Search for Scalar Top Admixture in the $t\bar{t}$ Lepton+Jets Channel at DØ

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on behalf of the DØ Collaboration
Overview

- Scalar Top ("Stop") Production and Decay
- Tevatron Collider
- DØ Detector

- Event Signature
- Background Processes
- Limit Setting Procedure
- Result and Conclusion
Stop Production

- Production in pairs (same diagrams as top pair production)

\[
\begin{align*}
\text{Stop:} & \quad (\text{PROSPINO NLO}) \\
\sigma(m_{\tilde{t}} = 175 \text{ GeV}) &= 0.579 \text{ pb} \\
\text{Top:} & \quad (\text{Kidonakis/Vogt NNLO}) \\
\sigma(m_t = 175 \text{ GeV}) &= 6.77 \text{ pb}
\end{align*}
\]

- Theoretical Cross Section (at 1.96 TeV):
  - \textit{Stop}: (PROSPINO NLO) \[\sigma(m_{\tilde{t}} = 175 \text{ GeV}) = 0.579 \text{ pb}\]
  - \textit{Top}: (Kidonakis/Vogt NNLO) \[\sigma(m_t = 175 \text{ GeV}) = 6.77 \text{ pb}\]

- Cross section highly dependent on mass
Stop Decay

- R-parity conserved, examples:

\[ \sigma \text{ [pb]} \]
\[
\begin{array}{cccc}
\text{m}_{t_1} & \text{m}_{\tilde{\chi}_i^+} & \text{m}_{\tilde{\chi}_i^0} & \text{m}_{\tilde{\chi}_i^0} \\
0.579 & 175 & 135 & 50 \\
0.579 & 175 & 120 & 50 \\
0.579 & 175 & 105 & 50 \\
1.00 & 160 & 120 & 50 \\
1.00 & 160 & 105 & 50 \\
1.80 & 146 & 105 & 50 \\
\end{array}
\]

A. Djouadi, Y. Mambrini, Phys. Rev. D 63, 115005 (2001)
Tevatron at Fermilab

- \( p\bar{p} \) collisions at center of mass energy \( \sqrt{s} = 1.96 \) TeV

- ~900 pb\(^{-1}\) analyzed
DØ Detector

- Multi-Purpose Detector
  - Acceptance:
    - Electrons $|\eta| < 3.0$
    - Muons $|\eta| < 2.0$
    - Jets $|\eta| < 4.2$

Tracking System
- Tracks
- Vertices

Calorimeter
- Electrons
- Photons
- Jets
- Missing $E_T$

Muon System
- Muons
Event Signature

Signature:
- 1 high $p_T$ lepton
- 2 b-jets
- 2 light jets
- Missing energy

Challenge:
tt̅ Production has the same signature

Decay channels determined by W decay:
- All jets
- Lepton + Jets
- Dilepton

stop pair:
Background Processes

- $t\bar{t}$ Production: main background, not reducible by cuts
- Other background processes same as in $t\bar{t}\rightarrow$lepton+jets measurements:
  - QCD multijet production
  - $W+$jets
  - $Z+$jets
  - Single top production
  - Diboson ($WW$, $WZ$, $ZZ$)

- Same methods to reduce and estimate them:
  - Preselection based on signal signature
  - $b$-tagging
  - Background estimation using data
Background Estimation

Preselection with loose lepton

Preselection with tight lepton

determine multijet background

W+jets

multijet

W+jets

W+jets

B-Tagging/Estimation of W+jets

Search Result

Likelihood Discriminant
### Yields

| Mass point | e+jets | μ+jets |
|------------|--------|--------|
| 175/135    | 4.0    | 3.1    |
| 175/120    | 3.1    | 2.3    |
| 175/105    | 2.8    | 2.0    |
| 160/120    | 3.6    | 2.4    |
| 160/105    | 3.8    | 2.7    |
| 145/105    | 4.5    | 3.0    |

**Expected Signal**

- 913 pb\(^{-1}\) in e+jets
- 871 pb\(^{-1}\) in μ+jets

| Sample    | e+jets | μ+jets |
|-----------|--------|--------|
| top       | 103.0  | 84.2   |
| Wbb       | 8.5    | 11.1   |
| Wcc       | 4.8    | 6.5    |
| Wlight    | 3.8    | 4.0    |
| Z+jets    | 2.8    | 3.3    |
| single top| 3.1    | 2.5    |
| diboson   | 1.4    | 1.2    |
| multijet  | 10.7   | 3.2    |
| SUM       | 138.1  | 116.0  |
| data      | 133    | 135    |

