



Experimental measurement of Heavy Flavors and jets

Meena (On behalf of ALICE, ATLAS, CMS & LHCb collaboration)

LHCP2021: 9th Edition of the Large Hadron Collider Physics Conference

9th June, 2021





Outline



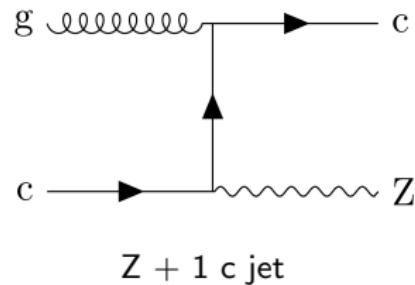
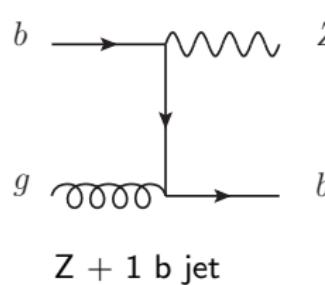
- $Z(\text{II}) + \geq 1 \text{ b/c jets, } b\bar{b}\text{- \& } c\bar{c}\text{-dijet:}$
 - Motivation
 - Cross section measurements of $b\bar{b}\text{- \& } c\bar{c}\text{-dijet}$ @ 13 TeV LHCb
 - Cross section measurements $Z(\text{II}) + \geq 1 \text{ c jets}$ @ 13 TeV CMS
 - Cross section ratio measurements $Z(\text{II}) + \geq 1 \text{ b/c jets}$ @ 13 TeV CMS
 - Cross section measurements $Z(\text{II}) + \geq 1 \text{ b jets}$ @ 13 TeV ATLAS
- J/ψ meson:
 - Study of J/ψ meson production inside jets at @8 TeV CMS
 - J/ψ production in jets @ 13 TeV LHCb
 - J/ψ and $\psi(2s)$ production in jets @ 13 TeV ATLAS
- Groomed jet substructure measurements of charm jets tagged with D^0 mesons @ 13 TeV ALICE
- Summary



Physics motivation



- Measurements heavy-flavor(b , c) jets & jets are important to test the electroweak & pQCD predictions
- $V + \text{HF}$ jets study at particle- & parton-level is good opportunity to be compared against different hadronization-fragmentation processes
- $V + \text{HF}$ jets also provides information on the strange, bottom and charm quark parton distribution functions(PDFs)
- $V + \text{HF/jets}$ are important background in many SM processes and BSM searches



Results: $b\bar{b}$ - and $c\bar{c}$ -dijet cross section at 13 TeV LHCb

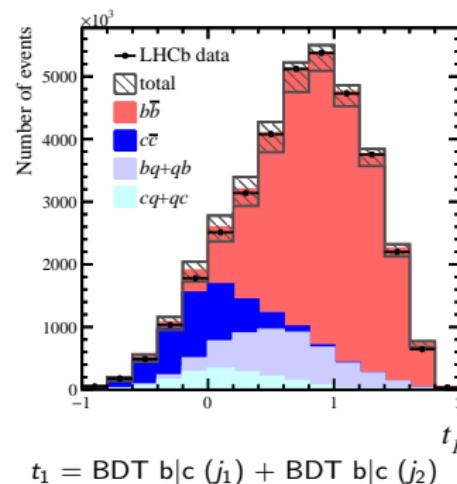
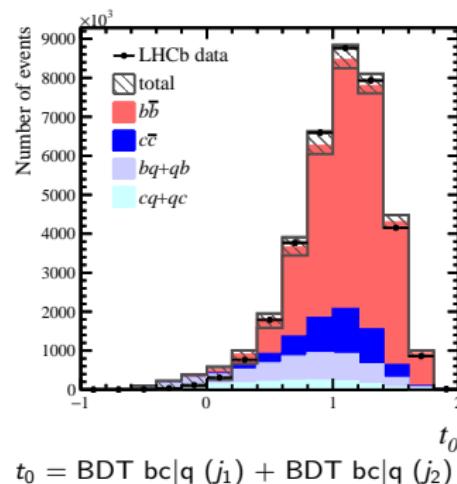
Event selection: $b\bar{b}$ - & $c\bar{c}$ -dijet

Jet(μ): $p_T(j_1/j_2) > 20 \text{ GeV}$, $2.2 < \eta(j_1/j_2) < 4.2$, $|\Delta\phi| > 1.5$

