Study of top-quark anomalous couplings through polarization

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Introduction

- LHC seems to re-confirm the standard model in the 7 TeV and 8 TeV runs
- A Higgs boson is so far 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

Utilizing top polarization

- Why?: Discriminating among top production scenarios
- How?: Measurement of top polarization:
  Charged lepton angular distributions in the lab. frame

Anomalous gluon couplings to $t\bar{t}$ in top pair production at the LHC

- Determination of polarization using charged lepton asymmetries
- Measuring anomalous couplings at the LHC

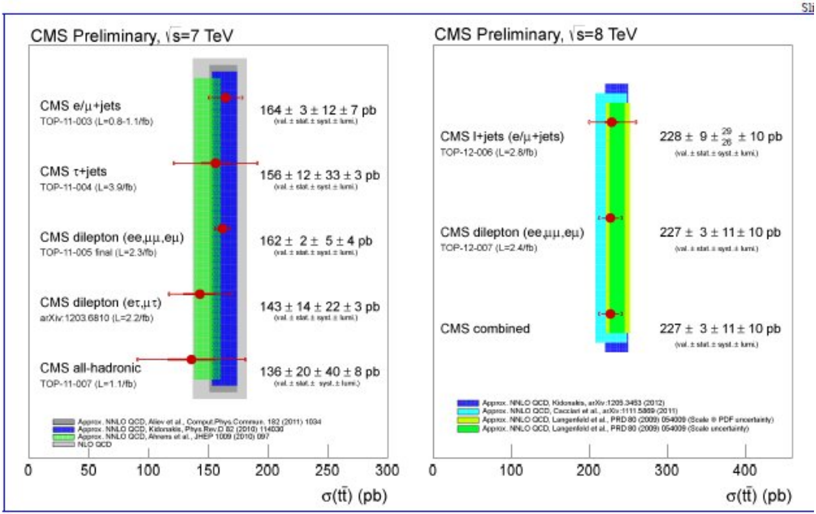
Top quark production at LHC

- 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 is heavy – it 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
  - $\ell\nu_\ell$ (lepton + missing energy) (B.R.1/9 for each lepton)
- Mass reconstruction better with two jets, but large background
- Leptonic signature cleaner, but mass reconstruction difficult
- For $t\bar{t}$ final state, the best detection channel is semileptonic
  - t decays into $b\ell^+\nu_\ell$
  - $\bar{t}$ decays into $\bar{b}$ + 2 jets
  - or vice versa

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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

How does knowing top polarization help?

- More information on production mechanism than just the (differential) cross section
- Enables measurement of parameters of the theory
- Polarization is parity violating, hence measures chiral couplings

Use of top polarization

Possible applications

- Measurement of anomalous colour dipole couplings
  [S. Biswal, SDR, P. Sharma, arXiv:1211.4075]
- 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]
- Discrimination of 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)]
- Determination of $t\bar{W}^-$, $t\bar{H}^-$ couplings in single-top production
  [P. Sharma, SDR, JHEP 11 (2011) 082
  P. Sharma, SDR, Phys. Lett. B 712 (2012) 413
  K. Huitu, S.K. Rai, K. Rao, SDR, P. Sharma, JHEP 04 (2011) 026
  R.M. Godbole et al., JHEP 01 (2012) 011]

Top spin correlation vs. single top polarization

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

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

θ_a, θ_b: angles between spin and some reference axis of t and $\bar{t}$

- 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
- Non-zero in SM, whereas 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

$$M(AB \to tX \to fX'X) = \sum_{\lambda} M(AB \to t(\lambda)X) \;\; M(t(\lambda) \to fX')$$

At transition probability level

$$|M(AB \to tX \to fX'X)|^2 = \sum_{\lambda,\lambda'} M(AB \to t(\lambda)X)\, M(AB \to t(\lambda')X)^*$$

$$\times M(t(\lambda) \to fX')\, M(t(\lambda') \to fX')^*$$

OR

$$|M(AB \to tX \to fX'X)|^2 = \sum_{\lambda,\lambda'} \sigma(\lambda, \lambda')\, \Gamma(\lambda, \lambda')$$

