Hunting for new Physics at the LHC
Run 2 and Future Prospects

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European School of High Energy Physics
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Outline

• How did we arrive to the LHC?

• Where do we {stand, go}?

• Experimental signatures and challenges in the hunt for new physics
Where do we {stand, go}?

$O(4\%)$ of the pieces identified
$O(96\%)$ to be found

(c) Todd McLellan
**ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits**

Status: July 2017

\[ \sqrt{s} = 8, 13 \text{ TeV} \]

\[ \int L \, dt = (3.2 - 37.0) \text{ fb}^{-1} \]

### Table of Results

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets†</th>
<th>( E_{\text{miss}}^{\tau} )</th>
<th>( \int L , dt [\text{fb}^{-1}] )</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD ( G_{KK} + g/a )</td>
<td>0, ( e, \mu )</td>
<td>1 – 4 j</td>
<td>Yes</td>
<td>36.1</td>
<td>( M_{G_{KK}} )</td>
<td>7.75 TeV</td>
</tr>
<tr>
<td>ADD non-resonant ( yy )</td>
<td>2 ( \gamma )</td>
<td>–</td>
<td>–</td>
<td>36.7</td>
<td>( M_{yy} )</td>
<td>8.6 TeV</td>
</tr>
<tr>
<td>ADD GBH</td>
<td>–</td>
<td>2 j</td>
<td>–</td>
<td>37.0</td>
<td>( M_{BH} )</td>
<td>8.9 TeV</td>
</tr>
<tr>
<td>ADD BH high ( \Sigma_{\text{BR}} )</td>
<td>( \geq 1, e, \mu ), ( \geq 2 j )</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
<td>( M_{BH} )</td>
<td>8.2 TeV</td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>( \geq 1, e, \mu ), ( \geq 3 j )</td>
<td>–</td>
<td>–</td>
<td>3.6</td>
<td>( M_{BH} )</td>
<td>9.55 TeV</td>
</tr>
<tr>
<td>RS1 ( G_{KK} \rightarrow yy )</td>
<td>2 ( \gamma )</td>
<td>–</td>
<td>–</td>
<td>36.7</td>
<td>( m_{G_{KK}} )</td>
<td>4.1 TeV</td>
</tr>
<tr>
<td>Bulk RS ( G_{KK} \rightarrow WW \rightarrow qq\ell\nu )</td>
<td>( 1, e, \mu )</td>
<td>1 j</td>
<td>Yes</td>
<td>36.1</td>
<td>( m_{G_{KK}} )</td>
<td>1.73 TeV</td>
</tr>
<tr>
<td>2UED / RPP</td>
<td>( 1, e, \mu )</td>
<td>( \geq 2 b, \geq 3 j )</td>
<td></td>
<td>13.2</td>
<td>( M_{KK} )</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>SSM ( Z' \rightarrow ff )</td>
<td>( 2, e, \mu )</td>
<td>–</td>
<td>–</td>
<td>36.1</td>
<td>( M_{Z'} )</td>
<td>4.5 TeV</td>
</tr>
<tr>
<td>SSM ( Z' \rightarrow \tau \tau )</td>
<td>( 2 \tau )</td>
<td>–</td>
<td>–</td>
<td>36.1</td>
<td>( M_{Z'} )</td>
<td>2.4 TeV</td>
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<tr>
<td>Leptophobic ( Z' \rightarrow bb )</td>
<td>–</td>
<td>( \geq 2 b )</td>
<td>–</td>
<td>3.2</td>
<td>( M_{Z'} )</td>
<td>4.0 TeV</td>
</tr>
<tr>
<td>Leptophobic ( Z' \rightarrow tt )</td>
<td>( 1, e, \mu ), ( \geq 1 b ), ( \geq 1 ) j</td>
<td>Yes</td>
<td>32.2</td>
<td>( M_{Z'} )</td>
<td>2.0 TeV</td>
<td></td>
</tr>
<tr>
<td>SSM ( W' \rightarrow t\bar{t} )</td>
<td>( 1, e, \mu )</td>
<td>–</td>
<td>–</td>
<td>36.1</td>
<td>( M_{W'} )</td>
<td>5.1 TeV</td>
</tr>
<tr>
<td>HVT ( V' \rightarrow WW \rightarrow qqqq ) model B</td>
<td>( 0, e, \mu ), ( 2 j )</td>
<td>–</td>
<td>–</td>
<td>36.7</td>
<td>( M_{V'} )</td>
<td>3.3 TeV</td>
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<tr>
<td>HVT ( V' \rightarrow WH/ZH model B ) multi-channel</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>36.1</td>
<td>( M_{V'} )</td>
<td>2.93 TeV</td>
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<tr>
<td>LRSM ( W_{L} \rightarrow tb )</td>
<td>( 1, e, \mu ), ( \geq 2 b, 0 ) j</td>
<td>Yes</td>
<td>20.3</td>
<td>( M_{W_{L}} )</td>
<td>1.92 TeV</td>
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<tr>
<td>LRSM ( W_{R} \rightarrow tb )</td>
<td>( 0, e, \mu ), ( \geq 1 b, 1 j )</td>
<td>Yes</td>
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<td>( M_{W_{R}} )</td>
<td>1.76 TeV</td>
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<tr>
<td>CI ( qqq )</td>
<td>–</td>
<td>2 j</td>
<td>–</td>
<td>37.0</td>
<td>( \Lambda )</td>
<td>21.8 TeV</td>
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<tr>
<td>CI ( fff )</td>
<td>( 2, e, \mu )</td>
<td>–</td>
<td>–</td>
<td>36.1</td>
<td>( \Lambda )</td>
<td>40.1 TeV</td>
</tr>
<tr>
<td>CI ( uut )</td>
<td>2(( e),( \gamma ))</td>
<td>( \geq 1 b, \geq 1 j )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \Lambda )</td>
<td>4.9 TeV</td>
</tr>
<tr>