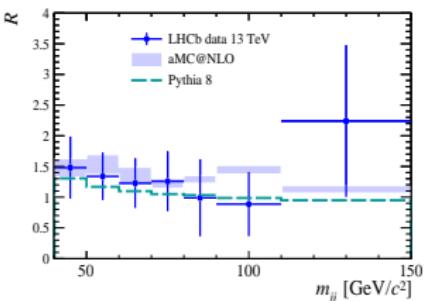
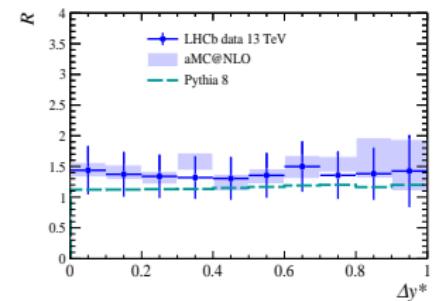
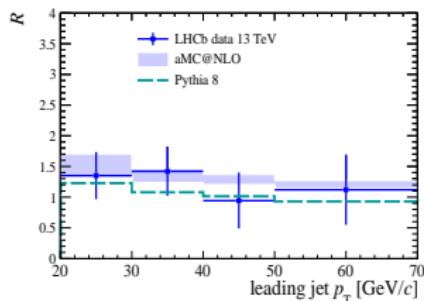
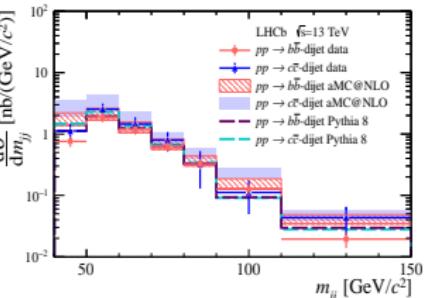
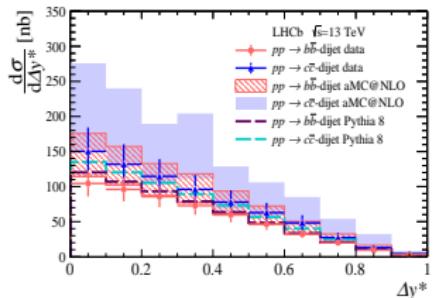
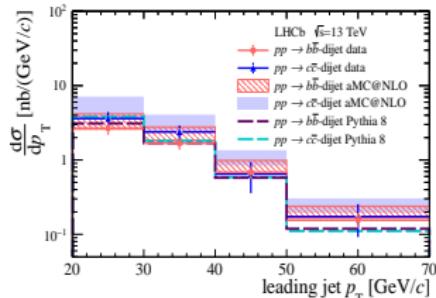
HF jets: Boosted decision tree(BTD) \rightarrow $\text{BDT}_{bc|q}$ (heavy-/light-jet separation) and $\text{BDT}_{b|c}$ (b -/ c -jet separation) ($q=u,d,s,g$) [BTD: used to discrimination between b , c , & light-parton jets]

Signal and background yield extraction:

- $b\bar{b}$, $c\bar{c}$, $bb\bar{q}$, $cc\bar{q}$ & qq' extracting by fitting templates of BTD distribution t_0 & t_1 obtained from simulation



Results: $b\bar{b}$ - & $c\bar{c}$ -dijet cross section at 13 TeV LHCb



- Diff cross section: Measurements are compared to the MC@NLO(NLO) and pythia(LO), are generally slightly below the predictions.

- Ratio: Measurements are compatible with the prediction within its uncertainties. **JHEP 02 (2021) 023**

	Measured	MC@NLO
$\sigma(b\bar{b})$ [nb]	$53.0 \pm < 0.1(\text{stat}) \pm 9.5(\text{stat+syst}) \pm 2.1(\text{lumi})$	$70.2^{+15.1}_{-14.7}(\text{scale})^{+1.4}_{-1.4}(\text{pdf})$
$\sigma(c\bar{c})$ [nb]	$72.6 \pm < 0.1(\text{stat}) \pm 16.1(\text{stat+syst}) \pm 2.9(\text{lumi})$	$97.9^{+34.5}_{-27.5}(\text{scale})^{+1.8}_{-1.8}(\text{pdf})$
$R \sigma(c\bar{c})/\sigma(b\bar{b})$	$1.37 \pm < 0.01(\text{stat}) \pm 0.27(\text{stat+syst})$	$1.39 \pm ^{+0.16}_{-0.13}(\text{scale})^{+0.03}_{-0.03}(\text{pdf})$

Event Selection:

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

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

Z(II) + ≥ 1 c jet: c jets \rightarrow deepCSV tight c-tag discriminators: CvsL > 0.59 & CvsB > 0.05

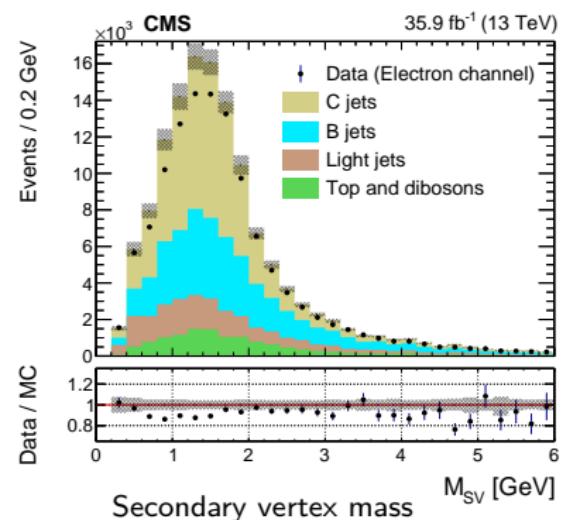
Z(II) + ≥ 1 HF jets: particle(parton)-level jets: $p_T > 30(15)$ GeV, MET < 40 GeV

b jets \rightarrow deepCSV medium b-tag discriminator > 0.8484

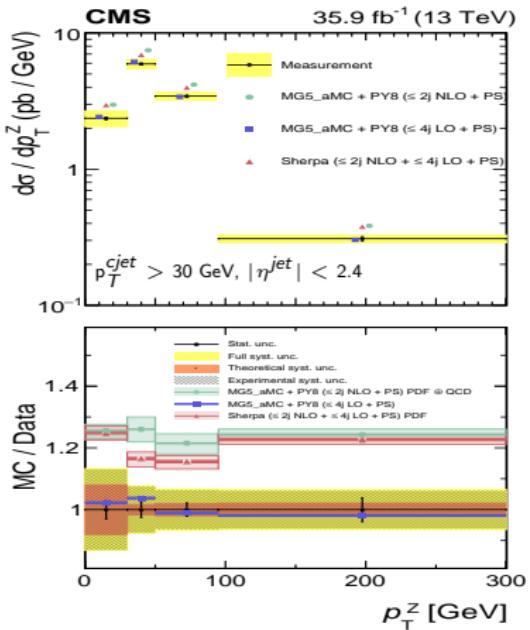
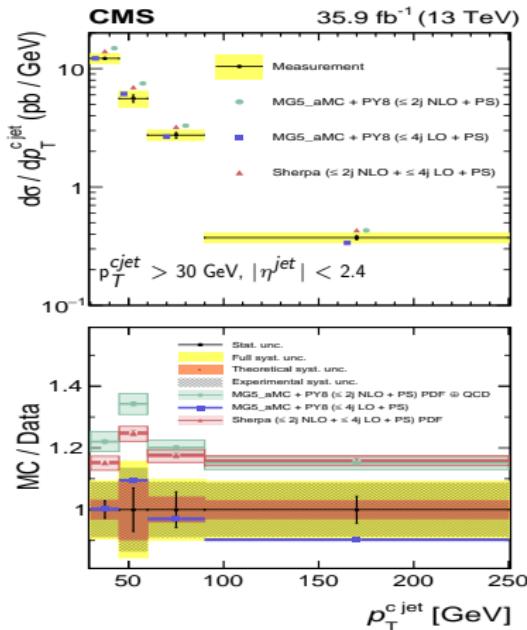
[deepCSV: combined tracks & secondary vertex characteristics using machine learning techniques]

