Highlights of ATLAS 13 TeV 2015 LHC Run2 Results

Haijun Yang
(on behalf of the ATLAS Collaboration)

Outline
- SM EW
- SM Top
- SM Higgs
- BSM Higgs Search
- SUSY Search
- Dark Matter Search
- Exotic Search
- Diboson Resonance

The France-China Particle Physics Laboratory (FCPPL)
Strasbourg, France
March 30 – April 2, 2016
LHC Restart at 13 TeV (Run2) in 2015

- LHC restart: April 2, 2015
- Proton beams circulating at 450 GeV: April 5, 2015
- Proton beam energy reaches 6.5 TeV: April 10, 2015
- ATLAS accumulated 4 fb\(^{-1}\) data: November 4, 2015
- LHC EOYE results: December 15, 2015
Inelastic pp Cross Section

- Using low pileup dataset ($\mu < 0.05$)
- Analysis with new MBTS scintillators ($2.1 < |\eta| < 3.9$)
- Result dominated by luminosity uncertainty ($\sim 9\%$)
- 4.2M events selected in 63 $\mu$b$^{-1}$, estimated 1% background

$N_{\text{MBTS}}$ above threshold (Data vs. MCs)

73.1 $\pm$ 0.9 (exp.) $\pm$ 6.6 (lum.) $\pm$ 3.8 (extr.) mb
Charged-particle Multiplicity

- Inclusive charged-particle measurements in pp collisions provide insight into the strong interaction in the low-energy, non-perturbative region of QCD.
- Charged-particle multiplicity for events with $n_{\text{ch}} \geq 1$, $p_T > 500 \text{MeV}$, $|\eta| < 2.5$ validate pileup modeling for early analysis at 13 TeV at Run2.
- Int. Lumi = 170 $\mu\text{b}^{-1}$, data sample of about 9M events
- The results highlight clear difference between MC models and measured distributions.
W/Z Cross Section

**ATLAS Preliminary Data 2015 ($\sqrt{s} = 13$ TeV)**

**ATLAS Preliminary Data 2015 ($\sqrt{s} = 13$ TeV)**
W/Z Production

• Ratio of $W^+$ to $W^-$ production fiducial cross sections (red) compared to predictions based on different PDF sets.

• Ratio of the electron- and muon-channel measurements of the Z and W boson, experimental check of the lepton universality
Z + Jets Cross Section

• Inclusive Z event selection
• Particle-level fiducial cross section
  • Jet $P_T > 30$ GeV, $|y| < 2.5$
• Main backgrounds from top, diboson
• Systematics dominated by Lumi, Jets
ZZ Cross Section

- ZZ → 4ℓ, P_T > 20 GeV, |η| < 2.47(2.4)
- M_{ZZ} ∈ 66-116 GeV
- Observed 63 events, N_bg = 0.62

\[ \sigma_{ZZ}^{tot} \text{(theory)} = 15.6^{+0.4}_{-0.4} \text{ pb} \]

\[ 16.7^{+2.2}_{-2.0} \text{(stat.)} +^{0.9}_{-0.7} \text{(syst.)} +^{1.0}_{-0.7} \text{(lumi.) pb} \]
Top pair cross section

- $t\bar{t} \rightarrow bbWW \rightarrow bb\, e\mu\nu\nu$ (OS-$e\mu$)
- 1 or 2 $b$-tag jets using MV2c20 @70%

$\sigma_{t\bar{t}} = 803 \pm 7$ (stat) $\pm 27$ (syst) $\pm 45$ (lumi) $\pm 12$ (beam) pb

- Measured cross section agrees well with NNLO+NNLL theoretical prediction

$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+40}_{-46}$ pb
ttW and ttZ Cross Section

- SS dilepton channel targets ttW production
- Trilepton and tetralepton channels are sensitive to ttZ production

