ATLAS @ LHC: status and recent results

28th International Symposium on Lepton Photon Interactions at High Energies

Sun Yat-Sen University, Guangzhou China
7 August 2017

Rob McPherson University of Victoria / IPP + TRIUMF
On behalf of the ATLAS Collaboration
• 182 Institutions in 38 Countries
  - Including 9 Chinese institutes
• ~ 2900 Scientific Authors
  ~ 1900 with PhD, contributing to M&O share
  ~ 1000 Students
Outline of Talk

• ATLAS data-taking and performance
• ATLAS recent physics analysis results
• ATLAS Upgrades
• Summary
Outline of Talk

- ATLAS data-taking and performance
- ATLAS recent physics analysis results
- ATLAS Upgrades
- Summary
Excellent but Challenging LHC Performance

- 2016 p-p $\mathcal{L}_{\text{PEAK}}$ record $\approx 1.4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  $\mu$ (peak) $\approx 44$ interactions per crossing
  $\int \mathcal{L} = 38.5$ fb$^{-1}$ delivered by LHC

- 2017 p-p $\mathcal{L}_{\text{PEAK}}$ already $\approx 1.7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
  $\mu$ (peak) $\approx 50$ interactions per crossing
  $\int \mathcal{L} = 11.7$ fb$^{-1}$ delivered by LHC (2017/08/04)

Pileup: average per fill

$\int \mathcal{L} = 51.9$ fb$^{-1}$

$\mu$ (peak) $\approx 25$ other interactions

Z$\rightarrow$\mu\mu with 25 other interactions
Trigger Performance in 2016

- Trigger menu: physics, monitoring, calibration requirements
  - ~2000 active menu items
  - Level-1 rate: up to 100 kHz, Physics output rate ~1kHz
  - **Challenge: non-linear growth of trigger rates with pileup**
    - *E*$_T^{\text{miss}}$ resolution badly degraded by pileup potentially ⇒ threshold increase?

### Typical trigger thresholds at 1.4x10$^{34}$ cm$^{-2}$s$^{-1}$:
- *E*$_T$(e) > 26 GeV
- *p*$_T$(μ) > 26 GeV
- *E*$_T^{\text{miss}}$ > 110 GeV
- *E*$_T$(jet) > 380 GeV
- *E*$_T$(γ) > 140 GeV
Physics Object Performance

- **Physics analyses start with detector data, then physics objects:**
  - electrons, muons, taus, jets, b-tagged jets, $E_t^{\text{miss}}$ etc.
- **Huge effort throughout 2016 and early 2017 to stabilize performance**
  - Eg: $m(ee)$ in $Z\rightarrow ee$:

  **Mean of $m(ee)$ for $Z\rightarrow ee$ events vs. pile-up showing sub per-mille stability in 2016**

  **2016**

  **2016 & 2017**

  **2017-08-07 Rob McPherson**
Outline of Talk

• **ATLAS** data-taking and performance
• **ATLAS** recent physics analysis results
• **ATLAS** Upgrades
• Summary
Outline of Talk

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Only a few selected results presented here
Standard Model Processes

Standard Model Production Cross Section Measurements

**ATLAS Preliminary**
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

**LHC pp $\sqrt{s} = 7$ TeV**
- Data $4.5 - 4.9$ fb$^{-1}$

**LHC pp $\sqrt{s} = 8$ TeV**
- Data $20.3$ fb$^{-1}$

**LHC pp $\sqrt{s} = 13$ TeV**
- Data $0.08 - 36.1$ fb$^{-1}$
W Boson Mass Measurement

- **4.6 fb\(^{-1}\) of 7 TeV data** (\(W \rightarrow e\nu/\mu\nu\))
- **Huge amount of work since 2011 to understand detector response and modelling of kinematic quantities, e.g. lepton \(p_T\), \(E_T^{\text{miss}}\)**
  - Calibration of W recoil with \(Z \rightarrow \ell\ell\) data critical
- **Similar precision to best previous single experiment measurement (from CDF)**
- **Result consistent with SM expectation**
- **Further progress requires improved modelling**

\[
m_W = 80.370 \pm 0.019 \text{ GeV} \\
[\pm 7 \text{ MeV (stat.)} \pm 11 \text{ MeV (syst.)} \pm 14 \text{ MeV (modelling)}]
\]
Top Quark Physics example: Zt

- Previously evidence for single top quark production at LHC in s-channel, t-channel and Wt associated production

- Now also evidence for Zt production
  - Significance \(4.2\sigma\) (\(5.4\sigma\) expected)
  - Cross-section \(620 \pm 170_{\text{stat}} \pm 140_{\text{syst}}\) fb consistent with SM expectation

- Also m(top), ttW, ttZ, etc.

