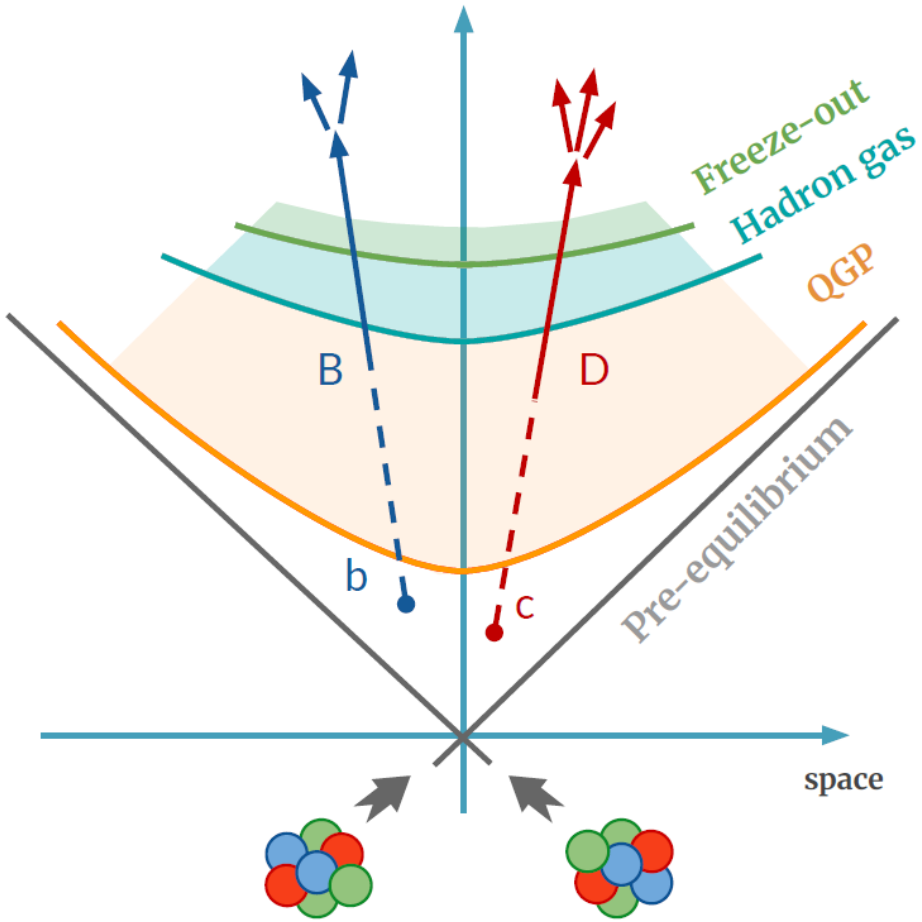
Open charm
Experimental results and prospects

Francesco Prino

Sezione di Torino

ECT*, Trento, July 22nd 2025

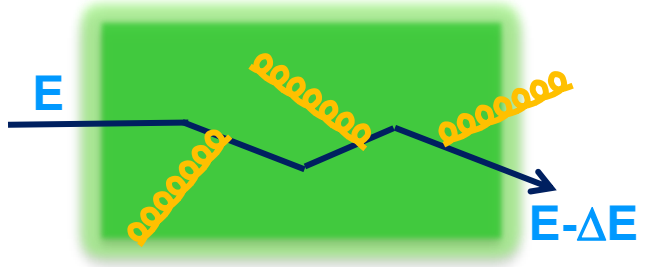
Heavy quarks as QGP probes



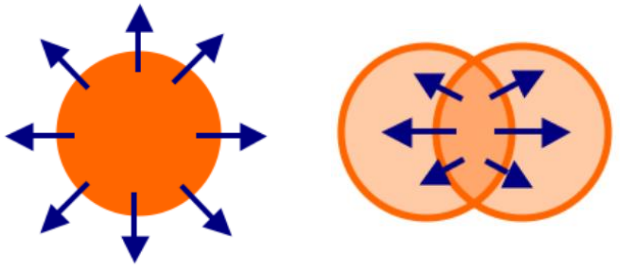
- Charm and beauty quarks: unique probes of the medium
  - ⇨ Produced at the **very early stage** of the collision in partonic scattering processes with large momentum transfer
    - ✓ Produced out-of-equilibrium
  - ⇨ Small rate of thermal production in the QGP ($m_{c,b} \gg T$)
  - ⇨ Large mass, short formation time ⟶ experience the entire evolution of the medium
- Traverse the hot and dense medium interacting with its constituents ⟶ energy-momentum exchanges with the medium
  - ⇨ Traceable probes that **probe the medium via interactions**

Heavy quarks as QGP probes

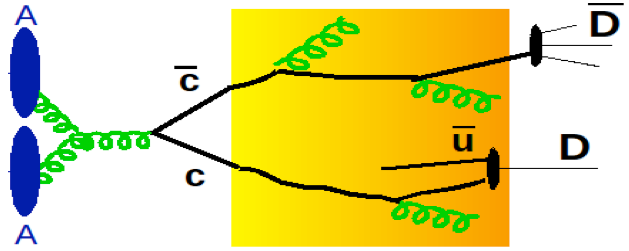
- Heavy quark interactions with QGP constituents:
  - ⇨ Energy loss of energetic partons → quenching
    - ✓ Elastic collisions + gluon radiation
    - ✓ Test **colour charge and quark mass dependence** of in-medium energy loss
    - ✓ Probe the medium at short-distance scales



  - ⇨ "Push" from the collective flow of the medium
    - ✓ Low-p_T heavy quarks experience Brownian motion → sensitive to **spatial diffusion coefficient** of the QGP
    - ✓ (Partial) **thermalization** of low/intermediate momentum charm (beauty?) quarks in the QGP?



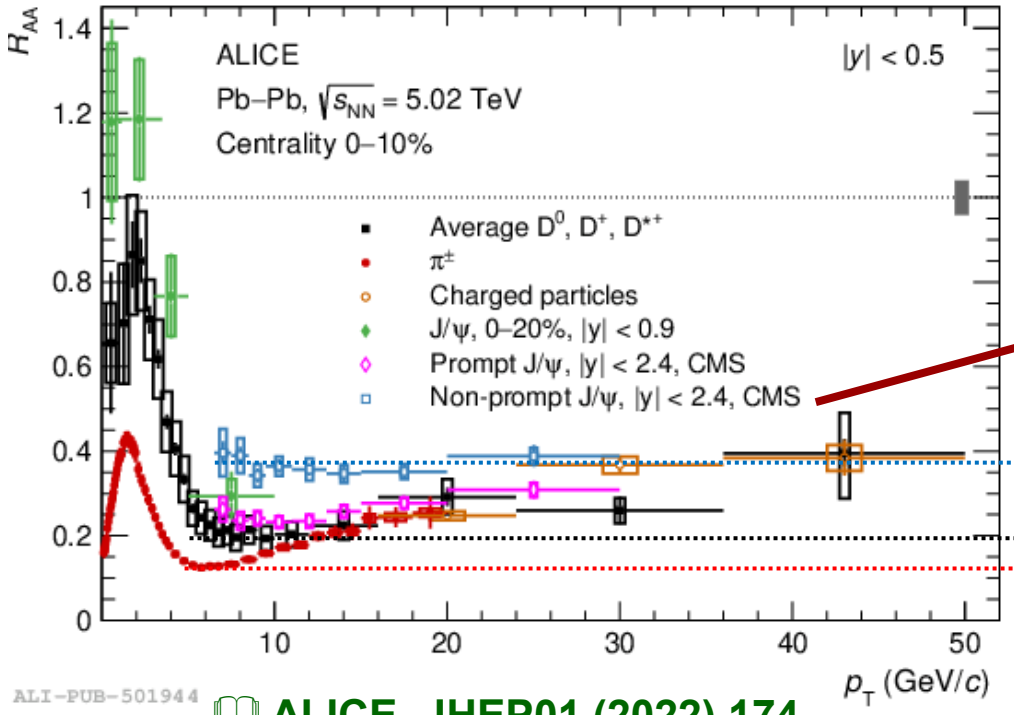
  - ⇨ In-medium hadronization
    - ✓ **Hadronization via recombination** of the charm/beauty quark with a (light) quark from the medium
    - ✓ Recombination vs. fragmentation → impact on hadron momentum distributions and relative abundances of hadron species



Snapshots at μ_B=0

R_{AA}: Charm vs. beauty vs. light flavours

- Strong suppression of charm and beauty hadron yields at mid and high p_T
  - ⇨ Due to parton in-medium energy loss
- Energy loss depends on **colour charge** and **mass** of the parton traversing the QGP
  - ⇨ Expected hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  - ⇨ Tested by comparing R_{AA} of light-flavour, charm and beauty hadrons

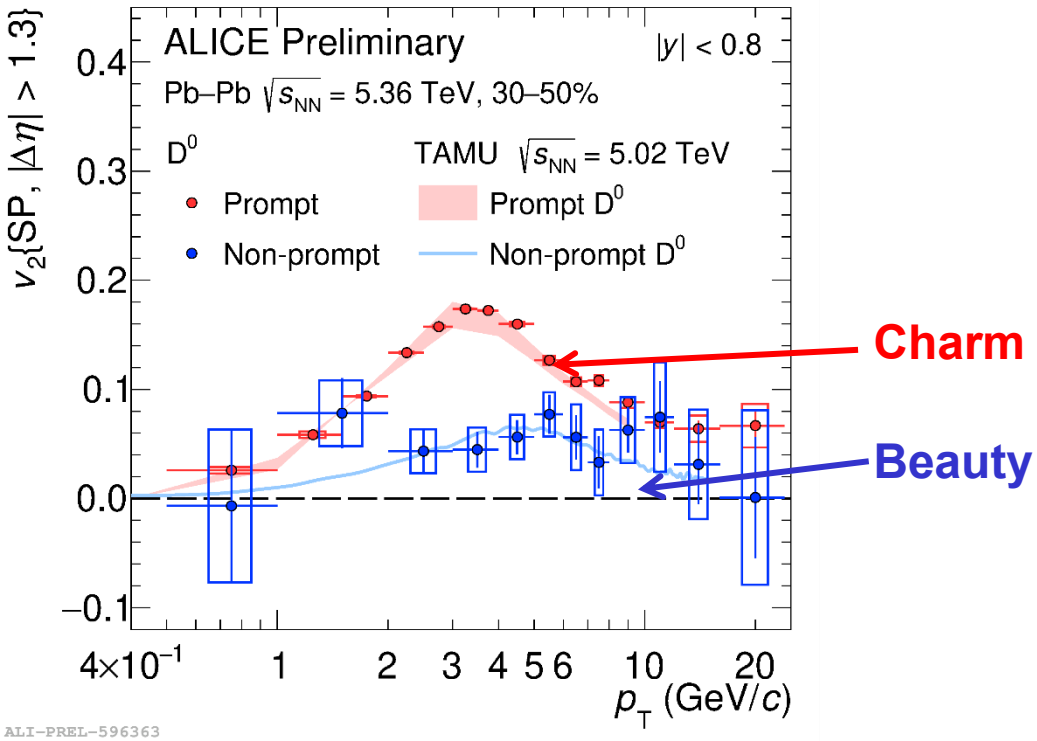


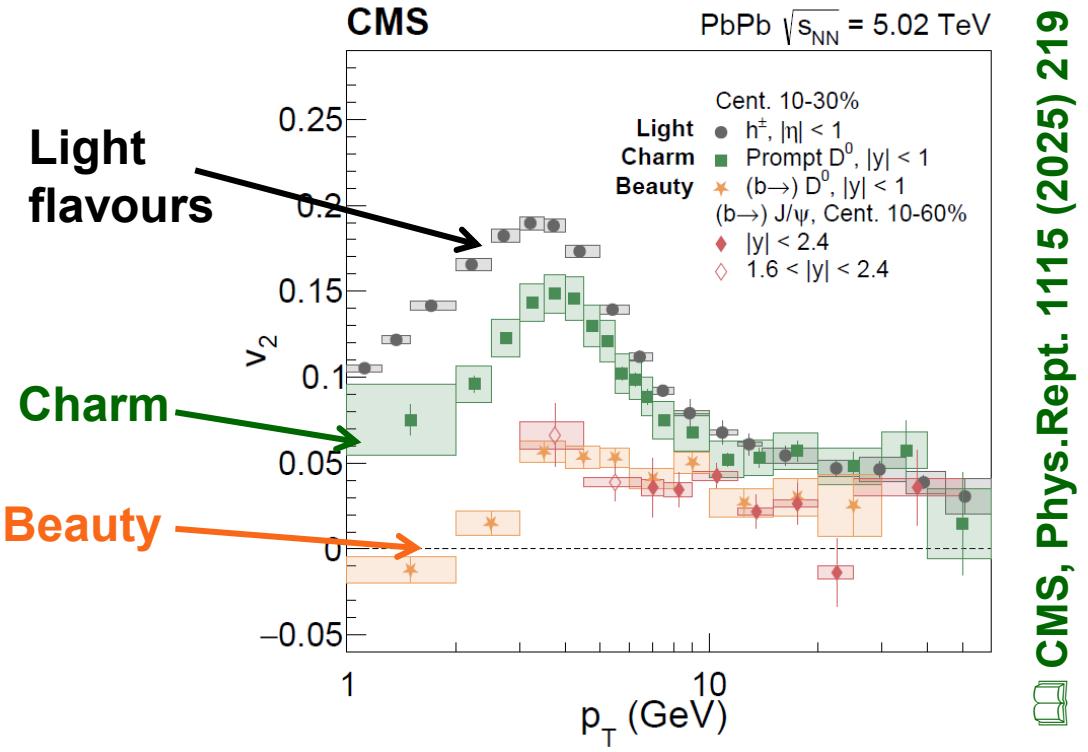
📖 ALICE, JHEP01 (2022) 174

R_{AA}(charm) > R_{AA}(light) for p_T<8 GeV/c
R_{AA}(beauty) > R_{AA}(charm) for p_T<20 GeV/c

As expected from parton in-medium energy loss

Elliptic flow of heavy-flavours at LHC



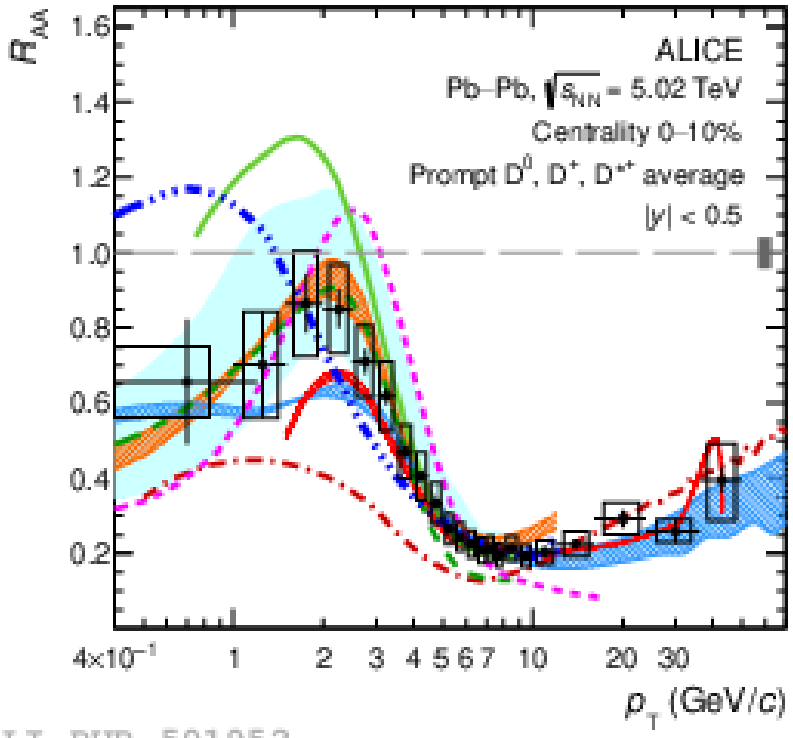


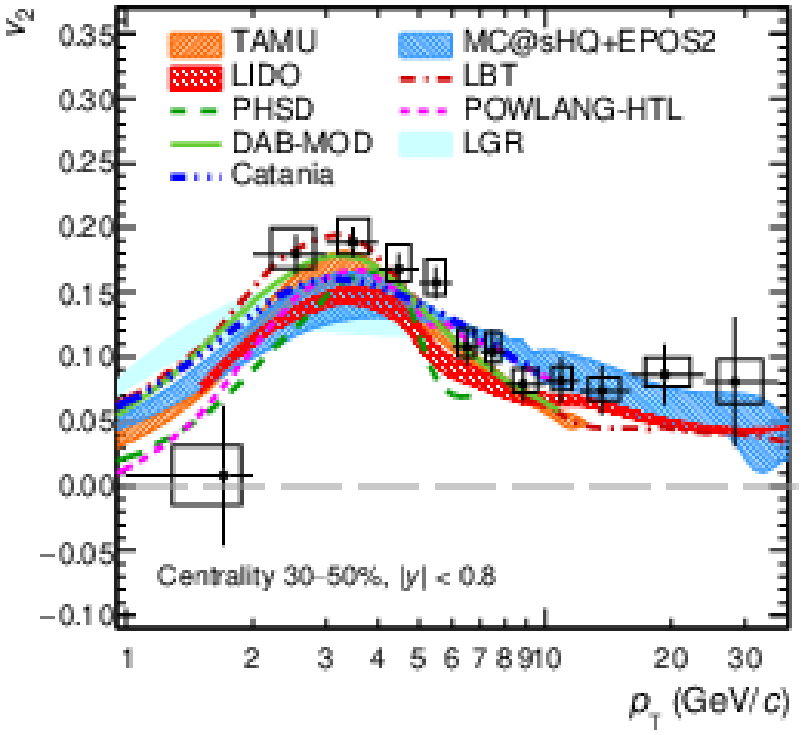
- Charm hadrons
  - ⇨ Large v_2 , similar magnitude as light flavour v_2
  - ⇨ Indication that low/mid-p_T **charm quarks (partially) thermalize in the QGP**

- Beauty hadrons (via non-prompt D and J/ψ)
  - ⇨ Smaller v_2 as compared to charm hadrons
  - ⇨ Stronger degree of equilibration for charm than for beauty quarks
    - ✓ Due to longer thermalization time of the heavier beauty quarks

Charm R_{AA} and v_2 phenomenology

- Simultaneous comparison of R_{AA} and v_2 to models can constrain QGP properties and the description of charm-quark interaction and diffusion in the medium
  - ⇨ Interplay of CNM effects, collisional and radiative energy loss, hadronisation via coalescence and fragmentation and realistic underlying medium evolution required to describe R_{AA} and v_2



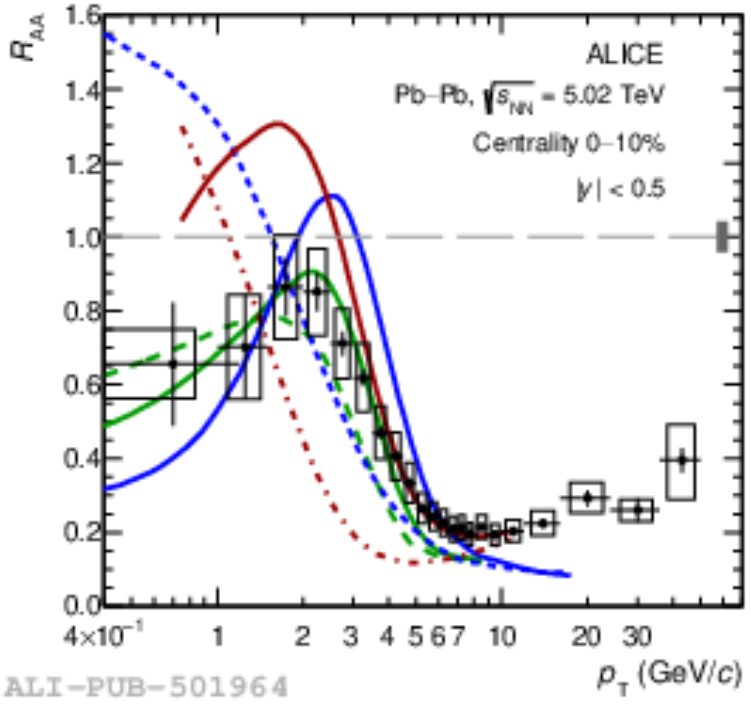


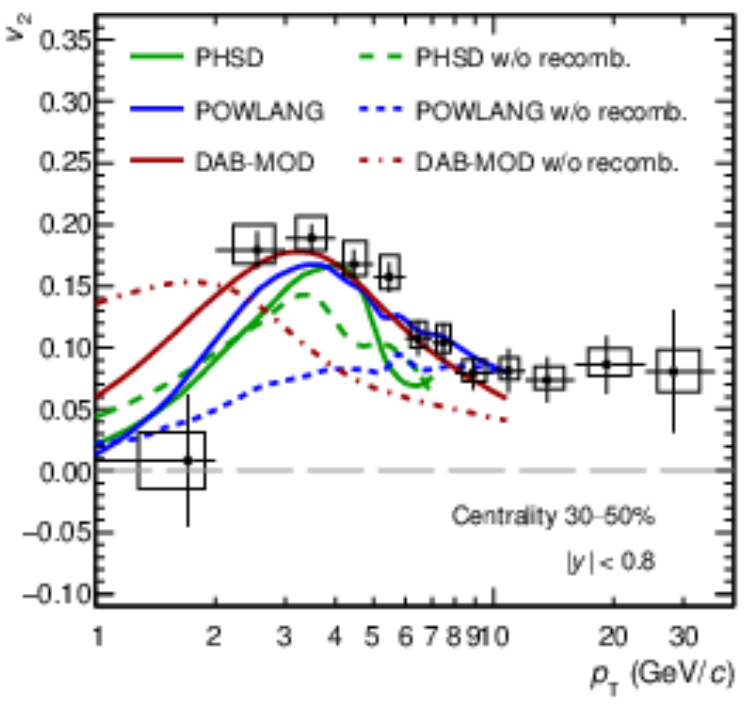
ALI-PUB-501952

📖 **ALICE, JHEP01 (2022) 174**

Charm R_{AA} and v_2 phenomenology

- Simultaneous comparison of R_{AA} and v_2 to models can constrain QGP properties and the description of charm-quark interaction and diffusion in the medium
  - ⇨ Interplay of CNM effects, collisional and radiative energy loss, hadronisation via coalescence and fragmentation and realistic underlying medium evolution required to describe R_{AA} and v_2