σ: production density matrix

Γ: decay density matrix

Anomalous *tbW* couplings

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

Anomalous couplings

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

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 (2002)]
- This is shown for any general process $A + B \to t + X$ in the c.m. frame
  [B. Grzadkowski, Z. Hioki (2003); R.M. Godbole, SDR, R.K. Singh (2006)]
- Assumes narrow-width approximation for the top

Measures of top polarization

- Charged-lepton angular distributions are more accurate probes of top polarization, rather than any energy distributions or *b* or *W* angular distributions
- On the other hand, energy distributions, *b*, *W* angular distributions help to study anomalous *tbW* couplings
- For boosted tops angular distributions may be difficult to use, and other methods may be needed.

  [B. Bhattacherjee, S.K. Mondal, M. Nojiri (2013); D. Krohn, J. Shelton, L.-T. Wang (2010)]

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:

$$\frac{1}{\Gamma}\frac{d\Gamma(\theta_{t\ell})}{d\cos\theta_{t\ell}} = \frac{1}{2}\frac{(1 - P_t\beta_t)(1 + P_t\cos\theta_{t\ell})}{(1 - \beta_t\cos\theta_{t\ell})^3}(1 - \beta_t^2)$$

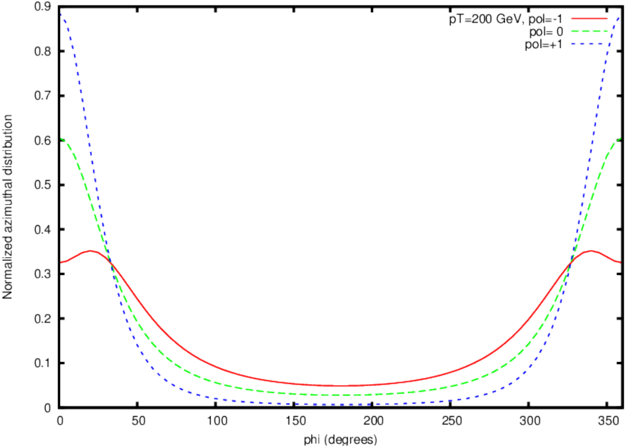
$$\beta_t = \frac{1}{\sqrt{1 - m_t^2/E_t^2}}$$

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

- 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

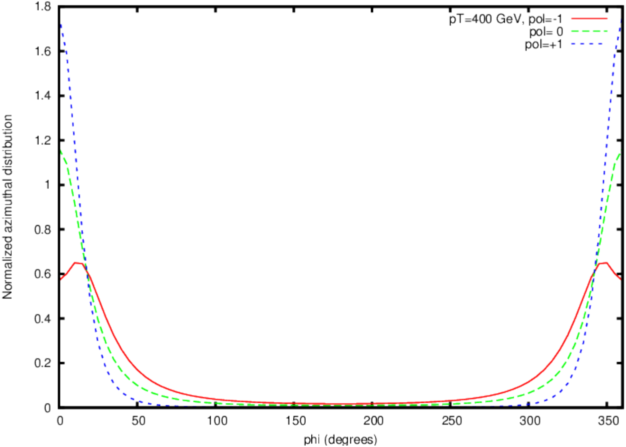
Lepton azimuthal distributions

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



Extra Z 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):

