Highlights of the SM Physics at the LHC

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(on behalf of the ATLAS and CMS Collaborations)

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Introduction

- **SMEW Multiboson Production**
  - Precision measurements and exploring new production channels
    - Di-boson/Tri-boson productions, Vector boson fusion/scattering
  - Indirect search for new physics BSM
    - Anomalous Triple / Quartic gauge boson self-couplings

- **Top Quark Production**
  - Evidence of S-channel single top
  - Observation of ttbar associated with vector boson W/Z
  - ttbar charge asymmetry

- **Some early results from LHC Run2 @ 13 TeV**
  - Inelastic pp cross section
  - Charged track multiplicity
  - W/Z/Z+jets/Top production cross sections
  - Event Display
Standard Model Production Cross Section Measurements

Status: March 2015

Several Orders of Magnitudes

Di-boson and Tri-boson Productions
Z/ZZ \rightarrow 4l Productions

- Very rich physics: resonant Z\rightarrow 4l, H\rightarrow ZZ^* \rightarrow 4l, SM ZZ \rightarrow 4l
- Differential cross section measurements in m_{4l} and P_T for inclusive 4l (80<m_{4l}<1000 GeV)
- First try to constraint gg\rightarrow 4l contribution from data
- Theoretical predictions available at different level of corrections

Theoretical Predictions:
qq \rightarrow ZZ: Powheg (NLO) on-shell H: Powheg (NLO) gg \rightarrow ZZ: MCFM (LO) H \rightarrow 4l & on-shell qq \rightarrow ZZ:
NNLO QCD + NLO EWK

arXiv: 1509.07844
ZZ Production

- **ZZ → 4l with 2 on-shell Z**
  - $60 < m_Z < 120$, POWHEG, GG2ZZ
  - $l = e, \mu, \tau$ (\(\tau\) only in \(\sigma\), not differential)
  - FSR $\gamma$ recovery for better $m_Z$ resolution
- Total $\sigma$ compared with NLO
  - $qq \rightarrow ZZ$ and LO $gg \rightarrow ZZ$
- Stat/Syst/Theo error all $O(6\text{-}7\%)$
  \[ \sigma(pp \rightarrow ZZ \rightarrow 4l) = 7.7 \pm 0.8 \text{ pb} \]
  \[ \sigma_{SM} = 7.7 \pm 0.6 \text{ pb} \]

- Measurement of $ZZ \rightarrow ll\nu\nu$ (Madgraph)
  - $P_T(ll) > 45$ GeV and MET $> 65$ GeV
  - $l = e, \mu$
- Predictions with MCFM (NLO)
  \[ \sigma(8 \text{ TeV}) = 6.9 \pm 0.8(\text{stat.})^{+1.8}_{-1.4}(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ pb} \]
  \[ \sigma_{SM} = 7.6^{+0.4}_{-0.3} \text{ pb} \]
  \[ \sigma(7 \text{ TeV}) = 5.2^{+1.5}_{-1.4}(\text{stat.})^{+1.4}_{-1.1}(\text{syst.}) \pm 0.2(\text{lumi.}) \text{ pb} \]
  \[ \sigma_{SM} = 6.2^{+0.3}_{-0.2} \text{ pb} \]
4l differential measurements

- $m(4l)$ unfolded measurement
  - NNLO normalization and shape for $m_{4l} > 2m_Z$
- Slight excess for off-shell $ZZ^*$ region

Compatible with $H \rightarrow ZZ \rightarrow 4l$, $\mu = 1.44$

- $P_T(4l)$ unfolded measurement
  - @NLO for the $qq$ production
- Low $P_T$ modeling affected by gluon resummation

Low $P_T(4l)$: Sensitive to QCD resummation
High $P_T(4l)$: Sensitive to $gg \rightarrow H$ and aTGC

arXiv: 1509.07844
At on-shell ZZ region, inclusive gg->4l contribution includes:
Off-shell Higgs, Non-resonant gg, and the interference
The derived signal strength w.r.t. current LO prediction

$$\mu_{gg} = 2.4 \pm 1.0({stat.}) \pm 0.5({syst.}) \pm 0.8({theory})$$
Zγ Production at 8 TeV

