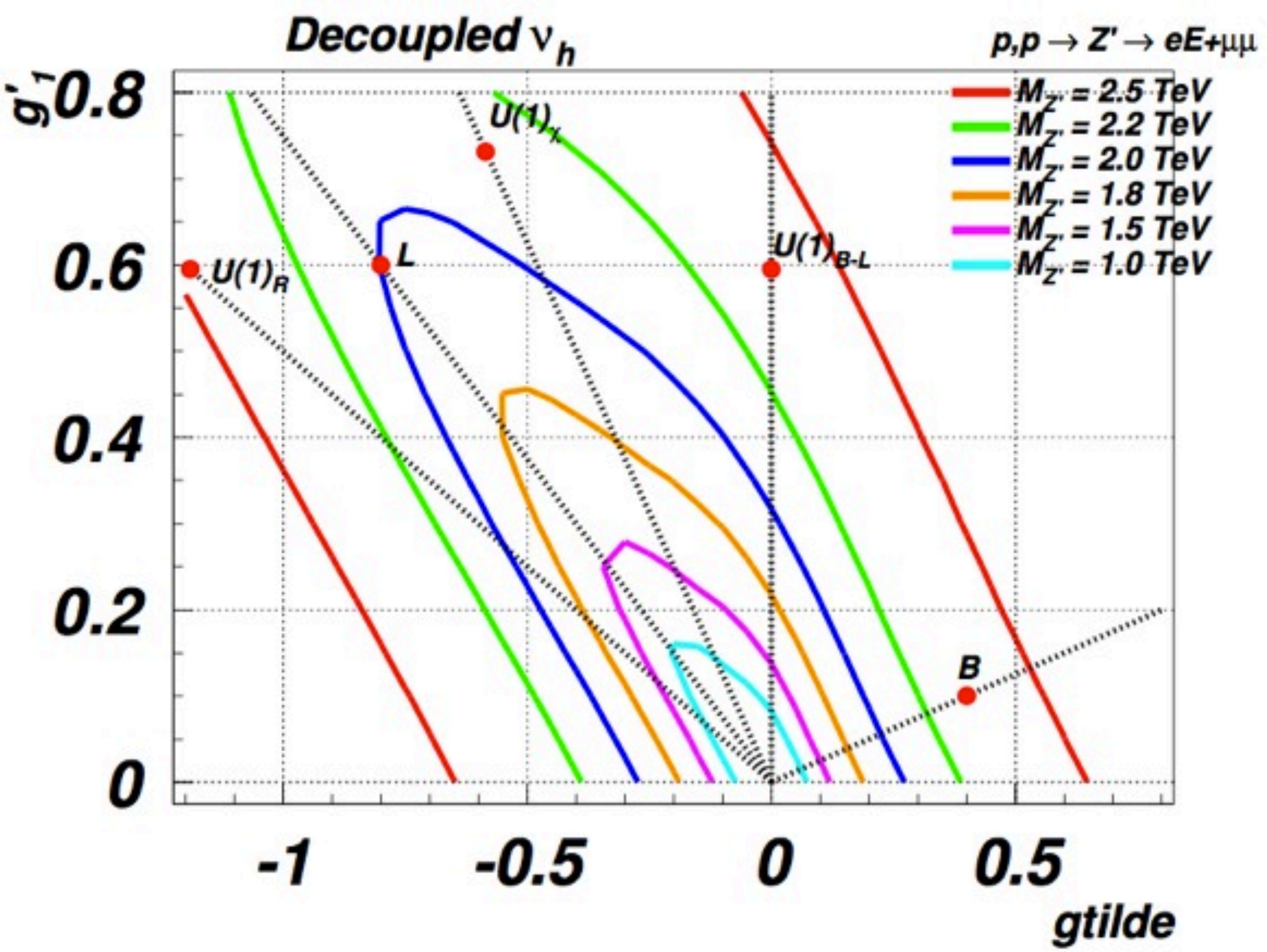
[L. Basso, KM, S. Moretti; JHEP 1211 (2012) 060]

Final States

- di-lepton (~90% reconstruction efficiency)
  - Precise, efficient channel in electrons and muons
  - Can only measure polarisation in hadronically decaying taus (~10% reconstruction efficiency)
- $t\bar{t}$: Complicated channel (~10% reco. efficiency)
  - All asymmetries accessible
- $b\bar{b}$: Speculative channel (~5% reco. efficiency)
  - Double b-tag efficiency too low at high pT and single b-tag suffer from a high mistag rate: require leptonic decays
  - Vertex detectors will be upgraded for 14 TeV run
  - We present results in this channel as potential observables

Experimental limits

- Recent CMS limits from di-lepton resonance searches in ee and μμ at 7 TeV, ~5 fb^{-1}



