Top-quark decay distributions for the study of new physics

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Introduction

- LHC is busy confirming the standard model
- The most important ingredient, the Higgs boson, is the prize discovery
- Perhaps hints of new physics ($B(H \to \gamma\gamma)$, vacuum stability, ...)
- If direct searches do not show new particles, LHC could look for possible anomalous couplings of SM particles: "indirect search"
- Couplings of the top quark important - possible hints for mechanism of spontaeous symmetry breaking

Polarization studies

- Basic measurement: Cross section
- More detailed tests through angular distributions, angular asymmetries
- Additional tool: polarization studies
- Particle polarization measurements, correlated with angle or with other spins, can give detailed information on interactions
- Polarization of heavy particles can be measured using distributions of decay particles

Outline

- Utilizing top polarization
  - Discriminating among top production scenarios
  - How top polarization can be measured: Charged lepton angular distributions
  - Example of a process for LHC
- Utilizing other top decay distributions
  - Measuring anomalous couplings
  - Example of a process for LHC

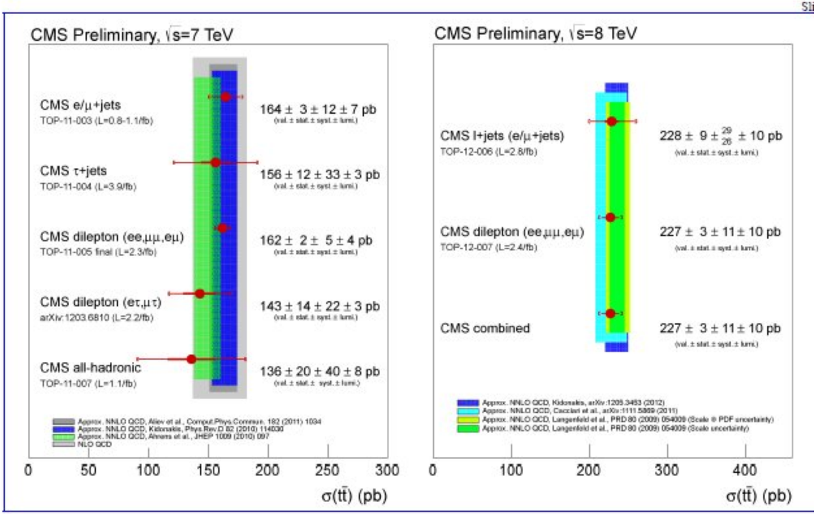
Top quark production at LHC

- Copious production of $t\bar{t}$ pairs at LHC
  $\sigma_{t\bar{t}} \approx 830$ pb at 14 TeV
- Also large single top production
  $\sigma_{1t} \approx 320$ pb at 14 TeV
- Top quarks can also arise in the decays of new particles – resonances, new gauge bosons, Higgs bosons, squarks, gluinos . . .
- Top being heavy decays before hadronization:

$$\Gamma_t \approx 1.5\mathrm{GeV} << \Lambda_{\mathrm{QCD}} \approx 200\mathrm{MeV}$$

- Spin information retained by decay products

Top-pair production at LHC



Detection of top quarks

- In SM, top decays almost entirely into $b + W$
- W then decays to
  - $u\bar{d}$ (two jets) (B.R. 2/3), or
  - $l\nu_l$ (lepton + missing energy) (B.R.1/3 for each lepton)
  - Mass reconstruction better with two jets, but large background
  - Leptonic signature cleaner, but mass reconstruction difficult

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  - Or vice versa
- In SM, $\bar{t}bW^+$ vertex is left-handed
- It can receive modifications beyond SM from loops

Production mechanisms and top polarization

- Top polarization can give more information about the production mechanism than just the cross section
- It can allow measurement of parameters of the theory
- It is parity violating, hence measures chiral couplings
- It can give a clue to anomalous colour dipole couplings

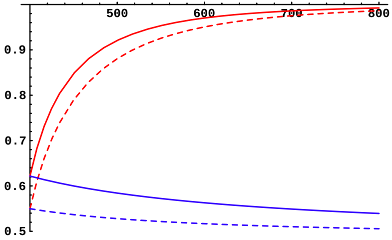
$$\mathcal{L} = \frac{g_s}{\Lambda} F_a^{\mu\nu} \left[\bar{t} \sigma_{\mu\nu} (\rho + i\rho' \gamma_5) T^a t \right]$$

[S. Biswal, SDR, P. Sharma, work in progress]

- It can give information on the theory in cascade decays
  [J. Shelton, Phys. Rev. D. 79, 014032 (2009)
  M. Nojiri, M. Takeuchi, JHEP 10 (2008) 025
  M. Perelstein, A. Weiler JHEP 03 (2009) 141]
- It can be used to discriminate models for top forward-backward asymmetry seen at Tevatron
  [D-W Jung, P. Ko, J.S. Lee, Phys. Lett. B 701 (2011) 248
  D. Choudhury, R.M. Godbole, SDR, P. Saha, Phys. Rev. D 84, 014023 (2011)]

Example of polarization in cascade decay

Top quark polarization vs. parent particle mass *M* in GeV
Purely chiral couplings.



