Fourth Generation

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In collaboration with J. Alwall, J.L. Feng, J. Kumar
arXiv: 1002.3366; 1103.xxxx.
Not the usual 4th generation ...
Direct searches

$m_{b'} > 372 \text{ GeV}$

$m_{t'} > 335 \text{ GeV}$

Daniel Whiteson, LHC West Coast Meeting @ Irvine
3/pb (ICHEP2010)
Just saw top. ~No sensitivity to t’, b’

40/pb (Moriond2011)
t’ → Wq → l+jets ~ 350 GeV
t’ → Wq → dileptons ~ 300 GeV
b’ → Wt → ss dileptons ~ 350 GeV

500/pb+ (LP2011?)
Up to 500 GeV+ ?

Daniel Whiteson, LHC West Coast Meeting @ Irvine
If $m_{t'} > m_{b'}$

$$
\begin{align*}
(0, 1) & \quad (1, 1) \\
\quad t' \rightarrow Wq & \quad t' \rightarrow WWb \\
\quad b' \rightarrow WWb & \quad b' \rightarrow WWb \\
(0, 0) & \quad (1, 0)
\end{align*}
$$

Flacco, DW, Bar-Shalom & Tait
arxiv: 1005.1077, PRL 2010

Daniel Whiteson, LHC West Coast Meeting @ Irvine

Wednesday, March 16, 2011
Exotic 4th Generation Mirror Quarks

S. Su
Exotic 4th Generation Mirror Quarks

chiral under SM gauge group
Exotic 4th Generation Mirror Quarks

- Chiral under SM gauge group
- Same charge
- Opposite chirality
Exotic 4th Generation Mirror Quarks

- chiral under SM gauge group
- charge under hidden symmetry
- same charge, opposite chirality

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New after LHC West Coast @ Irvine

- B'B' study @ Tevatron and LHC
- T'T' results from CDF
Outline

- Motivation: general / specific
- WIMPless model
- Constraints
- Simulations and cut analysis
- Exclusion and discovery reach
- Conclusion
Dark Matter motivation: general

**Dark Matter**: long-lived on cosmological time scale

- Charge under a new unbroken symmetry $\Rightarrow$ absolutely stable
- have only gravitational interaction with the SM
  - can not be discovered at colliders
- couple to SM through connector $Y$
  - YY production with $y \rightarrow fX$

![Diagram showing the interaction between DM, connector, and SM]
Dark Matter: long-lived on cosmological time scale

Charge under a new unbroken symmetry $\Rightarrow$ absolutely stable
- have only gravitational interaction with the SM
  can not be discovered at colliders
- couple to SM through connector $Y$  

YY production with $y \rightarrow f X$

- $X Y f$
- $\text{DM}$ connector $\text{SM}$
- $\text{SM charge} & \text{dark charge}$
Dark Matter motivation: general

**Dark Matter**: long-lived on cosmological time scale
- Charge under a new unbroken symmetry \( \Rightarrow \) absolutely stable
- have only gravitational interaction with the SM
- can not be discovered at colliders
- couple to SM through connector \( Y \)

\[ YY \text{ production with } y \rightarrow f X \]

<table>
<thead>
<tr>
<th>SUSY</th>
<th>neutralino</th>
<th>squark</th>
<th>quark</th>
<th>R-parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ExD</td>
<td>KK gauge boson</td>
<td>KK quark</td>
<td>quark</td>
<td>KK-parity</td>
</tr>
<tr>
<td><strong>Our study</strong></td>
<td>DM(no SM charge)</td>
<td>exotic quark</td>
<td>quark</td>
<td>dark charge</td>
</tr>
</tbody>
</table>

Wednesday, March 16, 2011
WIMP miracle

\[ \Omega h^2 \sim \frac{2.6 \times 10^{-10} \text{GeV}^{-2}}{\langle \sigma_A v \rangle} \]
\[ \langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_{\text{weak}}^2} 0.1 \sim 10^{-9} \text{GeV}^{-2} \]

\[ \Rightarrow \Omega h^2 \sim 0.3 \]

naturally around the observed value

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WIMP miracle

- $m_{\text{WIMP}} \sim m_{\text{weak}}$
- $g \sim g_{\text{weak}}$

\[ \Omega h^2 \sim \frac{2.6 \times 10^{-10} \text{GeV}^{-2}}{\langle \sigma_A v \rangle} \]
\[ \langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_{\text{weak}}^2} 0.1 \sim 10^{-9} \text{GeV}^{-2} \]

\[ \Rightarrow \Omega h^2 \sim 0.3 \]

naturally around the observed value
WIMPless miracle

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

- only fixes one combination of dark matter mass and coupling
- \( m_X/g_X^2 \sim m_{\text{weak}}/g_{\text{weak}}^2 \), \( \Omega h^2 \sim 0.3 \)

