Measurements of Vector Boson Fusion and Scattering and Triboson production with the ATLAS detector

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on behalf of ATLAS collaboration

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Introduction

- Vector boson fusion (VBF) and scattering (VBS): important test of electroweak (EW) sector of the standard model (SM)
  - How Higgs boson unitarizes scattering amplitude
  - Irreducible background for new physics searches

- Sensitive probe of anomalous triple and quartic gauge boson coupling (aTGC and aQGC)
  - New physics would appear as enhancements in high $p_T$ regions
  - Tri-boson production is also sensitive to aQGC

- Distinctive signature of VBF/VBS
  - Presence of two energetic hadronic jets in the forward and backward directions wrt the proton beamline.
  - No QCD colour exchanged in the processes → suppressed hadronic activity between the two jets ("rapidity gap")

In this talk,
- probe TGC via Vector Boson Fusion process (see L.Chevalier’s talk for a probe with diboson production)
- probe QGC via Vector Boson Scattering and tri-boson production
Many processes give final state with a Z boson and two jets
- **dominated by strong production** → data can provide important constraints on theoretical modeling

- Much rarer but very interesting: **pure electroweak Zjj** (t-channel exchange of a EW boson) in particular the vector boson fusion
  - similarity with VBF Higgs
  - sensitivity to anomalous WWZ triple gauge couplings

- **Signature of pure EWK process**: harder $m_{jj}$, smaller jet activity in rapidity gap, better $p_T$ balance of the system Z+2jets
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Signature of pure EWK process: harder $m_{jj}$, smaller jet activity in rapidity gap, better $p_T$ balance of the system $Z+2jets$

Measurements with 8 TeV data (20.3fb$^{-1}$) with ATLAS (e and $\mu$ channels)

Basic event selection:
  • 2 isolated leptons with $p_T$$>$25 GeV and $|\eta|$$<$(2.4,2.47) ($\mu$,e)
  • 2 antikT0.4 jets with $p_T$$>$25 GeV, $|y|$$<$4.4

Dominant backgrounds:
  • VZ, Top (estimated from simulation)
  • multijets (estimated from data by reversing electron ID or muon isolation criteria)
Inclusive fiducial cross section

\[ \sigma_{fid} = \frac{N_{obs} - N_{bkg}}{\int Ldt \cdot C} \]

\( C \) = correction factor for difference between reconstruction and particle level (0.8-0.9 muons, 0.4-0.7 electrons)

Measured in five fiducial regions:
- **Baseline**: most inclusive one
- **Control**: suppress EW contribution, >=1 jet in rapidity gap
- **Search**: no jet in rapidity gap
- **High-mass**: \( m_{jj} > 1 \text{ TeV} \)
- **High pT**: harder cut on jet pT

Combination of electron and muon channels

- Overall good description of data
- But indication of mismodelling at high \( m_{jj} \)

\[ \text{Data (2012)} \]
\[ \text{QCD Zjj} \]
\[ \text{EW Zjj} \]
\[ \text{VZ} \]
\[ \text{Top} \]
\[ \text{Multijets} \]

Good agreement found in the five regions
- Results compatible between the two channels
Differential $m_{jj}$ and $\Delta Y$ distributions

Comparison with Powheg and Sherpa 1.4.3

ATLAS
$\int L \, dt = 20.3 \, fb^{-1}$
$\sqrt{s} = 8 \, TeV$
Baseline region

Powheg better describes $m_{jj}$ and $\Delta Y$ dist. than Sherpa in QCD dominated region.
New NLO version of Sherpa (2.1.0) should improve agreement [1].
None of the two generators can fully reproduce data for all distributions in all fiducial regions
→ data can be used to constrain modelling of Zjj production

- Smaller jet activity in EW process than in strong one as expected
- Sherpa better describes variables sensitive to additional jet activity in event
Observation of EW Zjj

- Extract number of electroweak Zjj events by a fit to $m_{jj}$ distribution in search region.
- Data in control region used to constrain generator modelling of the background $m_{jj}$ shape → minimize experimental and theory uncertainties.
- Dominant systematics: JES and lepton identification.
- Fiducial cross section for EW component:
  - electron and muon channels compatible within 1.7σ
  - in good agreement with Powheg prediction.

