MODELING SOFT GLUONS AND FIDUCIAL CROSS SECTIONS: NEW PHYSICS OR OLD QCD?

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Yang Institute for Theoretical Physics
Stony Brook University

Based on:
D. Curtin, P. Jaiswal, PM 1206.6888
D. Curtin, P. Jaiswal, PM, P. Tien 1304.7011
D. Curtin, PM, P. Tien 1406.xxxx (wednesday night EDT)
PM, H. Ramani, M. Zeng 1406.xxxx
A LONG AND WINDING TALE...

Is new physics the theorists white whale?
A LONG AND WINDING TALE...
WHAT THEORISTS WERE SAYING PRE LHC

SUSY is right around the corner

We’ll see DM

We’ll see KK states

We’ll explain the baryon asymmetry

We’ll find hidden sectors
A LONG AND WINDING TALE...

BSM Physics

Pre LHC Theorists
POST 7 AND 8 TEV RUNS

Maybe SUSY is at 100 TeV

Maybe it’s just the Higgs

Maybe DM is an axion

Have we reached the end of particle physics?
A LONG AND WINDING TALE...

BSM Physics

Pre LHC Theorists

Post LHC
THERE'S OF COURSE A REASON FOR THIS…
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THERE'S OF COURSE A REASON FOR THIS...

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**ATLAS Exotics Searches** - 95% CL Exclusion

