HEFTY
$\bar{Q}$ COLLABORATION Q

Prospects for open charm and charmonium measurements at SPS energies

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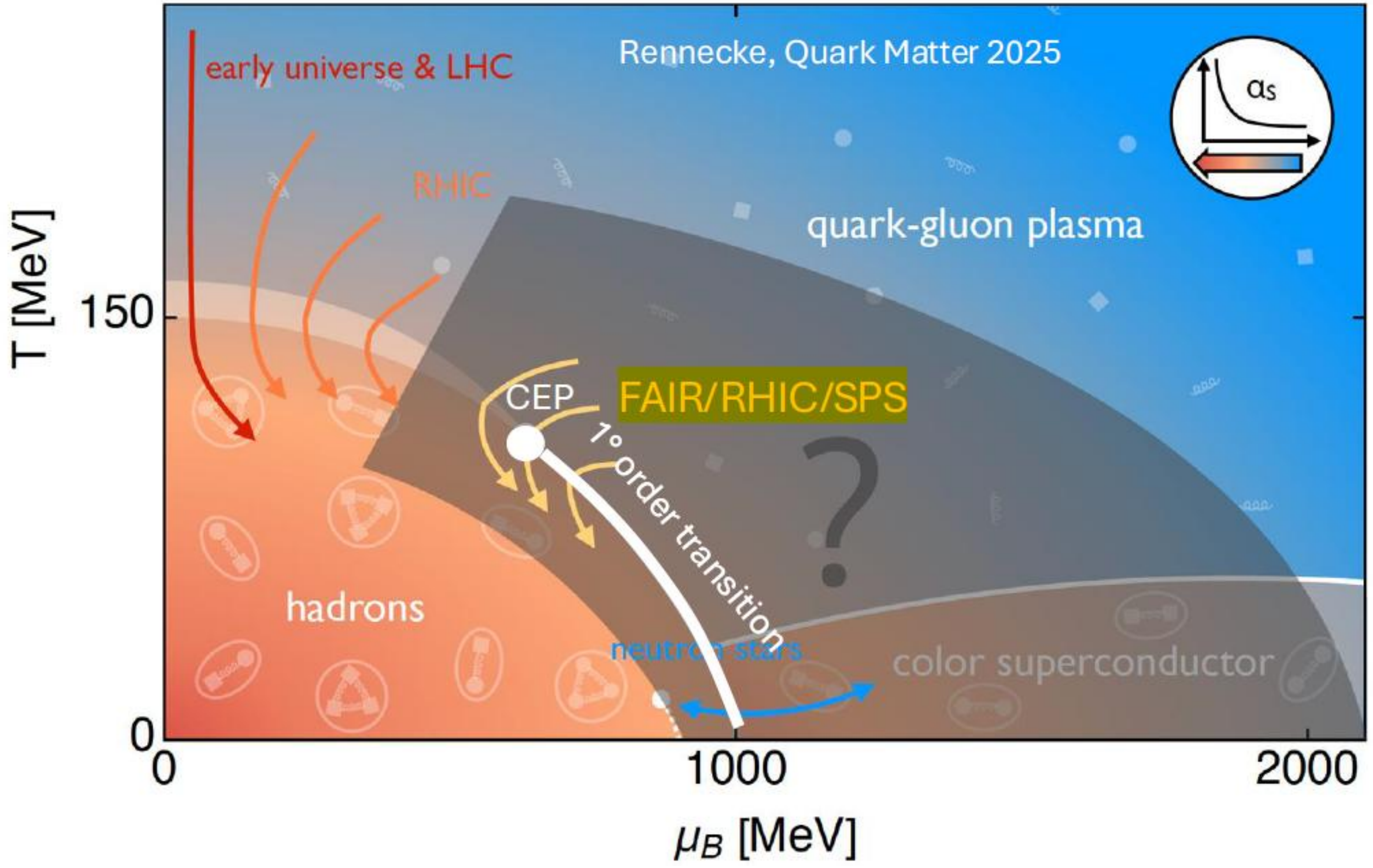
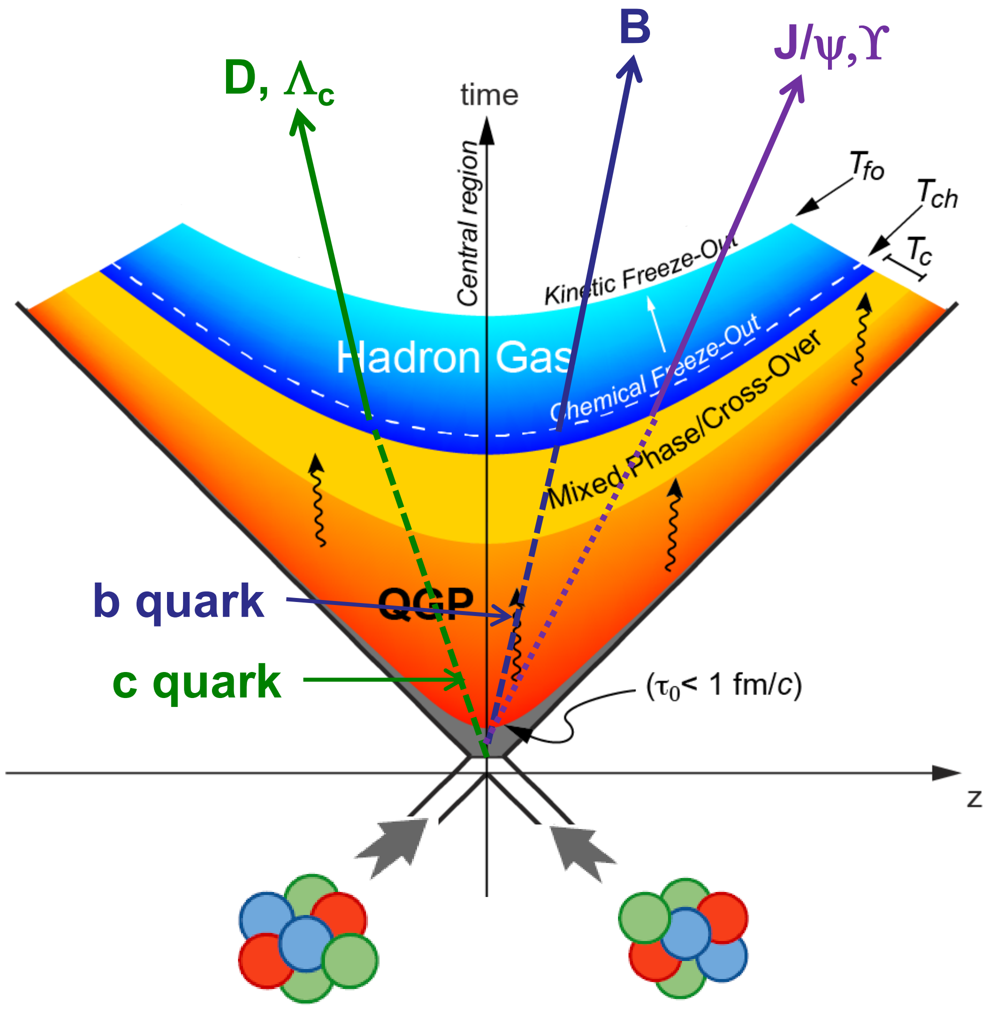
Heavy-ion collisions: the low $\sqrt{s_{NN}}$ frontier

- **Goal**: explore the QCD phase diagram at large μ_B
- Main questions:
  - ⇨ Presence of a **critical point**?
  - ⇨ First **order phase transition** at large μ_B?
  - ⇨ **Chiral symmetry** restoration?
  - ⇨ Onset of **deconfinement**
  - ⇨ Properties of the **QGP at large μ_B**



→ bridge between early Universe and Neutron Stars

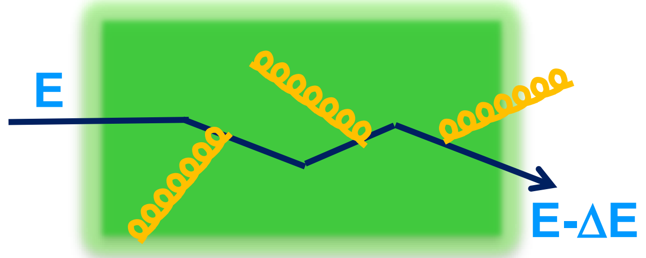
Heavy quarks as QGP probes



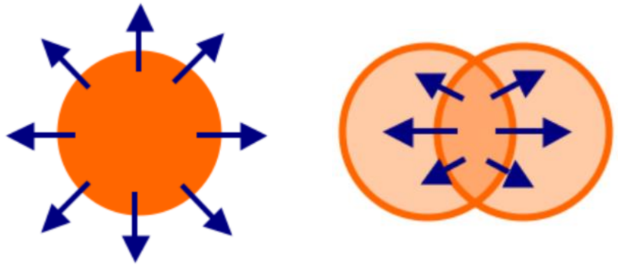
- Charm and beauty quarks: unique probes of the medium
  - ⇨ Produced at the **very early stage** of the collision in partonic scattering processes with large momentum transfer
    - ✓ Produced out-of-equilibrium
  - ⇨ Small rate of thermal production in the QGP ($m_{c,b} \gg T$)
  - ⇨ Large mass, short 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

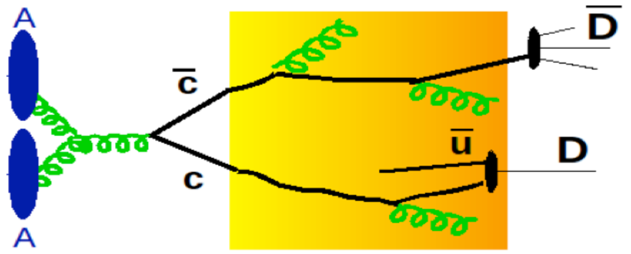
- Heavy quark interactions with QGP constituents:
  - ⇨ Energy loss of energetic partons → quenching
    - ✓ Elastic collisions + gluon radiation
    - ✓ Test **colour charge and quark mass dependence** of in-medium energy loss
    - ✓ Probe the medium at short-distance scales



  - ⇨ "Push" from the collective flow of the medium
    - ✓ Due to multiple soft scatterings with the medium constituents
    - ✓ 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?