\textbf{WIMPless DM}

J.L. Feng and J. Kumar, PRL 101, 231301 (2008)
J.L. Feng, M. Kaplinghat, H. Tu and H. Yu, JCAP 0907, 004 (2009)

- dark matter: no SM gauge interactions, not WIMP
- naturally obtain right relic density: similar to WIMP

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Dark matter is hidden no SM interactions
- DM sector has its own particle content, mass $m_X$, coupling $g_X$
- Connected to SUSY breaking sector

\[
\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}
\]
\[
\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}
\]

right relic density! (irrespective of its mass)

If no direct coupling to SM:
- interact only through gravity
- impact on structure formation
- no direct/indirect/collider signals
WIMPless: not hidden

- SUSY Breaking
  - MSSM
  - Hidden X
WIMPless: not hidden

\[ m_Y \sim \max (m_{\text{weak}}, m_X) \quad \text{interaction } \lambda X Y f \]
WIMPless: not hidden

\[ m_Y \sim \max (m_{\text{weak}}, m_X) \]

- **indirect detection**
  \[ XX \rightarrow ff, YY \]
- **direct detection**
  \[ Xf \rightarrow Xf \]
- **collider: 4th generation fermions**
WIMPless: not hidden

\[ m_Y \sim \max (m_{\text{weak}}, m_X) \]

interaction \( \lambda XYf \)

- indirect detection
  \[ XX \rightarrow ff, YY \]
- direct detection
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open new possibility for
- DM model parameters
- new experimental search windows

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WIMPeless: not hidden

\[ m_Y \sim \max (m_{\text{weak}}, m_X) \] interaction \( \lambda XYf \)

- indirect detection \( XX \rightarrow ff, YY \)
- direct detection \( Xf \rightarrow Xf \)
- collider: 4th generation fermions

light dark matter

open new possibility for
- DM model parameters
- new experimental search windows

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XENON100 (11.17 live days) Reply to the Comments on the XENON100 First Dark Matter Results.

Heated debate goes on and on and on ...

Collar and Mckinsey: 1005.3723 Response to arXiv:1005.2615
Dark matter motivation: specific

- light DM with large $\sigma_{SI}$

  - not generic in typical WIMP
    - $\sigma_{SI}$: chirality flip, proportional to Yukawa coupling


- can be easily accommodated in WIMPyless model with connector $Y$

Explaining DAMA: WIMPless

**WIMPless model (discrete symmetry)**

\[ V = \lambda \left[ X \bar{Q}_L q_L + X \bar{B}_R b_R + X \bar{T}_R t_R \right] \]

\[
Q'_L : (3, 2, \frac{1}{6}) \\
T'_R : (3, 1, \frac{2}{3}) \\
B'_R : (3, 1, -\frac{1}{3}) 
\]

**scattering:** \( Xq \rightarrow Q' \rightarrow Xq, \ q=b,t, \) induce coupling to gluon at 1-loop

Explaining DAMA: WIMPless

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\[ V = \lambda \left( X\bar{Q}'_L q_L + X\bar{B}'_R b_R + X\bar{T}'_R t_R \right) \]

not chirality
opposite chirality
of SM quark

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Exotic 4th-generation mirror quarks

scattering: \( Xq \rightarrow Q' \rightarrow Xq, q=b,t \), induce coupling to gluon at 1-loop

Explaining DAMA: WIMPless

WIMPless model

\[ m_X \sim 1-10 \text{ GeV}, \ m_{Q'} \sim 300-500 \text{ GeV}, \ \lambda \sim 0.3-1, \ \sigma_{SI} \text{ in right range} \]

3rd generation vs. the first two

- **first two generations, tree level scattering** $\Rightarrow \lambda \sim 0.03$

- **third generation**
  - loop level scattering, $\lambda \sim 0.3-1$, more natural
  - less constrained by FCNC
Collider Signature: exotic quarks

Y particle appears as exotic 4th generation mirror quarks Q’

 Collider Signal
T’T’ → ttXX, B’B’ → bbXX

differ from SUSY searches: cascade decay
differ from usual 4th generation quark T’ → Wb, B’ → Wt

appears in a general set of new physics scenarios
- asymmetric dark matter
- little Higgs with T-parity
- baryon and lepton number as gauge symmetry

B. Dutta and J. Kumar, arXiv: 1012.1341
Constraints

- **perturbativity constraints:** $m_{Q'} = y_{Q'} \nu$, $m_{Q'} \leq 600$ GeV
- **precision electroweak data:** $|m_{T'} - m_{B'}| \sim 50$ GeV
- **direct searches limits**