Distribution of NN discriminant in Zt search
## Searches for “Exotic” New Physics

### ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

**Status:** July 2017

\[
\int \mathcal{L} \, dt = (3.2 - 37.0) \text{ fb}^{-1} \quad \sqrt{s} = 8, 13 \text{ TeV}
\]

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets†</th>
<th>( E_{T}^{miss} )</th>
<th>( \int \mathcal{L} , dt ) [fb(^{-1})]</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD GKK + g/lq</td>
<td>0 e, ( \mu )</td>
<td>1, 2 j</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_0 )</td>
</tr>
<tr>
<td>ADD non-resonant ( g/\gamma )</td>
<td>2 e, ( \mu )</td>
<td>–</td>
<td>–</td>
<td>36.7</td>
<td>( \text{M}_0 )</td>
</tr>
<tr>
<td>ADD QbH</td>
<td>–</td>
<td>2 j</td>
<td>Yes</td>
<td>37.0</td>
<td>( \text{M}_0 )</td>
</tr>
<tr>
<td>ADD BH high ( \Sigma_{\ell\ell} )</td>
<td>( \geq 1 ) e, ( \mu )</td>
<td>2 j</td>
<td>–</td>
<td>3.2</td>
<td>( \text{M}_0 )</td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>–</td>
<td>3 j</td>
<td>–</td>
<td>3.6</td>
<td>( \text{M}_0 )</td>
</tr>
<tr>
<td>RS1 ( G_{\text{RS}} \rightarrow \gamma \gamma )</td>
<td>2 e, ( \mu )</td>
<td>1 J</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Gamm} )</td>
</tr>
<tr>
<td>RS1 ( G_{\text{RS}} \rightarrow WW \rightarrow q\bar{q}l\ell )</td>
<td>2 e, ( \mu )</td>
<td>1 J</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Gamm} )</td>
</tr>
<tr>
<td>2UED / RPP</td>
<td>1 e, ( \mu )</td>
<td>2, 3 j</td>
<td>Yes</td>
<td>13.2</td>
<td>( \text{M}_\text{RPP} )</td>
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<tr>
<td>Gauge bosons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM Z' \rightarrow \ell\ell</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Z'} )</td>
<td>4.5 TeV</td>
</tr>
<tr>
<td>SM Z' \rightarrow \tau\tau</td>
<td>2 ( \tau )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Z'} )</td>
<td>2.4 TeV</td>
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<tr>
<td>Leptophobic Z' \rightarrow bb</td>
<td>2 b</td>
<td>Yes</td>
<td>3.2</td>
<td>( \text{M}_\text{Z'} )</td>
<td>1.5 TeV</td>
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<tr>
<td>Leptophobic Z' \rightarrow rt</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Z'} )</td>
<td>2.0 TeV</td>
</tr>
<tr>
<td>SM W' \rightarrow t\bar{t}</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{W'} )</td>
<td>5.1 TeV</td>
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<tr>
<td>HVT ( V' \rightarrow WW \rightarrow qqqq )</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>36.7</td>
<td>( \text{M}_\text{W'} )</td>
<td>3.5 TeV</td>
</tr>
<tr>
<td>HVT ( V' \rightarrow WH/ZH )</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>36.7</td>
<td>( \text{M}_\text{W'} )</td>
<td>2.93 TeV</td>
</tr>
<tr>
<td>LRSM ( W'_L \rightarrow tb )</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_\text{W'} )</td>
<td>1.32 TeV</td>
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<tr>
<td>LRSM ( W'_R \rightarrow tb )</td>
<td>0 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_\text{W'} )</td>
<td>1.76 TeV</td>
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<td>DM</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Axial vector mediator (Dirac DM)</td>
<td>0 e, ( \mu )</td>
<td>1, 2 j</td>
<td>Yes</td>
<td>40.1 TeV</td>
<td>( \text{M}_\text{Dirac} )</td>
</tr>
<tr>
<td>Vector mediator (Dirac DM)</td>
<td>0 e, ( \mu ), 1 ( \gamma )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Dirac} )</td>
<td>4.3 TeV</td>
</tr>
<tr>
<td>VLX EFT (Dirac DM)</td>
