Standard Model studies at ATLAS

E.Yu. Soldatov
National Research Nuclear University “MEPhI”

On behalf of the ATLAS Collaboration

QFTHEP Conference,
Sochi, Russia
22-29 September 2019
Standard Model measurements

- Standard Model (SM) is extremely predictive theory since its inception, which successfully resists its falsification for about 50 years.

- One of the principles of scientific method is: “Never stop verification and falsification of existing theories” (Galileo).
  SM measurements fully follow this principle and their two main goals are the following:
  ▪ validate SM in new energy regime and improve precision of known SM parameters
  ▪ test SM for new physics contributions (indirect search: anomalous couplings, etc), provide information about SM processes – backgrounds to direct new physics searches

Almost 200 SM papers were published by ATLAS since the start of LHC. Only few latest analyses are presented in these slides, more available:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Selection of presented results, based on categories:
  ▪ Electroweak Physics: W and Z bosons, VBF/VBS, Dibosons/Tribosons...
  ▪ Direct photons
  ▪ Jet Physics
  ▪ Soft QCD, Diffraction and Forward Physics
LHC and ATLAS dataset

Run1:
2011: $\sqrt{s} = 7 \text{ TeV} - 4.6 \, \text{fb}^{-1}$
2012: $\sqrt{s} = 8 \text{ TeV} - 20.3 \, \text{fb}^{-1}$

Run2:
2015-2018: $\sqrt{s} = 13 \text{ TeV} - 139 \, \text{fb}^{-1}$
ALFA: elastic protons measurement (forward physics)

AFP: diffractive protons measurement
SM test measurements reached the range of about 14 orders of magnitude: from pp and jets down to rare triboson and VBS processes.
Electroweak physics: Single boson production

\[ \bar{q} \rightarrow W/Z \rightarrow f \]
Electroweak physics: Single boson production

- Benchmark process for fixed-order calculations and predictions MC simulations of perturbative QCD (pQCD)
- Precision allows to study PDFs

![Graph showing total production cross section vs. sqrt(s) in TeV for the ATLAS collaboration with data points and theoretical predictions.](image)

**Theory (NNLO)**
**Measurement**

- $pp \rightarrow W$
- $pp \rightarrow Z/\gamma^*$

**References**
2.76 TeV, 4 nb$^{-1}$, arXiv:1907.03567 (for Z/W)
8 TeV, 20.2 fb$^{-1}$, JHEP 02, 117 (2017) (for Z)
8 TeV, 20.2 fb$^{-1}$, arXiv:1904.05631 (for W)
13 TeV, 81 nb$^{-1}$, PLB 759 (2016) 601 (for W)
13 TeV, 32 fb$^{-1}$, JHEP 02, 117 (2017) (for Z)
**Z(\text{ee}) + jets @ 8 TeV**

Data: \( L = 19.9 \text{ fb}^{-1} \pm 1.9\% \)

MC signal: Sherpa NLO; Main bkg: multijet, W+jet, EWK+top.

- **Measurement of double differential \( \sigma \); constrains on PDFs.**

- Main systematics are from signal modelling and JER+JES.

Data-driven from MC sim.

Check of the PDF sets: all deviations (in NNLO case) covered by theoretical uncertainties.

NLO predictions are lower than data, but NNLO calculations compensate differences in most of bins.

- **ATLAS**

\( t\bar{s} = 8 \text{ TeV}, 19.9 \text{ fb}^{-1} \)

\( Z(\rightarrow \text{ee}) + \text{jets} \)

anti-\( k_t \), \( R = 0.4 \)

Data

ME+PS

SHERPA 1.4

ALPGEN+PY6

SHERPA 2.2

NLO

Data

NNPDF 3.1

CT14 PDF

MCFM 6.8

NNLOJET

\( 100 \text{ GeV} < p_T^{\text{jet}} < 200 \text{ GeV} \)
Data: $L=4.0 \, \text{pb}^{-1} \pm 3.1\%$ (low $\mu$)

**Leptonic decay modes used, where lepton=e/$\mu$**

MC signal: Powheg-Box+Pythia8 NLO; Main bkg: EWK+top, multijet (for Wjets)

