Beauty production with ALICE

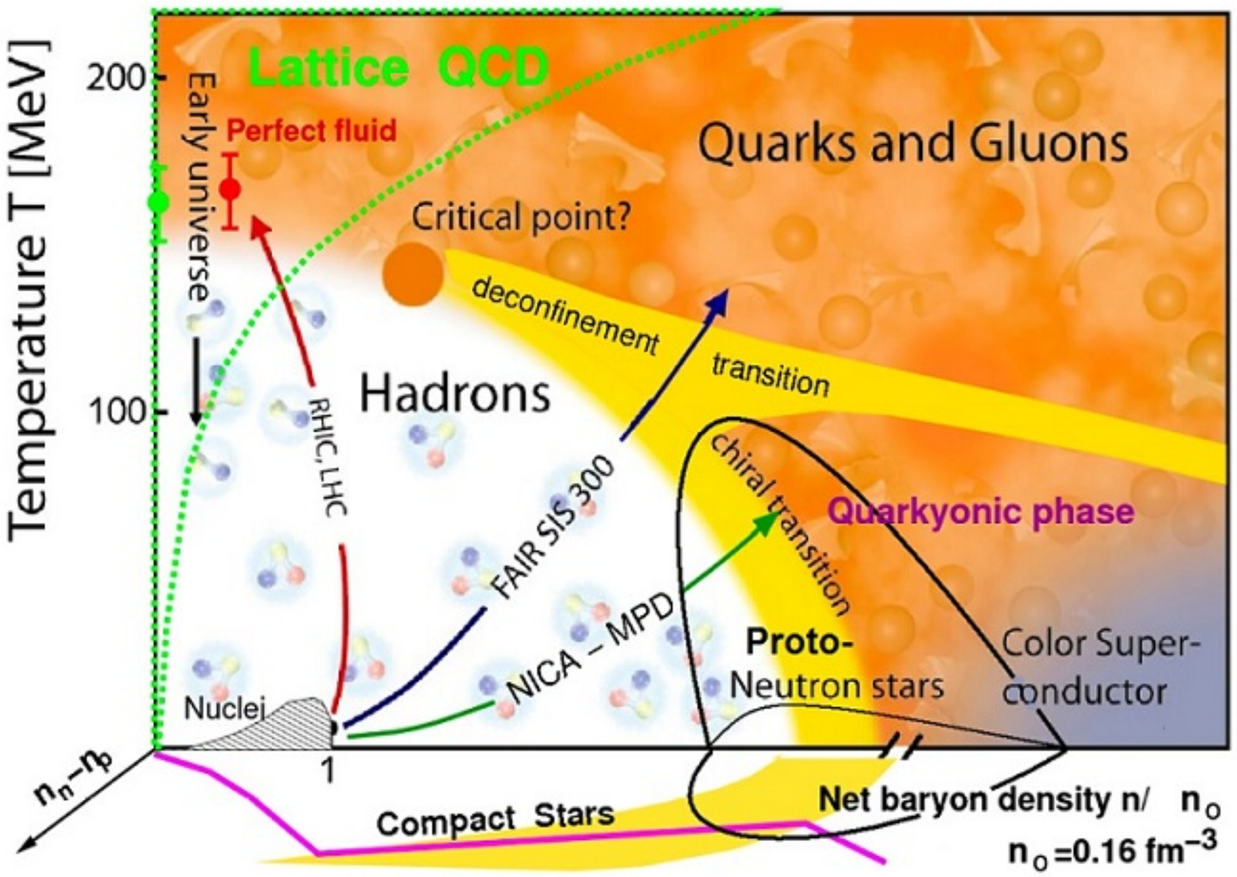
The 8th Asian Triangle Heavy-Ion Conference

2021 Nov 7

Jonghan Park

on behalf of ALICE Collaboration

Goal of ALICE experiment : quark-gluon plasma (QGP)



- Investigate a nuclear matter at extreme conditions of temperature and energy density
  - quark-gluon plasma : deconfined state of matter
  - lattice QCD predicts $T_c \sim 150$ MeV[1] and $\varepsilon_c \sim 0.5$ GeV·fm^{-3} [2]

[1] S. Borsányi et al. JHEP 09 (2010) 073

[2] F. Karsch, J. Phys. Conf. Ser 46 (2006) 122—131

- QGP can be produced in ultra relativistic heavy-ion collisions

Why heavy quarks are important

Heavy quarks (charm and beauty) : produced in initial hard scattering processes

In heavy-ion collisions

- Interact with medium constituents via collisional and radiative processes
- Evaluated by nuclear modification factor (R_{AA})
  - Mass dependence of the in-medium energy loss
  - Hadronization mechanism in the medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

In pp collisions,

- Test of pQCD calculations at the LHC energies

$$\sigma^{\mathrm{hard}}_{AB\to h} = \mathrm{PDF}(x_a, Q^2)\mathrm{PDF}(x_b, Q^2) \otimes \sigma^{\mathrm{hard}}_{ab\to c}(x_a, x_b, Q^2) \otimes D_{c\to h}(z_q, Q^2) \qquad \textit{factorization theorem}$$

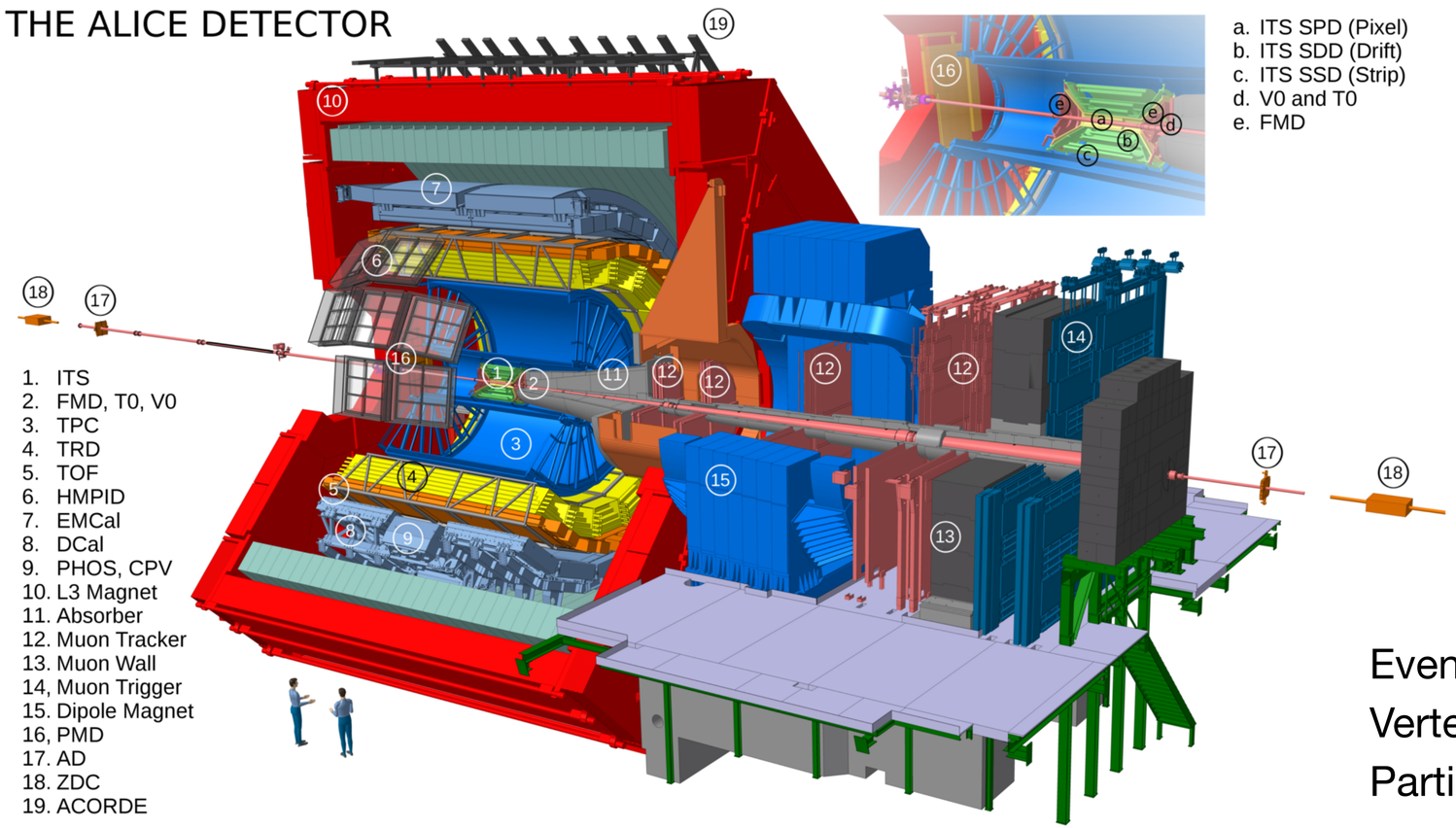
- Reference for measuring nuclear modifications

In p+Pb collisions,

- Cold Nuclear Matter (CNM) effects

A Large Ion Collider Experiment (ALICE)

Central barrel coverage : $|\eta| < 0.9$
0.5 T magnetic field parallel to the beam axis



Beauty production

non-prompt

$D^0 \to K^-\pi^+$

$D^+ \to K^-\pi^+\pi^+$

$D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$

semi-leptonic

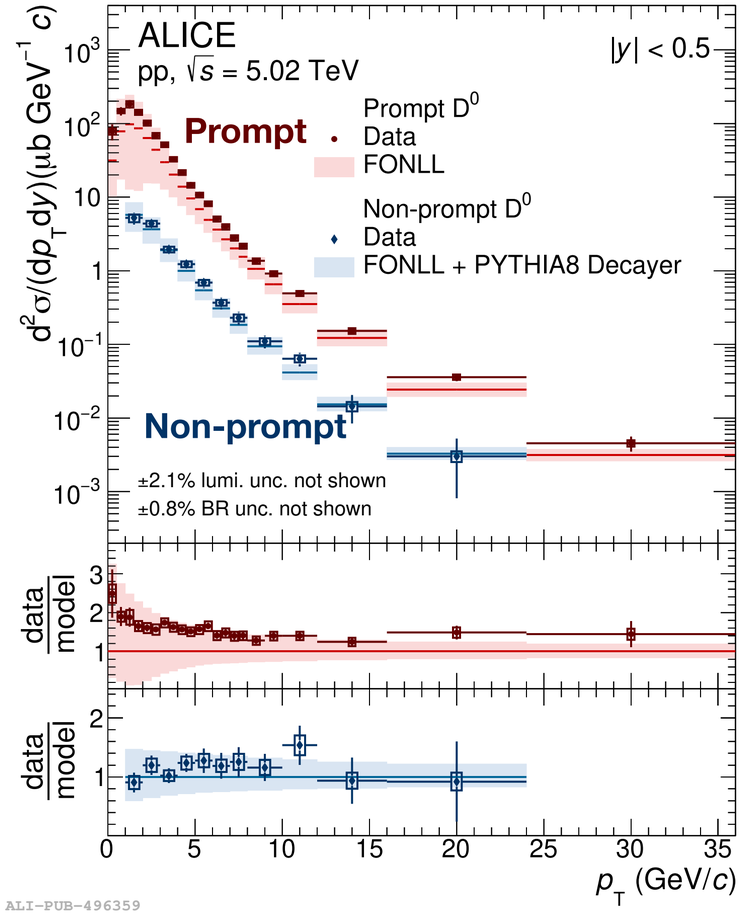
$B(\to D) \to e\nu_e X$

b-tagged jets

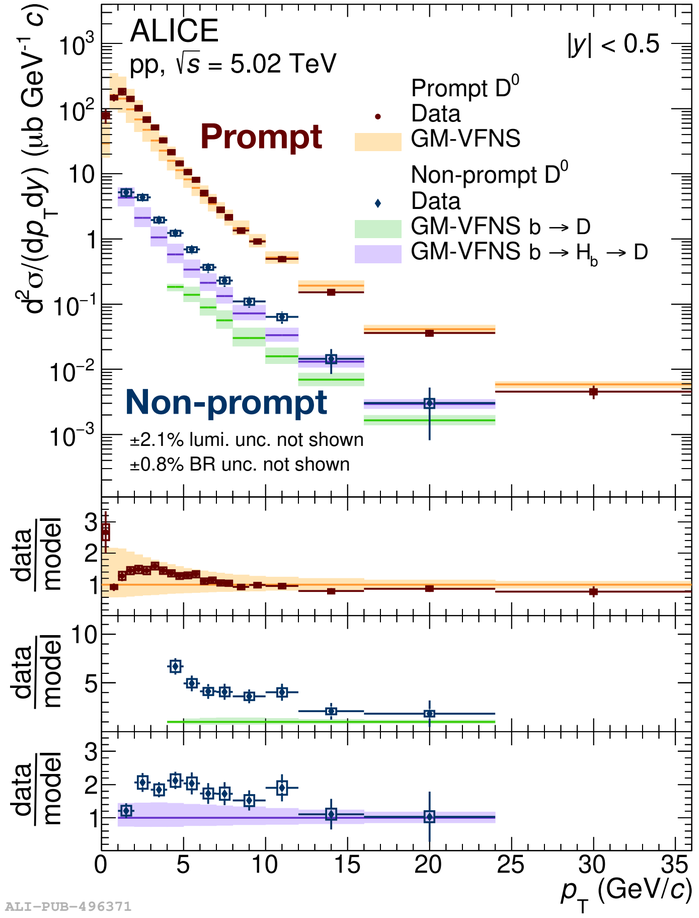
Event trigger : V0
Vertexer & Tracker : ITS, TPC
Particle identification : TPC, TOF, EMCal

Cross section of D^0 mesons in pp collisions

Compared with FONLL



Compared with GM-VFNS



D mesons : JHEP 05 (2021) 220

FONLL

- $f(b \to H_b)$ FFs from e^+e^- and PYTHIA8 to describe $H_b \to D + X$ decays
- Describe the non-prompt D^0 and D_s measurements within uncertainties