**Background-only hypothesis rejected with >5σ significance**

\[
\sigma_{EW} = 54.7 \pm 4.6 \text{ (stat)} + 9.8 \text{ (syst)} \pm 1.5 \text{ (lumi)} \text{ fb}
\]

\[
\sigma_{EW,Powheg} = 46.1 \pm 0.2 \text{ (stat)} \pm 0.8 \text{ (PDF)} \pm 0.5 \text{ (model)} \text{ fb}
\]
Limits on aTGC

- Measured in search region + cut on \( m_{jj} > 1\text{TeV} \)
  (region least affected by background normalisation)

- Effective Lagrangian for aTGC

\[
\frac{\mathcal{L}}{g_{WWZ}} = \left[ g_{1,Z} \left( W_{\mu
u}^+ W_{\mu}^\mu Z^\nu - W_{\mu\nu}^+ W_{\mu\nu}^\mu Z^\nu \right) + \kappa_Z W_{\mu}^+ W_{\nu} Z_{\mu\nu}^\nu + \frac{\lambda_Z}{m_W^2} W_{\rho\mu}^+ W_{\nu}^\mu Z_{\rho\nu}^\nu \right]
\]

*analysis sensitive to these parameters (=1 and =0 in SM)*

- Modify couplings by a dipole form factor, depending on unitarization scale \( \Lambda \)

<table>
<thead>
<tr>
<th>aTGC</th>
<th>( \Lambda = 6 \text{ TeV (obs)} )</th>
<th>( \Lambda = 6 \text{ TeV (exp)} )</th>
<th>( \Lambda = \infty \text{ (obs)} )</th>
<th>( \Lambda = \infty \text{ (exp)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta g_{1,Z} )</td>
<td>([-0.65, 0.33])</td>
<td>([-0.58, 0.27])</td>
<td>([-0.50, 0.26])</td>
<td>([-0.45, 0.22])</td>
</tr>
<tr>
<td>( \lambda_Z )</td>
<td>([-0.22, 0.19])</td>
<td>([-0.19, 0.16])</td>
<td>([-0.15, 0.13])</td>
<td>([-0.14, 0.11])</td>
</tr>
</tbody>
</table>

Complementary to measurements made with di-boson WZ [2] (space-like vs time-like propag.)
VBS WW+2j same sign

• First evidence for electroweak WWjj production
  • very interesting channel because strong production does not dominate

Two fiducial regions defined:
• Inclusive: 2 leptons with pT>25 GeV eta<2.5, 2jets with pT>30 GeV, η<4.5, m_{jj}>500 GeV
• VBS: add cut on ΔY_{jj} > 2.4

• Background = dominant uncertainty. Four different control regions built to test the different background predictions → good consistency found in all regions for all channels.

• Three decay channels: μμ, ee, μe

Excess of events over background expectation
Fiducial cross section and limit on aQGC

- Combined significance over background only hypothesis:
  - Inclusive region (EW+strong): 4.5σ (exp: 3.4σ)
  - VBS region: 3.6σ (exp: 2.8σ)

- Additional contribution to WWjj can be expressed in model-independent way using higher dim. operators → anomalous quartic gauge couplings (aQGC)

- VBS region used to set limits

- Deviation from SM parametrized in term of \((\alpha_4, \alpha_5)\) (both 0 in SM)
Triboson $W\gamma\gamma$

- First evidence for tri-boson production in $W\gamma\gamma$ final state
  - allow test of quartic gauge couplings (QGC)

- Measurement of inclusive and exclusive cross sections
  - exclusive: veto on event with $>=1$ jet

- Main background:
  - "fakes" (jet reco. as $\gamma$ or lepton): $Wj\gamma$, $Wjj$, $\gamma\gamma+$jets → from data driven (DD) techniques
  - prompt leptons/$\gamma$
    - $Z\gamma$, $Z\gamma\gamma$, $WZ$, $W(\tau\nu)\gamma\gamma$ (from Sherpa)
    - $tt\bar{t}$, single top, WW (from MC@NLO)
    - ZZ (from POWHEG)

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<table>
<thead>
<tr>
<th>Definition of the fiducial region</th>
</tr>
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<tbody>
<tr>
<td>$p_T^\ell &gt; 20$ GeV, $p_T^{\gamma} &gt; 25$ GeV, $</td>
</tr>
<tr>
<td>$m_T &gt; 40$ GeV</td>
</tr>
<tr>
<td>$E_T^\gamma &gt; 20$ GeV, $</td>
</tr>
<tr>
<td>$\Delta R(\ell, \gamma) &gt; 0.7$, $\Delta R(\gamma, \gamma) &gt; 0.4$, $\Delta R(\ell/\gamma, \text{jet}) &gt; 0.3$</td>
</tr>
</tbody>
</table>

Main uncertainties on fiducial cross section: 1) DD background (14-23%) 2) JES (5-7%) 3) Luminosity (3%)
Cross section and limits on $a_{QGC}$

- Combined significance over background only scenario: $>3\sigma$
- Fiducial cross section:

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{fid}^{MCFM}$ [fb]</th>
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<tbody>
<tr>
<td>Incl.</td>
<td>$6.1^{+1.1}_{-1.0}$(stat) ± 1.2(syst) ± 0.2(lumi)</td>
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<tr>
<td>Excl.</td>
<td>$2.9^{+0.8}<em>{-0.7}$(stat) $^{+1.0}</em>{-0.9}$(syst) ± 0.1(lumi)</td>
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</tbody>
</table>

higher than theory by 1.9$\sigma$ in inclusive case

- Limits on $a_{QGC}$ obtained from exclusive region + cut $m_{\gamma\gamma}>300$ GeV
- Channel very sensitive to $f_{T0} \rightarrow$ improve limit w.r.t previous publication [3]

23/07/15
Overall good agreement between data and simulation found in VBF, VBS and triboson cross section measurements and constrain on aTGC and aQGC limits have been set.