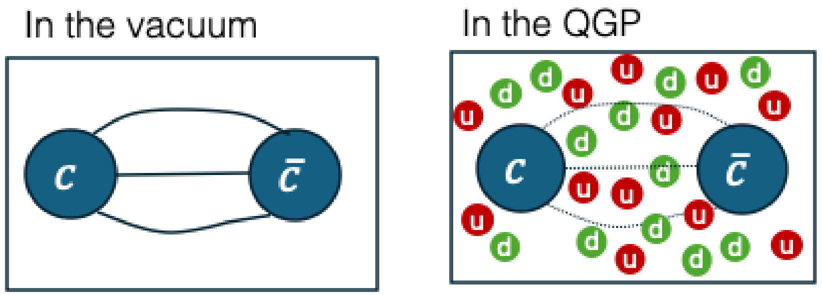


  - ⇨ In-medium hadronization
    - ✓ **Hadronization via recombination** of the charm/beauty quark with a quark from the medium
    - ✓ Recombination vs. fragmentation → impact on hadron momentum distributions and relative abundances of hadron species



Quarkonium: in-medium dissociation

- Dissociation of quarkonia in the QGP
  - ⇨ Original argument by Matsui&Satz: high density of free color charges in the QGP leads to a **screening of the QCD force** that binds the quarkonium states
  - ⇨ Recent studies show little modification of the real part of the potential and that **collision damping** plays a dominant role
  - ⇨ Quarkonium production **suppressed** in A-A collisions



📖 Matsui, Satz, PLB178 (1986) 416

📖 Bazavov et al., PRD109 (2024) 074504

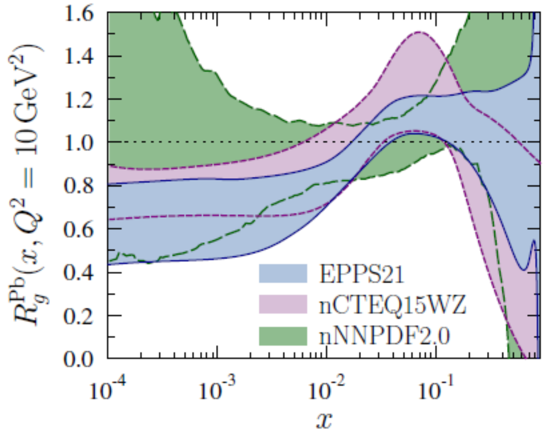
- Sequential pattern expected from the rich spectroscopic structure of quarkonia
  - ⇨ Different quarkonium states dissociate in the QGP at different temperatures, depending on their binding energy
    - ✓ *The more strongly bound the state is, the hotter must be the medium to dissociate it*
  - ⇨ **Sequential suppression** as a **QGP thermometer**

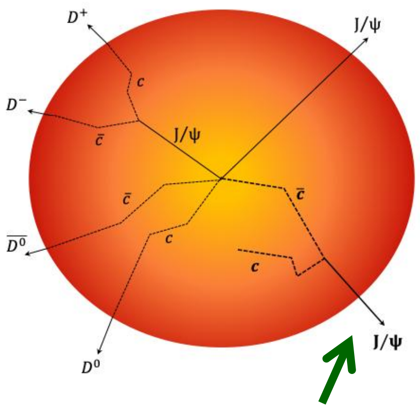
	J/ψ	χ_c	$\psi(2S)$
Mass (GeV)	3.10	3.53	3.68
E_B (GeV)	0.64	0.20	0.05

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass (GeV)	9.46	10.02	10.36
E_B (GeV)	1.10	0.54	0.20

Quarkonium: other effects

- Several effects lead to a more complex situation:
  - ⇨ **Cold nuclear matter (CNM) effects** affecting quarkonia
    - ✓ *Nuclear PDFs (shadowing, antishadowing, EMC effect)*
    - ✓ *Coherent energy loss in CNM*
    - ✓ *Absorption in nuclear matter (i.e. interactions with nucleons of projectile and target)*
  - ⇨ Production via **recombination** of uncorrelated quark pairs originated from different hard scattering processes
    - ✓ *Increases with increasing collision energy because charm (and beauty) production cross section increases with √s*
    - ✓ *More relevant for charm (more abundantly produced) than for beauty*
  - ⇨ Break-up by **comoving hadrons** in the hadronic phase
  - ⇨ **Feed-down** from decays of higher quarkonium states
    - ✓ *About 30% of final-state J/ψ originate from ψ(2S) and χ_c decays*



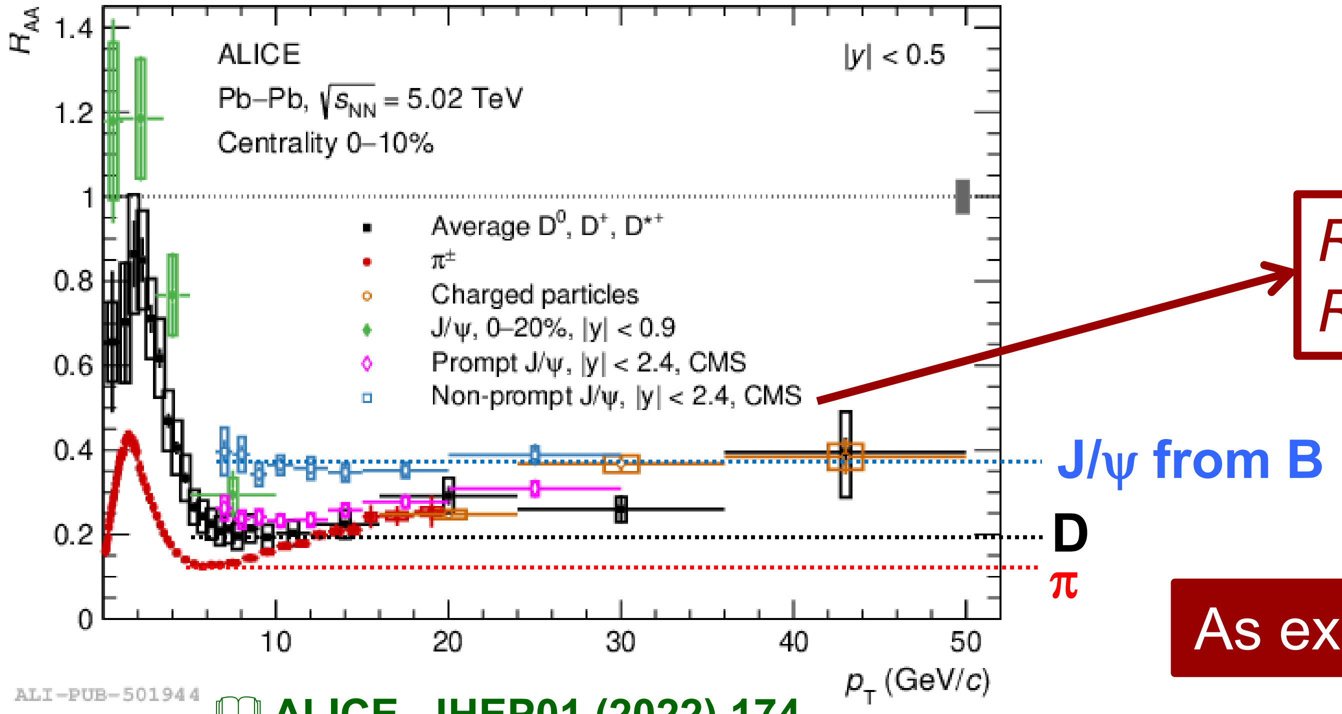


c$\bar{\text{c}}$ recombination

Open charm: what have we learned at collider energies (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



