Overview of recent heavy-flavour results from the ALICE experiment

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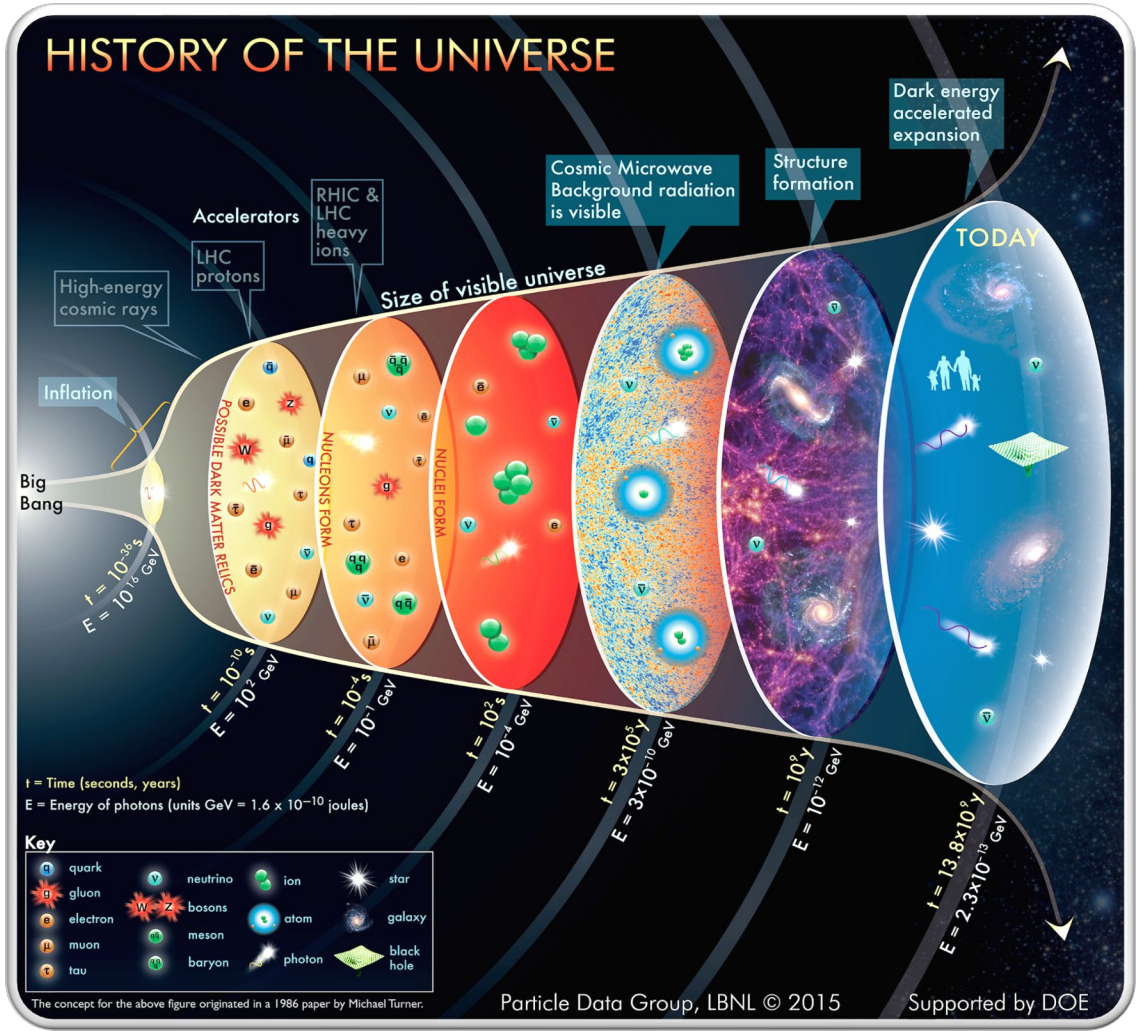
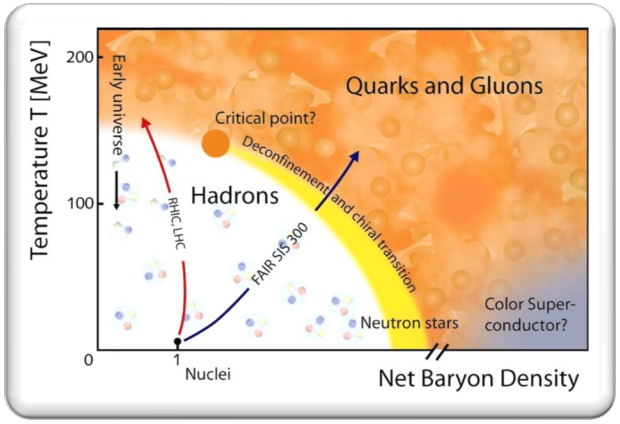
WHAT DOES ALICE STUDY? THE QGP





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

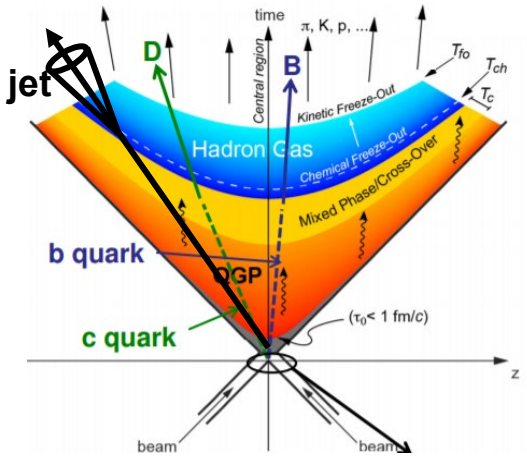
- Deconfined state of matter: **quark-gluon plasma** (**QGP**)
- From lattice QCD: T_c **~ 150 MeV** and ε_c **~ 0.5 GeV/fm³**

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

THE IMPORTANCE OF HEAVY-FLAVOURS

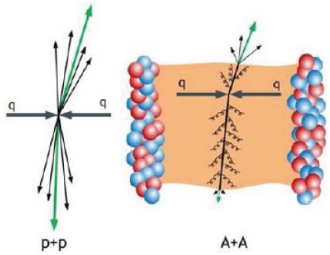
In Pb-Pb collisions

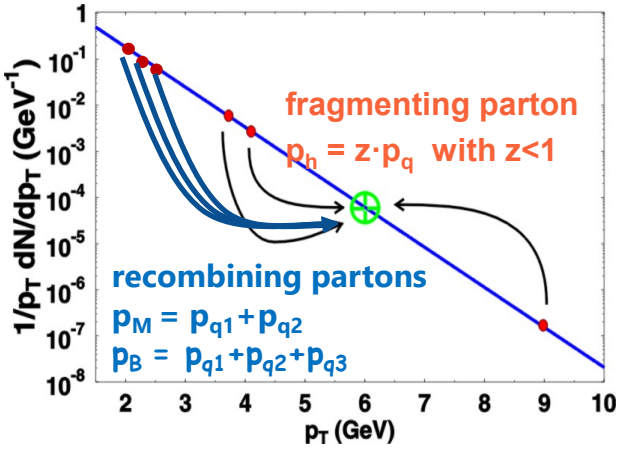
- **Charm** and **beauty**: produced before the QGP formation due to large mass + their number is roughly conserved
  - Experience the **whole evolution** of the collision
  - **QGP tomography** by studying its final-state particles



Open heavy flavour: microscopic picture of QGP

- Interactions of the hard-scattered parton with QGP constituents while traversing the medium, resulting in **partonic energy loss** from:
  - Elastic collisions → dominate at lower p_T
  - Gluon radiation → dominate at higher p_T





- QGP constituents subject to **collective motion** described by hydrodynamics: do heavy quarks participate to it?
- **Coalescence vs fragmentation** from hadron production measurements