- Di-lepton channel: isolated γ with $P_T > 15$ GeV, $\Delta R(l,\gamma) > 0.7$
- $Z \to \nu\bar{\nu} + \gamma$ channel: isolated γ with $P_T > 145$ GeV, $|\eta| < 1.44$
- Cross section measured agree with NLO/NNLO predictions

\[ \sigma_{\text{incl}} = 2063 \pm 19 \text{ (stat)} \pm 98 \text{ (syst)} \pm 54 \text{ (lumi)} \text{ fb} \]
\[ \sigma_{\text{incl}}^{\text{NNLO}} = 2241 \pm 22 \text{ (scale only)} \text{ fb} \]
\[ \sigma_{\text{incl}}^{\text{MCFM}} = 2100 \pm 120 \text{ fb} \]

- For lepton channel also differential measurements in $P_T(\gamma)$
  - NNLO/NLO $k$-factor important at high $P_T$
  - Sherpa (after global rescaling to NNLO) describes well the $P_T$ of the photon

![Diagram of Zγ production at 8 TeV](image-url)
Zγ Electroweak Production

3\sigma Evidence of: qq \rightarrow qqZγ (l^+l^- jj γ)

- High VV EWK cross section
- Can be fully reconstructed
  - m(Zγ) related to the VBS scale
- Significant strong production: Zγ+2j
  - Modeled from control region and subtracted
- Cross Section Phase Space:
  - 2 lep. + 1 γ P_T > 20 GeV (|η(γ)|<1.44)
  - 70 < m(ll) < 110 GeV
  - M_{jj} > 400 GeV and |Δη(jj)|>2.5

- Observed/expected significance: 3.0\sigma / 2.1\sigma

\[ \sigma_{\text{EWK}} = 1.86^{+0.89}_{-0.75}\text{(stat.)}^{+0.41}_{-0.27}\text{(syst.)} \pm 0.05\text{(lumi.) fb} \]

\[ \sigma_{\text{SM}} = 1.26 \pm 0.11\text{(scale)} \pm 0.05\text{(PDF)fb} \]
Previous LHC measurements indicated higher cross section than NLO prediction, at 1.5 \( \sigma \) level from both ATLAS and CMS with 8 TeV data.

Inclusive WW cross section prediction at 8TeV:
NLO \( q\bar{q} + \text{LO } gg + \text{NNLO } ggH \sim 58.7 \pm 3.0 \text{ pb} \)
NNLO \( q\bar{q} + \text{LO } gg + \text{NNLO } ggH \sim 63.2 \pm 2.0 \text{ pb} \)

\( \Rightarrow \) Important to test consistency with NNLO predictions using Run I data

\[ \text{Sizable NNLO correction } \sim 8\% \]
**Cross Section at total phase space**

\[
\int L dt = 20.3 \text{ fb}^{-1}
\]
\[\sqrt{s} = 8 \text{ TeV}\]

**WW**

**Fiducial cross sections:**

\[
\sigma_{e\mu}^{fid} = 377.8^{+6.9}_{-6.8} \text{(stat)}^{+25.1}_{-22.2} \text{(syst)}^{+11.4}_{-10.7} \text{(lumi)} \text{ fb}
\]

Compatible with approximate NNLO+NNLL calculation

\[357.9 \pm 14.4 \text{ fb}\]

**Measured total cross section**
- 10% precision (systematic unc.)
- Compatible with NNLO at 1 \(\sigma\)

**Remaining difference due to**
- Missing k-factor for gg->WW
- Modelling on gluon resummation (effect on Jet-Veto)

**arXiv:1410.4745**

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**SM Physics at LHC - Haijun Yang (SJTU)**

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**ATLAS Preliminary**

**Conf-2014-033**
Recent update from CMS with full 8 TeV dataset w/ few improvements
- $H \rightarrow WW$ included in bkg. (8%)
- NNLO calculations (7% higher)
- $WW P_t$ resummation reweighting
- Madgraph (LO) → Powheg (NLO)

Measurement done in the 0-jet, 1-jet, same / opposite flavor

Inclusive CMS WW cross section has good agreement between data and NNLO MC

\[
\sigma^{\text{data}} = 60.1 \pm 4.8 \text{ pb} \\
\sigma^{\text{NNLO}} = 59.8^{+1.3}_{-1.1} \text{ pb}
\]
**WW Scattering**

- $V_LV_L \rightarrow V_LV_L$ scattering linked to mechanism responsible for EWSB
  - The SM Higgs boson cancels increase for large $s$ preserving unitarity
- WW scattering essential to experimentally probe the nature of EWSB
  - Flagship EWK analysis for Run 2 and beyond!

