Top polarisation at colliders

◇ Top polarisation: what physics can it probe

◇ Probes of the top polarisation and effects of anomalous coupling on them.

◇ Example of use of angular distribution as probe of top spin
 – For a $t\bar{t}$ resonance.
 – $t\bar{t}$ spin spin correlation in $t\bar{t}H$ and $t\bar{t}jj$ production.

- Polarisation measures using energies of decay products

Based in part on

1)RG, Rindani and SinghJHEP 0612, 021 (2006),

2)D. Choudhury, R. G. , S.D. Rindani, R. Singh and K. Wagh, in hep-ph/0602198

3) RG, S.D. Rindani, Kumar Rao, Ritesh Singh.arXiv:1010.XXXX

4)D. Choudhury, RG, Pratishruti Saha (in preparation) arXiv: 10YY:XXXX

Top quarks at the LHC:

• Copious production of $t\bar{t}$ pairs at LHC **(SM c.s. $\approx$ 800 pb at** 14 **TeV)**

• Large single top production (seen at Tevatron)

• Important role in new physics signatures: Top quarks can also arise in the decays of new particles – resonances, new gauge bosons, Higgs bosons, squarks, gluinos . . .

• Template for issues in new physics : example of determination of spin and mass!

• Most important background to a lot of new physics. What features can be used effectively to de lineate SM from BSM tops!

• Polarisation can be one important handle.

• Top polarization can give more information about the production mechanism than just the cross section does.

• Top partners with the different spin (SUSY) or same spin UED/Little Higgs.. Shelton : PRD 79, Nojiri et al JHEP, Perelstein. Produce t in cascade decays of top partners and top polarisation can carry information on the model parameters.

Polarisation measurement can provide model parameter information, mdoel descrimination, kinematic features due to polarisation effects can be used efffectively to isolate signal from background in searches.

• Non zero polarisation requires parity violation, and hence measures left-right mixing. R-parity violating SUSY can give rise to nonzero top polarisation (Hikasa PRD, 1999).

• It can give a clue to CP violation through dipole couplings.

One example is $t\bar{t}$ resonance with Parity violating couplings. Look for illustration at an extra Z model.

Little Higgs model has an extra massive gauge boson Z_H with (left) right-handed couplings to fermions depending on one parameter (θ)

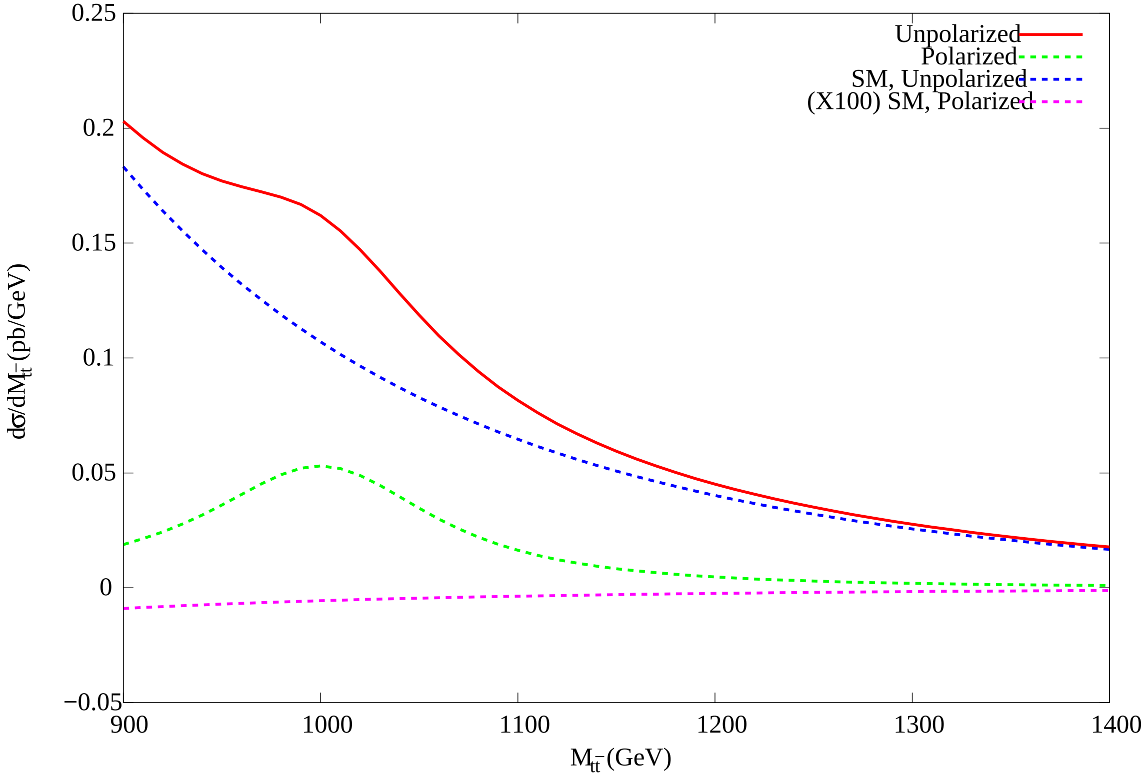
$$g_V^u = (-)g_A^u = g \cot\theta$$

$$g_V^d = (-)g_A^d = -g \cot\theta$$

$t\bar{t}$ production and decay via γ, Z, Z' depends only on two new parameters: $m_{Z'}$ **and** $\cot\theta$.

SM $t\bar{t}$ production through QCD.

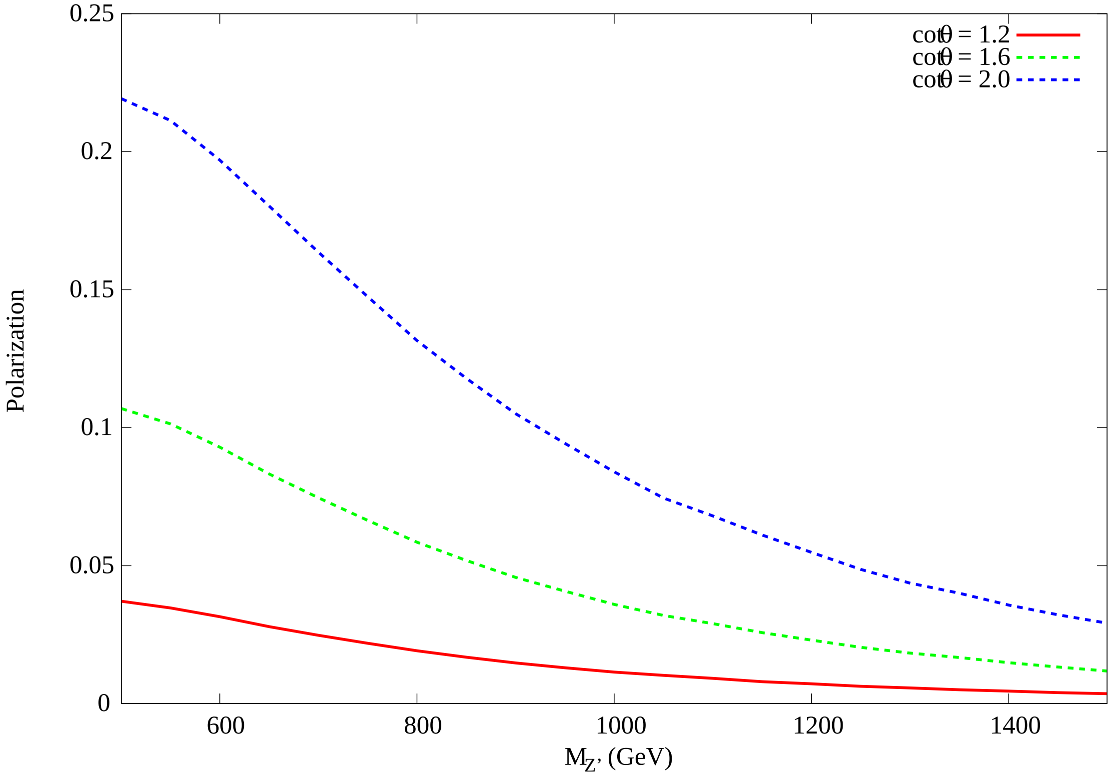
$m_{t\bar{t}}$ distribution for total (unpolarised) c.section and polarised ($d\sigma_R/dm_{t\bar{t}} - d\sigma_L/dm_{t\bar{t}}$) (only the new physics contribution).



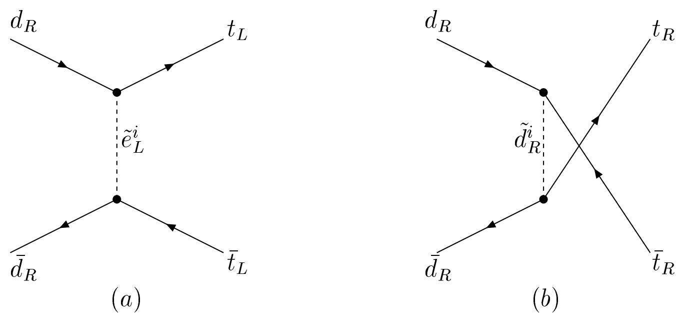
The model can be tested using the $t\bar{t}$ invariant mass distribution Polarization can be a further more sensitive test and also tool to get information on the couplings.

$$P_t \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

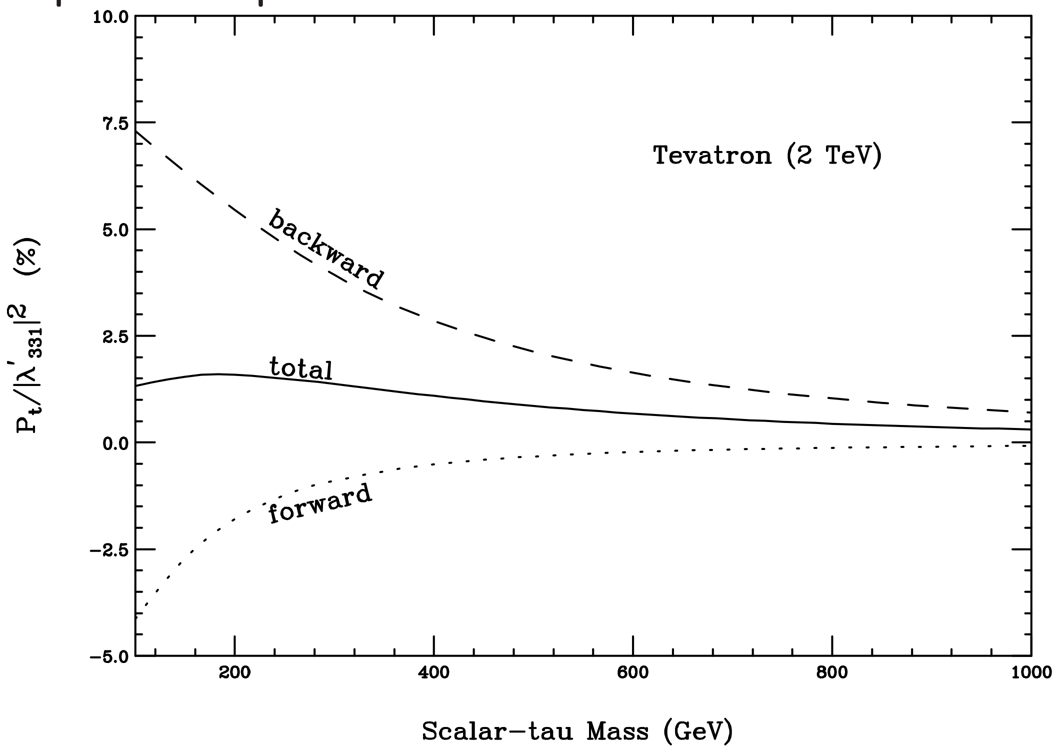
Can be enhanced using cuts on $m_{t\bar{t}}$



