Measurement of open heavy-flavour hadron production in pp, p-Pb and Pb-Pb collisions with ALICE

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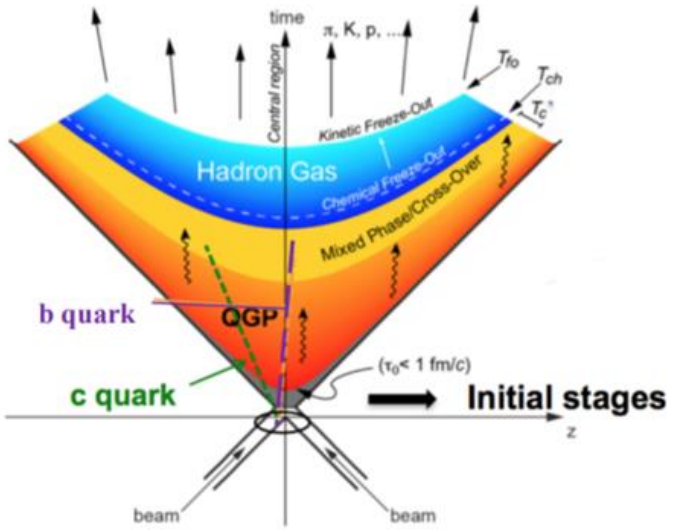
On behalf of the ALICE Collaboration

Initial Stages 2019 (IS2019)

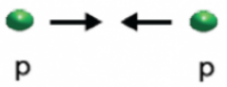
Physics motivations

- **Charm and beauty quarks** (heavy-flavours, HF) produced in initial **hard scattering** (large Q^2)
  → can be calculated in the pQCD framework down to low p_{T}

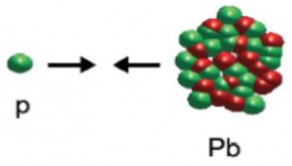
- **Full evolution** of the Quark-Gluon Plasma (QGP) produced in Pb-Pb collisions



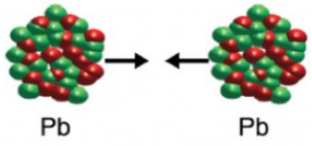
Measurements in pp collisions
- **Test** the **pQCD** calculations
- Insight into multi-parton interactions (MPI) and soft-hard processes
  → self-normalised yield
- **Experimental reference** for heavy-ion collisions



Measurements in p-Pb collisions
- **Cold-nuclear-matter (CNM) effects** → R_{pPb}
  → modification of parton distribution functions (PDF) in bound nucleons
- Possible final state effects in high multiplicity collisions



Measurements in Pb-Pb collisions
- **Hot-nuclear matter effects**
  → **Energy loss** in the medium → R_{AA}
  → Participation in the **collective motion** of the medium → v_2
  → Modification of **hadronization mechanisms**



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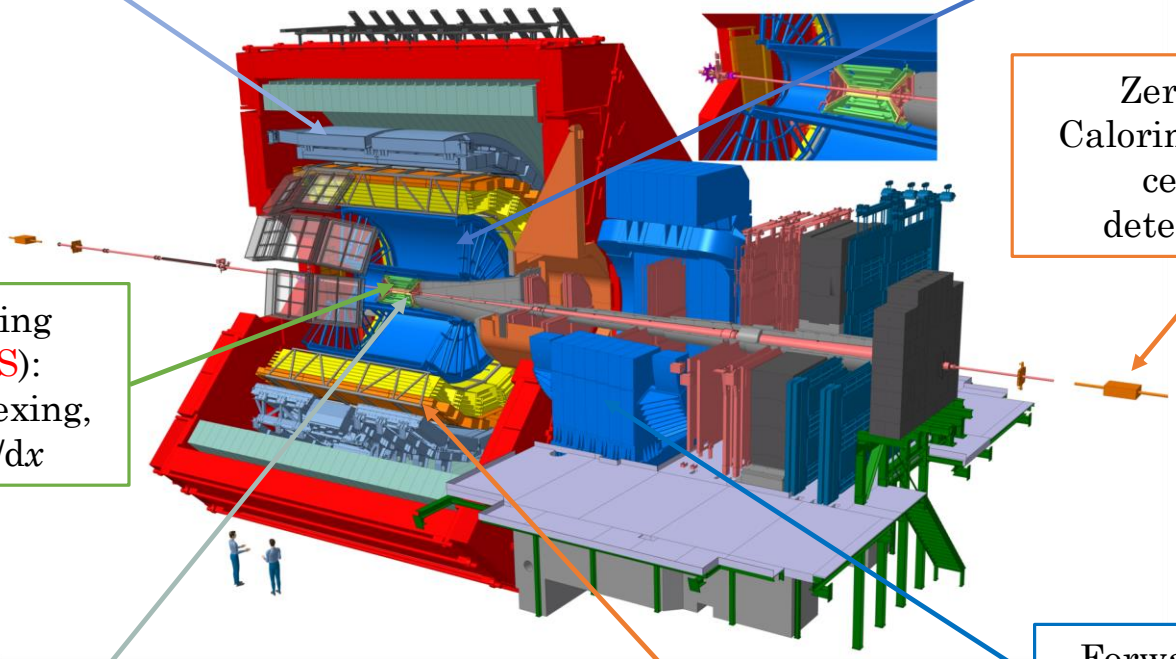
The ALICE detector

(systems used in the analyses)

ElectroMagnetic Calorimeter (EMCal): trigger, electron identification

Time Projection Chamber (TPC): tracking, PID via dE/dx

Zero Degree Calorimeter (ZDC): centrality determination



Inner Tracking System (ITS): tracking, vertexing, PID via dE/dx

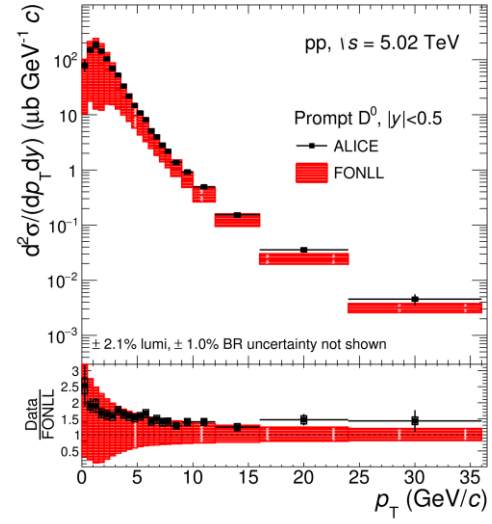
Forward muon spectrometer

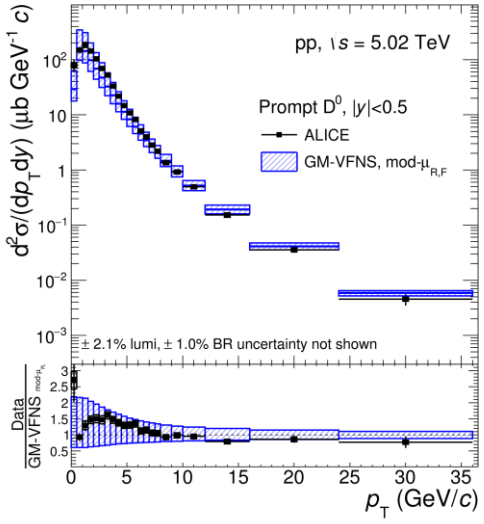
V0: trigger, centrality, event plane determination
T0: start for TOF, luminosity determination

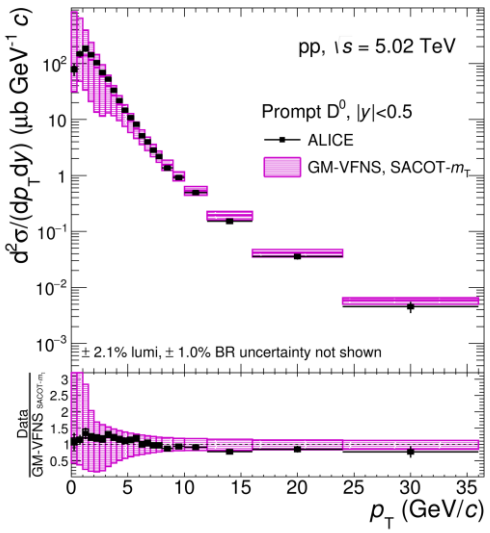
Time Of Flight (TOF): PID via time of flight

pp collisions

Prompt D-meson production



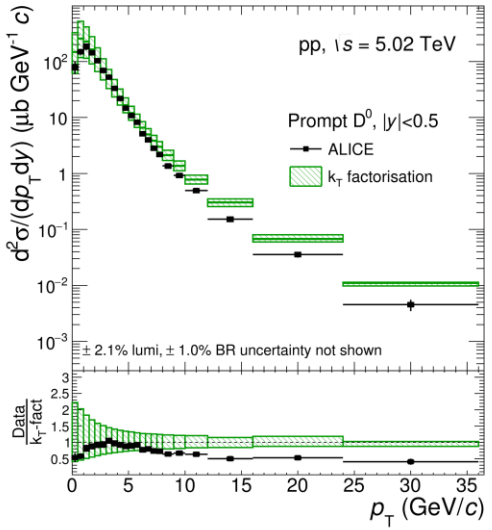




D⁰

JHEP 05 (1998) 007
JHEP (2012) 2012: 137
JHEP (2017) 2017: 21

Nucl. Phys. B, Volume 925 (2017), 415-430
JHEP (2018) 2018: 196
Phys. Rev. D 98, 014016

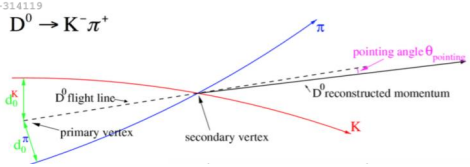


PUBLISHED ALICE Eur. Phys. J. C (2019) 79: 388

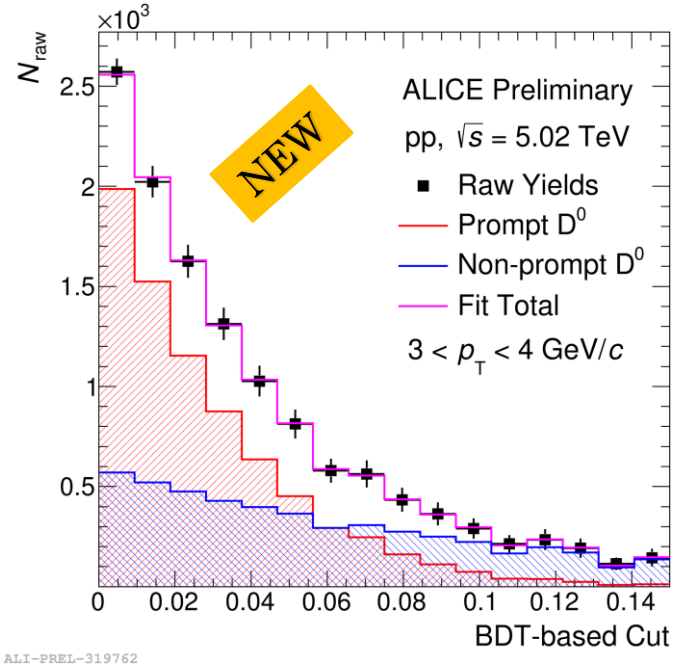
Method

- Non-strange (D^0, D^+, D^{*+}) and strange (D_s^+) D mesons through hadronic channels
- Topological and PID selections to reduce combinatorial background → invariant-mass fit
- For $p_T < 1$ GeV/c: no secondary vertex reconstruction
- Feed-down D mesons subtracted using FONLL calculations

- **Measured cross section compared** with **pQCD calculations** with different schemes:
  → FONLL
  → GM-VFNS, with two different factorization (μ_F) and regularization (μ_R) scale prescriptions
  → k_T-factorisation



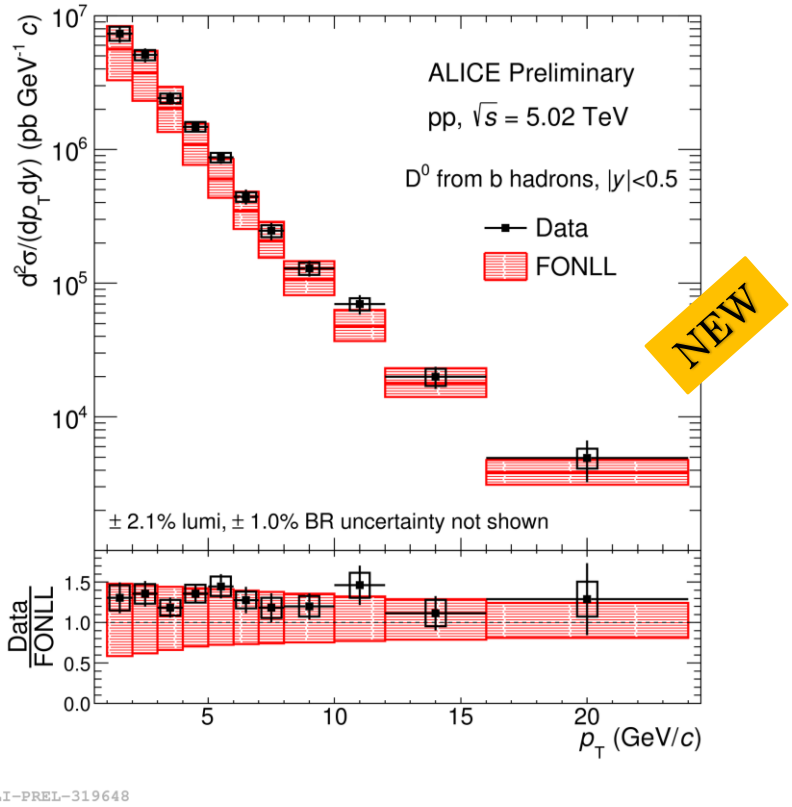
Beauty via non-prompt D^0 production



$N_{raw}(x) \approx N_{np} \cdot \varepsilon_{np}(x) + N_p \cdot \varepsilon_p(x)$

ε: efficiency

$$f_{np}(x) = \frac{N_{np} \cdot \varepsilon_{np}(x)}{N_{np} \cdot \varepsilon_{np}(x) + N_p \cdot \varepsilon_p(x)}$$



Method

- Machine learning tools
  → two-steps Boost-Decision-Trees (BDTs) to separate non-prompt D^0 from background (prompt D^0, combinatorial)
- Non-prompt fraction from template fit of the raw yield vs. BDT selection (x) value
  → high non-prompt fraction at low p_T ⇒ low systematic uncertainties

- **Measurement down to p_T = 1 GeV/c**
- The **measurement** lies on the **upper edge of the FONLL** uncertainty band

