Beauty and charm production in pp collisions via D-meson measurements with ALICE

CERN LHC seminar

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Outline

- Measurements of non-prompt and prompt D mesons at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV
- Production and hadronisation of beauty and charm quarks
- Paper recently submitted for publication ➔ arXiv:2102.13601

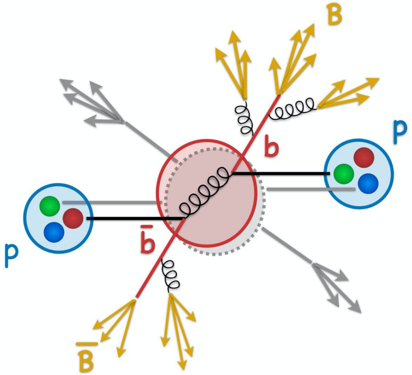
Heavy flavours in proton-proton collisions

- Heavy flavours (c and b quarks) produced in hadronic collisions from hard-scattering processes

- Production described with perturbative QCD calculations based on the factorisation theorem

$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = PDF(x_{\mathrm{a}}, Q^2)\ PDF(x_{\mathrm{b}}, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q\bar{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_{\mathrm{q}}, Q^2)$$

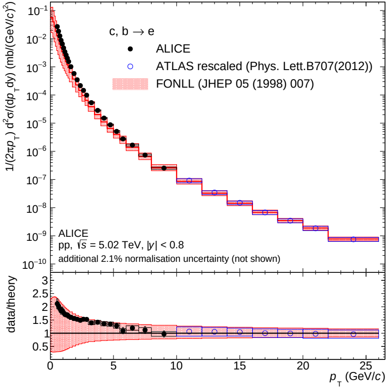
Parton distribution functions (non perturbative)
Partonic cross section (perturbative)
Fragmentation functions (non perturbative)



Heavy flavours in proton-proton collisions

- Heavy flavours (c and b quarks) produced in hadronic collisions from hard-scattering processes
- ALICE provides precise measurements of heavy flavours down to low p_{T} and at midrapidity where the bulk of the production is located

PLB 804 (2020) 135377



- Measurements in pp collisions
  - test of pQCD model calculations for charm and beauty-quark production

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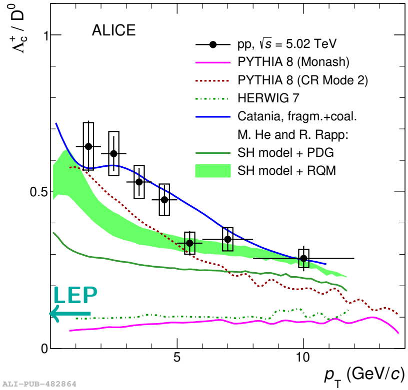
arXiv:2011.06079



- Measurements in pp collisions
  - test of pQCD model calculations for charm and beauty-quark production
  - insights on heavy-flavour hadronisation
- Measured Λ_c^+/D^0 ratio significantly higher than LEP average → hadronisation modified in pp collisions

LEP: L. Gladilin EPJ C75 (2015) 19

Heavy flavours in proton-proton collisions

- Heavy flavours (c and b quarks) produced in hadronic collisions from hard-scattering processes
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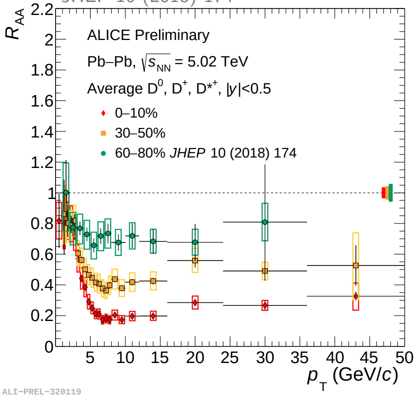
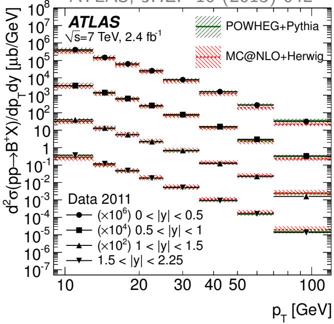
JHEP 10 (2018) 174



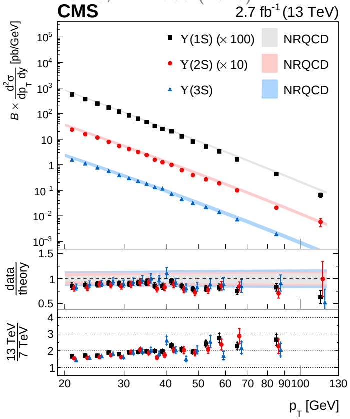
- Measurements in pp collisions
  - test of pQCD model predictions for charm and beauty-quark production
  - insights on heavy-flavour hadronisation
  - reference for the measurements in p–Pb and Pb–Pb collisions

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

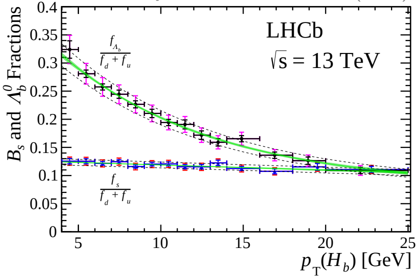
ATLAS, JHEP 10 (2013) 042



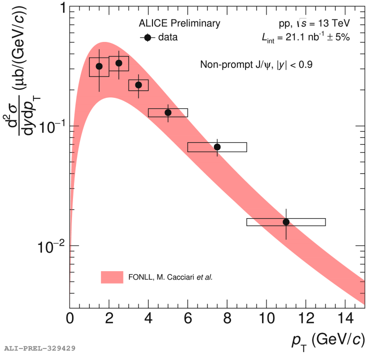
CMS, PLB 780 (2018) 251



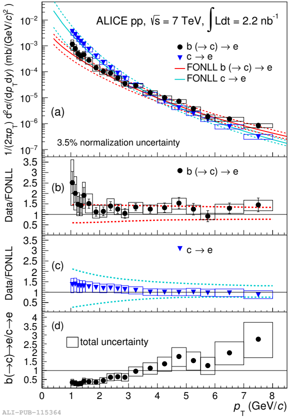
LHCb, Phys. Rev. D 100 031102 (2019)



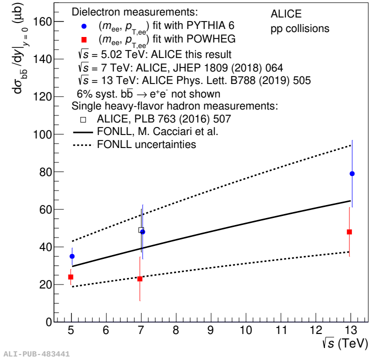
- Beauty-quark production and hadronisation well studied at the LHC with many interesting measurements performed over the years



PLB 721 (2013) 13-23

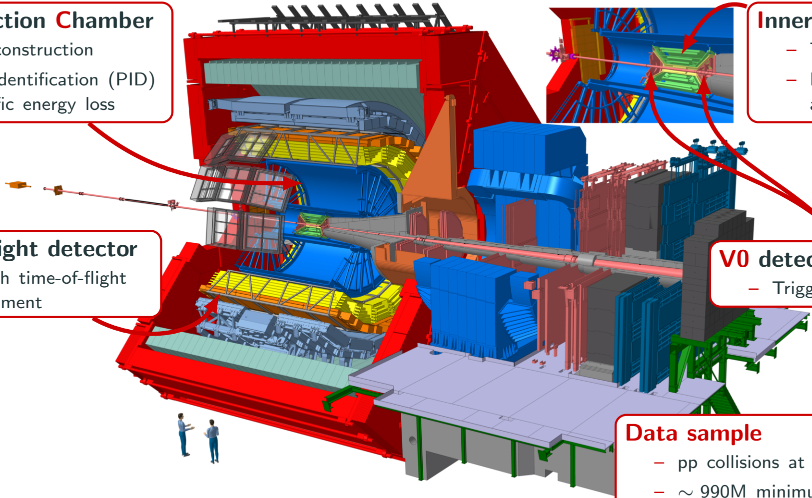


PRC 102 055204 (2020)



- ALICE measurements complementary to other experiments observations in terms of rapidity interval, center-of-mass energy, low-p_T reach and particle species

A Large Ion Collider Experiment



Time Projection Chamber
- Track reconstruction
- Particle identification (PID) via specific energy loss

Inner Tracking System
- Tracking
- Reconstruction of primary and decay vertices

Time of Flight detector
- PID with time-of-flight measurement

V0 detectors
- Trigger and event selection

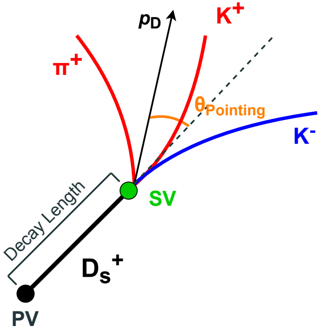
Data sample
- pp collisions at $\sqrt{s} = 5.02$ TeV
- $\sim$ 990M minimum-bias events
- $L_{\rm int} = (19.3 \pm 0.4)$ nb^{-1}

P.A. Zyla et al. (PDG) PTEP 2020 8, 083C01 (2020)