- Measurement of fiducial and total cross-sections at new collision energy point
  
  $\sigma_{W^+\to e^+\nu} = 2312 \pm 26$ (stat.) $\pm 27$ (syst.) $\pm 72$ (lumi.) $\pm 30$ (extr.) pb,

  $\sigma_{W^-\to e^-\bar{\nu}} = 1399 \pm 21$ (stat.) $\pm 17$ (syst.) $\pm 43$ (lumi.) $\pm 21$ (extr.) pb,

  $\sigma_{Z\to e^+e^-} = 323.4 \pm 9.8$ (stat.) $\pm 5.0$ (syst.) $\pm 10.0$ (lumi.) $\pm 5.5$ (extr.) pb.

Agreement within errors with NNLO QCD calculations.

- Measurement of cross-sections ratios and constrains on PDFs

  $R_W/Z = 10.95 \pm 0.35$ (stat.) $\pm 0.10$ (syst.);

  $R_{W/+W^-} = 1.797 \pm 0.034$ (stat.) $\pm 0.009$ (syst.).

All PDFs are in agreement with data within errors.

There is a slight tension between the data and the prediction using the ABMP16 PDF set.

Main uncertainties are from statistics, lepton reco+ID and multijet bkg (for Wjets).
Electroweak physics: VBF/VBS production
Why to measure?

➢ The rarest available SM processes: extremely sensitive tool to test SM predictions and search for the anomalous couplings
➢ VBS processes are irreducible backgrounds for the VBF Higgs boson production

Features:

➢ Due to backgrounds difficult to model, specific background enriched control regions (CRs) are used as a constraint
➢ Instead of a simple counting experiment to determine the signal cross section, a simultaneous fit is performed in bins of SR(s) and CR(s)
➢ Machine learning techniques are used to combine the sensitivity of many observables, sensitive to the difference between VBF/VBS signal and QCD background (+other backgrounds)
➢ VBF processes are sensitive to triple and VBS – to quartic anomalous gauge boson couplings (aTGCs/aQGCs), which are realized by EFT formalism:

\[
\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + ...
\]

where \( O_i \) and \( O_j \) are dimension-6 or dimension-8 operators, \( c_i \) – coefficients, \( \Lambda \) is the new physics scale.
Observation of EWK ZZ @ 13 TeV

Data: L=139 fb\(^{-1}\) ± 1.7%
MC signal: MG5+Pythia8 LO; Main bkgs: QCD ZZjj, WZjj (for 2l2v), WZjj (for 2l2v), Zjets

4l and 2l2v modes were used, where lepton=e/\(\mu\)

Measurement of integrated QCD+EWK and EWK-only cross-section

<table>
<thead>
<tr>
<th></th>
<th>Measured fiducial (\sigma) [fb]</th>
<th>Predicted fiducial (\sigma) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\ell\ell\ell\ell jj)</td>
<td>1.27 ± 0.12(stat) ± 0.02(theo) ± 0.07(exp) ± 0.01(bkg) ± 0.03(lumi)</td>
<td>1.14 ± 0.04(stat) ± 0.20(theo)</td>
</tr>
<tr>
<td>(\ell\ell\nu\nu jj)</td>
<td>1.22 ± 0.30(stat) ± 0.04(theo) ± 0.06(exp) ± 0.16(bkg) ± 0.03(lumi)</td>
<td>1.07 ± 0.01(stat) ± 0.12(theo)</td>
</tr>
</tbody>
</table>

Main uncertainties are from statistics, luminosity, the momentum scale and resolution of leptons and jets.

