Vector boson associated with jets in CMS

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Outline

Introduction

W+c differential cross section analysis @13 TeV
Z+c jet differential cross section analysis @13 TeV
Z+b jet differential cross section analysis @13 TeV
Z+HF jet differential cross section ratio analysis @13 TeV

Summary
Summary of current status

May 2021

- $W+c$ jets, $Z+c$ jets, $Z+b$ jets are measured at all available LHC center of mass energies. $Z+b$ results at 13 TeV not updated.
- In general, predictions agree with data within uncertainties.

All results at: http://cern.ch/go/pNj7

Fiducial $W$ and $Z$ as with $W \rightarrow l\nu$, $Z \rightarrow l\nu$ and kinematic selection

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
13 TeV CMS measurement ($L \leq 137$ fb$^{-1}$)
Theory prediction
Physics motivation

- Measurements of $V +$ heavy-flavor ($b$, $c$) jets ($V+$HF jets) are important to test the electroweak & pQCD predictions
- Good opportunity to be compared against different hadronization-fragmentation processes
- It also provides information on the strange, bottom, and charm quark parton distribution functions (PDFs)
- Important background in many SM processes and BSM searches

Cross section measurements of $W+c$ jet in pp collisions at 13 TeV [CMS-SMP-17-014](#)

Cross section measurements of $Z+c$ jet in pp collisions with the CMS experiment at 13 TeV [CMS-SMP-19-011](#)

Cross section measurements of $Z+b$ jet in pp collisions with the CMS experiment at 13 TeV [CMS-PAS-SMP-20-015](#)

Cross section ratio measurements of $Z+b$ jet and $Z+c$ jet w.r.t $Z+$ jets in pp collisions [CMS-SMP-19-004](#)
W+c cross section at 13 TeV

- W+c cross sections are measured in the muon channel
- c quarks are identifying through reconstruction of the c hadrons via the process:  
  \[ c \rightarrow D^{*\pm} \rightarrow D^0 + \pi_{slow}^\pm \rightarrow K^\mp \pi^\pm \pi_{slow}^\pm \]

W+c signal:
- c quark with \( p_T > 5 \) GeV in the final state
- W boson and the charm quark have opposite signs (OS)
- Odd number of c quarks (3, 5, ...) the one with OS and the highest \( p_T \) is chosen

W+c\( \bar{c} \):
- Large background from gluon splitting (\( g \rightarrow c\bar{c} \))
- Contains additional c quark with same sign (SS) as W boson
- Can be suppressed at reconstruction-level by subtracting SS from OS
**W+c cross section at 13 TeV**

**W+c**: $W(\rightarrow \mu \bar{\nu}) + D^*(2010)^{\pm} \rightarrow \mu \bar{\nu} + D^0 + \pi_{{\text{slow}}}^{\pm} \rightarrow \mu \bar{\nu} + K^{\mp} \pi^{\pm} + \pi_{{\text{slow}}}^{\pm}$

**Muon(\(\mu\)):** $p_T > 26$ GeV, $|\eta| < 2.4$

**Transverse mass ($M_T$):** $\geq 50$ GeV,  

$M_T := \sqrt{2.p_T^\mu . E_T^{{\text{miss}}}(1 - \cos(\phi_\mu - \phi_E^{{\text{miss}}}))}$

**D\(^0\):** $p_T^{K,\pi} > 1$ GeV, $|K^{\mp} + \pi^{\pm} - D_{{pdg}}^0| < 35$ MeV, $K^{\mp} + \pi^{\pm}$ must originate from Secondary vertex,

**D\(^*\)\(^\pm\):** $p_T^{\pi_{{\text{slow}}}^{\pm}} > 0.35$ GeV, $\Delta R(D^0, \pi_{{\text{slow}}}^{\pm}) < 0.15$, $p_T^{D^*_\pm}/\Sigma p_T > 0.2$ $p_T^{D^*_\pm} > 5$ GeV

The $D^*_{\pm}$ meson candidates are identified using the mass difference method via a peak in the $\Delta m(D^*_{\pm}, D^0)$ distribution.
Results: W+c cross section at 13 TeV

- Measurements are compared to the MCFM 6.8 NLO QCD prediction obtained using several PDF sets evaluated at NLO, except for ATLASepWZ16 (NNLO).
- Good agreements between predictions and data except ATLASepWZ16.