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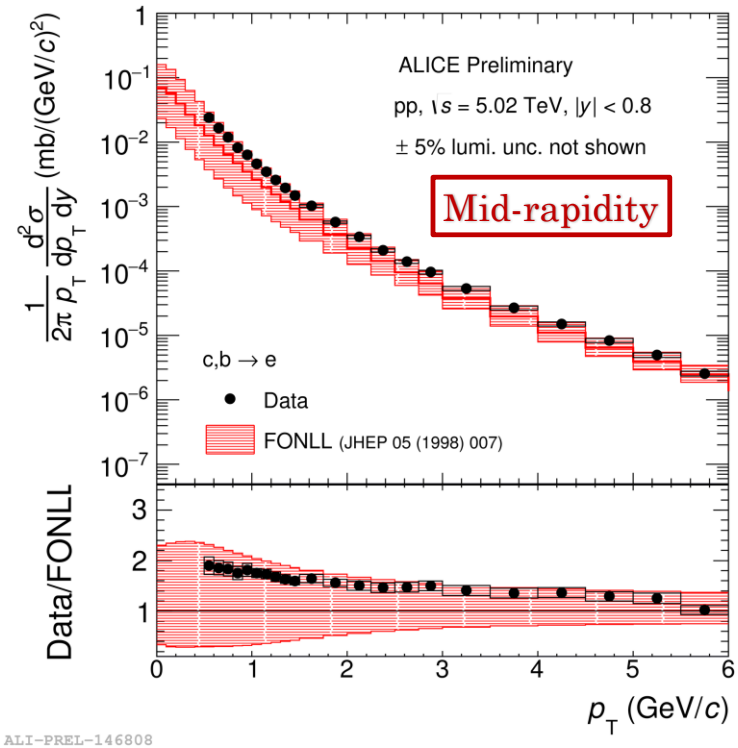
Leptons from HF-hadron decays



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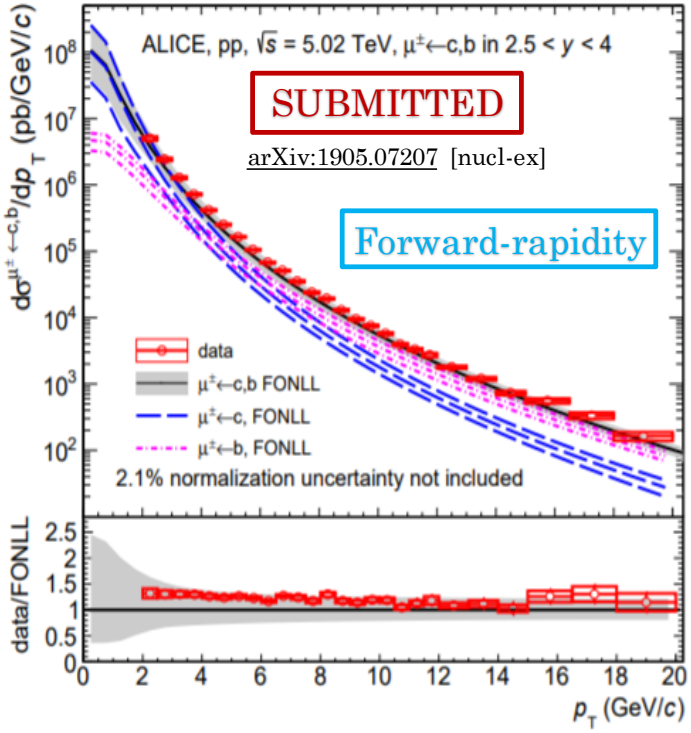
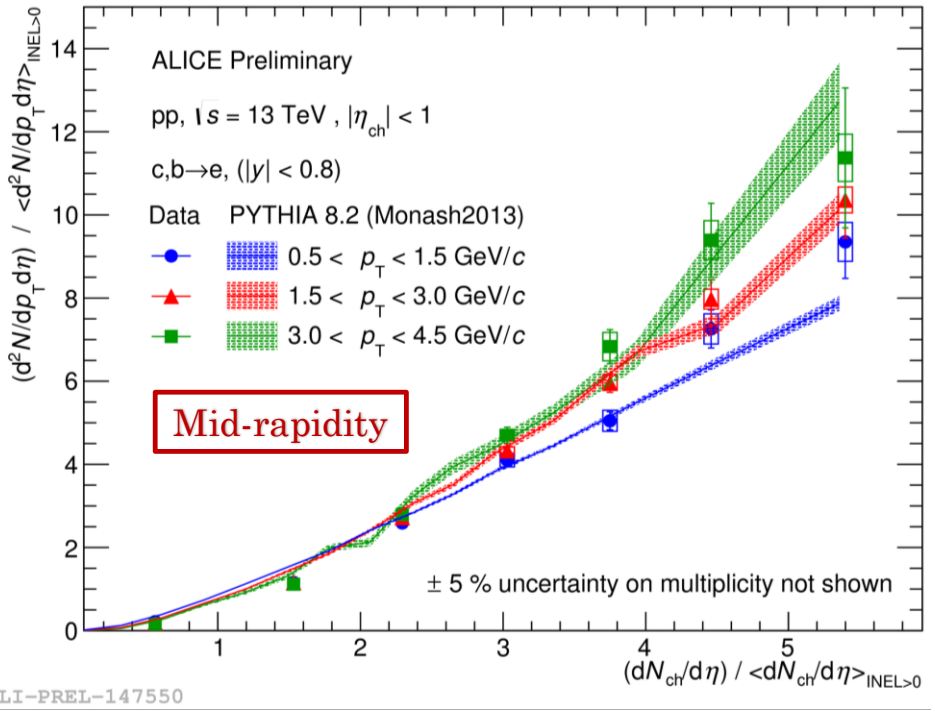


Method

- Measurement of electrons (central barrel) and muons (forward spectrometer) from semileptonic HF-hadron decays (HFh → $l\nu_l$X) in pp collisions
- Leptons from background sources ($\pi, \eta, W, ...$) subtracted

- Measured **cross section** on the **upper edge of FONLL** prediction
- Contribution from charm (beauty) decays dominant for $p_T \lesssim (\gtrsim)5$ GeV/c

Leptons from HF-hadron decays



Method

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- Leptons from background sources ($\pi, \eta, W, ...$) subtracted

- Self-normalized yield is sensitive to MPI and interplay between soft and hard processes
- **Faster-than-linear** trend vs. multiplicity
  → caveat: possible autocorrelation effects (yield and multiplicity both measured at mid-rapidity, see Eur. Phys. J. C (2019) **79**: 36)
    → described by PYTHIA

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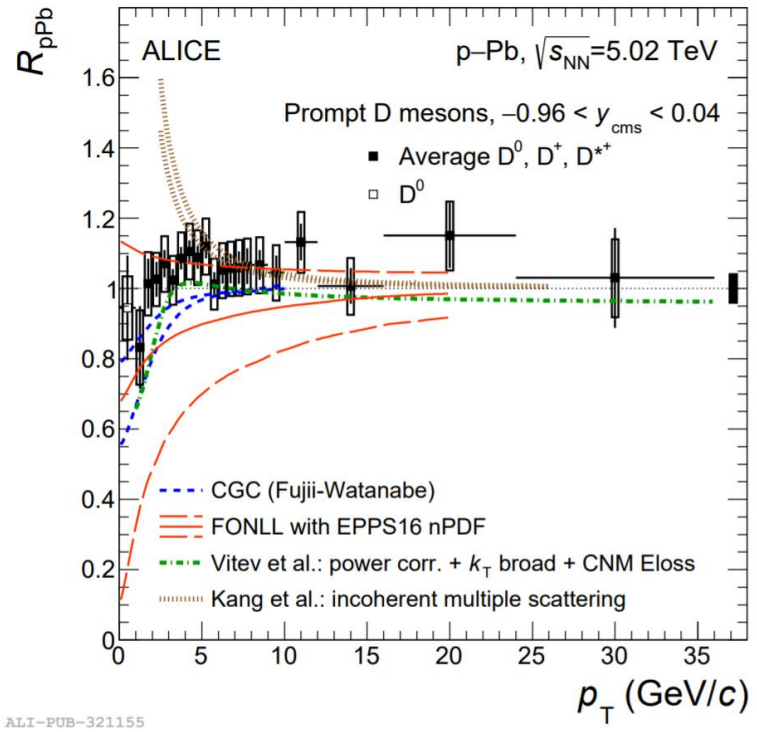
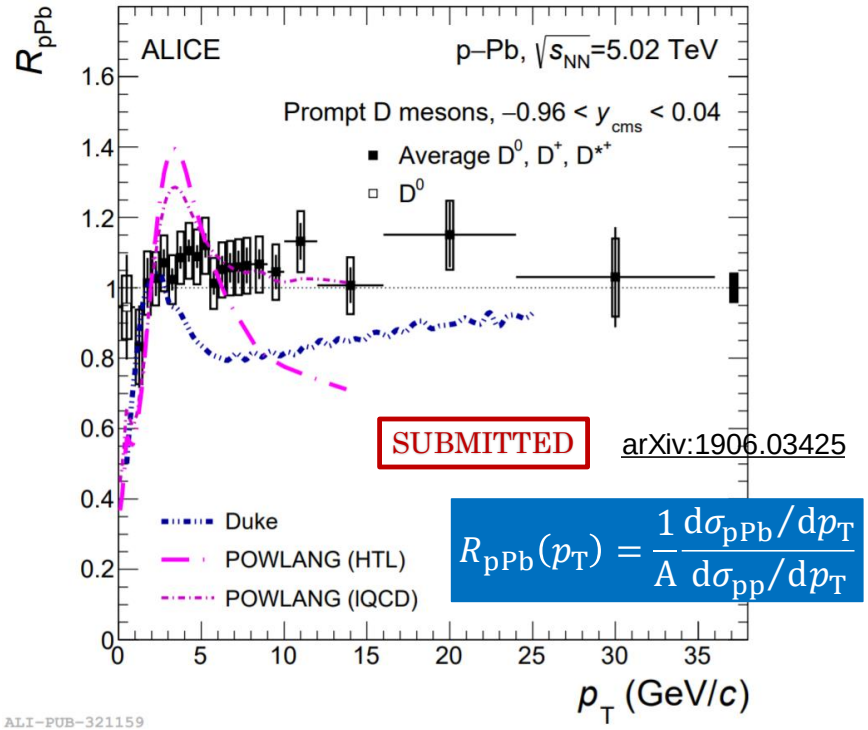
p-Pb collisions

Prompt D-meson production



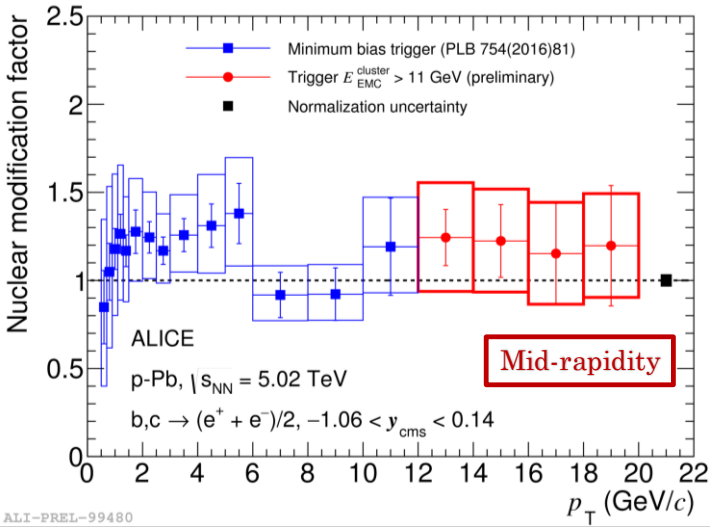


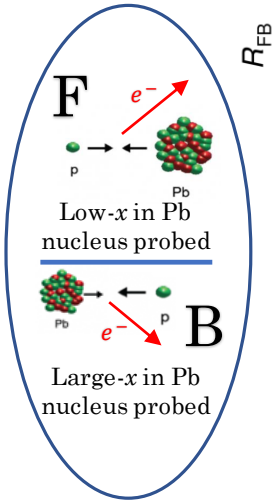
arXiv:1706.06728 [hep-ph]
JHEP 1210 (2012) 137, Eur. Phys. J. C77 no. 3, (2017) 163
Phys. Lett. B740 (2015) 23–29

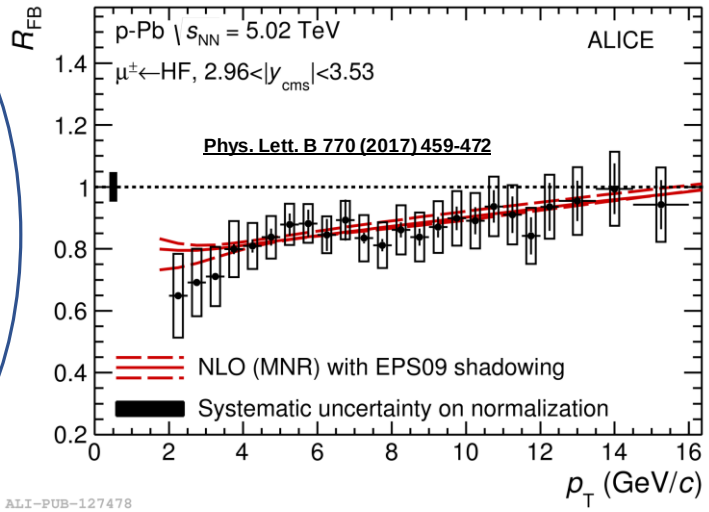
Phys.Rev. C80 (2009) 054902
Nucl. Part. Phys. Proc. 276-278 (2016) 225–228
JHEP 03 (2016) 123

- Colour Glass Condensate formalism describes the data within $< 2\sigma$
- FONLL calculation with CTEQ6M PDFs and EPPS16 NLO nuclear modification is compatible within uncertainties
- (Vitev et al.) LO pQCD calculation with k_T-broadening, shadowing and charm energy loss in CNM describes the data
- The measurement does not favour a scenario with QGP (Duke, POWLANG)

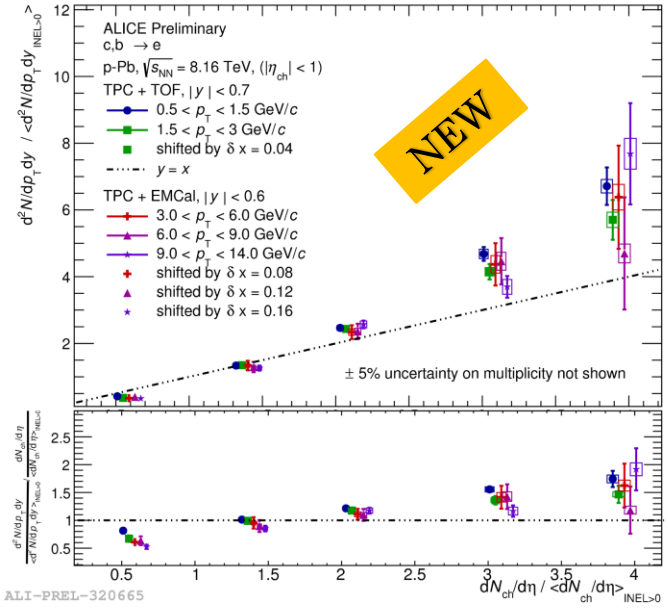
Leptons from HF-hadron decays





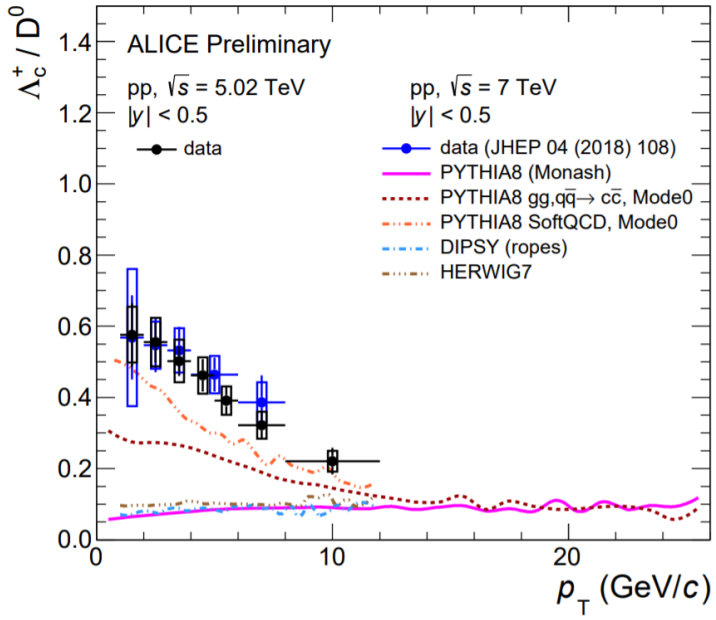


Nucl. Phys. B 373 (1992) 295-345
JHEP 04 (2009) 065 JHEP 10 (2003) 046



- R_{pPb} of HF→e compatible with 1
- Decreasing trend at low p_T
  → **nuclear shadowing**? Reduction of the uncertainties is mandatory
- Forward-to-backward R_{pPb} ratio of HF→μ shows a tendency to be below 1
  → reproduced by NLO pQCD calculations including PDFs modification in nuclei
- The self-normalised yield of HF→e shows a **faster-than-linear trend** vs. multiplicity
  → no perceived differences at different p_T

