Discriminating Top-Antitop Resonances using Azimuthal Decay Correlations

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14 April 2011
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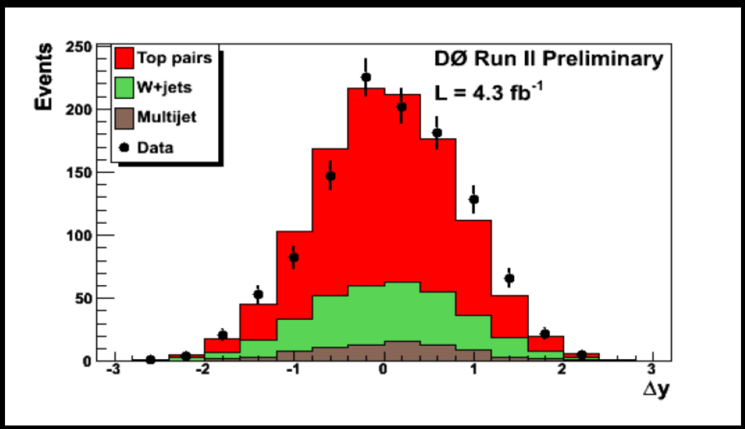
Baumgart and Tweedie, arXiv:1104.2043

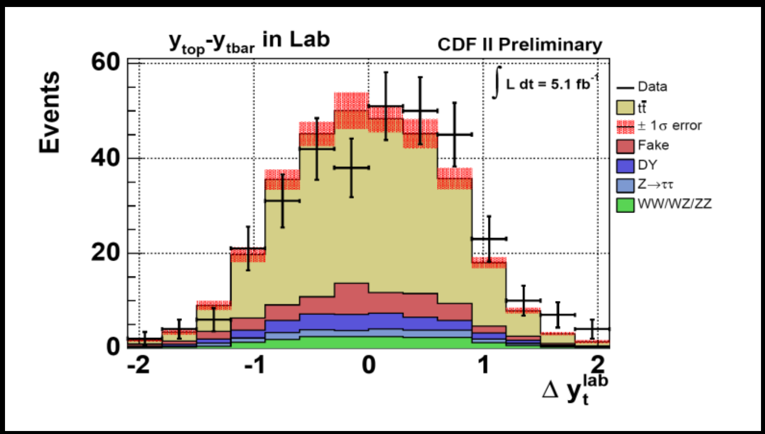
Overview

- Something weird seems to be going on with tops at the Tevatron
- To fully verify the story at the LHC, we may need to consider new variables that characterize top resonances
- Even if the Tevatron anomaly goes away, maybe we should have been thinking about these variables anyway

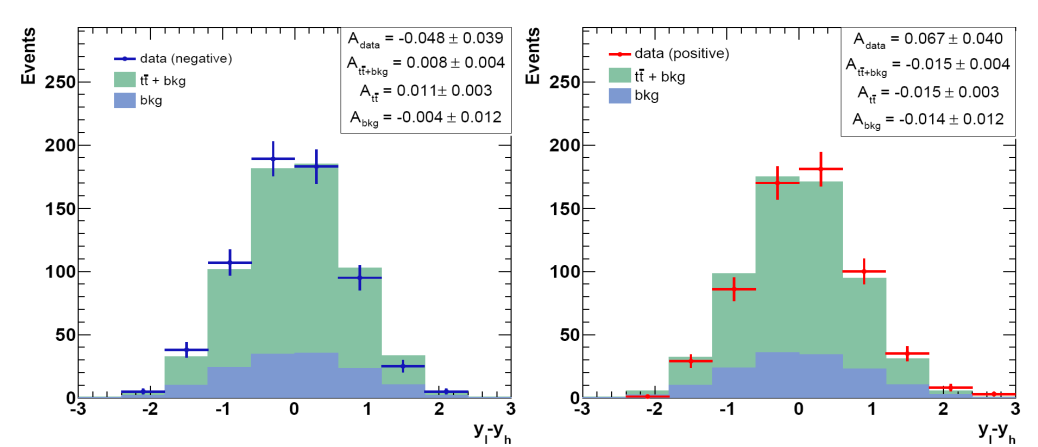
Hmmmm....



D0 Note 6062-CONF

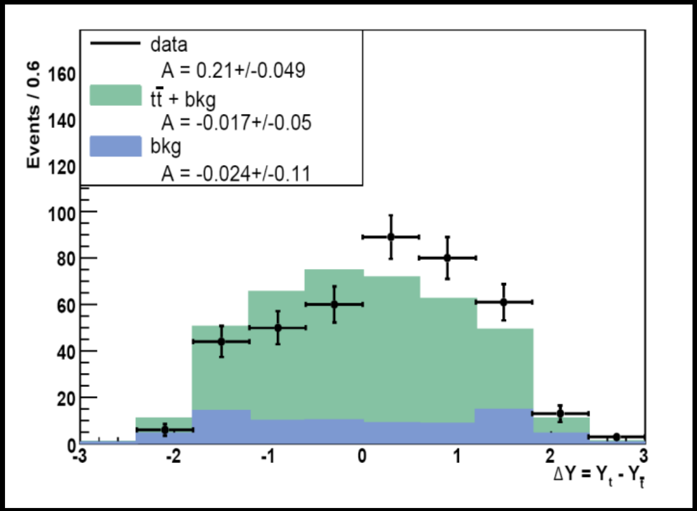


CDF Note 10436 (dileptonic)

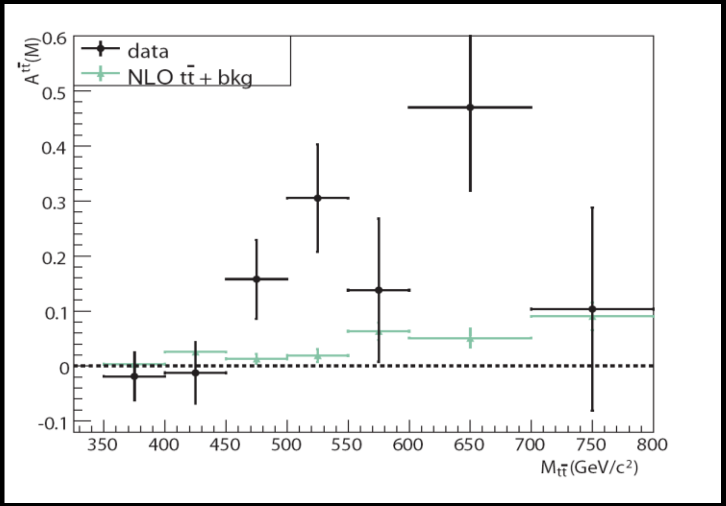


CDF arXiv:1101.0034

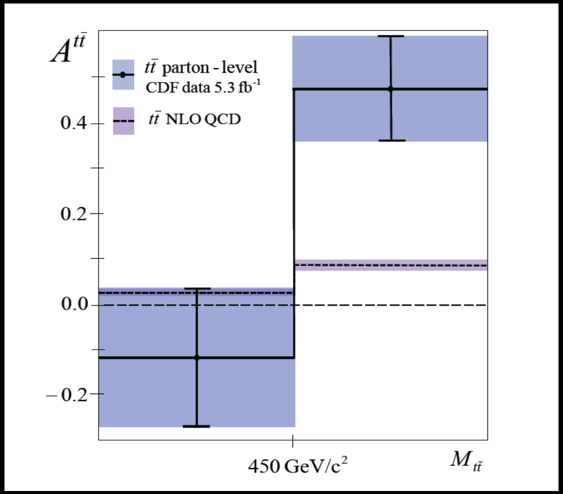
Evidence for New Physics?



m_{tt} > 450 GeV



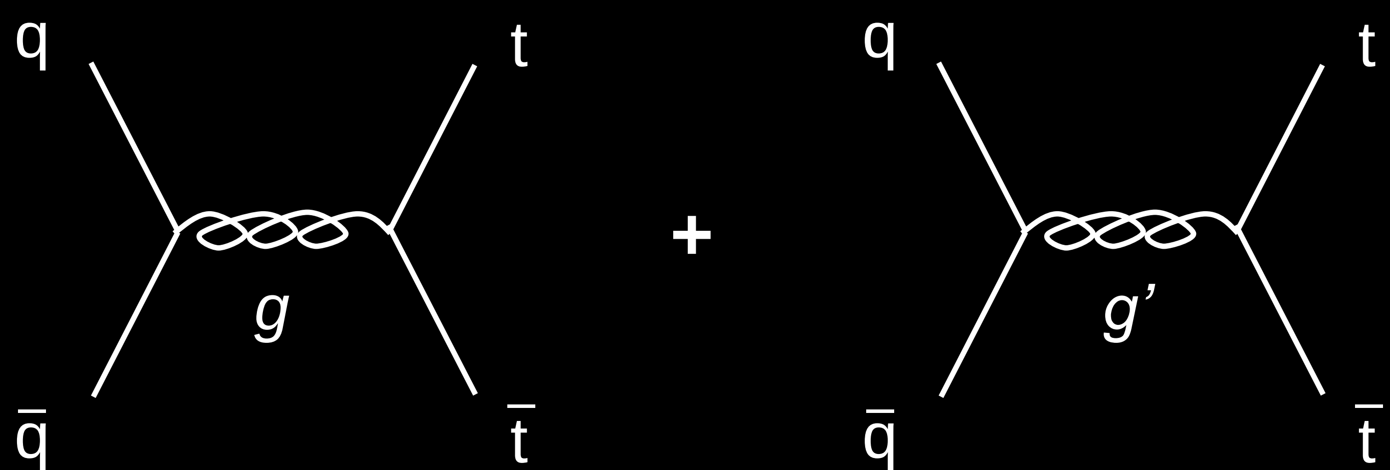
A_{FB} vs m_{tt}



3.4σ after unfolding

CDF arXiv:1101.0034

The Explanation I'm Selling Today: "Axigluons"

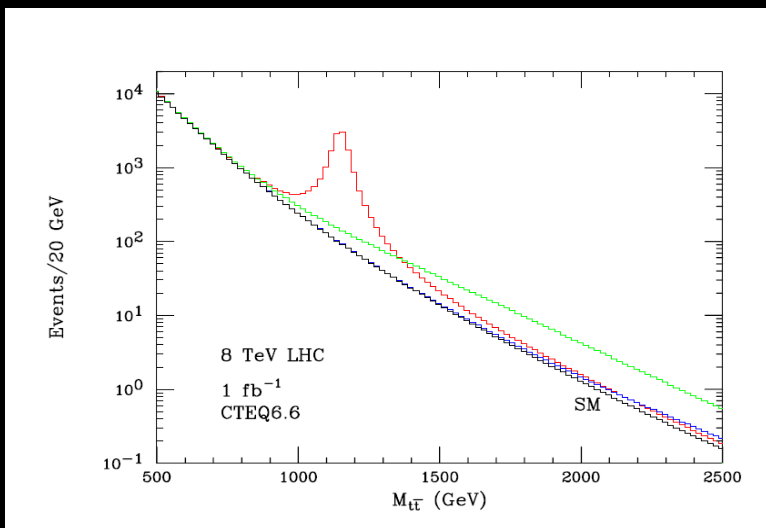


$A_{FB} \sim - g_A^q \, g_A^t$

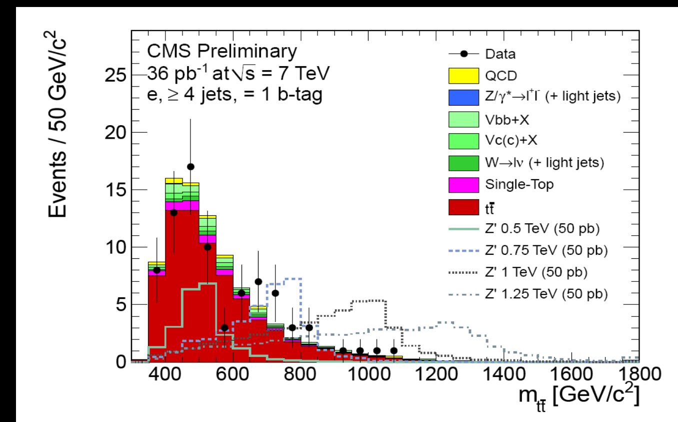
$\Rightarrow \; g_A^q > 0$ and $g_A^t < 0$