<table>
<thead>
<tr>
<th></th>
<th>(\sigma(W+c))</th>
<th>(\sigma(W^+ + c)/\sigma(W^- + c))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>1026 ± 31 (stat)(^{+76}_{-72}) (syst)</td>
<td>0.968 ± 0.055 (stat)(^{+0.015}_{-0.028}) (syst).</td>
</tr>
<tr>
<td>ABMP16nlo</td>
<td>1077.9 pb ± 2.1%(pdf)(^{+3.4%}_{-2.4%}) (scale)</td>
<td>0.975(^{+0.002}_{-0.002})</td>
</tr>
<tr>
<td>ATLASepWZ16nlo</td>
<td>1235.1 pb (^{+1.4%}<em>{-1.6%})(pdf)(^{+3.7%}</em>{-2.8%}) (scale)</td>
<td>0.976(^{+0.001}_{-0.001})</td>
</tr>
<tr>
<td>CT14nlo</td>
<td>992.6 pb ± (^{+7.2%}<em>{-8.4%})(pdf)(^{+3.1%}</em>{-2.1%}) (scale)</td>
<td>0.970(^{+0.005}_{-0.007})</td>
</tr>
<tr>
<td>MMHT14nlo</td>
<td>1057.1 pb (^{+6.5%}<em>{-8.0%})(pdf)(^{+3.2%}</em>{-2.2%}) (scale)</td>
<td>0.960(^{+0.023}_{-0.033})</td>
</tr>
<tr>
<td>NNPDF3.0nlo</td>
<td>959.5 pb (^{+5.4%}<em>{-8.0%})(pdf)(^{+2.8%}</em>{-1.9%}) (scale)</td>
<td>0.962(^{+0.034}_{-0.034})</td>
</tr>
<tr>
<td>NNPDF3.1nlo</td>
<td>1030.2 pb (^{+5.3%}<em>{-8.2%})(pdf)(^{+3.2%}</em>{-2.2%}) (scale)</td>
<td>0.965(^{+0.043}_{-0.043})</td>
</tr>
</tbody>
</table>
Z(\(ll\)) + \(\geq 1\) b/c jet cross section at 13 TeV

**Event Selection Z(\(\mu\mu/ee\)) + b/c jet**

\[Z(\mathbb{I}) : 71 < M_{ll} < 111 \text{ GeV}, |\eta(ll)| < 2.4\]

particle-level jets: \(p_T > 30 \text{ GeV}, |\eta(\text{jet})| < 2.4\), pileup jet id (to remove pileup)

\[Z(\mathbb{I}) + \geq 1 \text{ b jet: } p_T^{\text{miss}} < 50 \text{ GeV}\]

\[Z(\mathbb{I}) + \geq 1 \text{ b/c jet: b/c jets are selected with deepCSV tight b/c-tag discriminators,}\]

\[Z(\mathbb{I}) + \geq 1 \text{ HF jets cross section ratio: particle (parton)-level jets: } p_T > 30 (15) \text{ GeV}, p_T^{\text{miss}} < 40 \text{ GeV}, \text{ b jets are selected with deepCSV medium b-tag discriminator}\]

**deepCSV discriminators:** combined tracks & secondary vertex (SV) characteristics using machine learning techniques

**Background processes**

\(Z+b\) jets, \(Z+\text{light jets}\) extracting by fitting templates of sv mass distribution obtained from Drell-Yan simulation for \(Z + c\) jet analysis, & validated with different data driven methods for \(Z + \text{HF jets cross section ratio analysis}\).