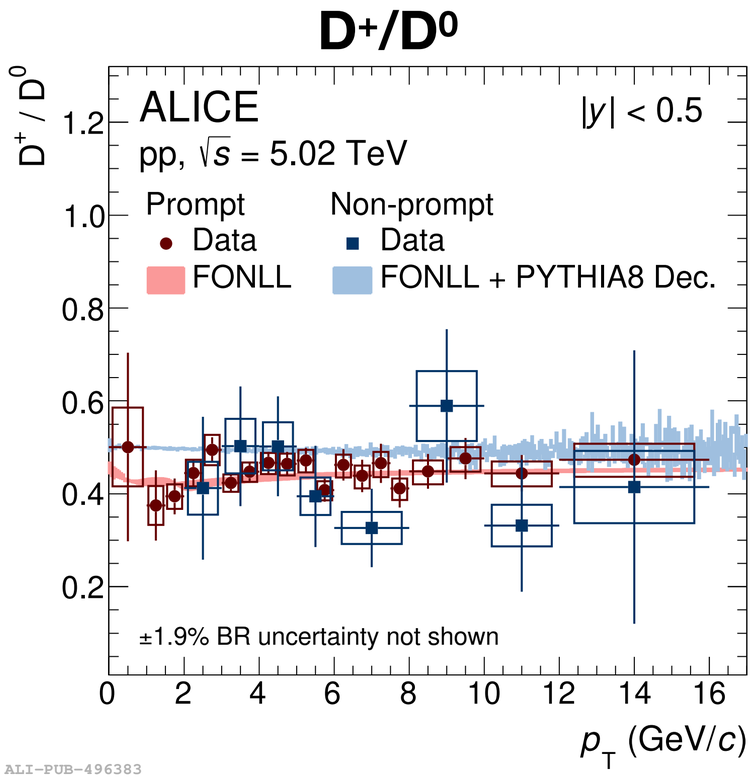
GM-VFNS for non-prompt D mesons

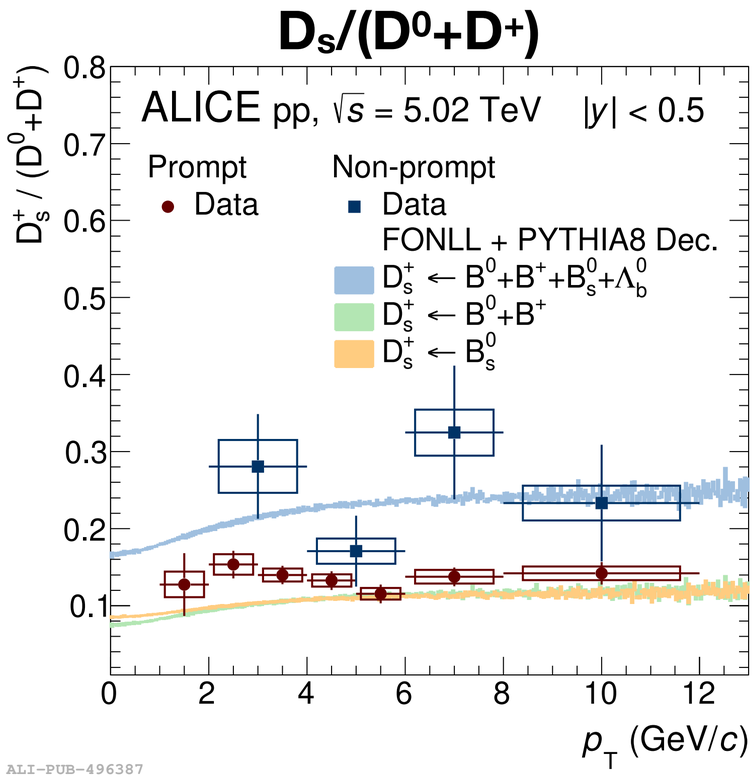
- "single-" and "two-" step approach $b \to D + X$ / $b \to B \to D$
- Predictions tend to underestimate the data at low and intermediate p_T
- Indication of an importance of terms of the factorization approach

FONLL : M. Cacciari et al, JHEP 05 (1998) 007
M. Cacciari et al, JHEP 03 (2001) 006
PYTHIA8 : T. Sjöstrand et al, JHEP 05 (2006) 026
T. Sjöstrand et al, CPC 191 (2015) 159—177

GM-VFNS :
M. Benzke et al, JHEP 12 (2017) 021
G. Kramer and H. Spiesberger, Nucl. Phys. B 925 (2017) 415—430
P. Bolzoni and G. Kramer, J. Phys. G 41 (2014) 075006

Ratio of D mesons in pp collisions





D mesons : JHEP 05 (2021) 220

FONLL : M. Cacciari et al, JHEP 05 (1998) 007
M. Cacciari et al, JHEP 03 (2001) 006
PYTHIA8 : T. Sjöstrand et al, JHEP 05 (2006) 026
T. Sjöstrand et al, CPC 191 (2015) 159—177

D^+/D^0 ratios

- p_T-independent in the measured p_T range
- Compatible with the FONLL predictions for prompt and non-prompt cases

$D_s/(D^0+D^+)$

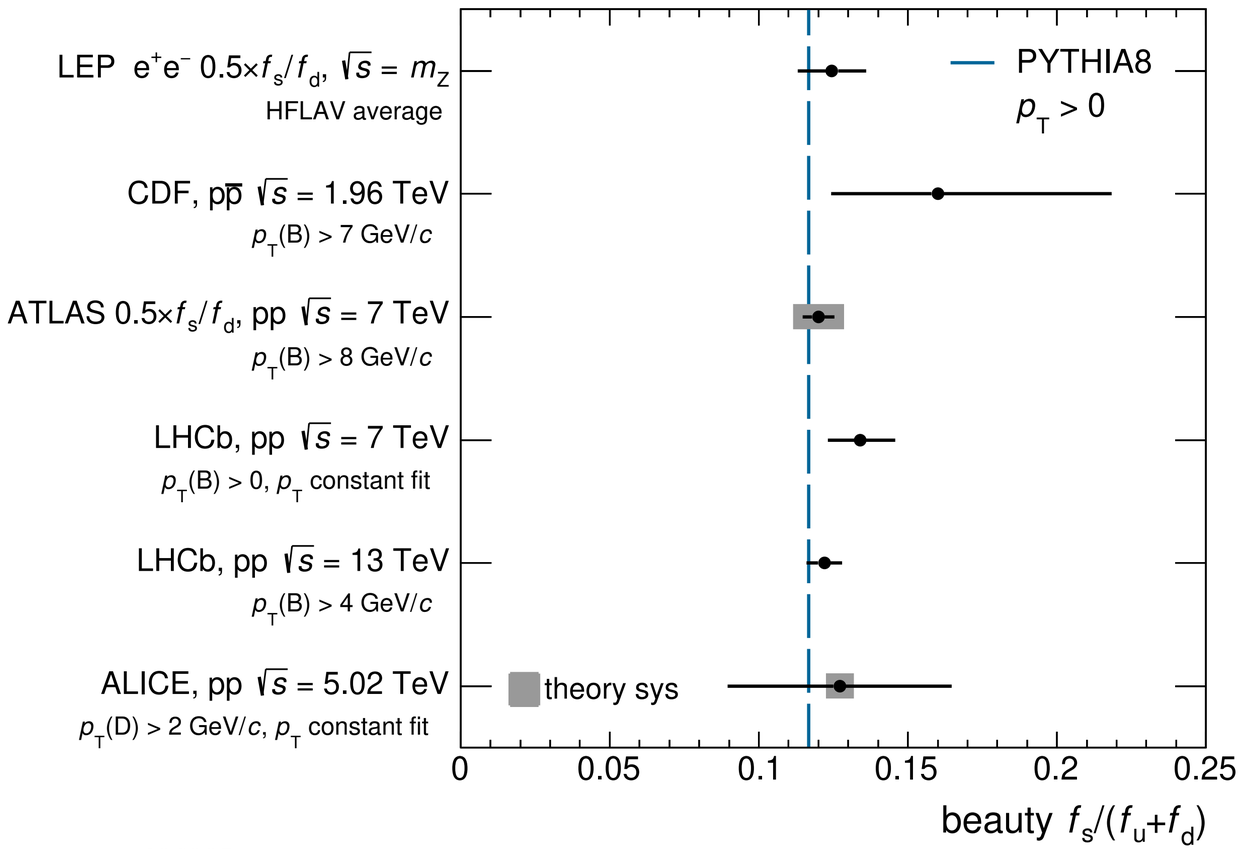
- Flat in p_T and higher for non-prompt D mesons due to substantial B_s-decay contribution

Fragmentation fraction of beauty quarks in pp collisions

PYTHIA8 : P. Skands et al, EPJC 74 (2014) 8, 3204
LEP : Y. Amhis et al, EPJC 81 (2021) 3, 226
CDF : T. Aaltonen et al, Phys. Rev. D 77 (2008) 072003

ATLAS : G. Aad et al, PRL 115 (2015) 26, 262001
LHCb, 7 TeV : R. Aaji et al, Phys. Rev. D 85 (2012) 032008
LHCb, 13 TeV : R. Aaji et al, Phys. Rev. D 100 (2019) 3, 031102

D mesons : JHEP 05 (2021) 220



ALI-PUB-496395

FFs of beauty quarks, $f_s/(f_u+f_d)$

- Obtained from constant fit to $D_s/(D^0+D^+)$
- Additional correction to account for
  - Non-prompt D_s originating from B^0, B^+
  - Non-prompt D^0 and D^+ originating from B_s
- Compatible with previous measurements and PYTHIA8

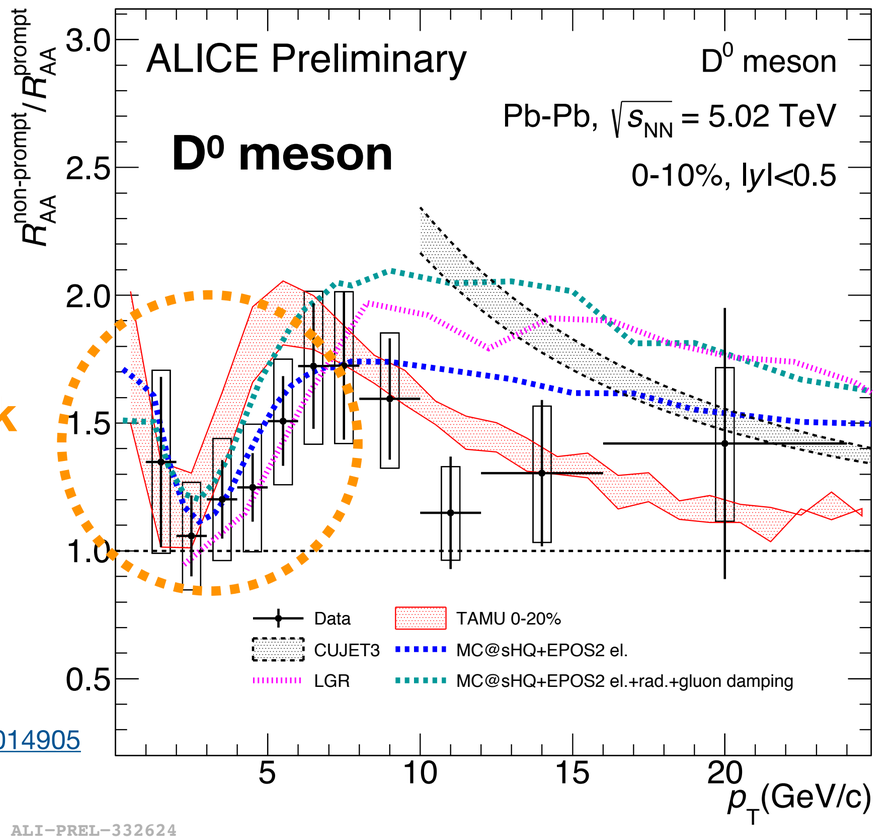
$$\left(\frac{f_s}{f_u+f_d}\right)_{\text{beauty}} = 0.127 \pm 0.036(\text{stat}) \pm 0.012(\text{syst})$$

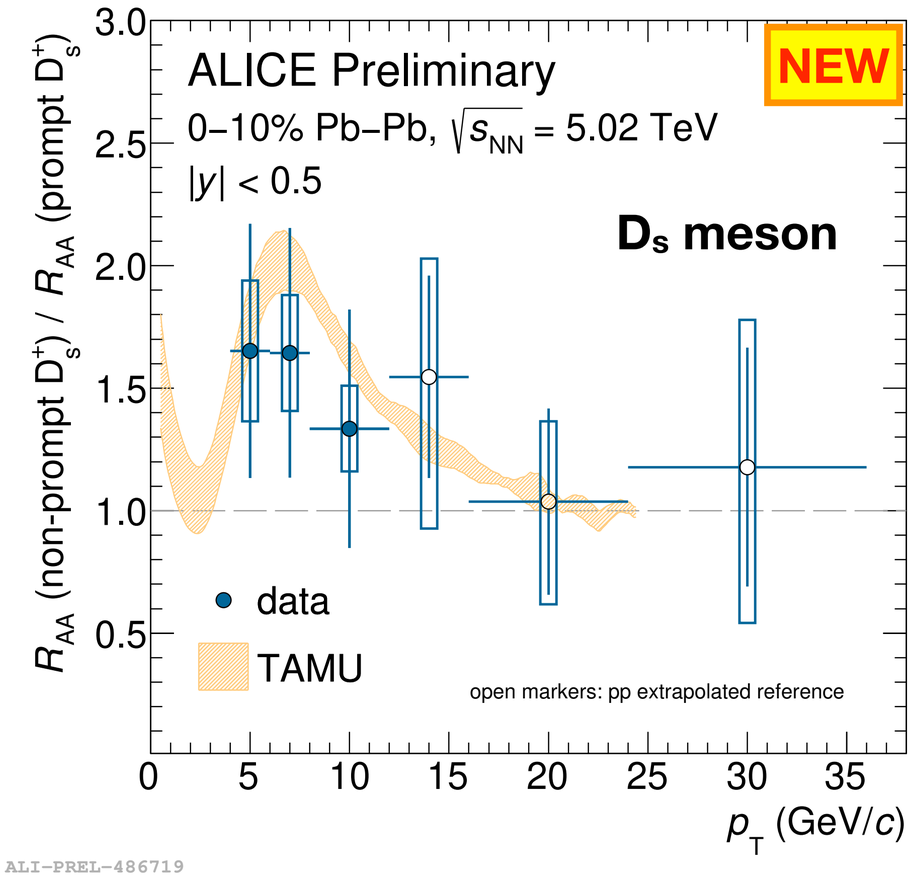
R_{AA} Ratio of D mesons in 0—10% Pb—Pb collisions

