Searches for physics beyond the standard model at the Tevatron and the LHC

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Cornell University
For the ATLAS, D0, CMS and CDF collaborations

PANIC '11
Particle Physics in one slide: Standard Model

- All matter is made up of spin $\frac{1}{2}$ fermions: quarks and leptons
- Four forces
  - (Gravity)
  - Electromagnetic
  - Weak
  - Strong
- Forces from spin 1 gauge bosons
  - $\gamma, Z, W, g$

Standard model tested to high precision
Particle Physics in one slide: Standard Model

- All matter is made up of spin ½ fermions: quarks and leptons
- Four forces:
  - (Gravity)
  - Electromagnetic
  - Weak
  - Strong
- Forces from spin 1 gauge bosons: \( \gamma, Z, W, g \)

Over the last 20 years, we have developed an orderly and elegant view of the universe: the "Standard Model of Elementary Particle Physics”

Extensively tests at current collider experiments: no experimental evidence contradicts it! (***)

Standard model tested to high precision
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>$O_{\text{meas}}$</th>
<th>$O_{\text{fit}}$</th>
<th>$I/O_{\text{meas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
<td></td>
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</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4959</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^0$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.479</td>
<td></td>
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</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>20.742</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,l}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{\text{l}}(P_{\tau})$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
<td></td>
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</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
<td>0.21579</td>
<td></td>
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</tr>
<tr>
<td>$R_c$</td>
<td>0.1721 ± 0.0030</td>
<td>0.1723</td>
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<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
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<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
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</tr>
<tr>
<td>$A_{\text{b}}$</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{\text{c}}$</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{\text{l}}(\text{SLD})$</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.399 ± 0.023</td>
<td>80.379</td>
<td></td>
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</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 ± 0.042</td>
<td>2.092</td>
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</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.3 ± 1.1</td>
<td>173.4</td>
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</tr>
</tbody>
</table>

July 2010
Measurement

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha^{(5)}_{\text{had}}(m_Z)$</td>
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</tr>
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<tr>
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</tr>
<tr>
<td>$R_l$</td>
<td>20.76</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,l}$</td>
<td>0.0171</td>
</tr>
<tr>
<td>$A_{\text{fb}}^l(P_\tau)$</td>
<td>0.146</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.2162</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.172</td>
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<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>0.099</td>
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<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>0.070</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.92</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.67</td>
</tr>
<tr>
<td>$A_{\text{fb}}^l(SLD)$</td>
<td>0.151</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$</td>
<td>0.232</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.39</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.08</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.00</td>
</tr>
</tbody>
</table>

July 2010
One missing piece:
Standard model does not predict masses for the bosons and fermions.
The Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism provides a solution
→ W and Z bosons acquire mass
→ photons does not
→ fermions can be made massive.
Predicts a spin-0 boson (Higgs) with unknown mass.

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July 2010
The Dark Side

We know _almost everything_ about _almost nothing_

- Astrophysics observation (WMAP, Supernovae…) indicates that SM can only account for 4% of the composition of the Universe

- 96%
  - Dark Matter
  - Dark Energy

What’s going on?
New physics motivation from an exp. POV

Two Major Drivers:

• Dark Matter from Cosmology
  • heavy, long-lived neutral particle

• Hierarchy Problem
  • scale for new physics around 1 TeV
New physics motivation from an exp. POV

Two Major Drivers:

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Two Major Drivers:

- Dark Matter from Cosmology
  - heavy, long-lived neutral particle
- Hierarchy Problem
  - scale for new physics around 1 TeV

→ Large Hadron Collider (and Tevatron) fits the bill to explore particles with properties and mass scale
→ We’re in the right place at the right time.
Direct searches vs indirect searches

- Two complementary methods to search for new physics
- Direct searches: look for decays of non-virtual particles decaying
- Indirect searches: look for evidence in interference with SM processes
  - Probe mass scales much higher than you can directly produce
- Precision test of SM physics looking for discrepancies between SM prediction and data via off-mass-shell weakly produces particles
  - Intensity frontier at FNAL, B factories, **LHCb at LHC**, ...
- Main focus in this talk: Direct searches.
Supersymmetry: Grand Dame of NP models

- Based on fundamental symmetries
- Hierarchy Problem solved
- How: double particle spectrum
  - Worked before: postulate positron for quantum mechanics
- Introduce “super-partners” of diff spin
  - Makes theory self-consistent
  - Also provides dark matter candidate
- But: where are they?
  - Mass of positron = Mass electron
  - But not so for missing selectron
  - SUSY is a broken symmetry

- SUSY partners should be visible at Tevatron/LHC

\[
\begin{array}{|c|c|}
\hline
\text{Particle} & \text{Super-partner} \\
\hline
e,\nu,u,d & \tilde{e},\tilde{\nu},\tilde{u},\tilde{d} \\
\hline
\gamma,W,Z,h & \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}, \tilde{\chi}_1^0 \ldots \tilde{\chi}_4^0 \\
\hline
\end{array}
\]

Dark Matter Candidate
Many other models exist too...