Diboson (WW, WZ, and ZZ), \(t\bar{t}\), \(W+\text{jets processes contributions are small and taken from MC}\)

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**Graph:**

- Events / 0.2 GeV
- 35.9 fb\(^{-1}\) (13 TeV)
- Data (Electron channel)
- C jets
- B jets
- Light jets
- Top and dibosons

**Axes:**

- Secondary vertex mass \(M_{SV} [\text{GeV}]\)
- Events / 0.2 GeV

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Results: $Z(\ell\ell) + \geq 1$ c jet cross section

 Integral cross section $Z(\ell\ell) + c$ jet

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured (Data)</td>
<td>405.4 ± 5.6 (stat) ± 24.3 (exp) ± 3.7 (th) pb</td>
</tr>
<tr>
<td>MG5_aMC (NLO Prediction)</td>
<td>524.9 ± 11.7 (th) pb</td>
</tr>
<tr>
<td>SHERPA (NLO Prediction)</td>
<td>485.0 pb</td>
</tr>
</tbody>
</table>

$\sum_{c} p_{T} > 30$ GeV, $|\eta_{\text{jet}}| < 2.4$

$\sigma_{\text{tot}}^Z p_{T}^c$ [GeV]

MC/Data: 1

Conclusion: NLO prediction pdf overestimate the charm quark content and will be useful in improving the existing constraints in simulation of the c-quark pdf.
Results: $Z(\ell\ell) + \geq 1$ b jet cross section

### Integral cross section $Z(\ell\ell) + \geq 1$ b jet

<table>
<thead>
<tr>
<th>Source</th>
<th>Cross Section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured (Data)</td>
<td>$6.52 \pm 0.04 \text{(stat)} \pm 0.40 \text{(exp)} \pm 0.14 \text{(th)}$</td>
</tr>
<tr>
<td>MG5_aMC (NLO Prediction) CUETP8M1 [CP5]</td>
<td>$7.86 \pm 0.51 \text{(th)} [7.03 \pm 0.47 \text{(th)}]$</td>
</tr>
<tr>
<td>SHERPA (NLO Prediction)</td>
<td>$8.02$</td>
</tr>
<tr>
<td>MG5_aMC (LO Prediction) CUETP8M1 [CP5]</td>
<td>$6.25 [6.34]$</td>
</tr>
</tbody>
</table>

$p_T \rightarrow$ shape of distribution is well described by all simulations, except for the MG5_aMC (LO, NNPDF 3.1, CP5) which deviates up to 25% in the higher $p_T$ region.

$\Delta Y \rightarrow$ agreement improved significantly with MG5_aMC at NLO w.r.t LO in high regions

Conclusion: NLO prediction pdf overestimate the b quark content and will be useful in improving the existing constraints in simulation of the b-quark pdf
Results: \( Z(\ell\ell) + \geq 2 \) b jets cross section

\[
\begin{align*}
\text{Integral cross section } Z(\ell\ell) + \geq 2 \text{ b jets} & \\
\text{Measured (Data)} & = 0.65 \pm 0.03 \text{(stat)} \pm 0.07 \text{(exp)} \pm 0.02 \text{(th)} \text{ pb} \\
\text{MG5\_aMC (NLO Prediction) CUETP8M1 [CP5]} & = 0.90 \pm 0.09 \text{(th)} \pm 0.77 \pm 0.07 \text{(th)} \text{ pb} \\
\text{SHERPA (NLO Prediction)} & = 0.84 \text{ pb} \\
\text{MG5\_aMC (LO Prediction) CUETP8M1 [CP5]} & = 0.63 \pm 0.71 \text{ pb}
\end{align*}
\]

\( \Delta R \rightarrow \) agreement improved significantly with MG5\_aMC at NLO w.r.t LO in high regions.

\( A_{Zbb} \rightarrow \) sensitive to extra emission of gluon at final state.

If no extra gluon radiation, then \( A_{Zbb} \sim 0 \).