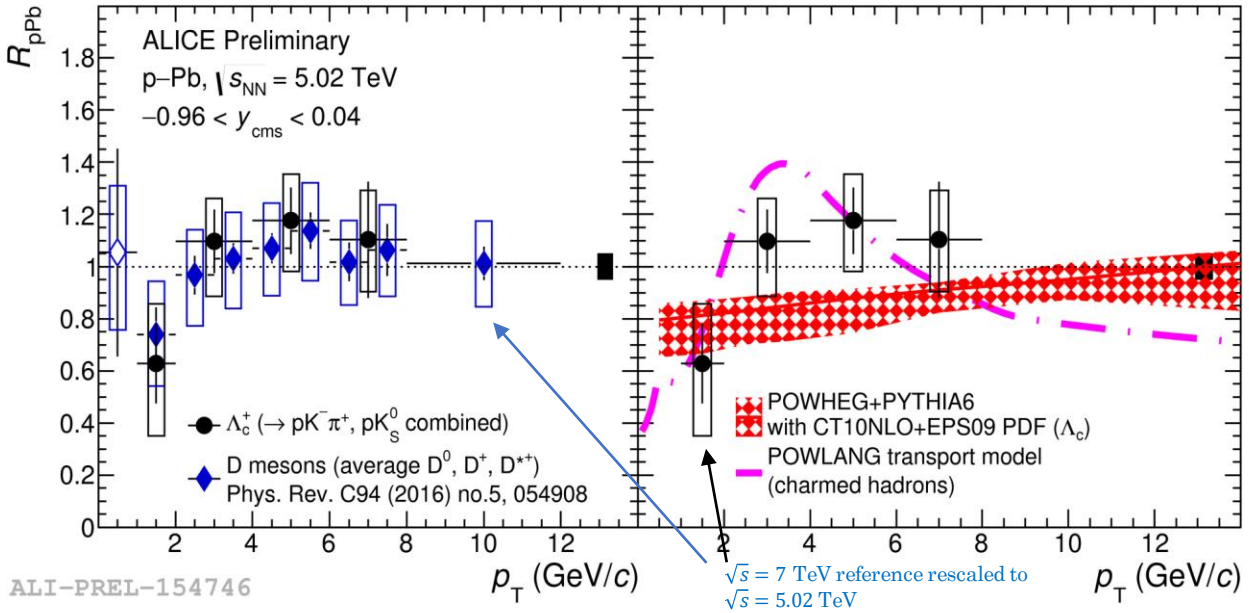
Charmed baryon production in pp and p-Pb



- Λ_c^+/D^0 compatible in pp and p-Pb collisions
- Higher than expectations from MC simulations with e^+e^- fragmentation functions
  → charm hadronization not fully understood in small systems

- R_{pPb} of Λ_c^+ compared with models
  - POWHEG+PYTHIA with CT10NLO+EPS09 PDF (CNM effects)
  - POWLANG (hot medium effects: 'small-size' QGP, collisional energy loss)
    → experimental precision does not allow to conclude

Λ_c^+



JHEP 09 (2007) 126, Phys. Rev. D82 (2010) 074024, JHEP 04 (2009) 065
JHEP 03 (2016) 123

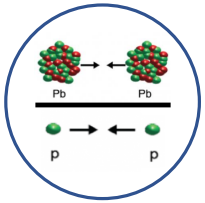
Pb-Pb collisions

2018 data taking campaign

→ improved p_{T} granularity

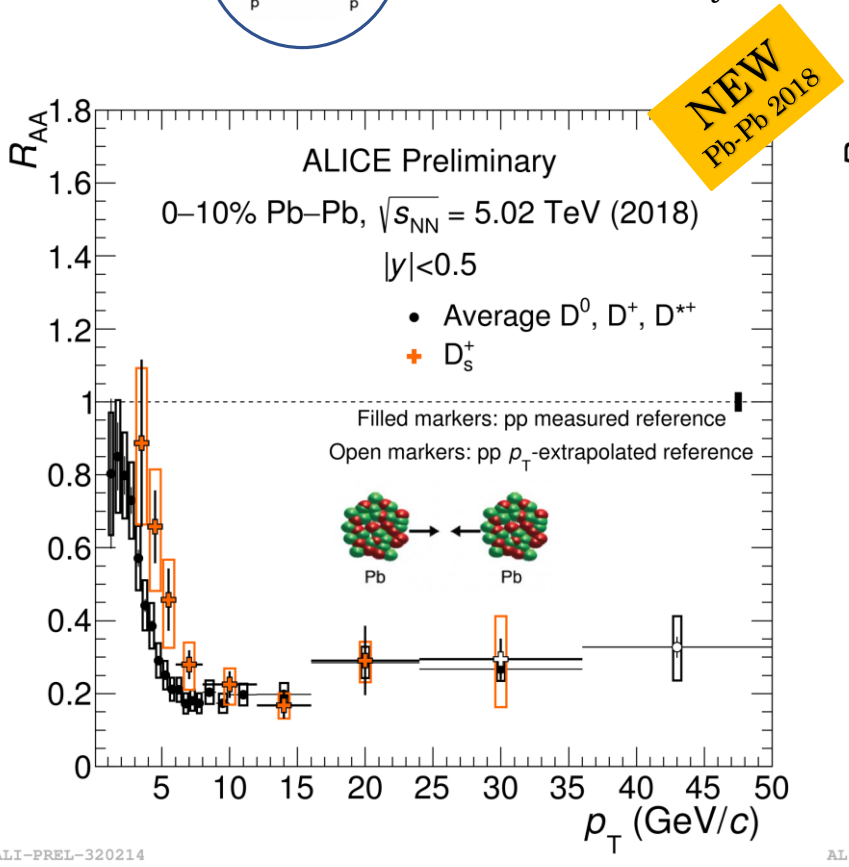
→ extended p_{T} interval

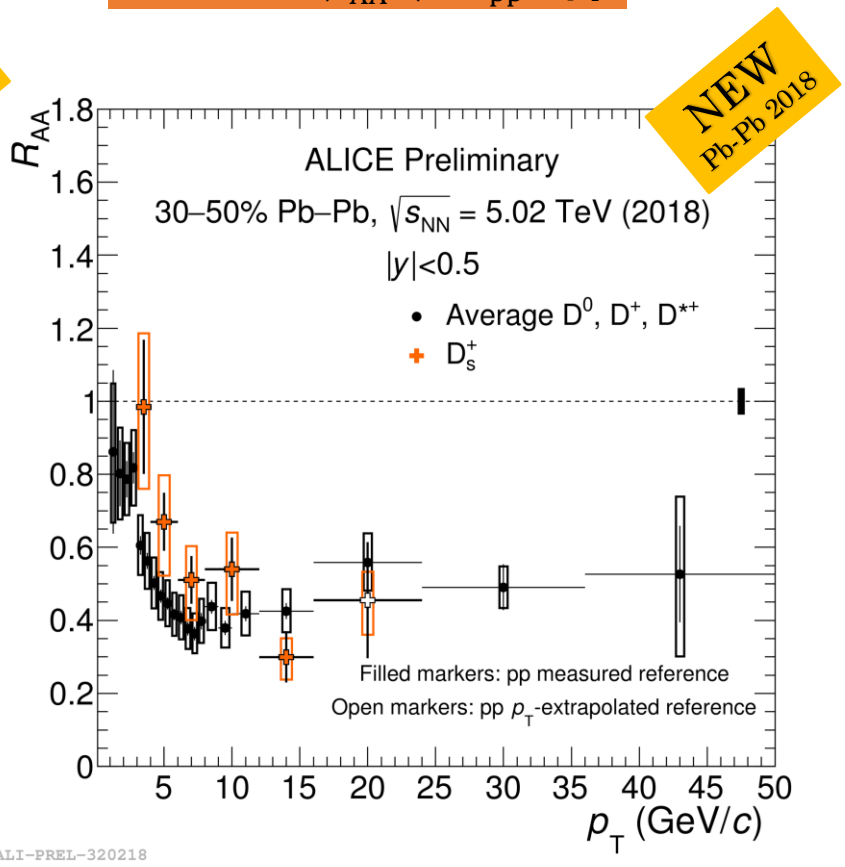
Prompt D-meson R_{AA}



vs. centrality

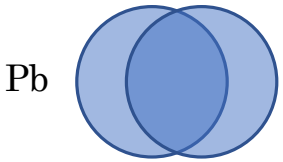
$$R_{AA}^{cent}(p_T) = \frac{1}{\langle T_{AA}^{cent} \rangle} \frac{dN_{pPb}^{cent}/dp_T}{d\sigma_{pp}/dp_T}$$



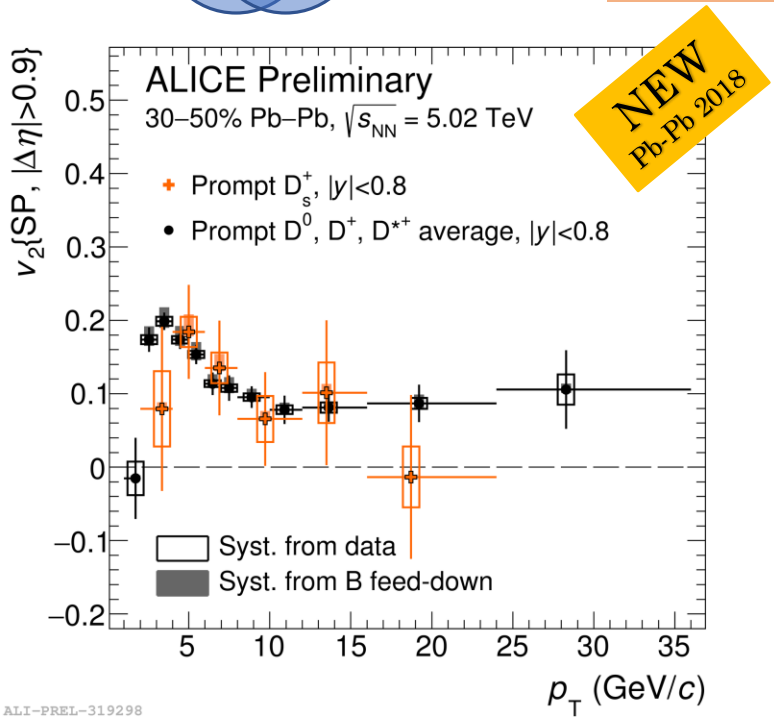


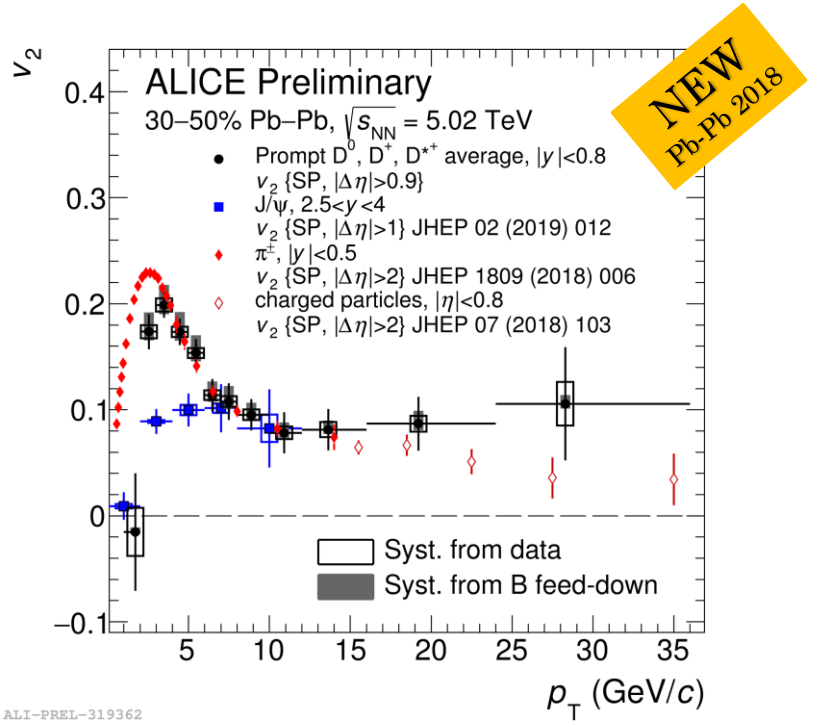
- $R_{AA} < 1$ at intermediate and high p_T
  → **parton energy loss** while traversing the QGP
- Hint of larger $R_{AA}(D_s^+) > R_{AA}(D^0, D^+, D^{*+})$
  → expected in case of **charm recombination** with light quarks

Prompt D-meson v_2



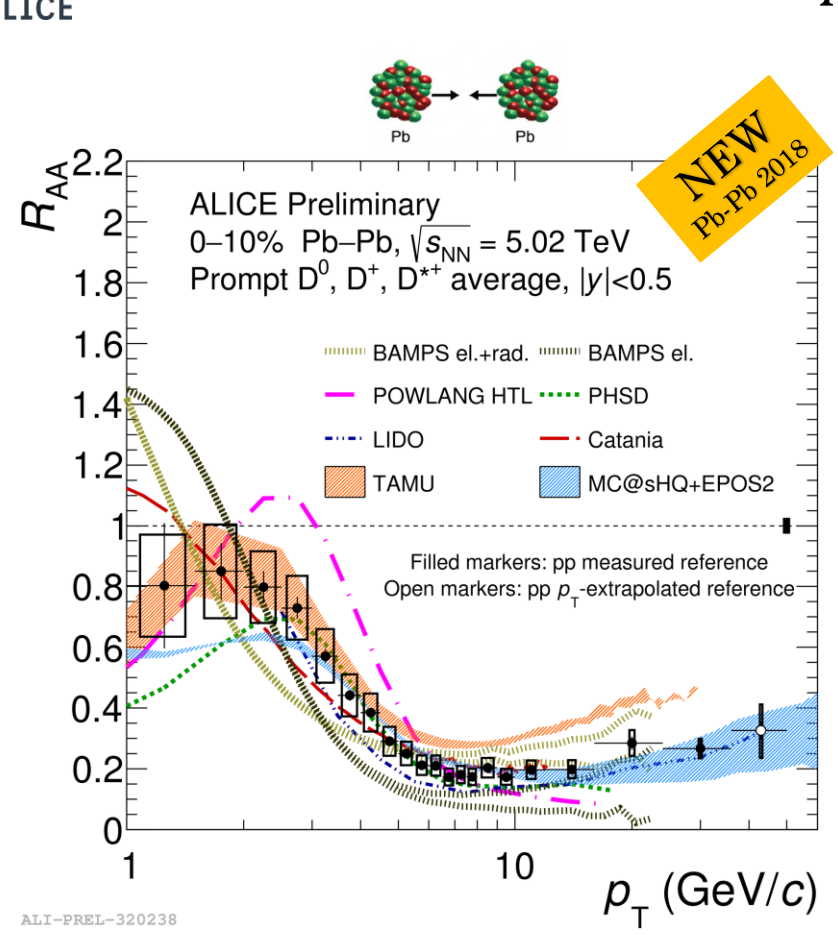
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)], \qquad v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

