VBF (Zjj/Wjj) and VBS measurements

From the current status to future prospective

Corinne Goy, LAPP CNRS/IN2P3
On behalf on the ATLAS and CMS collaborations

Ultimate precision at hadron colliders, Paris
Vector Boson Fusion (VBF): $Vjj$
Gauge structure ($a_{TGC}$)
$\sigma \sim 10^{-1}$ pb

Vector boson scattering (VBS): $VVjj$
Gauge structure ($a_{TGC}, a_{QCG}$) + EWSB mechanism
$\sigma \sim 10^{-3}$ pb

Exact? Cancellation of LL scattering
Main background: QCD production

\[ \alpha^2 \alpha_s^2 \]

\[ \alpha^4 \alpha_s^2 \]
EW / QCD ratio (Sherpa 1.1)
Clean experimental signature

- 2 fwd jets
- 1 or 2 central bosons

Multivariate analysis, BDT, NN

EW production is enhanced at large $M_{jj}$
End of run2: 140 fb^{-1}

**Standard Model Production Cross Section Measurements**

**ATLAS Preliminary**

Run 1, 2 \( \sqrt{s} = 5, 7, 8, 13 \) TeV

- **VVjj**: \( \sim 10^{-3} \) pb
  - 140 events/exp

- **Vjj**: \( \sim 10^{-1} \) pb
  - 14000 events/exp

Leptonic decays: \( e \) & \( \mu \)

- \( Z \rightarrow ll \): 3.3658(23) %
- \( W \rightarrow l \nu \): 10.86(9) %

Corinne Goy, Ultimate precision at hadron colliders, Paris, 03/12/2019
Compilation of current publications

<table>
<thead>
<tr>
<th>√s</th>
<th>Luminosity /fb</th>
<th>Channel</th>
<th>arXiv[hep-ex]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 TeV</td>
<td>4.7</td>
<td>Wjj</td>
<td></td>
</tr>
<tr>
<td>8 TeV</td>
<td>20.2</td>
<td>Zjj</td>
<td>1401.7610</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wjj</td>
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</tr>
<tr>
<td>13 TeV</td>
<td>3.2</td>
<td>Zjj</td>
<td>1709.10264</td>
</tr>
<tr>
<td>CMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 TeV</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>8 TeV</td>
<td>19.3</td>
<td>Wjj</td>
<td>1607.06975</td>
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<tr>
<td>13 TeV</td>
<td>35.9</td>
<td>Zjj</td>
<td>1712.09814</td>
</tr>
</tbody>
</table>
Statistics:
- 4%

Systematics exp:
- Jet Energy Scale: 3%

Systematics:
- QCD scale
  - 4% (QCD)
  - 6% (EW)
- Intf EW-QCD: 2 – 3%
- Parton Shower: 4%
VBF – aTGC (wwz)

Effective field theory description

\[ \mathcal{L}^{\text{eff.}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c^i_6}{\Lambda^2} \mathcal{O}^i_6 + \sum_i \frac{c^i_8}{\Lambda^4} \mathcal{O}^i_8 + \ldots \]

3 CP conserving parameters : cWWW, cW, cB
2 C or P violating parameters
Distributions used for aTGC

- **Wjj**: jet-linked variables
  - $p_T^{\text{leading jet}}$
  - $p_T^{jj}$
  - $\Delta \phi(j_1,j_2)$

- **Zjj**: $p_T^Z$
  - well measured
  - In principle well modelled
Better sensitivity with muons final states: endpoint 1.2 TeV (900 GeV with electrons)

NLO-EW corrections sizeable at 1 TeV, but decrease the expected cross-sections (conservative effect)
aTGC via Inclusive Production

Off Shell: potentially large \( q_2 \)

On Shell: smaller \( q_2 \)

**CMS: Zjj**

<table>
<thead>
<tr>
<th>Coupling constant</th>
<th>Expected 95% CL interval ( (\text{TeV}^{-2}) )</th>
<th>Observed 95% CL interval ( (\text{TeV}^{-2}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_{WWW}/\Lambda^2 )</td>
<td>([-3.7, 3.6])</td>
<td>([-2.6, 2.6])</td>
</tr>
<tr>
<td>( c_W/\Lambda^2 )</td>
<td>([-12.6, 14.7])</td>
<td>([-8.4, 10.1])</td>
</tr>
</tbody>
</table>