**Experimental Signature:**
- Dilepton + MET + 2jets
- Combine EWK and QCD ($O(\alpha_S^2 \alpha_{EW}^4)$)

**Same sign channel needed:**
- To suppress huge $t\bar{t}$ background
- To suppress “QCD” (no gg initial state)
WW Scattering

- Sensitivity increases in phase space with $m_{jj} > 500\text{GeV}$ & $|\Delta\eta| > 2.5$
- ATLAS and CMS had sensitivity for the first evidence of WW scattering, observed (expected) significances are: ATLAS $3.6\sigma$ (2.8$\sigma$), CMS $1.9\sigma$ (2.9$\sigma$)

$\sigma_{\text{SM}} = 5.8 \pm 1.2 \text{ fb}$

PRL 114 (2015) 051801
PRL 113 (2014) 141803
Exclusive $\gamma\gamma \rightarrow WW$ Production

- Probing the $\gamma\gamma WW$ vertex with exclusive production
- $e\mu$ channel to suppress DY and $\gamma\gamma \rightarrow l^+l^-$ exclusive process
  - $\gamma\gamma \rightarrow ee, \mu\mu$ used as control sample at $P_T(l\ell) \sim 0$ to study charged track veto
- Signal signature: 2 lepton tracks from same primary vertex and no other charge particles and characterize to correct for non-elastic contributions
  - Signal region: $m(e\mu) > 20$ GeV and $p_T(e\mu) > 30$ GeV
- Results: Expected Signal events = $5.3 \pm 0.1$; Background = $3.5 \pm 0.5$; Data = 13
  Observed significance is $3.6\sigma$ over background-only hypothesis)

\[
\sigma(pp \rightarrow p^*WWp^* \rightarrow p^*e\mu\nu
\nu p^*) = 12.3^{+5.5}_{-4.4} \text{ fb}
\]

SM prediction is $6.9 \pm 0.6 \text{ fb}$
Evidence of $W\gamma\gamma$ production

- Tri-boson production with relative large cross section
  - Final state: lepton + $E_{T}\text{miss}$ + two photons
  - Main backgrounds: $W\gamma j + Wjj$
  - Sensitive to the $WW\gamma\gamma$ aQGC
- First time have $3\sigma$ evidence of $W\gamma\gamma$

<table>
<thead>
<tr>
<th></th>
<th>$\sigma^{\text{fid}}$ [fb]</th>
<th>$\sigma^{\text{MCFM}}$ [fb]</th>
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</thead>
<tbody>
<tr>
<td>Inclusive ($N_{\text{jet}} \geq 0$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu\nu\gamma\gamma$</td>
<td>7.1 $^{+1.3}_{-1.2}$ (stat.) $\pm 1.5$ (syst.) $\pm 0.2$ (lumi.)</td>
<td>2.90 $\pm 0.16$</td>
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<tr>
<td>$ev\gamma\gamma$</td>
<td>4.3 $^{+1.8}<em>{-1.6}$ (stat.) $^{+1.9}</em>{-1.8}$ (syst.) $\pm 0.2$ (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$t\nu\gamma\gamma$</td>
<td>6.1 $^{+1.0}_{-1.0}$ (stat.) $\pm 1.2$ (syst.) $\pm 0.2$ (lumi.)</td>
<td></td>
</tr>
<tr>
<td>Exclusive ($N_{\text{jet}} = 0$)</td>
<td></td>
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<tr>
<td>$\mu\nu\gamma\gamma$</td>
<td>3.5 $^{+0.9}<em>{-1.0}$ (stat.) $^{+1.1}</em>{-1.0}$ (syst.) $\pm 0.1$ (lumi.)</td>
<td>1.88 $\pm 0.20$</td>
</tr>
<tr>
<td>$ev\gamma\gamma$</td>
<td>1.9 $^{+1.4}<em>{-1.0}$ (stat.) $^{+1.4}</em>{-1.0}$ (syst.) $\pm 0.1$ (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$t\nu\gamma\gamma$</td>
<td>2.9 $^{+0.8}<em>{-0.7}$ (stat.) $^{+1.0}</em>{-0.9}$ (syst.) $\pm 0.1$ (lumi.)</td>
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Definition of the fiducial region

