Measurements of single and multi-boson production with the ATLAS detector

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Topics

Measurements of:
1. single real W/Z
2. Drell-Yan
3. Diboson
4. VBF/VBS
5. Triboson

Physics Motivations:
a) probe predictions, improve parameter bounds & modelling for SM
b) constrain PDF
c) understand bkg for many (Higgs, BSM, ...) analyses
d) search/constrain new physics (anomalous couplings)

crucial interplay: precise measurements ↔ good modelling
Reference Guides

1) Measurement of W and Z Boson Production Cross Sections in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector [ ATLAS-CONF-2015-039 ]

2) Measurement of the Production Cross Sections of a Z Boson in Association with Jets in collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector [ ATLAS-CONF-2015-041 ]

3) Measurement of the transverse momentum and $\Phi_n$ distributions of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector [ ArXiv:1512.02192, submitted on 7 Dec 2015 ]


6) Measurement of the $W^+W^-$ production cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector [ ATLAS-CONF-2014-033 ]

7) Measurement of the $WW+WZ$ cross section and limits on anomalous triple gauge couplings using final states with one lepton, missing transverse momentum, and two jets with the ATLAS detector at $\sqrt{s} = 7$ TeV [ JHEP 01(2015)049 ]

8) Measurement of the electroweak production of dijets in association with a Z-boson and distributions sensitive to vector boson fusion in proton-proton collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector [ JHEP 04(2014)031 ]

9) Evidence for Electroweak Production of $W^+W^0jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector [ Phys. Rev. Lett. 113, 141803 (2014) ]

Some Ingredients
Cross Section Estimation

- Use decays to leptons to get a better background suppression
- Selecting high $p_T$ leptons/jets
- Require high missing $E_T$ if $\nu$ involved
- Apply selection based on process topology

- Irreducible backgrounds (estimated using simulation)
- Backgrounds including non prompt leptons using data-driven methods ($t\bar{t}$, $V+$ jets)

\[
\sigma_{fid}^{tot} = \frac{N_{data} - N_{backg.}}{A \times BR \times C \times \int Ldt}
\]

- Extrapolation to full phase space via an acceptance factor (A) (and the branching ratio)
- Correction for detector inefficiencies

- Estimate systematic uncertainties from:
  - Experimental: energy-resolution/scale, reconstruction, ID, luminosity, …
  - Theoretical: PDFs, parton shower, renorm./fact. scale, …

8 January 2016
Anomalous Couplings

- Non abelian structure of $SU(2)_L \times U(1)_Y$ allows boson self-coupling

**Anomalous Triple Gauge Couplings (aTGC.s):** dibosons, VBF

**Anomalous Quartic Gauge Couplings (aQGC.s):** tribosons, VBS

- Possible to introduce additional parameter in effective field theories that parametrize SM forbidden couplings

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anomalous Triple Gauge Couplings (aTGC.s): dibosons, VBF
anomalous Quartic Gauge Couplings (aQGC.s): tribosons, VBS

Ref.: http://arxiv.org/abs/1305.3773
[The MC Generator Zoo] Large efforts on theory side to provide the most appropriate modelling ... almost each analysis uses a different set of generators.

**Low \( P_T \) (multiple soft-gluon radiation):**
- Resummation up to NNLL (RESBOS, w/ 2 different non-perturbative parameterization to perform the resummation)
- Parton shower (PS) techniques (PYTHIA, HERWIG)
- ME+PS with ME \( O(\alpha_s) \) (MC@NLO, POWHEG)

**High \( P_T \) (hard-gluon emission):**
- Fixed-order calculations up to \( O(\alpha_s^2) \) (FEWZ, DYNNLO)
- Multi-leg tree-level ME+PS (SHERPA, ALPGEN)

**Not-exhaustive List!!**

**PDF.s:** CT10, CTEQ6L1, NNPDF3.0, ...
2015 LHC Performance

Peak luminosity (before final calibration):

Run1: $7.6 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$
Run2: $5.2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$
2015 ATLAS Performance

