Study for vector bosons production in association with heavy-flavor jets in proton-proton collisions

Meena (On behalf of CMS collaboration)

14 December, 2020
Outline

Introduction

Z + c jet differential cross section analysis @13 TeV

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

Summary
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.
**Introduction (ii) : CMS detector component**

- **Interaction point**: Center of detector at which proton-proton collisions occurs
- **Tracker**: Identify charged particles & measure their momenta.
- **Electromagnetic Calorimeter (ECAL)**: Measure the energies of particles showing electromagnetic interaction.
- **Hadron Calorimeter (HCAL)**: Measure the energies of strongly interacting particles.
- **Muon chamber**: Identify & measure the momenta of muons
Physics motivation

- Important to test the electroweak & pQCD predictions by comparing experimental cross section with theoretical predictions
- It also provides information on the bottom and charm quark parton distribution functions (PDFs)
- Important background in many SM processes (single top, $t\bar{t}$, vector boson fusion, WW scattering) and BSM searches (Supersymmetry, HV($H \rightarrow b\bar{b}$)) and it help to distinguish signal from irreducible backgrounds

![Diagram of Z + 1 b jet](image)

- Cross section measurements of $Z + c$ jet in pp collisions with the CMS experiment at 13 TeV [CMS-SMP-19-011](https://link)
- 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](https://link)
**Event selection** $Z(\mu\mu/ee) + b/c$ jets

**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 from 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)
Z(\(\mu\mu/ee\)) + 1 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 < \(M_{ll}\) < 111, \(\eta(\mu\mu) < 2.4\)
jets: \(p_T > 30 \text{ GeV}\), \(\eta(\mu\mu) < 2.4\), pileup jet id (to remove pileup) > -0.89
c jets: deepCSV tight c-tag discriminators: CvsL > 0.59 & CvsB > 0.05

Background processes

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

Data (Electron channel)

Events / 0.2 GeV

Data / MC

Secondary vertex mass

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

MG_aMC(LO) are describing well differential cross section distribution of $p_T^{\ell\ell}$ & $p_T^{c\text{jet}}$ within 10% while MG5_aMC & SHERPA at NLO tend to deviate upto 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(\(\mu\mu/ee\)) + c jet**

**Event Selection**

- **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(\(ll\)):** \(71 < M_{ll} < 111, \eta(ll) < 2.4, \text{MET} < 40\) GeV
- **Jets:** \(p_T > 30\) GeV, \(\eta(ll) < 2.4\)
- **b jets:** deepCSV medium b-tag discriminators : 0.8484

**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 considered from MC

![Graph showing secondary vertex mass distribution](image-url)
Result: \( Z(\ell\ell) + \geq 1 \) HF jet cross section ratio

### Cross section ratio at particle level

<table>
<thead>
<tr>
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<th>Measured (Data)</th>
<th>MG_aMC (NLO,FxFx)</th>
<th>MG_aMC(LO,MLM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R(c/j) )</td>
<td>0.102±0.002(stat)+±0.009(syst)</td>
<td>0.111±0.003(pdf)+0.010(_{-0.011}^{+0.010}) (scale)</td>
<td>0.103±0.003(pdf)+0.028(_{-0.026}^{+0.028}) (scale)</td>
</tr>
<tr>
<td>( R(b/j) )</td>
<td>0.0633±0.0004(stat)±0.0015(syst)</td>
<td>0.067±0.002(pdf)±0.006(scale)</td>
<td>0.062±0.002(pdf)+0.018(_{-0.015}^{+0.018}) (scale)</td>
</tr>
<tr>
<td>( R(c/b) )</td>
<td>1.62±0.03(stat)±0.15(syst)</td>
<td>1.64±0.05(pdf)+0.15(_{-0.16}^{+0.15}) (scale)</td>
<td>1.67±0.06(pdf)+0.54(_{-0.40}^{+0.54}) (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

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

**Comparison at parton & particle level** give an idea about relative effect coming from fragmentation / hadronization / MPI / underlying-events
Results: cross section ratio $Z(\ell\ell)^+\geqslant 1\ c\ jet/Z(\ell\ell)^+\geqslant 1\ jet$

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

MG\_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 $p_T^{\ell\ell}$

Conclusion: MG\_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 $Z(\ell\ell)^+ >= 1 \ b\ jet / Z(\ell\ell)^+ >= 1 \ jet$

All MC: MG_aMC, MCFM(pdf: NNPDF 3.0), MCFM(pdf: MMHT14) at NLO & LO prediction are describing well both distribution within 10%, except higher $p_T^{jet}$ and $p_T^{ll}$ 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 compare to MG_aMC within 10%, except in higher \(p_T^{\text{jet}}\) and \(p_T^{\ell\ell}\)
Summary

- **Cross section Z (l\)\(\ell\)\(^+\) \(> = 1\) c jet:**
  - Z (l\(\ell\)\(^+\)) \(> = 1\) c jet measured cross section is overestimated by MG5\(_aMC\) and SHERPA NLO predictions and will be useful in improving the 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 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).

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**Thank You**