**Status:** April 2014

**Reference**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell, \gamma$</th>
<th>Jets</th>
<th>$E_{T}^{min}$</th>
<th>$\int L dt [fb^{-1}]$</th>
<th>Mass limit</th>
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<tr>
<td>ADD $g_{ux} \rightarrow g/q$</td>
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<td>ADD $HH \rightarrow t\bar{t}$</td>
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<td>6.2 TeV</td>
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<tr>
<td>RS1 $G_{ux} \rightarrow t\bar{t}$</td>
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<td>-</td>
<td>-</td>
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<td>6.2 TeV</td>
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<tr>
<td>RS1 $G_{ux} \rightarrow ZZ \rightarrow t\bar{t} t\bar{t}$</td>
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<tr>
<td>RS1 $G_{ux} \rightarrow WW \rightarrow t\bar{t} t\bar{t}$</td>
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<td>$\geq 1 b, \geq 1.5/j$</td>
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<td>$S1/Z_{2}'$ EED</td>
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<td>UED</td>
<td>2, $\gamma$</td>
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<tr>
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<td><strong>Extra dimensions</strong></td>
<td>---</td>
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<td>SSM $Z' \rightarrow t\bar{t}$</td>
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<td>7.86 TeV</td>
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<td>SSM $W' \rightarrow t\bar{t}$</td>
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<td>-</td>
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<td>7.86 TeV</td>
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<tr>
<td>EGM $W' \rightarrow WW \rightarrow t\bar{t} t\bar{t}$</td>
<td>3, $\nu$</td>
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<td>-</td>
<td>203</td>
<td>7.86 TeV</td>
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<td>LRSM $W_{L} \rightarrow tb$</td>
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<td>6.7 TeV</td>
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<td>CI $qq\gamma$</td>
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<td>-</td>
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<td>6.7 TeV</td>
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<td>CI $qqf$</td>
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<td>-</td>
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<td>6.7 TeV</td>
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<td>-</td>
<td>4.8</td>
<td>6.7 TeV</td>
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<tr>
<td>DM EFT $DS$ operator</td>
<td>1, $\nu_{\mu}$</td>
<td>1 j</td>
<td>Yes</td>
<td>10.5</td>
<td>2.4 TeV</td>
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<td>DM EFT $D_{s}$ operator</td>
<td>1, $\nu_{\mu}$</td>
<td>1 j</td>
<td>Yes</td>
<td>10.5</td>
<td>2.4 TeV</td>
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<tr>
<td>Scalar LR $1^{st}$ gen</td>
<td>2, $\nu$</td>
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<td>Yes</td>
<td>14.3</td>
<td>6.7 TeV</td>
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<td>Scalar LR $2^{nd}$ gen</td>
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<td>Yes</td>
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<td>6.7 TeV</td>
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<tr>
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<td>14.3</td>
<td>6.7 TeV</td>
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<tr>
<td>Vector-like quark $TT \rightarrow H_{L} + X$</td>
<td>1, $\gamma$</td>
<td>$\geq 2 b, \geq 4 j$</td>
<td>Yes</td>
<td>14.3</td>
<td>6.7 TeV</td>
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<tr>
<td>Vector-like quark $TT \rightarrow H_{h} + X$</td>
<td>1, $\gamma$</td>
<td>$\geq 2 b, \geq 4 j$</td>
<td>Yes</td>
<td>14.3</td>
<td>6.7 TeV</td>
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<tr>
<td>Vector-like quark $RR \rightarrow Zh + X$</td>
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<td>6.7 TeV</td>
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<tr>
<td>Vector-like quark $RR \rightarrow Wh + X$</td>
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<td>6.7 TeV</td>
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<tr>
<td>Excited quark $q' \rightarrow q + \gamma$</td>
<td>1, $\gamma$</td>
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<td>20.3</td>
<td>7.6 TeV</td>
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<tr>
<td>Excited quark $q' \rightarrow q + g$</td>
<td>1, $\gamma$</td>
<td>1 j</td>
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<td>20.3</td>
<td>7.6 TeV</td>
</tr>
<tr>
<td>Excited quark $q' \rightarrow W_{L} + X$</td>
<td>1 or 2, $\gamma$</td>
<td>$\geq 2 b, \geq 4 j$</td>
<td>Yes</td>
<td>14.3</td>
<td>6.7 TeV</td>
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<tr>
<td>Excited lepton $e' \rightarrow e + \gamma$</td>
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<td>1 j</td>
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<tr>
<td>LSRS Majorana</td>
<td>2, $\mu$</td>
<td>2 j</td>
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<td>2.1</td>
<td>1.5 TeV</td>
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<tr>
<td>Type III Seesaw</td>
<td>2, $\mu$</td>
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<td>4.7</td>
<td>6.7 TeV</td>
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<tr>
<td>Higgs triplet $H^{++} \rightarrow t\bar{t}$</td>
<td>2, $\nu$</td>
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<td>-</td>
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<tr>
<td>Multi-charged particles</td>
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<td>4.4</td>
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<tr>
<td>Magnetic monopoles</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>6.7 TeV</td>
</tr>
</tbody>
</table>

**$\sqrt{s} = 7$ TeV**

*Only a selection of the available mass limits on new states or phenomena is shown.*
THERE’S OF COURSE A REASON FOR THIS...