- $p_{T}^{j} > 20$ GeV, $p_{T}^{\nu} > 25$ GeV, $|\eta_{l}| < 2.5$
- $m_{T} > 40$ GeV
- $E_{T}^{j} > 20$ GeV, $|\eta^{j}| < 2.37$, iso. fraction $e_{k}^{j} < 0.5$
- $\Delta R(\ell, \gamma) > 0.7$, $\Delta R(\gamma, \gamma) > 0.4$, $\Delta R(\ell/\gamma, \text{jet}) > 0.3$

Exclusive: no anti-$k_{T}$ jets with $p_{T}^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 4.4$
Di-boson Cross Section Ratio (CMS)

![Graph showing CMS measurements vs. NLO (NNLO) theory for various di-boson processes with 7 TeV and 8 TeV CMS measurements (stat,stat+sys).](image)

Production Cross Section Ratio: $\frac{\sigma_{\text{exp}}}{\sigma_{\text{theo}}}$

All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)
### Multiboson Cross Section Measurements

**Status: March 2015**

<table>
<thead>
<tr>
<th>Process</th>
<th>Theory</th>
<th>Observed</th>
<th>Stat + Syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{fid}}(gg) [\Delta R_{gg} &gt; 0.4]$</td>
<td>$44.0 \pm 3.2 \pm 8.5$ (theory)</td>
<td></td>
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<tr>
<td>$\sigma_{\text{fid}}(Wg \to \ell \nu \gamma)$</td>
<td>$2.77 \pm 0.31 \pm 0.36$ (data)</td>
<td>$1.76 \pm 0.03 \pm 0.22$ (data)</td>
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<tr>
<td>$\sigma_{\text{fid}}(Zg \to \ell \ell)$</td>
<td>$1.31 \pm 0.02 \pm 0.12$ (data)</td>
<td>$1.05 \pm 0.02 \pm 0.11$ (data)</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(Wg \gamma \to \ell \nu \gamma)$</td>
<td>$6.1 \pm 1.1 \pm 1.0 \pm 1.2$ (data)</td>
<td>$2.9 \pm 0.8 \pm 0.7 \pm 1.0 \pm 0.9$ (data)</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(pp \to WW \ell \nuqq)$</td>
<td>$1.37 \pm 0.14 \pm 0.37$ (data)</td>
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<tr>
<td>$\sigma_{\text{fid}}(W^+W^-jj)$ EWK</td>
<td>$1.3 \pm 0.4 \pm 0.2$ (data)</td>
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<tr>
<td>$\sigma_{\text{total}}(pp \to WW)$</td>
<td></td>
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<td></td>
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<tr>
<td>$\sigma_{\text{fid}}(WW \to ee)$</td>
<td>$71.4 \pm 6.5 \pm 9.0$ (data)</td>
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<tr>
<td>$\sigma_{\text{fid}}(WW \to \mu\mu)$</td>
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<tr>
<td>$\sigma_{\text{fid}}(WW \to e\mu)$</td>
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<tr>
<td>$\sigma_{\text{total}}(pp \to WZ)$</td>
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<tr>
<td>$\sigma_{\text{fid}}(WZ \to \ell \nu \ell \ell)$</td>
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<tr>
<td>$\sigma_{\text{total}}(pp \to ZZ)$</td>
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<tr>
<td>$\sigma_{\text{fid}}(ZZ \to 4\ell)$</td>
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<tr>
<td>$\sigma_{\text{fid}}(ZZ^* \to 4\ell)$</td>
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<tr>
<td>$\sigma_{\text{fid}}(ZZ^* \to \ell \nu \gamma)$</td>
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</tbody>
</table>