• Large Extra Dimensions:
  • Another formulation of the Hierarchy problem: why is Gravity so weak?
• Universal Extra Dimensions:
  • Models of many extra dimensions can mimic SUSY in some of the phenomenology
• Hidden Valley:
  • How to explain the apparent lack of new physics in the Tevatron and LEP data? They’re in a hidden sector
• Technicolor models of EWK symmetry breaking...

• No questioning the fertile imagination of today’s theory community!
Many other models exist too...

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The cast of characters
The cast of characters
The cast of characters
The cast of characters
The cast of characters

LHC

ATLAS
The cast of characters

CMS
Tevatron: CDF and D0

- Run 2 experiments very similar
  - strong central tracking in solenoidal field ($\eta \sim 1-2$), Si innermost
  - good hermetic calorimetry (em & had, $\eta \sim 2-2.5$)
  - extensive muon coverage ($\eta \sim 1-2$)
  - sophisticated trigger and DAQ systems to collect interesting events
- Very similar performance as measured by physics results
LHC: ATLAS and CMS

- Next generation - learn from previous hadron collider experiments
- Higher performance detectors
  - Better coverage:
    - Central tracking coverage out to $|\eta|<2.5$ (incl muons)
    - Calorimeter coverage to $|\eta|<5$
  - Finer segmentation in all areas
    - Handle more demanding conditions of LHC (7x higher energy, $10^2$ x inst. lumi, ≥ 5x pileup, 5x shorter beam crossing time)
- Beautiful devices for physics measurement
Tevatron Performance

- The machine is performing very well
  - Delivering record inst. luminosities (>440E30)
  - Integrating lots of data with high efficiency (>1./fb accumulated in FY11 already)
- Today: 9/fb, results, have >11/fb in the can
- On track for another great year
- Will have more than 12/fb in can by end of Run 2 (9/30/2011)
- Tevatron will retire with an impressive list of achievements
  - Thanks to FNAL AD for their tireless works during all of Run 2!
LHC Performance

→ Accumulating >45/pb/day - more than 2010 data set!
→ Already achieved 2011 goal (1/fb); crush it by 5x
→ Possibly reach inst. design lumi this year
→ Thanks to LHC teams for their great work
The challenge - pile-up at LHC

Reach 25 soft collisions in 2011?
Many new developments

- Ever-increasing Tevatron data samples: 9/fb results today
- Fundamental change: probe of new energy scale with LHC
  - results today with \textbf{30 times} larger LHC data samples than we had six months ago
- All avenues being explored
  - direct searches
    - … in hadronic final states
    - … in leptonic final
    - … in mixed final states
  - indirect searches
    - … subtle deviations from SM
  - with many tools
    - … counting experiments
    - … sophisticated jet tools
    - … multivariate discriminators
Many new developments

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Some hints - but no smoking guns yet.
Many new developments

- Ever-increasing Tevatron data samples: 9/fb results today
- Fundamental change: probe of new energy scale with LHC
  - results today with **30 times** larger LHC data samples than we had six months ago
- All avenues being explored
  - direct searches
    - ... in hadronic final states
    - ... in leptonic final states
    - ... in mixed final states
  - indirect searches
    - ... subtle deviations from SM
  - with many tools
    - ... counting experiments
    - ... sophisticated jet tools
    - ... multivariate discriminators

Shown is a sampling of all the results now available. Many more not covered!
Much more to be seen, esp from ATLAS & CMS

<table>
<thead>
<tr>
<th>Additional NEW CMS RESULTS</th>
<th>Additional New ATLAS Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-11-015 dijet bump hunt</td>
<td>ATLAS-CONF-2011-097 $W+2$jet bumps 1/fb</td>
</tr>
<tr>
<td>EXO-11-002 Heavy $v$, right-handed $W'$</td>
<td>ATLAS-CONF-2011-087 $ttbar$ resonances $l +$ jets 200/pb</td>
</tr>
<tr>
<td>EXO-11-071 black holes</td>
<td>ATLAS-CONF-2011-095 dijet bump hunt 0.81/fb</td>
</tr>
<tr>
<td>EXO-11-037 RS Gravitons</td>
<td>ATLAS-CONF-2011-096 monojet + met 1/fb</td>
</tr>
<tr>
<td>EXO-11-051 t pairs in lepton + jets</td>
<td>ATLAS-CONF-2011-098 $bjets +$ met 0.83/fb</td>
</tr>
<tr>
<td>EXO-11-022 HSCP</td>
<td>EPS dilepton resonances 1.2/fb</td>
</tr>
<tr>
<td>EXO-11-020 stopped HSCP</td>
<td>ATLAS-CONF-2011-091 Same-sign dileptons 35/pb</td>
</tr>
<tr>
<td>SUS-11-010 LSDIL + MET + jets($e$, $\mu$, $\tau$)</td>
<td>ATLAS-CONF-2011-109 $e\mu$ resonances 0.87/fb</td>
</tr>
<tr>
<td>SUS-11-017 Z+met</td>
<td>EPS $W'\rightarrow \ell \nu$ 1/fb</td>
</tr>
<tr>
<td>SUS-11-011 OS DIL + MET</td>
<td>arXiv:1107.0561 $\gamma + \gamma +$ MET 35/pb</td>
</tr>
</tbody>
</table>