Background estimation:

- Z+b jets/Z+c jet, Z+light jets extracting by fitting templates of secondary vertex mass distribution obtained from Drell-Yan simulation for Z+c jet analysis & validated with different data driven methods for Z+HF-jets analysis



Results: $Z(\text{II}) + \geq 1 \text{ c jet}$ cross section at 13 TeV CMS



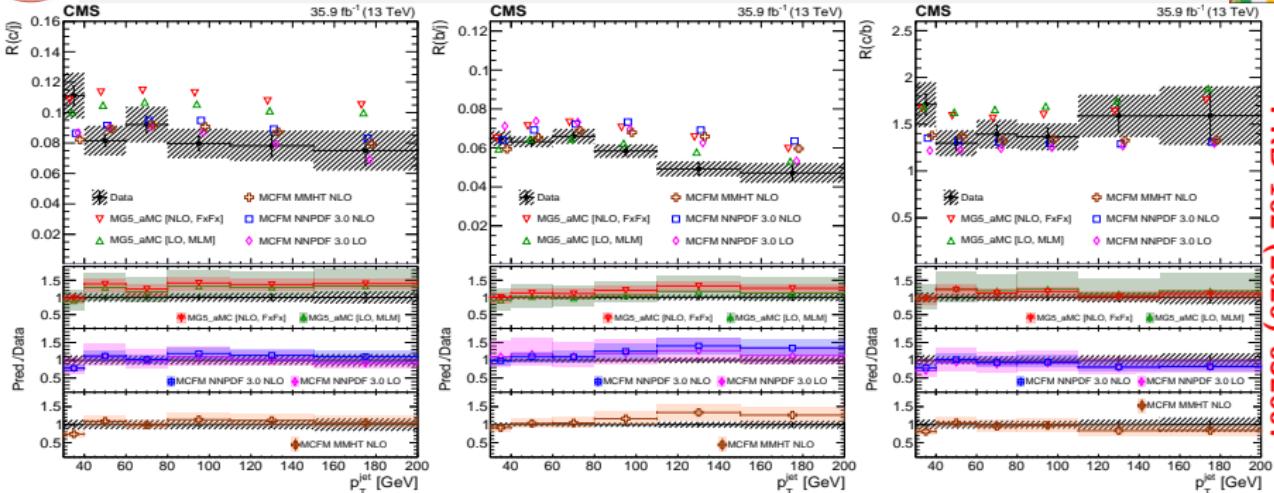
Integral cross section $Z(\text{II}) + \text{c jet}$

Measured (Data)	$405.4 \pm 5.6 (\text{stat}) \pm 24.3 (\text{exp}) \pm 3.7 (\text{th}) \text{ pb}$
MG5_aMC (NLO Prediction)	$524.9 \pm 11.7 (\text{th}) \text{ pb}$
SHERPA (NLO Prediction)	485.0 pb

MG5.aMC(LO) are describing well differential cross section distribution of p_T^Z & $p_T^{c\text{jet}}$ 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

Results: cross section ratio $Z(\text{II}) + \geq 1 \text{ b/c jet}/Z(\text{II}) + \geq 1 \text{ jet}$ at 13 TeV CMS

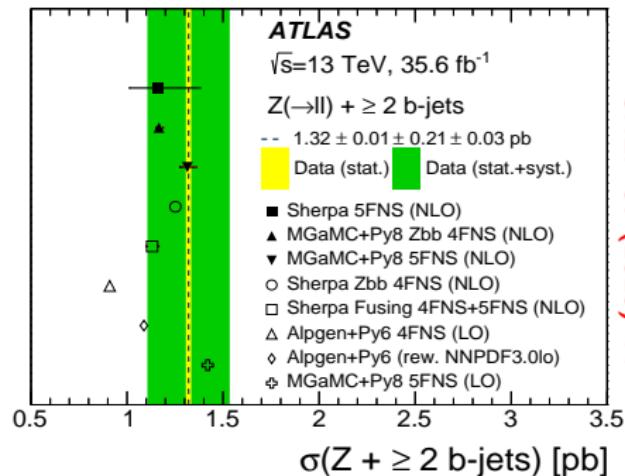
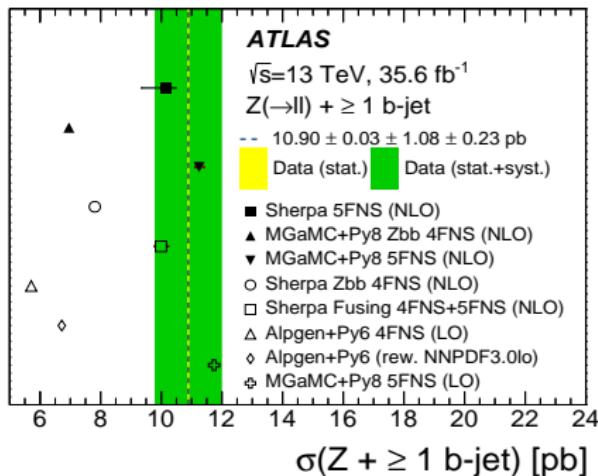