<td>0 e, ( \mu ), 1 ( j \gamma )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_\text{Dirac} )</td>
<td>4.3 TeV</td>
</tr>
<tr>
<td>Scatter DM 1st gen</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>3.2</td>
<td>( \text{M}_{\chi} )</td>
<td>700 GeV</td>
</tr>
<tr>
<td>Scatter DM 2nd gen</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>3.2</td>
<td>( \text{M}_{\chi} )</td>
<td>1.05 TeV</td>
</tr>
<tr>
<td>Scatter DM 3rd gen</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>3.2</td>
<td>( \text{M}_{\chi} )</td>
<td>1.05 TeV</td>
</tr>
<tr>
<td>LO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VLO ( TT \rightarrow Ht \rightarrow X )</td>
<td>0 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_{\chi} )</td>
<td>540 GeV</td>
</tr>
<tr>
<td>VLO ( TT \rightarrow Zt \rightarrow X )</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_{\chi} )</td>
<td>540 GeV</td>
</tr>
<tr>
<td>VLO ( TT \rightarrow WW \rightarrow X )</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_{\chi} )</td>
<td>540 GeV</td>
</tr>
<tr>
<td>VLO ( BR \rightarrow Hb \rightarrow X )</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\chi} )</td>
<td>700 GeV</td>
</tr>
<tr>
<td>VLO ( BR \rightarrow Zb \rightarrow X )</td>
<td>2 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\chi} )</td>
<td>700 GeV</td>
</tr>
<tr>
<td>VLO ( BR \rightarrow Vt \rightarrow X )</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>36.1</td>
<td>( \text{M}_{\chi} )</td>
<td>1.23 GeV</td>
</tr>
<tr>
<td>VLO ( QQ \rightarrow WqWq )</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\chi} )</td>
<td>600 GeV</td>
</tr>
<tr>
<td>Excited fermions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excited quark ( q' \rightarrow q )</td>
<td>–</td>
<td>2 j</td>
<td>Yes</td>
<td>37.0</td>
<td>( \text{q'} )</td>
</tr>
<tr>
<td>Excited quark ( q' \rightarrow q )</td>
<td>–</td>
<td>2 j</td>
<td>Yes</td>
<td>37.0</td>
<td>( \text{q'} )</td>
</tr>
<tr>
<td>Excited quark ( b' \rightarrow b )</td>
<td>–</td>
<td>2 j</td>
<td>Yes</td>
<td>37.0</td>
<td>( \text{b'} )</td>
</tr>
<tr>
<td>Excited quark ( b' \rightarrow b )</td>
<td>–</td>
<td>2 j</td>
<td>Yes</td>
<td>37.0</td>
<td>( \text{b'} )</td>
</tr>
<tr>
<td>Excited lepton ( l' )</td>
<td>3 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{l'} )</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>Excited lepton ( l' )</td>
<td>3 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{l'} )</td>
<td>1.5 TeV</td>
</tr>
<tr>
<td>LqRM Majorana v</td>
<td>0 e, ( \mu )</td>
<td>2 j</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\text{Majorana}} )</td>
</tr>
<tr>
<td>Higgs triplet ( H^{+} \rightarrow \ell \ell )</td>
<td>3 e, ( \mu )</td>
<td>2 j</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\text{Majorana}} )</td>
</tr>
<tr>
<td>Higgs triplet ( H^{+} \rightarrow \ell \ell )</td>
<td>3 e, ( \mu )</td>
<td>2 j</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\text{Majorana}} )</td>
</tr>
<tr>
<td>Monopole (non-res prod)</td>
<td>1 e, ( \mu )</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\text{Majorana}} )</td>
<td>607 GeV</td>
</tr>
<tr>
<td>Dipole (multi-charged particles)</td>
<td>–</td>
<td>Yes</td>
<td>20.3</td>
<td>( \text{M}_{\text{Majorana}} )</td>
<td>785 GeV</td>
</tr>
<tr>
<td>Magnetic monopole</td>
<td>–</td>
<td>Yes</td>
<td>7.0</td>
<td>( \text{M}_{\text{Majorana}} )</td>
<td>1.32 TeV</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 \( j \) (\( J \)).
Resonance Searches - Dilepton, Lepton+E_{T}^{miss}