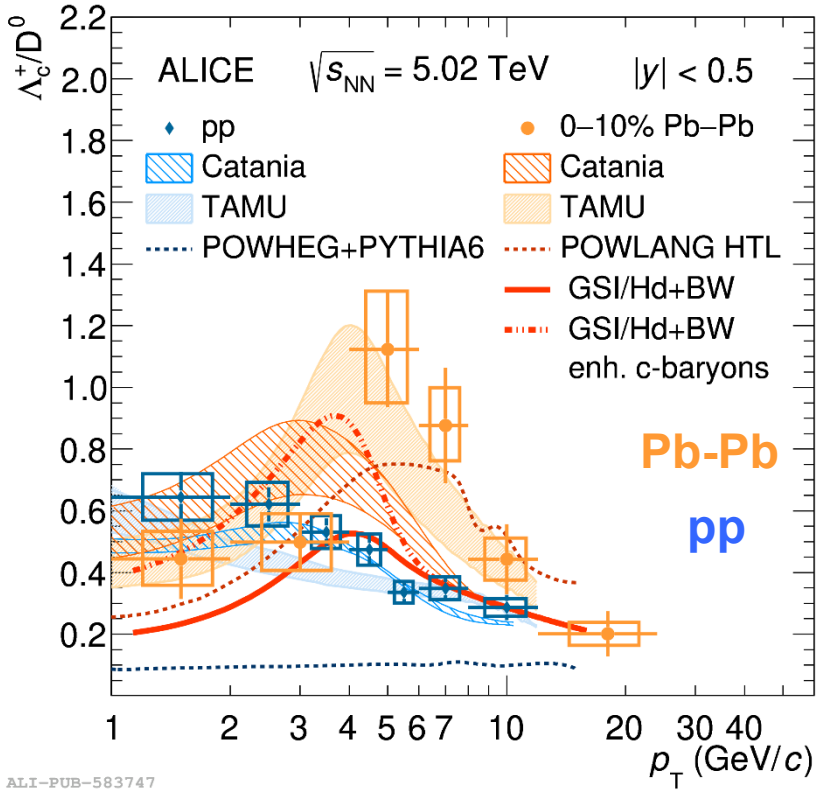


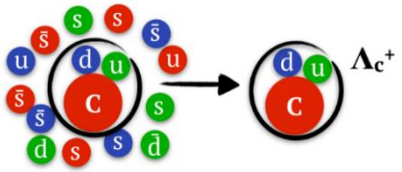
ALICE, JHEP01 (2022) 174

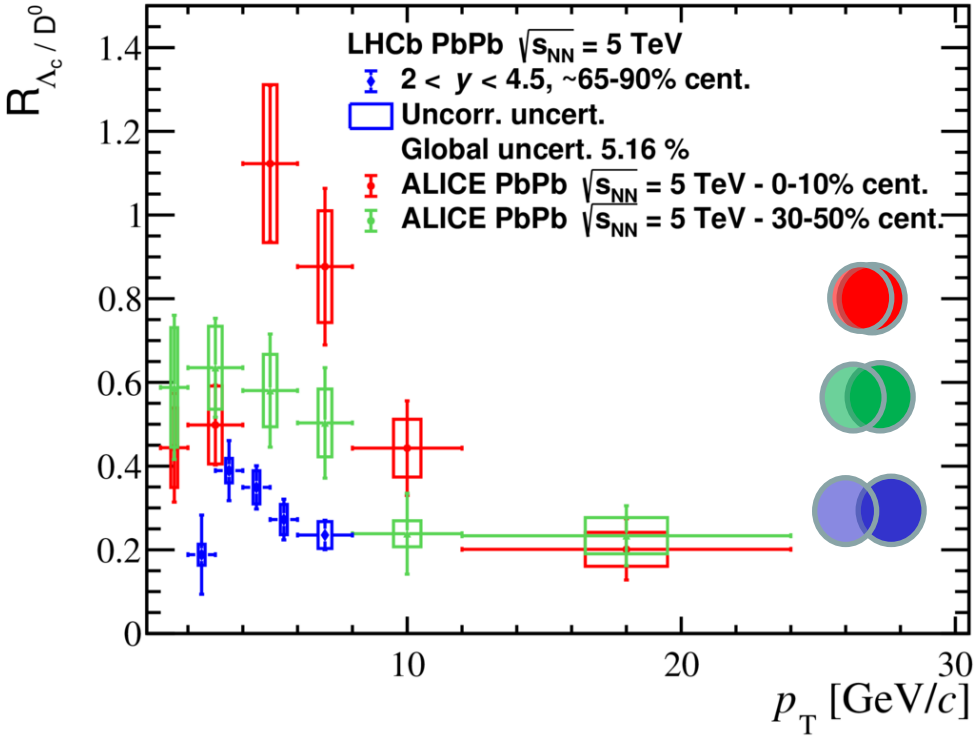
→ in-medium hadronization is needed to describe the data

Charmed baryons in Pb-Pb

ALICE, EPJC 84 (2024) 813



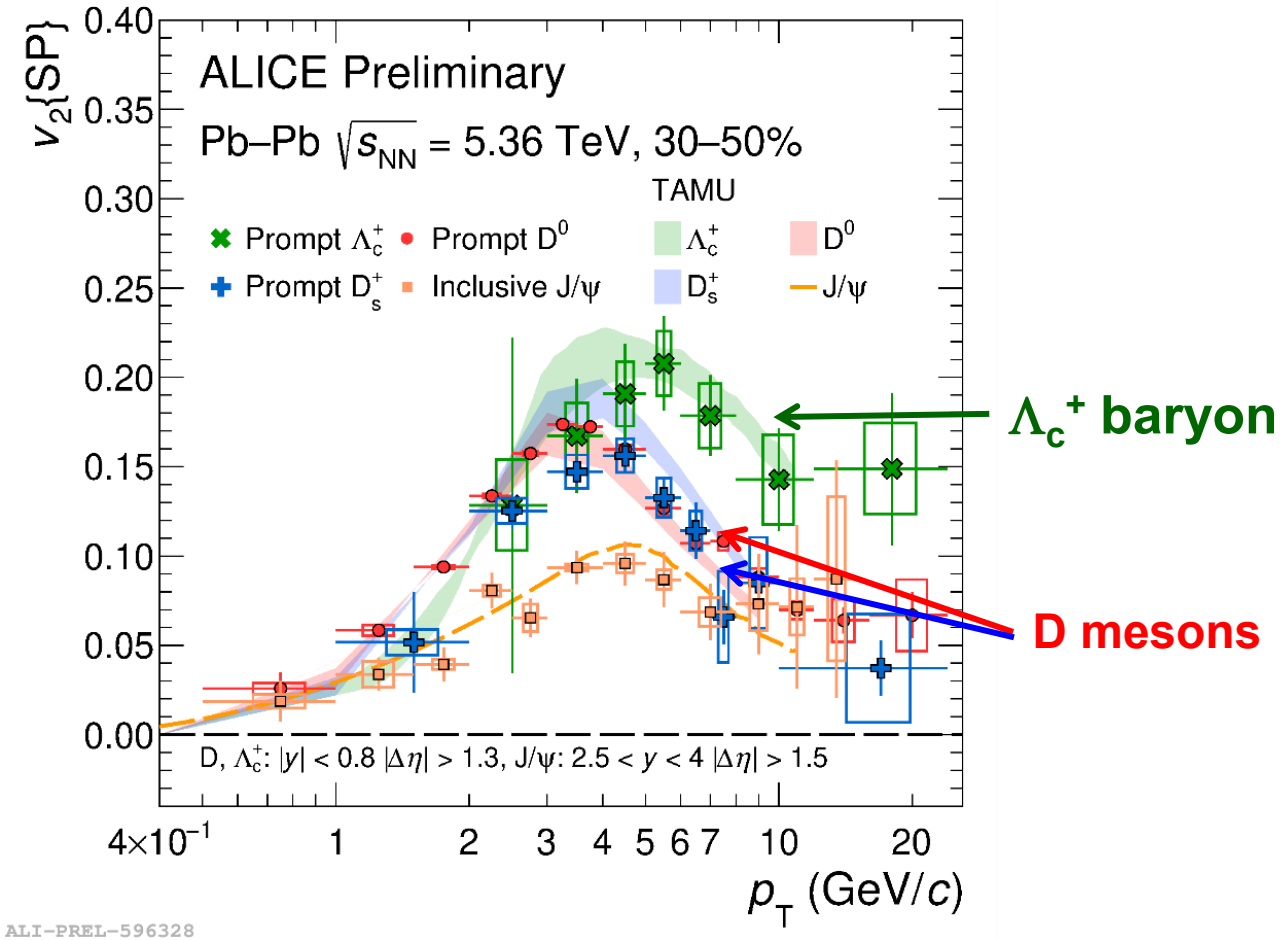




LHCb, JHEP 06 (2023) 132

- Λ_c/D^0 ratios at intermediate p_T (4< p_T <10 GeV/c) enhanced in Pb-Pb compared to pp
  - ⇨ Enhancement increases from peripheral to central collisions
  - ⇨ Described by models including hadronization via recombination with light quarks from the bulk

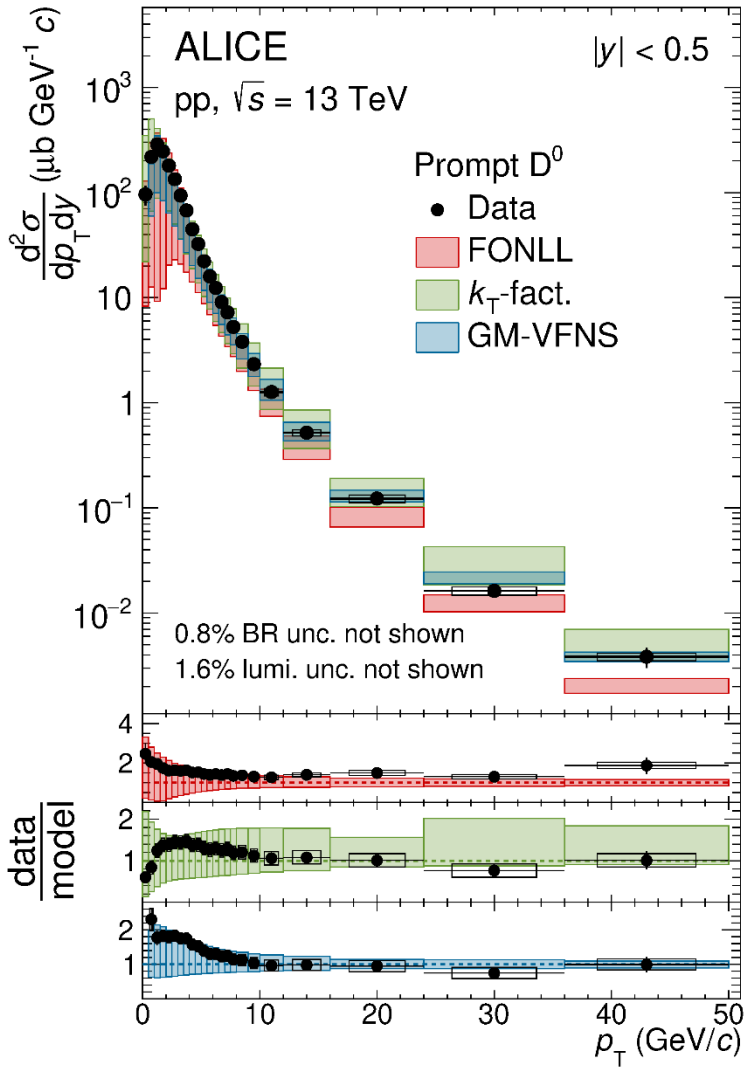
Elliptic flow of charmed baryons



- First measurement of Λ_c v_2
  - ⇨ First evidence (at 3.6σ) of charm baryon/meson splitting at intermediate p_T (p_T>4 GeV/c)
  - ⇨ As expected from (partial) thermalization of c quarks in the QGP and hadronization via recombination
  - ⇨ Models with charm quark transport in QGP and hadronization via recombination describe the measured v_2, capturing the main features of baryon/meson splitting

→ in-medium hadronization is needed to describe the data

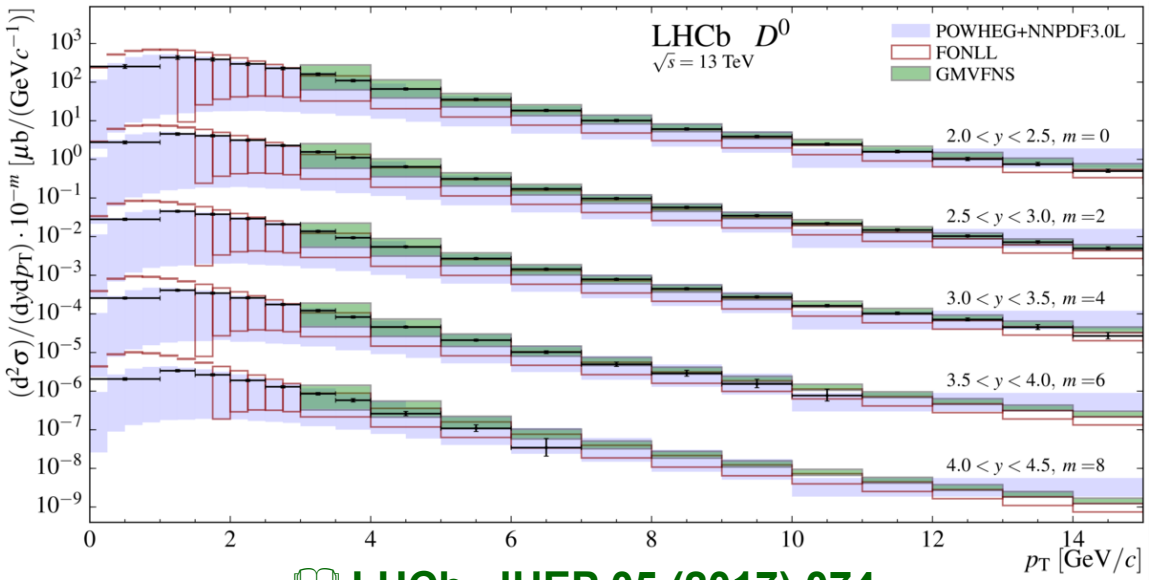
What about charm in pp at the LHC?



ALI-PUB-567836

📖 ALICE, JHEP 12 (2023) 086

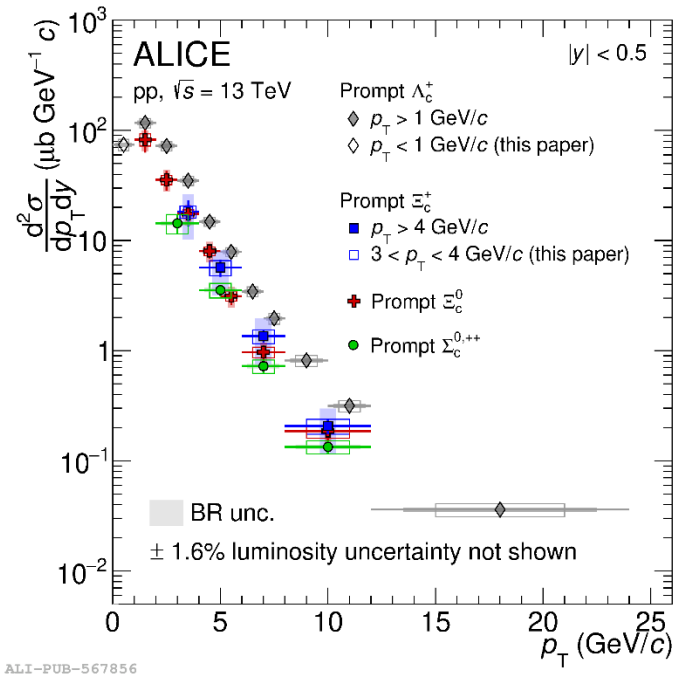
- D-meson production in pp collisions
  - ⇨ Measured in a wide p_T range, down to low p_T , at mid and forward rapidity and different center-of-mass energies
  - ⇨ D-meson cross sections described by pQCD calculations
    - ✓ Measured values on the upper edge of theory uncertainties for FONLL and GM-VFNS at low p_T



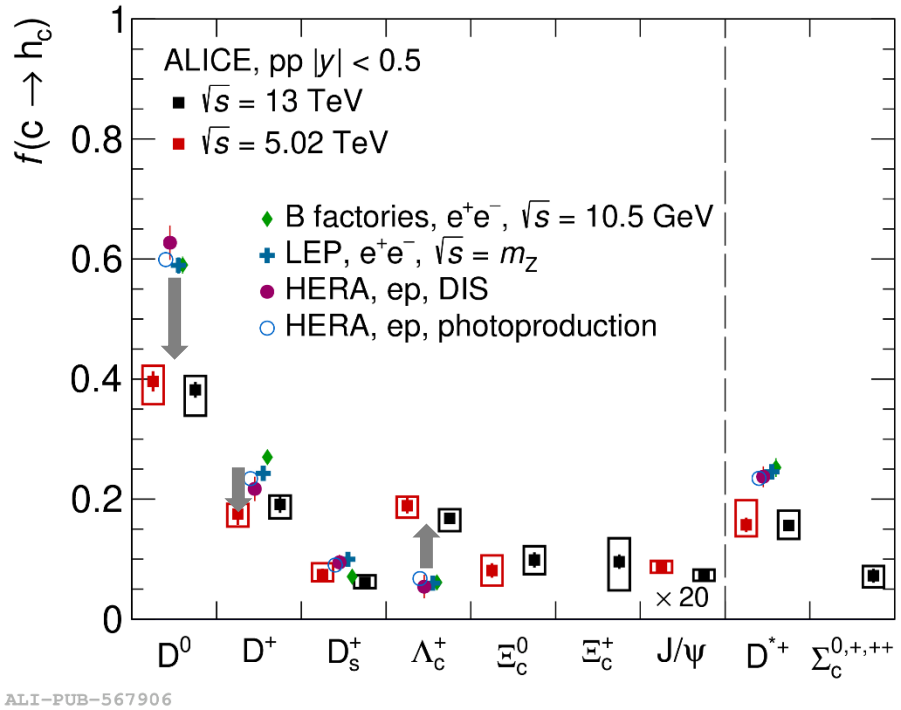
📖 LHCb, JHEP 05 (2017) 074

Charmed baryons in pp at the LHC

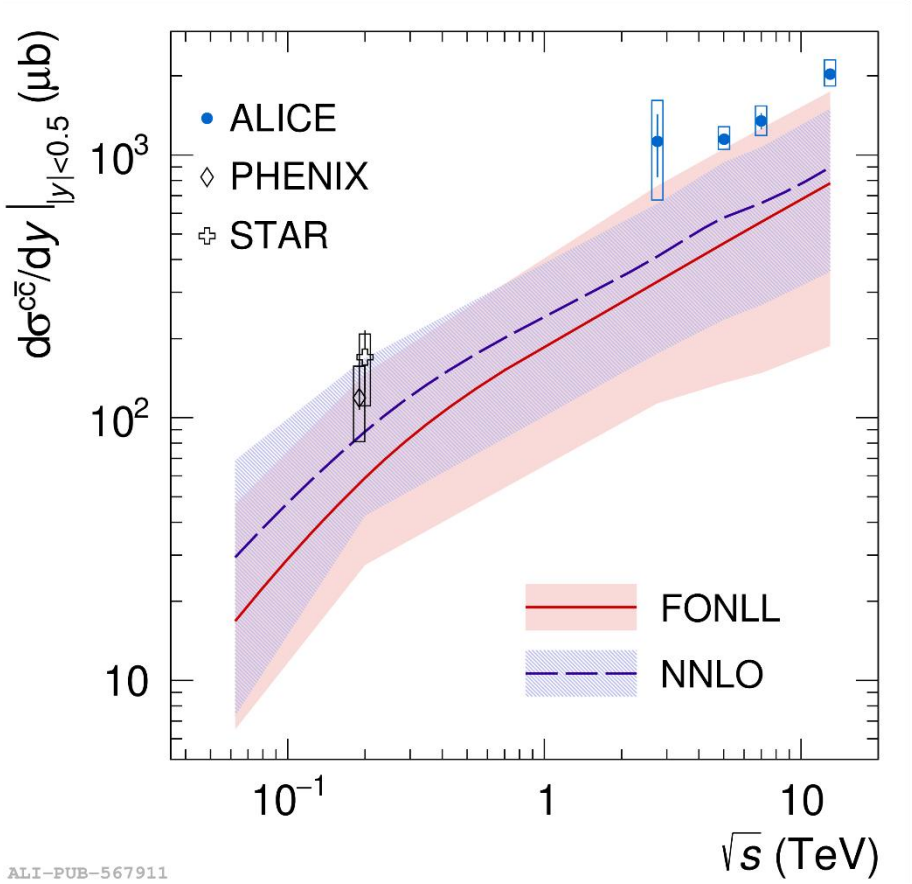
- Charm baryon production in pp collisions
  - ⇨ Measured at midrapidity in a wide p_T range, down to low p_T for Λ_c, Ξ_c^0, Ξ_c^+ and Σ_c
  - ⇨ Λ_c relative abundance in pp collisions at LHC substantially higher than in e^+e^- ad ep collisions
  - ⇨ Indicates a **breakdown of the universality** of charm quark **fragmentation functions**