Solid curves: Stop decaying into top and neutralino

The red (upper) curve has a fixed neutralino mass of 200 GeV. The blue (lower) curves have neutralino mass of $M - 200$ GeV.

Dashed curves: Spin-1/2 heavy quark *T* decaying into top and spin-1 particle.

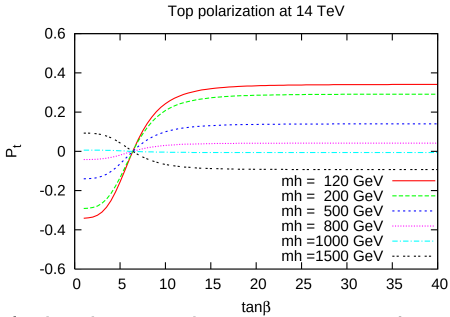
[J. Shelton, Phys. Rev. D. 79, 014032 (2009)]

Top polarization charged Higgs decay

- In type II two Higgs doublet model charged Higgs bosons coupling to top depends on $\tan\beta$ (ratio of vev's)

$$g_{tbH^-} = \frac{g}{\sqrt{2}m_W}(m_t \cot\beta P_L + m_b \tan\beta P_R)$$

  - The chiral couplings lead to top polarization in tH^- production



- Polarization can be a measure of $\tan\beta$ if $m_H^{\pm}$ is known

[K. Huitu, K. Rao, SDR, P. Sharma, JHEP 04 (2011) 026]

Top spin correlation vs. single top polarization

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

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

- This has been very well studied theoretically
- Also experimentally feasible
- Needs reconstruction of both t and $\bar{t}$ rest frames
- It is conceivable that single top polarization can give better statistics
- At Tevatron or LHC, single top polarization implies new physics

Measuring polarization

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

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

where

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

Analyzing power for various channels

The analyzing power k_f for various channels is given by:

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

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

$$\kappa_{\ell^+} = \kappa_d = 1$$

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 $\kappa_j \simeq 0.5$

Corrections to the analyzing power

- 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
- To take into account spin correlations – need a spin density matrix formalism

Spin density matrix

At amplitude level

$$M(A{+}B \to t{+}X \to f{+}X'{+}X) = M(A{+}B \to t(\lambda)X)\ \ M(t(\lambda) \to fX')$$

At transition probability level

$$\begin{aligned}|M(AB \to tX \to fX'X)|^2 = \ & M(AB \to t(\lambda)X)\, M(AB \to t(\lambda')X)^* \\ & \times M(t(\lambda) \to fX')\, M(t(\lambda') \to fX')^*\end{aligned}$$

OR

$$|M(A + B \to t + X \to f + X' + X)|^2 = \rho(\lambda, \lambda')\ \Gamma(\lambda, \lambda')$$

ρ: production density matrix
Γ: decay density matrix

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

A "theorem"

- The angular distribution of charged leptons (down quarks) from top decay is not affected by anomalous *tbW* couplings (to linear order)
- Checked earlier for $e^- e^+ \to t\bar{t}$ [Grzadkowski & Hioki, SDR (2000)] and for $\gamma\gamma \to t\bar{t}$ [B. Grzadkowski & Z. Hioki; R.M. Godbole, SDR, R.K. Singh]
- This is shown for any general process $A + B \to t + X$ in the c.m. frame [R.M. Godbole, SDR, R.K. 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

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- 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
- On the other hand, energy distributions, *b*, *W* angular distributions help to study anomalous *tbW* couplings

Factorization property

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

$$\langle \Gamma(\lambda, \lambda') \rangle \propto A(\lambda, \lambda')\; F(E_\ell^0)$$

where

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

How do we measure polarization in the lab. frame?