**Background**
Data-MC Comparisons

- **$\mu$+jets, $\geq 4$ jets, before b-tagging**
  - $p_T$ of lepton
  - $p_T$ of reconstructed leading jet
  - Missing $E_T$

- **$e$+jets, $\geq 4$ jets, after b-tagging**
  - $p_T$ of lepton
  - $p_T$ of reconstructed leading jet
  - Missing $E_T$


**tt Background**

- Need discrimination variable against tt
- Missing transverse energy likely candidate, but neutralinos are back-to-back:
- Minor differences in some distributions
- Kinematic fitter very helpful (fits to tt hypothesis)

\[ \Rightarrow \] Combine all differences into a likelihood discriminant
Likelihood Discriminant

- Example: $m_{\text{stop}} = 175$ GeV, $m_{\text{chargino}} = 135$ GeV, e+jets

- $p_T$ of leading b-jet
- $\Delta R$ (b-jet, leading other jet)
- Reconstructed top mass

Reconstructed $\cos \theta^* (b,b)$

Likelihood for stop 175/135

**DØ Preliminary**
- stop
- top
- W+jets
Data-MC Comparisons

- ≥4 jets, after b-tagging and convergence of kinematic fitter

\[ p_T \text{ of leading b-jet} \]

\[ \Delta R(\text{b-jet, leading other jet}) \]

\[ \text{reconstructed top mass} \]

\[ \text{reconstructed } \cos \theta^*(b, b) \]

Likelihood for stop 175/135
Limit Setting Procedure

- Bayesian approach
- Assume Poisson distribution for observed counts
- Build probability function for each bin of the discriminant
- Flat prior for signal cross section
- Integrate over nuisance parameters with Gaussian priors

- Posterior probability density as function of cross section gives limit at 95% confidence level

- \( \text{tt contribution fixed to its theoretical cross section} \)
• Also possible to calculate posterior probabilities for both stop and top simultaneously (cross check):

Expected Limits

| Sample     | limit [pb] | limit [pb] | tt σ [pb] |
|------------|------------|------------|-----------|
| 175/135    | 3.28       | 3.27       | 6.56      |
| 175/120    | 4.97       | 5.21       | 6.34      |
| 175/105    | 5.16       | 5.42       | 6.30      |
| 160/120    | 5.42       | 5.50       | 6.56      |
| 160/105    | 5.63       | 5.80       | 6.45      |
| 145/105    | 7.27       | 7.36       | 6.64      |
*Observed Limits*

- Observed limits at 95% C.L. for e+jets and μ+jets combined

| Sample     | theory $\sigma$ [pb] | limit [pb] | limit [pb] | tt $\sigma$ [pb] |
|------------|-----------------------|------------|------------|------------------|
| 175/135    | 0.579                 | 5.57       | 5.59       | 6.36             |
| 175/120    | 0.579                 | 6.58       | 6.90       | 6.45             |
| 175/105    | 0.579                 | 5.55       | 5.64       | 6.14             |
| 160/120    | 1.00                  | 7.45       | 7.64       | 6.51             |
| 160/105    | 1.00                  | 9.71       | 9.98       | 6.01             |
| 145/105    | 1.80                  | 12.32      | 12.56      | 6.46             |

**limit on stop (fixed top)**

**limit on stop (floating top)**

**top cross section**
Conclusion

- First search for scalar top admixture in the $t\bar{t}$ signal at DØ
- No evidence for signal
- Upper cross section limits at 95% C.L.
- Factor $\approx 7$-12 above MSSM prediction
BACKUP SLIDES
### Current Limits