<table>
<thead>
<tr>
<th>Process</th>
<th>t\bar{t} decay</th>
<th>Boson decay</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}W^\pm$</td>
<td>$(\mu^\pm v b)(q\bar{q} b)$</td>
<td>$\mu^\pm \gamma$</td>
<td>SS dimuon</td>
</tr>
<tr>
<td></td>
<td>$(\ell^\pm v b)(\ell^\mp \bar{v} b)$</td>
<td>$\ell^\pm \gamma$</td>
<td>Trilepton</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>$(\ell^\pm v b)(q\bar{q} b)$</td>
<td>$\ell^+ \ell^-$</td>
<td>Trilepton</td>
</tr>
<tr>
<td></td>
<td>$(\ell^\pm v b)(\ell^\mp \bar{v} b)$</td>
<td>$\ell^+ \ell^-$</td>
<td>Tetralepton</td>
</tr>
</tbody>
</table>

$\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb

**ttW (SS-dimuon):**
$N_{\text{obs}} = 9$, $N_{\text{bg}} = 2.9$, $N_{ttZ} = 0.65$, $N_{ttW} = 5.45$

**ttW (Trilepton):**
$N_{\text{obs}} = 10$, $N_{\text{bg}} = 4.7$, $N_{ttZ} = 1.4$, $N_{ttW} = 3.7$

$\sigma_{t\bar{t}W} = 1.4 \pm 0.8$ pb
SM Higgs and BSM Higgs

- Higgs cross section
- Higgs $\rightarrow$ di-photon
- High mass Higgs $\rightarrow$ di-photon
- Higgs $\rightarrow$ ZZ* $\rightarrow$ 4l
- High mass Higgs $\rightarrow$ ZZ* $\rightarrow$ 4l, 2l2q, 2l2ν
- High mass resonance X $\rightarrow$ WH, ZH
- Double Higgs HH $\rightarrow$ bbγγ, bbbb
- MSSM H/A $\rightarrow$ ττ
Higgs Cross Section

- Total cross sections are measured for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^{*} \rightarrow 4\ell$ using 7, 8 and 13 TeV data.

- LHC-XS theory predictions based on Higgs mass of 125.09 GeV, and calculation up to NNLO in QCD.

- The measured cross sections are compatible within quoted uncertainties.
Higgs $\rightarrow$ di-photon

- For $m_H = 125.09$ GeV, the expected S/B ratio is 4.2% for 90% of signal.
- The observed (expected) significance above no-signal hypothesis is $1.5\sigma$ ($1.9\sigma$)

\[
N_{\text{exp}} = 143 \pm 71 \text{ (stat.)} +39_{-6} \text{ (syst.)}
\]
\[
N_S = 113 \pm 74 \text{ (stat.)} +43_{-25} \text{ (syst.)}
\]

### Fiducial Selection Cuts

| Two highest-$p_T$ photons: | $|\eta^\gamma| < 2.37$ |
|--------------------------|---------------------|
| Relative-$p_T$:          | $E_T^\gamma / m_{\gamma\gamma} \geq 0.35$, $E_T^{\gamma_i} / E_T^{\gamma_j} \geq 0.25$ |
| Mass window:             | $105 \text{ GeV} \leq m_{\gamma\gamma} < 160 \text{ GeV}$ |
| Photon isolation:        | $E_{T,\text{iso}} < 0.1 \times E_T^\gamma + 1 \text{ GeV}$ |

### Fiducial Cross Section

\[
\sigma_{\text{tot}} = \frac{N_S}{L_{\text{int}} B A C} = \sigma_{\text{fid}}
\]

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Measured total cross section [pb]</th>
<th>LHC-XS prediction [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$35 \pm 12 \text{ (stat.)} \pm 4 \text{ (syst.)} \pm 1 \text{ (lumi.)}$</td>
<td>$17.5 \pm 1.6$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$30.5 \pm 7.1 \text{ (stat.)} +2.6_{-2.5} \text{ (syst.)} \pm 0.9 \text{ (lumi.)}$</td>
<td>$22.3 \pm 2.0$</td>
</tr>
<tr>
<td>13 TeV</td>
<td>$40 \pm 26 \text{ (stat.)} +16_{-10} \text{ (syst.)} \pm 2 \text{ (lumi.)}$</td>
<td>$50.9_{-4.4}^{+4.5}$</td>
</tr>
</tbody>
</table>
A search for new resonance decays to two photons with $m_{\gamma\gamma} > 200$ GeV, predicted in models with an extended Higgs sector.