<td>Axial-vector mediator (Dirac DM)</td>
<td>( 0, e, \mu ), ( \geq 1 b, \geq 1 j )</td>
<td>Yes</td>
<td>36.1</td>
<td>( m_{\text{mod}} )</td>
<td>1.5 TeV</td>
<td></td>
</tr>
<tr>
<td>Vector mediator (Dirac DM)</td>
<td>( 0, e, \mu, 1 \gamma )</td>
<td>( \leq 1 j )</td>
<td></td>
<td>36.1</td>
<td>( m_{\text{mod}} )</td>
<td>1.2 TeV</td>
</tr>
<tr>
<td>( VV_{\chi\chi} ) EFT (Dirac DM)</td>
<td>( 0, e, \mu ), ( 1 \gamma, \leq 1 j )</td>
<td></td>
<td></td>
<td>32</td>
<td>( m_{\chi} )</td>
<td>700 GeV</td>
</tr>
<tr>
<td>Scalar ( LQ 1\text{st} ) gen</td>
<td>( 2 e ), ( \geq 2 j )</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
<td>( M_{LQ} )</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>Scalar ( LQ 2\text{nd} ) gen</td>
<td>( 2 e ), ( \geq 2 j )</td>
<td>–</td>
<td>–</td>
<td>3.2</td>
<td>( M_{LQ} )</td>
<td>1.05 TeV</td>
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<tr>
<td>Scalar ( LQ 3\text{rd} ) gen</td>
<td>( 1 e, \mu ), ( \geq 1 b, \geq 3 j )</td>
<td>Yes</td>
<td>20.3</td>
<td>( M_{LQ} )</td>
<td>640 GeV</td>
<td></td>
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<tr>
<td>VLL ( TT \rightarrow Ht + X )</td>
<td>( 0, e, \mu ), ( 1, e, \mu ), ( \geq 2 b, \geq 3 j )</td>
<td>Yes</td>
<td>13.2</td>
<td>( M_{1} )</td>
<td>1.2 TeV</td>
<td></td>
</tr>
<tr>
<td>VLL ( TT \rightarrow Zt + X )</td>
<td>( 1, e, \mu ), ( \geq 1 b, \geq 3 j )</td>
<td>Yes</td>
<td>36.1</td>
<td>( M_{2} )</td>
<td>1.16 TeV</td>
<td></td>
</tr>
<tr>
<td>VLL ( TT \rightarrow Wb + X )</td>
<td>( 1, e, \mu ), ( \geq 1 b, \geq 1 ) j</td>
<td>Yes</td>
<td>36.1</td>
<td>( M_{2} )</td>
<td>1.35 TeV</td>
<td></td>
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<tr>
<td>VLL ( BB \rightarrow Hb + X )</td>
<td>( 1, e, \mu ), ( \geq 2 b, \geq 3 j )</td>
<td>Yes</td>
<td>20.3</td>
<td>( M_{2} )</td>
<td>700 GeV</td>
<td></td>
</tr>
<tr>
<td>VLL ( BB \rightarrow Zb + X )</td>
<td>( 2 \leq 3 e, \mu ), ( \geq 2 \geq 1 b )</td>
<td>Yes</td>
<td>20.3</td>
<td>( M_{2} )</td>
<td>790 GeV</td>
<td></td>
</tr>
<tr>
<td>VLL ( BB \rightarrow Wt + X )</td>
<td>( 1, e, \mu ), ( \geq 1 b, \geq 1 ) j</td>
<td>Yes</td>
<td>36.1</td>
<td>( M_{2} )</td>
<td>1.25 TeV</td>
<td></td>
</tr>
<tr>
<td>VLL ( QQ \rightarrow WqWq )</td>
<td>( 1, e, \mu ), ( \geq 4 j )</td>
<td>Yes</td>
<td>20.3</td>
<td>( M_{2} )</td>
<td>690 GeV</td>
<td></td>
</tr>
<tr>
<td>Excited quark ( q' \rightarrow qg )</td>
<td>–</td>
<td>2 j</td>
<td>–</td>
<td>37.0</td>
<td>( q'^{\ast} )</td>
<td>6.0 TeV</td>
</tr>
<tr>
<td>Excited quark ( q' \rightarrow q\gamma )</td>
<td>( 1 \gamma )</td>
<td>1 j</td>
<td>–</td>
<td>36.7</td>
<td>( q'^{\ast} )</td>
<td>5.3 TeV</td>
</tr>
<tr>
<td>Excited top quark ( b' \rightarrow bg )</td>
<td>–</td>
<td>1 j, 1 j</td>
<td>–</td>
<td>13.3</td>
<td>( b'^{\ast} )</td>
<td>2.3 TeV</td>
</tr>
<tr>
<td>Excited top quark ( b' \rightarrow Wt )</td>
<td>( 1, e, \mu ), ( \geq 2 b, \geq 2 j )</td>
<td>Yes</td>
<td>20.3</td>
<td>( b'^{\ast} )</td>
<td>1.5 TeV</td>
<td></td>
</tr>
<tr>
<td>Excited lepton ( l' \rightarrow Zl )</td>
<td>( 3, e, \mu )</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>( l'^{\ast} )</td>
<td>3.0 TeV</td>
</tr>
<tr>
<td>Excited lepton ( l' \rightarrow Wl )</td>
<td>( 3, e, \mu, \tau )</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>( l'^{\ast} )</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>LRSM Majorana ( \nu )</td>
<td>( 2, e, \mu )</td>
<td>2 j</td>
<td>–</td>
<td>20.3</td>
<td>( N_{\nu} )</td>
<td>870 GeV</td>
</tr>
<tr>
<td>Higgs triplet ( H_{\pm} \rightarrow \ell \ell )</td>
<td>( 2, 3 e, \mu )</td>
<td>( \geq 2 j )</td>
<td>–</td>
<td>36.1</td>
<td>( H_{\pm} )</td>
<td>400 GeV</td>
</tr>
<tr>
<td>Higgs triplet ( H_{\pm} \rightarrow \tau \tau )</td>
<td>( 3, e, \mu, \tau )</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td>( H_{\pm} )</td>
<td>330 GeV</td>
</tr>
<tr>
<td>Monopole (non-res prod)</td>
<td>( 1, e, \mu ), ( \geq 1 b )</td>
<td>Yes</td>
<td>20.3</td>
<td></td>
<td>( m_{\text{monopole}} )</td>
<td>0.2</td>
</tr>
<tr>
<td>Multi-charged particles</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>20.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic monopoles</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