Conclusion: NLO prediction pdf overestimate the b quark content and will be useful in improving the existing constraints in simulation of the b-quark pdf.
Result: cross section ratio $Z(\mu\mu) + \geq 2 \text{ b jets}/Z(\mu\mu) + \geq 1 \text{ b jet}$

Integral cross section $Z(\mu\mu) + \geq 2 \text{ b jets}/Z(\mu\mu) + \geq 1 \text{ b jet}$

<table>
<thead>
<tr>
<th>Measured (Data)</th>
<th>$0.100 \pm 0.005(\text{stat}) \pm 0.007(\text{exp}) \pm 0.003(\text{th}) \text{ pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG5_aMC (NLO Prediction) CUETP8M1 [CP5]</td>
<td>$0.114 \pm 0.016(\text{th})$ [0.110 $\pm 0.013(\text{th})] \text{ pb}$</td>
</tr>
<tr>
<td>SHERPA (NLO Prediction)</td>
<td>$0.105 \text{ pb}$</td>
</tr>
<tr>
<td>MG5_aMC (LO Prediction) CUETP8M1 [CP5]</td>
<td>$0.102$ [0.112] $\text{ pb}$</td>
</tr>
</tbody>
</table>

Ratio gradually increases (from 0.05 to 0.25) with the leading b jet $p_T$ (ranging from 30 to 200 GeV), but is nearly independent of the pseudorapidity of the leading b jet.

All predictions describe measured ratios within uncertainties.
Result: $Z(\ell\ell) + \geq 1$ HF jet cross section ratio

Cross section ratio at particle-level in fiducial volume $p_T^{HF\ jet} > 30$ GeV & $|\eta^{HF\ jet}| < 2.4$

<table>
<thead>
<tr>
<th></th>
<th>Measured (Data)</th>
<th>MG5_aMC (NLO, FxFx)</th>
<th>MG5_aMC(LO, MLM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(c/j)$</td>
<td>$0.102\pm0.002$(stat)$\pm0.009$(syst)</td>
<td>$0.111\pm0.003$(pdf)$^{+0.010}_{-0.011}$(scale)</td>
<td>$0.103\pm0.003$(pdf)$^{+0.028}_{-0.026}$(scale)</td>
</tr>
<tr>
<td>$R(b/j)$</td>
<td>$0.0633\pm0.0004$(stat)$\pm0.0015$(syst)</td>
<td>$0.067\pm0.002$(pdf)$\pm0.006$(scale)</td>
<td>$0.062\pm0.002$(pdf)$^{+0.018}_{-0.015}$ (scale)</td>
</tr>
<tr>
<td>$R(c/b)$</td>
<td>$1.62\pm0.03$(stat)$\pm0.15$(syst)</td>
<td>$1.64\pm0.05$(pdf)$^{+0.15}_{-0.16}$(scale)</td>
<td>$1.67\pm0.06$(pdf)$^{+0.54}_{-0.40}$(scale)</td>
</tr>
</tbody>
</table>

- Measured $R(c/j)$ & $R(b/j)$ → MG5_aMC(LO) agree well, while overestimating by MG5_aMC(NLO)
- Measured $R(c/b)$ → MG5_aMC(NLO) agree well, while overestimating by MG5_aMC(LO)

Cross section ratio at parton-level in fiducial volume $p_T^{HF\ jet} > 15$ GeV & $|\eta^{HF\ jet}| < 2.4$

<table>
<thead>
<tr>
<th></th>
<th>MCFM (NLO)</th>
<th>MCFM(LO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(c/j)$</td>
<td>$0.090\pm0.003$(pdf)$^{+0.010}<em>{-0.012}$($^{+0.008}</em>{-0.007}$)(scale)</td>
<td>$0.087\pm0.003$(pdf)$^{+0.025}_{-0.022}$ (scale)</td>
</tr>
<tr>
<td>$R(b/j)$</td>
<td>$0.068\pm0.002$(pdf)$^{+0.008}_{-0.011}$($\pm0.006$)(scale)</td>
<td>$0.071\pm0.002$(pdf)$^{+0.023}_{-0.021}$ (scale)</td>
</tr>
<tr>
<td>$R(c/b)$</td>
<td>$1.33\pm0.04$(pdf)$^{+0.16}<em>{-0.21}$($^{+0.10}</em>{-0.12}$)(scale)</td>
<td>$1.20\pm0.04$(pdf)$^{+0.42}_{-0.38}$ (scale)</td>
</tr>
</tbody>
</table>