EWK process: \(\sigma(\text{obs}) = 0.82\pm0.21\ fb\) (\(\mu = 1.35\pm0.34\))

Obs.(exp.) significance = 5.5(4.3)\(\sigma\)

First observation of EWK ZZ!
Evidence of EWK $Z\gamma$ @ 13 TeV

Data: $L = 36.1 \pm 2.1$ fb$^{-1}$ only lepton decay modes were used, where lepton=$e/\mu$

MC signal: MG5+Pythia8 LO; Main bkgds: QCD $Z\gamma jj$, $t\bar{t}\gamma$, $Z$jets

From MC, data-driven normalization from the fit

- **Measurement** of integrated QCD+EWK and EWK-only cross-section

QCD+EWK:

$$\sigma_{Z\gamma jj}^{\text{fid.}} = \frac{71 \pm 2 \text{ (stat.)} +9 \text{ (exp. syst.)} +21 \text{ (mod. syst.)} \text{ fb}}{17}$$

$$\sigma_{Z\gamma jj}^{\text{fid., MadGraph+Sherpa}} = 88.4 \pm 2.4 \text{ (stat.)} \pm 2.3 \text{ (PDF + } \alpha_S)_{-19.1}^{+29.4} \text{ (scale) fb}$$

EWK process:

$$\sigma_{Z\gamma jj-\text{EW}}^{\text{fid.}} = \frac{7.8 \pm 1.5 \text{ (stat.)} +0.9 \text{ (syst.)} +1.0 \text{ (mod.) fb}}{1.4}$$

$$\sigma_{Z\gamma jj-\text{EW}}^{\text{fid., MadGraph+Sherpa}} = 7.75 \pm 0.03 \text{ (stat.)} \pm 0.20 \text{ (PDF + } \alpha_S) \pm 0.40 \text{ (scale) fb}$$

Obs.(exp.) significance = $4.1(3.8)\sigma$

ATLAS evidence of EWK $Z\gamma$!

Main uncertainties are from statistics, JES, HF tagging efficiency.
Observation of EWK WZ @ 13 TeV

Data: L=36.1 fb^{-1} ± 2.1%

only lepton decay modes were used, where lepton=e/\mu

MC signal: Sherpa LO; Main bkgs: QCD WZjj, ZZ, ttV, misID leptons

From MC, data-driven

normalization from the fit

- **Measurement** of integrated QCD+EWK and EWK-only cross-section

\[
\sigma_{W^\pm Z jj}^{\text{fid.}} = 1.68 ± 0.16 \text{ (stat.)} ± 0.12 \text{ (exp. syst.)} ± 0.13 \text{ (mod. syst.)} ± 0.044 \text{ (lumi.) fb}
\]

\[
\sigma_{W^+ Zjj}^{\text{fid., Sherpa}} = 2.15 ± 0.01 \text{ (stat.)} ± 0.05 \text{ (PDF)} ± 0.44 \text{ (scale) fb}
\]

- **Measurement** of differential QCD+EWK cross-sections (vs. m_{jj}, \Delta y_{jj}, N_{jets}, m_T[WZ], etc)

**QCD+EWK:**

**EWK process:**

\[
\sigma_{W^Z jj-JEW}^{\text{fid.}} = 0.57 ^{+0.14}_{-0.13} \text{ (stat.)} ^{-0.05}_{-0.04} \text{ (exp. syst.)} ^{+0.05}_{-0.04} \text{ (mod. syst.)} ^{+0.01}_{-0.01} \text{ (lumi.) fb}
\]

W^Zjj → e^+e^- or \nu\bar{\nu}

\[
\sigma_{W^Z jj-JEW}^{\text{fid., Sherpa}} = 0.321 ± 0.002 \text{ (stat.)} ± 0.005 \text{ (PDF)} ± 0.027 \text{ (scale) fb}
\]

Obs.(exp.) significance = 5.3(3.2)σ

First observation of EWK WZ!

Main uncertainties are from statistics, MC modelling, JES.

Observation of EWK $ssWW \rightarrow 13$ TeV

Data: $L = 36.1 \text{ fb}^{-1} \pm 2.1\%$

**only lepton modes were used, where lepton=e/\mu**

MC signal: Sherpa LO; Main bkg: QCD $ssWWjj$, $WZjj$, $V\gamma$, misID leptons bkg

From MC, normalization from the fit

- **Measurement** of integrated EWK cross-section

\[
\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48} \text{ (stat.)} +0.24^{+0.14}_{-0.16} \text{ (mod. syst.)} +0.08^{+0.06}_{-0.06} \text{ (lumi.)} \text{ fb}
\]

\[
(\mu = 1.44^{+0.26}_{-0.24} \text{ (stat.)} +0.28^{+0.28}_{-0.22} \text{ (syst.)})
\]

- Obs.(exp.) significance = \textbf{6.5(4.4)}$\sigma$

\textbf{ATLAS observation of EWK ssWW!}

Main uncertainties are from statistics, MC modelling, misID lepton bkg.
These rare processes become available for measurements just on LHC experiments.

