Search for Anomalous Kinematics in Top Dilepton Events at CDF

- Motivations and Goals
- Method
- Data Sample and Event Selection
- Results
- Conclusions

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Top Dilepton Decay Chain

Event Signature:
2 high-$E_T$ leptons (e or $\mu$), at least 2 high-$E_T$ jets ($b$-jets + ISR/FSR), large missing transverse energy due to neutrinos.

Motivation: Observed 9 events in Tevatron Run I, several events had kinematics that was incompatible with the Standard Model expectations.
In hep-ph/9607342, Barnett and Hall argue that some of the Run I Top Dilepton events have characteristics that are better accounted for by decays of supersymmetric quarks:

\[ \tilde{q} \rightarrow q\tilde{\chi}, \ \tilde{\chi} \rightarrow \nu\ell, \ \ell \rightarrow \ell\tilde{\chi}_1^0. \]

with

Masses: 310, 260, 130, 50 GeV
Goals of the Analysis

*(motivated by peculiarities seen in Run I Top Dilepton Sample)*

1: Determine how consistent the kinematic features of the dilepton events are with the SM.

2: Isolate events in a data sample with possible non-SM decays and quantify departure of those events from the SM.

Missing $E_T$ distribution

Run I dilepton sample
What kind of distortions in kinematic distributions are we looking for?

- Expect new physics to reveal itself in the high Pt region.

- We design a statistical technique (goodness-of-fit) for a generic search for new physics especially sensitive to the tails of kinematic distributions.

- Method is
  a) data-driven;
  b) defined a-priori;
  c) designed to isolate a subset of events most inconsistent with the SM and to assess significance of the deviation.
Kolmogorov-Smirnov test

Adopt KS test for comparison of kinematic distributions

\[ \Delta = \max_i | F(x_i) - S_{N}^{K}(x_i) | \]

Example: single variable \( x \)

- Randomly populate \( N \) events – this is a pseudo-experiment \( S_{N} \)
- Construct subset of events \( S_{N}^{K} \) -- from the \( K \) events at the right tail.
- Find the KS distance \( \Delta_{K} \) between Standard Model distribution \( F(x) \) and data \( S_{N}^{K}(x) \)
- Construct probability distribution functions \( F_{N}^{K}(\Delta_{K}) \) for each \( K \):
  \[ 1 \leq K \leq N \]
by generating a large number of pseudo-experiments
Isolating the most unlikely subset and quantifying significance of deviation

Define Statistic:

\[ P_K = \int_{\Delta_K}^{\infty} F_N^K (\Delta'_K) d\Delta'_K \]

Determines probability of consistency for subset of K events

Define Statistic:

\[ P = \min_{0 < K < N} P_K \]

Determines a subset revealing the largest discrepancy from the Standard Model (a subset of possible new physics events?!) 

Next, generate pseudo-experiments and calculate

\[ \alpha = \text{Prob} \ (P < P_{\text{data}}) \]

which quantifies significance level of departure of the most unlikely subset from the SM
Multi-Variate test

- We choose a statistic (Product KS)
  \[ P = (P_x \cdot P_y)^{1/2} \]
  - geometrical mean of 1D-KS probabilities \( P \).
  - Assign a weight to each event – measure of ‘unlikeness’.
  \[ w = (w_x \cdot w_y)^{1/2} \], where
  \[ w_x = \int_{x_0}^{1} f(x, y) \, dx \]
  - Construct unlikely K-subset from K events with smallest weights.
  - Proceed as in 1D-case.
Choice of kinematic variables

*New physics is likely to reveal itself in various kinematic distributions. Need to include many variables, but not too many – we don’t want to dilute the result.*

**New physics scenario:**

1. Decay of heavy particles leads to large transverse momenta objects with at least one hard lepton and a large missing Et. 
   (*Missing $E_T$, $P_T$ of the leading lepton*)

2. Conservation laws require large quantities to be back to back.
   ($\Delta \phi$ *leading lepton, met* - angle between them)

3. Final state quantities of a new physics event most likely do not satisfy the system of kinematic equations for the SM top quark decay. (*topological variable*)
Topological weight of an event

- \((P_l + P_\nu + P_b)^2 = M_t^2\)
- \((P_l + P_\nu)^2 = M_W^2\)

- Solve system of kinematic equations for neutrino momenta.
- Enhance neutrino solution phase space by accounting for ambiguities in two lepton-b-jets pairings, detector resolution and uncertainty in top mass.
- Integrate over enhanced phase space and get a topological weight per each event.

\[
T_w = \int \exp \left\{ -\left( \frac{\vec{E_T}^{predicted} - \vec{E_T}^{measured}}{2\sigma_{E_T}^2} \right)^2 \right\} d\vec{E_T}^{predicted}
\]

Top dilepton events have on average larger T than non-top SM background and new physics events.
MC comparison of ttbar with Barnett & Hall SUSY model