📖 **ALICE, JHEP 12 (2023) 086**



Charm cross section



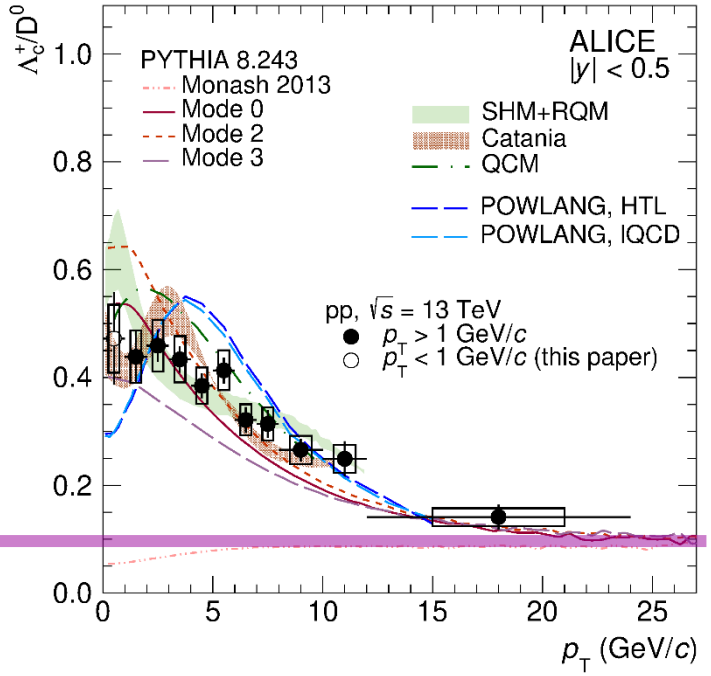
📖 **ALICE, JHEP 12 (2023) 086**

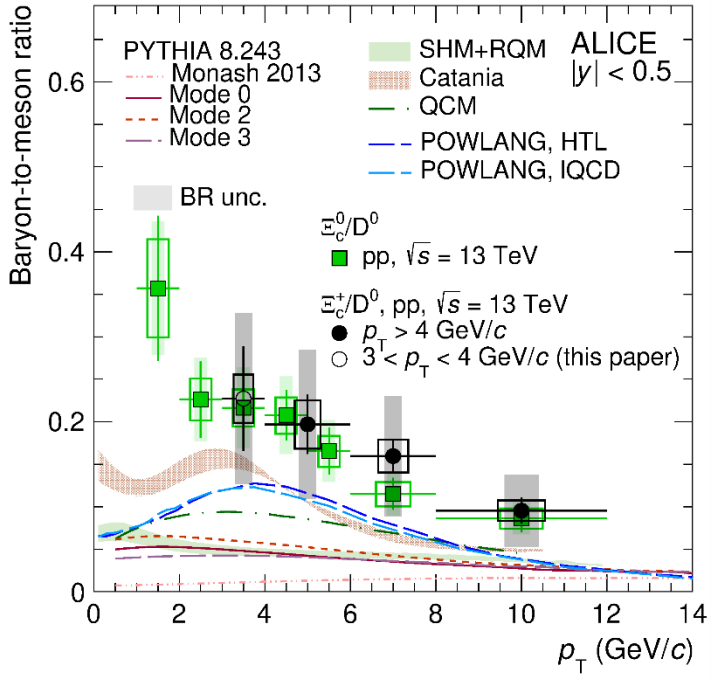
- Charm quark production in pp collsions
  - ⇨ Charm cross section at midrapidity calculated summing D^0, D^+, D_s^+, Λ_c^+ and Ξ_c^0, Ξ_c^+ and J/ψ
  - ⇨ Measured values on the upper edge of theory uncertainties (FONLL and NLO)

Charmed baryons vs p_T in pp at the LHC

- Baryon/meson ratios in pp collisions
  - ⇨ Enhanced at low/mid p_T, tend to the e^+e^- value ("vacuum-like" fragmentation?) at high p_T
  - ⇨ Captured (at least qualitatively) in theoretical models with different approaches:
    - ✓ Color reconnections beyond-leading-color in PYTHIA8
    - ✓ QGP droplet + hadronization via recombination
    - ✓ Statistical hadronization with additional baryonic resonances

e^+e^-@LEP

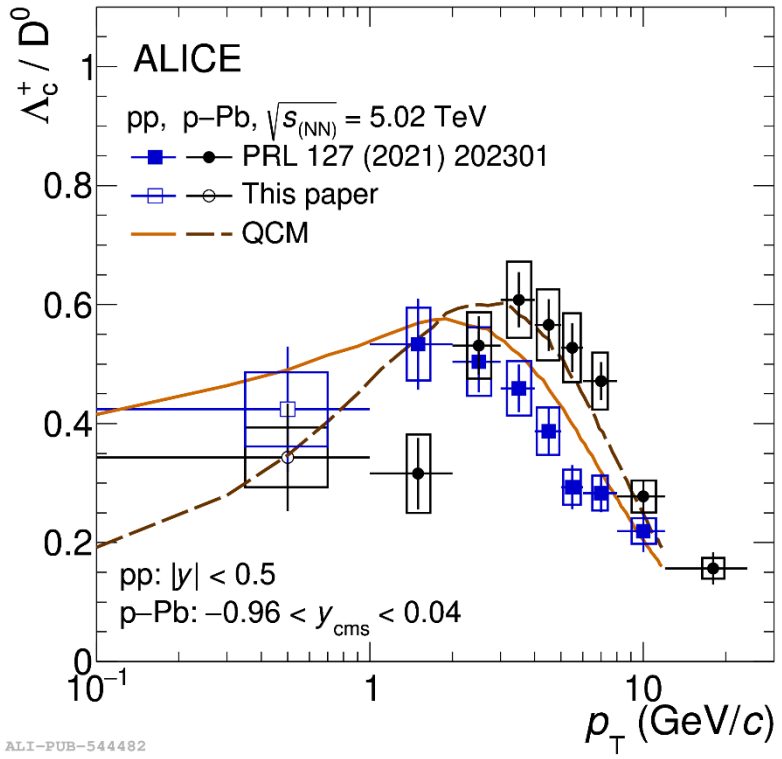


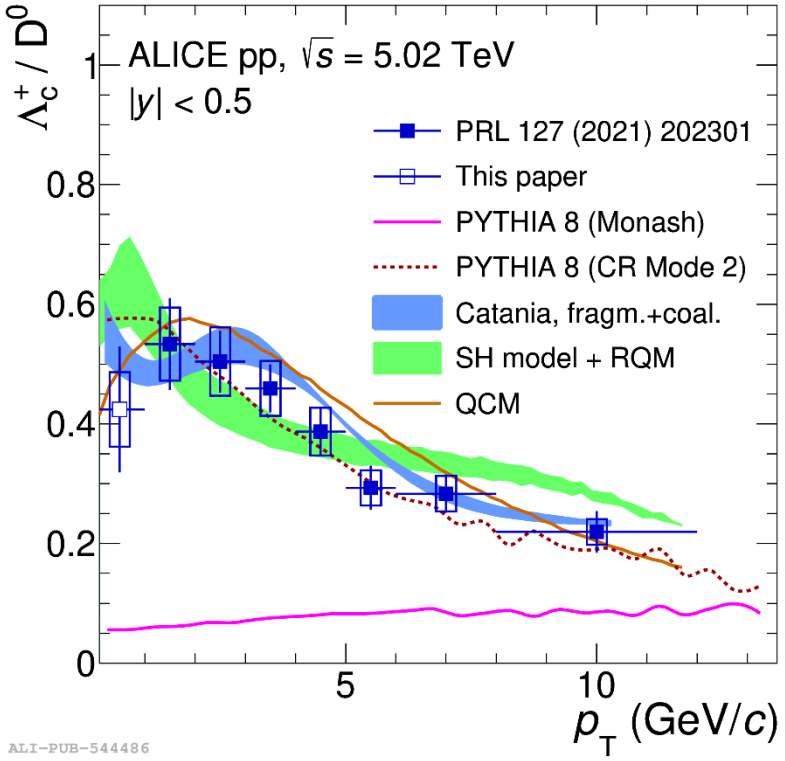


📖 **ALICE, JHEP 12 (2023) 086**

Charmed baryons vs p_T in p-Pb at the LHC

- Baryon/meson ratios from pp to p-Pb
  - ⇨ Hint of shift in Λ_c/D^0 ratio peak towards higher p_T in p-Pb
    - ✓ Radial flow effect?
  - ⇨ p-Pb data reasonably well described by models describing pp
    - ✓ Color reconnections beyond-leading-color in PYTHIA8
    - ✓ QGP droplet + hadronization via recombination
    - ✓ Statistical hadronization with additional baryonic resonances

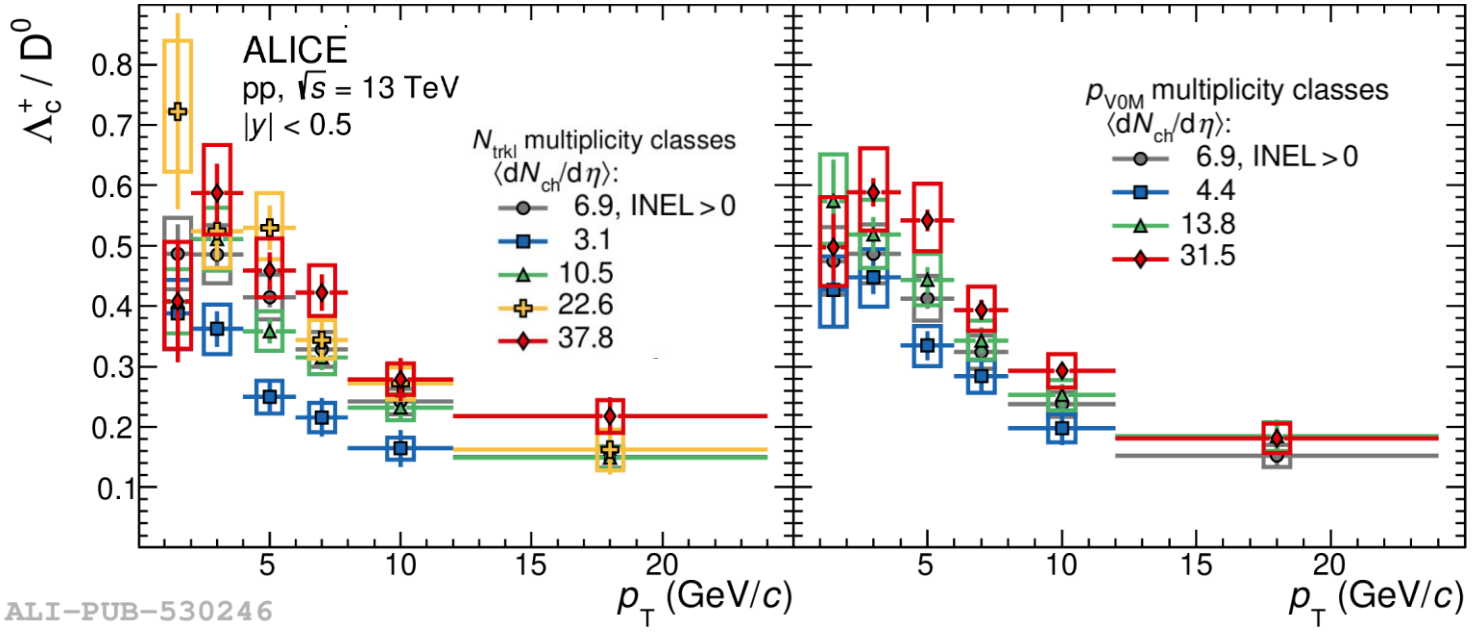




📖 **ALICE, PRC 107 (2023) 064901**

Charmed baryons vs. multiplicity

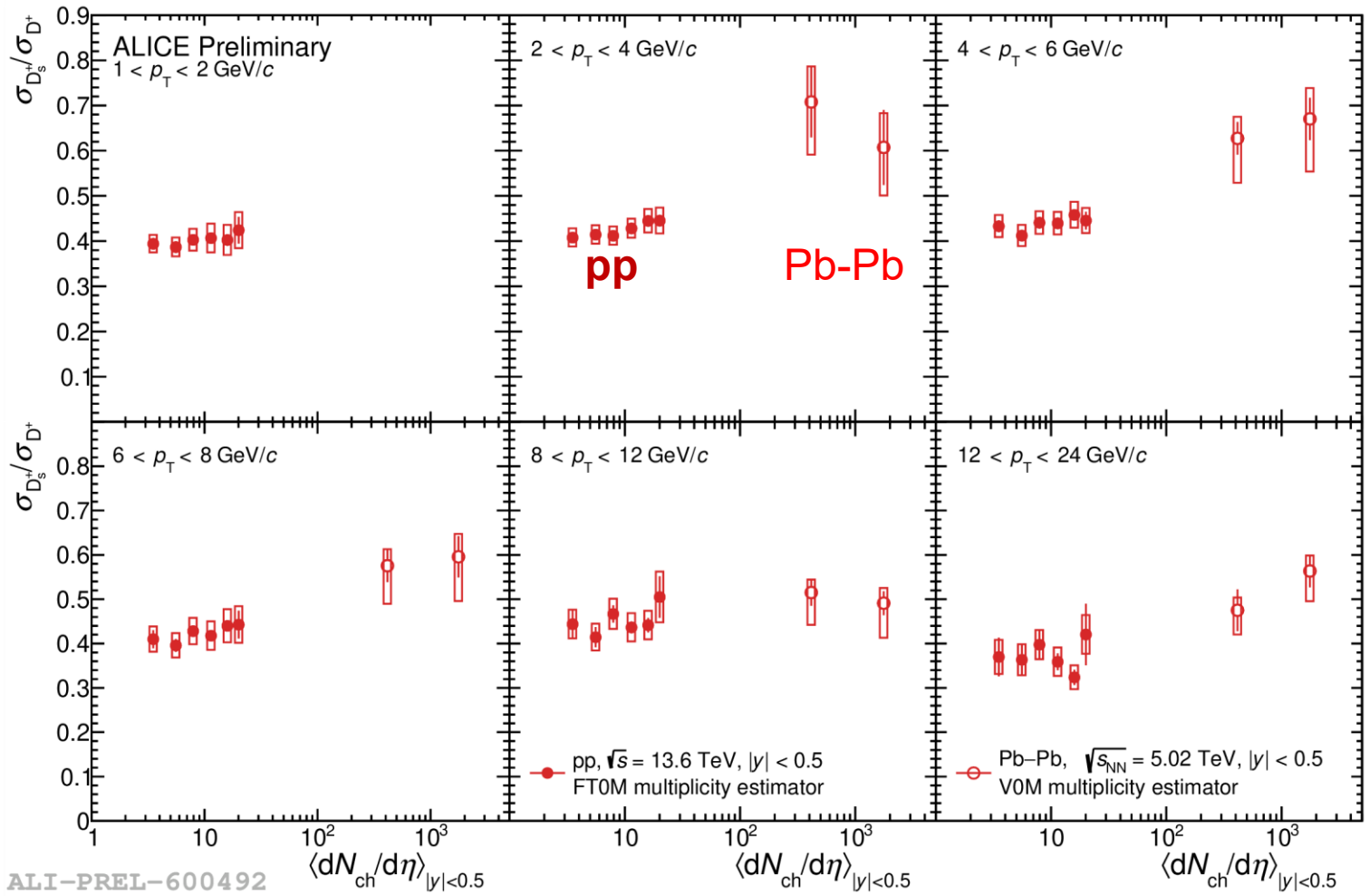
- Baryon/meson ratios vs. multiplicity
  - ⇨ Multiplicity-dependent enhancement for p_T<12 GeV/c
  - ⇨ Observed with both midrapidity and forward rapidity multiplicity estimators
    - ✓ Not a consequence of a possible bias arising from autocorrelations between the multiplicity estimator and charm jet fragmentation



📖 **ALICE, PLB 829 (2022) 137065**

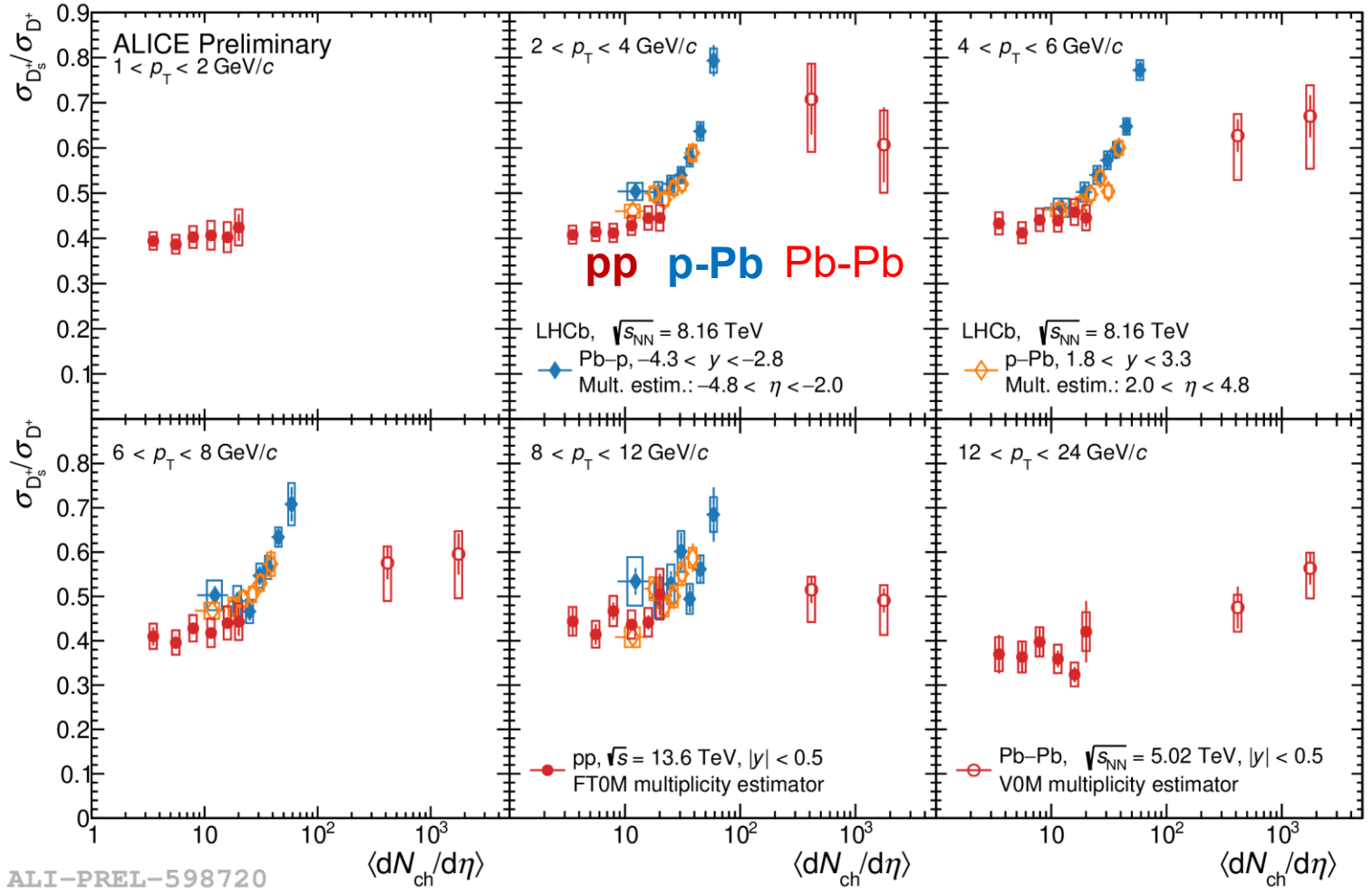
Charm-strange meson production

- Strange/non-strange ratio
  - ⇨ (Hint of) enhancement at low p_T in Pb-Pb compared to pp
    - ✓ Expected in case of QGP formation due to lifting of strangeness suppression + hadronization via recombination
  - ⇨ No multiplicity dependence in pp collisions at mid-rapidity



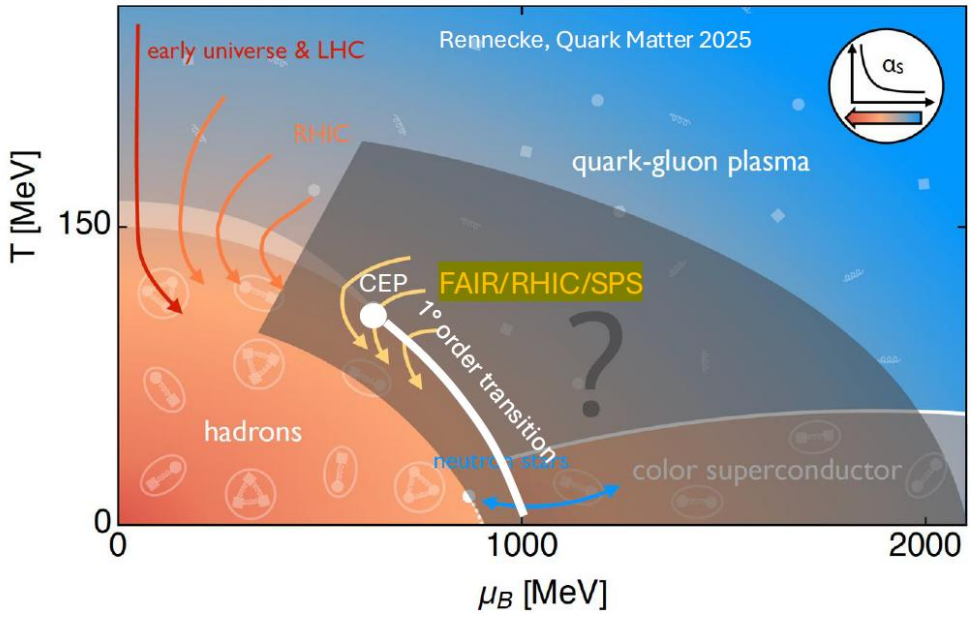
Charm-strange meson production

- Strange/non-strange ratio
  - ⇨ (Hint of) enhancement at low p_T in Pb-Pb compared to pp
    - ✓ Expected in case of QGP formation due to lifting of strangeness suppression + hadronization via recombination
  - ⇨ No multiplicity dependence in pp collisions at mid-rapidity
  - ⇨ Trend observed by LHCb in p-Pb at forward rapidity
    - ✓ Uses a multiplicity estimator in the same rapidity range of D meson measurements



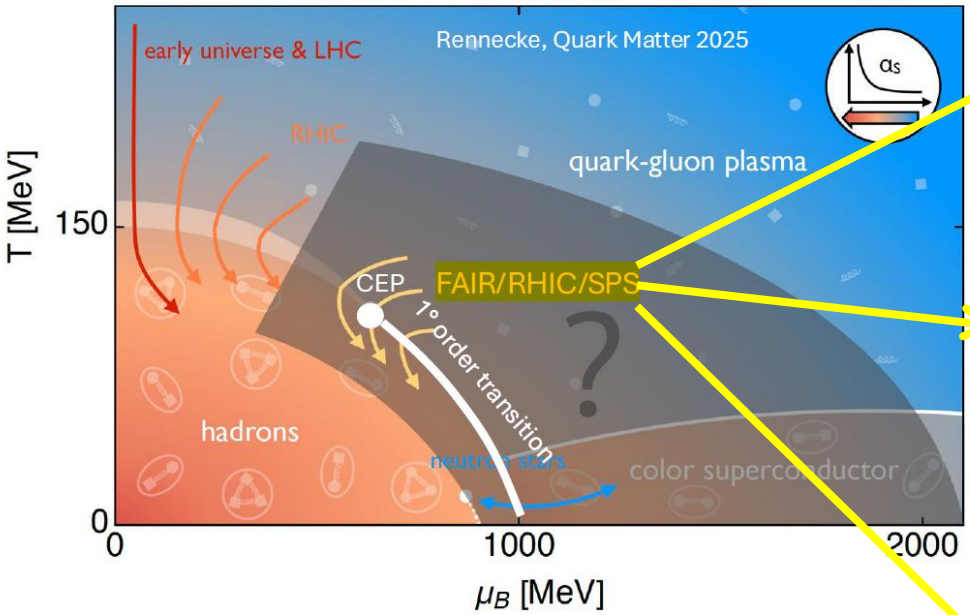
Towards the high μ_B region

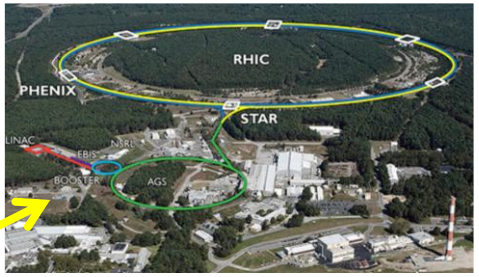
What can we learn at lower $\sqrt{s_{NN}}$