**ATLAS Exotics Searches* - 95% CL Exclusion**

Status: April 2014

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{min}} )</th>
<th>( \int L dt ) (fb(^{-1}))</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD ( a/\ell )</td>
<td>-</td>
<td>1-2</td>
<td>J</td>
<td>Yes</td>
<td>4.7</td>
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<tr>
<td>ADD non-resonant ( \ell\ell )</td>
<td>2 ( \gamma, \ell ), ( \mu, \equiv )</td>
<td>-</td>
<td>-</td>
<td>4.7</td>
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<tr>
<td>ADD ( qf \rightarrow q\ell )</td>
<td>1 ( e, \mu ), 1</td>
<td>J</td>
<td>20.3</td>
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<tr>
<td>ADD BH high ( N_0 )</td>
<td>2 ( \mu ) (SS)</td>
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<td>20.3</td>
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<td></td>
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<td>ADD BH high ( \Sigma^\pm )</td>
<td>( \pm )</td>
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<td>20.3</td>
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<tr>
<td>RS1 ( G_{0/0} \rightarrow \ell\ell )</td>
<td>2 ( \gamma, \ell ), ( \mu, \equiv )</td>
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<td>20.3</td>
<td></td>
<td></td>
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<tr>
<td>RS1 ( G_{0/0} \rightarrow ZZ \rightarrow \ell\ell\ell\ell )</td>
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<td></td>
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<tr>
<td>RS1 ( G_{0/0} \rightarrow WW \rightarrow \ell\ell )</td>
<td>2 ( \gamma, \ell ), ( \mu, \equiv )</td>
<td>-</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
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<tr>
<td>Bulk RS ( G_{0/0} \rightarrow HH \rightarrow b\bar{b}b\bar{b} )</td>
<td>1 ( e, \mu ), ( \pm )</td>
<td>2 ( b ), 1 ( j )</td>
<td>Yes</td>
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<td></td>
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<tr>
<td>Bulk HS ( G_{0/0} \rightarrow tt )</td>
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<td>1 ( b ), 1 ( j )</td>
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<td>S1/2 ( \ell, \gamma ) ED</td>
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<td>UED</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>4.8</td>
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**Extra dimensions**

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{min}} )</th>
<th>( \int L dt ) (fb(^{-1}))</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td>SSM ( Z' \rightarrow \ell\ell )</td>
<td>2 ( \gamma, \ell )</td>
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<td>SSM ( W' \rightarrow \ell\ell )</td>
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**Cl**

<table>
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<th>( \int L dt ) (fb(^{-1}))</th>
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<td>2 ( j )</td>
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**DM**

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<td>-</td>
<td>-</td>
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<td>EFT Dir operator</td>
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**Scalar LQ**

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<td>EFT US operator</td>
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<td>-</td>
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<td>EFT Dir operator</td>
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**Other**

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<td>Type III Seesaw</td>
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<td>Multi-charged particles</td>
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<td>Magnetic monopoles</td>
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<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.*

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Where is the BSM??????
It must be at higher mass scales!!!
LET’S MAKE SURE NOT TO LEAVE ANY SCALE BEHIND!
LET'S MAKE SURE NOT TO LEAVE ANY SCALE BEHIND!

*Not just a commentary on the USA being left behind on the Energy Frontier*
THE ONLY NEW PHYSICS WE’VE FOUND SO FAR IS THE HIGGS

Is there anything else lurking at the EW scale? (remember the CDF Wjj saga…)

It’s difficult to go after this scale… It runs contrary to deep ingrained desire of BSM experimentalists not to trust theorists and do everything in a “data-driven” manner
DATA-DRIVEN SEARCHES…

Theorists

No new physics here, go higher!

Experimentalists
DATA-DRIVEN SEARCHES...

- Based on being able to separate signal and control regions

- What if there isn’t a good place where the signal isn’t?

- Assumes shapes extrapolate almost perfectly, don’t trust MCs for normalizations...

- If there are exceptions, this doesn’t just have dire consequences for searches, but for the Higgs as well in principle!
ARE THERE ANY POTENTIAL DISCREPANCIES IN THE DATA?

- some discrepancies:
  - $p_T$ of the individual top quarks in $t\bar{t}$
  - $p_T$ of the leptons in $W^+W^-$
- difficult to describe both minimum bias (MB) and underlying event (UE) data with the same tune
- http://mcplots.cern.ch
  - a good overview of the distributions and comparisons (for many event generators and tunes)

---

$^2$There are some disagreements between ATLAS and CMS on which ones.
ARE THERE ANY POTENTIAL DISCREPANCIES IN THE DATA?

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---

2There are some disagreements between ATLAS and CMS on which ones.

S. Mrenna Talk

*I didn’t pay him to put this on his slide...*
THERE’S MORE TO IT!

Production Cross Section Ratio: $\frac{\sigma_{\text{exp}}}{\sigma_{\text{theo}}}$
VISUAL “EVIDENCE”

>3 sigma by naive combination...