| Decay                  | DØ limit                        | CDF limit                        | LEP limit                        |
|------------------------|---------------------------------|---------------------------------|---------------------------------|
| \( \tilde{t} \rightarrow c\tilde{\chi}^0_1 \) | 149 GeV (\( m_{\tilde{\chi}} = 63 \) GeV, \( 995 \text{pb}^{-1} \)) | 132 GeV (\( m_{\tilde{\chi}} = 48 \) GeV, \( 295 \text{pb}^{-1} \)) | 98 GeV (\( m_{\tilde{\chi}} = 40 \) GeV) |
| \( \tilde{t} \rightarrow (b\tilde{\chi}^+_1 \rightarrow)bl\bar{\nu} \) | 186 GeV (\( m_{\tilde{\chi}} = 71 \) GeV, \( 400 \text{pb}^{-1} \)) | none in Run II                   | 99 GeV (\( m_{\tilde{\chi}} = 40 \) GeV) |
| \( \tilde{t} \rightarrow b\tilde{\chi}^+_1 \rightarrow bW\tilde{\chi}^0_1 \) | \( \odot \)                       | none in Run II                   | none                            |

- LEP SUSY working group:
  - Limit on chargino mass: 103.5 GeV
  - Limit on neutralino LSP mass: 47 GeV for a large range of \( \tan \beta \)
Motivation

• For electroweak baryogenesis a strongly first order electroweak phase transition is needed

• Condition: $\Sigma (\text{light boson couplings})^3 / (\text{Higgs mass})^2$ has to be large

• In the SM, there are only the gauge bosons $\Rightarrow m_H < 40$ GeV

• MSSM provides new bosons with strong couplings

• Biggest contribution comes from a light stop: $m_{\text{stop}} < m_{\text{top}}$

![Graph showing m_H vs m_{st_R} with m_\sigma = 2$ TeV$]
Data and Monte Carlo Samples

• Data
  • 913 pb\(^{-1}\) for e+jets
  • 871 pb\(^{-1}\) for \(\mu\)+jets

• Monte Carlo
  • Stop samples produced in PYTHIA
  • PYTHIA \(\bar{t}t\) sample
  • ALPGEN Wlight, Wbb, Wcc with heavy flavor k-factor 1.17
  • ALPGEN Z+jets with heavy flavor k-factors and Z \(p_T\) reweighting
  • COMPHEP single top
  • PYTHIA WW, WZ, ZZ
SUSY Parameters

- $\tan \beta = 20$, $\mu = 225$ GeV, $M_A = 800$ GeV, $M_1 = 53$ GeV, $M_3 = 500$ GeV,
- Trilinear couplings $A_b = A_t = 200$ GeV,
- Scalar lepton masses $M_{\tilde{e}_L} = M_{\tilde{e}_R} = M_{\tilde{\tau}_L} = M_{\tilde{\tau}_R} = 200$ GeV,
- Scalar quark masses $M_{\tilde{q}_L} = M_{\tilde{q}_R} = M_{\tilde{b}_R} = M_{\tilde{t}_R} = 250$ GeV.

| Mass point | $\sigma_{\tilde{t}_1 \tilde{t}_1}$ | $A_t$ | $m_{\tilde{t}_1}$ | $M_2$ | $m_{\tilde{\chi}^\pm}$ | $M_1$ | $m_{\tilde{\chi}_1^0}$ |
|------------|----------------|-------|----------------|------|----------------|------|----------------|
| Stop 175/135 | 0.579 pb | 357 GeV | 175 GeV | 164 GeV | 135 GeV | 53 GeV | 50 GeV |
| Stop 175/120 | 0.579 pb | 357 GeV | 175 GeV | 144 GeV | 120 GeV | 53 GeV | 50 GeV |
| Stop 175/105 | 0.579 pb | 357 GeV | 175 GeV | 125 GeV | 105 GeV | 53 GeV | 50 GeV |
| Stop 160/120 | 1.00 pb | 387 GeV | 160 GeV | 144 GeV | 120 GeV | 53 GeV | 50 GeV |
| Stop 160/105 | 1.00 pb | 387 GeV | 160 GeV | 125 GeV | 105 GeV | 53 GeV | 50 GeV |
| Stop 145/105 | 1.80 pb | 414 GeV | 146 GeV | 125 GeV | 105 GeV | 53 GeV | 50 GeV |
Preselection