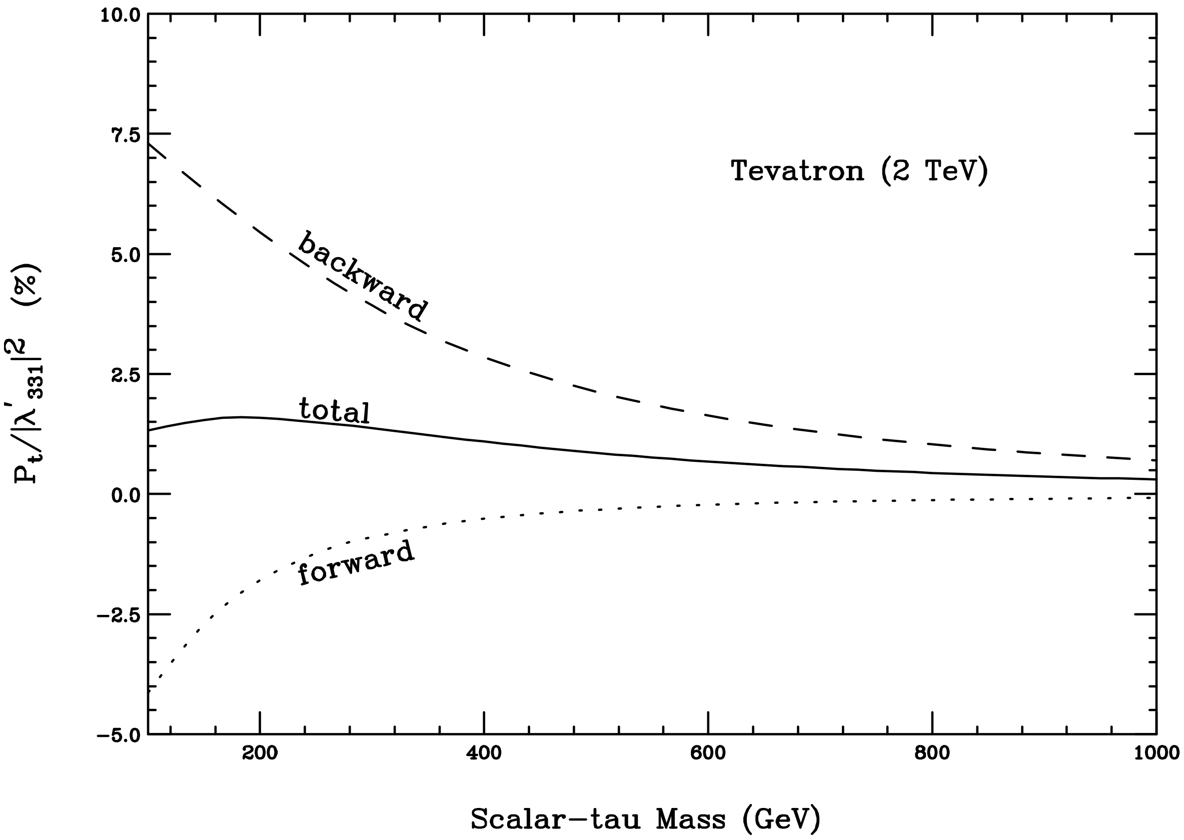
Hikasa PRD 60, 114041, 99



Expected polarisation at Tevatron:



Expected poalrisation at the Tevatron:



CDF and D0 reported FB asymmetry in $t\bar{t}$ production D0:PRL 100, 142002 (2008), CDF: PRL 101, 202001 (2008).

$A^t_{FB} = 0.193 \pm 0.0065 \pm 0.024$

CDF published result, newer value somewhat lower

SM expectation (NLO : Rodrigo/Kuehn) : 0.051

A host of new physics models:

Examples of some which explain most of the observed features 'satisfactorily'

1)t-channel colour triplet (sextet) scalar object: (generalisation of RPV case above, but **not necessarily chiral couplings**) J. Shu, T. M. P. Tait, K. Wang, PRL D81, 034012 (2010)

2) t-channel colour singlet vector exchange: S. Jung, H. Murayama, A. Pierce et al., PR D81, 015004 (2010) **Chiral couplings.**

3) s-channel strongly interacting vector exchange:

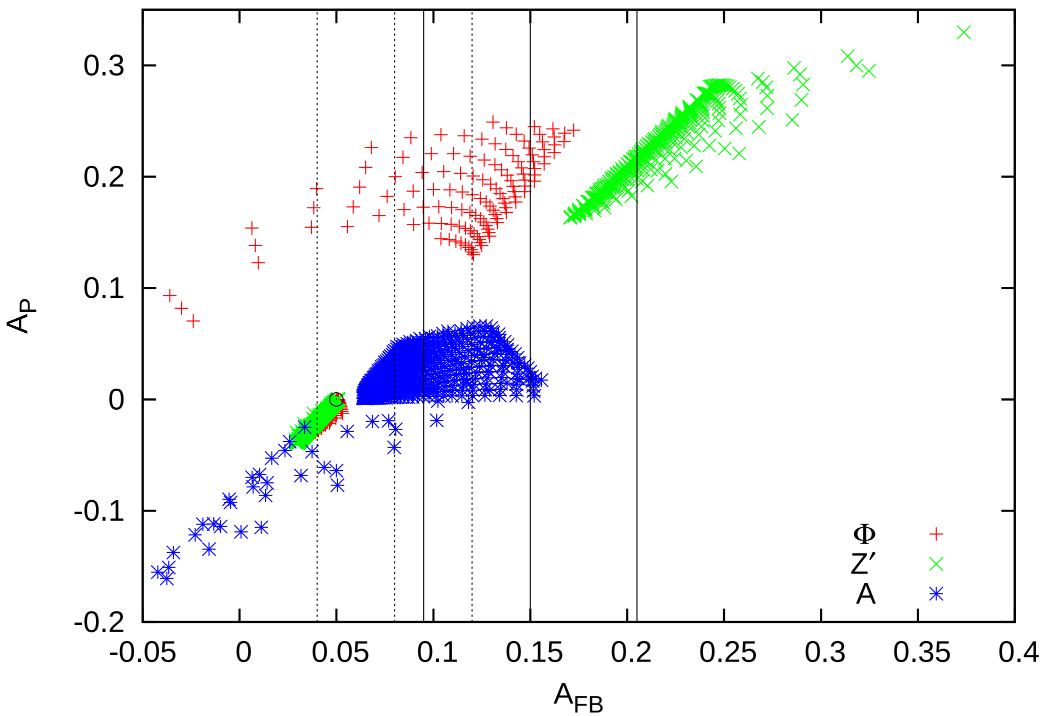
(axigluon: (pre)dicted :D. Choudhury, RG, Singh and Wagh, PLB 657 (2007) 69: alas wrong sign!)

Generalisation: flavour non-universal axigluon P. Frampton, J. Shu and K. Wang, PLB 683 (2010) 294. **Non-chiral couplings.**

The Forward backward top asymmetry origniates due to different reasons in different model explanations.

The chirality structure is also different.

Expected top polarisation can be different.



Φ : Tait et al colour triplet/sextet scalar

Z': Murayama, Wells t–channel vector

A: Flavour nonuniversal axigluons.

In all the three different models expected top polarisation quite different for different physics explanations.

Corrleation between top polarisation and FB asymmetry quite different.

Exploring Measurement of top polarisation a useful tool to get information on production mechanism.

When t and $\bar{t}$ are produced, a useful observable is top spin correlation:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_a d\cos\theta_b} = \frac{1}{4}(1 + B_1\cos\theta_a + B_2\cos\theta_b - C\cos\theta_a\cos\theta_b)$$

This has been very well studied theoretically (for example: $t\bar{t}H$, $t\bar{t}$ produced in RS Graviton decay etc.)

Needs reconstruction of both t and $\bar{t}$ rest frames.

It is conceivable that single top polarization can give better statistics.

Polarisation can be measured by studying the decay distribution of a decay fermion f in the rest frame of the top:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + P_t\kappa_f\cos\theta_f\right),$$

θ_f is the angle between the f momentum and the top momentum, P_t is the degree of top polarization, κ_f is the “analyzing power” of the final-state particle f.

κ_f depends on the weak isospin and the mass of decay product f.

The analyzing power k_f for various channels is given by:

$$\kappa_b = -\frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2} \simeq -0.4$$

$$\kappa_W = -\kappa_b \simeq 0.4$$

$$\kappa_{\ell+} = \kappa_d = 1; \qquad \kappa_u = \kappa_{\nu_l} = -0.31$$

- **The charged lepton or d quark has the best analysing power**

- d-quark jet cannot be distinguished from the u-quark jet.

- In the top rest frame the down quark is on average less energetic than the up quark. Thus the less energetic of the two light quark jets can be used. Net spin analyzing power is $\kappa_j \simeq 0.5$

Leading QCD corrections to κ_b and κ_j are of order a few per cent. QCD corrections decrease $|\kappa|$ [Brandenburg,Si,Uwer 2002]

κ also affected by corrections to the form of the tbW coupling ("anomalous couplings")

It is useful to have a way of measuring polarization independent of such corrections.

Also useful is distribution in lab. frame, rather than in top rest frame.

κ_f for ℓ^+ and down-quark is unchanged by anom. tbW vertex (RG, Rindani, Singh)

Angular distribution of the decay lepton l in the rest frame of the top is the most efficient polarisation observable.

Which of the kinematic observables of the decay lepton as measured in the lab frame carry this polarisation information faithfully?

What are the special issues here since LHC is a pp machine.

For highly boosted tops : what about rest frame reconstruction and angle measurements?

The angular distribution of charged leptons (down quarks) from top decay is not affected by anomalous tbW couplings (to linear order)

Rindani, Singh, Godbole

Checked earlier for $e^-e^+ \to t\bar{t}$ [Grzadkowski & Hioki, Rindani (2000)] and for $\gamma\gamma \to t\bar{t}$ [Grzadkowski & Hioki; Godbole, Rindani, Singh]

This is shown for any general process $A+B \to t+X$ in the c.m. frame [Godbole, Rindani, Singh (2006)]

Assumes narrow-width approximation for the top

This implies that charged-lepton angular distributions are more accurate probes of top polarization, rather than energy distributions or b or W angular distributions. How can these be best used?

Anomalous tbW couplings

General $\bar{t}bW$ vertex can be written as

$$\Gamma^\mu = \frac{g}{\sqrt{2}} \left[\gamma^\mu(f_{1L}P_L + f_{1R}P_R) - \frac{i\sigma^{\mu\nu}}{m_W}(p_t - p_b)_\nu (f_{2L}P_L + f_{2R}P_R)\right].$$

In SM, $f_{1L} = 1$, $f_{1R} = f_{2L} = f_{2R} = 0$.

Deviations from these values will denote “anomalous” couplings

Current liimits: Bernreuther, J. Phys. G., Nucl. Part. Phys. 35 (2008) Only f_{2R} can be nontrivial. $-0.57 < f_{2R} < 0.15$

Talk by Tony Liss at Top Workshop at CERN: $|f_{2R}|^2 < 0.20$

Lepton energy distribution and anomalous couplings

Various energy and angular distributions can be measured in top decay.

Energies of lepton, b jet, light jets, and their angular distributions can measure top polarization. However, they can be affected by anomalous couplings.

The angular distribution in the lab frame can be obtained from the one in the top rest frame.

Our calculations show that the normalised, energy averaged angular distributions of the decay lepton in the lab are not affected by the anomalous parts of the tbW vertex. I.e., there will be factors dependent on the top momentum etc. but nothing to do with the anomolous tbW vertex. Hence the correlation with top polarisation is faithfully reflected.

The decay lepton energy distributions in the laboratory contain some piece due to the anomalous couplings as well.

Our theorem depends on the factorization property of the decay density matrix in the rest frame of the top:

$$\langle \Gamma(\lambda, \lambda') \rangle = (m_t E_\ell^0)\ |\Delta(p_W^2)|^2\ A(\lambda, \lambda')\ F(E_\ell^0)$$

where

$$A(\pm, \pm) = (1 \pm \cos\theta_l), \qquad A(\pm, \mp) = \sin\theta_l e^{\pm i\phi_l} \tag{1}$$

For $A + B \to t + P_1 + ...P_n$, with $t \to b + W \to b + \ell + \nu_l$,

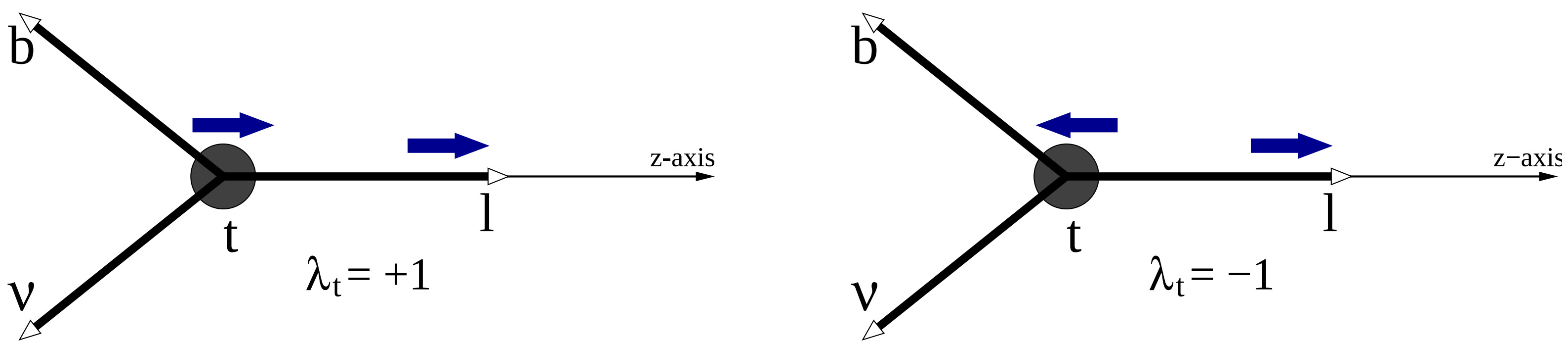
One can show:

$$d\sigma = \frac{1}{32\ \Gamma_t m_t (2\pi)^4} \left[\sum_{\lambda,\lambda'} d\sigma_{2\to n}(\lambda,\lambda') \ \times \ g^4 A(\lambda,\lambda') \right] dE_t \ d\cos\theta_t \ d\cos\theta_\ell$$
$$d\phi_\ell \times E_\ell \ F(E_\ell) \ dE_\ell \ dp_W^2.$$

The only terms dependent on tbW anom. coupling are $F(E_\ell)$ and Γ_t and to **leading order** *they cancel each other!*

A simple argument to understand the *independence of the angular distributions*

Thanks M. Peskin



The configuration with lepton momentum along the top quantization axis, the z axis.