$B'B' \rightarrow bbXX$, similar to sbottom pair production with $\tilde{b} \rightarrow b \tilde{\chi}_1^0$

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V. M. Abazov et al. [D0 Collaboration], 1005.2222
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- precision electroweak data: $|m_{T'} - m_{B'}| \sim 50$ GeV
- direct searches limits

$B'B' \rightarrow b\bar{b}XX$, similar to sbottom pair production with $\tilde{b} \rightarrow b\tilde{\chi}_1^0$

- $m_{sb} > 247$ GeV $\Rightarrow m_{B'} > 365$ (440) GeV

V. M. Abazov et al. [D0 Collaboration], 1005.2222

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B'B' → bbXX, similar to sbottom pair production with \( \tilde{b} \rightarrow b\tilde{\chi}^0_1 \)

Constraints

\[ m_{sb} > 230 \text{ GeV (95\% C.L.)} \]

CDF

\[ M_{\tilde{b}_1} < M_{\tilde{\chi}^0_1} + M_b \]

Observed Limit (95\% C.L.)

Expected Limit (95\% C.L.)

CDF (2650 pb\(^{-1}\))

D0 (310 pb\(^{-1}\))

CDF (295 pb\(^{-1}\))
**Constraints: direct search**

CDF, Run II, 2.5 fb⁻¹, gluino pair production, \( \tilde{g} \to b\tilde{b}, \tilde{b} \to b\tilde{\chi}^0_1 \)

two or more jets, large MET, 2b-tagging

T. Aaltonen et al. [CDF Collaboration], PRL 102, 221801 (2009).
**Constraints: direct search**

**CDF, Run II, 2.5 fb⁻¹, gluino pair production,**

\[ \tilde{g} \to \tilde{b} \tilde{b} \quad \tilde{b} \to b \tilde{\chi}_1^0 \]

**two or more jets, large MET, 2b-tagging**

T. Aaltonen et al. [CDF Collaboration], PRL 102, 221801 (2009).

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\[ p\bar{p} \to \tilde{g}\tilde{g} \text{ at } \sqrt{s}=1.96 \text{ GeV} \]

\[ m_{\text{gluino}} > 340 \text{ GeV for } \Delta m \sim 20 \text{ GeV} \implies m_{B'} > 370 \text{ GeV} \]

---

**CDF Run II (2.5 fb⁻¹)**

- 95% CL limit \((m[\tilde{b}]=250 \text{ GeV/c}^2)\)
- Expected limit
- 95% CL limit \((m[\tilde{b}]=300 \text{ GeV/c}^2)\)
- Expected limit

**CDF Run II (2.5 fb⁻¹)**

- \(\tilde{g} \to \tilde{b}b \text{ (100% BR)}\)
- \(\tilde{b} \to b\tilde{\chi}_1^0 \text{ (100% BR)}\)

**Gluino Mass vs. Cross Section**

\[ m(\tilde{g}) = m(\tilde{g}) \]

\[ m(\tilde{b}) = m(\tilde{b}) \]

\[ m(\tilde{\chi}_1^0) = 60 \text{ GeV/c}^2 \]

\[ m_\mu = m_\mu \]

\[ m_{B'} > 370 \text{ GeV} \]

**CDF Run II 156 pb⁻¹**

Excluded Region

**D0 Run II 310 pb⁻¹**

Sbottom Pair Production Excluded Region

**CDF Run I excluded**
Constraints: direct search

CDF, Run II, 2.7 fb⁻¹, stop pair production, \( \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^{0}l\nu \)

\( m_{s_t} > 150 - 185 \text{ GeV} \), weaker than sbottom limit

Signal: \( T'T' \rightarrow t(*)X \bar{t}(*)X \rightarrow bW^+X\bar{b}W^-X \)

- **hadronic channel**: large cross section
  - SM backgrounds, tt, W, have MET with lepton
  - irreducible background: \( Z \rightarrow \nu\nu + \text{jets} \)
- **semi-leptonic channel**: isolated lepton, suppress QCD background
- **purely leptonic channel**: suppressed cross section

**Similar analyses in the literature**

- **semileptonic mode, high mass, large luminosity**
  

- **hadronic mode, spin and mass determination**

Simulation

MadGraph - Pythia - PGS

Signal: $T'T' \rightarrow t^{(*)} X \bar{t}^{(*)} X \rightarrow bW^+ X \bar{b}W^- X$

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**Similar analyses in the literature**

- **semileptonic mode**, high mass, large luminosity
  

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Semileptonic channel: precuts