- Indication of **less suppression of non-prompt D mesons** for $4 < p_T < 8$ GeV/c
- Various theoretical calculations describe the measurements within uncertainties
  - Interplay of **heavy quark energy loss and hadronization in the medium**

$$\frac{\text{non prompt } R_{AA}}{\text{prompt } R_{AA}}$$

Due to charm quark coalescence

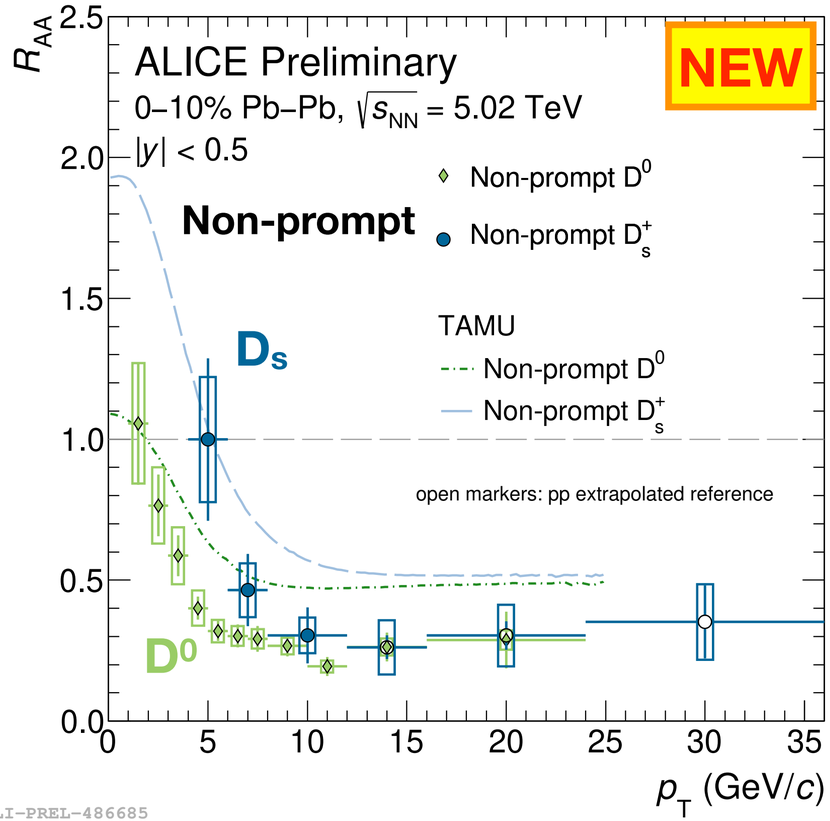


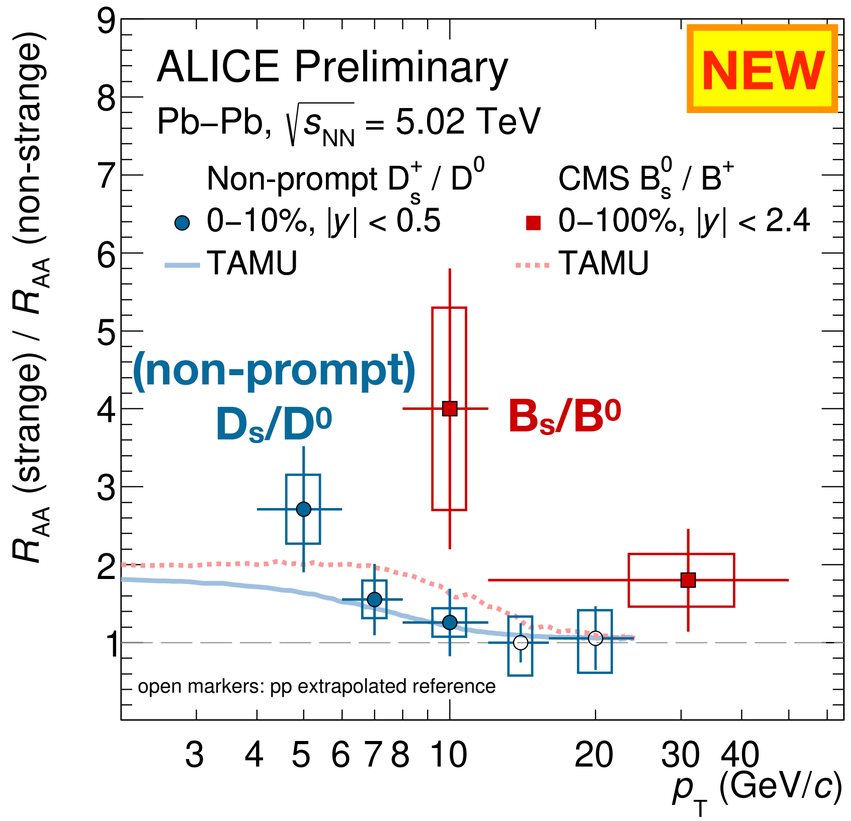


TAMU : Min He et al, PLB 735 (2014) 445—450
CUJET3 : Jiechen Xu et al, JHEP 1602 (2016) 169
LGR : S. Li and J. Liao, EPJC 80 7 (2020) 671
MC@sHQ+EPOS : M. Nahrgang et al, PRC 89, (2014) 014905

R_{AA} of non-prompt D mesons in 0—10% Pb—Pb collisions

- $R_{AA}(D_s)/R_{AA}(D^0)$ ratio is above unity for $p_T < 8$ GeV/c at low p_T
  - B_s production is enhanced by beauty hadronization via coalescence
- Larger $R_{AA}(B_s)/R_{AA}(B^+)$ ratio w.r.t non-prompt D meson
  - D_s from non-strange B meson decays → different decay kinematics





- TAMU models describe the observed trend
  - Implementing coalescence in transport models

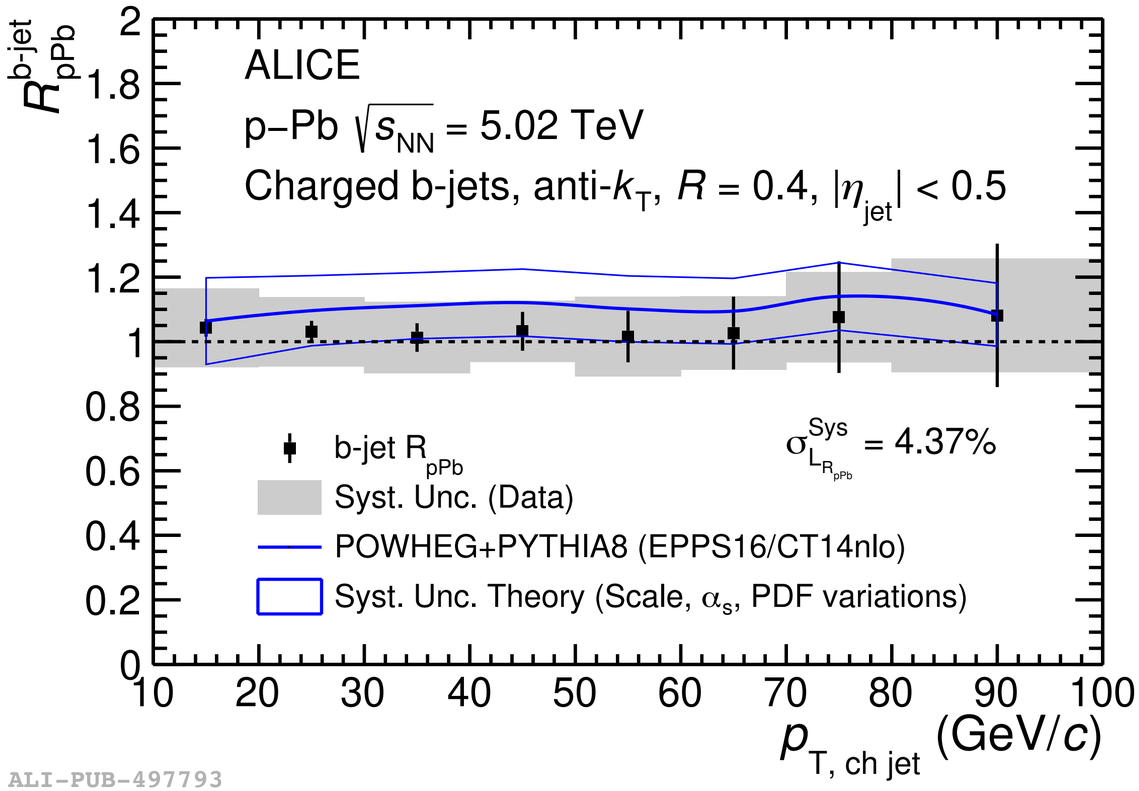
$$\frac{\text{strange } R_{AA}}{\text{non strange } R_{AA}}$$

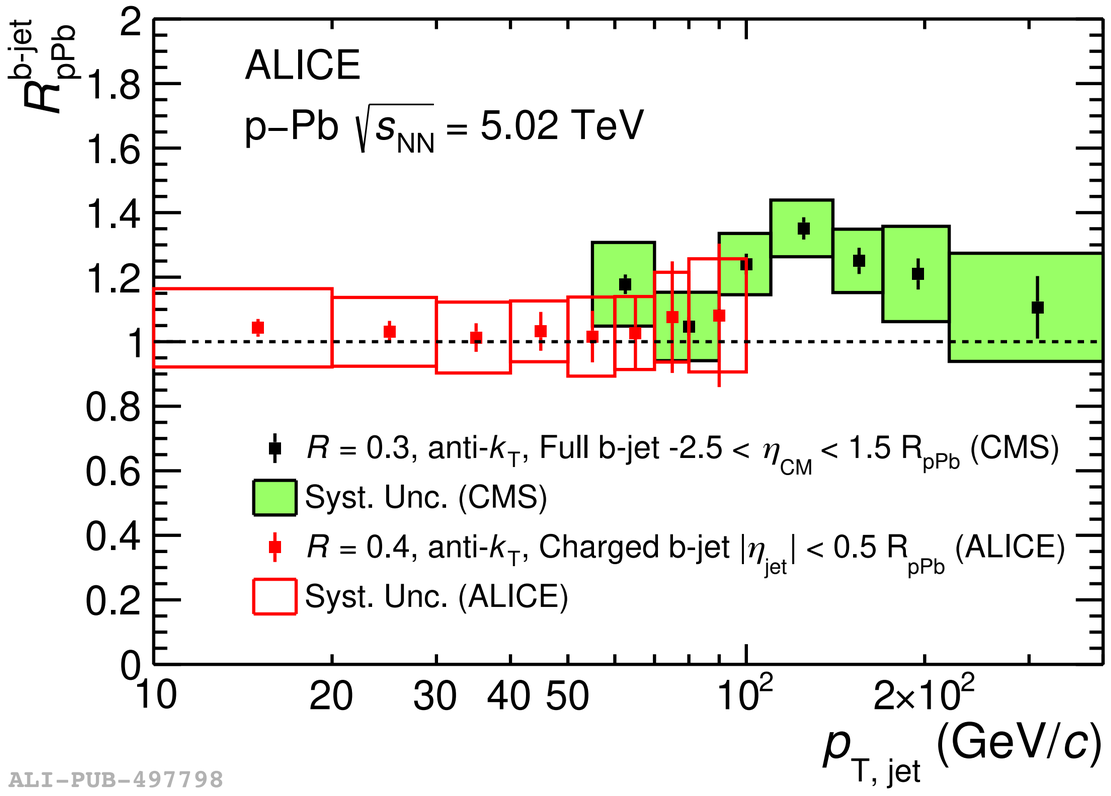
TAMU : Min He et al, PLB 735 (2014) 445—450
CMS : The CMS Collaboration, PLB 796 (2019) 168—190

R_{pPb} of b-jet in p—Pb collisions

- R_{pPb} of b-jet is unity within uncertainties
- Compatible with POWHEG predictions and CMS measurement in the overlapped region
- In the measured p_T range, no visible CNM effect within uncertainties

b-jet : arXiv:211006104, POWHEG : S. Frixione et al, JHEP 11 (2007) 070 , S. Alioli et al, JHEP 04 (2011) 081 , CMS : The CMS Collaboration, PLB 754 (2016) 59

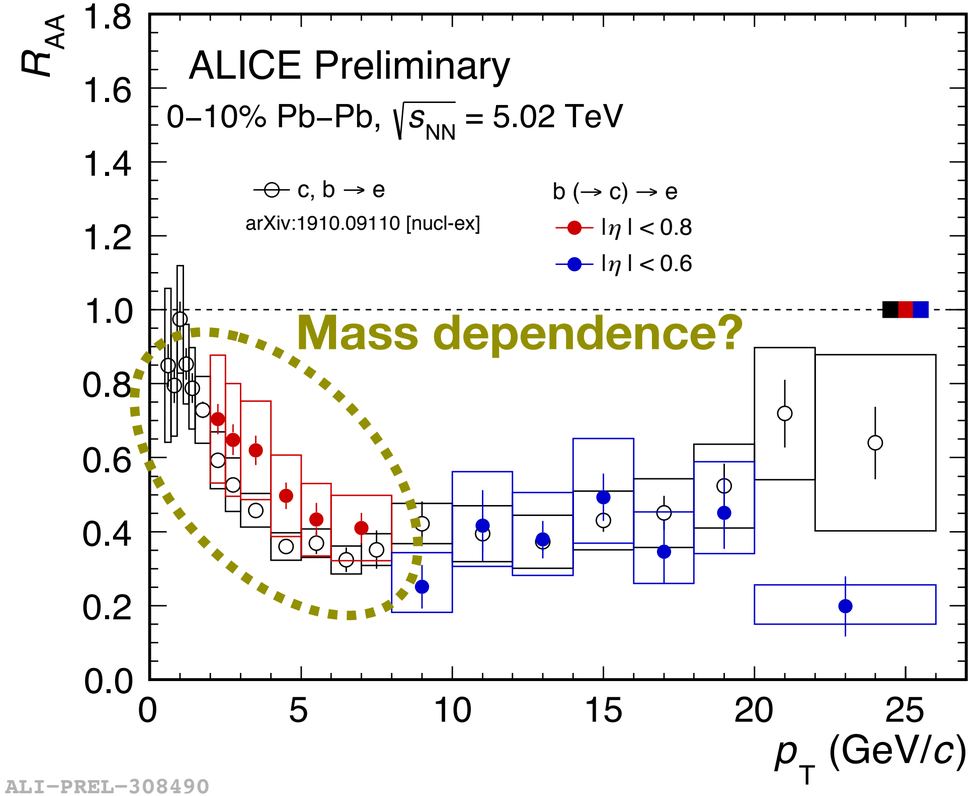


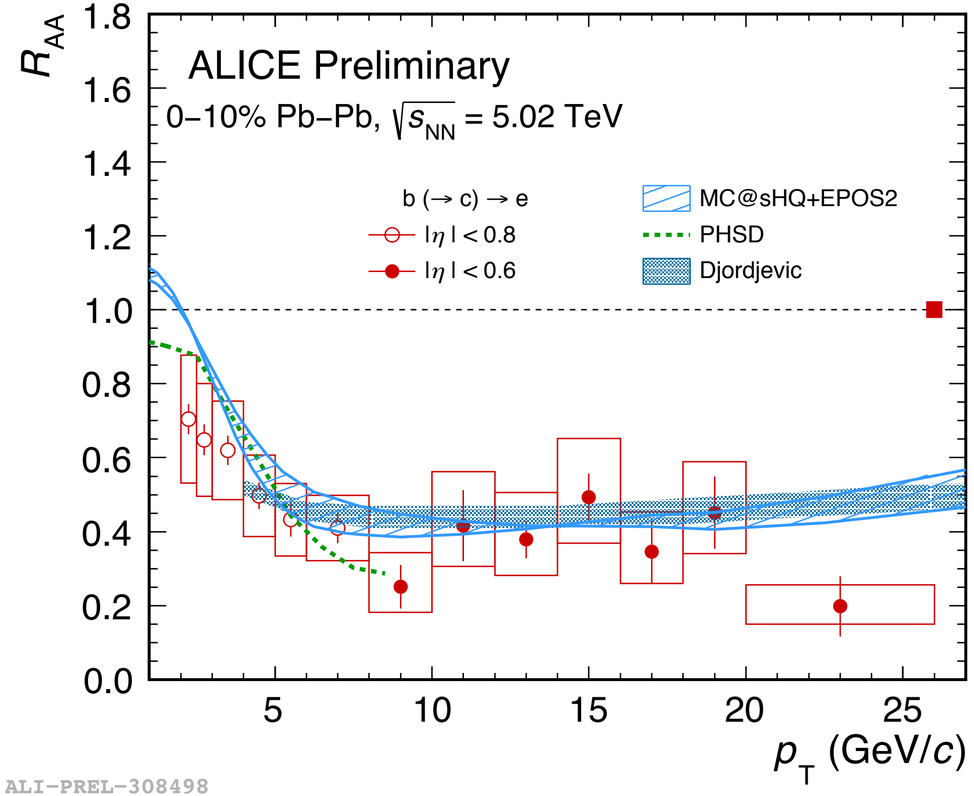


R_{AA} of b→e in Pb—Pb collisions

- Various transport models describe the data within uncertainties
  - Models include different quark energy loss processes and hadronization mechanisms
- Compare to c,b→e R_{AA} at the same collision system

