Vector boson plus heavy-flavor jets measurements at CMS

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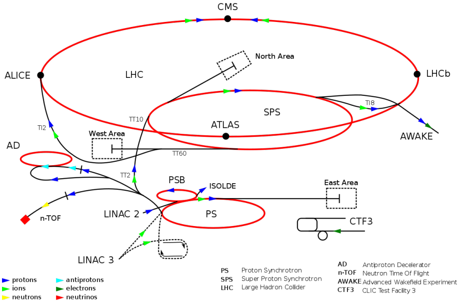
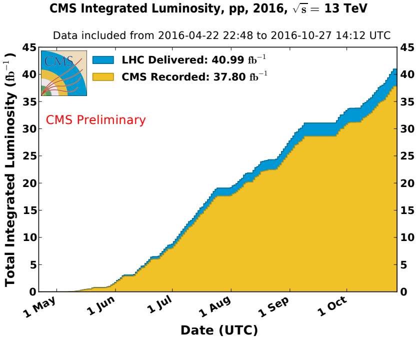
Outline

- 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.

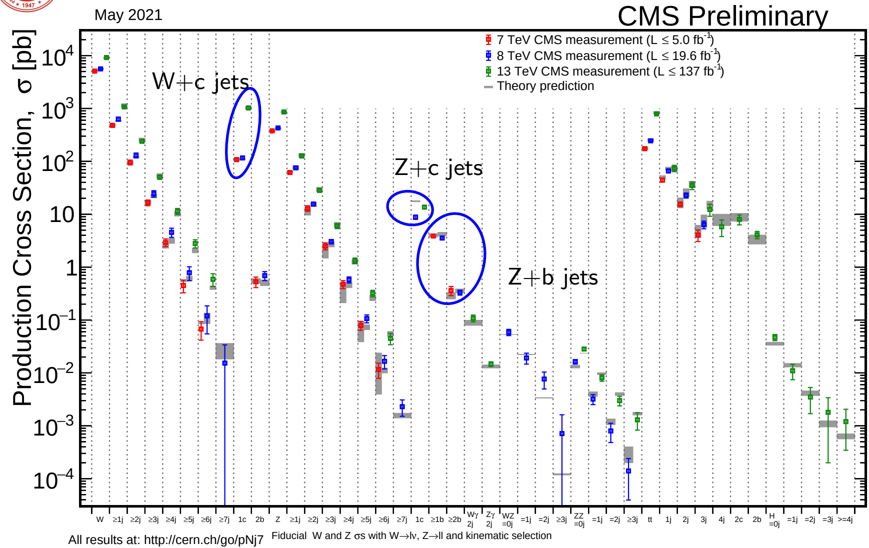


LHC



Luminosity recorded during 2016

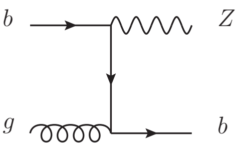
Summary of current status



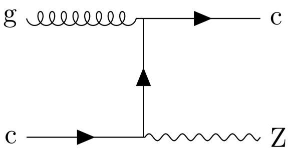
- W+c, Z+c are measured at all available LHC center of mass energies. Lacking Z+b results at 13 TeV
- In general, predictions agree with data within uncertainties

Physics motivation

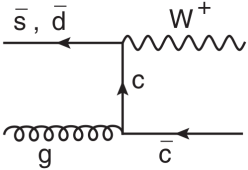
- Measurements of V + heavy-flavor (b, c) jets (V+HF jets) are important to test the electroweak & pQCD predictions
- Good opportunity to be compared against different hadronization-fragmentation processes
- It also provides information on the strange, bottom and charm quark parton distribution functions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



Z + 1 b jet



Z + 1 c jet



W^+ + 1 c jet

- Cross section measurements of W+c jet in pp collisions with the CMS experiment at 13 TeV [CMS-SMP-17-014 click here]
- 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 click here]
- Cross section measurements of Z+c jet in pp collisions with the CMS experiment at 13 TeV [CMS-SMP-19-011 click here]

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: $c \rightarrow D^{*\pm} \rightarrow D^0 + \pi^{\pm}_{slow} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$