- ≥4 jets in $|\eta|<2.5$, $p_T > 15$ GeV
- Leading jet > 40 GeV
- Tight lepton with track match, $p_T > 20$ GeV, electron in $|\eta|<1.1$ or muon in $|\eta|<2$, $\Delta R(\text{jet},\mu)<0.5$,
- 2nd lepton and opposite lepton veto (Z muon veto for $\mu+\text{jets}$)
- Primary Vertex: ≥3 tracks, $|z|<60\text{cm}$, $\Delta z(PV,\text{lepton})<1\text{cm}$
- Missing transverse energy $\text{MET} > 20/25$ GeV ($e/\mu$),
- Triangle cut on $\Delta \phi(\text{lepton},\text{MET})$ vs. MET
- ≥1 b-tags
- Convergence of kinematic fitter
### Signal Efficiency

- Full preselection efficiency for stop signal samples and \( t\bar{t} \)

| Sample     | \( \sigma \) [pb] | e+jets  | \( \varepsilon \) [%] | Events | \( \mu+jets \) | \( \varepsilon \) [%] | Events |
|------------|-------------------|---------|----------------------|--------|---------------|----------------------|--------|
| 175/135    | 0.579             | 4.43±0.10 | 4.0                  | 3.57±0.08 | 3.1           |
| 175/120    | 0.579             | 3.72±0.10 | 3.1                  | 2.90±0.09 | 2.3           |
| 175/105    | 0.579             | 3.20±0.10 | 2.8                  | 2.44±0.09 | 2.0           |
| 160/120    | 1.00              | 2.51±0.08 | 3.6                  | 1.78±0.06 | 2.4           |
| 160/105    | 1.00              | 2.52±0.08 | 3.8                  | 1.89±0.06 | 2.7           |
| 145/105    | 1.80              | 1.64±0.06 | 4.5                  | 1.16±0.05 | 3.0           |
| top        | 6.77              | 9.47     | 103.0                | 8.26    | 84.2          |
Background Processes

- **Physics Background W+jets:**
  - Electroweak W production with jets from radiated gluons

- **Instrumental Background “multijet”:**
  - QCD multijet production with misidentified lepton & missing $E_T$ (MET)
  - Misidentified electron from electromagnetic jet
  - Isolated muons from semileptonic $b$-decays with jet not reconstructed or far enough away
  - MET from misreconstructed calorimeter energy
  - Require high quality leptons
Tight Lepton Cut

- Electrons
- 7-parameter Likelihood:
  - EM fraction
  - $E_T^{\text{calorimeter}}/p_T^{\text{track}}$
  - Track match probability
  - Shower shape and more

- Muons
- Isolation variables
  - Calorimeter isolation
    (sum of calorimeter $E_T$ in hollow cone / $p_T$ of muon)

- Track isolation
  (sum of track $p_T$ in cone w/o muon track / $p_T$ of muon)

[Graph showing comparison of 6-parameter and 7-parameter likelihoods with cut indicated.]
QCD Multijet Background

\[ N_{\text{loose}} = N_{W+tt} + N_{QCD} \]
\[ N_{\text{tight}} = \varepsilon_{W+tt} N_{W+tt} + \varepsilon_{QCD} N_{QCD} \]

\( \varepsilon_{W+tt} \approx 84-85\% \)
\( \varepsilon_{QCD} \approx 18-27\% \) (from data)
W+Jets Normalization

- W+jets normalized to data before b-tagging:
  \[ N_{\text{data}} - N_{\text{QCD}} - N_{\text{MCBG}} = \alpha_W \times (N_{W\text{light}} + 1.17 N_{W\text{cc}} + 1.17 N_{W\text{bb}}) \]

- \( N_{\text{data}} \) = selected data events
- \( N_{\text{QCD}} \) from matrix method
- \( N_{\text{MCBG}} \) from cross sections: \(t\bar{t}, Z+\text{jets}, \text{single top}, \text{diboson}\)
- \( N_{W\text{light}}, N_{W\text{cc}}, N_{W\text{bb}}\) = selected MC W+jets events

- \( \alpha_W \) determined as shown and then applied to W+jets after b-tagging
## Background Yields Before b-tagging