- We look at a top quark produced with some fixed energy E_t
- If its p_T is fixed, so is its angle with the beam direction
- The rest frame distribution $\frac{1}{2}(1 + P_t \cos\theta_\ell^*)$ gets an appropriate boost:

$$N(\theta_{t\ell}) = \frac{1}{2} \frac{(1 - P_t\beta_t)(1 + P_t \cos\theta_{t\ell})}{(1 - \beta_t \cos\theta_{t\ell})^2}(1 - \beta_t^2)$$

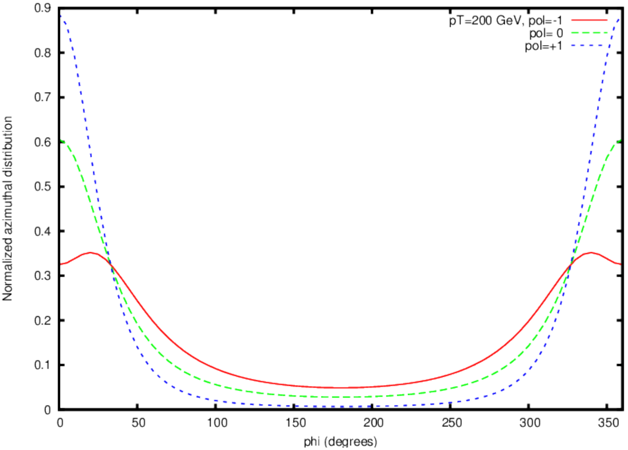
$$\beta_t = \frac{1}{\sqrt{1 - m_t^2/E_t^2}}$$

$$\cos\theta_{t\ell} = \cos\theta_t \cos\theta_\ell + \sin\theta_t \sin\theta_\ell \cos\phi_\ell$$

- This enhances the forward-backward asymmetry of the lepton
- However, at a pp collider there is no distinction between forward and backward
- More interesting: azimuthal distribution

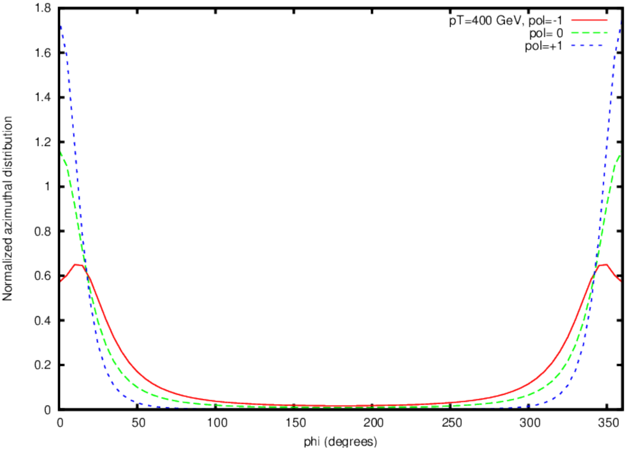
Lepton azimuthal distributions

Azimuthal distribution for $E_t = 600$ GeV, $p_t^T = 200$ GeV



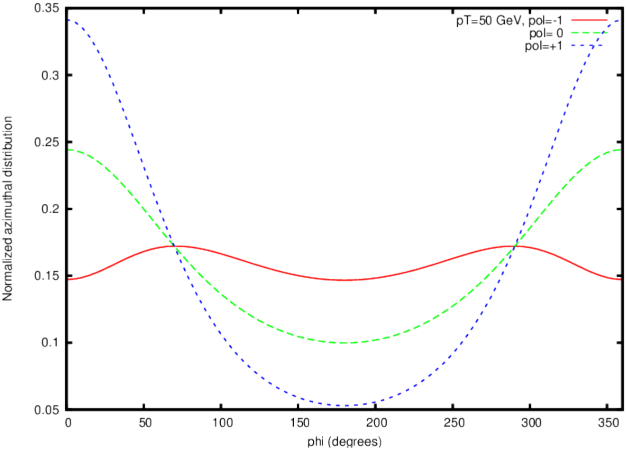
Lepton azimuthal distributions

Azimuthal distribution for $E_t = 600$ GeV, $p_t^T = 400$ GeV



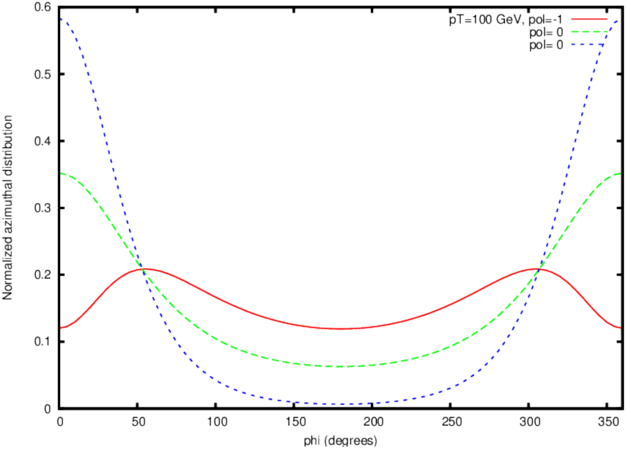
Lepton azimuthal distributions

Azimuthal distribution for $E_t = 200$ GeV, $p_t^T = 50$ GeV



Lepton azimuthal distributions

Azimuthal distribution for $E_t = 200$ GeV, $p_t^T = 100$ GeV



Toy model for top production

- Top production distribution: $a_0 + a_2 \cos^2\theta_t$
- The double distribution is then:

$$N(\cos\theta_t, \cos\theta_\ell) = \frac{1}{2}(1 + P_t \cos\theta_{t\ell})(a_0 + a_2\cos^2\theta_t)$$