**Signal:** $T'T' \rightarrow ttXX \rightarrow bbjj l + MET$

**Precuts**

- **one isolated electron or muon**
- **large MET**

$\bullet$ **large $m_T^W$**

\[
m_T^W \equiv m_T(p_T^l, \ldots) = \sqrt{2 |p_T^l||\not{p}_T| \cos(\Delta \phi(p_T^l, \ldots))}
\]
Semileptonic channel: precuts

Signal: $T'T' \rightarrow ttXX \rightarrow bbjj l + \text{MET}$

Precuts

- one isolated electron or muon
- large MET

large $m_T^W$

$$m_T^W \equiv m_T(p_T^l, \not{p}_T)$$

$$= \sqrt{2|p_T^l||\not{p}_T|\cos(\Delta\phi(p_T^l, \not{p}_T))}$$

SM bg peak around $m_W$

Cross section / bin (pb)

LHC10

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Semileptonic channel: precuts

- $N_{\text{jet}} \geq 4$

- Second, hadronically decay $W$

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**Semileptonic channel: Tevatron**

**Additional cuts:** MET, $m_T^W$, $H_T$

### Tevatron: semileptonic

<table>
<thead>
<tr>
<th>Cut</th>
<th>$T'$ (300)</th>
<th>$T'$ (400)</th>
<th>$T'$ (500)</th>
<th>$t\bar{t}$</th>
<th>W+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>203.2</td>
<td>16.33</td>
<td>1.11</td>
<td>5619</td>
<td>(5179)</td>
</tr>
<tr>
<td>1 $\mu/e$, no $\tau$</td>
<td>36.1</td>
<td>2.88</td>
<td>0.194</td>
<td>1041</td>
<td>(2060)</td>
</tr>
<tr>
<td>$E_T^\gamma &gt; 100$ GeV</td>
<td>17.7</td>
<td>2.00</td>
<td>0.157</td>
<td>107.2</td>
<td>(728.8)</td>
</tr>
<tr>
<td>$m_T^W &gt; 100$ GeV</td>
<td>10.7</td>
<td>1.38</td>
<td>0.114</td>
<td>22.6</td>
<td>(36.62)</td>
</tr>
<tr>
<td>$\geq 4$ jets</td>
<td>4.81</td>
<td>0.64</td>
<td>0.062</td>
<td>2.6</td>
<td>0.30</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W</td>
<td>&lt; 10$ GeV</td>
<td>4.13</td>
<td>0.51</td>
<td>0.049</td>
</tr>
<tr>
<td>All precuts</td>
<td>4.13</td>
<td>0.51</td>
<td>0.049</td>
<td><strong>2.19</strong></td>
<td><strong>0.19</strong></td>
</tr>
<tr>
<td>$m_T^W &gt; 150$ GeV</td>
<td>1.93</td>
<td>0.325</td>
<td>0.036</td>
<td>0.62</td>
<td>0.035</td>
</tr>
<tr>
<td>$E_T^\gamma &gt; 150$ GeV</td>
<td>1.75</td>
<td>0.367</td>
<td>0.041</td>
<td>0.281</td>
<td>0.035</td>
</tr>
<tr>
<td>$H_T &gt; 300$ GeV</td>
<td>1.93</td>
<td>0.353</td>
<td>0.042</td>
<td>1.18</td>
<td>0.07</td>
</tr>
<tr>
<td>$E_T^\gamma &gt; 150$, $H_T &gt; 300$</td>
<td>1.04</td>
<td>0.279</td>
<td>0.037</td>
<td>0.056</td>
<td>0.017</td>
</tr>
</tbody>
</table>
**Additional cuts:** MET, $m_T^W$, $H_T$

**LHC10: semileptonic**

<table>
<thead>
<tr>
<th>Cut</th>
<th>$T'$ (300)</th>
<th>$T'$ (400)</th>
<th>$T'$ (500)</th>
<th>$t\bar{t}$ (1 e/µ)</th>
<th>$t\bar{t}$ (1 τ)</th>
<th>$t\bar{t}$ (2 e/µ)</th>
<th>$W+$jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>14.89</td>
<td>3.16</td>
<td>0.922</td>
<td>66.67</td>
<td>43.96</td>
<td>10.62</td>
<td>(42.28)</td>
</tr>
<tr>
<td>1 µ/e, no τ</td>
<td>3.2</td>
<td>0.669</td>
<td>0.193</td>
<td>36.45</td>
<td>8.15</td>
<td>3.18</td>
<td>(15.74)</td>
</tr>
<tr>
<td>$E_T &gt; 100$ GeV</td>
<td>1.92</td>
<td>0.52</td>
<td>0.165</td>
<td>5.05</td>
<td>2.07</td>
<td>0.888</td>
<td>(10.33)</td>
</tr>
<tr>
<td>$m_T^W &gt; 100$ GeV</td>
<td>1.1</td>
<td>0.342</td>
<td>0.116</td>
<td>0.134</td>
<td>0.638</td>
<td>0.471</td>
<td>(0.235)</td>
</tr>
<tr>
<td>≥ 4 jets</td>
<td>0.357</td>
<td>0.116</td>
<td>0.043</td>
<td>0.056</td>
<td>0.091</td>
<td>0.062</td>
<td>0.028</td>
</tr>
<tr>
<td>$</td>
<td>m_{jj} - m_W</td>
<td>&lt; 10$ GeV</td>
<td>0.165</td>
<td>0.049</td>
<td>0.016</td>
<td>0.026</td>
<td>0.03</td>
</tr>
<tr>
<td>All precuts</td>
<td>0.165</td>
<td>0.049</td>
<td>0.016</td>
<td><strong>0.027</strong></td>
<td><strong>0.031</strong></td>
<td><strong>0.014</strong></td>
<td>0.01</td>
</tr>
</tbody>
</table>

