Tests of the electroweak sector with diboson final states at the ATLAS Experiment

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On behalf of ATLAS collaboration

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Introduction

- **Study of multibosons** - an essential piece in LHC physics program

**Electroweak Theory**

- Self-interactions due to Non-abelian Gauge Theory (diboson, triboson ...)

- Electroweak Symmetry Breaking
  
  \( H \rightarrow VV, \text{vector-boson-scattering} \)

- Precision test of the Standard Model

- Sensitive to new physics (SUSY, Little Higgs, Graviton, Dark Matter ...)

Production \( \sigma \): \( O(pb) - O(fb) \)

Only precisely accessible at LHC

8/24/2019

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First diboson measurements at ATLAS ("rediscovery" of electroweak theory)
- NLO QCD + shower simulation was new and sufficient to describe the data
- Many multiboson channels not/less explored in the past (LEP, Tevatron)
Many multiboson modes probed, Precision as good as 5%, requiring NNLO QCD + NLO EW to describe the data

Observations consistent with the Standard Model; Further scrutiny desirable with more data (better precision, rarer channels ...)

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Methodology

Decay channels
• Clean signature with leptonic decays of bosons
• Semileptonic decays of VV with good sensitivity to new physics

Selection and Estimation
• Cuts on kinematic information for precision channels
• Machine learning for rare processes (triboson, VBS)
• Backgrounds estimated with simulation & data

Measurements
• Differential $\sigma$ with “unfolding” techniques
• Often reported in fiducial regions, close to detector selection, to minimize theory dependence

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8/24/2019
## Updates Since Last Year

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<th>Luminosity @ CME</th>
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<tr>
<td>WW $\rightarrow$ $\ell\ell\nu\nu$</td>
<td>36.1 fb$^{-1}$ @ 13 TeV</td>
<td>arXiv:1905.04242</td>
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<td>WZ $\rightarrow$ $\ell\ell\nu\nu$</td>
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<td>Eur. Phys. J. C 79 (2019) 535</td>
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<td>ZZ $\rightarrow$ $\ell\ell\nu\nu$</td>
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<td>DPI ZZ $\rightarrow$ $\ell\ell\nu\nu$</td>
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<td>$Z\gamma$ $\rightarrow$ $b\bar{b}\gamma$</td>
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<td>VBS WZ</td>
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<td>VBS ZZ</td>
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*First evidence!*

Full Run-II!
Diboson Measurements

Nice to have (d), eventually (c)

data / theory compatibility
**WW and WZ Measurements**

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**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

**Differential \( \sigma \) with precision**

**Clean signature, reaching <5% precision for integrated \( \sigma \)**

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**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

**Data 2015+2016**

- Stat. & syst. uncertainty
- [NNLO(qq)+NLO(gg)]\( \oplus \)NLO(EW)
- Powheg-Box+Pythia8, \( k=1.13 \) *
- Powheg-Box+Herwig++, \( k=1.13 \) *
- Sherpa 2.2.2, \( k=1.0 \) *
- comb. w. Sherpa+OL gg→WW, \( k=1.7 \)

**Theory / Data**

**\( \Delta \phi_{\text{eq}} \)**

**Ratio to Sherpa**

- Data
- Sherpa 2.2.2
- Powheg+Pythia \( \times 1.18 \)
- Sherpa 2.1

**\( W^+Z \rightarrow \ell^+\nu \ell\ell \)**

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**Clean signature, reaching <5% precision for integrated \( \sigma \)**

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ZZ Measurements

Free of backgrounds with four charged-leptons

Rich physics in a single measurement

Measurement from Z pole to TeV

\[ B_{Z \rightarrow 4\ell} = [4.70 \pm 0.32 \text{(stat)} \pm 0.21 \text{(syst)} \pm 0.14 \text{(lumi)}] \times 10^{-6} \]

Differential \(\sigma\) used to make physics interpretations

Among best rare decay measurements

plus, extraction of gg\(\rightarrow\)4l contribution, off-shell Higgs contribution, and constraints on modified Higgs couplings; all comparable to dedicated detector-level studies

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ILνν decays more difficult, but managed to have a good precision of 7% for integrated $\sigma$

Clean channel to study double parton scattering

**Differential $\sigma$ used to constraint neutral TGCs:**

*More precise than 4l*

Exploit the angular correlation of two Zs and extract the signals using neutral network, upper limits set on DPS and on $\sigma_{\text{eff}}$
Zγ Measurements