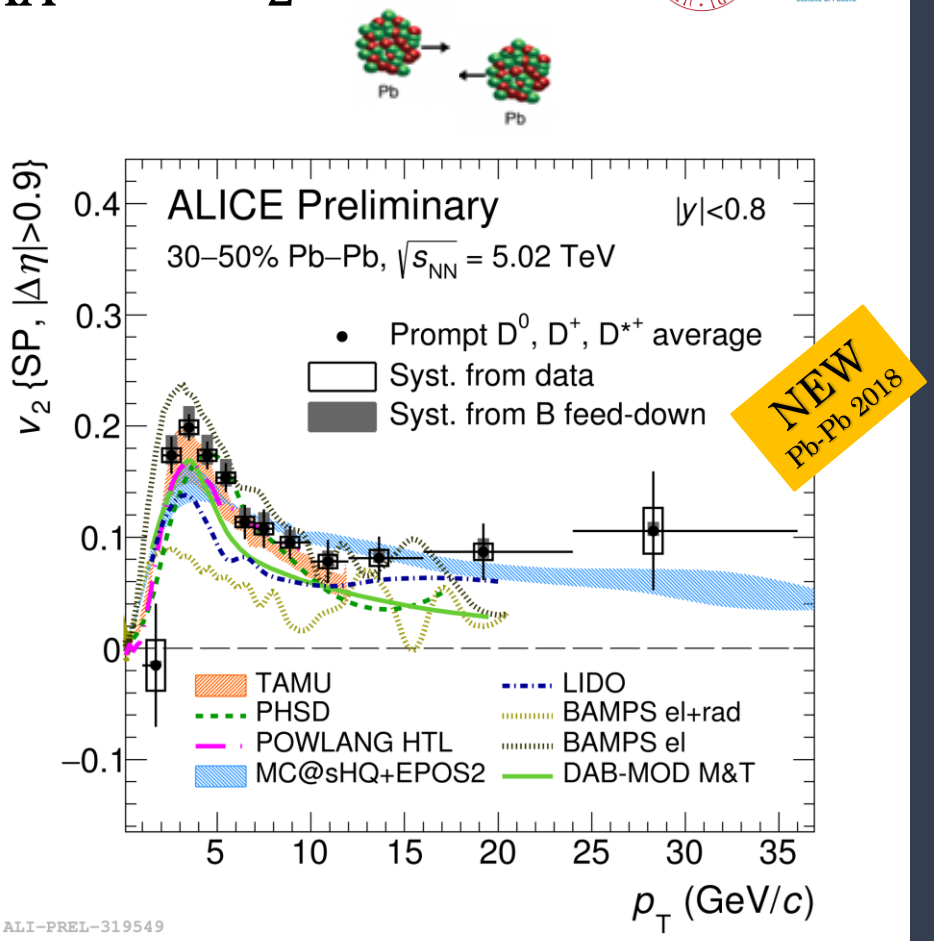




- Non-zero elliptic flow (v_2) for charmed mesons
  → **charm quarks** involved in the **QGP collective expansion**
- Non-strange D-mesons v_2 compatible with the $v_2(D_s^+)$ within the uncertainties
- Ordering at low and intermediate p_T: $v_2(J/\psi) < v_2(D) < v_2(\pi^{\pm})$
  → light quarks contribute to the open-charm v_2 ?
- Elliptic flow for different particles converges at **high p_T**
  → azimuthal asymmetry for all particles governed by **in-medium path-length dependent energy loss effects**

D-meson R_{AA} and v_2

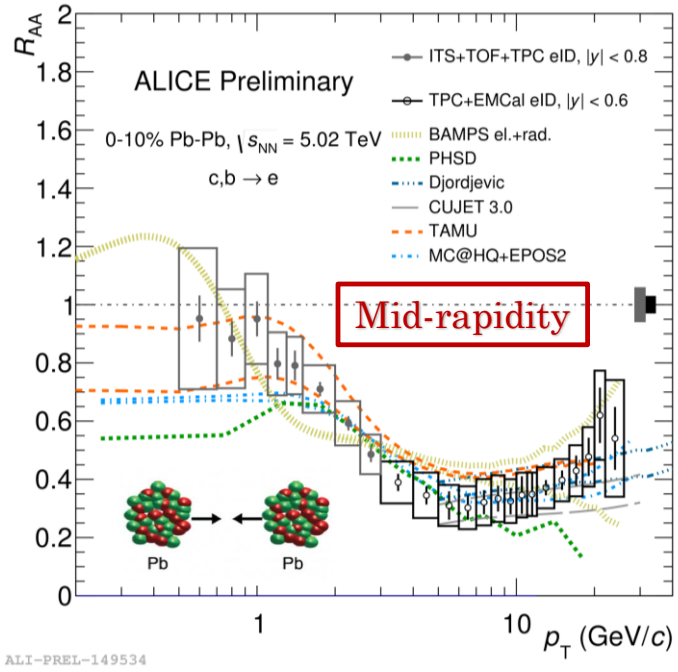


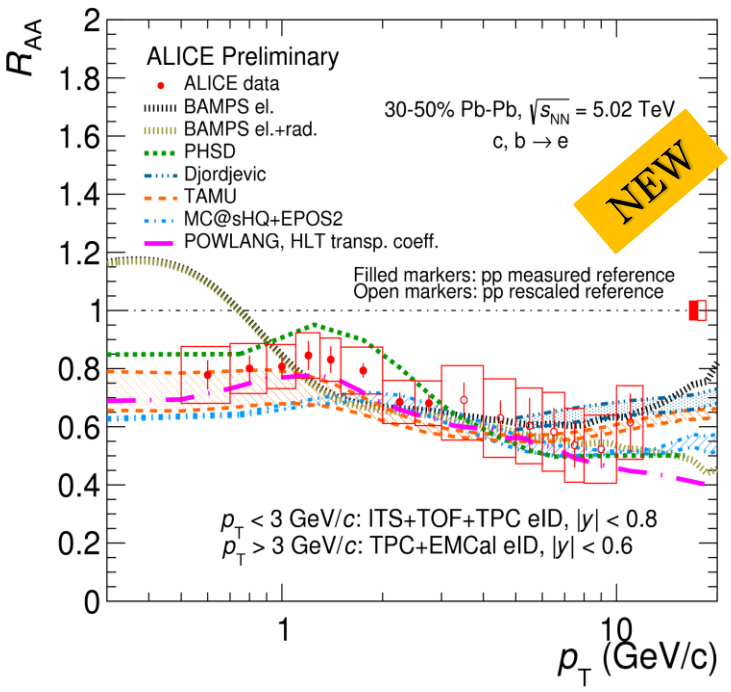


TAMU: PLB 735 (2014) 445
PHSD: PRC 92 (2015) 014910
POWLANG: EPJC 75 (2015) 121
MC@sHQ+EPOS: PRC 89 (2014) 014905
LIDO: PRC 98 (2018) 064901
BAMPS: JPG 42 (2015) 115106
DAB-MOD: PRC 96 (2017) 064903
SCET: JHEP 03 (2017) 146
CATANIA: Eur. Phys. J. C78 no. 4, (2018) 348

- Data precision constrains the description of charm-interaction and diffusion in the medium at low p_T
- Interplay of nuclear shadowing, collisional and radiative energy loss, coalescence, flows required to describe the data

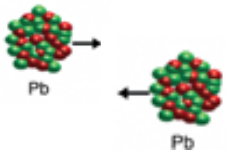
Leptons from HF-hadron decays

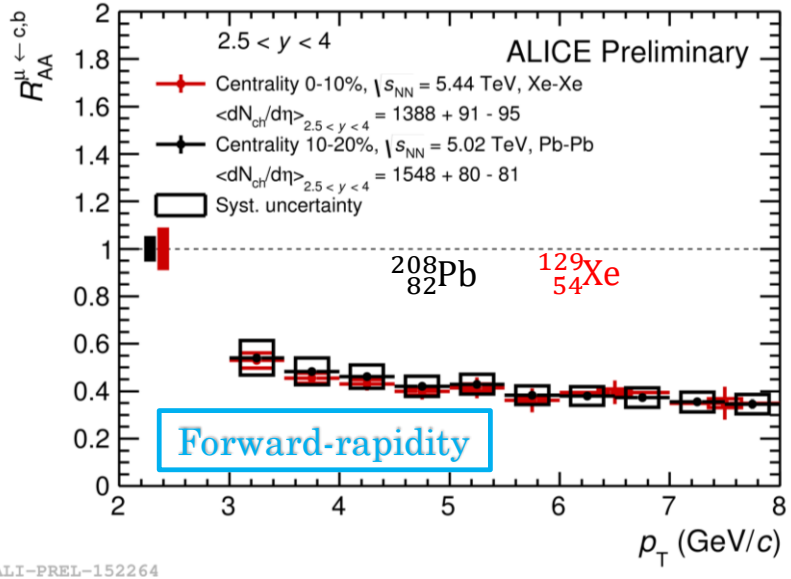




CUJET: JHEP 02, 169 (2016)

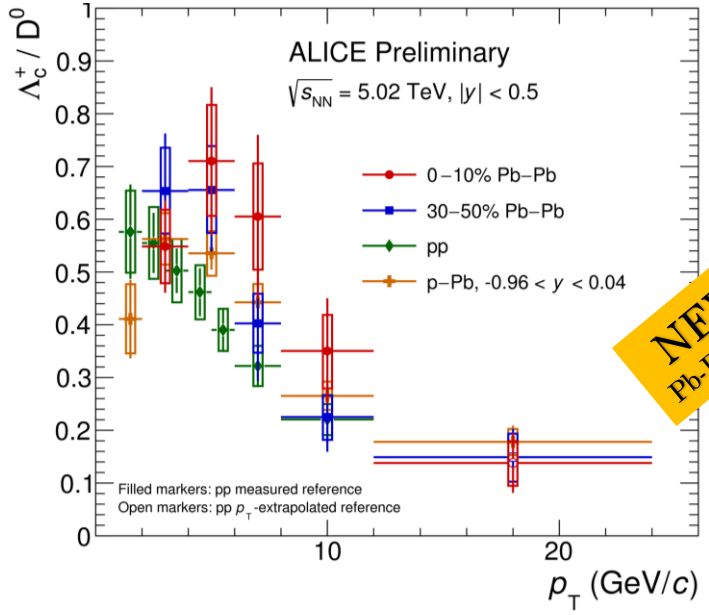
Djordevic: PRC 92, 024918 (2015)



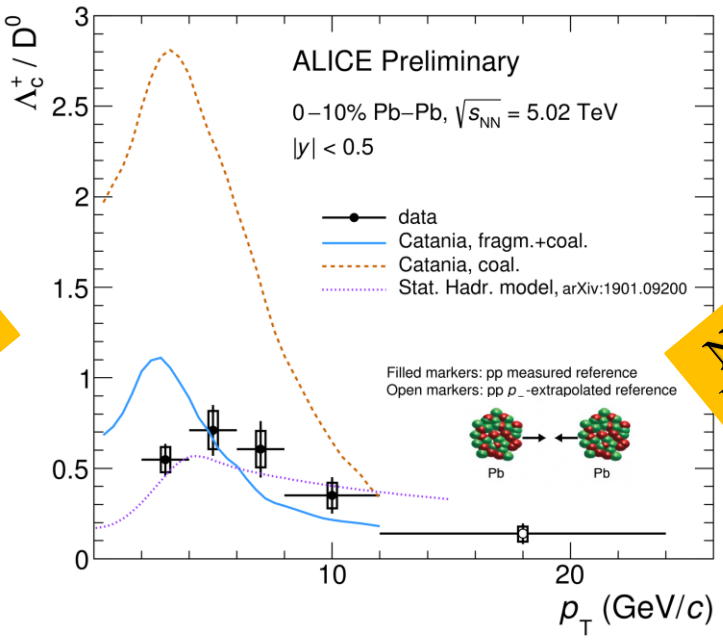


- HF → e R_{AA} is compatible with:
  - TAMU at low p_T→ **elastic collisions** energy loss
  - Djordjevic and CUJET → **radiative energy loss**
- **Nuclear shadowing** is a **necessary ingredient** for models to correctly describe the measured R_{AA}
- Similar R_{AA} for HF → μ in Pb-Pb and Xe-Xe collisions at similar $\langle dN_{ch}/d\eta \rangle$
  → possibility to further constrain model calculations

Charmed baryon production



NEW Pb-Pb 2018

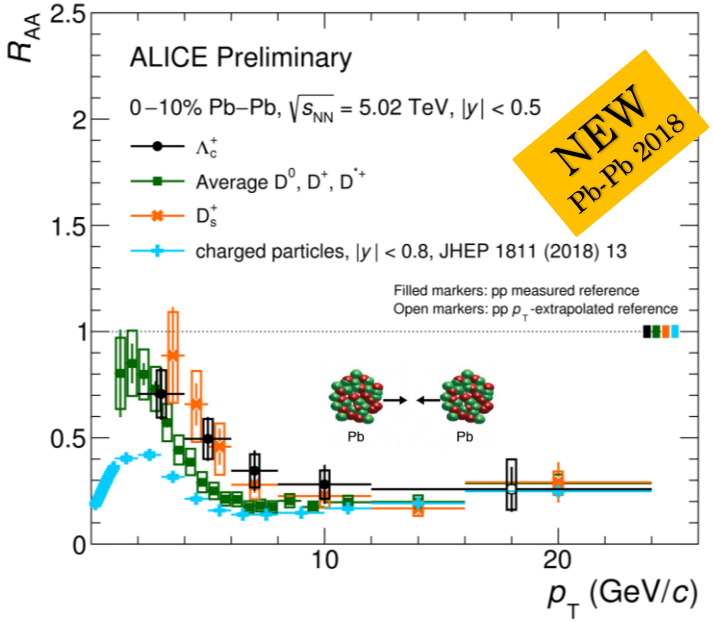


Λ_c^+

NEW Pb-Pb 2018

ALI-PREL-321706

ALI-PREL-321682



NEW Pb-Pb 2018

ALI-PREL-321872

Method

- Measurement of Λ_c^+ production in central (0-10%) and semi-central (30-50%) Pb-Pb collisions
- Signal extraction performed using BDT with AdaBoost and XGBoost boosting algorithms

- Hint of enhanced baryon-over-meson ratio in Pb-Pb collisions
- Hint of $R_{AA}(\Lambda_c^+) > R_{AA}(D^0, D^+, D^{*+})$ in both centrality classes

  → consistency with charm hadronization via coalescence and with the Statistical Hadronization Model

Summary

- Measurement of open heavy-flavour hadron production in pp, p-Pb and Pb-Pb collisions are performed by the ALICE experiment at LHC at the energy $\sqrt{s_{\mathrm{NN}}} = 5.02 \div 13$ TeV

Measurements in pp collisions
- Production cross-sections lie on the **upper edge of the FONLL** uncertainty band
- Λ_c^+/D^0 is higher than MC predictions
  → Similar p_{T}-trend of baryon-over-meson ratio in the light flavour sector

Measurements in p-Pb collisions
- Measurements sensitive to nuclear shadowing at low p_{T}
- Baryon-over-meson ratio similar to the one in pp collisions

Measurements in Pb-Pb collisions
- New results from the 2018 data taking campaign
  → higher statistics ⇒ better precision and improved p_{T} granularity
  → extended p_{T} range
- Measured R_{AA} and v_2 sensitive to cold- and hot- nuclear-matter effects
- Baryon-over-meson ratio is better explained by the interplay of fragmentation and coalescence hadronization mechanisms

… to be continued !

