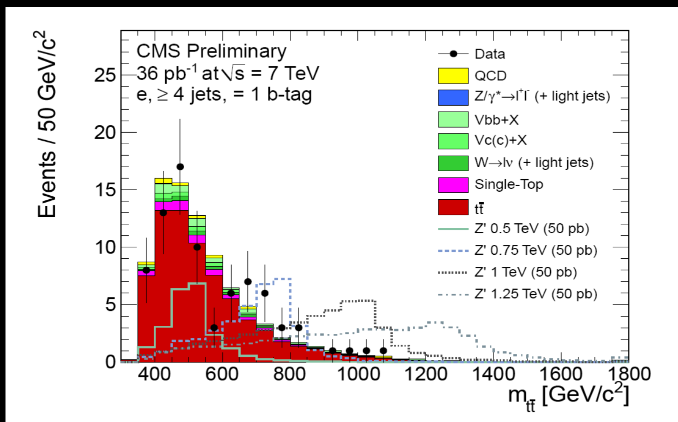
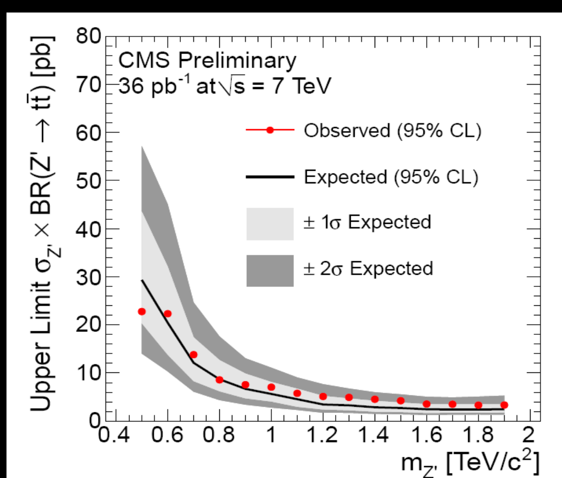
Azimuthal Decay Correlations of Boosted Top Pairs

Brock Tweedie
Boston University
24 May 2011
@ BOOST 2011, Princeton

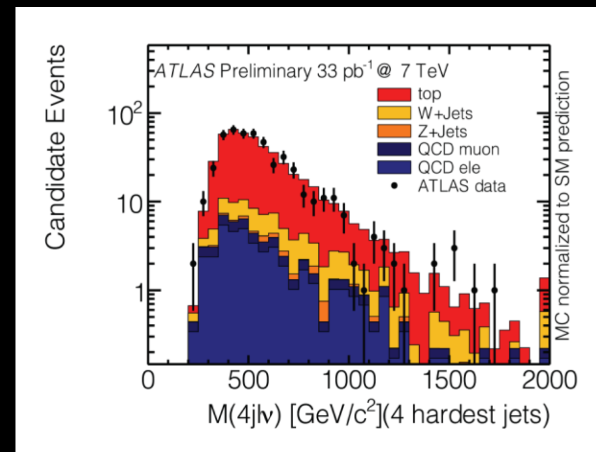
Baumgart and Tweedie, arXiv:1104.2043

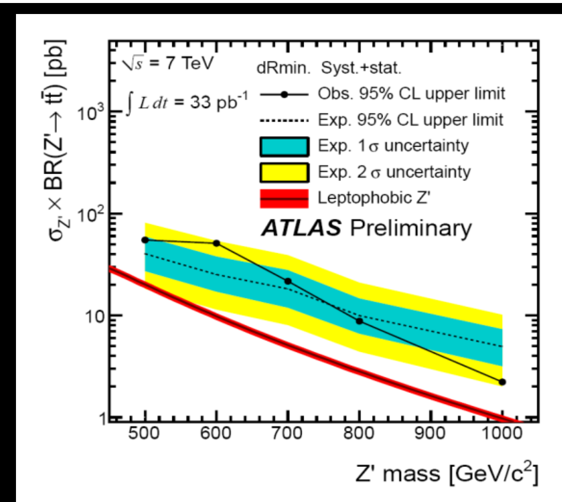
The Hunt is On





CMS PAS TOP-10-007





ATLAS-CONF-2011-070

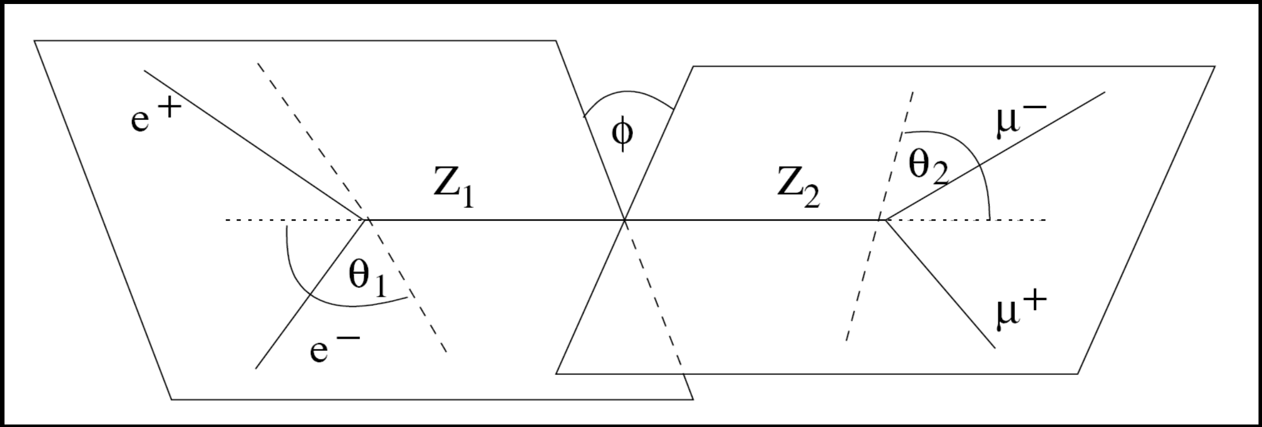
What if We Actually Find A Bump?

- What’s the spin?
- Are the tops polarized?
- What are the C/P/CP properties?

Our Goals for This Talk

- Show that the azimuthal decay angles of the two tops can be highly correlated, and that this correlation carries valuable information
  - Discrimination of spin-0 from higher spins (complementary to production angle method)
  - Simple measurement of CP phase for heavy spin-0
  - Measurement of signed ratio of chiral couplings for spin-1 & 2: discriminate pure vector / axial / chiral
  - Direct manifestation of top spin correlations within the SM itself
- Show that the correlation is straightforward to measure, even in dileptonic channel

Perhaps This Sounds Familiar?



$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

Maybe Less Familiar: Z->ττ at LEP

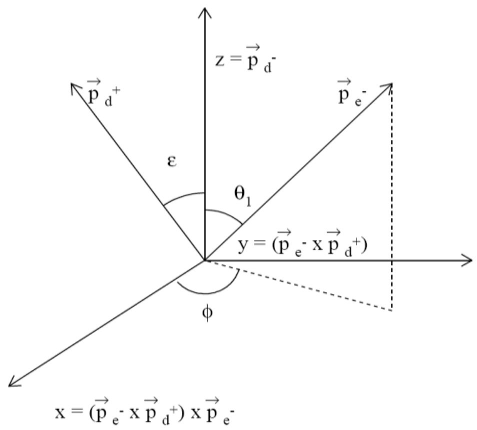


Figure 1: Coordinate system in the lab frame. $p_{d^\pm}$ is the direction of the $\tau^\pm$ decay product. p_{e^-} is the direction of the incident e^-.