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

- Theory
- Observed
- Stat + Syst

**LHC pp $\sqrt{s} = 8$ TeV**

- Theory
- Observed
- Stat + Syst

**Reference**

- JHEP 01, 086 (2013)
- PRD 87, 112003 (2013)
- PRD 87, 112003 (2013)
- JHEP 01, 049 (2015)
- PRL 113, 141803 (2014)
- PRD 87, 112001 (2013)
- ATLAS-CONF-2014-033
- PRD 87, 112001 (2013)
- EPJC 72, 2173 (2013)
- ATLAS-CONF-2013-021
- ATLAS-CONF-2013-021
- JHEP 03, 128 (2013)
- arXiv:1403.5657 [hep-ex]
- ATLAS-CONF-2013-020
- JHEP 03, 128 (2013)
- ATLAS-CONF-2013-020
- JHEP 03, 128 (2013)
Anomalous Gauge Boson Couplings
Anomalous Gauge Boson Couplings

- **Trilinear/Quartic Gauge boson Couplings**
  - Determined by SU(2) x U(1) gauge symmetry
    - Only charged couplings allowed
    - TGCs in VBF, VV; QGCs in VBS, VVV
  - Can be used to constrain new physics that modify bosonic self couplings
    - Anomaly can result in large derivation in production cross section or in differential distributions
    - Anomalous gauge couplings are sensitive to $\sqrt{s}$

No deviation from SM prediction is observed (Run I data) ➔ Stringent limits are set
  - aGCs parameters based on effective Lagrangian or EFT
  - Tighter or comparable to Tevatron/LEP results
Anomalous Gauge Boson Couplings

- Diboson and VBF Boson production sensitive to ATGC

- Triboson (1→3) and VBS VV (2→2) productions sensitive to AQGC
  - Dim-8 operators for AQGC (that not affect TGC)

- Unitarity problem: AT(Q)GC will violate unitarity at some scale
  - Form Factor or K-matrix method
    - Choice arbitrary and introduce model dependence
    - Not unitarize ($\Lambda_{\text{FF}} = \infty$)
    - Limits “over-sensitive” and argued to be “unphysical”
Anomalous Gauge Couplings

- AGC expected to be stronger at high s-hat
  - Search target observables related to the s-hat of the event, like $m_{VV}$, $m_{ll}$, $P_T(VV)$, $P_T(V)$
- Binned fit for a single observable
  - Binning/selection may be optimized for AGC
  - Sensitivity mostly from the last bins
  - Limited by signal stat. and bkgd uncertainty
  - Channels with higher BR usually have higher sensitivity, i.e. $ZZ \rightarrow ll\nu\nu$, $γZ(\rightarrow\nu\nu)$, $WγV(\rightarrow qq)$
- Different processes have different sensitivity for various AGC parameters
  - Limits depends on parameter choice (i.e. $\Lambda$)

$ZZ \rightarrow ll\nu\nu$ $P_T(ll)$: $a_{NTGC}$

$ZZ \rightarrow ll\nu\nu$ $m(4l)$: $a_{NTGC}$
Anomalous Gauge Couplings

- $Z\gamma\rightarrow ll\gamma\;P_T(\gamma):\;aTGC$
- $Z\rightarrow vv\gamma\;P_T(\gamma):\;aTGC$
- $W\gamma V\rightarrow l\nu\gamma jj\;p_T(\gamma):\;aQGC$
- $VBS\;ssWW\;M(ll):\;aQGC$
- $W\gamma\gamma\;M(\gamma\gamma):\;aQGC$
- $VBS\;Z\gamma\rightarrow ll\gamma jj\;M(l\gamma):\;aQGC$

References:
- PRL 114 (2015) 051801
- PRL 113 (2014) 0141803
- CMS PAS SMP-14-018
- PRD 90 (2014) 032008
aTGCs explored by fitting $P_T(jj)$ with $75 < m_{jj} < 95$ GeV
- Stringent limits set on aTGCs parameters or EFT dimension six parameters
Anomalous Quartic Gauge Boson Couplings

- $W\gamma\gamma$ aQGC more sensitive to $f_{T0}$ than $f_{Mi}$
  - Limit on dim-8 operators $f_{M2}$, $f_{M3}$ transformed to dim-6 $a_{C}$, $a_{0}$ operators for comparison
  - Non-unitarized limit shown, for comparison
- AQGC limit from $ssWW$ reported as non-unitarized dim-8 operators (CMS) and unitarized K-matrix formalism (ATLAS)

![Diagram showing AQGC limits and CMS and ATLAS results](image-url)
Top Quark Production
Evidence of s-channel Single Top

• Evidence of single top production in the s-channel was firstly observed at the pp collision (LHC/ATLAS) using 8 TeV data.

