Overview on heavy-flavour results from the ALICE experiment

Fabio Colamaria, for the ALICE Collaboration

Istituto Nazionale di Fisica Nucleare

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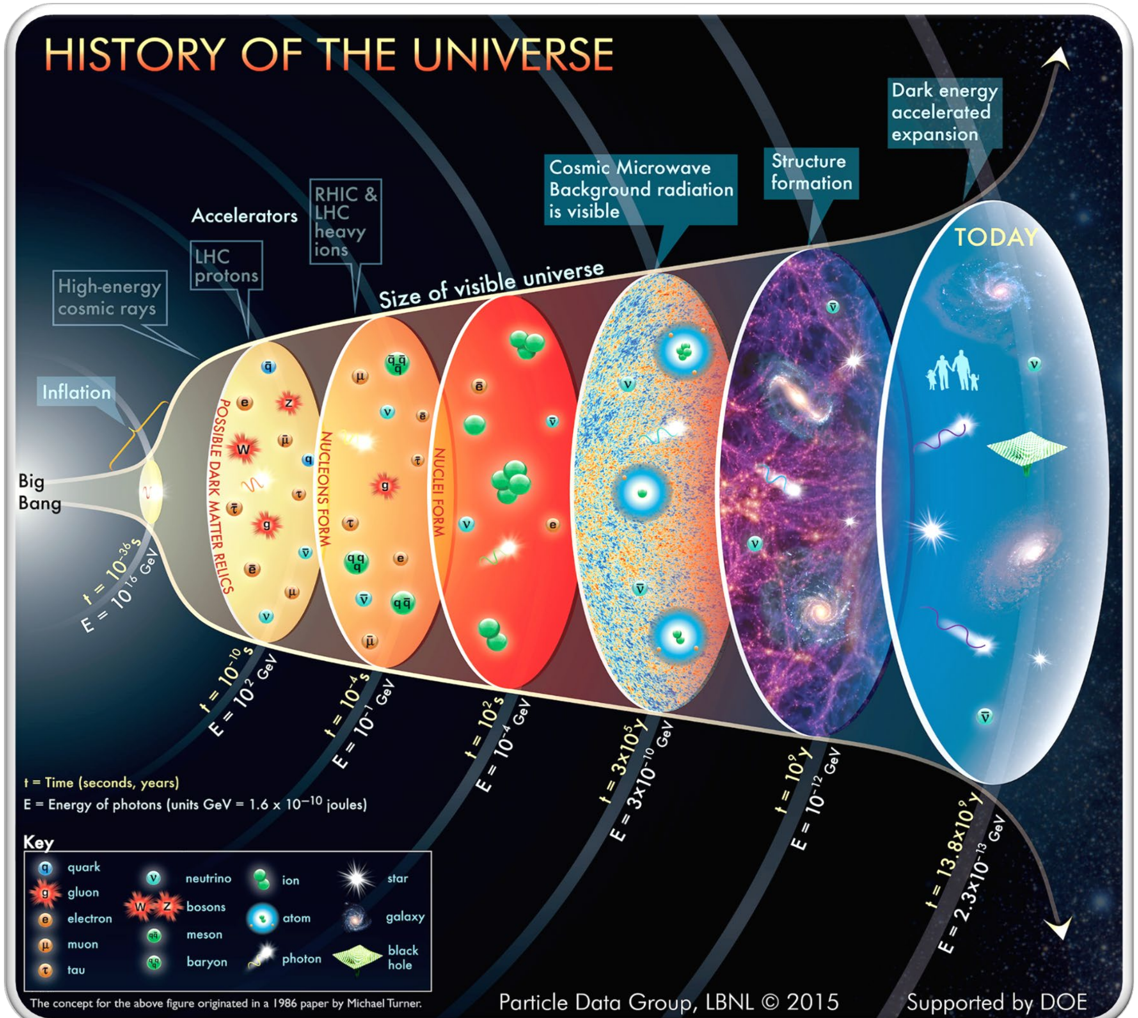
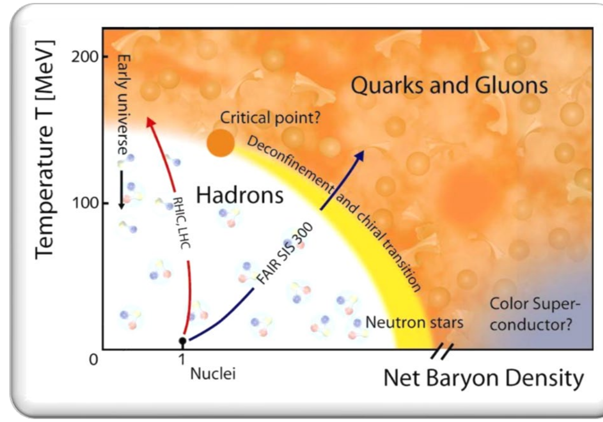
WHAT DOES ALICE STUDY? THE QGP





Goal: study the properties of nuclear matter at extreme conditions of temperature and energy density

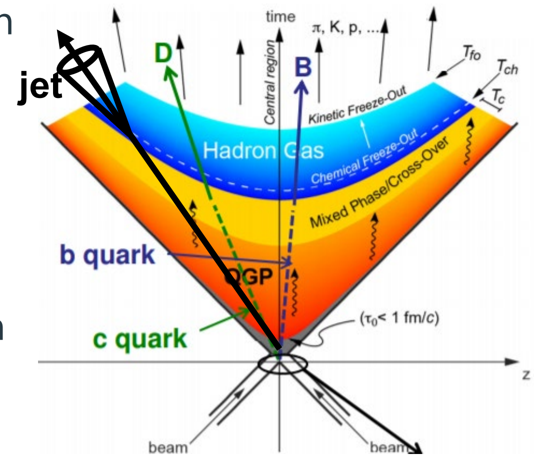
- Deconfined state of matter: **quark-gluon plasma** (**QGP**)
- From lattice QCD: $\boldsymbol{T_C \sim 150}$ **MeV** and $\boldsymbol{\varepsilon_C \sim 0.5}$ **GeV/fm³**

A QGP state can be produced (for few fm/*c*) in ultrarelativistic heavy-ion collisions

THE IMPORTANCE OF HEAVY-FLAVOURS

In Pb-Pb collisions

- **Charm** and **beauty** experience the **whole evolution** of the collision
  - ➢ **QGP tomography** by studying final-state HF particles
- Characterise **partonic energy loss** due to interactions with QGP constituents
- Do heavy quarks participate to QGP **collective motion**?
- Investigate **coalescence vs fragmentation** mechanisms for hadron formation



In pp collisions

- Probe perturbative QCD calculations for heavy-quark production
  - ➢ Heavy quarks produced in **hard-parton scatterings** with large Q^2 → pQCD can be used
- Study heavy-quark hadronisation mechanisms
- Reference for Pb-Pb measurements

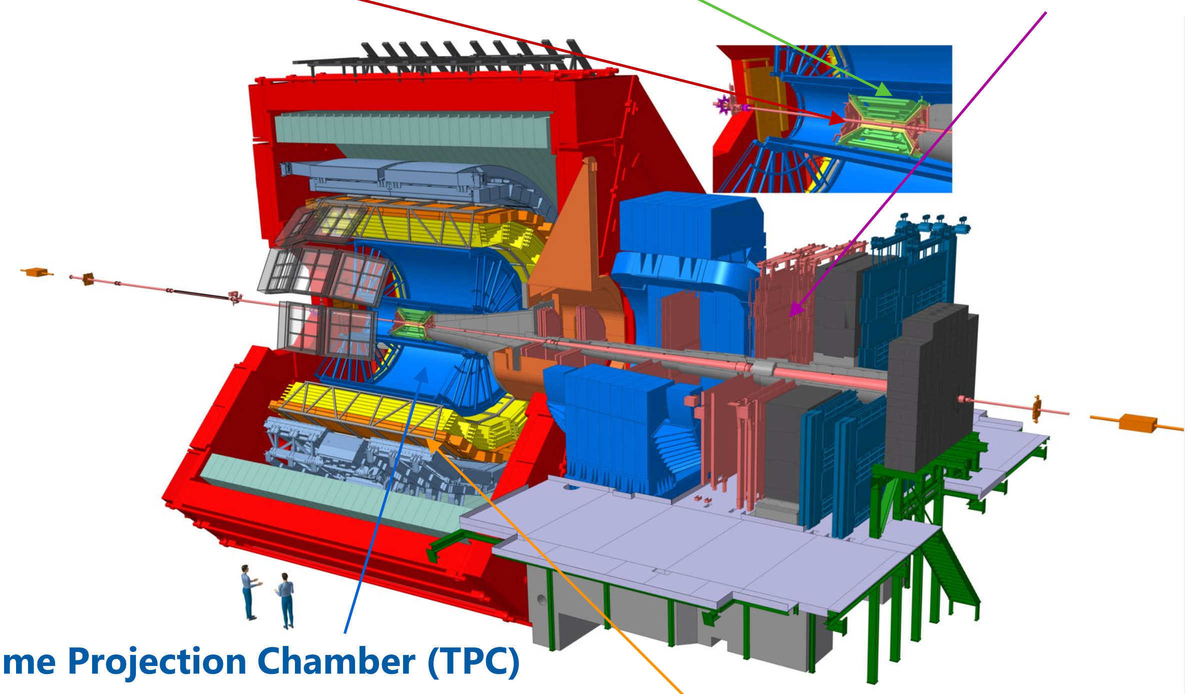
Also in high-multiplicity pp!

In p-Pb collisions

- Investigate impact of cold-nuclear-matter effects on observables studied in Pb-Pb
- Study possible final-state energy loss and formation of QGP in high-multiplicity events

THE ALICE EXPERIMENT

A multi-purpose experiment at the LHC, with focus on heavy-ion studies, excellent PID capabilities and tracking down to ≈100 MeV/*c*



HF mesons

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

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

$D^{*+} \rightarrow D^0 \pi^+$

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

$J/\psi \rightarrow e^- e^+$

$J/\psi, \psi(2S) \rightarrow \mu^- \mu^+$

$\Upsilon(1S, 2S, 3S) \rightarrow \mu^- \mu^+$

$D \rightarrow e(\mu)X$

$B \rightarrow e(\mu)X$

HF baryons

$\Lambda_c^+ \rightarrow K_S^0 p$

$\Lambda_c^+ \rightarrow \pi^+ K^- p$

$\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$

$\Xi_c^0 \rightarrow \Xi^- \pi^+$

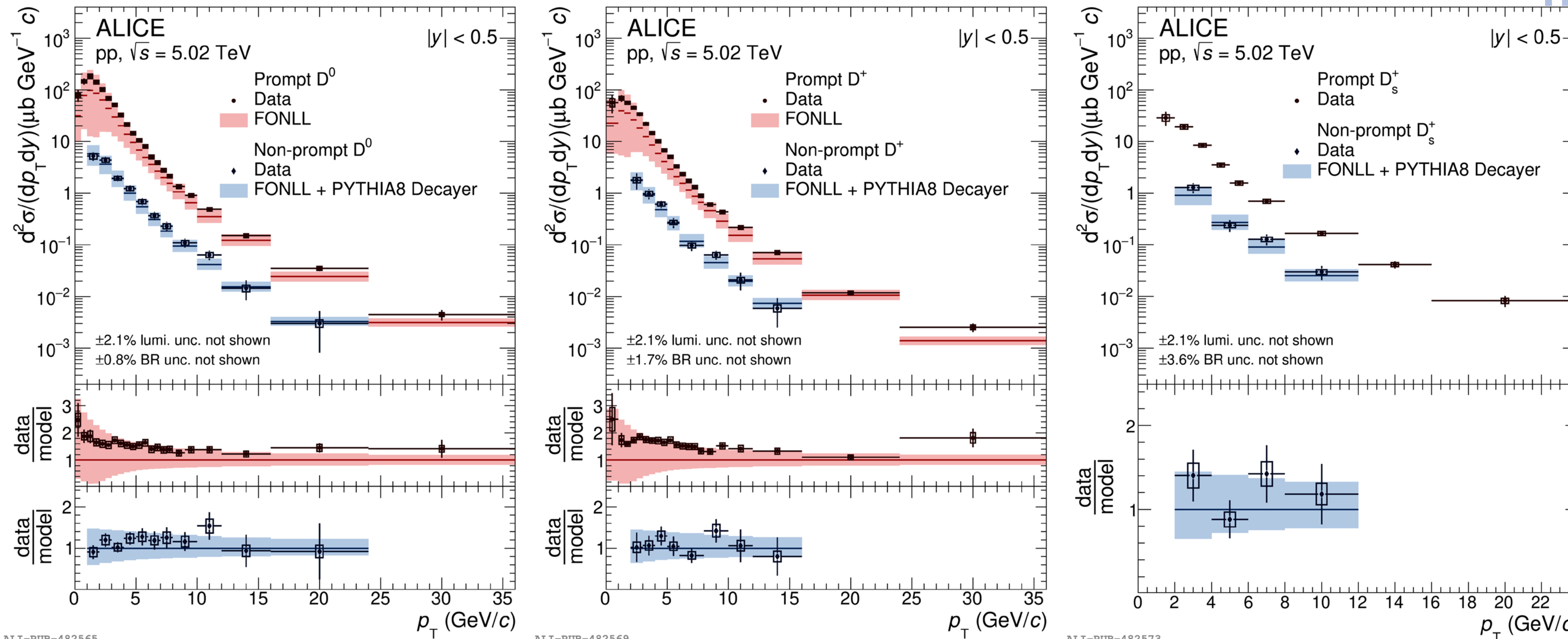
$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$