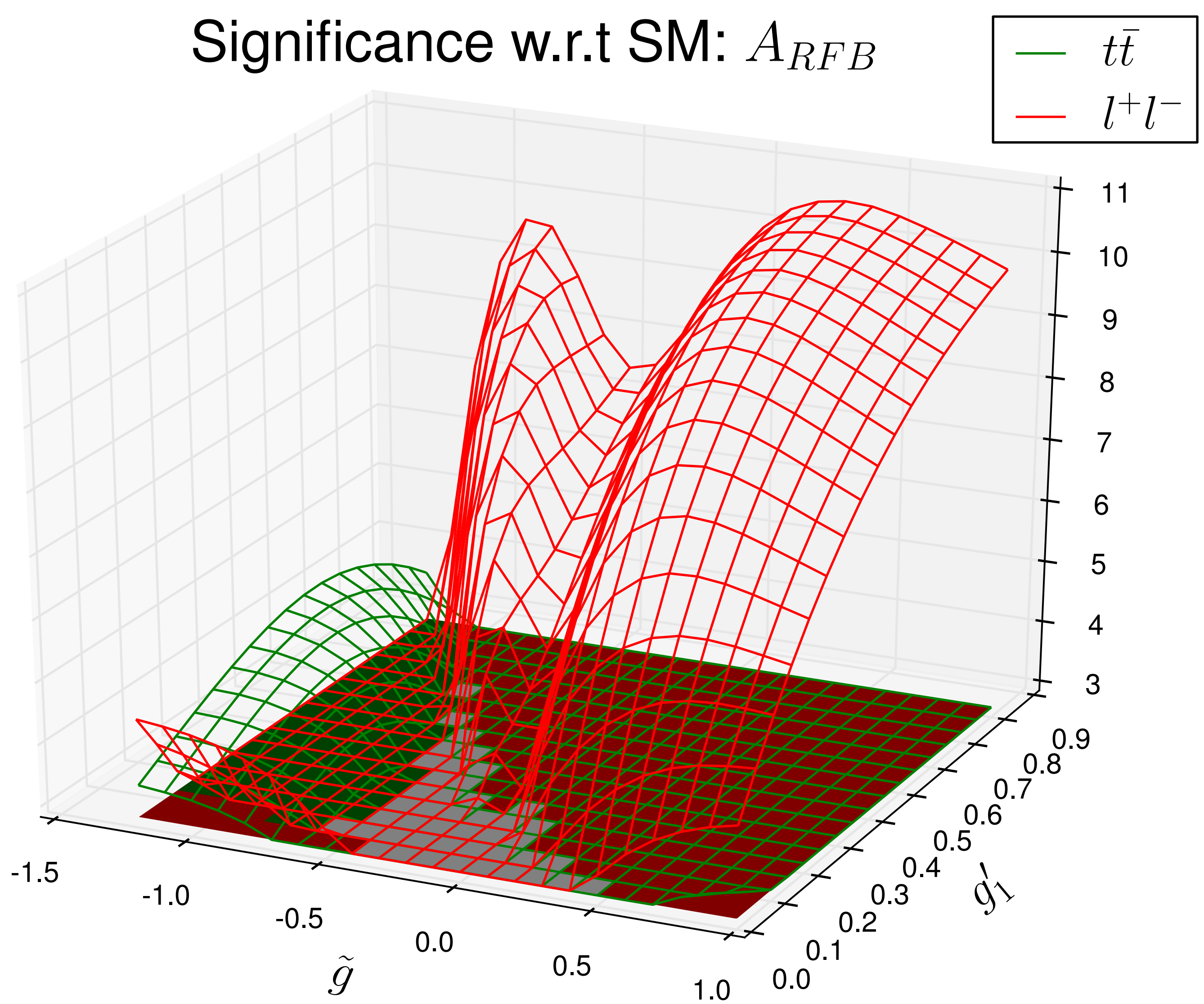
Details

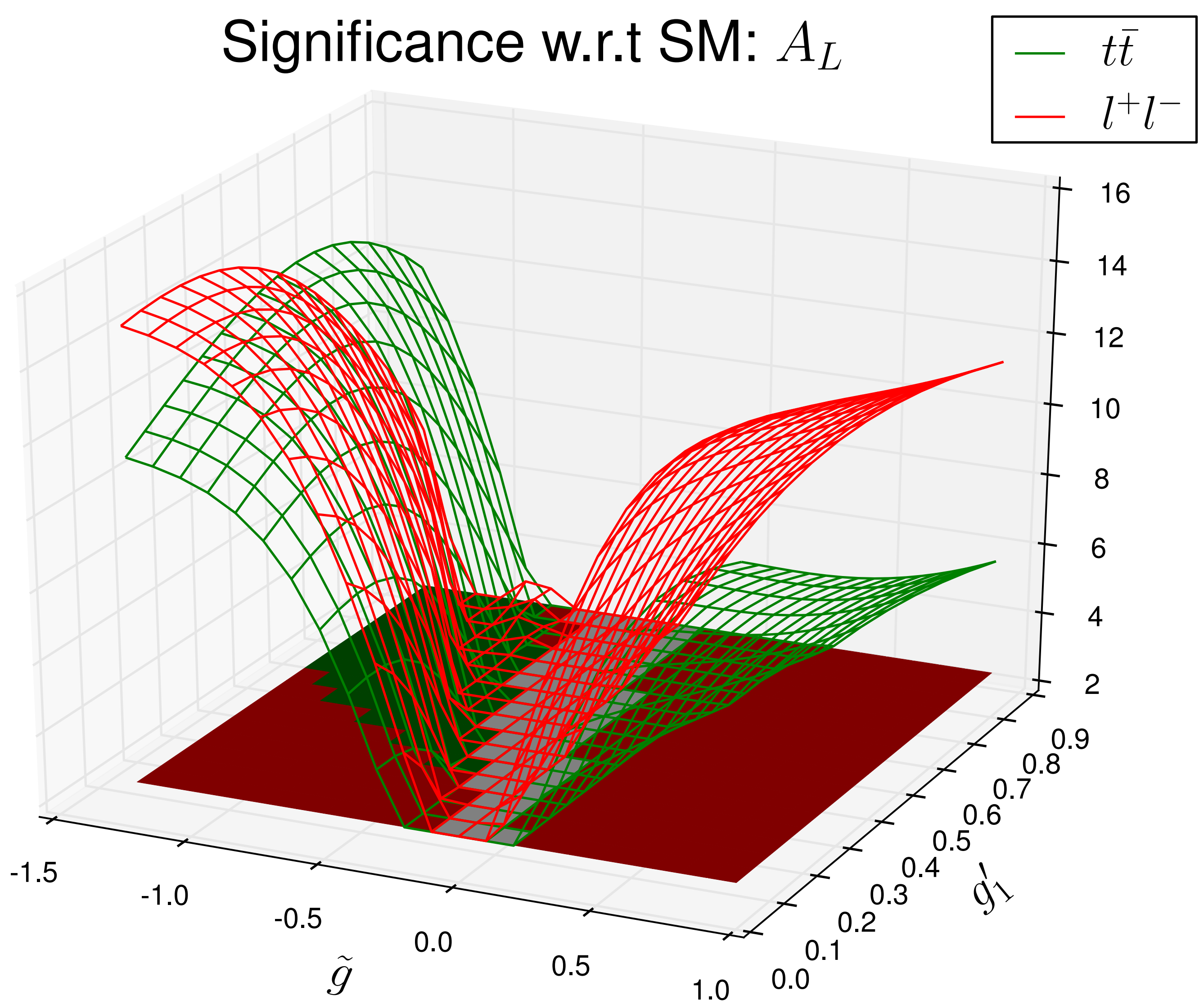
- Developed a tool based on HELAS/MADGRAPH that can output observables in f^+f^- final state for a generic NP process at the LHC @ 14 TeV, 100 fb^{-1}
  - CTEQ6 PDFs with $Q=M_{Z'}$
  - M_t=175 GeV, all other quarks massless
  - Folded in relevant reconstruction efficiencies
- Cuts to focus around the Z' peak: 2.5 TeV
  - $M(ff)<|M_{Z'}-100|$ GeV
  - $p_T(b)>300$ GeV to suppress SM backgrounds
- Included statistical error estimates and a definition of significance to distinguish predictions

$$\delta A \equiv \delta\left(\frac{N_F - N_B}{N_F + N_B}\right) = \sqrt{\frac{2}{\mathcal{L}\varepsilon}\left(\frac{\sigma_F^2 + \sigma_B^2}{\sigma_{Total}^3}\right)} \qquad s \equiv \frac{|A(1) - A(2)|}{\sqrt{\delta A(1)^2 + \delta A(2)^2}}$$

Significance

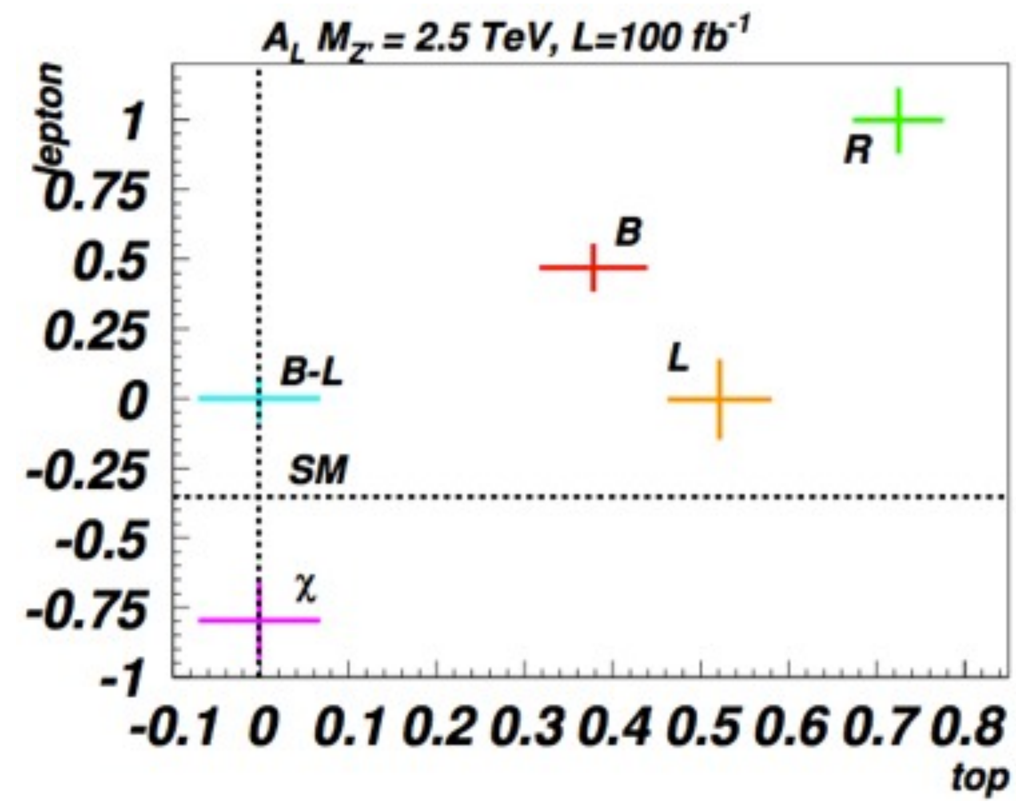
- Computed significance w.r.t SM of observables
  - Leptons almost always provide best visibility
  - Tops/b's provide coverage in areas where leptons are weak
  - Almost whole parameter space is covered





Distinguishing Z's

- Spin polarisation between benchmark models
  - Distinguishable: complementarity of final states
  - Significance table



A_L 50 \ dec	$\not{B}$ τ	t	b	R τ	t	b	$\not{L}$ τ	t	b	$B-L$ τ	t	b	χ τ	t	b
$\not{B}$		–		3.6	4.3	5.6	2.8	1.7	5.3	4.0	4.1	0	7.9	4.1	3.2
R	3.6	3.7	5.2		–		5.4	2.6	0.4	7.0	8.4	5.9	10.0	8.4	1.6
$\not{L}$	2.8	0.7	4.6	5.4	2.9	0.6		–		0	5.7	5.5	4.0	5.7	1.3
$B-L$	4.0	4.0	0	7.0	7.6	5.3	0	4.5	4.6		–		5.0	0	3.3
χ	7.9	3.9	2.9	10.0	7.5	2.4	4.0	4.5	1.8	5.0	0	3.0		–	

Extracting Z' couplings

- Ultimate goal would be to use a set of independent observables to extract the couplings of an observed resonance
  - Asymmetries and multiple final states could certainly benefit such an effort
- This has been investigated in the light lepton case
  [F. Petriello and S. Quackenbush, Phys. Rev. D 77 (2008) 115004]
- Construct 4 independent on-peak observables from di-lepton events using:
  - Total cross section
  - Forward backward asymmetry in two rapidity ranges
  - Rapidity ratio
- Fit 4 coefficients which are functions of the Z' couplings

Extracting Z' couplings

- Observables: $F(y) = \int_0^1 d\cos\theta \frac{d^2\sigma}{dy\,d\cos\theta}$ $B(y) = \int_{-1}^0 d\cos\theta \frac{d^2\sigma}{dy\,d\cos\theta}$

$$A_{FB}^{y_1} = \frac{[\int_{y_1}^{y_{max}} - \int_{-y_{max}}^{-y_1}][F(y) - B(y)]dy}{[\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{-y_1}][F(y) + B(y)]dy} \quad R_{y_1} = \frac{\int_{-y_1}^{y_1}[F(y) + B(y)]dy}{[\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{-y_1}][F(y) + B(y)]dy}$$

- Differential cross section (a's are PDF/PS factors):

$$\frac{d^2\sigma}{dy\,d\cos\theta} = \sum_{q=u,d}[a_1^{q'}(q_R^2 + q_L^2)(e_R^2 + e_L^2) + a_2^{q'}(q_R^2 - q_L^2)(e_R^2 - e_L^2)]$$

- Parametrise coupling combinations
  - parity symmetric: $c_q = \frac{M_{Z'}}{24\pi\Gamma}(q_R^2 + q_L^2)(e_R^2 + e_L^2)$
  - parity violating: $e_q = \frac{M_{Z'}}{24\pi\Gamma}(q_R^2 - q_L^2)(e_R^2 - e_L^2)$

$$\frac{d^2\sigma}{dy\,d\cos\theta} = \sum_{q=u,d}[a_1^q c_q + a_2^q e_q]$$

Extracting Z' couplings

- The fit:

$$\begin{aligned} F_< &= \int_{-y_1}^{y_1} dy F(y) \\ B_< &= \int_{-y_1}^{y_1} dy B(y) \\ B_> &= (\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1}) dy B(y) \\ F_> &= (\int_{y_1}^{y_{max}} + \int_{-y_{max}}^{y_1}) dy F(y) \end{aligned} \quad \rightarrow \quad \begin{pmatrix} c^u \\ c^d \\ e^u \\ e^d \end{pmatrix}$$

- However, even in most minimal assumption, there are 5 independent Z' couplings vs 4 fit parameters
  - Q_L, L_L, u_R,d_R,e_R (ν_R)
- A degeneracy exists between the leptonic and quark couplings in this parametrisation since they both appear in each coefficient
  - Can we use spin asymmetries or multiple final states to break this and fit all couplings?