- Measured $R(c/j)$ & $R(c/b)$ → underestimating by MCFM at NLO & LO
- Measured $R(b/j)$ → overestimating by MCFM at NLO & LO
- Prediction at NLO is somewhat better as compared to LO

Comparison at parton & particle level give an idea about relative effect coming from fragmentation /hadronization /MPI /underlying-events

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Results: cross section ratio $Z(\ell\ell) + > = 1$ c jet/$Z(\ell\ell) + > = 1$ jet

MG5_aMC(LO) prediction $\rightarrow$ describing well within 10% while MG5_aMC(NLO) deviate upto 20–30%. MCFM(pdf:NNPDF3.0), MCFM(pdf:MMHT14) predictions $\rightarrow$ at NLO & LO describing well $R(c/j)$ except in higher $p_T^{ll}$

Conclusion: MG5_aMC(NLO) prediction pdf overestimate the c quark content and will be useful in improving the the existing constraints in simulation of the c quark pdf
Result: cross section ratio $Z(\illo) + > = 1 \text{ b jet}/Z(\illo) + > = 1 \text{ jet}$

All MC: MG5_aMC, MCFM(pdf: NNPDF 3.0), MCFM(pdf: MMHT14) at NLO & LO prediction are describing well both distribution within 10%, except higher $p_T^{\text{jet}}$ and $p_T^{\illo}$ where prediction at NLO tend to deviate upto 20–30%.

Conclusion: All NLO prediction pdf overestimate the bottom quark content and will be useful in improving the the existing constraints in simulation of the b-quark pdf
Result: cross section ratio $Z(\ell\ell) + > = 1\ c\ jet/Z(\ell\ell) + > = 1\ b\ jet$

MCFM(pdf: NNPDF 3.0), MCFM(pdf: MMHT14) at NLO and LO prediction are describing better as compared to MG5_aMC within 10%, except in higher $p_T^{\text{jet}}$ and $p_T^{\ell\ell}$. 
Summary

- **Cross section $W(\mu\nu) + c$:**
  - The results were compared to theoretical predictions done with MCFM in combination with different PDF-sets.
  - A good agreement between the measurements and predictions is observed except ATLASepWZ16 prediction $W+c$ cross section.

- **Cross section $Z(\ell\ell) + > 1$ b/c jet:**
  - All NLO prediction PDFs overestimate the b/c quark content & will be useful in improving the existing constraints in simulation of the b/c-quark PDF.
  - Provide valuable inputs for tuning & constraining model parameters of advanced parton shower Monte Carlo programs.
Thank You

Backup
Identification of b/c jets via secondary vertex mass

**Jets:**
- Due to color confinement of parton (quark & gluon), hadronization takes place & produces colorless hadrons in cones of outgoing particles called jets.

**b/c Jets:**
- Initiated by b-quark/c-quark with characteristic lifetime (1.5/1.1 ps) of b/c hadron, will travel $\sim 1$ cm (at energy in the lab frame $\sim 10$-100 GeV) before decaying to several particles form new vertex (secondary vertex).

**Identification of b jets/c jets:**
- Reconstructable secondary vertex, time of flight.
- Displaced tracks with respect to primary interaction vertex.
- Sign of impact parameter (positive if track minimal approach to jet axis is downstream the Primary vertex along jet direction).
- Soft lepton information.
W+c differential cross section

CMS
35.7 fb⁻¹ (13 TeV)

W + c

- Data
- ABMP16
- ATLASepWZ16
- CT14
- MMHT14
- NNPDF 3.0
- NNPDF 3.1

p_T > 5 GeV, |η| < 2.4

CMS
35.7 fb⁻¹ (13 TeV)

W + D*(2010)+

- Data
- MADGRAPH5_aMC@NLO
- NNPDF3.0nlo

p_T > 5 GeV, |η| < 2.4

CMS
35.7 fb⁻¹ (13 TeV)

W + D*(2010)-

- Data
- MADGRAPH5_aMC@NLO
- NNPDF3.0nlo

p_T > 5 GeV, |η| < 2.4