• The major backgrounds: ttbar and W+jets

• Matrix Element method

• Obs/Exp significance: 3.2 / 3.9 $\sigma$

$$\sigma_s = 4.8 \pm 1.1 \text{(stat.)}^{+2.2}_{-2.0} \text{(syst.)} \text{ pb} = 4.8^{+2.5}_{-2.2} \text{ pb}$$

$$\sigma_s^{th} = 5.61 \pm 0.22 \text{ pb}$$

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-top s-channel</td>
<td>607.2 ± 2.4</td>
</tr>
<tr>
<td>Single-top t-channel</td>
<td>1238 ± 10</td>
</tr>
<tr>
<td>Assoc. Wt production</td>
<td>414 ± 17</td>
</tr>
<tr>
<td>$t\bar{t}$ production</td>
<td>8495 ± 23</td>
</tr>
<tr>
<td>W+light jets</td>
<td>280 ± 90</td>
</tr>
<tr>
<td>W+heavy flavour</td>
<td>2760 ± 40</td>
</tr>
<tr>
<td>Z+jets &amp; di-boson</td>
<td>337 ± 12</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>713 ± 20</td>
</tr>
<tr>
<td>Total expectation</td>
<td>14 840 ± 100</td>
</tr>
<tr>
<td>Data</td>
<td>15 556</td>
</tr>
</tbody>
</table>
Observation of $ttW/ttZ$

- The OS dilepton, trilepton and tetralepton channels are sensitive to $ttZ$ production
- SS dilepton channel targets $ttW$ production
- The observed and expected significance for background-only hypothesis with neither $ttZ$ nor $ttW$ production is excluded at $7.1\sigma$ and $5.9\sigma$.

\[
\sigma_{ttZ} = 176^{+52}_{-48} \, (\text{stat.}) \pm 24 \, (\text{syst.}) \, \text{fb} = 176^{+58}_{-52} \, \text{fb}
\]

\[
\sigma_{ttW} = 369^{+86}_{-79} \, (\text{stat.}) \pm 44 \, (\text{syst.}) \, \text{fb} = 369^{+100}_{-91} \, \text{fb}
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ttW$ significance</th>
<th>$ttZ$ significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>2$\ell$OS</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>2$\ell$SS</td>
<td>2.8</td>
<td>5.0</td>
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<tr>
<td>3$\ell$</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>4$\ell$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Combined</td>
<td>3.2</td>
<td>5.0</td>
</tr>
</tbody>
</table>

\[\sqrt{s} = 8 \, \text{TeV}, 20.3 \, \text{fb}^{-1}\]
Observation of $ttW/\text{ttZ}$

The observed/expected significances for ttZ and ttW are 6.4/5.7$\sigma$ and 4.8/3.5$\sigma$.

<table>
<thead>
<tr>
<th>Channels</th>
<th>Cross section (fb)</th>
<th>Signal strength ($\mu$)</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>OS</td>
<td>206$^{+182}_{-118}$</td>
<td>257$^{+158}_{-129}$</td>
<td>1.00$^{+0.77}_{-0.62}$</td>
</tr>
<tr>
<td>3$\ell$</td>
<td>206$^{+79}_{-63}$</td>
<td>257$^{+83}_{-67}$</td>
<td>1.00$^{+0.42}_{-0.32}$</td>
</tr>
<tr>
<td>4$\ell$</td>
<td>206$^{+153}_{-109}$</td>
<td>228$^{+130}_{-107}$</td>
<td>1.00$^{+0.77}_{-0.50}$</td>
</tr>
<tr>
<td>OS + 3$\ell$ + 4$\ell$</td>
<td>206$^{+62}_{-52}$</td>
<td>242$^{+168}_{-85}$</td>
<td>1.00$^{+0.34}_{-0.27}$</td>
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<td>Expected</td>
<td>Observed</td>
<td>Expected</td>
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<tr>
<td>SS</td>
<td>203$^{+135}_{-73}$</td>
<td>414$^{+135}_{-112}$</td>
<td>1.00$^{+0.45}_{-0.36}$</td>
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<tr>
<td>3$\ell$</td>
<td>203$^{+215}_{-194}$</td>
<td>210$^{+225}_{-203}$</td>
<td>1.00$^{+1.09}_{-0.96}$</td>
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<tr>
<td>SS + 3$\ell$</td>
<td>203$^{+84}_{-71}$</td>
<td>382$^{+117}_{102}$</td>
<td>1.00$^{+0.43}_{-0.35}$</td>
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</tbody>
</table>
Ttbar Charge Asymmetry

- BSM can alter $A_C$ with anomalous vector or axial-vector couplings or via interference with SM processes.
- Interest in measuring charge asymmetries in ttbar at the LHC has inspired by the CDF and D0 observation of larger $A_{FB}$ than SM predictions.