**CMS: WZ inc fully lep**

Complementary sensitivity
VBS

Pure QGC not accessible
Sensitivity of the VVjj search in pp collisions

Never observed before LHC ($\sigma \sim 10^{-3}$ fb)

<table>
<thead>
<tr>
<th>Ex</th>
<th>CoM</th>
<th>WWjj</th>
<th>ssWWjj</th>
<th>WZjj</th>
<th>ZZjj</th>
<th>Zγjj</th>
<th>Wγjj</th>
</tr>
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<tr>
<td>CMS</td>
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<td>~1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5.05/fb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>8 TeV</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(19.7/fb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(19.7/b)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>8 TeV</td>
<td>2.7</td>
<td>3.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(20.3(fb)</td>
<td>(20.3(fb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>13 TeV</td>
<td>5.5</td>
<td>2.2</td>
<td>2.7</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(35.9(fb)</td>
<td>(35.9(fb)</td>
<td>(35.9(fb)</td>
<td>(19.7(fb+35.9(fb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>13 TeV</td>
<td>6.5</td>
<td>5.3</td>
<td>5.5</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(36.1(fb)</td>
<td>(36.1(fb)</td>
<td>(139(fb)</td>
<td>(36.1(fb)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**ATLAS : ZZjj in 4l and 2l 2ν (139/fb)**

VBS analysis: Generalized usage of BDT

<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>$1.27 \pm 0.12$ (stat) $\pm 0.02$ (theo) $\pm 0.07$ (exp) $\pm 0.01$ (bkg) $\pm 0.03$ (lumi)</td>
<td>$1.14 \pm 0.04$ (stat) $\pm 0.20$ (theo)</td>
</tr>
<tr>
<td>$\ell\ell\nu\nu jj$</td>
<td>$1.22 \pm 0.30$ (stat) $\pm 0.04$ (theo) $\pm 0.06$ (exp) $\pm 0.16$ (bkg) $\pm 0.03$ (lumi)</td>
<td>$1.07 \pm 0.01$ (stat) $\pm 0.12$ (theo)</td>
</tr>
</tbody>
</table>
Described by dimension 8 operators

18 parameters

All H fields (S)
Mixing V & H fields (M)
All V fields (T)
2 events in the last bin
Other variables

WZjj

\[ + \sum |P_T(l)| \]

Zγjj

\[ + M_T(WW) \]

Reduced phase-space
M parameters

- 13 TeV sets better limits
- Semi-leptonic decays sets better limits
- ! Positivity of parameters not exploited
- Unitarity methods different (if any)

O(1), O(10)
A unique prescription to handle unitarity would be useful!
VBS – The future

\[ \sqrt{s} = 14 \text{ TeV}, \ 3000. \ fb^{-1} \]
Evolution of the experimental conditions

- Luminosity
  Peak: $5 \text{ - } 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  $<\text{PU}> = 200$
- Aging – radiation damages

To cope with
- Data rates
- Detector occupation
And to maintain:
- Trigger performance
- Pile-Up jet rejection
- Object performance

⇒ Upgrade of detectors
  Hardness
  Granularity

Tracking up to $|\eta| < 4$
Consequences for object reconstruction

| $|\eta|$ | CMS | ATLAS |
|-------|-----|-------|
| Track reconstruction: | 4. | |
| Electrons: | 3. | 4. |
| Muons: | 2.8 | 2.7 (4. with muon tagger) |
| PU rejection: Excellent in the tracker acceptance | 3. – 4. | 3.8 |

Poor resolution for muons: Affects variables like MT

Gain in acceptance (example):
- ATLAS: WZjj $\rightarrow$ 3$\ell$+18% (+25%)
- CMS: ZZjj $\rightarrow$ 4$\ell$ +13%
Cross-sections:

- $\text{ZZjj} : 8.5$ to $10.3\%$
- $\text{W}^\pm\text{W}^\pm\text{jj} : 4.5$ to $6\%$
- $\text{WZjj} : 3$ to $6\%$
VBS – Systematics
Systematic on $M_TWZ$
(potential variable for aQGC)

