Beyond Supersymmetry

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Wilhelm und Else Heraeus-Seminar
9.-12. December 2012
Physikzentrum Bad Honnef

ATLAS EXPERIMENT
Run Number = 189288
Event Number = 2779906
Z(ee)+jet mass = 1858.8 GeV

leading jet

associated jet

electrons

Leading electron pT = 485.1 GeV
Second electron pT = 335.1 GeV
Leading jet pT = 905.8 GeV
Associated jet pT = 96.5 GeV
Why look beyond Supersymmetry (SUSY)?

- SUSY is only one possible model among many others.
  - Many more ways to solve problems with Standard Model
  - What if nature has not chosen SUSY?
  - Make sure to cover every feasible corner…

- SUSY mass limits pushed to 1 TeV
  - SUSY becoming more “Exotic” the higher the mass limits get.
What Characterizes Exotics Searches?

- No specific Model to guide us.
- No unified parameter phase space to map results
What Characterizes Exotics Searches?

- Exotics Search Strategy
  - Cover wide range of final states
  - Largely Model independent
    - Look for resonances
    - Look for any disagreement from expectations
  - Cover interesting new BSM models

Poster: S. Beranek, et al.
The Role of Models in “most” Exotics Searches

Toscanelli’s model of the geography of the Atlantic Ocean, which directly influenced Columbus’s plans

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The Role of Models in “most” Exotics Searches

Columbus’ voyages
The Role of Models in “most” Exotics Searches

- Models used to quantify our reach.
  - How far did we get?
  - How do we compare to previous searches?
- We use so called Bench Mark Models
  - Used before by other experiments
  - Add new features: wider widths
- Simplified Models or generic resonances
Basic Principles of a Search

- Most important: Robust background estimation!
  - Data-driven
  - Use background MCs
  - Use data to normalize in control regions MCs

- Biases?
  - Fully blind not a realistic approach for Exotics searches
  - Need to think beforehand about control regions
  - Need to think beforehand about how to minimize bias.

- Trade-off between Signal and Background
  - Do NOT optimize towards a specific model
  - Selection cuts defined by triggers and background reduction.
Basic Principles of a Search

- You have a background estimate…what now?
- Check if data agrees with this expectation.
- If it does not agree…
  - Is the significance increasing with more data?
  - Look at time dependences…
  - Cross checks….
  - Discovery if significance is greater than 5 sigma.
- If it does agree…
  - How far did we explore the new physics phase?
  - Use Bench Mark models to quantify the search reach.
  - Make sure to publish also the acceptance for these models such that theorists can use your results to test other models.
Comment to Search Result Selection in this Talk

“What is the impact of the newly discovered boson on Exotics searches at the LHC?”

8 TeV Results
Exotics Searches

- Heavy resonances
  - Dileptons
  - Dijets
  - Ttbar

- 4th gen quarks and vector-like quarks

- Dark matter and extra dimension

- Displaced muonic lepton jets from light higgs
CMS Highest Dimuon Invariant Mass Event; 8 TeV

\[ m_{\text{inv}} = 1418 \text{ GeV} \]
Heavy Resonances Search: 8 TeV Dileptons

- Models:
  - Randall-Sundrum ED → Kaluza-Klein graviton
  - GUT-inspired theories, Little Higgs → heavy gauge boson(s)
  - Technicolor → narrow technihadrons

- Leptons reaching $p_T \sim 1$ TeV

Poster: Sarah Heim
Heavy Resonances Search: 8 TeV Dileptons

ATLAS-Electron selection
- diphoton trigger
- $E_{T}^{1} > 40$ GeV Use && $E_{T}^{2} > 30$ GeV
- $|\eta| < 2.47$, excluding crack regions
- Cluster ID cuts
- Leading electron isolated
  - $(\sum E_{T} - E_{T}^{1}) |_{|\Delta R|<0.2} < 7$ GeV
  - Reject jets faking electrons
- Require pixel hit
  - Rejects photon conversions
  - $A^{*}\varepsilon(Z \rightarrow ee, m=2$ TeV) $\sim 70\%$

