The “Top Priority” at the LHC

Tao Han
University of Wisconsin-Madison
(BMS-LHC, Northeastern University, June 2, 2009)
The “Top Priority” at the LHC
– Top quark: A Window to New Physics

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Terascale Physics at the LHC

- Unitarity argument for $W_L W_L$ scattering
  $\Rightarrow$ New physics must show up at the Terascale: A Higgs boson $m_H < 1 \text{ TeV}$ or alike.

- Naturalness argument for a $m_H$ or EW scale
  $\Rightarrow$ New physics needed beyond $H^0$ . . . .

- Gauge coupling unification
  $\Rightarrow$ New threshold at the Terascale.

- Particle dark matter
  $\Rightarrow$ WIMP at the Terasacle natural.
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  ⇒ New physics must show up at the Terascale: A Higgs boson $m_H < 1$ TeV or alike.

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  ⇒ WIMP at the Terascale natural.

What exact form is it realized in nature?
Fundamental scalar in a weakly coupled theory? (SUSY or alike)
Composite Higgs and strongly interacting dynamics? (TC, Little Higgs, Warped extra dim)
Extensions of gauge sector, fermion sector, ... ... ? ($Z', Q, N_R$)
Dark matter connection? (WIMP: LSP ...)

The LHC will tell!
Top quarks at the LHC

LHC is a top factory:

Event rate: 800K $t\bar{t}$ / fb$^{-1}$, or 8 Hz @ $10^{34}$/cm$^2$/s!

From Tevatron to LHC: $t\bar{t}$ increased by 100; EW increased by 10.
Production well predicted in the SM:

At the LHC: \( gg \ 90\%, \quad q\bar{q} \ 10\% \);  
(At the Tevatron: \( gg \ 10\%, \quad q\bar{q} \ 90\% \).)

\[
\sigma(\ell^\pm b\bar{b}jj E_T) \approx 300 \text{ pb}, \quad \sigma(m(tt) > 1 \text{ TeV}) \approx 5 \text{ pb}.
\]
Why Top Quarks? bread & butter:

- Top quark exists, as the heaviest particle in the SM.
- $m_t$ is the most precisely measured quark mass — Important for precision physics of the SM and beyond:
- Top decays before it hadronizes:

\[ \theta \approx \gamma^{-1} \approx m_t/E_t \]

Test ground for QCD, spin, couplings, CP property...

- Possible deep connection to electroweak symmetry-breaking:

\[ m_t \approx \frac{v}{\sqrt{2}}. \]
Why Top Quarks? A window to new physics:

- Largest Yukawa coupling (proportional to $m_t$, $\cot \beta$): $H, A \rightarrow t\bar{t}$.

- Strong Dynamics (TC, Topcolor/Top See-Saw, Little Higgs): $\rho_{TC}, \eta_{TC}, \pi_{TC}, Z_L \rightarrow t\bar{t}$.

- Extra-dimensions (warped and universal): $Z_{KK}, g_{KK}, G_{KK} \rightarrow t\bar{t}$.

- Flavor physics at high scale: $t \rightarrow Zc, \gamma c, gc (u)$.

- Supersymmetry ($\tilde{t}$ often the lightest squark): $\tilde{t}_R \rightarrow t\tilde{\chi}^0$.

- LH with T-parity (theories with naturalness argument): $T \rightarrow tA^0$, and thus the dark matter connection!

- To the least, precision test: $t\bar{t}Z, t\bar{t}H; t\bar{t}\gamma, g; t\bar{b}W...$
The Remainder of the Talk

- Search I: $t\bar{t}$ Resonant Production
  - Model-Independent Search for New Physics
  - Backgrounds
  - Coupling Determination
  - Fast-moving Top Quarks

- Search II: $t\bar{t}+\not{E}_T$ Signal
  - Signal Events Reconstruction
  - Backgrounds

- Conclusions
Search I: $t\bar{t}$ Resonant Production

- “Bump searches” in the $M_{t\bar{t}}$ distribution.

- Representative features:

<table>
<thead>
<tr>
<th>Model Class</th>
<th>Spin-0</th>
<th>Spin-1</th>
<th>Spin-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM :</td>
<td>narrow</td>
<td>narrow/broad</td>
<td>narrow/broad</td>
</tr>
<tr>
<td>Technicolor/Topcolor/LH:</td>
<td>narrow/broad</td>
<td>narrow/broad</td>
<td>narrow/broad</td>
</tr>
<tr>
<td>RS/Stringy :</td>
<td>narrow/broad</td>
<td>narrow/broad</td>
<td>narrow</td>
</tr>
</tbody>
</table>

- A model-independent approach: $^a$

  Parametrize each resonance with a few parameters: $m, \Gamma, \sigma$ - normalization, chirality, CP violation

Search for New Resonances in $m_{tt}$

- General searches for integer spin resonances via

$$gg \rightarrow \phi_0 \rightarrow \bar{t} + t$$
$$q\bar{q} \rightarrow V_1 \rightarrow \bar{t} + t$$
$$q\bar{q}, gg \rightarrow \tilde{h}_2 \rightarrow \bar{t} + t$$

where $\phi, V$ and $\tilde{h}$ are $J = 0, 1, 2$ resonances.