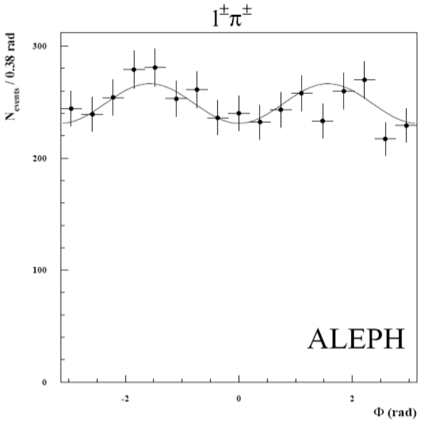
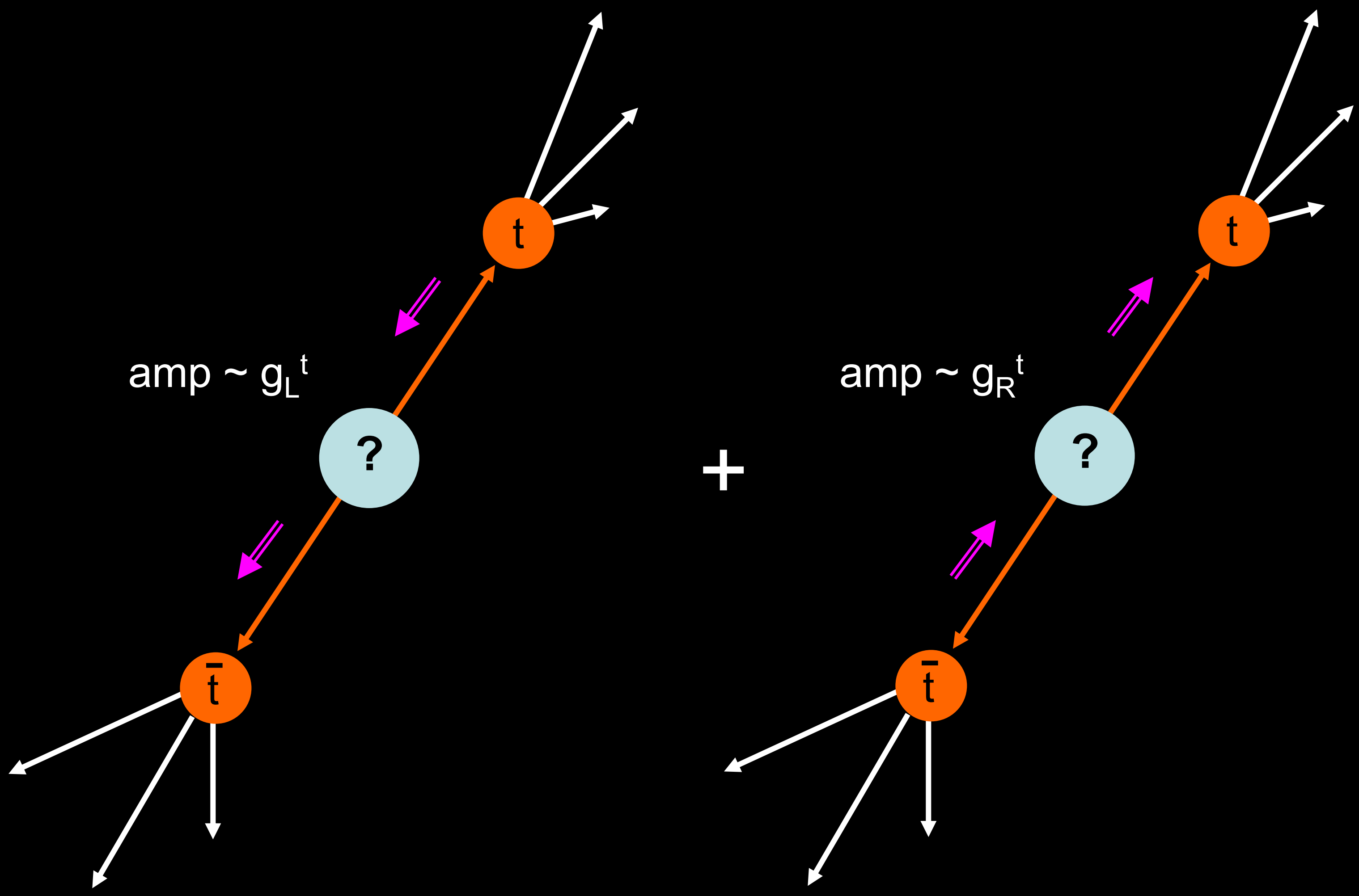


Figure 2: Comparison of the standard model $\cos(2\phi)$ asymmetry and the data for the $l^\mp\pi^\pm$ channel.

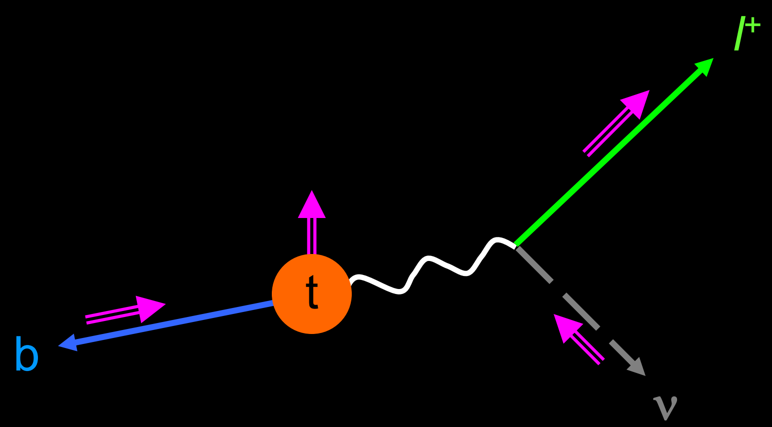
ALEPH, CERN OPEN-99-355

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

Helicity Interference



Lepton as Spin Analyzer

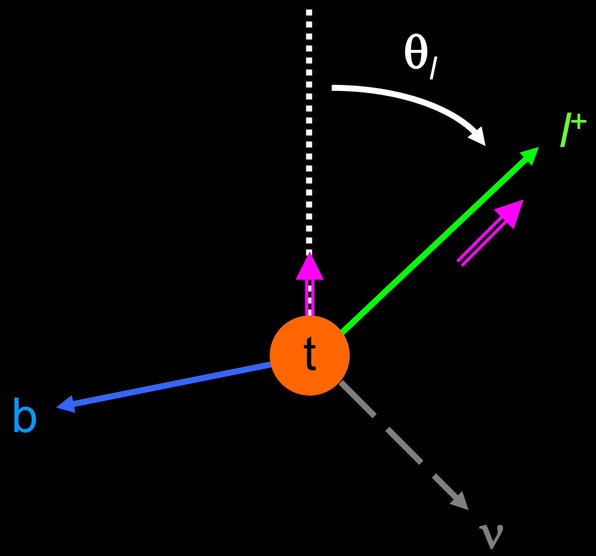


Fierz ->

$$\mathcal{M}(t \to b\ell^+\nu) \propto \left(u(t)_L^T\,\epsilon\,v(\ell)_L\right)\,\left(u(b)_L^\dagger\,\epsilon\,u(\nu)_L^*\right)$$

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

Lepton as Spin Analyzer



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + \mathcal{P}_t * \cos\theta_f\right)$$