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

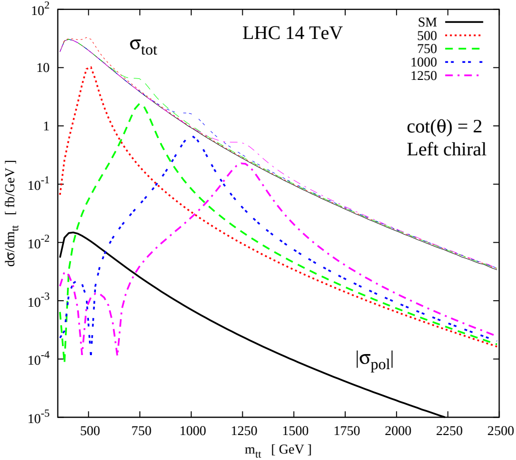
$$g_V^d = g_A^d = -g \cot\theta$$

- $t\bar{t}$ 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

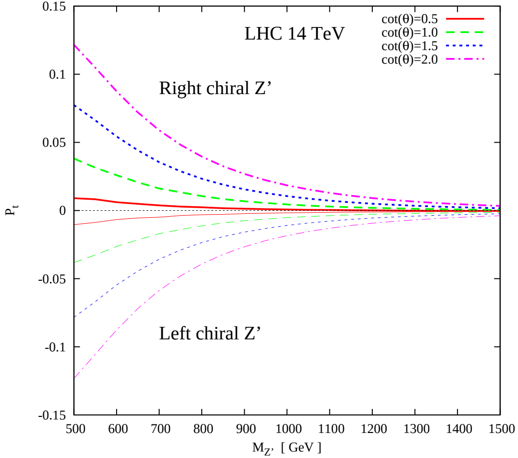


Polarization can be a further more sensitive test

Top longitudinal polarization

Degree of top polarization:

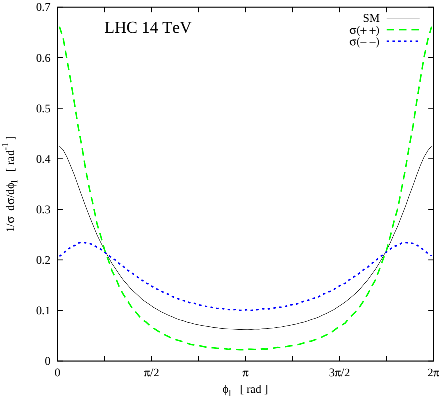
$$P_t \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



Azimuthal distribution of the charged lepton

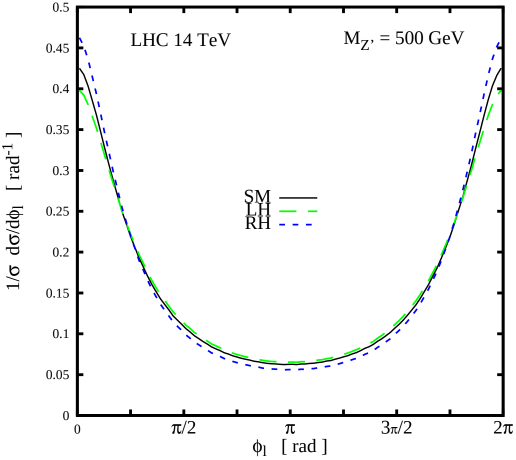
Azimuthal angle of the charged lepton ϕ_ℓ defined with:

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



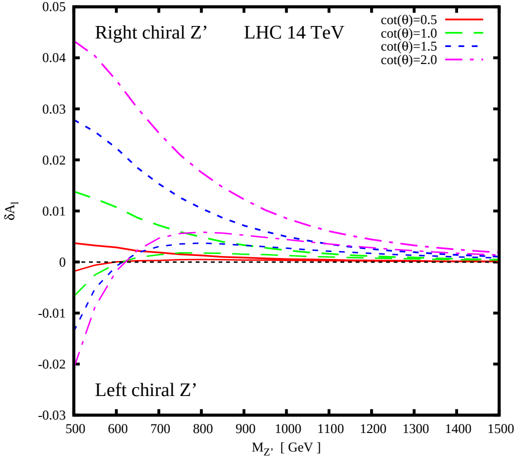
Azimuthal distribution of the charged lepton