$R(c/j)$: MG5_aMC(LO) prediction \rightarrow describing well within 10% while MG5_aMC(NLO) deviate upto 20–30%. MCFM(pdf:NNPDF3.0), MCFM(pdf:MMHT14) \rightarrow at NLO & LO describing well

$R(b/j)$: All MC at NLO & LO prediction are describing well both distribution within 10%, except higher p_T^{jet} where prediction at NLO tend to deviate upto 20–30%

$R(c/b)$: 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}

Conclusion: MG5_aMC(NLO) prediction pdf overestimate the b/c quark content and will be useful in improving the existing constraints in simulation of the b/c quark pdf



The 5FNS simulations adequately predict the inclusive cross-sections for both $Z + \geq 1 \text{ b-jet}$ & $Z + \geq 2 \text{ b-jets}$

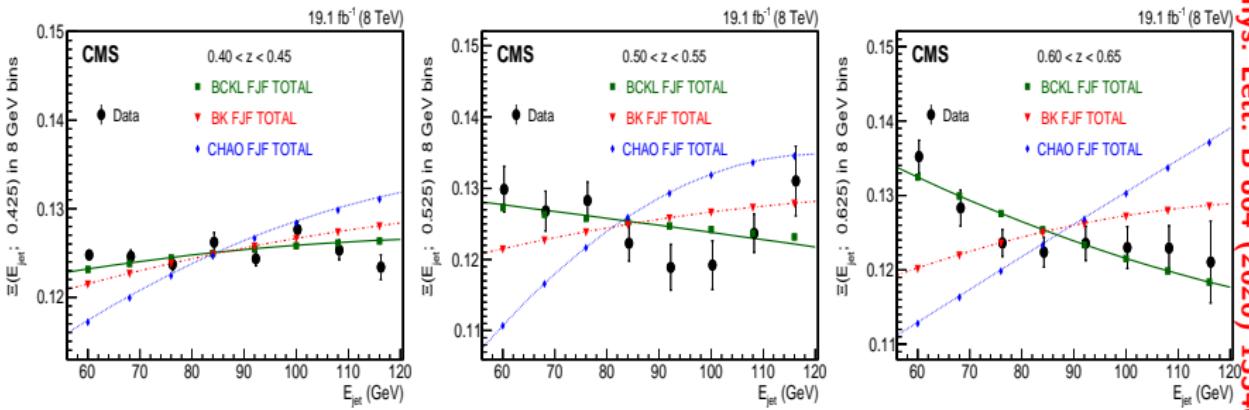
4FNS MC predictions are systematically lower than data in $Z + \geq 1 \text{ b-jet}$ case but agree with data in $Z + \geq 2 \text{ b-jets}$

Use of the NNPDF3.0lo PDF set in Alpgen predictions gives better agreement with data because of a higher acceptance in the fiducial region as compare to Alpgen+Py6 4FNS (LO)

The Sherpa Fusing 4FNS+5FNS (NLO) simulation (combines 4FNS with 5FNS) agrees with Sherpa 5FNS (NLO), showing that effects of merging are minor

Results: Study of J/ψ meson production inside jets at 8 TeV CMS

- Fragmenting jet function(FJF) model: $c\bar{c}$ pair is not produced directly in the hard scattering, but is a fragmentation product of a high- p_T jet & it uses NRQCD(includes both color-singlet &-octet amplitudes for $c\bar{c}$ that ultimately produces the J/ψ).
- BCKI, BK, Chao: decompose fragmentation function for gluon jets in terms of NRQCD amplitudes and long-distance matrix elements(LDME)= ${}^1s_0^{(8)}, {}^3s_1^{(8)}, {}^3s_0^{(1)}, {}^3s_J^{(8)}$
- Event selection $J/\psi \rightarrow \mu\mu$ & at least one jet:**
- J/ψ : energy > 15 GeV, $|y_{J/\psi}| < 1$, $p_T > 10$ GeV, $|\eta_{J/\psi}| < 1.01$
- jet: $p_T > 25$ GeV, $|\eta(\text{jet})| < 1$



Phys. Lett. B 804 (2020) 135409

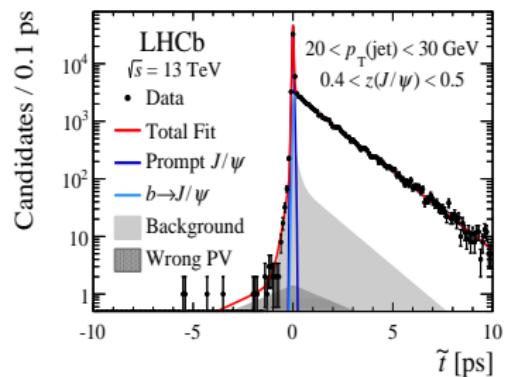
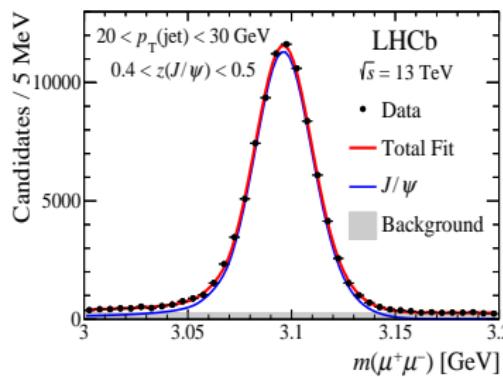
- $\Xi(E_c; z_1)$ = shape of the measured diff. cross section for J/ψ meson production as a jet constituent is compared to the FJF prediction for z , using 3 different LDME parameter sets.
- BCKL LDME match the data for all 3 z ranges while BK, Chao disagree for all 3 z ranges.
- BCKL LDME: constructed using inclusive hadronic production data with $p_T^{J/\psi} > 10$ GeV

