Electroweak and QCD aspects in V+jets in CMS

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On behalf of the CMS Collaboration
Overview

• Study of associated production of vector bosons and jets (V+jets) excellent test of QCD predictions.

Electroweak-initiated V+jets (VBF W/Z) processes important probe of VBF processes.

All results at: http://cern.ch/go/pNj7
• **Differential (QCD) V+jets:**
  
  - Stringent tests of perturbative QCD, Monte Carlo simulations.
  - Important background for many SM and BSM measurements/searches → crucial to measure with high precision.

• **Electroweak (EW) V+jets:**
  
  - Critical background for VBF Higgs searches/measurements.
  - Precision probe of modeling of VBF processes.
  - Test of soft QCD rapidity gap modeling.
  - Constraints on anomalous trilinear gauge couplings.

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**Outline**

- **W+jets:**
  - *Phys. Rev. D* 96 (2017) 072005

- **Z+jets:**

- **VBF Z:**

- **VBF W:**
  - *arXiv:1903.04040*, submitted to EPJC
Event selection:

- $\mu$ with $p_T > 25$ GeV, $|\eta_\mu| < 2.4$
- $p_T^{\text{jet}} > 30$ GeV, $|\eta^{\text{jet}}| < 2.4$
- $m_T(W) > 50$ GeV

Backgrounds:

- $t\bar{t}$ dominant, contamination increasing with $N_{\text{jet}}$
- QCD multijet. (data-driven)

Iterative d’Agostini unfolding

- Compared to predictions: LO($\leq 4j$) and NLO($\leq 2j$) MadGraph5_aMC@NLO; NNLO for one jet
- Measured: excl./incl. jet multiplicities, jet $p_T$, jet $\eta$, and $H_T$ up to $\geq 3$ jets
- Good agreement with predictions, but overall LO MadGraph5_aMC@NLO slightly underestimates data on the low-$p_T$ observables

**Event selection:**
- 2 e/\(\mu\) with \(p_T > 20\) GeV, |\(\eta_1\)| < 2.4
- \(p_T\) jet > 30 GeV, |\(\eta_{\text{jet}}\)| < 2.4
- |\(m(\ell\ell) - m(Z)\)| < 20 GeV

**Backgrounds:**
- tt dominant at large jet multiplicities (~15%).
- \(Z\rightarrow\tau\tau\) subtracted.

**Iterative d’Agostini unfolding**
- Compared to predictions: LO(\(\leq 4j\)) and NLO(\(\leq 2j\)) MadGraph5_aMC@NLO; NNLO + NNL\(L'\) GENEVA; NNLO fixed order for one jet
- Measured: jet multiplicities, \(p_T(Z)\), \(p_T\) balance, jet \(p_T\), jet \(\eta\), and \(H_T\) up to \(\geq 3\) jets
- Good agreement with predictions with NLO, significant discrepancies with LO for leading jet kinematics. NNL\(L'\) + NNLO\(0\) does not describe well \(p_T\) balance (sensitive to additional jets).
Signal defined as: $\ell\ell jj$ final state with $m(jj) > 120$ GeV, $p_T(j) > 25$ GeV, $m(\ell\ell) > 50$ GeV.

$\sigma_{LO}(EW \ell\ell jj) = 543^{+7}_{-9}$ (QCD scale) ± 22 (PDF) fb

Event selection:

- Two OS $e/\mu$: $p_T > 30$ (20) GeV, $|\eta| < 2.4$, $|m(\ell\ell) - m(Z)| < 15$ GeV
- At least two jets with $p_T > 50$ (30) GeV, $|\eta| < 4.7$
- $M(jj) > 200$ GeV

- Drell-Yan background dominant background.

- **Interference** between signal and DY background (~3% impact), generated with MG5_amc.
Signal vs. background discrimination

BDT trained to separate S from B.

S/BG separation:
- $m(jj)$, $\Delta \eta(jj)$
- $q_{gl}(1^{\text{st}}/2^{\text{nd}} \text{jets})$
- $p_T(jj)$
- $R(p_T^{\text{hard}})$, $z^{**}_{ll}$

$$y^* = y(Z) - \frac{y(j_1) + y(j_2)}{2}$$

$$z^* = \frac{y^*}{\Delta y_{jj}}$$

$$R(p_T^{\text{hard}}) = \frac{p_T(j_1) + p_T(j_2) + p_T(Z)}{p_T(j_1) + p_T(j_1) + p_T(Z)}$$

Cross section measurement

- Binned maximum-likelihood fit to BDT score.
- Measurement dominated by systematic uncertainties.
  - Primarily jet energy scale and signal theory uncertainties.
- In good agreement with LO prediction within uncertainties.

$\sigma_{\text{LO}}(EW \ell \ell jj) = 543_{-9}^{+7} \text{ (QCD scale)} \pm 22 \text{ (PDF)} \text{ fb}$

$\sigma(\text{EW } \ell \ell jj) = 554 \pm 34 \text{ (stat.)} \pm 70 \text{ (syst.) fb}$

$\sigma(\text{EW } \ell \ell jj) = 540 \pm 23 \text{ (stat.)} \pm 56 \text{ (syst.) fb}$

combined:

$\sigma(\text{EW } \ell \ell jj) = 552 \pm 19 \text{ (stat.)} \pm 55 \text{ (syst.) fb}$

$\sigma(\text{LO}) = 543_{-9}^{+7} \text{ (QCD scale)} \pm 22 \text{ (PDF)} \text{ fb}$


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EPS-HEP 2019

12/07/2019
Gap activity studies

- Signal-enriched sample selected with BDT > 0.92 ⇒ S/B ~ 1.