Data:
7 TeV \( L = 4.5 \, \text{fb}^{-1} \)
8 TeV \( L = 20.3 \, \text{fb}^{-1} \)
13 TeV \( L = 3.2 \, \text{fb}^{-1} \)

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<tr>
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<td>92 M</td>
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<tr>
<td>SCT Silicon Strips</td>
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<td>Hadronic endcap LAr calorimeter</td>
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<td>Forward LAr calorimeter</td>
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<tr>
<td>LVL1 Muon TGC trigger</td>
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<td>100%</td>
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<tr>
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<td>CSC Cathode Strip Chambers</td>
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<tr>
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</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>99.8%</td>
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</tbody>
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Single Boson Production @ 13 TeV
@13TeV - W/Z production

\[ W \rightarrow e\nu, \mu\nu (m_T > 50 \text{ GeV}) \]
\[ Z \rightarrow e^+e^-, \mu^+\mu^- (66 < m_{ll} < 116 \text{ GeV}) \]
\[ P_T(l,\nu) > 25 \text{ GeV} \]

Signal modelling: Powheg + Pythia 8 (normalised to NNLO predictions)

\[ \rightarrow \text{Cross-section ratios provide (partial) uncertainty cancellation} \]
\[ \rightarrow \text{Ratio } R_{w/z} \text{ may constraint strange-quark distribution} \]
\[ \rightarrow \text{Ratio } R_{w^+/w^-} \text{ sensitive to u-d valence quark distribution} \]

\[ \sigma_{\text{tot}}(W^+) = \left[ 10960 \pm 20(\text{stat}) \pm 440(\text{stat}) \pm 990(\text{lumi}) \right] \text{ pb} \]
\[ \sigma_{\text{tot}}(W^-) = \left[ 8380 \pm 20(\text{stat}) \pm 350(\text{stat}) \pm 750(\text{lumi}) \right] \text{ pb} \]
\[ \sigma_{\text{tot}}(Z) = \left[ 1869 \pm 7(\text{stat}) \pm 42(\text{stat}) \pm 168(\text{lumi}) \right] \text{ pb} \]
@13TeV - W/Z cross sections

\[ \sigma_W \times Br(W \to l_1 l_2) \quad [\text{nb}] \]

\[ \sigma_{Z\gamma^*} \times Br(Z\gamma^* \to l_1 l_2) \quad [\text{nb}] \]

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

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

\[ \langle s \rangle \quad [\text{TeV}] \]

\[ \sigma_{W^\pm}^\text{tot} \quad [\text{pb}] \]

\[ \sigma_Z^\text{tot} \quad [\text{pb}] \]

ATLAS Preliminary
13 TeV, 85 pb\(^{-1}\)

ATLAS Preliminary
13 TeV, 85 pb\(^{-1}\)

\(\text{MSTW2008 NNLO FEWZ}\)

\(\text{MSTW2008 NNLO FEWZ}\)
@13TeV - W/Z cross section ratios

General agreement with different PDF-set predictions

$R_{w+/w-}$ as PDF probe (mostly sensitive u-d valence quark PDF.s)

precision now at ~3% level → discrimination power threshold ~2%

ATLAS-CONF-2015-039
@13TeV - Z+jets

$Z \rightarrow e^+e^-, \mu^+\mu^-$

Jets defined by anti-$k_T$, $R=0.4$: $P_T > 30 \text{ GeV}$, $|y| < 2.5$

Important test of perturbative QCD

Ok for both Sherpa and MadGraph predictions
Drell-Yan Production
@ 8 TeV
**P\textsubscript{T,Z} vs. Φ\textsubscript{η}* for DY Pairs**

Correlation matrix (P\textsubscript{T,Z}, Φ)

\[ \phi_{\eta}^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin(\theta_{\eta}^*) \]
\[ \cos\theta_{\eta}^* = \tanh\left(\frac{\eta^- - \eta^+}{2}\right) \]

At born level: \( \sqrt{2} M_Z \phi_{\eta}^* \approx P_{T,Z} \)