All the other configurations can be obtained by simple rotations.'

Note in the SM:

$$\mathcal{M}(t_\uparrow \to l^+_\uparrow\ b\nu_l; \phi_b = 0) = C_{SM} + \mathcal{O}(f_i)$$

$$\mathcal{M}(t_\downarrow \to l^+_\uparrow\ b\nu_l; \phi_b = 0) = 0 + \mathcal{O}(f_i).$$

The second amplitude is nonzero only for anom. couplings.

Can be then easily shown that the ϕ_b averaged decay density matrix is,

Neglecting the terms of $\mathcal{O}(f_i^2)$ we get

$$\langle \Gamma_t \rangle \propto (1 + \mathcal{O}(f_i)) \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix},$$

where $\mathcal{O}(f_i)$ term comes as normalization of the density matrix.

Matrix upon rotation becomes

$$\langle \Gamma_t \rangle \propto (1 + \mathcal{O}(f_i)) \begin{bmatrix} 1 + \cos\theta_l & \sin\theta_l e^{i\phi_l} \\ \sin\theta_l e^{-i\phi_l} & 1 - \cos\theta_l \end{bmatrix}, \qquad (2)$$

Similar to the result mentioned before; all the anomalous dependence occurs in the normalization factor $F(E_l)$ and the angular dependence is un-altered

1) Discuss one possible way of tracking the polarisation through angular distribution in the laboratory frame.

2)How this may lead to a laboratory observable which tracks spin spin correlations

3)Effect of tbW anomalous couplings on probes of P_t using decay lepton energies.

Different candidates:

1) Angle between top and the decay lepton in the lab:

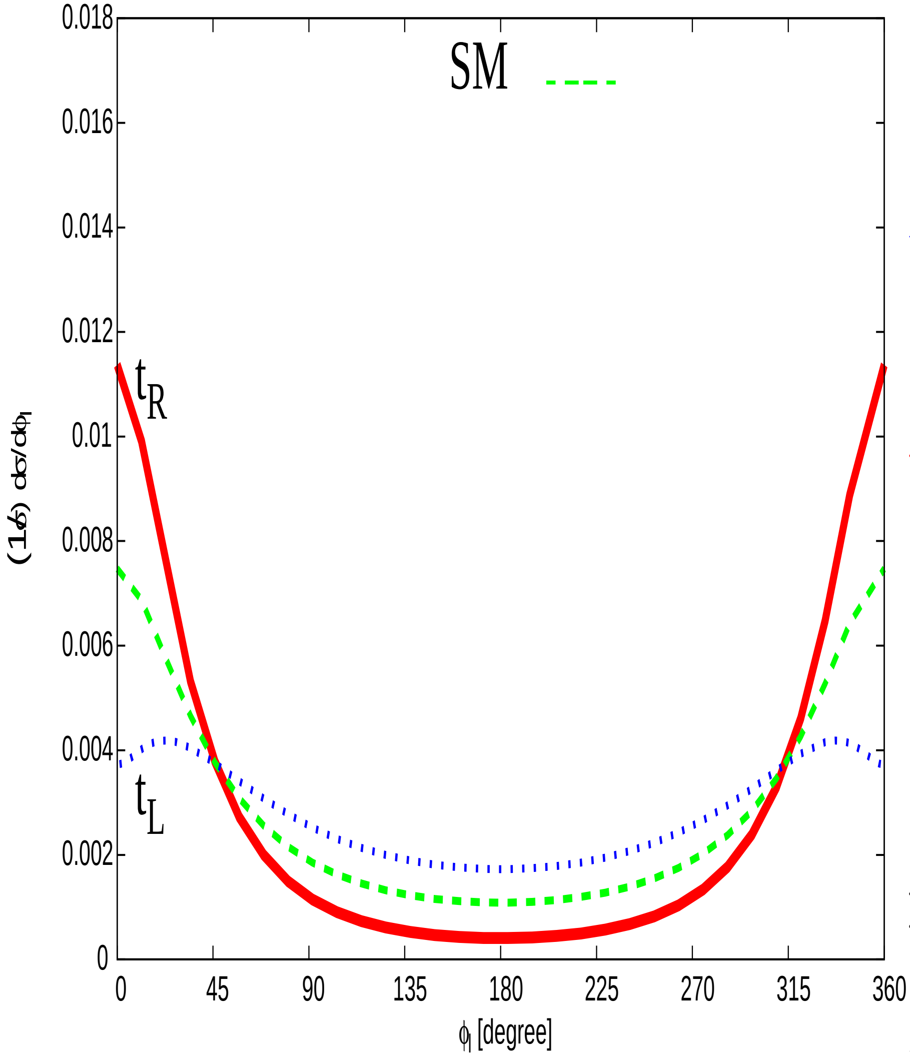
2) Angle between the decay lepton and the beam direction

For the Tevatron energies, we (RG, Poulose, Rindani) showed that in R-parity violating case, effect can be seen as FB asymmetry of the lepton.

The distributions for the LHC case will show no sensitivity.

This can work ONLY for an asymmetric collider : i.e there is a preferred direction. (Tevatron)

This can not happen at LHC: $x_1 - x_2$ symmetrisation will wipe it out.



Azimuthal distribution of the charged lepton in the lab.:

Distribution in ϕ_l, the azimuthal angle, defined with respect to the $t\bar{t}$ production plane, with beam direction as the z axis.

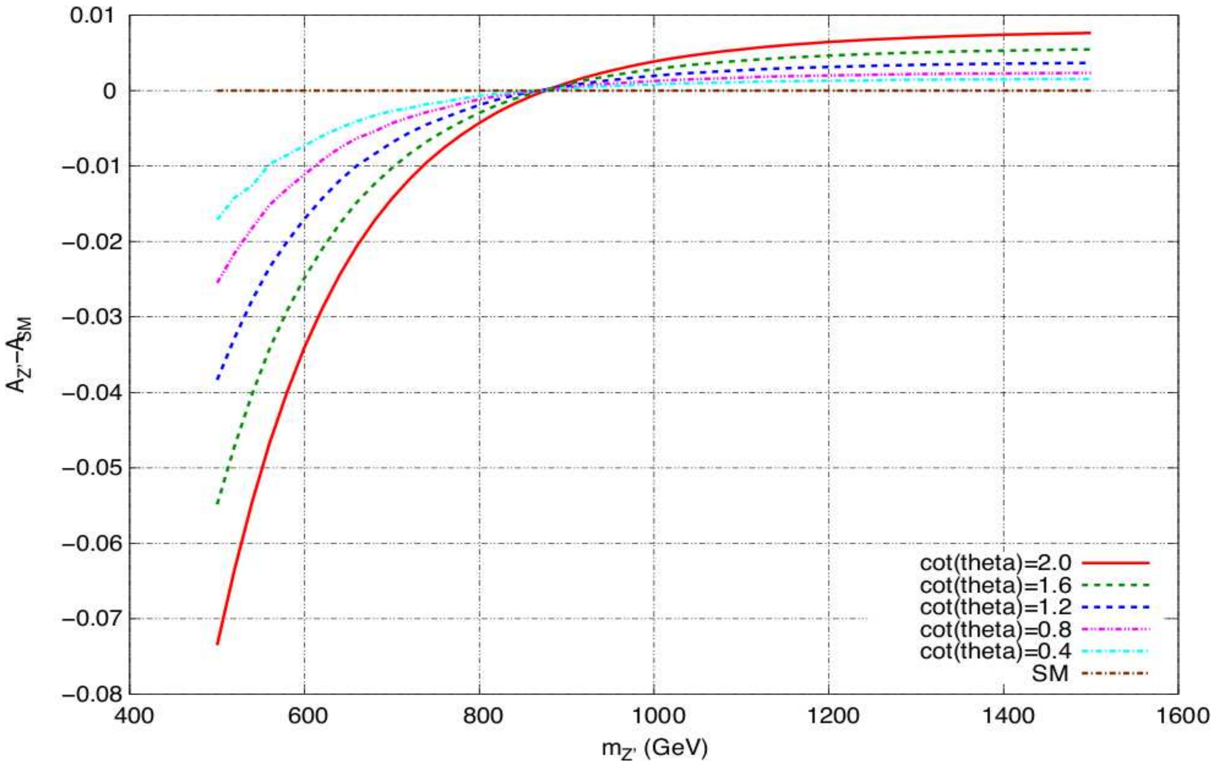
The two curves correspond to the top completely Left handed or right handed.

The choice of beam direction (ie. +ve or -ve) is not relevant as the distribution symmetric for ϕ_l to $2\pi - \phi_l$.

In practice effects of finite polarization and/or spin coherence effects from off diagonal elements need to be included.

Azimuthal asymmetry

$$\mathcal{A} = \frac{1}{\sigma}\left[\sigma(\phi_l < \pi/2) + \sigma(\phi_l > 3\pi/2) - \sigma(\pi/2 < \phi_l < 3\pi/2)\right]$$