Don't miss Fabio Colamaria's talk:
"Measurement of heavy-flavour jets and correlations and elliptic flow in small systems with ALICE"

Mattia Faggin - University and INFN, Padova (Italy)

Thank you for your attention

Mattia Faggin - University and INFN, Padova (Italy)

Backup

ALICE luminosity

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	$\sim 75\mu b^{-1}$
	2015	5.02	$\sim 250\mu b^{-1}$
	2018	5.02	$\sim 0.9nb^{-1}$
Xe-Xe	2017	5.44	$\sim 0.3\mu b^{-1}$
p-Pb	2013	5.02	$\sim 15nb^{-1}$
	2016	5.02, 8.16	$\sim 3nb^{-1}$, $\sim 25nb^{-1}$
pp	2009-2013	0.9, 2.76, 7, 8	$\sim 200\mu b^{-1}$, $\sim 100nb^{-1}$, $\sim 1.5pb^{-1}$, $\sim 2.5pb^{-1}$
	2015, 2017	5.02	$\sim 1.3pb^{-1}$
	2015-2018	13	$\sim 59pb^{-1}$

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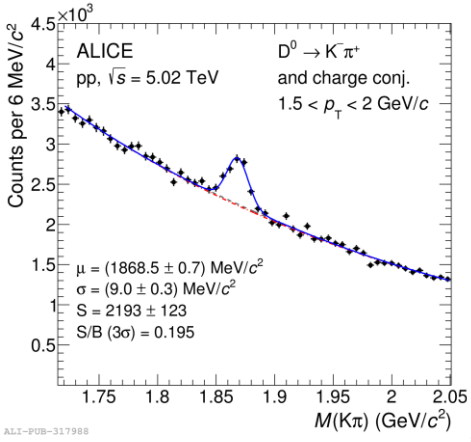
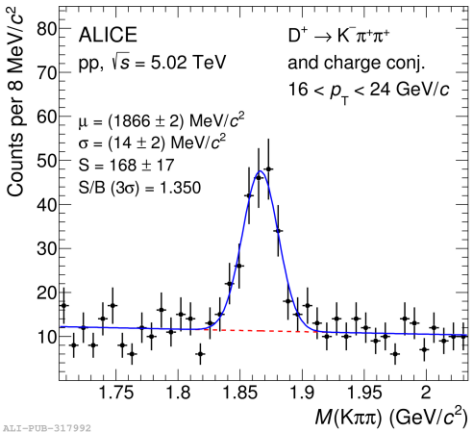
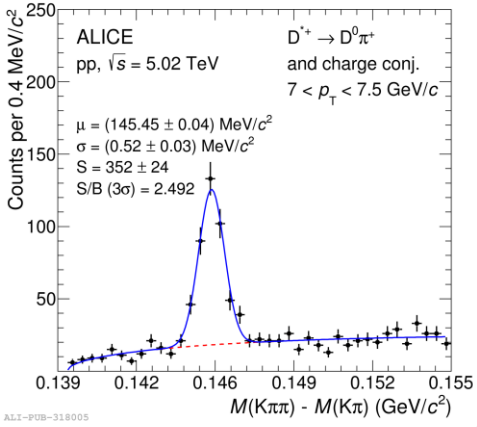
pp collisions

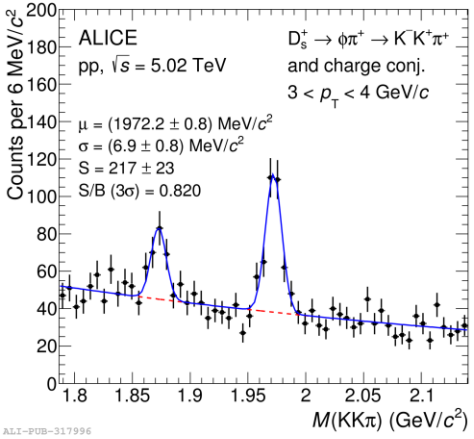
Prompt D-mesons production

PUBLISHED 10.1140/epjc/s10052-019-6873-6



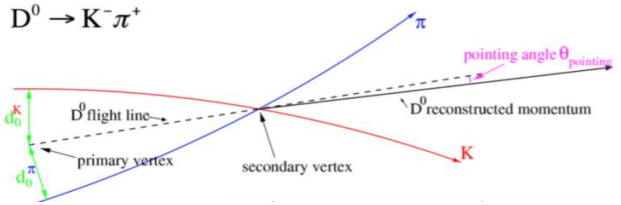






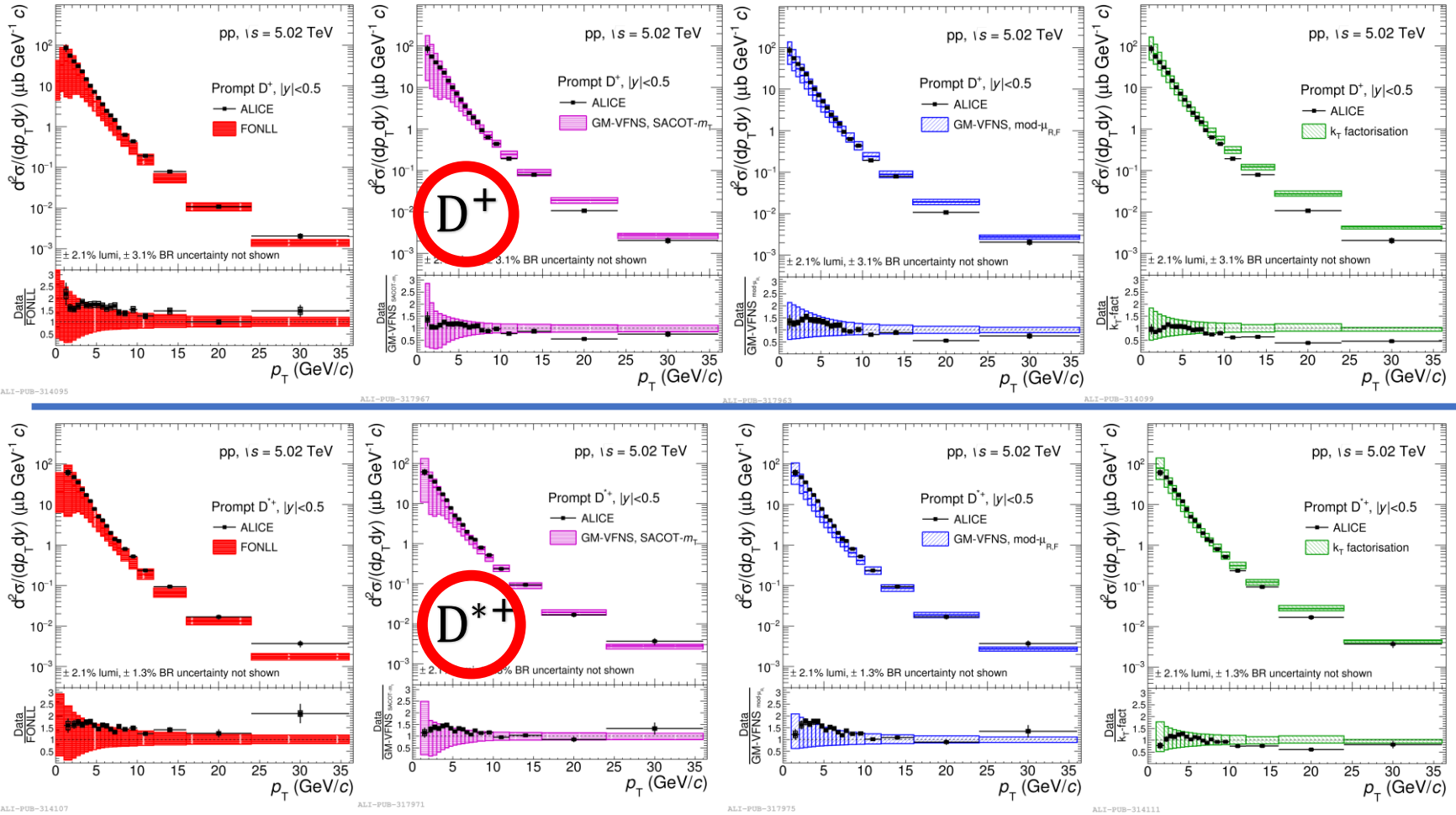
PHYSICAL REVIEW D 98, 030001 (2018)

$D^0 \rightarrow K^-\pi^+$	Br ~ 3.89%	$c\tau$ = 122.9 μm
$D^+ \rightarrow K^-\pi^+\pi^+$	Br ~ 8.98%	$c\tau$ = 311.8 μm
$D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$	Br ~ 2.63%	-
$D_s^+ \rightarrow \phi(\rightarrow K^-K^+)\pi^+$	Br ~ 2.27%	$c\tau$ = 151.2 μm

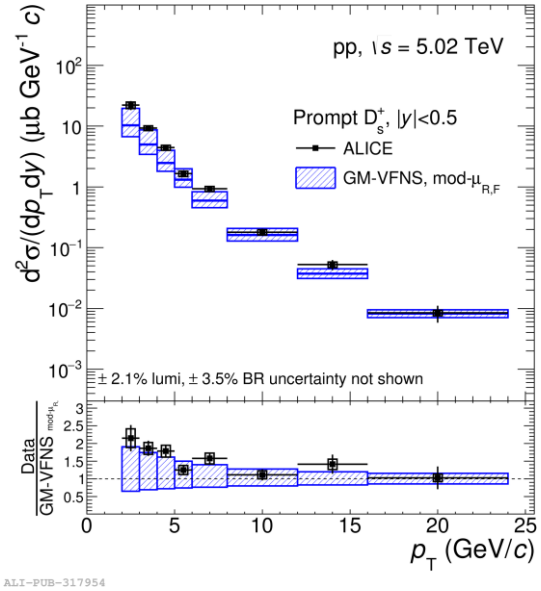


- D-mesons measured through their hadronic channel reconstruction in pp collisions at $\sqrt{s}$ = 5.02 TeV
  - ✓ Non-strange: D^0, D^+, D^{*+}
  - ✓ Strange: D_s^+
- Topological and PID selections to reduce combinatorial background
- Signal extraction via invariant-mass fit procedure
- Feed-down D-mesons are subtracted exploiting FONLL calculations with assumptions on feed-down nuclear modification factor

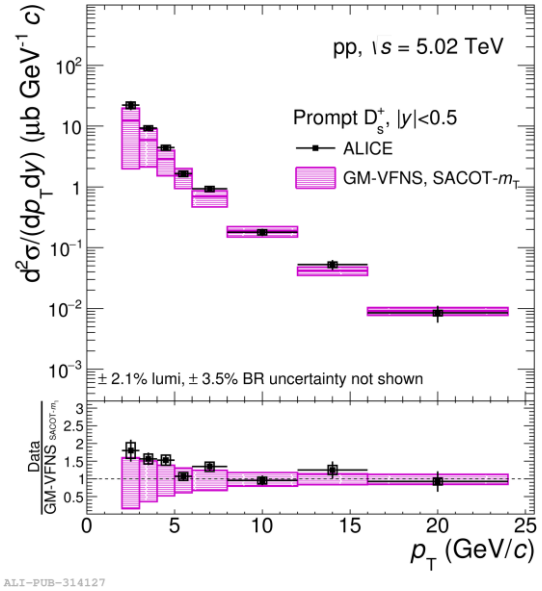
Prompt D-meson production



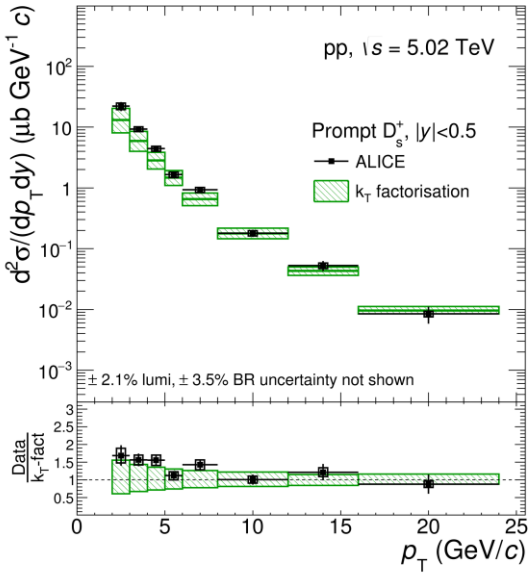
Prompt D-meson production



ALI-PUB-317954



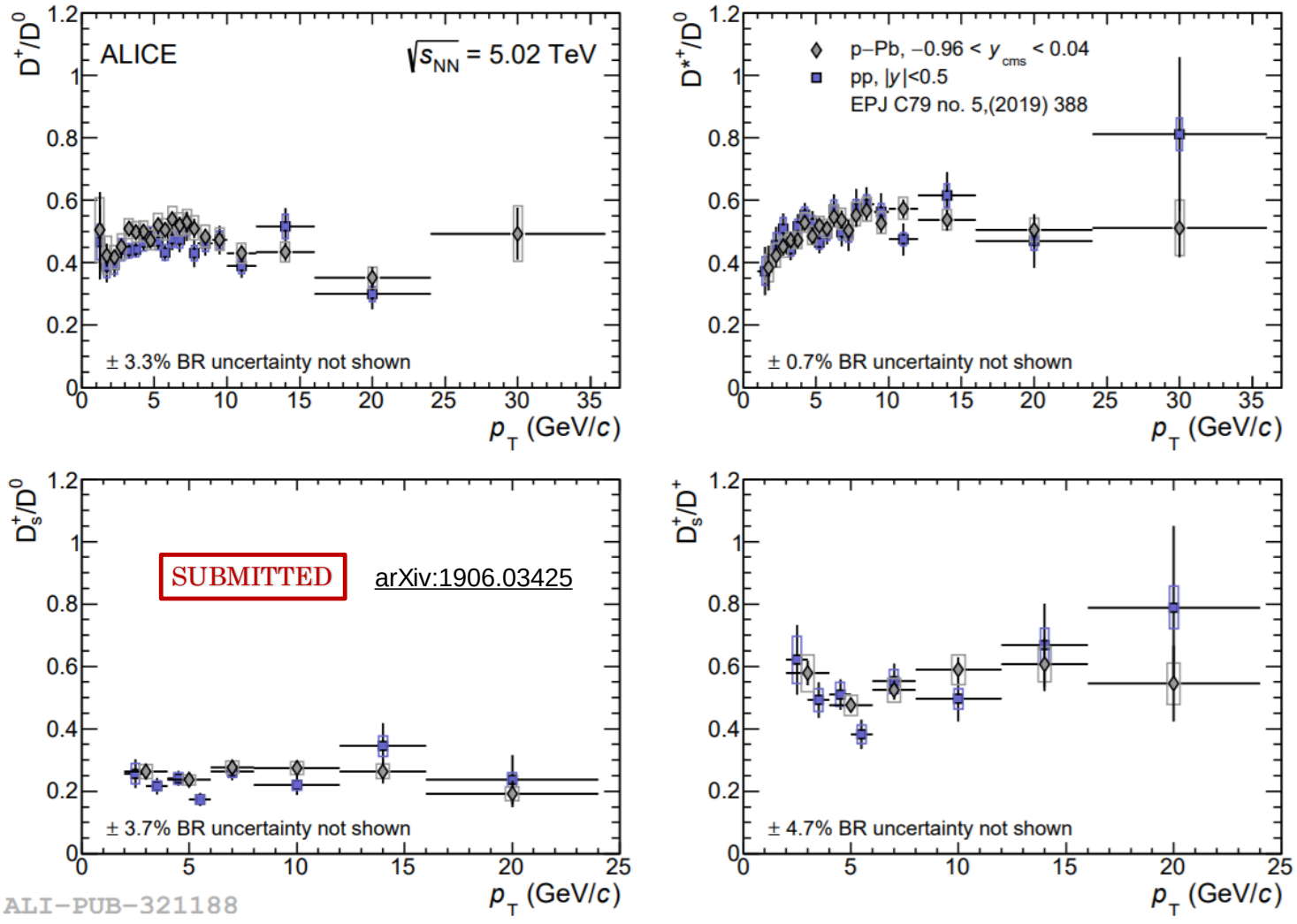
ALI-PUB-314127



ALI-PUB-314103

D_s^+

Prompt D-mesons production



- D-mesons cross-section ratios have no significant p_T dependence, both in pp and p-Pb collisions