- **P\textsubscript{T,Z}** range is governed by:
  - initial state parton radiation
  - intrinsic transverse momentum of the initial state parton inside the proton
  - is modelled by:
    - resummation of soft-gluon emission
    - parton shower model
  - High P\textsubscript{T,Z} range is governed by:
    - quark-gluon scattering
    - is modelled by:
      - perturbative QCD
    - Monte Carlo predicts three levels: Born, Dress, Bare

\( P_{T,Z} \) reconstruction is affected by energy and momentum measurement uncertainty to minimize systematics → Φ* as alternative probe of \( P_{T,Z} \)

Φ* provides a measure of the angular correlation between the leptons
@8TeV - $P_T$ & $\Phi_\eta^*$ Distributions for DY Pairs

predictions ok for ~low values of $\Phi_\eta^*$
@8TeV - $P_T$ & $\Phi_\eta$ * Distributions for DY Pairs

Parton Shower MC

for $5<P_T(\ell\ell)<100$, $m(\ell\ell)>46$ GeV agreement $\sim 10\%$

ArXiv:1512.02192
@8TeV - $P_T$ & $\Phi_\eta$ * Distributions for DY Pairs

Fixed-order MC
absolute predictions ~15%

note: not yet sensitive to NLO EW corrections

ArXiv:1512.02192
Diboson Production @ 13 & 8 TeV
@13TeV - ZZ

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions
4l channel: 2 OS-SF \([e,\mu]\) pairs

\(p_T > 20\text{GeV}, 66 < m_{ll} < 116\text{ GeV}\)

63 events in 3 channels, total exp. bkg.: \(0.62^{+1.08}_{-0.11}\)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>(O(\alpha_S^2)) prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{\text{fid}}^{ZZ\rightarrow e^+e^-e^+e^-})</td>
<td>(8.4^{+2.4}_{-2.0}) (stat.) (+0.4) (syst.) (+0.5) (lumi.) fb</td>
</tr>
<tr>
<td>(\sigma_{\text{fid}}^{ZZ\rightarrow e^+e^-\mu^+\mu^-})</td>
<td>(14.7^{+2.9}_{-2.5}) (stat.) (+0.6) (syst.) (+0.9) (lumi.) fb</td>
</tr>
<tr>
<td>(\sigma_{\text{fid}}^{ZZ\rightarrow \mu^+\mu^-\mu^+\mu^-})</td>
<td>(6.8^{+1.8}_{-1.5}) (stat.) (+0.3) (syst.) (+0.4) (lumi.) fb</td>
</tr>
<tr>
<td>(\sigma_{\text{fid}}^{ZZ\rightarrow \ell^+\ell^-\ell^+\ell^-})</td>
<td>(29.7^{+3.9}_{-3.6}) (stat.) (+1.0) (syst.) (+1.7) (lumi.) fb</td>
</tr>
<tr>
<td>(\sigma_{\text{tot}}^{ZZ})</td>
<td>(16.7^{+2.2}_{-2.0}) (stat.) (+0.9) (syst.) (+1.0) (lumi.) pb</td>
</tr>
</tbody>
</table>

\[\text{ArXiv:1512.05314}\]

8 January 2016
Cross-Section $\sqrt{s}$ Dependence

**Summary**

ZZ: predictions still miss a full $O(\alpha_s^2)$ simulation

ArXiv:1512.05314
@8TeV – 4l Cross Section

- probe SM predictions over a large mass range: 80-1000 GeV
- very small bkg (~5%)

2 OS, SF pairs of high-PT isolated leptons
$50 < m_{12} < 120$ GeV, $12 < m_{34} < 120$ GeV

476 ev. [ bkg $26.2 \pm 3.6$ ]

overall good agreement w/ predictions NNLO QCD, NLO EW for $qq/H \to 4l$ but only LO QCD $gg \to 4l$

\[ \sigma = \frac{476 \text{ ev}}{26.2 \pm 3.6} \]

\[ \sigma = 18.1 \pm 2.1 \text{ fb} \]

\[ \sigma_{\text{data}} = \frac{476 \text{ ev}}{26.2 \pm 3.6} \]

\[ \sigma_{\text{pred}} = \frac{18.1 \pm 2.1 \text{ fb}}{552 \text{ fb}} \]

\[ \sigma_{\text{m}} / \sigma_{\text{h}} = \frac{18.1 \pm 2.1 \text{ fb}}{552 \text{ fb}} \]