D^0, D^+ and D_s^+ mesons are measured via their hadronic decays

Meson	M (GeV/c^2)	$c\tau$ (µm)	Decay	BR (%)
D^0 ($c\bar{u}$)	$\sim$ 1.865	$\sim$ 123	$K^-\pi^+$	$\sim$ 3.95
D^+ ($c\bar{d}$)	$\sim$ 1.870	$\sim$ 312	$K^-\pi^+\pi^+$	$\sim$ 9.38
D_s^+ ($c\bar{s}$)	$\sim$ 1.968	$\sim$ 151	$\phi(\rightarrow K^-K^+)\pi^+$	$\sim$ 2.24

- ALICE able to reconstruct all decay products and resolve the secondary vertex **SV** from the primary one **PV**



- Candidates from pairs/triplets of tracks at midrapidity ($|\eta| < 0.8$) with proper charge-sign combination
- To reduce the combinatorial background
  - particle identification of decay tracks
  - geometrical and kinematic selections based on displaced decay-vertex topology

P.A. Zyla et al. (PDG) PTEP 2020 8, 083C01 (2020)

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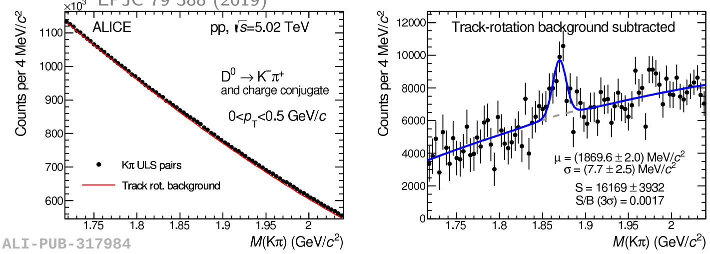
- ALICE able to reconstruct all decay products and resolve the secondary vertex **SV** from the primary one **PV**

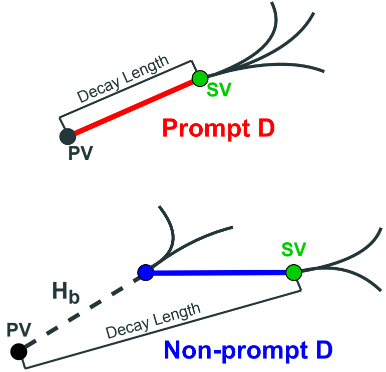
- Prompt D^0 at very low p_T
  - No selections on decay-vertex topology
  - Background distribution subtracted with track-rotation technique

EPJC 79 388 (2019)



P.A. Zyla et al. (PDG) PTEP 2020 8, 083C01 (2020)

- D mesons
  - Prompt, from charm-quark hadronisation or excited charm-hadron decays
  - Non-prompt, from beauty-hadron decays



- Non-prompt D mesons → beauty-quark production and hadronisation
  - different B-meson contributions for each D species

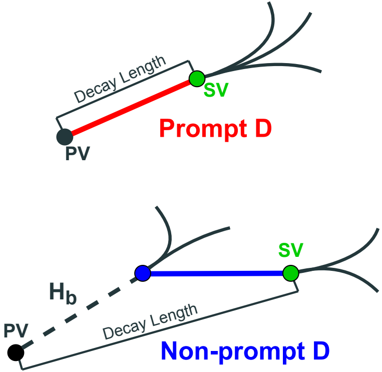
	from B^0	from B^+	from B^0_s
non-prompt D^0	$\sim$ 40%	$\sim$ 60%	–
non-prompt D^+	$\sim$ 75%	$\sim$ 25%	–
non-prompt D^+_s	$\sim$ 25%	$\sim$ 20%	$\sim$ 55%

(PDG BRs and FFs from $Z \to b\bar{b}$ decays, contributions from baryons negligible)

Prompt and non-prompt D mesons

P.A. Zyla et al. (PDG) PTEP 2020 8, 083C01 (2020)

- D mesons
  - Prompt, from charm-quark hadronisation or excited charm-hadron decays
  - Non-prompt, from beauty-hadron decays



- Non-prompt D mesons → beauty-quark production and hadronisation
  - different B-meson contributions for each D species

- Possible to separate prompt and non-prompt D mesons
  - beauty hadrons have $c\tau \simeq 500$ μm
  - non-prompt D on average more displaced from the interaction vertex
  - different topology and kinematic features

Analysis strategy

- D-meson candidate selection based on machine-learning (ML) techniques
  - loose linear selections on geometrical, kinematic and PID quantities applied for data reduction

Raw yields
- fit to candidate invariant-mass distributions

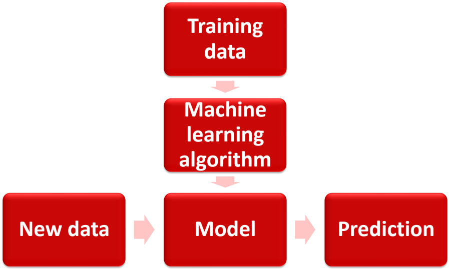
Selection efficiencies
- Monte Carlo simulations

Prompt/non-prompt fraction
- data-driven approach

Results
- p_{T}-differential cross sections
- ...

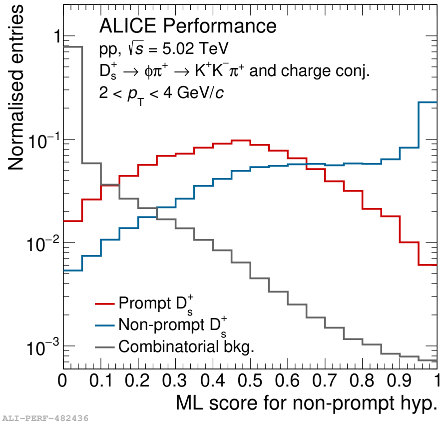
Analysis tools — Supervised machine learning

- Supervised ML models "learn" to make predictions from a set of examples, where the correct classification is known
- They can perform more complex selections w.r.t. the linear selections traditionally used



- To train the model a training set is needed. It is built from
  - Monte Carlo productions → prompt and non-prompt D mesons
  - data collected by the experiment → combinatorial background from sidebands of invariant-mass distribution
- After the training, the ML model is used to predict the class of unknown particle candidates

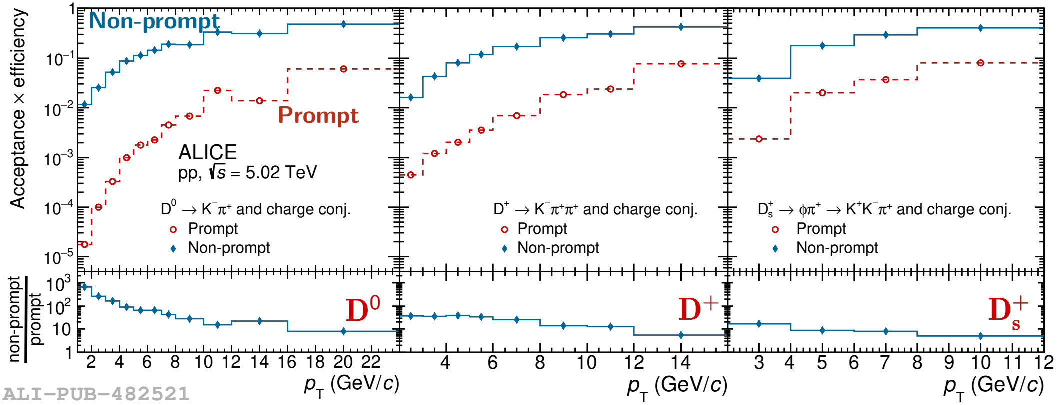
- Multi-class Boosted Decision Trees (BDT) employed to separate prompt D mesons, non-prompt D mesons and combinatorial background
  - different BDTs for D^0, D^+ and D_s^+ mesons and for different transverse-momentum (p_T) intervals



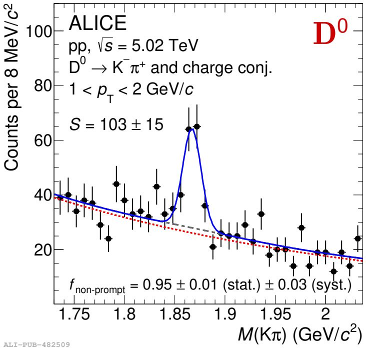
Prompt/Non-prompt D_s^+ from MC, bkg. from data

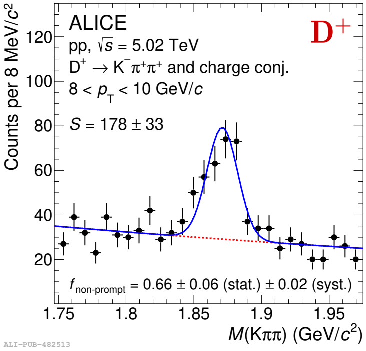
- BDT input: candidate kinematic, geometrical and PID quantities
- BDT output: 3 scores related to the candidate probability to be prompt, non-prompt and background
- Selections applied on these scores to reduce combinatorial background and reject prompt or non-prompt D mesons

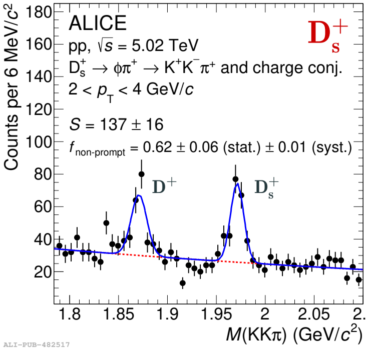
Non-prompt D mesons — Selection efficiencies