THE IMPORTANCE OF HEAVY-FLAVOURS

In pp collisions

- In general, heavy quarks produced in **hard-parton scatterings** with large Q^2
  - Perturbative approach can be applied for the hard-scattering cross section
- Final-state heavy-flavour particle production cross section obtained via **factorisation theorem**

QCD Factorization:

$$E_{\mathrm{C}}\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\mathrm{C}}^3}(\mathrm{AB}\to\mathrm{CX}) \propto \sum_{\mathrm{abcd}}\int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_{\mathrm{b}}\, f_{\mathrm{A}}^{\mathrm{a}}(x_{\mathrm{a}},Q^2) f_{\mathrm{B}}^{\mathrm{b}}(x_{\mathrm{b}},Q^2)\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\mathrm{ab}\to\mathrm{cd})\, D_{\mathrm{c}}^{\mathrm{C}}(z_{\mathrm{c}},\mathrm{Q}^2)$$

PDF — Partonic x-section — Fragmentation function

- Heavy-flavour measurements allow us to:
  - Probe perturbative QCD calculations for heavy-quark production
  - Study heavy-quark hadronisation mechanisms
- Reference for Pb-Pb measurements

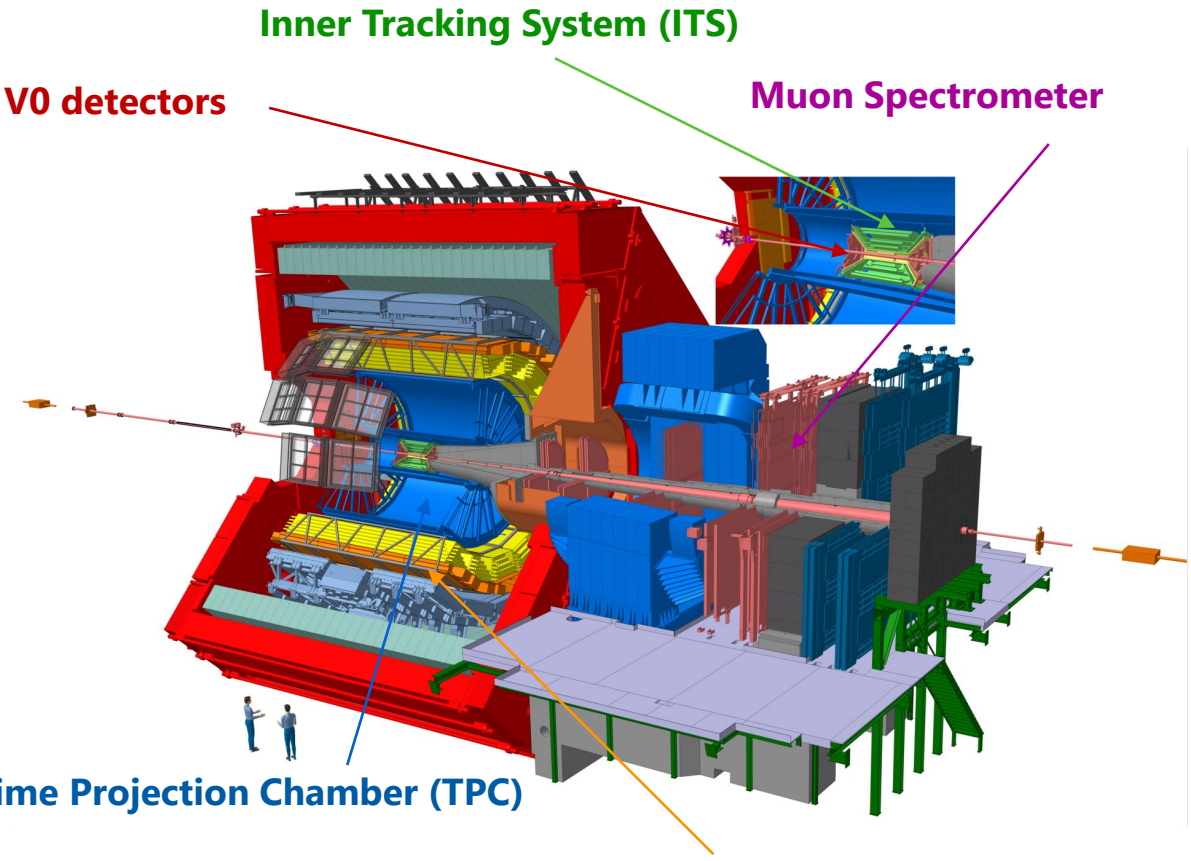
In p-Pb collisions

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

Also in high-multiplicity pp!

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*



charm mesons

$$D^0 \to K^-\pi^+$$
$$D^+ \to K^-\pi^+\pi^+$$
$$D^{*+} \to D^0\pi^+$$
$$D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$$
$$D \to e(\mu)X$$

charm baryons

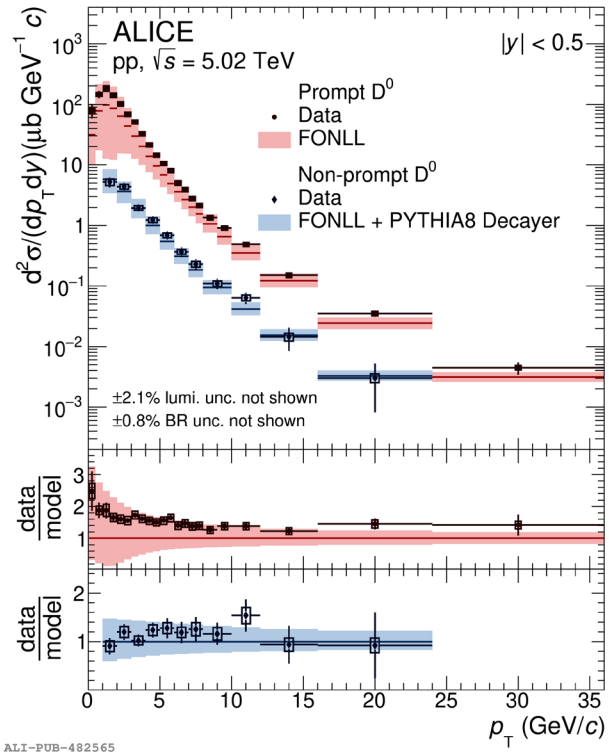
$$\Lambda_c^+ \to pK_S^0$$
$$\Lambda_c^+ \to \pi^+K^-p$$
$$\Sigma_c^{0,++} \to \Lambda_c^+\pi^{-,+}$$
$$\Xi_c^0 \to \Xi^-e^+\nu_e$$
$$\Xi_c^0 \to \Xi^-\pi^+$$
$$\Xi_c^+ \to \Xi^-\pi^+\pi^+$$
$$\Omega_c^0 \to \Omega^-\pi^+$$