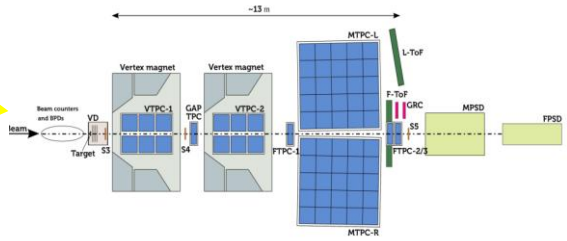
- Almost unexplored energy domain
  - ⇨ No results available below top SPS energy
- Charm production in p-A collisions
  - ⇨ Sensitive to **nuclear PDFs** (antishadowing and EMC)
  - ⇨ Possible sensitivity to **intrinsic charm**
- Charm hadron yield and v_2 in A-A collisions
  - ⇨ Probe the medium at lower temperatures as compared to LHC and RHIC top energy
  - ⇨ Constrain estimates of the **charm diffusion coefficient**
  - ⇨ Charm quark **thermalization** in a short-lived QGP
  - ⇨ Insight into **hadronization mechanism**
  - ⇨ Charm cross section sensitive to **chiral symmetry restoration**

Heavy-ion collisions at low $\sqrt{s_{NN}}$

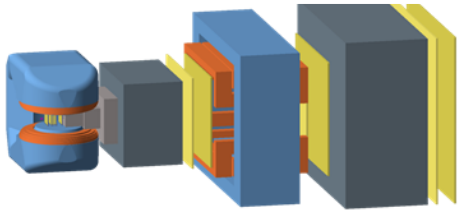




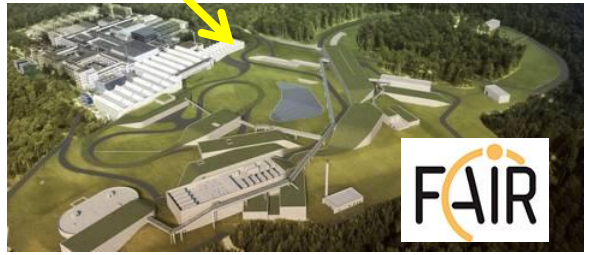
- **RHIC** Beam Energy scan
  - ⇨ Covers $\sqrt{s_{NN}}$ = 3-200 GeV
  - ⇨ Hadronic (soft) observables



- NA61/SHINE @ **SPS**
  - ⇨ Hadronic observables



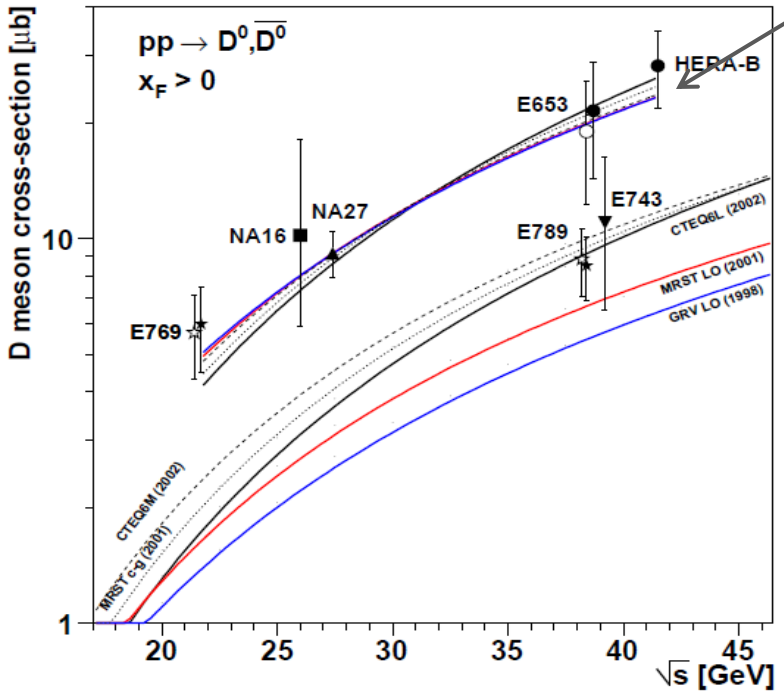
- New proposed experiment @ **SPS**: NA60+/DiCE
  - ⇨ Hard and electromagnetic probes



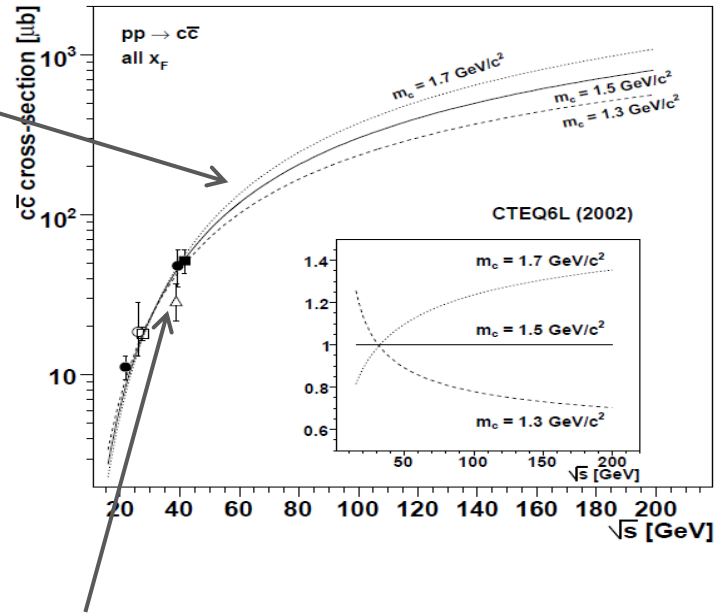
- Future CBM experiment @ **FAIR**
  - ⇨ $\sqrt{s_{NN}}$ = 2-7 GeV, high luminosity

Charm cross section in pp (p-A)

- Unexplored energy domain
- Comparison of existing data to PYTHIA (LO) event generator



PYTHIA LO cross sections scaled with appropriate K-factor



Total charm cross section from:

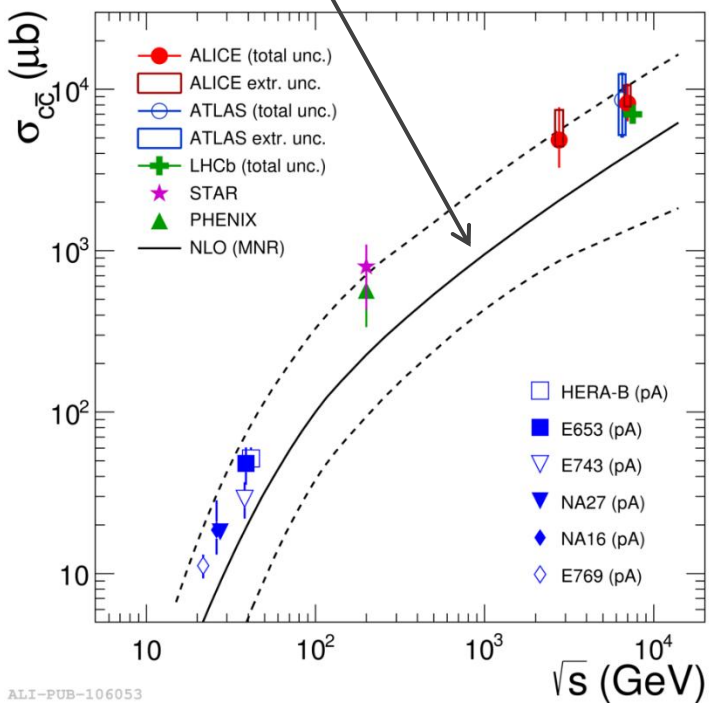
- Measured D^0 (D^+) cross sections
- Fragmentation fractions from e^+e^-

📖 **Lourenco, Wohri, Phys.Rept.433 (2006) 127**

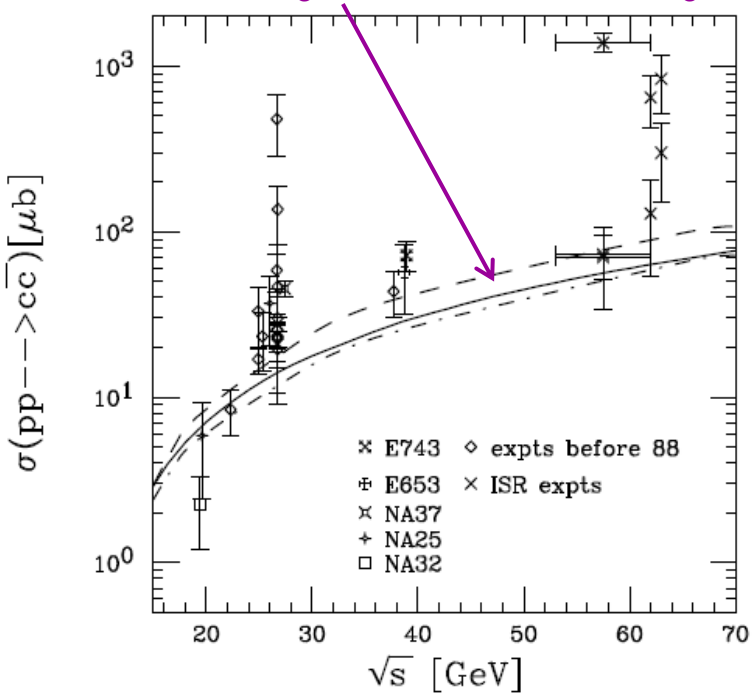
Charm cross section in pp (p-A)

- Unexplored energy domain
- Comparison of existing data to pQCD calculations (MNR) at NLO, NLL and NNLO

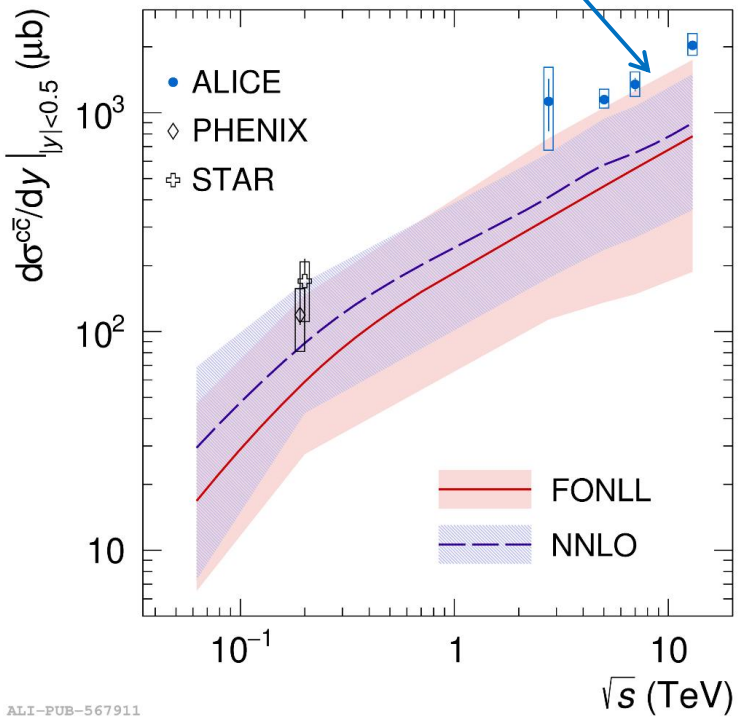
MNR, m_c=1.5 GeV, $\mu_F=\mu_R=m_T$



MNR, m_c=1.2 GeV , $\mu=2m_c$



Including measurements of Λ_c and Ξ_c baryons



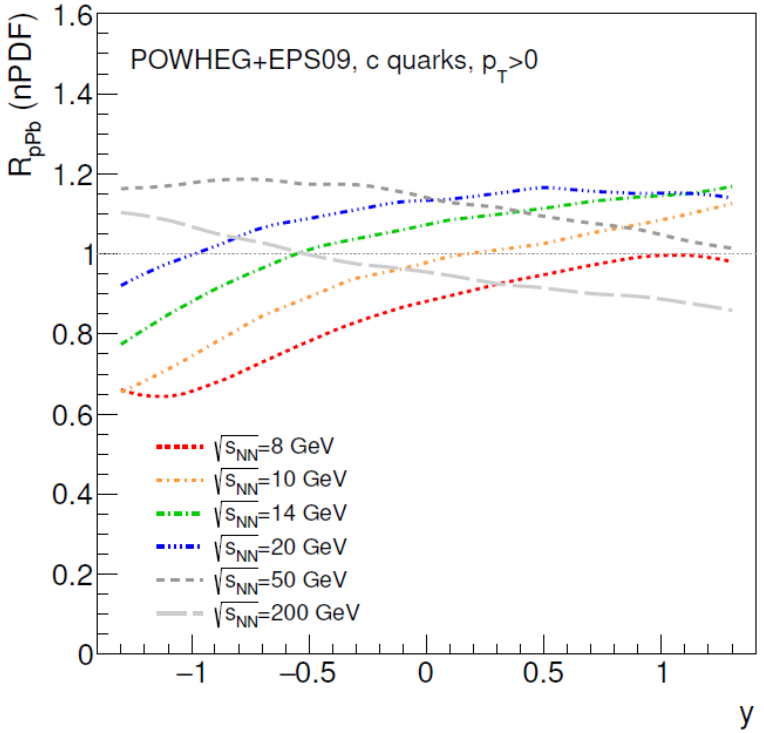
📖 ALICE, PRC94 (2016) 054908

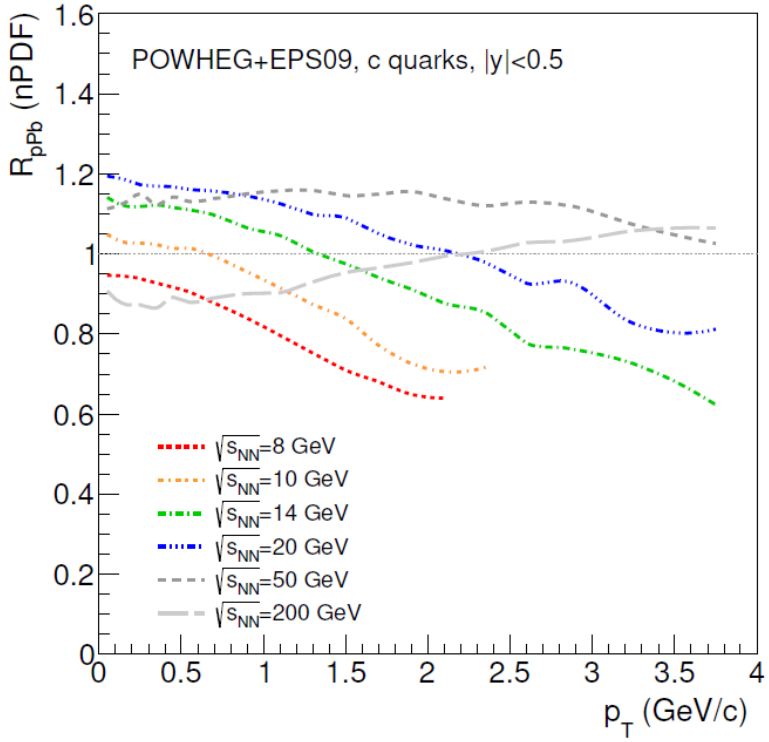
📖 Vogt, Int.J.Mod.Phys.E12 (2003) 211

📖 ALICE, JHEP 12 (2023) 086

Nuclear PDFs

- Sensitivity to **nuclear PDFs in p-A** collisions at SPS ($\sqrt{s_{NN}}$ ~ 10-20 GeV)
  - ⇨ Unique opportunity to investigate the large x_{Bj} region: $0.1<x_{Bj}<0.3$ at Q^2~10-40 GeV^2
    - ✓ Probe EMC and anti-shadowing regions
  - ⇨ Perform measurements with various nuclear targets to access the A-dependence of nPDF





Charm cross section in A-A

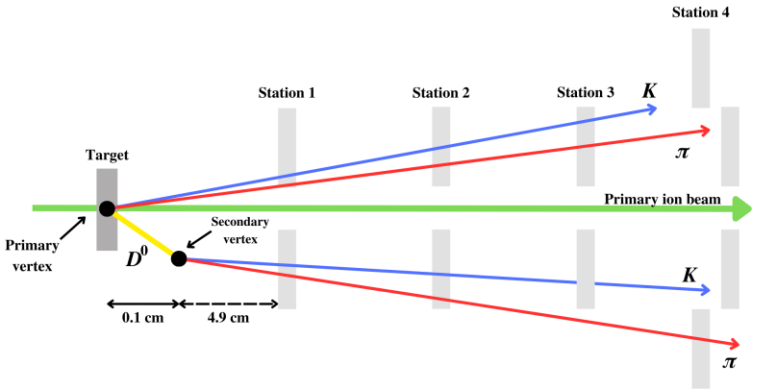
- Total charm cross section in A-A collisions at low $\sqrt{s_{NN}}$
  - ⇨ Measured so far by NA60 in In-In collisions from intermediate-mass dimuons with 20% precision
    📖 **NA60, EPJ C59 (2009) 607**
  - ⇨ Upper limit from NA49 measurements of D^0 mesons
    📖 **NA49, PRC73 (2006) 034910**

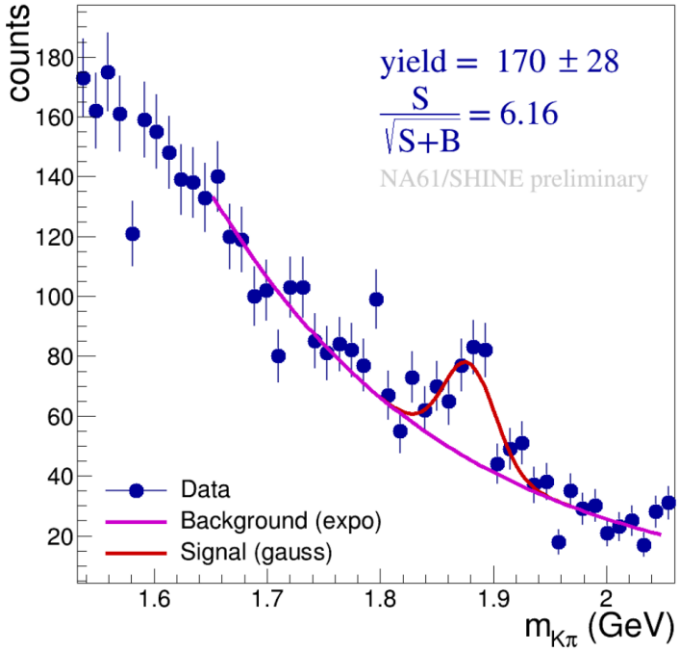
- Precise measurement requires to reconstruct all meson and baryon ground states (D^0, D^+, D_s^+ and Λ_c^+ and their antiparticles)

- Charm cross section at low $\sqrt{s_{NN}}$ **sensitive to chiral symmetry restoration?**
  - ⇨ Enhancement of charm production at chiral restoration where the threshold for production of a $D\bar{D}$ pair may be reduced
    📖 **Friman et al., Lect. Notes Phys. 814 (2011), 1**

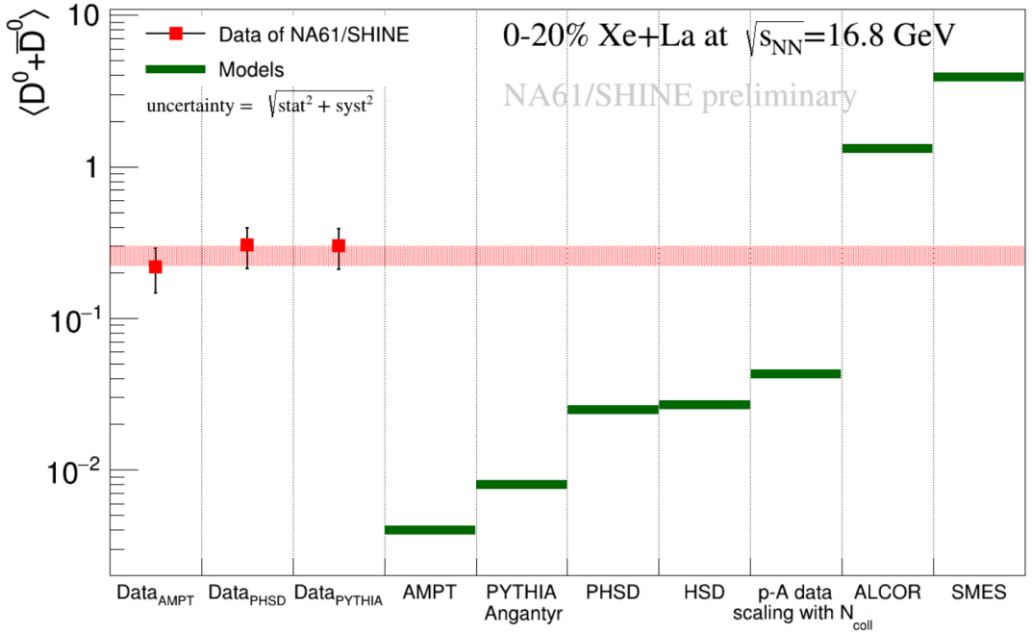
- Charm cross section **ideal reference for charmonia**