CMS-Electron selection
- Use dielectron trigger
- $E_{T}^{1,2} > 30$ GeV
- $|\eta| < 2.5$, excluding crack regions
- Cluster ID cuts
- Leading electron isolated
  - $(\sum P_{T} - P_{e_{T}}) |_{|\Delta R|<0.3} < 5$ GeV
  - $(\sum E_{T} - E_{e_{T}}) |_{|\Delta R|<0.3} < 3\% E_{e_{T}}$
  - $E_{Hcal}/E_{ECAL} |_{|\Delta R|<0.15} < 5\%$
  - $A^{*}\varepsilon(Z \rightarrow ee, p_{T}=100$ GeV) $\sim 90\%$
Heavy Resonances Search: 8 TeV Dileptons

Backgrounds

- **SM Drell-Yan:** $\gamma^*/Z \rightarrow l^+l^-$
  - shape taken from Monte Carlo
  - normalisation taken from Z peak in data

- **t-tbar:**
  - where $tt$ goes to $e^+e^-, \mu^+\mu^-$
  - est. from MC, cross-checked in data
  - also includes $Z \rightarrow \tau\tau$, $WW$, $WZ$

- **Jet Background:**
  - di-jet, $W$+jet events where the jets are misidentified as electrons/muons

- **Cosmic Ray Background:**
  - muons from cosmic rays
  - estimated <0.1 event after vertex and angular difference requirements

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Heavy Resonances Search: 8 TeV Dileptons

Backgrounds

<table>
<thead>
<tr>
<th>Source</th>
<th>Dimuon sample</th>
<th>Dielectron sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(120 – 200) GeV</td>
<td>&gt;200 GeV</td>
</tr>
<tr>
<td>Data</td>
<td>13831</td>
<td>3503</td>
</tr>
<tr>
<td>Total background</td>
<td>13007 ± 589</td>
<td>3627 ± 160</td>
</tr>
<tr>
<td>(Z/\gamma^*)</td>
<td>11703 ± 571</td>
<td>2919 ± 139</td>
</tr>
<tr>
<td>(t\bar{t} + ) others</td>
<td>1278 ± 146</td>
<td>698 ± 78</td>
</tr>
<tr>
<td>jets</td>
<td>26 ± 3</td>
<td>10 ± 1</td>
</tr>
</tbody>
</table>

No deviation from expectation found.
Heavy Resonances Search: 7+8 TeV Dileptons

\[ R_{\sigma}^{8 \, \text{TeV}} = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)} \]

CMS preliminary

8 TeV: ee (3.6 fb\(^{-1}\)) + \mu^+\mu^- (4.1 fb\(^{-1}\)), 7 TeV: ee (5.0 fb\(^{-1}\)) + \mu^+\mu^- (5.3 fb\(^{-1}\))

\[ m(\text{SSM } Z') > 2.59 \text{ TeV at 95\% CL} \]
Heavy Resonances Search: 8 TeV Dileptons

- No deviation from SM found → set limits

\[ m(\text{SSM } Z') > 2.49 \text{ TeV at 95\% CL} \]

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Many models possible

- right-handed $W'$ bosons with standard-model couplings
- left-handed $W'$ bosons including interference
- Kaluza-Klein $W'_{\text{KK}}$-states in split-UED
- Excited chiral boson ($W^*$)

Event Selection and Backgrounds

- back-to-back isolated lepton and $E_T^{\text{miss}}$
- Plot transverse mass of $\ell \nu$ system
- backgrounds from $W$, QCD, $tt+$single $t$, DY, VV from data

$$M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta \phi_{\ell,\nu})}$$
W' → ℓν in 8 TeV Data

<table>
<thead>
<tr>
<th>M(W'_{SSM}) 95% CL</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS e+µ, 2011, 4.7fb⁻¹</td>
<td>&gt; 2.55 TeV</td>
<td>&gt; 2.55 TeV</td>
</tr>
<tr>
<td>CMS e+µ, 2012, 3.7fb⁻¹</td>
<td>&gt; 2.80 TeV</td>
<td>&gt; 2.85 TeV</td>
</tr>
<tr>
<td>CMS e+µ, 2011+2012, 5.0+3.7 fb⁻¹</td>
<td>&gt; 2.85 TeV</td>
<td>&gt; 2.85 TeV</td>
</tr>
</tbody>
</table>