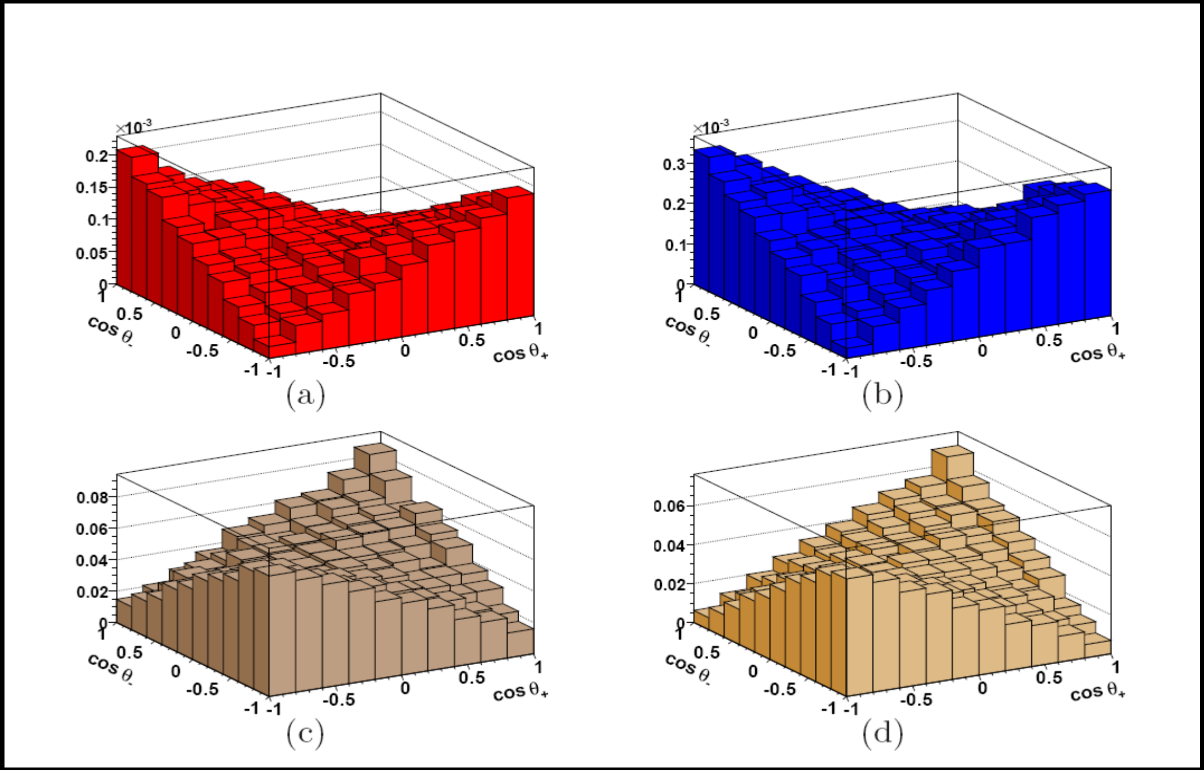
Traditional Spin Correlations and New Resonances

scalar

pseudoscalar

vector

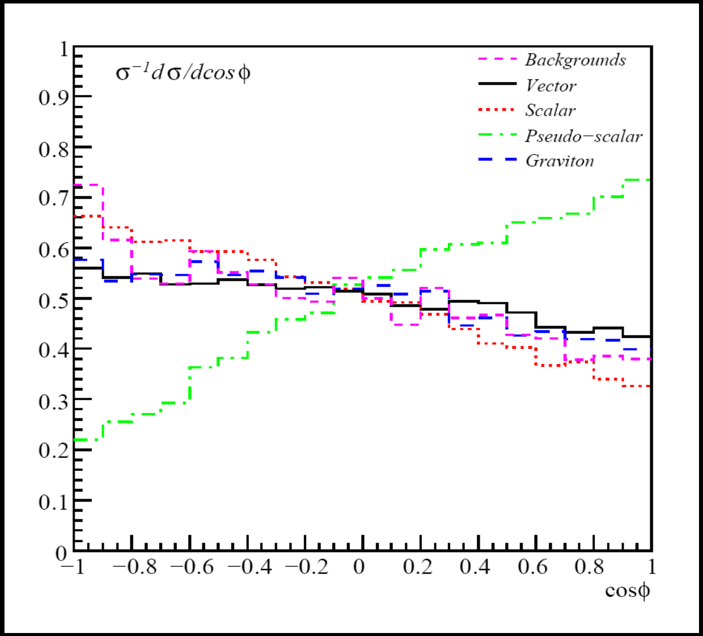
axial vector



800 GeV Resonances, helicity basis

Frederix & Maltoni, arXiv:0712.2355

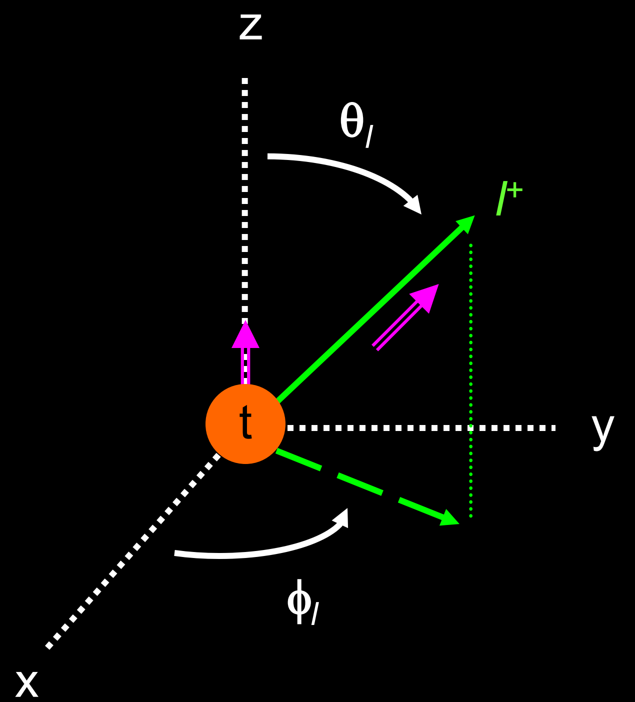
Traditional Spin Correlations and New Resonances



dilepton 3D opening angle
(after event reconstruction)

Bai & Han, arXiv:0809.4487

Lepton as Spin Analyzer

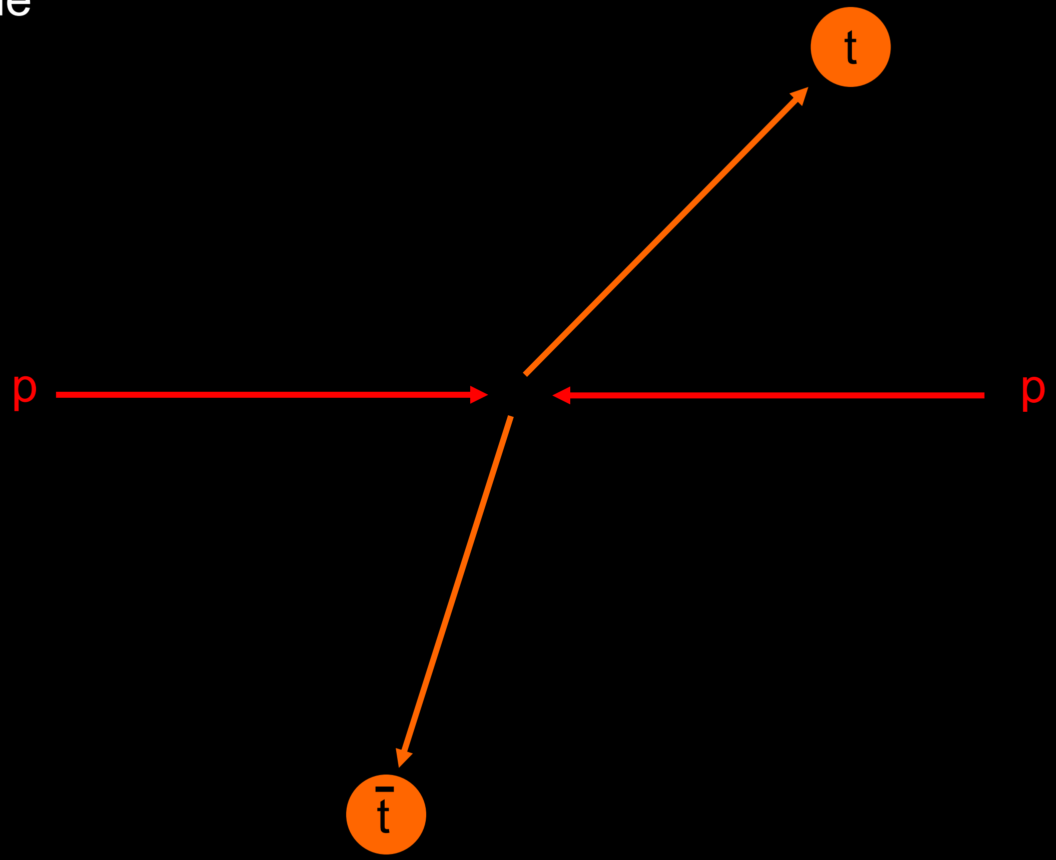


$$\mathcal{M}(t_\uparrow \to b\ell^+\nu) \propto e^{i\phi_\ell/2}\cos\frac{\theta_\ell}{2}$$