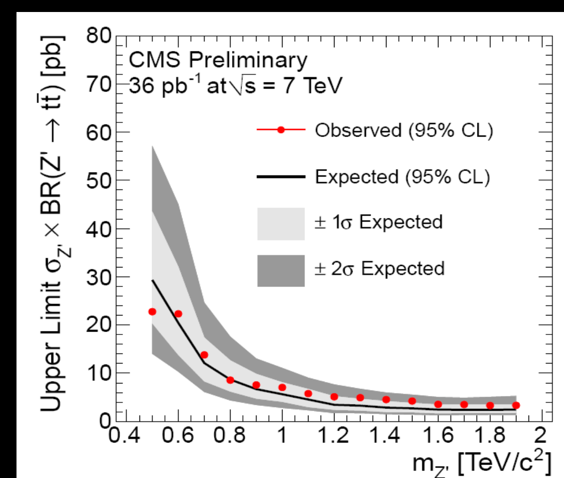
Frampton, Shu, Wang, arXiv:0911.2955

Tevatron Anomaly -> LHC Discovery



Bai, Kaplan, Hewett, Rizzo, arXiv:1101.5203

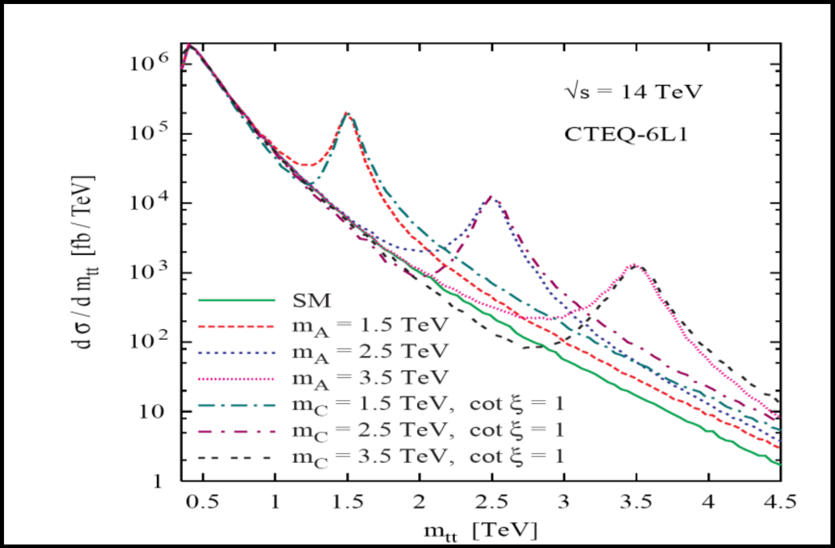




CMS PAS TOP-10-007

How Would We Know if It's an "Axigluon"?

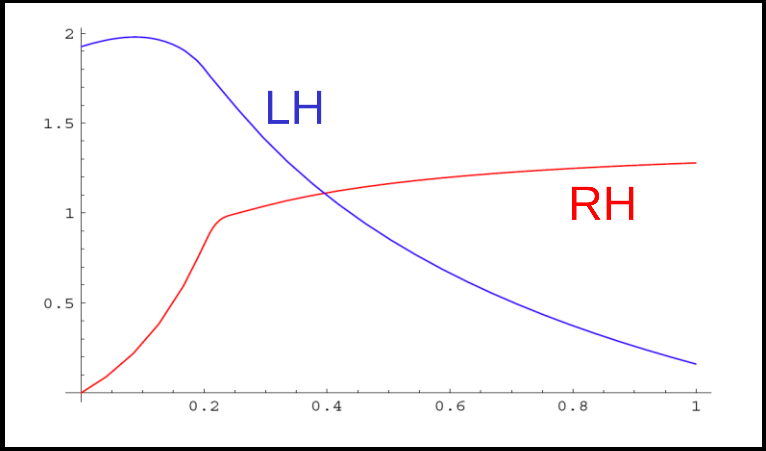
Lineshape interference ~ $g_V^q \, g_V^t$



Choudhury, Godbole, Singh, Wagh, arXiv:0705.1499

Top Polarization

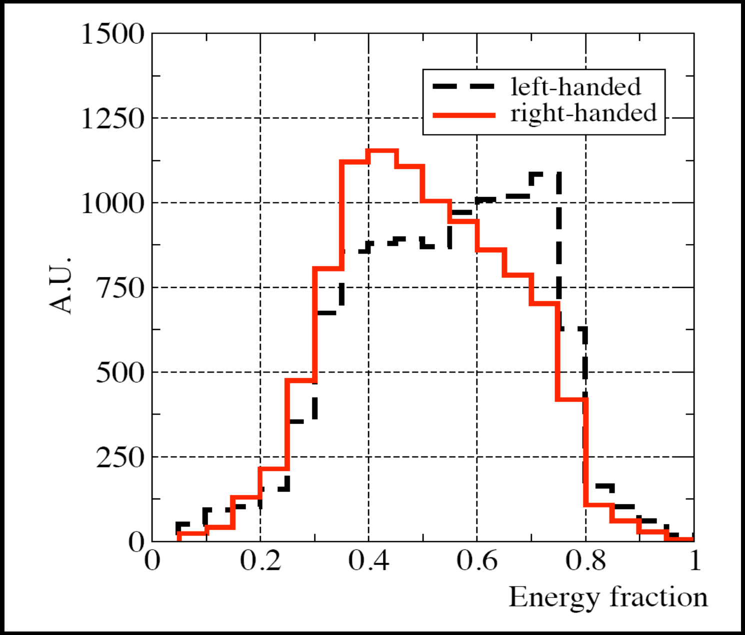
semileptonic energy ratio



$\mathcal{E}_\ell/(\mathcal{E}_\ell+\mathcal{E}_b)$

Shelton, arXiv:0811.0569

subjet energy ratios



Krohn, Shelton, Wang, arXiv:0909.3855

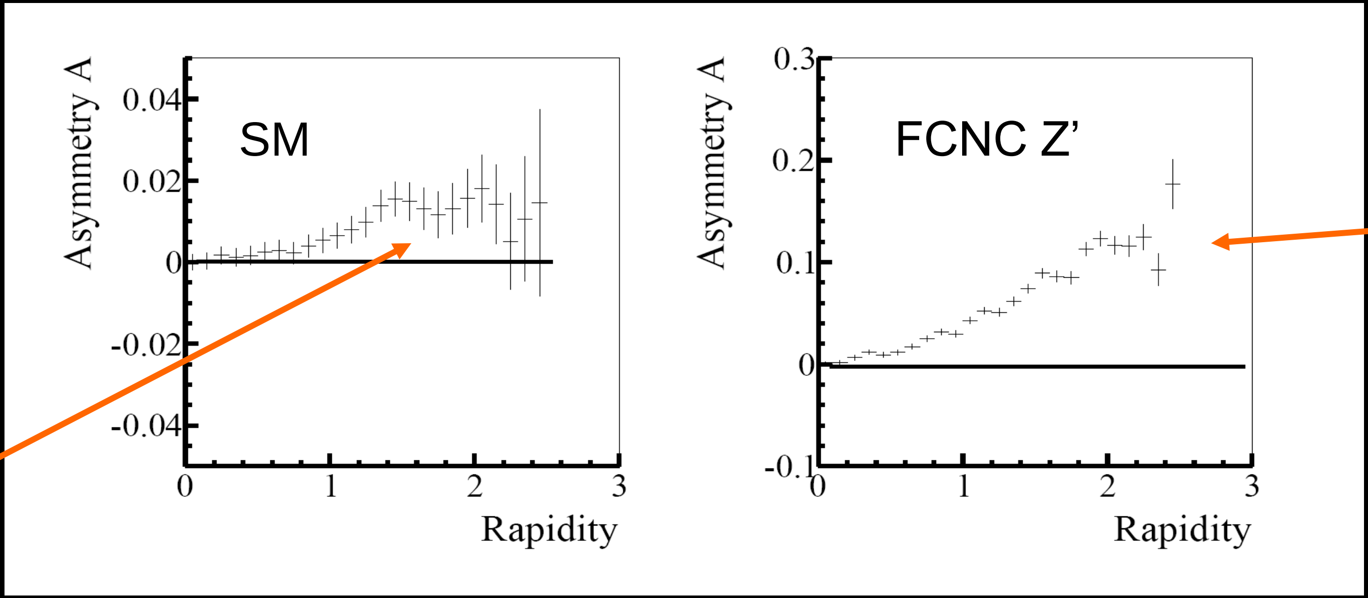
$g_L^t \neq g_R^t \Rightarrow g_A^t \neq 0$

* Also off-peak polarization asymmetry from interference ~ $g_V^q\, g_A^t$

Longer-Term Goal: Direct Measurement of A_{FB} at LHC

Forward charge asymmetry

$$\mathcal{A}_F(y_0) = \frac{N_t(y_0 < |y| < 2.5) - N_{\bar{t}}(y_0 < |y| < 2.5)}{N_t(y_0 < |y| < 2.5) + N_{\bar{t}}(y_0 < |y| < 2.5)}$$