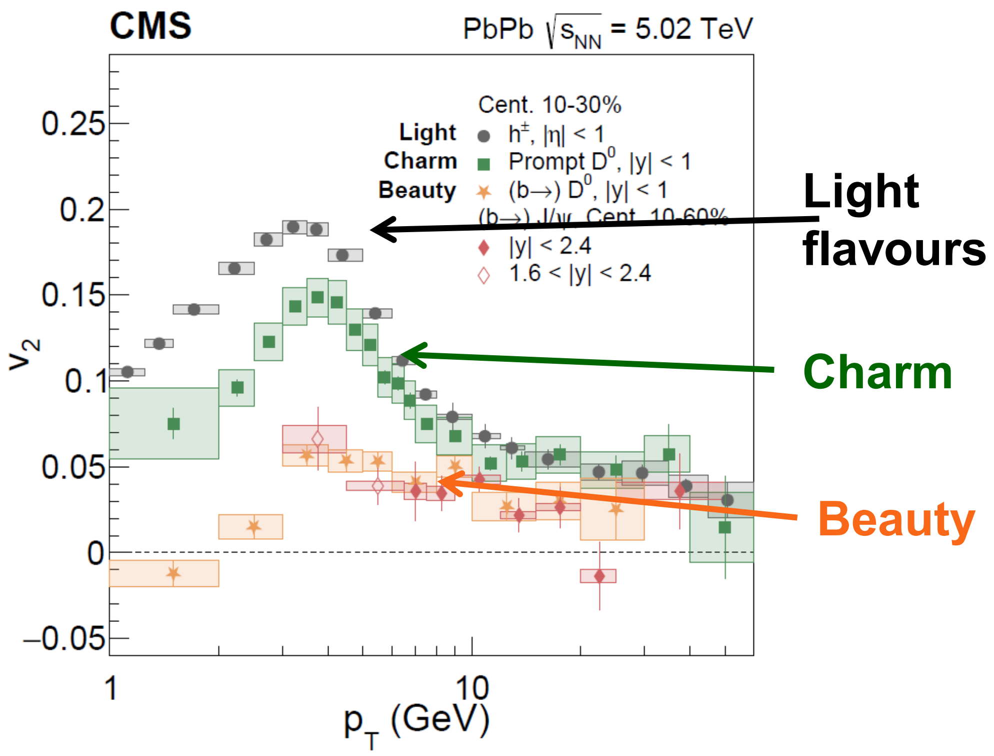
ALICE, JHEP01 (2022) 174

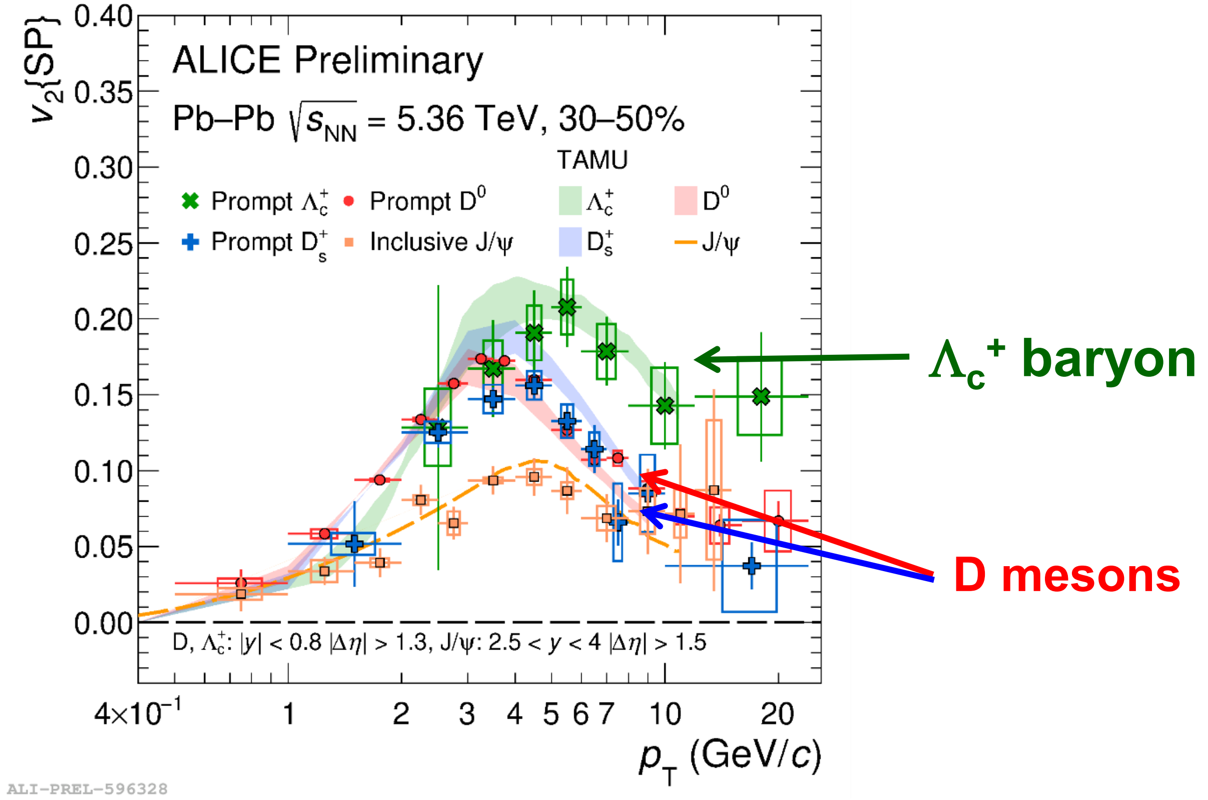
R_{AA}(charm) > R_{AA}(light) for p_T<8 GeV/c
R_{AA}(beauty) > R_{AA}(charm) for p_T<20 GeV/c

As expected from parton in-medium energy loss

Elliptic flow of heavy-flavours at LHC

CMS, Phys.Rept. 1115 (2025) 219

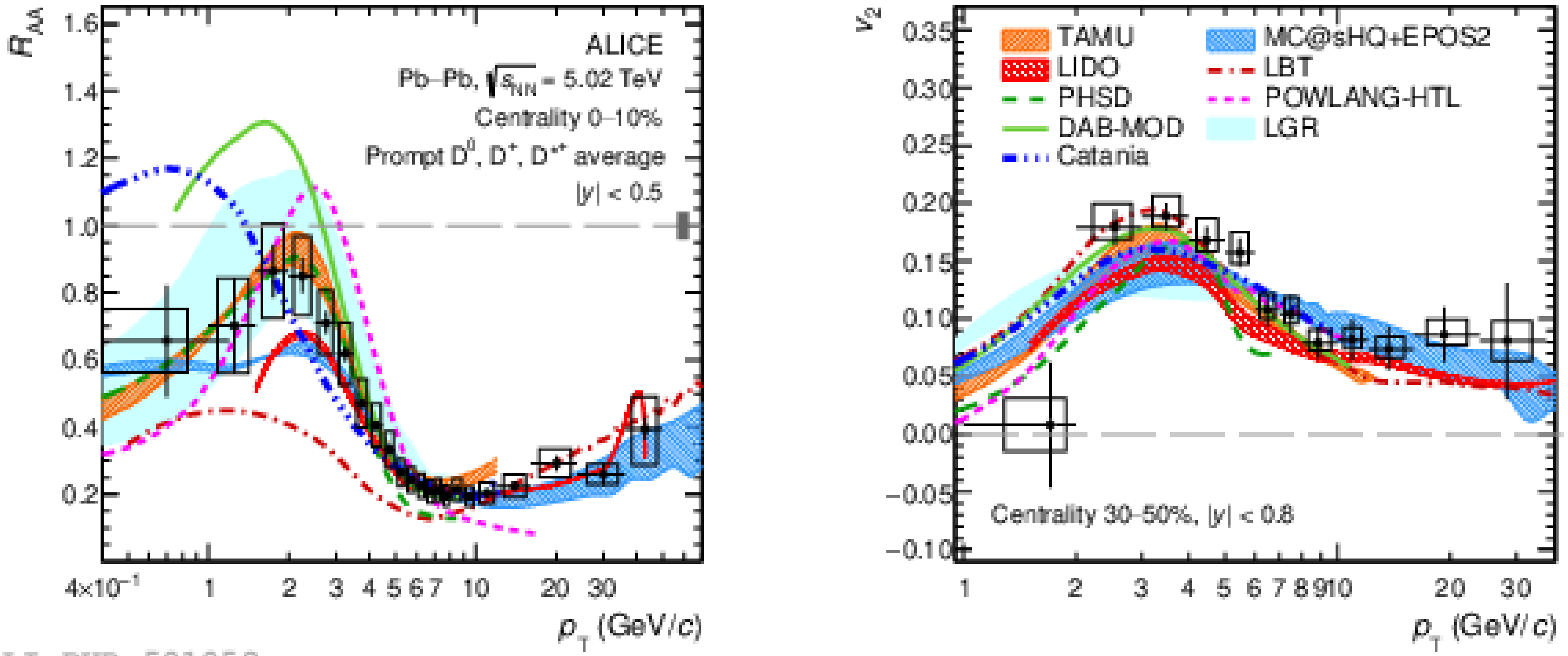




- Charm vs. light (vs. beauty)
  - ⇨ Large v_2 of D mesons, similar magnitude as light flavour v_2
  - ⇨ Indication that low/mid-p_T **charm quarks (partially) thermalize in the QGP**
- Charm mesons vs. baryons
  - ⇨ Baryon/meson splitting at intermediate p_T
  - ⇨ As expected from (partial) thermalization of c quarks in the QGP and **hadronization via recombination**