MC@sHQ+EPOS2 : M. Nahrgang et al, Phys. Rev. C 89 (2014) 014905
PHSD : T. Song et al, Phys. Rev. C 92 (2015) 014910
Djordjevic : D. Zigic, PLB 791 (2019) 236—241



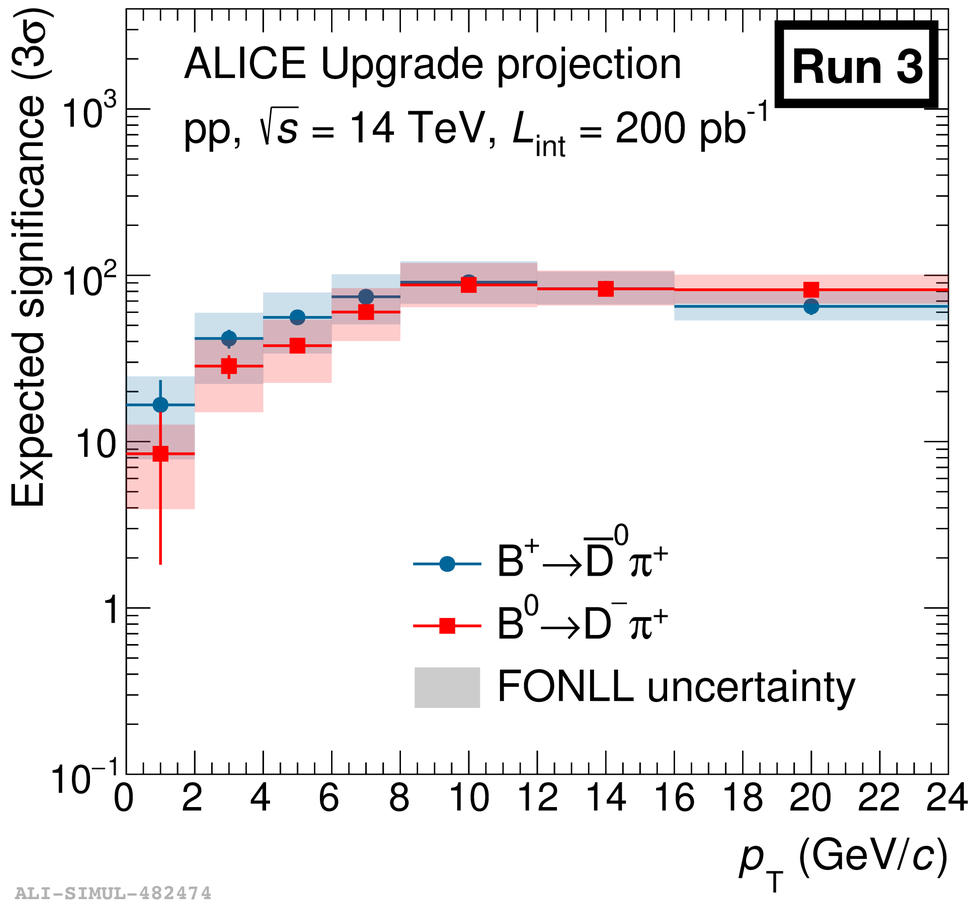


Summary and Outlook

- Beauty production via non-prompt D mesons, b-tagged jets, and beauty-decay electrons
- **In pp collisions** the measurements are in good agreement with pQCD calculations
- **In p—Pb collisions** no visible CNM effect for b-jets with the current precision
- **In Pb—Pb collisions** measured R_{AA} below unity
  - Hint of mass dependent in-medium energy loss
  - Insight into heavy-quark hadronization

Outlook

- Upgrade of the ALICE detector during LS2
  - Electronics for most ALICE sub-detectors
  - New silicon tracking detector (ITS2 based on MAPS tech.)
- Increase luminosity, tracking resolution and efficiency, etc.
- Measurement of B hadrons via full reconstruction



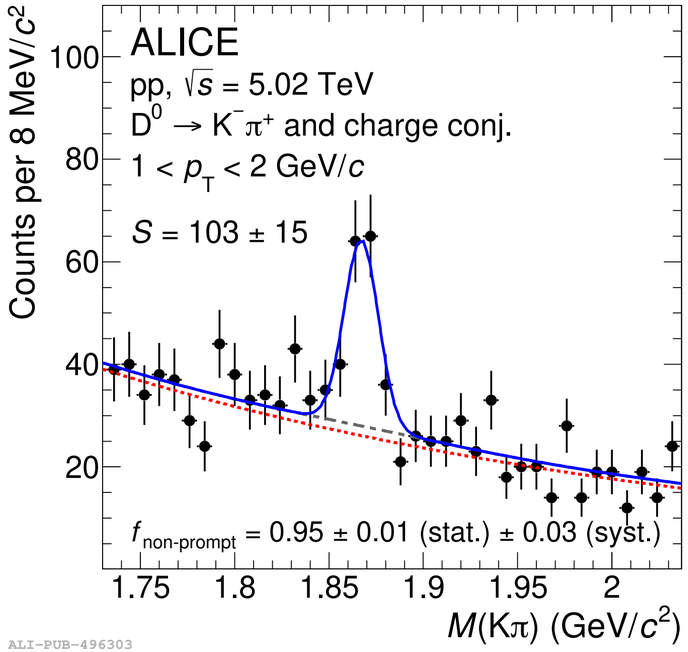
BACKUP

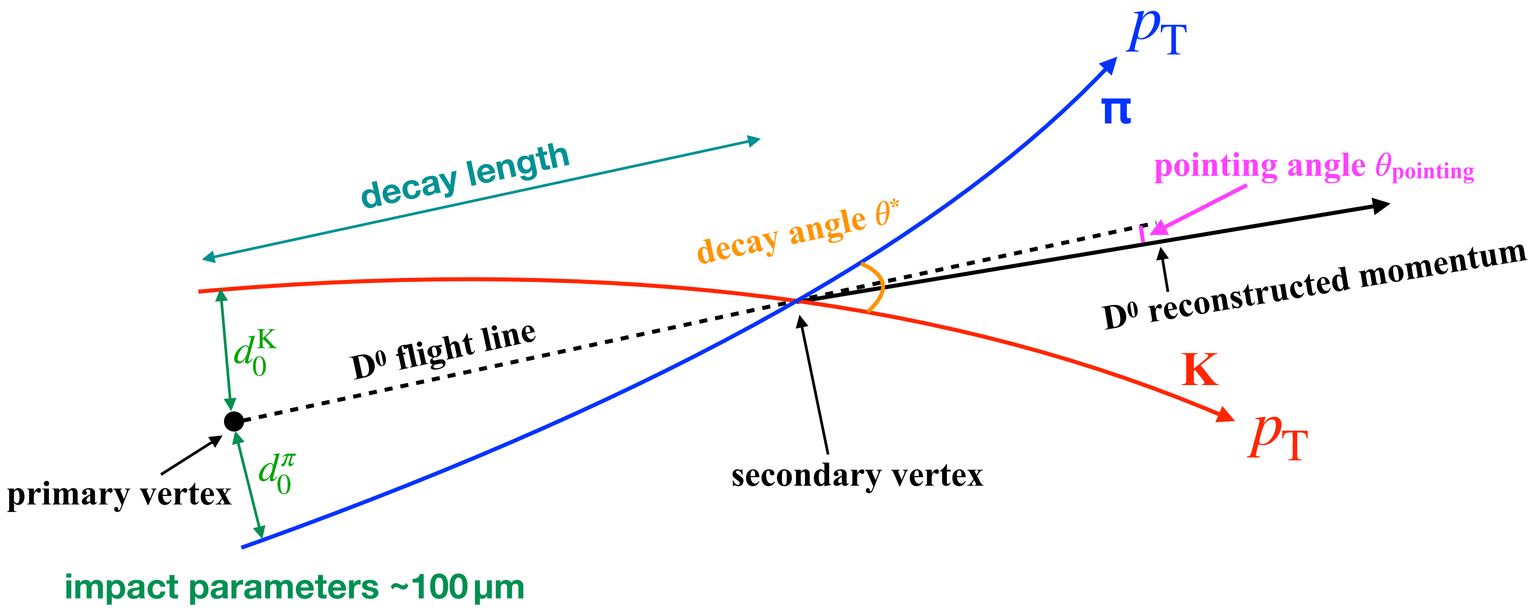
Non-prompt D mesons

- Reconstruct D mesons using invariant mass and secondary vertex from primary vertex

	D^0	D^+	D_s^+
Decay channel	$\to K^-\pi^+$	$\to K^-\pi^+\pi^+$	$\to \phi\pi^+ \to K^-K^+\pi^+$
Branching ratio	(3.88 ± 0.05)%	(9.13 ± 0.19)%	(2.24 ± 0.1)%
Decay length ($c\tau$)	123 μm	312 μm	150 μm

Example of D^0

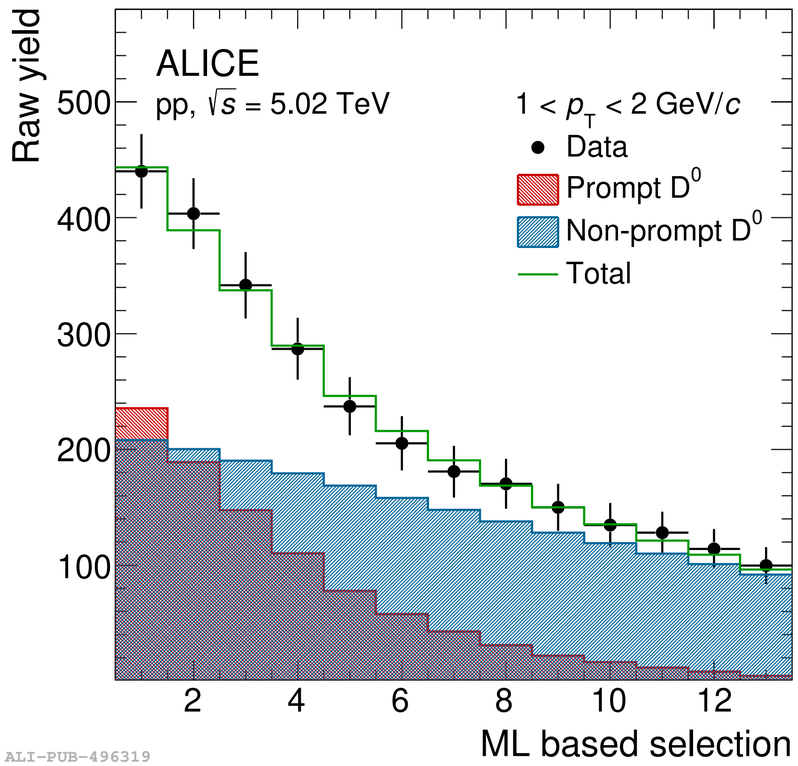


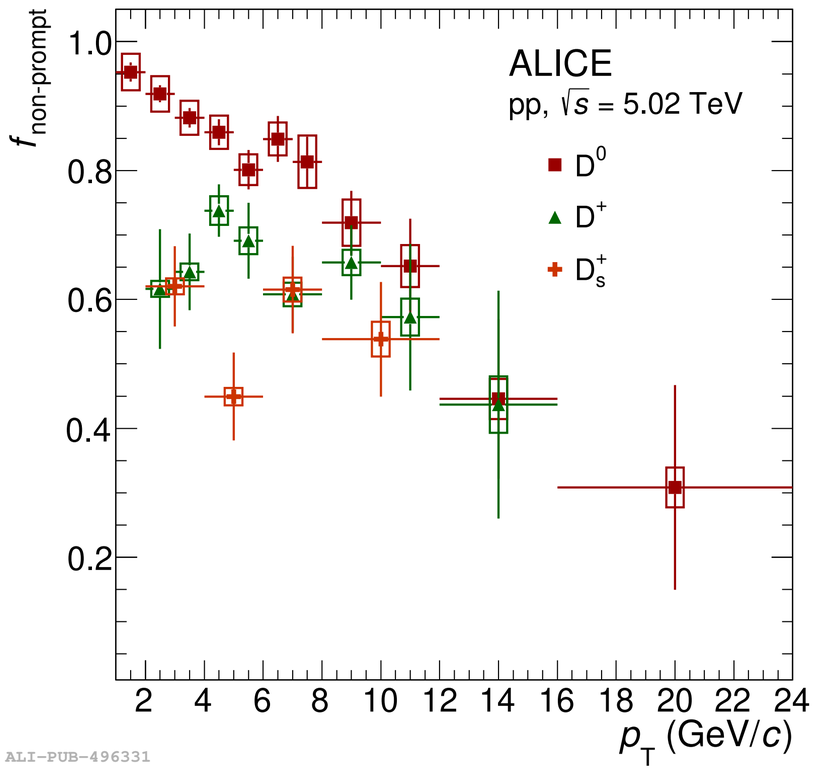


Non-prompt D mesons

- **BDT (Boosted Decision Trees)** utilizes geometrical variables from decay topology associated to the primary and secondary vertices
  - Suppress combinatorial background
  - Disentangle non-prompt D mesons from inclusive signals
  - Subtract prompt D mesons by exploiting a min-χ^2 approach with BDT cut variation on the raw yield

Example of D^0

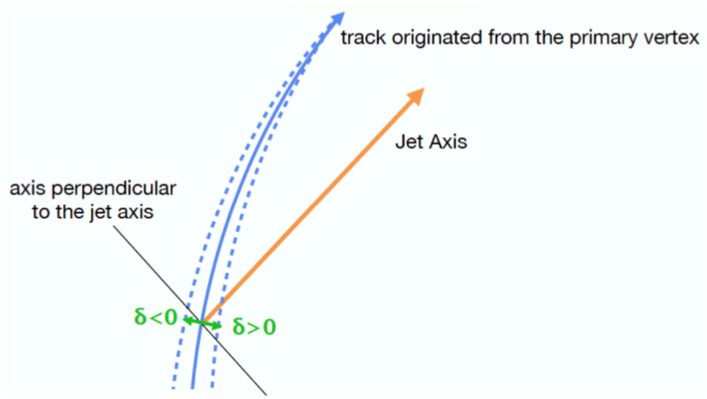


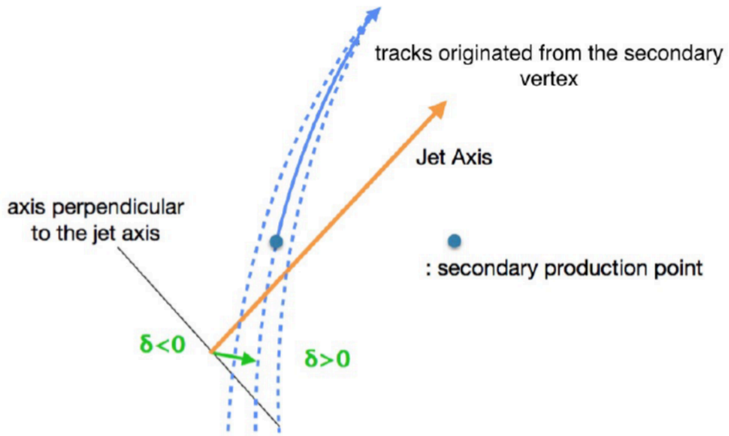


b-tagged jet

Two distinct b-jet tagging methods

1) Impact Parameter (IP) : distance of closest approach of jet constituents to primary vertex
2) Secondary Vertex (SV) : properties of most displaced 3-prong secondary vertex