- Non-prompt D-meson measurements → selections on BDT scores tuned to suppress the prompt contribution and enhance the non-prompt one in the raw yields
- Prompt efficiencies smaller by a factor $\sim 5 - 700$ depending on the species and p_T



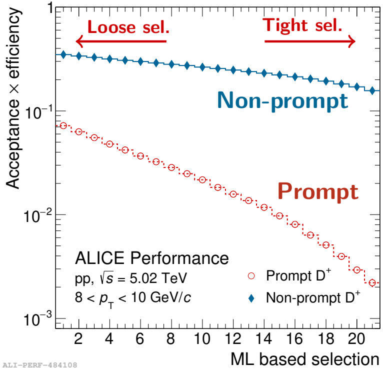




- D^0, D^+ and D_s^+ yields extracted from fit to the invariant-mass distributions of particle candidates
- Enhanced fraction of non-prompt D mesons in the raw yields ➔ estimated with a data-driven approach

Data-driven estimation of non-prompt fraction

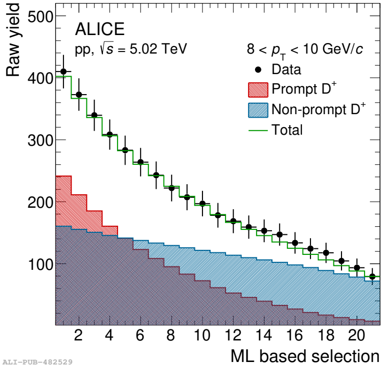
- Define n sets of selections with different prompt and non-prompt D-meson contributions
- For each selection set the raw yield and the efficiencies are related to the corrected yields of prompt N_{prompt} and non-prompt $N_{\mathrm{non\text{-}prompt}}$ D mesons
- An algebraic system is obtained

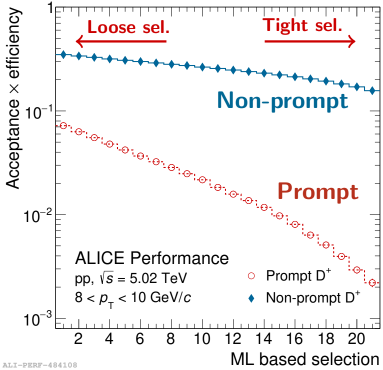


$$
\begin{cases}
(\mathrm{Acc}\times\epsilon)_1^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}} + (\mathrm{Acc}\times\epsilon)_1^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}} = Y_1 \\
\dots \\
(\mathrm{Acc}\times\epsilon)_n^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}} + (\mathrm{Acc}\times\epsilon)_n^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}} = Y_n
\end{cases}
$$

Data-driven estimation of non-prompt fraction

- Define *n* sets of selections with different prompt and non-prompt D-meson contributions





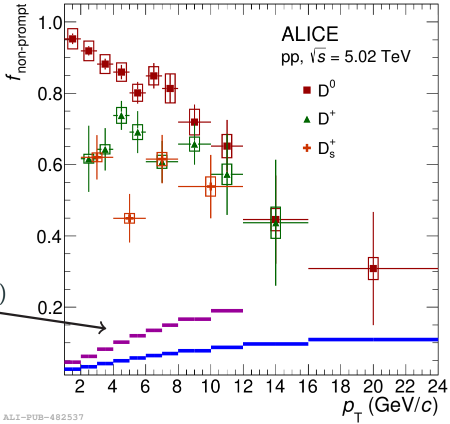
- Corrected yields of prompt and non-prompt D mesons obtained from χ^2 minimization of the system

Data-driven estimation of non-prompt fraction

- Define n sets of selections with different prompt and non-prompt D-meson contributions
- Corrected yields of prompt and non-prompt D mesons obtained from χ^2 minimization of the system

"Natural" $f_{\text{non-prompt}}$ (FONLL + PYTHIA)

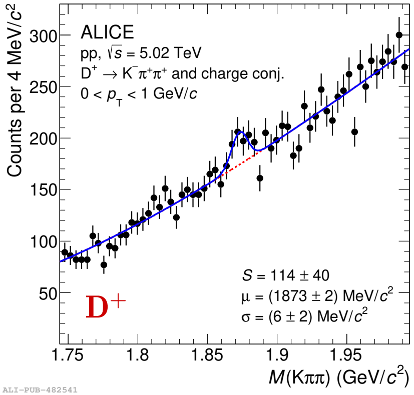
$\mathbf{D^0}$, $\mathbf{D^+}$ $\mathbf{D_s^+}$

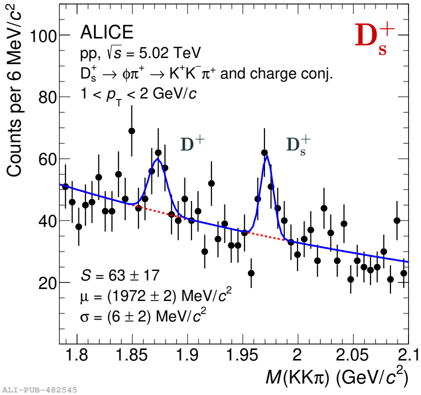


- Non-prompt fraction $f_{\text{non-prompt}}$ evaluated for a given set of selections as

$$f^{\text{i}}_{\text{non-prompt}} = \frac{(\text{Acc} \times \epsilon)^{\text{non-prompt}}_{\text{i}} \cdot N_{\text{non-prompt}}}{(\text{Acc} \times \epsilon)^{\text{non-prompt}}_{\text{i}} \cdot N_{\text{non-prompt}} + (\text{Acc} \times \epsilon)^{\text{prompt}}_{\text{i}} \cdot N_{\text{prompt}}}$$

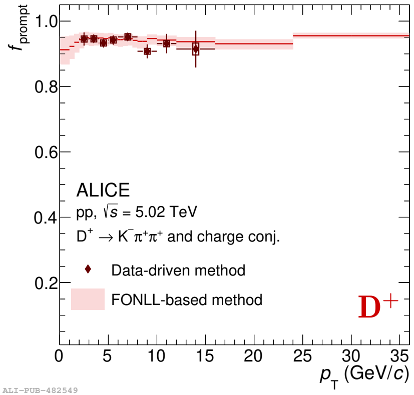
Prompt D^+ and D_s^+ mesons — Raw-yield extraction

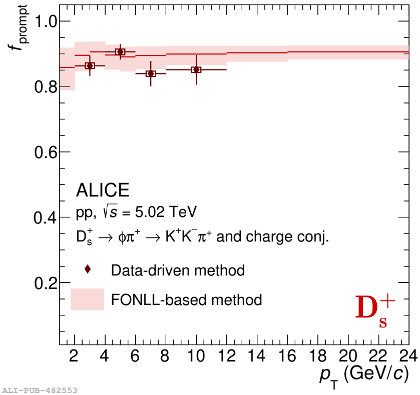




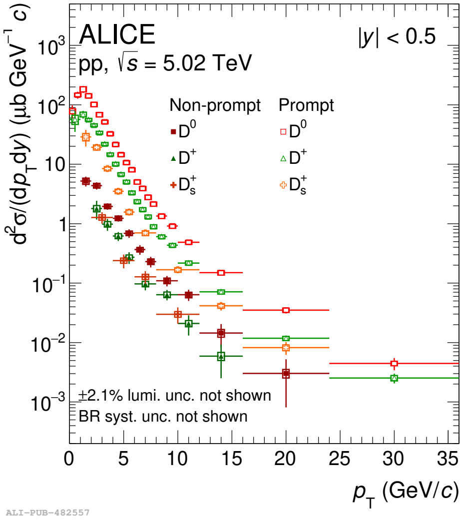
- Selections on BDT scores tuned to reject combinatorial background and non-prompt D mesons
- Measurements extended to lower p_T and total uncertainties reduced of $\sim 5 - 40\%$ w.r.t. previously published results based on linear selections (EPJC 79 388 (2019))

Prompt D^+ and D_s^+ mesons — Prompt fraction





- Data-driven approach not feasible in all the measured p_T intervals → prompt fraction from theory-driven method based on FONLL predictions for beauty-hadron production
- Good agreement with the data-driven approach where the comparison is possible

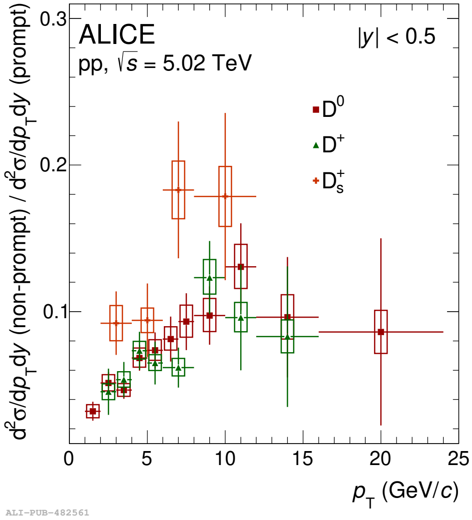


- Prompt and non-prompt D mesons measured down to very low transverse momenta
- Prompt D^0 from EPJC 79 388 (2019)
- Prompt D^+ and D_s^+ measurements updated using ML → larger p_T reach w.r.t. previous results

Prompt D^0: EPJC 79 388 (2019)