Motivation:

- J/ψ production occurs at the transition between the perturbative and non-perturbative regimes of(QCD), not fully understood yet
- Prediction (J/ψ are largely produced isolated except for any soft gluonic radiation & underlying) can be tested by the calculation of J/ψ production within jets using parton shower of a MC event generator

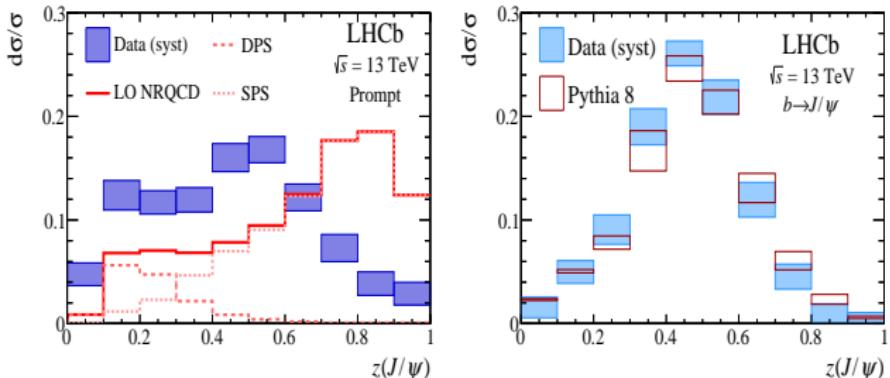
Event selection:

- $J/\psi \rightarrow \mu\mu$: $p_T(\mu_1/\mu_2) > 5(0.5)$ GeV, $2 < \eta(\mu)/(J/\psi) < 4.5$
- Jet(j): $p_T(j) > 20$ GeV, $2.5 < \eta(j) < 4$



- Left: Yield of $J/\psi \rightarrow \mu\mu$ (prompt & b-hadron decays) in each bin, determined by fitting unbinned maximum likelihood fit of $m_{\mu\mu}$
- Right: Fraction of J/ψ that originates from b-hadron decays determined by fitting pseudo-decay-time(\tilde{t})

Results: J/ψ production in jets at 13 TeV LHCb



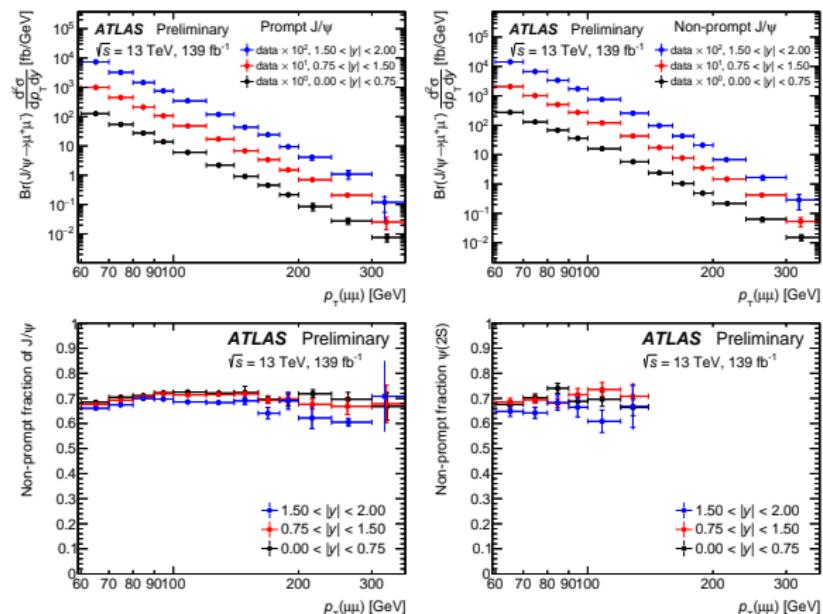
- Measurements are compared to the pythia, the prompt- J/ψ results do not agree with predictions, while b-hadron decays is consistent(Uncert: b-quark fragmentation)
- PYTHIA8 → predictions based on fixed-order NRQCD implemented in PYTHIA8
- prompt- J/ψ → at small $z(J/\psi)$ → Pythia 8 predicts that most of $p_T(\text{jet})$ arises from a parton-parton scatter other than the one that produced the J/ψ meson.
- Conclusion: Prompt J/ψ mesons in data are much less isolated than predicted, Lack of isolation in data may be related to long-standing quarkonium polarization puzzle
- Solution: If high- p_T J/ψ mesons are predominantly produced within parton showers, rather than directly in parton-parton scattering, then the observed lack of both polarization and isolation could be explained

1st measurement of the p_T fraction carried by prompt J/ψ in jets at any experiment!

Event selection $J/\psi(\psi(2s)) \rightarrow \mu\mu$:

- Muon(μ): $p_T(\mu_1/\mu_2) > 52.5(4)$ GeV, $|\eta(\mu)| < 2.4$
- $J/\psi(\psi(2s))$: $60 \leq p_T(j) < 360(140)$ GeV, $|y(j)| < 2$
- pseudo-proper decay time (τ) = $m_{\mu\mu} L_{xy}/p^{\mu\mu} \tau$ c, L_{xy} = transverse dist. b/w PV & $\mu\mu$ vertex
- Prompt & non-prompt yields of J/ψ and $\psi(2s) \rightarrow \mu\mu$ fit is performed in range $2.6 \leq m_{\mu\mu} \leq 4.2$ GeV & $-1 \leq \tau \leq 11$ ps.