Extracting Z' couplings

- Spin polarisation has a unique dependence on the fermionic couplings of the Z'
  - Give it a coefficient and incorporate tau polarisation
  - Can extract them in exactly the same way as in the previous study

$$f_{q=u,d} \propto (q_R^2 + q_L^2)(e_R^2 - e_L^2)$$

- Extra information?
  - Same degeneracy exists
  - f coefficients are in fact not linearly independent of c and e in the minimal assumption when $u_L=d_L$

$$f_{q=u,d} \propto c_q \frac{e_u - e_d}{c_u - c_d} \qquad \frac{f_u}{c_u} = \frac{f_d}{c_d} \equiv \frac{e_R^2 - e_L^2}{e_R^2 + e_L^2}$$

- Still useful!
  - Test of coupling universality
  - Extra constraints on the parameter fit, reduce systematics

Extracting Z' couplings

- Alternative final states such as $t\bar{t}$ polarisation asymmetry do not suffer from the same degeneracy
  - Fitting the corresponding coefficients would allow for the extraction of the chiral couplings of the Z' (up to a sign)
- Relaxing assumptions on couplings increases the number of parameters but can also bring tau polarisation back into play
  - eg $u_L \neq d_L$ by not requiring SM gauge multiplets to have the same U(1) charge (as can arise when the neutral gauge boson arises from the diagonal component of a more general group extension)
- Moving away from universality, one requires as many observables as possible, advocating all useful asymmetries in all measurable final states

Multiple Z's

- Special coupling dependence of asymmetries allows one to gain extra information on resonances not present in invariant mass distributions
  - Use them to disentangle multiple resonances with similar masses
- Considered a model of extra dimensions where neutral KK EW gauge bosons preferentially couple to quarks
- Absence of such resonances in high resolution di-lepton channel means that even a quasi-degeneracy in mass could mask the presence of multiple states

[E. Accomando, KM, S. Moretti arXiv:1304.4494]

The AADD model

- ‘Extension’ of the ADD model of large extra dimensions where a selection of the SM gauge/matter content is allowed to propagate in the bulk
  - Various combinations exists depending on which gauge group feels the extra dimension ($SU(3)_C$, $SU(2)_L$, $U(1)_Y$)
  - Delocalisation of fermions requires orbifold compactification to obtain chiral states
- Focus on (t, l, l) realisation where t and l denote ‘transverse’ and ‘longitudinal’ - referring to the orientation of the relevant gauge group w.r.t the extra dimension
  - Colour sector is localised (including quarks)
  - Electroweak sector travels in the bulk (including leptons)

[E. Accomando, I. Antoniadis, K. Benakli; Nucl. Phys. B579, 2000]

The AADD model

- Kaluza Klein tower of electroweak gauge bosons
  - Loop suppressed couplings to SM leptons due to KK parity conservation in the bulk EW sector: no di-lepton searches and weaker EWPT constraints
  - Enhanced couplings to quarks from KK decomposition structure
- Assume EWSB symmetry breaking occurs in the bulk but that these contributions (~gv) are small compared to the (~TeV) compactification scale R^{-1}
  - Expect a quasi-degenerate spectrum (M~n/R) up to radiative corrections
- Take a version of this model consistent with recent experimental bounds as an example of quasi-degenerate resonances in which $t\bar{t}$ asymmetries may help to resolve this degeneracy

Radiative corrections

- KK resonances in models of extra dimensions in which SM gauge/matter content propagates in the bulk are subject to a new set of radiative corrections
  [H.-C. Cheng, K. Matchev, M. Schmaltz; Phys. Rev. D66, 2002]

- Arise from the violation of Poincaré symmetry in 5D due to compactification
  - Circle compactification violates 5D Lorentz invariance at large distances (>R), accommodating loop diagrams with non-zero winding number around the extra dimension - 'bulk' corrections
  - Orbifold compactification introduces a new set of corrections associated to the fixed points - 'orbifold' corrections
  - Localised fermion sector will also contribute

- Tree level assumption that the spectrum is degenerate per KK-level is not necessarily a good one
  - Also consequences for subsequent mass mixing of neutral sector

Mixing & couplings

- Typically people postulate the presence of KK ‘photon’ and ‘Z’ with enhanced SM-like couplings
  - True at tree level where the mass mixing is driven by the small EW terms and KK mass contributions are degenerate
  - Radiative splitting for the two gauge bosons, W_3 and B, will be related to the compactification scale and dominate over EWSB contributions
  - Mixing driven back to the pure T_3 and Y gauge states

$$\text{Tree level:} \quad \begin{pmatrix} M_{KK}^2 & g^2 v^2 \\ g'^2 v^2 & M_{KK}^2 \end{pmatrix} \Rightarrow \theta_{mix} = \theta_W$$

$$\text{Corrections:} \quad \begin{pmatrix} M_{KK}^2 + \delta M_{W_3}^2 & g^2 v^2 \\ g'^2 v^2 & M_{KK}^2 + \delta M_B^2 \end{pmatrix} \Rightarrow \theta_{mix} \to 0$$

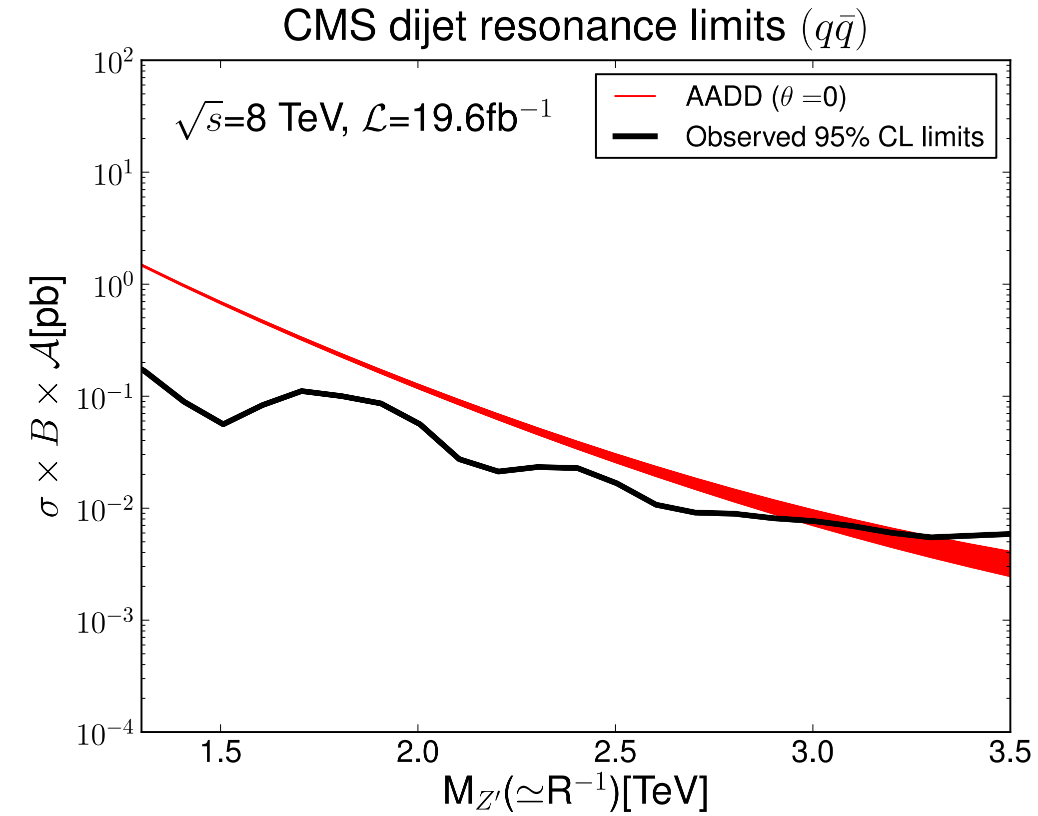
- Modified results from the paper considering the UED model and added the contribution from localised quarks
  - UED predict (~6%) splitting, localised fermions reduce this slightly
  - Seems small but significant as this is already greater than EWSB masses