M(W'_{SSM}) > 2.85 TeV 95% CL

[ATLAS hep-ex 1209.4446]
[CMS PAS EXO-12-010]
Dijet Event Display with $m_{\text{inv}} = 4.69$ TeV

$p_T = 2.29$ TeV

$p_T = 2.19$ TeV
Heavy Resonance Search: 8 TeV Dijets

- Strong gravity, excited quarks
- Selections
  - Two anti-kt 0.6 jets
  - $p_T > 150$ GeV $\&\& m_{jj} > 1$ TeV
  - $|y| < 2.8$ $\&\&$ dijet CM rapidity $|y^*| < 0.6$, $y^* = \pm 0.5(y_1 - y_2)$
  - Look for resonance above phenomenological fit of data

$$f(x) = p_1 (1 - x)^{p_2} x^{p_3} + p_4 \ln x$$

$$x \equiv m_{jj} / \sqrt{s}$$

Probing quark structure ~ 5 TeV

ATLAS-CONF-2012-148
Heavy Resonance Search: 8 TeV Dijets

- Good agreement btw data and fit.
  - Global $\chi^2$/NDF=15.5/18 = 0.86 → p-value = 0.61
  - good agreement btw data and fit
  - Bump Hunter
Heavy Resonance Search: 8 TeV Dijets

Gaussian resonance limits: mean mass, $m_G$, and $3\sigma_G$

Excited quark limit: $m > 3.84$ TeV at 95% CL
Heavy Resonance Search: 8 TeV Dijets

- Uses particle flow jets $R=0.5$
- $p_T > 30$ GeV, $|\eta| < 2.5$
- combines particle-flow jets into "wide jets" with $R = 1.1$
- two wide jets satisfy
  - $|\eta_{jj}| < 1.3$
  - $|\eta| < 2.5$
  - $M_{jj} > 890$ GeV
Heavy Resonance Search: 8 TeV Dijets

Pythia D6T + CMS Simulation

- $RSG \rightarrow qq$ 8 TeV
- $RSG \rightarrow gg$ 8 TeV
- $q^* \rightarrow qg$ 8 TeV

$M_{jj}$ [GeV]
Heavy Resonance Search: 8 TeV Dijets

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Search for Heavy Resonance: Dijet Angular

Lab frame

\[ y_c \]

\[ y_d \]

Centre-of-mass frame

\[ y^* = \frac{1}{2}(y_c - y_d) \]

\[ -y^* \]

\[ \bar{\theta} \]

Boost

\[ y_{\text{boost}} = \frac{1}{2}(y_c + y_d) \]

t-channel Spin-1 exchange

\[
\frac{d\hat{\sigma}}{d(\cos \hat{\theta})} \propto \sin^{-4}(\hat{\theta}/2)
\]

\[
\chi = \frac{1 + |\cos \hat{\theta}|}{1 - |\cos \hat{\theta}|} \sim \frac{1}{1 - |\cos \hat{\theta}|} \propto \frac{\hat{s}}{\hat{t}}
\]

\[
\frac{d\hat{\sigma}}{d\chi} \propto \frac{\alpha_s^2}{\hat{s}} \quad (\hat{s} \text{ fixed}) \quad \hat{s} = m_{jj}
\]

Constant in \( \chi \) for fixed \( m_{jj} \)
Search for Heavy Resonance: Dijet Angular

QCD is a bit more complicated.....
Search for Heavy Resonance: Dijet Angular

\[ \sqrt{s} = 7 \text{ TeV} \]

- **QCD** ~ flat in \( \chi \)

- **low** \( M_{jj} \) gg and qg dominate
- **high** \( M_{jj} \) qq dominate

**Andreas Dominik Hinzmann**

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Search for Heavy Resonance: Dijet Angular

arXiv:1210.1718
Search for Heavy Resonance: Dijet Angular

\[ F_\chi(m_{jj}) \equiv \frac{dN_{\text{central}}/dM_{jj}}{dN_{\text{total}}/dM_{jj}}, \]

Models and Limits:
- Quark contact interaction (quark compositeness)
  - \( \Lambda > 7.6 \text{ TeV} \) (7.7 TeV)
- Quantum Blackholes
  - \( M_D > 4.1 \text{ TeV} \) (4.2 TeV) \( n=6 \)
Boosted Top Event Candidate with $m_{\text{ttbar}}=2.5$ TeV
Top Reconstruction @ LHC: 3 Regimes