<table>
<thead>
<tr>
<th>$m^{WZ}_T$ [GeV]</th>
<th>150 – 200</th>
<th>200 – 250</th>
<th>250 – 300</th>
<th>300 – 400</th>
<th>$\geq$ 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sigma_{\text{tot.}}^{WZ}$ [fb]</td>
<td>0.49</td>
<td>0.64</td>
<td>0.24</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td>Relative Uncertainties [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>24.7</td>
<td>19.3</td>
<td>31.0</td>
<td>33.6</td>
<td>63.1</td>
</tr>
<tr>
<td>All systematics</td>
<td>16.9</td>
<td>11.8</td>
<td>10.6</td>
<td>9.9</td>
<td>18.4</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.8</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Total</td>
<td>29.9</td>
<td>22.6</td>
<td>32.7</td>
<td>35.0</td>
<td>65.7</td>
</tr>
<tr>
<td>Uncorrelated syst.</td>
<td>4.2</td>
<td>0.7</td>
<td>1.0</td>
<td>1.4</td>
<td>5.6</td>
</tr>
<tr>
<td>Unfolding</td>
<td>5.2</td>
<td>9.1</td>
<td>6.0</td>
<td>2.0</td>
<td>8.6</td>
</tr>
<tr>
<td>Electrons</td>
<td>1.5</td>
<td>1.4</td>
<td>2.0</td>
<td>2.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Muons</td>
<td>1.8</td>
<td>1.9</td>
<td>2.2</td>
<td>2.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Jets</td>
<td>8.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Red. Background</td>
<td>6.1</td>
<td>0.5</td>
<td>0.5</td>
<td>1.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Irred. Background</td>
<td>10.6</td>
<td>3.0</td>
<td>4.3</td>
<td>4.6</td>
<td>11.9</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.4</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

$\ell = \text{Electron or Muon}$

Corinne Goy, Ultimate precision at hadron colliders, Paris, 03/12/2019
Δϕ(W,Z)

<table>
<thead>
<tr>
<th>Δϕ(W,Z) [rad]</th>
<th>0.0 - 0.6</th>
<th>0.6 - 1.2</th>
<th>1.2 - 1.8</th>
<th>1.8 - 2.5</th>
<th>2.5 - 3.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δσ_{W±Z}^{fid.} [fb]</td>
<td>0.30</td>
<td>0.37</td>
<td>0.28</td>
<td>0.40</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Relative Uncertainties [%]

<table>
<thead>
<tr>
<th>Source</th>
<th>0.0 - 0.6</th>
<th>0.6 - 1.2</th>
<th>1.2 - 1.8</th>
<th>1.8 - 2.5</th>
<th>2.5 - 3.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>26.6</td>
<td>23.8</td>
<td>28.3</td>
<td>23.7</td>
<td>27.9</td>
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<tr>
<td>All systematics</td>
<td>11.7</td>
<td>9.5</td>
<td>10.9</td>
<td>10.0</td>
<td>13.9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.5</td>
<td>2.4</td>
<td>2.6</td>
<td>2.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Total</td>
<td>29.1</td>
<td>25.6</td>
<td>30.3</td>
<td>25.7</td>
<td>31.2</td>
</tr>
<tr>
<td>Uncorrelated syst.</td>
<td>1.9</td>
<td>1.2</td>
<td>1.5</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Electrons</td>
<td>1.6</td>
<td>1.4</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Muons</td>
<td>2.1</td>
<td>2.0</td>
<td>1.9</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Jets</td>
<td>7.4</td>
<td>6.5</td>
<td>6.0</td>
<td>5.2</td>
<td>7.1</td>
</tr>
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<td>Red. Background</td>
<td>4.3</td>
<td>2.9</td>
<td>2.7</td>
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<td>7.3</td>
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<td>9.9</td>
</tr>
<tr>
<td>Pileup</td>
<td>2.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

03/12/2019

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Dominant systematics

• Th. Modelling
  • QCD background / $\mu R,\mu F$ (20 -30%, LO generator )
    • Controlled by CR region
    • Extrapolation under the signal region
  • Interference EW/QCD
  • EW signal
    • NLO-QCD / NLO-EW larger in the tails