A local (global, LEE) significance of $3.6\sigma$ ($2\sigma$) was observed $\sim 750$ GeV. $m_X \in [200 \text{ } 2000]$ GeV.
Search for new resonance X decays into $Z\gamma$, $Z\rightarrow \ell\ell$ or jj

→ The data agree with MC expected background, the observed (exptected) limits range between 295 (230) fb for $m_x=340$ GeV and 8.2 (10) fb for $m_x=2.15$ TeV
Higgs → ZZ* → 4ℓ

ATLAS Preliminary

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal full mass range</th>
<th>Signal</th>
<th>ZZ*</th>
<th>Z + jets, t¯t</th>
<th>S/B</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4μ</td>
<td>1.79 ± 0.21</td>
<td>1.67 ± 0.20</td>
<td>0.64 ± 0.06</td>
<td>0.08 ± 0.03</td>
<td>2.3</td>
<td>2.39 ± 0.21</td>
<td>1</td>
</tr>
<tr>
<td>2e2μ</td>
<td>1.19 ± 0.14</td>
<td>1.06 ± 0.13</td>
<td>0.44 ± 0.04</td>
<td>0.07 ± 0.03</td>
<td>2.1</td>
<td>1.57 ± 0.14</td>
<td>1</td>
</tr>
<tr>
<td>2μ2e</td>
<td>1.07 ± 0.16</td>
<td>0.96 ± 0.15</td>
<td>0.34 ± 0.05</td>
<td>0.09 ± 0.02</td>
<td>2.2</td>
<td>1.40 ± 0.16</td>
<td>2</td>
</tr>
<tr>
<td>4e</td>
<td>1.01 ± 0.15</td>
<td>0.88 ± 0.13</td>
<td>0.32 ± 0.05</td>
<td>0.09 ± 0.02</td>
<td>2.1</td>
<td>1.30 ± 0.14</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>5.06 ± 0.60</td>
<td>4.57 ± 0.54</td>
<td>1.74 ± 0.19</td>
<td>0.34 ± 0.06</td>
<td>2.2</td>
<td>6.65 ± 0.58</td>
<td>4</td>
</tr>
</tbody>
</table>
Search for Heavy Higgs → ZZ

**ATLAS Preliminary**

- **$H \rightarrow ZZ^* \rightarrow 4l$**
  
- **$H \rightarrow ZZ^* \rightarrow 2l2q$**
  
- **$H \rightarrow ZZ^* \rightarrow 2l2\nu$**
Search for $X \rightarrow WH$ and $ZH$

- Search for a new resonance $X$ via $WH$ / $ZH$
- Heavy Vector Triplets (HVT) benchmark
  - Model A, $W' < 1490$ GeV is excluded at 95% CL
  - Model B, $W' < 1740$ GeV is excluded at 95% CL

<table>
<thead>
<tr>
<th>Two $b$-tags</th>
<th>$\nu\bar{\nu}b\bar{b}$</th>
<th>$\ell\bar{\nu}b\bar{b}$</th>
<th>$\ell\ell b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>backgrounds</td>
<td>$36.9 \pm 3.4$</td>
<td>$81 \pm 8$</td>
<td>$7.2 \pm 1.1$</td>
</tr>
<tr>
<td>data</td>
<td>$38$</td>
<td>$85$</td>
<td>$7$</td>
</tr>
</tbody>
</table>

ATLAS Preliminary

$\sqrt{s} = 13$ TeV $\int L dt = 3.2$ fb$^{-1}$

$W' \rightarrow WH$, $H \rightarrow b\bar{b}$

$A \rightarrow ZH$, $H \rightarrow b\bar{b}$
Search for BSM \( HH \rightarrow bb\gamma\gamma \)

- BSM: 2HDM, MSSM, twin or composite Higgs models predicts the existence of a heavy Higgs could decay into two lighter SM-like higgs.
- \( bb\gamma\gamma \) is promising for the search as it benefits from large \( h \rightarrow bb \) BR, clean peak with high \( h \rightarrow \gamma\gamma \) mass resolution.
- MadGraph5 MC@NLOv2.2.2 with Pythia8 parton shower