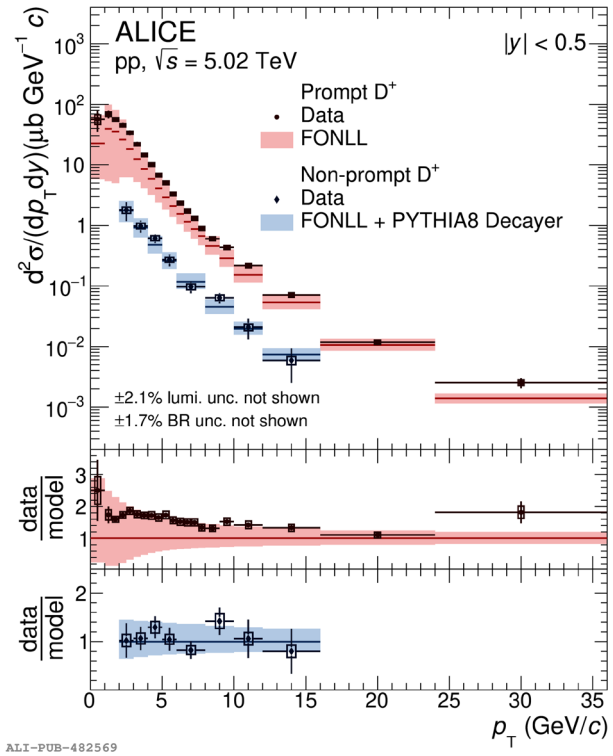
beauty

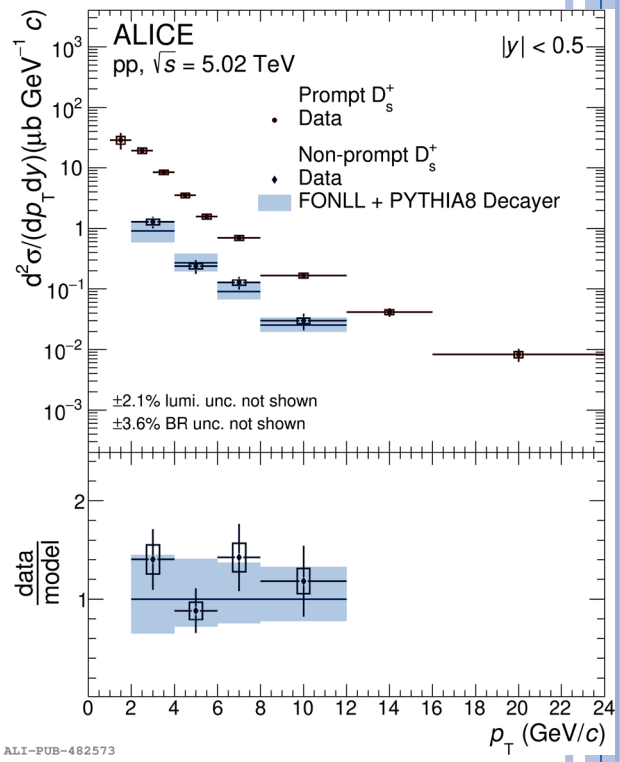
$$B \to e(\mu)X$$
$$B \to D$$
$$B \to J/\Psi \to e^+e^-$$

pp COLLISIONS

D MESON PRODUCTION IN pp COLLISIONS





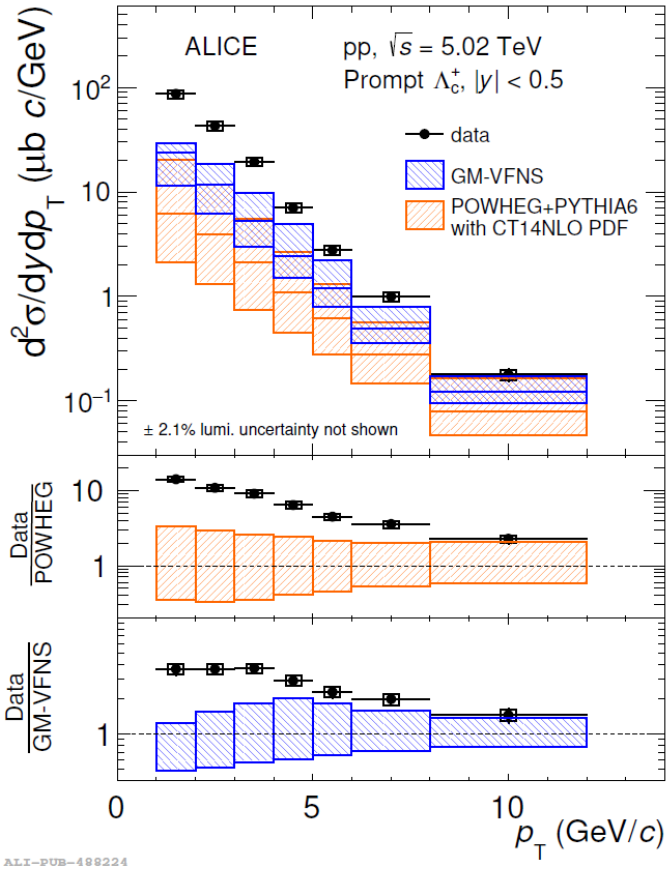


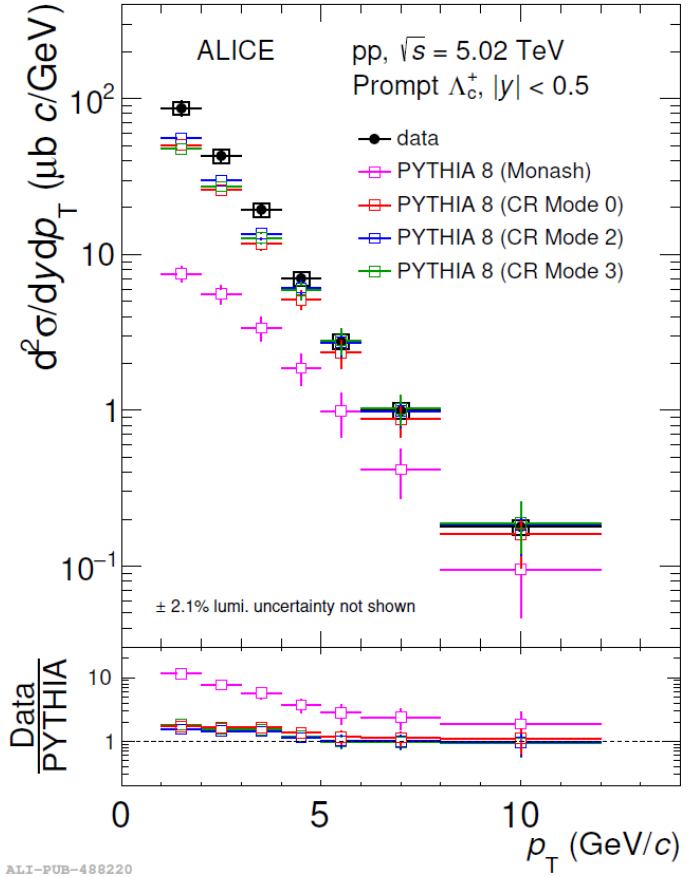
- Cross section of prompt and non-prompt D mesons measured with excellent precision down to $p_T = 0$ (for D^0, D^+)
- Comparison with perturbative QCD calculations (FONLL and GM-VFNS) based on universal fragmentation functions, measured in e^+e^- collisions
  - **Good description of the measurement 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!