• Unfolding
  • Depending of the distribution: ~5-10%

• Pile Up
  • Run2: $<\mu>$ = 35 to 200 but mitigating by extended tracker
  • Especially channels with a photon (wrong vertex association )

• Jet Energy Scale

<table>
<thead>
<tr>
<th></th>
<th>WZjj</th>
<th>ssWWjj</th>
<th>ZZjj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic: 3000/fb</td>
<td>&lt;2%</td>
<td>1%</td>
<td>~4%</td>
</tr>
<tr>
<td>Current th. systematics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EWjj</td>
<td>4.8%</td>
<td>3.1%</td>
<td>1-10%</td>
</tr>
</tbody>
</table>
| QCDjj     | 5.2% | 2.9%   | 10% +10%
| Intf      | 1.9% | 1.0%   |      |
| WZ        | 3.3% |        |      |

Mainly LO order event generators
Jet Energy Scale prospects

Baseline

Optimistic

ATLAS Preliminary

Projections from Run 2 data
anti-$k_t$, $R = 0.4$, EM+JES

Fractional JES uncertainty

ATLAS Preliminary

Projection from Run 2 data
anti-$k_t$, $R = 0.4$, EM+JES

Fractional JES uncertainty

ATL-PHYS-PUB-2019-005
Guidance

• In the choice of variables / diff. distributions
  • Likely to be less affected by Higher Orders corrections QCD & EW

• In conjunction with experimental systematics:
  • Unfolding
  • PU sensitivity
  • JES sensitivity

• Treatment of systematics linked to usage of MVA ?
VBS - polarized states

$V_x V_x \rightarrow V_x V_x$ Potentially 81 combinations of cross-sections

$X = L, R, 0$

$T = L + R, L/0$ longitudinal
\[ \cos \theta^*: \text{one of the most sensitive variable to the polarization of individual boson} \]

\[ \frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d \cos \theta_{\ell,W}} = \frac{3}{8} f_L (1 \pm \cos \theta_{\ell,W})^2 + \frac{3}{8} f_R (1 \pm \cos \theta_{\ell,W})^2 + \frac{3}{4} f_0 \sin^2 \theta_{\ell,W} \]

No cut on the individual leptons, boson rest frame

Coordinate Systems:
- Collins-Soper,
- Helicity,
- Mod-Helicity
VBS : event variables

Sensitive to the polarization of the final state boson.

Example : $\Delta \phi_{jj}$
VBS : several variables mentioned in literature

Linked to the jet system

• $\Delta \phi_{jj}$
• $\Delta \eta_{jj}$
• $\Delta R_{jj} = \sqrt{\Delta \eta_{jj} + \Delta \phi_{jj}}$
• $M_{jj}$

Linked to the final state bosons

• $\cos \theta^*$
• $\eta_V$
• $p_T^V$
• $p_{T_{lep}}$
• $\Sigma p_T^l$

$L_p = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$.

$\cos \theta_{2D} = \frac{\vec{p}_T(\ell^*) \cdot \vec{p}_T(W)}{|\vec{p}_T(\ell^*)||\vec{p}_T(W)|}$

CERN-LPCC-2018-03
Standard Model Physics at the HL-LHC and HE-LCH
• CERN-THESIS-2015-039, C. Bittrich
**Templates: Reweighting method**

**Longitudinal, Left and Right** fractions are determined with an analytic fit in bins of $p_T(V)$ and $Y_V$, in total phase-space.

→ Weights per event to create pure helicity state templates propagated to the reconstruction level in the fiducial phase space.