<table>
<thead>
<tr>
<th>Final state of EWK production</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>Observed</td>
</tr>
<tr>
<td>WZ</td>
<td>Observed</td>
</tr>
<tr>
<td>ssWW</td>
<td>Observed</td>
</tr>
<tr>
<td>Zγ</td>
<td>Evidence (4.7σ – CMS; 4.1σ - ATLAS)</td>
</tr>
<tr>
<td>Wγ</td>
<td>No evidence (2.7σ - CMS)</td>
</tr>
<tr>
<td>Z</td>
<td>Observed</td>
</tr>
<tr>
<td>W</td>
<td>Observed</td>
</tr>
</tbody>
</table>

Amazing progress during last years!
Electroweak physics: QCD multiboson production
Zγ @ 13 TeV

- Precision measurement, which checks NNLO theory predictions.
  - Data: L=139 fb^{-1} ± 1.7%
  - only lepton decay modes were used, where lepton=e/µ
  - MC signal: Sherpa; Main bkgs: Zjets, tτy, WZ

- Measurement of differential cross-sections (vs. E_T[γ], η[γ], m_{llγ}, p_T[llγ])

The MATRIX prediction agrees well with the data at NNLO, while the NLO - underestimates the cross-section.

Main uncertainties are from Zjets bkg, photon efficiency, statistics.

There is a possibility to get Z and γ from different primary vertices, which leads to so-called pile-up bkg (up to 5%)
Z(\nu\nu)\gamma @ 13 TeV

neutrino decay mode was used

Data: \(L = 36.1 \text{ fb}^{-1} \pm 2.1\%\)

MC signal: Sherpa NLO; Main bkgds: \(W\gamma, \gamma\text{jet, } e\rightarrow\gamma\text{ misID, jet}\rightarrow\gamma\text{ misID}

from MC with normalization from data CRs

- **Measurement** of integrated and differential cross-sections (vs. \(E_T[\gamma], p_{T[\text{miss}]}, N_{\text{jets}}\))

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limit 95% CL Measured [TeV^{-4}]</th>
<th>Expected [TeV^{-4}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{BW}/\Lambda^4)</td>
<td>((-1.1, 1.1))</td>
<td>((-1.3, 1.3))</td>
</tr>
<tr>
<td>(C_{BW}/\Lambda^4)</td>
<td>((-0.65, 0.64))</td>
<td>((-0.74, 0.74))</td>
</tr>
<tr>
<td>(C_{WW}/\Lambda^4)</td>
<td>((-2.3, 2.3))</td>
<td>((-2.7, 2.7))</td>
</tr>
<tr>
<td>(C_{BB}/\Lambda^4)</td>
<td>((-0.24, 0.24))</td>
<td>((-0.28, 0.27))</td>
</tr>
</tbody>
</table>

- **Setting limits** on anomalous TGC in \(h_i(V)\) vertex functions and EFT formalisms

Dim-8 EFT formalism:

- **Good agreement!**

Main uncertainties are from statistics, MC modelling, data-driven bkgds.
Data: L=36.1 fb$^{-1}$ ± 2.1%
Only lepton decay modes were used, where lepton=e/µ
MC signal: Powheg-Box+Pythia8 NLO; Main bkggs: top bkg, DY, Wjets
from MC with norm from data CR

**Measurement** of integrated and differential cross-sections (vs. $p_T$[lead l], $m_\text{e}\mu$, $\Delta\phi_{\text{e}\mu}$, etc)