Complete list of results is available at the following URL's:
- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults)
- [https://twiki.cern.ch/twiki/bin/view/AtlasPublic](https://twiki.cern.ch/twiki/bin/view/AtlasPublic)
Strongly produced particles: Probes with jet pairs

- Strong production is among the most sensitive probes at hadron colliders
- LHC is now probing new regimes
- Look for resonant production of new particles
  - excited quarks, contact interaction, …
- Sensitive to substructure of the quarks
  - Eg, excitations due to composite nature of quarks
  - Modern equivalent of classic Rutherford scattering experiment

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 0.81 \text{ fb}^{-1} \]

- Data
- Fit
- \( q^*(1000) \)
- \( q^*(1700) \)
- \( q^*(2750) \)

ATLAS Preliminary
Strongly produced particles:

Probes with jet pairs

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$E_T = 4\text{ TeV}$
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![Graph showing 95% C.L. Limit on $\sigma A$ [pb] vs. Mass [GeV] with legend for $\sigma_{\text{Gaussian}}$/mean with $\sqrt{s} = 7$ TeV, $\int L dt = 0.81$ fb$^{-1}$]
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![Mass vs. 95% C.L. Limit on σxA [pb]](image)

CMS EXO-11-015: 1.1/fb

ATL-CONF-2011-095
Events with one jet (Monojet)

- Most basic new physics signature: single high-pt jet with large missing energy
  - Example: LED signature
  - EWK vs Planck scales
  - qg→Gq, gg→Gg, qq→Gg
  - Graviton G escapes into ED, giving MET
- Main background:
  - Z(→νν) + jets
  - data-driven estimate
- Interpret null result in terms of ADD:
  - number of extra dimensions
  - MD (mass of higher-dim scale)

1/fb!
Events with one jet (Monojet)

- Most basic new physics signature: single high-\(p_T\) jet with large missing energy
  - Example: LED signature
    - EWK vs Planck scales
    - \(qg \rightarrow Gq, \; gg \rightarrow Gg, \; qq \rightarrow Gg\)
  - Graviton \(G\) escapes into ED, giving MET
- Main background:
  - \(Z(\rightarrow \nu \nu) + \) jets
  - data-driven estimate
- Interpret null result in terms of ADD:
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\[1/\text{fb}\]
Events with one jet (Monojet)

- Most basic new physics signature: single high-pt jet with large missing energy
  - Example: LED signature
    - EWK vs Planck scales
  - $qg \rightarrow Gq$, $gg \rightarrow Gg$, $qq \rightarrow Gg$
  - Graviton $G$ escapes into ED, giving MET
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  - $Z(\rightarrow \nu\nu) + \text{jets}$
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$1/fb!$
SUSY golden channel: jets + met

- Search for generic squarks and gluinos (1st two families)
  - jets + LSP in final state
- ATLAS new results: 1/fb
- Split signal region into 2, 3, ≥ 4 jets to target different decay modes
- Bkgnds: $Z(\rightarrow \nu\nu)+jets + W(\rightarrow \ell\nu)$ dominant
  - Estimates from data+MC combination

---

**Signal Region**

<table>
<thead>
<tr>
<th>$E_T^{miss}$</th>
<th>≥ 2 jets</th>
<th>≥ 3 jets</th>
<th>≥ 4 jets</th>
<th>High mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading jet $p_T$</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
</tr>
<tr>
<td>Second jet $p_T$</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>Third jet $p_T$</td>
<td>−</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>Fourth jet $p_T$</td>
<td>−</td>
<td>−</td>
<td>&gt; 40</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>$\Delta\phi$ (jet, $E_T^{miss}$)$_{min}$</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>$E_T^{miss}/m_{eff}$</td>
<td>&gt; 0.3</td>
<td>&gt; 0.25</td>
<td>&gt; 0.25</td>
<td>&gt; 0.2</td>
</tr>
<tr>
<td>$m_{eff}$ [GeV]</td>
<td>&gt; 1000</td>
<td>&gt; 1000</td>
<td>&gt; 500/1000</td>
<td>&gt; 1100</td>
</tr>
</tbody>
</table>