5σ w/ 60 fb^{-1} @LHC14

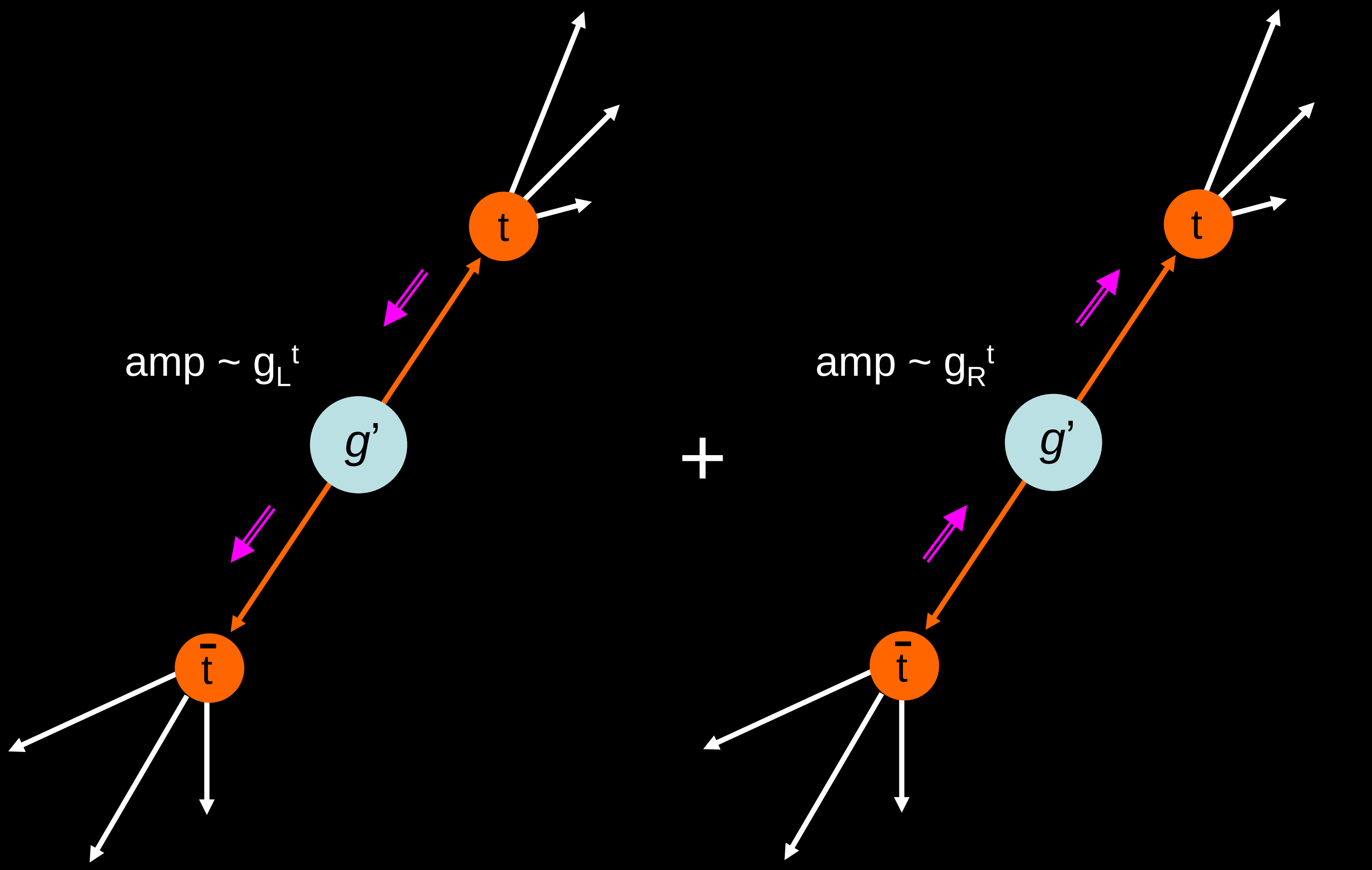
5σ w/ a few fb^{-1} @LHC14

Hewett, Shelton, Spannowsky, Tait, Takeuchi, arXiv:1103.4618

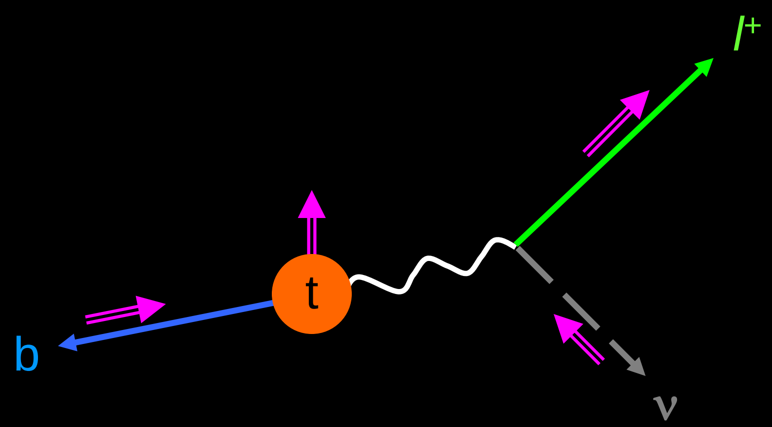
Lingering Issues

- Most observables entangle the top charges with the quark charges
  - absence of lineshape/polarization interference would only tell us that the quarks are axially charged, not the tops
- On-peak helicity bias tells us about the magnitude of g_L^t/g_R^t but not the relative sign
  - pure vector and pure axial look identical
- Might eventually measure A_{FB} directly, but this doesn't conclusively tell us that the resonance is responsible
  - maybe with a mass-binned measurement at LHC
- Is there any orthogonal information that we can gather?

Vector/Axial Composition via Helicity Interference



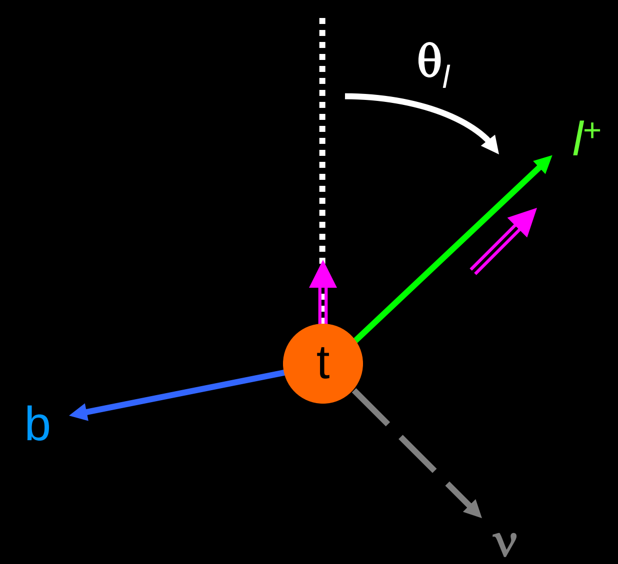
Lepton as Spin Analyzer



Fierz ->
$$\mathcal{M}(t \to b\ell^+\nu) \propto \left(u(t)^T_L\,\epsilon\, v(\ell)_L\right)\,\left(u(b)^\dagger_L\,\epsilon\, u(\nu)^*_L\right)$$

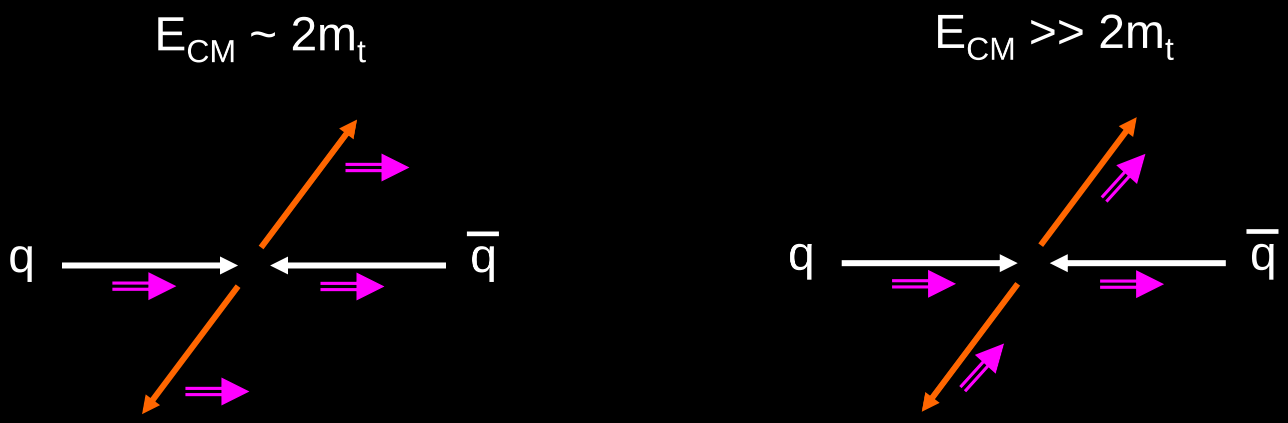
lepton spinor talks directly to top spinor…
maximum sensitivity to spin effects

Lepton as Spin Analyzer



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + \mathcal{P}_{t} \star \cos\theta_f\right)$$

Spin Correlations: The Standard Story



tops always produced in same-spin state

can interpolate kinematic regimes using off-diagonal spin basis

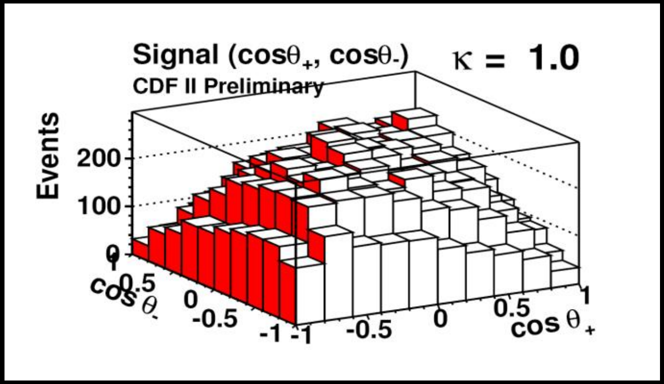
Cf. Peskin & Schroeder

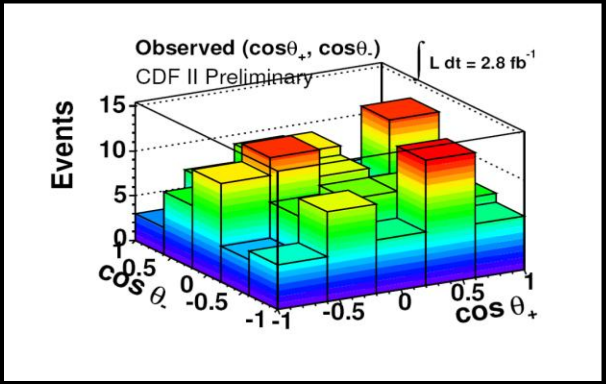
Mahlon & Parke, hep-ph/9706304

Dileptonic Spin Correlations at the Tevatron

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

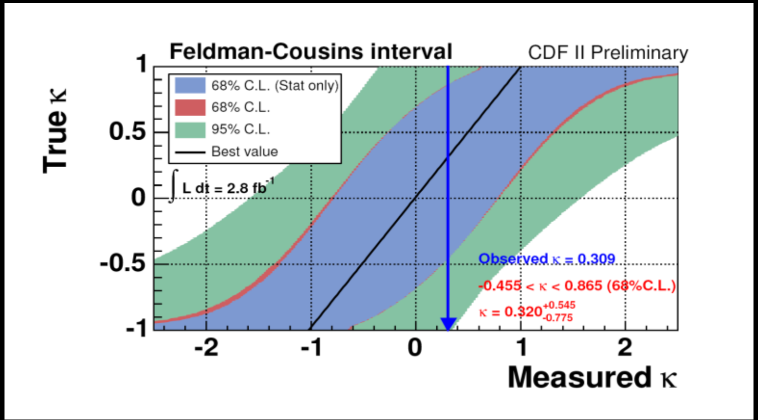
incl. gluon fusion, $\kappa = 0.8$





κ=1 fit template

data

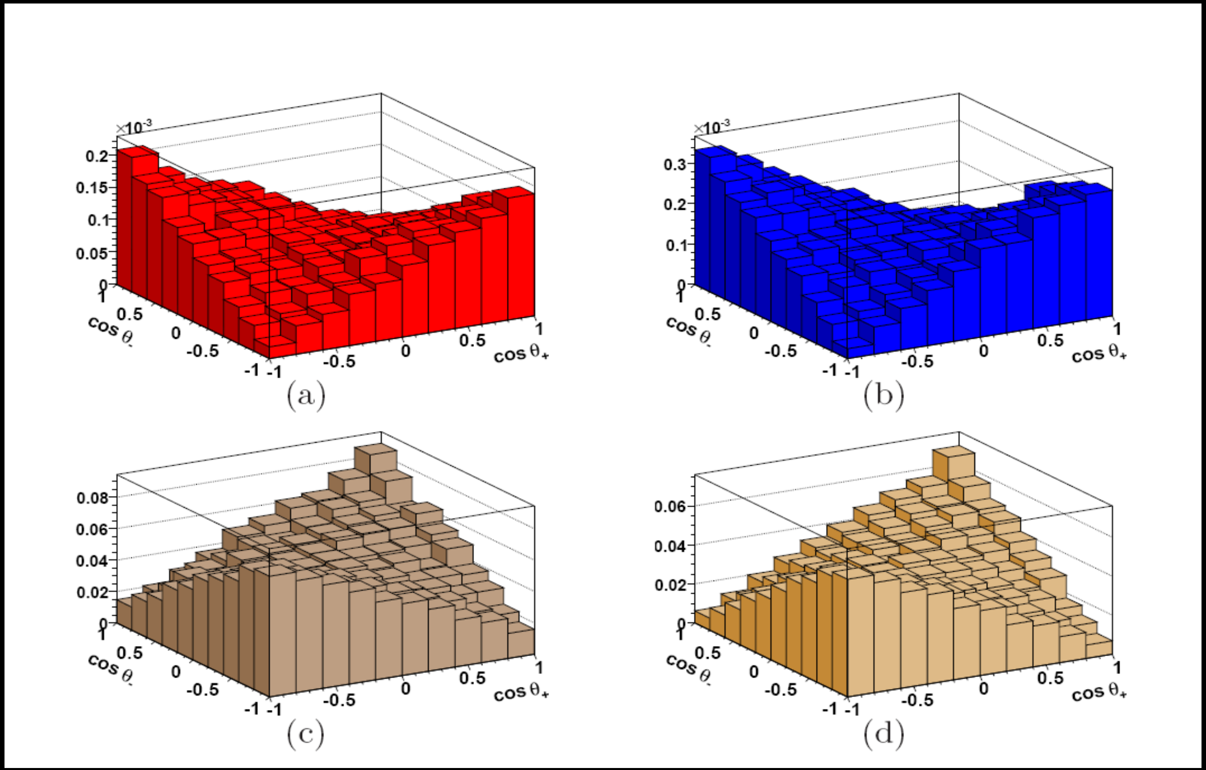


CDF Note 9824 (2.8 fb^{-1})