- Additional $m_T^W$ cut: $m_T^W > 150, 200$ GeV
- Additional $E_T$ cuts: $E_T > 150, 200, 250$ GeV.
- $H_T = \sum_{i=1}^{4} |p_T^i| + |p_T^l|$ cuts: $H_T > 400, 500$ GeV.
- Combinations of the cuts above.

82 fb
Hadronic channel: precuts

Signal: \(T'T' \rightarrow ttXX \rightarrow bbjjjj + \text{MET}\)

Precuts:
- No isolated electron, muon, tau-tagged jets
- large MET
- \(N_{\text{jet}} \geq 5\)

Background:
- leptonic \(W\) decay with lepton missed
- tau lepton mistagged as jets
- \(Z \rightarrow \nu \nu + \text{jets}\)

Hadronic channel: precuts

Signal: \(T'T' \rightarrow ttXX \rightarrow bbjjjj + \text{MET}\)

Precuts

Background:
- leptonic \(W\) decay with lepton missed
- tau lepton mistagged as jets
- \(Z \rightarrow \nu \nu + \text{jets}\)

No isolated electron, muon, tau-tagged jets
large MET

\(N_{\text{jet}} \geq 5\)

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leptonically-decaying

We also use the following additional cuts to optimize the signal to have fewer jets than the signal, which mainly consists of final states with signatures consisting of jets and missing energy. The signal is furthermore expected to have larger missing energy from the invisible particles. To be sure to avoid QCD multi-jet background, we apply the cuts:

- $\Delta \phi (p_T, p_T^j)$ to suppress QCD background
- No isolated electrons, muons or tau-tagged jets with $p_T > 20 \text{ GeV}$ (Tevatron) or $p_T > 40 \text{ GeV}$ (LHC).
- Minimum missing transverse energy: $E_T > 20 \text{ GeV}$ (Tevatron); $E_T > 30 \text{ GeV}$ (LHC10).
- At least 5 jets with $p_T > 200 \text{ GeV}$.

After precuts for the hadronic channel, the combined background after precuts (negligible after these backgrounds, while we can see from the distributions plotted after the cuts coming before it in the list, and the position of the precut is marked by a vertical dashed line. The bottom two panels are plotted after the cuts coming before it in the list, and the position of the precut is marked by a vertical dashed line. The top two panels are the distributions plotted after the cuts coming before it in the list, and the position of the precut is marked by a vertical dashed line. The bottom two panels are the distributions plotted after the cuts coming before it in the list, and the position of the precut is marked by a vertical dashed line.

The main remaining backgrounds after precuts for both the semi-leptonic and hadronic channel at the Tevatron and 8-13% at the LHC. A table of cross sections is found in Tables VII and VIII. The signal efficiency depends on the mass of the new particle and is 100% for the first, second and third leading jets (LHC). The signal efficiency for the first, second and third leading jets (LHC) is 21 fb for the semi-leptonic channel at the Tevatron and 1.4 pb for the 10 TeV LHC.
We also use the following additional cuts to optimize the signal and background cross sections after near-optimal cuts: 

- $\Delta \phi (p_T^1, p_T^2)$: suppress QCD background.

Distributions for the hadronic channel are plotted after the cuts coming before it in the list, and the precuts. For clarity, we have split the following precuts for some signal points are found in Tables VII and VIII.

The main remaining backgrounds after precuts for both the semi-leptonic and hadronic channels include tau leptons. One reason for this is that a tau background is important for new physics with jets and MET. The tau background is particularly important for the hadronic channel. It would be interesting to see an experimental study of tau background with large efficiency.