At rest: $M_{tt} < 500\,\text{GeV}$

Transition region: $500\,\text{GeV} < M_{tt} < 700\,\text{GeV}$

Mono-jet: $M_{tt} > 700\,\text{GeV}$

M. Villaplana (IFIC) - Boost2012 - Valencia

ATL-PHYS-PUB-2008-010
Heavy Resonances Search: Ttbar

- Lepton+jets channel
- Models: e.g. bulk-RS (esp. KK gluons) and Leptophobic Z’
  - Large Branching Ratio to top-antitop
- Taking full advantage of boosted techniques
- Combining resolved and boosted reconstructions

![Graphs showing reconstructed t\bar{t} mass vs. fraction of events for different mass values.](image)
### Event Selection

<table>
<thead>
<tr>
<th></th>
<th>resolved</th>
<th>boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>trigger</strong></td>
<td>single lepton trigger</td>
<td>fat jet (AKT10) trigger</td>
</tr>
<tr>
<td><strong>leptons</strong></td>
<td>1 lepton (e$^\pm$ or $\mu^\pm$), $p_T &gt; 25$ GeV</td>
<td>additional lepton (e$^\pm$ or $\mu^\pm$) veto, $p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lepton trigger match</td>
</tr>
<tr>
<td>$E_T$</td>
<td>e$^\pm$: $E_T &gt; 30$ GeV, $\mu^\pm$: $E_T &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td>$m_T^W$</td>
<td>e$^\pm$: $M_T(W) &gt; 30$ GeV, $\mu^\pm$: $M_T(W) + E_T &gt; 60$ GeV</td>
<td></td>
</tr>
<tr>
<td><strong>jets</strong></td>
<td>$\geq 4(3)$ jets</td>
<td>“leptonic jet”: AKT4 jet</td>
</tr>
<tr>
<td></td>
<td>(if one jet $m_{jet} &gt; 60$ GeV)</td>
<td>“hadronic jet”: AKT10 jet</td>
</tr>
<tr>
<td><strong>b-tag</strong></td>
<td>$\geq 1$ b-tag using AKT4 jets ($\varepsilon_b = 70%$)</td>
<td></td>
</tr>
</tbody>
</table>
Heavy Resonances Search: Ttbar

- Improve efficiency at high t-tbar mass with:
  - Lepton “mini-isolation”:
    - cone shrinks at high momentum
  - Trigger:
    - use Fat Jet trigger (anti-kt jet R=1.0, pT>240 GeV)
    - Better efficiency than lepton trigger at high mass

- Combine resolved and boosted selection:
  - If event is reconstructed by both methods, use the boosted one (better mass resolution)
Heavy Resonances Search: Ttbar

\[ \int L = 4.66 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV} \]

ATLAS Preliminary

Boosted selection

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Heavy Resonances Search: Ttbar

- \( m_{\tilde{t}\tilde{t}} \)-resolved + boosted in e+jets and \( \mu+jets \)
Heavy Resonances Search: Ttbar

- $m(Z') > 1.7 \text{ TeV}\ @95\% \ CL$
- $\Gamma/m(Z') = 1.2\%$

- $m(g_{KK}) > 1.9 \text{ TeV}\ @95\% \ CL$
- $\Gamma/m(g_{KK}) = 15\%$

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Heavy Resonance Search: $t\bar{t}$bar hadronic channel

CMS, $L = 5$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV

$m_{W}^{\text{DATA}} = 83.0 \pm 0.7$ GeV/c$^2$

$m_{W}^{\text{MC}} = 82.5 \pm 0.3$ GeV/c$^2$

- Data
- $t\bar{t}$
- $W+$Jets
- Non-W MJ
- Data fit
- MC fit

CMS, $L = 5$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV

Observations (95% CL)

Expected (95% CL)

$\pm$ 1 s.d. Expected

$\pm$ 2 s.d. Expected

$Z'$, 1.2% width, Harris et al

$Z'$, 3.0% width, Harris et al

$Z'$, 10.0% width, Harris et al
## 4th Generation and Heavy Quarks

<table>
<thead>
<tr>
<th>Quarks</th>
<th>u</th>
<th>c</th>
<th>t</th>
<th>t'</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
<td>b'</td>
<td></td>
</tr>
<tr>
<td>Leptons</td>
<td>(\nu_e)</td>
<td>(\nu_\mu)</td>
<td>(\nu_\tau)</td>
<td>(\nu')</td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>(\mu)</td>
<td>(\tau)</td>
<td>(\tau')</td>
</tr>
</tbody>
</table>

