Vector boson plus heavy-flavor jets measurements at CMS

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Outline

Introduction

$W+c$ differential cross section analysis @13 TeV

$Z+c$ jet differential cross section analysis @13 TeV

$Z+HF$ jet differential cross section ratio analysis @13 TeV

Summary
Introduction: Large hadron collider (LHC)

- World’s largest & highest energy particle accelerator (Geneva, Switzerland & France)
- Collision b/w two counter-rotating particle beams at an energy of 6.5 TeV per particle.

LHC

CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = 13$ TeV

Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC

LHC Delivered: 40.99 fb$^{-1}$
CMS Recorded: 37.80 fb$^{-1}$

Luminosity recorded during 2016
Summary of current status

May 2021

CMS Preliminary

Production Cross Section, σ [pb]

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

- 7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
- 8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
- 13 TeV CMS measurement (L ≤ 137 fb⁻¹)
- Theory prediction

- W+c, Z+c are measured at all available LHC center of mass energies. Lacking Z+b results at 13 TeV
- In general, predictions agree with data within uncertainties

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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 with the CMS experiment at 13 TeV [CMS-SMP-17-014](#)  
Cross section ratio measurements of $Z+b$ jet and $Z+c$ jet w.r.t $Z+$ jets in pp collisions with the CMS experiment [CMS-SMP-19-004](#)  
Cross section measurements of $Z+c$ jet in pp collisions with the CMS experiment at 13 TeV [CMS-SMP-19-011](#)
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:
  \[ c \rightarrow D^{*\pm} \rightarrow D^0 + \pi^\pm_{\text{slow}} \rightarrow K^\mp \pi^\pm \pi^\pm_{\text{slow}} \]

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

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

**Transverse mass ($M_T$)**: $\geq 50$ GeV, $[M_T := \sqrt{2p_T^\mu E^\mu_{miss}(1 - \cos(\phi_\mu - \phi_\mu^\mu))}]$

$D^0$: $p_T^{K^\mp \pi^\pm - D^0_{pdg}} < 35$ MeV, $K^\mp \pi^\pm$ must originate from Secondary vertex,

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

\[
\sigma(W+c) = 1026 \pm 31 \text{ (stat)} \pm 76 \text{ (syst)} \text{ pb}
\]

\[
\sigma(W^+ + c)/\sigma(W^- + c) = 0.968 \pm 0.055 \text{ (stat)} \pm 0.015 \text{ (syst)}.
\]
Z(\(\mu\mu/ee\)) + c jet cross section at 13 TeV

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

Muon(\(\mu\)): \(p_T(l_1/l_2) > 26/10 \text{ GeV}, |\eta(l_1/l_2)| < 2.4\)
Electron(\(e\)): \(p_T(l_1/l_2) > 29/10 \text{ GeV}, |\eta(l_1/l_2)| < 2.4, 1.4442 < |\eta_{SC}| < 1.556\)
Z(\(\mu\mu\)): \(71 < M_{\mu\mu} < 111 \text{ GeV}, |\eta(\mu\mu)| < 2.4\)
Jets: \(p_T > 30 \text{ GeV}, |\eta(\text{jet})| < 2.4, \text{pileup jet id (to remove pileup)} > -0.89\)
c Jets: deepCSV tight c-tag discriminators: CvsL > 0.59 & CvsB > 0.05, [deepCSV: combined tracks and secondary vertex characteristics using machine learning techniques]

Background processes

Z+b jets, Z+light jets extracting by fitting templates of secondary vertex mass distribution obtained from Drell-Yan simulation
Diboson (WW, WZ, and ZZ), \(t\bar{t}\), W+jets processes contributions are small and taken from MC

Data / MC
Results: $Z(\ell\ell) + c$ jet cross section

CMS 35.9 fb$^{-1}$ (13 TeV)

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>$405.4 \pm 5.6 \text{(stat)} \pm 24.3 \text{(exp)} \pm 3.7 \text{(th)} \text{ pb}$</td>
</tr>
<tr>
<td>MG5_aMC (NLO Prediction)</td>
<td>$524.9 \pm 11.7 \text{(th)} \text{ pb}$</td>
</tr>
<tr>
<td>SHERPA (NLO Prediction)</td>
<td>$485.0 \text{ pb}$</td>
</tr>
</tbody>
</table>

MG5\_aMC(LO) are describing well differential cross section distribution of $p_T^{\ell\ell}$ & $p_T^{cjet}$ within 10% while MG5\_aMC & SHERPA at NLO tend to deviate up to 20–30%.

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.
Z(\(\mu\mu/ee\)) + HF jet cross section ratio

Event Selection Z(\(\mu\mu/ee\)) + HF jet at parton- and particle-level

- Muon(\(\mu\)): \(p_T(l_1/l_2) > 25/25\) GeV, |\(\eta(l_1/l_2)\)| < 2.4
- Electron(e): \(p_T(l_1/l_2) > 25/25\) GeV, |\(\eta(l_1/l_2)\)| < 2.4, \(1.4442 < |\eta_{SC}| < 1.556\)
- Z(\(ll\)): \(71 < M_{ll} < 111\) GeV, |\(\eta(ll)\)| < 2.4, MET < 40 GeV
- Jets particle(parton)-level: \(p_T > 30(15)\) GeV, |\(\eta(jet)\)| < 2.4
- HF jets: deepCSV medium b-tag discriminator > 0.8484, [deepCSV: combined tracks and secondary vertex characteristics using machine learning techniques]