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

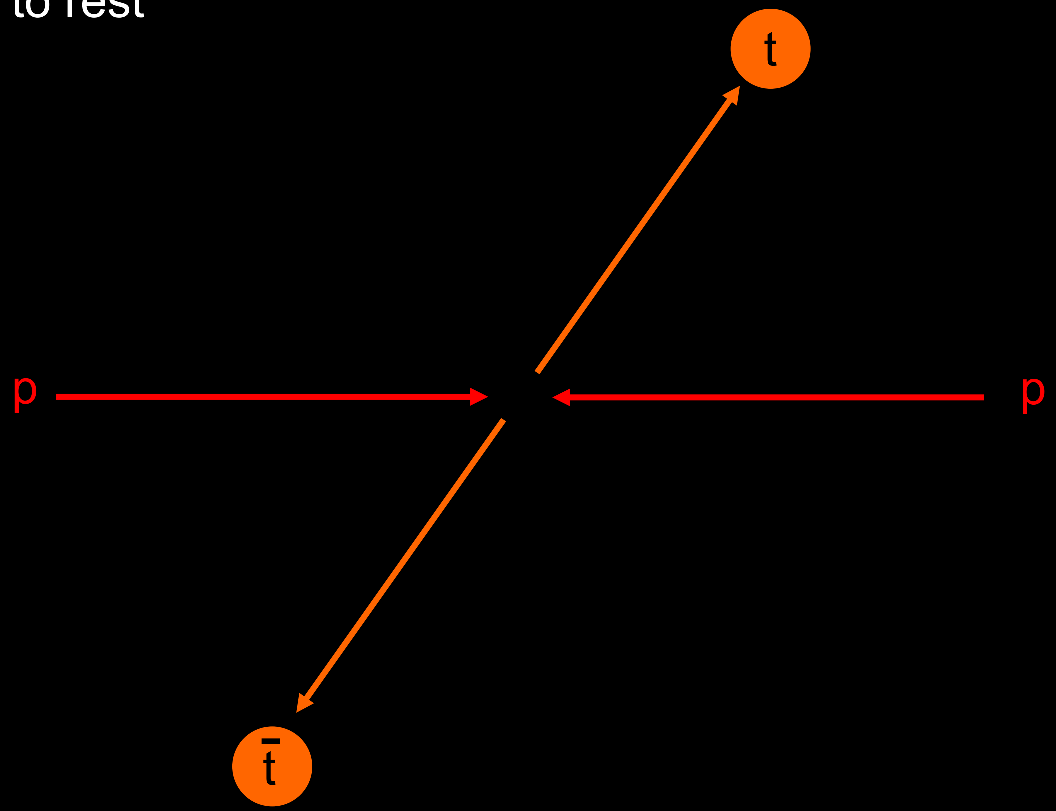
Coordinates

start in lab frame



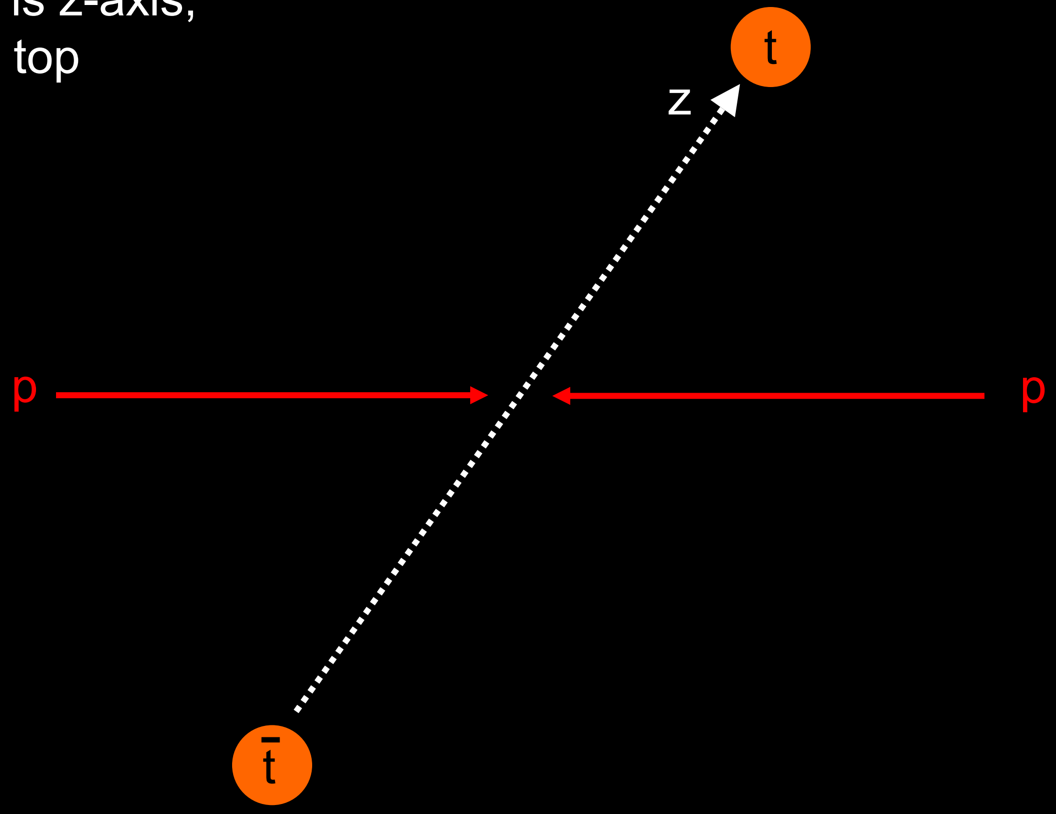
Coordinates

boost tt system to rest



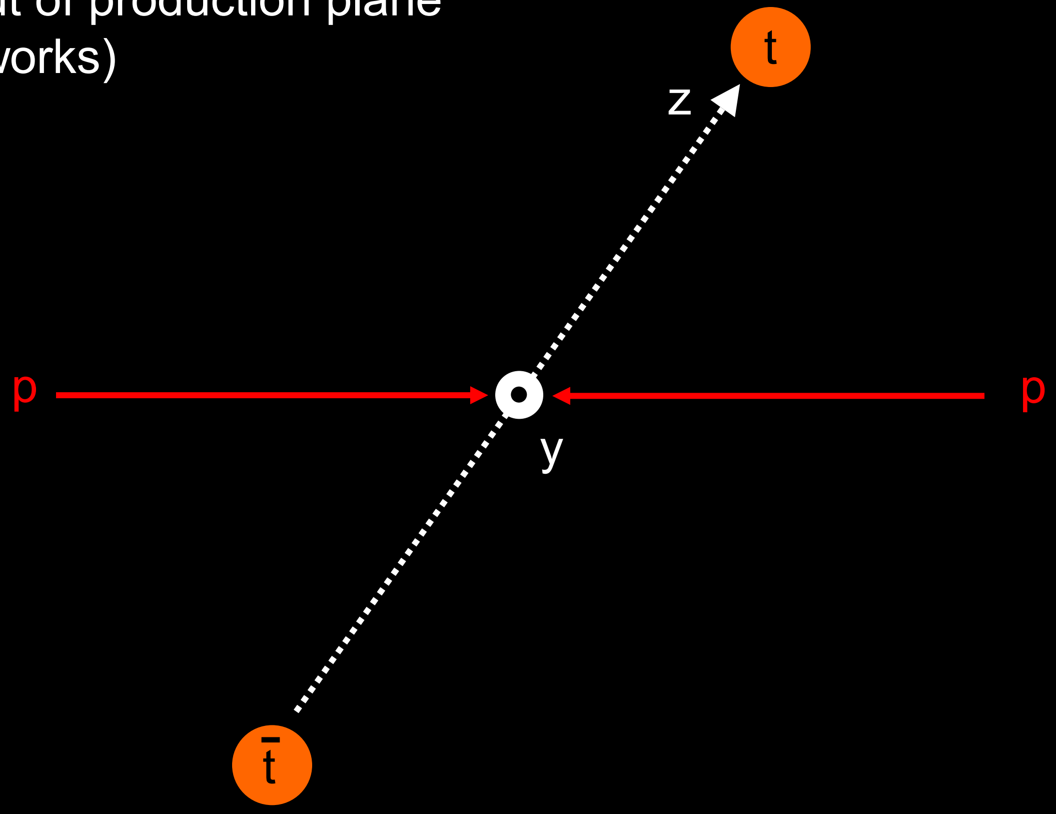
Coordinates

production axis is z-axis,
pointing toward top



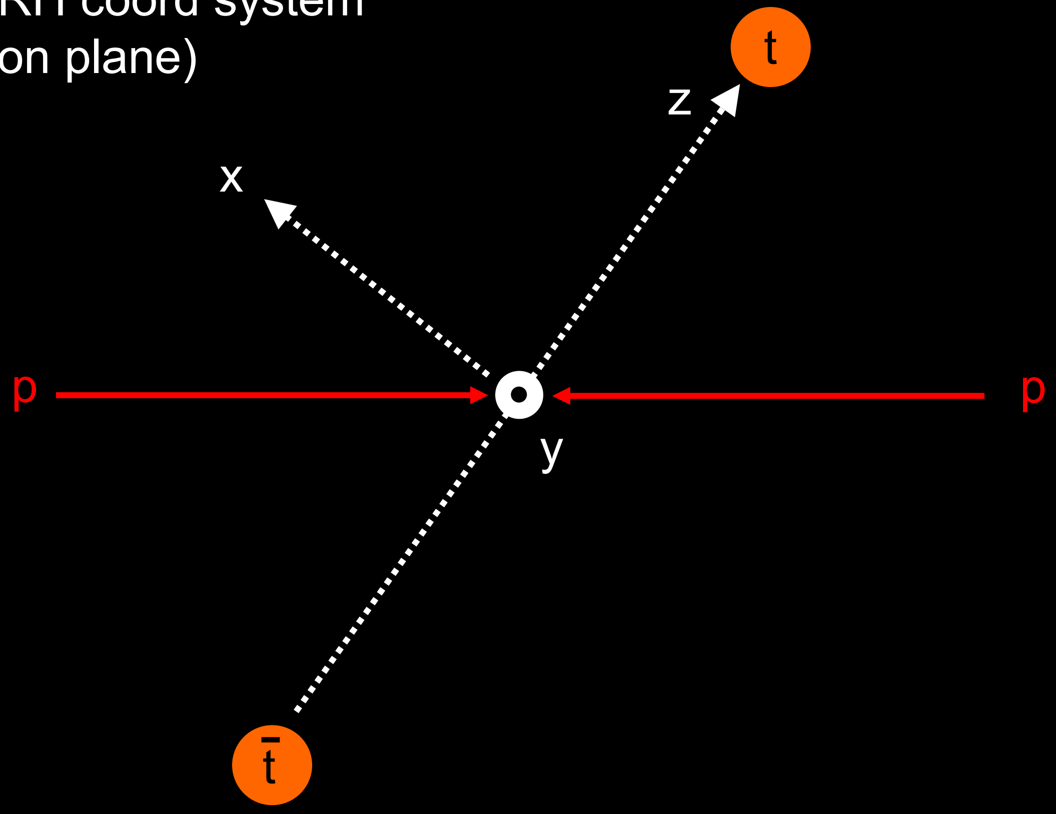
Coordinates

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



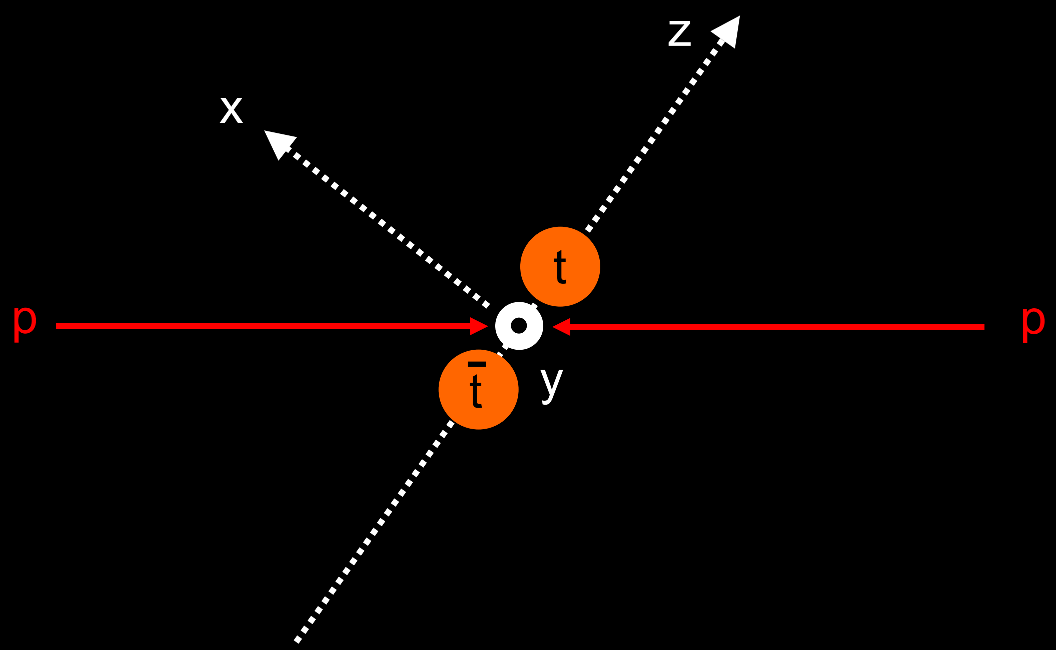
Coordinates

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



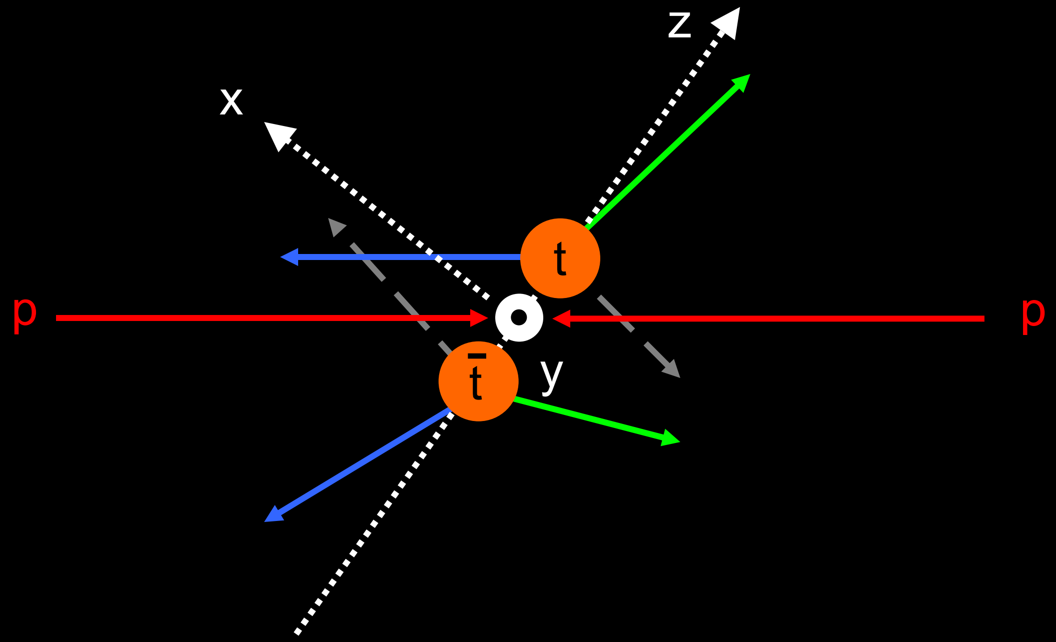
Coordinates

boost the tops to rest



Coordinates

and look at their decay products



Full Helicity Interference in Boosted Production Limit

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

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

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

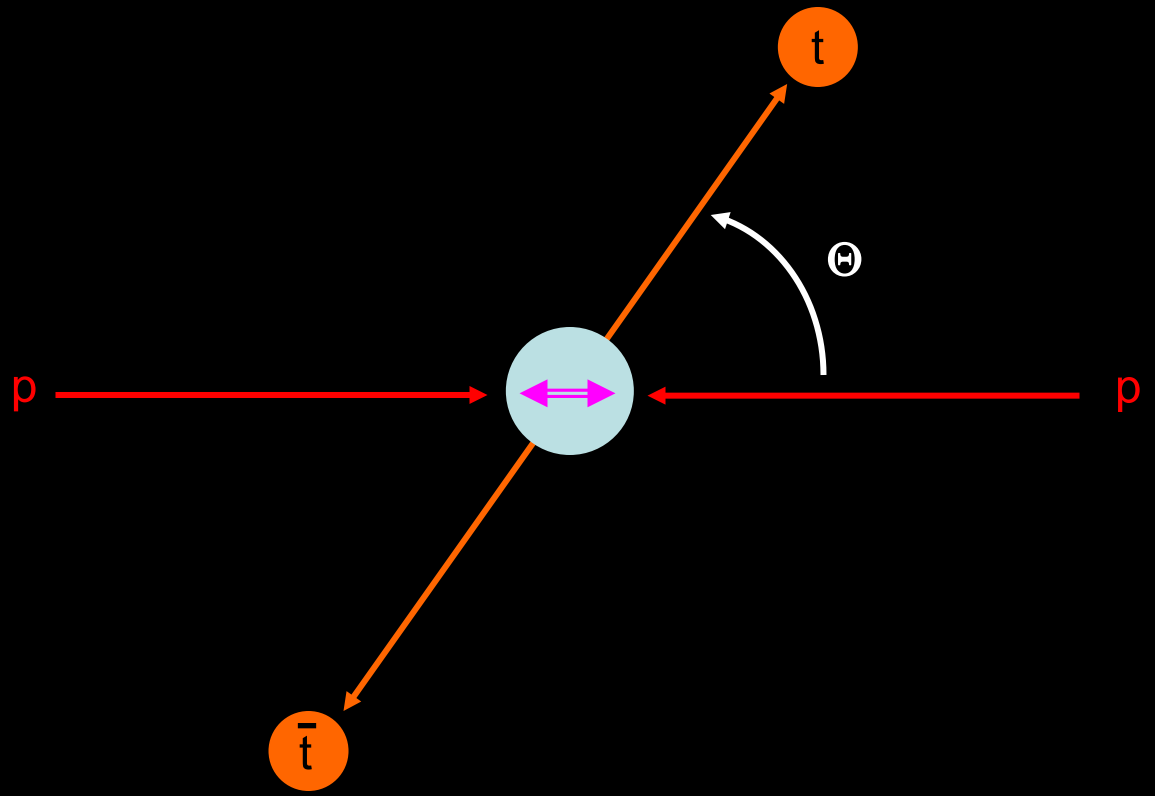
If We Just Measure ϕ

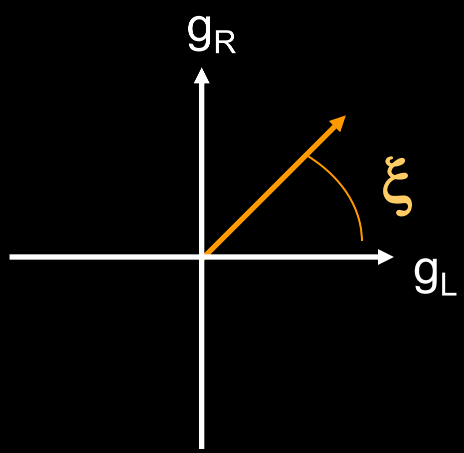
$$\frac{d\Gamma}{d(\phi_\ell - \bar{\phi}_\ell)} \propto 1 - \left(\frac{\pi}{4}\right)^2 \cos(\phi_\ell - \bar{\phi}_\ell + 2\alpha)$$

60% modulation

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

Spin-1





Spin-1

$$\frac{d^2\Gamma_{J_{\rm beam}=\pm1}}{d(\phi_\ell+\bar\phi_\ell)\,d\cos\Theta} \propto (1+\cos^2\Theta) - \left(\frac{\pi}{4}\right)^2 \sin(2\xi)\sin^2\Theta\cos(\phi_\ell+\bar\phi_\ell)$$

integrate out Θ

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

pure vector: -30%

pure axial: +30%

pure chiral: 0

-/+ 60% for central production

Other Scenarios, Other Coefficients

gg -> spin-1 (color octet)

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

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

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

gg -> spin-2

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

Three (Rather Important) Questions

- Is it possible to isolate the resonance region in dileptonic mode?
- Even if we can, are these angles robust to measurement uncertainties?
- Dileptonic is annoying, can't we use l+jets?

Dileptonic Resonance Peak

perfect (*1/2)