---

- Fine binning & closure test
- Some effects like interference, off-shell incorporated
- Build in consistency

Drawback: cannot reweight any other variables
Templates : generation of separate distributions L, R, 0

- Phantom / Madgraph
  - LO generation
  - INTF in presence of lepton cut:
    3 states do not sum up to full
    Few % discrepancy

A. Ballestrero, E. Maina, G. Pellicioli
ssWWjj: $W^\pm W^\pm \rightarrow l^\pm l^\pm \nu\nu$

most promising channel

Helicity distributions obtained with MadGraph+DECAY
00 fraction: 6 – 7%
ZZjj: ZZ → 4l

$Z_T Z_T, Z_0 Z_T$ components considered as an additional background in a BDT with added variables

e ($\mu$) acceptance

| $|\eta|$ coverage | significance |
|-----------------|-------------|
| $|\eta| < 2.5(2.4)$ | $1.22\sigma$ |
| $|\eta| < 3.0(2.8)$ | $1.38\sigma$ |
| $|\eta| < 4.0(2.8)$ | $1.43\sigma$ |
Fit of all contributions: more problematic

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ATL-PHYS-PUB-2018-023

4 contributions: TT, T0 & 0T, 00 (+ τ bkg only)

- Regression NN to approximate \( \cos \theta^* \) from 14 kinematic variables.
- 3 components: TT, 00, 0T
- 2D

WZjj

ssWWjj

arXiv:1510.01691 J Searcy et al
Observations

• Studies on $VV \rightarrow V_{L/0}V_{L/0}$
• Polarisation of initial state
  • Does jet-linked variable access instead initial state polarisation ?
  • Access to Initial state polarization in MC ?
• Exploiting semi-leptonic decays
  • tagging jet-linked variables
  • $|\cos\theta^*|$
• Polarisation
  • End of run3 (300/fb) : promising 1$\sigma$ in ssWW
  • Multi-variate analysis not fully exploited
27 TEV: would be promising

Cross-section

$X \times 4$

aQGC:

Limits improved by a factor 5 -10

Polarisation

Fiducial phase space

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>$\sqrt{S} = 14$ TeV</th>
<th>$\sqrt{S} = 27$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ W^+ jj$</td>
<td>2.33 fb</td>
<td>8.65 fb</td>
</tr>
<tr>
<td>$W^+ W^+ jj$ ($</td>
<td>\Delta y_{jj}</td>
<td>&gt; 2.4$)</td>
</tr>
<tr>
<td>$W^+ Zjj$</td>
<td>0.82 fb</td>
<td>3.16 fb</td>
</tr>
<tr>
<td>$ZZjj$</td>
<td>0.11 fb</td>
<td>0.44 fb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>14 TeV</th>
<th>27 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZjj$</td>
<td>$W^\pm W^\pm jj$</td>
</tr>
<tr>
<td>$f_{S0}/\Lambda^4$</td>
<td>[-8.8]</td>
</tr>
<tr>
<td>$f_{S1}/\Lambda^4$</td>
<td>[-18,18]</td>
</tr>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>[-0.76, 0.76]</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda^4$</td>
<td>[-0.5, 0.50]</td>
</tr>
<tr>
<td>$f_{M0}/\Lambda^4$</td>
<td>[-3.8, 3.8]</td>
</tr>
<tr>
<td>$f_{M1}/\Lambda^4$</td>
<td>[-5.0, 5.0]</td>
</tr>
</tbody>
</table>

NB 1 param fit

<table>
<thead>
<tr>
<th>significance</th>
<th>VBS $Z_L Z_L$ fraction uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/ syst. uncert.</td>
<td>w/o syst. uncert.</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>1.4 $\sigma$</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>5.2 $\sigma$</td>
</tr>
</tbody>
</table>

CERN-LPCC-2018-03

colliders, Paris, 03/12/2019
Conclusion

• VBF Z & W
  • Will be well measured at the end of Run3
  • aTGC limits complementary to those with inclusive VV

• VBS will enter an interesting phase with HL-LHC
  • Tot cross-section : few %
  • Polarization $V_0V_0 : 1-3 \sigma / \exp$
  • Polarisation not useful for aTGC
    • Lep heritage: only for CP violating parameter
    • for aQGC ?