Theory:
NLO $q\bar{q} \rightarrow W^+ W^-$
$+ \quad gg \rightarrow W^+ W^-$

Generators:
MC@NLO, POWHEG, MG, MCFM, The Kitchen Sink
WW CROSS SECTION

• In principle the LHC makes 8 measurements highly sensitive to the WW cross section

  • SM WW at CMS7, ATLAS7, CMS8, ATLAS8

  • $h \rightarrow WW$ at CMS7, ATLAS7, CMS8, ATLAS8

• What’s the status?

  Every reported* measurement is higher than the SM
Control Region estimates at 8TeV-ATLAS

<table>
<thead>
<tr>
<th>Estimate</th>
<th>(N_{\text{obs}})</th>
<th>(N_{\text{bkg}})</th>
<th>(N_{\small\text{sig}})</th>
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<tbody>
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<td>(WW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N_{\text{jet}} = 0)</td>
<td>2224</td>
<td>1970 ± 17</td>
<td>31 ± 0.7</td>
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<tr>
<td>(N_{\text{jet}} = 1)</td>
<td>1897</td>
<td>1893 ± 17</td>
<td>1.9 ± 0.3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>(N_{\text{WW}})</th>
<th>(N_{\text{VV}})</th>
<th>(N_{\text{tt}})</th>
<th>(N_{t})</th>
<th>(N_{Z/\gamma^*})</th>
<th>(N_{W+\text{jets}})</th>
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</thead>
<tbody>
<tr>
<td>1383 ± 9.3</td>
<td>100 ± 6.8</td>
<td>152 ± 4.4</td>
<td>107 ± 4.3</td>
<td>68 ± 10</td>
<td>160 ± 3.6</td>
</tr>
<tr>
<td>752 ± 6.8</td>
<td>88 ± 5.5</td>
<td>717 ± 9.5</td>
<td>243 ± 6.7</td>
<td>37 ± 7.5</td>
<td>56 ± 2.5</td>
</tr>
</tbody>
</table>

NOT JUST THE SM GROUPS

Full luminosity @ 8 TeV!

Discrepancy **must** exist with full lumi when SM groups publish
**The Nobel Prize in Physics 2013**

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.”

**Control Region Estimates at 8 TeV-ATLAS**

<table>
<thead>
<tr>
<th>Estimate</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{bkg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{jet}} = 0$</td>
<td>2224</td>
<td>1970</td>
</tr>
<tr>
<td>$N_{\text{jet}} = 1$</td>
<td>1897</td>
<td>1893</td>
</tr>
</tbody>
</table>

**Table 4: Control Region Yields for 8 TeV Data**

For the ggF signal contribution in the $W^+W^-$ channel, the yield is 1383 events with 46 events expected. The composition of background is 127 events due to $Z\gamma^*$, 578 events from $VV$ processes, 117 events from $t\bar{t}$, 64 events from $W^+W^-$, and 21 events from $WW$. The total number of events is 184 events.

Discrepancy *must* exist with full lumi when SM groups publish.
WW CROSS SECTION

• In principle the LHC makes 8 measurements highly sensitive to the WW cross section
  • SM WW at CMS7, ATLAS7, CMS8, ATLAS8
  • $h \to WW$ at CMS7, ATLAS7, CMS8, ATLAS8

• What’s the status?

   **Every reported* measurement is higher than the SM**

   **NOT Bicep2 high... only a few sigma**
WW CROSS SECTION

• In principle the LHC makes 8 measurements highly sensitive to the WW cross section
  • SM WW at CMS7, ATLAS7, CMS8, ATLAS8
  • $h \rightarrow WW$ at CMS7, ATLAS7, CMS8, ATLAS8

• What’s the status?
  Every reported* that

NOT Bicep2 high...

Not astrophysics either...
Not just rate!
Looks pretty good...
CMS8

Doesn't look too bad?

Looks pretty good...
NO EXTRA NORMALIZATION...