$\Omega_c^0 \rightarrow \Omega^- \pi^+$

$\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^{-,+}$

pp COLLISIONS

D-MESON PRODUCTION IN pp COLLISIONS

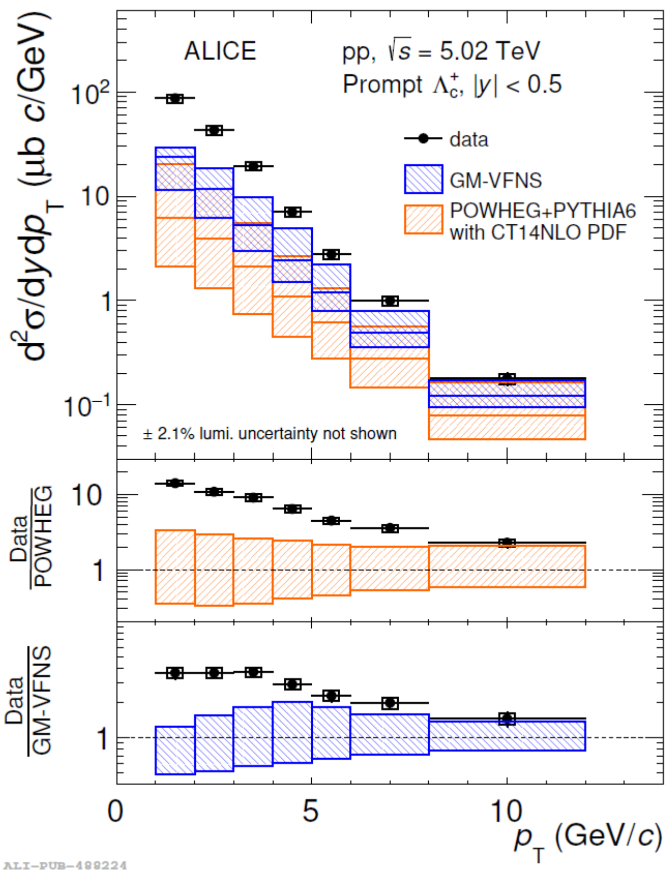


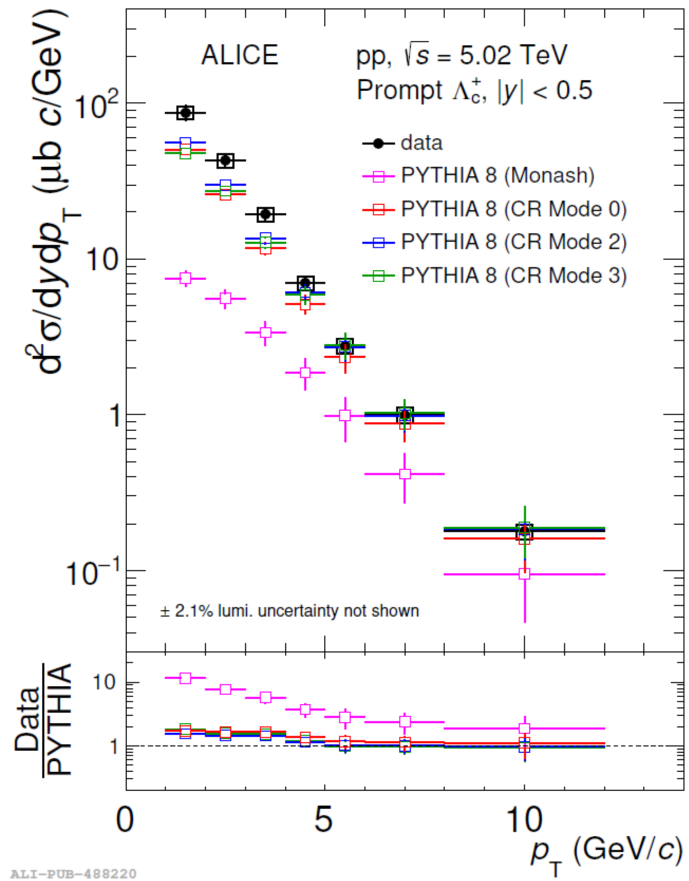
- Cross section of prompt and non-prompt D mesons measured with excellent precision down to $p_T = 0$ (for D^0, D^+)
- Comparison with perturbative QCD calculations (FONLL and GM-VFNS) which assume universal fragmentation functions across collision systems
  - ➢ **Good description of the measurement for D mesons**

ALICE, JHEP 05 (2021) 220
FONLL: JHEP 1210 (2012) 137

Λ_c^+ PRODUCTION IN pp COLLISIONS

Very different picture for charm baryons!

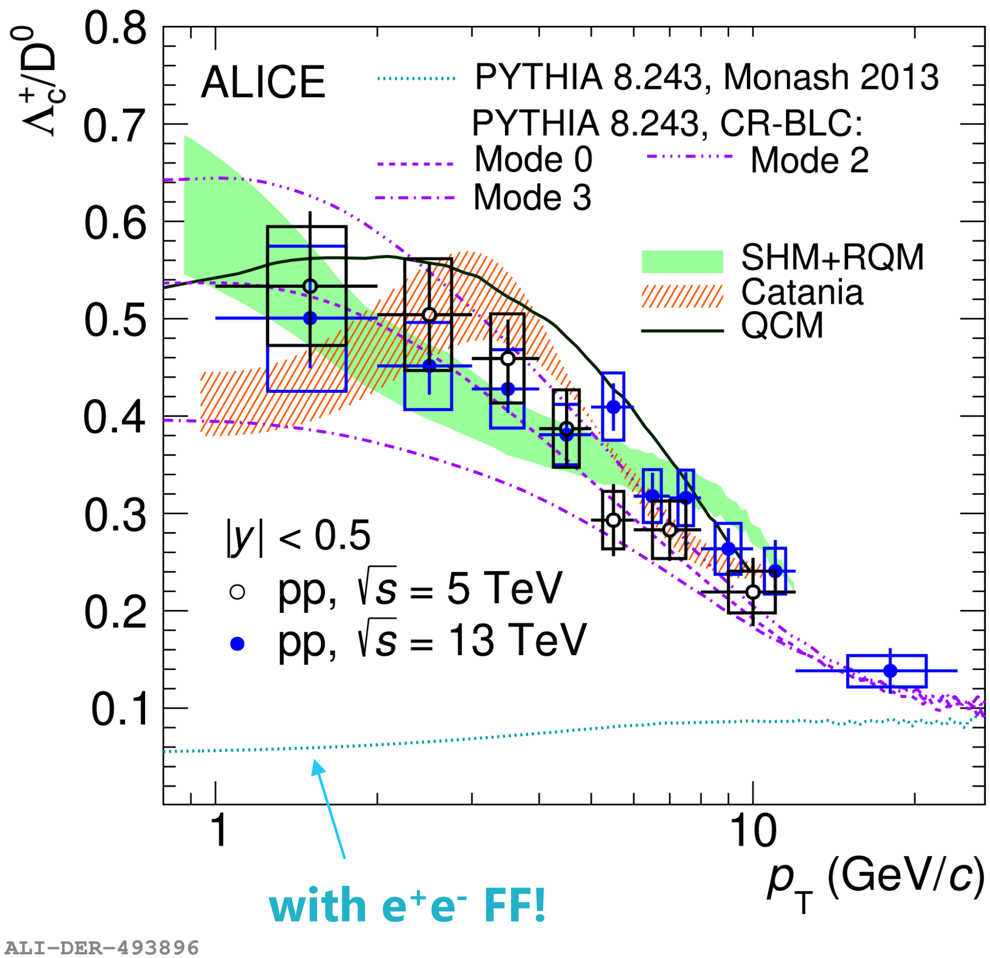




ALICE: arXiv:2011.06079
GM-VFNS: EPJ C72 (2012) 2082
POWHEG: JHEP 09 (2007) 126
PYTHIA6: JHEP 05 (2006) 026
PYTHIA8: arXiv:0710.3820

- Severe underestimation of Λ_c^+ production cross section by pQCD calculations (GM-VFNS), and models/generators based on standard fragmentation (POWHEG+PYTHIA6, PYTHIA8 Monash)
- Proper description needs specific mechanisms to enhance baryon production in pp collisions

Λ_c^+ PRODUCTION IN pp COLLISIONS



ALICE, arXiv:2011.06078
ALICE, arXiv:2011.06079
ALICE, arXiv:2106.08278

PYTHIA8+CR: JHEP 08 (2015) 003
SHM+RQM: PLB 795 (2019) 117-121
Catania: arXiv:2012.12001
QCM: EPJ C78 no. 4 (2018) 344

Large disagreement of Λ_c^+/D^0 ratios in pp collisions w.r.t. PYTHIA8 Monash

- Enhanced Λ_c production, in particular at low p_T
- PYTHIA8 Monash FF based on data from e^+e^- collisions

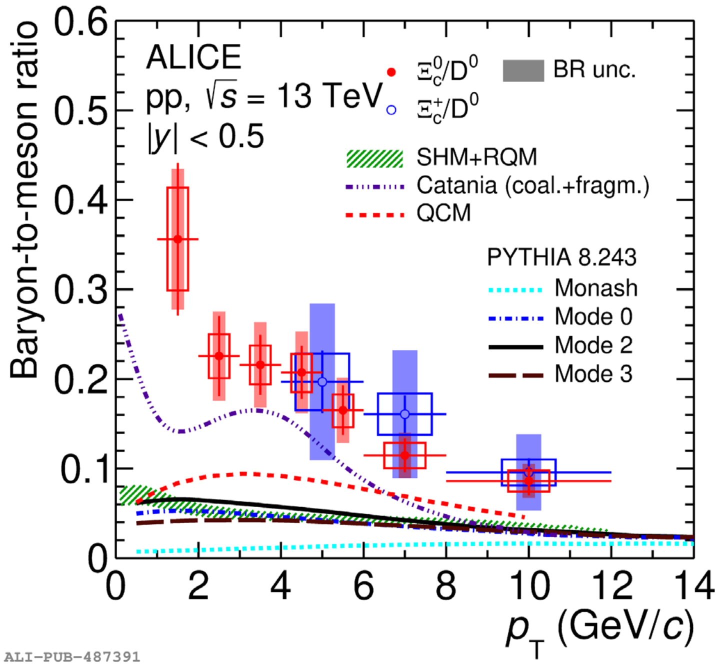
Better description by models with baryon production enhancement mechanisms:

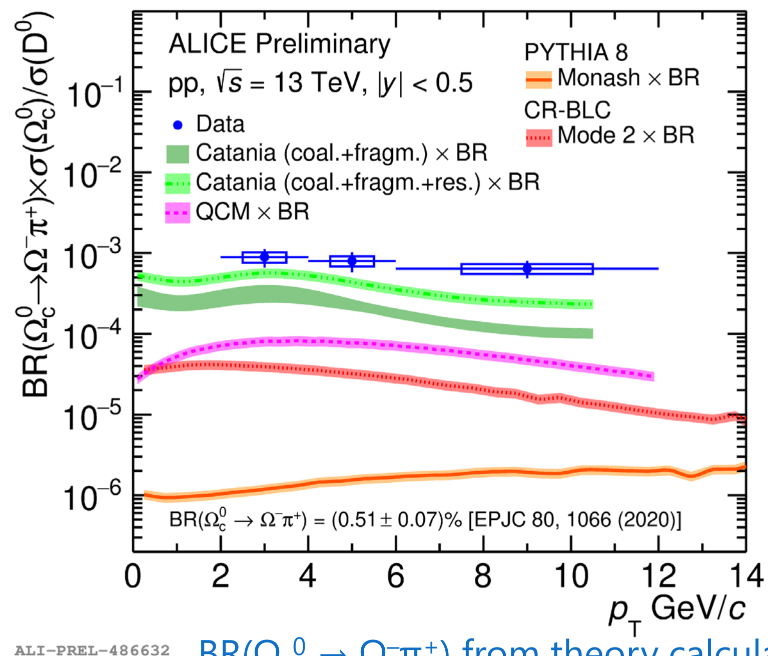
- Color reconnection beyond leading-colour approximation
  → PYTHIA8 CR-BLC
- Statistical hadronisation with enlarged set of excited charm baryons
  → SHM+RQM
- Λ_c^+ hadronisation via recombination mechanism
  → Catania (w/ fragmentation)
  → QCM

CHARM BARYONS IN pp COLLISIONS

ALICE

Ξ_c^0 quark content: d s c Ξ_c^+ quark content: u s c Ω_c^0 quark content: s s c





BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$) from theory calculations

Even stronger enhancement for s+c states

For $\Xi_c^{0,+}/D^0$ ratios, only Catania gets close to data

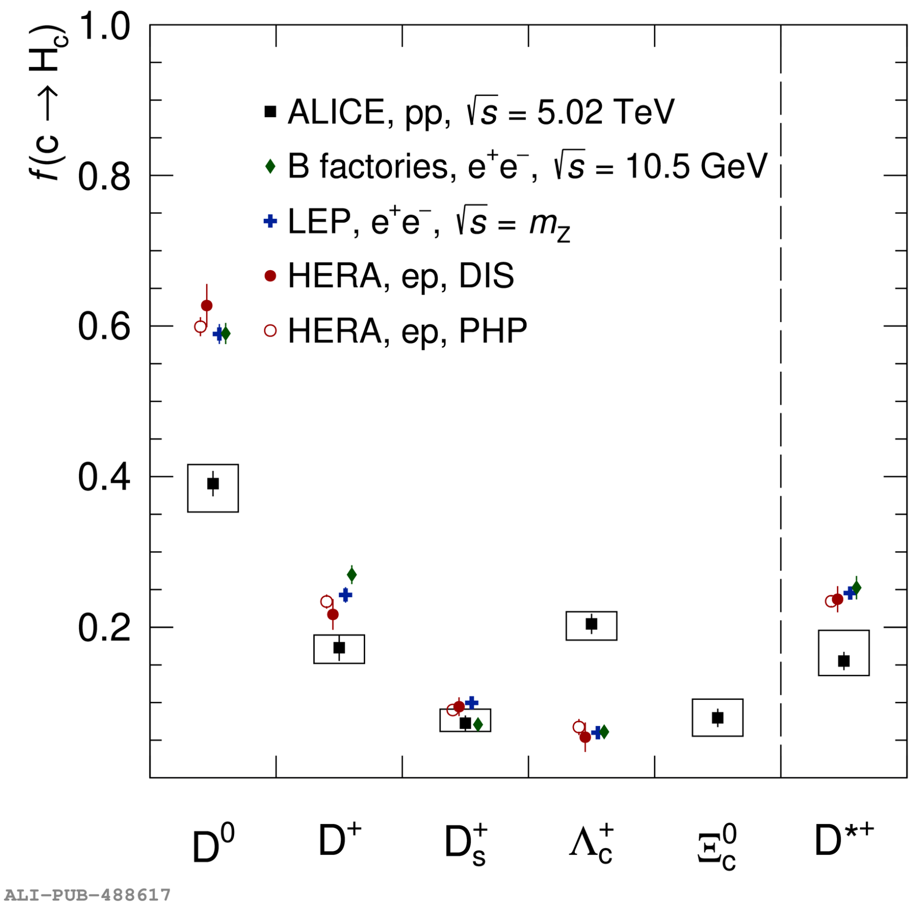
- Both coalescence and fragmentation mechanisms in pp?