The signal is furthermore expected to have larger missing energy from the invisible particle, followed by the semi-leptonic and hadronic channels. To be sure to avoid QCD multi-jet background, since with large $p_T$ the dominant background is from decays with at least one tau lepton, semi-leptonic decay (negligible after these cuts), and purely leptonic decay (which are negligible with these cuts).

The following additional cuts optimize the signal and background cross sections after near-optimal cuts:

- $\Delta \phi (p_T^1, p_T^2)$: suppress QCD background.

The top two panels of Fig. 2, the LHC, are shown in Tables VII and VIII. The top two panels of Fig. 2, the LHC, are shown in Tables VII and VIII. The main remaining backgrounds after precuts for both the semi-leptonic and hadronic channels include tau leptons. One reason for this is that a tau background is important for new physics with jets and MET.
### Table III: As in Table I, but for the hadronic channel at the Tevatron and with cross sections in fb. The $Z$ cross sections in parentheses were simulated with a cut on $\not{E}_T > 80$ GeV and at least 3 jets in the parton-level generation.

<table>
<thead>
<tr>
<th>Cut</th>
<th>$T'$ (300)</th>
<th>$T'$ (400)</th>
<th>$T'$ (500)</th>
<th>$t\bar{t}$</th>
<th>$W$ + jets</th>
<th>$Z$ + jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>203.24</td>
<td>16.33</td>
<td>1.11</td>
<td>5619.1</td>
<td>(5179.06)</td>
<td>(3030.09)</td>
</tr>
<tr>
<td>0 isolated leptons</td>
<td>82.88</td>
<td>6.97</td>
<td>0.499</td>
<td>2265.54</td>
<td>(1756.96)</td>
<td>(2545.12)</td>
</tr>
<tr>
<td>$\not{E}_T &gt; 100$ GeV</td>
<td>42.86</td>
<td>5.28</td>
<td>0.422</td>
<td>125.93</td>
<td>(663.5)</td>
<td>(1219.22)</td>
</tr>
<tr>
<td>$\geq 5$ jets</td>
<td>22.64</td>
<td>3.07</td>
<td>0.273</td>
<td>22.11</td>
<td>3.3</td>
<td>2.6</td>
</tr>
<tr>
<td>$\Delta \phi$ cuts</td>
<td>19.0</td>
<td>2.74</td>
<td>0.245</td>
<td>15.8</td>
<td>2.8</td>
<td>2.2</td>
</tr>
<tr>
<td>All precuts</td>
<td>19</td>
<td>2.74</td>
<td>0.245</td>
<td>15.8</td>
<td>2.8</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- Additional $\not{E}_T$ cuts: $\not{E}_T > 150, 200, 250$ GeV.
- $H_T = \sum_{i=1}^{5} |p_T^j|_i$ cuts: $H_T > 300, 350, 400$ GeV.
- At least 6 jets with $|p_T^j| > 20$ GeV.
- Combinations of the cuts above.

*S. Su*
**Hadronic channel: LHC10**

**Additional cuts:** MET, $H_T$, $N_{\text{jet}}$

**LHC10: hadronic**

<table>
<thead>
<tr>
<th>Cut</th>
<th>$T'$ (300)</th>
<th>$T'$ (400)</th>
<th>$T'$ (500)</th>
<th>$t\bar{t}$ ($1 \ \tau$)</th>
<th>$t\bar{t}$ ($1 \ e/\mu$)</th>
<th>$t\bar{t}$ (had)</th>
<th>$W+\text{jets}$</th>
<th>$Z+\text{jets}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cut</td>
<td>14.89</td>
<td>3.16</td>
<td>0.922</td>
<td>43.96</td>
<td>66.67</td>
<td>104.59</td>
<td>(42.28)</td>
<td>(18.86)</td>
</tr>
<tr>
<td>0 isolated leptons</td>
<td>6.75</td>
<td>1.5</td>
<td>0.45</td>
<td>16.88</td>
<td>13.11</td>
<td>72.29</td>
<td>(16.8)</td>
<td>(15.71)</td>
</tr>
<tr>
<td>$E_T &gt; 100$ GeV</td>
<td>4.15</td>
<td>1.21</td>
<td>0.394</td>
<td>3.91</td>
<td>2.67</td>
<td>0.097</td>
<td>(11.25)</td>
<td>(11.48)</td>
</tr>
<tr>
<td>$\geq 5$ jets</td>
<td>1.34</td>
<td>0.406</td>
<td>0.135</td>
<td>0.664</td>
<td>0.47</td>
<td>0.031</td>
<td>0.305</td>
<td>0.212</td>
</tr>
<tr>
<td>$\Delta \phi$ cuts</td>
<td>1.19</td>
<td>0.374</td>
<td>0.125</td>
<td>0.56</td>
<td>0.41</td>
<td>0.01</td>
<td>0.265</td>
<td>0.187</td>
</tr>
<tr>
<td>All precuts</td>
<td>1.19</td>
<td>0.374</td>
<td>0.125</td>
<td><strong>0.56</strong></td>
<td><strong>0.41</strong></td>
<td><strong>0.01</strong></td>
<td>0.265</td>
<td>0.187</td>
</tr>
</tbody>
</table>