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

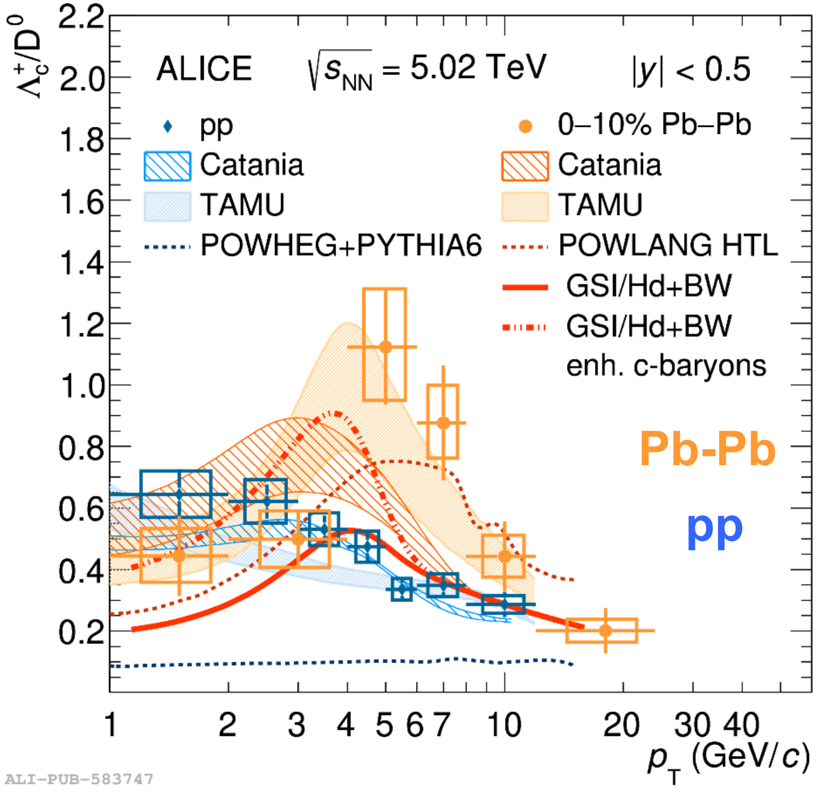


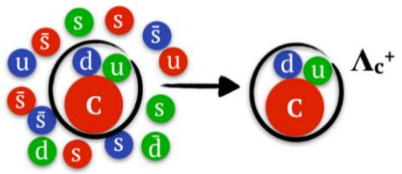
📖 **ALICE, JHEP01 (2022) 174**

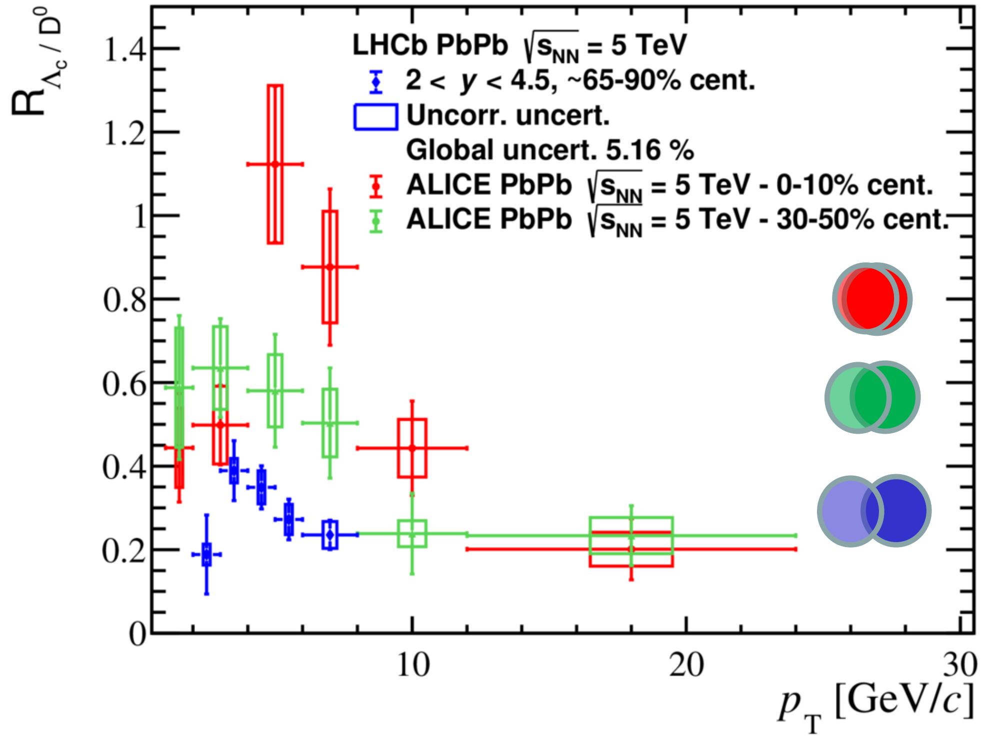
Charmed baryon yield in Pb-Pb

- 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

ALICE, EPJC 84 (2024) 813





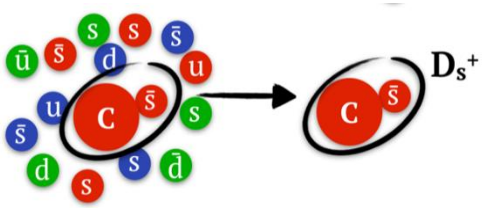


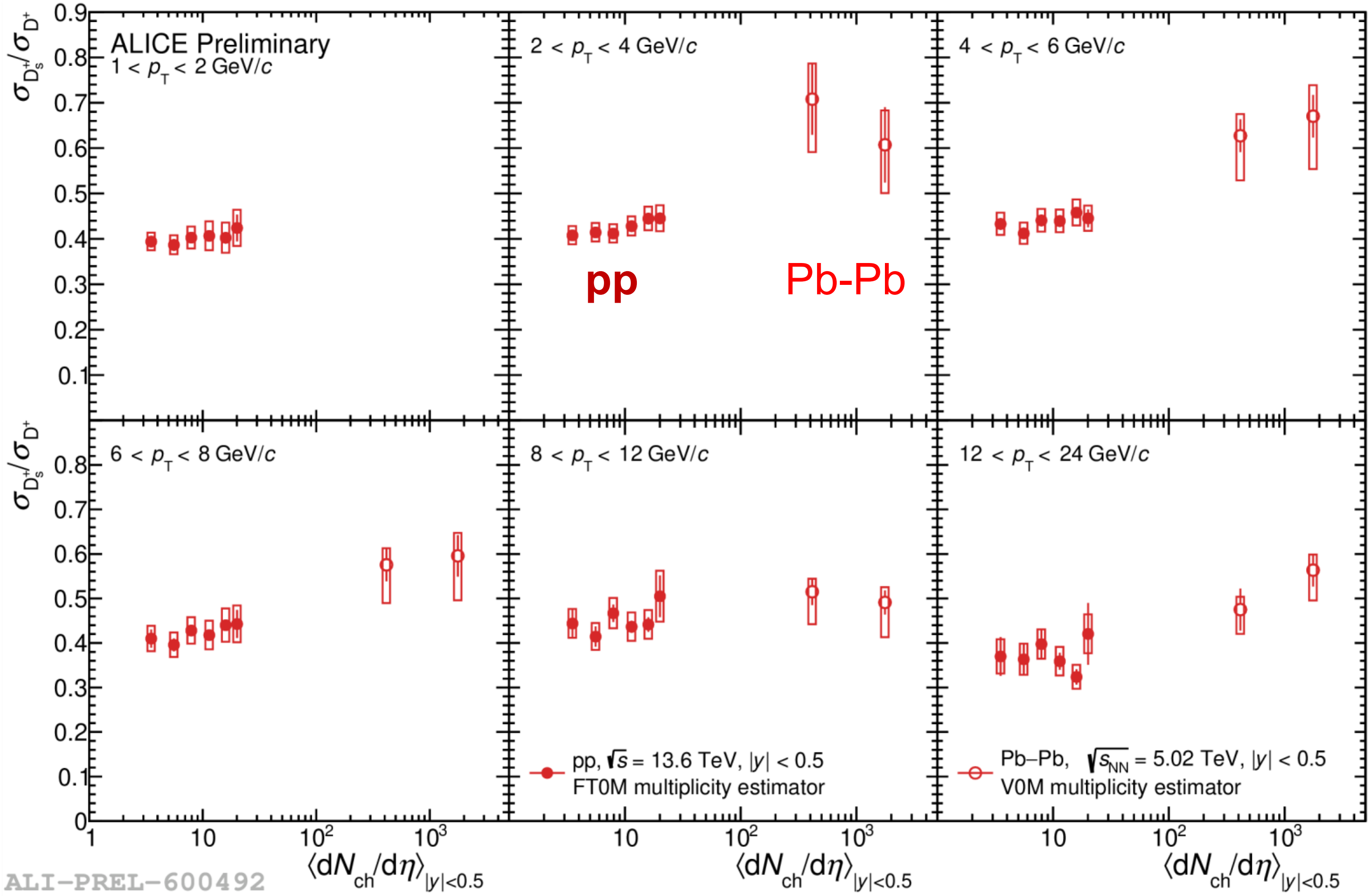
LHCb, JHEP 06 (2023) 132

→ in-medium hadronization is needed to describe the data

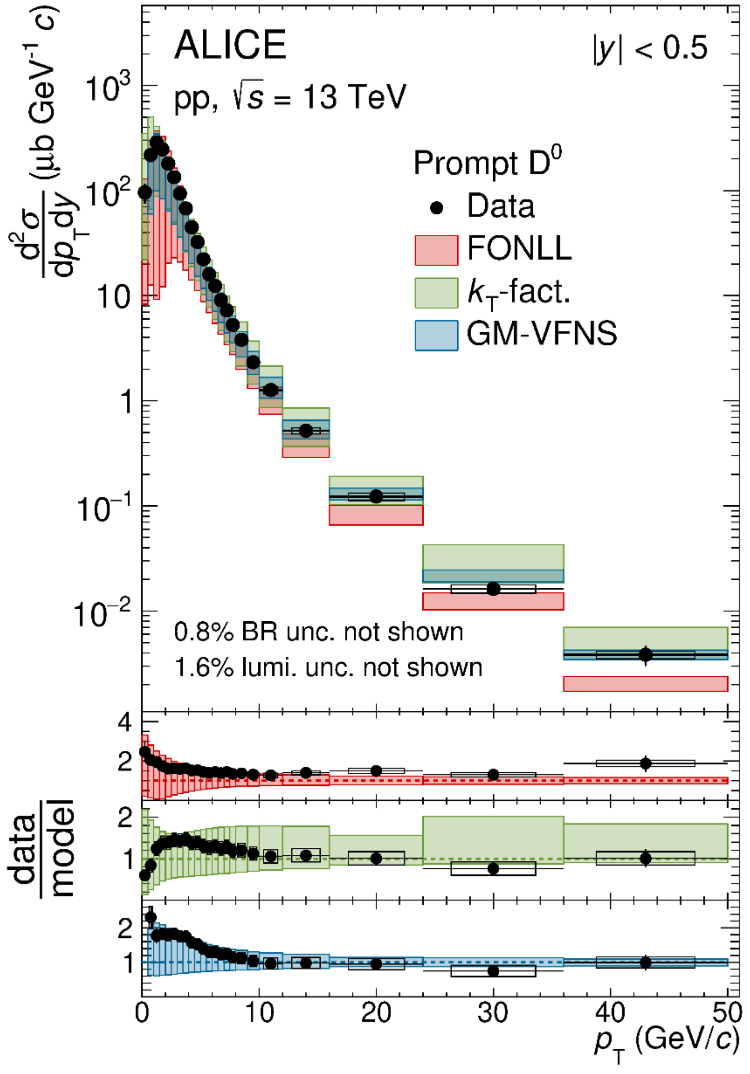
Charm-strange mesons from pp to Pb-Pb

- Strange/non-strange ratio