NA61/SHINE results: D^0 in Xe-La





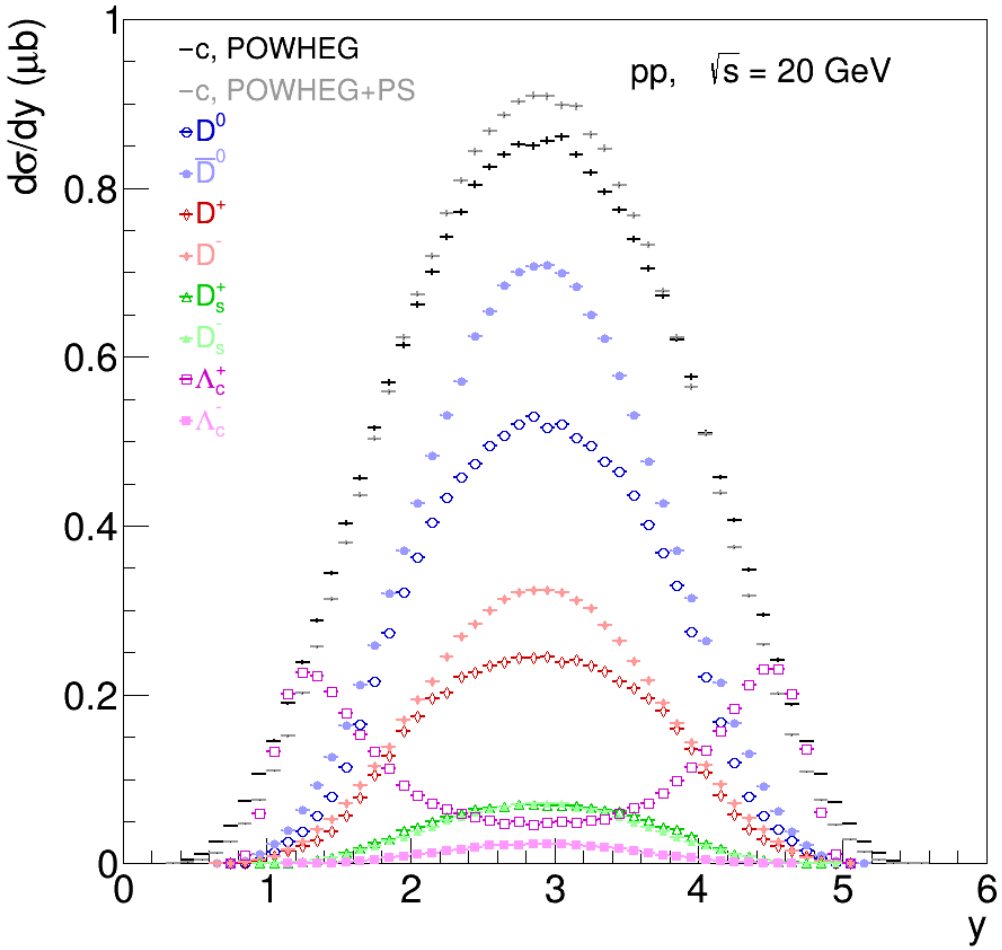
- $D^0 \rightarrow K^-\pi^+$ decays reconstructed exploiting the Small Acceptance Vertex Detector in -0.5<y<1
  - ⇨ Resolution on the secondary vertex along beam axis ~ 150 μm
- Different models (AMPT, PHSD, PYTHIA) used to extrapolate the measured yield to 4π
  - ⇨ Data allow to discriminate among models



📖 NA61, arXiv:2410.24014

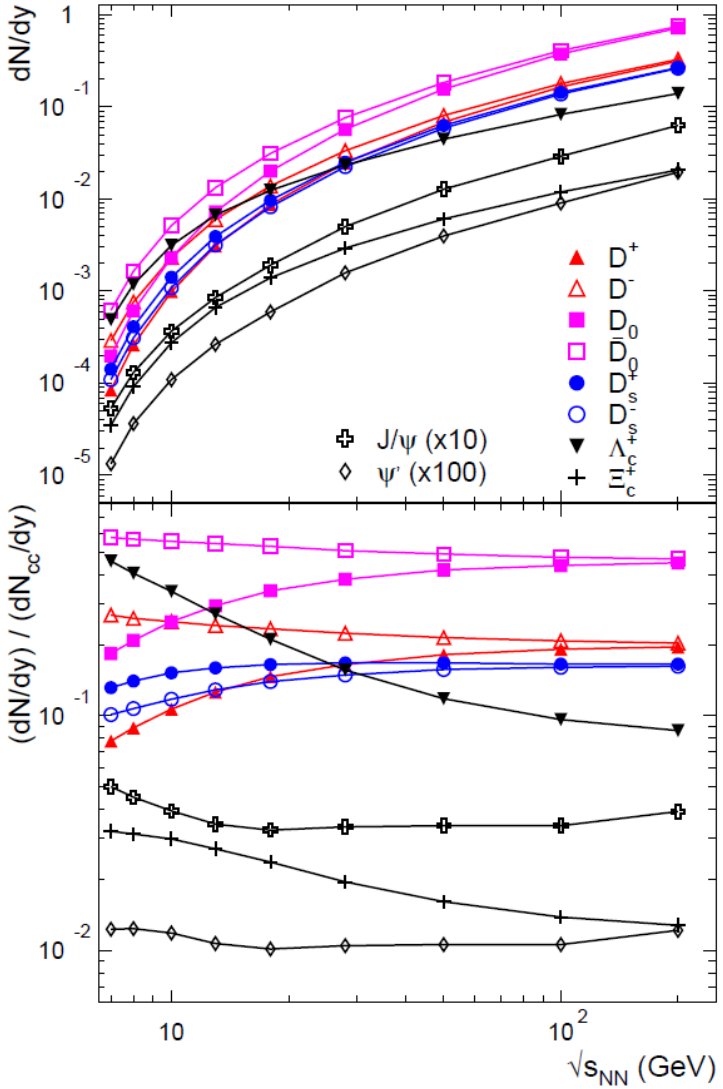
Open (and closed) charm hadrons

- Relative abundances at collision energies near the production threshold in pp collisions:
  - ⇨ J/ψ / D should be enhanced because the threshold for J/ψ production is lower than that for $D\overline{D}$
  - ⇨ $\Lambda_c^+\overline{D}$ associate production, $\overline{D}$ enhanced with respect to D
    - ✓ Features qualitatively present also in PYTHIA6 hadronization via string fragmentation in POWHEG+PYTHIA simulations
- How are these ratios affected by the medium produced in the heavy-ion environment?
  - ⇨ Production thresholds are sensitive to mass variations
  - ⇨ Charm hadron yield ratios sensitive to potential mass changes (modified spectral functions) of the charm particles in the produced medium



Open (and closed) charm hadrons

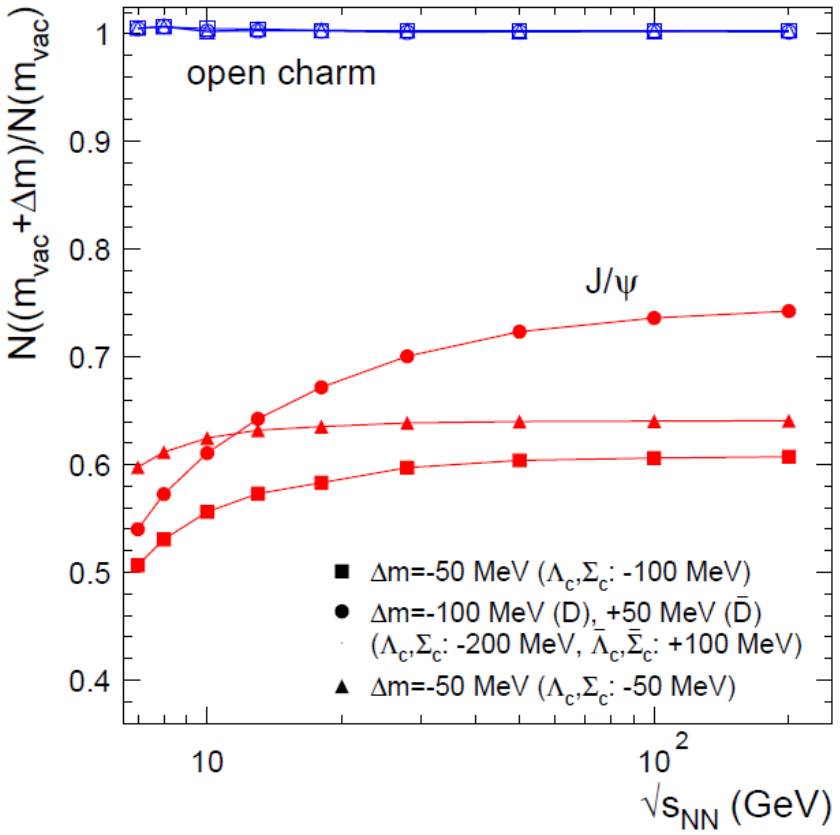
- Statistical hadronization model for charm
  - ⇨ Initial production of charm quarks in hard scatterings (pQCD+nPDF)
    - ✓ Charm yield determined by **charm cross section**, not by fireball temperature
  - ⇨ Charm conserved in the QGP
    - ✓ Accounted for by **charm balance equation** leading to a fugacity g_c
  - ⇨ Assume full thermalization: charm hadrons formed at phase boundary according to thermal weights
    - ✓ Relative yields depend on hadron mass, temperature, and μ_B
- Hadron abundances
  - ⇨ Baryon (Λ_c^+ and $\Xi_c^{0,+}$) relative abundances increase with decreasing $\sqrt{s_{NN}}$ due to increasing μ_B
  - ⇨ J/ψ / $c\bar{c}$ increases with decreasing $\sqrt{s_{NN}}$ when approaching the threshold



📖 Andronic et al, PLB 659 (2008) 149

Open (and closed) charm hadrons

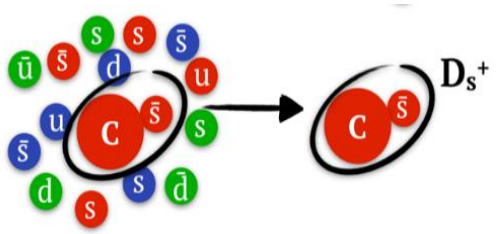
- Modification of charm hadron masses in the hot medium near the phase boundary?
  - ⇨ Due to the onset of chiral symmetry restoration or to rescattering with the constituents of the medium (or in the dense hadron gas)
  - ⇨ Mass shift could be different for D mesons and charmonia
  - ⇨ Modification of (open and closed) charm hadron abundances due to “redistribution” of charm quarks across the various species
  - ⇨ Tested scenarios in SHM show sensitivity of J/ψ / D ratio to mass modifications

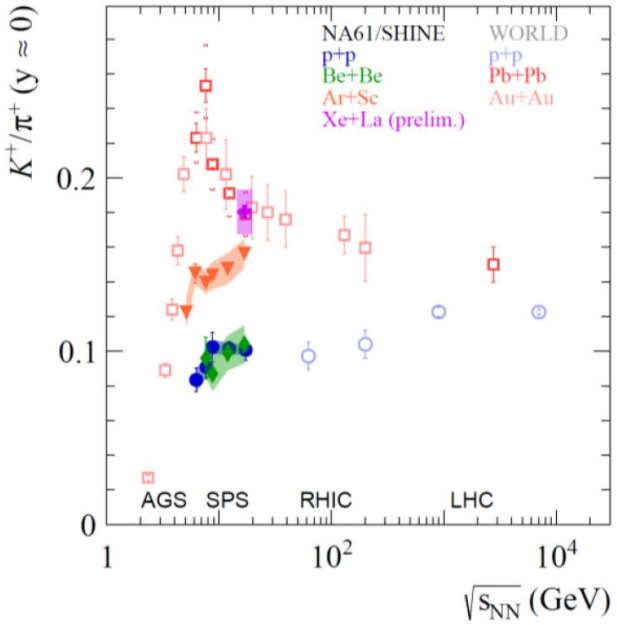


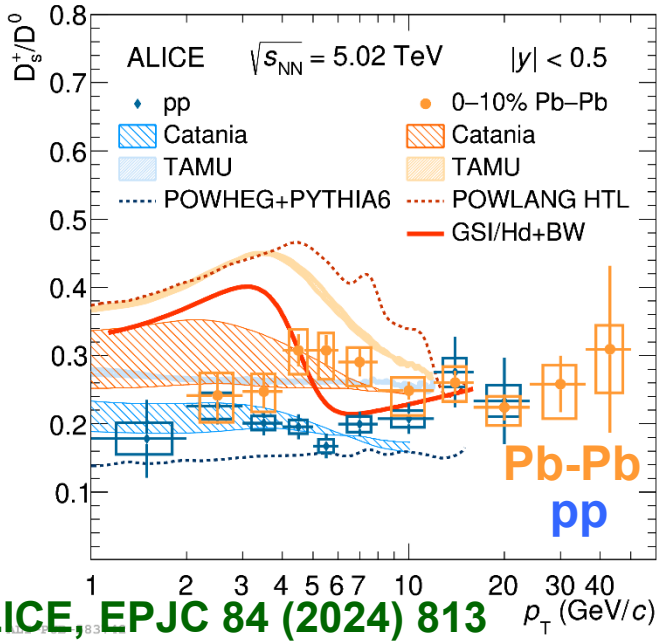
📖 Andronic et al, PLB 659 (2008) 149

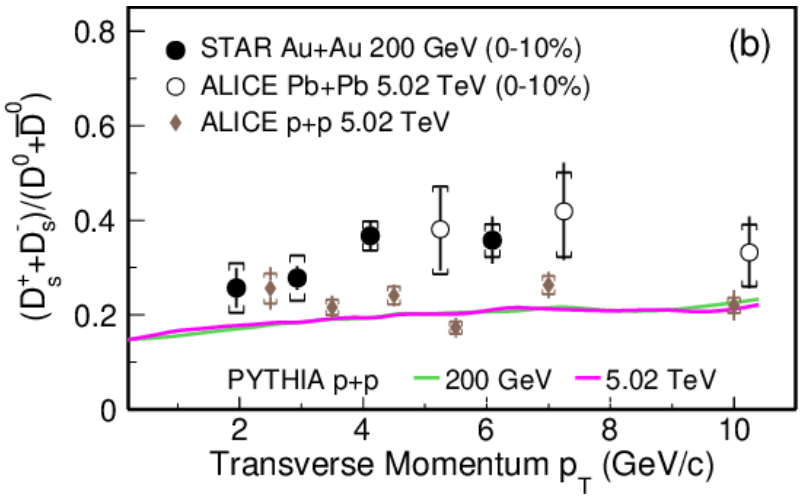
Open charm hadrochemistry

- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Strange/non-strange** meson ratio (D_s/D):
  - ⇨ D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP
  - ⇨ Complement studies of strangeness production by NA61/SHINE







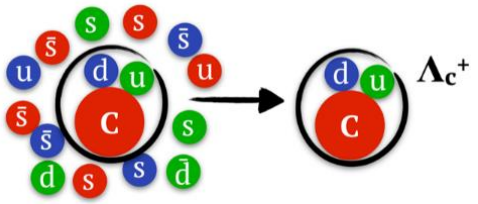


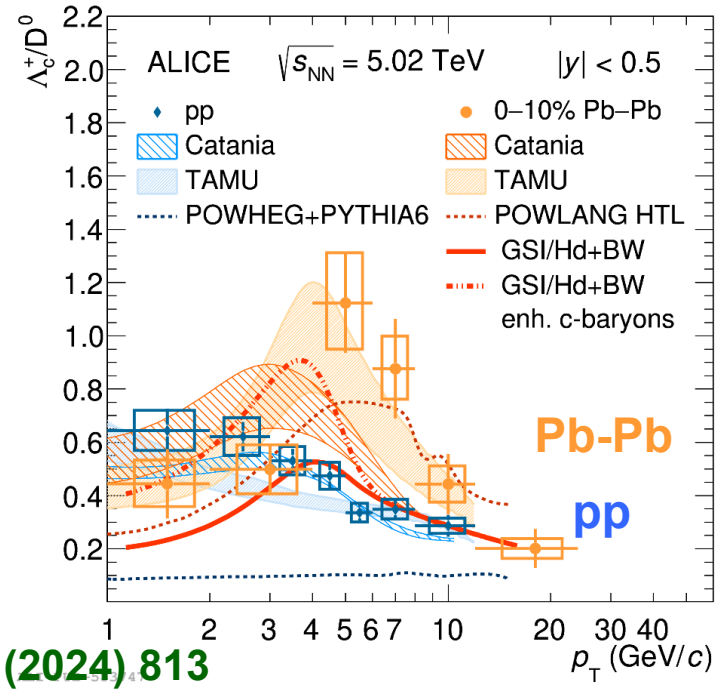
📖 ALICE, EPJC 84 (2024) 813

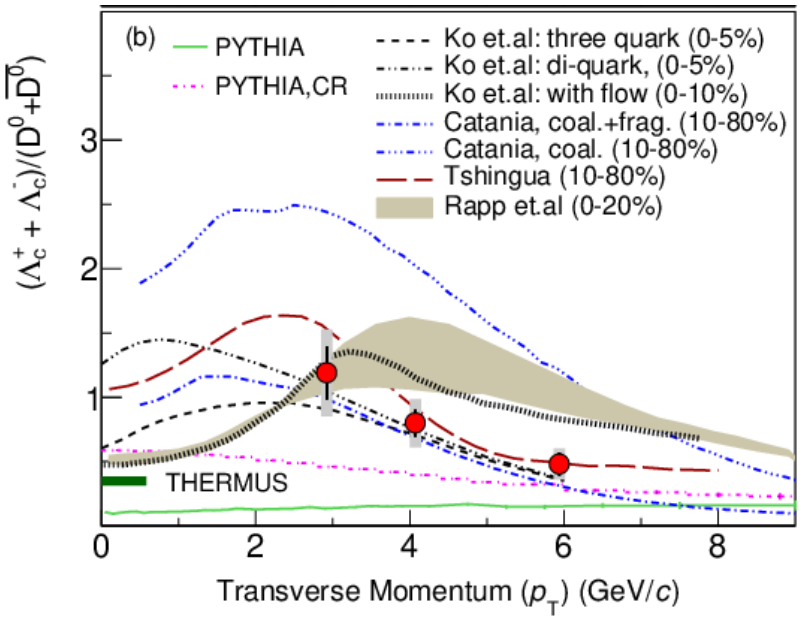
📖 STAR, PRL 127 (2021) 092301

Open charm hadrochemistry

- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Baryon/meson** ratios (Λ_c/D):
  - ⇨ Expected to be enhanced in A-A in case of hadronisation via coalescence
  - ⇨ Interesting also in p-A since Λ_c/D^0 in pp (p-Pb) at LHC is higher than in e^+e^-





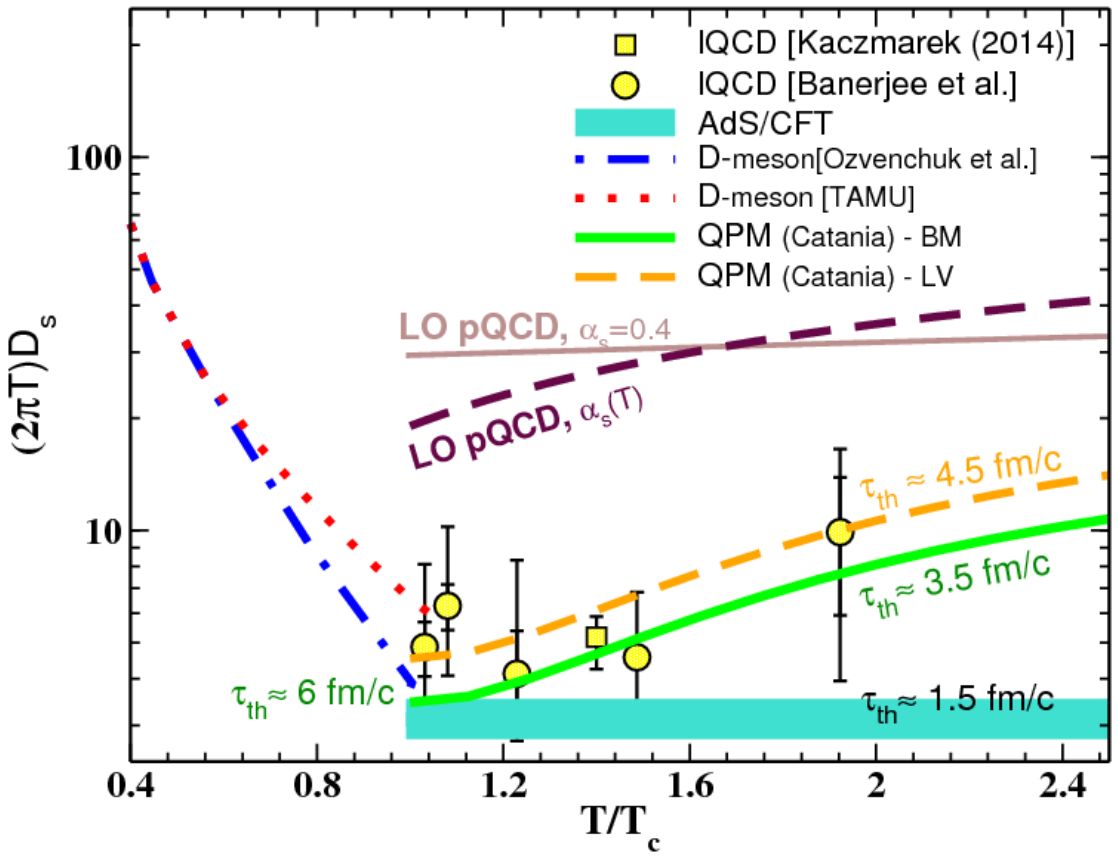


📖 ALICE, EPJC 84 (2024) 813

📖 STAR, PRL 124 (2020) 172301

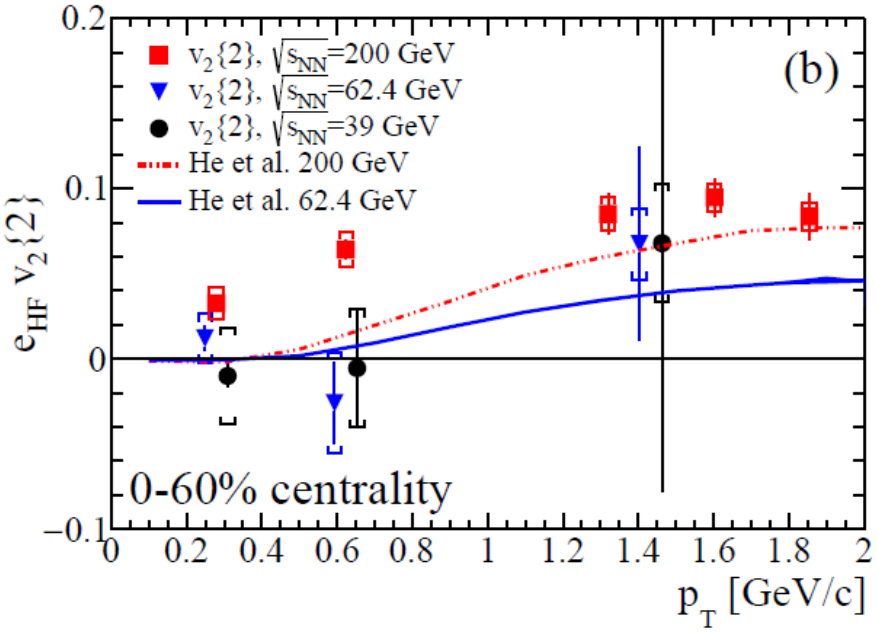
Charm in Pb-Pb: dN/dp_T and R_{AA}

- Insight into **QGP transport properties**
  - ⇨ Charm diffusion coefficient has a minimum around the (pseudo)critical temperature T_{pc} and it is larger in the hadronic phase than in the late QGP phases
  - ⇨ Can be tested at SPS energies where:
    - ✓ Lower initial temperature of the fireball enhances the sensitivity to the properties of the QGP at temperatures close to T_{pc}
    - ✓ Hadronic phase represents a large part of the collision evolution at SPS energies
    - ✓ Test models which predict strongest in-medium interactions in the vicinity of the quark-hadron transition
  - ⇨ Measurement also important for precision estimates of diffusion coefficients at the LHC