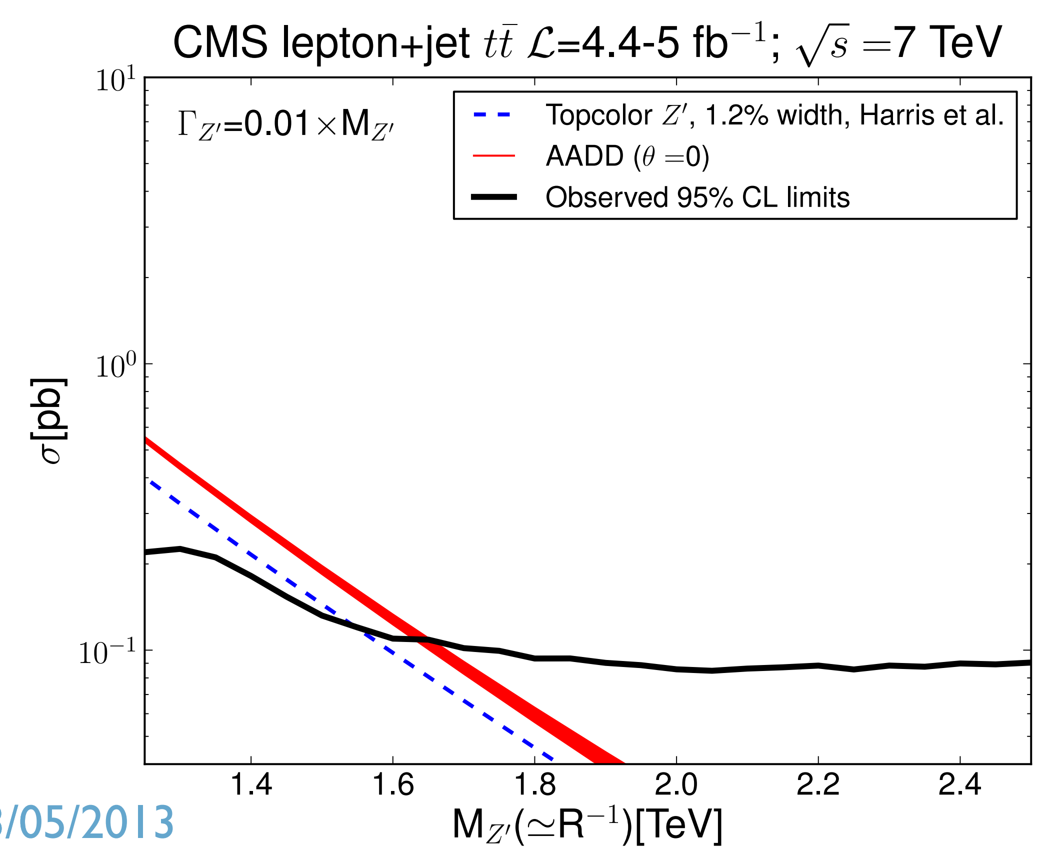
Mixing & couplings

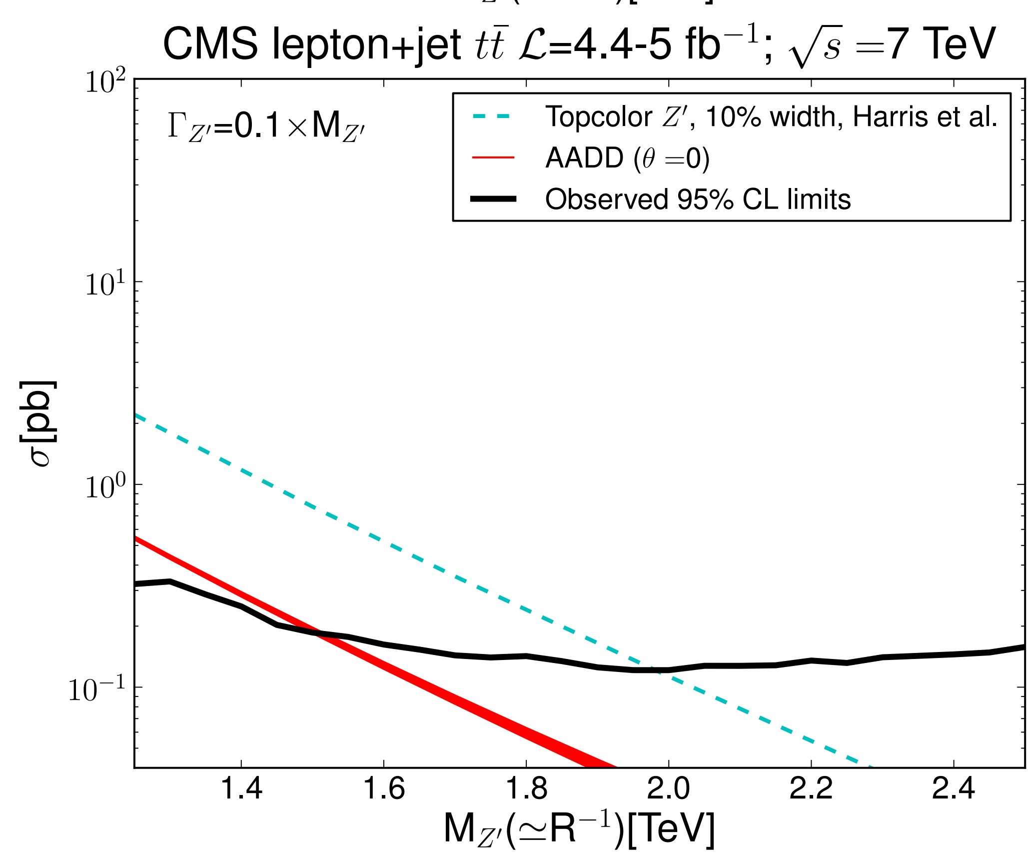
- Mass splitting and subsequent mixing angle correction
  - Asymmetries could be useful when quasi-degeneracy persists, splitting is within mass resolution of discovery channel
  - Cross section observables may not be able to resolve peaks
  - Our rough LHC limits indicate this could be the case
- We take the fully degenerate limit as a 'worst case scenario' and examine asymmetry observables
  - In this limit, mass mixing angle should not be a physical parameter
  - Importance of including off-diagonal width effects
- LHC constraints on R^{-1} are discussed in this limit
  - Enhanced quark couplings means di-jet ($t\bar{t}$) resonance searches will be sensitive
  - Degenerate, single peak corresponds better to the assumed signal shape in 'bump hunts' and makes published data easier to use while still providing an instructive scale up to which the model is likely excluded

LHC limits on R^{-1}

- LHC limits on resonance mass from di-jet and boosted top searches
- Different widths assumed in $t\bar{t}$
- R^{-1} > 3 TeV from di-jet
- Mass splitting at this scale is ~150 GeV
- Comparable to the resolution of either channel

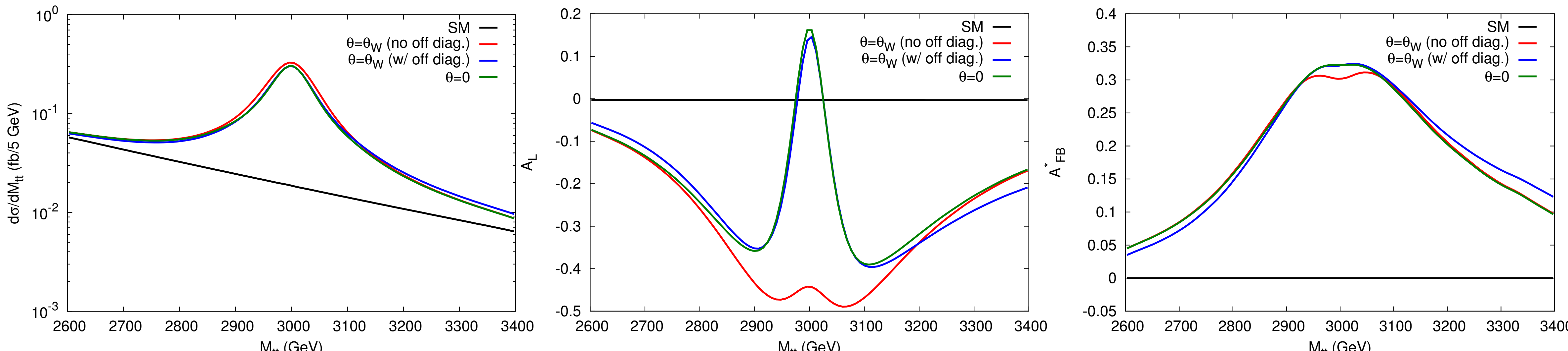






Off diagonal widths

- When two resonances have common production/decay channels, off diagonal widths can become important *[G. Cacciapaglia, A. Deandrea, S. De Curtis; Phys. Lett. B682, 2009]*
  - Off diagonal contributions are similar in size to actual widths and mass splitting
  - Treat the two particle system simultaneously with a matrix propagator
- In the degenerate case of AADD, these are important
  - Without them, the mixing angle appears to be a physical parameter
  - Confirm that the θ=0 scenario is indeed the correct one with pure, unbroken gauge states and negligible off diagonal widths



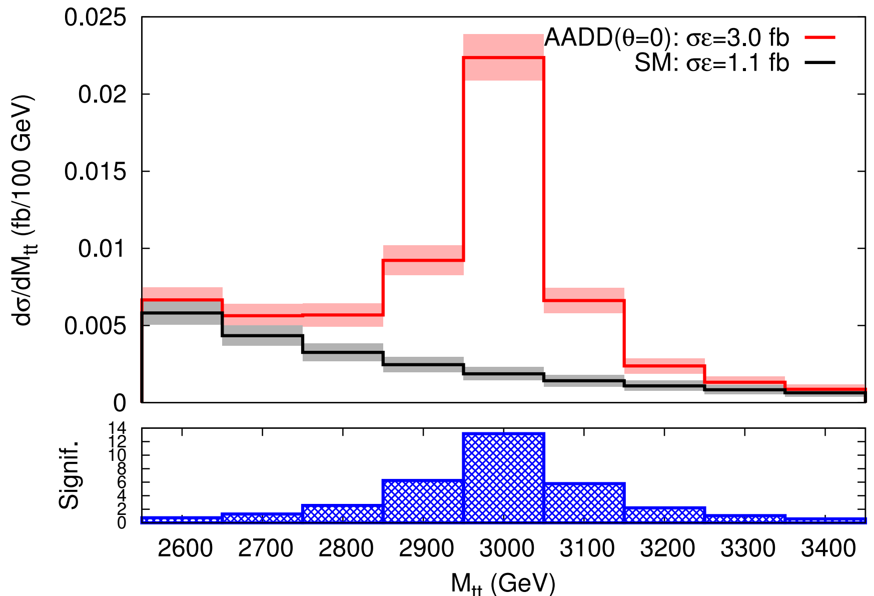
LHC observables

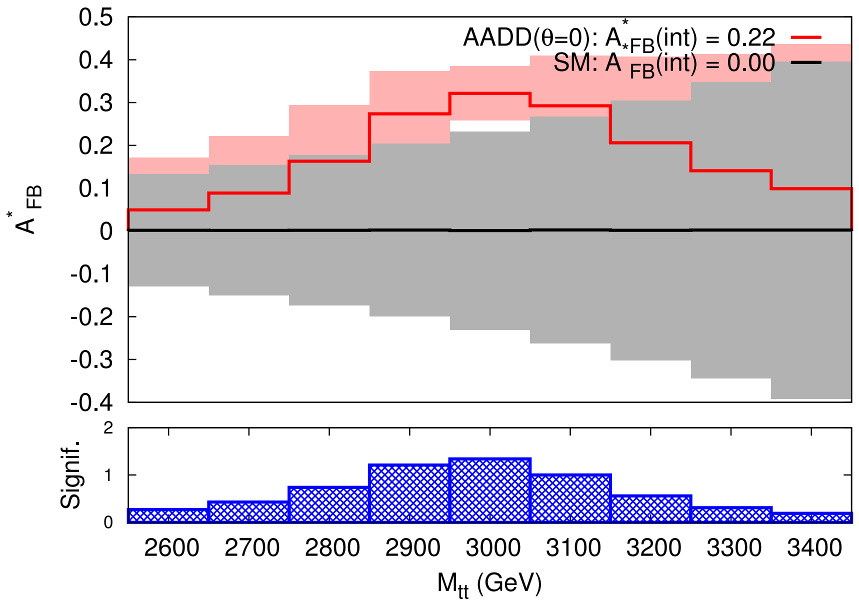
- Compute on-peak observables binned in invariant mass compared to the SM prediction folding in estimated reconstruction efficiencies
  - 10% for cross section and A^{*}_{FB}, 5% for A_L
- Statistical uncertainties and binned significance measure for the 14 TeV LHC run and 100 fb^{-1}
  - Assume a resolution of 100 GeV
  - May be difficult for measuring spin polarisation in particular due to boosted topology
  - Move towards integrated quantities not as reliant on reconstructing full $t\bar{t}$ system
- Compared split and unsplit spectrum
  - Split spectrum still does not allow the resolution of two peaks
  - Actually does better in spin polarisation due to the two resonances not competing with one another at the same mass point