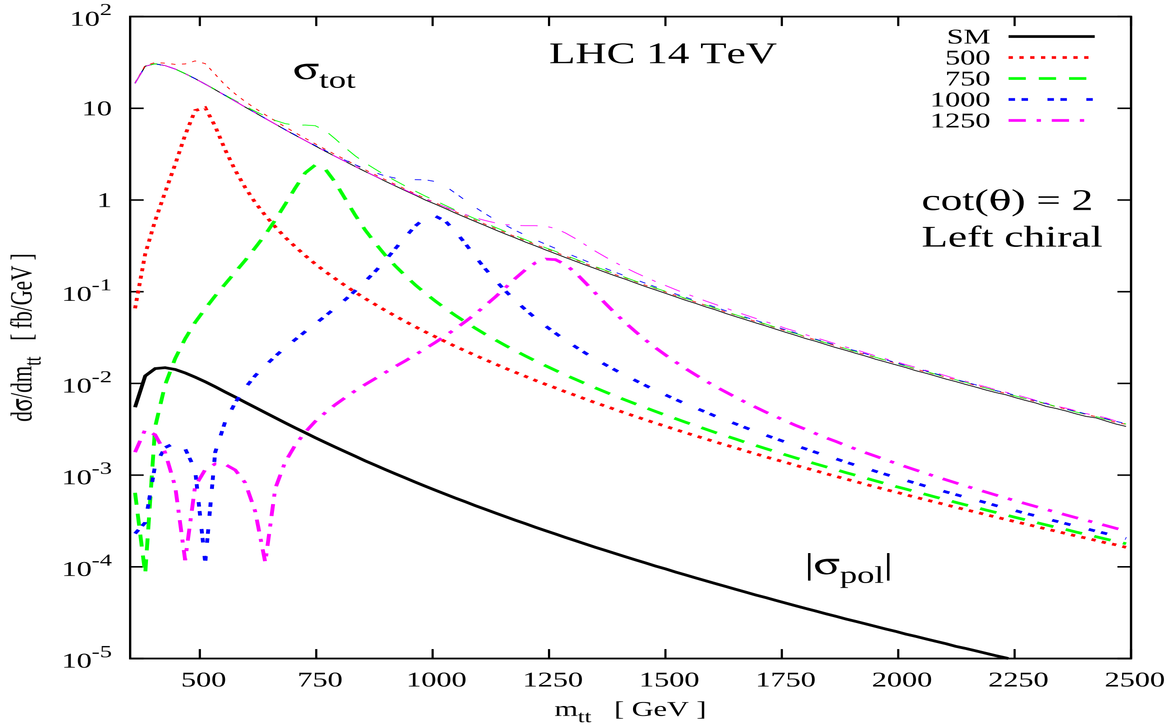


$$\mathcal{O} = \mathcal{A} - \mathcal{A}_{SM}$$

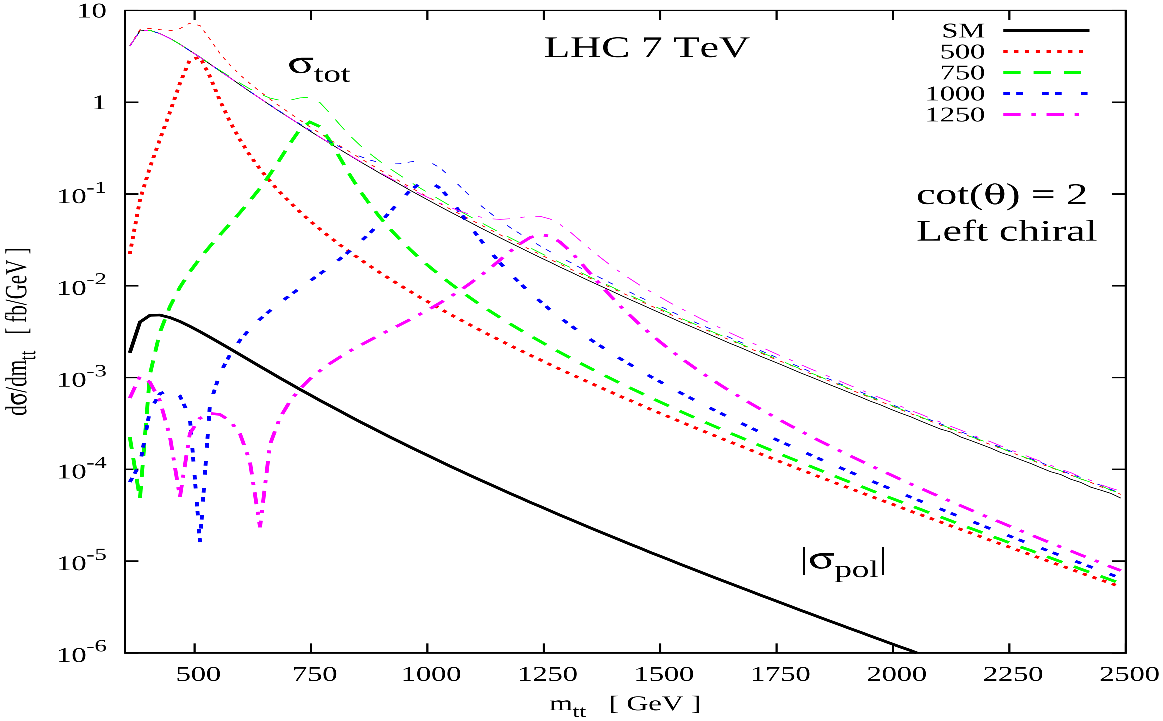
But this does not even reflect the sign of polarisation over the entire range!

How to optimise and how to make this asymmetry a true reflector of polarisation?

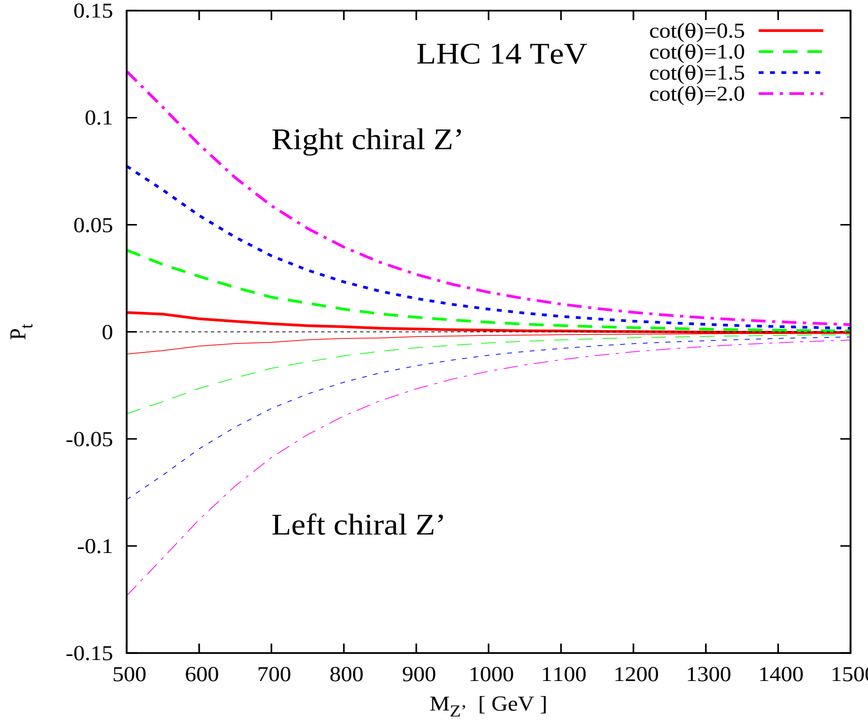
Look at polarisation as a function of kinematic variables: First once again $d\sigma/dm_{t\bar{t}}$ (polarised and unpolarised)

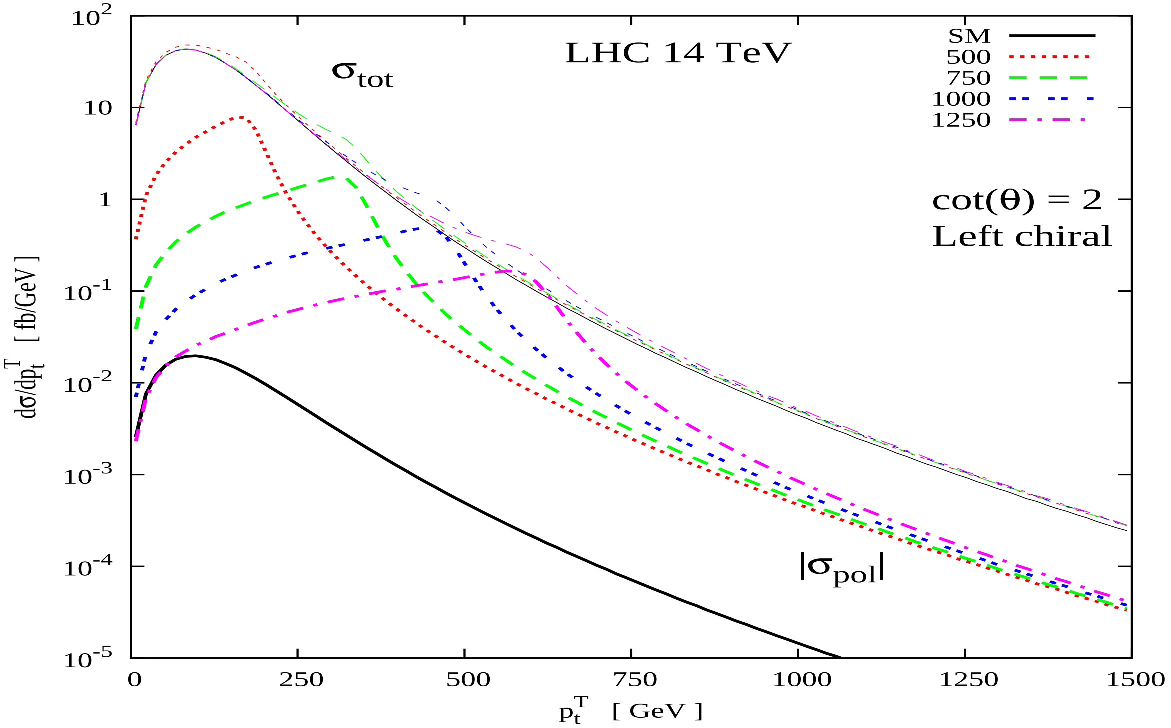


Same for 7 TeV



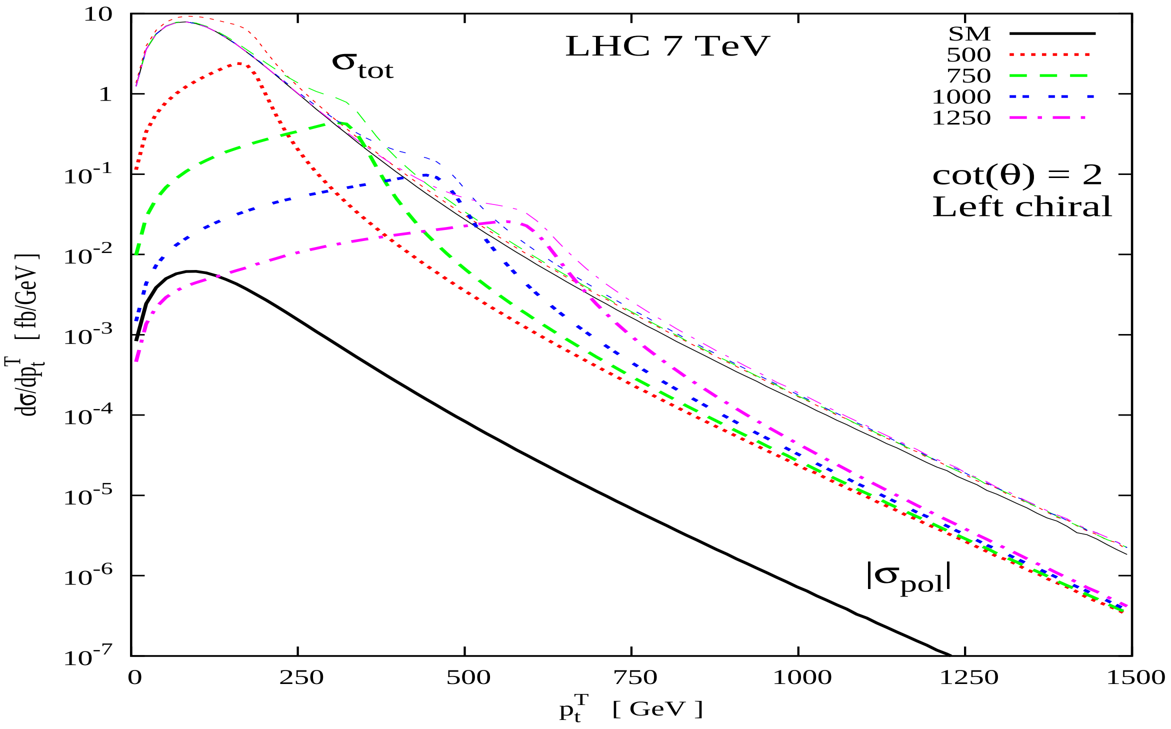
Polarisation for 7 TeV and Tevatron:

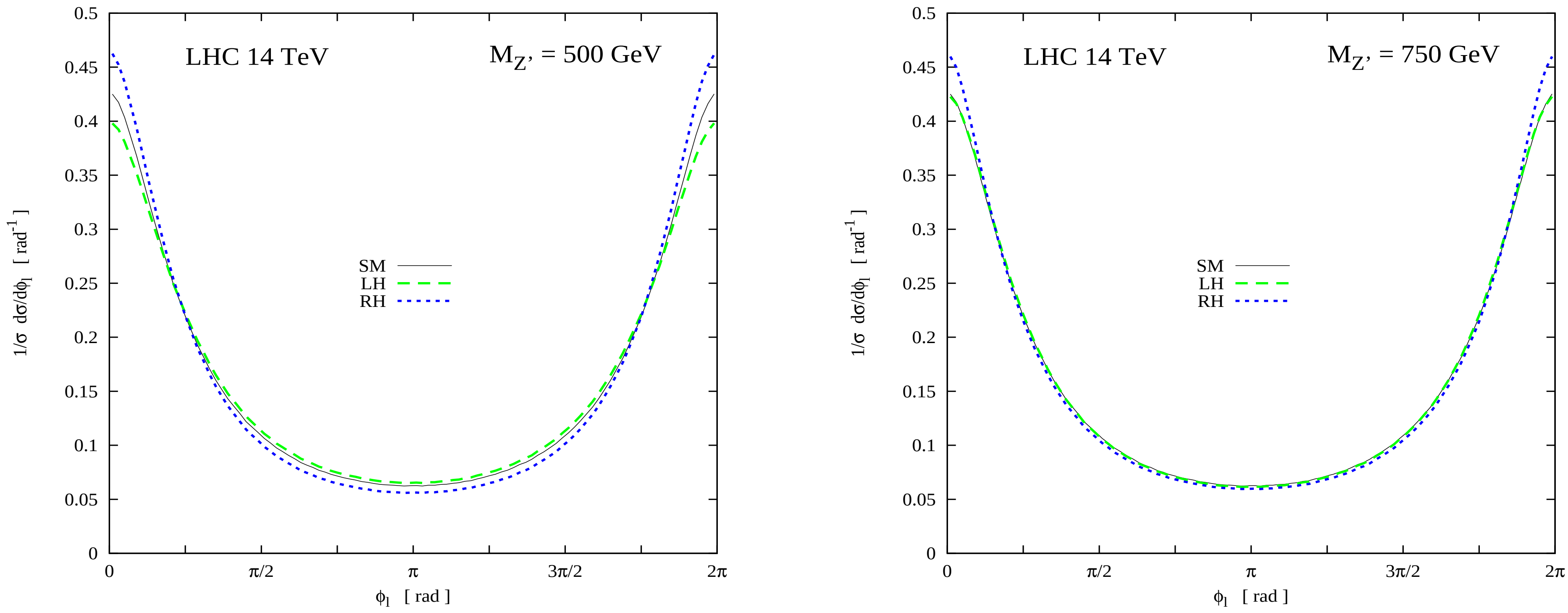




Peak occurs at $p_t^T = \beta_M M_{Z'}/2$. Use this information to optimise the polarization observables