- Setting limits on anomalous TGC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed 95% CL [TeV$^{-2}$]</th>
<th>Expected 95% CL [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{WWW}/\Lambda^2$</td>
<td>$[-3.4, 3.3]$</td>
<td>$[-3.0, 3.0]$</td>
</tr>
<tr>
<td>$c_W/\Lambda^2$</td>
<td>$[-7.4, 4.1]$</td>
<td>$[-6.4, 5.1]$</td>
</tr>
<tr>
<td>$c_B/\Lambda^2$</td>
<td>$[-21, 18]$</td>
<td>$[-18, 17]$</td>
</tr>
<tr>
<td>$c_{WWW}/\Lambda^2$</td>
<td>$[-1.6, 1.6]$</td>
<td>$[-1.5, 1.5]$</td>
</tr>
<tr>
<td>$c_W/\Lambda^2$</td>
<td>$[-76, 76]$</td>
<td>$[-91, 91]$</td>
</tr>
</tbody>
</table>

Main uncertainties are from b-tagging, MC modelling, JES.

Good agreement!
Evidence of WVV @ 13 TeV

Data: L=79.8 fb\(^{-1}\) ± 2.0%

WWW→lℓvqq, WWW→lℓvlvlv, WWZ→lqqll, WWZ→lℓvlvlv, WZZ→qqlllll, where l=e/µ

MC signal: Sherpa; Main bkgs: WZjets, non-prompt lepton bkg from MC, data-driven

- Measurement of integrated cross-sections

\[ \sigma_{WWW} = 0.65^{+0.16}_{-0.15}\text{ (stat.)}^{+0.16}_{-0.14}\text{ (syst.) pb} \]
\[ \sigma_{WZZ} = 0.55 ± 0.14\text{ (stat.)}^{+0.15}_{-0.13}\text{ (syst.) pb} \]

Good agreement!

Combined obs.(exp.) significance = \(4.1(3.1)\sigma\)

Evidence of triboson WVV!

Main uncertainties are from statistics, MC modelling, data-driven bkg estimations.

Accepted by PLB
Direct photons
Inclusive photon ratios @ 13 TeV/8 TeV

- Test of pQCD with hard colourless probe
- Testground for MC models of prompt-photon production

Data: L=20.2 fb⁻¹ @ 8 TeV & 3.2 fb⁻¹ @ 13 TeV

- Measurement of differential cross-sections ratios

Photons are isolated, EMC shower shapes ID applied, $E_T[\gamma]>125$ GeV

“Direct” photons: from $qg\rightarrow q\gamma$, $qq\rightarrow g\gamma$ (ME)

Results are in agreement with theory within errors in most of bins. Photon energy scale syst become comparable with others.
Important test of pQCD
Data: $L=36.1\,fb^{-1} \pm 2.1\%$
MC signal: Pythia and Sherpa;
Main bkgd: jet→γ
Photons are isolated, EMC shower shapes ID applied, $E_T[γ]>125\,GeV$

Measurement of differential cross-sections (vs. $E_T[γ]$, $η[γ]$)

Data-driven from 2D-sideband method

NNLO QCD prediction gives an excellent description of the data

Main uncertainties are from photon energy scale and photon ID.
Jet physics
Jet physics: Multi-scale dynamics in jet-based observables

- **Study of jets** is an important test of QCD (strong coupling, PDF...) in hadron collider experiments.
- It can be used also to **distinguish the origin of jets** between light quarks, gluons and hadronic decays of heavy particles.

Multiscale dynamics studies provide:
- Exploring the evolution of high energy quarks and gluons into hadrons
  - Multi-scale problem which straddles perturbative and non-perturbative effects
  - Good understanding necessary for precise control over observables in many physics analyses

- **What’s Interesting?**
  - Testing showering and hadronization models against event shape and individual jet observables
  - Measuring how these variables evolve in a wide range of phase-space and with different jet flavors
  - Probing the structure of hadronic resonances
Jet shapes @ 13 TeV

Data: L=33 fb\(^{-1}\) ± 2.2%

- Measurement of many jet substructure observables for trimmed and Soft Drop jets
  \(N_{\text{subjets}}, \lambda_2^{\text{LHA}}, e_2, e_3, C_2, D_2, T_{21}, T_{32}\)