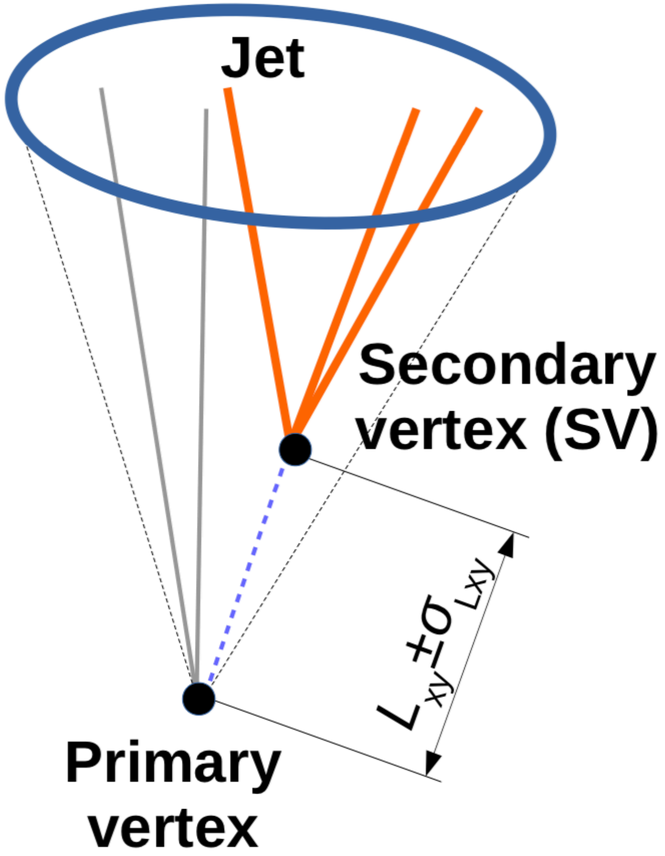
b-jet tagging based on impact parameter

- Impact parameter significance, $Sd_{xy} = \delta \cdot d_{xy}/\sigma_{dxy}$
  - δ : sign of the impact parameter
  - d_{xy} : impact parameter in xy-plane
  - σ_{dxy} : impact parameter resolution
- Sorting Sd_{xy} in descending order
- b-jets were tagged with following conditions:
  - Second largest impact parameter significance value
  - $Sd_{xy} > Sd_{xy}^{min}$ $(Sd_{xy}^{min} = 2.5)$

b-tagged jet

Two distinct b-jet tagging methods

1) Impact Parameter (IP) : distance of closest approach of jet constituents to primary vertex
2) Secondary Vertex (SV) : properties of the most displaced 3-prong secondary vertex (SV)



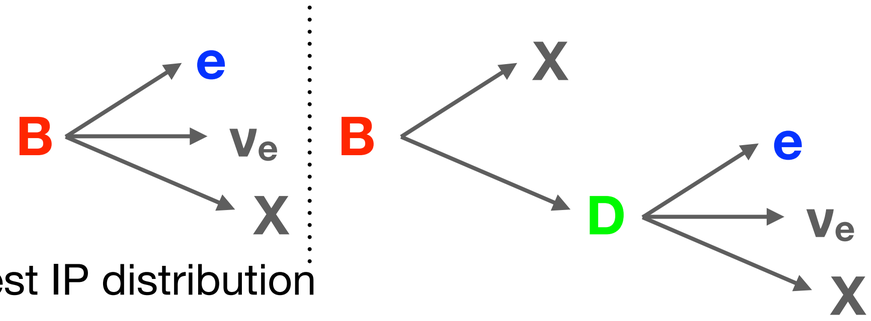
b-jet tagging based on secondary vertex (SV)

- Reconstruct SV inside the jets from 3-prong jet constituents
- Select for b-jet tagging by considering the most displaced SV
- Dispersion of the reconstructed SV, σ_{SV} :

  $\sigma_{\mathrm{SV}} = \sqrt{d_1^2 + d_2^2 + d_3^2}$ where $d_{1,2,3}$ are DCA of three tracks to SV
- Significance of the decay length : $SL_{xy} = L_{xy}/\sigma_{Lxy}$
  - L_{xy} : distance between PV and SV (decay length)
  - σ_{Lxy} : uncertainty of L_{xy} measurements
- b-jet tagging with $SL_{xy} > 7$ and $\sigma_{\mathrm{SV}} > 0.03$ cm

Beauty hadrons via semi-leptonic decays

- Beauty production via beauty-hadron decay electrons
  - Substantial branching ratio : ~10%
- Exploit the track impact parameter distribution
  - Sizable decay length ($c\tau \approx$ 400–500 μm) of beauty hadrons → widest IP distribution
- Statistical extraction of beauty-hadron decay electrons using the impact parameter
  - Maximum likelihood approach, *Barlow-Beeston, CPC 77(2) 1993*



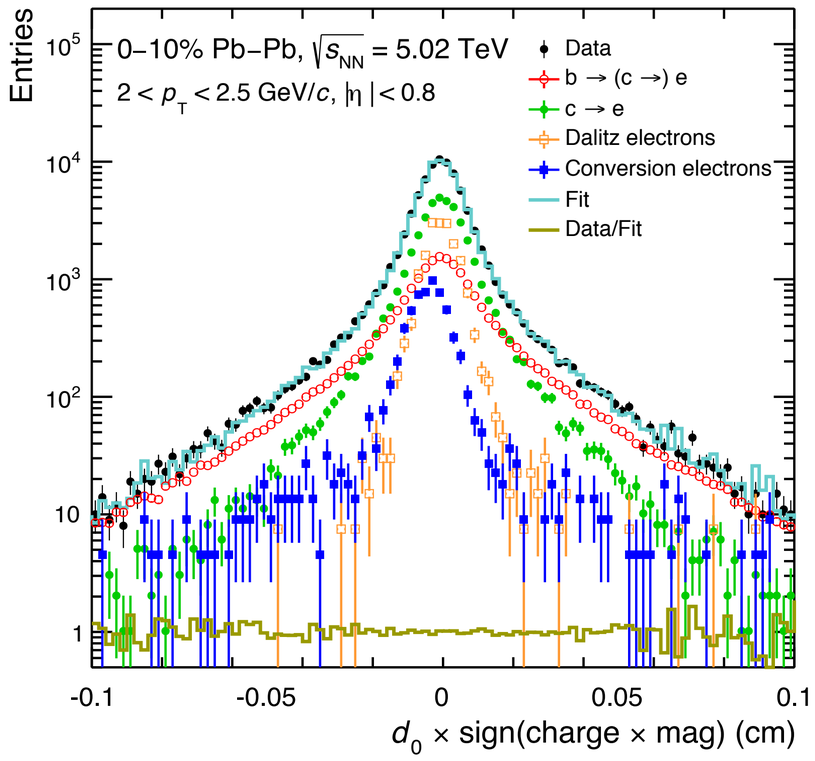
$$\log L = \sum_{\text{bin}} \text{data(bin)} \cdot \log \text{fit(bin)} - \text{fit(bin)}$$

$$+ \sum_{\text{bin}} \sum_{\text{source}} N_{\text{source}}(\text{bin}) \cdot \log A_{\text{source}}(\text{bin}) - A_{\text{source}}(\text{bin})$$

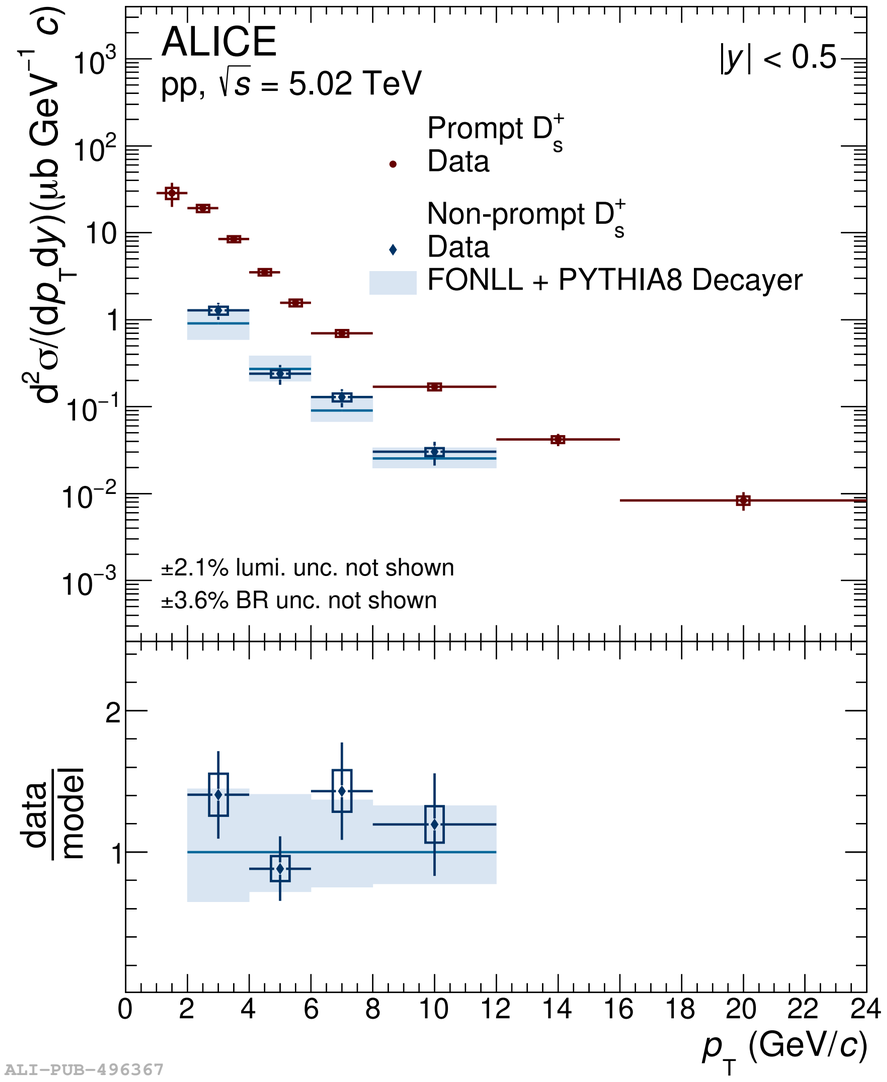
$$\text{fit(bin)} = \sum_{\text{source}} p_{\text{source}} \cdot A_{\text{source}}(\text{bin})$$

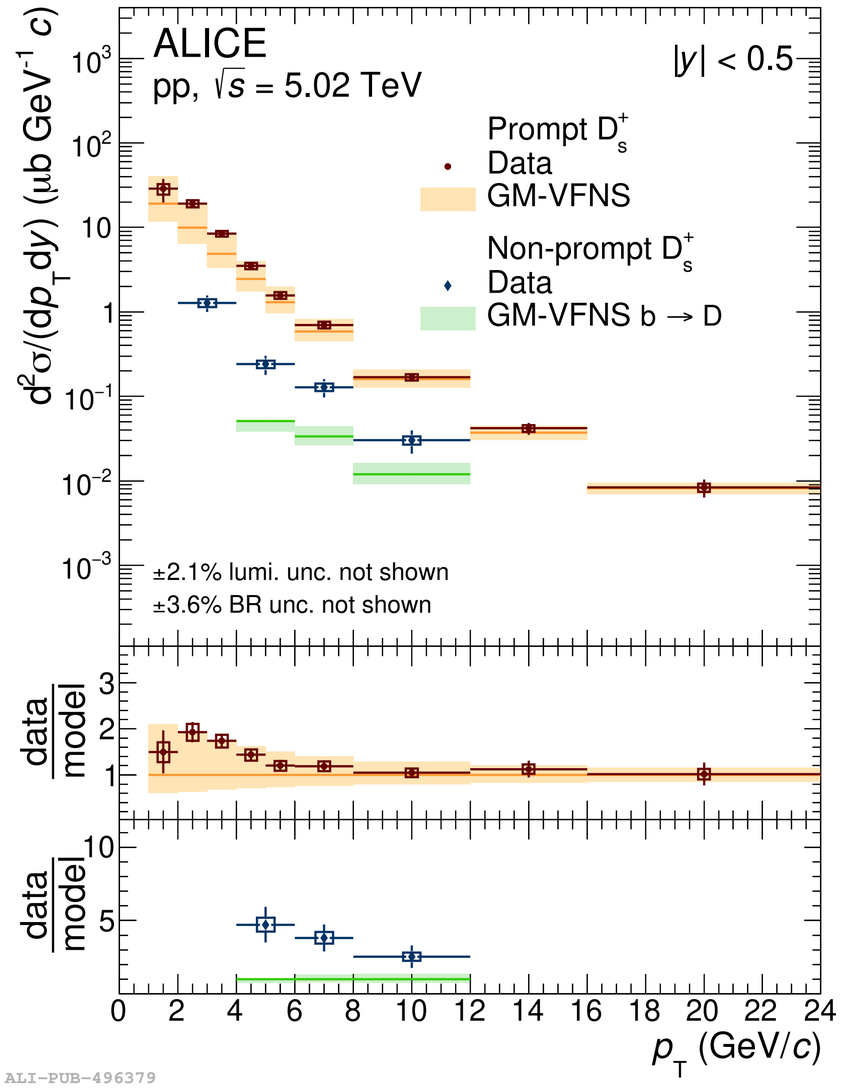
Likelihood for weighted sum of expectation values to correspond to data

Likelihood for expectation values to correspond to MC templates



Non-prompt D_s mesons in pp collisions at 5.02 TeV





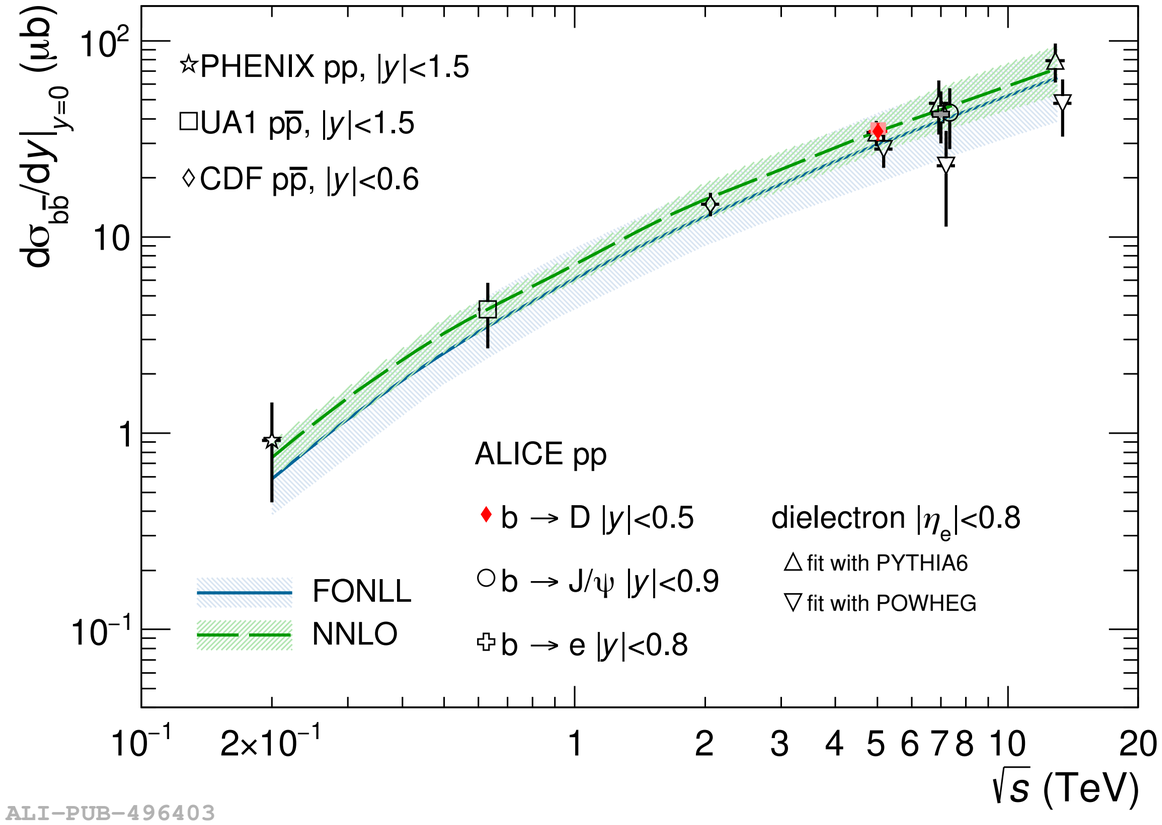
D mesons : JHEP 05 (2021) 220

FONLL : JHEP 05 (1998) 007
JHEP 03 (2001) 006
PYTHIA8 : JHEP 05 (2006) 026
CPC 191 (2015) 159—177

GM-VFNS :
JHEP 12 (2017) 021
Nucl. Phys. B 925 (2017) 415—430
J. Phys. G 41 (2014) 075006