All models underestimate Ω_c^0/D^0 production cross section ratios

- PYTHIA8 Monash off by orders of magnitude
- Catania gives again the closest description, though still below data

ALICE, arXiv:2105.05187

CHARM FRAGMENTATION FRACTIONS



Compared to e^+e^- / e^-p collisions;

- Increased contribution of ≈x3 for Λ_c
- Decreased production by ≈x1.4 for D mesons

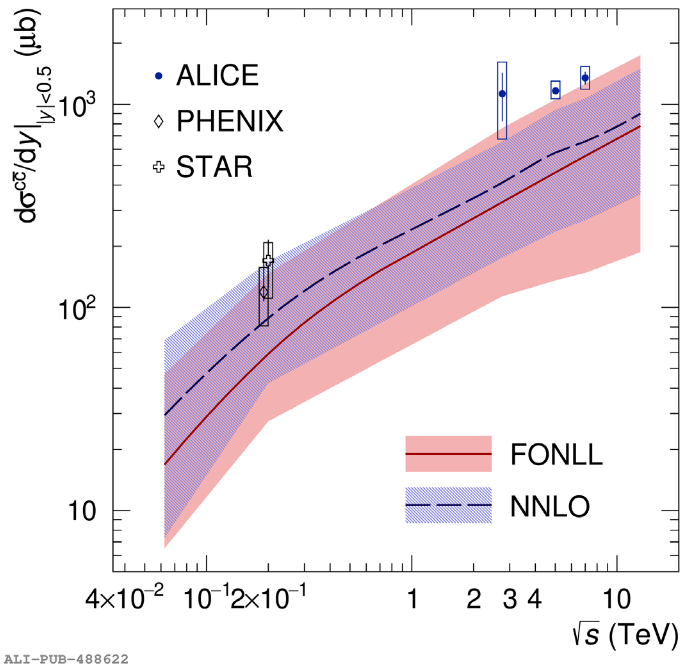
First measurement of Ξ_c^0 fragmentation fractions

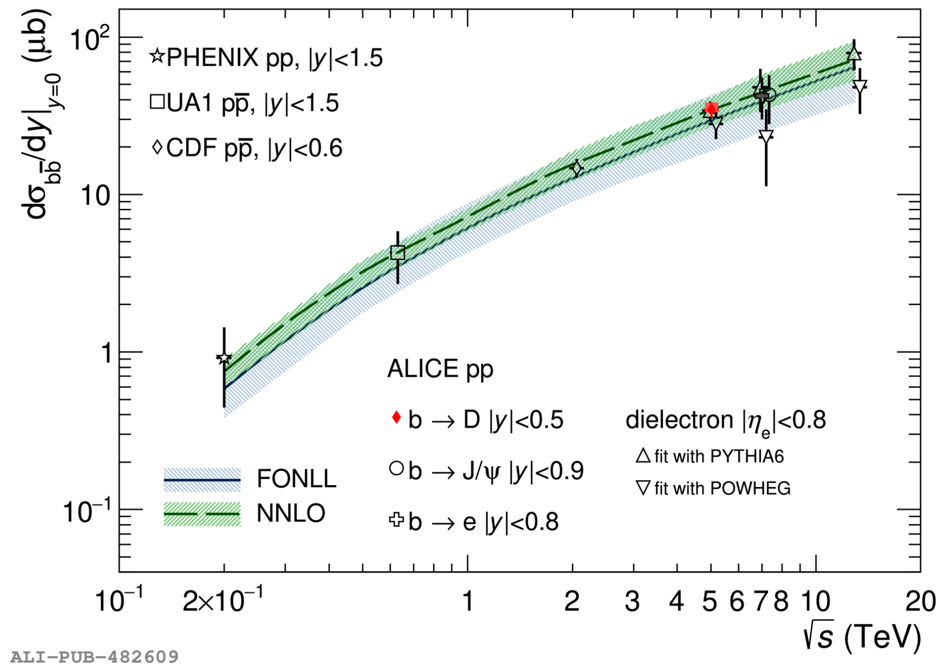
H_c	$f(c \to H_c)[\%]$	
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$	
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$	
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$	
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$	
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$	x2 (Ξ_c^+)
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$	Into $D^{0,+}$

ALICE, arXiv:2105.06335
HERA: EPJC 76 no. 7 (2016) 397 √s=5.02 TeV
LEP: EPJC 76 no. 7 (2016) 397
B factories: EPJC 76 no. 7 (2016) 397

- For pp collisions, important contribution of charm baryons to total charm cross section
- **Charm fragmentation is not universal!**

CHARM AND BEAUTY PRODUCTION CROSS SECTION





- $c\bar{c}$ production cross section at midrapidity at √s = 5.02 TeV:

  $(d\sigma^{c\bar{c}}/dy)_{|y|<0.5} = 1165 \pm 44(\text{stat.})^{+134}_{-101}\,(\text{syst})\ \mu b$

- Re-evaluation of cross section at √s = 7 and 2.76 TeV (≈+40%)
- Data on upper edge of FONLL and NNLO calculation

- $b\bar{b}$ production cross section at midrapidity at √s = 5.02 TeV:

  $(d\sigma^{b\bar{b}}/dy)_{|y|<0.5} = 34.5 \pm 2.4\,(\text{stat.})^{+4.6}_{-2.9}\,(\text{tot. syst.})\ \mu b$

- From non-prompt D-meson measurements
- Good description by FONLL and NNLO calculations over a wide range of energy

ALICE: arXiv:2105.06335, JHEP 05 (2021) 220, JHEP 11 (2015) 065, PLB 721 (2013) 13-23, PRC 102 (2020) 5, 055204;
PHENIX: PRC 84 044905 (2011), PRL 103 082002 (2009); STAR: PRD 86 (2012) 072013; CDF: PRD 71 032001 (2005); UA1: PLB 256 (1991) 121

Pb-Pb COLLISIONS

SPECIFIC OBSERVABLES FOR PROBING THE QGP

- The **nuclear modification factor R_{AA}** quantifies modifications to particle production yields induced by QGP effects on the traversing partons, for a given collision centrality:

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

- At high p_T:
  - R_{AA} = 1 in case of binary scaling
  - R_{AA} < 1: partonic energy loss and/or cold-nuclear-matter effects

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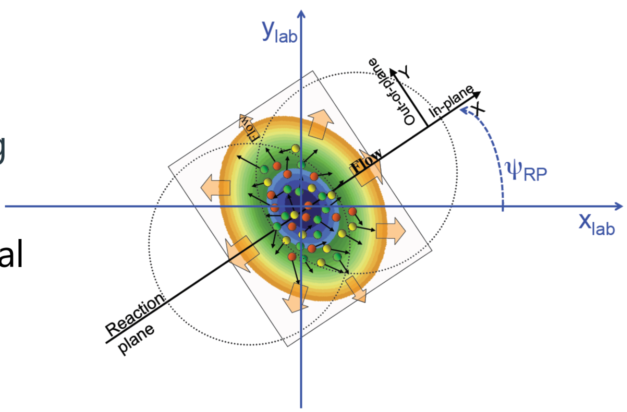
- Hydrodynamic treatment describes well the QGP evolution
- Non-central collisions: initial spatial anisotropy of the overlapping region translates into momentum anisotropy:
- Anisotropy quantified by a Fourier decomposition of the azimuthal distribution, w.r.t. reaction plane → **v_n coefficients**



$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{N_0}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty} v_n\,(p_{\mathrm{T}})\cos\left[n\left(\varphi - \Psi_{\mathrm{RP}}\right)\right]\right\}$$

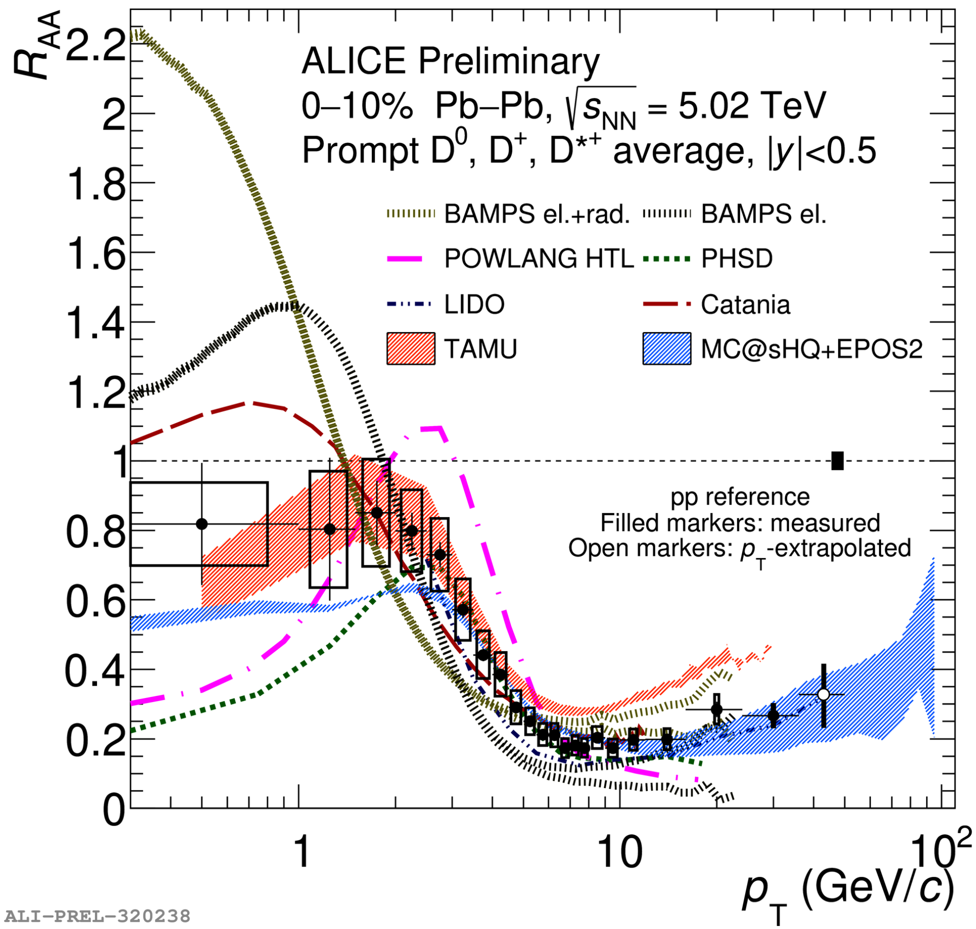
$$v_n = \langle \cos\left[n\left(\varphi - \Psi_{\mathrm{RP}}\right)\right]\rangle$$

v_2: sensitive to collision initial geometry

v_3, v_4, ...: sensitive to event-by-event fluctuations

PROMPT D-MESON R_{AA}

ALICE

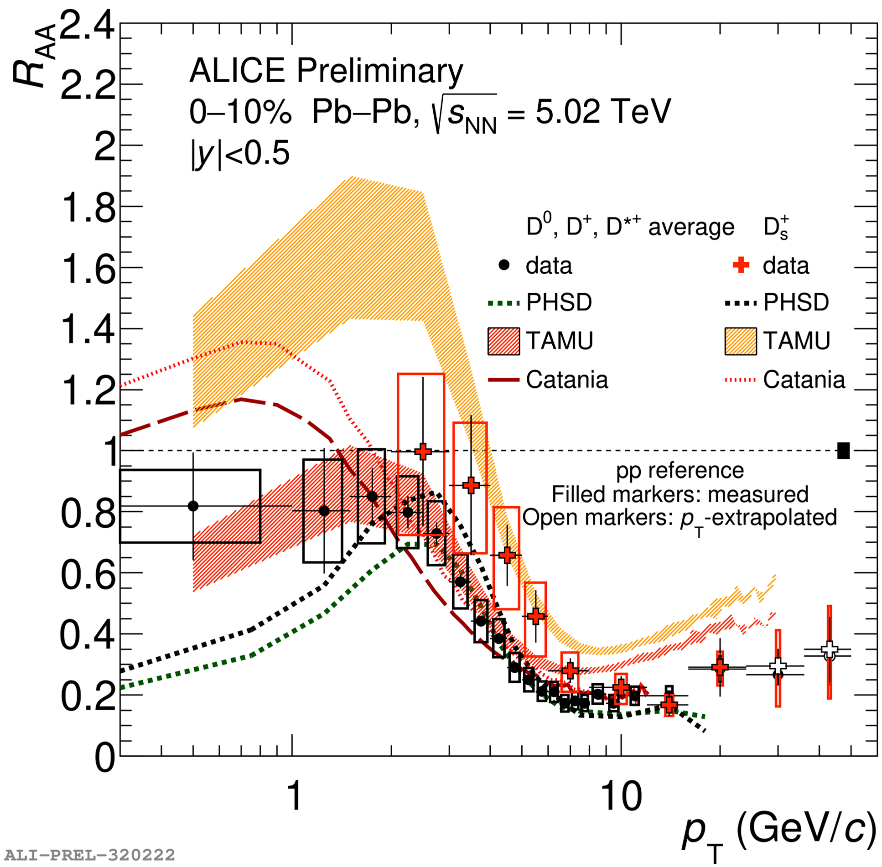


- Prompt D mesons strongly suppressed in central Pb-Pb collisions
  - Factor ≈5.5 at 6-10 GeV/c