- Modeling of these observables is important for taggers (e.g. D2 is one of the most common variables to use for tagging W bosons)

For each observable, subtract the background, then unfold to particle level

None of the MC generators completely model the data (different MC generators model well different observables)
Lund jet plane @ 13 TeV

- New proposal to represent internal structure and formation of jets
  A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon
  - **Lund Plane**: ln(1/z) vs ln(1/θ)
    - z = relative momentum of emission wrt jet core
    - θ = opening angle of emission relative to the jet core

- **Measurement** of double differential cross-section of Lund jet plane
  Data: L=139 fb⁻¹ ± 1.7%
  Using R = 0.4 jets
  Unfolding to charged particle level

- The Lund Plane is the phase space of these emissions: it naturally factorizes perturbative and non-perturbative effects, UE/MPI, etc

- Can be used in ML-based jet discriminants
Soft QCD, Diffraction and Forward Physics

Diagram:

\[ \begin{align*}
  &\text{p} \\
  &\text{p} \\
  &\text{p} \\
\end{align*} \rightarrow X(M_x) \]

\[ \begin{align*}
  &\text{p} \\
  &\text{p} \\
  &\text{p} \\
\end{align*} \rightarrow X(M_x) \]

\[ \begin{align*}
  &\text{p} \\
  &\text{(t)} \\
  &\text{p} \\
\end{align*} \rightarrow Y(M_y) \]

\[ \begin{align*}
  &\text{p} \\
  &\text{(t)} \\
  &\text{p} \\
\end{align*} \]
Single Diffractive Dissociation using ALFA @ 8 TeV

- Most of diffraction kinematics domain is characterized by soft scales
- Can not be described by pQCD
- An important tool to probe strong interaction in its non perturbative regime
- Interactions mediated by Pomerons
- Phenomenological approach (QCD + models)

Diffraction studies are carried on special LHC runs with high $\beta^*$ and consequently low luminosity. Forward ALFA detector is used.

**Kinematic variables:**
- $t$ – squared four-momentum transferred from the proton
  \[ t \approx -p_T^2 \]
- $\xi$ – momentum fraction of the proton carried by the pomeron
  \[ \xi = 1 - E/E_0 = M_X^2/s \approx \sum_i (E_i^j \pm p_z^i)/\sqrt{s} \]
- $\Delta \eta$ – (pseudo)rapidity gap from the tracker edge
Single Diffractive Dissociation using ALFA @ 8 TeV

ATLAS-CONF-2019-012

- Measurement of differential cross-section of Single Diffractive Dissociation

- Diffractive plateau is visible
- MCs do not describe the overall cross-section
- Shape description is fine

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_{MC}/\sigma_{data}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA 8, A2 tune</td>
<td>2.3</td>
</tr>
<tr>
<td>PYTHIA 8, A3 tune</td>
<td>1.5</td>
</tr>
<tr>
<td>HERWIG 7.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

In agreement with Pythia 8 prediction:

- PYTHIA8 A2: 7.82 GeV^{-2}, PYTHIA8 A3: 7.10 GeV^{-2}

Main systematic uncertainty from overlay background subtraction

Measured exponential slope:

$B = 7.60 \pm 0.23$ (stat.) $\pm 0.22$ (syst.) GeV^{-2}
Summary

➢ Early full Run2 analyses and precision Run1 analyses provide very stringent tests of SM.

➢ New measurements for soft QCD / Diffraction / Forward Physics, Electroweak studies, Jet Physics and Direct Photons were presented:
  ▪ **W/Z data and photons**: consistent with SM at NNLO
  ▪ **VBF/VBS**: most of channels were observed and the rest will be observed in near future
  ▪ **Dibosons/Tribosons**: no surprizes so far - constraints on anomalous couplings
  ▪ **Jets**: Lund plane is very promising method of factorizing many different effects
  ▪ **Forward physics**: first single diffractive proton-proton cross-section measured

➢ LHC Run2 was very successfull: a lot of data still to be analysed!