---

**Diagrams**

- Squark-squark
- Gluino-squark
- Gluino-gluino

---

ATLAS-CONF-2011-086 (165/pb, paper in preparation)
ATLAS jets + met: Consistent with SM

- Extract final counts with likelihood fit, no BSM signal observed
- Sensitive to cross sections $O(20 \text{ fb})$
- Set limits in a simplified low-mass model (assume $m_{n1}=0 \text{ GeV}$)
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- Extract final counts with likelihood fit, no BSM signal observed
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### Signal Region

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<th>Process</th>
<th>$\geq 2$-jet</th>
<th>$\geq 3$-jet</th>
<th>$\geq 4$-jet, $m_{\text{eff}} &gt; 500 \text{ GeV}$</th>
<th>$\geq 4$-jet, $m_{\text{eff}} &gt; 1000 \text{ GeV}$</th>
<th>High mass</th>
</tr>
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<tr>
<td>$Z/\gamma + \text{jets}$</td>
<td>$32.5 \pm 2.6 \pm 6.8$</td>
<td>$25.8 \pm 2.6 \pm 4.9$</td>
<td>$208 \pm 9 \pm 37$</td>
<td>$16.2 \pm 2.1 \pm 3.6$</td>
<td>$3.3 \pm 1.0 \pm 1.3$</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>$26.2 \pm 3.9 \pm 6.7$</td>
<td>$22.7 \pm 3.5 \pm 5.8$</td>
<td>$367 \pm 30 \pm 126$</td>
<td>$12.7 \pm 2.1 \pm 4.7$</td>
<td>$2.2 \pm 0.9 \pm 1.2$</td>
</tr>
<tr>
<td>$t\bar{t}$ Single Top</td>
<td>$3.4 \pm 1.5 \pm 1.6$</td>
<td>$5.6 \pm 2.0 \pm 2.2$</td>
<td>$375 \pm 37 \pm 74$</td>
<td>$3.7 \pm 1.2 \pm 2.0$</td>
<td>$5.6 \pm 1.7 \pm 2.1$</td>
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<tr>
<td>QCD jets</td>
<td>$0.22 \pm 0.06 \pm 0.24$</td>
<td>$0.92 \pm 0.12 \pm 0.46$</td>
<td>$34 \pm 2 \pm 29$</td>
<td>$0.74 \pm 0.14 \pm 0.51$</td>
<td>$2.10 \pm 0.37 \pm 0.83$</td>
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<td>Total</td>
<td>$62.3 \pm 4.3 \pm 9.2$</td>
<td>$55 \pm 3.8 \pm 7.3$</td>
<td>$984 \pm 39 \pm 145$</td>
<td>$33.4 \pm 2.9 \pm 6.3$</td>
<td>$13.2 \pm 1.9 \pm 2.6$</td>
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<td>58</td>
<td>59</td>
<td>1118</td>
<td>40</td>
<td>18</td>
</tr>
</tbody>
</table>
ATLAS jets + met: Consistent with SM

- Extract final counts with likelihood fit, no BSM signal observed
- Sensitive to cross sections $\mathcal{O}(20 \, \text{fb})$
- Set limits in a simplified low-mass model (assume $m_{n1} = 0$ GeV)

$$m_{\tilde{g}} (m_{\tilde{q}}) > 800 \ (850) \ \text{GeV} \ \text{for} \ m_{\tilde{q}} (m_{\tilde{g}}) < 2 \ \text{TeV}$$

$$m_{\tilde{g}} > 1075 \ \text{GeV} \ \text{for} \ m_{\tilde{g}} = m_{\tilde{q}}$$
CMS: attack same problem using $\alpha_T$

- Look for events with high $H_T$
  - interaction’s $q^2$
- Same signature as ATLAS search:
  - but use new discriminating variable
- Main background to preselection: mis-measured $2\rightarrow 2$ QCD dijet production
  - Suppress with $\alpha_T$ variable (orig: Randall & Tucker), $\Delta\Phi^*$
  - $\alpha_T > 0.55$
- Small residual dijet contamination estimated from data
**α\textsubscript{T}: New Physics in dijets**

- Same backgrounds
- W+jets
  - derive from tagged \( W \rightarrow \mu \nu \)
- Z(→ ν ν)+jets
  - derive from γ + jets
- Evaluate result in bins of \( H_T \) (like \( q^2 \))
- Null result, interpret in mSugra SUSY model

\[
H_T = \sum_i E_T^i
\]

\[
\alpha_T \equiv \frac{E_T^{\text{jet}2}}{M_T^{1,2}}
\]
\( \alpha_T: \) New Physics in dijets