  - ⇨ No multiplicity dependence in pp collisions at mid-rapidity
  - ⇨ (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





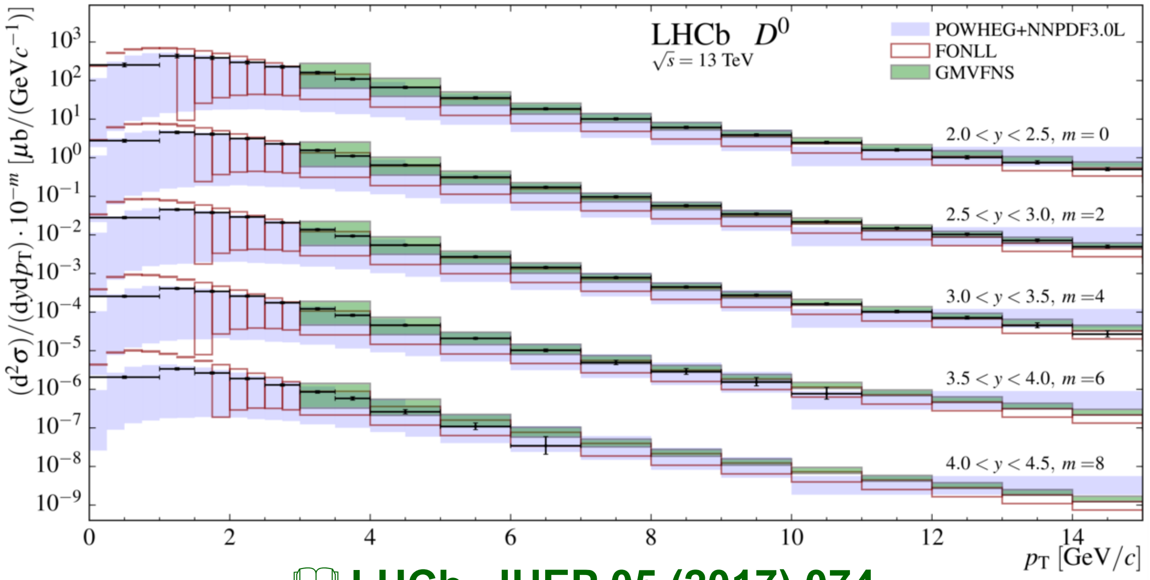
What about charm in pp at the LHC?



ALI-PUB-567836

📖 **ALICE, JHEP 12 (2023) 086**

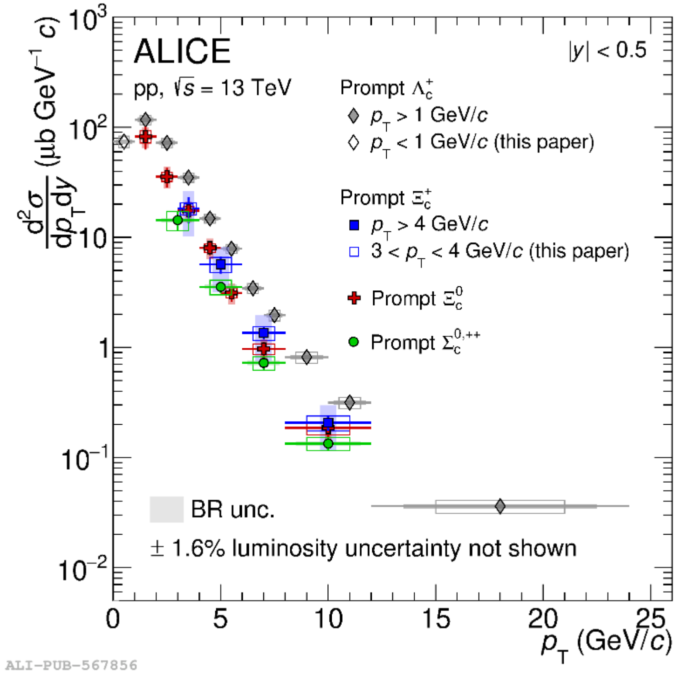
- D-meson production in pp collisions
  - ⇨ Measured in a wide p_T range, down to low p_T , at mid and forward rapidity and different center-of-mass energies
  - ⇨ D-meson cross sections described by pQCD calculations
    - ✓ Measured values on the upper edge of theory uncertainties for FONLL and GM-VFNS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