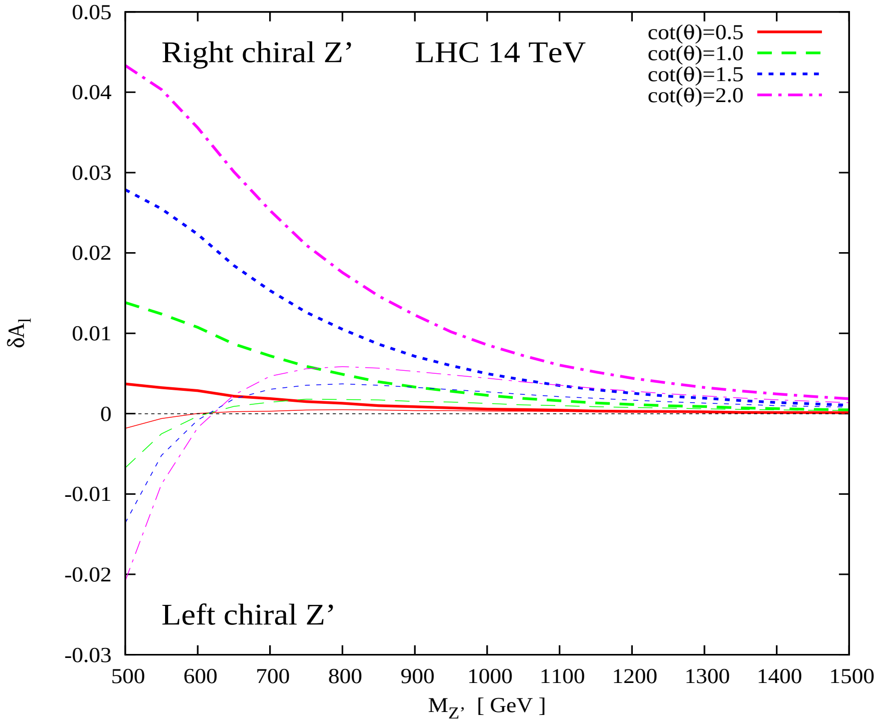
For 7 TeV:

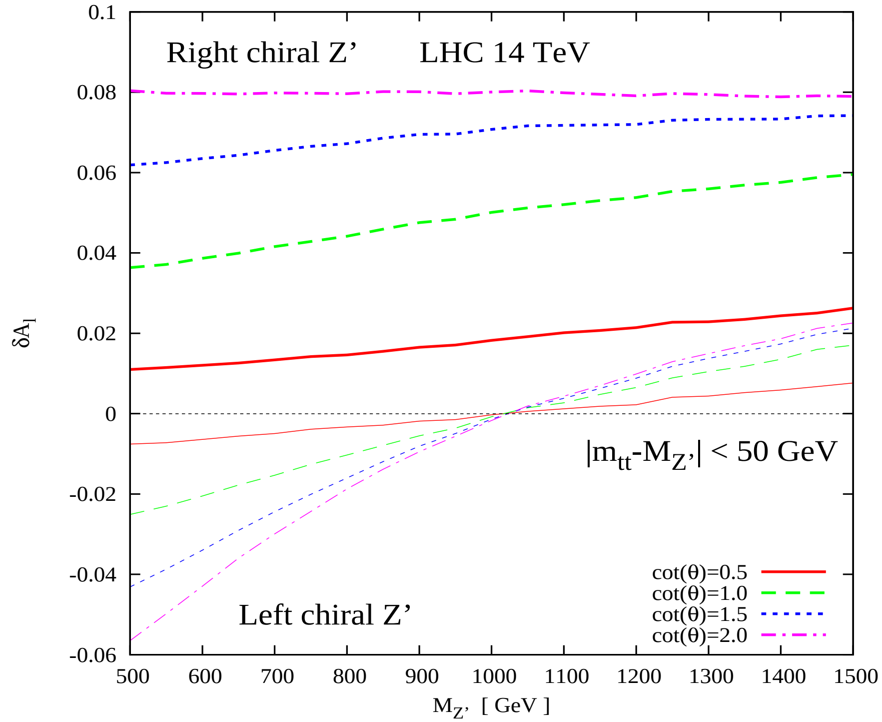

LHC 7 TeV
σ_{tot}
$|\sigma_{pol}|$
SM
500
750
1000
1250
cot(θ) = 2
Left chiral
dσ/dp$_t^T$ [fb/GeV]
p$_t^T$ [GeV]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
250
500
750
1000
1250
1500



The ϕ_ℓ distribution has two effects : 1)Polarization dependent effect and 2)Polarization independent effect depending on the boost from the rest frame of the t. For right chiral couplings (positive polarisation) effect NOT diluted.

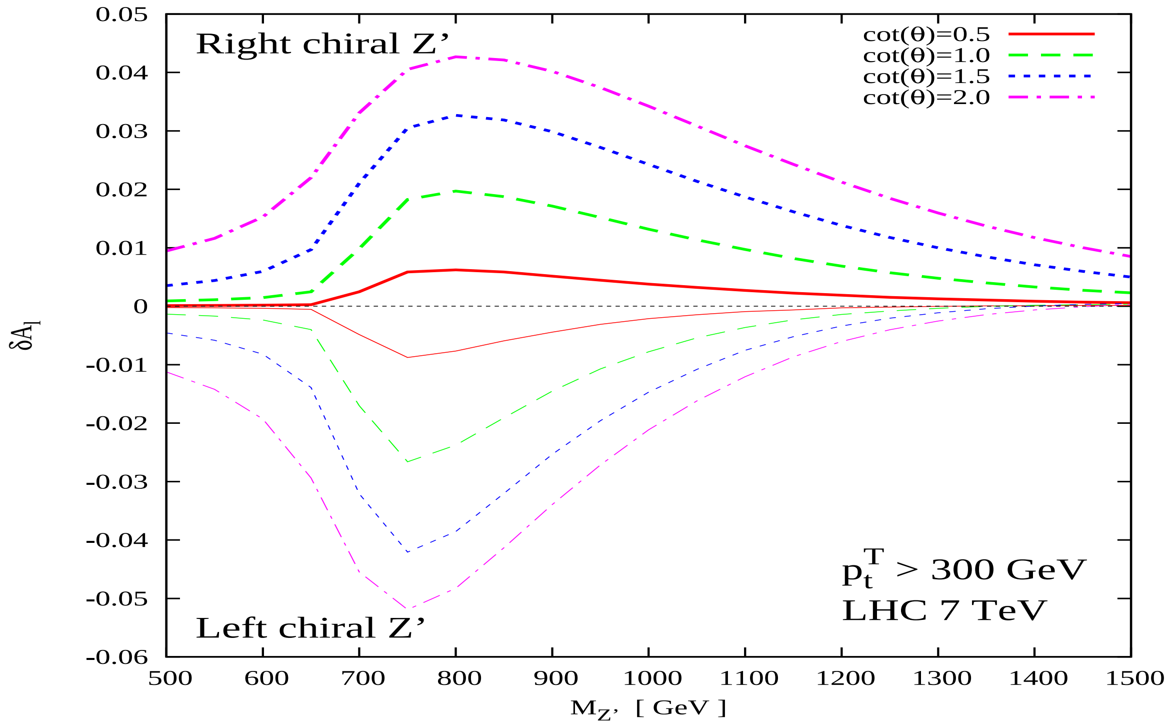
Want to make cuts such that only the polarisation dependent effects are projected out.



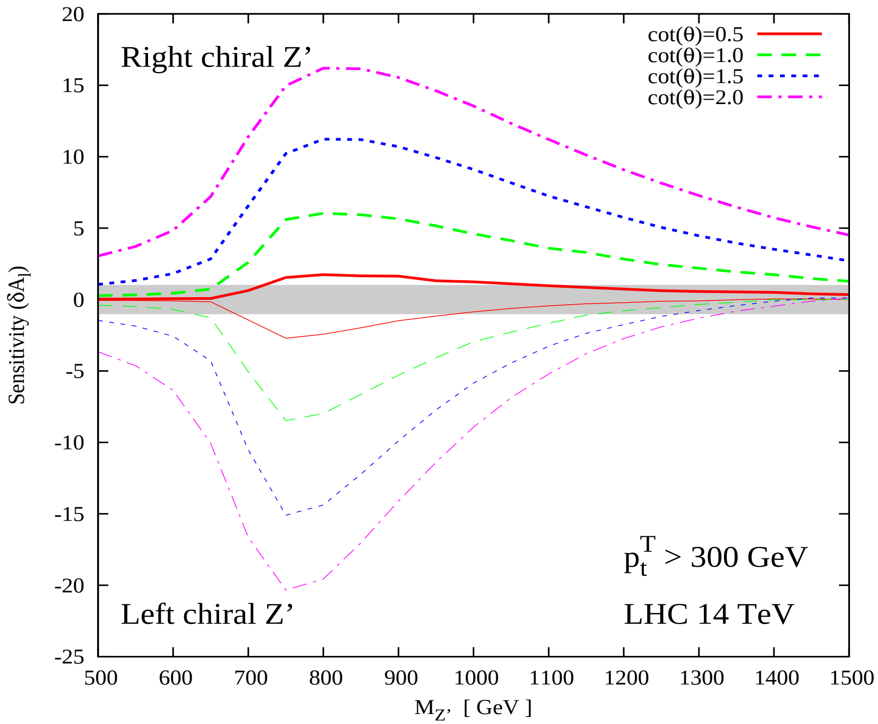


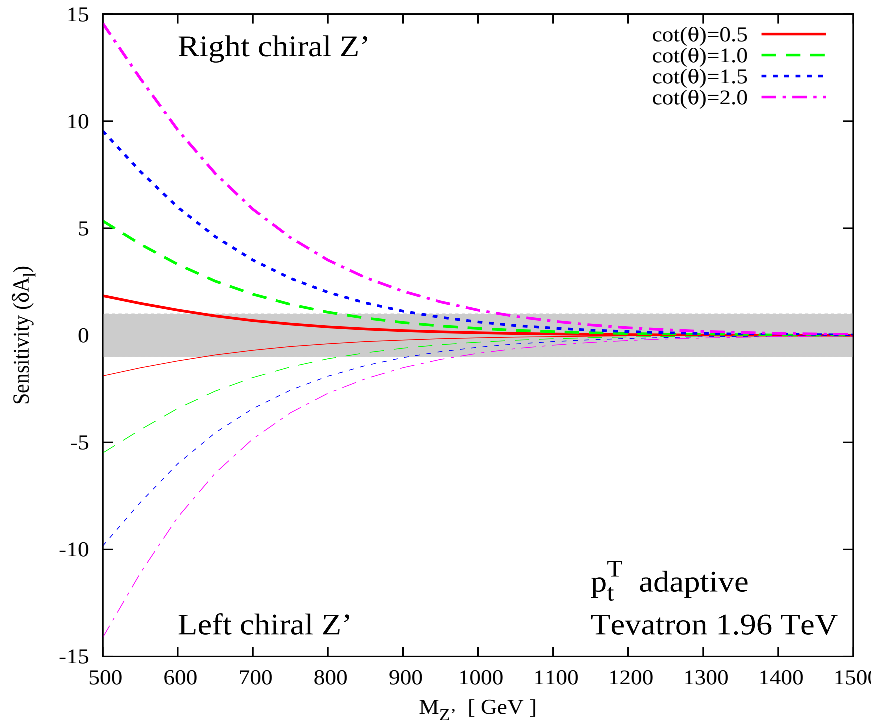
Choose $m_{t\bar{t}}$ around the $M_{Z'}$ window.

Asymmetry at 7 TeV.



Asymmetry now faithfully tags the polarisation sign and magnitude.