Clean signature $Z(\rightarrow ll) + \gamma$

Great precision enables a scrutiny of the process in details

Studied a “new” type of pile-up contributions due to boson from different bunch crossing
Zγ Measurements

Difficult channel with $Z(\rightarrow \nu\nu) + \gamma$, managed with harsh cuts on Missing $E_T$

Nice channel to study merged boson jets, $Z(\rightarrow bb)$ boosted against a high-$p_T \gamma$

Probing larger $p_T$ or mass range than leptonic decays, yielding better constraint on neutral couplings
Rare Channels

Explore the unexplored
Production of three massive boson only accessible by combining all final states

Same-sign, different flavor lepton pairs to suppress backgrounds, BDT discriminants => obs. sig. of 4.1 $\sigma$

First evidence!
Selection of $Z(\rightarrow ll) + \gamma + jj$, and enhancement of VBS with BDT

Modelling uncertainties play a large role

Observed significance for EW $Z\gamma jj$ is $4.1\sigma$

Combing 0, 1, 2-lepton channels, each with different event categories, and with BDT

$\rightarrow$ Observed significance of $2.7\sigma$
VBS same-sign WW

Requirements of same-sign lepton pair and VBS topology keeps the final state ~clean

Fit on mjj to extract EW WWjj contribution

- Observed significance of 6.5 $\sigma$
- Major systematic uncertainties from background modelling/estimation and jets

Demonstration of power of unitarization
VBS WZ

WZ($\rightarrow 3l$) selection plus requirement of two jets with VBS topology

BDT discriminants fitted: observation of EW WZjj with $5.3\sigma$ (expected $3.2\sigma$)

$$\frac{\sigma_{\text{EW}}^{\text{meas}}}{\sigma_{\text{EW}}^{\text{pre}}} = 1.8 \pm 0.5$$

First observation!

Differential measurements provided for inclusive WZjj in a fiducial region
Combination of both $\ell\ell\ell\ell jj$ and $\ell\ell\ell\ell\nu jj$ to search for the rarest VBS process:

- $\ell\ell\ell\ell jj$ channel dominates
- Observed (expected) significance: $5.5 \ (4.3) \ \sigma$

First observation!

Relatively a clean channel to access energy range up to TeV

A milestone in the physics program, closing the “discovery” phase of VBS
Many updates of multiboson studies in ATLAS since last conference have been presented – it is a very active area in the LHC physics program.

Measurements of diboson processes enter into precision mode, careful scrutiny of precision channels and exploration of difficult channels are ongoing.

Started to carry out physics interpretations using differential measurements.

Good progress on exploration of rare processes, especially in triboson and VBS production.

Stay tuned for more updates with full Run-II data soon.

No obvious deviations from the SM were observed. We are pushing further the battleground to deeper inside the fundamental electroweak theory.
Bonus

[Image of a desert road with text overlay: ??? 1 ab, 1 zb]
Backup
ATLAS Detector
A diboson event
WZ\rightarrow e\nu\mu\mu Candidate
$e\nu\nu$ only, jet-veto to suppress top
Dominant systematic unc. from backgrounds

**Differential $\sigma$ with precision**

**Sizable backgrounds**

**Testing jet-veto calculations, large modelling unc. in theory**
WZ Measurement

Clean signature, reaching <5% precision for integrated $\sigma$

Multiple differential $\sigma$ reported to scrutiny of different phase spaces

Polarization study with angular variables
Clean signature $Z(\rightarrow ll) + \gamma$

Great precision enables a scrutiny of the process in details

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Selection of $Z(\rightarrow ll) + \gamma + jj$, and enhancement of VBS with BDT

Modelling uncertainties play a large role

Observed significance for EW $Z\gamma jj$ is $4.1\sigma$
Semileptonic channels have good sensitivity to high-energy region; however challenging task

Combing 0, 1, 2-lepton channels, each with different event categories, and with BDT ➔ Observed significance of 2.7 $\sigma$
Vector boson scattering

⇒ **Probe of EWSB dynamics and Sensitive to new physics in EWSB sector**

⇒ **Delicate cancellation needed to unitarize at TeV scale**

⇒ **Historically, one of main motivations for a Higgs boson!**

- Studied in the process of electroweak production of VVjj; irreducible background from QCD production of VVjj

- Signature involves: 1) no color flow between scattering partons; 2) two QCD jets relatively forward, with large mjj and rapidity separation