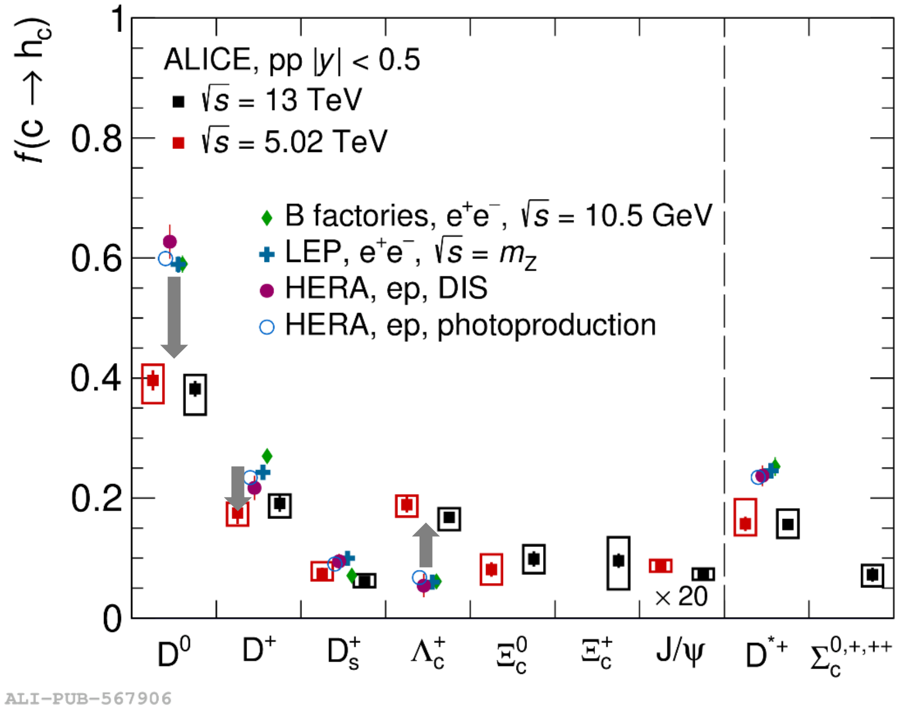


📖 **LHCb, JHEP 05 (2017) 074**

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**



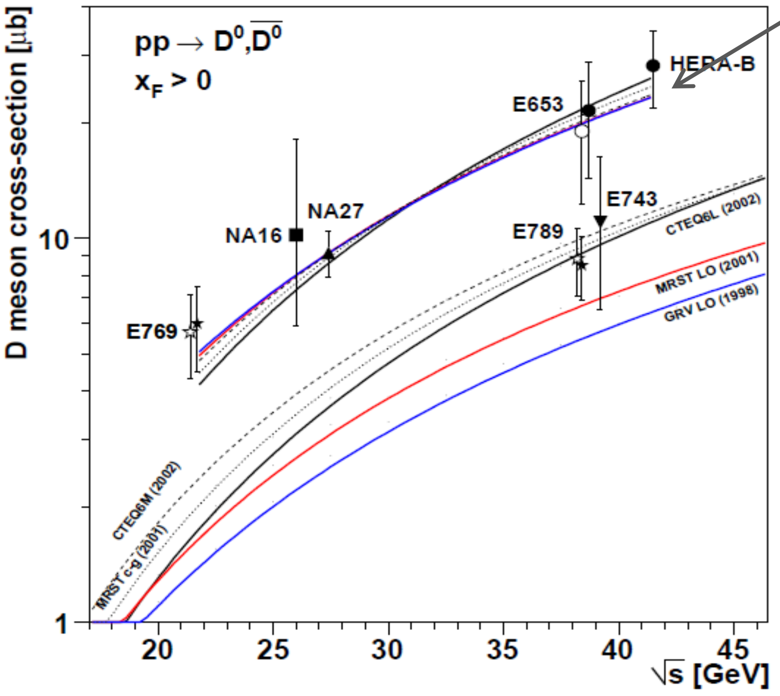


📖 **ALICE, JHEP 12 (2023) 086**

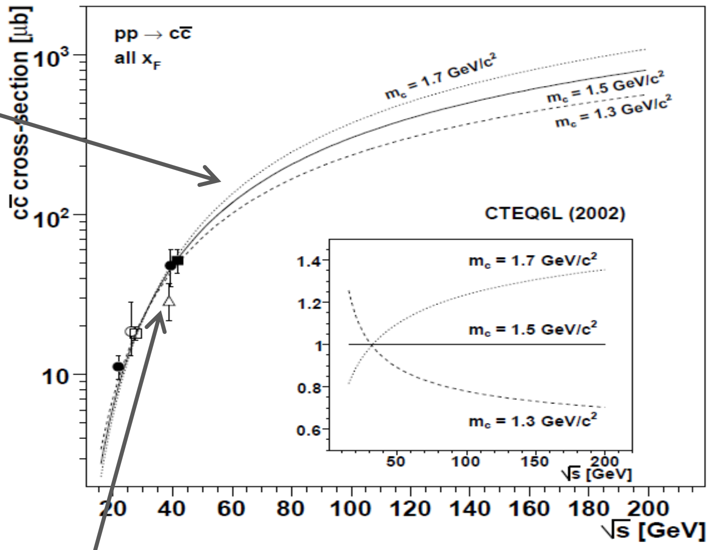
Open charm: what do we already know in the SPS energy range?

Charm cross section in pp (p-A)

- Unexplored energy domain at √s < 20 GeV
- Comparison of existing data to PYTHIA (LO) event generator



PYTHIA LO cross sections
scaled with appropriate K-factor



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

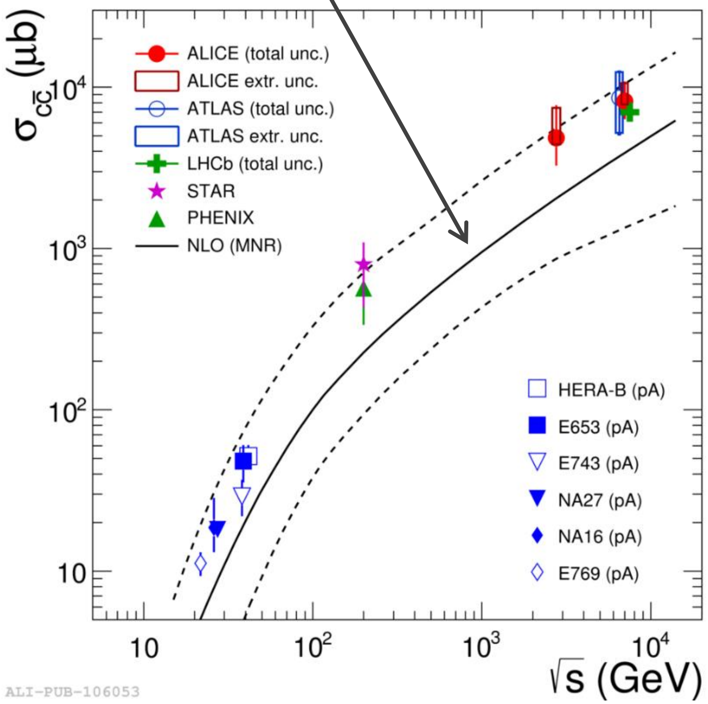
Total charm cross section from:

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

Charm cross section in pp (p-A)

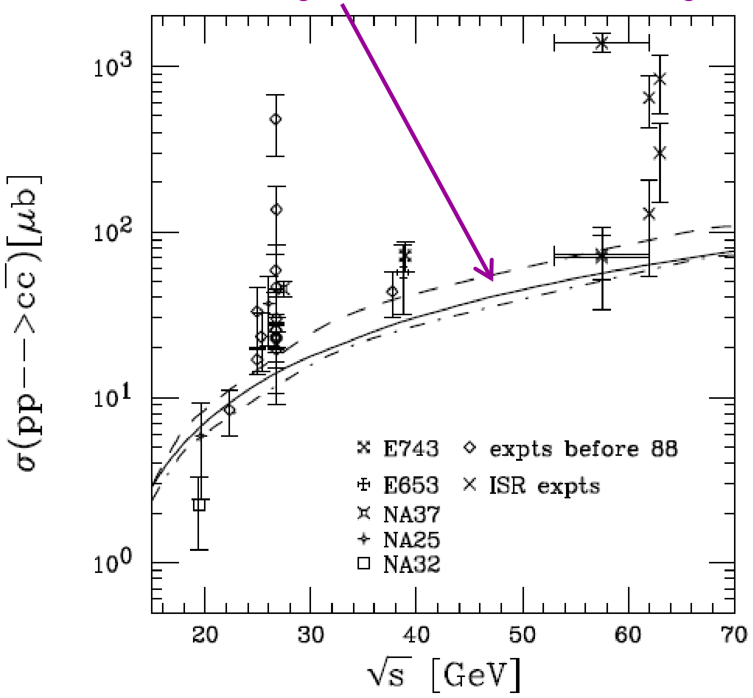
- Unexplored energy domain at $\sqrt{s}$ < 20 GeV
- Comparison of existing data to pQCD calculations (MNR) at NLO, NLL and NNLO