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Fine-Tuning Problem in Electromagnetism

\[(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}\]

\[\Delta E_{\text{Coulomb}} = \frac{1}{4\pi \varepsilon_0} \frac{e^2}{r_e},\]

\[r_e \lesssim 10^{-17} \text{ cm} \quad \implies \quad \Delta E \gtrsim 10 \text{ GeV}\]

\[0.511 = -9999.489 + 10000.000 \text{ MeV}\]

Fine tuning!

Murayama hep-ph/9410285
Fine-Tuning Problem in Electromagnetism

- Picture not complete:
  - Positron cancels \(1/r_e\) term
  - New symmetry:
    - particle/anti-particle

\[
(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} \left[ 1 + \frac{3 \alpha}{4 \pi} \log \frac{\hbar}{m_e c r_e} \right]
\]

- Correction to bare mass becomes small
Supersymmetry

- Same problem with Higgs

\[ \Delta \mu_{\text{top}}^2 = -6 \frac{h_t^2}{4\pi^2} \frac{1}{r_H^2} \sim (100 \text{ GeV})^2 \]

125 GeV = (huge number) - (huge number) even more fine tuned!

Add new particles (spin symmetry): SUSY

\[ \Delta \mu_{\text{stop}}^2 + \Delta \mu_{\text{top}}^2 = -6 \frac{h_t^2}{4\pi^2} (m_{\tilde{t}}^2 - m_{\tilde{t}}^2) \log \frac{1}{r_H^2 m_{\tilde{t}}^2} \]
But there is another way….look at QCD

Pion mass is not divergent.

Why?

It is a composite particle!

Assume Higgs is a composite particle

- Changes couplings
- Introduces new partners to top quarks
- Vector-like quarks…
- Solves fine-tuning problem….
4th Generation and Heavy Quarks

- 4th generation would significantly enhance Higgs production cross section
  - (almost) excluded by observed Higgs cross-section
  - $t't' \to WbWb$ (100%): just like $t\bar{t}$ but heavier
  - $b'b' \to WtWt$ (100%): just like $t\bar{t}$ but messier

- Beyond 4th generation: Vector-Like Quarks in Composite Higgs theories
  - More diverse phenomenology
  - $T'$: Decays to $Wb, Zt, Ht$
  - $B'$: Decays to $Wt, Zb, Hb$

- Loose constraints on $\text{CKM4} \to$ decays to light quarks possible!
Search for Heavy Quarks

- Up-type heavy quark: $t't' \rightarrow WbWb$
- $l + M_{E_T} + 4 \text{ jets (}\ell=e,\mu) + b\text{-tagging}$
- Reconstruct boosted had. $W$ decays

$m(t') > 656\text{GeV at 95}\% \text{ CL (exp. 638GeV)}$
Vector-like Quarks Coupling to Light Generations

- Mixing to first generations is not excluded
- Benchmark model: degenerate VLQ doublets \((U^{2/3}, Y^{2/3}, D^{-1/3}, X^{5/3})\)
- Single Production
- \(e\) and \(\mu\) channel

\[
\begin{align*}
\text{m}(D^{-1/3}) &> 1120\text{GeV}, \\
\text{m}(X^{5/3}) &> 1420\text{GeV}, \\
\text{m}(U^{2/3}) &> 1080\text{GeV} \quad \text{(not shown)}
\end{align*}
\]
Exotic Same-Sign Dilepton Signatures: $b'$, $T_{5/3}$

- 2 isolated same-sign leptons ($e$ or $\mu$)
- $M_{T} > 40$ GeV
- $\geq 2$ jets ($\geq 1$ b-tagged jet)
- Large overall transverse momentum
  - $H_{T} > 550$ GeV

4 events observed

Expected background of 5.6±1.7

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Exotic Same-Sign Dilepton Signatures: $b', T_{5/3}$