†Small-radius (large-radius) jets are denoted by the letter j (jL).
Should the new physics scale be at the LHC reach?

- $K^0, D^0, B^0, B^0_s$ mass splittings yield tight constraints on new physics contributions

$$\delta \mathcal{L} = \frac{z_{qq'}}{\Lambda^2} \left( \bar{q}_L \gamma_\mu q'_L \right)^2 \Rightarrow \frac{\Delta m_h}{m_h} \sim \frac{|z_{qq'}|}{3} \left( \frac{f_h}{\Lambda} \right)^2$$

- If flavour structure is trivial ($z \sim 1$)
  \[ \Lambda \approx O(100 \text{ TeV}) \]

  ⇒ only glimpses of NP observed at the LHC?

- If $\Lambda \sim O(1 \text{ TeV})$
  
  NP flavour structure is far from trivial

  ⇒ flavour measurements are good probe of NP

Both cases ⇒ higher precision at the LHC
Searching for subtle NP effects in data

- If the energy probed does not yet resolve the mass of the new particles
  - look for deviations induced by Fermi-like interactions

$$\delta L = \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \mathcal{O} \left( \frac{1}{\Lambda^4} \right) \quad \Rightarrow \quad \delta \sigma = \sum \frac{c_i^2}{\Lambda^2} \sigma_i + \sum \frac{c_i c_j}{\Lambda^4} \sigma_{ij} + \ldots$$

- Several start moving in the direction of a global scan of allowed NP contributions

Interference with the SM expectations although suppressed by $1/\Lambda^4$ may be non-negligible!
Searching for subtle NP effects in data

**Boson scattering and anomalous couplings**

- Boson scattering topologies start complementing the sensitivity to anomalous couplings
  - triple and quartic gauge couplings enter in the diagrams
  - typical t-channel signature: \( t = (q_i - q_f)^2 = -2|\vec{q}_i||\vec{q}_f|(1 - \cos \theta) \Rightarrow \Delta \eta \gg 1 \)

<table>
<thead>
<tr>
<th>Coupling ( f_{\ell N}/\Lambda^4 )</th>
<th>Exp.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{T0}/\Lambda^4 )</td>
<td>([-0.53,0.51])</td>
<td>([-0.46,0.44])</td>
</tr>
<tr>
<td>( f_{T1}/\Lambda^4 )</td>
<td>([-0.72,0.71])</td>
<td>([-0.61,0.61])</td>
</tr>
<tr>
<td>( f_{T2}/\Lambda^4 )</td>
<td>([-1.4,1.4])</td>
<td>([-1.2,1.2])</td>
</tr>
<tr>
<td>( f_{T8}/\Lambda^4 )</td>
<td>([-0.99,0.99])</td>
<td>([-0.84,0.84])</td>
</tr>
<tr>
<td>( f_{T9}/\Lambda^4 )</td>
<td>([-2.1,2.1])</td>
<td>([-1.8,1.8])</td>
</tr>
</tbody>
</table>

\( \sigma_{EW}(pp \rightarrow ZZjj \rightarrow 4\ell jj) = 0.40^{+0.21}_{-0.16}^{(\text{stat})}^{+0.13}_{-0.09}^{(\text{syst})} \text{ fb} \)
Searching for subtle NP effects in data

**Boson scattering and anomalous couplings**

- Boson scattering topologies start complementing the sensitivity to anomalous couplings
  - triple and quartic gauge couplings enter in the diagrams
  - typical t-channel signature: 
    \[
    t = (q_i - q_f)^2 = -2 |\vec{q}_i| |\vec{q}_f| (1 - \cos \theta) \Rightarrow \Delta \eta \gg 1
    \]
  - note: unitarity bounds are however strict on possible new physics contributions
  - decomposing the amplitude in partial waves (S, P, etc.)
    \[
    A = 16\pi \sum_{l=0}^{\infty} (2l + 1) P_l(\cos \theta) a_l
    \]
    \[
    \hat{\sigma} = \frac{16\pi}{\hat{s}} \sum_{l=0}^{\infty} (2l + 1) |a_l|^2 \quad \leftrightarrow \quad \hat{\sigma} = \frac{1}{\hat{s}} \text{Im} [A(\theta = 0)]
    \]
    **optical theorem**
  - contributions to each wave are therefore limited to
    \[
    |\text{Re}(a_l)| < \frac{1}{2}
    \]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Exp.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_{T0}/\Lambda^4</td>
<td>[-0.53,0.51]</td>
<td>[-0.46,0.44]</td>
</tr>
<tr>
<td>f_{T1}/\Lambda^4</td>
<td>[-0.72,0.71]</td>
<td>[-0.61,0.61]</td>
</tr>
<tr>
<td>f_{T2}/\Lambda^4</td>
<td>[-1.4,1.4]</td>
<td>[-1.2,1.2]</td>
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<tr>
<td>f_{T8}/\Lambda^4</td>
<td>[-0.99,0.99]</td>
<td>[-0.84,0.84]</td>
</tr>
<tr>
<td>f_{T9}/\Lambda^4</td>
<td>[-2.1,2.1]</td>
<td>[-1.8,1.8]</td>
</tr>
</tbody>
</table>

find details on ft in arXiv:hep-ph/0606118

unitarity bounds ~2-3 TeV
(~10^{-4} smaller than current limits)
Searching for subtle NP effects in data

**Boson scattering and anomalous couplings**

- Boson scattering topologies start complementing the sensitivity to anomalous couplings
  - triple and quartic gauge couplings enter in the diagrams
  - typical t-channel signature: \( t = (q_i - q_f)^2 = -2|\vec{q}_i||\vec{q}_f|(1 - \cos \theta) \Rightarrow \Delta \eta \gg 1 \)
  - consider also central exclusive WW production, light-by-light scattering (PbPb)

In classic electrodynamics
- Maxwell equations are linear
- fields can super-impose

Scattering driven by quantum loops

\[
\sigma(PbPb(\gamma\gamma) \to Pb^*Pb^*\gamma\gamma) = 70 \pm 24_{\text{stat}} \pm 17_{\text{syst}} \text{ nb}
\]

\[\begin{align*}
\gamma\gamma \to \gamma\gamma \text{ MC} \quad &\quad \gamma\gamma \to e^+e^- \text{ MC} \quad &\quad \text{CEP } \gamma\gamma \text{ MC} \\
\text{Data, } 480 \mu\text{b}^{-1} &\quad \text{ATLAS} &\quad \text{Pb+Pb } s_{\text{NN}} = 5.02 \text{ TeV} &\quad \mu_{\gamma\gamma} \quad &\quad \text{Observed} &\quad \text{SM expected}
\end{align*}\]

\[Aco = 1 - \Delta \phi_{\gamma\gamma}\]
Searching for subtle NP effects in data

**Boson scattering and anomalous couplings**

- Boson scattering topologies start complementing the sensitivity to anomalous couplings
  - triple and quartic gauge couplings enter in the diagrams
  - typical t-channel signature: \( t = (q_i - q_f)^2 = -2|\vec{q}_i||\vec{q}_f| (1 - \cos \theta) \Rightarrow \Delta \eta \gg 1 \)
  - consider also central exclusive WW production, light-by-light scattering (PbPb)

In classic electrodynamics
- Maxwell equations are linear
- fields can super-impose

Unless there is new physics
- e.g. massive-like contribution
- leads to different acoplanarity

Search for B-I monopoles at the LHC
- \( M_M > 11 \) TeV

\[ \delta \mathcal{L}_{\text{Born-Infeld}} = \beta^2 \left[ 1 - \sqrt{1 + \frac{1}{2\beta^2} F_{\mu \nu} F^{\mu \nu} - \frac{1}{16\beta^4} (F_{\mu \nu} \tilde{F}^{\mu \nu})^2} \right] \]
### Limits on gauge couplings