M_{Tcl}

minimal ν

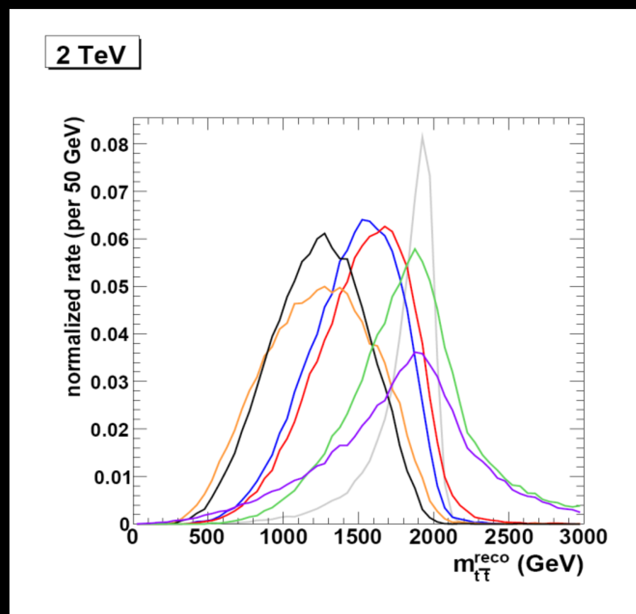
visible

M_{eff}

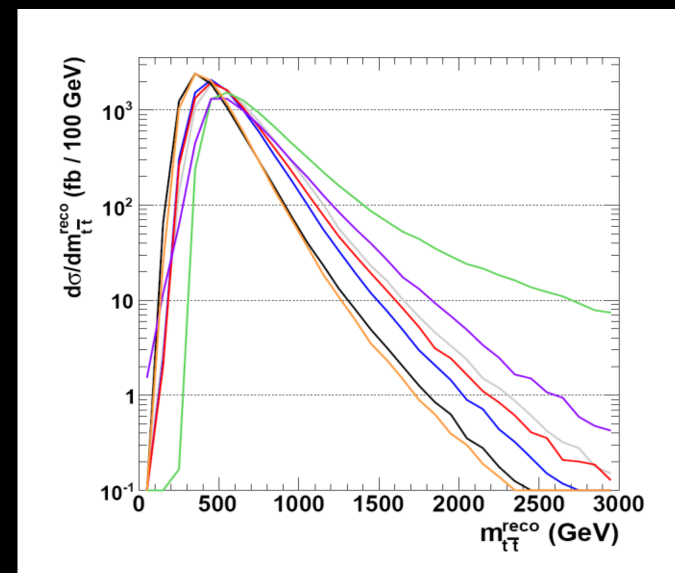
real quartic

Bai-Han

narrow 2 TeV vector



SM continuum (LHC14)



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.)