Traditional Spin Correlations and New Resonances

scalar

pseudoscalar



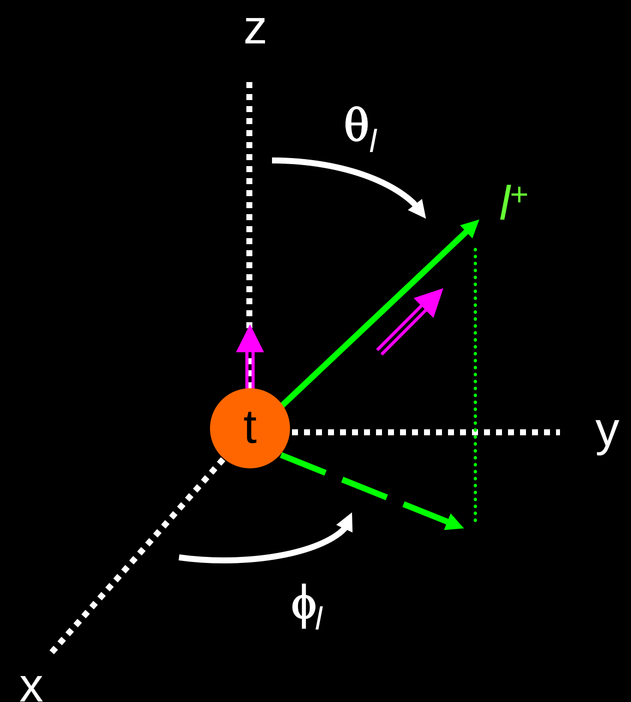
vector

axial vector

800 GeV Resonances, helicity basis

Frederix & Maltoni, arXiv:0712.2355

Lepton as Spin Analyzer

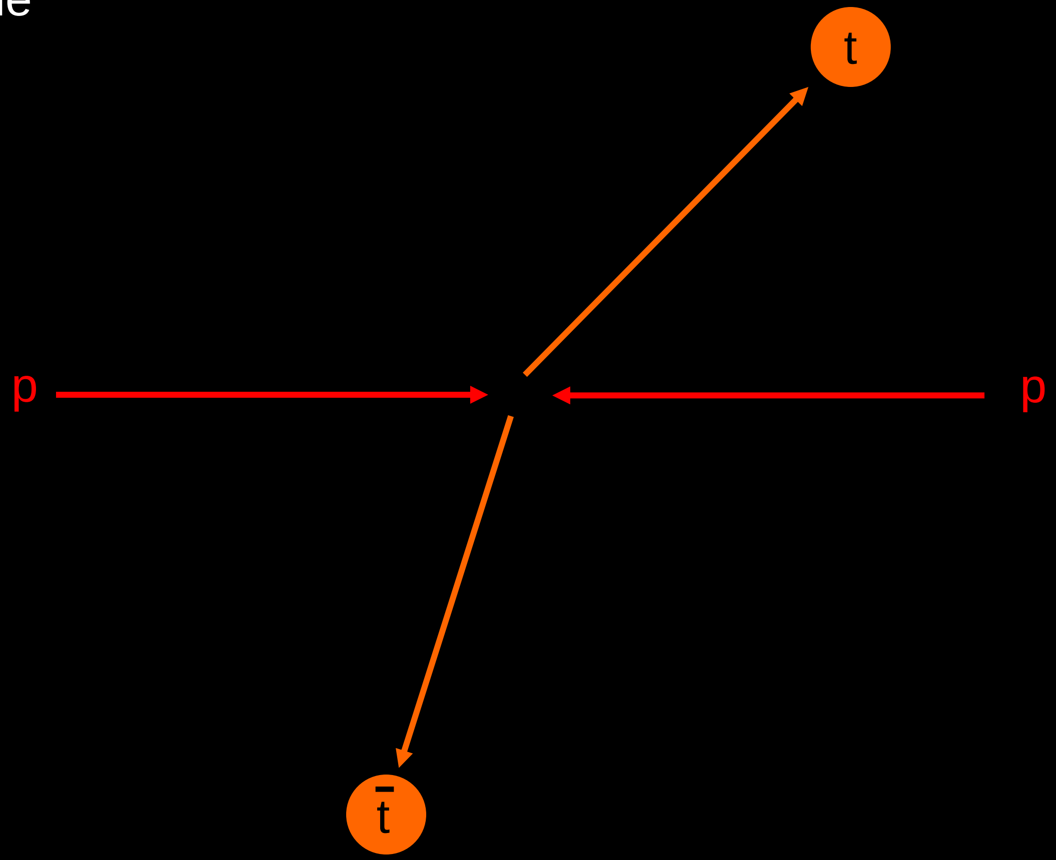


$$\mathcal{M}(t_\uparrow \to b\ell^+\nu) \propto e^{i\phi_\ell/2}\cos\frac{\theta_\ell}{2}$$

$$\mathcal{M}(t_\downarrow \to b\ell^+\nu) \propto e^{-i\phi_\ell/2}\sin\frac{\theta_\ell}{2}$$