- Best description by models with radiative and collisional energy loss + quark recombination
  - Set constraints on models describing in-medium interactions of heavy quarks

BAMPS: J. Phys. G: Nucl. Part. Phys. 42 115106
POWLANG: EPJ C 75, 121 (2015)
LIDO: Phys. Rev. C 98 (2018) 064901
PHSD: T. Song et al. PRC 92 014910 (2015)
TAMU: M. He et al. PLB 735 445-450 (2014)
Catania: EPJC 78, 348 (2018)
MC@sHQ: Phys. Rev. C 89, 014905 (2014)

PROMPT D-MESON R_{AA} (STRANGE VS NON-STRANGE)



D^0 quark content: ū c

D^+ quark content: d̄ c

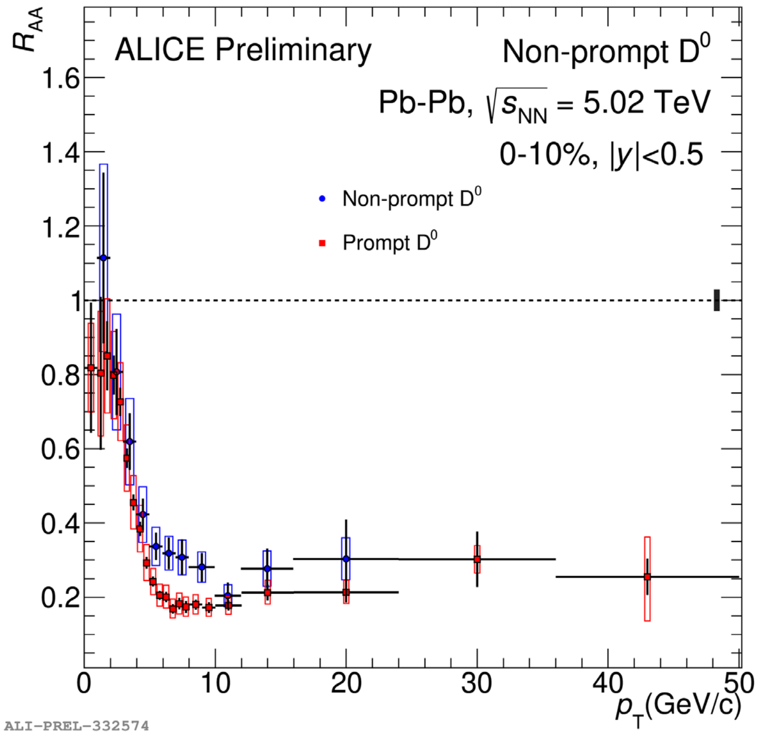
D^{*+} quark content: d̄ c

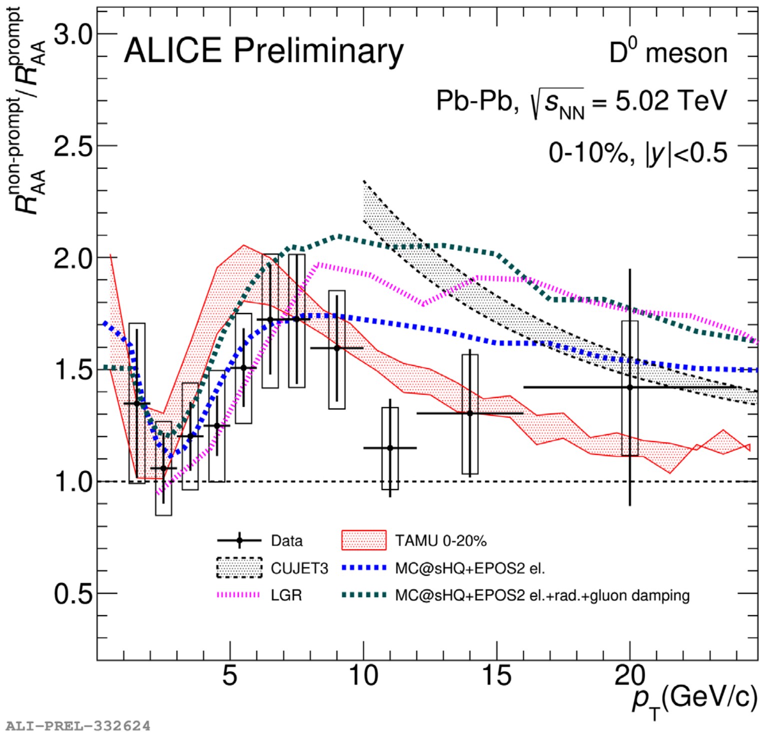
D_s^+ quark content: s̄ c

- Hint of smaller suppression for D_s^+ compared to non-strange D mesons for p_T < 8 GeV/c
- Explained due to strangeness enhancement in QGP + hadronization via recombination
- Hierarchy is well described by models including hadron formation via recombination

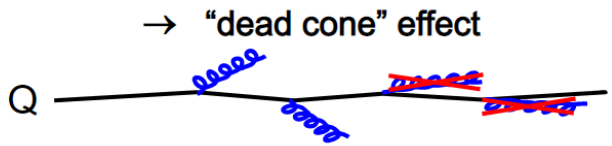
PHSD: T. Song et al. PRC 92 014910 (2015)
TAMU: M. He et al. PLB 735 445-450 (2014)
Catania: S. Plumari et al. EPJC 78 348 (2018)

NON-PROMPT D-MESON R_{AA}

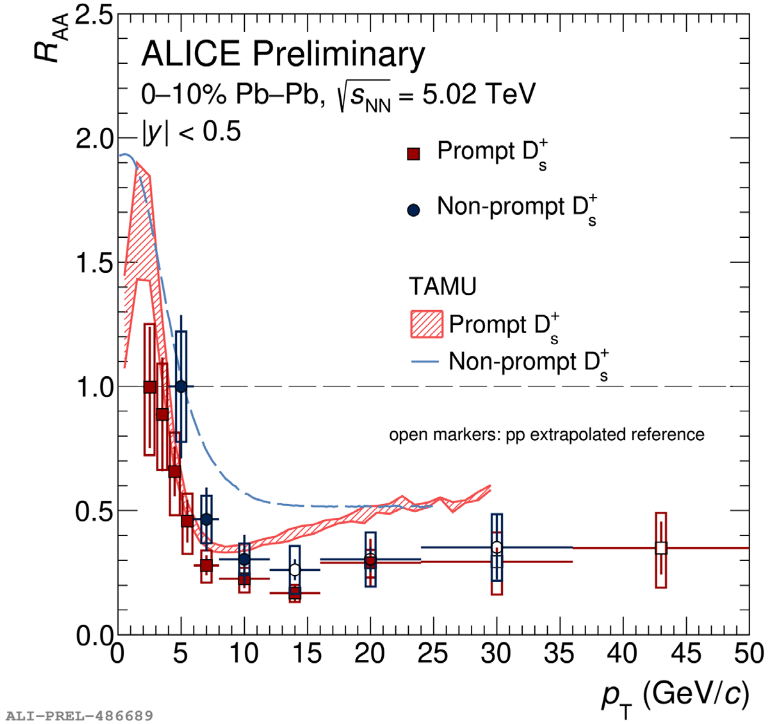


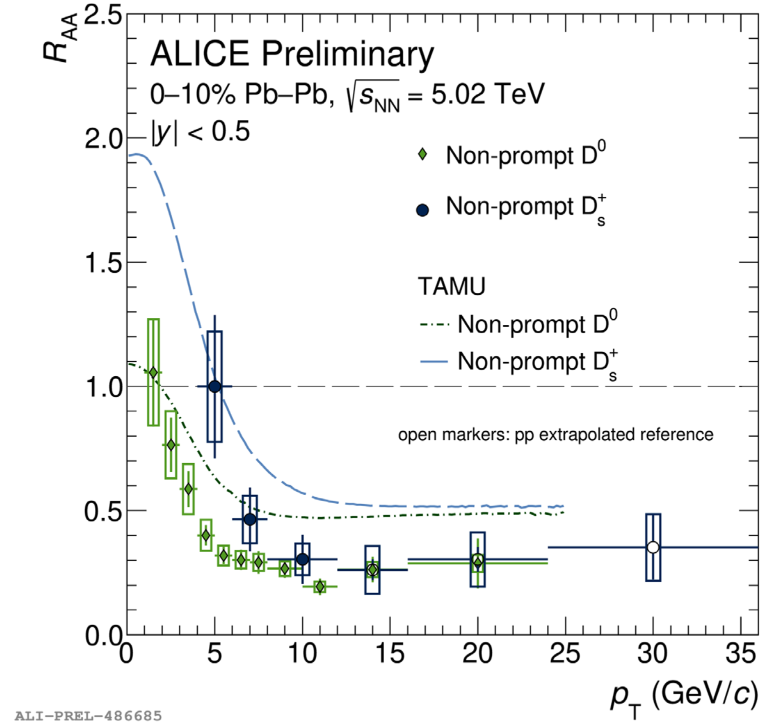


- Decreased suppression for non-prompt D^0 compared to prompt D^0
  - ΔE(*b*) < ΔE(*c*) from dead-cone effect (gluon radiation vetoed for $\theta < m/E$)
  - Translates into $R_{AA}(H_b \rightarrow D^0) > R_{AA}(c \rightarrow D^0)$
- Double ratio of non-prompt/prompt D^0 R_{AA} well described by most of the transport models



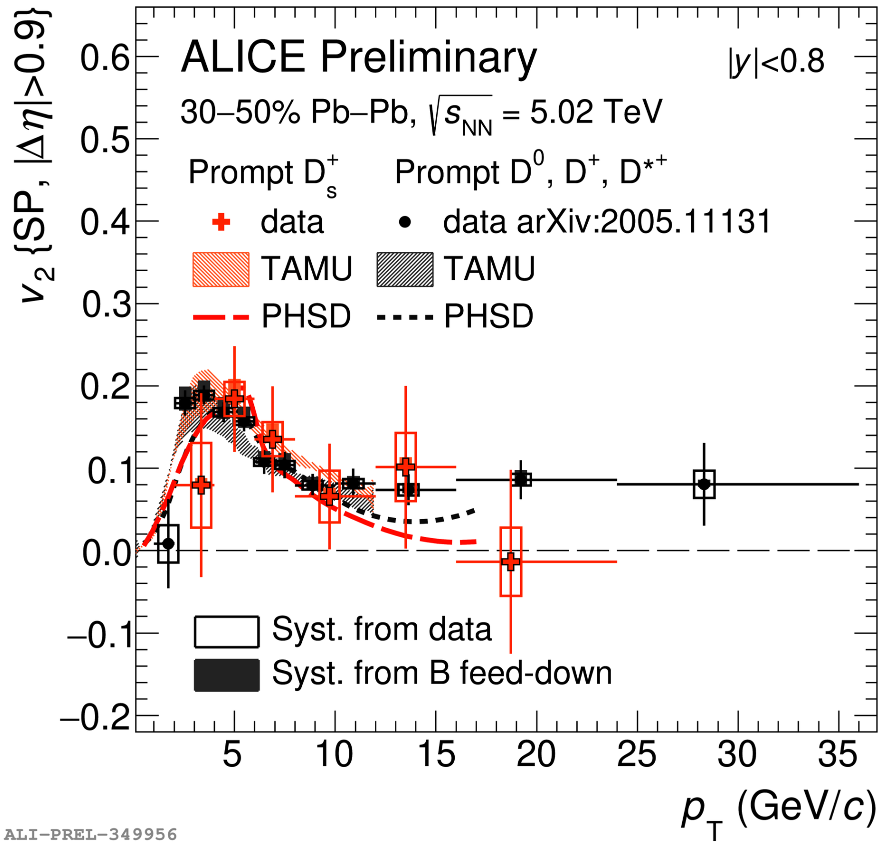
NON-PROMPT D_s^+-MESON R_{AA}



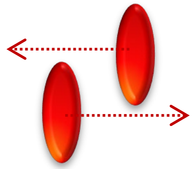


- First measurement of non-prompt D_s^+ mesons in central Pb-Pb collisions
- At low p_T, hint of reduced suppression w.r.t. prompt D_s^+ and non-prompt D^0 mesons
- TAMU model (collisional energy loss + recombination) describes well the difference of R_{AA}, though generally overestimating their absolute values