Spin-0 Azimuthal Modulations

perfect

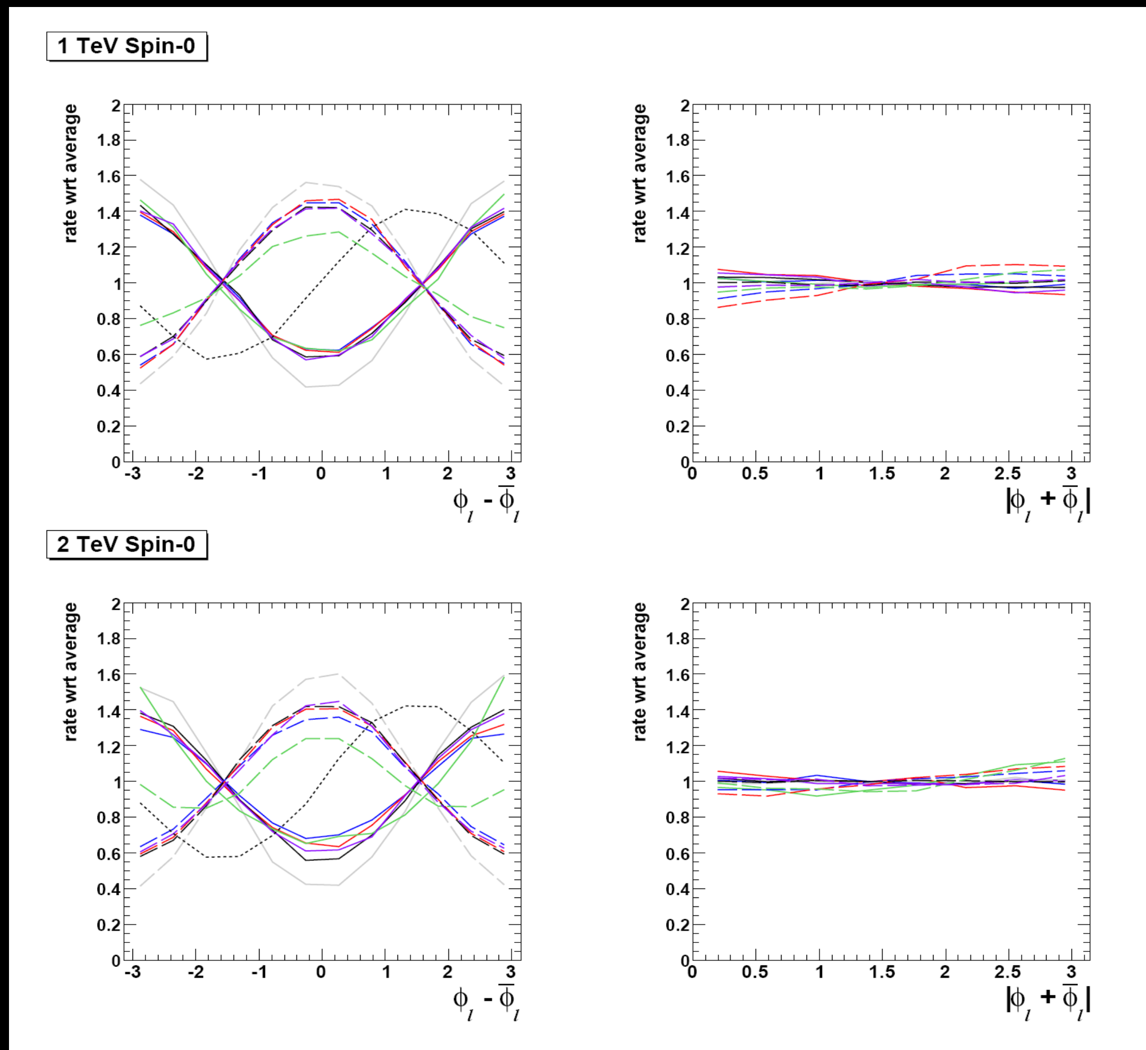
M_{Tcl}

minimal ν

visible

real quartic

Bai-Han



* MadGraph topBSM

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

Spin-1 Azimuthal Modulations

perfect

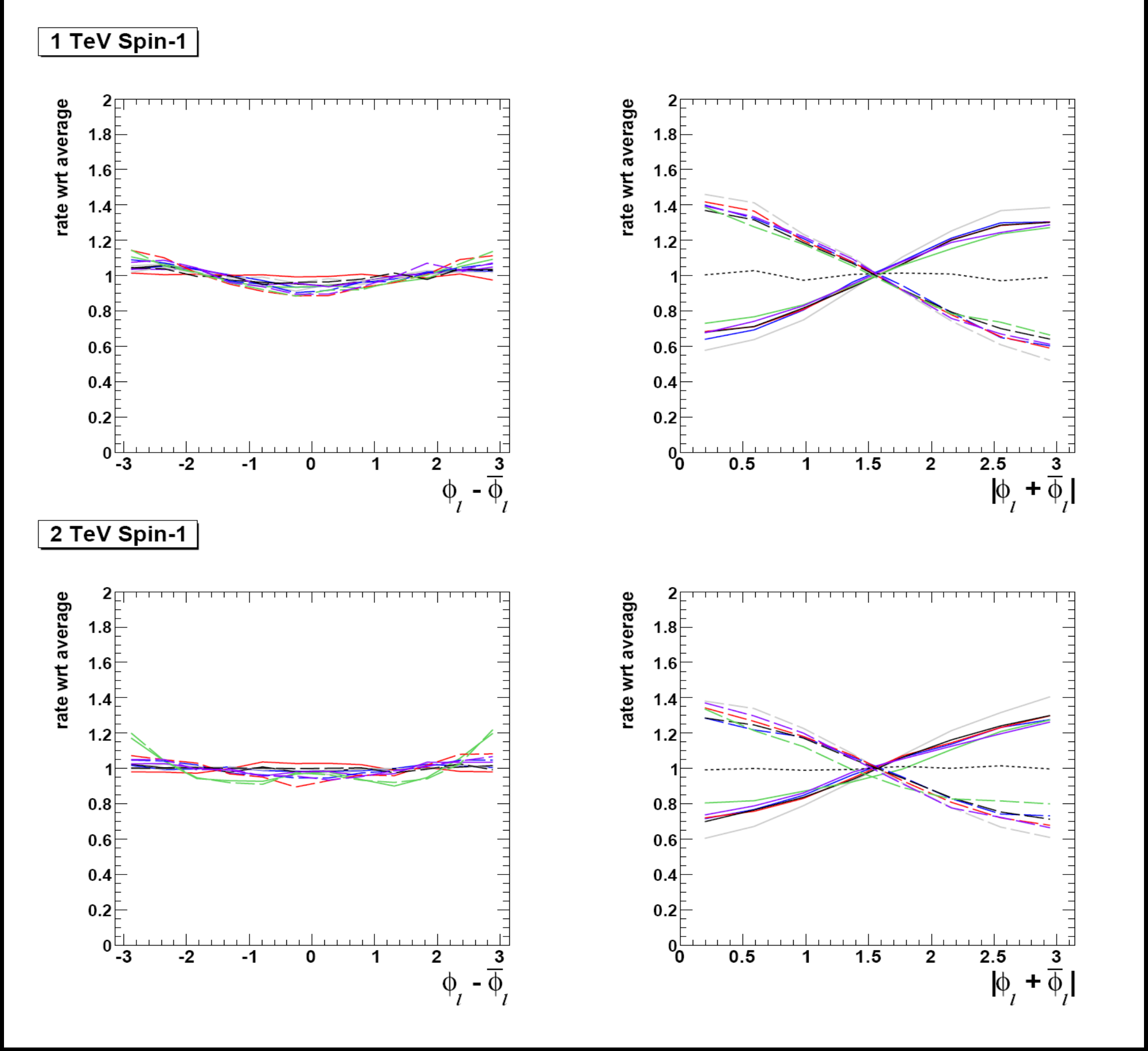
M_{Tcl}

minimal ν

visible

real quartic

Bai-Han



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

SM Azimuthal Modulations

perfect

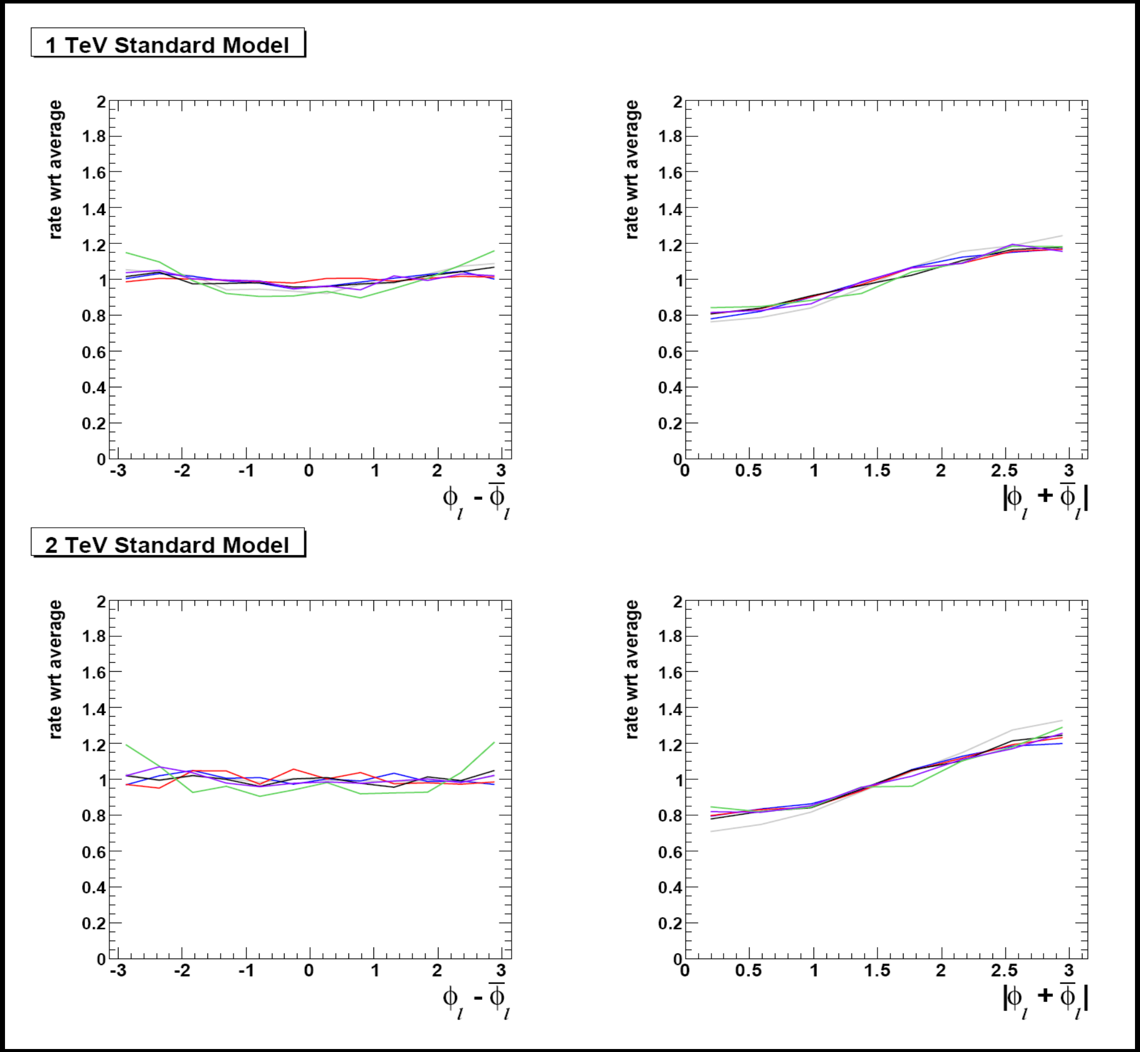
M_{Tcl}

minimal ν

visible

real quartic

Bai-Han

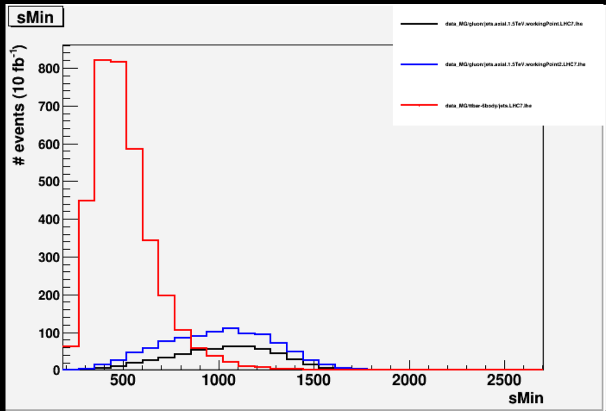


l+Jets

- Pros
  - rate X 6
    - e.g., probe up to higher-mass resonances
    - more stats allows harder centrality cuts to enhance modulations
  - easier to fully reconstruct
    - better peak -> better S/B with less severe cuts
- “Cons”
  - smaller modulation effects
    - 40% if we correlate lepton with a b-(sub)jet
    - 50% if we correlate lepton with softest (sub)jet in top rest frame
  - need some (sub)jet identification
    - b-tag or internal kinematics

Hand-Selected Tevatron A_{FB} Example Model

- $g_A^q = 0.7$, $g_A^t = -3.0$ (g_V's = 0), M = 1.5 TeV
- safe from (30 fb-1) resonance and contact interaction searches, pushes A_{FB} up to within 1σ of CDF
- σ x BR(tt) = 4 pb (LHC7), Γ = 17%
  - 5 fb^{-1} => 20,000 resonance events
  - 1000 dileptonic
  - 200 pass into our analysis (S/B ~ 10)
    - enough to distinguish vector from axial at ~3σ using 2-bin (asymmetry) analysis



Summary

- 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
  - also visible in the SM continuum boosted tops
- 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?