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



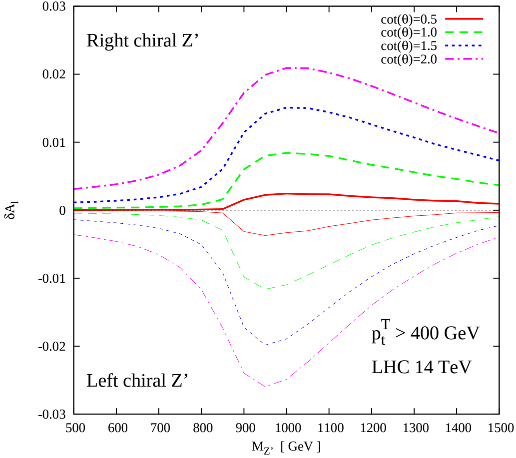
Azimuthal asymmetry of charged lepton

$$A_\phi = \frac{1}{\sigma}\left[\sigma(\cos(\phi_\ell) > 0) - \sigma(\cos(\phi_\ell) < 0)\right]$$



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

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]

Anomalous $t\bar{t}g$ couplings through top polarization in top pair production at the LHC

Based on S. Biswal, SDR, P. Sharma, arXiv:1211.4075

Anomalous $t\bar{t}g$ couplings

Anomalous chromomagnetic and chromoelectric couplings:

$$\Gamma_a^\mu = \frac{g_s}{m_t}\, \sigma^{\mu\nu} \left(\rho + i\rho' \gamma_5\right) q_\nu\ T_a,$$

q_ν is momentum of the gluon

ρ, ρ': complex form factors

ρ term is P, T, CP conserving

ρ' term is P, T, CP violating

- In the **Standard Model** ρ and ρ' are **zero** at tree level.
- ρ arises at one loop (-5.6×10^{-2}), while ρ' arises at three loops
- Some one-loop calculations in other models:
  - MSSM [T. Ibrahim, P. Nath, PRD (2011)]
  - 2HDM, TC2, UED [R. Martinez, M.A. Perez, N. Poveda, EPJ C (2008)]
  - LH models [Q. -H. Cao et al., PRD (2009), L. Ding, C.-X. Yue, CTP (2008)]

Some recent work

Signatures of anomalous couplings at hadron colliders have been studied recently by

- W. Bernreuther, Z.-G. Si [arXiv:1305.2066]
- S.K. Gupta, G. Valencia [PRD 81, 034013 (2010)]
- S.K. Gupta, A.S. Mete, G. Valencia [PRD 80, 034013 (2009)]
- Z. Hioki, K. Ohkuma [EPJ C 65, 127 (2010), PRD 83, 114045 (2011), Phys. Lett. B 716, 310 (2012)]
- H. Hesari, M.M. Najafabadi [arXiv:1207.0339]
- D. Choudhury, P. Saha [Pramana 77, 1079 (2011)]

Density-matrix formalism

For the calculation of the final-state charged-lepton distributions arising from t or $\bar{t}$, we need to use

The spin density matrix formalism

$$\overline{\sum}|\mathcal{M}(gg \to t\bar{t} \to (b\ell\nu_\ell)\bar{t})|^2 = \frac{\pi\delta(p_t^2 - m_t^2)}{\Gamma_t m_t}\left(\sum_{\lambda,\lambda'} \sigma^{\lambda\lambda'}\,\Gamma^{\lambda\lambda'}\right),$$

$\sigma^{\lambda\lambda'}$, $\Gamma^{\lambda\lambda'}$: 2×2 production and decay spin density matrices

Since $\Gamma_t \approx 1.5$ GeV $<< m_t$, the narrow-width approximation is used.

Analytical expressions at parton level possible

General considerations

- SM contributes only to diagonal elements of the density matrix
- The diagonal density matrix elements can depend only on the couplings Re ρ and Im ρ'
- The off-diagonal elements get a real contribution from Im ρ' and an imaginary contribution from Im ρ
- There is no sensitivity to Re ρ' –
  Re ρ' remains undetermined!
- Top polarization is P odd, hence gets contribution only from Im ρ'
- t and $\bar{t}$ polarizations are equal in magnitude and opposite in sign

Numerical calculations

- Parton level distributions calculated analytically
- Numerical integration for parton distributions (CTEQ6L) and phase space.
- Cuts: acceptance cuts on charged-lepton transverse momentum

$$p_T^\ell > 20\mathrm{GeV}$$

  and on charged-lepton rapidity

$$|\eta| < 2.5$$

- Integrated luminosities assumed for various cases:

Tevatron:	8 fb^{-1}
LHC (7 TeV):	5 fb^{-1}
LHC (8 TeV):	10 fb^{-1}
LHC (14 TeV):	10 fb^{-1}

Observables

- Top-quark polarization: P odd, T even

$$P_t = \frac{\sigma(\vec{s}_t \cdot \vec{p}_t > 0) - \sigma(\vec{s}_t \cdot \vec{p}_t < 0)}{\sigma(\vec{s}_t \cdot \vec{p}_t > 0) + \sigma(\vec{s}_t \cdot \vec{p}_t < 0)}$$

- Lepton charge asymmetry (with cut-off θ_0): CP odd, T even

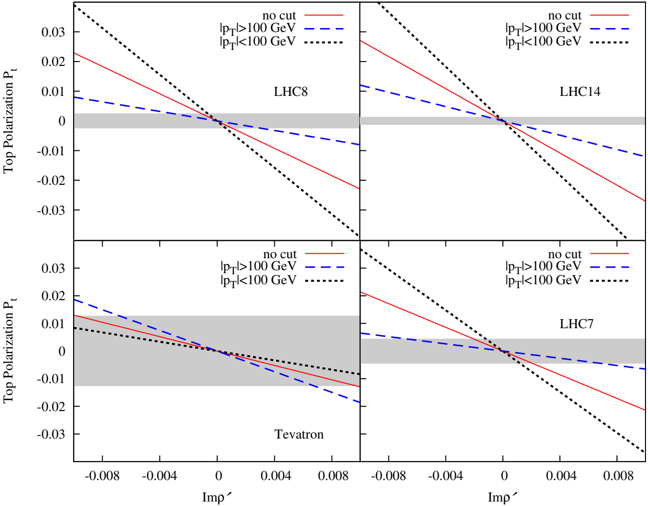
$$A_{\rm ch}(\theta_0) = \frac{1}{2\sigma_{\rm SM}(\theta_0)} \int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left(\frac{d\sigma^+}{d\cos\theta} - \frac{d\sigma^-}{d\cos\theta} \right)$$

- Lepton azimuthal asymmetry: P even, T even

$$A_\phi = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)},$$

Top polarization P_t in $t\bar{t}$ production.

$$P_t \propto \mathrm{Im}\, \rho'$$



Grey band : 3σ error interval in the SM without p_T cut.

Polar angle distribution

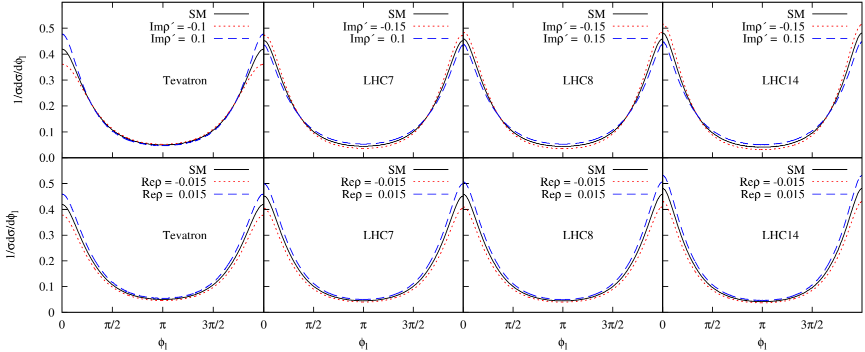
Polar angle θ: Angle between direction of charged lepton and the proton beam direction

Studied by Hioki and Ohkuma (EPJC 2010, 2011)

- At the Tevatron, the polar-angle distribution are sensitive to anomalous *ttg* couplings, but not at the LHC
- Possible in principle to have a forward-backward asymmetry at the Tevatron.
- Chromomagnetic and chromoelectric couplings do not generate an asymmetry