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limits</th>
<th>$\hat{t}_{10}/\Lambda^4$</th>
<th>$\hat{t}_{11}/\Lambda^4$</th>
<th>$\hat{t}_{12}/\Lambda^4$</th>
<th>$\hat{t}_{15}/\Lambda^4$</th>
<th>$\hat{t}_{16}/\Lambda^4$</th>
<th>$\hat{t}_{17}/\Lambda^4$</th>
<th>$\hat{t}_{18}/\Lambda^4$</th>
<th>$\hat{t}_{19}/\Lambda^4$</th>
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</thead>
<tbody>
<tr>
<td>$W\gamma$</td>
<td>$[-3.6e+01, 3.6e+01]$</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
<td>20.2 fb$^{-1}$</td>
<td>8 TeV</td>
<td>20.2 fb$^{-1}$</td>
<td>8 TeV</td>
<td>20.2 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$[-1.6e+01, 1.6e+01]$</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
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<tr>
<td>$WW$</td>
<td>$[-1.8e+01, 1.8e+01]$</td>
<td>20.2 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.3 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$[-2.5e+01, 2.5e+01]$</td>
<td>19.3 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$[-4.2e+00, 4.2e+00]$</td>
<td>19.4 fb$^{-1}$</td>
<td>8 TeV</td>
<td>35.9 fb$^{-1}$</td>
<td>13 TeV</td>
<td>35.9 fb$^{-1}$</td>
<td>13 TeV</td>
<td></td>
<td></td>
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- Extensive summaries of triple, quartic gauge couplings available @ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC
Higgs as a portal

- Still a (experimental) large room for invisible Higgs decays: BR<0.24 @ 95%CL
  - significant changes in this BR could be due to new neutral particles : dark matter?
- It may also be that the Higgs sector is more complex and accompanied by partners
  - resonant associated (VH) and hh production, high-mass diboson resonances, ….
Dark matter and Higgs

- The limits on the invisible BR of the Higgs can be re-casted to limits dark matter production

\[
\sigma_{S-N}^{\text{SI}} = \frac{4 \Gamma_{\text{inv}} f_N^2}{m_H^2 v^2 \beta (M_X + m_N)^2}, \\
\sigma_{N-N}^{\text{SI}} = \frac{16 \Gamma_{\text{inv}} m_X^4}{m_H^3 v^2 (m_H^4 - 4M_X^2 m_N^2 + 12M_X^4) (M_X + m_N)^2}, \\
\sigma_{\gamma-N}^{\text{SI}} = \frac{8 \Gamma_{\text{inv}} m_X^2}{m_H^5 v^2 \beta^3 (M_X + m_N)^2}.
\]

- Latest re-interpretations in terms of mediator-WIMP mass (see CERN-LPCC-2016-001)

\[m_N - \text{nucleon mass } \sim 0.939 \text{ GeV} \]
\[v = 246/\sqrt{2} \text{ GeV (vev)} \]
\[f_N \sim 0.326 \text{ central value for coupling (from lattice)}^* \]

\[\beta = \frac{1}{\sqrt{1 - 4M_X^2/m_H^2}}.\]
\[\Gamma_{\text{inv}} = \Gamma_{\text{SM BR}_{\text{inv}}/(1-BR_{\text{inv}})} \]


CMS

4.9 fb\(^{-1}\) (7 TeV) + 19.7 fb\(^{-1}\) (8 TeV) + 2.3 fb\(^{-1}\) (13 TeV)

\[\text{B}(H \rightarrow \text{inv}) < 0.20 \]

90% CL limits

ATLAS

\[\bar{s}s = 13 \text{ TeV, 36.1 fb}^{-1} \]

Axial-vector, Dirac, \(g_q = 0.25, g_\chi = 1.0\)

ee+\(\mu\)
Direct searches for dark matter at the LHC

- Wide range of searches for associated production of dark matter: mono-X, jet+ISR, top, H
- spin-dependent re-interpretation is unavoidable
- nevertheless, nicely complements direct searches from dedicated experiments
• Experimentalists rely on this type of model landscape to gauge their findings
  • but the point is not so much what we plot/quote as limit
  • we want to fill in the puzzle by leaving no stone unturned
Outstanding questions

@ the dawn of the LHC

Electroweak symmetry breaking
• does the Higgs boson exist?

Dark matter
• composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
• one type or more?
• only gravitational or other interactions?

Quarks and leptons
• why 3 families?
• masses and mixing
• CP violation in the lepton sector
• matter and antimatter asymmetry
• baryon and charged lepton number violation

Neutrinos
• \( \nu \) masses, their origin - Higgs role?
• Majorana or Dirac?
• CP violation
• additional species?
• sterile \( \nu \)?

Physics at the highest E-scales:
• how is gravity connected with the other forces?
• do forces unify at high energy?

Universe’s accelerated expansion:
• primordial: is inflation correct? which (scalar) fields? role of quantum gravity?
• today: dark energy (why is \( \Lambda \) so small?) or gravity modification?
Outstanding questions
@ middle of LHC Run 2

Electroweak symmetry breaking
- $m_H$ natural or fine-tuned?
- if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? new dynamics?
- elementary or composite Higgs?
- is it alone or are there other Higgs bosons?
- origin of couplings to fermions
- coupling to dark matter?
- does it violate CP?
- cosmological EW phase transition

Quarks and leptons
- why 3 families?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Neutrinos
- $\nu$ masses, their origin - $H(125)$ role?
- Majorana or Dirac?
- CP violation
- additional species?
- sterile $\nu$?

Dark matter
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
- one type or more?
- only gravitational or other interactions?

Physics at the highest E-scales:
- how is gravity connected with the other forces?
- do forces unify at high energy?

Universe’s accelerated expansion:
- primordial: is inflation correct? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is $\Lambda$ so small?) or gravity modification?

adapted from I. Shipsey @ ICHEP2016
be happily unsettled and search for new physics
Experimental signatures and challenges

What do we effectively measure at the LHC?
Experimental signatures and challenges
Where theory meets experiment
What do we effectively measure at the LHC?

We count…

\[ \sigma_{tot} = \frac{1}{A} \sigma_{fid} = \frac{1}{A} \cdot \frac{N_{signal}}{\mathcal{L} \cdot \varepsilon \cdot SF} \]

theory@experiment?