Non-prompt D mesons in pp collisions at 5.02 TeV

D mesons : arXiv:2102.13601



PHENIX : PRL 103 (2009) 082002
UA1 : PLB 256 (1991) 121—128
CDF : Phys. Rev. D 71 (2005) 032001
b→J/ψ : JHEP 11 (2012) 065
b→e : PLB 721 (2013) 13–23
Dielectron, 7 TeV : JHEP 09 (2018) 064
Dielectron, 13 TeV : PLB 788 (2019) 505—518
FONLL : JHEP 05 (1998) 007
JHEP 03 (2001) 006
JHEP 10 (2012) 137
NNLO : arXiv:2010.11906 [hep-ph]

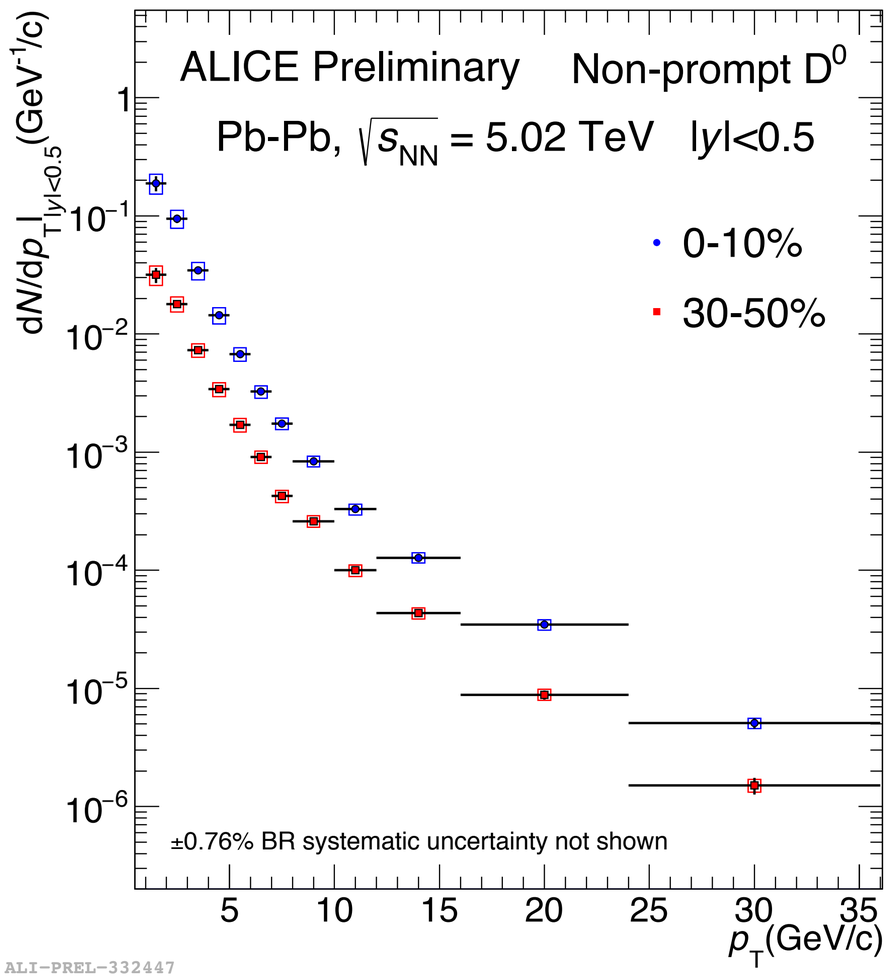
$$\frac{d\sigma_{b\bar{b}}}{dy}_{|y|<0.5} = 34.5 \pm 2.4(\mathrm{stat})^{+4.7}_{-2.9}(\mathrm{tot.syst})\,\mu\mathrm{b}$$

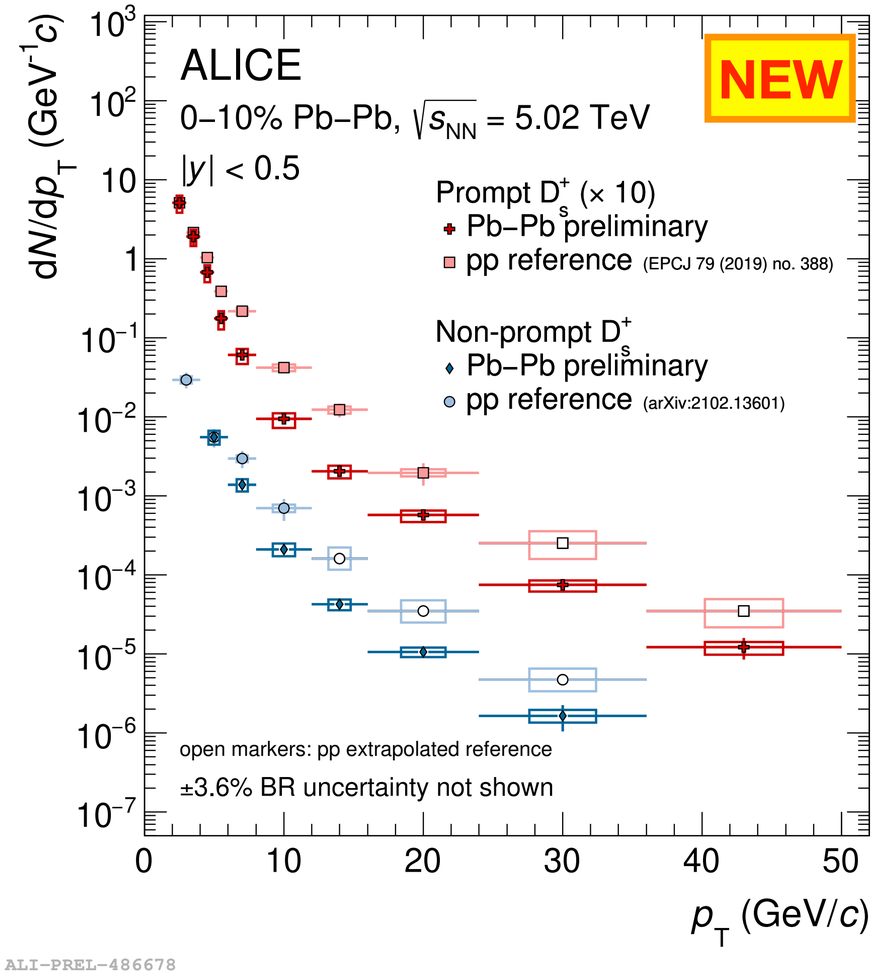
From non-prompt D meson measurements

- Beauty production cross section per rapidity unit at midrapidity as a function of $\sqrt{s}$ described by **FONLL** and **NNLO** calculations
- Good agreement with the predictions within uncertainties

Non-prompt D mesons in Pb—Pb collisions at 5.02 TeV

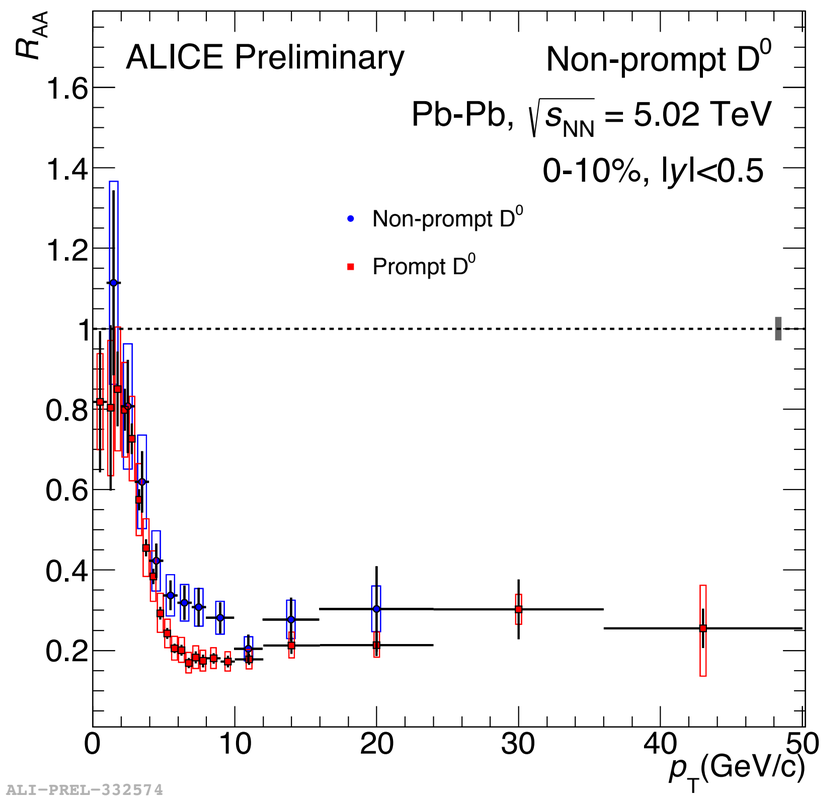
- First measurements of non-prompt D^0 and D_s mesons in Pb—Pb collisions in ALICE

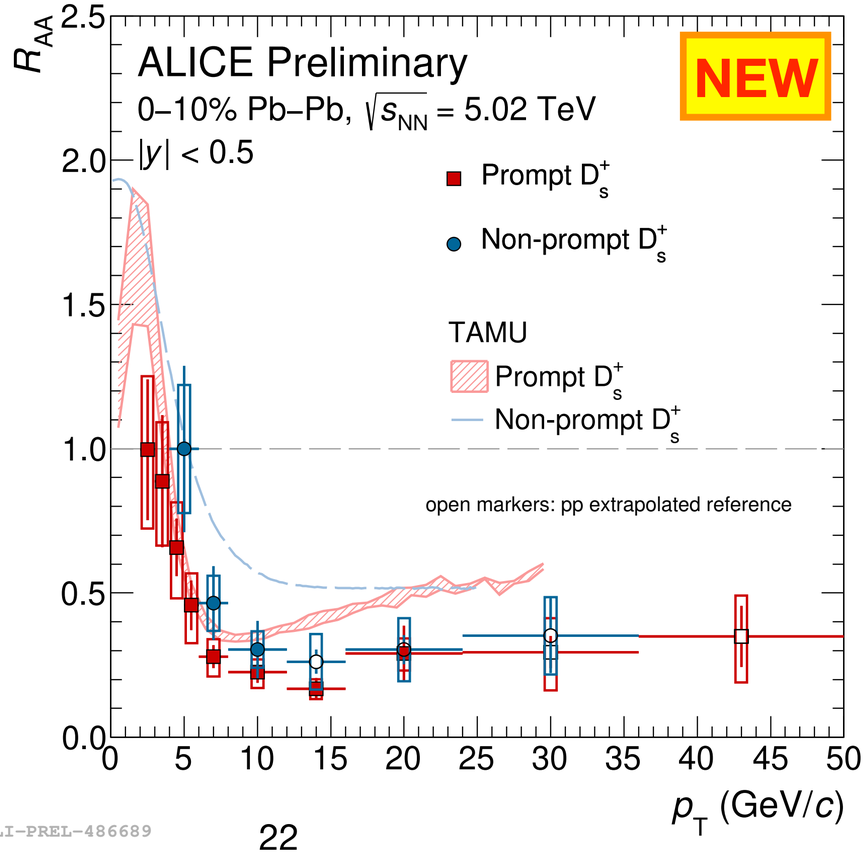




Non-prompt D mesons in Pb—Pb collisions at 5.02 TeV

- R_{AA} of prompt and non-prompt D^0 and D_s mesons in 0—10% Pb—Pb collisions at 5.02 TeV
- Provide a hint of mass dependent parton energy loss in the medium : $\Delta E_c > \Delta E_b$
  - Non-prompt D^0 R_{AA} > prompt D^0 R_{AA} in the intermediate p_T
  - Non-prompt D_s > prompt D^0 R_{AA} at low p_T region