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

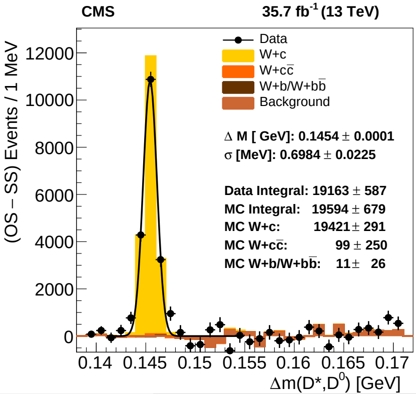
Muon(μ): $p_T > 26$ GeV, $|\eta| < 2.4$

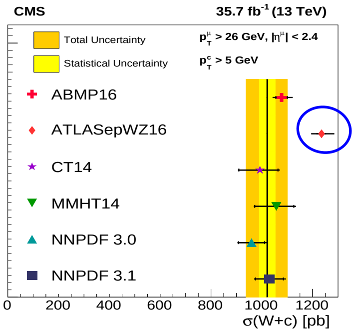
Transverse mass (M_T): ≥ 50 GeV, $[M_T := \sqrt{2.p_T^{\mu}.E_T^{miss}.(1 - cos(\phi_{\mu} - \phi_{E_T^{miss}}))}]$

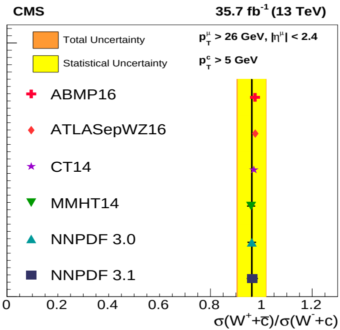
D^0: $p_T^{K,\pi} > 1$ GeV, $|K^{\mp}+\pi^{\pm}$- $D^0_{pdg}| < 35$ MeV, $K^{\mp}+\pi^{\pm}$ must originate from Secondary vertex,

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







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- 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.

	σ(W+c)	$\sigma(W^+ + c)/\ \sigma(W^- + c)$
Measured	$1026 \pm 31\ (\text{stat})^{+76}_{-72}\ (\text{syst})$	$0.968 \pm 0.055\ (\text{stat})^{+0.015}_{-0.028}\ (\text{syst})$.
ABMP16nlo	1077.9 pb $\pm\ 2.1\%(\text{pdf})^{+3.4\%}_{-2.4\%}(\text{scale})$	$0.975^{+0.002}_{-0.002}$
ATLASepWZ16nnlo	1235.1 pb $^{+1.4\%}_{-1.6\%}(\text{pdf})^{+3.7\%}_{-2.8\%}(\text{scale})$	$0.976^{+0.001}_{-0.001}$
CT14nlo	992.6 pb $\pm\ ^{+7.2\%}_{-8.4\%}(\text{pdf})^{+3.1\%}_{-2.1\%}(\text{scale})$	$0.970^{+0.005}_{-0.007}$
MMHT14nlo	1057.1 pb $\pm\ ^{+6.5\%}_{-8.0\%}(\text{pdf})^{+3.2\%}_{-2.2\%}(\text{scale})$	$0.960^{+0.023}_{-0.033}$
NNPDF3.0nlo	959.5 pb $\pm\ 5.4\%(\text{pdf})^{+2.8\%}_{-1.9\%}(\text{scale})$	$0.962^{+0.034}_{-0.034}$
NNPDF3.1nlo	1030.2 pb $\pm\ 5.3\%(\text{pdf})^{+3.2\%}_{-2.2\%}(\text{scale})$	$0.965^{+0.043}_{-0.043}$

Z(ll) + >= 1 c jet cross section at 13 TeV

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

Muon(μ): $p_T(l_1/l_2) > 26/10$ GeV, $|\eta(l_1/l_2)| < 2.4$

Electron(e): $p_T(l_1/l_2) > 29/10$ GeV, $|\eta(l_1/l_2)| < 2.4$, $1.4442 < |\eta_{SC}| < 1.556$

Z(ll): $71 < M_{ll} < 111$ GeV, $|\eta(ll)| < 2.4$

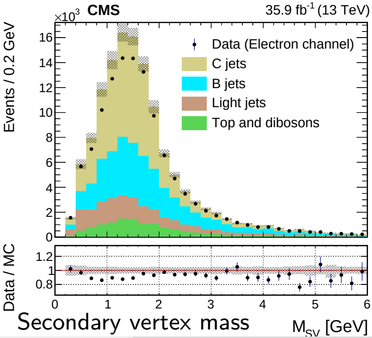
jets: $p_T > 30$ GeV, $|\eta(jet)| < 2.4$, pileup jet id (to remove pileup) > -0.89