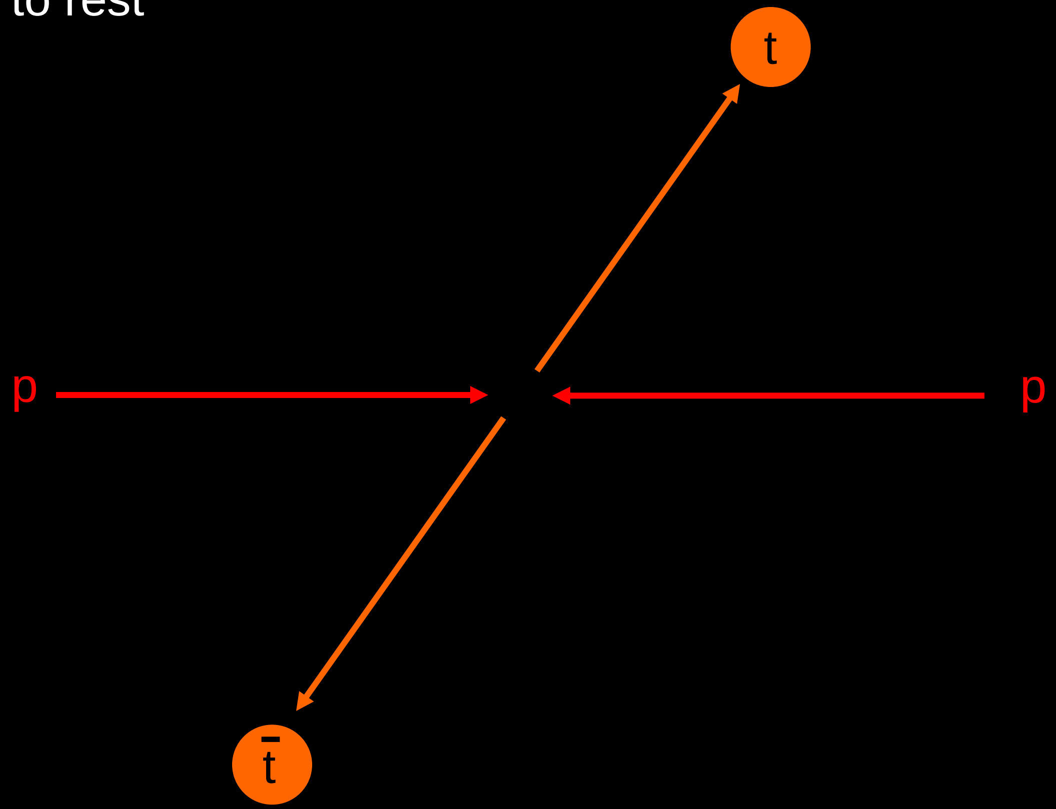
Coordinates

start in lab frame



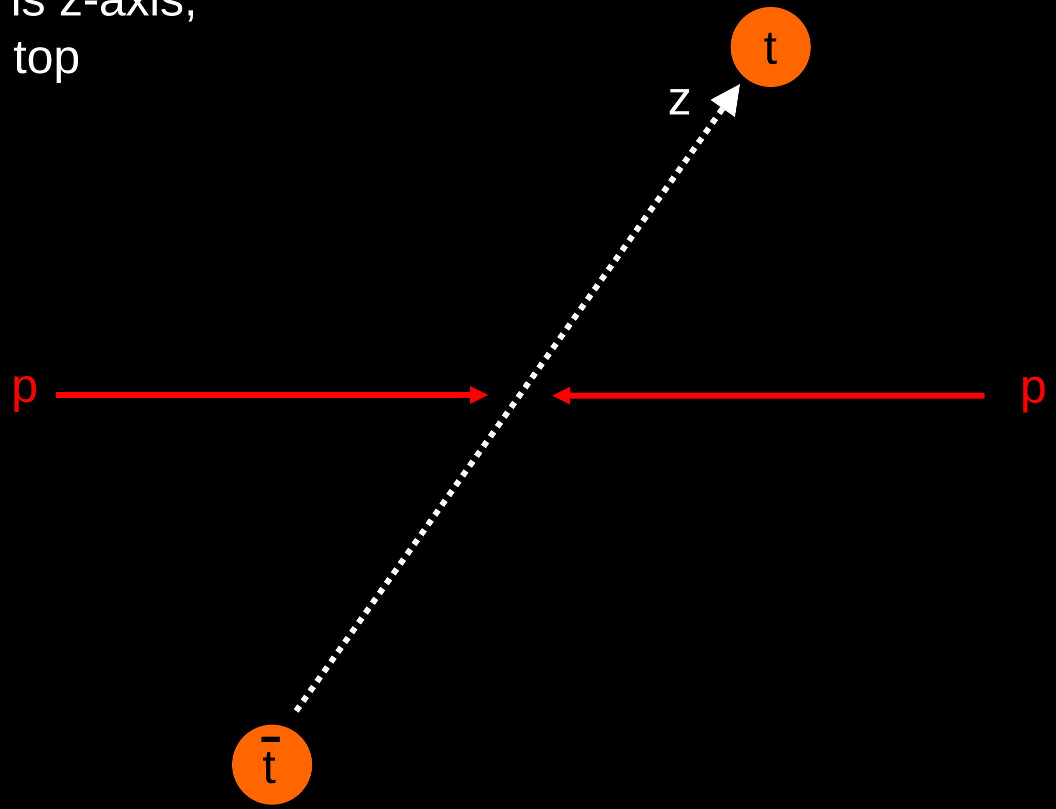
Coordinates

boost tt system to rest



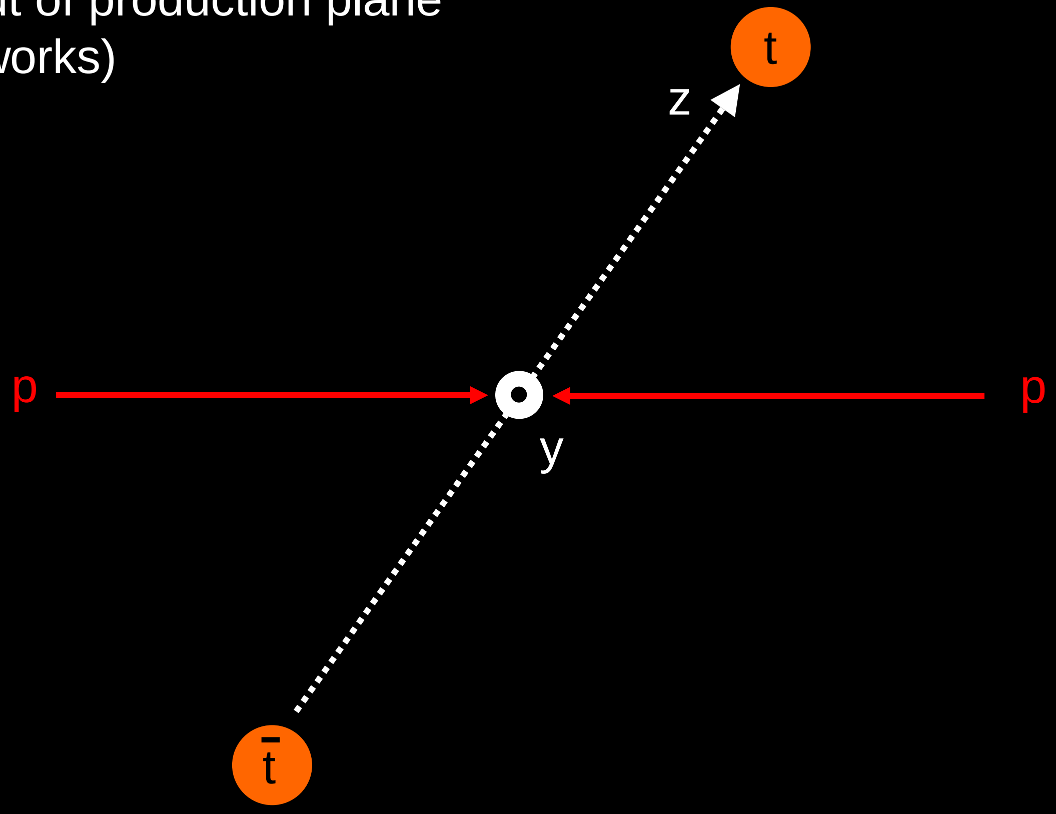
Coordinates

production axis is z-axis,
pointing toward top



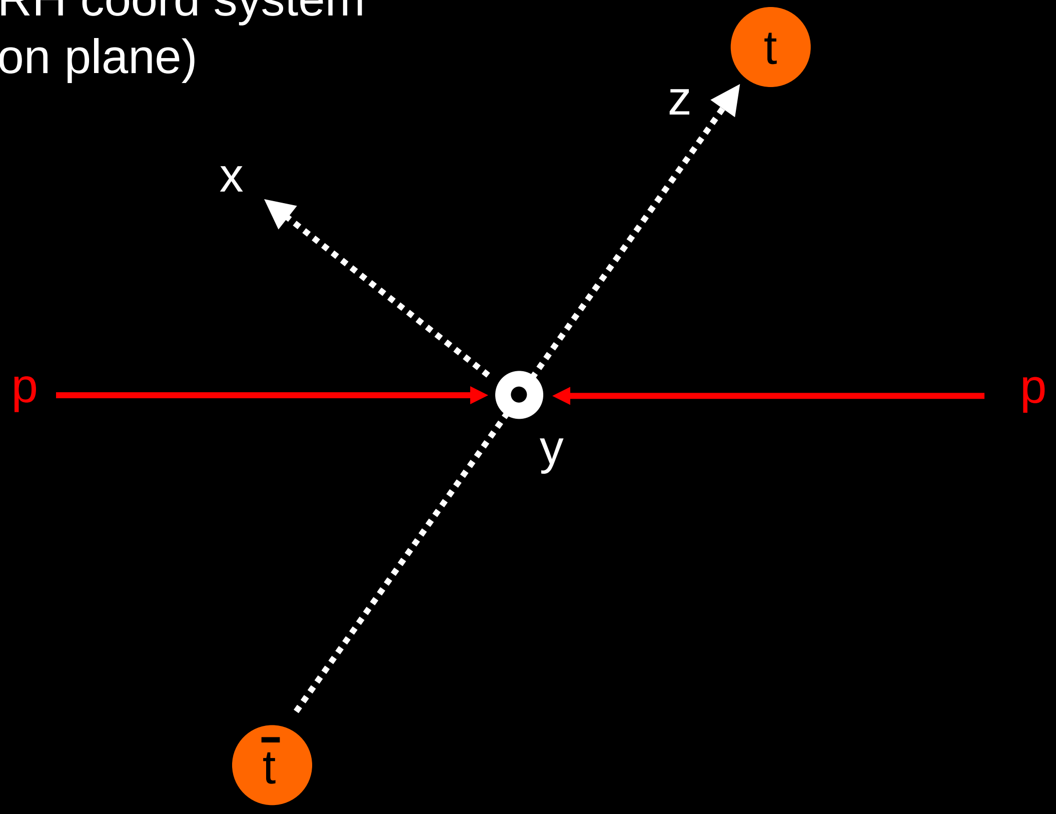
Coordinates

y-axis points out of production plane
(either choice works)



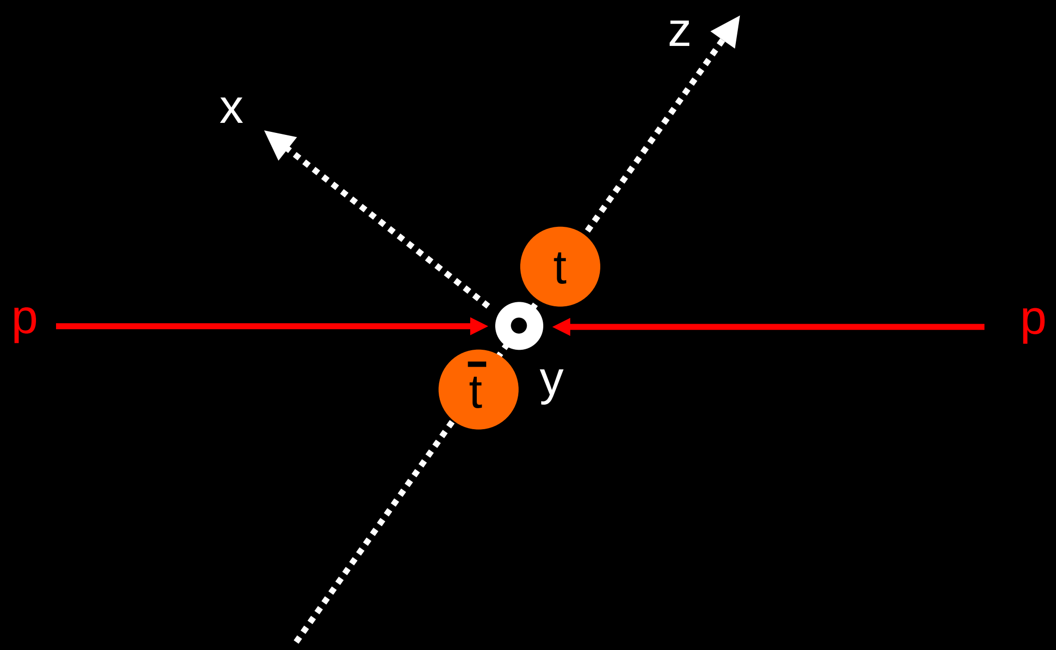
Coordinates

x-axis to make RH coord system
(lies *in* production plane)



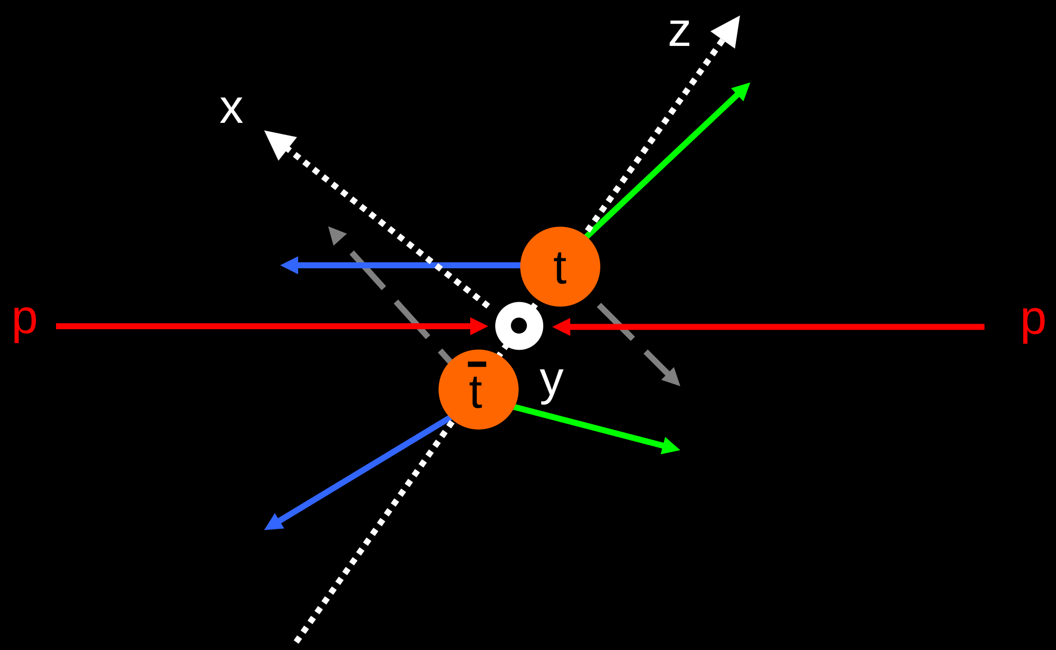
Coordinates

boost the tops to rest



Coordinates

and look at their decay products



$$\Big(v(\ell)^T_L\,\epsilon\,u(t)_L\Big)\ \Big(u(t)^\dagger\,\Gamma\,v(\bar t)\Big)\ \Big(v(\bar t)^\dagger_L\,\epsilon\,u(\bar l)^*_L\Big)\ \rightarrow\ \Big(v(\ell)^T_L\Lambda^T\,\epsilon\,\Lambda u(t)_L\Big)\ \Big(u(t)^\dagger\,\Gamma\,v(\bar t)\Big)\ \Big(v(\bar t)^\dagger_L\bar\Lambda^\dagger\,\epsilon\,\bar\Lambda^* u(\bar l)^*_L\Big)$$

decay production decay

Full Helicity Interference

$$\mathcal{M}_{\rm tot}(X_0 \to b\,\ell^+\nu\bar{b}\,\ell^-\bar{\nu}) \sim \mathcal{M}(X_0 \to t_\uparrow \bar{t}_\downarrow)\, e^{i(\phi_\ell - \bar{\phi}_\ell)/2} \cos\frac{\theta_\ell}{2}\cos\frac{\bar{\theta}_\ell}{2} \; + \\ \mathcal{M}(X_0 \to t_\downarrow \bar{t}_\uparrow)\, e^{-i(\phi_\ell - \bar{\phi}_\ell)/2} \sin\frac{\theta_\ell}{2}\sin\frac{\bar{\theta}_\ell}{2}$$

$$\mathcal{M}_{\rm tot}(X_{1(2)} \to b\,\ell^+\nu\bar{b}\,\ell^-\bar{\nu}) \sim g_R{}^t\, e^{i(\phi_\ell + \bar{\phi}_\ell)/2} \cos\frac{\theta_\ell}{2}\sin\frac{\bar{\theta}_\ell}{2} \; + \\ g_L{}^t\, e^{-i(\phi_\ell + \bar{\phi}_\ell)/2} \sin\frac{\theta_\ell}{2}\cos\frac{\bar{\theta}_\ell}{2}$$