- Same backgrounds
- \( W + \text{jets} \)
  - derive from tagged \( W \rightarrow \mu \nu \)
- \( Z(\rightarrow \nu \nu) + \text{jets} \)
  - derive from \( \gamma + \text{jets} \)
- Evaluate result in bins of \( H_T \) (like \( q^2 \))
- Null result, interpret in mSugra SUSY model

\[
H_T = \sum_i E_T^{i}\]

\[
\alpha_T \equiv \frac{E^{\text{jet}_2}_T}{M_T^{1,2}}
\]
\( \alpha_T \): New Physics in dijets

- Same backgrounds
- \( W+\text{jets} \)
  - derive from tagged \( W \to \mu \nu \)
- \( Z(\to \nu \nu )+\text{jets} \)
  - derive from \( \gamma + \text{jets} \)
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- Null result, interpret in mSugra SUSY model

\[
1.1/\text{fb} \quad \text{CMS SUS-11-003}
\]

\[
H_T = \sum_i E_T^{\text{jet}_i}
\]

\[
\alpha_T \equiv E_T^{\text{jet}_2^2}/M_T^{1,2}
\]

CMS preliminary \( \alpha_T \) \( L = 1.08 \text{ fb}^{-1} \) \( \sqrt{s} = 7 \text{ TeV} \)

- 95\% C.L. Limits:
  - Observed Limit (NLO), PL
  - Median Expected Limit
  - Expected Limit \pm 1\sigma

- 50\% C.L. Limits:
  - CDF \( \tilde{g}, \tilde{g}, \tan\beta=5, \mu<0 \)
  - D0 \( \tilde{g}, \tilde{g}, \tan\beta=3, \mu<0 \)
  - LEP2 \( \tilde{\chi}_1^\pm \)
  - LEP2 \( \tilde{\tau} \)

- \( \tan\beta = 10, A_0 = 0, \mu > 0 \)

- \( \tilde{g} \) (1250 GeV)
  - \( \tilde{q} \) (1000 GeV)
  - \( \tilde{g} \) (750 GeV)
  - \( \tilde{q} \) (500 GeV)

- \( m_{1/2} \) (GeV)

- \( m_0 \) (GeV)

\[ \text{1J-3, Matthias SCHROEDER} \]

\[ \text{PANIC 2011} \]

- **Strong limits on SUSY model**
Third Generation is special

- Another search for squarks, this time with b quarks
  - Third family is special in many super-symmetric theories

\[ pp \rightarrow \tilde{g}\tilde{g} \rightarrow \tilde{b}\tilde{b}\tilde{b}\tilde{b} \]

\[ pp \rightarrow \tilde{b}\tilde{b} \]

\[ \tilde{b} \rightarrow b\tilde{\chi}^0_1 \]

- Enrich b content with tagging
- Look for exactly one, and more than one b jet, lepton veto
- Test background with top-enriched control regions, lepton selection
Third Generation is special

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- Enrich b content with tagging
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- Most stringent limits to date on b squarks
$B_s \rightarrow \mu\mu$: The race is on

- BR($B \rightarrow \mu\mu$) is a sensitive model for new physics
  - very small BR in SM- btw $10^{-9}$ and $10^{-10}$ for $B$ and $B_s$.
  - New Physics can enhance (or suppress)
  - SUSY: $\tan \beta$ sensitivity at sixth power
- Long history of $B \rightarrow \mu\mu$ searches, including LHC recently (LHCb very strong)

- **New Tevatron result** (CDF)
  - update to 7/fb
  - Increase $\mu$ acceptance ($0.6 < |\eta| < 1.0$)
  - improve bkgrnd discrimination NN
• First suggestion of the $B_s$ decay?

---

**Expected 95% CL:**

\[ \mathcal{B}(B_d^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9} \]
\[ \mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8} \]

**Observed 95% CL:**

\[ \mathcal{B}(B_d^0 \to \mu^+\mu^-) < 6.0 \times 10^{-9} \]
\[ \mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.0 \times 10^{-8} \]

\[ \mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8} \]

• Assume excess is $B_s$ signal
Result from CDF

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- First suggestion of the $B_s$ decay?
- See excess CC in pure region of $\nu_{NN}>0.97$; p-value assuming SM signal + bkgnd is ~2%
- Assume excess is $B_s$ signal
Result from CDF

• First suggestion of the $B_s$ decay?