I see what you did there.
WW → 2\ell 2\nu at 8 TeV: systematics & results

\begin{align*}
\sigma &= 69.9 \pm 2.8 \text{ (stat)} \pm 5.6 \text{ (sys)} \pm 3.1 \text{ (lum)} \text{ pb} \\
\text{NLO prediction (MCFM)}: &\quad 57.25 \left( +^{2.35}_{-1.60} \right) \text{ pb}
\end{align*}

- Already 4% statistical precision
- About 1.8\sigma higher than the NLO prediction

It grows at 8 TeV even faster!

\begin{align*}
\left( \frac{\sigma(8)}{\sigma(7)} \right)_{\text{th}} &= 1.21 \\
\left( \frac{\sigma(8)}{\sigma(7)} \right)_{\text{exp}} &= 1.33
\end{align*}
Upward fluctuations in all measurements or a trend?

If a trend... then what explains it??

SM calculation wrong

“Old QCD?”

New Physics

Need around a 20% effect on WW!!!
A LONG AND WINDING TALE...
INGREDIENTS FOR AN EXPLANATION

- Need to first understand what it MEANS to measure the WW cross section!

\[
\sigma_{WW} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{WW} \times A_{WW} \times \text{BR} \times \mathcal{L}}
\]

Total cross section

Count opposite sign dileptons + MET in a fiducial region with a jet veto and a few other requirements
INGREDIENTS FOR BSM EXPLANATION

• ATLAS and CMS both measure OS dileptons + MET with a jet VETO

• Final state needs to be OS leptons+MET with nothing else essentially

• Does NOT imply there have to be REAL W’s

• Need a cross section of a few pb!
EXAMPLE SUSY TOPOLOGIES FOR “WW” + MET

A few pb implies O(100) GeV surely this is ruled out???
EXAMPLE SUSY TOPOLOGIES FOR “WW”+MET

A few pb implies O(100) GeV surely this is ruled out???

PERFECTLY OKAY
$\chi^2$ cut in half compared to SM

BETTER THAN OKAY!
CHARGINOS FROM STRONG PRODUCTION?

\[ \tilde{t}_1 \rightarrow \tilde{\chi}^\pm_1 b \rightarrow \tilde{\chi}^0_1 W^{(*)} b \rightarrow \tilde{\chi}^0_1 \ell \nu b \]

Rolbiecki and Sakurai 1303.5696
Squeeze the b’s and you get WW production

Rolbiecki and Sakurai 1303.5696
TURNS OUT SLEPTONS FIT JUST AS WELL...

\[ 110 \text{ GeV} \quad \equiv \quad \tilde{e}, \tilde{\mu}, \tilde{\tau}_{L,R} \]

\[ 60 \text{ GeV} \quad \equiv \quad \chi_1^0 \]

\[ \tilde{l} \]

\[ \chi^\pm \]
SLEPTONS DO A LOT MORE!

Bino DM works with light sleptons - BLUE

g-2 anomaly - RED Dashed

WW improvement - RED contours

This model ALSO changes the interpretation of the Higgs!!

(b) $\tan \beta = 4$, $\mu = 600$ GeV
MANY MORE POSSIBILITIES

D. Curtin, PM, P. Tien (1406.xxxx tomorrow morning)

Figure 1: The four types of squeezed spectra which could account for the $WW$ excess via stop pair production. The top and bottom of the spectrum are at $\sim 200$ GeV and $\sim 100$ GeV, with $W$'s (green) being produced when decaying across the big gap in the spectrum. Small gaps are $\sim 10$ GeV. The 2-body decays of each state are shown as blue vertical arrows, with SM decay products on the right of each spectrum. The red color for $Z$ and $b$ indicates that these are not produced from stop pair production but from a different processes (direct $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production). The soft $b$'s (orange) should be practically undetectable.