MNR, m_c=1.5 GeV, μ_F=μ_R=m_T



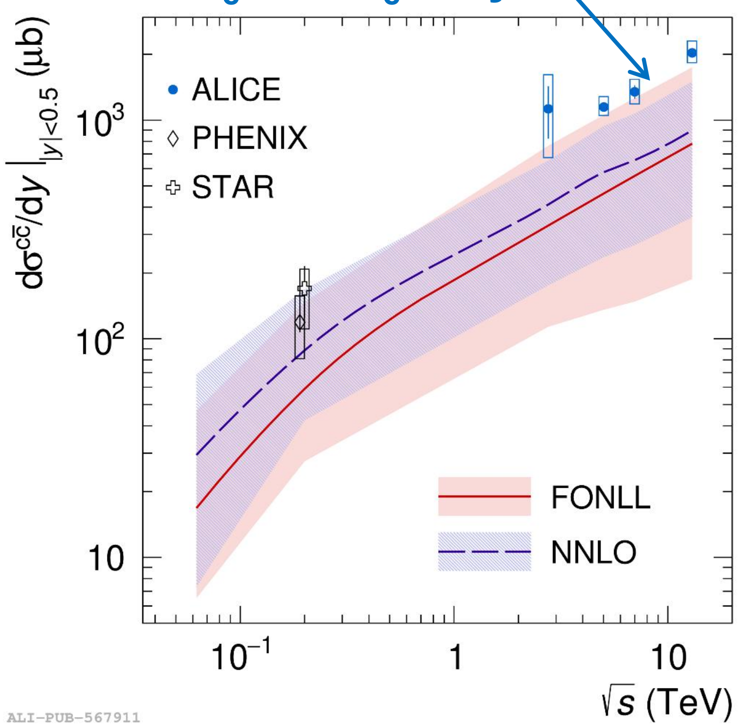
📖 **ALICE, PRC94 (2016) 054908**

MNR, m_c=1.2 GeV , μ=2m_c



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

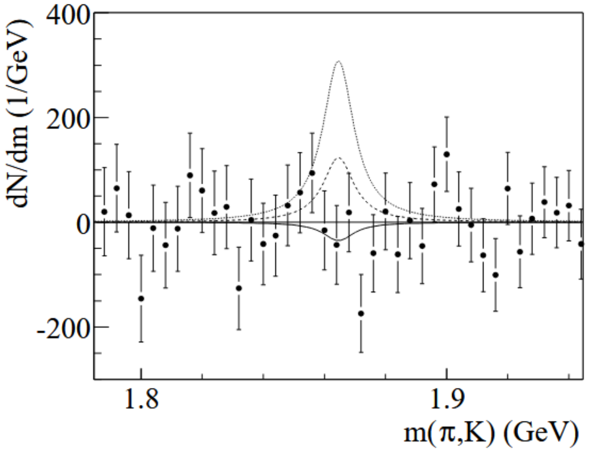
Including measurements of Λ_c and Ξ_c baryons



📖 **ALICE, JHEP 12 (2023) 086**

Charm cross section in A-A

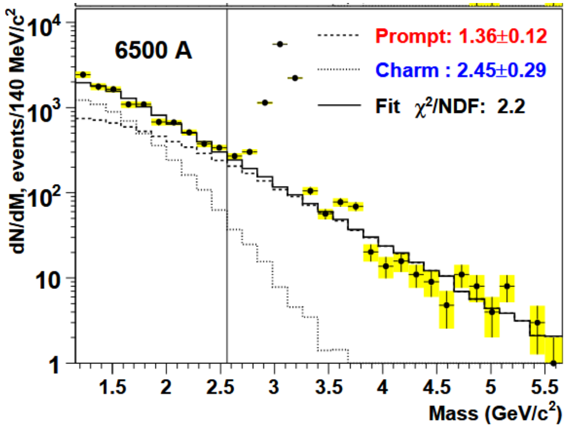
- Upper limit for central Pb-Pb from NA49 measurements of D^0 mesons

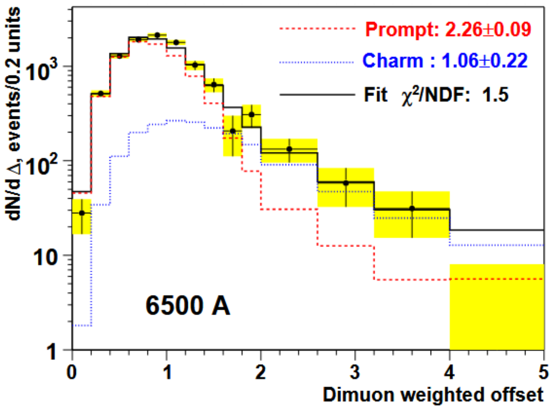


> $P(N|\text{data})$. Using the fitted values of μ and σ, the upper limit for the total yield is found to be $M(D^0 + \bar{D}^0) = 1.5$ per event at 98% CL.
>
> Because no D^0 signal has been observed it is not possible to directly verify the Monte Carlo prediction of the

📖 **NA49, PRC73 (2006) 034910**

- Measured by NA60 in In-In from intermediate-mass dimuons (~20% precision)

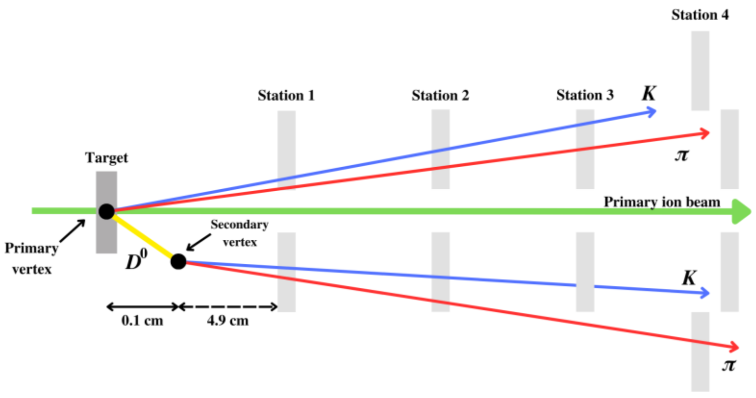


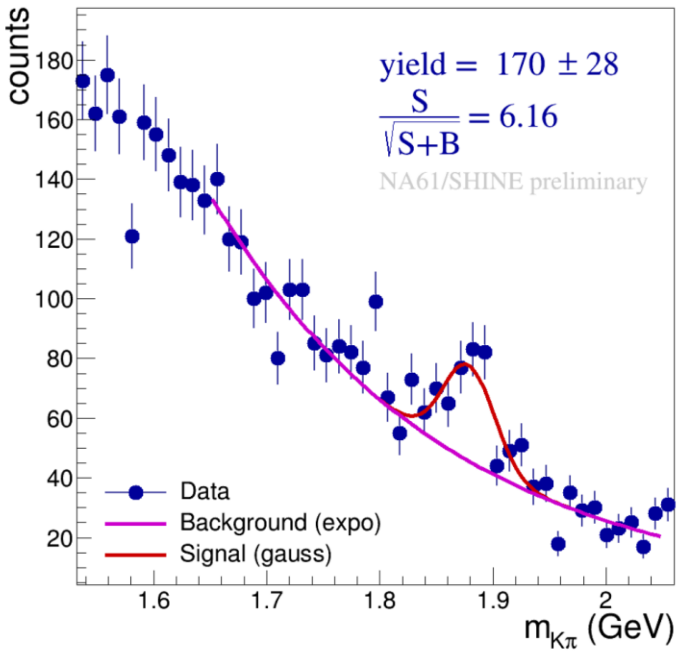


> – The observed yield of muon pairs from D meson decays leads to $\sigma_{c\bar{c}} = 9.5 \pm 1.3(stat) \pm 1.4(syst)$ μb (the systematic error does not reflect the uncertainty related to the kinematic distribution of the c and $\bar{c}$ quarks)