- acceptance \( \frac{N_{fid}}{N_{tot}} \) _gen_
- luminosity
- efficiency \( \frac{N_{sel}}{N_{gen}} \) _fid_
- efficiency corrections

… that easy ?
Setting up the coordinates

Kinematics at the LHC 101: a reminder

• Initial longitudinal momentum of the constituents is unknown
  • in addition many particles produced escape the acceptance of the detectors
  ⇒ “visible” longitudinal momentum and energy are not conserved

• Transverse quantities: \( (p_T, \phi) \)
  • fully reconstructed (modulo scale/resolution uncertainties)
  • it is Lorentz-invariant under transformations along \( z \)

• Rapidity: \( y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) = \frac{1}{2} \ln \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right) \)
  • \( m << p_T \)
  • \( \eta = -\ln \tan \frac{\theta}{2} \)
  • it’s an alternative measure of \( \theta \)
  • it’s additive under Lorentz transformations

\[
y = y^* + y_{\text{boost}} = y^* + \frac{1}{2} \ln \left( \frac{1 - \beta}{1 + \beta} \right)
\]
i.e. rapidity distances are Lorentz-invariant

\[|p_{z,i}| = x_i \frac{\sqrt{s}}{2}\]

\[E_i^* = \frac{\sqrt{s}}{2}\]
Angular distances must therefore be expressed as function of $y$ (or $\eta$) and $\phi$.

Four-momenta are expressed as:

\[
(E, p_x, p_y, p_z) = (m_T \cosh y, p_T \cos \phi, p_T \sin \phi, m_T \sinh y)
\]

where the transverse mass is

\[
m_T = \sqrt{m^2 + p_T^2}
\]

Element in kinematics phase space:

\[
\frac{d^3p}{E} = p_T dp_T dy d\phi = \pi dy dp_T^2
\]

This is the basis for the representation of the detectors and our measurements.
Although energy is not Lorentz-invariant the peak of its distribution may be

- consider an unpolarized two-body decay: $\pi^0 \rightarrow \gamma\gamma$, $t \rightarrow Wb$
- expect uniform angle distribution in the rest-frame (S-wave emission)

\[
E_b = \frac{m_t^2 - m_W^2}{2m_t} \Rightarrow m_t = E_b \left[ 1 + \sqrt{1 + \left( \frac{M_W}{2E_b} \right)^2} \right]
\]

- energy peak in the lab preserves rest-frame mono-chromatic emission (largest contribution at each boost)
Experimental challenges

First things first: luminosity determination

- Usually determined from dedicated Van-der-Meer scans ([CERN-ISR-PO-68-31](CERN-ISR-PO-68-31))
  - beams are scanned and the shape and size of the luminous region is measured
  - measure relative interaction rate as function of the separation of the beam \( \mathcal{L} = \frac{N}{\sigma} \)

- Counting hits establishes a “visible min. bias cross section”
  - width of the beam determined from scan
  - hits counted in the detector (e.g. pixel clusters)

- Largest uncertainties from
  - \( x-y \) dependencies, length scale calibration
  - sub-detector checks

\[ \frac{\delta \sigma}{\sigma} \bigg|_{\text{Run 2}} \approx 3.2\% \text{ ATLAS} \ (2.5\% \text{ CMS}) \]
Reducing x-y dependencies in the luminosity calibration

\[ \mathcal{L} = \left( f \cdot N_b N_p \right) N_{p'} \Omega \]

- LHCb tracking system is able to measure the beams overlap integral very accurately
  - direct measurement of the beam profile without need for displacement - complements VdM scan
  - x-y dependency is measured in situ, minimizing potential bias in the VdM scan
  - after combination \( \left. \frac{\delta \sigma}{\sigma} \right|_{\text{LHCb } 8 \text{ TeV}} = 1.2\% \)
Experimental challenges

Understand the signature

- Leptons, photons, jets, missing transverse energy, …
  - …but also displaced objects, disappearing tracks, out-of-time decays,…
- **Signal**: theory predictions forecast signature but *how does it look in the detector?*
- **Backgrounds**: sometimes no trustworthy theory

…and so the fun begins!

\[ N_{\text{jets}} = 9 \]
\[ S_T = \Sigma p_T = 2.6 \text{ TeV} \]
Experimental challenges

Know thy (in)efficiencies

- Use data as much as possible to check the expected efficiencies
- E.g. $D^* \rightarrow K+n\pi$, $J/\psi$ or $Z \rightarrow \ell\ell$: “easy” to trigger, yield resonant decay products
  - count events which pass and fail selection requirements: trigger, tracking, id, isolation,…
  - events in each category are related by the efficiency of the requirement
    \[ \frac{N_{\text{pass}}}{N_{\text{fail}}} = \varepsilon \]
- Difference between data and simulation can be used as correction factor

![Diagram with graphs and data points]

$|m_{\ell\ell} - M_Z| < 10$ GeV

tag=tight lepton
probe lepton

$\varepsilon = \frac{N_{\text{pass}}}{N}$
Experimental challenges

Energy scale calibration (ATLAS LAr example)

- Several steps correcting as much as possible from the data the initial MC-based energy regression
  - *inter-calibration* (longitudinal sections): use MIP deposits from $Z\rightarrow\mu\mu$
  - *upstream material corrections*: ratio of super cluster energies in different longitudinal sections ($e, \gamma_{unc.}$)
  - *residual differences in response and resolution* are probed using shift and width of the $Z\rightarrow ee$ peak

\[
E_{\text{data}} = [1 + \alpha(\eta)] E_{\text{MC}}
\]
\[
\delta E \bigg|_{\text{data}} = \frac{\delta E}{E} \bigg|_{\text{MC}} \oplus c(\eta)
\]
\[
m_{ee} \bigg|_{\text{data}} = m_{ee}^{MC} \left[ 1 + \frac{\alpha(\eta_1) + \alpha(\eta_2)}{2} \right]
\]
\[
\delta m \bigg|_{\text{data}} = \frac{\delta m}{m} \bigg|_{\text{MC}} \oplus \left[ \frac{c(\eta_1) + c(\eta_2)}{2} \right]
\]
Experimental challenges

Monitoring the response throughout the run (CMS ECAL example)

- Continuous monitoring of the detector is needed
  - radiation induces coloured centres in crystals
  - significant loss of response at high luminosity
- Laser used for transparency corrections in CMS ECAL
  - $\pi^0 \rightarrow \gamma\gamma$ can be used to check response and dispersion
**Experimental challenges**

**Further refinements at analysis level (CMS muons example)**

- Improve over the standard muon reconstruction by taking into account:
  - local modifications of the magnetic field \( ((A-1) \sim 0.0005) = \) multiplicative factor
  - residual misalignment effects \( (M \sim 10^{-4}/\text{GeV}) = \) additive factor, charge dependent
  - imperfect material modelling effects \( (\varepsilon \sim 4\text{MeV}) = \) depends on \( \sin \theta \)

\[
k_c^c = \frac{1}{p_T^c} = (A - 1)k + qM + \frac{k}{1 + k\varepsilon \sin \theta}
\]

Translated to \( \sim 14\text{MeV} \) uncertainty on \( M_W \) using only \( p_T \) information
Jet clustering algorithms are extensively used in hadron colliders