• Benefice of combination CMS/ATLAS
  • Experimental syst (JES) not correlated

• But th. modelling is a concern
BACKUP
Other EW diagrams partly included in the signal

Resonant, irreducible

Non resonant
aTGC

Change of paradigm from LEP & Run I description

Effective field theory description
Low energy theory

\[ \frac{\mathcal{L}_{WWV}}{g_{WWW}} = i g_1^V \left( W_{\mu
u}^I W_{\mu \nu}^V - W_{\mu \nu}^I V_{\mu \nu} W_{\mu \nu}^V \right) + i \kappa \lambda W_{\mu \nu}^I V_{\mu \nu} \]

\[ + \frac{i \lambda}{m_W^2} W_{\rho \sigma}^I W_{\mu \nu}^I (\partial_\mu V_\nu + \partial_\nu V_\mu) \]

\[ + \frac{g_5^V}{m_W^2} \epsilon_{\mu \nu \rho \sigma} (W_{\mu}^I \partial_{\rho} W_{\nu}) V_{\sigma} + i \kappa V W_{\mu}^I W_{\nu} \bar{V}_{\mu \nu} \]

\[ + \frac{i \lambda}{m_W^2} W_{\rho \sigma}^I W_{\mu \nu} \bar{V}_{\mu \nu} \]

\[ \mathcal{L}^{\text{eff.}} = \mathcal{L}^{\text{SM}} + \sum_i \frac{c_i^j}{\Lambda^2} \mathcal{O}_6^i + \sum_i \frac{c_i^j}{\Lambda^4} \mathcal{O}_8^i + \ldots \]

H Milder @ MBI
R Aggleton @ MBI

03/12/2019
aTGC via Inclusive Production

Off Shell: potentially large q2

On Shell: smaller q2

End point: ~½ TeV
RED is CMS ; BLUE is ATLAS

S parameters

O(1 -10)

O(0.1)

T parameters

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Positivity

Not used yet!
Evolution of the experimental conditions

• Luminosity
  Peak: 5 - 7.5 $10^{34}$ cm$^{-2}$s$^{-1}$

• Aging – radiation damages

  To cope with
  Data rates
  Detector occupation

  And to maintain:
  Trigger performance
  Pile-Up jet rejection
  Object performance

⇒ Upgrade of detectors
  Hardness
  Granularity

≈ 130 vertices

→ 200 vertices, on average
→ 1.6 vtx/mm
Tracking up to $|\eta| < 4$

Pile Up rejection

ATLAS Simulation Preliminary

ITk Layout

Pythia8 dijet

$30 \text{ GeV} < p_T < 50 \text{ GeV}$

$|\eta| < 1.5$

$1.5 < |\eta| < 2.5$

$2.5 < |\eta| < 3.8$

Pixel size: 25×100 $\mu$m$^2$ (open)

50×50 $\mu$m$^2$ (tilled)

Efficiency for hard-scatter jets

Track efficiency

ATLAS Simulation Preliminary

ITk Layout, $<\mu> = 200$

Run-2, $<\mu> = 20$

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Timing detector: a new dimension

ATLAS: $2.4 < |\eta| < 4$.

CMS: $0 < |\eta| < 3$. 

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Corinne Goy, Ultimate precision at hadron colliders, Paris, 03/12/2019
Prospective - 4 methods

• Full simulation of signal and background
  • Rare

• Parametric simulation of detector effects
  • Experimental effects taken into account by parametrizations based on detector performance studies with the full simulation
  • The effect of the high pileup at the HL-LHC is incorporated by overlaying pileup jets onto the hard-scatter events with 2% efficiency

• Fast simulation using DELPHES

• Extrapolation from Run2 results
  • Scale of cross-sections
  • Scale of acceptance for leptons
  • Object performance using DELPHES
ssWWjj: $W^\pm W^\pm \rightarrow \ell^\pm \ell^\pm \nu\nu$

- **CMS**: full simulation (except for jets at large eta) and a cut-based selection
- **ATLAS**: parametric simulation and a cut-based selection
- Main background is not QCD
WZjj: WZ→3ℓν

- Parametric simulation
- Conservative bkg approach, loose event selection
- S/B = 0.11

WZjj-QCD: Phys. Lett B 793 (2019) has shown that could be over estimated by 40% in certain regions of the PS, (but within 2σ.)