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\[
B(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}
\]

LHCb and CMS also are expected to have results this week.

 excess CC in pure region of $\nu_{NN}>0.97$; p-value assuming SM signal + bkgnd is ~2%

• Assume excess is $B_s$ signal
Final States with Gauge Bosons:

W+ 2jets - Tevatron

- $W \rightarrow \ell \nu$, $\ell = e$ or $\mu$
- Exactly 2 jets
  - $E_T > 30$ GeV, $|\eta| < 2$
  - dijet pt > 40 GeV
- Compute invariant mass spectrum of jets and compare to expectation
  - Expectation derived from MADGRAPH event generator

- Selection dominated by signal (wjj)
  - ttbar, multi-jet

- See statistically significant excess in falling spectrum
  - Originally $>3\,\sigma$, now $>4\,\sigma$
  - Suggestive structure in background-subtracted plot

D0: We cannot confirm the CDF results

- Same event selection
  - duplicate CDF as much as possible
- Results shown both with and without dR reweighting (to mimic CDF results)

- No signal (at level of CDF result) observed in 4.3/fb of data (same L as first CDF result)
  - Rule out CDF-like excess at >3σ
  - Many tests to show sensitivity

- Experiments trying to resolve differences now; LHC also weighs in
  - ATLAS-CONF-2011-097 (null res.)
  - Still a lot of good data to mine at Tevatron!

D0: Anomalous multi-muon events

- Look at semi-lepton decays of B mesons in two ways
  - count number of same-sign pairs
  - look at overall charge in B decays

- Recently updated to 9/fb

- Discrepancy now at 3.9 $\sigma$

- Evidence for anomalous CP in B system

\[ A_{sl}^{b} = \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} \]
\[ a = \frac{n^{+} - n^{-}}{n^{+} + n^{-}} \]

\[ A_{sl}^{b} = [-0.787 \pm 0.172\text{(stat)} \pm 0.093\text{(syst)}]\% \]

\[ A_{sl}^{b}\text{(SM)} = [-0.028^{+0.005}_{-0.006}]\% \]

PANIC 2011


arXiv:1106.6308v1 (9/fb)
**D0: Anomalous multi-muon events**

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\]


arXiv:1106.6308v1 (9/fb)
CDF: $A_{FB}$ in top pair production

- Hints in Tevatron data?
- Look for forward-backward asymmetry in top pair production

- Tevatron: proton-anti-proton collider
- In Standard Model, anti-top-quark is mostly along direction of anti-proton
- SM predicts a small asymmetry (6%)
- Test this in data

- Both CDF and D0 have always seen high value - now increased significance
Latest CDF results

• Look at both di-lepton and lepton + jets top channels
• Construct asymmetry variable from decay products
• Convert raw asymmetry to parton-level asymmetry and compare to prediction
• See biggest discrepancy in di-lepton at high mass

\[ \Delta \eta_l = \eta_{l+} - \eta_{l-} \]
\[ A^{\Delta \eta_l} = \frac{N(\Delta \eta_l > 0) - N(\Delta \eta_l < 0)}{N(\Delta \eta_l > 0) + N(\Delta \eta_l < 0)} \]

CDF Public Note 10436 (dilepton)
Latest CDF results

• Look at both di-lepton and lepton + jets top channels
• Construct asymmetry variable from decay products
• Convert raw asymmetry to parton-level asymmetry and compare to prediction
• See biggest discrepancy in di-lepton at high mass

\[ A_{FB} = 0.15 \pm 0.05 \text{(raw)} \]
\[ = 0.42 \pm 0.15 \text{(stat)} \pm 0.05 \text{(sys)} \]

measured vs expectation, >2 \( \sigma \) discrepancy

CDF Public Note 10436 (dilepton)
Latest CDF results

- Look at both di-lepton and lepton + jets top channels
- Construct asymmetry variable from decay products
- Convert raw asymmetry to parton-level asymmetry and compare to prediction

- See biggest discrepancy in di-lepton at high mass

$A_{FB} = 0.15 \pm 0.05 (\text{measured})$
$A_{FB} = 0.15 \pm 0.05 (\text{expectation})$

Awaiting D0 result
LHC: pp means no SM asymmetry; non-SM still visible?