3 Squeezed Scenarios

3.1 One Light Stop, $W$ from EWino

Refer to Fig. 2, also chargino 'signal' that might account for less-than-expected exclusion of chargino-neutralino search for both ATLAS and CMS

3.2 One Light Stop, $W$ from Stop

same preferred region as Fig. 2. refer to sbottom bounds Fig. 3. discussion that sbottom bounds can be evaded for small massgap. also make sure Br is 1 (easy)

3.3 Two Light Stops, $W$ from EWino

Refer to Fig. 4. don't care about higgs mass. sbottom bounds also apply. could modify sbottom bounds with sbottom mixing?

YOU CAN HAVE NATURAL SUSY AS ENVISIONED
SURELY YOU JEST??
Figure 2: Regions of the stop-neutralino mass-plane excluded and preferred by the different $W^+W^-$ cross section measurements in Scenario A (“One Light Stop, $W^+W^-$ from EWino”). We fix $m_{\tilde{t}_1} = \tilde{\chi}_1^\pm \lesssim 10$ GeV to avoid hard b-jets. Solid (dashed) orange line: 95% exclusion from the $W^+W^-$ measurement with fixed (floating) normalization of SM contribution. Thin blue contours show values of $m_{\tilde{t}^\pm}/m_{\tilde{t}^\mp}$, with the thick contour indicating the region most preferred by the $W^+W^-$ measurement. Exclusions from ATLAS stop searches shown in red [36] and green [12]. Observed (expected) exclusion from ATLAS trilepton search [29] shown as solid (dot-dashed) brown line: note how an excess compatible with the $W^+W^-$ preferred region pushes the observed bounds down in Bino mass.

(a) ATLAS 7 TeV 5 fb$^{-1}$ [18]

(b) CMS 7 TeV 5 fb$^{-1}$ [19]

(c) CMS 8 TeV 3.5 fb$^{-1}$ [20]
Figure 2: Regions of the stop-neutralino mass-plane excluded and preferred by the different $W^+W^-$ cross section measurements in Scenario A (“One Light Stop, $W$ from EWino”). We fix $m_{\tilde{t}} = \tilde{\chi}_1^0 = 10 \pm 1$ GeV to avoid hard b-jets. Solid (dashed) orange line: 95% exclusion from the $W^+W^-$ measurement with fixed (floating) normalization of SM contribution. Thin blue contours show values of $\frac{\sigma_{SM+\text{stops}}}{\sigma_{SM}}$, with the thick contour indicating the region most preferred by the $W^+W^-$ measurement. Exclusions from ATLAS stop searches shown in red [36] and green [12]. Observed (expected) exclusion from ATLAS trilepton search [29] shown as solid (dot-dashed) brown line: note how an excess compatible with the $W^+W^-$ preferred region pushes the observed bounds down in Bino mass.

Anomaly was based on OS dileptons

Somehow trileptons love light stops…?
CAVEATS OF COURSE

• Doesn’t account for Higgs Mass, but go to D-terms/NMSSM/model build

• Light stops will affect higgs couplings via loops! Status is still uncertain…

J. Fan, M. Reece
1401.7671
+ Private Comm.
MANY POSSIBILITIES...

- Charginos at $O(100)$ GeV
- Sleptons at $O(100)$ GeV
- Stops at $O(200)$ GeV
- All can improve the measurement of the WW cross section compared to the SM!!!!!!

- Consistent with other LHC Data
- Can explain DM/g-2
- Can give a natural SUSY spectra

It just seems easier to do than many other “excesses”

- $A_{FB}$, multi-muons, CDF $Wjj$
- CDF inclusive signal charged particle
TESTABLE CONSEQUENCES OF NEW PHYSICS

• Charginos lead to SS dileptons

• Sleptons lead to a flavor diagonal excess

• Stops eventually lead to higgs shifts/trileptons/soft b searches

• Important to note that all of these are NP signatures that IMPROVE on the SM as we know it…

• Other new physics can/is being hidden normally within error bars, even if the parameter space is cut it will be important to look at these possibilities that live in the “space beyond errors…”
SM/EXPERIMENTAL POSSIBILITIES???