- Additional $E_T$ cuts: $E_T > 150, 200, 250, 300$ GeV.
- $H_T = \sum_{i=1}^{5} |p_T^i|$ cuts: $H_T > 400, 500$ GeV.
- At least 6 jets with $|p_T^j| > 40$ GeV.
- Combinations of the cuts above.

S. Su

32
Exclusion for $T' \bar{T}' \rightarrow t \ X \ \bar{t} \ X$ at the Tevatron

- **optimal cuts (after precuts)**
- **S/B > 0.1, more than 2 events**
- **Poisson statistics**

**Semileptonic channel**

**Hadronic channel**

<table>
<thead>
<tr>
<th>$m_T$ (GeV)</th>
<th>$m_X$ (GeV)</th>
<th>$m_T = m_X + m_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 fb$^{-1}$</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>10 fb$^{-1}$</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>5 fb$^{-1}$</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>2 fb$^{-1}$</td>
<td>180</td>
<td></td>
</tr>
</tbody>
</table>

$95\%$ C.L.
Optimal cuts (after precuts)

- S/B > 0.1, more than 2 events
- Poisson statistics

Exclusion for $T' \bar{T}' \rightarrow t \bar{X} \bar{t} X$ at the Tevatron

- Semileptonic channel
- $m_T = m_X + m_t$
- $m_X$ (GeV)
- $m_T$ (GeV)
- 95% C.L.
- 20 fb$^{-1}$
- 10 fb$^{-1}$
- 5 fb$^{-1}$
- 2 fb$^{-1}$

- Hadronic channel
- $m_T = m_X + m_t$
- $m_X$ (GeV)
- $m_T$ (GeV)
- 95% C.L.
- 20 fb$^{-1}$
- 10 fb$^{-1}$
- 5 fb$^{-1}$
- 2 fb$^{-1}$

Soft decay products

By Gaussian equivalent, we mean that we have converted the on

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Wednesday, March 16, 2011
Search for Production of Heavy Particles Decaying to Top Quarks and Invisible Particles in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen et al. [CDF Collaboration], arXiv:1103.2482

![Graph showing search for production of heavy particles decaying to top quarks and invisible particles in proton-antiproton collisions at the Tevatron. The graph plots $m_x$ versus $m_T$, with observed and expected exclusions shown as solid and dashed lines, respectively. The graph highlights the 95% C.L. exclusion region for semileptonic events with a mass of 4.8 fb$^{-1}$.](image-url)
LHC 10 exclusion

Exclusion for $T' \overline{T} \rightarrow t \bar{X} \bar{t} X$ at 10 TeV LHC

Semileptonic channel

$300 \text{ pb}^{-1}$

$200 \text{ pb}^{-1}$

$100 \text{ pb}^{-1}$

95% C.L.

$300 \text{ pb}^{-1}$

$200 \text{ pb}^{-1}$

$100 \text{ pb}^{-1}$

95% C.L.

Exclusion for $T' \overline{T} \rightarrow t \bar{X} \bar{t} X$ at 10 TeV LHC

Hadronic channel

$300 \text{ pb}^{-1}$

$200 \text{ pb}^{-1}$

$100 \text{ pb}^{-1}$

95% C.L.

$300 \text{ pb}^{-1}$

$200 \text{ pb}^{-1}$

$100 \text{ pb}^{-1}$

95% C.L.

S. Su

Wednesday, March 16, 2011
Exclusion for $T' \bar{T} \rightarrow t \bar{t} X$ at 10 TeV LHC

**Semileptonic channel**

- $m_{\gamma} = m_X + m_t$
- $300 \text{ pb}^{-1}$
- $200 \text{ pb}^{-1}$
- $100 \text{ pb}^{-1}$

**Hadronic channel**

- $m_{\gamma} = m_X + m_t$
- $300 \text{ pb}^{-1}$
- $200 \text{ pb}^{-1}$
- $100 \text{ pb}^{-1}$

95% C.L.
FIG. 4: 3σ (Gaussian equivalent) Tevatron discovery contours for the semi-leptonic channel (left) and the hadronic channel (right) for integrated luminosities 2, 5, 10, and 20 fb⁻¹. For each point in parameter space, the cut with the best significance has been chosen.