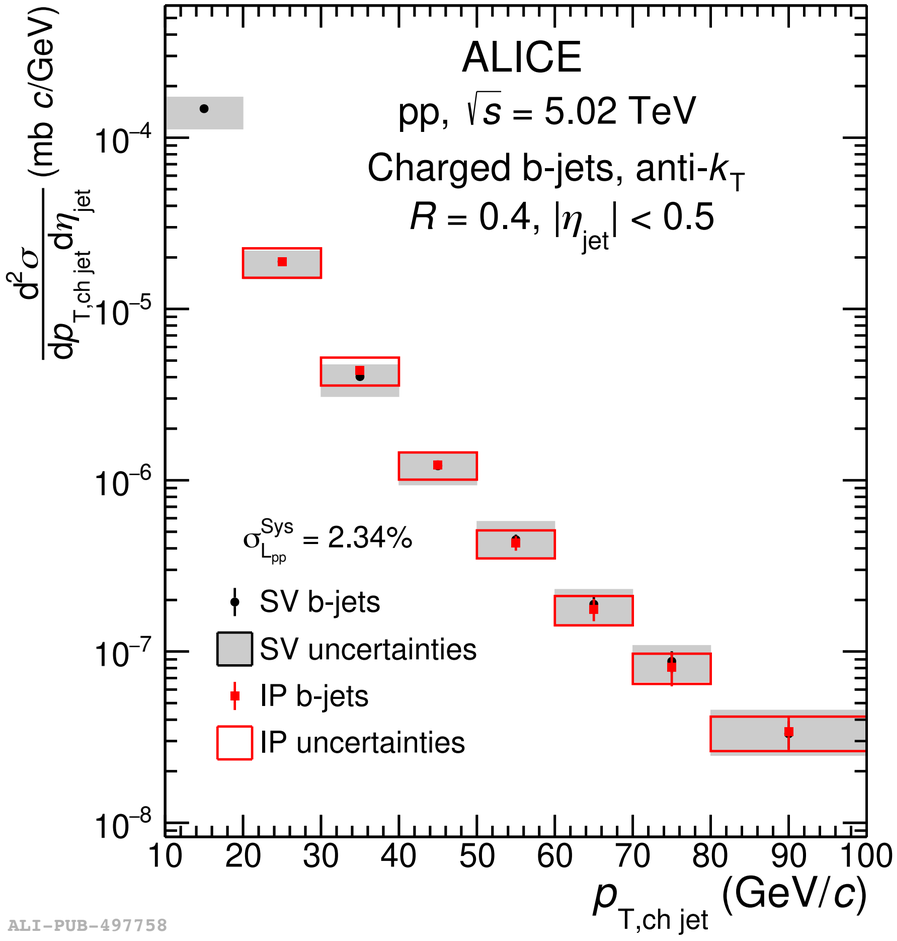


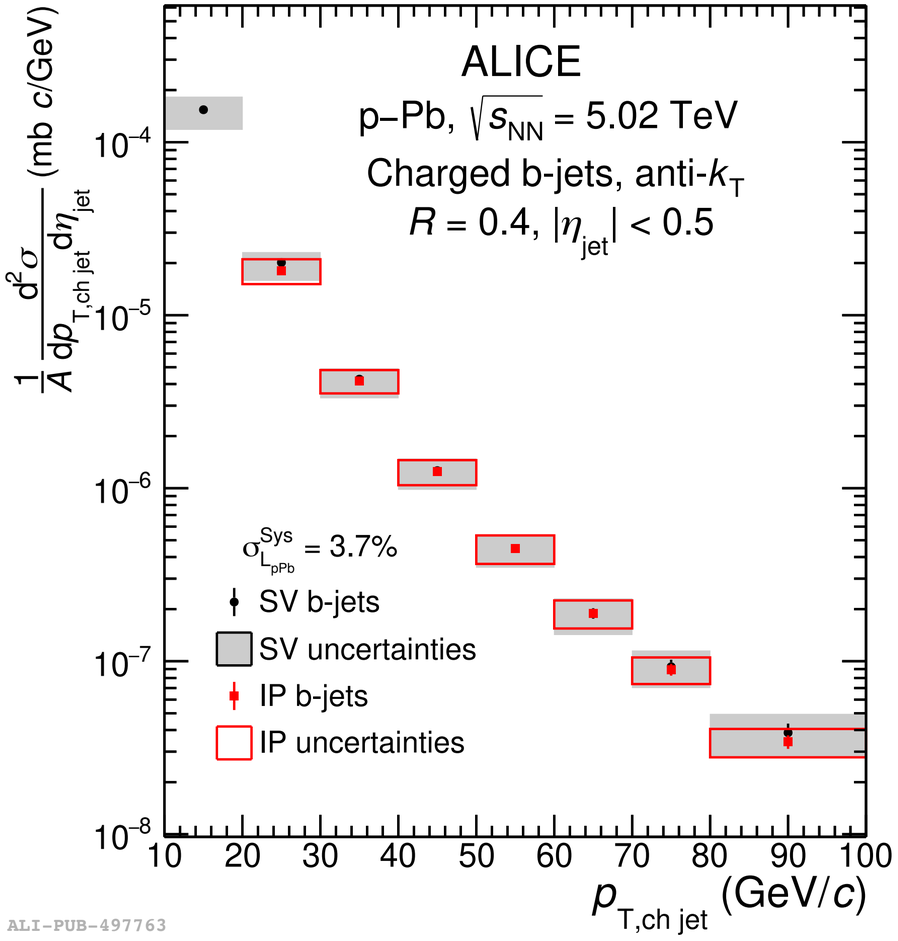


TAMU : PLB 735 (2014) 445—450

b-jet in pp and pPb collisions at 5.02 TeV

- b-jet production cross section in pp and pPb collisions
- Different methods yield consistent results

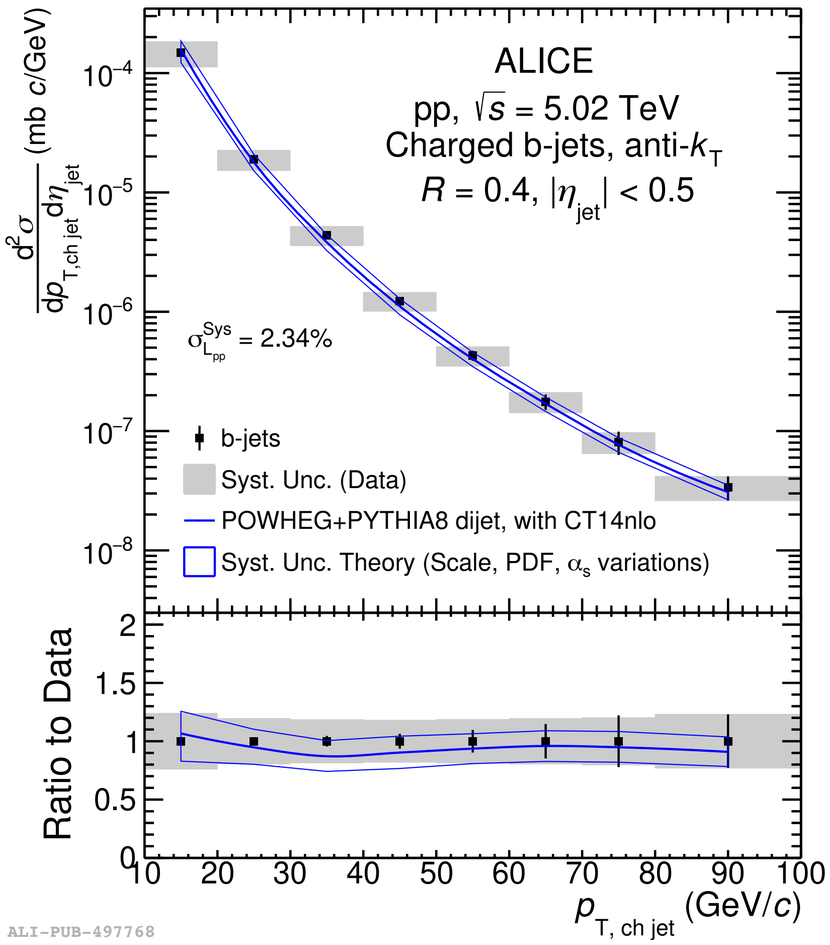


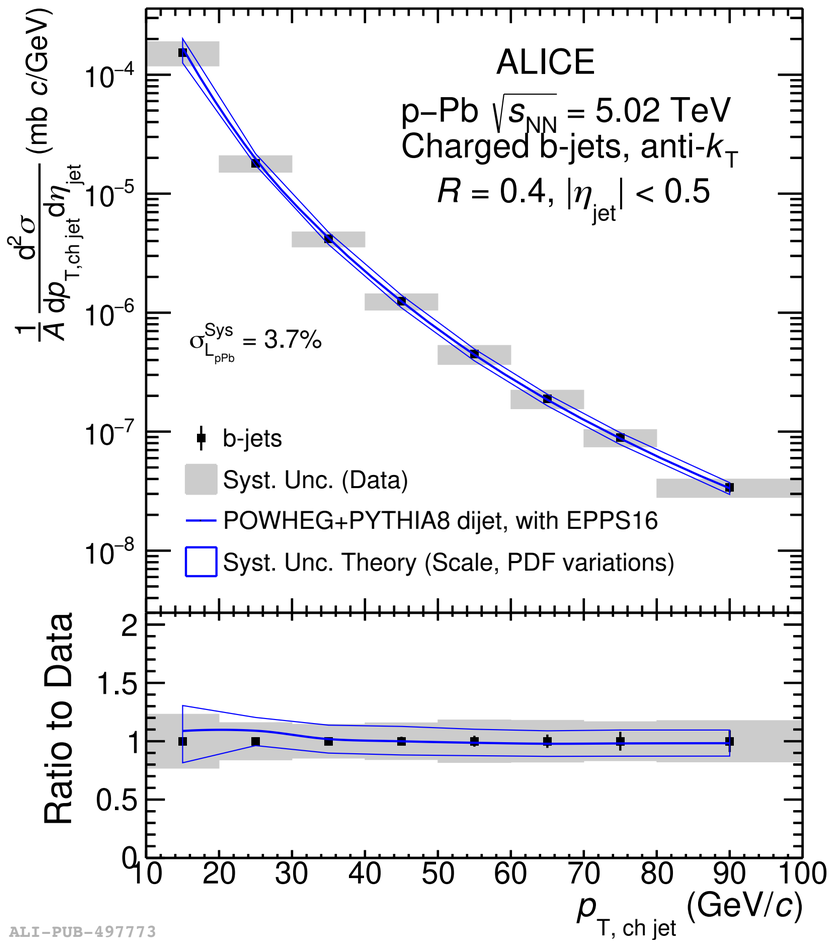


b-jet : arXiv:211006104

b-jet production cross section in pp and p—Pb collisions

- b-jet production cross section in pp and pPb collisions
- Good agreement with POWHEG calculations (based on HF-jet spectra by NLO)

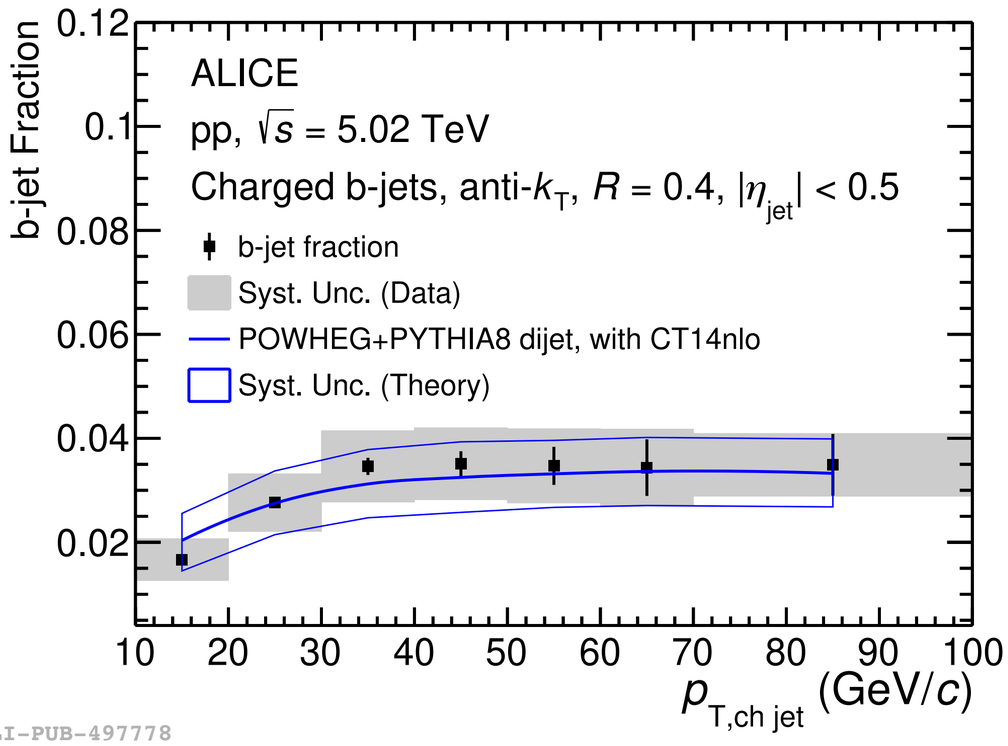


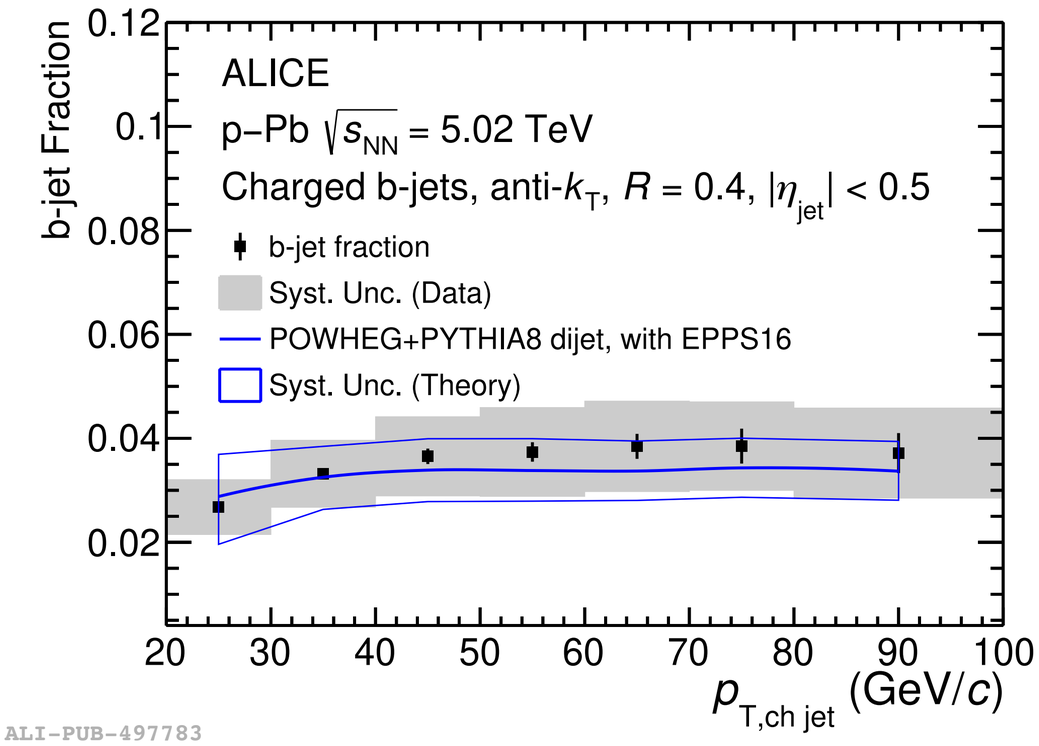


b-jet : arXiv:211006104
POWHEG : S. Frixione et al, JHEP 11 (2007) 070
S. Alioli et al, JHEP 04 (2011) 081

b-jet in pp and pPb collisions at 5.02 TeV

- The measured b-jet fraction is consistent with the POWHEG predictions within uncertainties
- Inclusive charged-particle jet cross sections were taken from
  Phys. Rev. D 100 no.9 (2019) 092004 for **pp** and PLB 749 (2015) 68—81 for **pPb**