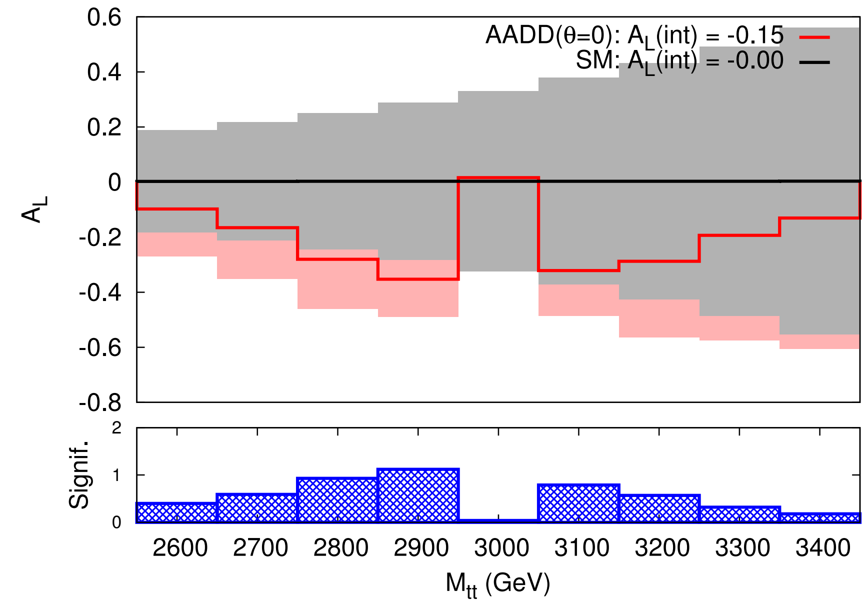
LHC observables

$d\sigma/dM_{t\bar{t}}$ A^*_{FB} A_L

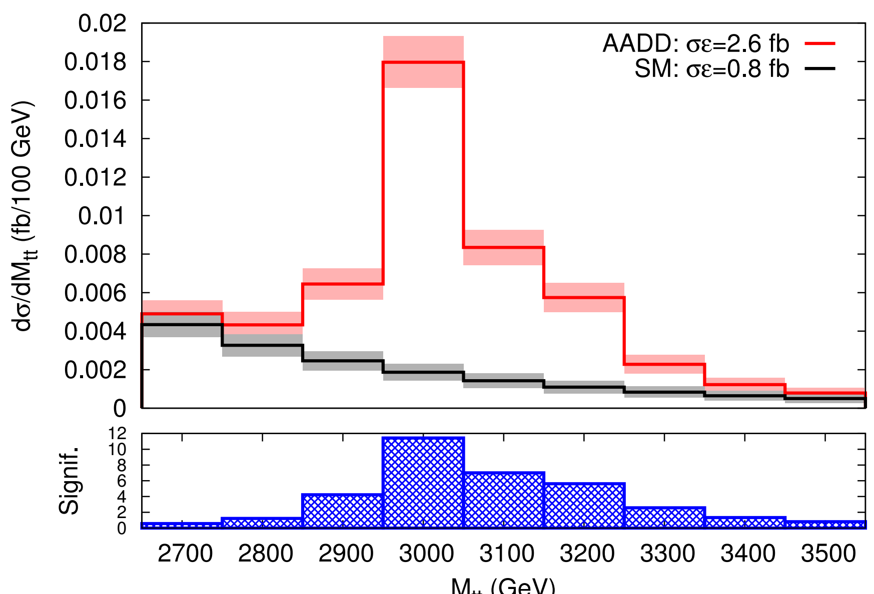
Unsplit:

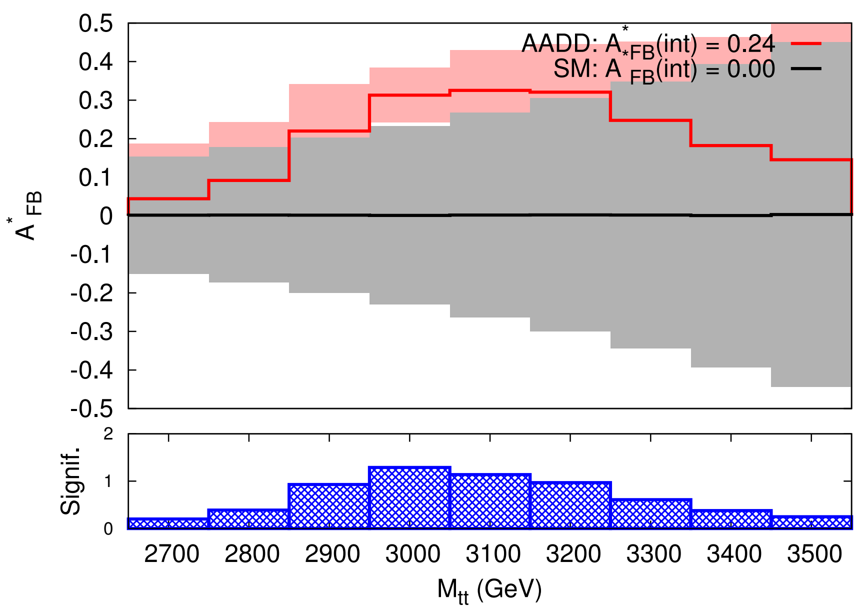


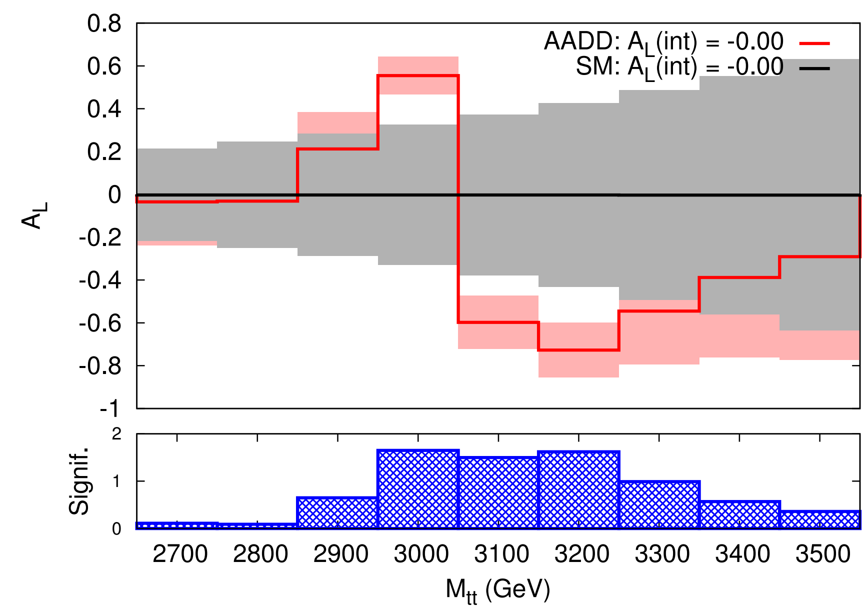




Split:

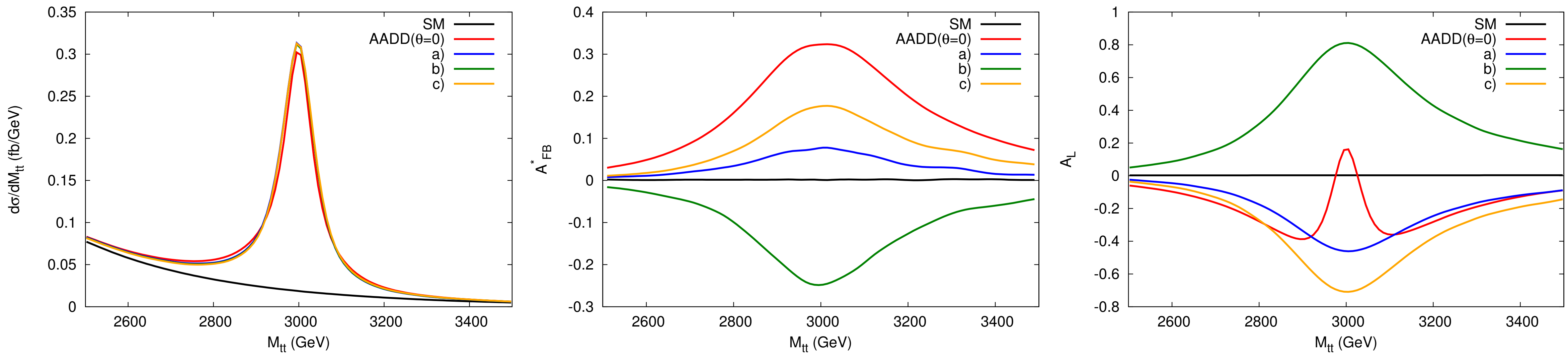






One vs two resonances

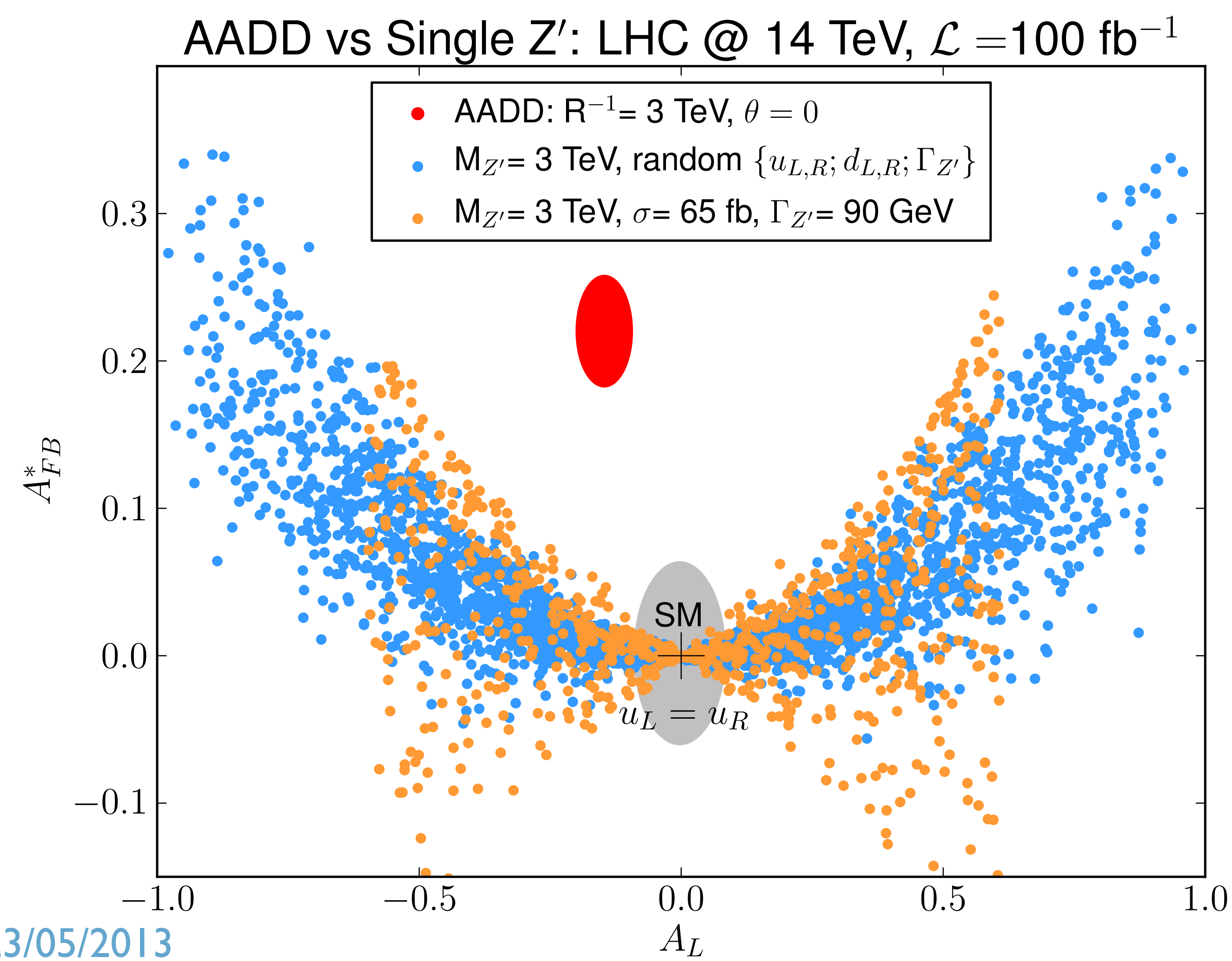
- Presence of two peaks can lead to cancellation effects in asymmetries which do not happen in the differential cross section
  - By comparing predictions of A^{*}_{FB} and A_L, it may be possible to determine the presence of multiple resonances hiding under one peak
  - Performed scan over 'toy' models with a single, generation universal Z'
  - Chiral couplings to up and down type quarks were varied freely within the limits of producing an identical differential cross section to the unmixed AADD model



