MULTIBOSON MEASUREMENTS WITH Run 2 data at CMS

Alessandro Da Rold, on behalf of the CMS Collaboration

LHCP 2020, Paris (Virtual), 27 May 2020
Overview

- Introduction
  - Introduction and motivation
  - Experimental features
  - EFT and interpretation of results

- Multi-boson analyses
  - $W^+W^-$ CMS-PAS-SMP-18-004
  - $VVV$ CMS-PAS-SMP-19-014

Vector Boson Scattering
See Mariarosaria’s talk on Friday!
INTRODUCTION AND MOTIVATION

- Non-abelian gauge structure of the SM allows for **vector boson self interactions** → Triple (TGC) and Quartic Gauge Couplings (QGC)

- Multiboson final states important test of the **electro-weak sector** of the Standard Model → Precise measurement of the coupling values

- Probing the strength of the couplings is an **indirect search for new physics**

- Many multiboson final states are **backgrounds** to searches for new physics → Fundamental to have a detailed description

- Two main groups of processes: QCD production and Vector Boson Scattering (VBS)
Experimental Challenges

- Multiboson processes have a very low cross section ⟹ High statistics is needed, CMS Run2 140 fb⁻¹
- Complex final state (high particle multiplicity)
- High precision needed in the measurements ⟹ Small deviations can be linked to the presence of new physics, EFT interpretation
- Measurement of inclusive cross sections and evidence/observation of processes never measured before
Sequential cuts selection

- 2 opposite charge isolated leptons (e, μ), $m_\ell\ell > 20$ GeV
- Projection of $p_T^{\text{miss}}$ perpendicular to lepton momentum $> 20$ GeV → Reduce nonprompt background
- MVA to discriminate DY background, for same flavour leptons $|m_\ell\ell - M_Z| > 15$ GeV
- 0 or 1 jets with $p_T > 30$, b-jet veto

Important background source in searches for new particles
- Production from $q\bar{q}$, gg (at higher order) or $H \rightarrow WW$

Analysis performed with sequential cuts and Random Forest Classifiers
Random Forest Classifier (RFC): aggregate of binary decision trees trained independently and in parallel → **Mitigates overfitting**

- Main background sources form DY and tt→ **Build two RFC to better reduce contamination**
- RFC score ≈1 for the signal and ≈0 for background
- Signal **efficiency and purity higher** than sequential cuts analysis

<table>
<thead>
<tr>
<th>RFC score</th>
<th>Signal region</th>
<th>DY control</th>
<th>tt control</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDY</td>
<td>&gt; 0.96</td>
<td>&lt; 0.6</td>
<td>&gt; 0.6</td>
</tr>
<tr>
<td>S_{tt}</td>
<td>&gt; 0.6</td>
<td>&gt; 0.6</td>
<td>&lt; 0.6</td>
</tr>
</tbody>
</table>

**Selection**

- 2 opposite charge isolated leptons (e, μ), m_{ll} > 30 GeV
- For same flavour leptons |m_{ll} - M_Z| > 15 GeV
- b-veto applied to jets

**Pure signal region after tt and DY suppression**
Backgrounds

**tt and single top**
- CR with at least 1 b-jet to normalise
- CR with S_{DY}>0.6 & S_{tt}<0.6 to normalise

**Drell-Yan**
- SF: normalisation from events inside and outside peak region
- DF: Z→ττ, CR with m_{eμ} < 80 GeV
- CR with S_{DY}<0.6 & S_{tt}>0.6, good data-MC agreement, yield use to normalise

**Nonprompt (W+jets)**
- Fake rate from data-driven pass-fail (p_T, η)
- CR with 2 same sign leptons (dominated by nonprompt), transfer factor from CR to SR

Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Statistical</th>
<th>1.2 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt normalisation</td>
<td>2.0 %</td>
<td></td>
</tr>
<tr>
<td>DY normalisation</td>
<td>1.4 %</td>
<td></td>
</tr>
<tr>
<td>Lepton efficiencies</td>
<td>2.1 %</td>
<td></td>
</tr>
<tr>
<td>JES and JER</td>
<td>2.3 %</td>
<td></td>
</tr>
<tr>
<td>Total experimental</td>
<td>4.6 %</td>
<td></td>
</tr>
<tr>
<td>μR μF</td>
<td>0.4 %</td>
<td></td>
</tr>
<tr>
<td>Higher order QCD</td>
<td>1.4 %</td>
<td></td>
</tr>
<tr>
<td>PDFs</td>
<td>0.4 %</td>
<td></td>
</tr>
<tr>
<td>Total theoretical</td>
<td>1.6 %</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.7 %</td>
<td></td>
</tr>
</tbody>
</table>
TOTAL CROSS SECTION