- Backgrounds Wrong - Negligible effect?
- WW cross section wrong (k-factors 1.6ish need a 20% NNLO effect, not demonstrated in ZZ very recently)
  - higgs interferes destructively
  - EW NLO reduces as well
- Systematics

**WHY DOES** \( \sigma(pp \rightarrow ZZ) \) **AGREE?**
ZZ production at hadron colliders in NNLO QCD

F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi and E. Weihs

<2% effect...
HOW DO WE IMPROVE QCD PREDICTION?

• NNLO

• Resummation for WW

  • threshold  (S.Dawson et al 1307.3249)

  • pT resummation  (Grazzini 0510337, Wang et al, 1307.7520, PM, H. Ramani, M. Zeng to appear)

• jet veto
Age-old procedure

Resum large logarithms:

\[
\frac{d\sigma}{d\mathcal{O}} = (\alpha_s + \cdots) \exp \left[ \sum_n \left( \alpha_s^n \log^{n+1} \mathcal{O} + \alpha_s^n \log^n \mathcal{O} + \cdots \right) \right]
\]

Methods of resummation

Analytical Effective Theory Methods: Resummation by renormalization

Monte Carlo Parton Shower: Numerical approximation to all-orders matrix element

Whenever there’s factorization, there’s evolution, and whenever there’s evolution there’s resummation

G. Sterman
Given the jet veto, this *all* is dependent on soft QCD. Need this to get things right like W mass measurements (D0 used Collins, Soper, Sterman formalism to attain precision).
### Differences w/ Parton Shower

**ResBos Website**

<table>
<thead>
<tr>
<th>Analytical $Q_T$ resummation</th>
<th>Parton showering programs (Pythia, MC@NLO, Sherpa...)</th>
</tr>
</thead>
<tbody>
<tr>
<td>● evaluate(s) effects of multiple parton radiation in hadronic scattering</td>
<td>● apply to a wide range of observables; exclusive with respect to hadronic radiation</td>
</tr>
<tr>
<td>● applies to a restricted class of processes and observables (e.g., lepton distributions in Drell-Yan-like processes); inclusive with respect to hadronic radiation</td>
<td>● no factorization proofs for individual observables</td>
</tr>
<tr>
<td>● is proved to all orders in the QCD coupling by special factorization theorems devised for each qualified observable</td>
<td>● beyond the leading order, radiative contributions and high-$p_T$ tails may be difficult to implement</td>
</tr>
<tr>
<td>● streamlined computation of higher-order corrections and high-$p_T$ contributions</td>
<td>● modern showering programs approach NLO accuracy</td>
</tr>
<tr>
<td>● NLO $Q_T$ resummation formulated in 1979-1997; modern $Q_T$ resummation approaches NNLO accuracy</td>
<td>● resummation of leading logarithms $ln \frac{Q_T^2}{Q^2}$</td>
</tr>
<tr>
<td>● resummation of all logarithms $ln \frac{Q_T^2}{Q^2}$</td>
<td>● nonperturbative scattering is evaluated in one of several available models</td>
</tr>
<tr>
<td>● nonperturbative contributions are constrained by invoking their universality in the considered class of processes</td>
<td>● more flexible; more parameters to tune to describe various hadronic scattering effects</td>
</tr>
<tr>
<td>● more strict and precise; relies on first principles of perturbative QCD</td>
<td></td>
</tr>
</tbody>
</table>

Transverse momentum resummation changes **shape** not **cross section**!
CAN’T DO THIS SOLELY ANALYTICALLY - FIDUCIAL CROSS SECTION

\[ \sigma_{fid} = \sigma_{total} \epsilon \cdot A \cdot Br \]

However if resummation causes a shape difference…

Full Phase-space. Both curves Normalized to unity.