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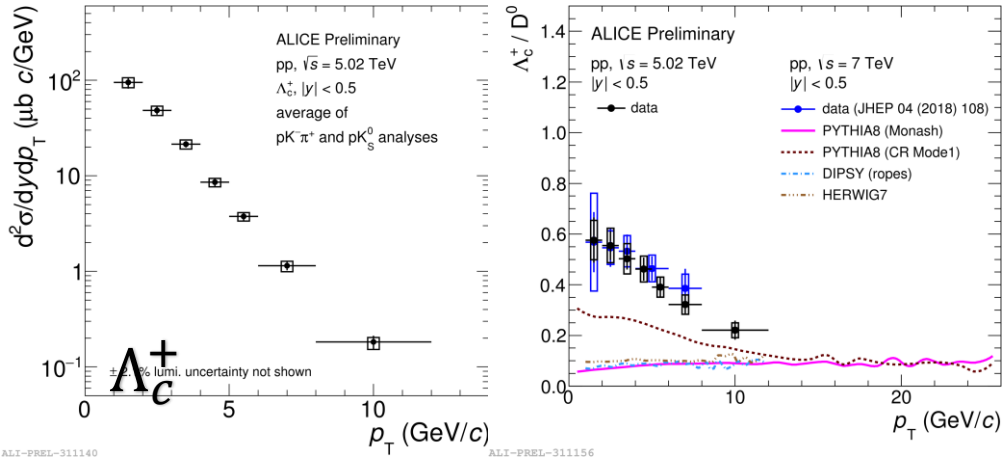
Charmed baryon production

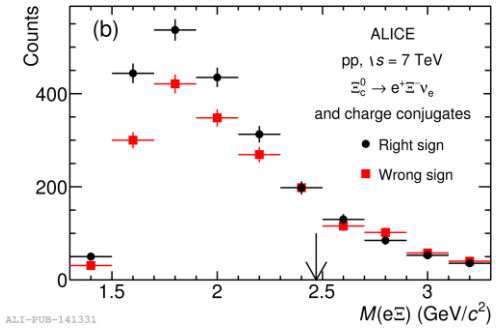


PHYSICAL REVIEW D 98, 030001 (2018)

$\Lambda_c^+ \to pK_S^0$	B.R. ~1.58 %	$c\tau$ = 59.9 μm
$\Lambda_c^+ \to pK^-\pi^+$	B.R. ~ 6.23 %	"
$\Xi_c^0 \to e^+\Xi^-\nu_e$	B.R. ~ 3.1 %	$c\tau$ = 132 μm

Method

- Λ_c^+ baryon reconstructed in two hadronic decay channels in pp collisions at 5.02 TeV and 7 TeV
- Signal extraction via invariant-mass fit procedure
- $(\Lambda_b \to) \Lambda_c$ subtracted exploiting FONLL calculations



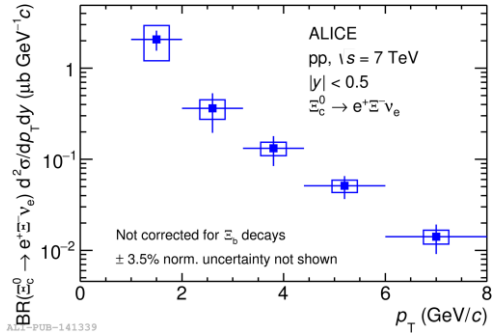
Ξ_c^0

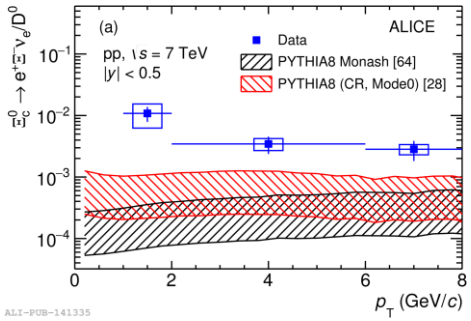
10.1016/j.physletb.2018.03.061
10.1007/JHEP08(2015)003
10.1140/epjc/s10052-008-0798-9

PUBLISHED

- Ξ_c^0 explored in a semi-leptonic channel in pp collisions at $\sqrt{s} = 7$ TeV
- Ξ_c^0 signal extracted by subtracting the wrong-sign $e^-\Xi^+$ pairs from the invariant mass distribution of right-sign $e^+\Xi^-$ pairs
- Ξ_c^0 spectrum unfolded from $e^+\Xi^-$ one
- No feed-down subtraction

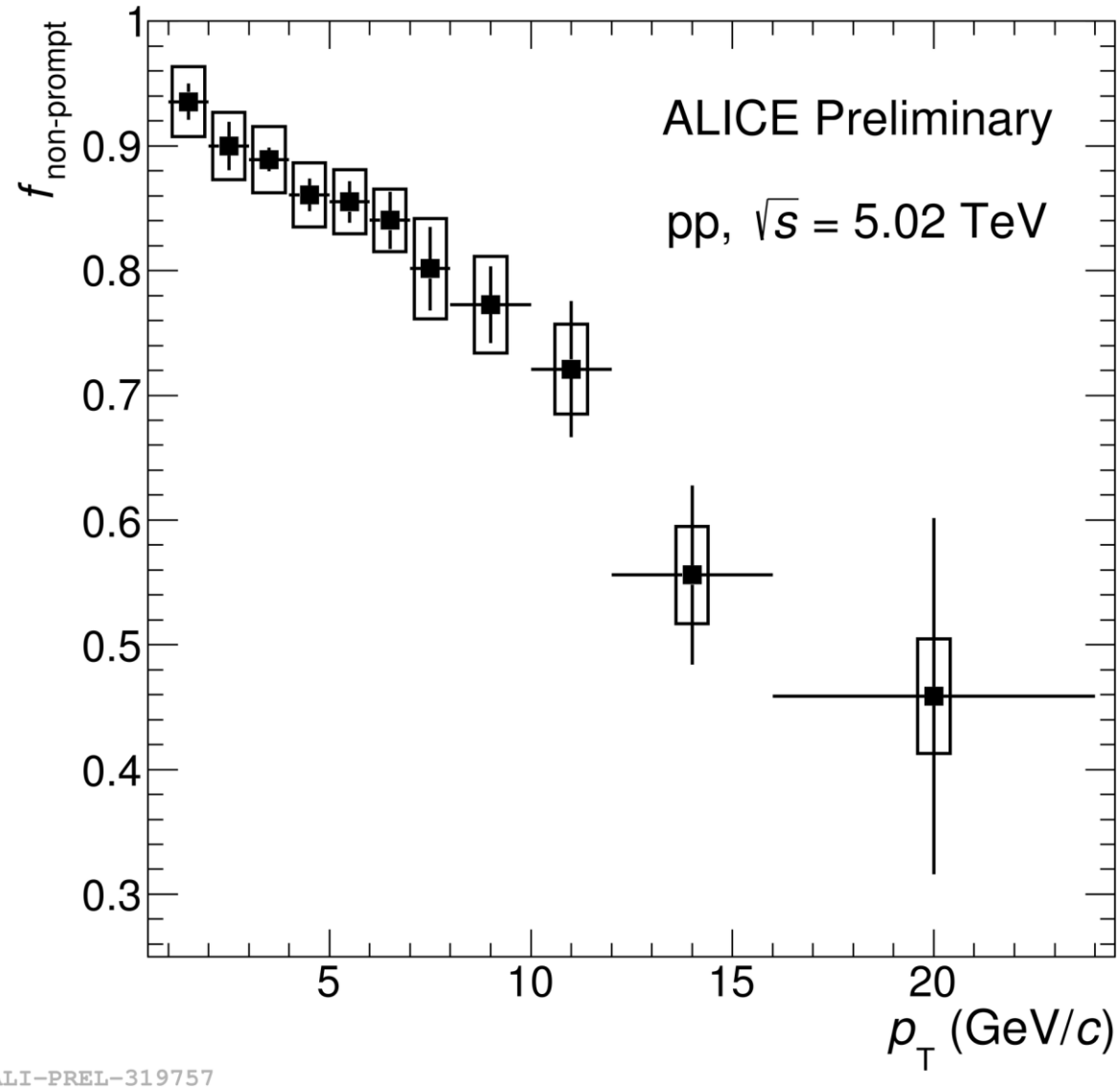
Unknown Br





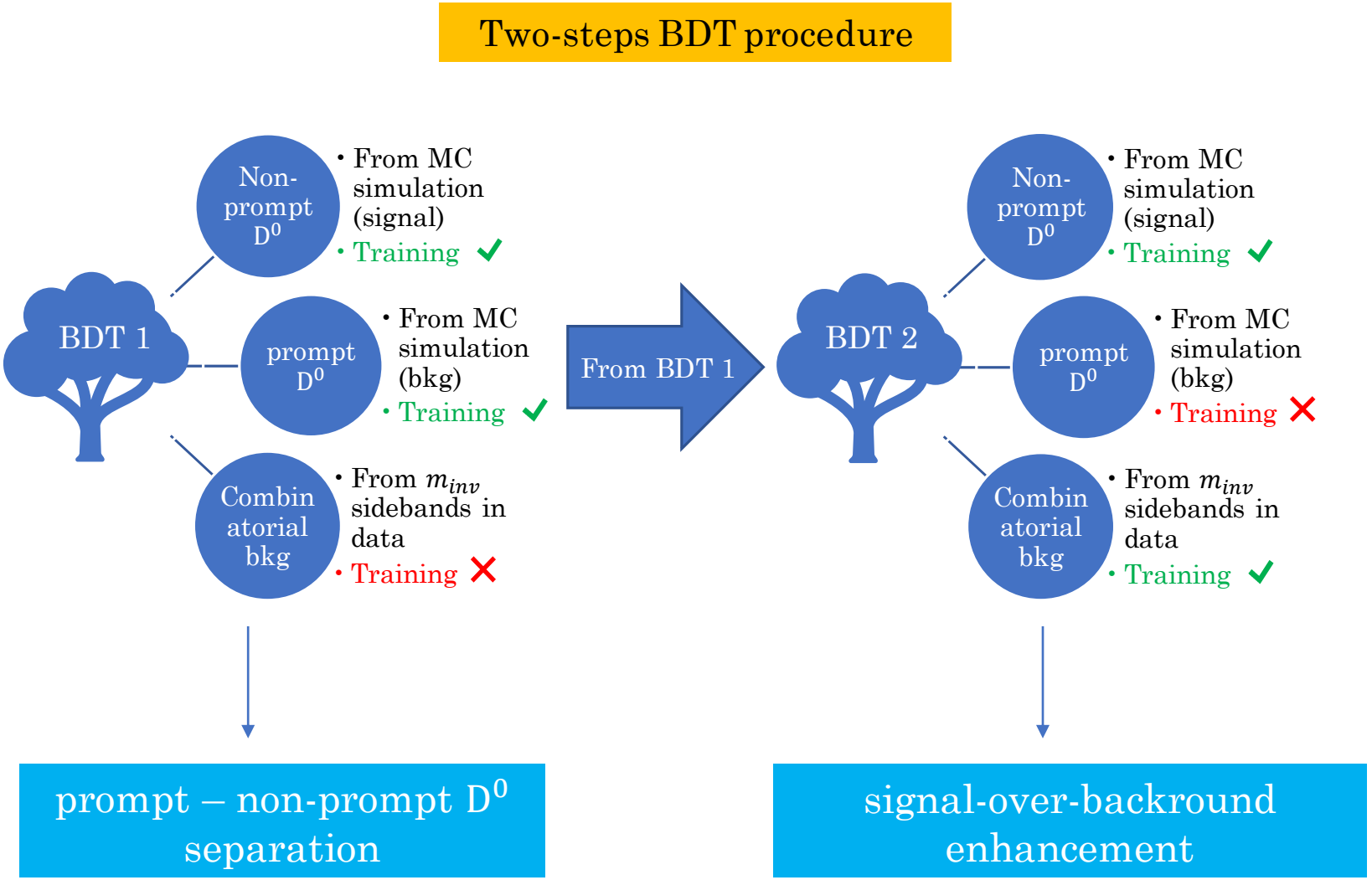
- $\Lambda_c^+(\Xi_c^0 \times \mathrm{Br})/D^0$ ratio is larger than the predictions
  → contribution from hadronization mechanisms different from fragmentation?