FIG. 5: 95% CL exclusion contours for a 10 TeV LHC run in the semi-leptonic channel (left) and the hadronic mode (right), for integrated luminosities 100, 200, and 300 pb⁻¹. For each point in parameter space, the cut with the best significance has been chosen.

200, and 300 pb⁻¹ integrated luminosity for the semi-leptonic channel. The exclusion region for the hadronic channel covers almost the entire interesting mass parameter space with 300 pb⁻¹ luminosity. Note that at the LHC, we could tolerate much smaller m_{T'} - m_X; in particular, we start probing the off-shell decay region T' → t∗t̄X → bWX for m_{T'} - m_X < m_t.

Figure 6 shows the 3σ (Gaussian equivalent) discovery contours for a 10 TeV LHC run, in the semi-leptonic and hadronic channels for integrated luminosities 100, 200, and 300 pb⁻¹. Although the reach in both m_{T'} and m_X is limited for the semi-leptonic mode, the hadronic channel...
Discovery for $T' \bar{T}' \rightarrow t \bar{t} X \bar{t} X$ at 10 TeV LHC

**Semileptonic channel**

- $m_T = m_X + m_t$

**Hadronic channel**

- $m_T = m_X + m_t$

**LHC @7TeV, multiply luminosity by a factor of 3.**

S. Su
Tevatron Search

Signal: $B'B' \rightarrow bbXX$

Bg: $W(l\nu)jj$, $Z(\nu\nu) jj$, WZ, ttbar

Precuts

- no lepton
- 2 or 3 jets, with $|\eta_j|<2.5$, $P_{Tj} > 20$ GeV
- $\alpha_{j1j2} < 164^\circ$
- $\text{MET} \geq 40$ GeV, $\text{MET}/\text{GeV} > 80 - 40X\Delta\phi_{\text{min}}$ (MET, jets)
- $\geq 2$ b-jets, including leading jet
- $\Delta \phi(\text{MET, jets}) > 0.6$, $A=(\text{MET-MHT})/(\text{MET+MHT})$, $-0.1 < A < 0.2$
- $X_{jj} = (P_{Tj1}+P_{Tj2})/\text{HT}$, $X_{jj} > 0.75$
- $H_T > 60$ GeV

Additional cuts

- $P_{Tj1}$, MET, $X_{jj}$, HT
Preliminary results for $B'B' \rightarrow bbXX$

- optimal cuts (after precuts)
- $S/B > 0.1$, more than 2 events
- Poisson statistics

95% C.L.
LHC7 Search

Signal: $B'B' \rightarrow bbXX$

Bg: $W(l\nu)jj$, $Z(\nu\nu)jj$, $WZ$, $ttbar$

Precuts

- no lepton
- 2 or 3 jets, with $|\eta_j|<2.5$, $P_{Tj} > 100, 40$ (40) GeV
- $MET \geq 80$ GeV
- $f=MET/M_{eff}$, $f>0.3$ for 2 jets, $f>0.25$ for 3 jets
- $\Delta \phi(MET, jets) > 0.2$
- Sphericity $S_T>0.2$
- $\geq 1$ b-jets, including leading jet

Additional cuts

- $P_{Tj1}$, $MET$, $M_{eff}$, additional btag
LHC Reach

Preliminary results for $B'B' \rightarrow bbXX$

- optimal cuts (after precuts)
- $S/B > 0.1$, more than 2 events
- Poisson statistics

S. Su
Conclusions

- Pair production of exotic quarks $\rightarrow$ DM + SM particles

  - DM motivated, WIMPless scenario
    - natural obtain the right relic density
    - explain DAMA results: light DM, large $\sigma_{SI}$

  - $T'T' \rightarrow ttXX$ semileptonic mode and hadronic mode

- Current CDF exclusion (4.8 fb$^{-1}$): 360 GeV

- Exclusion: LHC @ 10 TeV, 300 pb$^{-1}$

- Discovery:
  - $m_X < 130$ GeV, $m_{T'} < 405$ GeV for Tevatron 20 fb$^{-1}$
  - $m_X < 170$ GeV, $m_{T'} < 490$ GeV for LHC10 300 pb$^{-1}$
Conclusions

B’B’ → bbXX

- current exclusion (5.2 fb\(^{-1}\), D0): 440 GeV
- Tevatron 20 fb\(^{-1}\), exclusion, 470 GeV
- LHC @ 7 TeV, 1 fb\(^{-1}\), discovery: 545 GeV

identify signal as \( T'\bar{T}' \rightarrow t\bar{t}XX \), comparing with SUSY \( \tilde{t}\tilde{t}^* \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \)

- Need ILC ...

complementary between collider studies and DM searches

- small \( \lambda \), DM searches unsuccessful
- displaced vertex at collider