Theoretical prediction: $\sigma_{\text{tot}}^{\text{NNLO}} = 118.8 \pm 3.6 \, \text{pb}$

Sequential cuts

- Fit SR + t\bar{t} CR, same and different flavour, 0 and 1 jets
- Consistency of signal strength proves consistency of the model

<table>
<thead>
<tr>
<th>Category</th>
<th>Signal strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>DF</td>
</tr>
<tr>
<td>0-jet</td>
<td>SF</td>
</tr>
<tr>
<td>1-jet</td>
<td>DF</td>
</tr>
<tr>
<td>1-jet</td>
<td>SF</td>
</tr>
<tr>
<td>0-jet &amp; 1-jet</td>
<td>DF</td>
</tr>
<tr>
<td>0-jet &amp; 1-jet</td>
<td>SF</td>
</tr>
<tr>
<td>0-jet &amp; 1-jet</td>
<td>DF &amp; SF</td>
</tr>
</tbody>
</table>

$\sigma_{\text{tot}}^{\text{SC}} = 117.6 \pm 1.4 \, \text{(stat)} \pm 5.5 \, \text{(syst)} \pm 3.2 \, \text{(lumi)} = 117.6 \pm 6.8 \, \text{pb}$

Random Forest Classifier

- Higher order QCD calculations taken into account by reweighting $p_T^{WW}$ spectrum
- Result more sensitive to theoretical correction
- Sensitive to smaller $p_T^{WW} \rightarrow$ Mainly 0 jet

$\sigma_{\text{tot}}^{\text{RFC}} = 131.4 \pm 1.3 \, \text{(stat)} \pm 6.0 \, \text{(syst)} \pm 3.5 \, \text{(lumi)} = 131.4 \pm 8.7 \, \text{pb}$
Fiducial and Differential $\sigma$

- **Fiducial cross section** in agreement with SM
  \[ \sigma^{\text{fid}} = 1.529 \pm 0.087 \text{ pb} \quad \sigma_{\text{NNLO}}^{\text{fid}} = 1.531 \pm 0.043 \text{ pb} \]

- **Measured jet dependent** cross section
  \[ \sigma^{\text{fid}}(0\text{-jet}) = 1.61 \pm 0.10 \text{ pb} \quad \sigma^{\text{fid}}(1\text{-jet}) = 1.35 \pm 0.11 \text{ pb} \]

- **Differential** cross sections measured for $m_{ll}$, $p_T^l$ and $\Delta \phi_{ll}$

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**JETS MULTIPLICITY**

- **Probe of theoretical calculations** and events generators

- **Signal region** with $S_{DY} > 0.96$ & $S_{t\bar{t}} > 0.2$ to reduce efficiency dependence on $p_{T}^{WW}$

- **Possible migration** of $N_j$ events due to pileup and jet energy measurement → **Unfolding** with $R_{PU}$ and $R_{DET}$
LIMITS ON ATGC

One parameter scan

Two parameters scan

Different flavour $m_{e\mu}$ mass, high mass values more sensitive

Dimension 6 operators with massive boson fields $O_{WWW}$, $O_W$, $O_B$

<table>
<thead>
<tr>
<th>Coefficients (TeV$^{-2}$)</th>
<th>68% CL interval</th>
<th>95% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{WWW}/\Lambda^2$</td>
<td>$[-1.78, 1.82]$</td>
<td>$[-2.67, 2.71]$</td>
</tr>
<tr>
<td>$c_W/\Lambda^2$</td>
<td>$[-3.67, 2.68]$</td>
<td>$[-5.28, 4.22]$</td>
</tr>
<tr>
<td>$c_B/\Lambda^2$</td>
<td>$[-9.45, 8.40]$</td>
<td>$[-13.9, 12.8]$</td>
</tr>
</tbody>
</table>
Measure both inclusive and single channel cross sections

\[ \text{WWW} \rightarrow l^{±l^{±}} 2v \text{ qq}' \]