$\Delta \eta_l = \eta_l^+ - \eta_l^-$

$A_{FB} = 0.42 \pm 0.15$

$LHC: pp \text{ means no SM asymmetry; non-SM still visible?}$
New Gauge Bosons

$W' \rightarrow \ell \nu$ ($\ell = e, \mu$)

- Simple search for stiff lepton and large missing momentum (MET)
- Backgrounds: extrapolate data in mT distribution to high values in both channels
  - dominant: SM $W^* \rightarrow \ell \nu$
- No excess, limits on $W'$ in Altarelli Model (carbon copy of SM W at higher mass)

Combined limit in SSM:
Expected: $m(W') > 2.20$ TeV
Observed: $m(W') > 2.27$ TeV

413 Alexander Gude
$Z' \rightarrow ll$ (new CMS result)

- Brand new: 1.1/fb
  - data collected through June
- Very clean signature: two leptons of opposite electric charge
- Resonant production on top of Drell-Yan spectrum
  - This is dominant background
- So far no significant excess
Z' → ℓℓ (new CMS result)\[1.1/fb\]

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  - Data collected through June
- Very clean signature: two leptons of opposite electric charge
- Resonant production on top of Drell-Yan spectrum
  - This is dominant background
- So far no significant excess
• Limit on ratio to SM Z cross section measured in data
• for SSM Z’ m>2 TeV

CMS preliminary, $\int L dt = 1.1 \text{fb}^{-1}$

- median expected
- 68\% expected
- 95\% expected
- $Z'_\text{SSM}$
- $Z'_\psi$
- $G_{KK} k/M_{Pl} = 0.1$
- $G_{KK} k/M_{Pl} = 0.05$
- 95\% C.L. limit
New development: focus on details of jets


• Fruitful area of research between theory and experiment
• Several motivations
  • better understanding of jets (cone vs sequential recombination)
  • how to deal with very boosted objects at LHC
• Result:
  • many new tools to best get back at parton-level information
• See Sal Rapoccio’s, D. Krohn’s talks in parallel, Gavin Salam’s talk in plenary
CMS: look for high-$p_T$ tail of the $Z' \rightarrow ttbar$ signal

- At higher momenta: top merged into “fat jets”
- Utilize “top tagger” to look for such boosted jets
- Hadronic-$ttbar$: 6 jets, 2 b’s, single-jet trigger (>240 GeV)
- Break jets apart; look for sub-jets of merged top (bqqbar’) or merged W only (qqbar’); check mass against hypothesis
- Only consider events consistent with ttbar-enhancing selection
- 60% efficiency for ttbar $p_T>600$ GeV
- A difficult, background-dominated measurement! (ttbar and qcd)
CMS: look for high-\(p_T\) tail of the \(Z' \rightarrow \text{ttbar}\) signal
Testing higher-mass $Z' \rightarrow \text{t}\text{t}\overline{\text{b}}\overline{\text{b}}$

- Perform counting experiment in mass bins; no excess observed in 886/pb

- As a result: sensitive to higher-mass $Z'$ signals
  - Sub-pb sensitivity for masses above 1 TeV
  - No sensitivity below 1 TeV
  - Complementary to ATLAS result on $Z' \rightarrow \text{t}\text{t}\overline{\text{b}}\overline{\text{b}}$ w/traditional jet techniques (ATL-CONF-2011-087)

- Demonstration of jet substructure methodology in action
ATLAS: new physics with *lepton jets* (40/pb)

- Leptonic decay of light, highly boosted new particles lead to *lepton jets*
  - Example: dark photons in Hidden Valley scenarios
  - Cosmic ray results?
  - → collimated, isolated leptons
- Challenge: separate these from QCD
  - Estimate from data ($J/\Psi$, $\Upsilon$)
  - Isolation controls QCD
- Good prospect for future measurements with more data

---

### Table

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<th>2 LJ</th>
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CMS: EXO-11-013
D0: PRL 105, 211802 (2011)
ATLAS: new physics with **lepton jets** (40/pb)

- Leptonic decay of light, highly boosted new particles lead to **lepton jets**
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CMS: EXO-11-013
D0: PRL 105, 211802 (2011)
This was just a taste .... much more to be done

- LHC: CMS and ATLAS results are available:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic

- Tevatron: CDF and D0 results are available:
  - http://www-d0.fnal.gov/results/index.html

- Other talks LHC and Tevatron searches
  - 1J-1 Search for Squarks and Gluinos Using Different Final States with the ATLAS Detector, Marc HOHLEFELD
  - 1J-3 Search for Supersymmetry at CMS in all-hadronic final states, Matthias SCHROEDER
  - 1J-4 Search for R- Parity violating SUSY and Long Lived Particles with the ATLAS Detector, Michael MAZUR
  - 1J-6 Search for Supersymmetry at CMS in lepton or photon final states, Konstantinos THEOFILATOS
  - 2I-2 Searches for new physics through rare decays from CDF, Robert HARR
  - 3I-4 Like-sign dimuon charge asymmetry at D0, Penny Kasper
  - 3K-2 Jets and Jet Substructure, Sal RAPPOCCIO
  - 4I-1 Searches for new physics in top decays at DO, Marc-Andre PLEIER
  - 4I-3 Search for a heavy neutrino and right-handed W of the left-right symmetric model with CMS detector, Alexander GUDE
  - 4I-5 Exotics Searches for New Physics with the ATLAS Detector, Jalal ABDALLAH
In Summary