- collect the final state products after the hadronisation
- \[ d_{ab} = \min \left\{ p_{T,a}^{2n}, p_{T,b}^{2n} \right\} \frac{\Delta R_{ab}^2}{R^2} \quad d_{aB} = p_{T,a}^{2n} \] define the metrics
- at each step find smallest: if \( d_{ab} \) recombine, if \( d_{aB} \) a jet is found
- (anti-)k\( _{\text{T}} \) algorithm uses \( n = 1 \) (-1), Cambridge-Aachen uses \( n = 0 \)

\[ \begin{align*}
\text{Electron} & : p_T = 22.89 \text{ GeV} \\
 & \quad \eta = -0.626 \\
 & \quad \Phi = 2.663 \\
\text{Muon} & : p_T = 79.60 \text{ GeV} \\
 & \quad \eta = -1.893 \\
 & \quad \Phi = -2.974 \\
\text{Jet} & : p_T = 91.94 \text{ GeV} \\
 & \quad \eta = -1.822 \\
 & \quad \Phi = 1.706 \\
\text{Jet} & : p_T = 37.26 \text{ GeV} \\
 & \quad \eta = 0.354 \\
 & \quad \Phi = 0.483 \\
\text{Jet} & : p_T = 112.71 \text{ GeV} \\
 & \quad \eta = 1.132 \\
 & \quad \Phi = -0.345 \\
\text{Jet} & : p_T = 59.51 \text{ GeV} \\
 & \quad \eta = 1.036 \\
 & \quad \Phi = -0.805 \\
\text{Jet} & : p_T = 30.22 \text{ GeV} \\
 & \quad \eta = 1.036 \\
 & \quad \Phi = -0.805 \\
\text{Jet} & : p_T = 59.51 \text{ GeV} \\
 & \quad \eta = 1.036 \\
 & \quad \Phi = -0.805 \\
M & : p_T = 95.83 \text{ GeV} \\
 & \quad \eta = -2.117 \\
 & \quad \Phi = -1.487
\end{align*} \]

\( \leftarrow \text{ttZ event with anti-k}_{\text{T}} \) with \( R=0.4 \)

The particle flow algorithm yields a close to generator level reconstruction of the jet constituents
Jet clustering algorithms are extensively used in hadron colliders

- collect the final state products after the hadronisation
- $d_{ab} = \min \left\{ p_{T,a}^{2n}, p_{T,b}^{2n} \right\} \frac{\Delta R_{ab}^2}{R^2}$, $d_{aB} = p_{T,a}^{2n}$ define the metrics
- at each step find smallest: if $d_{ab}$ recombine, if $d_{aB}$ a jet is found
- (anti-)$k_T$ algorithm uses $n=1$ (-1), Cambridge-Aachen uses $n=0$

The event minimum $\{d_{ab}, d_{aB}\}$ tells us at which point a N jet event is resolved to N+1
Experimental challenges

Hadronic event shapes

- Jet cross section @ TeV scale with early data
  - sensitive to PDFs, $\alpha_s$
- Compare to NLO QCD prediction (NLOJet++)
  - non-perturbative corrections can be $\sim 15\%$ (large R)
  - EWK corrections up to 5% (at high $p_T$)

![Graph showing jet cross section with early data and various subprocesses labeled from 1 to 7. The graph includes settings for $|y| < 0.5$ and various $|y|$ intervals with corresponding $p_T$ values.](#)

< 71 pb$^{-1}$ (13 TeV)
Where theory meets experimental challenges

Splittings and azimuthal decorrelations

- Azimuthal angles in N-jets
  - how well is QCD splitting predicted?
  - soft / collinear / hard regimes probed

CMS Preliminary

\[ \Delta \phi_{1,2} \]

Pythia, Herwig

\[ \Delta \phi_{1,2} \]

Madgraph

\[ p_T^{\text{max}} \]

Pythia\text{8} \text{ CUETP}8M1

Herwig++ \text{ CUETH}ppS1

\text{ MadGraph + Pythia}8 \text{ CUETP}8M1

35.9 fb\(^{-1}\) (13 TeV)

nJets \geq 2

3.5 < p_T < 1200 GeV

nJets \geq 4

800 < p_T^{\text{max}} < 1000 GeV

1000 < p_T^{\text{max}} < 1200 GeV

600 < p_T^{\text{max}} < 700 GeV

700 < p_T^{\text{max}} < 800 GeV

400 < p_T^{\text{max}} < 500 GeV

500 < p_T^{\text{max}} < 600 GeV

200 < p_T^{\text{max}} < 300 GeV

300 < p_T^{\text{max}} < 400 GeV

\[ \phi \]

\[ \phi \]

\[ \phi \]

\[ \phi \]
Experimental challenges

Jet mass an interesting probe of the jet nature

- Jet splitting from pQCD evolution
  - have soft singularities in $z = E_{\text{emitted}}/E_{\text{parent}}$
    (except $g \rightarrow \text{qq}$ - asymmetric in $z$)
  - mass drop at each split moderated by Sudakov factor
    form factor rapidly vanishing $\Delta_q(t) \sim \left[ \frac{\alpha_S(t)}{\alpha_S(t_0)} \right]^{p \ln t}$
    $\Rightarrow$ soft mass drops expected in splittings

Quarks, gluons, acquire a “visible” mass through the process of QCD shower

First emission yields the dominant contribution to the observed jet mass

\[
< m^2 > \approx p_T^2 \int_0^{R^2} d\theta^2 \int dz \, z(1-z)\theta^2 \frac{\alpha_S}{2\pi} \mathcal{P}(z) \approx \frac{\alpha_S}{\pi} \frac{3}{8} C_F p_T^2 R^2
\]
Jet mass an interesting probe of the jet nature II

- Jet splitting from a decay occurs
  - in one step: $A \rightarrow ab$
  - at a hard scale $m^2 \approx 2 \vec{p}_{T,a} \cdot \vec{p}_{T,b} \Rightarrow \Delta R^2_{a,b} \approx z(1 - z) \left( \frac{p_{T,A}}{m} \right)^2$
  - uniform distribution in $z = p_{T,a}/p_{T,A}$
  - expect however "pollution" from further emissions

- "splitting" algorithm: clean up the soft, collinear radiation, identify hard splitting
  - start by clustering the jet (usually a large jet cone is used)
  - unwind the process one step at a time checking if it's hard and symmetric
    \[ \text{max}(m_a, m_b) < \mu m_A \quad y_{i,j} > y_{\text{cut}} \]
  - if not discard the softest of (a,b)
  - stop if condition is met or you ran out of splittings to unwind
Experimental challenges