ATLAS-CONF-2012-130

$\sigma [pb] \times BR(b'\rightarrow tW)$

$\int L dt = 4.7 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

$m(b'/T_{5/3}) > 0.67 \ (0.64) \ \text{TeV}$

at 95% confidence level, when produced in pairs
Inclusive Same-Sign Dilepton Search

- Model independent approach
  - Limit presented in terms of fiducial cross-section limit

\[ \sigma_{95}^{\text{fid}} = \frac{N_{95}}{\varepsilon_{\text{fid}} \times \int L dt} \]

95% CL upper limit on yield (given \( N_{\text{obs}} \) and \( N_{\text{bkg}} \))

- \( \sigma^{\text{fid}} \) is (almost) model-independent
- Can turn \( \sigma^{\text{fid}} \) into \( \sigma^{\text{total}} \) with generator-level information only
- Caveat: not exactly model-independent → must be conservative

Reconstruction and Selection efficiency
Within acceptance

\[
\begin{array}{|c|c|c|}
\hline
\text{Leading lepton } p_T & p_T > 25 \text{ GeV} & p_T > 20 \text{ GeV} \\
\text{Sub-leading lepton } p_T & p_T > 20 \text{ GeV} & p_T > 20 \text{ GeV} \\
\text{Lepton } |\eta| & |\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.47 & |\eta| < 2.5 \\
\text{Isolation} & p^{\text{cone0.3}}_T / p_T < 0.1 & p^{\text{cone0.4}}_T / p_T < 0.06 \text{ and } p^{\text{cone0.4}}_T < 4 \text{ GeV} + 0.02 \times p_T \\
\hline
\end{array}
\]
Inclusive Same-Sign Dilepton Search

$\int L dt = 4.7 \, fb^{-1}$
\(\sqrt{s} = 7 \, TeV\)

$e^+e^-$

$\mu^+\mu^-$
Inclusive Same-Sign Dilepton Search

- 95% upper limits
  - 1.7 fb and 64 fb

<table>
<thead>
<tr>
<th>Mass range</th>
<th>e^+e^-</th>
<th>e^+μ^-</th>
<th>μ^+μ^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>m &gt; 15 GeV</td>
<td>23.2^{+8.6}_{-5.8}</td>
<td>25.7</td>
<td></td>
</tr>
<tr>
<td>m &gt; 100 GeV</td>
<td>12.0^{+5.3}_{-2.8}</td>
<td>18.7</td>
<td></td>
</tr>
<tr>
<td>m &gt; 200 GeV</td>
<td>4.9^{+1.9}_{-1.2}</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>m &gt; 300 GeV</td>
<td>2.9^{+1.0}_{-0.6}</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>m &gt; 400 GeV</td>
<td>1.8^{+0.8}_{-0.4}</td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>

Fiducial cross section upper limits

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Models explaining non-zero neutrino masses predict $H^{++/-}$
- e.g. minimal type II seesaw model
  - additional scalar field
  - triplet (under $SU(2)_L$ with $Y=2$): $H^{++/-}, H^{+/0}$

**Signature: same-sign leptons**
Doubly Charged Higgs Limits

- Used e.g. limits on doubly charged Higgs

\[ \sigma(pp \rightarrow H^{++} H^{--}) \times BR(H^{++} \rightarrow e^+e^-) \]

- Pair production: \( M(H^{++/-}) > 409 \text{ GeV} \)

**ATLAS**

\[ \int L dt = 4.7 \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

\[ m(H^{++}) \] [GeV]
Doubly Charged Higgs Limits

- Example of more optimized search
- Includes also $\tau$-channel and associate production.

Combined $e\mu$: $M(H^{++/\pm \pm}) > 455$ GeV
Combined $\tau\tau$: $M(H^{++/\pm \pm}) > 198$ GeV

arXiv:1207.2666
Mono Jet Event Display

Run Number: 189090, Event Number: 2069763
Date: 2011-09-10 17:17:48 CEST
Search for Dark Matter and Extra Dimensions

Mono jet

Mono photon

Analyses are not optimized for benchmark models
Mono jet & Mono Photon Limits on Extra Dimensions

**Mono jet**

**Mono photon**
Effective theory with only 2 parameters
- $M^*$: characterize interaction strength of the interactions with SM particles
- $m_\chi$: mass of dark matter candidate