- Cross section ratios of non-prompt and prompt D mesons increase with p_T up to 12 GeV/c
  - beauty-hadron p_T distribution harder than D mesons
- Hint of larger ratio for D_s^+ mesons
  - larger contribution of beauty-hadron decays compared to non-strange D mesons

$$b \to c\bar{c}s \qquad \bar{b} \to c\bar{c}\bar{s}$$



Comparison with pQCD calculations

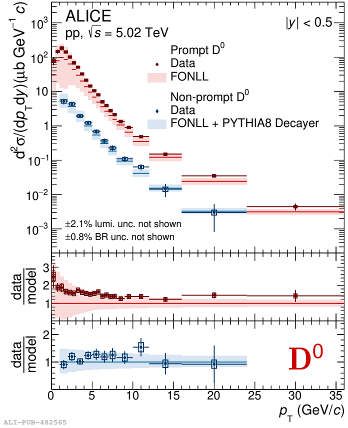
FONLL: M. Cacciari et al. JHEP 1210 137 (2012)   PYTHIA8: T. Sjöstrand et al. JHEP 05 026 (2006)   GM-VFNS: G. Kramer et al., Nucl. Phys. B 925 415-430 (2017)

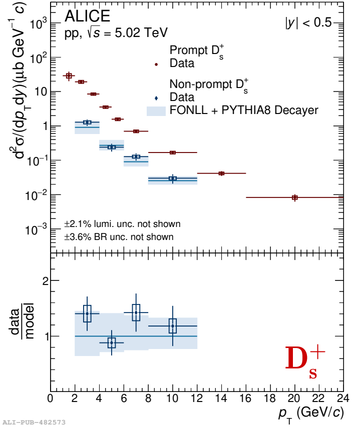
D-meson measurements compared with pQCD calculations at next-to-leading-order with next-to-leading log resummation

- FONLL
  - $m_{\mathrm{c}} = 1.5\ \mathrm{GeV}/c^2$ and $m_{\mathrm{b}} = 4.75\ \mathrm{GeV}/c^2$
  - CTEQ6.6 PDFs
  - Prompt D ➔ $f(\mathrm{c} \rightarrow \mathrm{D})$ from LEP average, $\mathrm{D_s^+}$ not available
  - Non-prompt D ➔ $f(\mathrm{b} \rightarrow \mathrm{H_b})$ from $\mathrm{e^+e^-}$ and PYTHIA8 for $\mathrm{H_b} \rightarrow \mathrm{D} + \mathrm{X}$ decay kinematics and BRs
- GM-VFNS
  - $m_{\mathrm{c}} = 1.3\ \mathrm{GeV}/c^2$ and $m_{\mathrm{b}} = 4.5\ \mathrm{GeV}/c^2$
  - CTEQ14 PDFs
  - Prompt D ➔ $f(\mathrm{c} \rightarrow \mathrm{D})$ from $\mathrm{e^+e^-}$ measurements
  - Non-prompt D
    - 'single step' with $\mathrm{b} \rightarrow \mathrm{D} + \mathrm{X}$ FFs from $\mathrm{e^+e^-}$ (T. Kneesch et al. Nucl. Phys. B 799 34-59)
    - 'double step' with $f(\mathrm{b} \rightarrow \mathrm{H_b})$ and $\mathrm{H_b} \rightarrow \mathrm{D} + \mathrm{X}$ decays (P. Bolzoni et al. J. Phys. G 41 075006)

Results — Comparison with pQCD calculations

Prompt $\mathrm{D^0}$: EPJC 79 388 (2019) FONLL: M. Cacciari et al. JHEP 1210 137 (2012) PYTHIA8: T. Sjöstrand et al. JHEP 05 026 (2006)



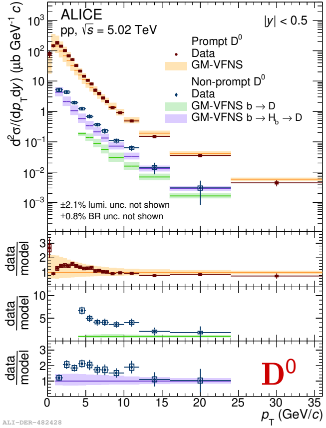


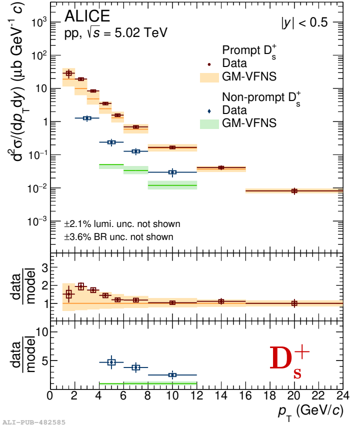
- D-meson p_{T}-differential cross sections described by FONLL calculations down to low p_{T}

- Prompt $\mathrm{D^0}$ mesons on FONLL upper edge. Non-prompt D compatible with central values
  - $f(\mathrm{c} \to \mathrm{D})$ and $f(\mathrm{b} \to \mathrm{H_b})$ fragmentation fractions (FFs) from $\mathrm{e^+e^-}$ measurements
  - non-prompt D mesons ➔ PYTHIA8 to describe $\mathrm{H_b} \to \mathrm{D} + \mathrm{X}$ decays

Results — Comparison with pQCD calculations

Prompt D^0: EPJC 79 388 (2019) GM-VFNS: G. Kramer et al, Nucl. Phys. B 925 415-430 T. Kneesch et al. Nucl. Phys. B 799 34-59 P. Bolzoni et al. J. Phys. G 41 075006

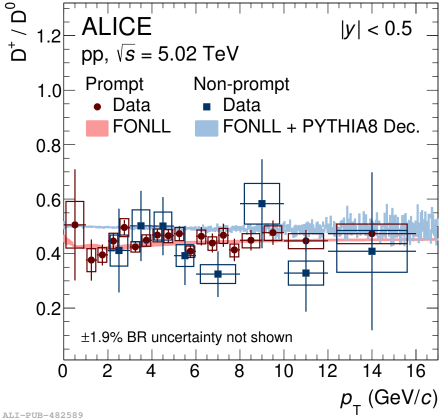


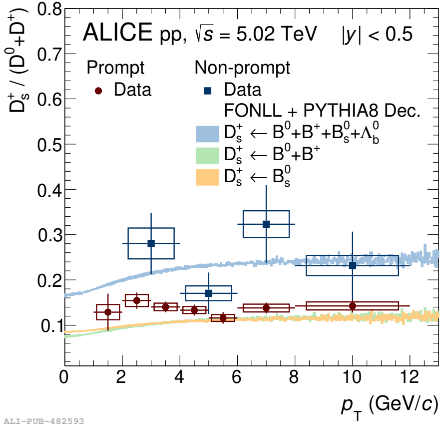


- GM-VFNS calculations describe within uncertainties the prompt D-meson measurements

- Non-prompt D mesons constrain the non-perturbative terms of the factorisation theorem
  - approach using FFs for $b \to D + X$ from e^+e^- measurements underestimate the measurements
  - better description with separate $b \to H_b$ fragmentation and $H_b \to D + X$ decay kinematics

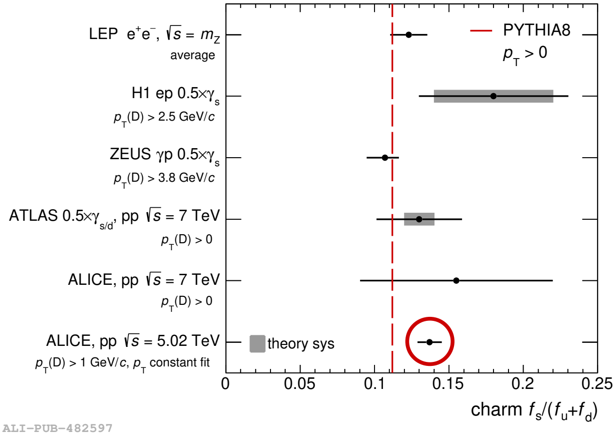
FONLL: M. Cacciari et al. JHEP 1210 137 (2012)   PYTHIA8: T. Sjöstrand et al. JHEP 05 026 (2006)





- D-meson ratios flat in p_T and in good agreement with FONLL predictions
  - Compatible prompt and non-prompt D^+/D^0 ratios
  - $D_s^+/(D^0+D^+)$ ratio higher for non-prompt D mesons. Substantial B_s^0-decay contribution

PYTHIA8: P. Skands et al. EPJC 74 3024 (2014)
LEP: L. Gladilin EPJC 75 19 (2015)
H1: EPJC 38 447-459 (2005)
ZEUS: JHEP 09 058 (2013)
ATLAS: Nucl. Phys. B 907 717-763 (2016)
ALICE, 7 TeV: PLB 718 279-294 (2012)