Many other ATLAS measurements to come soon: VBF $W$, VBS $WZ$, tri-boson $Z\gamma\gamma$
References

• [1]: MEPS@NLO merging: « QCD matrix elements + parton showers: The NLO case» arXiv:1207.5030


Back-up
WZ aTGC

Z+2j, definition of fiducial regions

Table 1. Summary of the selection criteria that define the fiducial regions. ‘Interval jets’ refer to the selection criteria applied to the jets that lie in the rapidity interval bounded by the dijet system.

<table>
<thead>
<tr>
<th>Object</th>
<th>baseline</th>
<th>high-mass</th>
<th>search</th>
<th>control</th>
<th>High-p_T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
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<tr>
<td>Dilepton pair</td>
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<tr>
<td>Jets</td>
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<tr>
<td>Dijet system</td>
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<tr>
<td>Interval jets</td>
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<tr>
<td>Zjj system</td>
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Differential distributions

- **Sensible distributions to:**
  - kinematics of the two tagging jets: $m_{jj}$, $\Delta Y_{jj}$, …
  - difference in colour flow between EW and strong production: $N_{\text{jet}}^{\text{gap}}$, $p_{T}^{\text{bal}}$, …

- **Method:** iterative Bayesian unfolding in same 5 regions as defined previously
  - 1\textsuperscript{st} step, detector response matrix (=prior) from Sherpa
  - 2\textsuperscript{nd} step prior = unfolded distribution from data

- **Dominant systematic uncertainties**
  - jet related uncertainties (energy scale, resolution, jet vertex fraction)
  - theoretical modelling

- **Comparisons between Powheg (accurate to NLO in pQCD) and Sherpa (accurate to LO) generators**

- **Results:**
  - Smaller jet activity in EW process than in strong one as expected
  - None of the two generators can fully reproduce data for all distributions in all fiducial regions → **unfolded data can be used to constrain modelling of $Z_{jj}$ production in specific phase-space**

23/07/15 19 EPS conference
\[ \int L dt = 20.3 \, fb^{-1} \quad \sqrt{s} = 8 \, TeV \]

**Baseline region**

- Data (2012)
- Sherpa Zjj (QCD + EW)
- Sherpa Zjj (QCD)
- Powheg Zjj (QCD + EW)
- Powheg Zjj (QCD)

**Search region**

- Data (2012)
- Sherpa Zjj (QCD + EW)
- Sherpa Zjj (QCD)
- Powheg Zjj (QCD + EW)
- Powheg Zjj (QCD)

*Veto on additional jet activity*

**ATLAS**

- \( m_{jj} \) in [500, 3000] GeV

23/07/15

EPS conference
ATLAS
\( \int L \, dt = 20.3 \, \text{fb}^{-1} \)
\( \sqrt{s} = 8 \, \text{TeV} \)
baseline region

- Data (2012)
- Sherpa Zjj (QCD + EW)
- Sherpa Zjj (QCD)
- Powheg Zjj (QCD + EW)
- Powheg Zjj (QCD)

\[ \langle N_{\text{jet}}^{\text{pair}} \rangle \]

\[ m_{jj} \, [\text{GeV}] \]

\[ |\Delta y| \]
$\int L \, dt = 20.3 \, fb^{-1}$
$\sqrt{s} = 8 \, TeV$
control region

$N_{\text{obs}} / 250 \, GeV$

Data (2012)
Background
Background + EW Zjj

$Data / MC$

$p_0 + p_1 m_{jj} + p_2 m_{jj}^2$
$p_0 + p_1 m_{jj}$
• Prediction taken from Powheg+CT10 PDF + Pythia for parton showering
  • constructive interference between EW and strong process: +12% in inclusive region, +7% in VBS one

• Three decay channels: $\mu\mu$, ee, $\mu e$
<table>
<thead>
<tr>
<th></th>
<th>Observed [TeV$^{-4}$]</th>
<th>Expected [TeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>$[-0.9, 0.9] \times 10^2$</td>
<td>$[-1.2, 1.2] \times 10^2$</td>
</tr>
<tr>
<td>$f_{M2}/\Lambda^4$</td>
<td>$[-0.8, 0.8] \times 10^4$</td>
<td>$[-1.1, 1.1] \times 10^4$</td>
</tr>
<tr>
<td>$f_{M3}/\Lambda^4$</td>
<td>$[-1.5, 1.4] \times 10^4$</td>
<td>$[-1.9, 1.8] \times 10^4$</td>
</tr>
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*no form factor applied*