- Parametrize each interaction with five parameters:
  - $m$ – mass of the resonance (Benchmark: 1 TeV)
  - $\Gamma$ – total width
    - Benchmark studies: $\Gamma_\phi = 0.5 \frac{(m_\phi/\text{TeV})^3}{\text{GeV}^2}$, $\Gamma_V = 5\% \, m_V$, $\Gamma_{\tilde{h}} = 1.2\% \, m_{\tilde{h}}$
  - $\omega$ – cross section normalization factor
    - $\omega_\phi = 1$ recovers SM higgs
    - $\omega_V = 1$ recovers $Z'$ with electroweak couplings
    - $\omega_{\tilde{h}} = 1$ recovers RS graviton
  - Chirality, CP violation ...

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Strategy

To maximumly extract the resonant information:
(Spin, chirality couplings, CP properties ...)
⇒ Need full kinematics and top-ID.

- Using the clean channel: “Semi-leptonic"

\[ t\bar{t} \rightarrow b\ell^\pm \nu, \quad bj j \rightarrow 2b 2j \ell^\pm E_T. \]

- Total Hadronic Channel: \( \sigma_{t/t\bar{t}} \times (6/9)^2 \) ⇒ large background, no top-ID ...
- Semi-Leptonic Channel: \( \sigma_{t/t\bar{t}} \times 6/9 \times 2/9 \times 2 \) ⇒ current interest.
- Pure leptonic Channel: \( \sigma_{t/t\bar{t}} \times (2/9)^2 \) ⇒ small rate, incomplete kinematics ...
- Semi-leptonic/hadronic ratio: 2/3
- Leptonic/hadronic ratio: 1/9

- Top quarks can be reconstructed via \( M_W, m_t \) constraints.
- Full kinematics available.
Background Considerations

W + jets, Z + jets, WW, WZ, ZZ backgrounds:

Consider table of efficiencies reproduced from the ATLAS TDR (Volume II, p. 624). The expected events are in the last column.

<table>
<thead>
<tr>
<th>Process</th>
<th>Efficiency with ( p_{T} &gt; 20 \text{ GeV} )</th>
<th>As before, with ( E_{T \text{miss}} &gt; 20 \text{ GeV} ) plus ( N_{\text{jet}} \geq 4 )</th>
<th>As before, with ( N_{b-\text{jet}} \geq 2 )</th>
<th>Events per 10 ( fb^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} ) signal</td>
<td>64.7</td>
<td>21.2</td>
<td>5.0</td>
<td>126,000</td>
</tr>
<tr>
<td>W + jets</td>
<td>47.9</td>
<td>0.1</td>
<td>0.002</td>
<td>1658</td>
</tr>
<tr>
<td>Z + jets</td>
<td>15.0</td>
<td>0.05</td>
<td>0.002</td>
<td>232</td>
</tr>
<tr>
<td>WW</td>
<td>53.6</td>
<td>0.5</td>
<td>0.006</td>
<td>10</td>
</tr>
<tr>
<td>WZ</td>
<td>53.8</td>
<td>0.5</td>
<td>0.02</td>
<td>8</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.8</td>
<td>0.04</td>
<td>0.008</td>
<td>14</td>
</tr>
<tr>
<td>Total Background</td>
<td></td>
<td></td>
<td></td>
<td>1922</td>
</tr>
<tr>
<td>S/B</td>
<td></td>
<td></td>
<td></td>
<td>65</td>
</tr>
</tbody>
</table>
Reconstructing the hadronic decay ($\bar{t}$, say):

- From ATLAS collaboration (ATLAS TDR, Volume II, p. 625): The $\bar{t}$ is reconstructed via the hadronic decay $\bar{b}jj$. The wrong $b$ may have some contamination (shaded area).
Determine minimal $\omega$ for a $5\sigma$ discovery

\[ \frac{S}{\sqrt{B + S}} = 5 \]
Angular Distributions in $t\bar{t}$ c.m. frame

- $(M_W, m_t)$ and small angle selection, respectively

Red dashed: scalar $\to$ flat;
Black dots: Chiral vector $\to d_{11}^1 \Rightarrow (1 + \cos \theta^*)^2$;
Blue dash-dots: graviton from $gg \to d_{2\pm 1}^2 \Rightarrow \sin^2 \theta^*$;
Black solid: graviton from $q\bar{q} \to d_{1\pm 1}^2 \Rightarrow \sin^4 \theta^* + ...$
Forward/Backward Asymmetry for Parity-Violation:

\[ A_{\text{had}}^f = \frac{N_F - N_B}{N_F + N_B} \]

- \( N_F \) (\( N_B \)) is the number of events with the top quark momentum \( \vec{p}_{top} \) in the forward (backward) direction defined relative to the quark moving direction \( \vec{p}_q \).
- "Forward" for the final state top is defined w.r.t. the initial quark.
- Gluon contributions are homogeneous and subtracted out.
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- Gluon contributions are homogeneous and subtracted out.