Mass drop and filtering yield a pileup robust result

- “filtering step”: due to underlying event, pileup the mass drop scale may be distorted

\[
\frac{d < m^2 >}{dR} \approx \Lambda_{\text{soft}} (p_T R) R^2
\]

re-cluster the jet found with \[ R_{\text{filt}} = \min(\Delta R_{ab}/2, 0.3) \]

\[ \int L = 35 \text{ pb}^{-1} \]

\[ \text{ATLAS} \]

\[ \text{Before Splitting/Filtering} \]
\[ \text{After Splitting/Filtering} \]
\[ \text{After Splitting Only} \]

Cambridge-Aachen R=1.2 jets
Split/Filtered with R_{qq} > 0.3
p_T > 300 GeV, y_{ly} < 2

Mean Jet Mass [GeV] / 1 PV

\[ \frac{d m}{d N_{\text{PV}}} = 2.9 \pm 0.3 \text{ GeV} \]
\[ \frac{d m}{d N_{\text{PV}}} = 0.1 \pm 0.2 \text{ GeV} \]
\[ \frac{d m}{d N_{\text{PV}}} = 4.2 \pm 0.1 \text{ GeV} \]

\[ \text{MC/Data} \]

Jet mass [GeV]

JHEP 1205 (2012) 128
Experimental challenges

Soft drop condition as a probe of the medium

- Soft drop works as the “splitting” step (see s36)
  - discard softer of the jets until condition is met

- Splitting scale can be probed from max. “declustering” scale found
  - useful observable to probe the medium

\[ \frac{p_{T,2}}{p_{T,1} + p_{T,2}} < z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta \]

soft-drop: JHEP 1405 (2014) 146

\[ z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \]
Experimental challenges

Jets and fragmentation

- Hardest hadrons preserve residual sensitivity to partonic charge
  - sensitivity can be used as probe for fragmentation
  - simple / effective $p_T$-weighted average

$$Q^x = \frac{1}{(p_T^{jet})^x} \sum_i Q_i(p_T^i)^x$$

[ArXiv:1706.05868]

\textbf{CMS}

$19.7 \text{ fb}^{-1} (8 \text{ TeV})$

$|\eta| < 1.5$

$P_T > 400 \text{ GeV}$
Experimental challenges
Using fragmentation properties to discriminate q/g

- Simple variables can be joined to build up multivariate discriminator
  - gluon jets: diffuse, softer fragmentation, higher multiplicity
  - a scan of O(10^3) variables @ http://jets.physics.harvard.edu/qvg/
  - validation needed: use q-enriched (Z) / g-enriched (dijets) to correct expectations

---

CMS Preliminary

2.6 fb^{-1} (13 TeV)

**Efficiency (LD > 0.5)**

- Quark (Herwig++)
- Gluon (Herwig++) before reweighting
- Quark (Pythia8)
- Gluon (Pythia8) after reweighting

---

**Jet p_T [GeV]**

- Z+jets, |η| < 2.0

---

CMS DP - 2016/070 and arXiv:1104.1175
Experimental challenges

Heavy flavour jets and fragmentation

- Heavy quark fragmentation tuned from $Z \rightarrow b\bar{b}$ @ LEP
  - mass leads to most of the energy being carried by single hadron
  - charm and bottom mesons are long-lived hadrons
    \[ f(z) \propto \frac{1}{z} (1-z)^a \exp \left( -\frac{b m^2}{z} \right) \]
  - \Rightarrow displaced vertices which can be reconstructed in the tracker

- Explicit reconstruction of charmed mesons in b jets
  - probe fragmentation properties of heavy quarks
Secondary vertex: most discriminating variables

- but also track impact parameters, soft leptons etc.
- efficiency/mistag rate must be validated in data

Gain from exploring further the sub-structure

- use the sub-jettiness axis to guide the regions of interest

Experimental challenges

Using b/c fragmentation properties to discriminate from udsg
Experimental challenges

Ingredients to measure efficiency in-situ

• Mass dependency on $p_T$ shapes backgrounds when hard cuts are applied
  
  • make background look as uniform as possible independently of the jet $p_T$: $m \rightarrow \log(m^2/p_T^2)$

  • transform selection variables such that they preserve background shape

  e.g. cuts on N-subjettiness usually shape the backgrounds due to $p_T$

  linear transformation based on average behavior tends to flatten the background

  $$\tau'_{21} = \tau_2/\tau_1 - \alpha \rho - \log p_T/\mu$$

  crucial to make the analysis scale with statistics: simultaneous fit pass and fail regions
**Experimental challenges**

**Ingredients to observe H→bb**

- **Fail category:** Z,W peaks allow further calibration of the signal
- **Pass category:** bias on signal efficiency kept to a minimum

---

![Graphs showing data and signal](image-url)
Experimental challenges

Modelling backgrounds and statistical flukes
Experimental challenges

Modelling backgrounds and statistical flukes
Experimental challenges

Modelling backgrounds and statistical flukes

(c) Geotripper blog
A parametrization $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b \cdot \log(m_{\gamma\gamma})}$ models the main characteristics of the background. Calibrated in simulation using several test regions: extra correction terms added in order to keep the pulls bias <0.5.
Largest deviation for narrow width at 750 GeV with local significance $3.9\sigma$ ($3.4\sigma$). Taking into account the effect of testing all the signal hypotheses considered, the global significance is approximately $2.1\sigma$ ($1.6\sigma$).
Experimental challenges

Modelling backgrounds and statistical flukes

(c) A. David
Experimental challenges

Modelling backgrounds

- **Reducible background can be understood**
  - from detector response
  - applying tighter filter procedures

- **Irreducible backgrounds mimic the signal**
  - usually generated by high $\sigma$ processes
  - need extrapolation by several orders of magnitude
  - hard to believe (or generate) only simulated events

- **Blind analysis: often help to minimize bias**
  - optimize selection while understanding backgrounds
  - make sure uncertainties are in before opening box
Experimental challenges

Statistical flukes

• Anomalies shall appear!
  • apply 5-σ criterium: $P(\text{data} \mid \text{null hypothesis}) = 2.7 \times 10^{-5}\%$
  • size of the parameter space (mass range, models...) enhances probability of observing local deviations

• The look-elsewhere-effect can’t be neglected (see EPJC70:525-530,2010)
  • throw background-only toys and for each run background-only fit
  • how many of those trials surpassed the maximum local significance observed in data?
ATLAS+CMS: These are the most stringent limits on Randall-Sundrum graviton production to date.

Interpreting the 750 GeV digamma excess: a review

Alessandro Strumia

(Submitted on 30 May 2016 (v1), last revised 5 Aug 2016 (this version, v2))

We summarise the main experimental, phenomenological and theoretical issues related to the 750 GeV digamma excess


Report number: CERN–TH–2016–131

Cite as: arXiv:1605.09401 [hep-ph]
(or arXiv:1605.09401v2 [hep-ph] for this version)
Where theory meets the experimental challenges

Reprise: what do we measure at the LHC?