- $X \rightarrow \ell^{+}\ell^{-}$ (eg Z')
  - $m(\ell^{+}\ell^{-})$ Peak

- $Y \rightarrow \ell^{\pm} + E_{T}^{miss}$ (eg W')
  - $m_{T}(\ell^{\pm})$ Peak/edge

- No significant excess over SM expectation

- 95% CL exclusion limits extracted in various new physics scenarios
Resonance Searches - Dibosons

- \( X \rightarrow VV, VH, HH \) (\( V=W/Z \))
  - \( VV \rightarrow qqqq / qq\ell\nu / qq\ell\ell \)
  - \( VH \rightarrow bbqq / bb\ell\nu / bb\ell\ell \)

- Merged jets at high \( p_T \) using substructure

- “boson-tagging”

Dijet mass in \( VV\rightarrow qqqq \) search with boson-tagged jets
Resonance Searches - $\tau^+ \tau^-$

- $X \rightarrow \tau^+ \tau^-$
  - Heavy Higgs, eg from SUSY
- No significant excesses over SM expectation

\[ \tan \beta > 45 \text{ for } m_A = 1.5 \text{ TeV} \]
Searches for Dark Matter (DM)

- **Something + DM** where DM $\rightarrow E_T^{\text{miss}}$
  - Jet(s) + $E_T^{\text{miss}}$
  - $\gamma$ + $E_T^{\text{miss}}$
  - $H$ ($\rightarrow \gamma\gamma/\text{bb}$) + $E_T^{\text{miss}}$

- Complementary to direct dark matter searches
- Use “simplified models” to guide analyses and interpret results

**Spin-Dependent $\sigma_{SD}$ - m_{DM} plane – Axial-vector Mediator**

- Axial-vector mediator, Dirac DM
  - $g_q = 0.25$, $g_\ell = 0$, $g_{DM} = 1$

**Spin-Independent $\sigma_{SI}$ - m_{DM} plane – Vector Mediator**

- Vector mediator, Dirac DM
  - $g_q = 0.1$, $g_\ell = 0.01$, $g_{DM} = 1$

**ATLAS-CONF-2017-060**

**$E_T^{\text{miss}}$ distribution in monojet search**

**Data/SM**

**DM Mass [GeV]**

- $\sigma_{SD}$ (DM-nucleon) [cm$^{-2}$]
- $\sigma_{SI}$ (DM-nucleon) [cm$^{-2}$]
# Searches for Supersymmetry

**ATLAS SUSY Searches** - 95% CL Lower Limits

**May 2017**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell$, $\mu$, $\tau$, $\gamma$ Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\sqrt{s}$ TeV</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0 $\ell$, 2-10 jets 3 $b$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.85 TeV</td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{q}, \tilde{t}$ (compressed)</td>
<td>mono-jet 1-3 jets</td>
<td>Yes</td>
<td>3.2</td>
<td>0.57 TeV</td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{W}/\tilde{Z}$</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
</tr>
<tr>
<td>GMSB (2 NLSP)</td>
<td>1-2 $\ell$, 0-1 $t$</td>
<td>Yes</td>
<td>3.2</td>
<td>2.02 TeV</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>2 $\gamma$</td>
<td>Yes</td>
<td>3.2</td>
<td>1.85 TeV</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>$\gamma$, 1 $b$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.37 TeV</td>
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<tr>
<td>GGM (higgsino NLSP)</td>
<td>2 $\gamma$, 2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.37 TeV</td>
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<td>Chargino LSP</td>
<td>0 mono-jet</td>
<td>Yes</td>
<td>20.3</td>
<td>0.57 TeV</td>
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**1st gen. squarks and sleptons**

<table>
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<tr>
<th>Model</th>
<th>$\tilde{g}, \tilde{q}, \tilde{t}$</th>
<th>$\tilde{b}, \tilde{t}$</th>
<th>$\tilde{W}/\tilde{Z}$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\sqrt{s}$ TeV</th>
<th>Mass limit</th>
</tr>
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<tbody>
<tr>
<td>0, 2 $\ell$</td>
<td>0, 2 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
<td></td>
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<tr>
<td>0-2 $\ell$, 0-2 jets</td>
<td>2.4 TeV</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
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<td>2.02 TeV</td>
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<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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**Higgs bosons**