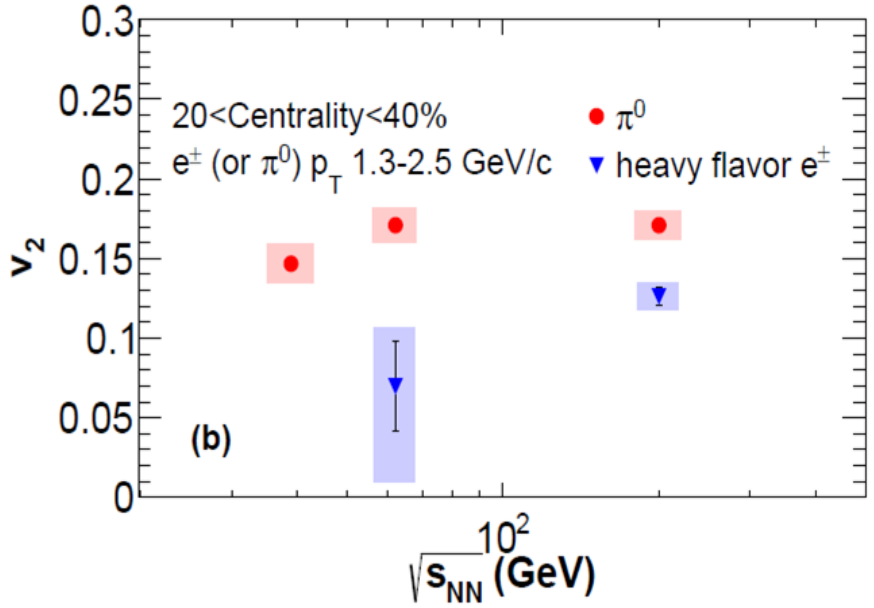


Charm in Pb-Pb: elliptic flow

- Study **charm thermalization** (hydrodynamization…) in the shorter-lived medium at lower collision energies
  - ⇨ Current measurements of HF-decay electron v_2 at $\sqrt{s_{NN}}$=39 and 62 GeV/c from RHIC BES show:
    - ✓ Smaller v_2 than at $\sqrt{s}$=200 GeV
    - ✓ Not conclusive on v_2>0



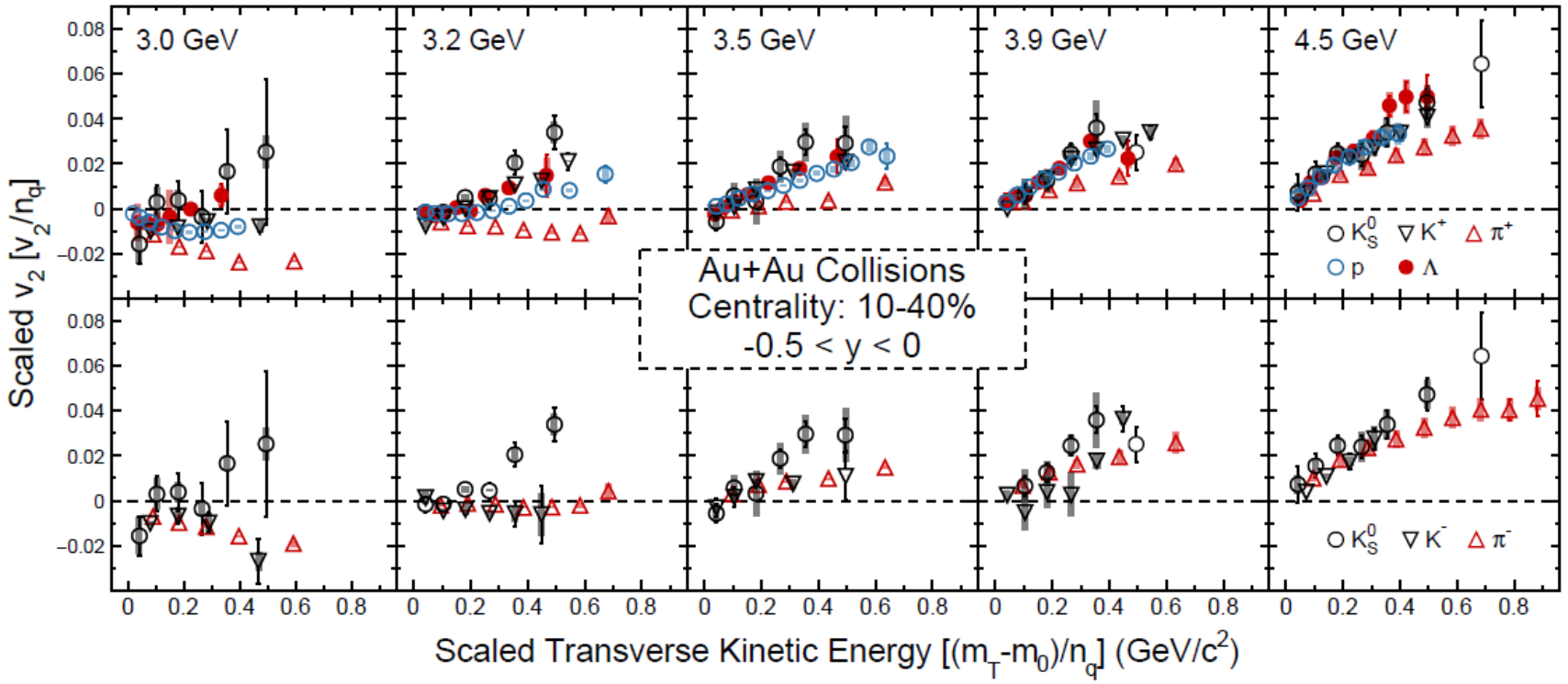
📖 STAR, PRC 95 (2017) 034907

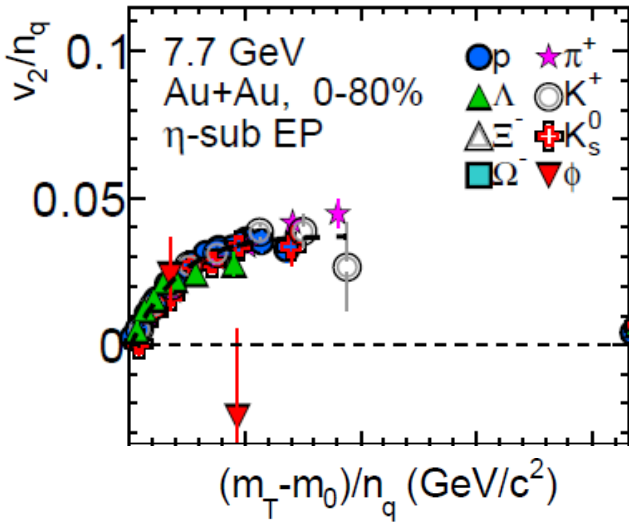


📖 PHENIX, PRC 91 (2015) 044907

Guideline from light-flavours at RHIC BES

- Scaling of v_2 with number of constituent quarks (NCQ) expected to reflect the effective degrees of freedom of the medium
- Results from beam energy scan at RHIC:
  - ⇨ NCQ scaling completely broken for $\sqrt{s_{NN}} \leq 3.2$ GeV
  - ⇨ Gradual onset of NCQ scaling in the region
  - ⇨ Dominance of partonic interactions for $\sqrt{s_{NN}} > 4.5$ GeV → **Onset of partonic collectivity**



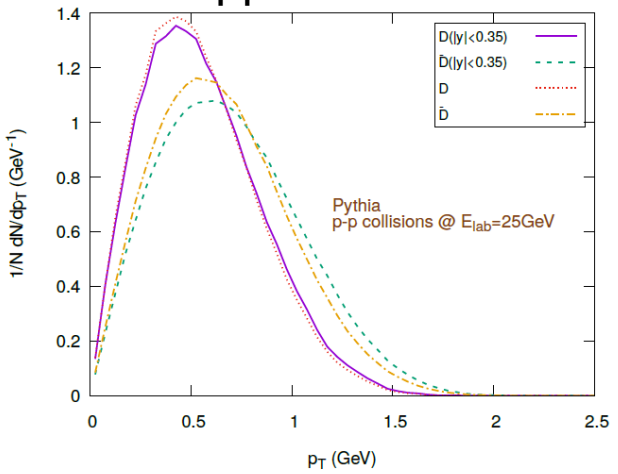


📖 **STAR, arXiv:2504.02531,**
📖 **STAR, PRC 88 (2013) 014902**

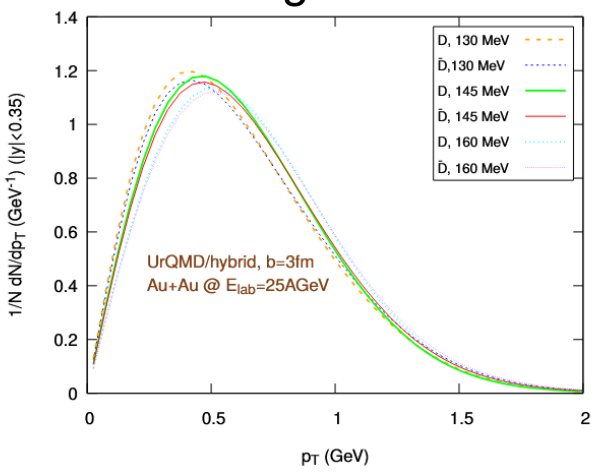
Diffusion at the production threshold

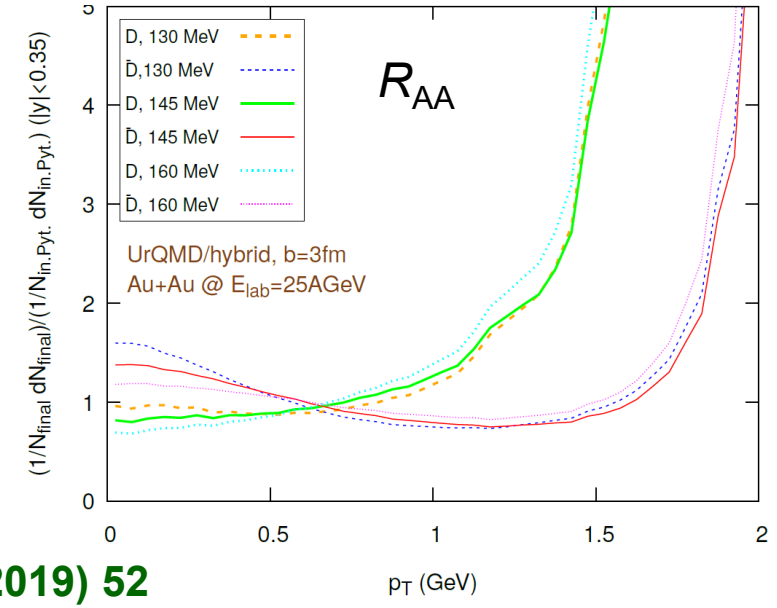
- Unique possibility at center-of-mass energies that are not too far above the charm production threshold
  - ⇨ Diffusion of charm particles (quark and/or hadrons) in the medium can drive them to higher momenta
  - ⇨ Could lead to an increase (even divergence) of the nuclear modification factor vs. p_T as the maximal p_T set by the kinematic limit in pp collisions is approached (or surpassed)
    - ✓ The rise could be different for different charm hadron species depending on their kinematic limits and their diffusion properties in the hadron gas
  - ⇨ Provide constraints on the diffusion coefficient of charm particles

pp: PYTHIA



Au-Au: Langevin + UrQMD



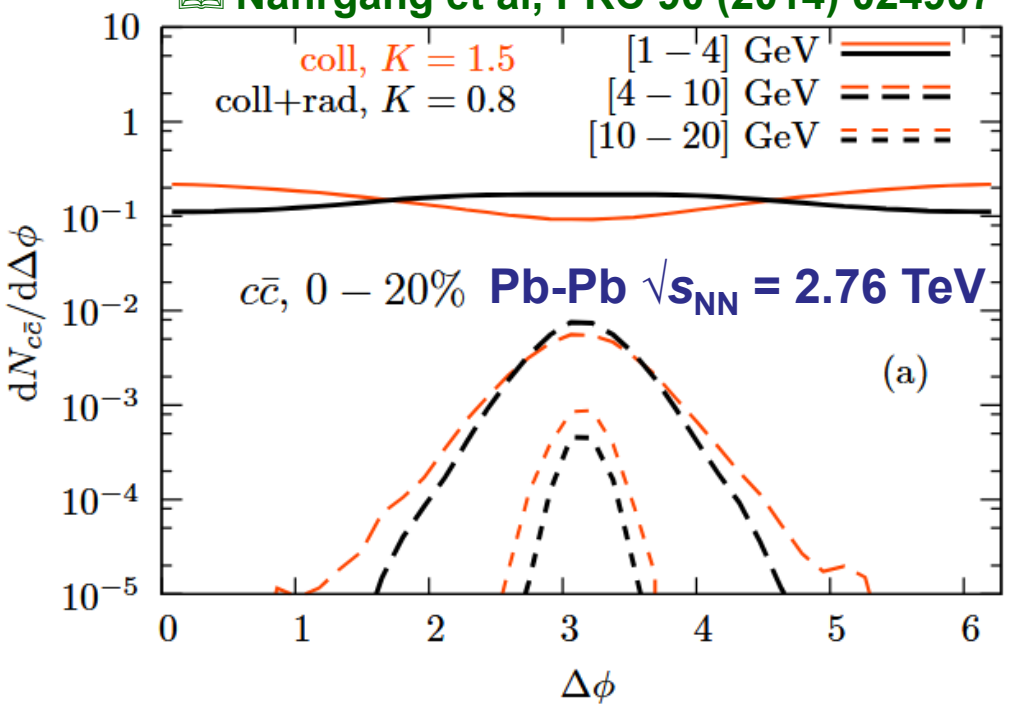


📖 **Inghirami et al, EPJC 79 (2019) 52**

$D\bar{D}$ angular correlations

- What can we learn from $D\bar{D}$ correlations?
  - ⇨ At leading order, $c\bar{c}$ pairs produced back-to-back in azimuth
  - ⇨ Higher-order processes (+ initial and final state radiation and hadronization) result in a moderate broadening around $\Delta\varphi = \pi$ (also in pp)
  - ⇨ Further broadening / acoplanarity in heavy-ion collisions due to medium interactions
    - ✓ In the limit of full equilibration: directions of charm quarks fully randomized → no remnant of the initial correlation would be visible.
- Opportunity for NA60+/DiCE and CBM to measure $D\bar{D}$ correlations?
  - ⇨ No background from pairs of charm quarks originating from different hard scatterings
    - ✓ E.g.: 0.2 charm quark pairs per event expected in central Pb-Pb collisions at top SPS energy

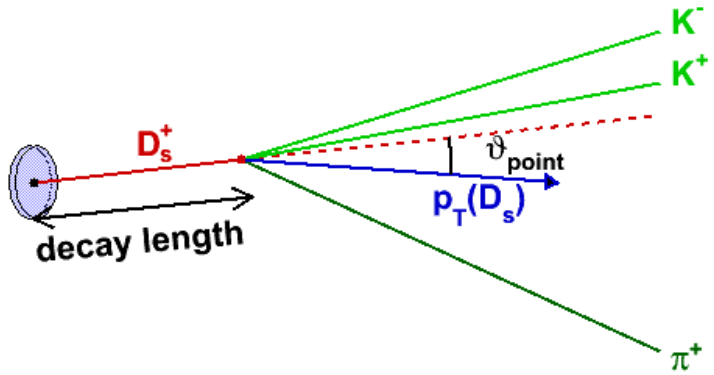
📖 Nahrgang et al, PRC 90 (2014) 024907



Open charm: prospects with NA60+/DiCE

Charm hadron reconstruction

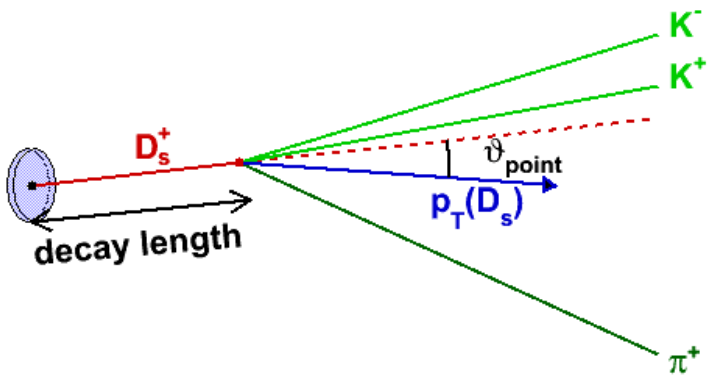
- Charmed mesons and baryons can be reconstructed from their decays into 2 or 3 charged hadrons
- Small production cross section + small(ish) BRs
  - ⇨ Require large samples of minimum-bias collisions
- Mean proper decay lengths $c\tau$ ~60-300 μm
  - ⇨ High precision on tracking and vertexing required to discriminate the charm-hadron decay vertex from the interaction point



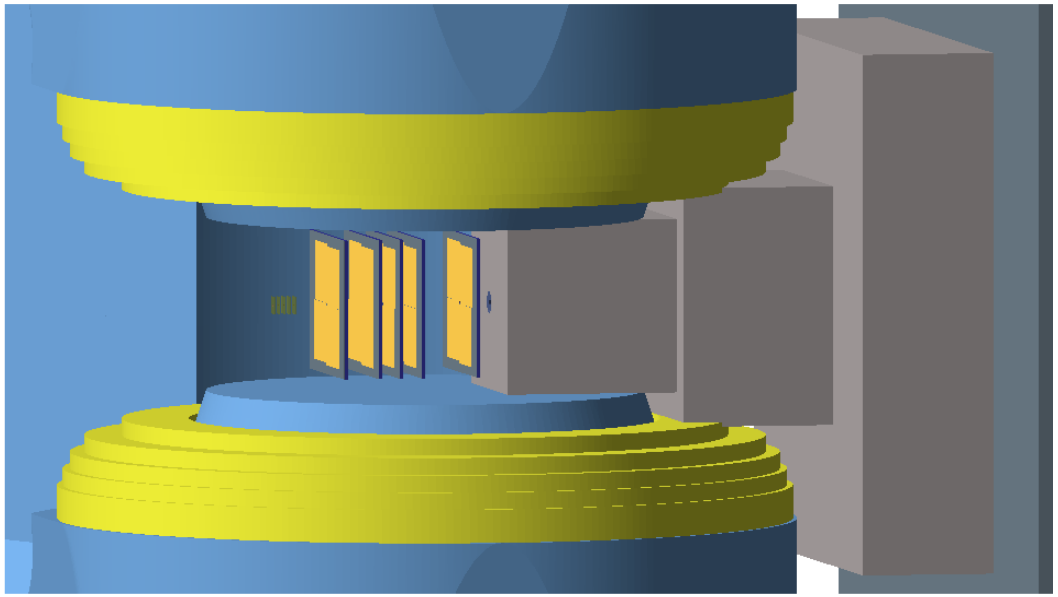
Hadron	Mass (MeV/c^2)	$c\tau$ (μm)	Decay	BR
D^0	1865	123	$\rightarrow K^-\pi^+$	3.945%
D^+	1869	312	$\rightarrow K^-\pi^+\pi^+$	9.38%
D_s^+	1968	147	$\rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$	2.25%
Λ_c^+	2285	60	$\rightarrow pK^-\pi^+$ $\rightarrow pK^0_s$ $\rightarrow \Lambda\pi^+$	6.35% 1.61% 1.31%

Charm hadron reconstruction

- Charmed mesons and baryons can be reconstructed from their decays into 2 or 3 charged hadrons
- Invariant mass analysis of fully reconstructed displaced decay-vertex topologies
  - ⇨ Decay products reconstructed in the vertex spectrometer
  - ⇨ Background reduction via geometrical selections based on displaced decay vertex topology ($c\tau$ ~60-300 μm)

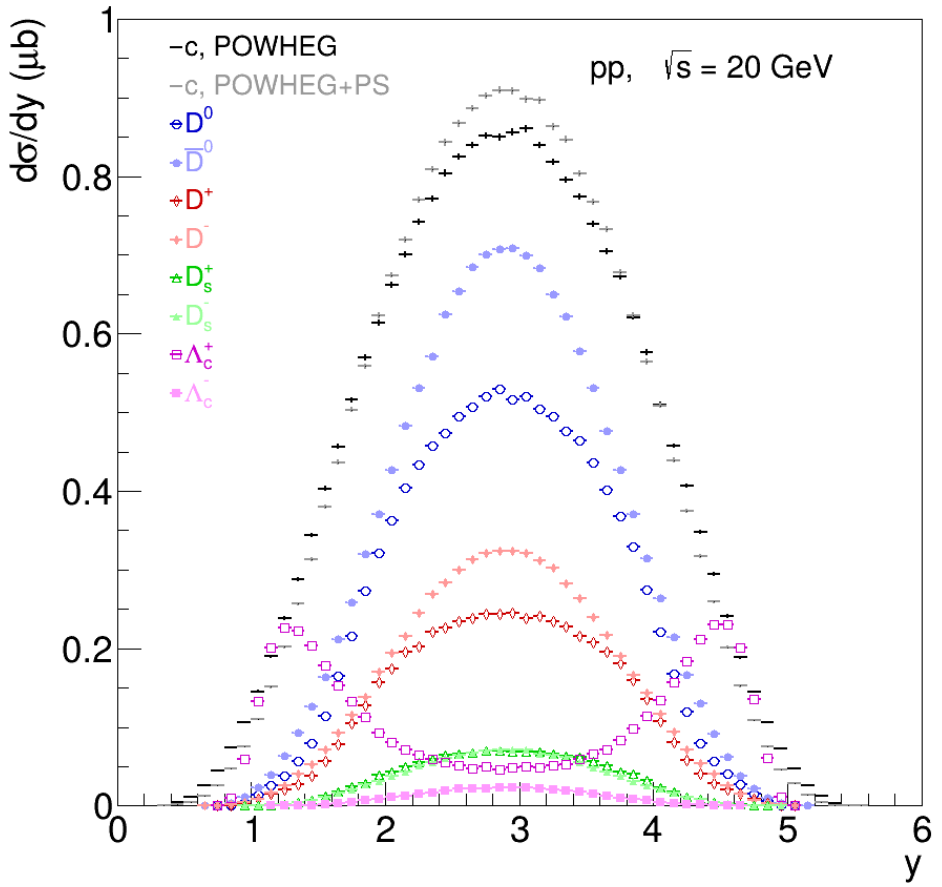


- Detector requirements:
  - ⇨ High precision on track and vertex reconstruction
  - ⇨ Low material budget