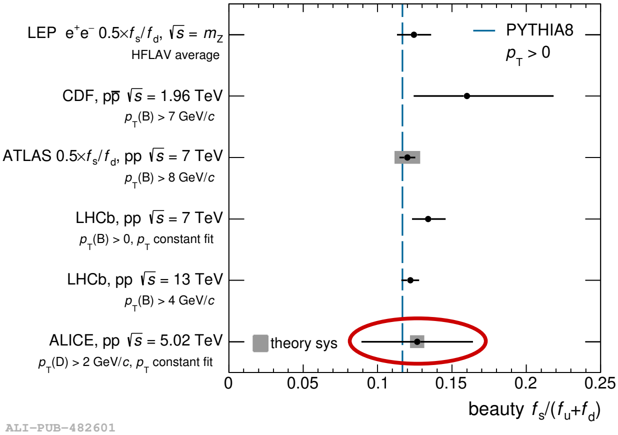


- Charm-quark $f_s/(f_u + f_d)$ ratio from constant fit to prompt $D_s^+/(D^0 + D^+)$
- Very precise measurement in agreement with previous observations
- Compatible with PYTHIA8 Monash-13 tune simulations (2.7 σ)

$$\left(\frac{f_s}{f_u + f_d}\right)_{\text{charm}} = 0.137 \pm 0.005(\text{stat}) \pm 0.008(\text{tot.syst})$$

Results — Fragmentation fractions of beauty quarks

PYTHIA8: P. Skands et al. EPJC 74 3024 (2014)
LEP: Y. Amhis et al. (HFLAV) arXiv:1909.12524
CDF: Phys. Rev. D 77 072003 (2008)
ATLAS: PRL 115 262001 (2015)
LHCb, 7 TeV: Phys. Rev. D 85 032008 (2012)
LHCb, 13 TeV: Phys. Rev. D 100 031102 (2019)

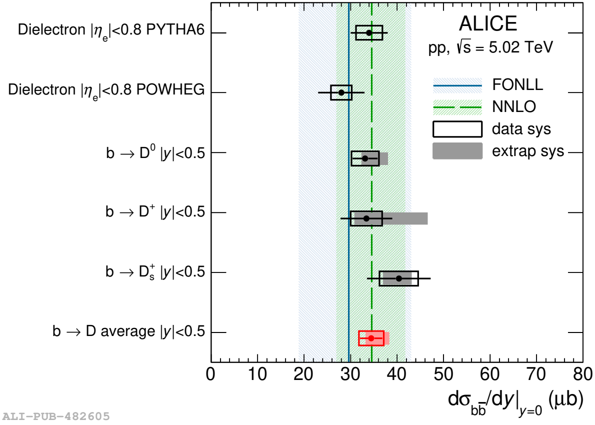


- Beauty-quark $f_s/(f_u + f_d)$ from constant fit to non-prompt $D_s^+/(D^0 + D^+)$ ratio
- Correction to account for non-prompt D_s^+ mesons from B^0 and B^+ decays
- Value compatible with previous measurements and PYTHIA8

$$\left(\frac{f_s}{f_u + f_d}\right)_{\text{beauty}} = 0.127 \pm 0.036(\text{stat}) \pm 0.014(\text{tot.syst})$$

Dielectron: Phys. Rev. C 102 055204 (2020)   FONLL: M. Cacciari et al. JHEP 1210 137 (2012)   NNLO: S. Catani et al. JHEP 03 029 (2021)

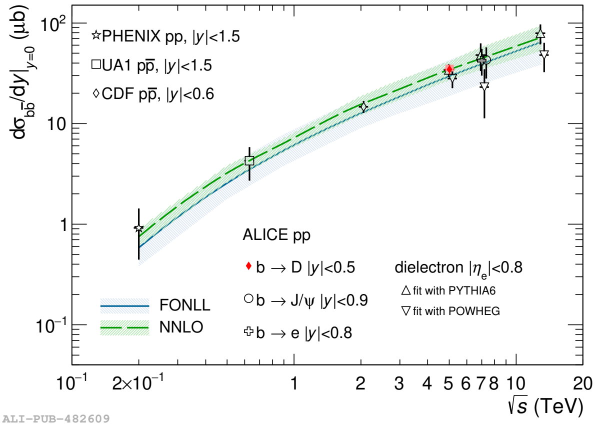
- p_T-differential non-prompt D-meson measurement → p_T-integrated cross section → $b\bar{b}$ production cross section at midrapidity



- D-meson average compatible with previous ALICE measurements
- Good agreement with FONLL and calculations including NNLO QCD radiative corrections

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

Results — Beauty-quark production cross section



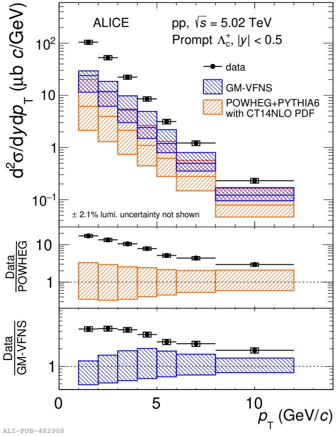
PHENIX: PRL 103 082002 (2009)
UA1: PLB 256 121–128 (1991)
CDF: Phys. Rev. D 75 012010 (2007)
b → J/Ψ: JHEP 11 065 (2012)
b → e: PLB 721 13-23 (2013)
Dielectron, 5 TeV: PRC 102 055204 (2020)
Dielectron, 7 TeV: JHEP 09 064 (2018)
Dielectron, 13 TeV: PLB 788 505-518 (2019)
FONLL: M. Cacciari et al. JHEP 1210 137 (2012)
NNLO: S. Catani et al. JHEP 03 029 (2021)

- Beauty-quark production described by FONLL and NNLO calculations over a wide interval of center-of-mass energies

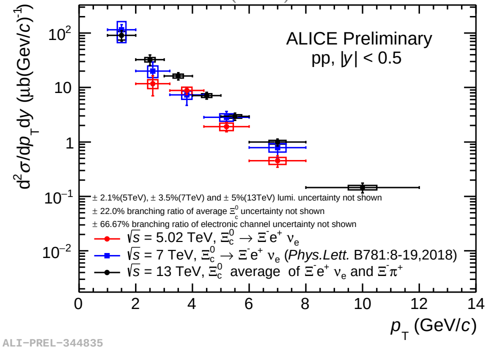
Towards the total charm cross section in pp at 5 TeV

- Production of Λ_c^+ and Ξ_c^0 measured in pp collisions at $\sqrt{s} = 5.02$ TeV

arXiv:2011.06079



PLB 781 8-19 (2018)



- Precise D-meson measurements down to zero p_{T} and recent measurements of charmed baryon states ➔ crucial for the evaluation of $c\bar{c}$ cross section at midrapidity

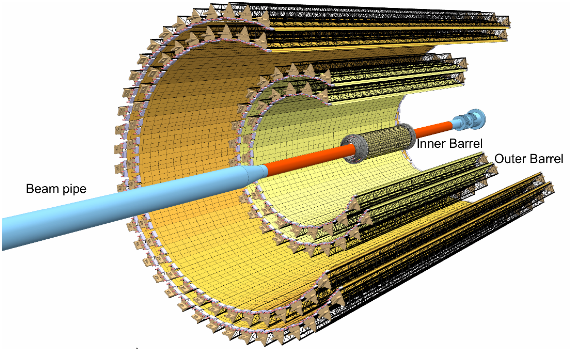
Prospects for Run 3

J. Phys. G 41 087001 (2014)

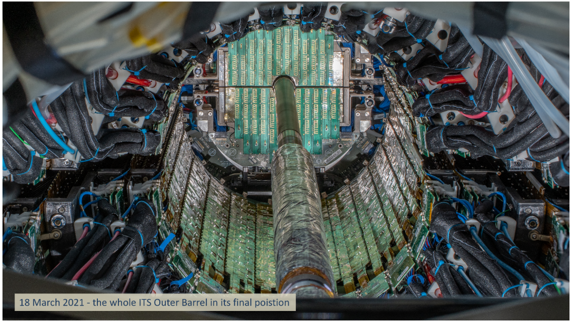
- Major upgrade of ALICE detectors and read-out electronics ongoing

- New Inner Tracking System (ITS2) crucial for heavy-flavour measurements

	ITS	ITS2
# of layers	6	7
$\boldsymbol{X/X_0}$	1.14%	0.38%
innermost radius	39 mm	22 mm
pixel size	$50 \times 425\ \mathrm{m\mu}^2$	$30 \times 30\ \mathrm{m\mu}^2$
read-out rate	1 kHz	few 100s kHz pp 50 kHz Pb–Pb

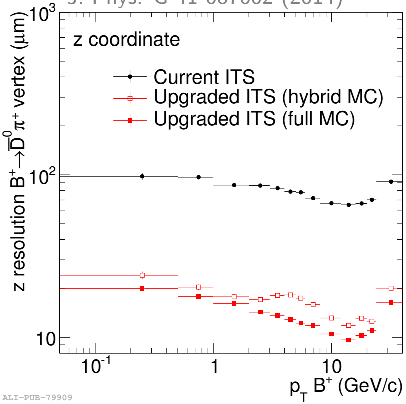


Prospects for Run 3

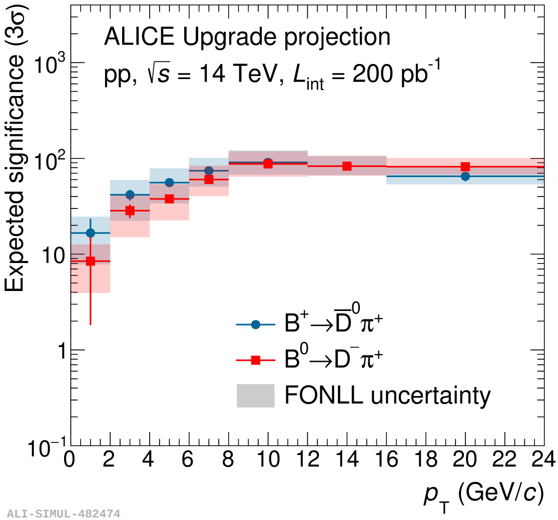


- Upgraded Inner Tracking System → improved track and secondary-vertex resolution