<table>
<thead>
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<th>Model</th>
<th>$\tilde{g}, \tilde{q}, \tilde{t}$</th>
<th>$\tilde{b}, \tilde{t}$</th>
<th>$\tilde{W}/\tilde{Z}$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\sqrt{s}$ TeV</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td>0, 2 $\ell$</td>
<td>0, 2 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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<tr>
<td>0-2 $\ell$, 0-2 jets</td>
<td>2.4 TeV</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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</tr>
<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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</table>

**E.W. direct**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\tilde{g}, \tilde{q}, \tilde{t}$</th>
<th>$\tilde{b}, \tilde{t}$</th>
<th>$\tilde{W}/\tilde{Z}$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\sqrt{s}$ TeV</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 2 $\ell$</td>
<td>0, 2 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>2.02 TeV</td>
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<td>0-2 $\ell$, 0-2 jets</td>
<td>2.4 TeV</td>
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<td>0, 2 $\ell$</td>
<td>1 $b$</td>
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<td>36.1</td>
<td>2.02 TeV</td>
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<tr>
<td>0, 2 $\ell$</td>
<td>1 $b$</td>
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<td>36.1</td>
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**Long-lived particles**

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<th>$\tilde{g}, \tilde{q}, \tilde{t}$</th>
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<th>$\tilde{W}/\tilde{Z}$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\sqrt{s}$ TeV</th>
<th>Mass limit</th>
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<tbody>
<tr>
<td>Direct $\tilde{g}, \tilde{q}, \tilde{t}$</td>
<td>Disapp. trk 1 jet</td>
<td>Yes</td>
<td>36.1</td>
<td>1.85 TeV</td>
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<tr>
<td>Stable $\tilde{g}, \tilde{q}, \tilde{t}$</td>
<td>trk 1 jet</td>
<td>Yes</td>
<td>27.9</td>
<td>1.85 TeV</td>
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<tr>
<td>Stable $\tilde{g}, \tilde{q}, \tilde{t}$</td>
<td>Disapp. trk 1 jet</td>
<td>Yes</td>
<td>27.9</td>
<td>1.85 TeV</td>
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<tr>
<td>CMSB stable $\tilde{g}, \tilde{q}, \tilde{t}$</td>
<td>1-2 $\ell$</td>
<td>Yes</td>
<td>19.1</td>
<td>1.85 TeV</td>
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<td>CMSB, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</td>
<td>2 $\gamma$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.85 TeV</td>
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<tr>
<td>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</td>
<td>disp. trk $\mu^{-}+\mu^{-}$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.85 TeV</td>
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<tr>
<td>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</td>
<td>disp. trk $\ell^{-}+\ell^{-}$</td>
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<td>20.3</td>
<td>1.85 TeV</td>
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**Other**

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<th>Model</th>
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<th>$\tilde{W}/\tilde{Z}$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$</th>
<th>$\sqrt{s}$ TeV</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar charm, $2\rightarrow \ell^\pm\chi_1^0$</td>
<td>0, 2 $b$</td>
<td>Yes</td>
<td>36.1</td>
<td>1.85 TeV</td>
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</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
**SUSY: 3rd Generation and Electroweak Limits in m(t_{1}) – m(\chi_{0}^{1}) plane**

- **“Natural SUSY”**
  - light 3rd generation squarks and higgsinos cancel Higgs mass loop corrections
  - Direct stop (\tilde{t}_{1})
    - b-jets + E_{T}^{miss}
    - Many different signal regions:
      - Highly optimized

Limits on m(\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{2}^{0}) – m(\tilde{\chi}_{1}^{0})

- Direct production of charginos and neutralinos with
  - 2 or 3 leptons + E_{T}^{miss}
  - Many different signal regions:
    - Highly optimized

---

**Limits in m(\tilde{t}_{1}) – m(\tilde{\chi}_{1}^{0}) plane**

Status: May 2017

- ATLAS Preliminary
- m(\tilde{t}_{1}) > 950 GeV

- \tilde{t}_{1} production, t\rightarrow b f f \tilde{\chi}_{1}^{0}, t\rightarrow c f f \tilde{\chi}_{2}^{0}, t\rightarrow W b \tilde{\chi}_{1}^{0} / t\rightarrow W b \tilde{\chi}_{1}^{+} / t\rightarrow t f f \tilde{\chi}_{1}^{0}