In chiral limit (m_t / M -> 0)

- Spin-0 will exhibit ϕ-$\bar{\phi}$ modulation
- Spin-1(2) will exhibit ϕ+$\bar{\phi}$ modulation

Spin-0

$$\mathcal{L}_{\rm int} \to -y\,\phi\left(e^{i\,\alpha}\,\bar{t}_R t_L \,+\, e^{-i\,\alpha}\,\bar{t}_L t_R\right)$$

pure scalar: $\alpha = 0$

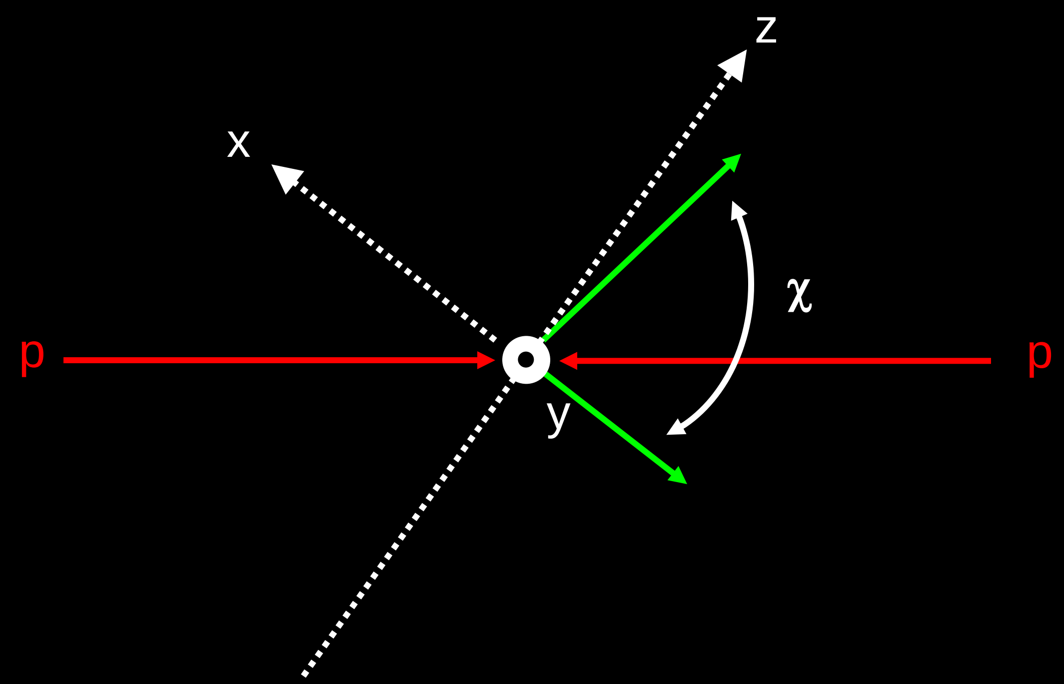
pseudoscalar: $\alpha = \pi/2$

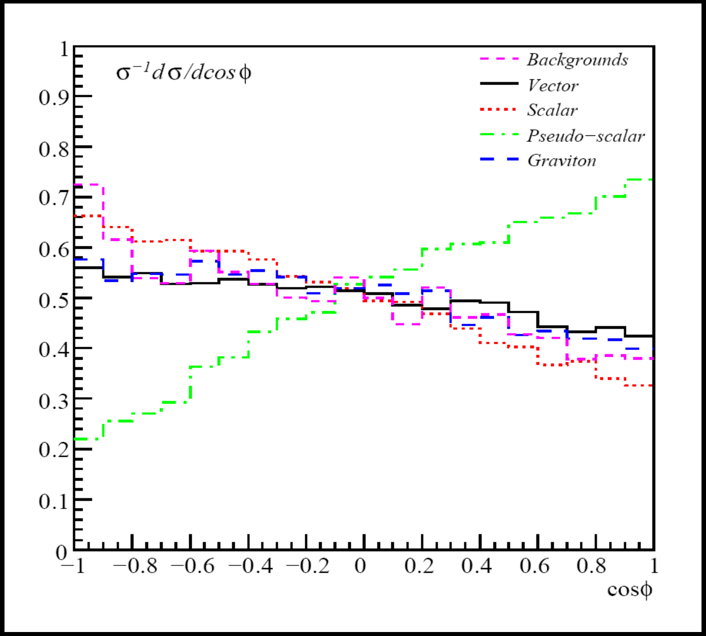
$$\frac{d^4\Gamma}{d\Omega_\ell\, d\bar{\Omega}_\ell} \propto 1 + \cos\theta_\ell\, \cos\bar{\theta}_\ell - \sin\theta_\ell\, \sin\bar{\theta}_\ell\, \cos\left(\phi_\ell - \bar{\phi}_\ell + 2\alpha\right)$$

all other top decay variables factorize off

(lepton energies, b & ν orientations)

One Option: 3D Angle





Bai & Han, arXiv:0809.4487
(fully reconstructed)

$$\frac{d\Gamma}{d\cos\chi} \propto 1 + \frac{1 - 2\cos(2\alpha)}{3}\cos\chi$$

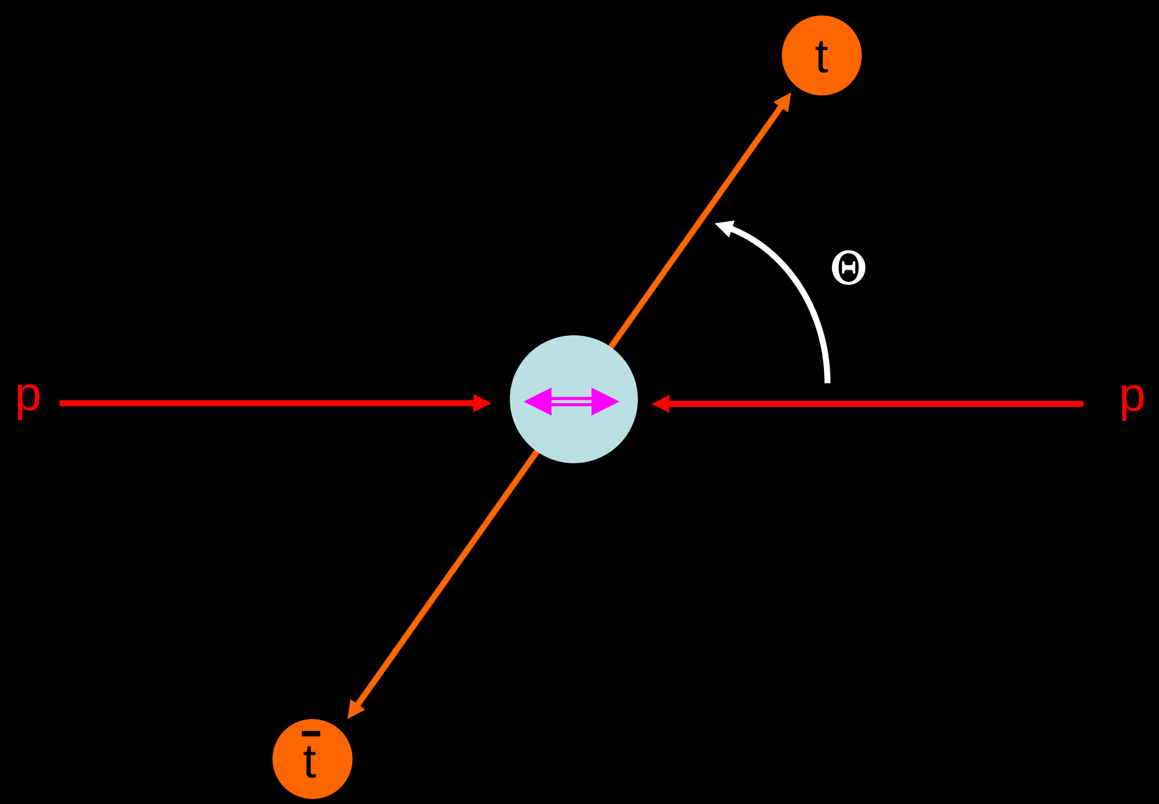
But We Could Just Measure ϕ

$$\frac{d\Gamma}{d(\phi_\ell - \bar{\phi}_\ell)} \propto 1 - \left(\frac{\pi}{4}\right)^2 \cos(\phi_\ell - \bar{\phi}_\ell + 2\alpha)$$

60% modulation

- Don’t need to measure the polar angles
- Spin-1(2) doesn’t modulate in this variable, nor does the SM continuum
  - cleaner discrimination from other spins
  - cleaner discrimination from background

Spin-1



Spin-1

$$\mathcal{L}_{\text{int}} \to \; A_\mu \left(g_L \, \bar{t}_L \gamma^\mu t_L + g_R \, \bar{t}_R \gamma^\mu t_R \right)$$

$$g_L = g \cos \xi$$
$$g_R = g \sin \xi \, .$$

$$\frac{d^2 \Gamma_{J_{\text{beam}}=\pm 1}}{d(\phi_\ell + \bar{\phi}_\ell) \, d\cos\Theta} \propto \; (1 + \cos^2\Theta) - \left(\frac{\pi}{4}\right)^2 \sin(2\xi) \sin^2\Theta \cos(\phi_\ell + \bar{\phi}_\ell)$$

integrate out Θ

$$\frac{d\Gamma_{J_{\text{beam}}=\pm 1}}{d(\phi_\ell + \bar{\phi}_\ell)} \propto \; 1 - \frac{1}{2} \left(\frac{\pi}{4}\right)^2 \sin(2\xi) \cos(\phi_\ell + \bar{\phi}_\ell)$$

pure vector: -30%

pure axial: +30%

pure chiral: 0

Even More Formulas!

gg -> spin-1

$$\frac{d^2\Gamma_{J_{\mathrm{beam}}=0}}{d(\phi_\ell+\bar{\phi}_\ell)\,d\cos\Theta} \propto \sin^2\Theta\left[1+\left(\frac{\pi}{4}\right)^2\sin(2\xi)\cos(\phi_\ell+\bar{\phi}_\ell)\right]$$

q$\bar{\mathrm{q}}$ -> spin-2

$$\frac{d\Gamma_{J_{\mathrm{beam}}=\pm1}}{d(\phi_\ell+\bar{\phi}_\ell)} \propto 1+\frac{1}{6}\left(\frac{\pi}{4}\right)^2\sin(2\xi)\cos(\phi_\ell+\bar{\phi}_\ell)$$

gg -> spin-2

$$\frac{d\Gamma_{J_{\mathrm{beam}}=\pm2}}{d(\phi_\ell+\bar{\phi}_\ell)} \propto 1-\frac{2}{3}\left(\frac{\pi}{4}\right)^2\sin(2\xi)\cos(\phi_\ell+\bar{\phi}_\ell)$$

Aside: Z->ττ at LEP

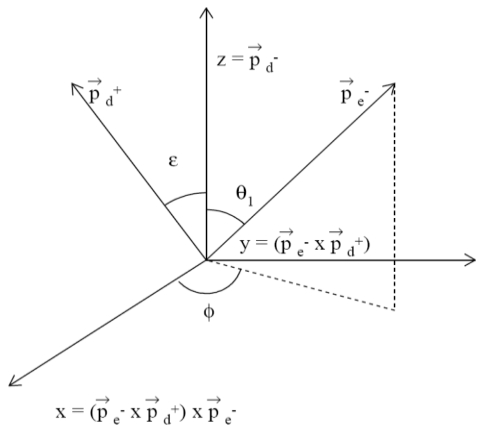


Figure 1: Coordinate system in the lab frame. $p_{d^\pm}$ is the direction of the $\tau^\pm$ decay product. p_{e^-} is the direction of the incident e^-.