HF ELLIPTIC FLOW COEFFICIENTS



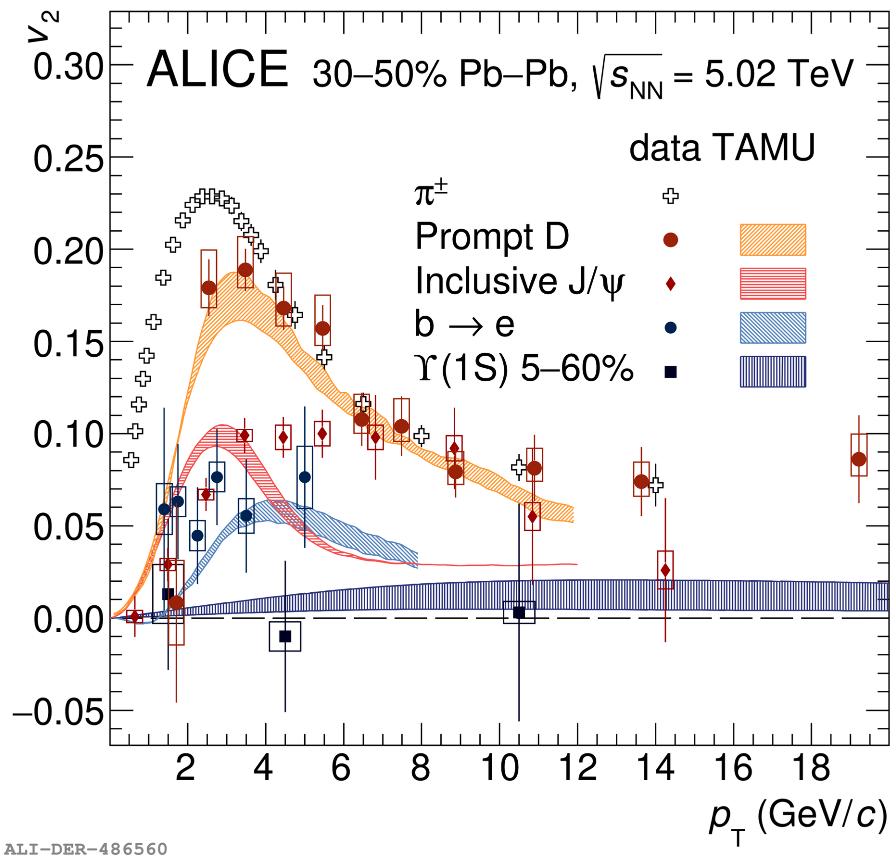
- Positive v_2 of prompt D mesons
  - Participation of charm quarks to collective motion of QGP medium
- Similar strength of elliptic flow for strange and non-strange D mesons
- TAMU and PHSD transport models describe well the measurements
  - Both models include charm + strange quark coalescence for D_s^+ formation



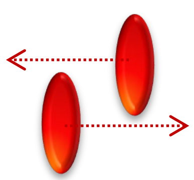
Semi-central collision

ALICE, Phys. Lett. B 813 (2021) 136054
PHSD: T. Song et al. PRC 92 014910 (2015)
TAMU: M. He et al. PLB 735 445-450 (2014)

HF ELLIPTIC FLOW COEFFICIENTS



- v_2 coefficient ordering: $v_2(\pi^{+/-}) > v_2(D) > v_2(J/\psi)$, points toward larger flow for light quarks rather than for charm
- Beauty sector: smaller v_2 for beauty-hadron decay electrons, and no flow for Y(1S) state
- TAMU model describes well the data, except for J/ψ above 4 GeV/c
- High-precision measurements allow for setting constraints to models for charm diffusion coefficient:
  - $1.5 < 2\pi T_c D_s < 7$ for T_c = 155 MeV

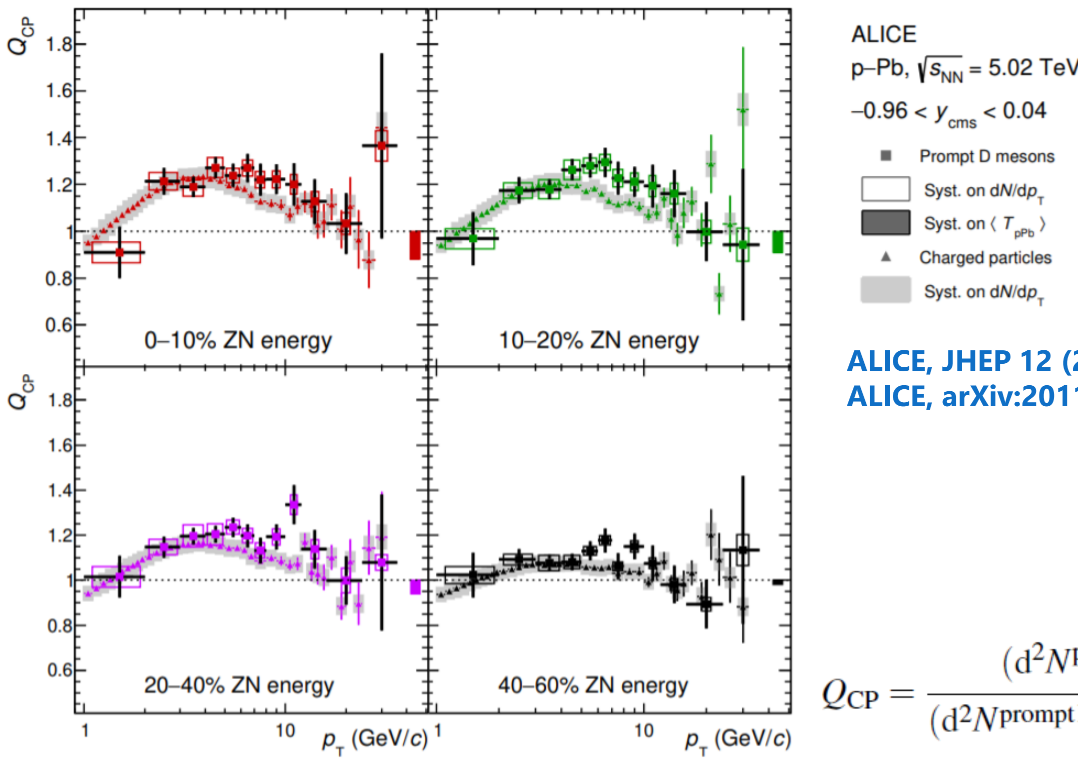


Semi-central collision

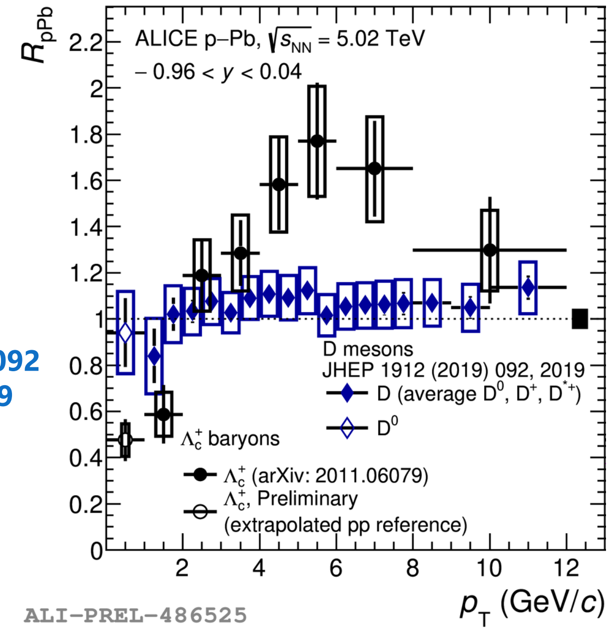
ALICE, Phys. Lett. B 813 (2021) 136054
ALICE, JHEP 09 (2018) 006
ALICE, JHEP 10 (2020) 141
ALICE, Phys. Rev. Lett. 126 (2021) 162001
TAMU: M. He et al. PLB 735 445-450 (2014)

p-Pb COLLISIONS

HEAVY-FLAVOUR ENERGY LOSS IN p-Pb



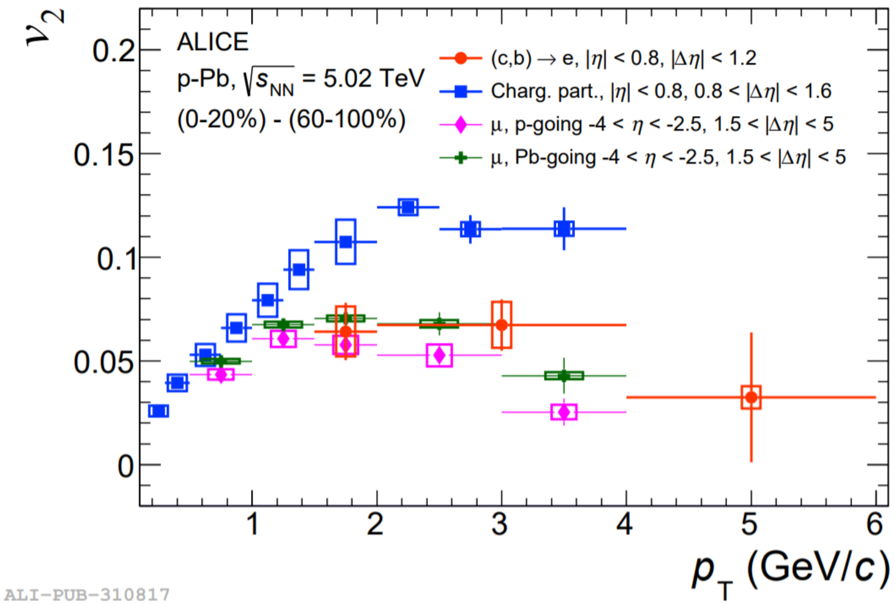
ALICE, JHEP 12 (2019) 092
ALICE, arXiv:2011.06079

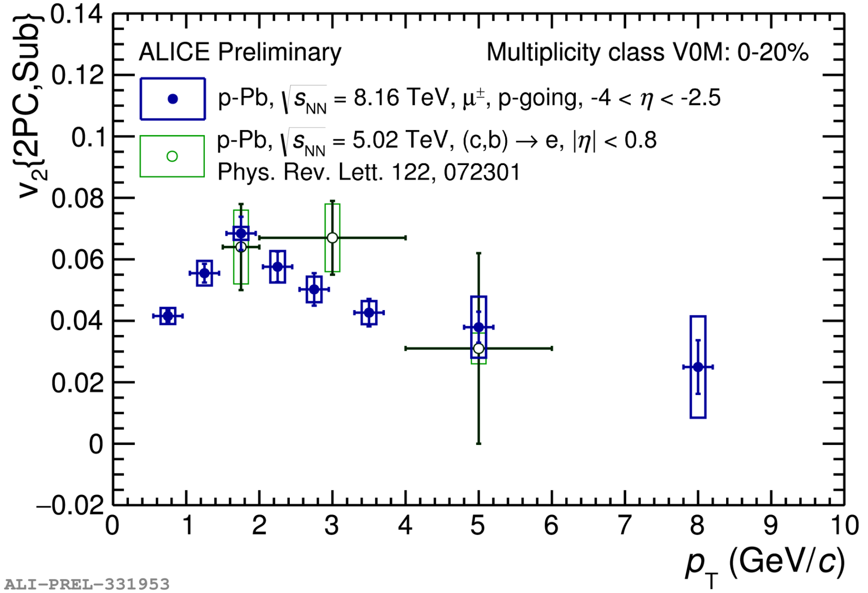


$$Q_{\mathrm{CP}} = \frac{(\mathrm{d}^2 N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{\mathrm{i}}_{\mathrm{p-Pb}} / \langle T_{\mathrm{pPb}} \rangle_{\mathrm{i}}}{(\mathrm{d}^2 N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{60-100\%}_{\mathrm{p-Pb}} / \langle T_{\mathrm{pPb}} \rangle_{60-100\%}}$$

- D-meson R_{pPb} consistent with 1, described by models with only initial-state effects
  - Q_{CP} > 1 points toward possible radial-flow 'push' of D-meson spectra in HM p-Pb
- New Λ_c^+ measurement down to 0 in p-Pb!
- R_{pPb} of Λ_c^+ larger than unity for $4 < p_{\mathrm{T}} < 8$ GeV/c
  - ➢ Potentially also from radial flow in p-Pb? Possible effect of recombination?

HEAVY-FLAVOUR ELLIPTIC FLOW IN p-Pb





- Measurements of **positive v_2** for heavy-flavour hadron decay muons and electrons in 0-20% multiplicity class!
- Consistent values for electrons and muons (but different η), smaller than charged particle v_2
  - ➢ Caveat: different hadron→parton p_T scale w.r.t. light-flavour particles + decay kinematics
- From collective motion in high-multiplicity p-Pb collisions due to final state effects (QGP droplet)? Or related to initial-state effects (e.g. gluon saturation)?

ALICE, PRL 122, 072301 (2019)

CONCLUSIONS

ALICE

pp collisions

- Precise measurements of production cross section for several charm hadrons, **total charm cross section** and **charm fragmentation fractions**
- Measurements point toward **non-universality** of the FF

Pb-Pb collisions

- Strong **suppression** of open heavy-flavour particles in central Pb–Pb collisions
- Charm and beauty quarks participate to QGP **collective motion**, though possibly with less strength than light quarks

p-Pb collisions

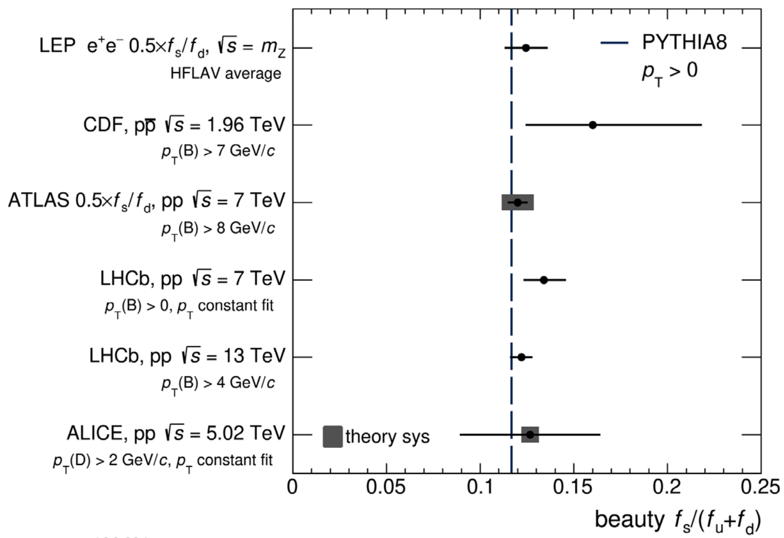
- No evidence of energy loss in p-Pb collisions…
- …But non-zero elliptic flow for heavy-flavour particles at high multiplicity + $Q_{CP} > 1$ for D mesons: puzzle still unsolved

Stay tuned!