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 processess

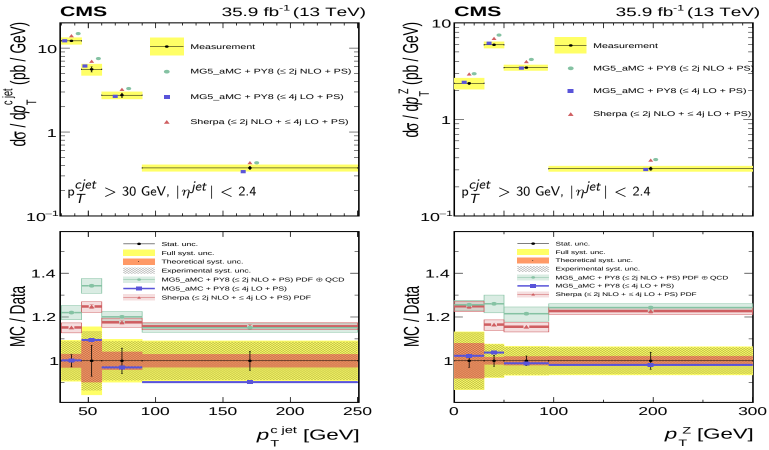
Z+b jets, Z+light jets extracting by fitting templates of secondary vertex mass distribution obtained from Drell-Yan simulation

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



Secondary vertex mass

Results: Z(ll) + >= 1 c jet cross section



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Integral cross section Z(ll) + c jet

Measured (Data)	**405.4±5.6(stat)±24.3(exp)±3.7(th) pb**
MG5_aMC (NLO Prediction)	**524.9 ± 11.7(th) pb**
SHERPA (NLO Prediction)	**485.0 pb**

MG5_aMC(LO) are describing well differential cross section distribution of p_T^{ll} & p_T^{cjet} 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

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

Muon(μ): $p_T(l_1/l_2) >$ 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

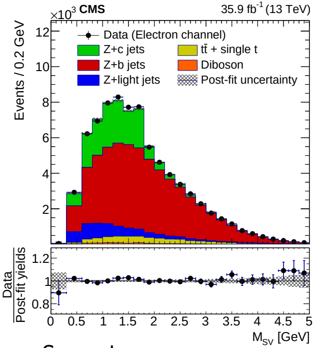
jets particle(parton)-level: $p_T > 30(15)$ GeV, $|\eta(jet)| < 2.4$

HF jets: deepCSV medium b-tag discriminator > 0.8484, [deepCSV: combined tracks and secondary vertex characteristics using machine learning techniques]

Background processess

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



Secondary vertex mass

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

	Measured (Data)	MG5_aMC (NLO, FxFx)	MG5_aMC(LO, MLM)
R(c/j)	0.102 ± 0.002(stat)±0.009(syst)	0.111 ± 0.003(pdf)$^{+0.010}_{-0.011}$(scale)	0.103 ± 0.003(pdf)$^{+0.028}_{-0.026}$(scale)
R(b/j)	0.0633 ± 0.0004(stat)±0.0015(syst)	0.067 ± 0.002(pdf)±0.006(scale)	0.062 ± 0.002(pdf)$^{+0.018}_{-0.015}$ (scale)
R(c/b)	1.62 ± 0.03(stat)±0.15(syst)	1.64 ± 0.05(pdf)$^{+0.15}_{-0.16}$(scale)	1.67 ± 0.06(pdf)$^{+0.54}_{-0.40}$(scale)

- 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)

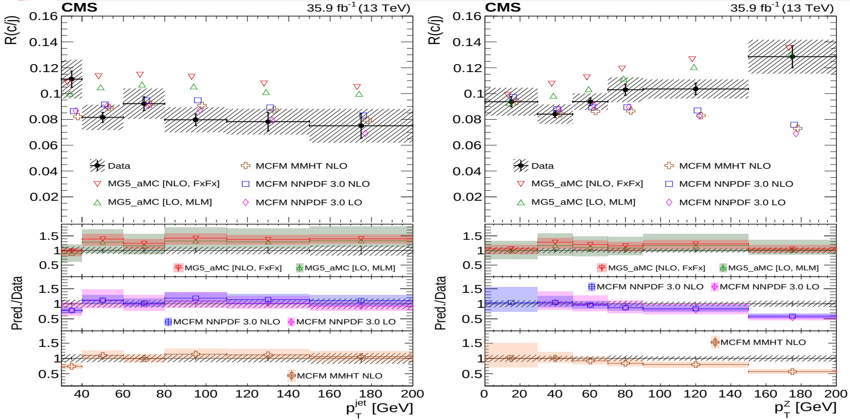
Cross section ratio at parton-level in fiducial volume $p_T^{HF\ jet} > 15$ GeV & $|\eta^{HF\ jet}| < 2.4$

	MCFM (NLO)	MCFM(LO)
R(c/j)	0.090 ± 0.003(pdf)$^{+0.010}_{-0.012}$($^{+0.008}_{-0.007}$)(scale)	0.087 ± 0.003(pdf)$^{+0.025}_{-0.022}$(scale)
R(b/j)	0.068 ± 0.002(pdf)$^{+0.008}_{-0.011}$(±0.006)(scale)	0.071 ± 0.002(pdf)$^{+0.023}_{-0.021}$ (scale)
R(c/b)	1.33 ± 0.04(pdf)$^{+0.16}_{-0.21}$($^{+0.10}_{-0.12}$)(scale)	1.20 ± 0.04(pdf)$^{+0.42}_{-0.38}$(scale)