Beauty via non-prompt D-mesons



ALI-PREL-319757

Beauty via non-prompt D-mesons



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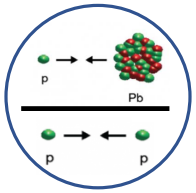
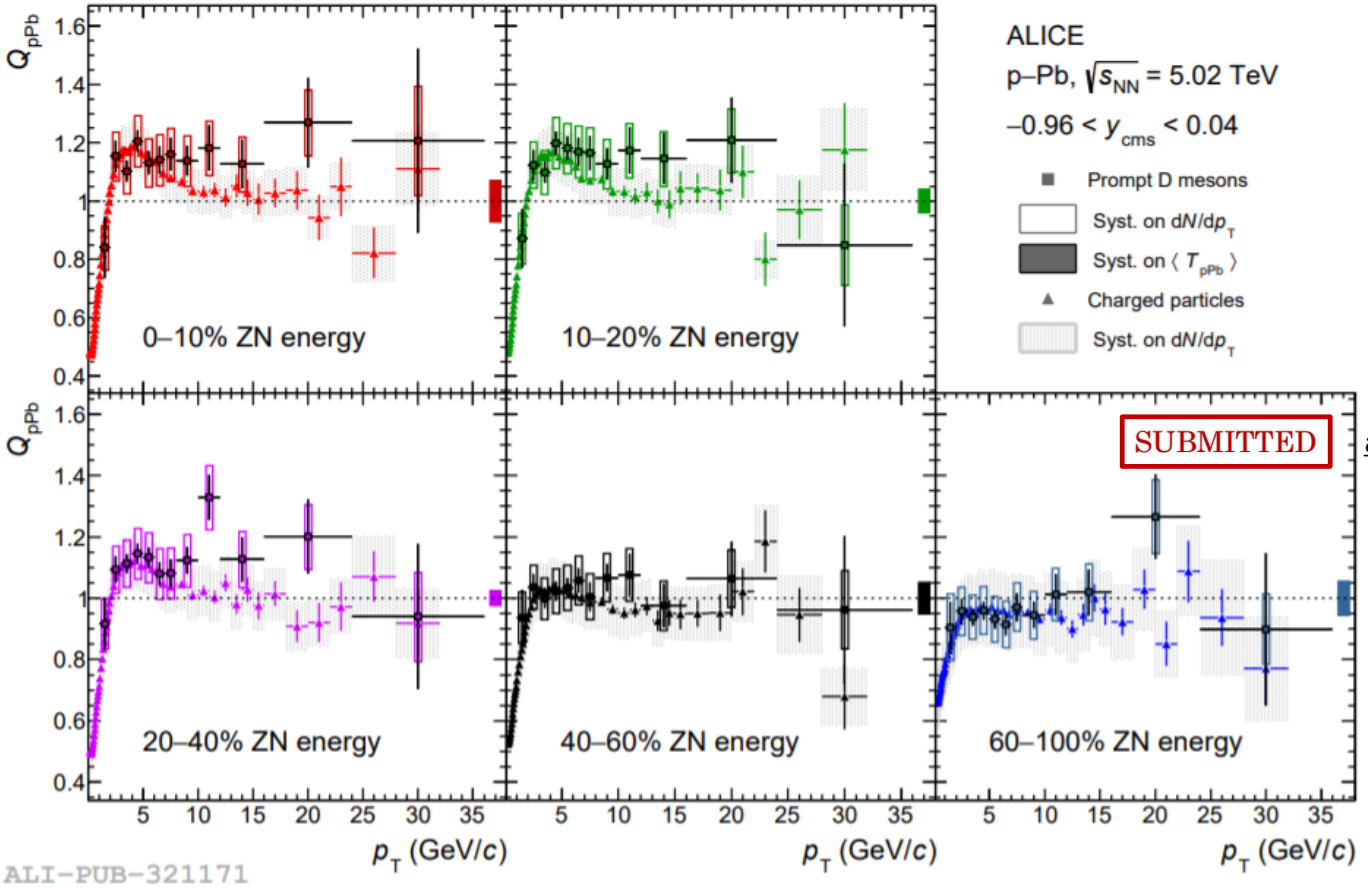
p-Pb collisions

Prompt D-meson production



vs. event activity
(determined with ZDC)

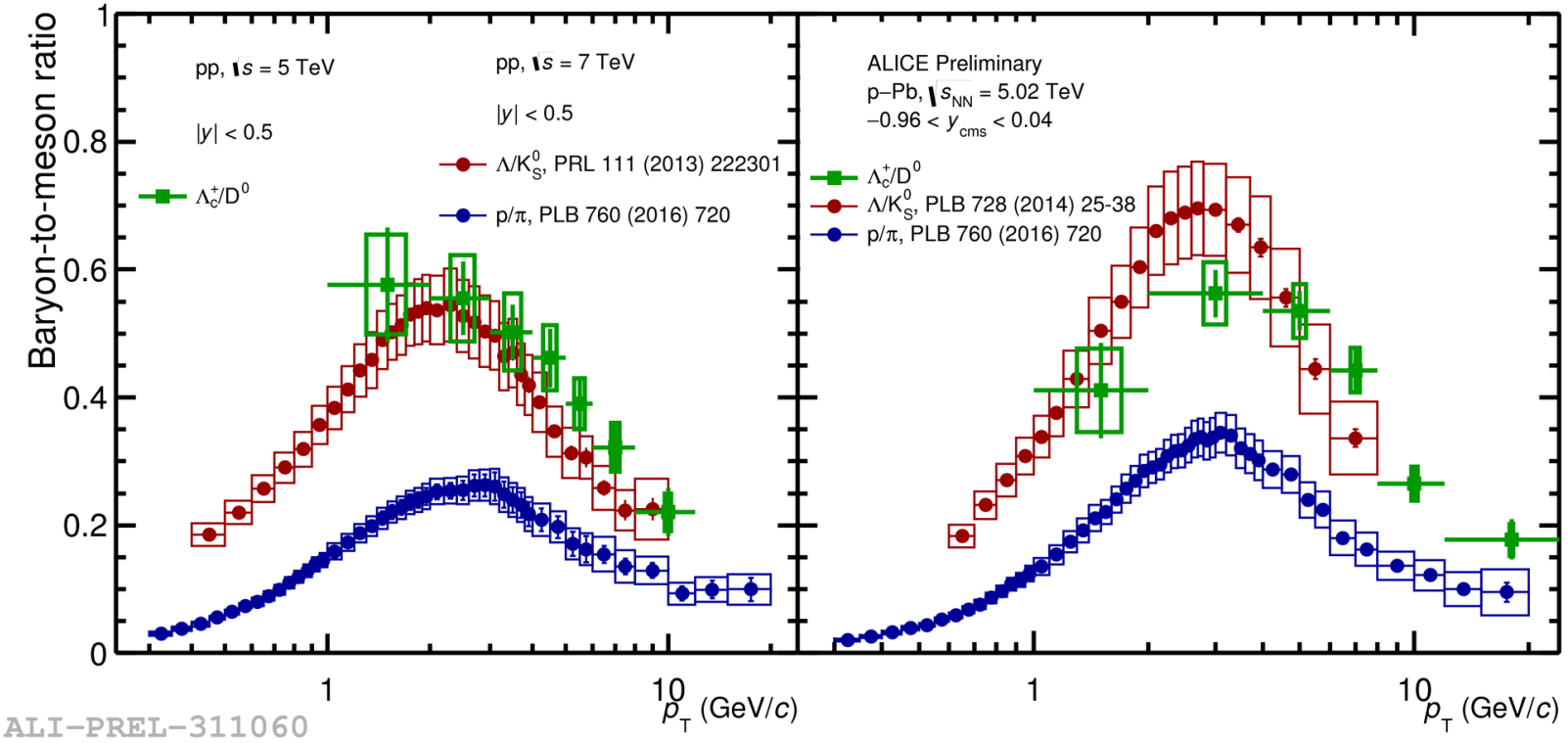
$$Q_{\mathrm{pPb}}^{\mathrm{cent}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{pPb}}^{\mathrm{cent}} \rangle} \frac{\mathrm{d}N_{\mathrm{pPb}}^{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} \qquad \langle T_{\mathrm{pPb}}^{\mathrm{cent}} \rangle = \langle N_{\mathrm{coll}} \rangle^{\mathrm{cent}} / \sigma_{\mathrm{NN}}$$



arXiv:1906.03425

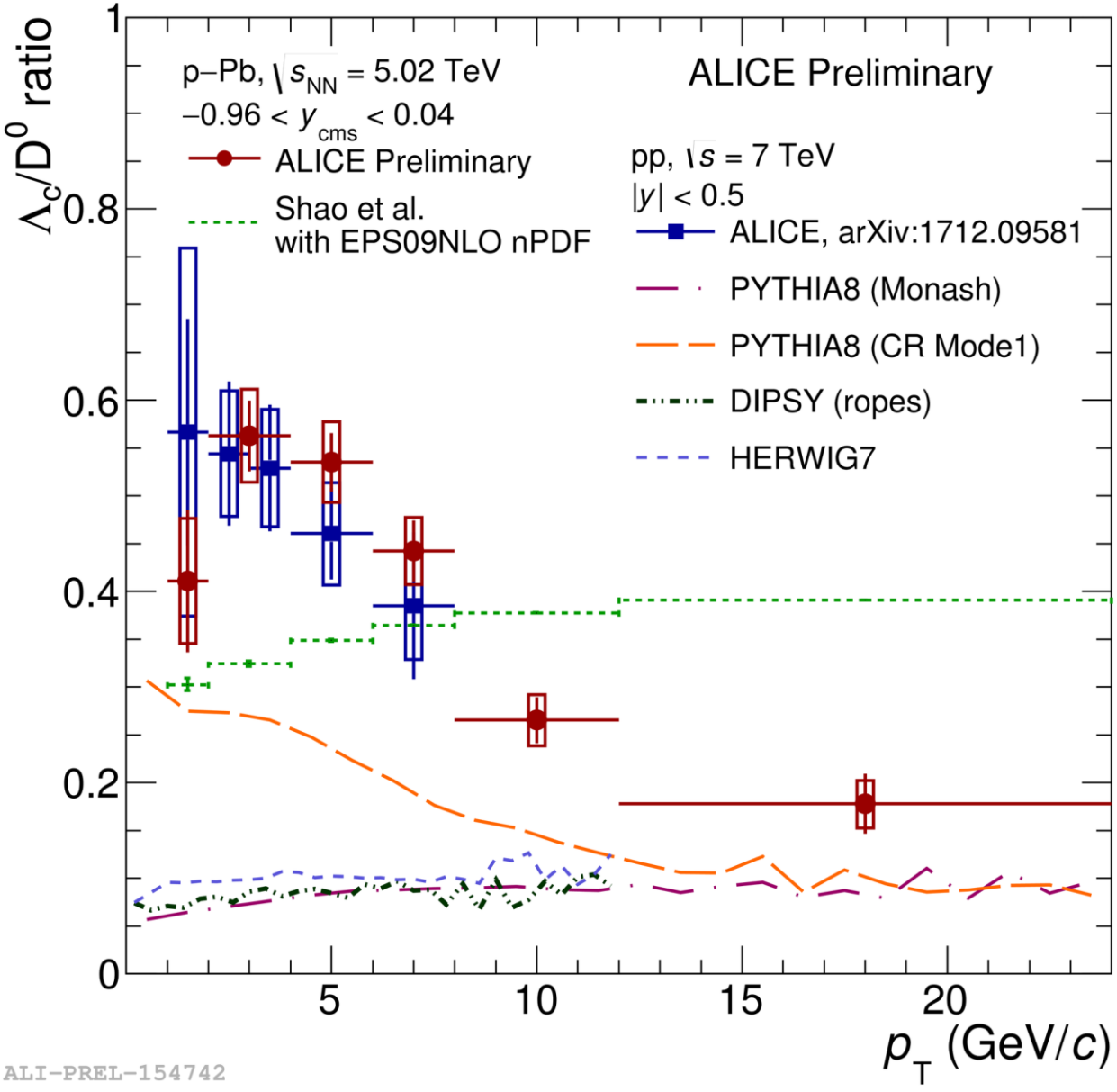
- Hint of enhancement at $2 < p_{\mathrm{T}} < 6$ GeV/c in 0-10% centrality class
  → Final state effects? More details in Fabio's talk
- Similar behaviour observed for charged particles

Charmed baryon production



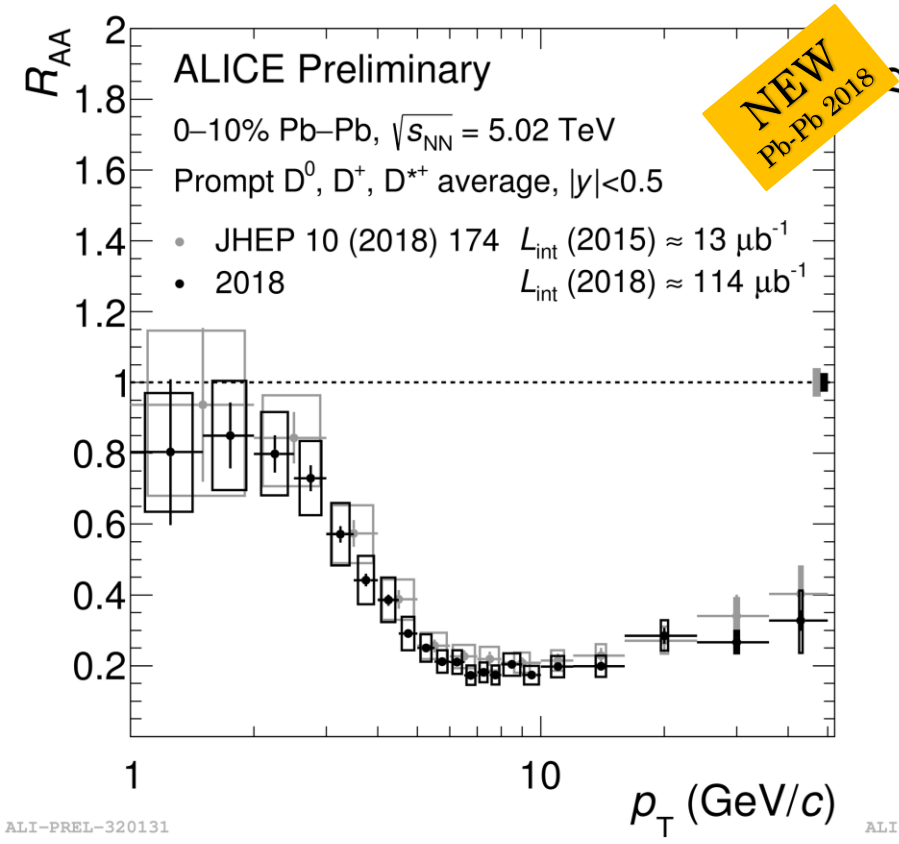
- Λ_c^+/D^0 shows a decreasing trend above $p_\mathrm{T} = 4$ GeV/c, as in the light-flavour sector