- 2 same sign leptons, ≥ 1 jets
- 9 categories: lepton flavour (ee, eμ, μμ), 1 jet and 2 jets with 65 < m_{jj} < 95 GeV and outside
- Backgrounds: lost lepton, SS leptons + jets, nonprompt

\[ \text{WWW} \rightarrow l^{±l^{±}} 3v \]

- 0, 1 or 2 same-flavour opposite charge lepton pairs (SFOS)
- m_{ll} incompatible with M_Z
- Backgrounds: lost lepton, SS leptons + jets, nonprompt

\[ \text{W}^{±}\text{W}^{±}\text{Z} \rightarrow l^{±l^{±}} 2v (l^{±l^{±}}) \]

- SFOS lepton pair with m_{ll} within 10 GeV of M_Z
- Dominant background from ZZ production

\[ \text{WZZ} \rightarrow l v (l^{±l^{±}}) (l^{±l^{±}}) \]
\[ \text{ZZZ} \rightarrow (l^{±l^{±}}) (l^{±l^{±}}) (l^{±l^{±}}) \]

- Very small cross sections and BR
- 5l: must have 2 SFOS close to M_Z, p_T^{miss} > 50 GeV, backgrounds from ZZ and nonprompt leptons
- 6l: 3 SFOS pairs, very small background from ttH and ZZ
Nonprompt lepton background estimated form data exploiting isolation variables

Boosted Decision Tree trained with simulated background and signal

Two BDT applied in sequence for channels with more than one background categories (for WWW: nonprompt and others)

4l WWZ category main background contribution from $ZZ \rightarrow p_T^{\text{miss}}$ cut

Systematic uncertainties

- Limited statistic in control regions 5-25%
- Nonprompt bkg estimation up to 50%
- Higher order corrections and PDFs 3-15%
Pulls: difference between observed and predicted

Data and prediction

Data ± stat. uncertainty
Background ± systematics

Triboson signals

WWW (μ_{WWW} = 1.15^{+0.45}_{-0.40})
WWZ (μ_{WWZ} = 0.86^{+0.35}_{-0.31})
WZZ (μ_{WZZ} = 2.24^{+1.92}_{-1.25})
ZZZ (μ_{ZZZ} = 0.0^{+1.30}_{-0.00})

Bkg. in same-charge / 3 lep.

Lost / three leptons
Charge misassignment
Irreducible
Nonprompt leptons
γ → lepton

Backgrounds in 4/5/6 lep.

ZZ  tWZ  Others
- Measured signal strength in agreement with SM prediction
- Discrimination of signal and background enhanced with BDT approach

### Observed (expected) significances

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cut-and-count</th>
<th>BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWW *</td>
<td>2.5 (2.9)</td>
<td>3.3 (3.1)</td>
</tr>
<tr>
<td>WWZ</td>
<td>3.5 (3.6)</td>
<td>3.4 (4.1)</td>
</tr>
<tr>
<td>WZZ</td>
<td>1.6 (0.7)</td>
<td>1.7 (0.7)</td>
</tr>
<tr>
<td>ZZZ</td>
<td>0.0 (0.9)</td>
<td>0.0 (0.9)</td>
</tr>
</tbody>
</table>

* 2016 only (35.9 fb$^{-1}$) result: 0.60 (1.78)
Sum of $p_T$ of leptons and jets ($S_T$) exploited to study aQGC at high values ($S_T > 1.5$ TeV in 2l+2j and > 2 TeV in 3l)

- Study of axion like particle (ALP) production: $W_a \rightarrow WWW$ has largest production cross section for $m_a > 2m_W$

- SM WWW treated as background, no evidence for an excess

- $W$+ALP production excluded up to 480 GeV
With LHC Run 2 data, multi-boson processes accessible

Cross sections measured for many different processes

Limits on anomalous couplings more and more stringent, increased sensitivity on new physics processes

Some explicit BSM models tested and excluded up to high energies

From experimental measurements, information on processes at theoretical level (improvement of Monte Carlo simulations)