@8TeV - 4l Cross Section

→ try to estimate NLO gg→4l contribution from data

estimation of signal strength μ_{gg} = \frac{σ(data)}{σ(gg→4l; LO)} for m_{4l} > 180 GeV

\[
μ_{gg} = 2.4 \pm 1.0(stat.) \pm 0.5(syst.) \pm 0.8(theory)
\]
@8TeV - WW→llll Cross Section

- total and fiducial cross section measurements
- test of SM non-abelian structure
- sensitive to anomalous triple gauge couplings (aTGC)
- irreducible bkg to Higgs searches

Backgrounds:
- top, drell-yan. W+jets (data driven)
  other dibosons (MC based)
- hard criteria on $E_T^{miss}$ and jet-veto against $t\bar{t}$
@8TeV - WW Cross Section

- individual channels compatible
- \( \sim 2\sigma \) discrepancy wrt partial-NNLO predictions

\[
\sigma_{WW}^{\text{tot}} = 71.4^{+1.2}_{-1.2} \text{(stat)} \pm 5.0 \text{(syst)} \pm 2.2 \text{(lumi)} \text{ pb} \quad \sigma_{WW}^{\text{predicted}} = 58.7^{+3.0}_{-2.7} \text{ pb}
\]

- compatible at \( \sim 1\sigma \) w/ full-NNLO predictions
@7TeV – WZ/WW→lvjj

Backgrounds:
- W/Z+jets: ~89% (data driven)
- multi-jets: ~5% (data driven)
- top: ~4% (MC)

Total bkg modeled w/ combined LH fit

Measured (tot. comb.) [pb] | 68 ±7(stat.)±19(sys.)
Theory pred. [pb] | 61.1±2.2

agreement w/ SM → limits on aTGC couplings

JHEP 01(2015)049
Vector Boson Fusion/Scattering @ 8 TeV
@8TeV - Zjj VBF

a) differential cross section → constrain theor. models

b) EW cross section → limits on aTGC

2 high-$P_T$, isolated leptons in Z mass range
2 jets w/ $P_T > 25$ GeV

+ tighter cuts for EW Zjj estimate

Both MC generators don’t fully describe the data → constraints for modelling
Probe EW symmetry breaking

- 2 isolated SS leptons, $P_T > 25$ GeV
- $\geq 2$ jets $P_T > 30$ GeV, $|\eta| < 4.5$
- $E_T^{\text{miss}} > 40$ GeV

Inclusive

$|\Delta y_{jj}| > 2.4$

Main bkg from $t\bar{t}$ (charge flip), $WZ$
Main sys. uncertainty from bkg determination

Combined signal over bkg only hypothesis
- inclusive (EW+ strong): 4.5σ (exp. 3.4σ)
- VBS (EW only): 3.6σ (exp. 2.8σ)
Triboson Production
@ 8 TeV
@8TeV – Wγγ

- 1 isolated lepton $p_T > 20$ GeV; $|\eta| < 2.47$ (2.4) (muons)
- $p_T > 20$ GeV; $|\eta_\gamma| < 2.37$ **Inclusive**
- $E_T^{miss} > 25$ GeV; $m_T > 40$ GeV
- $N_{jets} = 0$ **Exclusive**

Backgrounds:
- multijet (data driven)
- prompt leptons (MC)

<table>
<thead>
<tr>
<th>Incl.</th>
<th>$\sigma_{fid}^{[fb]}$</th>
<th>$\sigma_{MCFM}^{[fb]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$6.1^{+1.1}_{-1.0}$ (stat) $\pm 1.2$ (syst) $\pm 0.2$ (lumi)</td>
<td>$2.90 \pm 0.16$</td>
</tr>
<tr>
<td>Excl.</td>
<td>$2.9^{+0.8}<em>{-0.7}$ (stat) $^{+1.0}</em>{-0.9}$ (syst) $\pm 0.1$ (lumi)</td>
<td>$1.88 \pm 0.20$</td>
</tr>
</tbody>
</table>