- Study additional hadronic activity in region between VBF jets.
  - Suppressed for EW VBF signal.

- Consider additional jets with $p_T > 15$ GeV jets in the gap (first bin are events with no additional jets).

- Use track-only “soft activity” jets (pileup-resistant) to probe lower in $p_T$ (bottom row).


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Gap activity veto efficiencies

- Consider fraction of events without jet activity in rapidity gap above a given threshold.
  - Efficiency of potential veto to enhance in VBF signals.
- Quantitive measure of reliability of simulation in modeling soft hadronic activity in VBF-enriched region.

Data prefer signal model with HERWIG PS at low gap activity.

**Signal defined as:** $\ell \nu jj$ final state with $m(jj) > 120$ GeV, $p_T(j) > 25$ GeV

$$\sigma_{LO}(EW \ell \nu jj) = 6.81^{+0.03}_{-0.06} \text{(QCD scale)} \pm 0.26 \text{(PDF)} \text{ pb}$$

**Event selection:**

- One e ($\mu$) with $p_T > 30$ (25) GeV, $|\eta| < 2.4$
- $p_T^{miss} > 40$ (20) GeV, $m_T(W) > 40$ GeV
- At least two jets with $p_T > 50$ (30) GeV, $|\eta| < 4.7$
- $m(jj) > 200$ GeV, $R(p_T) < 0.2$

- QCD $W$+jets dominant background, but significant contributions as well from top and QCD multijet.

- **Interference** between signal and $W$+jets background ($\sim 3\%$ impact), generated with MG5_amc.

**arXiv:1903.04040**, submitted to EPJC
Cross section measurement

- Factor $\sim 10$ more statistics than VBF Z.
- Measurement entirely systematics-dominated.
- In good agreement with LO prediction within uncertainties.

$\mathcal{W} \rightarrow e\nu$

$$\sigma(EW \ell \nu jj) = 6.22 \pm 0.12 \text{ (stat.)} \pm 0.74 \text{ (syst.) pb}$$

$\mathcal{W} \rightarrow \mu\nu$

$$\sigma(EW \ell \nu jj) = 6.27 \pm 0.19 \text{ (stat.)} \pm 0.80 \text{ (syst.) pb}$$

Combined:

$$\sigma(EW \ell \nu jj) = 6.23 \pm 0.12 \text{ (stat.)} \pm 0.61 \text{ (syst.) pb}$$

$$\sigma_{LO}(EW \ell \nu jj) = 6.81^{+0.03}_{-0.06} \text{ (QCD scale)} \pm 0.26 \text{ (PDF) pb}$$

arXiv:1903.04040, submitted to EPJC
• Require BDT > 0.95 to achieve S/B ~ 1.

• Consider same set of gap activity observables as in VBF Z.

• Higher statistics with respect to VBF Z allows probing more granularly at low p_T.

Consistent with VBF Z: data prefer signal model with HERWIG PS at low gap activity.

arXiv:1903.04040, submitted to EPJC
• Anomalous trilinear gauge couplings (aTGC’s) can be constrained via measurement of diboson and VBF W/Z production.

• Particularly in high-energy tails of kinematic distributions.

• Consider experimentally clean $p_T(Z)$ and $p_T(\ell)$ distributions to limit systematic uncertainties.

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W^{\rho}_\mu,$$

$$\mathcal{O}_W = \frac{c_W}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^{\nu} \Phi),$$

$$\mathcal{O}_B = \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^{\nu} \Phi).$$
• Combined fit of $p_T(Z)$ from VBF $Z$ and $p_T(\ell)$ from VBF $W$.

• Constraint in VBF $W$ channel improved by 20-25% by requiring BDT > 0.5 in preselection.

<table>
<thead>
<tr>
<th>Coupling constant</th>
<th>Expected 95% CL interval (TeV$^{-2}$)</th>
<th>Observed 95% CL interval (TeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{WWW}/\Lambda^2$</td>
<td>$[-2.3, 2.4]$</td>
<td>$[-1.8, 2.0]$</td>
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<tr>
<td>$c_{W}/\Lambda^2$</td>
<td>$[-11, 14]$</td>
<td>$[-5.8, 10.0]$</td>
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<tr>
<td>$c_{B}/\Lambda^2$</td>
<td>$[-61, 61]$</td>
<td>$[-43, 45]$</td>
</tr>
</tbody>
</table>

Most stringent limit to date on $c_{WWW}$.

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Summary

- Extensive unfolded measurements of jet kinematics for W/Z+jets performed at 13 TeV.
  - Generally good agreement between data and NLO predictions.

- Measurements of electroweak-initiated (VBF) W/Z processes at 13 TeV.
  - Cross sections measured with 10% precision.
  - Quantitive measure of modeling of VBF processes in region with high VBF purity.
  - Most stringent constraints to date on some anomalous trilinear gauge couplings.
Thank you!
Additional Material
Gap activity studies: VBF W

• Signal-enriched sample selected with BDT > 0.95 ⇒ S/B ~ 1.

• Study additional hadronic activity in region between VBF jets.
  • Suppressed for EW VBF signal.

• Consider additional jets with \( p_T > 15 \) GeV jets in the gap (first bin are events with no additional jets).

• Use track-only “soft activity” jets (pileup-resistant) to probe lower in \( p_T \) (bottom row).

\[ \text{arXiv:1903.04040}, \text{ submitted to EPJC} \]
Gap activity veto efficiencies: validation

- Require BDT < 0.95 to deplete signal.

- Simulation models well the background throughout the full spectrum of the observables.

arXiv:1903.04040, submitted to EPJC