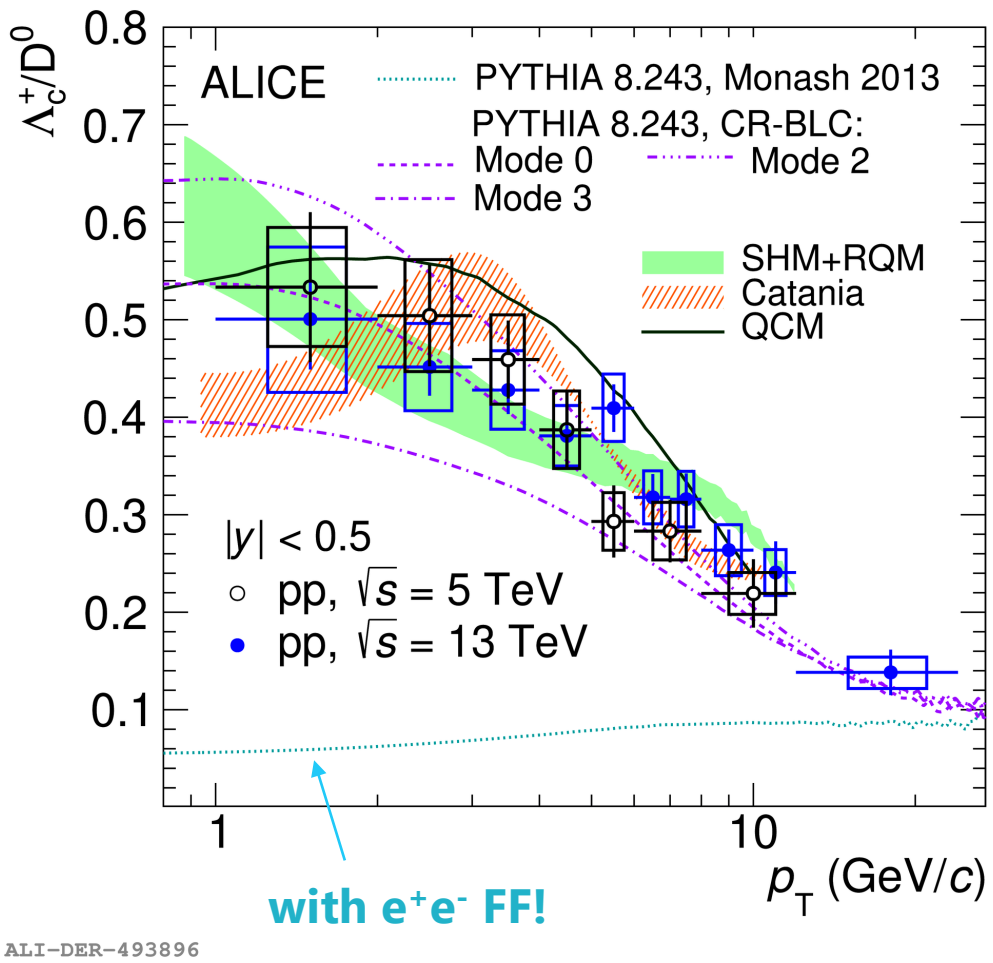


Λ_c^+ quark content:

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



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:

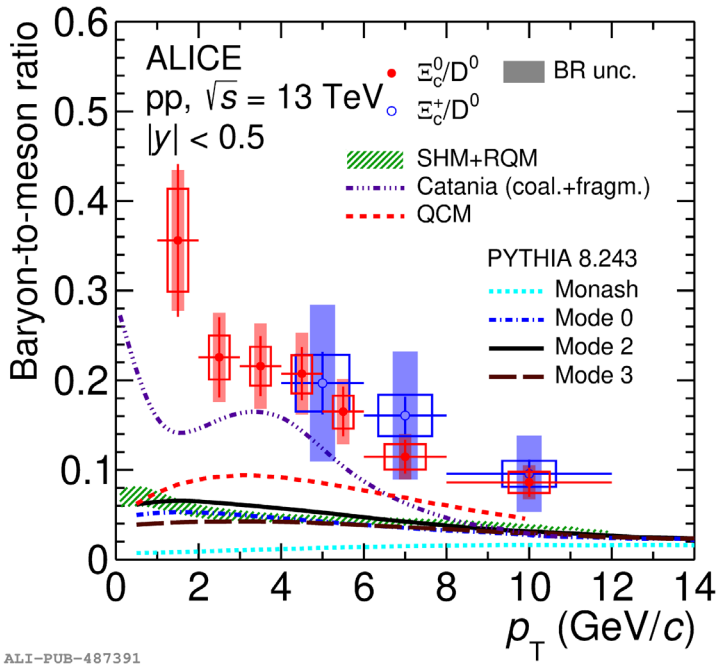
- Color reconnection beyond leading-colour approximation → PYTHIA8 CR-BLC
- Statistical hadronisation with enlarged set of excited charm baryons → SHM+RQM
- Λ_c^+ hadronisation via recombination mechanism → Catania (w/ fragmentation), QCM

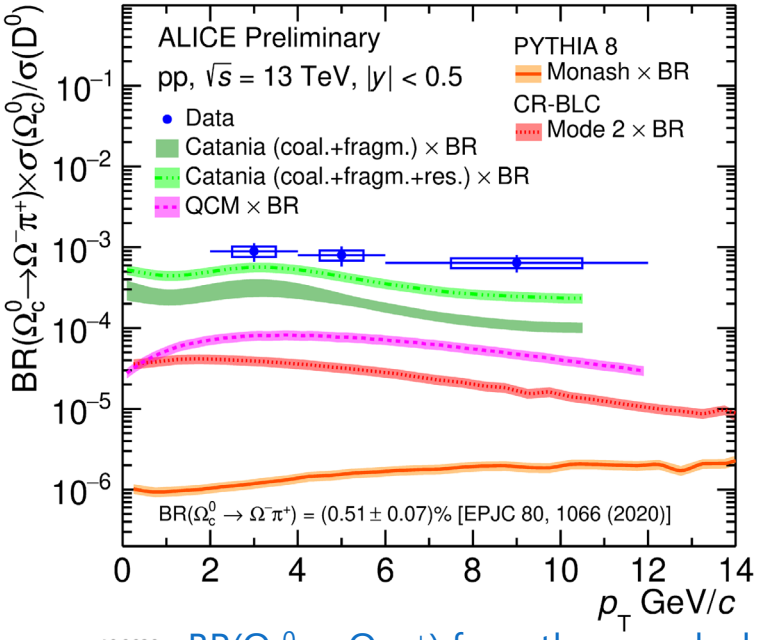
ALICE, arXiv:2011.06078
ALICE, arXiv:2011.06079
ALICE, arXiv:2106.08278

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 COLLISIONS

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





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

Even further enhancement for s+c states

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

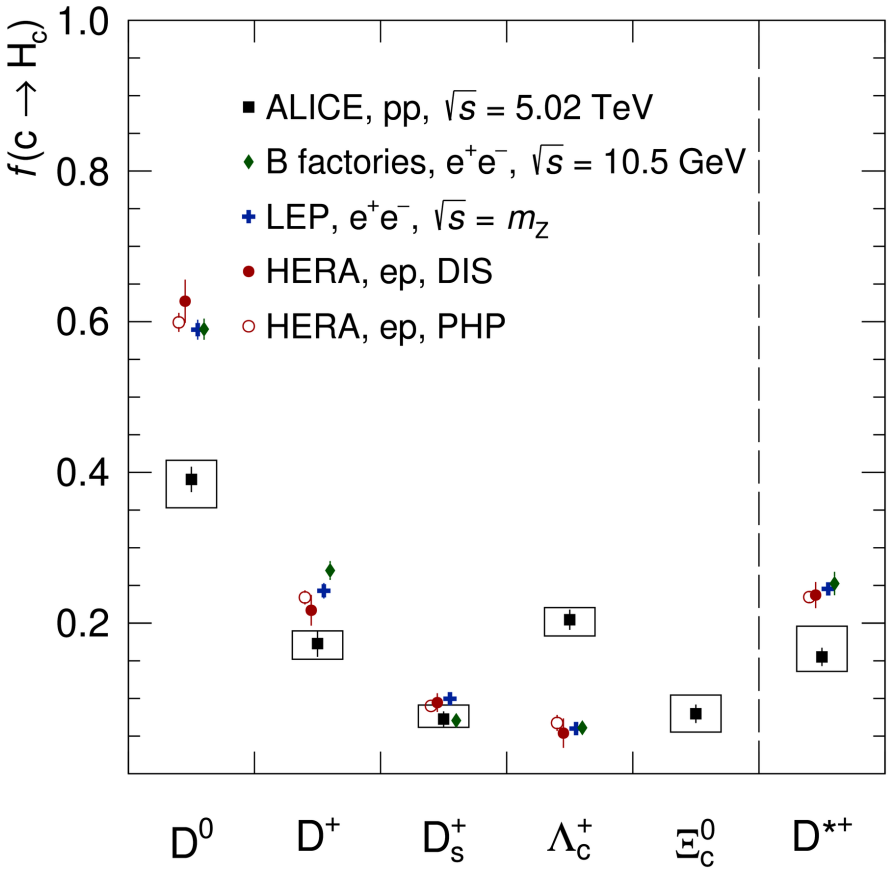
- Both coalescence and fragmentation mechanisms in pp?