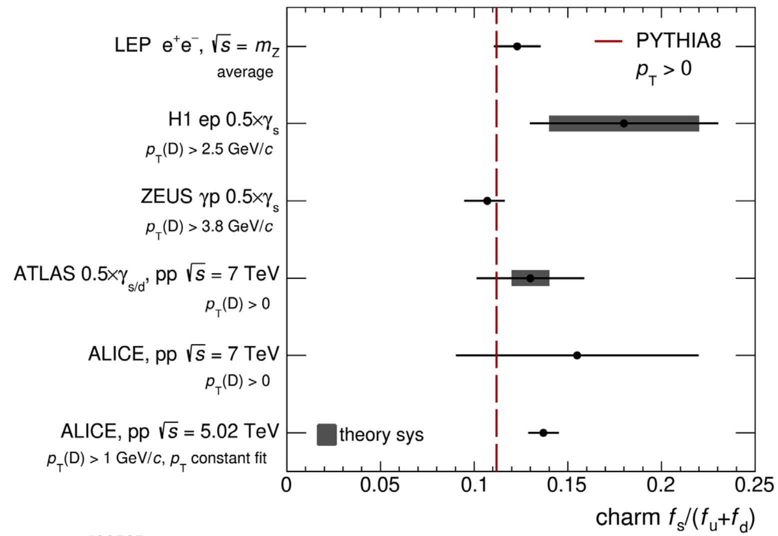
- ALICE upgrade expected to dramatically improve the precision of heavy-flavour studies and allow for further, unexplored measurements!

BACKUP SLIDES

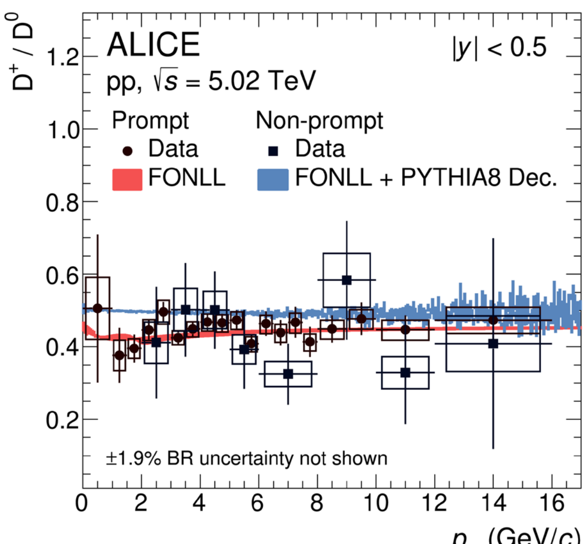
D MESON PRODUCTION IN pp COLLISIONS



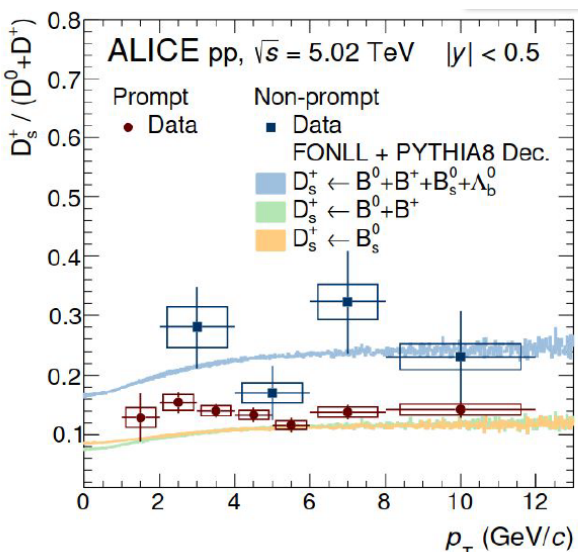
ALI-PUB-482601



ALI-PUB-482597

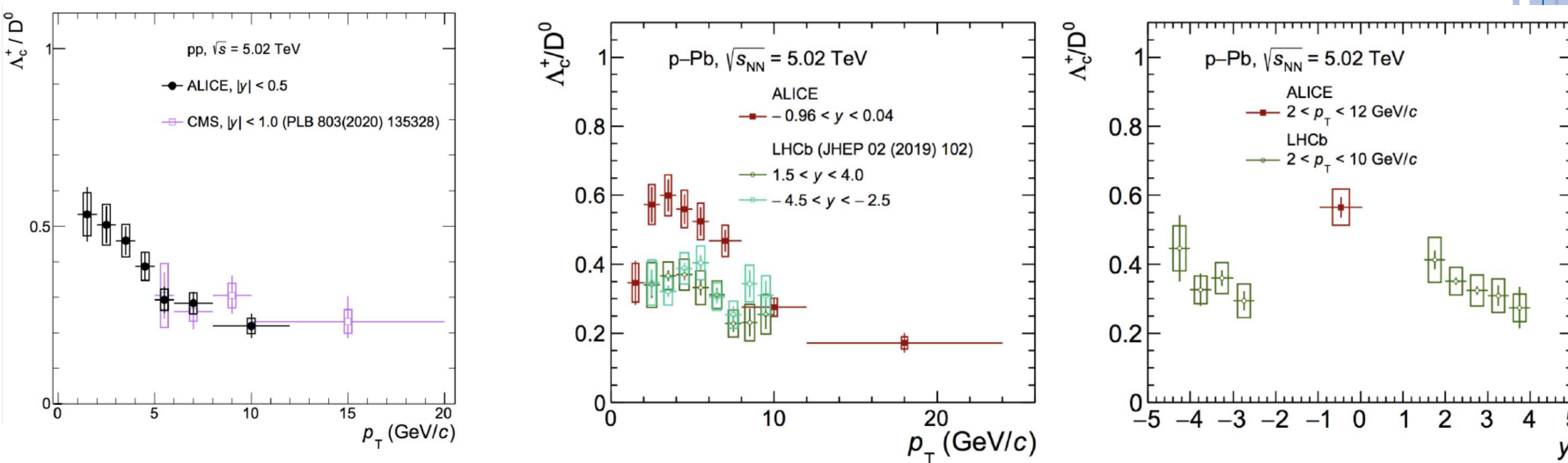


ALI-PUB-482589



- Strange over non-strange production ratios, for D mesons (prompt and non prompt)
- Well described by pQCD calculations

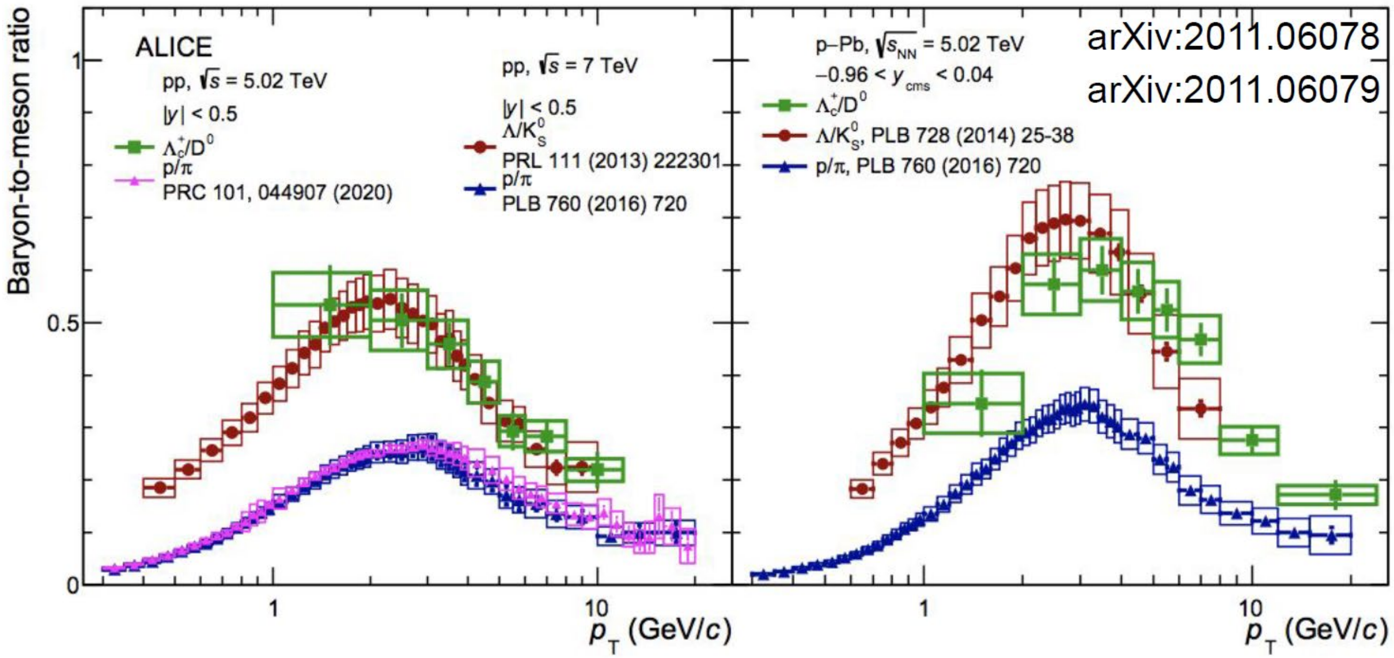
Λ_c^+ IN pp VS OTHER EXPERIMENTS



- Combination with CMS measurements shows a clear p_T dependence
  - Deviation w.r.t. e^+e^- mainly at low p_T, at high p_T a similar value is reached
- Non-trivial trend of rapidity dependence of Λ_c^+/D^0 ratios (ALICE + LHCb)

ALICE, arXiv:2011.06078
ALICE, arXiv:2011.06079

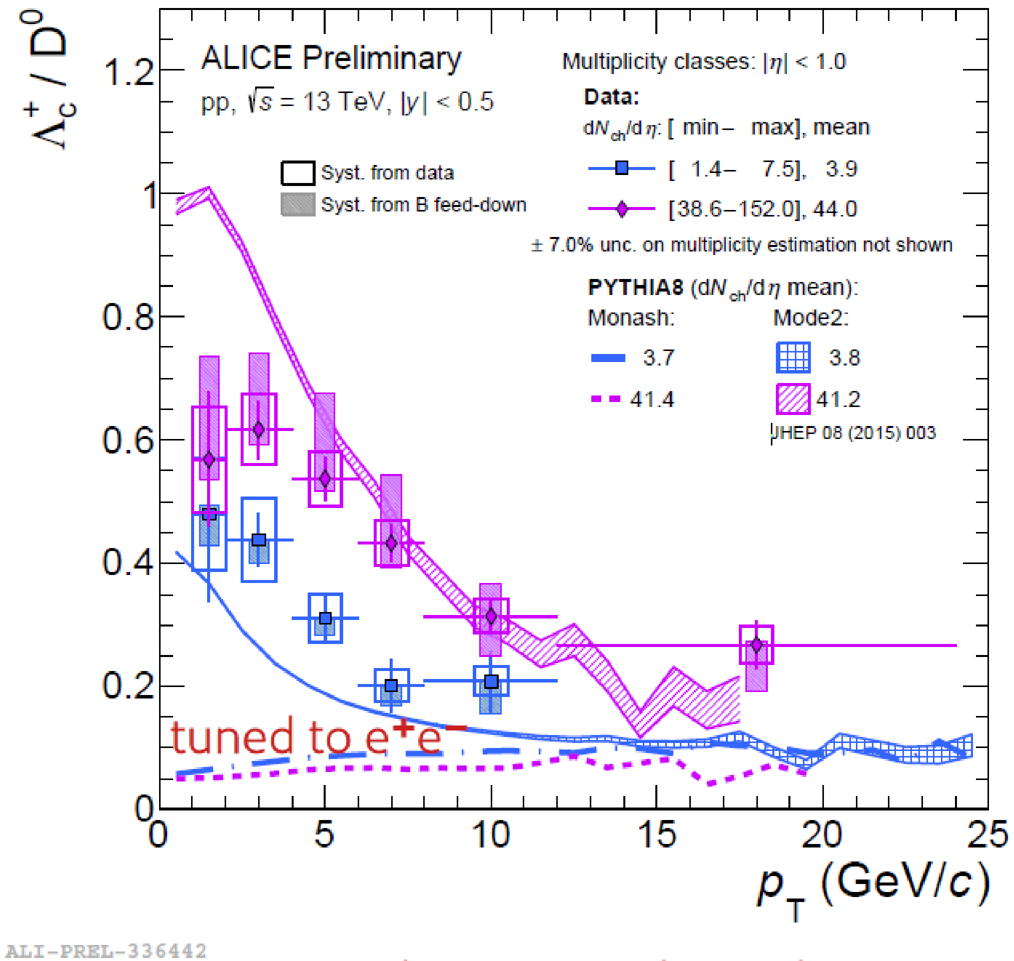
Λ_c^+ IN pp VS OTHER EXPERIMENTS



- Very similar situation for baryon-to-meson ratio in HF and LF sector!
  - Similar shape for p/π, similar shape+values for Λ/K^0_s
- Points toward similar modification of hadronisation in pp collisions