<table>
<thead>
<tr>
<th>Process</th>
<th>0-tag</th>
<th>2-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum background</td>
<td>35.8 ± 2.1</td>
<td>1.63 ± 0.30</td>
</tr>
<tr>
<td>SM single-Higgs</td>
<td>1.8 ± 1.5</td>
<td>0.14 ± 0.05</td>
</tr>
<tr>
<td>SM di-Higgs</td>
<td>&lt;0.001</td>
<td>0.027 ± 0.006</td>
</tr>
</tbody>
</table>

Observed limit ranges between 7pb and 4pb for Resonance X with masses in range 275-400 GeV.
Search for BSM HH→bbbb

- Randall-Sundrum (RS) model, spin-2 Kaluza-Klein (KK) excitations of the graviton $G^*_{KK}$ are produced via ggF, $G^*_{KK}→hh→bbbb$

- The sensitivity is best in bbbb channel for resonance mass above 500GeV if comparing with bbττ, bbγγ, γγWW final states

- Two analyses: “resolved” analysis is focused for low-mass hh system where 4 b-jet can be well separated, “boosted” analysis focuses on high-mass hh system where two b-jets cannot be resolved due to high boost.

- 95% CL upper limit for mass [600,3000] GeV: $\sigma(pp→G^*_{kk}→hh→bbbb) < 70 \text{ fb}$
Search for MSSM H/A $\rightarrow \tau\tau$

- MSSM is an extension of the SM which provides a framework addressing the naturalness problem, gauge coupling unification and existence of dark matter.
- The MSSM contains two Higgs doublets: two CP-even (h,H), one CP-odd (A) and two charged Higgs (H$^{\pm}$).
- Neutral MSSM Higgs in the $\tau\tau$ decay mode with at least one tau hadronic decays, cross section limits for ggF (b-associated) are:
  \[ \sigma \times BR > 2.7(2.7) \text{ pb at } m_\phi = 200 \text{ GeV} \]
  \[ \sigma \times BR > 0.030(0.023) \text{ pb at } m_\phi = 1.2 \text{ TeV} \]
2HDMs: $A \rightarrow Zh \rightarrow \ell\ell bb$

- Search for heavy, CP-odd Higgs boson, $A \rightarrow Zh \rightarrow \ell\ell bb$
- $Z \rightarrow ee, \mu\mu, \nu\nu$ are considered
- No evidence for production of $A$ boson is observed

$$m_{Zh}^2 = \sqrt{(E_T^h + E_{T\text{miss}})^2 - (p_T^h + E_{T\text{miss}})^2}$$
SUSY, Dark Matter, Exotic, Diboson

- SUSY: stop, sbottom, gluino
- Dark Matter – mono W/Z
- Dark Matter associated with Higgs
- $W' \rightarrow \ell \nu$
- $Z' \rightarrow \ell \ell$
- Heavy Gravity $\rightarrow$ multi-jets
- LFV $X \rightarrow e\mu$
- Diboson resonance: $WW$, $WZ$, $ZZ$
Search for stop pair

→ SUSY is a natural solution to the hierarchy problem. If R-parity is conserved, SUSY particles are produced in pairs and LSP is stable. The stop is expected to be light due to its large contribution to the Higgs mass radiative correction.

→ **Scenario #1**: Gluino-mediated pair production, assuming 100% BR via stop $\rightarrow$ c + neutralino, and mass splitting of 5 GeV. $M_{\text{Gluino}} < 1460$ GeV is excluded

→ **Scenario #2**: direct pair production of stop

(→ top + neutralino), excludes stop mass from 745 to 780 GeV for a massless neutralino at 95% CL.
Search for stop (2-lepton)

- In the framework of a generic R-parity conserving MSSM, SUSY particles are produced in pairs, the LSP is stable and candidate for DM.
- Cross sections $>1.3(2.1)\, \text{fb}$ for SRDF (SRSF) are excluded at 95% CL.
- Stop mass below 577 GeV are excluded at 95% CL.