- Observed limits
- Expected limits
- All limits at 95% CL

---

**Limits on m(\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{2}^{0}) – m(\tilde{\chi}_{1}^{0})**

May 2017

- ATLAS Preliminary
- \sqrt{s}=8,13 TeV, 20.3-36.1 fb^{-1}

- m(\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{2}^{0}) > 580 GeV

- Expected limits
- Observed limits

- All limits at 95% CL

---

**2 or 3 leptons + E_{T}^{miss}**
Higgs Boson Studies ...

- Higgs-like particle discovery by ATLAS and CMS announced July 4th, 2012. ATLAS paper:
  - 7503 citations (as of 2017-08-03)

- March 2013: key papers on particle properties
  - new particle declared “a Higgs boson”

- Citation for 2013 Nobel Prize in Physics
Higgs Boson Production at $\sqrt{s} = 13$ TeV

- Measurements use $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels
  - Larger $\sqrt{s}$ & data $\Rightarrow$ more measurements possible
    - Fiducial cross-sections
    - Differential cross-sections
    - Total production cross-sections (assumes SM branching ratios)
- Combined global signal strength compatible with Standard Model:

  \[
  \mu = 1.09 \pm 0.12
  \]

  \[
  = 1.09 \pm 0.09 \text{ (stat.)} + 0.06 \text{ (syst.)} + 0.06 \text{ (th.)}
  \]

2017-08-07

Theory uncertainty reduced: N3LO ggF calculations
**Higgs Boson Cross-Sections**

- **Higgs differential cross-sections**
  - Possible with increased data sets and $\sqrt{s}$
- **Interpret in terms of cross-sections for production processes**
  - $\text{ggF}$: gluon fusion
  - $\text{VBF}$: vector boson fusion

**ATLAS-CONF-2017-032**

**ATLAS-CONF-2017-047**

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, $36.1$ fb$^{-1}$

- $H \rightarrow ZZ^* \rightarrow 4\ell$
- $m_H = 125.09$ GeV, $|y_H|<2.5$

**Cross-section vs. $p_T(4\ell)$**

- Data
- Syst. uncertainties
- HRes $k = 1.1$, $+XH$
- NNLOPS $k = 1.1$, $+XH$
- MG5 FxFx $k = 1.47$, $+XH$
- $p$-value NNLOPS = 25%
- $p$-value MG5 FxFx = 42%
- $p$-value HRes = 21%

**Higgs entering into precision measurement era with increased data sets and improved theoretical predictions**
Measurement of the Higgs Boson Mass

- $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma \gamma$
- **Measurements complementary:**
  - 4$\ell$ channel stat uncertainty dominates with very small systematics
    - Will continue to improve as ATLAS acquires more data even into HL-LHC era
  - $\gamma \gamma$ channel syst uncertainty dominates (photon energy scale calibration)
- In 4$\ell$ channel measurements consistent among electron/muon sub-channels
- 4$\ell$ and $\gamma \gamma$ measurements consistent
- Combined measurement consistent with Run-1

\[
\begin{align*}
\text{ATLAS Preliminary} & \\
\sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} & \\
\text{LHC Run 1} & \\
H \rightarrow ZZ^* \rightarrow 4\ell & \quad 124.88 \pm 0.37 \ (\pm 0.37 \pm 0.05) \text{ GeV} \\
H \rightarrow \gamma \gamma & \quad 125.11 \pm 0.42 \ (\pm 0.21 \pm 0.36) \text{ GeV} \\
\text{Combined} & \quad 124.98 \pm 0.28 \ (\pm 0.19 \pm 0.21) \text{ GeV}
\end{align*}
\]
**H→bb: analysis strategy and validation**

- **H→bb mode dominates Higgs decays (BR~58%)**
- **Most sensitive channel exploits VH(→bb), V=W/Z**
- **Combined Tevatron significance at m_H=125 GeV 2.8σ**
- **Combined Run-1 ATLAS+CMS significance 2.6σ**

- **ATLAS analysis combines Z and W final states:**
  - 2-lepton (Z→ℓℓ)
  - 1-lepton (W→ℓν)
  - 0-lepton (Z→vv)
- **MVA-based (Boosted Decision tree), cross-checked by cut-based selection**

- **Validation of performance and systematics understanding from independent search for VZ(→bb)**
  - Obs. (exp.) significance: 5.8σ (5.3σ)
  - Observed signal strength:

\[
\mu_{VZ} = 1.11^{+0.12}_{-0.11} \text{(stat.)}^{+0.22}_{-0.19} \text{(syst.)}
\]
Evidence for $H \rightarrow bb$