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



ALI-PUB-488617

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

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

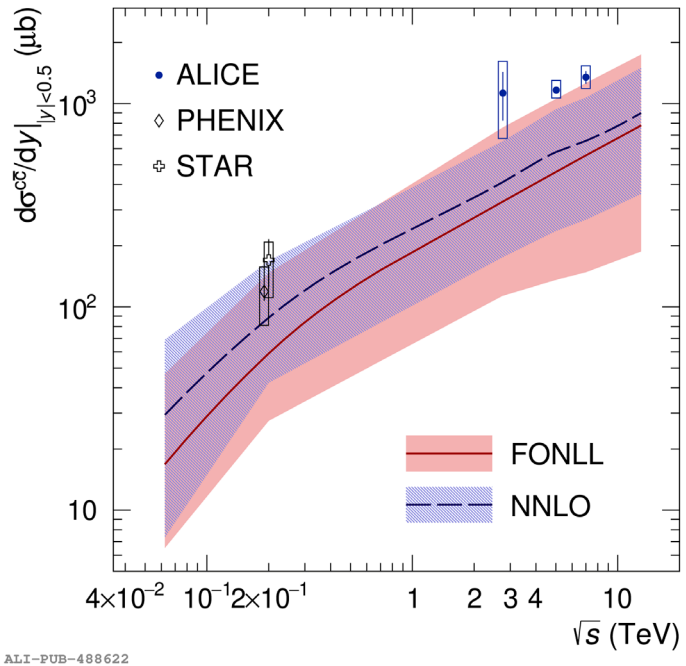
First measurement of Ξ_c^0 FF

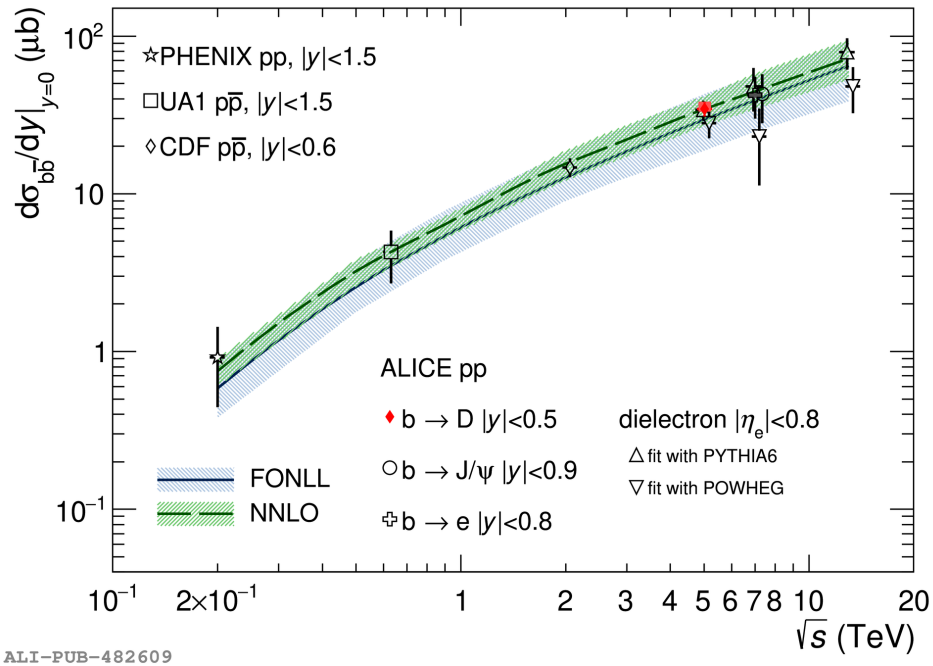
H_c	$f(c \to H_c)[\%]$	
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$	
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$	
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$	
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$	
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$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





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

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

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

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

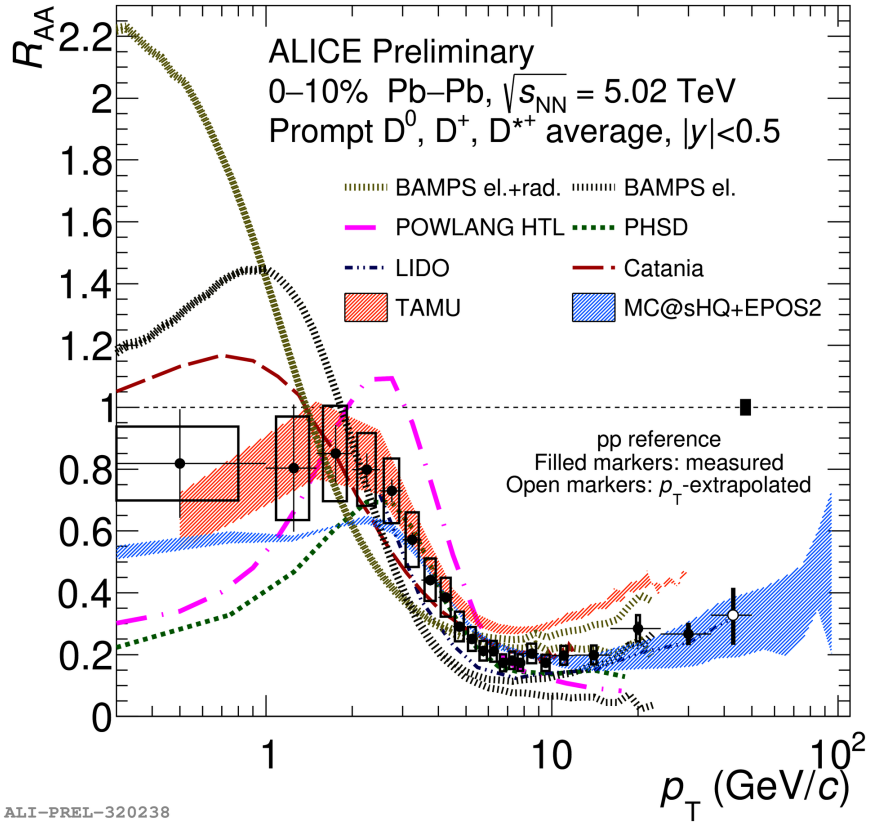
  $(d\sigma^{b\bar{b}}/dy)_{|y|<0.5} = 34.5 \pm 2.4$ (stat.) $^{+4.6}_{-2.9}$ (tot. syst.) μb

- 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

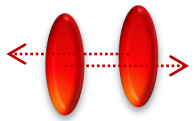
PROMPT D-MESON R_{AA}

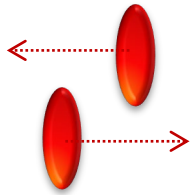


- The nuclear modification factor R_{AA} quantifies modifications to particle production yields induced by QGP effects on the traversing partons:

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

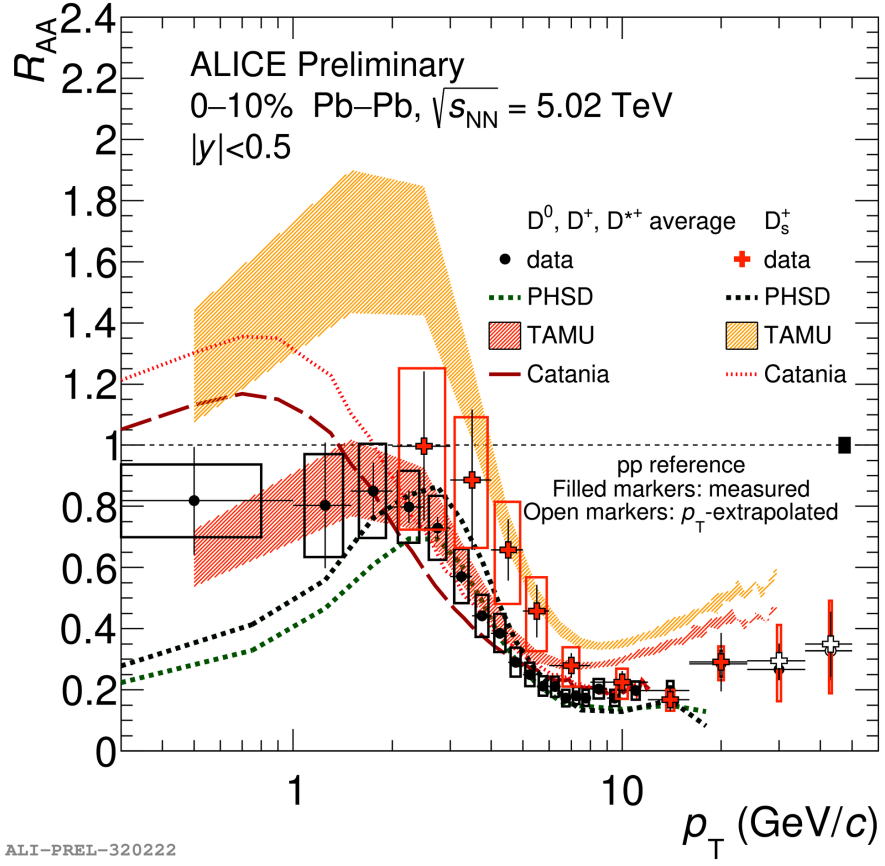
  - R_{AA} = 1 in case of binary scaling (incoherent superposition of nucleon-nucleon collisions)





- 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

PROMPT D-MESON R_{AA}

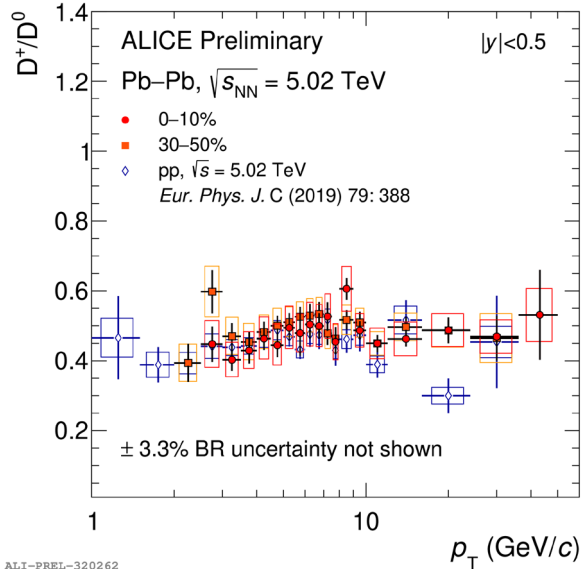


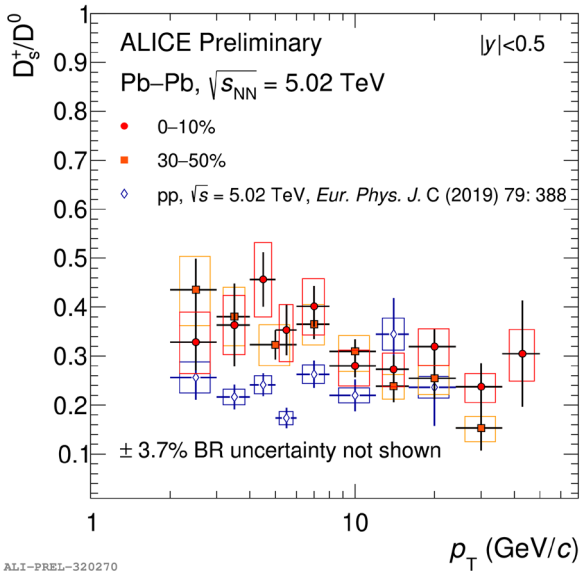
D^0 quark content:	$\bar{u}$ c
D^+ quark content:	$\bar{d}$ c
D^{*+} quark content:	$\bar{d}$ c
D_s^+ quark content:	$\bar{s}$ c

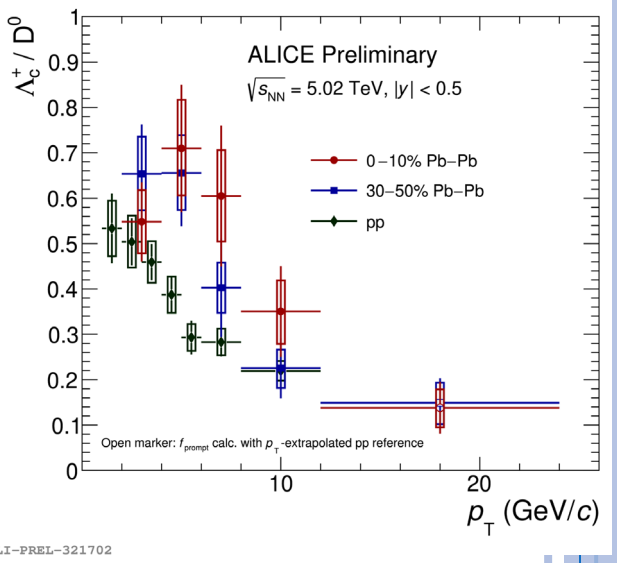
- Hint of smaller suppression for D_s^+ compared to non-strange D mesons for p_T < 8 GeV/c
- Explained due to strangeness enhancement in QGP + hadronization via recombination
- Hierarchy is well described by models including hadron formation via recombination

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)