3 randomly selected toy benchmarks compared to AADD

One vs two resonances

- Orange: single Z' points tuned to match the differential cross section
- Blue: random scan over any pair of chiral up and down quark couplings within {0,1} and any width up to 300 GeV (10%)
- Red: degenerate unmixed AADD (θ=0) with statistical uncertainties and reconstruction efficiency estimates
- Observables integrated over a 500 GeV either side of the resonance mass



$$\mathcal{A}_{ch} \sim \left((C^i_L)^2 - (C^i_R)^2\right)\left((C^f_L)^2 - (C^f_R)^2\right)$$

$$\mathcal{A}_{pol} \sim \left((C^i_L)^2 + (C^i_R)^2\right)\left((C^f_L)^2 - (C^f_R)^2\right)$$

- Even for random couplings and widths, the allowed values for these observables are constrained by the correlation between them
- Multiple resonances can move out of this area and observing values of A^*_{FB} and A_L outside of these would be a smoking gun for multiple quasi degenerate resonances

Conclusion

- Overview of a phenomenological study of spin and spatial asymmetries of multiple final states in a continuous parametrisation of a minimal Z' model
- Examined ability to distinguish these models from the SM and among themselves
- Showed that several final states can complement one another in probing the majority of the parameter space and distinguishing benchmark points with 14 TeV LHC data and 100 fb^{-1}
- Discussed a strategy of fitting Z' couplings and how spin polarisation and multiple final states could be essential in improving such an analysis
- Certainly $t\bar{t}$ observables can contribute in this area of searches traditionally dominated by di-leptons

Conclusion

- Took a model of extra dimensions as an example of quasi degenerate resonances in which $t\bar{t}$ asymmetries could help to resolve said degeneracy
- Radiative mass corrections have an important role in such model
- Demonstrated the potential importance of off diagonal width effects in the degenerate regime
- Showed that, multiple degenerate states lead to predictions for charge and spin asymmetries in $t\bar{t}$ that cannot be replicated by a single resonance
- Applicable to other models (e.g. composite Higgs) of multiple resonances near in mass

Thank you

Reconstructing tops

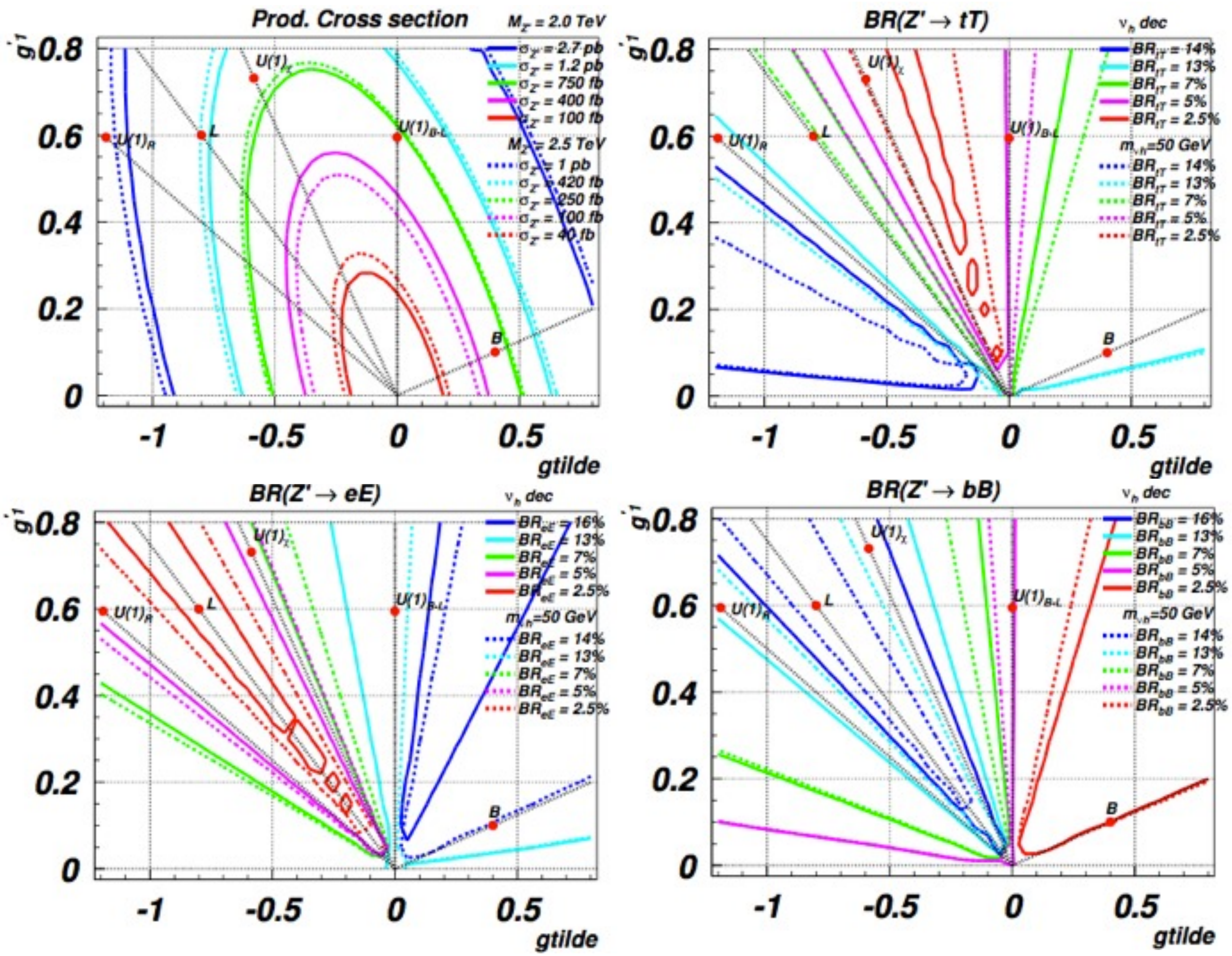
- Presence of 2 b's: 'b tagging'
  - Lifetime, secondary vertex information, semi-leptonic decay of B hadrons → Multivariate techniques
  - Distinguish from light flavour jets (particularly c)
  - Efficiencies decrease with jet energy
- W decay products
  - 2(4) jets
  - 1(2) leptons + MET
- Large uncertainties
  - Jet energy scale
  - Monte Carlo
  - Underlying event
  - Increasing 'pileup'

Systematic uncertainty	Δm_{top} [GeV]
Jet energy scale factor	0.43
Method calibration	0.07
Signal MC generator	0.33
Hadronisation	0.15
Pileup	< 0.05
Underlying event	0.59
Colour reconnection	0.55
ISR and FSR (signal only)	1.01
Proton PDF	0.10
W+jets normalisation	0.37
W+jets shape	0.12
QCD multijet normalisation	0.20
QCD multijet shape	0.27
Jet energy scale	0.66
b-jet energy scale	1.58
b-tagging efficiency	0.29
Jet energy resolution	0.07
Jet reconstruction efficiency	< 0.05
Missing transverse momentum	0.13
Total	**2.31**

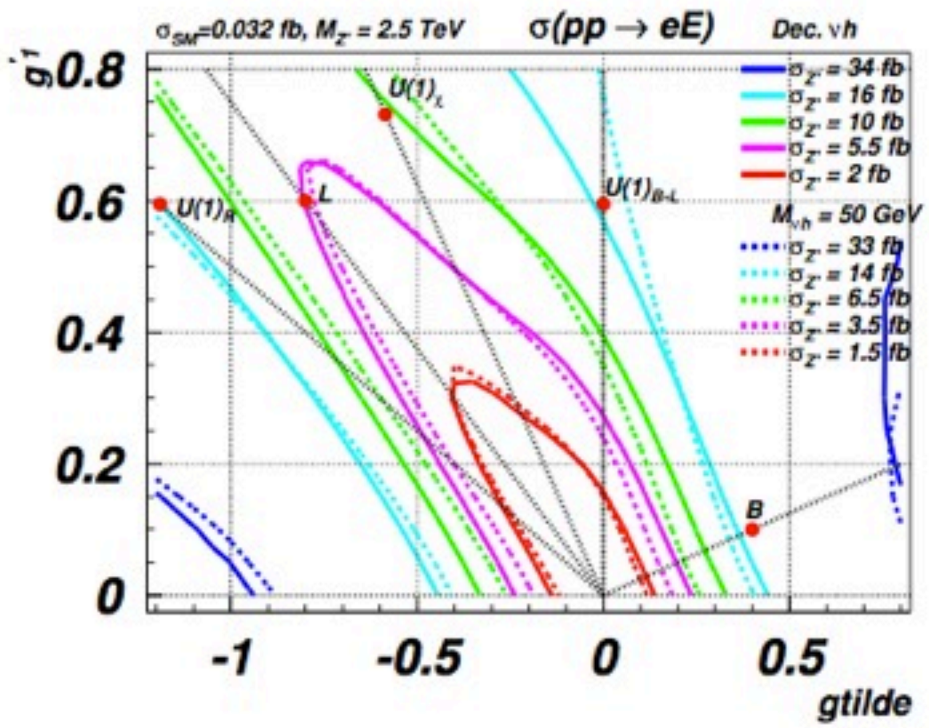
ATLAS M_t uncertainties (lepton + jet)
ATLAS-TOPQ-2011-15
Eur.Phys.J. C72 (2012) 2046

