Top Polarization as a Probe of New Physics

Kumar Rao

Helsinki Institute of Physics

(With Saurabh Rindani, Rohini Godbole and Ritesh Singh)
Top quark properties important input to precision electroweak physics

Is the Top quark exotic in some way?

Useful to discover new particles (Higgs produced in association with $t\bar{t}$ pair)

Top quark events backgrounds to New Physics

Huge mass $\sim 171$ GeV, sensitive probe of Electroweak Symmetry Breaking/New Physics
Top lifetime extremely short, \( \tau_t = 1/\Gamma_t \simeq 5 \times 10^{-25} \) s, with decay mode \( t \to bW^+ \)

For comparison lifetime of \( b \) hadrons \( \tau_{b\text{hadron}} \simeq 1.5 \times 10^{-12} \) s

Top lifetime order of magnitude smaller than hadronization time scale \( \tau_{\text{had}} \simeq 1/\Lambda_{QCD} \simeq 3 \times 10^{-24} \) s

Top decays before it hadronizes and does not form bound states \( \Rightarrow \) study of “bare” top possible

Thus top spin polarization/ spin-spin correlations not diluted by hadronization but imprinted on characteristic angular distributions/correlations of decay products
In SM $t$ decays almost exclusively into $b \, W^+$ with BR 0.998 and $\Gamma_t = 1.44$ GeV

$\Gamma_t/m_t \simeq 0.008$, hence can factorize processes into on-shell production and decay using Narrow Width Approximation

$W$ then decays to
- $u \bar{d}$ (two jets) with BR 2/3
- $l \nu_l$ (lepton + missing energy), BR 1/3 for each lepton
  - Mass reconstruction better with hadronic decay but large background
  - Leptonic channel cleaner but mass reconstruction difficult due to missing energy

For $t\bar{t}$ final state optimal detection channel is semileptonic:
- $t \rightarrow b \, l^+ \nu_l$
- $\bar{t} \rightarrow b + 2$ jets

In SM $tbW^+$ vertex is left handed

Can be modified from beyond SM and loops

New Physics in $tbW^+$ vertex can affect kinematic distributions of decay products
Uses of Top Polarization

- Degree of top pol. depends on production process; thus can probe SM/BSM scenarios
- Gives more information on production mechanism than just cross section
- Can allow measurements of parameters of the model/new particles
- Requires parity violation and thus measures left-right mixing
- Even in QCD though top is produced unpolarized, spin of $t$ is correlated with $\bar{t}$ ⟷ different rates for opposite helicity and same helicity $t\bar{t}$ production
- Can probe CP violation through dipole couplings
Measuring Polarization

- Decay Distribution of fermion $f$ in Top rest frame

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

- $\theta_f$ is angle between $f$ and top Polarization vector
- $P_t$ is Degree of Top Polarization
- $\kappa_f$ is “Spin Analyzing power” of $f$
- $\kappa_b = -\kappa_W \approx -0.4$, $\kappa_+^l = -\kappa_d = 1$
- Charged lepton or $d$ quark has best analyzing power
Spin Correlation extensively studied for hadronic $t\bar{t}$ production

$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_+ d \cos \theta_-} = \frac{1}{4} (1 + B_1 \cos \theta_+ + B_2 \cos \theta_- - C \cos \theta_+ \cos \theta_-)$$

$$C \propto \frac{\sigma(t_{\uparrow}\bar{t}_{\uparrow}) + \sigma(t_{\downarrow}\bar{t}_{\downarrow}) - \sigma(t_{\uparrow}\bar{t}_{\downarrow}) - \sigma(t_{\downarrow}\bar{t}_{\uparrow})}{\sigma(t_{\uparrow}\bar{t}_{\uparrow}) + \sigma(t_{\downarrow}\bar{t}_{\downarrow}) + \sigma(t_{\uparrow}\bar{t}_{\downarrow}) + \sigma(t_{\downarrow}\bar{t}_{\uparrow})}$$

But needs reconstruction of $t$ and $\bar{t}$ rest frames, difficult at LHC

Conceivable that *single top polarization* can give better statistics
Spin Density Matrix for Top production and Decay

Amplitude for Top production and Decay

\[ \mathcal{M}(A B \rightarrow t X \rightarrow f X' X) = \sum_{\lambda} \mathcal{M}(A B \rightarrow t(\lambda)X) \mathcal{M}(t(\lambda) \rightarrow f X') \]

Transition probability

\[ |\mathcal{M}(A B \rightarrow t X \rightarrow f X' X)|^2 = \sum_{\lambda,\lambda'} \mathcal{M}(AB \rightarrow t(\lambda)X)\mathcal{M}^*(AB \rightarrow t(\lambda')X) \]
\[ \times \mathcal{M}(t(\lambda) \rightarrow fX')\mathcal{M}^*(t(\lambda') \rightarrow fX') \]

\[ |\mathcal{M}(A B \rightarrow t X \rightarrow f X' X)|^2 = \sum_{\lambda,\lambda'} \rho(\lambda, \lambda')\Gamma(\lambda, \lambda') \]

\( \rho(\lambda, \lambda') \): Production Density Matrix
\( \Gamma(\lambda, \lambda') \): Decay Density Matrix
Production Spin Density Matrix

\[ \rho(\lambda, \lambda') = \sigma_{tot} P_t(\lambda, \lambda') \]

\[ P_t = \frac{1}{2} \begin{pmatrix} 1 + \eta_3 & \eta_1 - i\eta_2 \\ \eta_1 + i\eta_2 & 1 - \eta_3 \end{pmatrix}, \]