\[
\tilde{t}_1 \rightarrow \tilde{\chi}_1^\pm b \rightarrow \tilde{\chi}_1^0 W b \hspace{1cm} m(\tilde{t}_1) - m(\tilde{\chi}_1^\pm) = 10 \, \text{GeV}
\]

\[
m_{T2}(p_T,1, p_T,2, p_T^{\text{miss}}) = \min_{q_T,1 + q_T,2 = p_T^{\text{miss}}} \left\{ \max\left[ m_T(p_T,1, q_T,1), m_T(p_T,2, q_T,2) \right] \right\}
\]
Search for sbottom pair

- Search for bottom squarks pair decaying exclusively as b-quark and LSP neutralino. The signature has 2 b-jets and large MET. \( \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 \)

- Bottom squark mass \(< 800\) GeV are excluded for neutralino mass below \(360\) GeV at \(95\%\) CL.
Search for gluino pair

ATLAS Preliminary

$\tilde{g}$ production, $\tilde{g} \rightarrow tt + \tilde{\chi}_1^0$, $m(\tilde{g}) \gg m(\tilde{t})$

**ATLAS Preliminary**

- Data 2015
- Total background
  - tt
  - Single top
  - tt + W/Z/h
  - Z+jets
  - W+jets
  - Diboson

**Gluino**
- $m_{\tilde{g}} = 1700, 200$
- $m_{\tilde{t}} = 1400, 800$

**Events/50 GeV**

$E_T^{miss}$ [GeV]

- SR-Gbb-B
  - Events 3-4

**Events/50 GeV**

$E_T^{miss}$ [GeV]

- SR-Gbb-B
  - Events 3-4

**ATLAS Preliminary**

$\tilde{g}$ production, $\tilde{g} \rightarrow bb + \tilde{\chi}_1^0$, $m(\tilde{g}) \gg m(\tilde{b})$

**ATLAS Preliminary**

- Data 2015
- Total background
  - tt
  - Single top
  - tt + W/Z/h
  - Z+jets
  - W+jets
  - Diboson

**Gluino**
- $m_{\tilde{g}} = m_{\tilde{b}} + 2m_b$

**Events/50 GeV**

$E_T^{miss}$ [GeV]

- SR-Gbb-B
  - Events 3-4

2016.3.30
Highlights of ATLAS at Run2 - H. Yang (SJTU)
Search for DM with mono-W/Z

- Search for DM associated with a jet, a photon, a W/Z, a Higgs boson plus large MET etc.
- Models: $ZZ\chi\chi$ EFT and vector-mediated simplified model
- No significant excess over the SM is observed.
Search for Higgs + DM

- To search for Dark Matter (MET) associated with a Higgs boson.

No significant excess is found in search for Higgs boson with large MET.

Vector mediator $hZ'$

Scalar mediator $hS$

<table>
<thead>
<tr>
<th>Process</th>
<th>High-$E_T^{miss}$ category ($E_T^{miss} &gt; 100$ GeV)</th>
<th>Low-$E_T^{miss}$ category ($E_T^{miss} &lt; 100$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$(2.1 \pm 0.6) \cdot 10^{-2}$</td>
<td>$4.9 \pm 0.5$</td>
</tr>
<tr>
<td>$ZZ^*$</td>
<td>$(0.7 \pm 0.4) \cdot 10^{-2}$</td>
<td>$4.4 \pm 0.4$</td>
</tr>
<tr>
<td>$Z$+jets and $t\bar{t}$</td>
<td>$(3.1 \pm 1.2) \cdot 10^{-2}$</td>
<td>$0.8 \pm 0.5$</td>
</tr>
<tr>
<td>$ZH(\ell\nu\nu)$</td>
<td>$(1.2 \pm 0.6) \cdot 10^{-5}$</td>
<td>$(5.8 \pm 0.8) \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$ZH(\ell\nu\nu)$</td>
<td>$(1.3 \pm 0.8) \cdot 10^{-7}$</td>
<td>$(8.2 \pm 1.5) \cdot 10^{-7}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$(5.9 \pm 1.6) \cdot 10^{-2}$</td>
<td>$10.1 \pm 1.0$</td>
</tr>
<tr>
<td>Vector mediator signal $m_\chi = 1$ GeV, $m_{med} = 200$ GeV</td>
<td>$(9.7 \pm 3.3) \cdot 10^{-2}$</td>
<td>$(1.3 \pm 0.6) \cdot 10^{-1}$</td>
</tr>
<tr>
<td>Scalar mediator signal $m_\chi = 1$ GeV, $m_{med} = 300$ GeV</td>
<td>$0.41 \pm 0.14$</td>
<td>$0.44 \pm 0.09$</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>9</td>
</tr>
</tbody>
</table>
BSM models predict new spin-1 boson (SSM $W'$), it is heavier version of the SM $W$ boson.