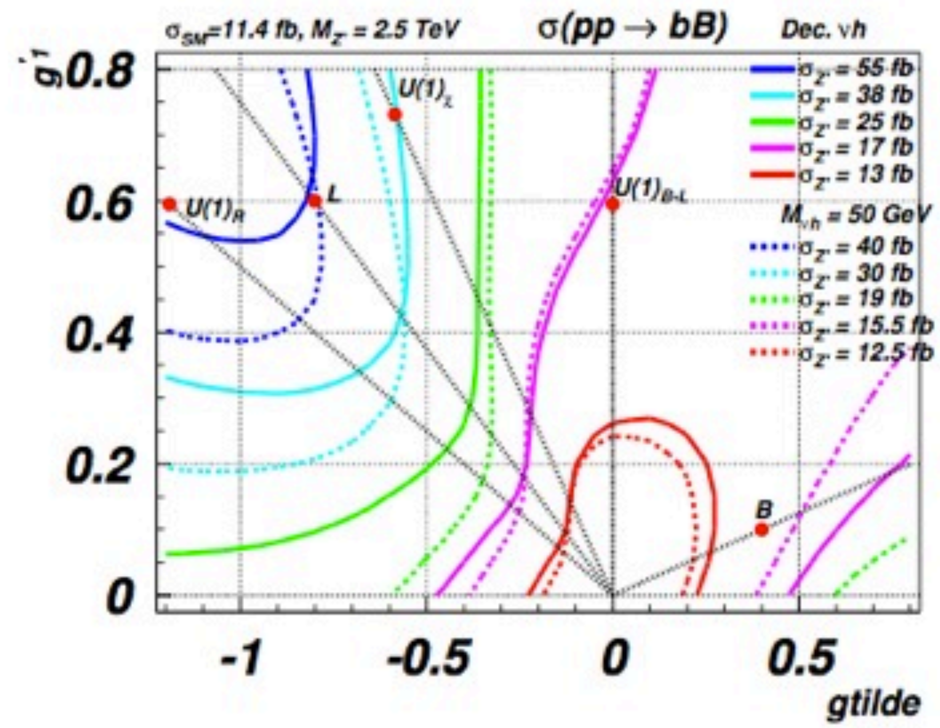
Cross-section and BRs

- Production cross section and branching ratios to $t\bar{t}$, ll and $b\bar{b}$



Event rates





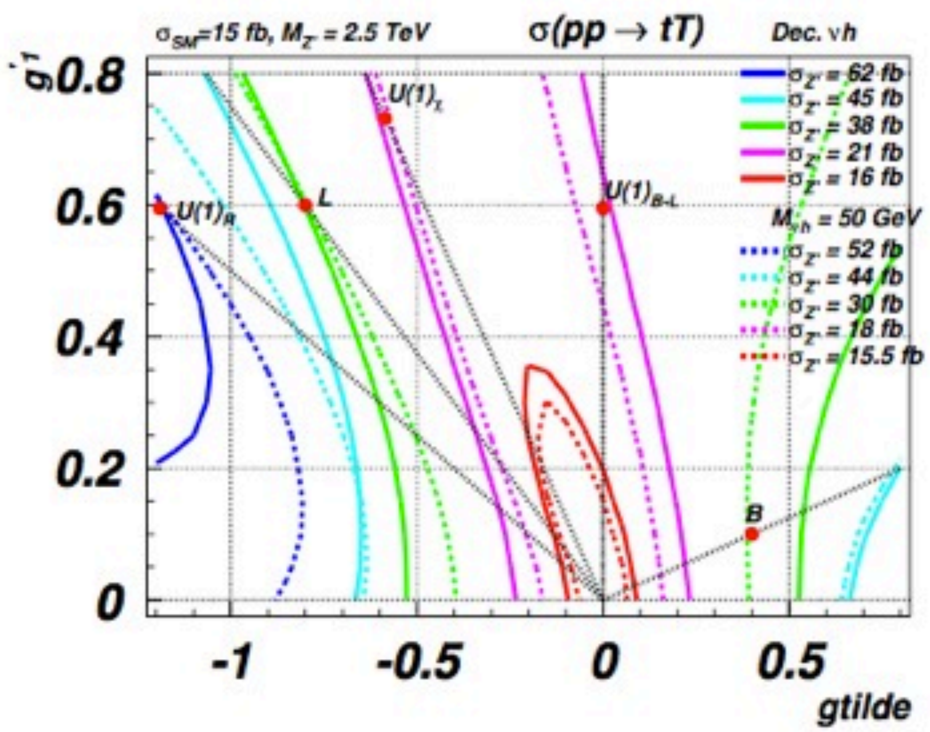
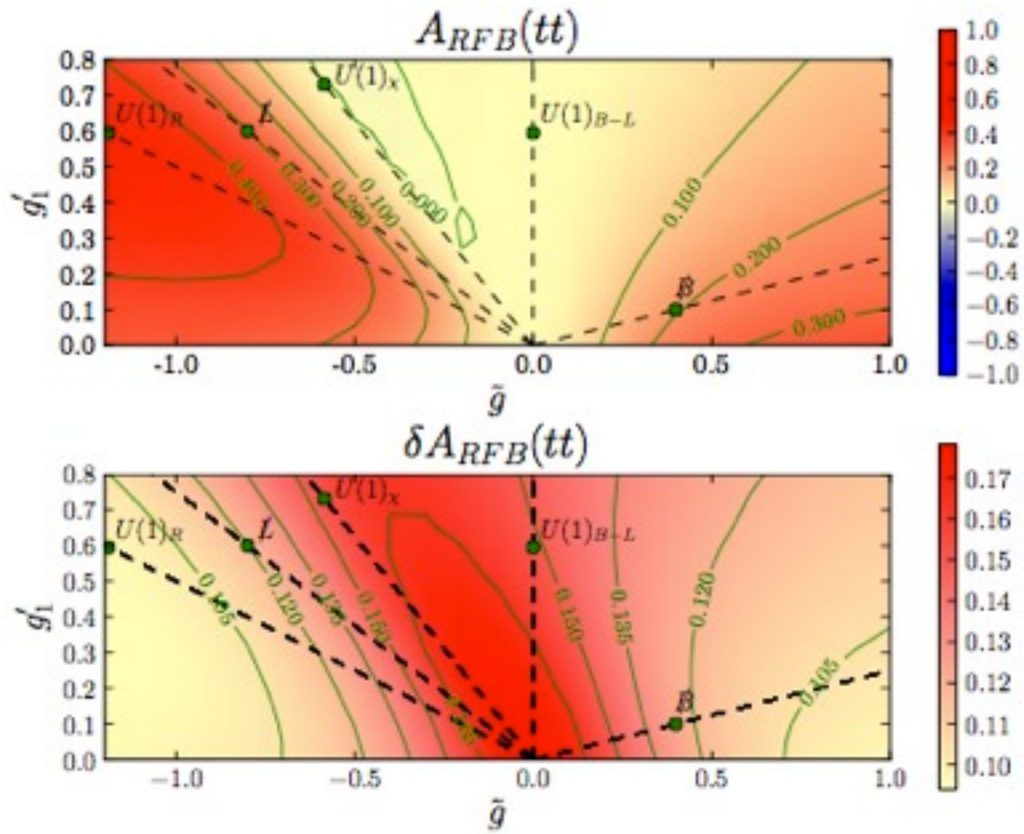
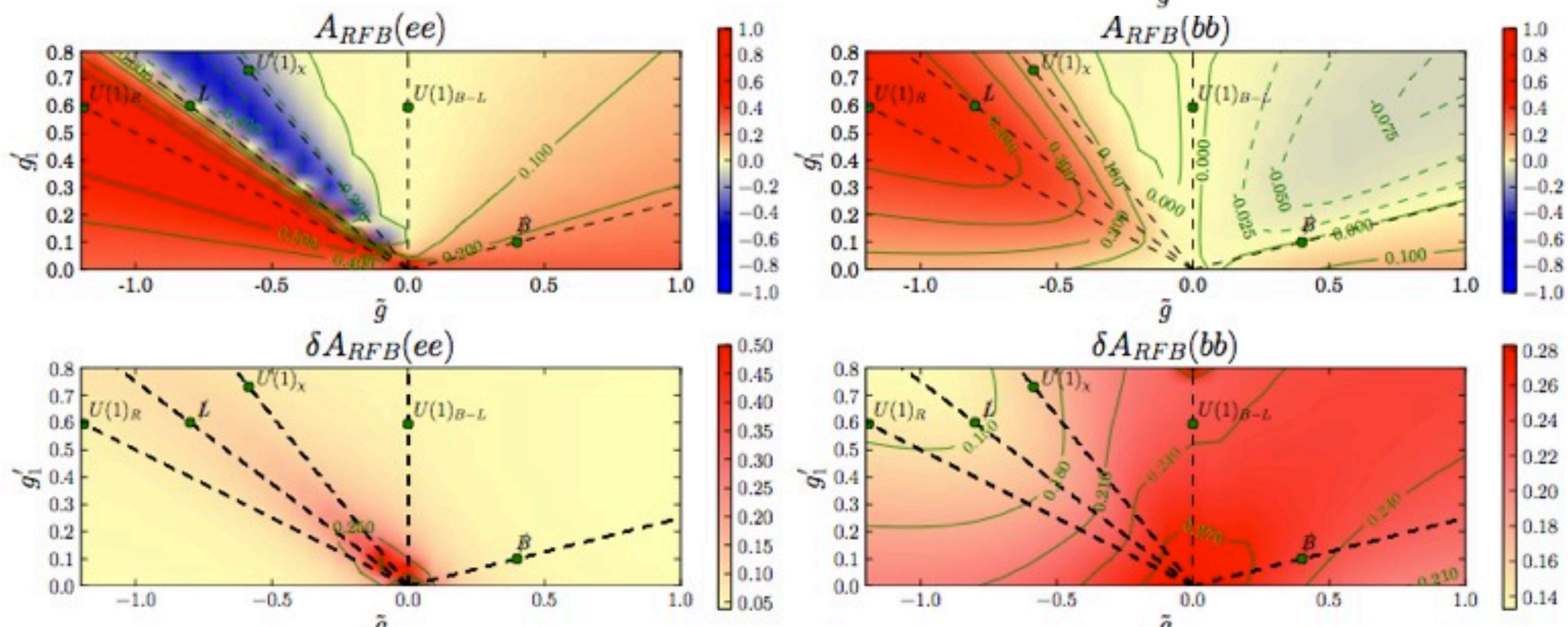


Figure 4: Total cross section in fb (signal plus background) on peak $|M_{f\bar{f}} - M_{Z'}| < 100$ GeV, for $M_{Z'} = 2.5$ TeV for $Z' \to e^+e^-$, $b\bar{b}$ and $t\bar{t}$, in the $(g'_1, \widetilde{g})$ plane, for decoupled neutrino (solid lines) and for $m_{\nu_h} = 50$ GeV (dashed lines). The benchmark models are highlighted as (red) dots on the (dotted) scenario lines.