Shape effect translates to different Fiducial cross-section
There are various different ways to do transverse momentum resummation, typically you don’t work in $q_T$ you work in “$b$” space - problem is how to deal with small $q_T$

- Work in $q_T$ space directly in some approx (Dokshitzer and others)
- CSS formalism - cut off $b$ space softly (ResBos uses this)
- CDG formalism - play with contour integral in $b$ space
- others as well
CAN GET LARGE SHAPE DIFFERENCES FROM MATCHING IN RESUMMATION

- We use CDG formalism, in this there is a matching/resummation scale $Q$ between fixed order and resummation

\[ \frac{d\sigma}{dq_T} \] [pb/GeV]

**Q variation more important than hard scale**

PM, H. Ramani, M. Zeng 1406.xxxx

Implemented at approx NNLL+LO
THE PROBLEM WITH TRANSVERSE MOMENTUM RESUMMATION AND COLLIDERS

• We don’t have events, we’ve summed over all our gluons!

• There isn’t an “unfolded” $WW$ pt from experiments

• Have to come up with a proxy to get to fiducial cross section… come up with proxy, reweight MC events a la the Higgs group to see if underlying differences persist!
## Fiducial Cross Section Effects Example

### Cut-flow vs reweighted events

<table>
<thead>
<tr>
<th>Cut</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>exactly 1 pair of oppositely charged leptons +MET</td>
<td>0</td>
</tr>
<tr>
<td>$p_t$ and $\eta$ cuts on leptons</td>
<td>0.06%</td>
</tr>
<tr>
<td>mll cuts</td>
<td>-0.32%</td>
</tr>
<tr>
<td>$E_{TMiss,rel}$</td>
<td>1.16%</td>
</tr>
<tr>
<td>Jet Veto</td>
<td>8.37%</td>
</tr>
<tr>
<td>$pTll$</td>
<td>8.50%</td>
</tr>
</tbody>
</table>
Transverse Momentum Resummation can have an effect, but it should be UNIVERSAL…

<table>
<thead>
<tr>
<th>MC</th>
<th>Percentage Increase Q=mW/2</th>
<th>Percentage Increase Q=mW</th>
<th>Percentage Increase Q=2mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powheg+Pythia</td>
<td>4.05</td>
<td>0.16</td>
<td>-5.35%</td>
</tr>
<tr>
<td>aMC@NLO +Herwig</td>
<td>8.50</td>
<td>2.98</td>
<td>-0.82</td>
</tr>
<tr>
<td>Madgraph +Pythia</td>
<td>-1.13</td>
<td>-5.94</td>
<td>-8.88</td>
</tr>
</tbody>
</table>
The agreement between PowHEG and ZZ is very good. 

Correlation then with PowHEG and resummation in WW is crucial.
EXPLORING JET VETO EFFECTS DIRECTLY?

• Jet veto scale ~25-30 GeV introduces a new scale in the problem, and hence logs

• A number of groups have investigated this for Higgs/Drell-Yan
  Banfi, Salam, Zanderighi/Stewart, Tackmann, Walsh, Zuberi and others

• This should be studied directly for SM WW
  • Similar to Banfi et al 1203.5773 comparison between HqT and jet vetoes
CONCLUSIONS...

• There could be BSM right around the corner: understand WW!!!!

• Charginos, Sleptons, Stops all can fit better than the SM, or certainly exist at low energies!!!!!!!!!!!

• Can also set new bounds better than experimentalists using SM cross sections! 1304.7011

• Important to get QCD predictions/MC as accurate as possible to push back on experimentalists

  • Transverse momentum resummation can have an effect on WW, but it can go both ways, and we have to understand the best scale choice

  • jet veto resummation or joint pt/eta resummation would be useful to investigate

• Experimentalists need to care just as much about background shapes as signal

• Crucially important to get EW scale correct before pushing higher, as it can have serious implications for Higgs physics! Experimentalists also tend not to revisit things…