$W' \rightarrow \ell \nu$ channel

$$m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell \nu})}$$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$m_{W'}$ limit [TeV]</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W' \rightarrow e\nu$</td>
<td>4.03</td>
<td>3.98</td>
<td></td>
</tr>
<tr>
<td>$W' \rightarrow \mu\nu$</td>
<td>3.66</td>
<td>3.42</td>
<td></td>
</tr>
<tr>
<td>$W' \rightarrow \ell\nu$</td>
<td>4.18</td>
<td>4.07</td>
<td></td>
</tr>
</tbody>
</table>

2016.3.30

Highlights of ATLAS at Run2 - H. Yang (SJTU)
BSM models predict new spin-1 boson (Z')

Dilepton (ee or \( \mu \mu \)) is a key search channel

<table>
<thead>
<tr>
<th>Model</th>
<th>Width [%]</th>
<th>( ee ) [TeV]</th>
<th>( \mu \mu ) [TeV]</th>
<th>( \ell \ell ) [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exp</td>
<td>Obs</td>
<td>Exp</td>
</tr>
<tr>
<td>( Z'_S )</td>
<td>3.0</td>
<td>3.17</td>
<td>3.18</td>
<td>2.91</td>
</tr>
<tr>
<td>( Z' )</td>
<td>1.2</td>
<td>2.87</td>
<td>2.88</td>
<td>2.64</td>
</tr>
<tr>
<td>( Z' )</td>
<td>0.5</td>
<td>2.58</td>
<td>2.58</td>
<td>2.32</td>
</tr>
</tbody>
</table>

Sequential SM (\( Z'_{SSM} \)) provides a common benchmark

GUT inspired models based on E6 gauge group, two neutral bosons (\( Z'_\psi, Z'_\chi \)) mix with an angle \( \theta_{E6} \).

\[
Z'(\theta_{E6}) = Z'_\psi \cos \theta_{E6} + Z'_\chi \sin \theta_{E6}
\]

Topcolour-assisted technicolor

\( Z' \rightarrow tt \rightarrow bWbW, \) 1 W leptonic decay

\( Z' \) in 0.7-2.2 TeV excluded at 95% CL
Search for BSM LFV $e\mu$ Resonance

- LF is conserved in SM, however, LFV is allowed in some extensions of the SM with additional gauge symmetries, eg. SSM $Z'$, RPV SUSY, low-scale gravity model QBH.

- di-lepton channels: $e\mu$, currently adding $e\tau$, $\mu\tau$ final states

![Diagram with $e^-$ and $\mu^+$ labels](image)

**Table: Expected Limits**

<table>
<thead>
<tr>
<th>Model</th>
<th>Expected Limit [TeV]</th>
<th>Observed Limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'$ SSM</td>
<td>3.19</td>
<td>3.01</td>
</tr>
<tr>
<td>QBH ADD n=6</td>
<td>4.62</td>
<td>4.54</td>
</tr>
<tr>
<td>QBH RS n=1</td>
<td>2.56</td>
<td>2.44</td>
</tr>
</tbody>
</table>

![Graph showing $\sigma B$ vs $M_{Z'}$](graph)
Search for Diboson Resonance

- Search for heavy resonances in diboson final states (eg. $\ell\ell qq$, $\nu\nu qq$, $\ell\nu qq$, $ qq qq$), well-motivated extensions to the SM and has very rich phenomenology. LHC Run1 observed some excess which needs cross check using 13 TeV data at Run2
  - Heavy Vector Triplet (HVT) model A, $\text{BR}(W' \to WZ) \sim 2\%$
  - Kaluza-Klein (KK) modes in Randall-Sundrum(RS) graviton model, $\text{BR}(G^* \to ZZ) \sim 8\text{--}10\%$
  - Generator: MadGraph5 2.2.2 (NNPDF23LO)