J. Phys. G 41 087002 (2014)



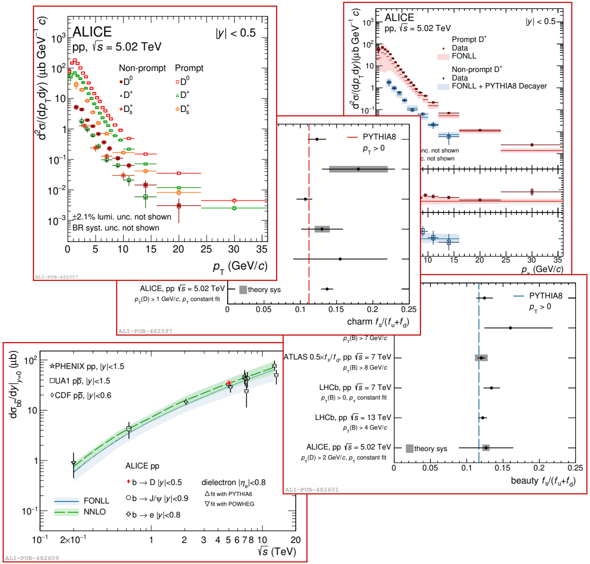
CERN-LHCC-2020-018



- Upgraded Inner Tracking System ➔ improved track and secondary-vertex resolution
- Expected large increase ($\sim 5 \cdot 10^3$) of integrated luminosity L_{int}
  - dedicated software triggers for heavy-flavour hadron selection
- Very precise measurements of non-prompt D and B mesons down to $p_{\mathrm{T}} = 0\ \mathrm{GeV}/c$

Conclusions

- Prompt and non-prompt D mesons measured with high precision down to low p_{T} using ML techniques
- Addition to ALICE HF measurements
  - potential to constrain pQCD calculations
  - precise study of $\mathrm{b\bar{b}}$ production and hadronisation
  - crucial for $\mathrm{c\bar{c}}$ cross section measurement
- Just an appetizer for ALICE beauty measurements of Run 3 with upgraded detectors and larger data samples



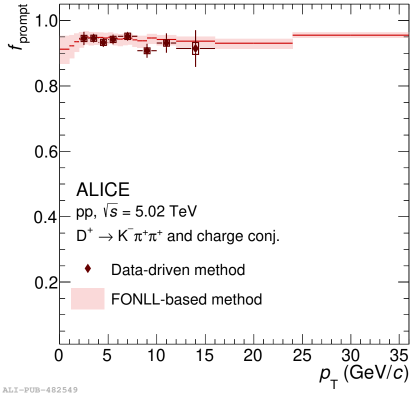
Backup

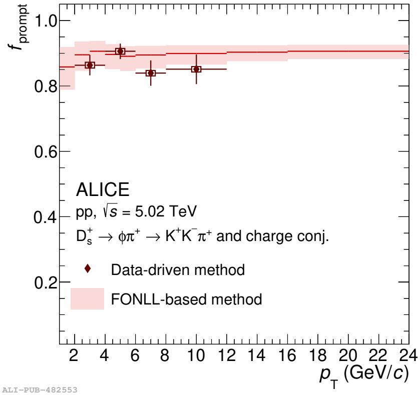
Beauty-quark fragmentation fractions

PDG: PTEP 2020 8, 083C01 (2020)

b-hadron	Fraction at Z (%)	Fraction at $p\bar{p}$ (%)
B^0, B^+	40.8 ± 0.7	34.4 ± 2.1
B_s^0	10.0 ± 0.8	11.5 ± 1.3
Λ_b^0	8.4 ± 1.1	19.8 ± 4.6

Prompt D^+ and D_s^+ mesons — Prompt fraction



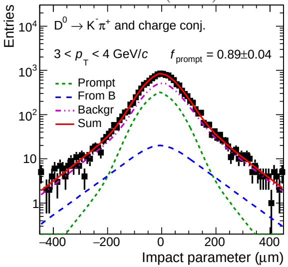


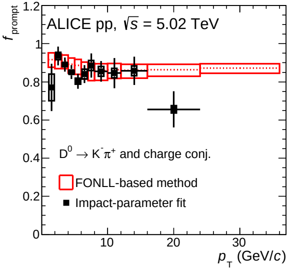
- Prompt fraction from theory-driven method based on FONLL predictions

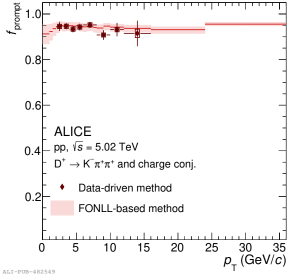
$$f_{\text{prompt}} = 1 - \frac{N_{\text{raw}}^{\text{D non-prompt}}}{N_{\text{raw}}^{\text{D}}} = 1 - \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right)^{\text{FONLL}}_{\text{non-prompt}} \cdot \frac{(\text{Acc}\times\epsilon)_{\text{non-prompt}} \cdot \Delta y \Delta p_{\mathrm{T}} \cdot \text{BR} \cdot L_{\text{int}}}{N^{\mathrm{D}+\overline{\mathrm{D}},\text{raw}}/2}$$

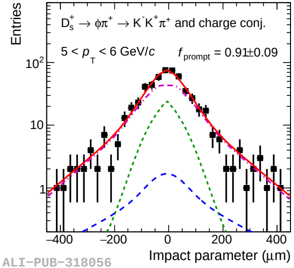
Prompt fraction — Impact-parameter method

EPJC 79 388 (2019)

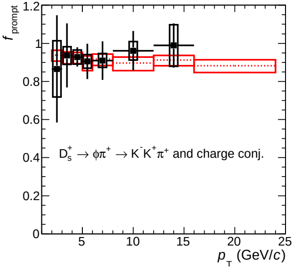


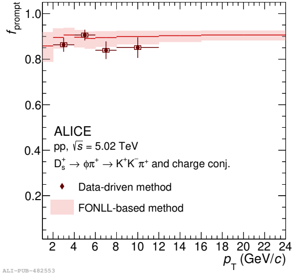




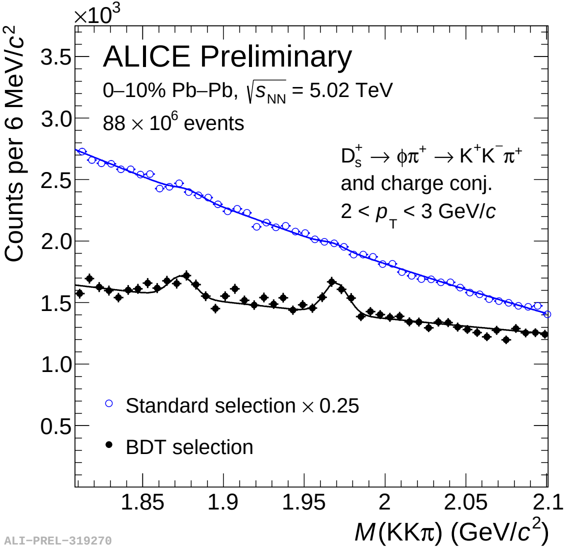


ALI-PUB-318056





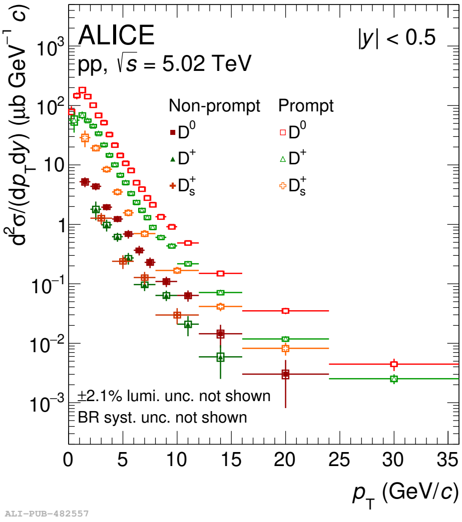
Selections improved with machine learning



ALI−PREL−319270

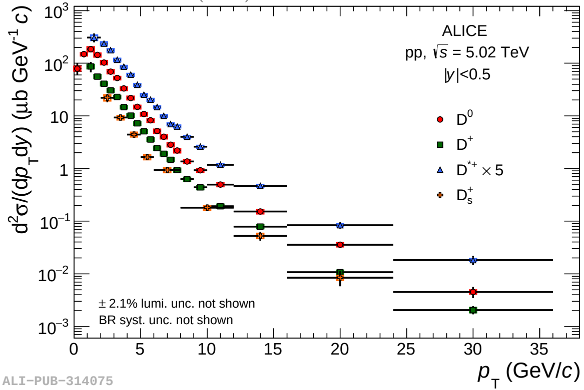
- Example from Pb–Pb collisions
- Using ML selections it is possible to extract the signal in a region $(2 < p_{\mathrm{T}} < 3\ \mathrm{GeV}/c)$ where the linear selections do not give a clear $\mathrm{D_s^+}$ peak