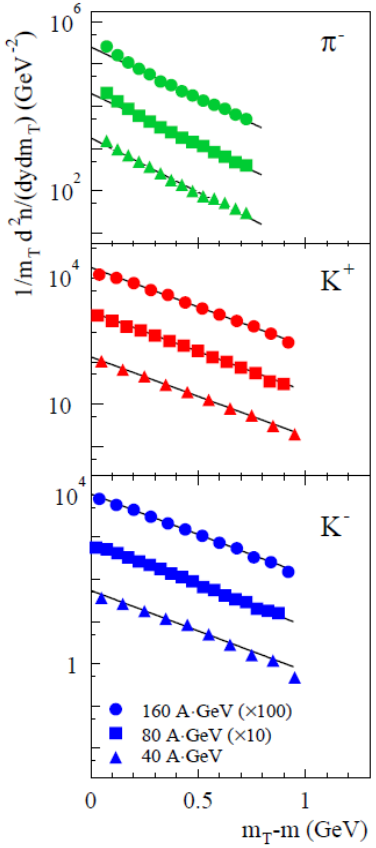
D-meson performance studies

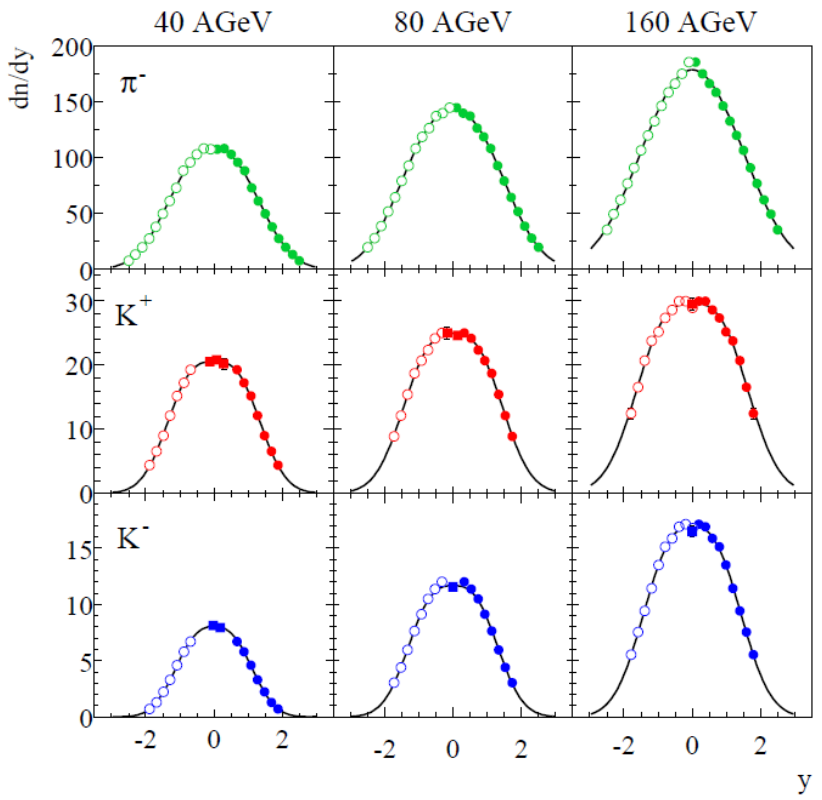
- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA



D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49

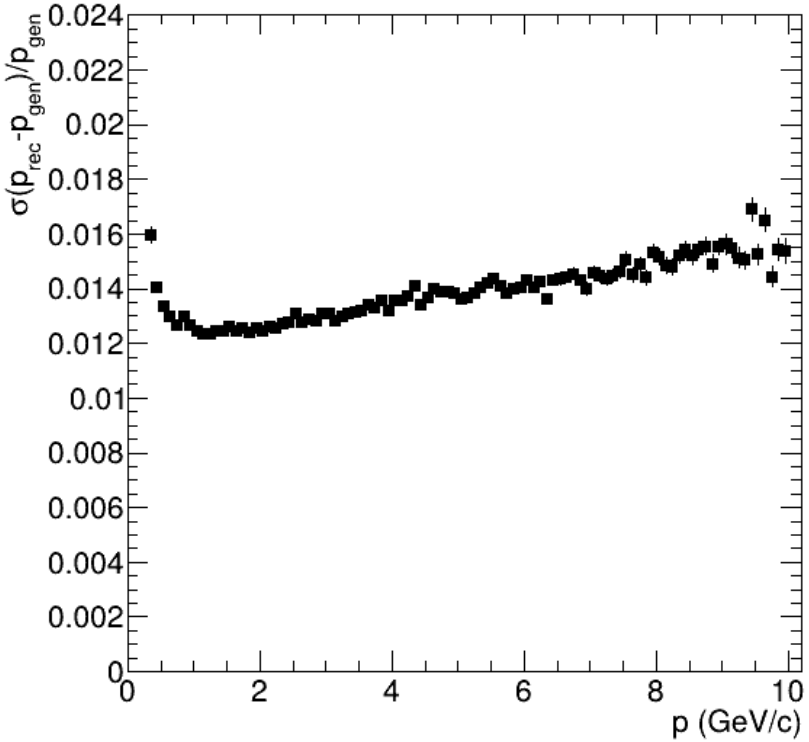


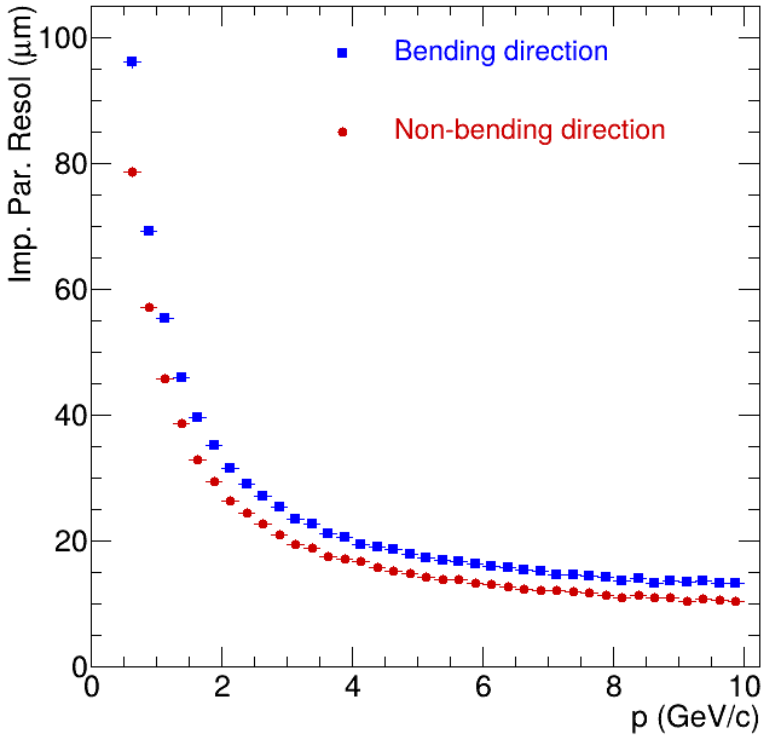


📖 **NA49, PRC 66 (2002) 054902**

D-meson performance studies

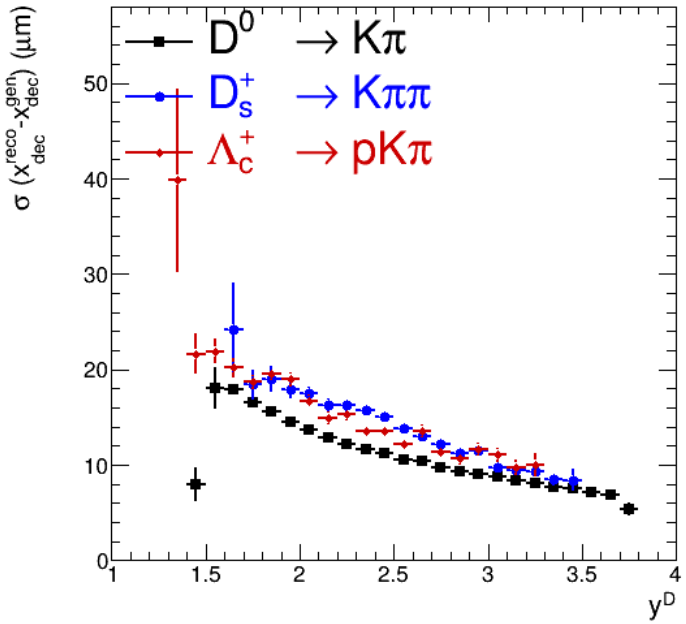
- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT resolution + track reconstruction with Kalman filter

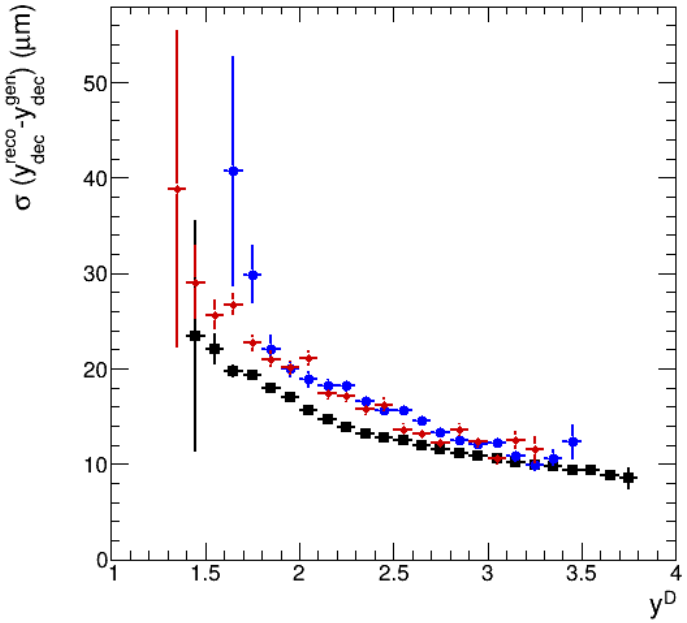


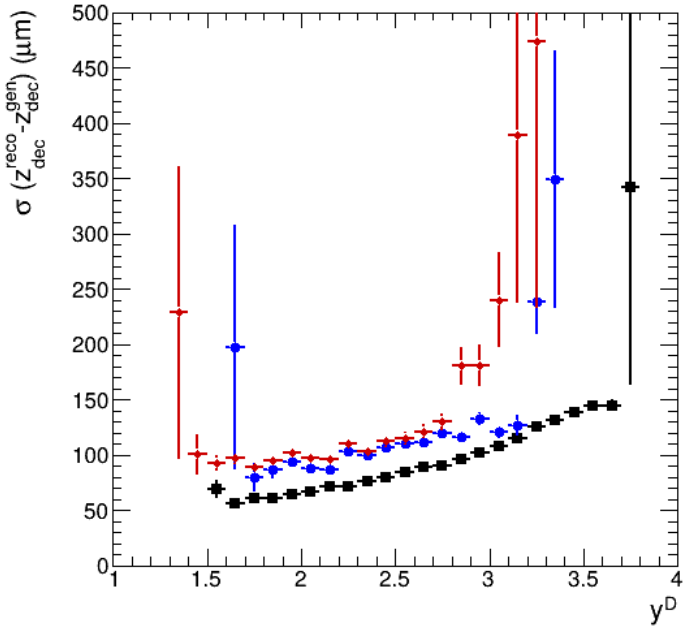


D-meson performance studies

- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT resolution + track reconstruction with Kalman filter
  - ⇨ Reconstruct D-meson decay vertex from decay tracks

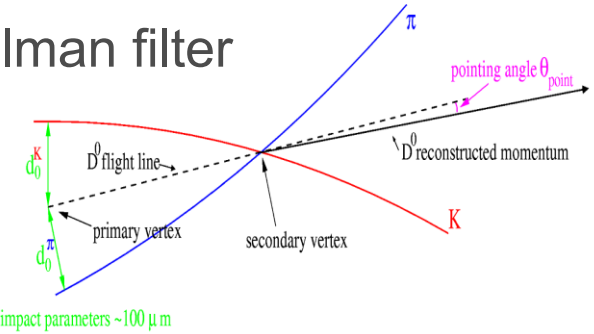


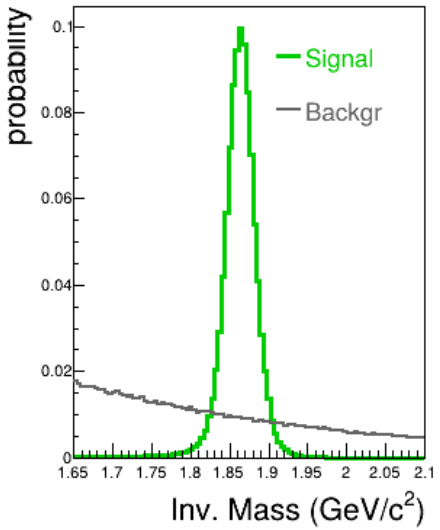


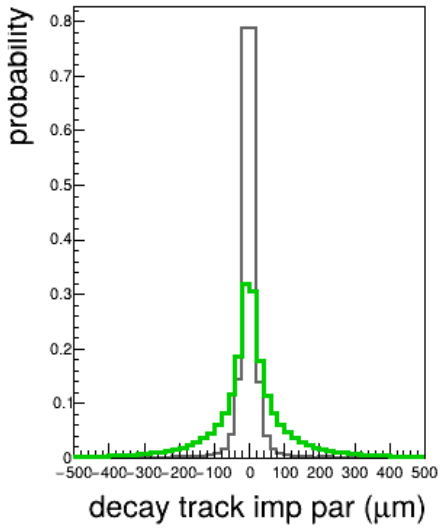


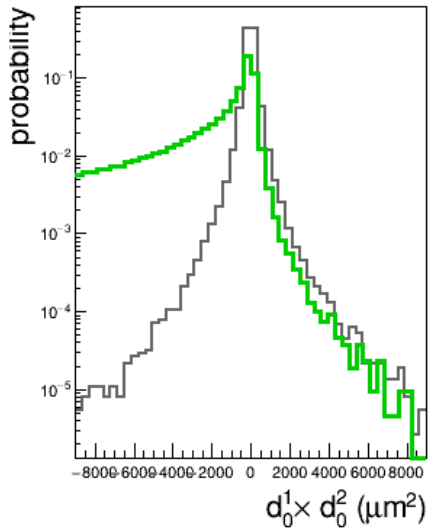
D-meson performance studies

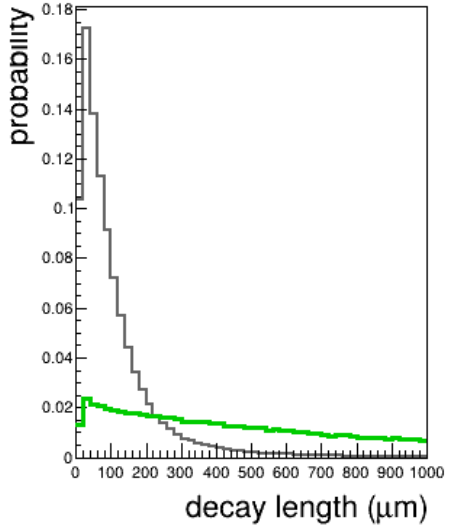
- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT resolution + track reconstruction with Kalman filter
  - ⇨ Reconstruct D-meson decay vertex from decay tracks
  - ⇨ Geometrical selections on displaced decay vertex topology

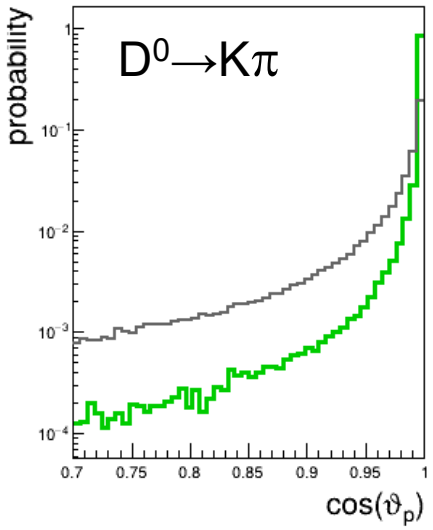






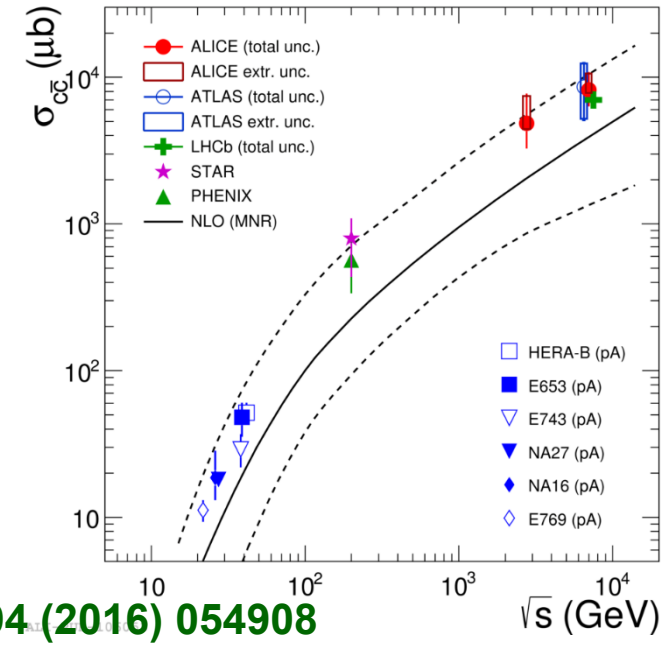


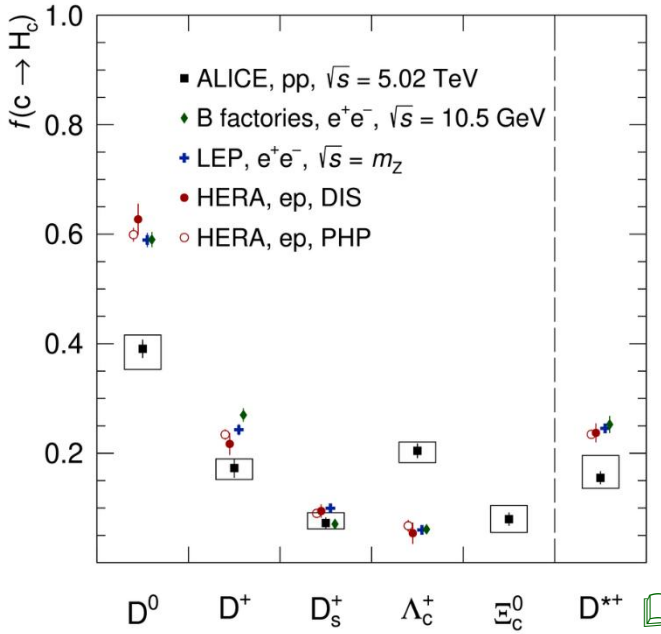




Normalization of signal

- Normalization of **signal yield per event** based on:
  - ⇨ (Assumption on) charm production cross section: $\sigma_{c\bar{c}}$ = 5 μb at top SPS energy
  - ⇨ Nuclear overlap function T_{AA} (Glauber)
  - ⇨ Fragmentation fractions of charm quarks in different charm hadron species, f(c→H_c)
    - ✓ Not universal: different in pp at LHC and e^+e^- (ep) collisions
    - ✓ Assumption: f(c→D^0)=55%; f(c→D^+)=19%; f(c→D_s^+)=10%; f(c→Λ_c^+)=10%