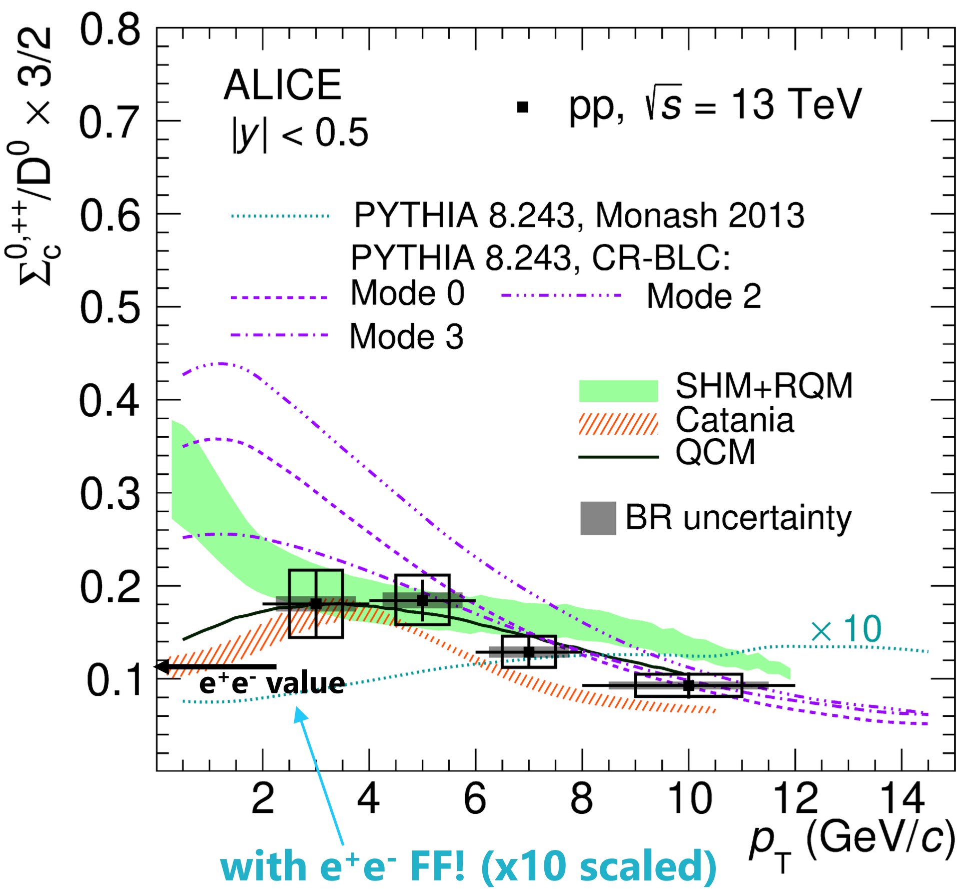
ALICE, arXiv:2011.06078
ALICE, arXiv:2011.06079

Λ_c^+ IN pp VS MULTIPLICITY



- Multiplicity-differential measurements of Λ_c^+/D^0 in pp collisions at 13 TeV
- Increased enhancement of ratios w.r.t. of Pythia8 Monash at larger event multiplicities
  - But excess already present in lowest-multiplicity range
- Pythia8 with CR Mode2 describes better the data

CHARM BARYONS IN pp COLLISIONS



ALI-DER-493901

Similar behaviour for the $\Sigma_c^{0,++}$ states

Σ_c^{0} quark content: d d c

Σ_c^{++} quark content: u u c

- First measurement of $\Sigma_c^{0,++}$ in hadronic collisions
- Low-p_T enhancement of $\Sigma_c^{0,++}/D^0$ ratios w.r.t. PYTHIA8 Monash
- Proper description provided by PYTHIA8 CR-BLC, SHM+RQM, Catania, and QCM models, due to enhanced production of baryons
- Also important to probe feed-down contribution to Λ_c^+!

ALICE, arXiv:2106.08278

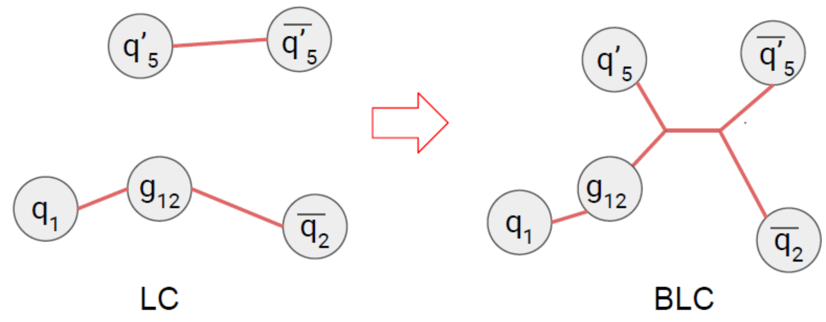
PYTHIA8+CR: arXiv:1505.01681
SHM+RQM: PLB 795 (2019) 117-121
Catania: arXiv:2012.12001
QCM: EPJ C78 no. 4 (2018) 344

CHARM BARYONS IN pp - MODELS

ALICE

PYTHIA + COLOR RECONNECTION (CR)

- Includes mechanism of string formation beyond leading-colour approximation
- Increased baryon production from junction connection topologies
  - Partons from different MPI and beam remnants can be connected
- New CR Modes in PYTHIA 8 largely enhance the baryon yield and describe Λ_c^+ and $\Sigma_c^{0,++}$ data



SHM MODEL

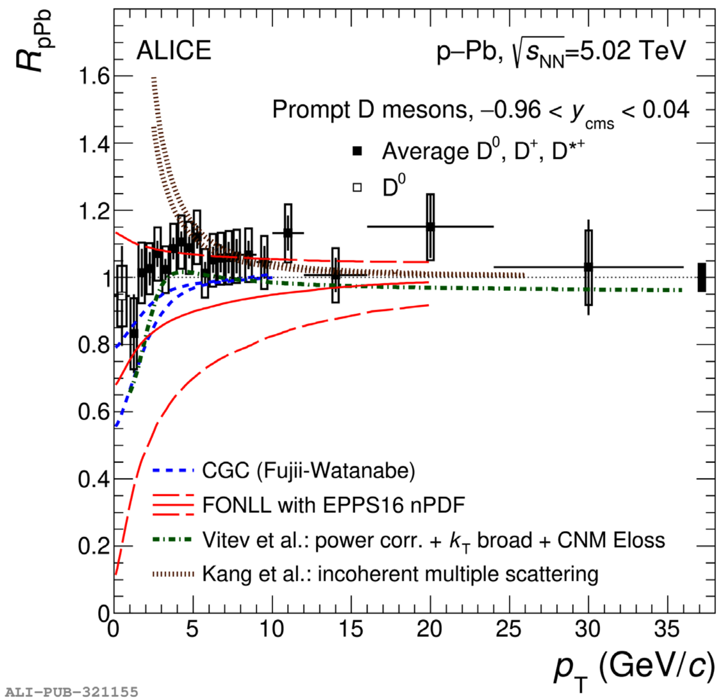
Hadronization process ruled by thermo-statistical weights depending on hadron masses at a universal hadronization temperature T_H

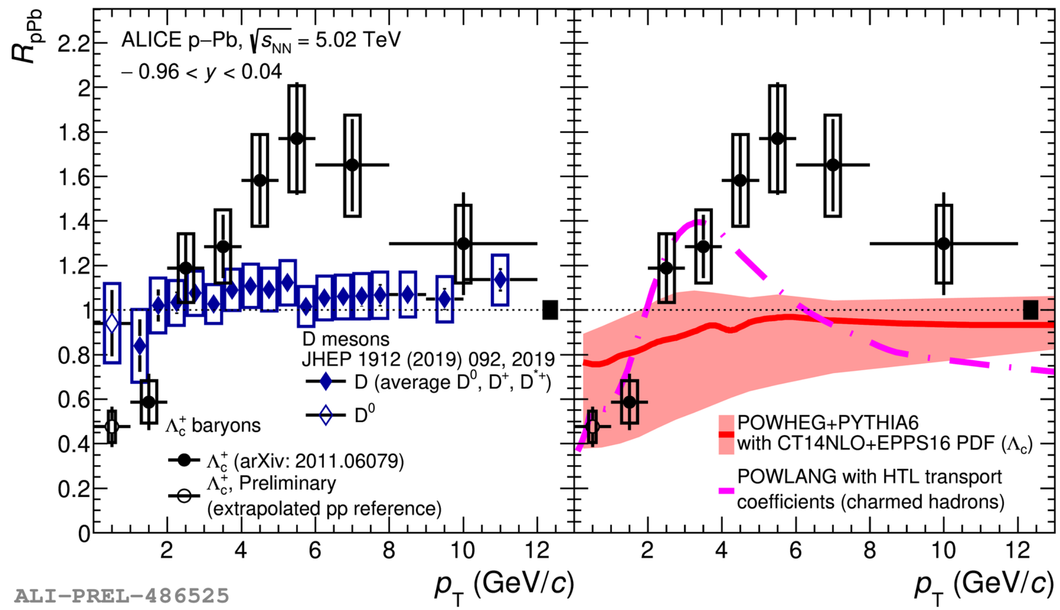
- Two configurations available:
  - ➢ Including states only listed in PDG:
    → 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
  - ➢ Including additional excited baryon states predicted by the Relativistic Quark Model (RQM), not yet observed:
    → 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

CATANIA

- Assumes hot, dense and thermalised QCD medium also in pp collisions
- Interplay of fragmentation + coalescence hadronisation mechanisms
  - ➢ Coalescence is imposed to be the only mechanism at $p_T \to 0$

HEAVY-FLAVOUR R_{pPb} IN p-Pb

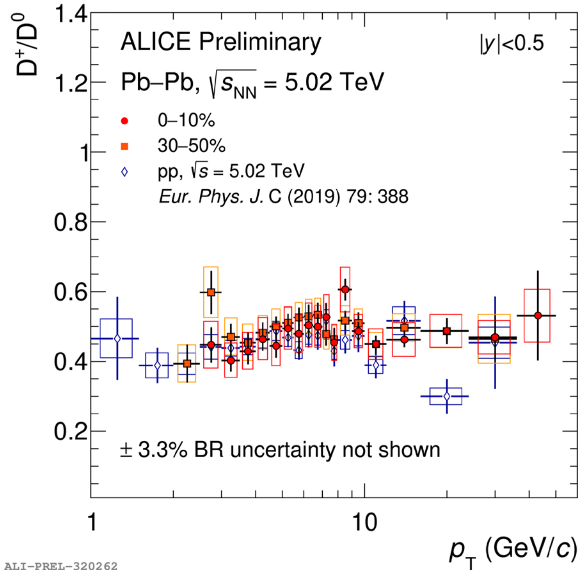


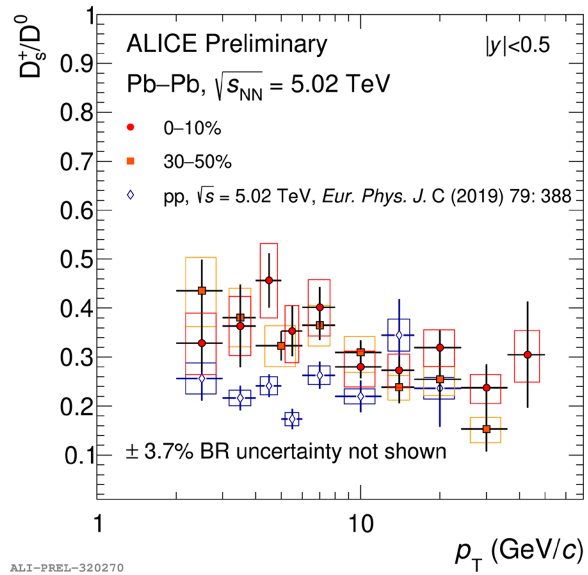


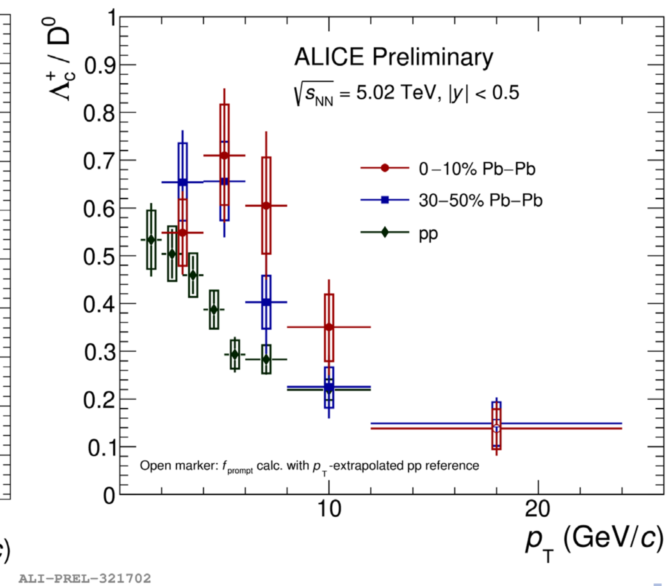
- D-meson R_{pPb} consistent with 1, described by models with only initial-state effects
- Λ_c^+ now measured down to 0 in p-Pb!
- For Λ_c^+, hint of a different shape as a function of p_T
  - ➢ Possible effect of recombination? Radial flow in p-Pb?