- Combined significance over background only: 3.6 $\sigma$
- Consistent within SM $\rightarrow$ Limits set on aQCG

8 January 2016

Limits on aTGCs (Summary)

Cross sections would be higher for aTGC
aTGC mostly affect high $P_T$ regions
Parametrization of aTGC in a perturbative, model independent way
Parameters ($\Delta \kappa_\gamma$, $\lambda_\gamma$, ... ) all 0 in SM
→ no deviation from SM predictions found
A Search @ 13, 8 TeV
Fully Hadronic JJ Diboson Searches

- Modest excess at Run-1: 3.4σ local / 2.5σ global

- Analysis very similar to Run 1, with functional fit of the background

- No significant excess is observed however sensitivity not high enough for conclusive probe of the Run 1 excess
Standard Model Production Cross Section Measurements

**ATLAS** Preliminary
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

*Status: Nov 2015*

LHC pp $\sqrt{s} = 7$ TeV
- Data $4.5 - 4.9$ fb$^{-1}$

LHC pp $\sqrt{s} = 8$ TeV
- Data $20.3$ fb$^{-1}$

LHC pp $\sqrt{s} = 13$ TeV
- Data $85$ pb$^{-1}$
Conclusions

Large (non-exhaustive) set of ATLAS results from the analysis of single and multi boson final states have been presented. In particular:

a) $W$, $Z$, $Z+$jets, $ZZ$ cross sections at 13 TeV
b) $D$-$Y$, $ZZ$, $WW$, $ZW$, cross sections at 13 / 8 TeV, limits on $a_{TGC}$
c) Electroweak production of $Zjj$, sensitive to vector boson fusion
d) First evidence of vector boson scattering
e) First measurement of triboson ($Wyy$) production, limits on $a_{QGC}$

→ Many results, no evidence for new physics, but significant input for improving SM theoretical modelling
→ New, better results likely soon but ... systematics often already dominating [ i.e. will improve but not as $\sqrt{\text{(statistics)}}$ ]
Thank for Your Attention [ and Patience ]
Backup
@8TeV - WZ→llllv Cross Section

a) 3 high-$P_T$, isolated leptons
b) $E_T^{miss} > 25$ GeV
c) $66 < M_{ll} < 116$ GeV

Backgrounds:
- Z+jets: ~15% (data driven)
- ZZ: ~5% (MC)
- W/Z+ν: ~3 (MC)

$\sigma^{tot}_{WZ} = 20.3^{+0.8}_{-0.7}\text{(stat.)}^{+1.2}_{-1.1}\text{(syst.)}^{+0.7}_{-0.6}\text{(lumi.)}$ pb
$\sigma^{exp}(NLO) = 20.3 \pm 0.8$ pb

- very precise measurement
- limits on WWZ aTGC not yet updated,
@7TeV - Wγ/Zγ Cross Sections

\[ Wγ/Zγ \rightarrow lνγ, l lγ, ννγ \]

- a) high \( P_T \), isolated \( γ/\text{leptons} \)
- b) \( ν \rightarrow \) high \( E_T^{\text{miss}} \)
- c) \( γ/l \) well separated

**Exclusive (Njet=0) region more sensitive to aTGC**

**Backgrounds:**

- \( W+\text{jets} \): 15-25\% (data driven)
- \( Z+\text{jets} \): ~10\% (data driven)
- \( γ+\text{jets} \): 5-10\% (data driven)
- \( tt \): <5\% (MC)

**New theoretical predictions**

- \( \text{d} \) \( \text{d}E_T^{γ} \) at high \( E_T^{γ} \)
- improve w/ NNLO corrections

\[ \text{Phys.Rev.D 87,112003 (2013)} \]
SM Cross Sections

Standard Model Production Cross Section Measurements

<table>
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<tr>
<th>Process</th>
<th>ATLAS Preliminary</th>
<th>Status: Nov 2015</th>
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<tr>
<td>$W^+W^-jj_{EWK}$</td>
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$\sigma$ [pb] vs. data/theory