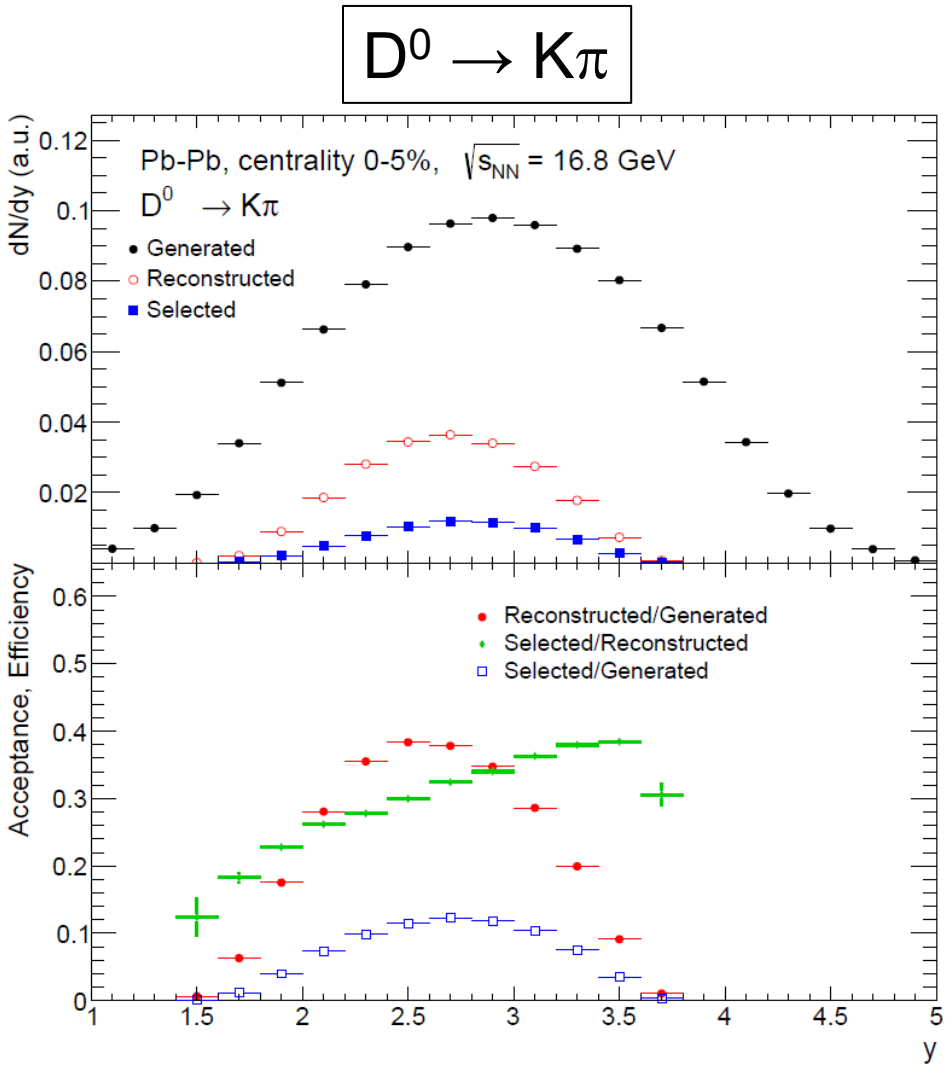


📖 ALICE, PRC94 (2016) 054908

📖 ALICE, arXiv:2105.06335

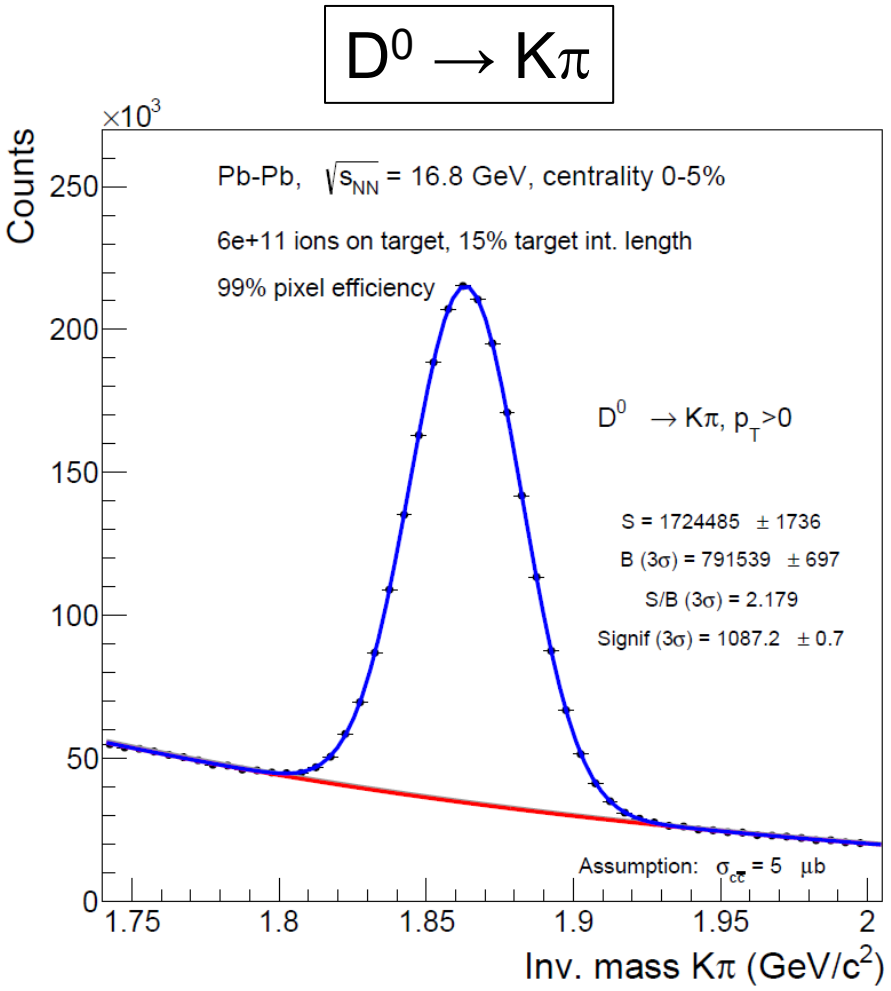
NA60+ physics performance : D^0

- Selections tuned to have high statistical significance and high efficiency, but not fully optimized
  - ⇨ Initial S/B ~ 10^{-7} → after selections S/B ~ 2



NA60+ physics performance : D^0

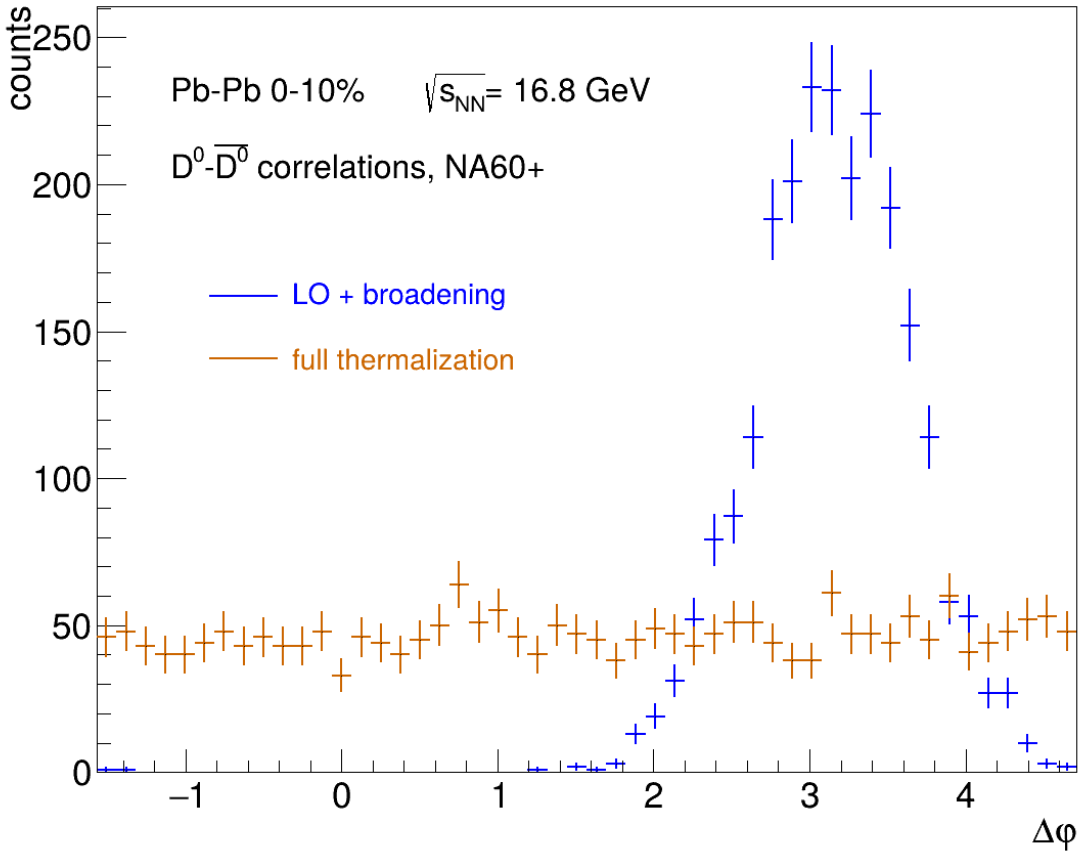
- Selections tuned to have high statistical significance and high efficiency, but not fully optimized
  - ⇨ Initial S/B ~ 10^{-7} → after selections S/B ~ 2
- With 6×10^{11} Pb ions on target at E_{beam} = 150 GeV and 15% target interaction length (1 month of data taking)
  - ⇨ Statistical significance ~ 1000 → statistical uncertainties at the permil level
  - ⇨ More than 1.7×10^6 reconstructed and selected D^0 in central Pb-Pb collisions at $\sqrt{s_{NN}}$=17.3 GeV
- Allows for differential studies of yield and v_2 vs. p_T, y and centrality
- Measurement feasible also at lower collision energies with statistical precision at the percent level



NA60+ physics performance : D^0

- Opportunity for NA60+/DiCE to measure $D\overline{D}$ correlations at SPS?
  - ⇨ Large number of reconstructed D^0 mesons → about 2500 $D^0\overline{D^0}$ pairs reconstructed and selected in 0-10% centrality class
    - ✓ Can be increased considering D^0D^- and D^+D^- pairs
  - ⇨ No background from pairs of charm quarks originating from different hard scatterings
    - ✓ 0.2 charm quark pairs per event expected in central Pb-Pb at top SPS energy
  - ⇨ Very high purity can be reached for D^0 with topological cuts
    - ✓ Combinatorial background (and many other aspects) neglected in this very first and very rough plot → not to be taken seriously…

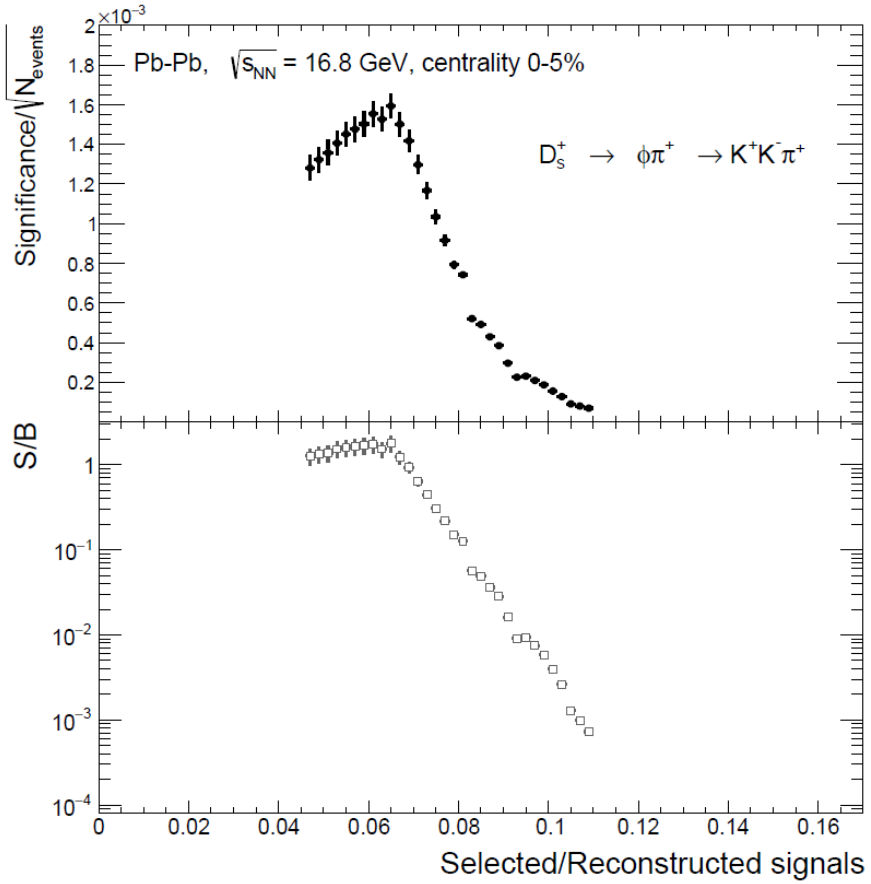
$D^0 \rightarrow K\pi$



NA60+ physics performance : D_s^+

- Selections on **displaced decay vertex topology** and **K^+K^- invariant mass**
  - ⇨ Initial S/B ~ 3×10^{-10} → after selections S/B ~ 1

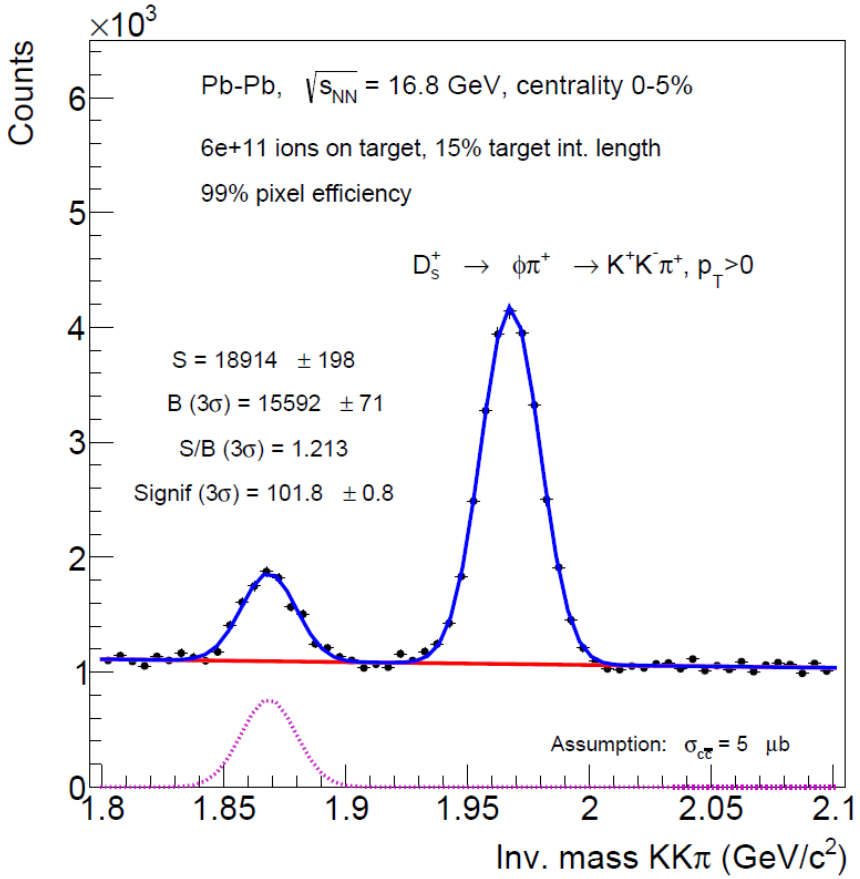
$$D_s^+ \rightarrow \phi\pi \rightarrow KK\pi$$



NA60+ physics performance : D_s^+

- Selections on **displaced decay vertex topology** and **K^+K^- invariant mass**
  - ⇨ Initial S/B ~ 3×10^{-10} → after selections S/B ~ 1
- With 6×10^{11} Pb ions on target at E_{beam} = 150 GeV and 15% target interaction length (1 month of data taking)
  - ⇨ Statistical significance ~ 100 → statistical uncertainties at the percent level
- Allows for differential studies of yield and v_2 vs. p_T, y and centrality
- $D^+ \to KK\pi$ peak visible near the D_s^+ one, but D^+ performance will be better in the $K\pi\pi$ channel (with 10 times higher BR)

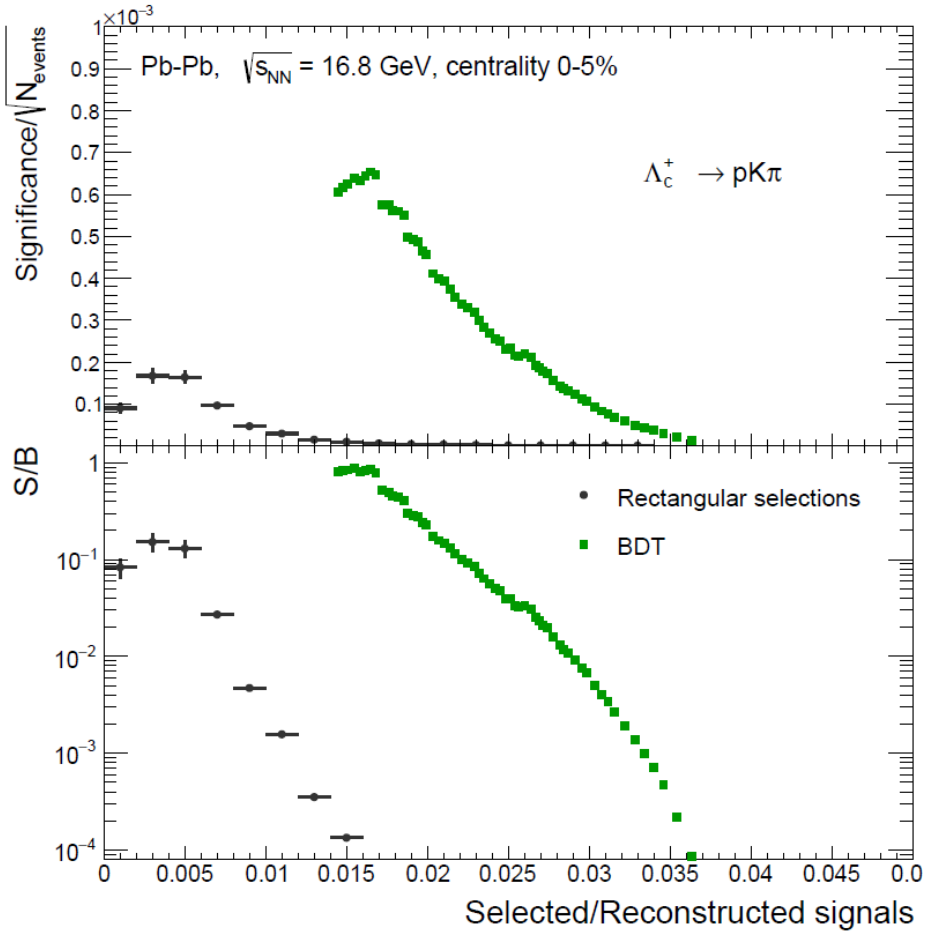
$D_s^+ \to \phi\pi \to KK\pi$



NA60+ physics performance : Λ_c^+

- Selections on **displaced decay vertex topology**
  - ⇨ More challenging separation of S and B due to the shorter lifetime of Λ_c^+: $c\tau$ = 60 μm compared to 150 μm of D_s^+
  - ⇨ Use BDTs for the selection
    - ✓ Much better performance than using rectangular cuts
  - ⇨ Initial S/B ~ 10^{-9} (assuming f(c →Λ_c)=10%) → after selections S/B ~ 0.1 with 2% selection efficiency

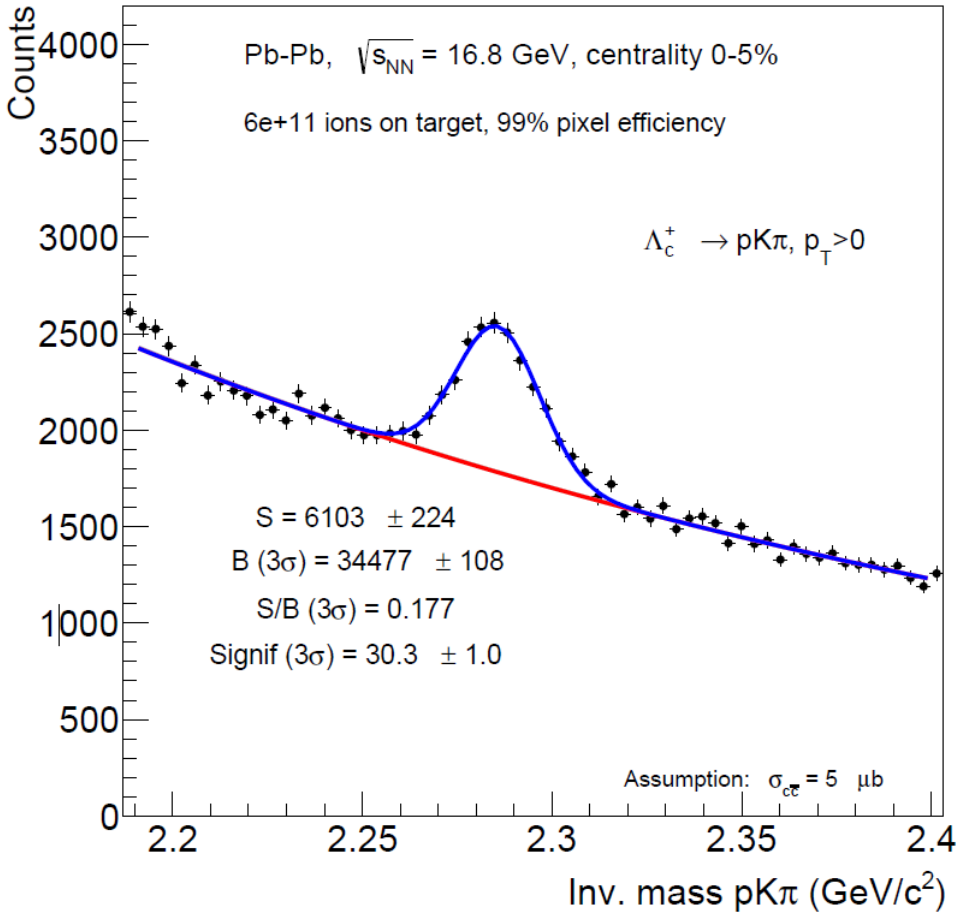
$\Lambda_c^+ \rightarrow pK\pi$



NA60+ physics performance : Λ_c^+

- Selections on **displaced decay vertex topology**
  - ⇨ Initial S/B ~ 10^{-9} (assuming f(c $\rightarrow\Lambda_c$)=10%) → after selections S/B ~ 0.1 with 2% selection efficiency
- With 6×10^{11} Pb ions on target at E_{beam} = 150 GeV and 15% target interaction length (1 month of data taking)
  - ⇨ About 6000 reconstructed and selected Lc+, with statistical significance ~ 30
- Allows for charmed baryon yield measurements in different centrality classes with statistical precision of few percent

$\Lambda_c^+ \rightarrow pK\pi$



Summary and prospects

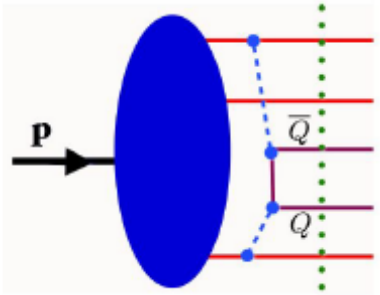
- Clear **physics case** for measurements of open charm hadrons in heavy-ion (and p-A) collisions at SPS energies and below
  - ⇨ Probe the medium at lower temperatures as compared to LHC and RHIC top energy
  - ⇨ Sensitive to **nuclear PDFs** (antishadowing and EMC)

- Charming perspectives for **open charm reconstruction** with NA60+/DiCE
  - ⇨ Measure production in an (almost) unexplored energy domain
  - ⇨ Characterize transport properties and hadronization of QGP at high mB by measuring **yield, v_2 and relative abundances** of different **charm meson and baryon** species

Backup

Intrinsic charm?

- Existence of a nonperturbative intrinsic heavy quark component in the nucleon is a rigorous QCD prediction
  - ⇨ Extrinsic contributions arise from gluon splitting in pQCD
  - ⇨ Intrinsic charm: nonperturbative component in proton wave function
    - ✓ E.g. 5-quark Fock state |uudcc>
- Unambiguous experimental confirmation still missing
  - ⇨ Intrinsic charm (IC) contribution dominant at large x and high p_T



📖 S. J. Brodsky, Adv.High Energy Phys. (2015) 231547