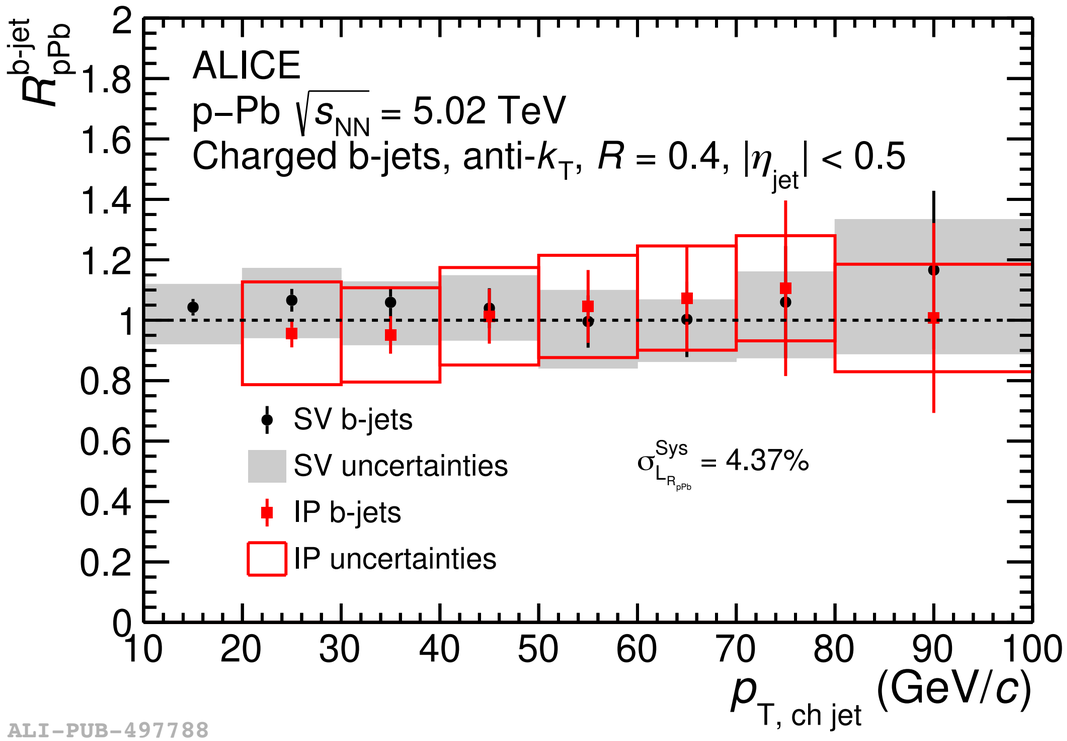
b-jet : arXiv:211006104 , POWHEG : JHEP 11 (2007) 070 JHEP 04 (2011) 081

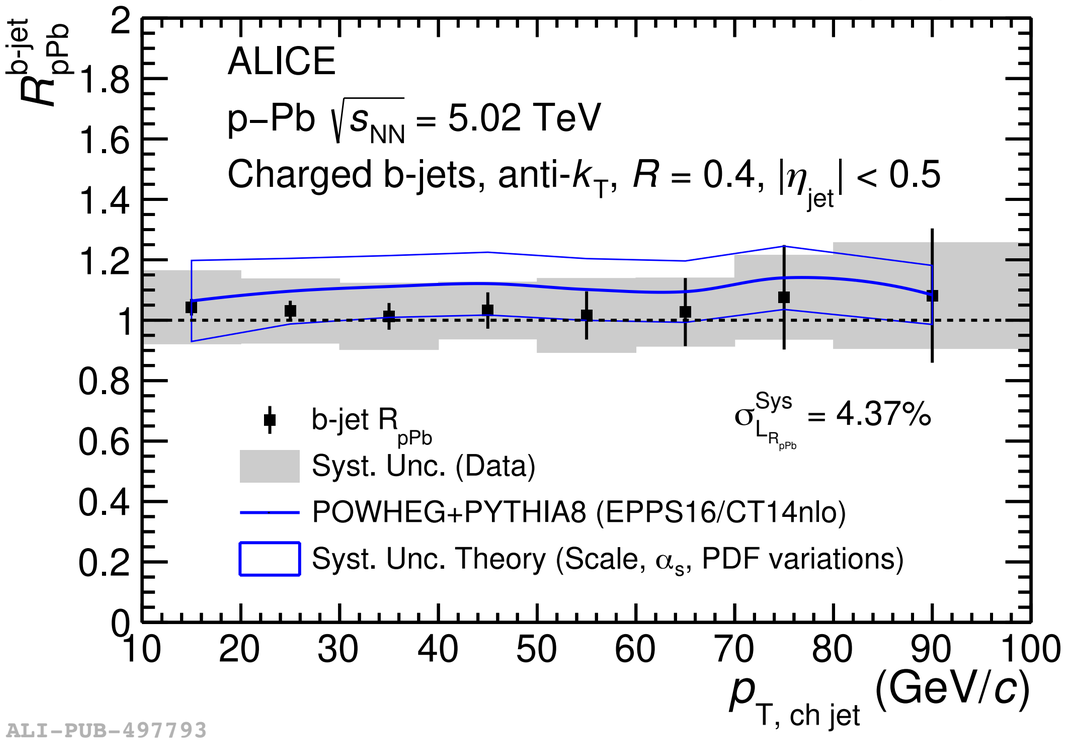
b-jet in pp and pPb collisions at 5.02 TeV

- Consistent between SV and IP methods for R_{pPb} within uncertainties
- Compatible with POWHEG predictions

  → Insensitive to the CNM effect in pPb collisions

b-jet : arXiv:211006104
POWHEG : JHEP 11 (2007) 070
JHEP 04 (2011) 081

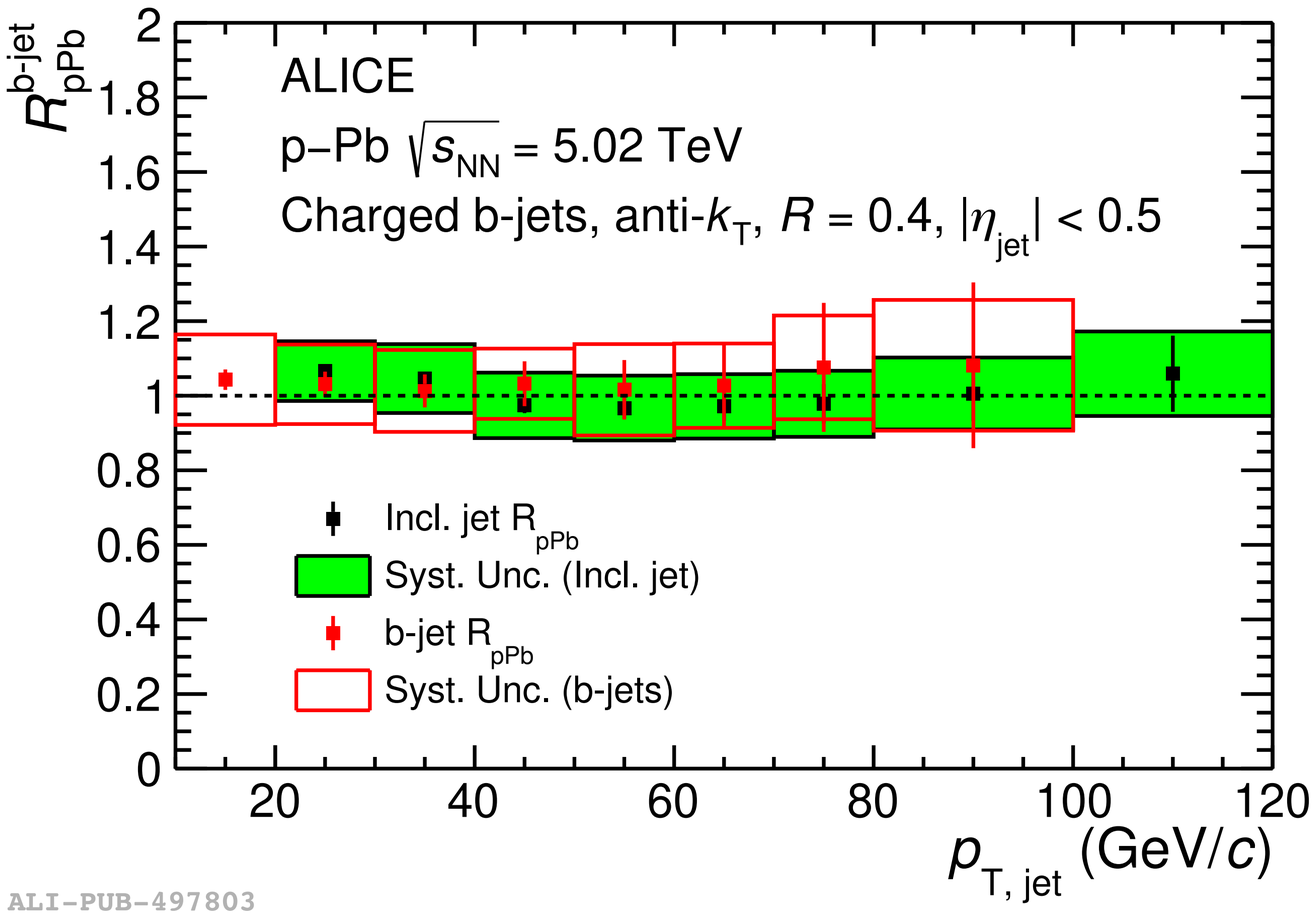




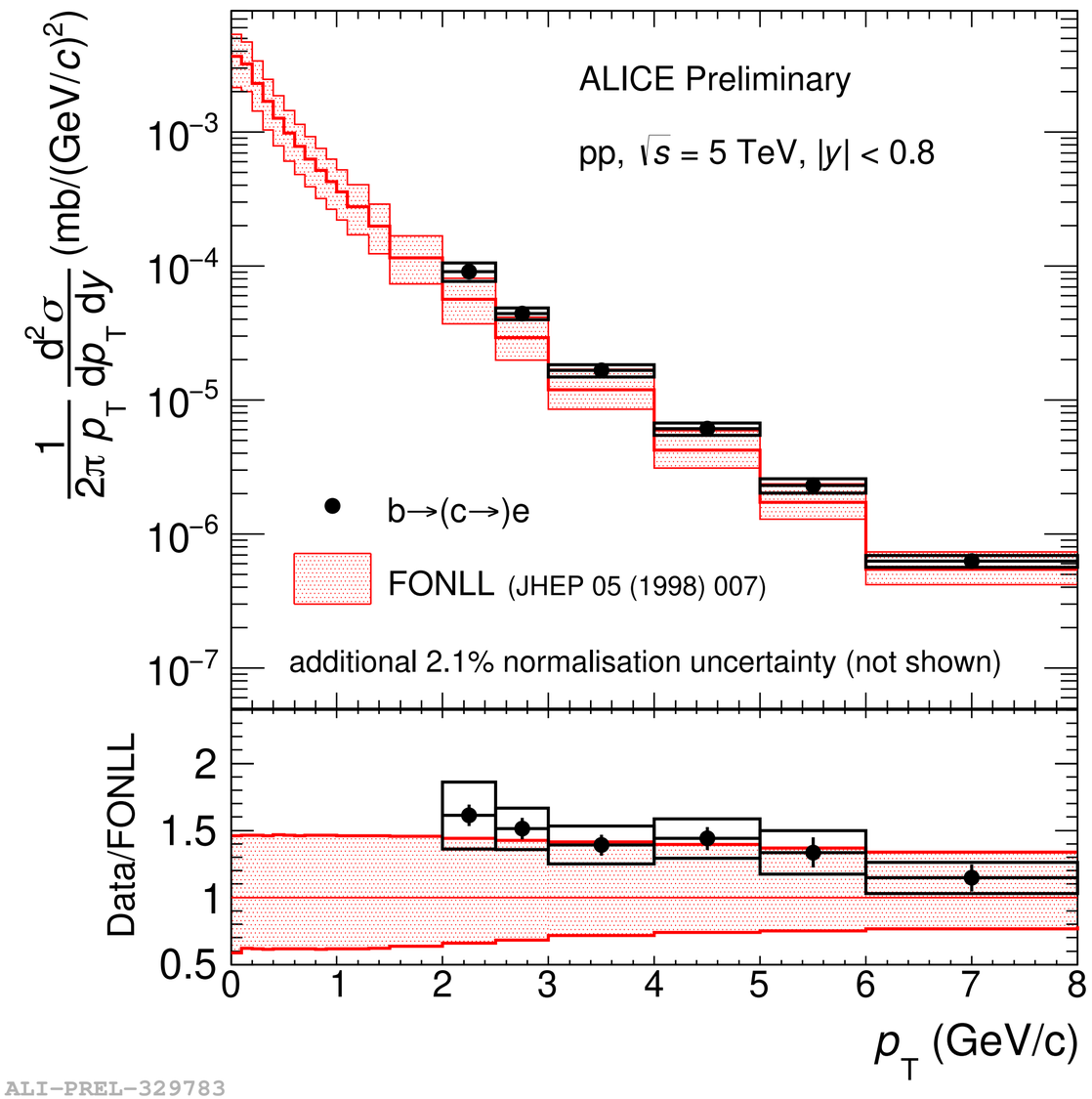
b-jet in pp and pPb collisions at 5.02 TeV

- Both inclusive-jet and b-jet are consistent with unity
  → Mild cold nuclear effect

b-jet : arXiv:211006104 , inclusive-jet : PLB 749 (2015) 68—81

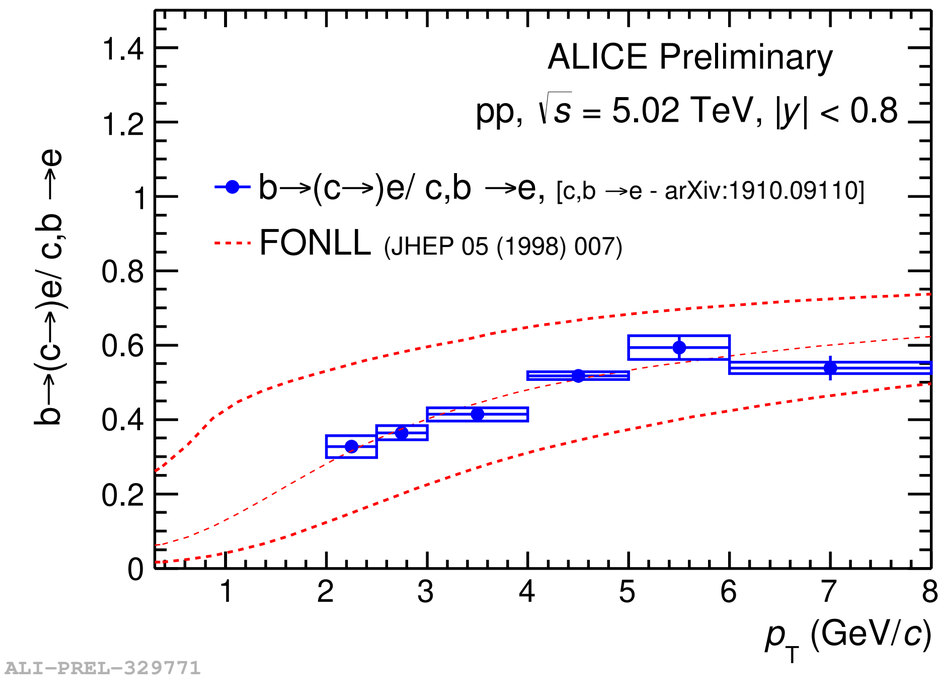


Cross section of b→e in pp collisions



ALI-PREL-329783

- Cross section of b→e in pp collisions
- Compared with FONLL calculation
  - Lying on the upper edge of the prediction
  - Comparable within uncertainties
- Agreement of b→e / b,c→e with FONLL



ALI-PREL-329771

b→e in pp and Pb—Pb collisions at 5.02 TeV

- Comparison of p_T-differential yields of b→e in pp and Pb—Pb collisions
  - pp reference is scaled by the nuclear thickness function
  - FONLL prediction is used as reference for $p_T > 8$ GeV/c