- 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(ll) + >= 1 c jet/Z(ll) + >= 1 jet



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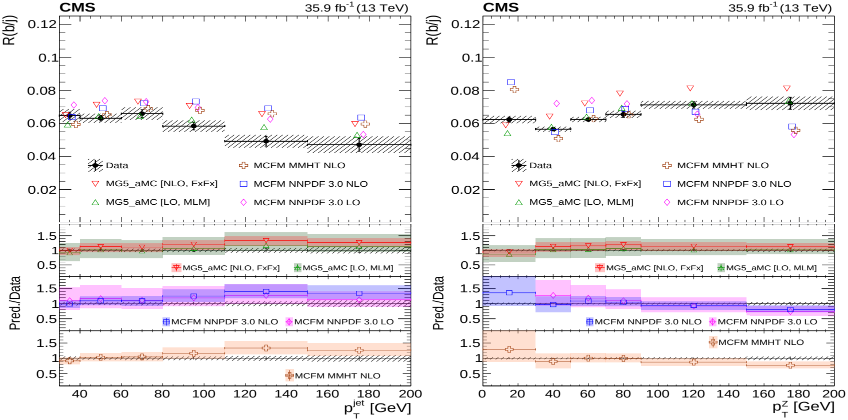
MG5_aMC(LO) prediction → describing well within 10% while MG5_aMC(NLO) deviate upto 20−30%. MCFM(pdf:NNPDF3.0), MCFM(pdf:MMHT14) predictions → at NLO & LO describing well R(c/j) except in higher p_T^{ll}

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 $Z(ll) + >= 1$ b jet$/Z(ll) + >= 1$ jet



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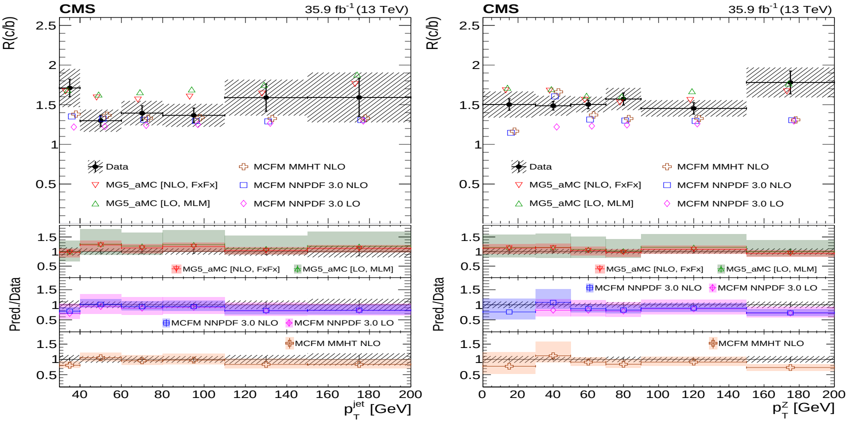
All MC: MG5_aMC, MCFM(pdf: NNPDF 3.0), MCFM(pdf: MMHT14) at NLO & LO prediction are describing well both distribution within 10%, except higher p_T^{jet} and p_T^{ll} where prediction at NLO tend to deviate upto 20−30% .

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 $Z(ll) + >= 1$ c jet/$Z(ll) + >= 1$ b jet



PRD 102 (2020) 032007

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^{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 ATLASepWZ16 prediction W+c cross section

- Cross section Z(ll)$+ >= 1$ c jet:

  Z(ll) $+ >= 1$ 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).

Thank You

Backup

Jets:

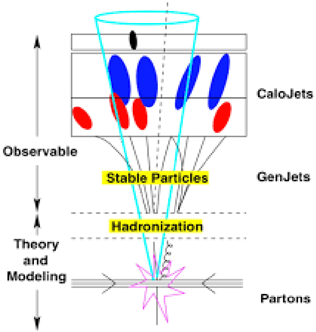
- Due to color confinement of parton (quark & gluon), hadronization takes place & produces colorless hadrons in cones of outgoing particles called jets

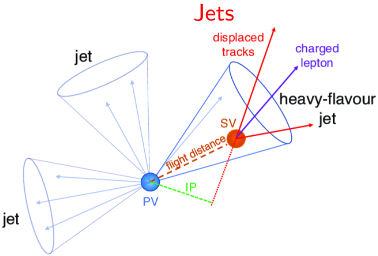
b/c Jets:

- 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