Prompt D^{+} and D_s^{+} cross sections vs. 2019 paper



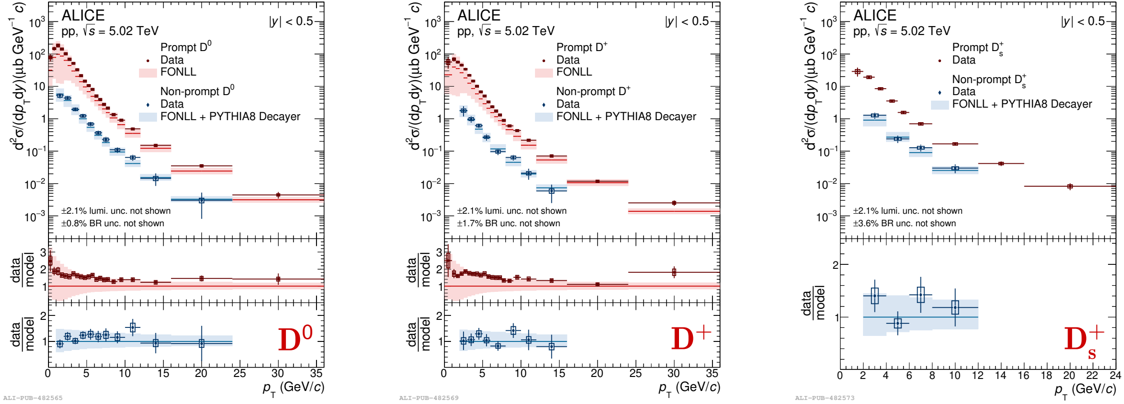
- Measurement of prompt D^{+} and D_s^{+} mesons updated using ML → extension to lower transverse momenta w.r.t. 2019 result

EPJC 79 388 (2019)



Results — Comparison with pQCD predictions

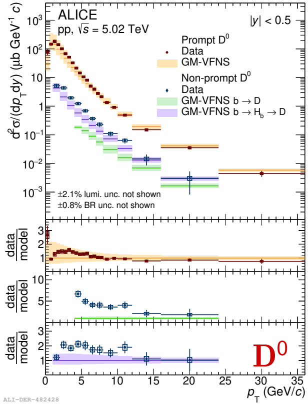
Prompt D^0: EPJC 79 388 (2019) FONLL: JHEP 1210 137 (2012) PYTHIA8: JHEP 05 026 (2006)

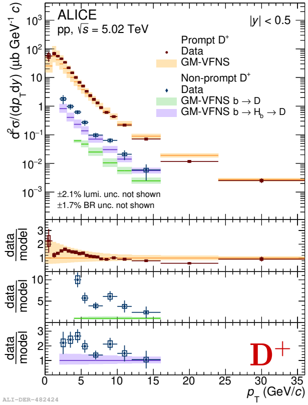


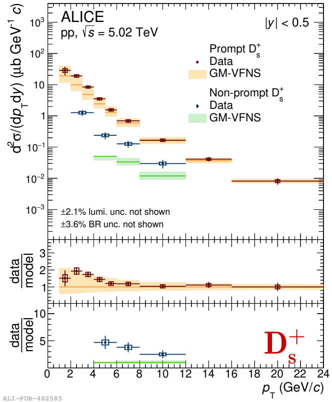
- D-meson p_{T}-differential cross sections described by FONLL calculations down to low p_{T}
  - prompt D^0 and D^+ mesons on FONLL upper edge. Non-prompt D compatible with central values
  - $f(\mathrm{c} \to \mathrm{D})$ and $f(\mathrm{b} \to \mathrm{H_b})$ fragmentation fractions (FFs) from $\mathrm{e^+e^-}$ measurements
  - non-prompt D mesons → PYTHIA8 to describe $\mathrm{H_b} \to \mathrm{D} + \mathrm{X}$ decays

Results — Comparison with pQCD predictions

Prompt D^0: EPJC 79 388 (2019) GM-VFNS: Nucl. Phys. B 925 415-430 (2017) Nucl. Phys. B 799 34-59 (2008) J. Phys. G 41 075006 (2014)







- GM-VFNS calculations describe within uncertainties the prompt D-meson measurements
- Non-prompt D mesons constrain the non-perturbative terms of the factorisation theorem
  - approach using FFs for $\mathrm{b} \to \mathrm{D} + \mathrm{X}$ from $\mathrm{e}^{+}\mathrm{e}^{-}$ measurements underestimate the measurements
  - better description with separate $\mathrm{b} \to \mathrm{H_b}$ fragmentation and $\mathrm{H_b} \to \mathrm{D} + \mathrm{X}$ decay kinematics

Visible p_{T}-integrated cross sections

Table 3: p_{T}-integrated production cross sections in the measured p_{T} range for prompt and non-prompt D mesons in the range $|y| < 0.5$ in pp collisions at $\sqrt{s} = 5.02$ TeV.

Meson	Kinematic range (GeV/c)	Visible cross section (μb)
Prompt		
D^0	$0 < p_{\mathrm{T}} < 36$	$440 \pm 19(\mathrm{stat}) \pm 29(\mathrm{syst}) \pm 9(\mathrm{lumi}) \pm 3(\mathrm{BR})$
D^+	$0 < p_{\mathrm{T}} < 36$	$195 \pm 23(\mathrm{stat}) \pm 16(\mathrm{syst}) \pm 4(\mathrm{lumi}) \pm 3(\mathrm{BR})$
D_s^+	$1 < p_{\mathrm{T}} < 24$	$64 \pm 9(\mathrm{stat})^{+6}_{-7}(\mathrm{syst}) \pm 1(\mathrm{lumi}) \pm 2(\mathrm{BR})$
Non-prompt		
D^0	$1 < p_{\mathrm{T}} < 24$	$14.5 \pm 1.2(\mathrm{stat}) \pm 1.3(\mathrm{syst}) \pm 0.3(\mathrm{lumi}) \pm 0.1(\mathrm{BR})$
D^+	$2 < p_{\mathrm{T}} < 16$	$4.1 \pm 0.7(\mathrm{stat}) \pm 0.4(\mathrm{syst}) \pm 0.1(\mathrm{lumi}) \pm 0.1(\mathrm{BR})$
D_s^+	$2 < p_{\mathrm{T}} < 12$	$3.4 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst}) \pm 0.1(\mathrm{lumi}) \pm 0.1(\mathrm{BR})$

Total p_T-integrated cross sections

Table 4: Production cross sections of prompt and non-prompt D mesons in the range $|y| < 0.5$ in pp collisions at $\sqrt{s} = 5.02$ TeV.

Meson	Extr. factor to $p_T > 0$	$d\sigma/dy\|_{\|y\|<0.5}$ (μb)
Prompt		
D^0	$1.0000^{+0.0003}_{-0.0000}$	$440 \pm 19(\text{stat}) \pm 29(\text{syst}) \pm 9(\text{lumi}) \pm 3(\text{BR})$
D^+	$1.0000^{+0.0003}_{-0.0000}$	$195 \pm 23(\text{stat}) \pm 16(\text{syst}) \pm 4(\text{lumi}) \pm 3(\text{BR})$
D_s^+	$1.28^{+0.35}_{-0.12}$	$82 \pm 12(\text{stat}) \pm 8(\text{syst}) \pm 2(\text{lumi}) \pm 3(\text{BR})^{+23}_{-8}(\text{extr})$
Non-prompt		
D^0	$1.28^{+0.01}_{-0.04}$	$18.4 \pm 1.5(\text{stat}) \pm 1.6(\text{syst}) \pm 0.4(\text{lumi}) \pm 0.1(\text{BR})^{+0.1}_{-0.6}(\text{extr})$
D^+	$2.22^{+0.05}_{-0.19}$	$9.0 \pm 1.5(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi}) \pm 0.2(\text{BR})^{+0.2}_{-0.8}(\text{extr})$
D_s^+	$2.03^{+0.04}_{-0.15}$	$6.9 \pm 1.2(\text{stat}) \pm 0.7(\text{syst}) \pm 0.1(\text{lumi}) \pm 0.2(\text{BR})^{+0.1}_{-0.5}(\text{extr})$

Total D-meson cross section ratios

Table 5: Ratios of the measured production cross sections of prompt and non-prompt D mesons in the $|y| < 0.5$ in pp collisions at $\sqrt{s} = 5.02$ TeV.