- BDT trained separately for VH($\rightarrow bb$) search
- Observed significance $3.5\sigma$ ($3.0\sigma$ expected)
- Cross-check with cut-based analysis gives $3.5\sigma$ observed ($2.8\sigma$ expected)
- Combination of MVA result with ATLAS Run-1 gives $3.6\sigma$ observed ($4.0\sigma$ expected)
- Evidence for $H \rightarrow bb$, consistent with SM
$W(\rightarrow e\nu)H(\rightarrow bb)$ candidate
• Submitted or published 656 papers (as of 4 August 2017)
  – Including 79 with Run II data
  – Still steady rate of Run I data papers (measurements)
Outline of Talk

• ATLAS data-taking and performance
• ATLAS recent physics analysis results
• **ATLAS Upgrades**
• Summary
Upgrade examples in pictures

- **Phase-I: new muon small wheel**
  - Micromegas and thin-gap chambers

- **Phase-II: new inner tracker**
  - All silicon design strips and pixels

H8 test beam

Itk strip module placement on petals
Outline of Talk

• ATLAS data-taking and performance
• ATLAS recent physics analysis results
• ATLAS Upgrades
• Summary
Summary

- ATLAS detector, trigger, computing and analysis are coping well with luminosities approaching twice LHC design
- Many measurements from collision data
  - Challenging theory calculations in many final states
  - Entering precision measurement era for H(125)
  - Evidence for $H \rightarrow bb$ and closing in on rare Higgs processes
  - Wide spectrum of results I cannot cover – see later talks this week eg. B-hadron physics, heavy ions, QCD
- Huge range of searches for BSM physics
  - No significant excesses have persisted so far
- ATLAS Upgrade program also very active preparing for HL-LHC
  - LHC program still in its infancy. Only a $\approx$ percent of full data so far.
- We are approaching sensitivities for new, weakly-coupled electroweak-scale physics of any form.
- Huge credit and thanks to the LHC and injector teams who are delivering extraordinary luminosities!

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ATLAS results

• For further ATLAS results and details of the ones shown here:
  - ATLAS public results page: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - Talks at this symposium include the following:
    • Elisabetta Pianori: Higgs in diboson modes
    • Keti Kaadze: Higgs in fermionic modes
    • Soshi Tsuno: BSM Higgs
    • Iacopo Vivarelli: SUSY searches
    • Sunil Somalwar: Exotic Searches
    • Oliver Buchmueller: Searches for DM
    • Yuji Yamazaki: top-quark measurements
    • Qiang Li: EW measurements
    • Gabriella Pasztor: Hard QCD
    • Marek Tasevsky: Soft QCD
    • Alexander Kalweit: Experimental Heavy Ion results
    • Yuan-Ning Gao: Hadron Spectroscopy
• Additional Material
Resonance Searches - $\gamma\gamma$

- $X \rightarrow \gamma\gamma$
  - New heavy spin-0 scalars, e.g. heavy Higgs
  - Spin-2 (eg, gravitons)

- No significant excesses over SM expectation

Mass limits from $\gamma\gamma$ spin-0 search

arXiv:1707.04147
High Mass Diphoton Mass Distributions

ATLAS

\[ \text{Data} \]

\[ \text{Background-only fit} \]

Spin-0 Selection
\[ \sqrt{s} = 13 \text{ TeV, 36.7 fb}^{-1} \]

ATLAS

\[ \text{Data} \]

\[ \text{Background-only fit} \]

Spin-2 Selection
\[ \sqrt{s} = 13 \text{ TeV, 36.7 fb}^{-1} \]

arXiv:1707.04147

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High Mass Diphoton Limits

ATLAS

Observed $\CL_s$ limit
Expected $\CL_s$ limit
Expected $\pm 1\sigma$
Expected $\pm 2\sigma$

$\ell s = 13$ TeV, 36.7 fb$^{-1}$
Spin-0 Selection
NWA ($\Gamma X = 4$ MeV)

Expected CL$_s$ limit
Observed CL$_s$ limit from pseudo-exp.
Expected CL$_s$ limit from pseudo-exp.