|                | e+jets |                | μ+jets |                |                |                |                |                |
|----------------|--------|----------------|--------|----------------|--------|----------------|--------|----------------|
|                | =1 jet | =2 jets        | =3 jets | ≥4 jets        | =1 jet | =2 jets        | =3 jets | ≥4 jets        |
| $\alpha_W$     | 1.42   | 1.46           | 1.32   | 0.86           | 1.48   | 1.60           | 1.62   | 1.25           |
| top            | 11.6   | 71.5           | 131.9  | 170.0          | 7.1    | 48.3           | 95.7   | 137.1          |
| Wbb            | 248.3  | 226.1          | 84.2   | 22.2           | 190.1  | 204.7          | 84.7   | 28.0           |
| Wcc            | 764.6  | 630.4          | 211.4  | 45.5           | 610.8  | 548.8          | 219.8  | 57.2           |
| Wlight         | 11702.8| 4974.1         | 1102.4 | 211.4          | 9754.8 | 4456.9         | 1143.1 | 263.7          |
| Z+jets         | 238.2  | 277.2          | 120.9  | 50.0           | 847.6  | 446.1          | 160.7  | 63.2           |
| single t       | 13.2   | 39.0           | 17.5   | 6.2            | 9.4    | 30.0           | 13.7   | 4.8            |
| diboson        | 95.0   | 201.0          | 65.7   | 18.1           | 71.1   | 169.1          | 55.1   | 15.3           |
| QCD            | 506.4  | 754.8          | 375.0  | 139.6          | 114.2  | 148.0          | 65.4   | 24.6           |
| SUM            | 13580  | 7174           | 2109   | 663            | 11605  | 6052           | 1838   | 594            |
| data           | 13580  | 7174           | 2109   | 663            | 11605  | 6052           | 1838   | 594            |
Background Yields After b-tagging

|                | e+jets | μ+jets |
|----------------|--------|--------|
|                | =1 jet | =2 jets | =3 jets | ≥4 jets | hitfit | =1 jet | =2 jets | =3 jets | ≥4 jets | hitfit |
| α_W           | 1.42   | 1.46    | 1.32    | 0.86    | 0.86   | 1.48   | 1.60    | 1.62    | 1.25    | 1.25   |
| top           | 4.9    | 39.3    | 77.6    | 108.3   | 103.0  | 3.1    | 27.8    | 58.5    | 89.8    | 84.2   |
| Wbb           | 70.6   | 86.0    | 35.4    | 9.1     | 8.5    | 56.5   | 79.8    | 36.1    | 12.2    | 11.1   |
| Wcc           | 39.5   | 46.8    | 20.1    | 5.0     | 4.8    | 27.2   | 39.6    | 22.2    | 6.9     | 6.5    |
| Wlight        | 124.5  | 59.0    | 13.2    | 4.0     | 3.8    | 89.0   | 51.3    | 19.3    | 4.4     | 4.0    |
| Z+jets        | 2.9    | 7.5     | 5.2     | 3.0     | 2.8    | 14.3   | 14.8    | 6.9     | 3.9     | 3.3    |
| singlet       | 5.1    | 19.3    | 9.3     | 3.6     | 3.1    | 3.7    | 15.2    | 7.5     | 2.9     | 2.5    |
| dibos         | 3.1    | 11.6    | 4.2     | 1.4     | 1.4    | 2.8    | 10.2    | 3.8     | 1.4     | 1.2    |
| QCD           | 16.2   | 41.1    | 22.3    | 11.1    | 10.7   | 6.6    | 12.0    | 3.0     | 2.9     | 3.2    |
| SUM           | 266.8  | 310.7   | 187.2   | 145.6   | 138.1  | 203.1  | 250.7   | 157.5   | 124.3   | 116.0  |
| data          | 255    | 329     | 193     | 145     | 133    | 189    | 265     | 163     | 146     | 135    |
Data-MC Comparisons

- e+jets, ≥4 jets, before b-tagging

- µ+jets, ≥4 jets, after b-tagging

DØ Preliminary
Data-MC Comparisons

- \( \geq 4 \) jets, after b-tagging and convergence of kinematic fitter \( \mu \)

- \( p_T \) of leading b-jet

- \( \Delta R(b\text{-}jet, \text{leading other jet}) \)

- Reconstructed top mass

- Reconstructed \( \cos \theta^*(b, b) \)
Systematic Uncertainties

- Two classes of systematic uncertainties
- Taken into account correctly with correlations between samples
- Change likelihood discriminant distribution shape:
  - Jet Energy Scale
  - Heavy flavor contribution in W+jets (k-factors)
  - b-tagging (b-TRF)
- Only change yields:
  - Luminosity, Monte Carlo Cross Sections
  - Top Quark Mass
  - Matrix Method
  - W normalization
  - PV, lepton ID, trigger efficiency