ALICE, JHEP 12 (2019) 092
ALICE, arXiv:2011.06078
ALICE, arXiv:2011.06079

CHARM-HADRON RATIOS IN Pb-Pb

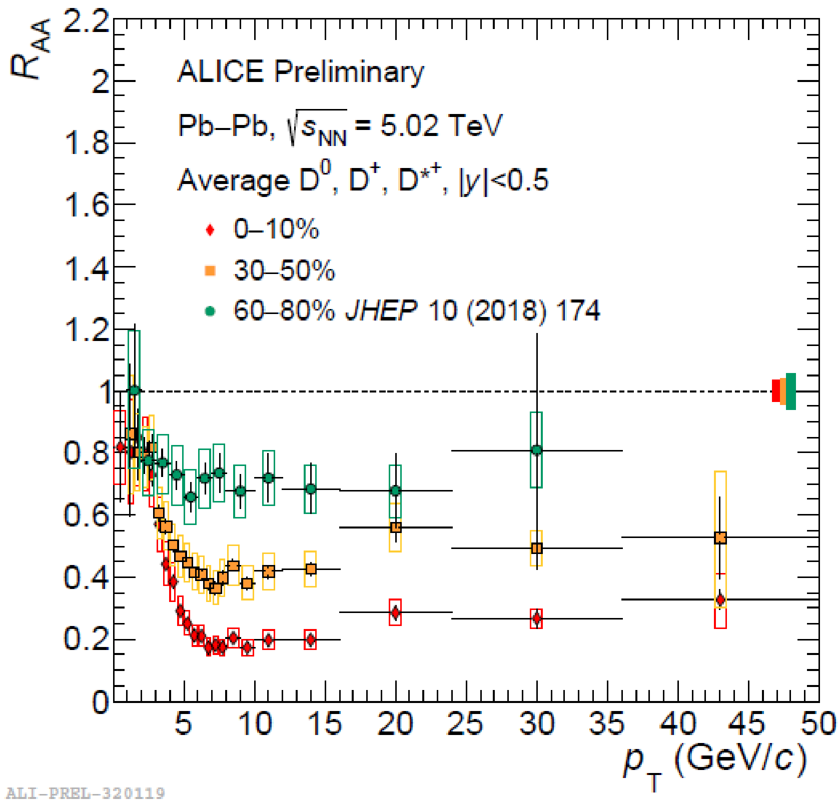




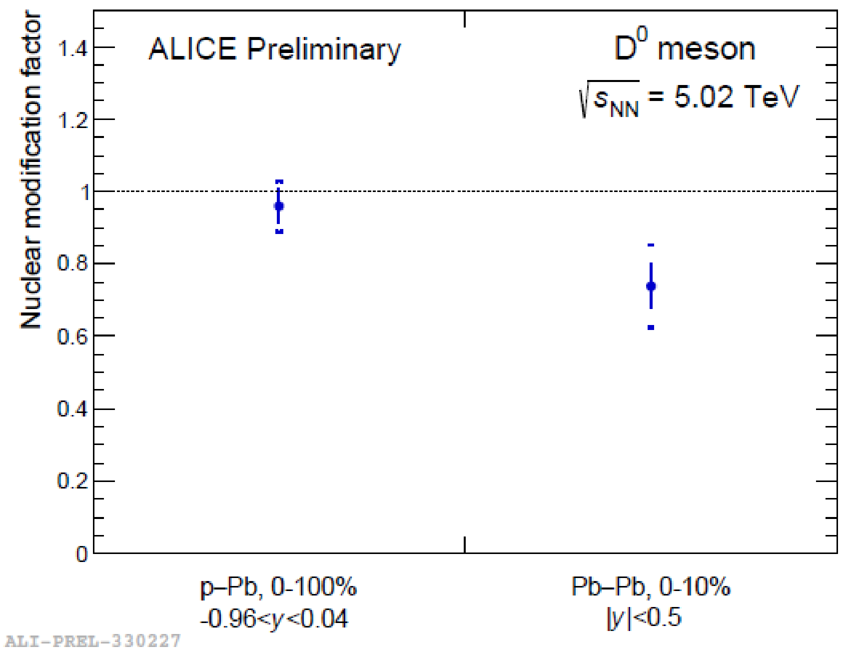


- **D^+/D^0**: no modification of relative production from pp to Pb-Pb collisions
- **D_s^+/D^0**: seemingly larger in Pb-Pb collisions compared to pp
  - ➢ As for larger $R_{AA}(D_s^+) > R_{AA}(D^0)$, related to strangeness enhancement + recombination
- **Λ_c^+/D^0**: hint of enhanced Λ_c^+ in Pb-Pb collisions compared to pp
  - ➢ Baryon enhancement from quark recombination + radial flow push

D-MESON R_{AA} - DETAILS

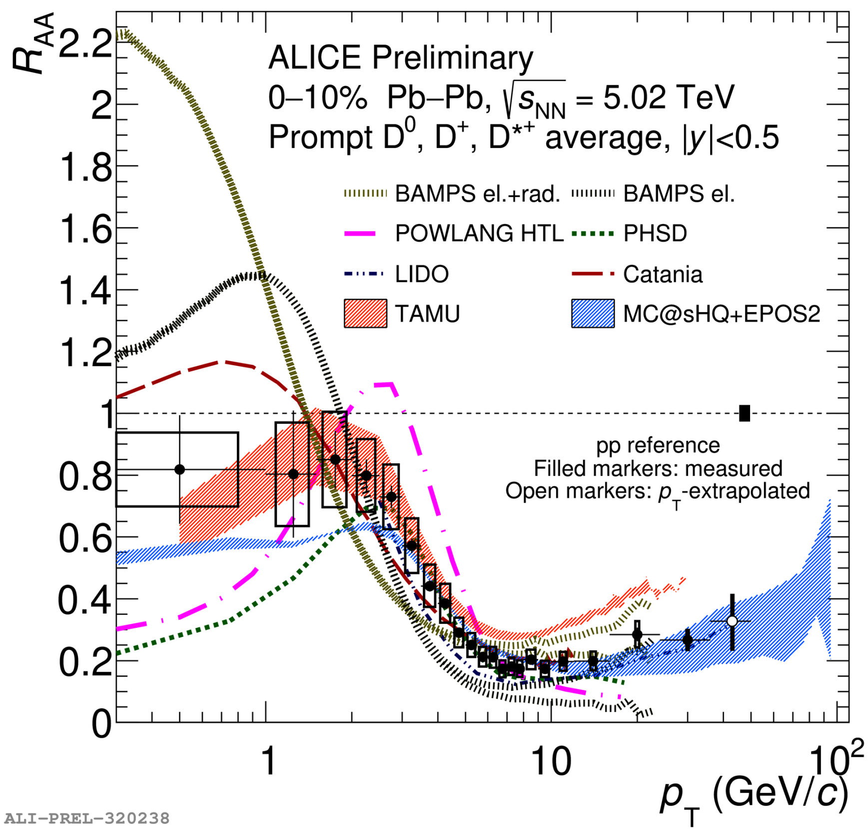


- Increased D meson suppression with collision centrality ad intermediate and high p_T



- Integrated nuclear modification factor consistent with 1 in p-Pb
- Hint of R_{AA} smaller than 1 in Pb-Pb
  - Final-state effect leads to charm production suppression?

D-MESON R_{AA} - DETAILS



Model references:

BAMPS: arXiv:1408.2964

POWLANG: arXiv:1410.6082

LIDO: Phys. Rev. C 98 (2018) 064901

PHSD: T. Song et al. PRC 92 014910 (2015)

TAMU: M. He et al. PLB 735 445-450 (2014)

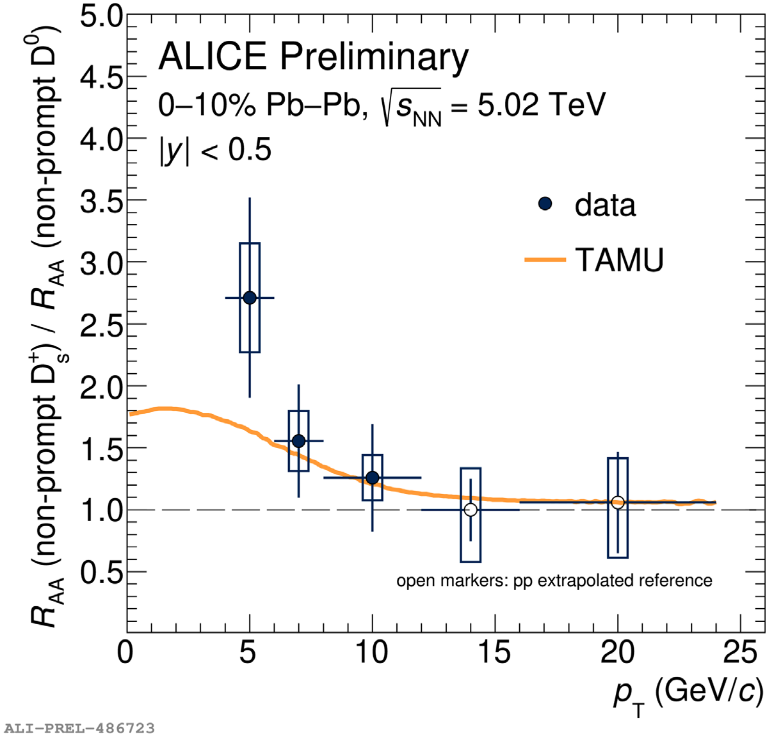
Catania: EPJC 78, 348 (2018)

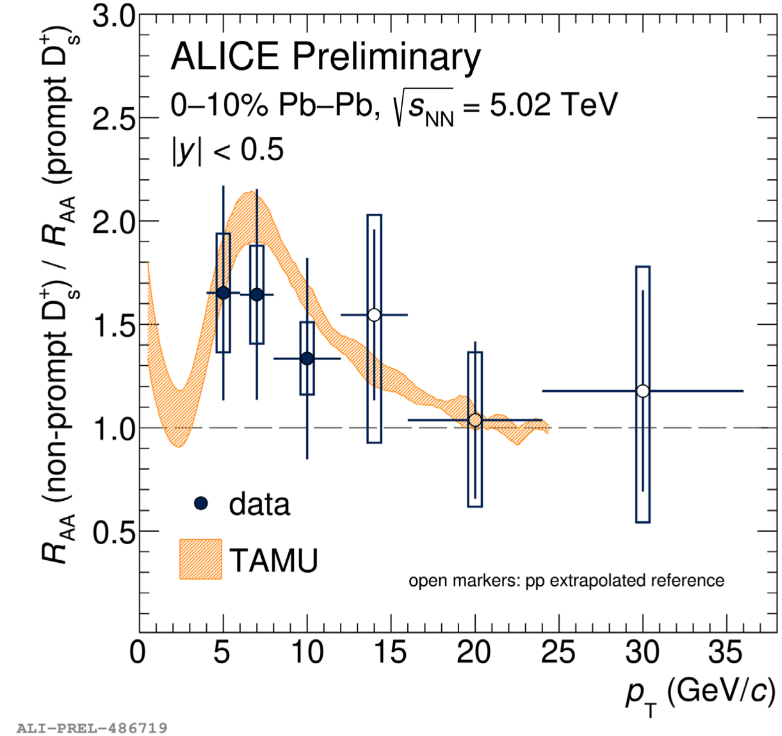
MC@sHQ: arXiv:1305.6544

PROSPECT OF MODELS (PREDICTING R_{AA} & v_2)

TRANSPORT MODELS	Collisional Energy loss	Radiative Energy loss	Coalescence	Hydro	nPDF
BAMPS + rad.	✓	✓	✗	✓	✗
LBT	✓	✓	✓	✓	✓
PHSD	✓	✓	✓	✓	✓
POWLANG	✓	✗	✓	✓	✓
TAMU	✓	✗	✓	✓	✓
MC@sHQ+EPOS	✓	✓	✓	✓	✓
pQCD Eloss MODELS	**Collisional Energy loss**	**Radiative Energy loss**	**Coalescence**	**Hydro**	**nPDF**
CUJET3.0	✓	✓	✗	✗	✗
Djordevic	✓	✓	✗	✗	✓
SCET	✓	✓	✗	✗	✓

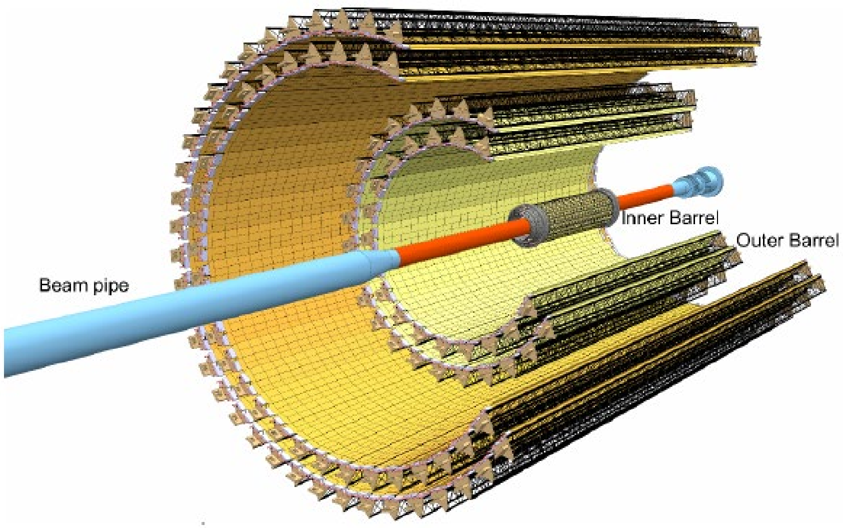
DETAILS ON D_s^+ MESON R_{AA}





- $R_{AA}(D_s^+)/R_{AA}(D^0)$ ratio for non-prompt above one at low p_T
  - About 50% non-prompt D_s^+ mesons originate from B_s^0 meson decays (enhanced by beauty hadronisation via coalescence)
- TAMU model describes well both R_{AA}(non-prompt D_s^+)/R_{AA}(non-prompt D^0) and R_{AA}(non-prompt D_s^+)/R_{AA}(prompt D^0) ratios

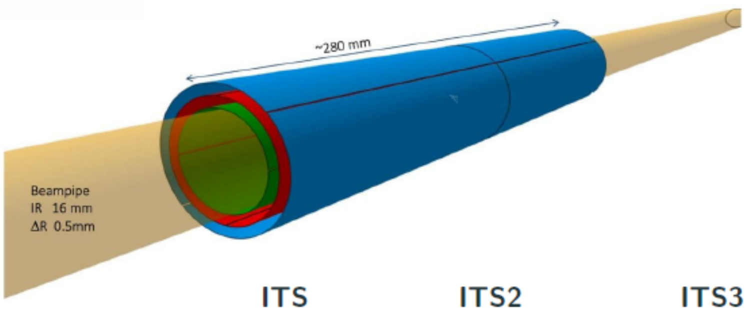
ITS UPGRADE



J. Phys. G 41 087001 (2014)

- Run3: Inner Tracking System (ITS) upgrade is crucial for heavy-flavour measurements

- Run4: set of 3 truly cylindrical layers made of ultra-thin curved silicon-pixel sensors



	ITS	ITS2	ITS3
# of layers	6	7	7
X/X_0	1.14%	0.38%	0.05%
innermost radius	39 mm	22 mm	18 mm
pixel size	$50 \times 425\ \mu m^2$	$30 \times 30\ \mu m^2$	$\mathcal{O}(15 \times 15\ \mu m^2)$

CERN-LHCC-2019-018