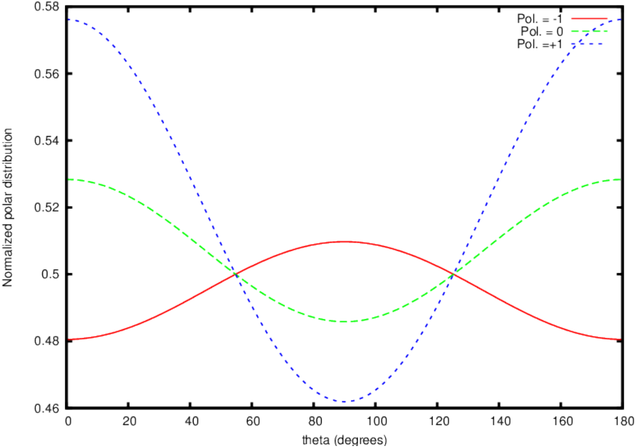
- Reduces to

$$\frac{1}{2}(1 + P_t \cos\theta_{t\ell})$$

  on integration over $\cos\theta_t$
- Consider lepton polar and azimuthal distributions in lab. frame

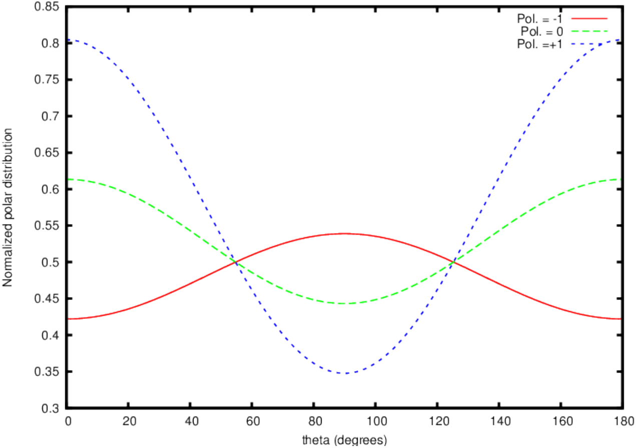
Lepton polar distribution

Choice of model: $a_0 = 1, a_2 = 0$: **Flat** distribution
Choice of model: $a_0 = 1, a_2 = 1$, $E_t = 200$ GeV:



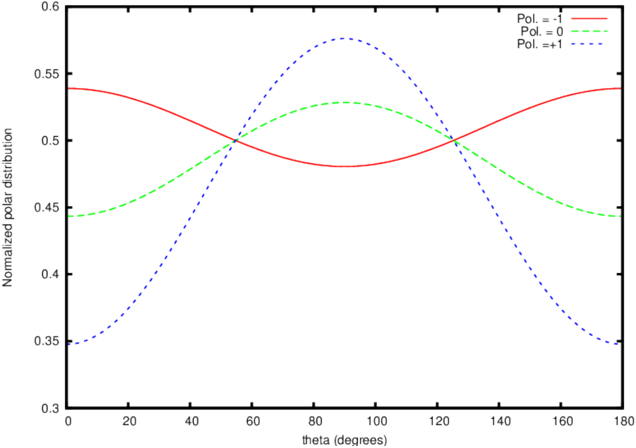
Lepton polar distribution

Choice of model: $a_0 = 0, a_2 = 1$, $E_t = 200$ GeV:



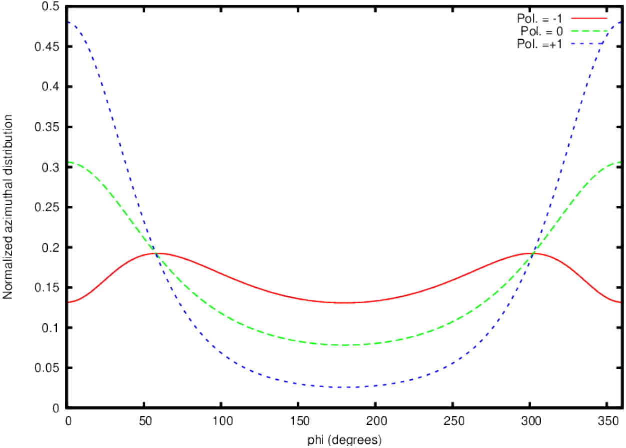
Lepton polar distribution

Choice of model: $a_0 = 1, a_2 = -1$, $E_t = 200$ GeV:



Lepton azimuthal distribution

Choice of model: $a_0 = 1, a_2 = 0$, $E_t = 200$ GeV:



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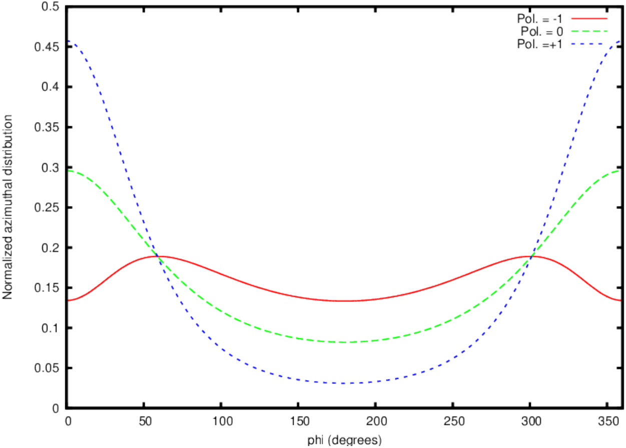
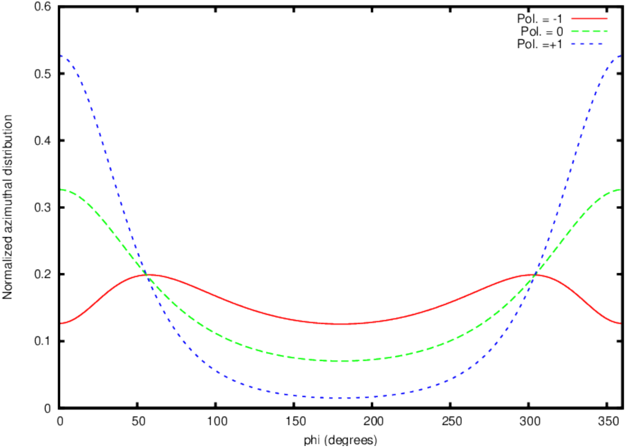


Lepton azimuthal distribution

Choice of model: $a_0 = 1, a_2 = -1$, $E_t = 200$ GeV:



Little Higgs Model

- We choose for illustration and extra Z model
- Litle Higgs model has an extra massive gauge boson Z_H with left-handed couplings to fermions depending on one parameter (θ):

$$g_V^u = g_A^u = g \cot\theta$$

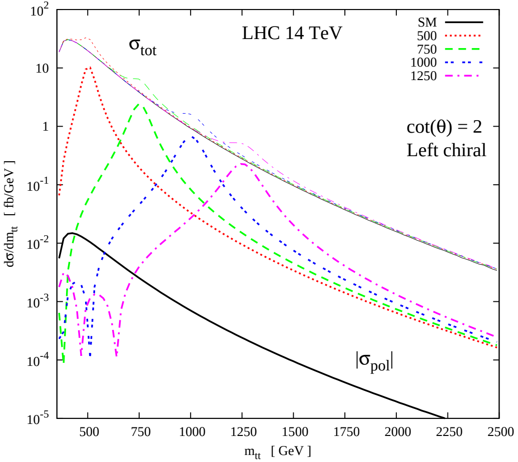
$$g_V^d = g_A^d = -g \cot\theta$$

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

[R. Godbole, K. Rao, SDR, R.K. Singh, JHEP 11 (2010) 144]

$t\bar{t}$ invariant mass distribution

The model can be tested using the $t\bar{t}$ invariant mass distribution

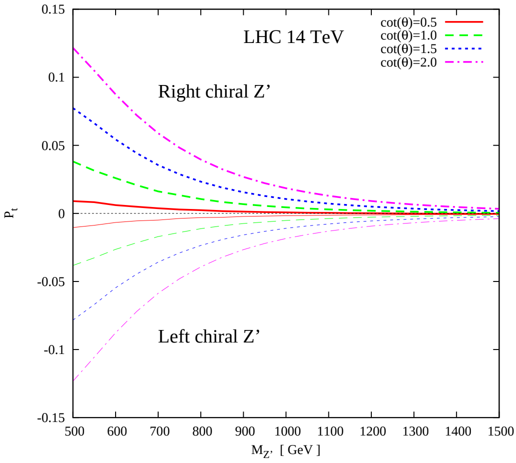


Polarization can be a further more sensitive test

Top longitudinal polarization

Degree of top polarization:

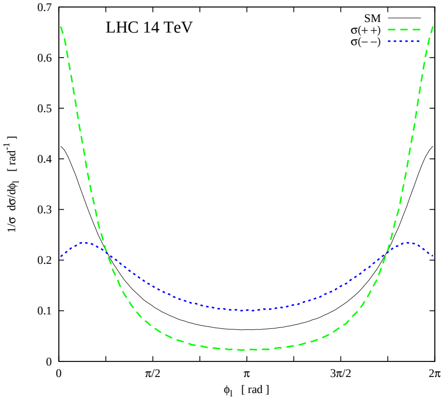
$$P_t \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



Azimuthal distribution of the charged lepton

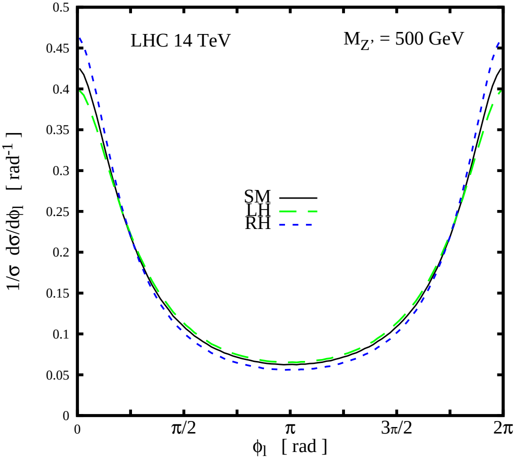
Azimuthal angle of the charged lepton ϕ_l defined with:

- beam axis as Z axis
- $t\bar{t}$ production plane as the XZ plane



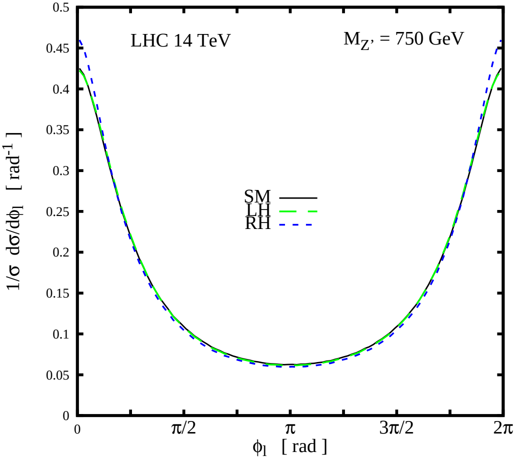
Azimuthal distribution of the charged lepton

Normalized ϕ_l distribution, $m_{Z'} = 500$ GeV



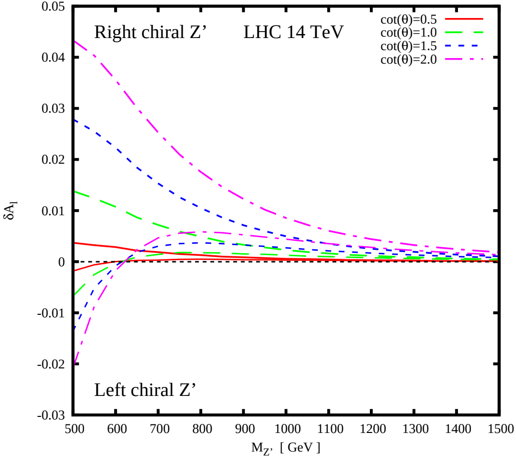
Azimuthal distribution of the charged lepton

Normalized ϕ_l distribution, $m_{Z'} = 750$ GeV



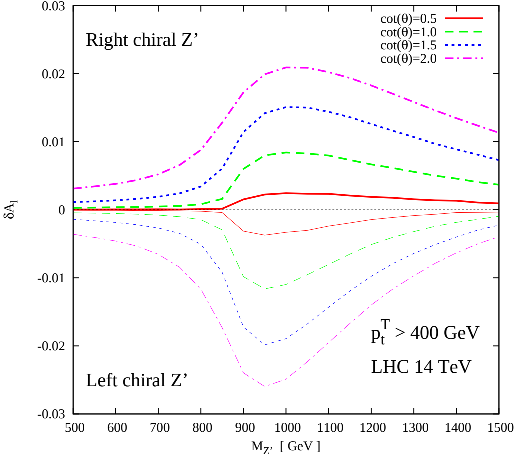
Azimuthal asymmetry of charged lepton

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



Azimuthal asymmetry with cut-off

For better discrimination, use a cut-off in p_t^T:



Hints for polarization determination

- Azimuthal distribution in lab. frame non-trivial in SM (with ≈ 0 polarization)
- This is a pure *kinematic effect*
- There is also an effect of polarization
- Choose kinematical region to enhance the polarization effect
- Choosing large transverse momentum sample seems to work

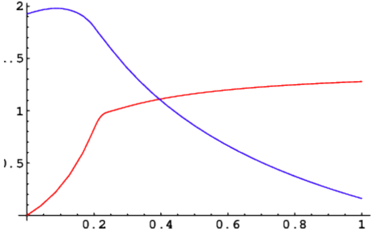
Collimated top quarks

Systems with large invariant mass of $t\bar{t}$ can produce highly boosted tops – with collimated decay products

- 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.

$$u = \frac{E_\ell}{E_\ell + E_b},$$

[J. Shelton PRD 79, 014032 (2009)]



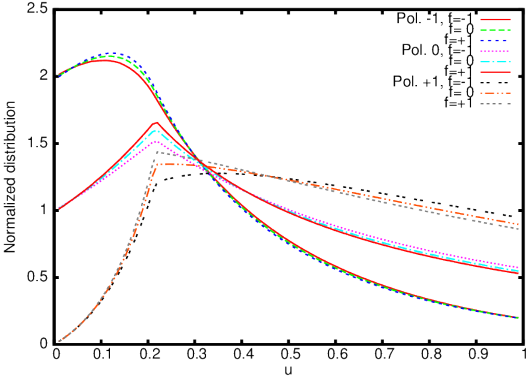
Blue: right-handed; Red: left-handed

Top polarization for large β_t

Anomalous $\bar{t}bW^+$ vertex can be written as

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

Effect of anomalous coupling may not be distinguishable from effect of polarization



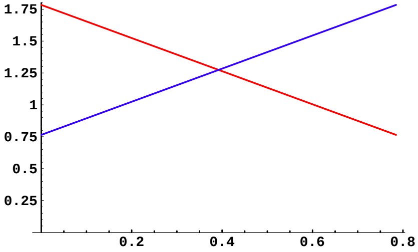
Collimated top quarks

Another variable: fraction of the visible energy carried by the *b* quark

$$z = \frac{E_b}{E_\ell + E_b},$$

[J. Shelton PRD 79, 014032 (2009)]

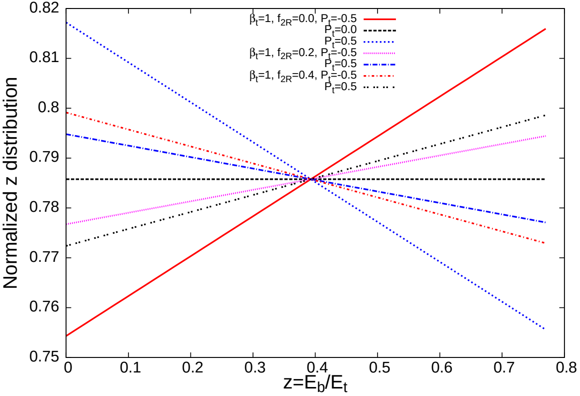
Red: positive helicity top; Blue: Negative helicity top



z

Top polarization for large β_t

z distributions with different polarizations and different anomalous couplings can be confused



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
- On the other hand – they can be used to measure anomalous couplings
- Example: Single-top production in association with *W* at the LHC

  [SDR, P. Sharma JHEP 11 (2011) 082]

  [Including CP violation: PLB 712 (2012) 413]

Associated single-top W production at LHC

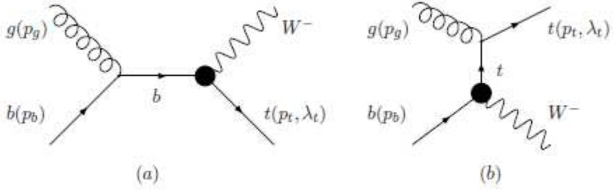
Single-top production in association with W^- has been seen at LHC

- ATLAS: $16.8 \pm 2.9(\mathit{syst}) \pm 4.9(\mathit{stat})$ pb
- CMS: $22^{+9}_{-7}(\mathit{syst} + \mathit{stat})$ pb

- Theory: $15.6 \pm 0.4(\mathit{scale})^{+1.0}_{-1.2}(\mathit{PDF})$ pb

- Direct measurement of $V_{tb} = 1.03^{+0.16}_{-0.19}$ (ATLAS)