Prompt	
D^+/D^0	$0.442 \pm 0.055(\text{stat}) \pm 0.033(\text{syst}) \pm 0.008(\text{BR})$
D_s^+/D^0	$0.186 \pm 0.028(\text{stat}) \pm 0.015(\text{syst}) \pm 0.007(\text{BR})^{+0.051}_{-0.018}(\text{extr})$
D_s^+/D^+	$0.420 \pm 0.078(\text{stat}) \pm 0.041(\text{syst}) \pm 0.017(\text{BR})^{+0.116}_{-0.040}(\text{extr})$
$D_s^+/(D^0 + D^+)$	$0.129 \pm 0.020(\text{stat}) \pm 0.010(\text{syst})^{\pm}0.005(\text{BR})^{+0.036}_{-0.012}(\text{extr})$
Non-prompt	
D^+/D^0	$0.487 \pm 0.090(\text{stat}) \pm 0.055(\text{syst}) \pm 0.009(\text{BR})^{+0.007}_{-0.027}(\text{extr})$
D_s^+/D^0	$0.374 \pm 0.071(\text{stat}) \pm 0.041(\text{syst}) \pm 0.014(\text{BR})^{+0.004}_{-0.016}(\text{extr})$
D_s^+/D^+	$0.769 \pm 0.183(\text{stat}) \pm 0.086(\text{syst}) \pm 0.030(\text{BR})^{+0.003}_{-0.010}(\text{extr})$
$D_s^+/(D^0 + D^+)$	$0.252 \pm 0.047(\text{stat}) \pm 0.023(\text{syst}) \pm 0.009(\text{BR})^{+0.001}_{-0.006}(\text{extr})$

Beauty FF ratio and cross section corrections

- Correction for beauty-quark FF ratio

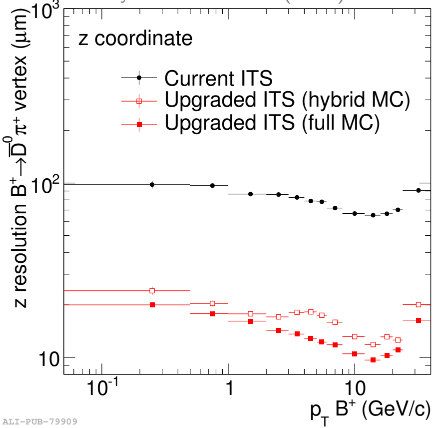
$$\left(\frac{f_{\rm s}}{f_{\rm u}+f_{\rm d}}\right)_{\rm beauty} = \left[\frac{N({\rm D_s^+} \leftarrow {\rm B_s^0})}{N({\rm D_s^+} \leftarrow {\rm H_b})} \cdot \frac{N({\rm D^0},{\rm D^+} \leftarrow {\rm H_b})}{N({\rm D^0},{\rm D^+} \leftarrow {\rm B^{0,+}})}\right]^{\rm FONLL+PYTHIA\ 8} \cdot \left(\frac{\rm D_s^+}{\rm D^0+D^+}\right)_{\rm non-prompt}$$

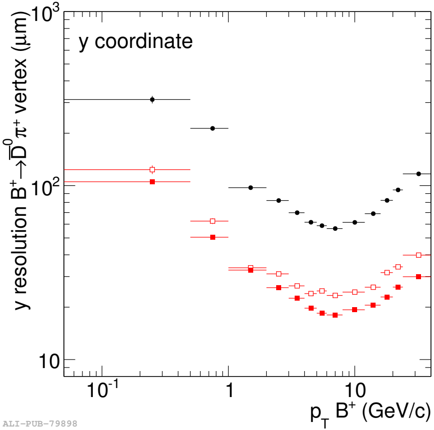
- Extrapolation factor for beauty-quark cross section

$$\alpha_{\rm extr}^{\rm b\bar{b}} = \frac{{\rm d}\sigma_{\rm b\bar{b}}/{\rm d}y|_{|y|<0.5}^{\rm FONLL}}{\sigma_{\rm b\to D}^{\rm FONLL+PYTHIA\ 8}(p_{\rm T}^{\rm min} < p_{\rm T} < p_{\rm T}^{\rm max}, |y| < 0.5)}$$

Prospects for Run 3 — ITS upgrade

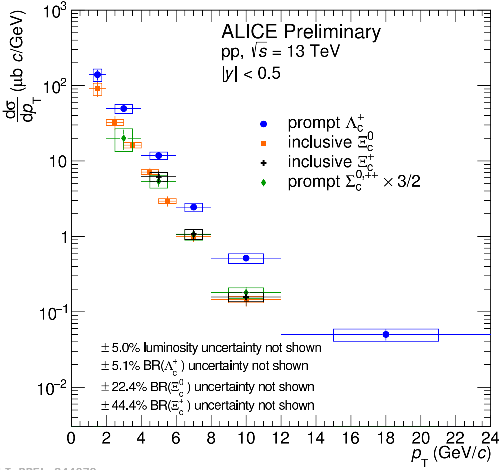
J. Phys. G 41 087002 (2014)





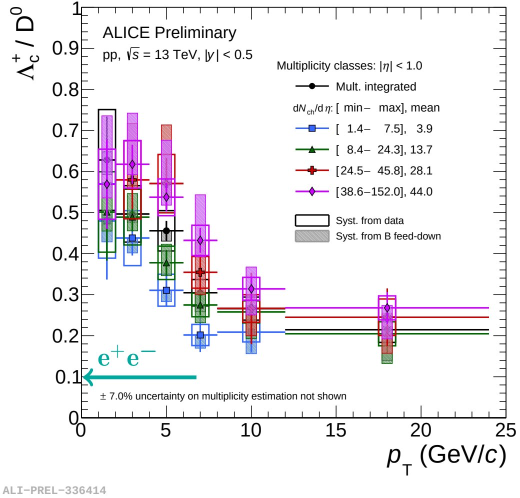
Charmed-baryon production in pp at 13 TeV

- Production of Λ_c^+, Ξ_c^0, Ξ_c^+ and Σ_c measured in pp collisions at $\sqrt{s} = 13$ TeV using the full Run 2 data sample
- New Ξ_c^+ and Σ_c measurements, improved precision and extended p_T range:
  - better constrain charm-quark total cross section
  - investigate the charmed-baryon hadronisation



ALI-PREL-344679

Λ_c^+/D^0 vs. multiplicity in pp at 13 TeV



$\langle dN_{ch}/d\eta \rangle_{|\eta|<1} \sim 3.9$

$\langle dN_{ch}/d\eta \rangle_{|\eta|<1} \sim 7$ (MB)

$\langle dN_{ch}/d\eta \rangle_{|\eta|<1} \sim 13.7$

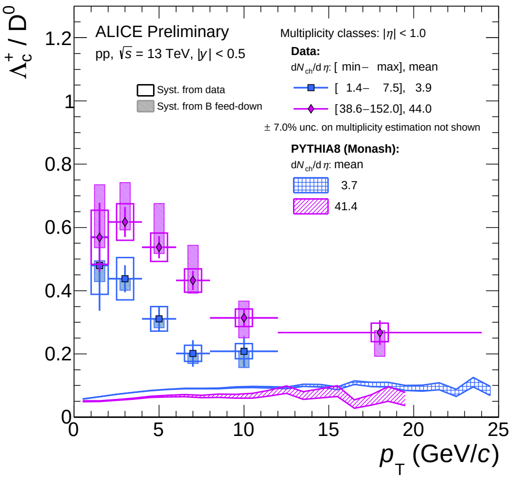
$\langle dN_{ch}/d\eta \rangle_{|\eta|<1} \sim 28.1$

$\langle dN_{ch}/d\eta \rangle_{|\eta|<1} \sim 44$

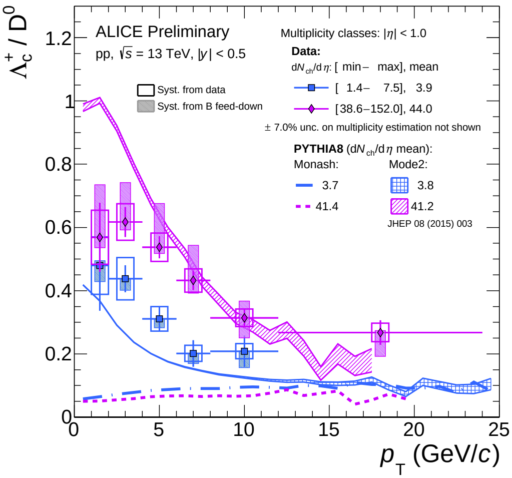
- Λ_c^+/D^0 ratio higher than what observed in e^+e^- and increasing with multiplicity
  → indication of recombination in pp?

L. Gladilin: EPJ C75 (2015) 19

Λ_c^+/D^0 vs. multiplicity in pp at 13 TeV



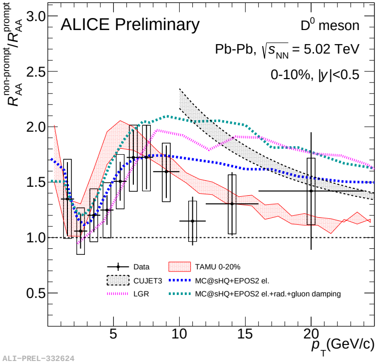
ALI-PREL-336426

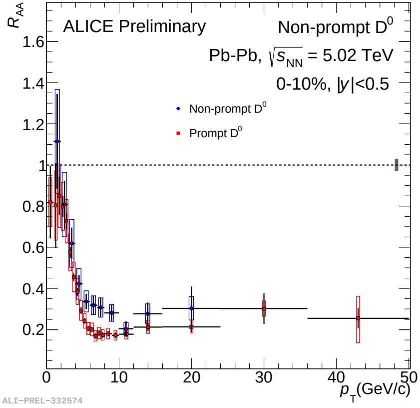


ALI-PREL-336442

Non-prompt D-meson R_{AA}

- Smaller suppression of D^0 mesons from B than prompt ones at intermediate p_T → described by models





- Hint of mass dependence of in-medium energy loss

$$\Delta E_c > \Delta E_b$$

LGR: arXiv:1912.08965
CUJET3.0: JHEP 02 (2016) 169
TAMU: PLB 735, 445-450 (2014)
MC@sHQ+EPOS: PRC 89, 014905 (2014)