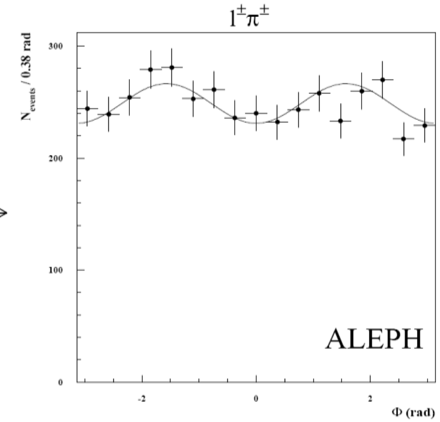


Figure 2: Comparison of the standard model $\cos(2\phi)$ asymmetry and the data for the $l^\mp\pi^\pm$ channel.

ALEPH, CERN OPEN-99-355

- Directly measured vector/axial admixture of Z coupling to taus
- Double one-prong events
  - no attempt to reconstruct neutrinos
  - know the CM frame anyway, get to sit on resonance
- Azimuthal angle of one visible particle about the other follows cos(2ϕ) distribution

Wait a Minute…

Top decays also produce neutrinos. How do we reconstruct any of this in dileptonic mode? How do we even find the resonance??

- 6 lost dof's
- 2 recaptured in MET
- 4 mass constraints (2 tops, 2 W's)
- => exactly soluble up to 4-fold, 2-fold, or 0-fold(!) ambiguity

How to Cook the Math?

- Our workaround
  - always get 4 complex solutions for neutrino momenta
  - take the real parts, pick solution with smallest m_{tt}
- Bai & Han
  - allow solutions that aren’t too imaginary and don’t have neutrinos dominating the event energy
  - norm out the complex reconstructed top momenta
  - all good solutions weighted equally
- The “correct” way: χ^2 minimization over visible & invisible kinematics
  - assuming leptons are perfectly measured, still a 10-parameter minimization
  - we didn’t try this!

But Also Many Simpler Options

- M_{Tcl}
  - transverse mass of visible 4-vector (2 leptons + 2 b's) and MET
  - effectively one neutrino with $\eta_\nu = y_{VIS}$
- "Minimal neutrino"
  - similar idea, but set $\eta_\nu = \eta_l$ (lepton closest to MET)
- M_{eff}
  - scalar-sum visible p_T's and MET
- M_{VIS}
  - just take the mass of the visible 4-vector

Performance Comparison

narrow 2 TeV vector

SM continuum (LHC14)

perfect (*1/2)

M_{Tcl}

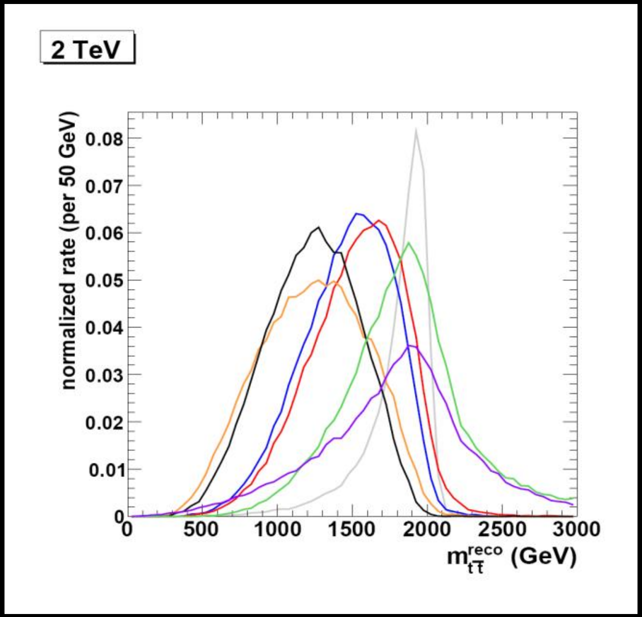
minimal ν

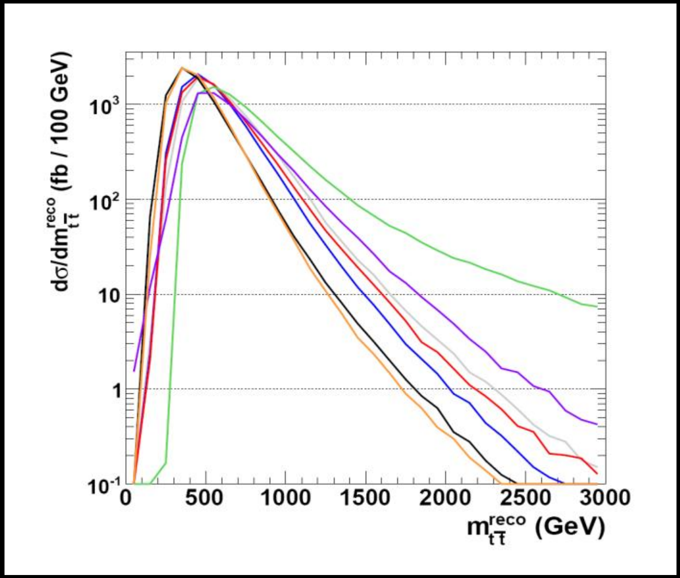
visible

M_{eff}

real quartic

Bai-Han





Hadron-level MadGraph+PYTHIA simulations include jet reconstruction and jet/lepton energy smearings as per CMS, simple lepton (mini)isolation, hemisphere-based jet-lepton pairing, no b-tags. MET defined to just balance b-jets and leptons. (Reduc. backgrounds highly subleading.)

Performance Comparison

scan over mass windows & transversity cuts (M_{eff}/M_{reco})

perfect (*1/2)

M_{Tcl}

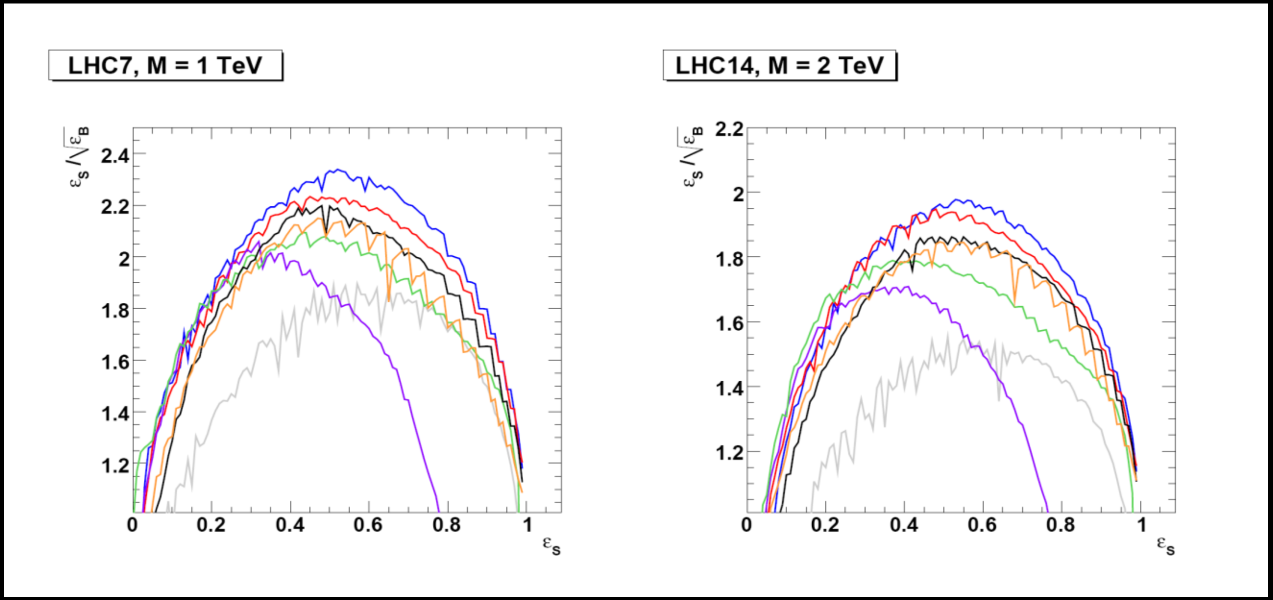
minimal ν

visible

M_{eff}

real quartic

Bai-Han



For maximizing significance of the resonance region, M_{Tcl} seems to win.

Doesn't necessarily carve out a well-defined peak, but we'll already know where to look from l+jets discovery.

Our LHC7 Cuts

LHC 7	Mass/Transversity Cuts	$\varepsilon_S^{\text{selection}}$	$\varepsilon_S^{\text{selection+cuts}}$	σ_B
1 TeV, Narrow	$M_{T\text{cl}} = [750, 1025]$ GeV, $M_{\text{eff}}/M_{T\text{cl}} > 0.65$	0.38	0.24	21 fb
1 TeV, 15%-Width	$M_{T\text{cl}} = [700, 1450]$ GeV, $M_{\text{eff}}/M_{T\text{cl}} > 0.65$	0.33	0.19	24 fb
2 TeV, Narrow	$M_{T\text{cl}} = [1600, 2100]$ GeV, $M_{\text{eff}}/M_{T\text{cl}} > 0.50$	0.58	0.20	0.07 fb
2 TeV, 15%-Width	$M_{T\text{cl}} = [1425, 2925]$ GeV, $M_{\text{eff}}/M_{T\text{cl}} > 0.75$	0.40	0.09	0.17 fb