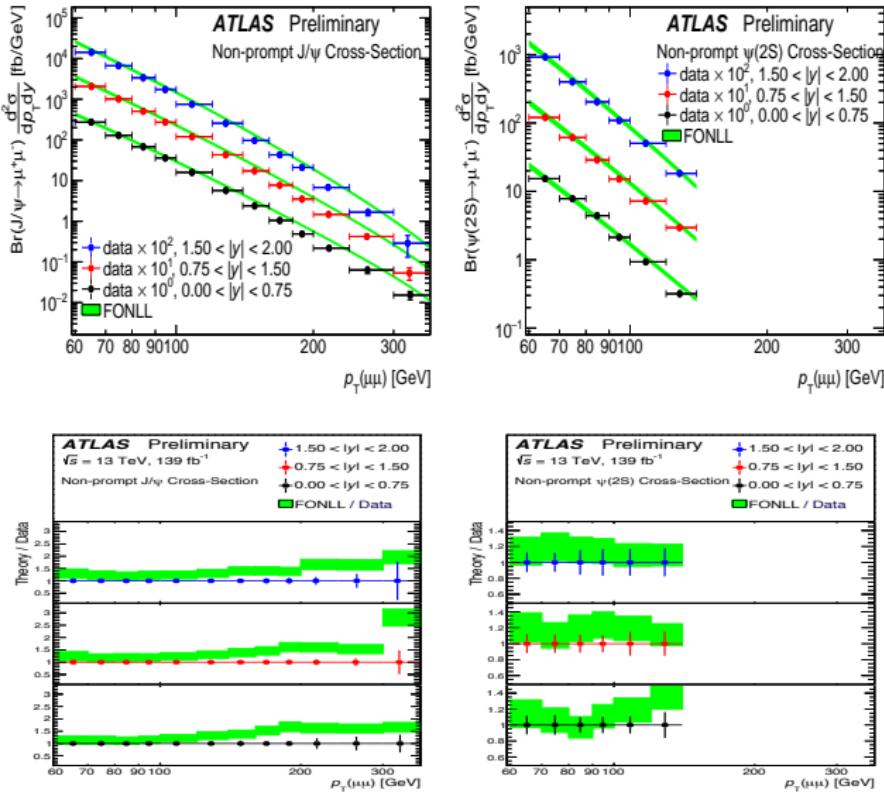
- Similar p_T -dependence for prompt and non-prompt differential cross sections



ATLAS-CONF-2019-047

Results: J/ψ and $\psi(2s)$ production in jets at 13 TeV ATLAS

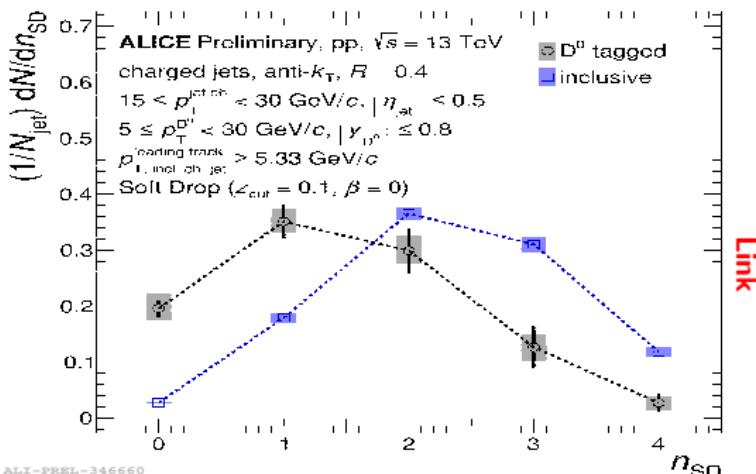
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- Non-prompt: Measurements are compared with the FONLL model, FONLL shows good comparison at lower p_T , but somewhat higher cross-sections at high- p_T

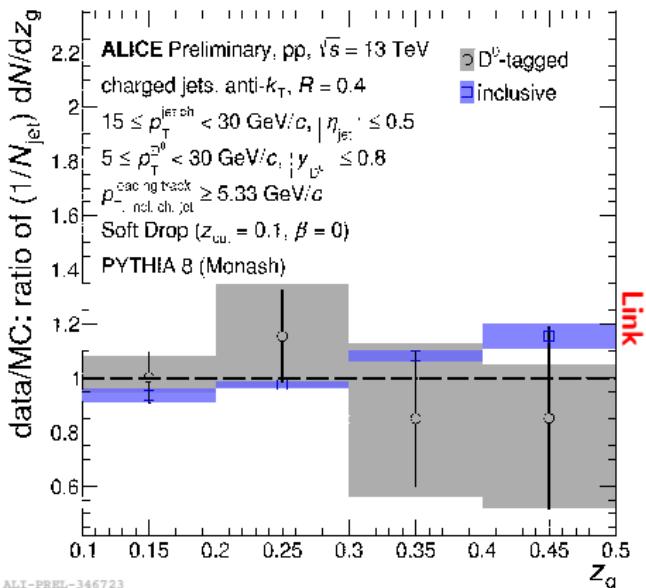
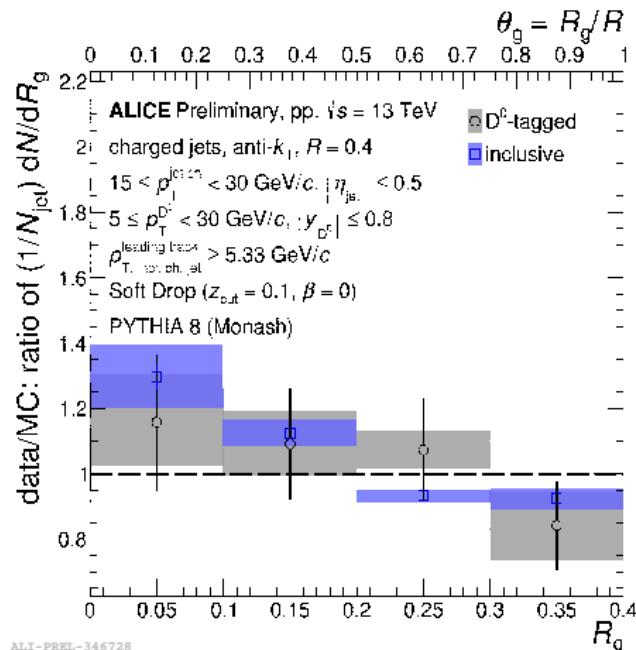
Results: Groomed jet substructure measurements of charm jets tagged with $D^0(\rightarrow K^-\pi^+)$ mesons at 13 TeV ALICE