- Two heavy Higgs-like boson hypotheses are tested ( $H \to WW \to \ell\nu qq$):
  - Narrow Width Assumption (NWA, SM Higgs width of 4MeV),
  - Large Width Assumption (LWA, 5-15% of heavy Higgs mass)

- No evidence is observed, masses below 1060 GeV and 1250 GeV are excluded at 95% CL for spin-2 RS $G^* \to WW$ and $H \to WW$. Upper limits on $\sigma \times \text{BR}(H \to WW)$ with NWA/LWA $\in [0.02, 0.3] \text{pb}$
Search for Diboson Resonance

**Observed $W' > 1.4$ TeV**

- $W' \rightarrow WZ \rightarrow llqq$

**$G^* > 850$ (expected $>790$) GeV**

- $G^* \rightarrow ZZ \rightarrow llqq$
- $G^* \rightarrow ZZ \rightarrow ννqq$
- $W' \rightarrow WZ \rightarrow llqq$
- $H \rightarrow WZ \rightarrow ννqq$

**$W' > 1.6$ TeV**
Search for Diboson Resonance

- Focus on ZZ/WW/WZ decay into four-quark final states ➔ two fat jets
- Two anti-kt jets with $R=1.0$, $n_{\text{trk}}<30$, jet $P_T>200$ GeV, $|\eta|<2.0$, $m_{\text{jet}}>50$ GeV

Results exclude HVT $W'$ model in the mass range from 1.38 to 1.6 TeV at 95% CL through its decay to WZ.
Summary

ATLAS made tremendous efforts and progresses based on the LHC Run2 13 TeV data collected in 2015, ranging from SMEW, Top, Higgs, and extensive searches for BSM Higgs, SUSY, Dark Matter, Exotic and Diboson resonances etc.

More interesting results from LHC Run2 are coming, please stay tuned!

Thank you very much!
Several Orders of Magnitudes
Search for SUSY Gluino and sbottom
Search for Gravity

- Some models of gravity postulate a fundamental gravitational scale comparable to EW scale, allowing production of micro Black Hole and String Balls at LHC.

- BH decay is considered to be a stochastic process, different number of particles (jets) has identical kinematic distributions. It motivates search in inclusive jet multiplicity slices.

**Search Strategy:** three regions of $H_T$
- Control region: $C < H_T < V$
- Validation region: $V < H_T < S$ ($N_{MC}>20$)
- Signal region: $H_T > S$ ($\Delta N_{extrap} \sim 0.5$)

**Four steps:** $6.5pb^{-1}$, $74pb^{-1}$, $0.44fb^{-1}$, $3.0fb^{-1}$

No excess is seen at large $H_T$, cross section $> 1.6$ fb with $H_T > 5.8$ TeV are excluded for models with $> 3$ jets.

2016.3.30

Highlights of ATLAS at Run2 - H. Yan
Z candidates: two leptons with pt $> 25$ GeV, $66 < M(ll) < 116$ GeV

$|\eta_\mu| < 2.4$, $|\eta_e| < 2.47$ excluding $[1.37, 1.52]$
Higgs Fiducial and Total Cross Section

- Total and fiducial cross section measurement.

\[
\sigma_{\text{tot}} = \frac{N_s}{A \cdot C \cdot B \cdot L_{\text{int}}},
\]

\[
\sigma_{\text{fid}}^{4\ell} = \frac{N_s}{C \cdot L_{\text{int}}},
\]

At 13 TeV, an upper limit on Higgs production cross section of 69pb is derived at 95% CL.