- D0 and CDF continue to mine the Tevatron dataset
  - Some hints - what will LHC say?
- We thank our FNAL AD team for the great performance of the Tevatron Run 2
- LHC machine is performing spectacularly and we thank our colleagues in CERN AD
- CMS and ATLAS: data samples 30x bigger than in the winter
  - Will have much more in the coming months and coming year
    ➡️ Maybe 20/fb by end of 2012
- This talk: a sampling of all Tevatron and LHC results
  - See other talks in coming days for more information
  - No smoking gun yet but …

→ If there is TeV-scale new physics, its discovery is around the corner - stay tuned!
Backup Slides
AFB: New Physics implications and LHC

- To accommodate this signal need new physics to interfere with qqbar → ttbar
- s-channel: exchange of spin 1 color octet
- t-channel: exchange of spin 0, 1; several color structures possible
- LHC: pp vs ppbar
  - no defined direction
  - g-g initial state dominant
  - SM effect is much smaller
- Difficult measurement at LHC
  - forward-central charge asymmetry
  - Large non-SM effects could be visible in 2011 data

\[
\mathcal{A}_F(y_0) = \frac{N_t(y_0 < |y| < 2.5) - N_{\bar{t}}(y_0 < |y| < 2.5)}{N_t(y_0 < |y| < 2.5) + N_{\bar{t}}(y_0 < |y| < 2.5)}
\]

CDF Bs to $\mu\mu$ full NN output

- Excess limited to most sensitive region
- Probability for background only fluctuation small
- Central fit value $\sim$5 times SM
- Prob. of SM value sig + bgnd to fluctuate to this level is 2%
Z to $\mu\mu$ tag and probe w/early data

- Study di-muon mass spectrum from Z-peak to high masses
- High mass region almost free of SM events but mis-reconstruction can yield additional background → alignment needs to be understood

- Overall muon efficiency (from MC tag-and-probe) at the Z-peak = (97.6±0.6)%
  Simulation shows no dependence on $p_T$ within 1%
- Require opposite charges
  charge mis-assignment measured with cosmics to be <0.5%@500 GeV and <1.5%@1TeV

Performance results from cosmics data

Cosmics momentum

Muon momentum resolution up to $O$(TeV)

Di-muon mass spectrum for 50 pb$^{-1}$ at 7 TeV in case of evidence for a Z' with $m = 1.24$ TeV

Developed method to combine electron and muon channel based on likelihoods
CDF Result details (backup)

<table>
<thead>
<tr>
<th>NN Bins</th>
<th>Mass bins</th>
<th>5.31-5.334</th>
<th>5.334-5.358</th>
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<td>1</td>
<td>3</td>
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<tr>
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<td>Exp</td>
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<td><strong>CF</strong></td>
<td>Exp</td>
<td>2.38±0.56</td>
<td>2.34±0.55</td>
<td>2.31±0.54</td>
<td>2.28±0.54</td>
<td>2.25±0.53</td>
</tr>
<tr>
<td></td>
<td>Obs</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>0.970&lt;NN&lt;0.987</strong></td>
<td>Exp</td>
<td>0.67±0.24</td>
<td>0.66±0.24</td>
<td>0.65±0.24</td>
<td>0.64±0.23</td>
<td>0.63±0.22</td>
</tr>
<tr>
<td></td>
<td>Obs</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>0.995&lt;NN&lt;1.000</strong></td>
<td>Exp</td>
<td>0.56±0.39</td>
<td>0.54±0.38</td>
<td>0.53±0.38</td>
<td>0.52±0.37</td>
<td>0.51±0.36</td>
</tr>
<tr>
<td></td>
<td>Obs</td>
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<td>1</td>
<td>0</td>
<td>1</td>
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</tr>
</tbody>
</table>

- Results in bins of NN discriminant and di-\(\mu\) mass for \(B_s\) window
- CC shows excess across high-purity mass range
$E_T^{\text{Miss}}$ resolution vs total event energy

Particle Flow

Figure: Data vs MC: PF $\vec{E}_{xy}$ resolution as function of PF $\Sigma E_T$
Virdee - PLHC

$W^\pm$ and $Z^0$ Bosons as Standard Candles!

**electrons**

![Electron Distribution](image1)

**muons**

![Muon Distribution](image2)

**taus**

![Tau Distribution](image3)

**Z boson**

![Z boson Distribution](image4)

**W boson**

![W boson Distribution](image5)
A Top Candidate Event: \( e\mu + 2 \text{ b-jets} + \text{MET} \)
Ideal channel to probe detector performance

Efficiency 40-60% 
Mis-tag rate : 0.2-