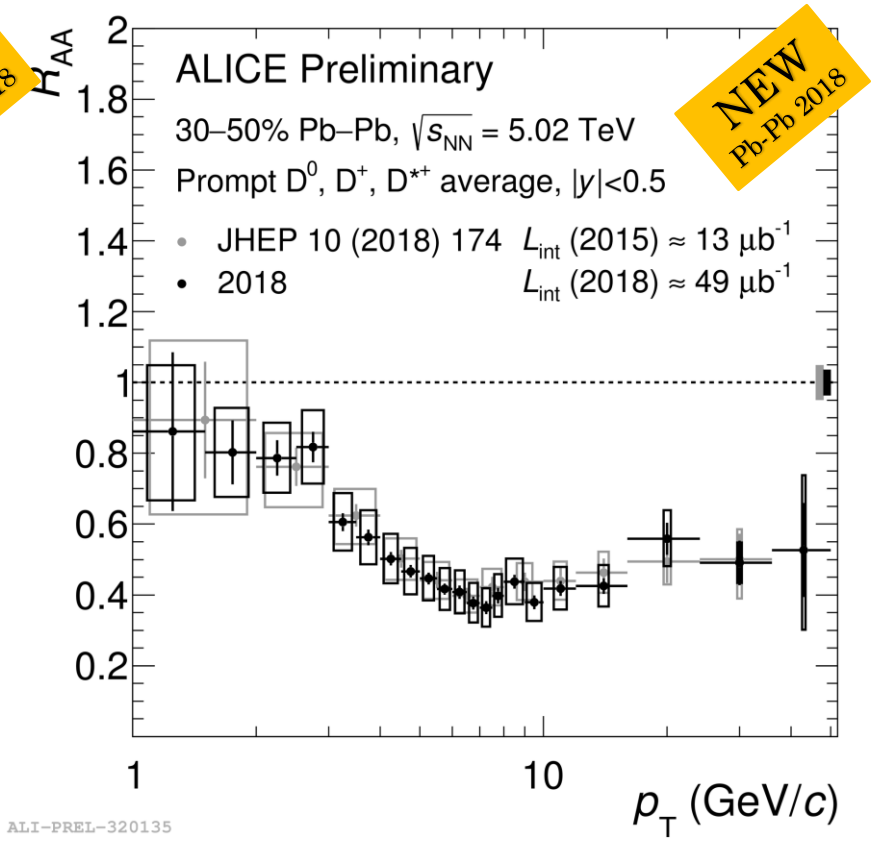
Charmed baryon production



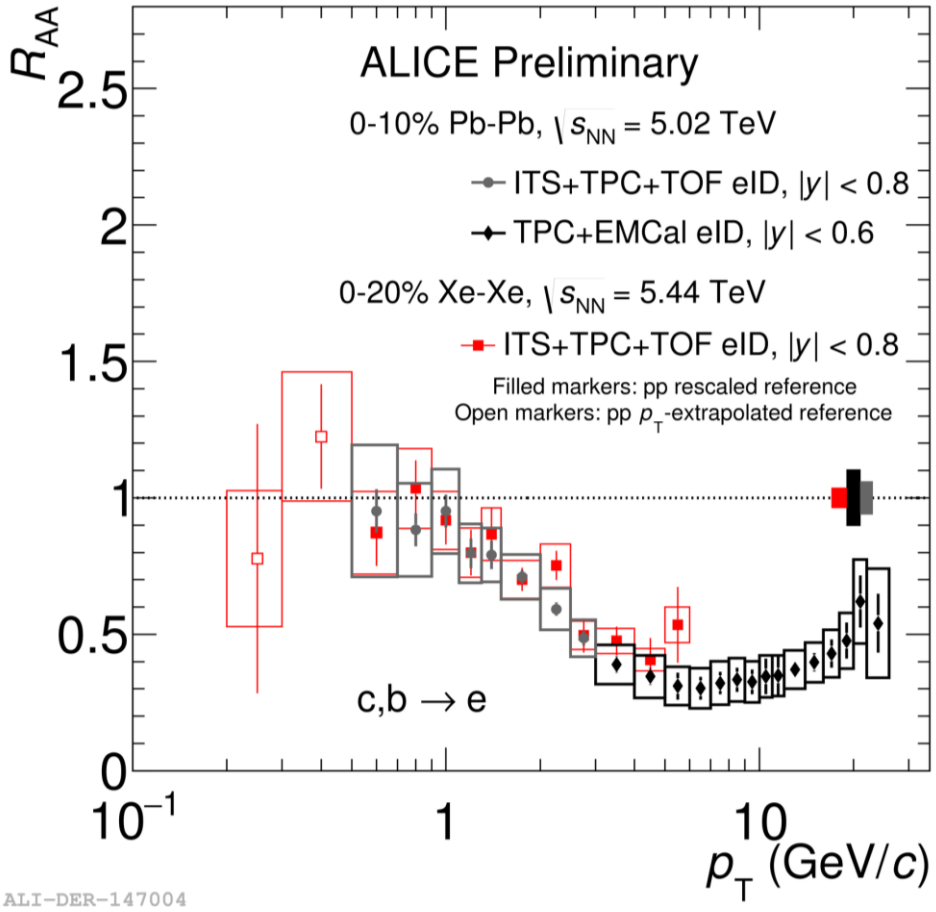
Pb-Pb collisions

D-mesons R_{AA} and v_2



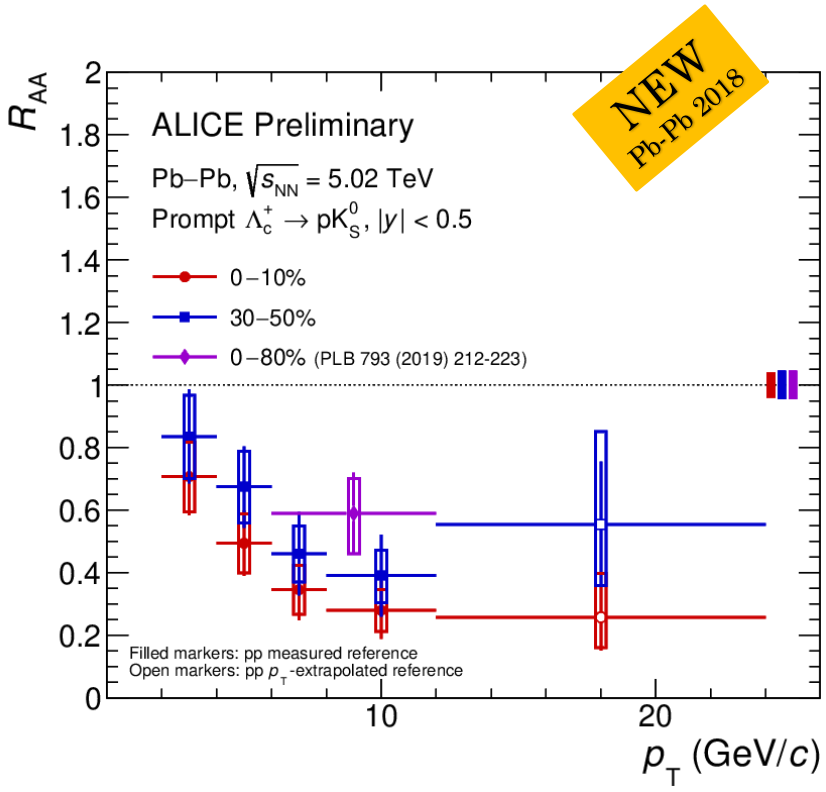


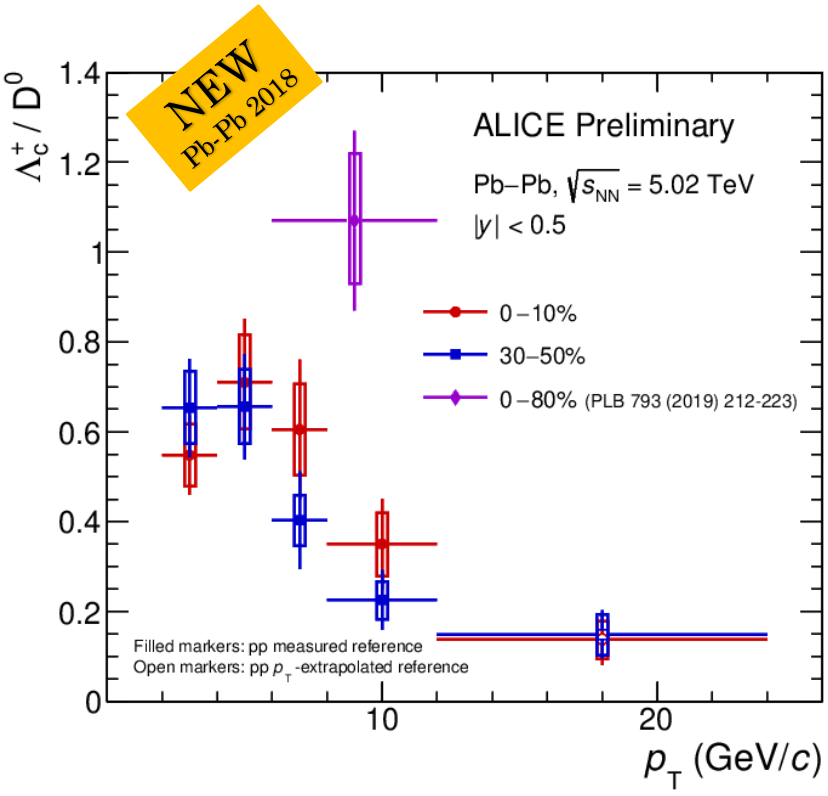
Leptons from HF-hadron decays



- Comparison of R_{AA} measurements at different N_{part} or N_{ch} may add sensitivity to probe the path-length dependence of in-medium parton energy loss
- Similar R_{AA} for HF→e in Pb-Pb and Xe-Xe collisions at similar $\langle dN_{ch}/d\eta \rangle$
  → possibility to further constrain model calculations

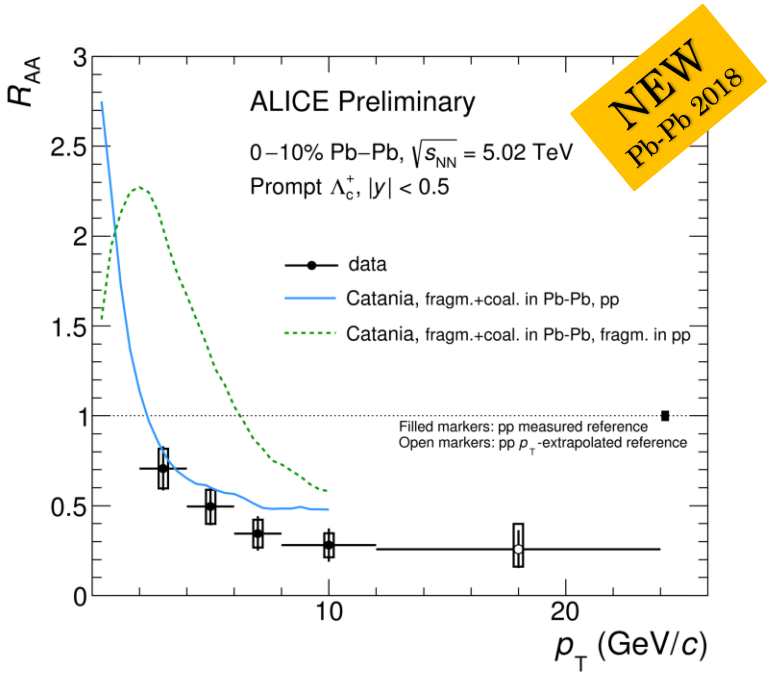
Charmed baryon production

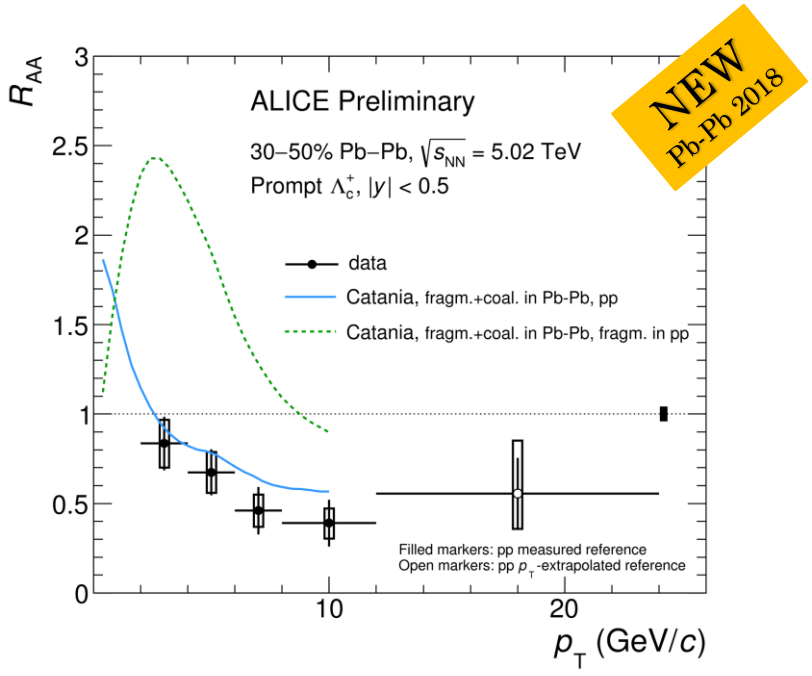


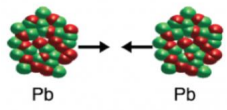


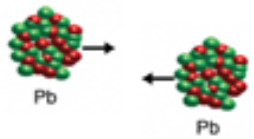
- 2015 result in 0-80% in $6 < p_T < 8$ GeV/c compatible within 2σ with 0-10% result

Charmed baryon production

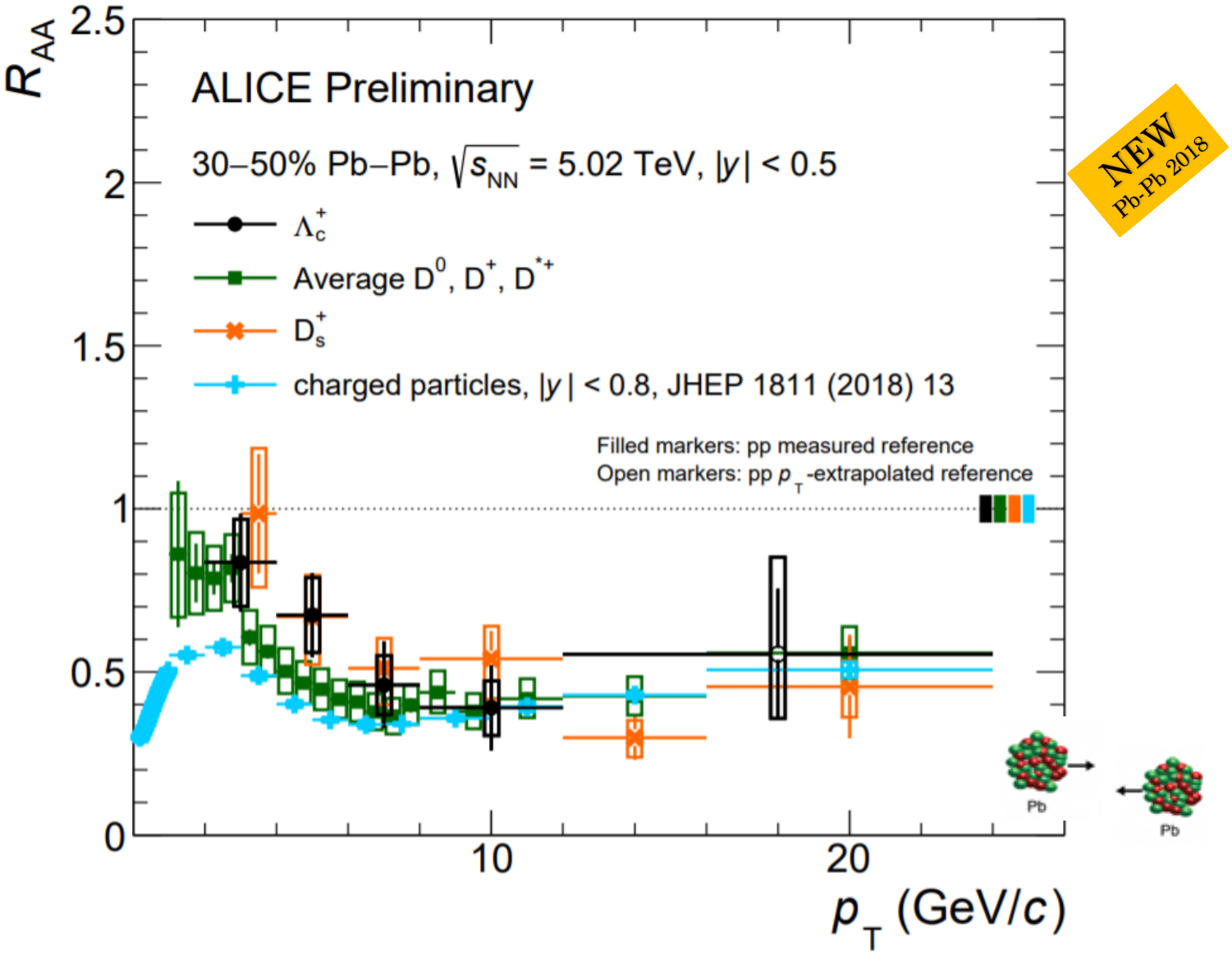








Charmed baryon production



ALI-PREL-321908

D^0 directed flow

- High magnetic field in heavy ion collisions
- Faraday effect: electric field induced by reducing magnetic field with time (spectators)
- Hall effect: Lorentz force induced on moving charges (QGP expansion)

- D-mesons v_1 expected to be larger than light hadrons
  - → Charm formation time comparable to maximum B
  - → Relaxation time similar to QGP lifetime

- Hint of positive slope (2.7 σ)
  - → ~1000 times larger effects than the one on light hadrons