Right chiral Z'
Left chiral Z'
cot(θ)=0.5
cot(θ)=1.0
cot(θ)=1.5
cot(θ)=2.0
p_t^T > 300 GeV
LHC 14 TeV
Sensitivity (δA_l)
$M_{Z'}$ [GeV]


Right chiral Z'
Left chiral Z'
cot(θ)=0.5
cot(θ)=1.0
cot(θ)=1.5
cot(θ)=2.0
p_t^T adaptive
Tevatron 1.96 TeV
Sensitivity (δA_l)
$M_{Z'}$ [GeV]

Consider $t\bar{t}H$ production:

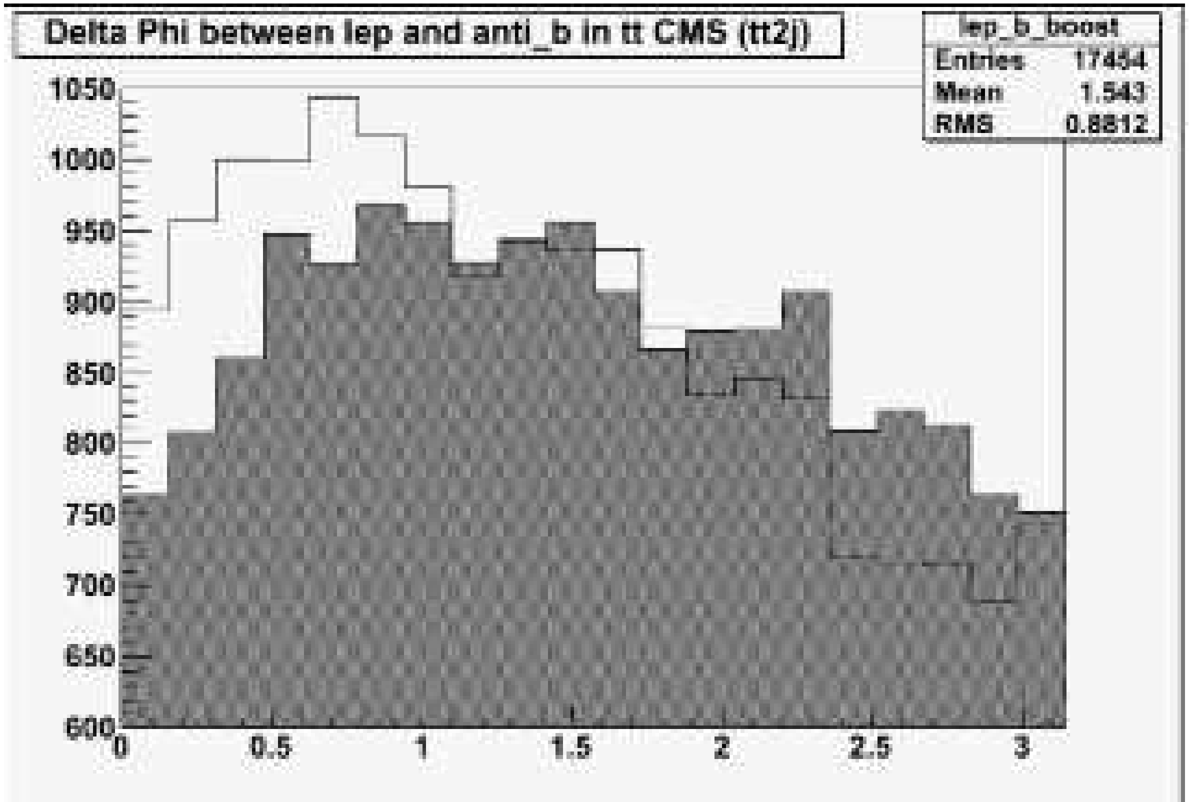
The Higgs is emitted from t by a chirality flipping Yukawa coupling for $t\bar{t}H$ production.

Main background $t\bar{t}jj$:

A jet is produced by the chirality preserving QCD coupling, apart from effects of t mass. This can give rise to different spin-spin correlation for $t\bar{t}H$ and $t\bar{t}jj$ case.

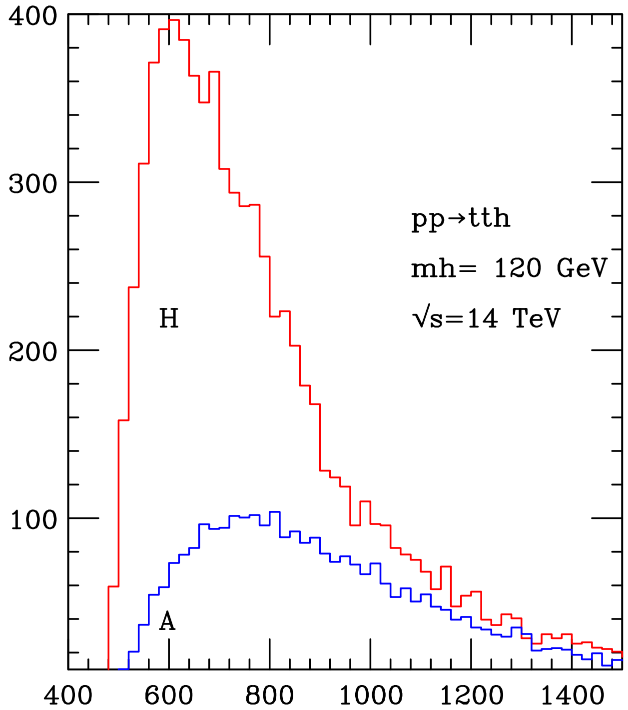
Azmimuthal distributions in the **laboratory** can probe such correlations (RG, SDR, Ritesh K. Singh: JHEP, Dec. 2006)

S. Parke: CERN top workshop , similar results for SM $t\bar{t}$ production.



This is the distribution in the azmimuthal angle between lepton from the deacy of the t and the b-quark from the decay of the $\bar{t}$ (or vice versa).

Different for the $t\bar{t}H$ signal and $t\bar{t}jj$ background!



Characteristic shape of the distribution in the invariant mass of $t\bar{t}\phi$ system. [PRL 100, 051801 (2008), Djouadi, RG, et al]: Observation for e^+e^- production.

The $pp \longrightarrow t\bar{t}\phi$:

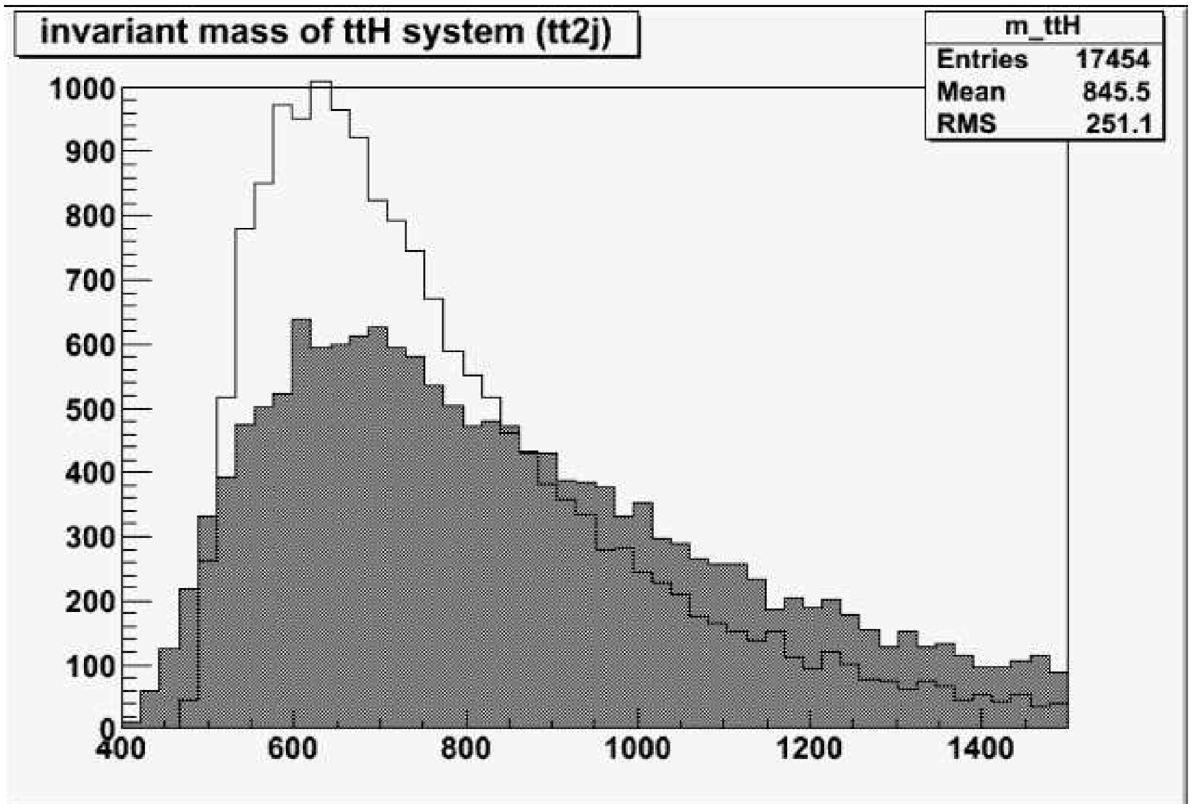
Idea: can one use this feature along with the azimuthal angle distriutions to control the bkgd?

The $b\bar{b}$ in the $t\bar{t}b\bar{b}$ QCD background is produced from a spin 1 gluon.

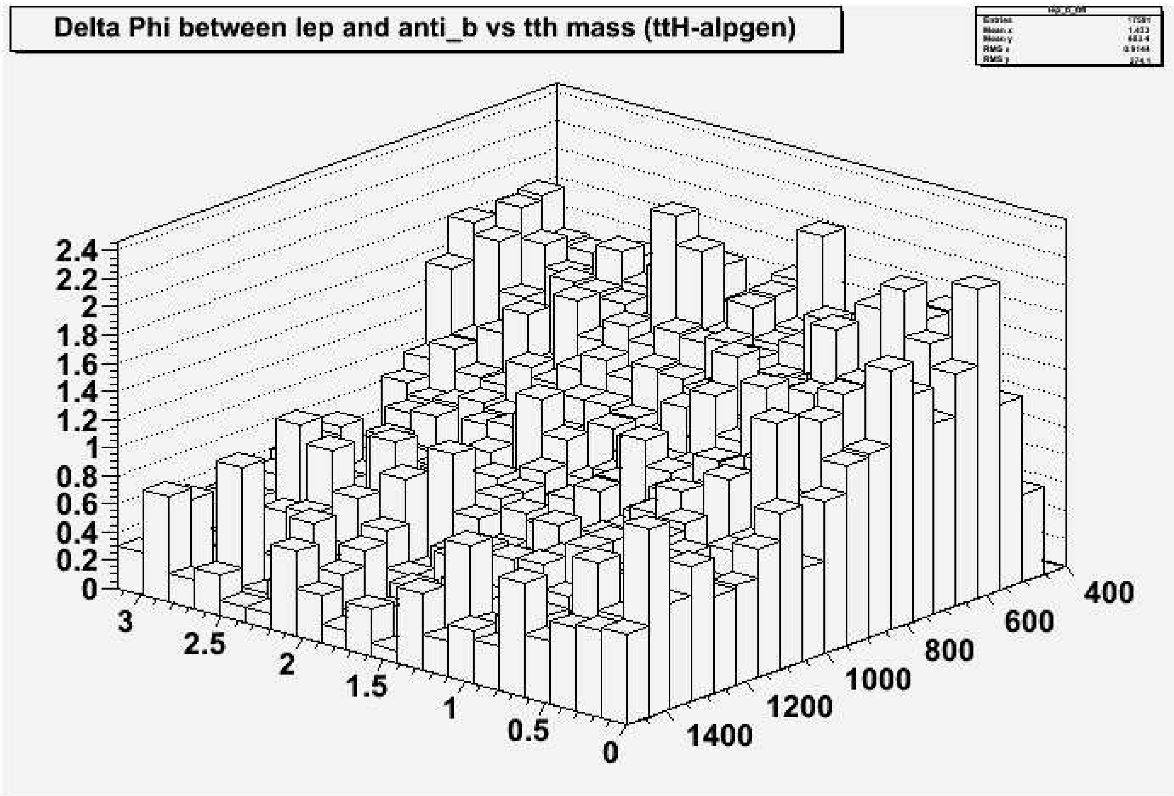
Djouadi, S. Ferrag, RG, Fabio Maltoni, F. Picininni (in progress).

1) Clean variable to decide the CP at large luminosity

2)Perhaps use this feature to help clean up the signal?



The shapes of the signal and background are quite different.



Can the differences in shape be utilized effectively to distinguish signal from the background?

Systems with large invariant mass of $t\bar{t}$ can produce highly boosted tops – with collimated decay products Lian-Tao wang, Thaler; G. Perez, Sterman..