typically ~20% of dileptonics => ~1% of all tt

Spin-0 Azimuthal Modulations

perfect

M_{Tcl}

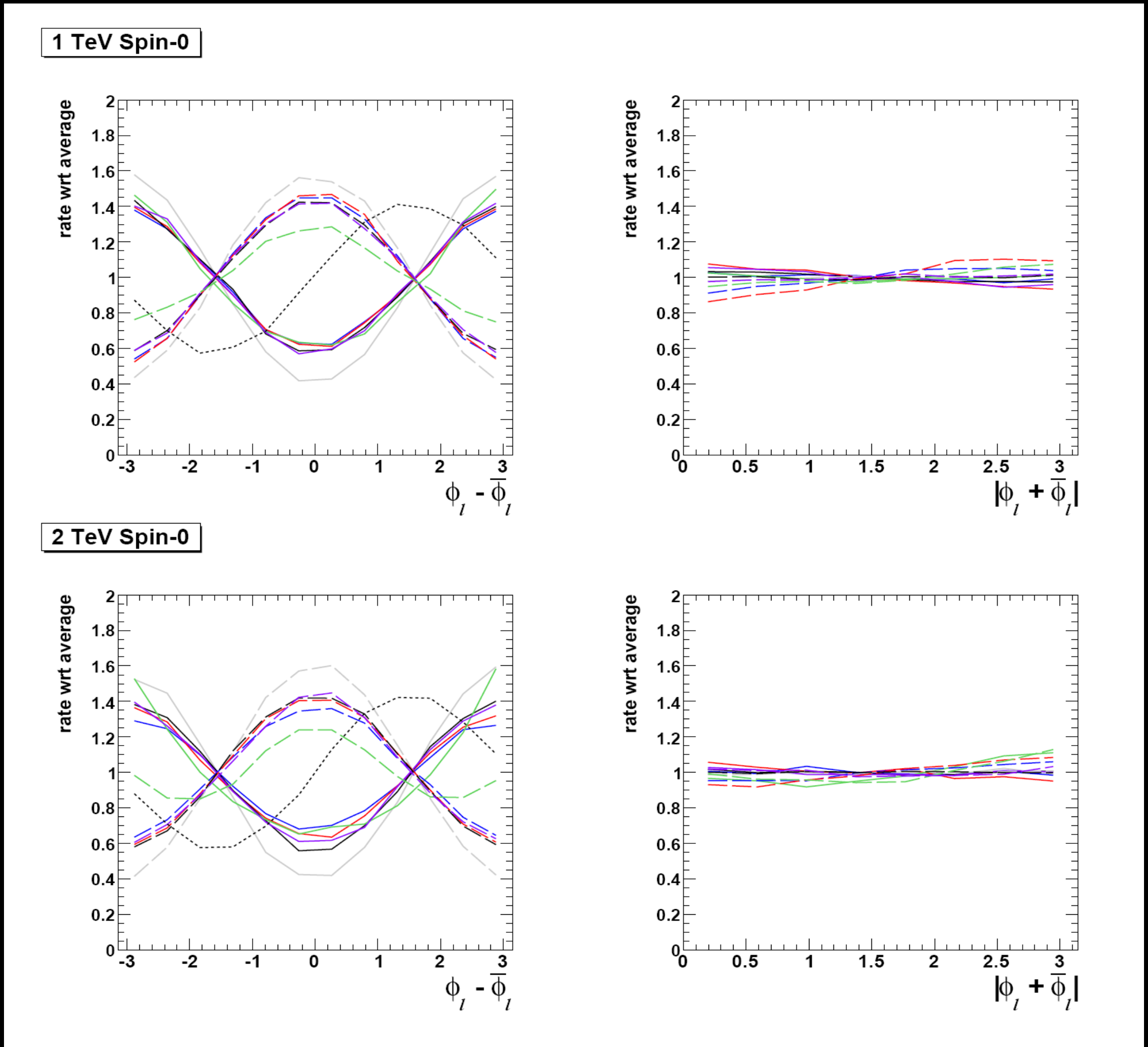
minimal ν

visible

real quartic

Bai-Han

* MadGraph topBSM



solid: pure scalar, dashed: pseudoscalar, dotted: mixed CP

Spin-1 Azimuthal Modulations

perfect

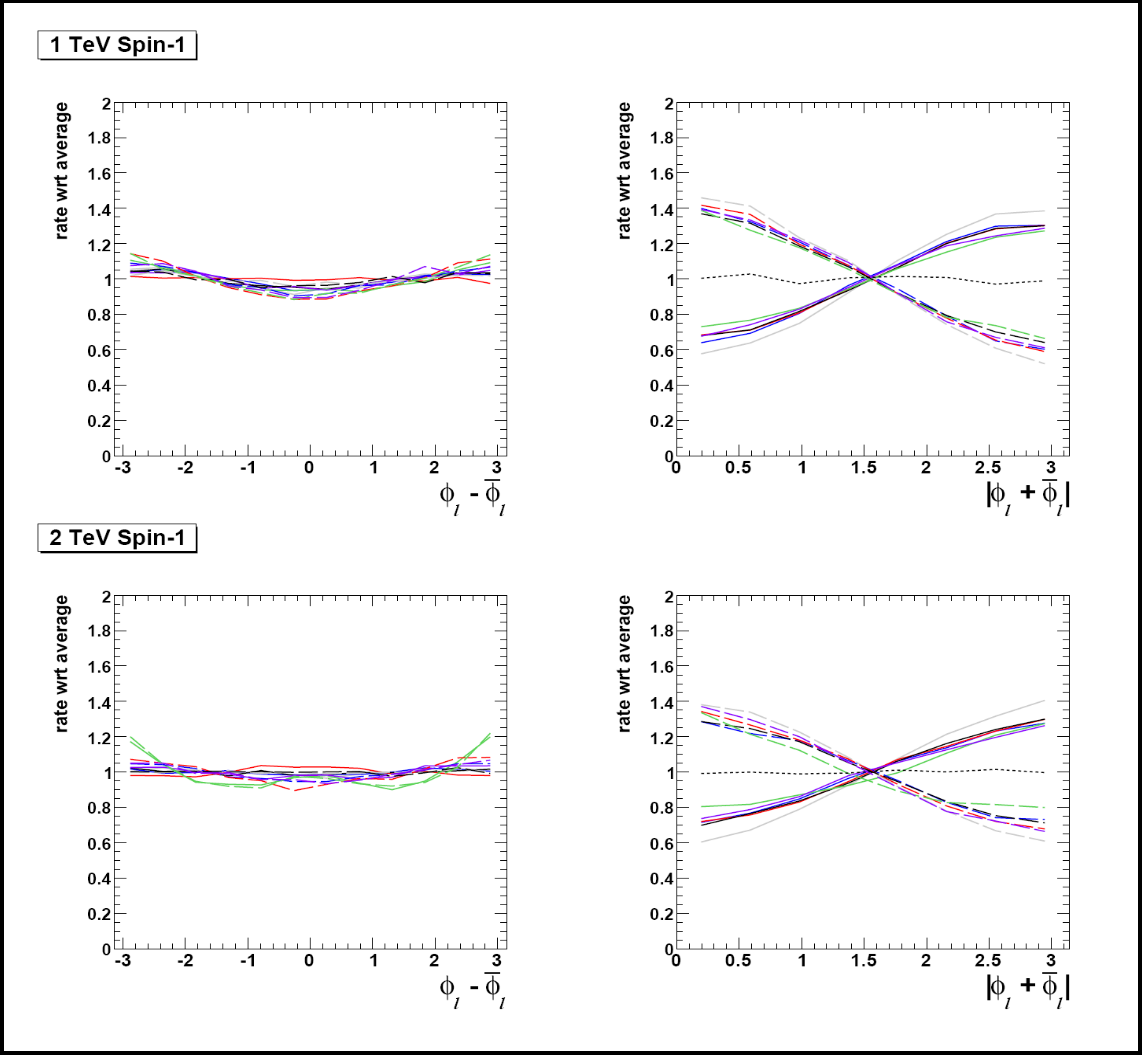
M_{Tcl}

minimal ν

visible

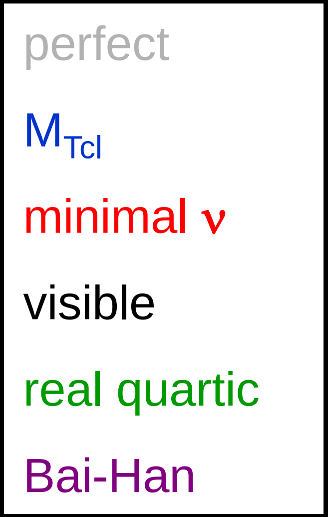
real quartic

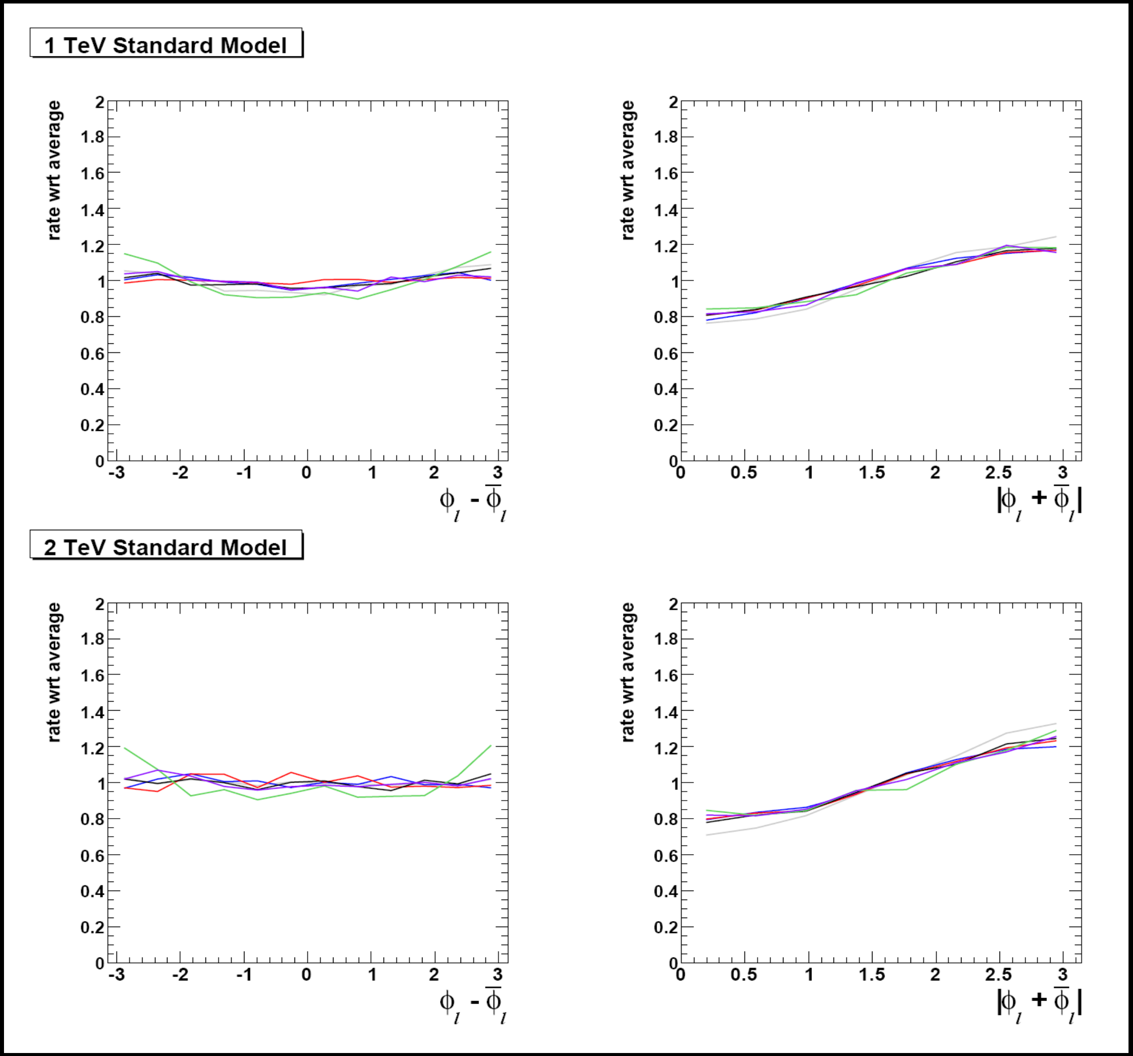
Bai-Han



solid: pure vector, dashed: axial vector, dotted: LH chiral

SM Azimuthal Modulations





Hand-Selected A_{FB} Example Model

- $g_A^q = 0.5$, $g_A^t = -2.5$ (g_V's = 0), M = 1.5 TeV
- safe from resonance and contact interaction searches, pushes A_{FB} up to within 2σ of CDF
- σ x BR(tt) = 2 pb (LHC7), Γ = 12%
  - 5 fb^{-1} => 10,000 resonance events
  - 500 dileptonic
  - 100 pass into our analysis (S/B ~ 10)
    - enough to distinguish vector from axial at ~3σ using 2-bin (asymmetry) analysis

l+Jets

- Pros
  - rate X 6
    - e.g., probe up to higher-mass resonances
  - easier to fully reconstruct
    - better peak -> better S/B with less severe cuts
- “Cons”
  - smaller modulation effects: 40% as big if we correlate lepton and b
    - formally need 6X higher stats…convenient coincidence
    - can try to boost correlation through smarter choice of jet
  - need to identify b-(sub)jet
    - b-tag or internal kinematics

Summary

- If nothing else the Tevatron A_{FB} anomaly motivates us to think hard about discriminating top-antitop NP scenarios
  - spin-1 vector/axial coupling to top is a notable semi-blind spot
- Azimuthal decay correlations directly encode helicity interference effects and tell us about top couplings to new resonances
  - discriminate vector from axial vector
  - directly measure scalar CP phase
  - discriminate spin-0 from spin > 0
- They look surprisingly easy to reconstruct in dileptonic mode, even though two neutrinos
  - largest modulations amongst top decay modes
  - can still reconstruct the resonance, more or less…simple m_{tt} estimators seem to work best
- Might be testable for A_{FB}-relevant spin-1 octet models without waiting for LHC14 (if we're lucky)
- Improvable in l+jets?