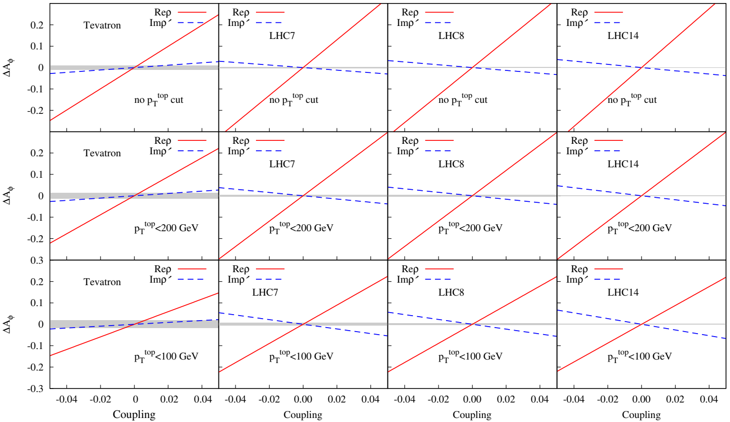
Lepton azimuthal angle ϕ_ℓ: defined with beam direction as *z* axis and top production plane as *xz* plane

Normalized azimuthal distribution of the charged lepton

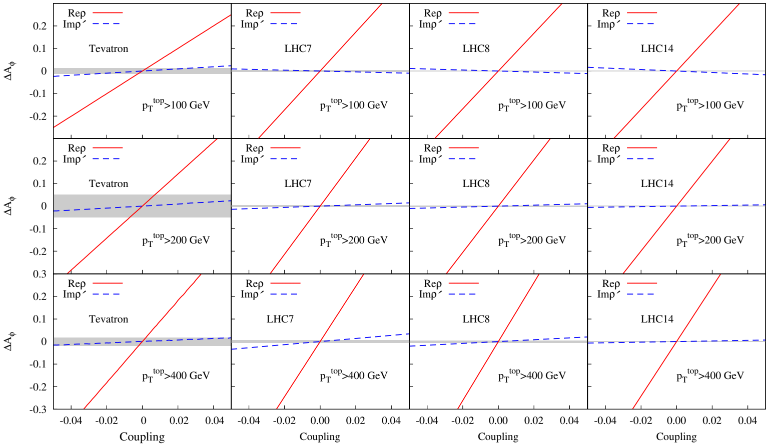


Charged-lepton azimuthal asymmetry (lower p_T)

$$A_\phi = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)}$$

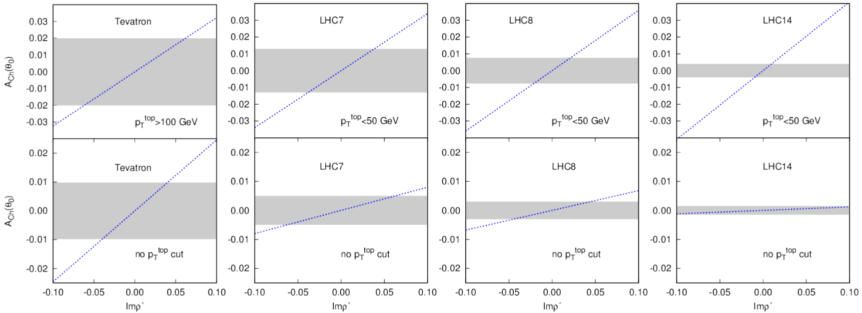


Lepton azimuthal asymmetry (higher p_T)



- A lower (upper) cut on top p_T enhances (reduces) the top polarization at Tevatron
- The reverse is true at LHC

$$A_{\rm ch}(\theta_0) = \frac{1}{2\sigma_{\rm SM}(\theta_0)} \int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left(\frac{d\sigma^+}{d\cos\theta} - \frac{d\sigma^-}{d\cos\theta} \right)$$



Charge asymmetry $A_{\rm ch}(\theta_0)$ for $\theta_0 = \pi/8$.