WZjj-EW: Signal suffers from the color flow feature in Sherpa (Sherpa/MadGraph = 87%)

<table>
<thead>
<tr>
<th>Process</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZjj – EW</td>
<td>3889</td>
<td>2757</td>
</tr>
<tr>
<td>WZ – QCD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttV</td>
<td>3145</td>
<td>–</td>
</tr>
<tr>
<td>tZ</td>
<td>2221</td>
<td>–</td>
</tr>
<tr>
<td>tV/VVV</td>
<td>–</td>
<td>1374</td>
</tr>
<tr>
<td>Non prompt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>1970</td>
<td>–</td>
</tr>
<tr>
<td>VV</td>
<td>–</td>
<td>398</td>
</tr>
<tr>
<td>Zγ</td>
<td>–</td>
<td>296</td>
</tr>
</tbody>
</table>

- Extrapolation from the Run 2 (2.2σ)
- Tight selection
- S/B = 0.41
- WZ-QCD main background, but not as dominant
WZ → 3ν : polarization of the individual boson W or Z

3 parameters: N_{sig}, F_0, FL-FR
Using 3 templates and bkg normalisation
Syst on background normalization: 20 - 2.5 %

Simultaneous fit of 4 independent channels not exploited: e\mu, \mu\mu, ...
WZ→3ℓν : LL fraction

Helicity fractions obtained with MadGraph+DECAY
LL fraction : 5%

LL contribution extracted alone
TT & LT considered as a fixed additional background in the Mjj vs Rjj plane

L : longitudinal/0
T : transverse (Left + Right)
No HIGGS!

Extreme case

Sensitivity to EWSB

Effect enhanced in considering only the longitudinal production

\[ V_L V_L \to V_L V_L \]

Polarization fractions as functions of \( M_{WW} \)

**Corinne Goy, Ultimate precision at hadron colliders, Paris, 03/12/2019**

---


A. Ballestrero, E. Maina, G. Pellicioli

03/12/2019
Alternative method on the same line

\[
\frac{d\sigma}{d\sigma d\cos \theta d\phi} = \frac{3}{16\pi} \left[ (1 + \cos^2 \theta) + A_0 \frac{1}{2} (1 - 3 \cos^2 \theta) + A_1 \sin(2\theta) \cos \phi \\
+ A_2 \frac{1}{2} \sin^2 \theta \cos(2\phi) + A_3 \sin \theta \cos \phi + A_4 \cos \theta \\
+ A_5 \sin^2 \theta \sin(2\phi) + A_6 \sin(2\theta) \sin \phi + A_7 \sin \theta \sin \phi \right],
\]

Ai coefficients can be calculated as expectation values of trigonometric functions:

- \( A_0 = 4 - <10\cos 2\theta> \) & \( A_4 = <4\cos \theta> \)

And the polarization fractions expressed as:

\[
\begin{align*}
 f_L^{W^\pm} &= \frac{1}{4} (2 - A_0^{W^\pm} \mp A_4^{W^\pm}), \\
 f_R^{W^\pm} &= \frac{1}{4} (2 - A_0^{W^\pm} \pm A_4^{W^\pm}), \\
 f_0^{W^\pm} &= \frac{1}{2} A_0^{W^\pm}, \\
 f_L^{Z} &= \frac{1}{4} (2 - A_0^Z + \frac{1}{c} A_4^Z), \\
 f_R^{Z} &= \frac{1}{4} (2 - A_0^Z - \frac{1}{c} A_4^Z), \\
 f_0^{Z} &= \frac{1}{2} A_0^Z.
\end{align*}
\]

Computation in fiducial phase-space;
No template, borned functions
Semi-leptonic – 27 TeV

\[ M(WWjj) + W\text{-jet variables, lepton} + Mjj \]

Figure 9: Observed significance as a function of integrated luminosity (left) and expected cross-section uncertainty (right) for the VBS $W_L W_L$ signal, assuming a 10% $W_L W_L$ fraction predicted by the MadGraph generator, in the $\ell \nu qq$ channel at $\sqrt{s} = 27$ TeV. The solid and dashed lines on the left shows the expected significance obtained by fitting to the total invariant mass of the VBS system and the BDT output, respectively. The dot-dashed line shows the expected significance from the combination of all the three semi-leptonic channels assumed to have sensitivity similar to the $\ell \nu qq$ channel.