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

ATLAS: $A_C = 0.009 \pm 0.005$
CMS: $A_C = 0.0033 \pm 0.0042$
SM: $A_C = 0.0111 \pm 0.0004$
LHC Run2 @ 13 TeV

ATLAS Online Luminosity

- LHC Delivered
- ATLAS Recorded

Total Delivered: 4.34 fb$^{-1}$
Total Recorded: 4.00 fb$^{-1}$

\[ \sqrt{s} = 13 \text{ TeV} \]
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 (~9%)
- 4.2M events selected in 63 $\mu$b$^{-1}$, estimated 1% background

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

Fiducial cross-section: $65.2 \pm 0.8$ (exp) $\pm 5.9$ (lum) mb

ATLAS MBTS data extrapolated using Pythia implementation of Donnachie-Landshoff model with $c = 0.085$ for dN/d$\eta$.
Charged-particle Multiplicity

- CMS detector was operated at zero magnetic field, based on hit pairs and straight-line tracks of CMS pixel detector
- ATLAS: charged-particle multiplicity for events with $n_{\text{ch}} \geq 1$, $p_T > 500\text{MeV}$, validate pileup modeling for early analysis at Run2.
W/Z Cross Section

**ATLAS Preliminary**

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

**MSTW2008 NNLO**

---

**ATLAS Preliminary**

13 TeV, 85 pb$^{-1}$

- **Z**:
  - lumi ± exp. uncertainty
  - exp. uncertainty
  - ABM12LHC
  - CT10nnlo
  - NNPDF3.0
  - MMHT14nnlo68CL (inner uncert.: PDF only)

- **W$^\pm$**:
  - lumi ± exp. uncertainty
  - exp. uncertainty
  - ABM12LHC
  - CT10nnlo
  - NNPDF3.0
  - MMHT14nnlo68CL (inner uncert.: PDF only)
W/Z Production

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

\[
R_{W^+W^-} = \frac{\sigma_{W^+}^{\text{fid}}}{\sigma_{W^-}^{\text{fid}}}
\]

- 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
**Ttbar Cross Section**

**ATLAS:** $829 \pm 50 \text{(stat)} \pm 56 \text{ (syst)} \pm 83 \text{ (lumi)} \text{ pb}$

**CMS:** $769 \pm 60 \text{(stat)} \pm 55 \text{ (syst)} \pm 92 \text{ (lumi)} \text{ pb}$

$\sigma_{t\bar{t}}^{\text{NNLO+NNLL}} = 832^{+40}_{-46} \text{ pb}$

→ Measured cross sections agree well with NNLO+NNLL theoretical predictions.
Top Quark Production
ZZ candidate @ 13 TeV

Invariant masses of two Z candidates: 94 GeV and 86 GeV

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions
High-mass dijet candidate @ 13 TeV

Invariant mass of two jets: 6.9 TeV
$P_T(\text{jet1}) = 1.3$ TeV, $P_T(\text{jet2})=1.2$ TeV

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions
Summary

- Some latest SMEW measurements are presented
  - Overall consistency with SM prediction
  - Several discrepancies can be reduced by adding higher order corrections, start to be sensitive to NNLO corrections
  - Stringent limits on anomalous trilinear/quartic gauge couplings
  - Open new channels, e.g. Tri-boson

- Some new results about Top quark production including observation of s-ch top quark, ttW/ttZ, and charge asymmetry

- Some early results from LHC Run2

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

ATLAS (A Toroidal LHC ApparatuS): 44×25m, 7000t  
Inner tracking $|\eta|<2.5$, EM calo $|\eta|<3.2$, Hadronic calo $|\eta|<4.9$, Muon system $|\eta|<2.7$  
ATLAS collaboration 3k physicists from 38 countries
13 TeV W plots