- Motivation: clean tool for studying parton fragmentation, differences between quark and gluon fragmentation
- Groomed jet: Find the widest hard jet splitting by declustering and following the hardest branches.
 - Get subjets SJ1, SJ2: $p_T^{SJ1} \geq p_T^{SJ2}$
 - Test the Soft Drop condition ($z_{cut} = 0.1$, $\beta = 0$): Only splittings where the subleading prong carries at least 10% of the combined transverse momentum are accepted.
 - $z = \frac{p_T^{SJ2}}{p_T^{SJ1} + p_T^{SJ2}} \geq z_{cut} \left(\frac{\Delta R_{1,2}}{R_{jet}} \right)^\beta$, if condition met: $z_g = z$, $R_g = \Delta R_{1,2}$, $n_{SD} += 1$, else: decluster SJ1 and test again, $n_{SD} \rightarrow$ number of splittings satisfying the grooming jet
- n_{SD} with the distributions shifted to smaller values of n_{SD} for the D^0 -tagged jets, indicates that the fragmentation of the charm quark is hard throughout the showering procedure.





Results: Groomed jet substructure measurements of charm jets tagged with $D^0(\rightarrow K^-\pi^+)$ mesons at 13 TeV ALICE



- The PYTHIA simulations describing the data qualitatively well for all measured observables.



Summary



- Cross section $Z(\text{II}) + \geq 1 \text{ b/c jet}(\text{CMS \& ATLAS}), b\bar{b}\text{-\& } c\bar{c}\text{-dijet(LHCb)}$:
 - These study will be useful in improving the the existing constraints in simulation of the b/c quark pdf
- Study of J/ψ meson production inside jets at 8 TeV CMS: BCKL LDME: not only describes the production of high- p_T J/ψ mesons as constituents of jets but also predicts small J/ψ meson polarization
- J/ψ production in jets at 13 TeV LHCb: Data agree with pythia prediction in b-hadron decays, but prompt- J/ψ results do not agree may be due to lack isolation in data, which related to long-standing quarkonium polarization puzzle
- J/ψ and $\psi(2s)$ production in jets at 13 TeV ATLAS: Non-prompt → FONLL shows good comparision with measurements at lower p_T , but somewhat higher cross-sections at high- p_T
- Groomed jet substructure measurements of charm jets tagged with D^0 mesons at 13 TeV ALICE: indicates that the fragmentation of the charm quark is hard throughout the showering procedure

Thank You



W+c cross section at 13 TeV



- W+c cross sections are measured in the muon channel
- c quarks are identified 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: $W(\rightarrow \mu\bar{\nu}) + D^*(2010)^\pm \rightarrow \mu\nu + D^0 + \pi_{slow}^\pm \rightarrow \mu\bar{\nu} + K^\mp\pi^\pm\pi_{slow}^\pm$