Individual 3σ Limits

	P_t	A_ϕ		$A_{\rm ch}(\theta_0 = \pi/8)$
	Imρ'	Reρ	Imρ'	Imρ'
Tevatron	1.50×10^{-2}	2.65×10^{-2}	3.35×10^{-1}	–
LHC7	1.37×10^{-3}	8.51×10^{-3}	2.26×10^{-2}	1.78×10^{-2}
LHC8	7.82×10^{-4}	4.41×10^{-3}	1.20×10^{-2}	1.14×10^{-2}
LHC14	3.51×10^{-4}	1.85×10^{-3}	6.09×10^{-3}	5.19×10^{-3}

Cuts:

$p_T <$100 GeV
$p_T <$50 GeV (for $A_{\rm ch}$)

Integrated luminosities:

Tevatron: 8 fb^{-1}
LHC7: 5 fb^{-1}
LHC8: 10 fb^{-1}
LHC14: 10 fb^{-1}

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)

Summary

- We investigated the sensitivity of the Tevatron and LHC to anomalous *ttg* couplings using lepton angular variables
- Only Re ρ and Im ρ' give significant contributions at linear order.
- Azimuthal asymmetry of charged leptons to study polarization and anomalous couplings
- Leptonic charge asymmetry $A_{\rm ch}(\theta_0)$ can measure Im ρ'.
- Limits on anomalous couplings of a few times 10^{-3} should be possible at the next run of LHC
- Detailed simulation studies including appropriate cuts, detector efficiencies, etc. needed, as also NLO contributions

Back-up slides

Factorization property

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

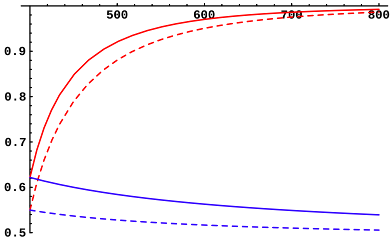
$$\langle \Gamma(\lambda, \lambda') \rangle \propto A(\lambda, \lambda')\ F(E_\ell^0)$$

where

$$A(\pm, \pm) = (1 \pm \cos\theta_\ell), \qquad A(\pm, \mp) = \sin\theta_\ell e^{\pm i\phi_\ell}$$

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.

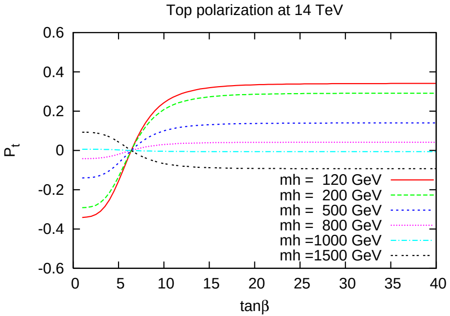
[J. Shelton, Phys. Rev. D. 79, 014032 (2009)]

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]

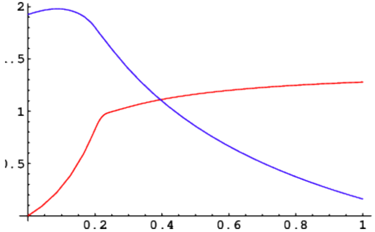
Collimated top quarks

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)]



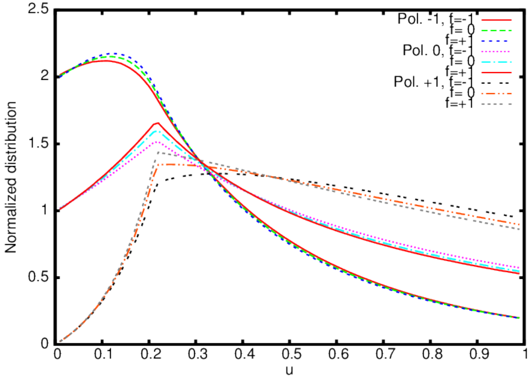
Blue: right-handed; Red: left-handed

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



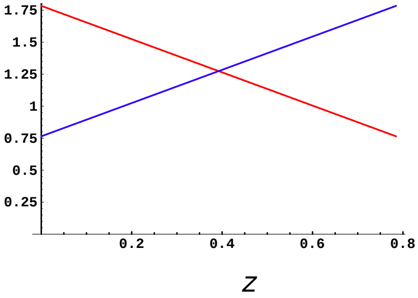
Collimated top quarks

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



Top polarization for large β_t

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