**Drawbacks:**

- Which "Forward"? The final state top is thus defined w.r.t. the boost direction from the resonance c.m. frame (because the valence quarks tend to carry a higher-momentum fractions than the sea (anti-) quarks.)

- Symmetric \(g_L \leftrightarrow g_R\): can’t tell a left-, right- chiral coupling.
Top-quark Spin Correlations: 

Consider $V \rightarrow t + X \rightarrow \ell^+ b \nu + X$:

$$\frac{d\sigma}{d\cos\theta_l} = \frac{1}{2} \sigma \left\{ 1 + 2A \cos\theta_l \right\},$$

$$A = \frac{\sigma(\cos\theta_l > 0) - \sigma(\cos\theta_l < 0)}{\sigma(\cos\theta_l > 0) + \sigma(\cos\theta_l < 0)} \propto \left( \frac{g_R^t \, g_L^t}{g_R^t + g_L^t} \right)^2 .$$

where $\theta_l$ is defined to be the angle between $\vec{p}_l$ and $\vec{p}_t$. 

each in their parent rest-frame.

\[a\] Gopalakrishna, Han, Lewis, Si, Zhou, to appear.
At high $M_{t\bar{t}}$, the tops are boosted. That helps select $(\ell^+ b)$, rather than $(\ell^+ \bar{b})$. 

![Cos θ between lepton and b quarks](image1)

500 GeV Invariant Mass Cut

- **Solid** - Lepton/leptonic b quark cos θ
- **Dashed** - Lepton/hadronic b quark cos θ

![Cos θ between lepton and b quarks](image2)

1000 GeV Invariant Mass Cut

- **Solid** - Lepton/leptonic b quark cos θ
- **Dashed** - Lepton/hadronic b quark cos θ
Event topology different for highly boosted top quarks:

How many observable “objects”? ☐

Objects versus $p_T^{\text{top}}$  

\[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.4: \]

\[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.4: \]

---

Quite generically, \[ pp \rightarrow T\bar{T}X \rightarrow t\bar{t} A^0 A^0 X \]
\[ \rightarrow b\ell_1 j_2 \bar{b}\ell\bar{\nu} A^0 A^0 X \rightarrow \ell^\pm b\bar{b} + 2 \text{ jets} + \slashed{E}_T. \]

\[ \sigma(T\bar{T}) \approx 8\sigma(t\bar{t}). \]

Features: No Bump, but much $E_T$

Due to more missing particles from both $T$ and $\bar{T}$, no $p_\nu$ can be reconstructed. Instead, may lead to larger $E_T$:

$$m_T = 1 \text{ TeV}, \ m_A = 200, \ 800 \text{ GeV}.$$
$p_\nu$ reconstruction by $M_W$ may yield complex solutions:

$$(p_\nu^{rec} + p_\ell)^2 = M_W^2, \quad m_t^2(rec) = (p_b + p_\ell + p_\nu^{rec})^2.$$
LHC Reach for $T\bar{T}$ Signal

After judicious cuts, plus $|m_t - m_t^{rec}| > 110$ GeV, the $T\bar{T} \rightarrow t\bar{t} + \not{E}_T$ signal:

\[ m_T = 1 \text{ TeV}: m_A = 200 - 700 \text{ GeV}. \]
May learn $m_T - m_A$, but not $m_A$. 

The “Top Priority” at the LHC – p.25/27
Conclusions

- LHC is a top factory – providing 8 million $t\bar{t}$'s per 10 fb$^{-1}$. Good channel to probe (all kinds of) physics beyond SM. May serve as an early indicator for new physics.

- For the resonant signal $t\bar{t}$:
  Reconstruct semi-leptonic $t\bar{t}$ events at high-invariant mass, study resonant spin, chiral couplings, CP properties ...

- For non-resonant signal $t\bar{t} + E_T$: Observation of the semi-leptonic channel promising, but kinematics difficult: No direct information for the missing particle mass $m_A, m_{\chi^0}$. 

The “Top Priority” at the LHC – p.26/27
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Top quark studies are of high priority!