CHARM-SPECIE RATIOS IN Pb-Pb

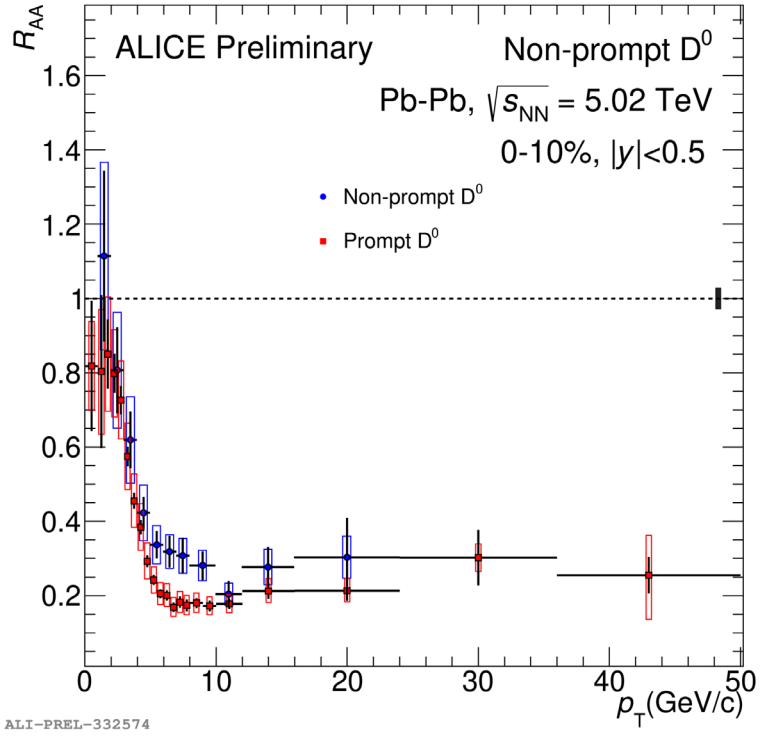


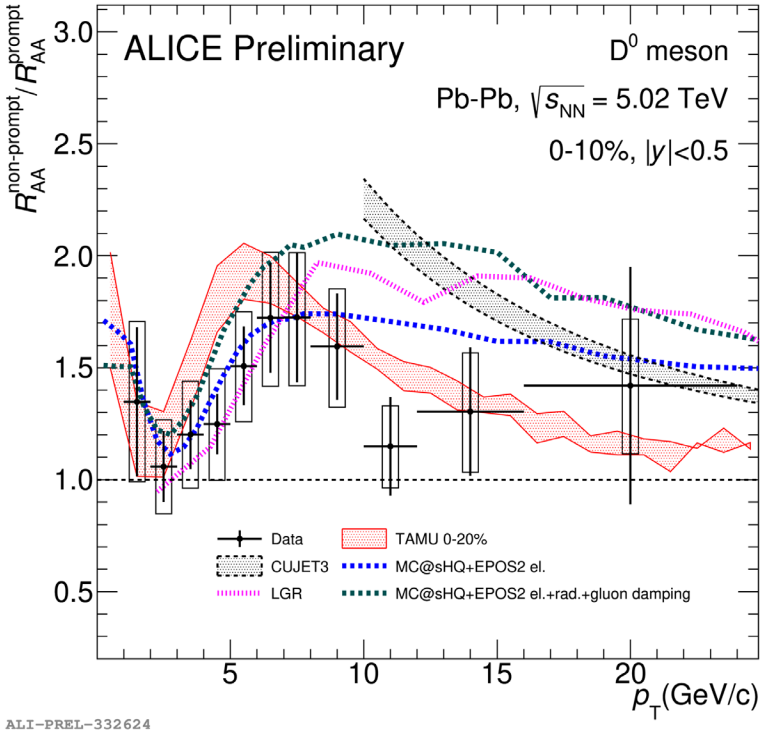




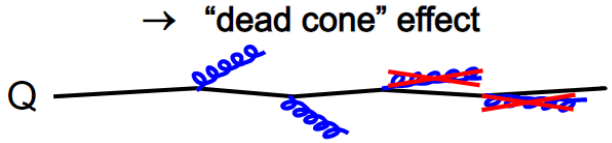
- **D^+/D^0**: relative production in Pb-Pb not modified w.r.t pp
- **D_s^+/D^0**: seemingly larger in Pb-Pb collisions compared to pp
  - As for larger $R_{AA}(D_s^+) > R_{AA}(D^0)$, related to strangeness enhancement + recombination
- **Λ_c^+/D^0**: hint of enhanced Λ_c^+ in Pb-Pb collisions compared to pp
  - Baryon enhancement from quark recombination + radial flow push

NON-PROMPT D-MESON R_{AA}

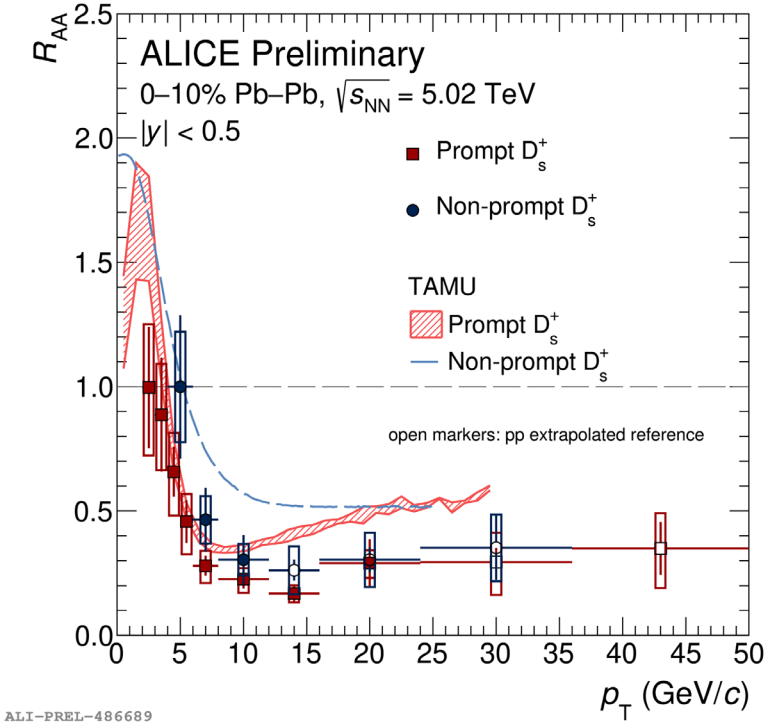


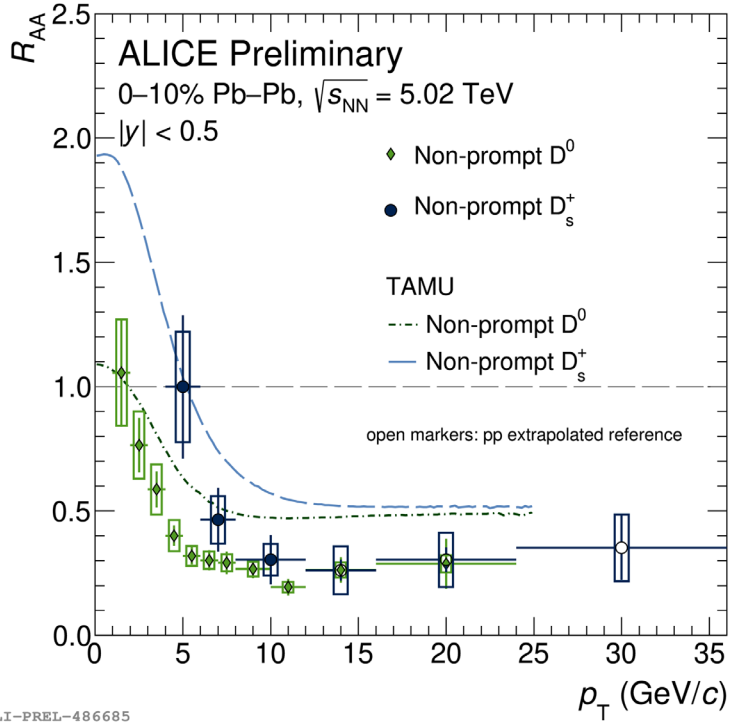


- Decreased suppression for non-prompt D^0 compared to prompt D^0
  - $\Delta E(b) < \Delta E(c)$ from dead-cone effect → Translates into $R_{AA}(H_b \rightarrow D^0) > R_{AA}(c \rightarrow D^0)$
  - Low-p_T structure in double ratio due to prompt D^0 formation via recombination
- Double ratio of non-prompt/prompt D^0 R_{AA} well described by most of the transport models



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



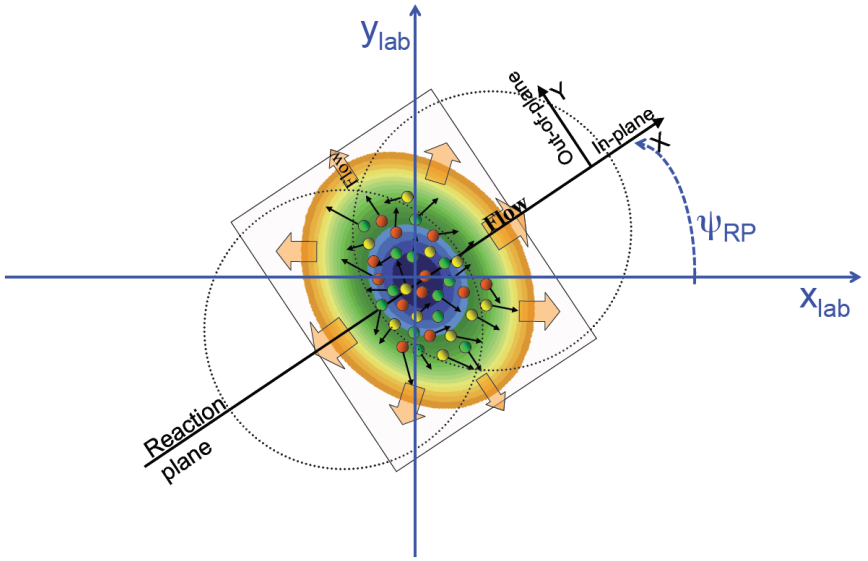


- First measurement of non-prompt D_s^+ mesons in central Pb-Pb collisions
- At low p_T, hint of reduced suppression w.r.t. prompt D_s^+ and non-prompt D^0 mesons
- TAMU model (collisional energy loss + recombination) describes well the difference of R_{AA}, though generally overestimating their absolute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