Very early Run II data, reasonable agreement with MC

W candidates: lepton pt $> 25$ GeV, Etmiss $> 20$ GeV, $M_T > 50$ GeV

$|\eta_\mu| < 2.4$, $|\eta_e| < 2.47$ excluding [1.37, 1.52]
Z candidates: two leptons with pt > 25 GeV, 66<M(\ell\ell)<116 GeV

\[ |\eta_\mu| < 2.4, \ |\eta_e| < 2.47 \text{ excluding [1.37, 1.52]} \]
**WW+WZ measured in \( l\nu jj \) final state**

- **WW/WZ Semi-leptonic decay final state**
  - lepton + Etmiss + two jets with inv. mass consistent with W/Z
  - Large irreducible background from W/Z+jets
  - Complementary sensitivity to aTGCs \( \sigma_{\text{tot}} = 68 \pm 7 \text{ (stat.)} \pm 19 \text{ (syst.) pb} \)

\[ \int L \, \text{dt} = 4.6 \, \text{fb}^{-1} \]

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

**ATLAS**

*JHEP01(2015)049*

Compatible with NLO prediction of 61.1±2.2 pb
Anomalous Gauge Boson Couplings

- Self couplings of gauge bosons, consequence of the non-Abelian nature of the EWK theory and fixed in SM
- BSM effects can manifest as deviation from the predicted SM couplings
  - How to quantify the deviations? Or constrain them?
- Different model independent parametrizations of BSM on the market
  - Effective Lagrangian, for example for aTGC:
    \[ \mathcal{L}_{WWW} = i g_{WWV} \left( g_1 \left( W_{\mu}^{+} W_{-\mu}^{-} - W_{+\mu}^{+} W_{-\mu}^{-} \right) V_{\nu}^{\nu} + \kappa V W_{\mu}^{+} W_{\nu}^{-} V^{\mu\nu} \right. 
    + \left. \frac{\lambda_{V}}{M_{W}^{2}} V^{\mu\nu} W_{\nu}^{+\rho} W_{\rho\mu}^{-} \right) \]
  - Effect field theory (EFT) approach, scale of new physics \( \Lambda \) large far from accessible energy \( (s << \Lambda^2) \). Adding new operators at higher dimension. SM restored for \( \Lambda \rightarrow \infty \)
  - Similar to Fermi approach for \( \beta \)-decay, \( G_{\nu} \) coupling for \( s << M_{W} \)

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d} \sum_{i} \frac{C_{i}^{(d)}}{\Lambda^{d-4}} \mathcal{O}_{i}^{(d)} \]
Di-boson: WW Production

- Differential measurements and comparison with different MC (Madgraph+Pythia, MC@NLO+Herwig, Powheg+Pythia), all normalized with NNLO prediction ➔ still has some shape discrepancies.
### Anomalous Triple Gauge Boson Couplings

#### Charged ATGC

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<th>WW</th>
<th>Wy</th>
<th>WV</th>
<th>WW</th>
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<th>WV</th>
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<th>D0 Combined</th>
<th>LEP Combined</th>
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<td>-1.3e-01 - 9.5e-02</td>
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**aTGC Limits @95% C.L.**

#### Neutral ATGC

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<th>$\lambda_\gamma$</th>
<th>WW</th>
<th>Wy</th>
<th>WV</th>
<th>WW</th>
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<th>WW</th>
<th>WV</th>
<th>WV</th>
<th>D0 Combined</th>
<th>LEP Combined</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-6.5e-02 - 6.1e-02</td>
<td>-5.0e-02 - 3.7e-02</td>
<td>-4.8e-02 - 4.8e-02</td>
<td>-2.4e-02 - 2.4e-02</td>
<td>-3.5e-02 - 4.0e-02</td>
<td>-3.8e-02 - 3.0e-02</td>
<td>-3.6e-02 - 4.4e-02</td>
<td>-5.9e-02 - 1.7e-02</td>
<td>8.6e-01</td>
<td></td>
</tr>
</tbody>
</table>

**aTGC Limits @95% C.L.**

#### Additional Information

- Charged ATGC: Only one analysis at 8 TeV so far (WW), best limit ~ to LEP
- Neutral ATGC: 8 TeV results best limit, $\gamma\gamma\gamma$ channel very powerful