For further discussion, Zoom link: 516-275-3909
BACKUP
Results Interpretation

- Presence of effects beyond the SM (BSM) can change the value of the couplings → Anomalous Gauge Couplings

- Effective Field Theories (EFT) provide a model-independent extension of the SM

\[ \mathcal{L}_{aQGC} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \ldots \]

\( \Lambda \) is the energy scale of the new physics, \( d \) is the dimension of the operator, \( f_i \) is the strength of the coupling

- aGC effect enhanced for high-energy (-mass) regions

- Probe explicit BSM models at high energies
Important **test of NNLO QCD calculations** (production via $q\bar{q}$ and gluon fusion at higher order)

- Backgrounds from $Z$+jets and $WZ$+jets estimated with “contamination factors” from data control regions

**Selection**
- 2 pairs of opposite sign isolated leptons ($e$, $\mu$)
- Combinatorial solved with closeness to $M_Z$
- $60 < m_{Z1}, m_{Z2} < 120$ GeV

**Systematic uncertainties**
- Lepton efficiency 2-8%
- PDF + scale variations 1%
- Lepton misidentification probability 1%

**Data / Pred.**

- 137 fb$^{-1}$
- CMS-PAS-SMP-19-001
Analysis performed for 2017 and 2018 and then combined with previous CMS results with 2016 data (CERN-EP-2017-219)

Simultaneous fit performed on all decay channels (eeee, eεµµ, µµµµ)

Measured cross section in agreement with SM predictions (both POWHEG and MCFM)

Both CMS and ATLAS results in agreement with theoretical prediction at different energies

<table>
<thead>
<tr>
<th>Year</th>
<th>Total cross section, pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>17.5^{+0.6}_{-0.5} (stat) ± 0.6 (syst) ± 0.4 (theo) ± 0.4 (lumi)</td>
</tr>
<tr>
<td>2017</td>
<td>16.8 ± 0.5 (stat) ± 0.5 (syst) ± 0.4 (theo) ± 0.4 (lumi)</td>
</tr>
<tr>
<td>2018</td>
<td>16.8 ± 0.4 (stat) ± 0.6 (syst) ± 0.4 (theo) ± 0.4 (lumi)</td>
</tr>
<tr>
<td>Combined</td>
<td>17.1 ± 0.3 (stat) ± 0.4 (syst) ± 0.4 (theo) ± 0.3 (lumi)</td>
</tr>
</tbody>
</table>
**WW DOUBLE PARTON SCATTERING**

\[
\sigma_{DPS}^{AB} = \frac{n \sigma_A \sigma_B}{2 \sigma_{eff}} \quad \text{Single hadron scattering xsec}
\]
\[
\beta_{AB} = \frac{\sigma_{AB}}{\sigma_{A} \sigma_{B}} \quad \text{Double parton scattering xsec}
\]

- SM WW production has two additional jets
- Two same-sign leptons final state is clean
- DPS WW never observed
  - Test of factorisation approach (useful for MC simulations)
  - Background for SUSY searches

**Selection**
- Same charge eµ or µµ
- \(p_T^{\text{miss}} > 15 \text{ GeV}\)
- At most one non-b jet

**Backgrounds**
- True same charge leptons (WZ)
- Nonprompt leptons (tight-to-loose in data)

**Boosted Decision Tree**
- Based on presence of Lorentz boost in WZ processes
- Two classifier for the two backgrounds
**WW DOUBLE PARTON SCATTERING**

- Theoretical prediction of DPS xsec has very low precision
  - PYTHIA prediction $\sigma_{\text{DPS}} = 1.92$ pb, expected significance 5.4$\sigma$
  - Factorisation approach $\sigma_{\text{DPS}} = 0.87$ pb, expected significance 2.5$\sigma$

- Measured cross section and significance do not depend on predicted ones
  \[ \sigma_{\text{DPS}(WW)} = 1.41 \pm 0.20\text{(stat)} \pm 0.28\text{(syst)} \text{ pb} \quad \text{Significance 3.9$\sigma$} \]

- $\sigma_{\text{EFF}} = 12.7^{+5.0}_{-2.9}$ mb consistent with previous measurements with different final states

- Systematics
  - Estimation of nonprompt lepton contribution 25-40%
  - Charge misid background 30%
  - WZ (ZZ) bkg 16(6)%