Pair production of DM:
- Events with $M_{E_T}$, recoiling against additional hadronic radiation
DM-nucleon scattering cross sections

**Mono jet analysis**

limits competitive with than limits by direct and indirect experiments

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DM-nucleon scattering cross sections

Mono photon analysis

90% CL, Spin Dependent
- SIMPLE
- CDF, D8, $q\bar{q} \to j(\chi\chi)_{\text{Dirac}}$
- CMS (5 fb$^{-1}$), D8, $q\bar{q} \to \gamma(\chi\chi)_{\text{Dirac}}$
- Picasso

90% CL, Spin Independent
- XENON100
- CDMS
- CDF, D5, $q\bar{q} \to j(\chi\chi)_{\text{Dirac}}$
- CoGeNT
- CMS (5 fb$^{-1}$), D5, $q\bar{q} \to \gamma(\chi\chi)_{\text{Dirac}}$
- ATLAS, D5, $q\bar{q} \to \gamma(\chi\chi)_{\text{Dirac}}$
- ATLAS, D1, $q\bar{q} \to \gamma(\chi\chi)_{\text{Dirac}}$

**ATLAS** \( \sqrt{s} = 7 \text{ TeV}, \int L dt = 4.6 \text{ fb}^{-1} \)

\[10^{-45} \quad 10^{-44} \quad 10^{-43} \quad 10^{-42} \quad 10^{-41} \quad 10^{-40} \quad 10^{-39} \quad 10^{-38} \quad 10^{-37} \quad 10^{-36} \quad 10^{-35} \quad 10^{-34} \quad 10^{-33} \]

\[1 \quad 10 \quad 10^2 \quad 10^3 \quad 1 \quad 10 \quad 10^2 \quad 10^3 \]

\[m_\chi \text{ [GeV]} \quad m_\chi \text{ [GeV]} \]
Search for long-lived neutral particles

- Limits on
  - \( H \rightarrow \) hidden-sector neutral long-lived particles
  - Focus on 100 GeV to 140 GeV mass range
    - Derive constraints on additional Higgs-like bosons
    - placing bounds on BR of discovered 126 GeV resonance into a hidden sector

- Relevant for other distinct models
  - heavier Higgs boson doublets,
  - singlet scalars
  - Z’ that decay to a hidden sector

arXiv:1210.0435
Displaced Muonic Lepton Jets from Light Higgs

- Neutral particles
  - with large decay lengths
  - with collimated final states
  - challenge for the trigger and for the reconstruction

<table>
<thead>
<tr>
<th>Higgs boson mass [GeV]</th>
<th>excluded $c\tau$ [mm] $\text{BR}(100%)$</th>
<th>excluded $c\tau$ [mm] $\text{BR}(10%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$1 \leq c\tau \leq 670$</td>
<td>$5 \leq c\tau \leq 159$</td>
</tr>
<tr>
<td>140</td>
<td>$1 \leq c\tau \leq 430$</td>
<td>$7 \leq c\tau \leq 82$</td>
</tr>
</tbody>
</table>

arXiv:1210.0435
ATLAS Exotics Summary

Limits pushed into 1 TeV regime

Extra dimensions
Contact interaction
Heavy gauge bosons
Lepto quarks
New quarks
Excited fermions
Other

C. Issever, University of Oxford
Conclusion (1)

- New Physics BSM was not “around the corner”...
  ... unless the Higgs is not a SM Higgs...
  - Continue exploration **beyond TeV regimes**
  - Push $\sigma$-limits at **low invariant masses** down.

- Role of models in Exotics
  - Models are used map our search reach
  - They give us some guidance where to look
  - But, Exotics searches are mainly model-independent.

- Exotics searches coverage
  - Vast range of final states
  - Vast range of models
Conclusion (2)

- Exotics searches will continue broad range of searches
  - Technicolor and SM4 are in trouble.
  - Most other models live well with a light Higgs.
- Interesting searches after Higgs boson discovery
  - Invisible Higgs: $Higgs \rightarrow LSP's$ (cf monojet analysis) interesting
  - Higgs to exotic objects.
    - E.g. Hidden Valley dark photon $\rightarrow LLP's$ or leptonjets arXiv:1210.0435
  - From now on we must consider heavy particle decays to Higgs systematically (esp. Heavy Quarks, e.g. $t' \rightarrow tH$)
Backup Slides
Z’ in 2011 Data?