Results: A_{RFB}

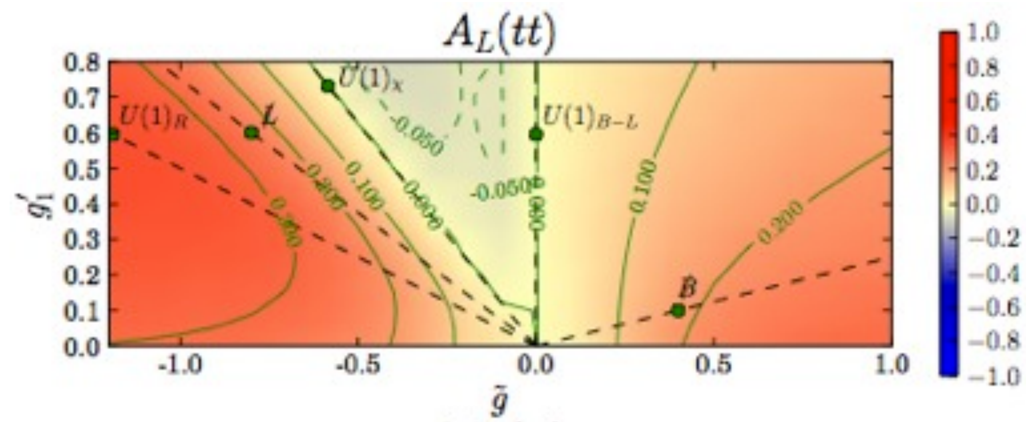
- Asymmetry vanishes along corresponding benchmark line (C_V or C_A=0)
- Stat. error scales inversely to the total cross section
- lepton measurement most powerful due to large positive SM value, smaller/negative Z' value
- Insensitive to relative sign in C_V,C_A

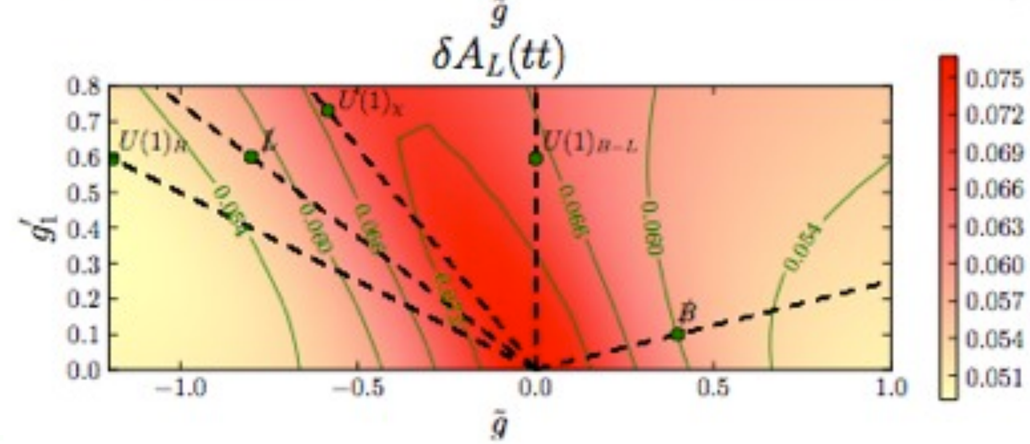


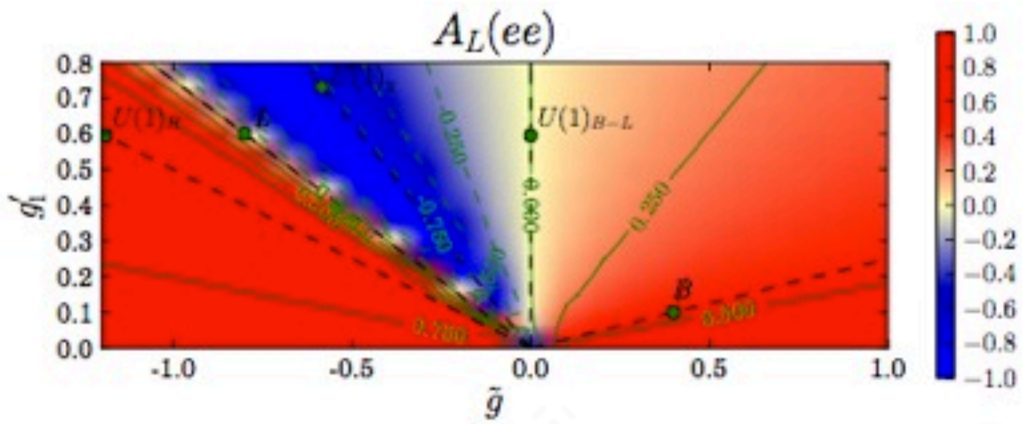


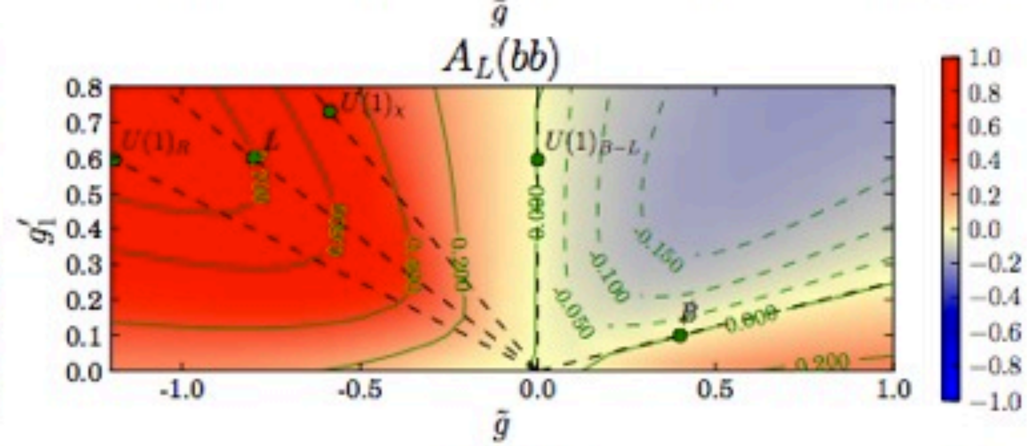
Results: A_L

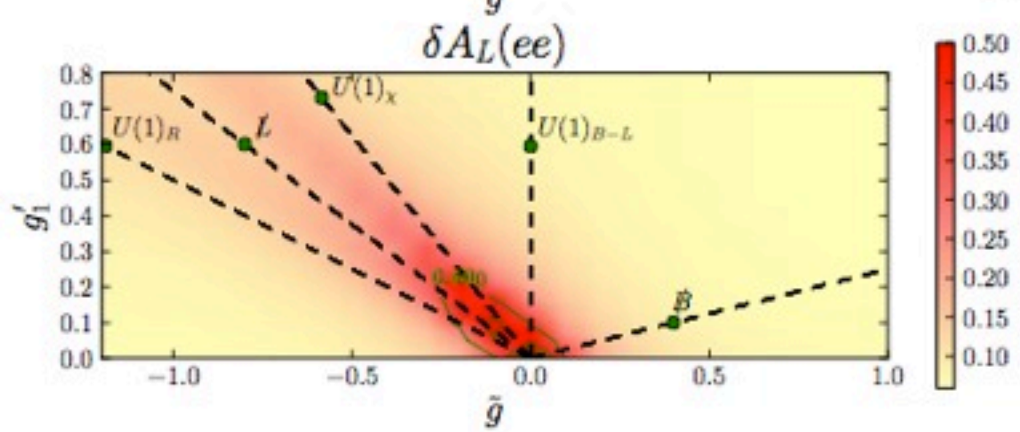
- Asymmetry changes sign corresponding to a change in relative sign of C_V,C_A or, equivalently, a crossover between sizes of C_L,C_R
- Leptonic measurement comes from taus and again is most powerful from large negative SM value (next slide)
- Uncertainties are smaller than for A_{RFB}

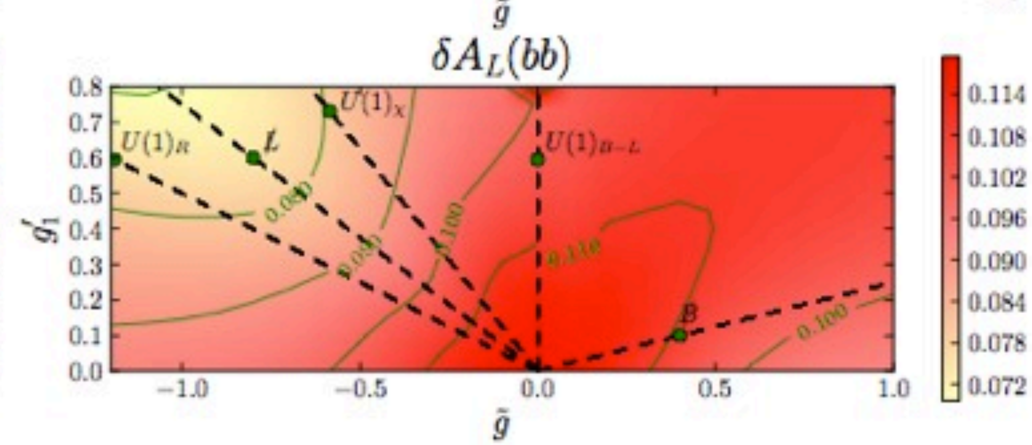












Distinguishing Z's

- Select pair of points in parameter space that tops and leptons cannot distinguish through spin polarisation
- Were the observable to become available in b final states, some of the degeneracy would be lifted
- Information from other observables such as differential cross sections, lineshapes may be complementary