Determination of anomalous *tbW* couplings



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

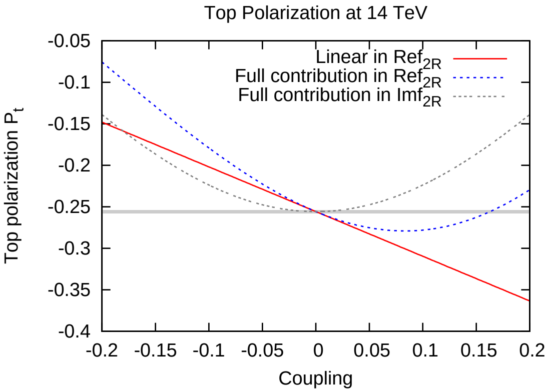
$$\Gamma^\mu = \frac{g}{\sqrt{2}} \left[\gamma^\mu (f_{1L} P_L + f_{1R} P_R) - \frac{i\sigma^{\mu\nu}}{m_W} (p_t - p_b)_\nu \, (f_{2L} P_L + f_{2R} P_R) \right]$$

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

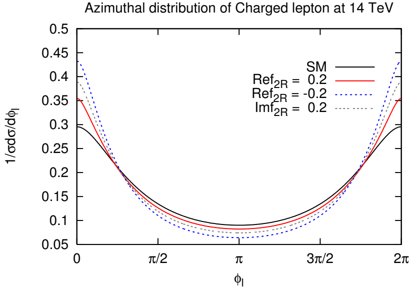
To a good approximation, only f_{2R} contributes

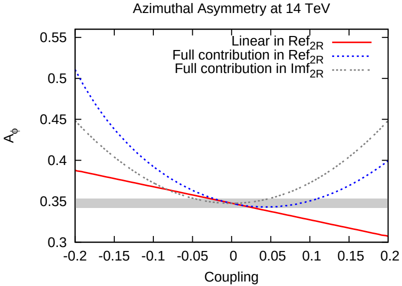
Polarization in single-top production

Polarization of the top quark in $pp \to tW^- + X$

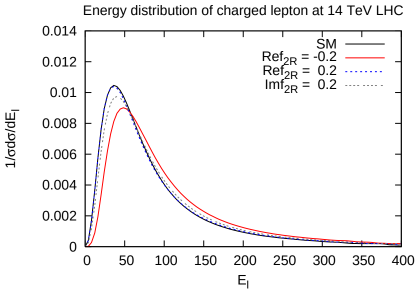


Determination of anomalous *tbW* couplings



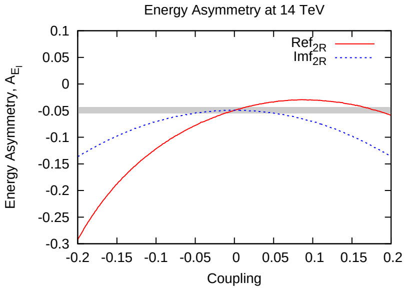


Determination of anomalous tbW couplings



The curves intersect at $E_l = 62$ GeV

Construct A_{E_ℓ}, asymmetry about $E_l = 62$ GeV



Sensitivity

For LHC at $\sqrt{s} = 14$ TeV with integrated luminosity 10 fb^{-1}, possible 90% CL limits:

- $[-0.034, 0.086]$ on $\mathrm{Re} f_{2\mathrm{R}}$ from A_ϕ
- A_{E_ℓ} is the most sensitive
- Limit on $\mathrm{Re} f_{2\mathrm{R}}$ of $[-0.006, 0.009]$ possible.

W helicity measurement

- Helicity fractions of W in top decay are given by

$$F_0 = \frac{M_t^2}{(M_t^2 + 2M_W^2)} = 0.703 + 0.002(m_t - 175)$$
$$F_L = \frac{2M_W^2}{(M_t^2 + 2M_W^2)} = 0.297 - 0.002(m_t - 175)$$
$$F_R = 0$$

- Suggestion has been made to measure W helicity to study anomalous couplings
  [F. del Aguila, J. Aguilar-Saavedra, PRD 67, 014009 (2003)
  C.-R. Chen, F. Larios, C.-P. Yuan, hep-ph/0503040]

Summary

- Top polarization could be useful in many different theoretical scenarios where top is one of the particles produced at LHC
- A relatively clean signature of top polarization is the secondary lepton angular distribution
- Azimuthal distribution of charged lepton is a particularly sensitive test.
- Polarization contribution can be enhanced by appropriate cuts (e.g. p_T)
- Lepton energy distribution and *b*-quark energy and angular distributions can be used to measure anomalous couplings in decay.
- Many other interesting scenarios deserve study
- Detailed study including appropriate cuts, parton showering, needed
- Comparison of sensitivities with of single top and spin correlations needed