Background processes

- \(Z+c\) jets, \(Z+\)light jets extracting by fitting secondary vertex mass template (validated with different data driven methods)
- Diboson (WW, WZ, and ZZ), \(t\bar{t}\), W+jets processes are taken from MC
**Result:** $Z(\ell\ell) + \geq 1$ HF jet cross section ratio

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

<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>$0.102 \pm 0.002 \text{(stat)} \pm 0.009 \text{(syst)}$</td>
<td>$0.111 \pm 0.003 \text{(pdf)} ^{+0.010}_{-0.011} \text{(scale)}$</td>
<td>$0.103 \pm 0.003 \text{(pdf)} ^{+0.028}_{-0.026} \text{(scale)}$</td>
</tr>
<tr>
<td>$R(b/j)$</td>
<td>$0.0633 \pm 0.0004 \text{(stat)} \pm 0.0015 \text{(syst)}$</td>
<td>$0.067 \pm 0.002 \text{(pdf)} \pm 0.006 \text{(scale)}$</td>
<td>$0.062 \pm 0.002 \text{(pdf)} ^{+0.018}_{-0.015} \text{(scale)}$</td>
</tr>
<tr>
<td>$R(c/b)$</td>
<td>$1.62 \pm 0.03 \text{(stat)} \pm 0.15 \text{(syst)}$</td>
<td>$1.64 \pm 0.05 \text{(pdf)} ^{+0.15}_{-0.16} \text{(scale)}$</td>
<td>$1.67 \pm 0.06 \text{(pdf)} ^{+0.54}_{-0.40} \text{(scale)}$</td>
</tr>
</tbody>
</table>

- Measured $R(c/j)$ & $R(b/j) \rightarrow$ MG5\_aMC(LO) agree well, while overestimating by MG5\_aMC(NLO)
- Measured $R(c/b) \rightarrow$ MG5\_aMC(NLO) agree well, while overestimating by MG5\_aMC(LO)

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

<table>
<thead>
<tr>
<th></th>
<th>MCFM (NLO)</th>
<th>MCFM(LO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(c/j)$</td>
<td>$0.090 \pm 0.003 \text{(pdf)} ^{+0.010}<em>{-0.012} \pm ^{+0.008}</em>{-0.007} \text{(scale)}$</td>
<td>$0.087 \pm 0.003 \text{(pdf)} ^{+0.025}_{-0.022} \text{(scale)}$</td>
</tr>
<tr>
<td>$R(b/j)$</td>
<td>$0.068 \pm 0.002 \text{(pdf)} ^{+0.008}<em>{-0.011} \pm ^{+0.006}</em>{-0.007} \text{(scale)}$</td>
<td>$0.071 \pm 0.002 \text{(pdf)} ^{+0.023}_{-0.021} \text{(scale)}$</td>
</tr>
<tr>
<td>$R(c/b)$</td>
<td>$1.33 \pm 0.04 \text{(pdf)} ^{+0.16}<em>{-0.21} \pm ^{+0.10}</em>{-0.12} \text{(scale)}$</td>
<td>$1.20 \pm 0.04 \text{(pdf)} ^{+0.42}_{-0.38} \text{(scale)}$</td>
</tr>
</tbody>
</table>

- Measured $R(c/j)$ & $R(c/b) \rightarrow$ underestimating by MCFM at NLO & LO
- Measured $R(b/j) \rightarrow$ 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
Results: cross section ratio \( Z(\ell\ell) + > = 1 \text{ c jet}/Z(\ell\ell) + > = 1 \text{ jet} \)

- **MG5_aMC(LO) prediction**: describing well within 10% while MG5_aMC(NLO) deviate up to 20–30%.
- **MCFM(pdf:NNPDF3.0), MCFM(pdf:MMHT14) predictions**: at NLO & LO describing well \( R(c/j) \) except in higher \( p_{T}^{\ell\ell} \).

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

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 $p_T^\parallel$ 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 $Z(ll) + > 1 c \text{ jet}/Z(ll) + > 1 b \text{ jet}$

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 $p_T^{ll}$.
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 for the ATLASepWZ16 prediction. W+c cross section.

- **Cross section $Z(\ell\ell)+ > = 1$ c jet:**
  $Z(\ell\ell)+ > = 1$ c jet measured cross section is overestimated by MG5_aMC and SHERPA NLO predictions and will be useful in improving the existing constraints in simulation of the c-quark pdf.

- **Cross section ratio measurements $R(c/j), R(b/j)$ and $R(c/b)$**
  - The MG5_aMC predictions are higher in most of the bins, except for the $R(c/j)$ versus jet $p_T$, where the deviations are more pronounced.
  - The measured cross section ratio are better described with MG5_aMC (LO) compared to MG5_aMC (NLO), useful in improving the existing constraints in simulation of the b/c quark pdf.
  - The MCFM predictions for $R(c/j)$ and $R(b/j)$ disagree with data at high jet and $Z p_T$, except for $R(c/j)$ versus jet $p_T$, where good agreement with LO or NLO calculations (for both pdf).
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**:
  - $p_T^c > 26$ GeV, $|\eta^c| < 2.4$
  - $p_T^c > 5$ GeV

- **W+D*(2010)**:
  - $p_T^c > 26$ GeV, $|\eta^c| < 2.4$
  - $p_T^c > 5$ GeV, $|\eta^c| < 2.4$

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