- Interesting features in dilepton spectra
  - around $2\sigma$ each for CMS & ATLAS in $e+\mu$
  - similar in scale to 2011 Higgs excess

[ATLAS hep-ex 1209.2535]
[hep-ex 1206.1849]
“Although the results of this analysis are interpreted in terms of the ADD model and WIMP pair production, the event selection criteria have not been tuned to maximise the sensitivity to any particular BSM scenario. To maintain sensitivity to a wide range of BSM models, four sets of overlapping kinematic selection criteria, designated as SR1 to SR4, are defined (table 2).”
Limits on Dark Matter – Mono Jet

90% CL lower limits on $M^*$

$\sqrt{s} = 7$ TeV

$\int Ldt = 4.7$ fb$^{-1}$

$M^*$ at which WIMPs of a given mass result in required relic abundance

Operator D1, SR3, 90%CL

- Expected limit ($\pm 1\sigma_{\text{exp}}$)
- Observed limit ($\pm 1\sigma_{\text{theory}}$)
- Thermal relic

convert
Limits on the annihilation rate of WIMPs

**ATLAS**

\( \sqrt{s} = 7 \text{ TeV}, 4.7 \text{ fb}^{-1}, 95\% \text{CL} \)

- 2 \times (\text{Fermi-LAT dSphs} (\chi\chi)_{\text{Majorana}} \rightarrow b\bar{b})
- D5: \text{q}\bar{q} \rightarrow (\chi\chi)_{\text{Dirac}}
- D8: \text{q}\bar{q} \rightarrow (\chi\chi)_{\text{Dirac}}
- \sigma_{\text{theory}}$

**Annihilation rate** \(\langle \sigma v \rangle\) for \(\chi\bar{\chi} \rightarrow \text{qq}\) [cm\(^3\)/s]

- **Vector couplings**
- **Axial-vector couplings**

**WIMP mass** \(m_\chi\) [GeV]
Majorana Neutrino Search in same-sign leptons

- Two same-sign muons
- \( \geq 2 \) jets and low ME\(_T\)

ATLAS-CONF-2012-139

The observed limits range from 28 to 3.4 fb for heavy neutrino masses between 100 and 300 GeV.
Search for Heavy Resonance: dilepton channel

- Limits as a function of RS graviton mass and coupling
  \[ m(\text{RS graviton}, \frac{k}{M_{\text{Pl}}} = 0.1) > 2.16 \text{ TeV at 95\% CL} \]
Exotic Same-Sign Dilepton Signatures: $b'$, $T^{5/3}$

- 2 isolated same-sign leptons ($e$ or $\mu$)
- $\mathcal{M}_{T} > 40$ GeV
- $\geq 2$ jets ($\geq 1$ b-tagged jet)
- Large overall transverse momentum
  - $H_T > 550$ GeV

4 events observed
Expected background of $5.6 \pm 1.7$

C. Issever, University of Oxford
Jet Grooming

- “Pruning”:
- Start with a fat jet ($R \sim 1$ or more)
- Run $k_t$ or C/A algorithm on clusters within the fat jet
- At each step, if merging of two clusters fails, remove cluster with smallest $p_T$

Initial jet $\xrightarrow{k_t \text{ or C/A}}$ $p_T^{j_2}/p_T^{j_1+j_2} > z_{cut}$ or $\Delta R_{j_1,j_2} < R_{cut}$ $\xrightarrow{}$ Pruned jet
“Trimming”:
- Start with a fat jet ($R \sim 1$ or more)
- Run $k_t$ algorithm on clusters within the fat jet
- Keep only jets with $p_T > p_T^\text{fat jet} \cdot f_{\text{cut}}$
HEPTopTagger (Filtering)

1. Decompose until $m_{j_1} < 30$ GeV with mass drop requirement
   $m_{j_1} < \mu m_{\text{large jet}}$
2. Investigate 3 subjets and their constituents
3. Re-cluster using C/A with parameter
   $R = \min(0.3, \min_{ij} \Delta R(j_i,j_j)/2)$
4. Use only 5 hardest subjets of last step
5. Build exactly 3 subjets from the selected constituents

S. Fleischmann
\( \sigma_m \)