We count…

• There is (almost) no measurement without a supporting theory

\[
\sigma_{tot} = \frac{1}{A} \sigma_{fid} = \frac{1}{A} \cdot \frac{N_{signal}}{\mathcal{L} \cdot \varepsilon \cdot SF}
\]

• Result depends on the order of the calculation, non-perturbative models available
  - extrapolation through acceptance needs a theory model behind

• Theory may also enter in the fiducial measurement
  - Rare signals often need signal vs. background discriminator to be constructed
  - expected signal kinematics may also enter through efficiency term
Where theory meets the experimental challenges

Comparing back to theory

- Correcting a differential measurement = unfolding
  - brings in theory assumptions: \( \text{(data) } \rightarrow \text{(data} \otimes \text{detector simulation+theory priors)} \)
  - often requires regularisation procedures to allow for smooth matrix inversion
Where theory meets the experimental challenges

Simulation

- **Event generation using state-of-the-art Monte-Carlo**
  - NLO (LO) QCD matrix elements up to 2 (5) partons
  - matching to parton showers (Pythia, Herwig, Sherpa, …)

- **Final state particles passed through detector simulation**
  - usually based on Geant4 (transport and interaction with matter)
  - crucial step to get the best calibrated objects, e.g. jets:
    - Simulated hits are used to emulate the electronics behavior
    - Reconstruction from “digis” as if standard data

- **Notice: most data volume stored on tape is simulation**
  - order 5 billion events needed in 2016 for 37 fb\(^{-1}\) of data
Where theory meets the experimental challenges

The ubiquity of parton shower generators

- Widely used to predict the final outcome of a pp collision
- **Hard process (matrix element⊗PDF) needs to be dressed with**
  - shower evolution of the leptons and partons (strong and EWK ISR/FSR) + ME to PS matching
  - intrinsic $k_T$, multi-parton interactions, beam remnants and associated colour (re)-connections, etc.
- **Phenomenological models used to model non-perturbative QCD regime**
  - can be tuned but are ultimately an “uncertainty barrier for measurements”
Several processes have been computed at NNLO QCD

- scale band is 2-10% but in many cases does not encompass NLO!

EWK corrections start to matter:

- e.g. at high $p_T$ can contribute $O(10\%)$ to dijet rate
Where theory meets the experimental challenges

Cross sections II

- $p_T$ distributions span a wide range in theory predictions
- Small (large) $p_T$ dominated by resummed higher order (QCD at fixed-order)
  - electroweak corrections become also non-negligible at high $p_T$
  - are non-perturbative QCD effects under control down to <1%?
- Experimental precision competitive with NNLO ($Z$ $p_T$, top $p_T$)
  - use to extract PDFs, $\alpha_s$, couplings or are we biasing future measurements/searches?

![Graph showing $p_\perp$ distributions for leptons and jets with $m_T$ and $p_T$ ranges on the x-axis and y-axis with data and theoretical predictions]

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$\mu\mu$-channel

$66$ GeV $\leq m_\ell < 116$ GeV, $|y_\ell| < 2.4$

- Data statistics
- Detector
- Background
- Model
- Total systematic

**NNLOJET**

NNPDF 3.0

- p p $\rightarrow Z + 0$ jet ($p_T > 20$ GeV)

- ATLAS $\sqrt{s} = 8$ TeV

- $0 < |y^Z| < 2.4$

Where theory meets the experimental challenges

Strong coupling constant

- Contributes with relevant uncertainty at the LHC
  - World average yields 1.1% unc. on $\alpha_s(M_Z)$
  - Expansion parameter in PDFs, matrix elements, …
  - Increasingly relevant to probe new physics more accurately

\[ \sigma(gg\to H) \text{ at } N^3\text{LO} \]
\[ \sigma(t\bar{t}) \text{ at } N^2\text{LO}+\text{NNLL} \]

![Graph of $\alpha_s(M_Z)$](arXiv:1602.00695)

![Graph of $\sigma(gg\to H)$](arXiv:1303.6254)
Where theory meets the experimental challenges

Strong coupling constant

- Measurements at different $Q^2$ brought to $M_Z$ reference
  - use the running of $\alpha_s$: \[ \mu^2 R \frac{d\alpha_s}{d\mu^2_R} = \beta(\alpha_s) = -(b_0 \alpha_s^2 + b_1 \alpha_s^3 + b_2 \alpha_s^4 + \cdots) \]
  - extrapolation from LHC data limited by theory: 5% jets, 3% tt data
  - is going beyond 1% in the hands of lattice QCD?
Where theory meets the experimental challenges

PDF uncertainties

- Inclusive jet production, W/Z, top measurements from Run I
  - provide different sensitivity to gluon and quark PDFs

![Graph showing theoretical and experimental data for jet production]
Where theory meets the experimental challenges

PDF uncertainties

- Inclusive jet production, $W/Z$, top measurements from Run I
  - provide different sensitivity to gluon and quark PDFs

- Currently $O(2-3\%)$ parton luminosity unc.
  - significant improvement from Run I results
  - but we need more, to profit from new data

- Further improvements need
  - improved luminosity determinations
  - reducing np-QCD uncertainties
  - reduce circularities in measure $\rightarrow$ fit/tune
  - precision determination of $\alpha_s$, $m_c$, $m_b$, $m_t$
Summary

“Não procures a noite por não suportares o dia.”
“If the day is beyond your endurance, do not seek the night.”
V. Ferreira
most of this talk as of today
most of this talk as of today
Summary

• The LHC has been shedding light on the missing pieces of matter and interactions
  • Higgs boson is definitely the greatest achievement so far
  • direct searches haven’t yet uncovered striking new phenomena
  • precision measurements (many not referred here) are a crucial piece in the hunt

• Detector development is a fundamental part of the experiments physics programme
  • to reach successfully the goal of measuring Higgs couplings, probe fully the TeV scale
  • new proposals including new trackers, calorimeters, trigger/DAQ systems under development

The goal is clear, the path to get there is open to your imagination!
Spares
Pileup mitigation techniques I

- Pileup can be mitigated using track association to the primary vertex (PV)
  - identify jets from pileup based on the fraction of tracks associated to PVs
  - can also remove tracks entering the fits of other PVs before clustering
    (improves resolution over standard particle flow, in particular at high pileup)
Experimental challenges

Pileup mitigation techniques II

- At calorimeter level PV association is more difficult (needs pointing and timing capabilities)
  - combined fit of pulses from different bunch crossings: mitigate out-of-time pileup
  - topological clustering: start from seeds above noise and iterate to add high significance neighbours