Assuming 50% dilepton candidates from this SUSY model, the PKS method would find less than 1% consistency 60% of the time with 13 events sample.
Run II Top Dilepton Selection

- Event Selection used in Run II top cross section measurement named ‘DIL’ ([hep-ex/0404036 accepted to PRL](https://arxiv.org/abs/hep-ex/0404036))
- Two leptons $E_T > 20$ GeV (at least one isolated);
- Opposite charge;
- Two jets $E_T > 15$ GeV, $|\eta| < 2.5$
- Reduce Drell-Yan events and other SM backgrounds:
  - Missing $E_T > 25$ GeV;
    - $|\Delta\phi_{(\text{lepton},\text{Met})}| > 20$deg if Met $< 50$ GeV;
  - in Z mass region - 76 GeV $< M_{ll} < 106$ GeV:
    - jet Significance $> 8$;
    - $|\Delta\phi_{(\text{jet OR lepton},\text{Met})}| > 20$deg
- $H_T$ (scalar energy sum of all objects) $> 200$ GeV.

Observe 13 events;
expect 2.7 +/- 0.7 from non-top backgrounds, 8.2 +/- 1.1 from ttbar ($\sigma = 6.7$ pb)
Kinematics in Run II Top Dilepton Sample

Observe most unlikely subset of all 13 events, which is $\alpha = 1.6\%$ consistent with SM primarily due to an excess of low $P_T$ leptons.
Dilepton events in $(P_{Tl}, T)$ plane

Low $P_T$-lepton events are accompanied with b-jets - likely being from $t\bar{t}$bar

$\alpha = 1.6\%$
Systematic Uncertainties

Make Use of $\pm 1\sigma$ templates

<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha\ '$</th>
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<tbody>
<tr>
<td>Background Estimates</td>
<td>0.010-0.027</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>0.021-0.026</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>0.012-0.016</td>
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<tr>
<td>PDFs</td>
<td>0.019</td>
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<td>Top Mass</td>
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<tr>
<td>MC Generator</td>
<td>0.016</td>
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<tr>
<td>Combined</td>
<td>0.010-0.045</td>
</tr>
</tbody>
</table>

Procedure:
Find $\alpha\ '$ for each systematic uncertainty.

For combining all systematic effects use combinations of the worst scenarios.
Conclusions

- We have assessed the top dilepton sample’s consistency with the Standard Model in the four-variable space (missing $E_T$, $P_T$ of the leading lepton, $\Delta \phi$ between these quantities and $T$) and find a probability of consistency $1.0 - 4.5\%$.
- The distributions are consistent with the SM expectations. The lepton $P_T$ distribution exhibits a mild excess at low $P_T$ consistent with a statistical fluctuation of SM top.
- No anomalies are seen in the kinematic regions expected to be populated by events containing new heavy particles. New physics scenarios invoked by Run I events are not favored by the Run II data.
- This analysis is based on $193\text{ pb}^{-1}$, another $\sim 200\text{ pb}^{-1}$ are collected, expect $\sim 4000 - 9000\text{ pb}^{-1}$ with Run II by 2009.
Backup Slides
Validation of MC simulation
on the sample of W + 3 jets events

**Event Selection:**
- one high $P_T > 20$ GeV electron or muon (trigger);
- At least three jets ( $E_T > 15$ GeV, $|\eta| < 2.5$ )
- $\text{Met} > 25$ GeV
  (QCD removal: if $\text{Met} < 35$ GeV, $0.5 < \Delta\Phi(\text{Met,leading jet}) < 2.5$)
- $|Z_{\text{primary vertex}} - Z_{0, \text{lepton}}| < 5.0$ cm

Observe: 973 events. Main Backgrounds: QCD $\sim 8.8\%$; ttbar $\sim 11.2\%$

Require 4 – th jet to “simulate” T:
- treat the first two jets as b-jets and the other two jets as a second lepton and neutrino;
- reconstruct an event if it was top dilepton.
‘W+Jets’ kinematic distributions

CDF II preliminary

1. $W + \geq 3$ jet data (193 pb$^{-1}$)
   - $W + 3p$ ALPGEN MC
   - $t\bar{t}$ MC PYTHIA ($\sigma = 0.7$ pb)
   - QCD

   $KS = 0.75$

2. $W + \geq 4$ jet data (193 pb$^{-1}$)
   - $W + 4p$ MC ALPGEN
   - $t\bar{t}$ MC PYTHIA ($\sigma = 0.7$ pb)
   - QCD

   $KS = 0.97$

CDF II preliminary

1. $W + \geq 3$ jet data (193 pb$^{-1}$)
   - $W + 3p$ ALPGEN MC
   - $t\bar{t}$ MC PYTHIA ($\sigma = 0.7$ pb)
   - QCD

   $KS = 0.18$

2. $W + \geq 4$ jet data (193 pb$^{-1}$)
   - $W + 4p$ MC ALPGEN
   - $t\bar{t}$ MC PYTHIA ($\sigma = 0.7$ pb)
   - QCD

   $KS = 0.16$