Longitudinal Polarization

\[ \eta_3 = \frac{(\sigma(+, +) - \sigma(-, -))}{\sigma_{tot}} \]

Transverse Pol. in production plane

\[ \eta_1 = \frac{(\sigma(+, -) + \sigma(-, +))}{\sigma_{tot}} \]

Transverse Pol. perpendicular to production plane

\[ i \eta_2 = \frac{(\sigma(+, -) - \sigma(-, +))}{\sigma_{tot}} \]
Anomalous $tbW^+$ Vertex

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

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

In SM $f_{1L} = 1, f_{1R} = f_{2L} = f_{2R} = 0$
Angular distributions of charged leptons/d quarks from top decay not affected by anomalous $tbW^+$ vertex (to linear order)

Shown earlier for $e^+e^- \rightarrow t\bar{t}$ [Grzadkowski & Hioki; Rindani, 2000] and $\gamma\gamma \rightarrow t\bar{t}$ [Grzadkowski & Hioki; Godbole, Rindani, Singh 2006]

Proved for general process $A + B \rightarrow t + X$ [Godbole, Rindani, Singh JHEP 12, 021, 2006]

Uses Narrow Width Approximation for the Top

Implies that charged lepton angular dis. more accurate probes of Top Pol. and thus to New physics in Top production

Energy distributions, $b/W$ angular distributions “contaminated” by anomalous $tbW$ vertex
The above result depends on the factorization of the decay density matrix into angular and energy dependent parts in Top rest frame:

\[
\langle \Gamma(\lambda, \lambda') \rangle = (m_t E^0_l) |\Delta(p^2_W)|^2 g^4 A(\lambda, \lambda') F(E^0_l)
\]

where

\[
A(\pm, \pm) = 1 \pm \cos \theta_l \quad , \quad A(\pm, \mp) = \sin \theta_l e^{\pm i \phi_l}
\]
Polarizations in terms of Lepton Angular Asymmetries

\[
\frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} = C \, \sigma_{\text{tot}} \left[ 1 + \eta_3 \, \cos \theta_\ell + \eta_1 \, \sin \theta_\ell \cos \phi_\ell + \eta_2 \, \sin \theta_\ell \sin \phi_\ell \right] (1)
\]

\[
\eta_3 = \frac{1}{4\pi \, C \, \sigma_{\text{tot}}} \left[ \int_{0}^{2\pi} \int_{0}^{2\pi} \frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} - \int_{0}^{2\pi} \int_{0}^{-1} \frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} \right]
\]

\[
\eta_2 = \frac{1}{4\pi \, C \, \sigma_{\text{tot}}} \left[ \int_{-1}^{0} \int_{0}^{\pi} \frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} - \int_{-1}^{0} \int_{\pi}^{2\pi} \frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} \right]
\]

\[
\eta_1 = \frac{1}{4\pi \, C \, \sigma_{\text{tot}}} \left[ \int_{-1}^{0} \int_{-\pi/2}^{\pi/2} \frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} - \int_{-1}^{0} \int_{\pi/2}^{3\pi/2} \frac{d\sigma}{d \cos \theta_\ell \, d\phi_\ell} \right]
\]

Here \(4\pi C = BR(t \to bl\nu)\)
• Has a massive spin 1 resonance $Z_H$ with left handed couplings to fermions
  
  $$(v_f, a_f) = \pm (g \cot \theta/4, -g \cot \theta/4) \quad \text{for } T_3 = \pm \frac{1}{2}$$

• Additional s-channel contribution of $Z_H$ to $t\bar{t}$ production at LHC along with $\gamma, Z, \text{gluon}$

• Only two new parameters $M_{Z'}$ and $\cot \theta \ (\cot \theta \leq 2)$

• Non-Zero axial coupling, contributes unequally to $\bar{t}_- t_-$ vs $\bar{t}_+ t_+$ and $\bar{t}_- t_+$ vs $\bar{t}_+ t_-$. 
$M_{Z'} = 1000$ GeV, $\cot \theta = 2$
Top Longitudinal Polarization

\[ P_t \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]
Qualitative Probes of Top Polarization

- Kinematic variables to probe Top Pol. built out of lepton variables alone convenient and robust at LHC
- Lepton energy dis. sensitive to magnitude and sign of $P_t$ but depend on anomalous $tbW$ vertex as well
- FB Asymmetry (Polar angle measured w.r.t Top direction in parton cm frame) only mildly sensitive to $P_t$
- Azimuthal distribution can probe Top polarization
Azimuthal Distribution of $l^+$ measured w.r.t beam direction as $Z$ axis and $t\bar{t}$ production plane.
Azimuthal Asymmetry of $l^+$

$$A \equiv \frac{\sigma(1, 4) - \sigma(2, 3)}{\sigma(1, 4) + \sigma(2, 3)}$$
Top Polarization can be a sensitive probe of new physics in its production.

Lepton angular distributions *independent* of anomalous $tbW$ vertex.

Thus pure probes of new physics in Top production.

Azimuthal lepton distributions seem to be particularly sensitive to $Z'$ models at the LHC.

Work in progress; also applying formalism to single Top production in association with a charged Higgs at the LHC.