Spin Correlation in $t\bar{t}$ Production at the Tevatron

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Spin Correlation in $t\bar{t}$ Production

- At the Tevatron, SM predicts that 90% of the $t\bar{t}$ cross section comes from $q\bar{q}$ annihilation.

- An optimal spin basis can be found (G. Mahlon and S. Parke)
  - In the off-diagonal basis, 92% of $t\bar{t}$ pairs have unlike spins.
  - In the more familiar helicity basis, 70% of $t\bar{t}$ pairs have unlike helicities.

Off-diagonal

Helicity
No Spin Decorrelation in Decay

- **SM predicts that top will decay before it hadronizes**
  - $\Gamma^{-1}(t \to Wb) \ll 1/\Lambda_{QCD}$
- **Moreover, the spin flip time via coupling through its chromomagnetic moment is even longer**
  - $1/\Lambda_{QCD} \ll m_{top}/\Lambda_{QCD}^2$
- **We expect the top quark's helicity will be transmitted to its decay products**
Polarized Top Decays

- Let $\theta_i$ be the angle between the chosen spin axis and the $i$'th decay product

$$\frac{dN}{d(\cos \theta_i)} = \frac{1 + \alpha_i \cos \theta_i}{2}$$

<table>
<thead>
<tr>
<th>Particle,</th>
<th>$\alpha_i$ at $m_t = 175$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell^+$ or d</td>
<td>1</td>
</tr>
<tr>
<td>$v$ or u</td>
<td>-0.31</td>
</tr>
<tr>
<td>$W^+$</td>
<td>0.41</td>
</tr>
<tr>
<td>b</td>
<td>-0.41</td>
</tr>
</tbody>
</table>

- We use the angular distribution of the charged leptons to determine the top quark spin direction
- Define $\cos\theta_+$ and $\cos\theta_-$ as shown.
- Decay rate $\sim 1 + \kappa \cos\theta_+ \cos\theta_-$.
- Spin correlation $\kappa$ describes fractional difference between like and unlike spins.
  - $\kappa = +1$ for qq events in the off-diagonal basis.
  - $\kappa = +0.88$ when the gg contributions are added.
Strategy and Motivation

• How?
  - Use top to dilepton events
    ▶ Requires reconstruction of the neutrinos
  - Determine the spin correlation $k$ from the angular correlation $\cos\theta_+ \text{ versus } \cos\theta_-$
    ▶ Asymmetry method
    ▶ Likelihood method

• Why?
  - Tests that indeed top decays before its spin flips and sets and upper bound on the lifetime
  - Places a lower limit on $|V_{tb}|$ without assuming there are three families
  - Searches for non-SM physics in the production or weak decay of top
Top to Dilepton Selection

- 2 high $P_T$ leptons $> 15$ GeV
- $\geq 2$ jets with $E_T > 20$ GeV
- missing $E_T > 20$ GeV
- $H_T > 120$ GeV
- 6 events observed
Top to Dilepton Reconstruction

• Assume $m_t = 175$ GeV
  ♦ system can be solved yielding 0 to 4 solutions

• $\nu$-weighted Event Fitter
  ♦ $\eta_1$ and $\eta_2$ are sampled according to the expected distribution in $t\bar{t}$ decays
  ♦ Jet and lepton energies are smeared
  ♦ 2 permutations for a 2 jet event
  ♦ Likelihood weights are assigned to each solution by comparing $\Sigma p_k(\nu \nu)$ and $E_k$

• 6 unknowns
  momenta of 2 neutrinos

• 5 constraints
  ♦ $m(\ell\nu) = m_W$
  ♦ $m(\ell\nu) = m_W$
  ♦ $m(\ell b\nu) = m(\ell b\nu)$
  ♦ Missing $E_T$ (2 constraints)
\( \nu \) Reconstruction

- 10000 events with \( \eta_\nu \) around 1.0 selected
- Weights returned from the event fitter
Asymmetry Analysis

- Define a single variable
  - \( \xi = \cos\theta_+ \cos\theta_- \)
- Define an asymmetry
  - \( A = \frac{(R - L)}{(R + L)} \)
- For perfect acceptance, resolution, and reconstruction
  - \( A = \kappa / 4 \)
Asymmetry from Data

- Use all solutions together with their likelihood weights
  - Smear energies of jets and leptons 2000 times
  - Apply $\nu$-weighted event fitter
- $\langle A \rangle = 0.31 \pm 0.22$
Asymmetry from Monte Carlo

- **Monte Carlo studies**
  - Generate 40k events in each ee, eμ, and μμ channels
  - Create 1500 ensembles of 6 events containing the appropriate mixture of signal (Pythia) and background

- **Monte Carlo results**
  - For $\kappa = 1$, $A = 0.207 \pm 0.006$
  - For $\kappa = 0$, $A = 0.115 \pm 0.005$
  - $\sigma_A = 0.22$
Extracting $k$ from $A$

- Monte Carlo studies show
  - $A$ is positively biased
  - $A$ is diluted
- Bias
  - Wrong lepton-jet pairing in the event fitter
- Dilution
  - Neutrino scanning
  - Detector resolution
  - Physical and instrumentation backgrounds
- Little effect
  - Top quark mass
  - Gluon radiation
Asymmetry Analysis Result

- $A = 0.31 \pm 0.22$
  $\Rightarrow \kappa = 2.3 \pm 2.5$

- The measured asymmetry gives a probability density for $\kappa$ such that the 1\(\sigma\) region for
  - Entire region
    - $-0.2 < \kappa < 4.8$
  - Physical region
    - $-0.18 < \kappa < 1.0$
Binned Likelihood Analysis

- Use the \((\cos \theta_+, \cos \theta_-)\) distribution from data
- \((\cos \theta_+, \cos \theta_-)\) space is divided into a 3x3 grid
- All solutions from the event fitter are used with their likelihood weights
- The distribution of weights for each event is normalized to 1
- Create probability densities from Monte Carlo events using different values of \(K\)
- Find the likelihood for as a function of \(K\)
Calculating the Likelihood

- To calculate $L(\kappa)$
  - Form the covariance matrix for weights using Monte Carlo and diagonalize
  - Transform the weights into new independent variables
  - Construct likelihood functions $f_i$ for the new variables
  - Transform the data weights into new variables $d_i$
  - Find the likelihood of a given $\kappa$
    \[ L = \prod_i f_i(d_i) \]
Binned Likelihood Result

- The likelihood of the data is calculated using the probability densities from Monte Carlo with different values of $K$

- $K > -0.25$ at 68% CL
Outlook for Run II

- Given the 2 fb\(^{-1}\) of data expected in Run II, we expect to collect \(~150\) dilepton events.
- Estimate the Run II reach by applying the binned likelihood method to ensembles of 150 events.
- Find we can distinguish \(\kappa = 0\) from \(\kappa = 1\) at greater than \(2\sigma\).
- Lepton plus jets channel?
Conclusions

• We have searched for spin correlation in $t\bar{t}$ production at the Tevatron
• We find $\kappa > -0.25$ at 68% CL
• We eagerly look forward to the 20x larger top samples expected in Run II