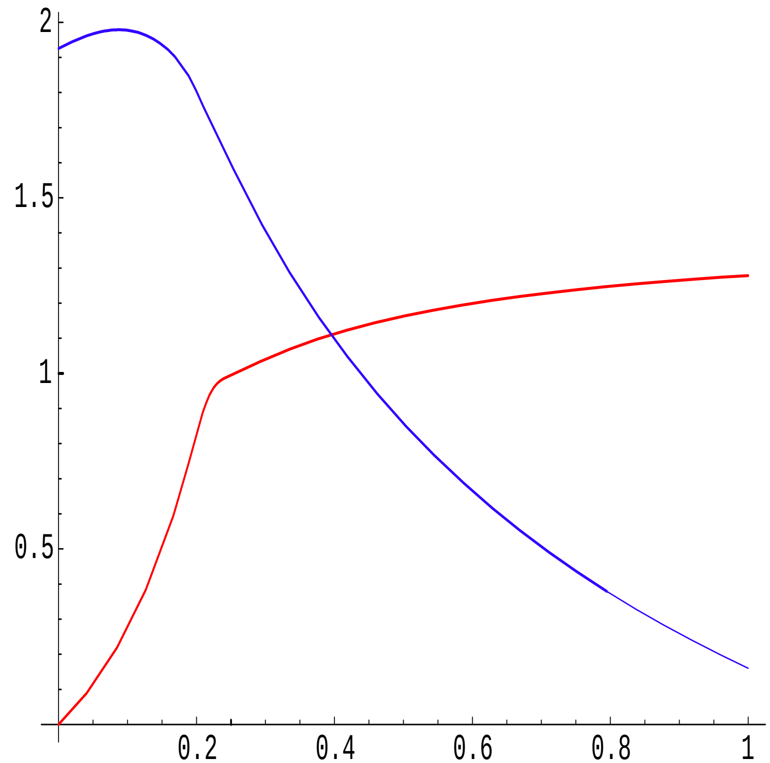
Collimated leptonic top quarks allow the energy of the lepton and the b-jet to be separately measured, but not the angular distributions.

The momentum fraction of the visible energy carried by the lepton provides a natural polarimeter.

$u = E_\ell/(E_\ell + E_b)$,

[J. Shelton arXiv:0811.0569]

$(1/\Gamma)(d\Gamma/du)$ as a function of u.

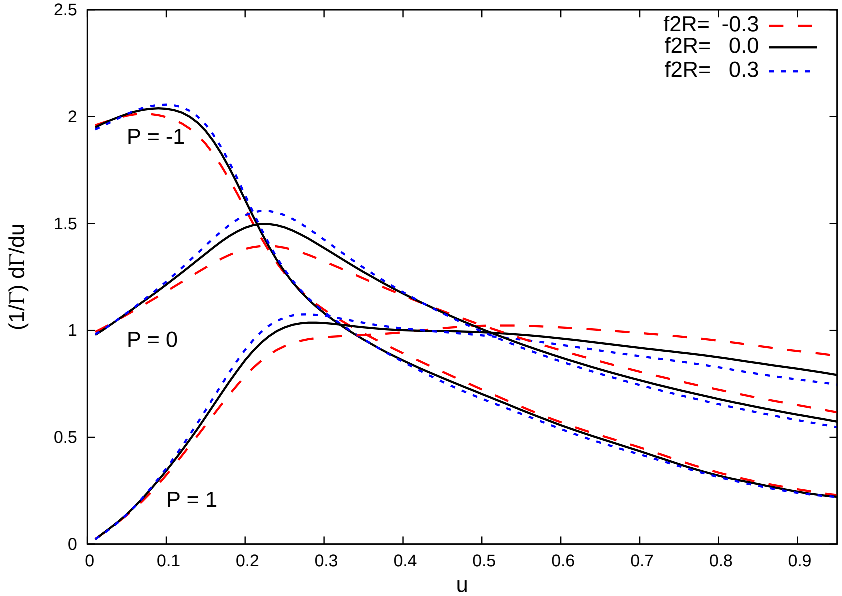


Blue line: Negative helcity top

Red line: positive helicity top

$\beta = 1$

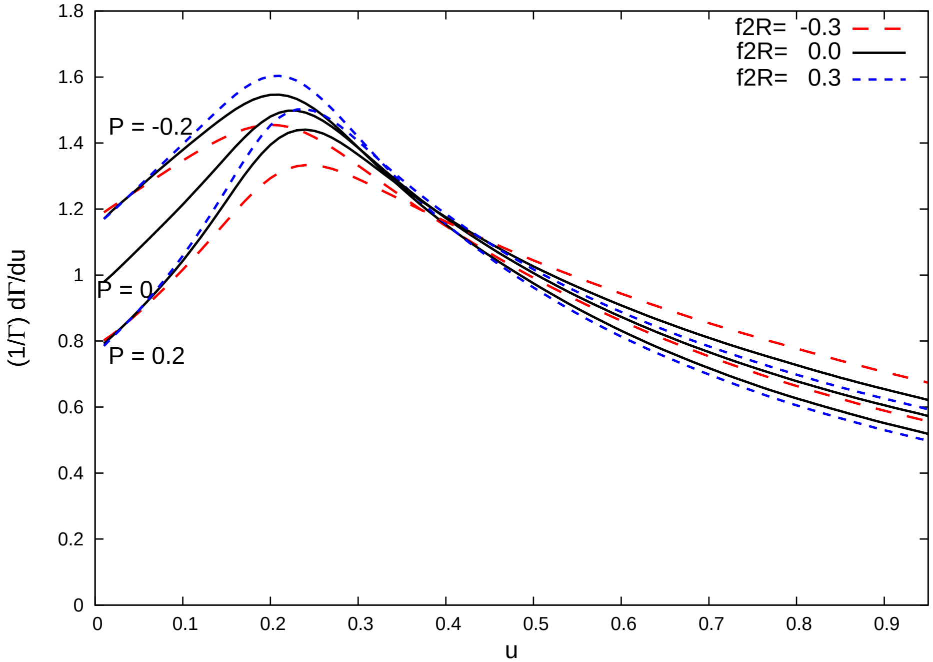
Can one use the u variable? Need to study Effect of anomalous couplings on the u distribution:



If the expected polarisation is large then contamination by the anom. couplings seems small.

Recall that shape of lepton energy distn. did not change too much with anomalous coupling. Position of the peak shifted.

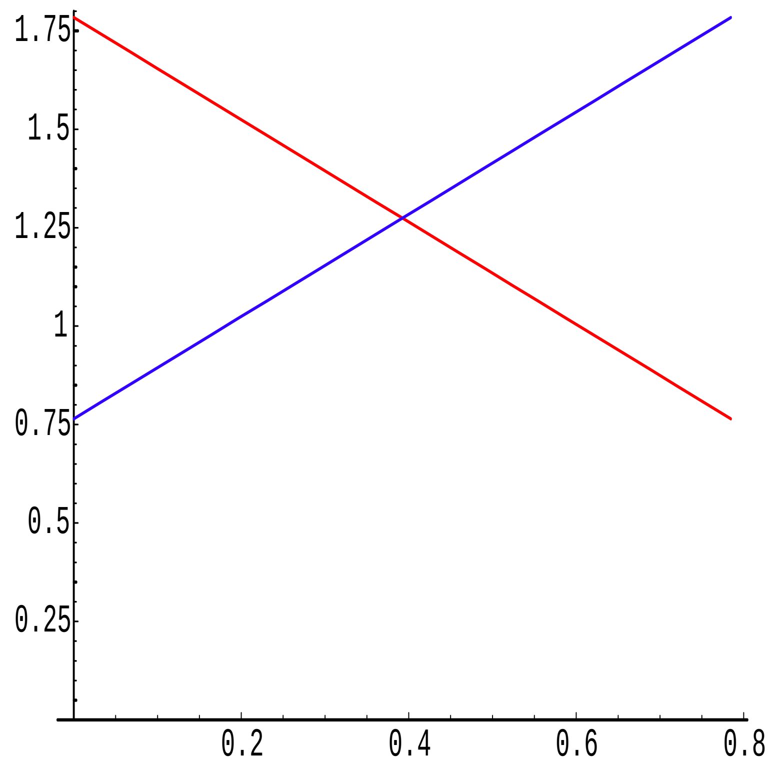
For top polarisation = 0.2:



Restricted to $f_{2R} = 0.3$. Need to include quadratic terms for higher values?.

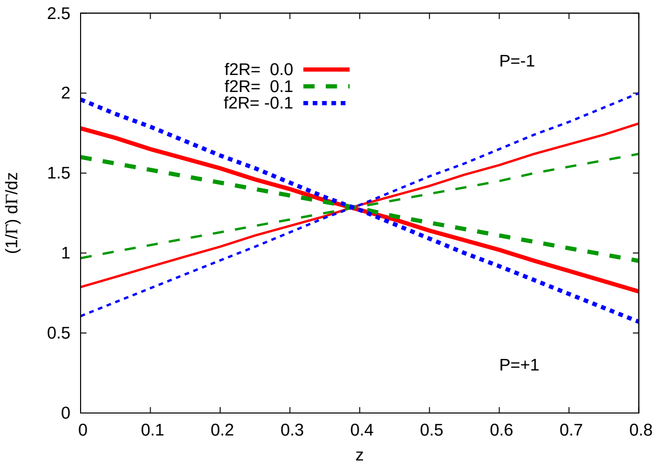
Aim: for the current limits on the anom. couplings what is the minimum value of expected polarisation where this probe can work?

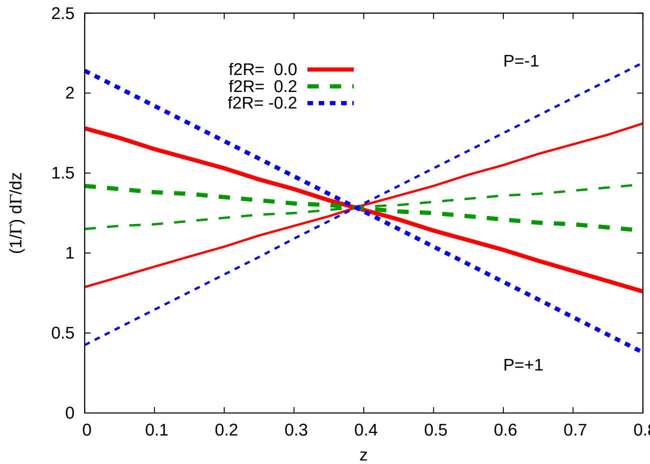
For hadronically decaying tops she suggests:
$z = E_b/E_t$
Blue line: negative helicity.
Red line: positive helicity.
(Almeida,Sung, Perez et al had also similarly suggested the distribution of the total p_T of b jet.)



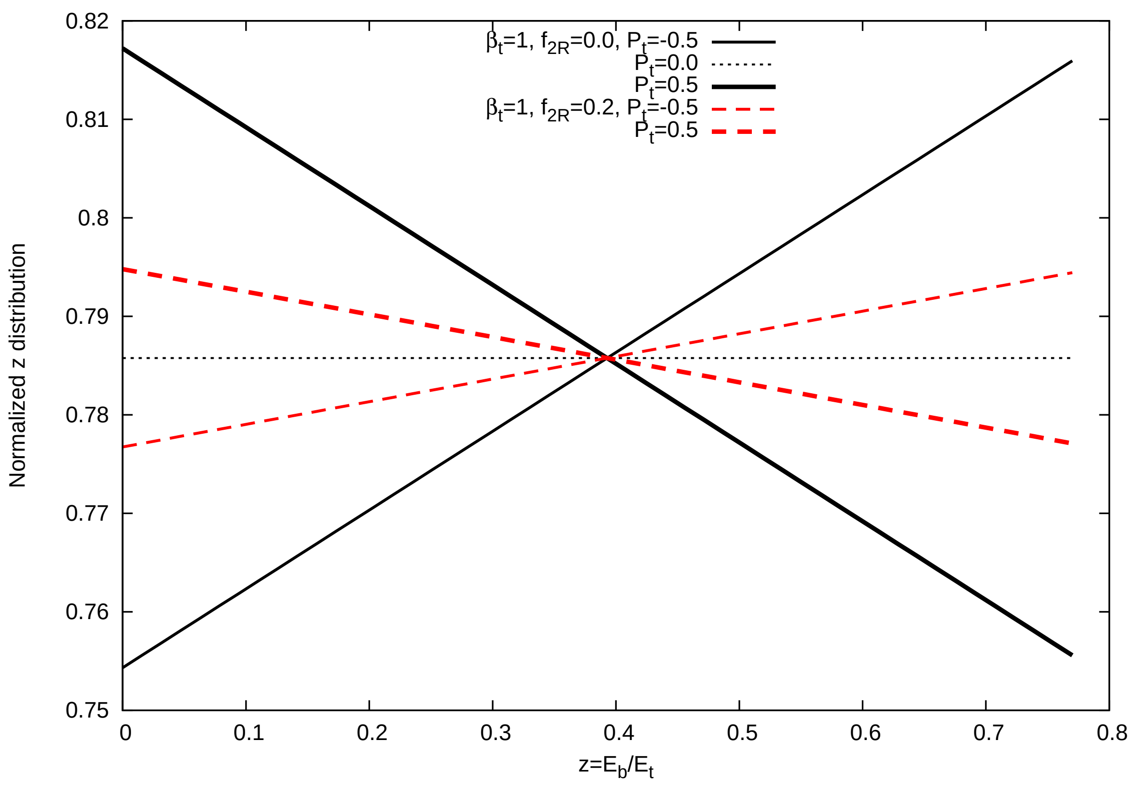
$$\frac{1}{\Gamma}\frac{d\Gamma}{dz} = \frac{m_t^2}{\beta(m_t^2 - m_w^2)}\left(1 + P_t\kappa_b\left(-\frac{1}{\beta} + \frac{2m_t^2 z}{\beta(m_t^2 - m_w^2)}\right)\right)$$

with $\kappa_b = -0.406 + 1.43 f_{2R}$.