Further details and results: **S. Politano**, 14/9, - 10:00 (sezione 1)

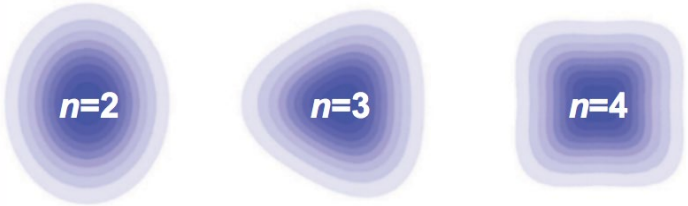
COLLECTIVE MOTION IN Pb-Pb

- **Hydrodynamic treatment** describes well QGP medium evolution
- Non-central collisions: initial spatial anisotropy of the overlap region becomes a momentum anisotropy:
  - Larger pressure gradients imply more particles emitted in that direction
- Anisotropy quantified by a Fourier decomposition of the azimuthal distribution, w.r.t. reaction plane
  - **v_n coefficients**



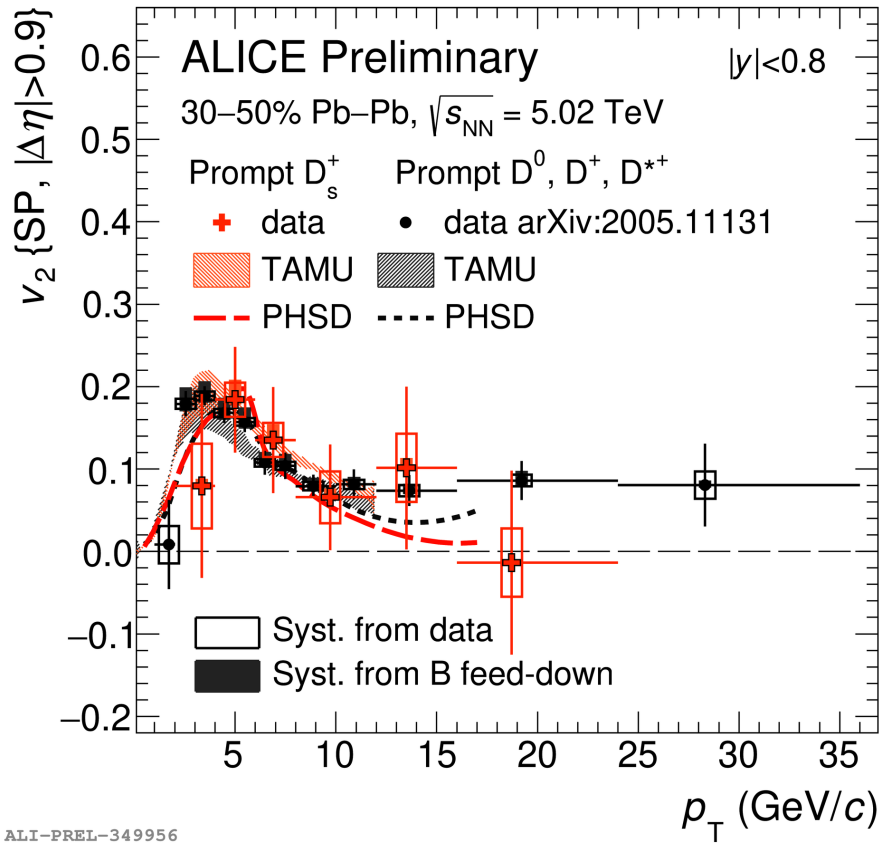
$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{N_0}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty} v_n\left(p_{\mathrm{T}}\right)\cos\left[n\left(\varphi - \Psi_{\mathrm{RP}}\right)\right]\right\}$$

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

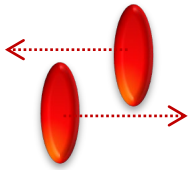


- v_2: sensitive to collision initial geometry
- v_3, v_4, …: sensitive to event-by-event fluctuations

HF ELLIPTIC FLOW COEFFICIENTS



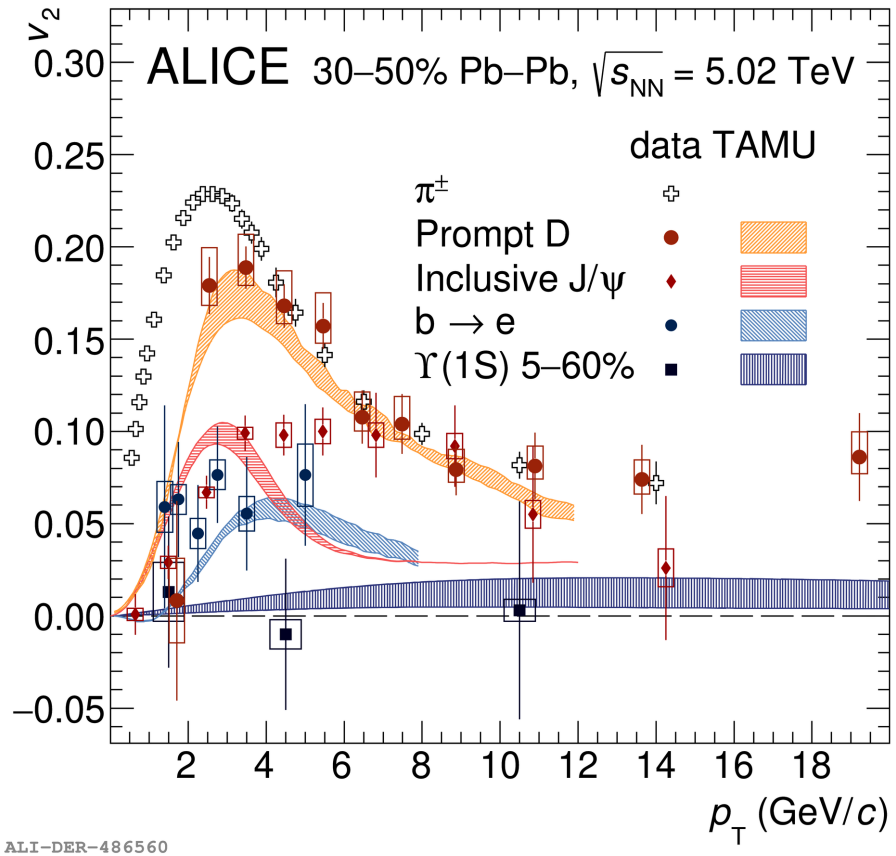
- Positive v_2 of prompt D mesons
  - Participation of charm quarks to collective motion of QGP medium
- Similar strength of elliptic flow for strange and non-strange D mesons
- TAMU and PHSD transport models describe well the measurements
  - Both models include charm + strange quark coalescence for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



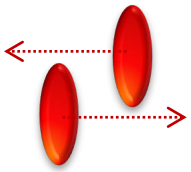
Semi-central collision

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)

CONCLUSIONS

pp collisions

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

Pb-Pb collisions

- Strong **suppression** of open heavy-flavour particles in central Pb–Pb collisions
- Comparison of specie-by-specie measurements support **color charge and mass dependence** of in-medium energy loss + hadronisation via quark **recombination**
- Charm and beauty quarks participate to QGP **collective motion**, though possibly with less strength than light quarks

- Just a selection of results shown here! Many other HF ALICE measurements available
  - p-Pb system, differential studies as HF correlation and jets, multiplicity-dependent observables, ...
- ALICE upgrade expected to dramatically improve the precision of heavy-flavour studies and allow for further, unexplored measurements