8 January 2016
Summary of Run-2 Total Cross Section Measurements

\begin{align*}
\sigma \text{ [pb]} & \\
\begin{array}{c}
\text{Prediction} \\
\text{Measurement}
\end{array} & \\
\text{inelastic} & \\
\text{pp} & \rightarrow W \\
\text{pp} & \rightarrow Z / \gamma^* \\
\text{pp} & \rightarrow t\bar{t} \\
\text{pp} & \rightarrow tq \\
\text{pp} & \rightarrow H \\
\text{pp} & \rightarrow ZZ
\end{align*}

\textbf{ATLAS Preliminary}

\begin{itemize}
\item \textbf{pp} \rightarrow W
  \begin{itemize}
  \item 7 TeV, 20 pb\textsuperscript{-1}, Nat. Commun. 2, 463 (2011)
  \item 13 TeV, 63 pb\textsuperscript{-1}, ATLAS-CONF-2015-038
  \end{itemize}
\item \textbf{pp} \rightarrow Z / \gamma^*
  \begin{itemize}
  \item 7 TeV, 36 pb\textsuperscript{-1}, PRD 85, 072004 (2012)
  \item 13 TeV, 85 pb\textsuperscript{-1}, ATLAS-CONF-2015-039
  \end{itemize}
\item \textbf{pp} \rightarrow t\bar{t}
  \begin{itemize}
  \item 7 TeV, 36 pb\textsuperscript{-1}, PRD 85, 072004 (2012)
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  \end{itemize}
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  \begin{itemize}
  \item 7 TeV, 4.6 fb\textsuperscript{-1}, Eur. Phys. J. C 74:3109 (2014)
  \item 8 TeV, 20.3 fb\textsuperscript{-1}, Eur. Phys. J. C 74:3109 (2014)
  \item 13 TeV, 78 pb\textsuperscript{-1}, ATLAS-CONF-2015-049
  \end{itemize}
\item \textbf{pp} \rightarrow H
  \begin{itemize}
  \item 7 TeV, 4.5 fb\textsuperscript{-1}, arXiv:1507.04548
  \item 8 TeV, 20.3 fb\textsuperscript{-1}, arXiv:1507.04548
  \item 13 TeV, 3.2 fb\textsuperscript{-1}, ATLAS-CONF-2015-069
  \end{itemize}
\item \textbf{pp} \rightarrow ZZ
  \begin{itemize}
  \item 7 TeV, 4.6 fb\textsuperscript{-1}, JHEP 03, 128 (2013)
  \item 8 TeV, 20.3 fb\textsuperscript{-1}, ATLAS-CONF-2013-020
  \item 13 TeV, 3.2 fb\textsuperscript{-1}, arXiv:1512.05314
  \end{itemize}
\end{itemize}
Vector Boson Scattering

Confirm that Higgs Boson provides cancellation of divergences at HE

Generic EFT framework: add all possible gauge-invariant boson couplings

[Diagram of Vector Boson Scattering]

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Vector Boson Scattering (2)

Parameterize BSM using higher dimensional operator

ZZ dim-6 operator \[ \rightarrow \]

\[ \mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \text{Tr}(W^{\mu \nu} W_{\mu \nu}) \phi^\dagger \phi \]

ssWW dim-8 operator \[ \rightarrow \]

\[ \mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu \phi)^\dagger D_\nu \phi] \times [(D^\mu \phi)^\dagger D^\nu \phi] \]

WZ dim-8 operator \[ \rightarrow \]

\[ \mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \text{Tr} [\hat{W}_{\alpha \nu} \hat{W}^{\mu \beta}] \times \text{Tr} [\hat{W}_{\mu \beta} \hat{W}^{\alpha \nu}] \]

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the road to HL-LHC

**Goal:** fully exploit the LHC potential

[ Sergio Bertolucci LHCP 2015 ]