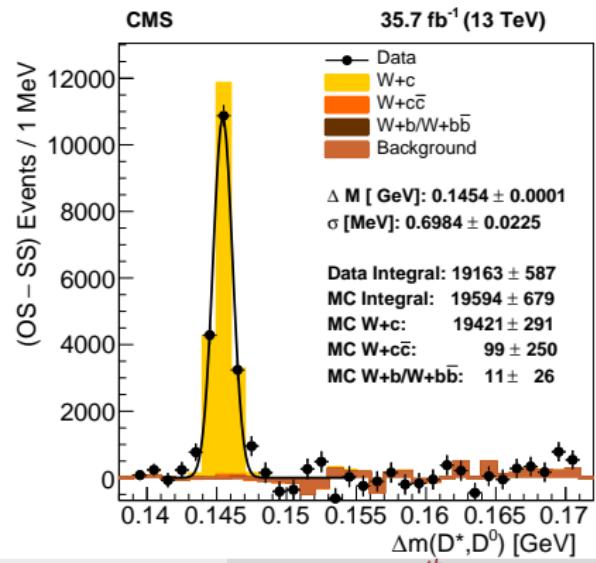
Muon(μ): $p_T > 26$ GeV, $|\eta| < 2.4$

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

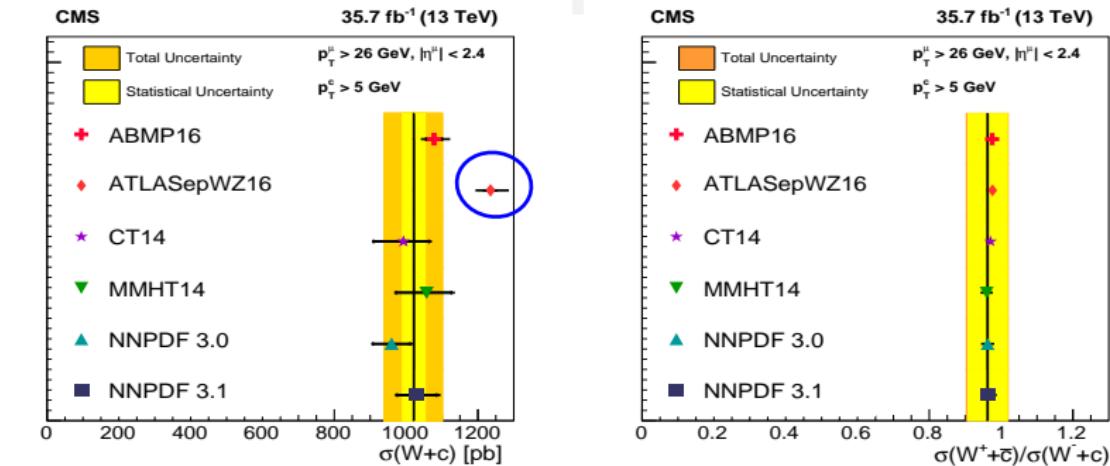
D^0 : $p_T^{K,\pi} > 1$ GeV, $|K^\mp + \pi^\pm - D_{pdg}^0| < 35$ MeV, $K^\mp + \pi^\pm$ must originate from Secondary vertex,

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

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

Identification of b/c jets via secondary vertex mass

Jets:

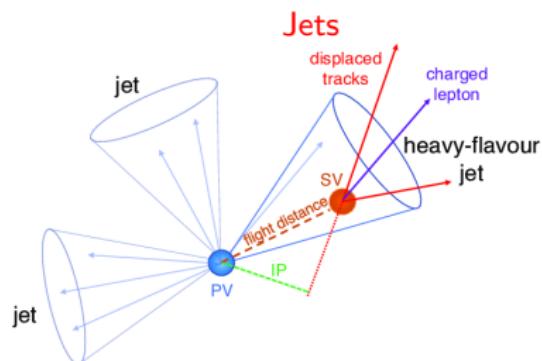
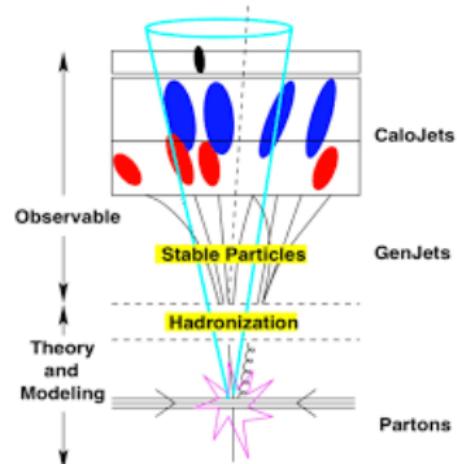
- Due to color confinement of parton (quark & gluon), hadronization takes place & produces colorless hadrons in cones of outgoing particles called jets

b/c Jets:

- Initiated by b-quark/c-quark with characteristic lifetime($1.5/1.1$ ps) of b/c hadron, will travel ~ 1 cm(at energy in the lab frame $\sim 10\text{-}100$ 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





Result: Z(II) + ≥ 1 HF jet cross section ratio



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

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

- 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)

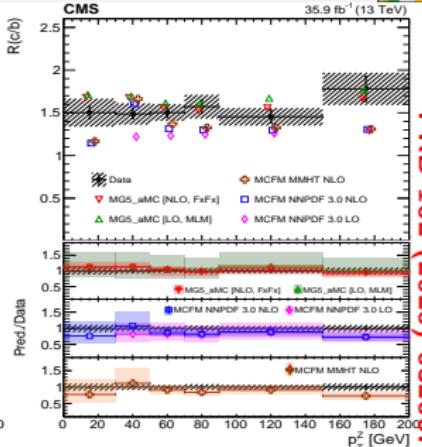
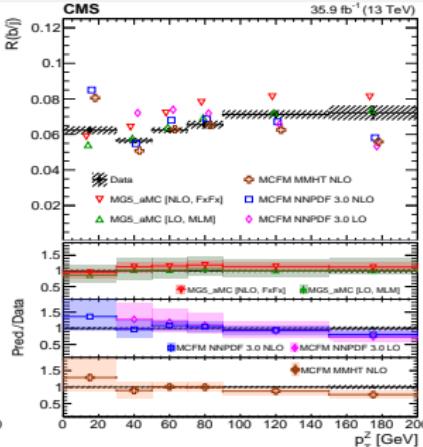
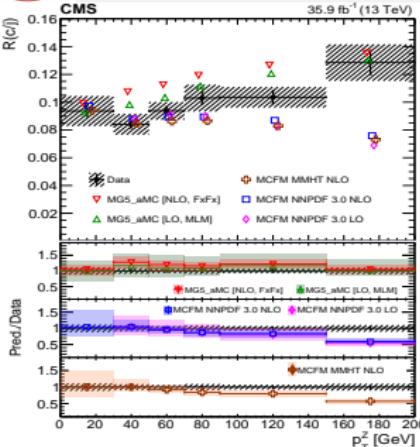
Cross section ratio at parton-level in fiducial volume $p_T^{HF\ jet} > 15 \text{ GeV}$ & $|\eta^{HF\ jet}| < 2.4$

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

- 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

Results: cross section ratio $Z(\text{II}) + \geq 1 \text{ c jet}/Z(\text{II}) + \geq 1 \text{ jet}$



$R(c/j)$: 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^{jet}

$R(b/j)$: 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% .

$R(c/b)$: 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}

Conclusion: MG5_aMC(NLO) prediction pdf overestimate the b/c quark content and will be useful in improving the existing constraints in simulation of the b/c quark pdf