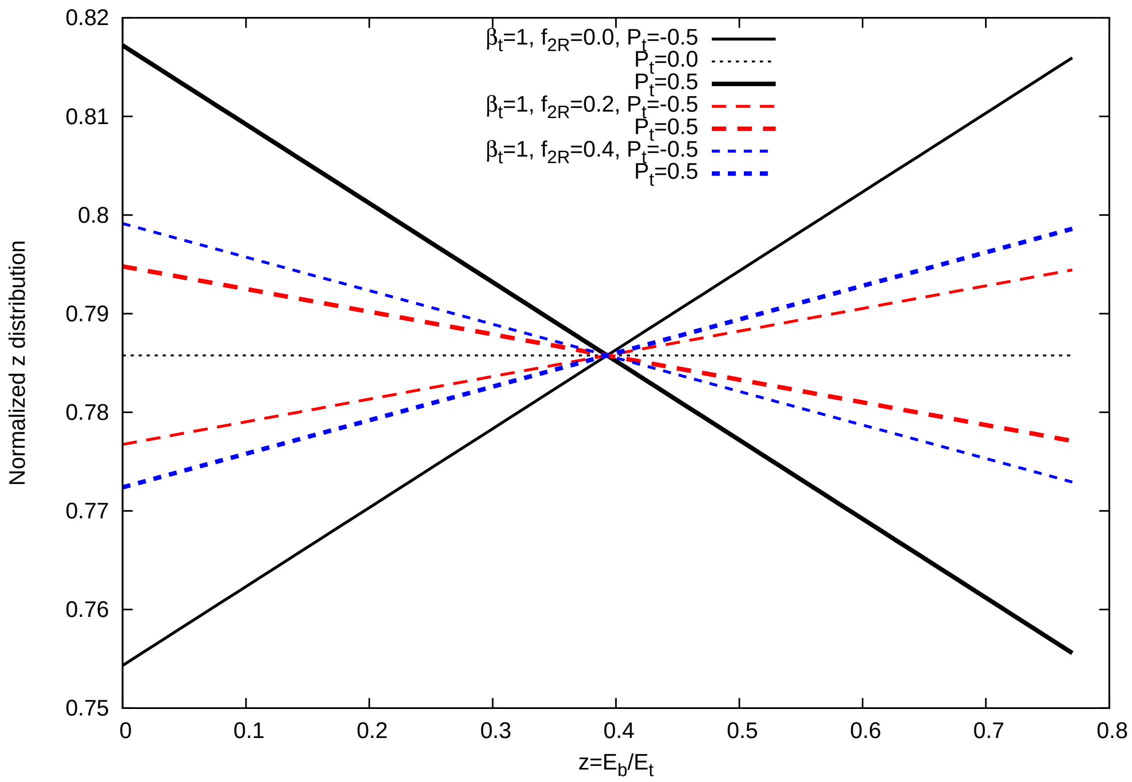


Effect for lower values of expected polarisation:



For the b–jet distributions the effect of anomalous couplings on the enerrgy fraction distribution in the lab is large.

Effect for lower values of expected polarisation:



With $f_2R = 0.4$ even the sign of the slope changes!

Conclusions

- Measurement of Top polarization can be a very good probe of some types of BSM physics

- Secondary decay lepton angular distributions are the most faithful polariometers, robust to effects of non standard tbW couplings as well as higher order corrections.

- At the LHC showed that ϕ distibutions can be used to construct obeservables which directly probe the polarisation produced in the decay of a resnonance. An example of an extra Z' decaying into $t\bar{t}$ was presented.

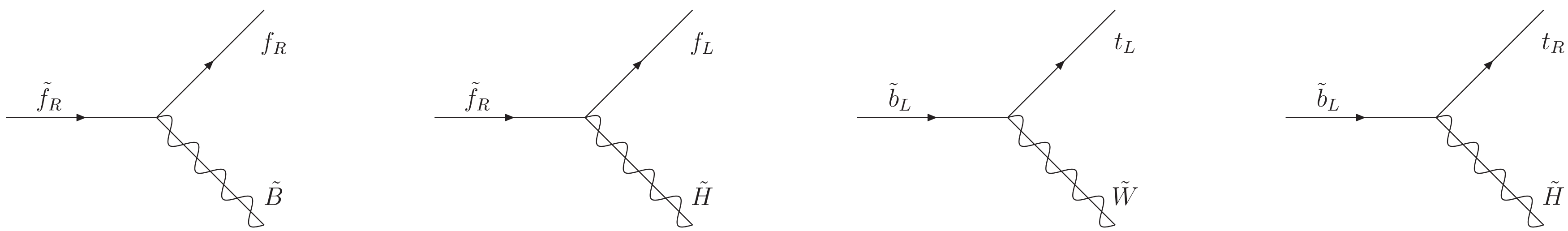
- The distribution in azimuthal angle between the decay fermions of the t and $\bar{t}$ in the **laboratory** frame reflects faithfully the spin-spin correlations between the t and $\bar{t}$.

- Energy fraction of the lepton and b–jet can be used for the boosted tops. Lepton distribution less sensitive to the anom. coupling and hence a better probe.

Additiomal slides

M. Nojiri, PRD **51** (1995) 6281 [hep-ph/9412374] for τ

$f = t/\tau$



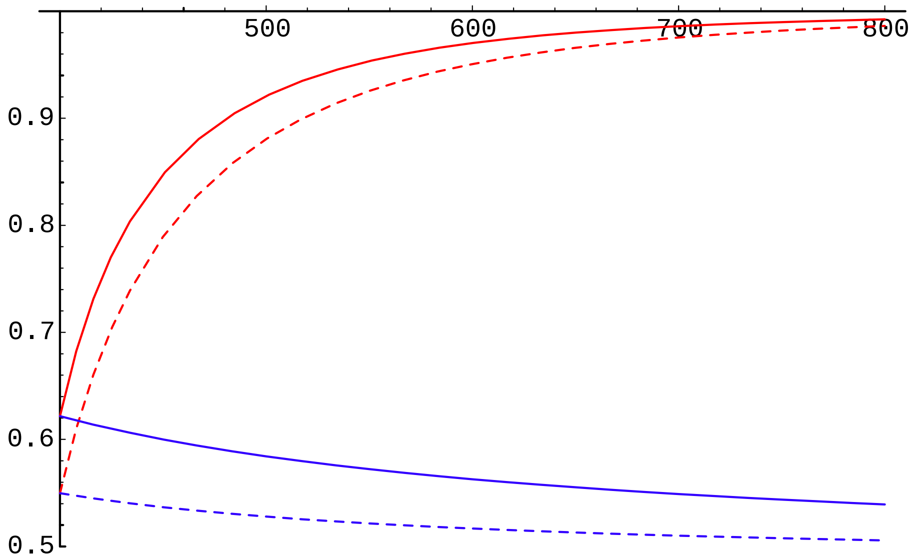
- In MSSM mass eigenstates of $\tilde{f}$ (sleptons/squarks) $\tilde{f}_1, \tilde{f}_2$, are mixtures of $\tilde{f}_L$ and $\tilde{f}_R$, $f = t, \tau$.

- Mixing affects gauge couplings of $\tilde{f}_i, i = 1, 2$ and hence the production rates.

- The $\tilde{\chi}_j^{\pm}, j = 1, 2$, $\tilde{\chi}_j^0, j = 1, 4$ are mixtures of higgsinos and gauginos.

- Couplings of sfermions with higgsinos flip chirality whereas those with gauginos do not.

- Net helicity of produced f in the decay $\tilde{f}_i \to \tilde{\chi}_j^0 f$ AND $\tilde{f}_i \to \tilde{\chi}_j^{\pm} f'$ depends on the L–R mixing in the sfermion sector and on the gaugino-higgsino mixing.



Shelton: 0811.0569, Phys. Rev. D 79, 014032, 2009.

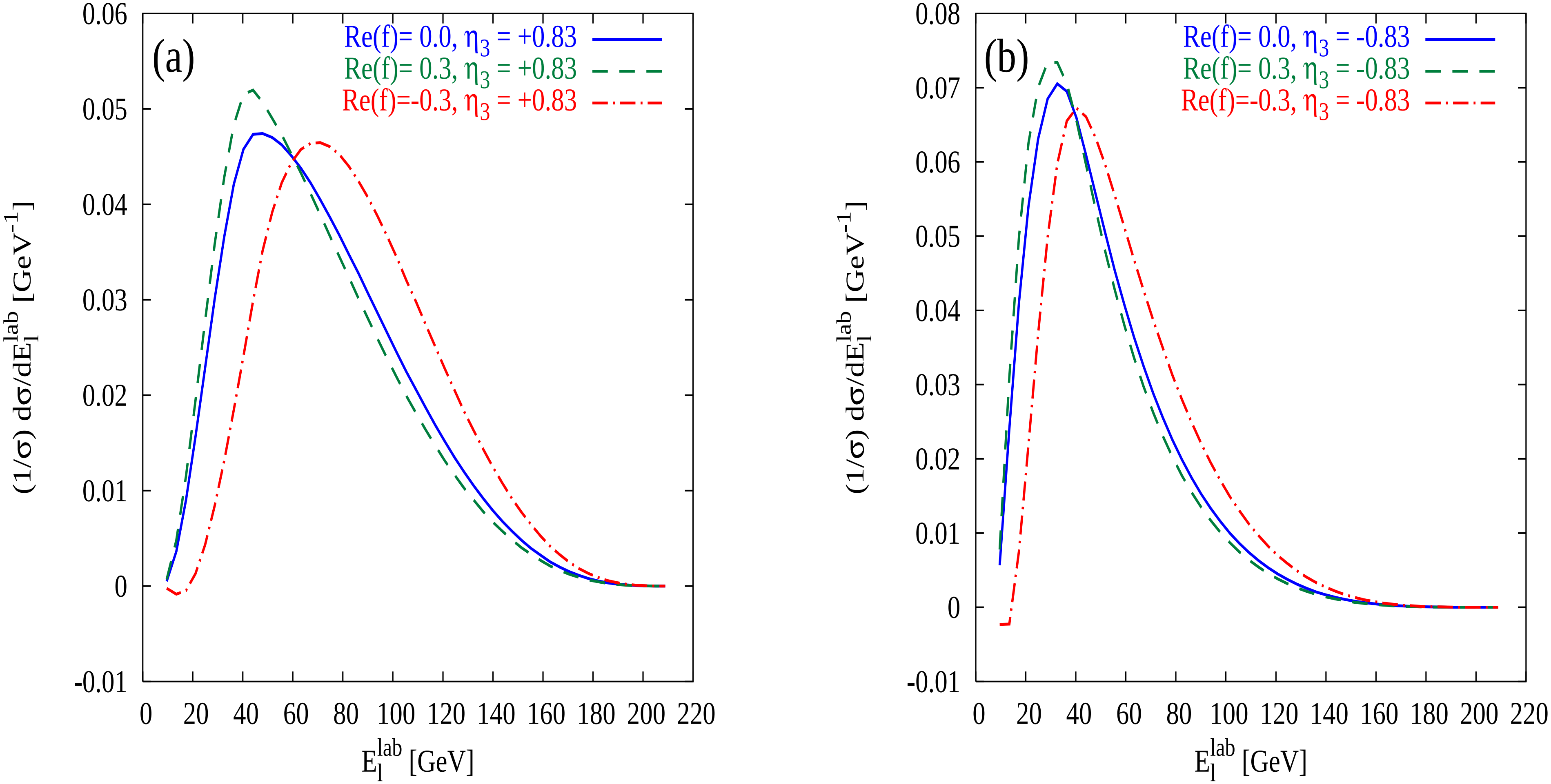
For purely chiral couplings.

Solid lines for opposite spin partners (SUSY)

Dashed lines for same spin partner (little Higgs/UED..)

Blue lines for a fixed mass difference between decaying particle and the χ_0/heavy boson partner , red for a fixed mass of the boson partner.

Top polarisation for the same spin cascade is less than that for the opposite spin cascade.


(a)
Re(f)= 0.0, η3 = +0.83
Re(f)= 0.3, η3 = +0.83
Re(f)=-0.3, η3 = +0.83
(1/σ) dσ/dE_l^lab [GeV^-1]
E_l^lab [GeV]
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0 20 40 60 80 100 120 140 160 180 200 220
(b)
Re(f)= 0.0, η3 = -0.83
Re(f)= 0.3, η3 = -0.83
Re(f)=-0.3, η3 = -0.83
(1/σ) dσ/dE_l^lab [GeV^-1]
E_l^lab [GeV]
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0 20 40 60 80 100 120 140 160 180 200 220