ATLAS

Observed $\CL_s$ limit
Expected $\CL_s$ limit
Expected $\pm 1\sigma$
Expected $\pm 2\sigma$

$\ell s = 13$ TeV, 36.7 fb$^{-1}$
Spin-2 Selection
$G^{*\rightarrow \gamma\gamma}$, $k/M_{Pl} = 0.10$

arXiv:1707.04147

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Searches with Dijets

- dijet mass and angular distributions
- No significant excesses over SM expectation
- Significantly extend limits. e.g.
  - Excited quarks: \( m(q^*) > 6.0 \text{ TeV} \) (5.8 TeV exp.)
  - Add. gauge bosons: \( m(W') > 3.6 \text{ TeV} \) (3.7 TeV exp.)
  - Quantum Black Holes: \( m(\text{BH}) > 8.9 \text{ TeV} \) (8.9 TeV exp.)
  - Contact Interactions: \( \Lambda > 13.1 \text{ TeV} \) (\( \eta_{LL} = +1/-1 \))
- Limits also set on generic Gaussian resonances

Limits on generic Gaussian resonance

\[ m(q^*) > 6 \text{ TeV} \]
Higgs Production Mode Signal Strength

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
\( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^{*} \rightarrow 4l \)
\( m_H = 125.09 \text{ GeV}, |y_H| < 2.5 \)

4D compatibility with SM: 5%

Cross section normalized to SM
Physics with B Hadrons

- Kinematics of products from decay $B_d^0 \rightarrow K^* \mu^+ \mu^-$ measured to constrain components of generic expression for amplitude
- $P5'$ parameter (amplitude normalised by fraction of longitudinally polarised $K^*$) measured to exceed SM expectation at moderate $q^2 = m(\mu\mu) \sim 5$ GeV$^2$ by LHCb and Belle
- ATLAS analysis with 8 TeV Run-1 data consistent with SM expectation in this bin, but also with LHCb and Belle measurements
Evidence for light-by-light scattering $\gamma \gamma \rightarrow \gamma \gamma$ in 5 TeV Ultra-Peripheral Pb-Pb collisions

Further evidence that production of strongly interacting particles is increasingly suppressed as density of nuclear medium increases.

- Evidence for jet suppression up to ~1 TeV

Results with novel sub-event cumulant method removing dijet contributions from pp and p-Pb elliptic flow measurements (ATLAS-CONF-2017-002)

Acoplanarity of photon pairs in low activity ultra-peripheral Pb-Pb collisions
• **WLCG has been fundamental to ATLAS physics analysis**
  • Fully leverage all pledged resources
  • Aggressively use non-pledged CPU resources
High Performance Computing, Clouds

- Increasing opportunistic use of clouds and HPCs: ~15%
  - event generation and Monte Carlo production
- Integration of non-Grid resources in ATLAS: big investment, big return

2017-08-07

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### ATLAS Upgrade Timelines

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase 0 Upgrade</th>
<th>Phase I Upgrade</th>
<th>Phase II Upgrade</th>
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<tbody>
<tr>
<td>2010</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2011</td>
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<tr>
<td>2012</td>
<td></td>
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<tr>
<td>2013</td>
<td>Consolidation, $\sqrt{s}=13$ TeV, 25nsec bunch spacing, $\mathcal{L} \approx 1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ ($\mu \approx 30-50$) $\int \mathcal{L} \approx 150$ fb$^{-1}$</td>
<td>Likely $\sqrt{s}=14$ TeV</td>
<td>$\mathcal{L} \approx 7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ ($\mu \approx 200$) $\int \mathcal{L} \approx 3000$ fb$^{-1}$</td>
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<td>2014</td>
<td>New insertable pixel b-layer (IBL)</td>
<td>All new Tracking Inner Detector</td>
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<tr>
<td>2015</td>
<td>New Al beam pipe</td>
<td>Calorimeter Electronics Upgrades</td>
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<td>2016</td>
<td>New pixel services</td>
<td>Muon system upgrades</td>
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<td>2017</td>
<td>New evaporative cooling plant</td>
<td>Level-1 track trigger</td>
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<tr>
<td>2018</td>
<td>Consolidation (calorimeter power supplies)</td>
<td>Trigger-DAQ</td>
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<tr>
<td>2019</td>
<td>Neutron Shielding</td>
<td>High Granularity Timing Detector (R&amp;D)</td>
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<tr>
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<td>Finish EE muons installation</td>
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<td>Upgrade magnet cryo</td>
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