**ATLAS-CONF-2015-059**

<table>
<thead>
<tr>
<th>Data set [TeV]</th>
<th>$N_s$</th>
<th>$\sigma_{\text{fid}}^{4\ell}$ [fb]</th>
<th>$\sigma_{\text{fid}}^\text{theory}$ [fb]</th>
<th>$\sigma_{\text{tot}}$ [pb]</th>
<th>$\sigma_{\text{tot}}^\text{theory}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>$4.5^{+2.8}_{-2.2}$</td>
<td>$1.9^{+1.2}_{-0.9}$</td>
<td>$1.03 \pm 0.11$</td>
<td>$33^{+21}_{-16}$</td>
<td>$17.5 \pm 1.6$</td>
</tr>
<tr>
<td>8</td>
<td>$24.0^{+6.0}_{-5.3}$</td>
<td>$2.1 \pm 0.5$</td>
<td>$1.29 \pm 0.13$</td>
<td>$37^{+9}_{-8}$</td>
<td>$22.3 \pm 2.0$</td>
</tr>
<tr>
<td>13</td>
<td>$1.0^{+2.3}_{-1.5}$</td>
<td>$0.6^{+1.3}_{-0.9}$</td>
<td>$2.74 \pm 0.28$</td>
<td>$12^{+25}_{-16}$</td>
<td>$50.9 \pm 4.5$</td>
</tr>
</tbody>
</table>
In the MSSM $m_{h}^{\text{mod+}}$ scenario, the parameters are chosen such that radiative corrections give a light CP-even Higgs mass of $\sim 126 \text{ GeV}$ in the decoupling limit. This search excludes $\tan \beta > 10$ for $m_{A} = 200 \text{ GeV}$ at 95% CL.
**A bit about the models...**

**Charged (WZ)**
- Sequential Standard Model (\(W',\) spin-1)
  - Trilinear \(WWWZ\) coupling set by Extended Gauge Model: \(\sim (M_W/M_{W'})^2\)

**Neutral (WW, ZZ, HH)**
- Randall-Sundrum graviton (RS G*, spin-2)
  - Traditional benchmark model with extra dimensions
- Bulk RS graviton (Bulk G*, spin-2)
  - Graviton couples more with heavy particles (W, Z, t)
  - Smaller \(\sigma\), but larger branching ratio to WW, ZZ

**Minimal Walking Technicolor (R₁, R₂, charged and neutral)**
- Technicolor with minimal ingredients, can decay to ZH and WH

**HVT (Simplified Lagrangian)**
- **Model A**
  - weakly coupled vector resonances from extension of the gauge group
- **Model B**
  - produced in a strong scenario e.g. composite higgs model
ZZ & WZ → llqq

ATLAS  See also poster by E. Cheremushkina

Symmetric $p_T$ requirement on the dilepton / dijet pair used to split the analysis in 3 categories:
- **Low-Resolved**: 100 GeV
- **High-Resolved**: 250 GeV
- **High-Merged**: $R=1.2$ large radius jet, 400 GeV

Both analyses require a dilepton pair compatible with the decay of a Z boson. Treatment of hadronic boson decay varies.

In both cases, excellent agreement is found between SM predictions and data...
3.4σ local excess in WZ channel (2.5σ global)!

Dedicated selection for all 3 channels based on W/Z jet mass requirements (26 GeV windows), implying statistical overlap between channels.

2 large CA R=1.2 jets with n_{trk} < 30 are required in the events, satisfying boson tagging requirements (grooming & filtering). Extra topology requirements are used to reduce QCD backgrounds.

ATLAS

CMS

Require 2 CA R=0.8 jets in the events along with topology requirements to reduce backgrounds.

Jets are W/Z-tagged based on a combination of pruned mass and subjettiness requirements. Separate events into 1/2 tag category, and use same HP/LP classification as in the llqq analysis.
ATLAS

Limits set on RS Gravitons and EGM W'

Excesses seen in all 3 channels (overlapping), at 3.4\sigma, 2.9\sigma and 2.4\sigma local significance

CMS

Limits set on RS Gravitons and W'

Due to single tag category, unique sensitivity to excited quark scenarios (q*\rightarrow qW/qZ)!

\( m_{q^*} < 3.2 \text{ TeV ruled out} \)
**WW / WZ / ZZ Combination**

**ATLAS only**

*New!*

**W’ Limit increased by 220 GeV**

Combination of four statistically independent searches (of which \(|VV|\) is the only one not shown in this talk, see arxiv:1406.4456)

**G* Limit increased by 50 GeV**