📖 **NA60, EPJ C59 (2009) 607**

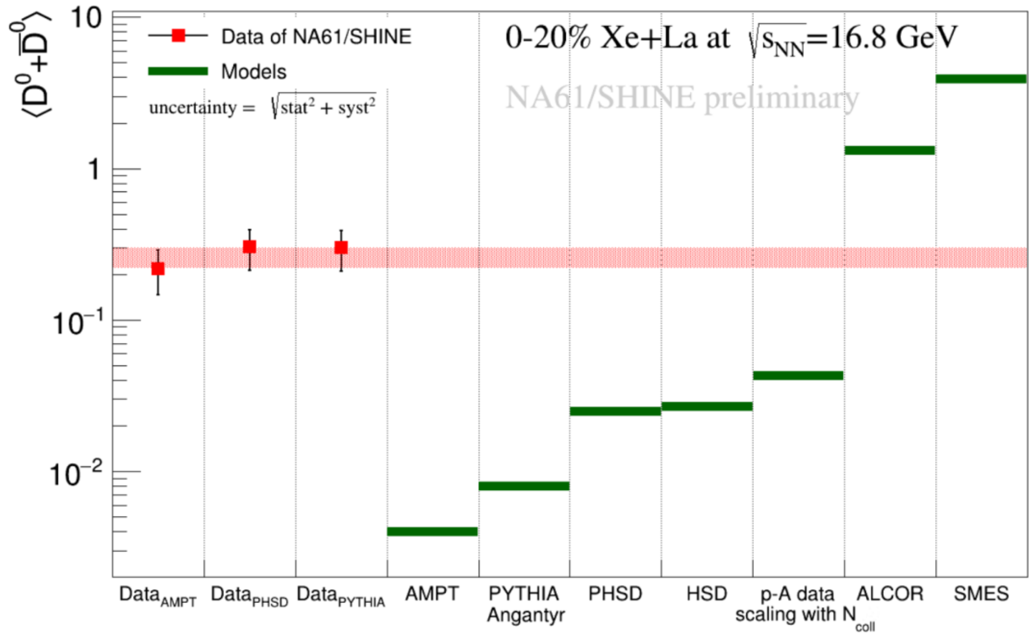
NA61/SHINE recent results: D^0 in Xe-La





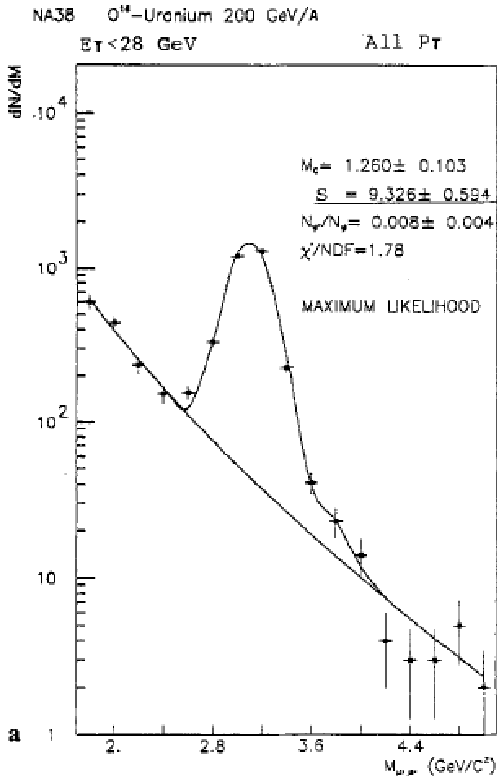
- $D^0 \rightarrow K^-\pi^+$ decays reconstructed exploiting the Small Acceptance Vertex Detector in $-0.5<y<1$
  - ➩ Resolution on the secondary vertex along beam axis ~ 150 μm
- Different models (AMPT, PHSD, PYTHIA) used to extrapolate the measured yield to 4π
  - ➩ Data (still preliminary) may allow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

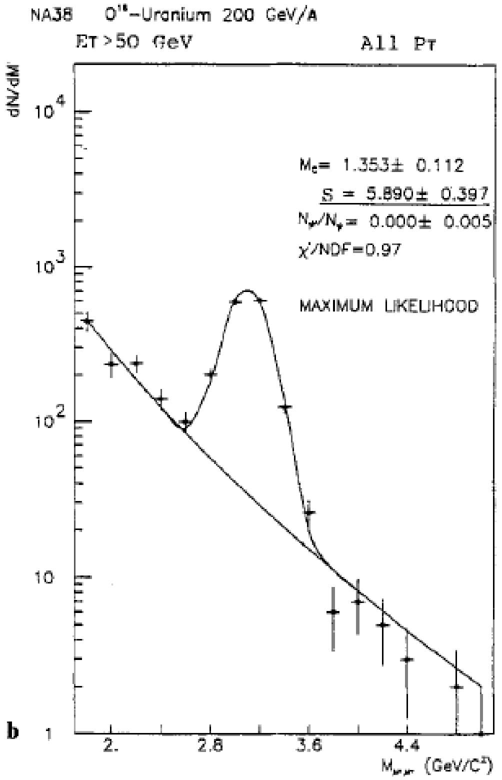
📖 **NA61, arXiv:2410.24014**



Charmonia: what do we already know in the high μ_B region?

The first J/ψ measurements: NA38



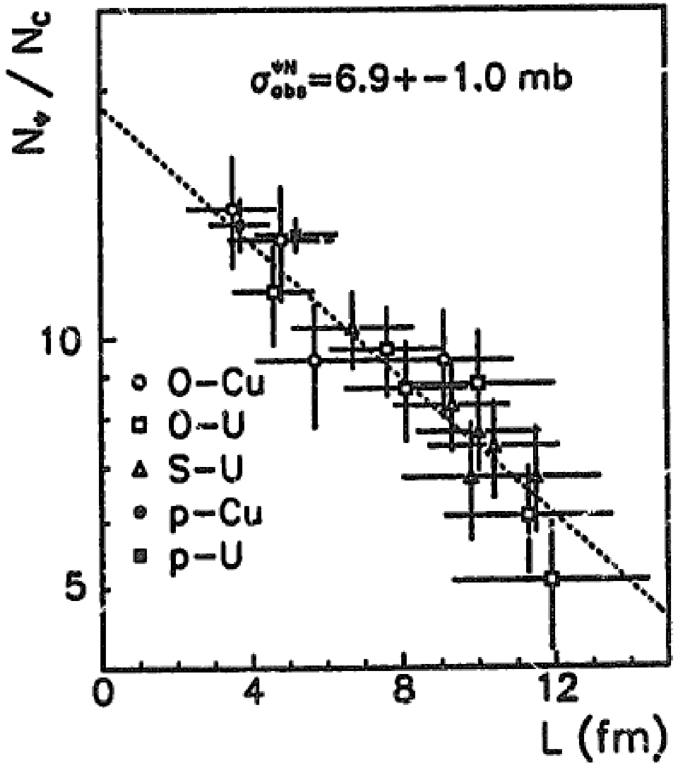


📖 **NA38, Quark Matter 1987**

- Evidence of **J/ψ suppression in O-U and S-U** collisions
  - ⇨ 30% suppression in central (high E_T) O-U collisions compared to peripheral ones
- Question:
  - ⇨ Signature of deconfinement? Or just a consequence of dense (hadronic) matter formation?

The role of Cold Nuclear Matter effects

- Can competing sources of J/ψ dissociation involving hadronic interactions (with cold nuclear matter and/or hadronic medium) reproduce the NA38 data?

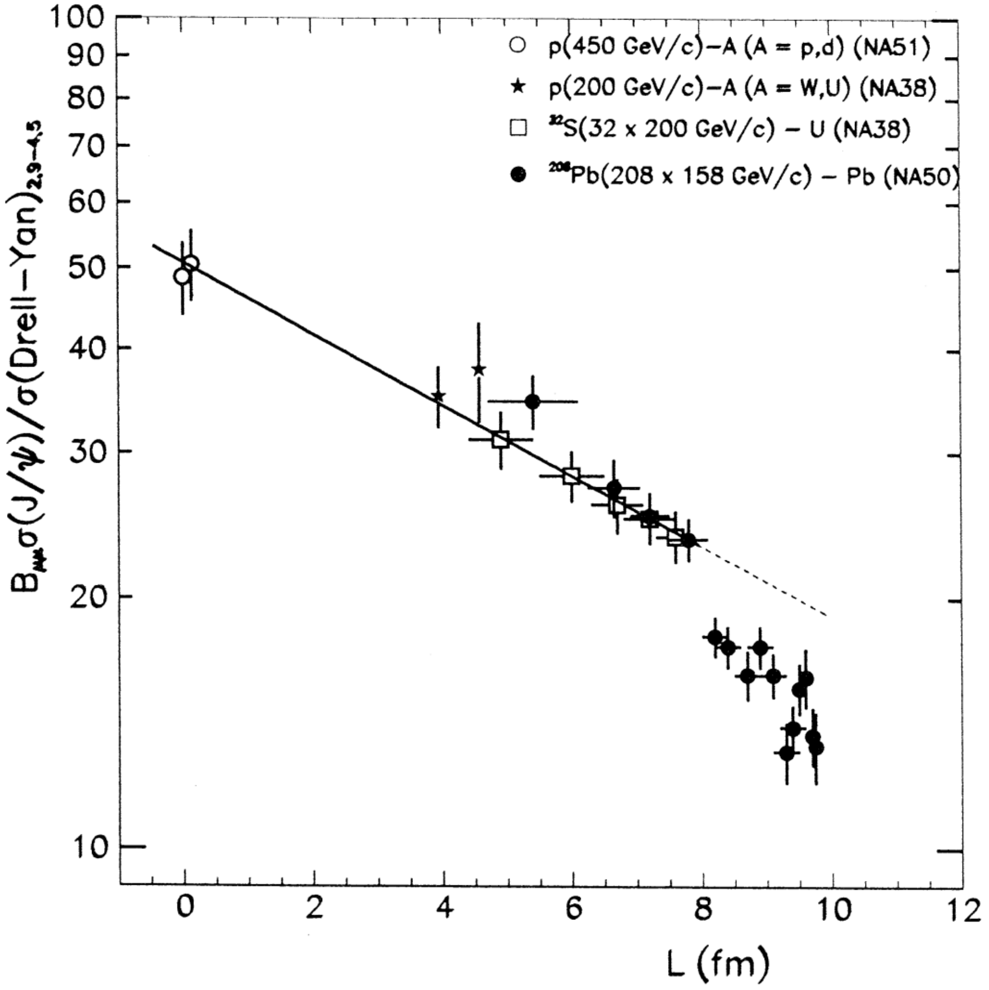


- Suppression observed also in p-A collisions
  - ⇨ Exponential trend as a function of the length L of traversed nuclear matter (L is related to collision centrality)
- Implies significant J/ψ dissociation cross sections in cold nuclear matter
  - ⇨ Charmonium break-up in interactions with the nucleons of the colliding ions
- Effective absorption cross section $\sigma_{\mathrm{abs}}^{\mathrm{J}/\psi}$ extracted from fit to data

📖 **Gerschel, Hufner, PLB 207 (1988) 253**

→ Cold Nuclear Matter effects are a crucial ingredient in the interpretation of the data

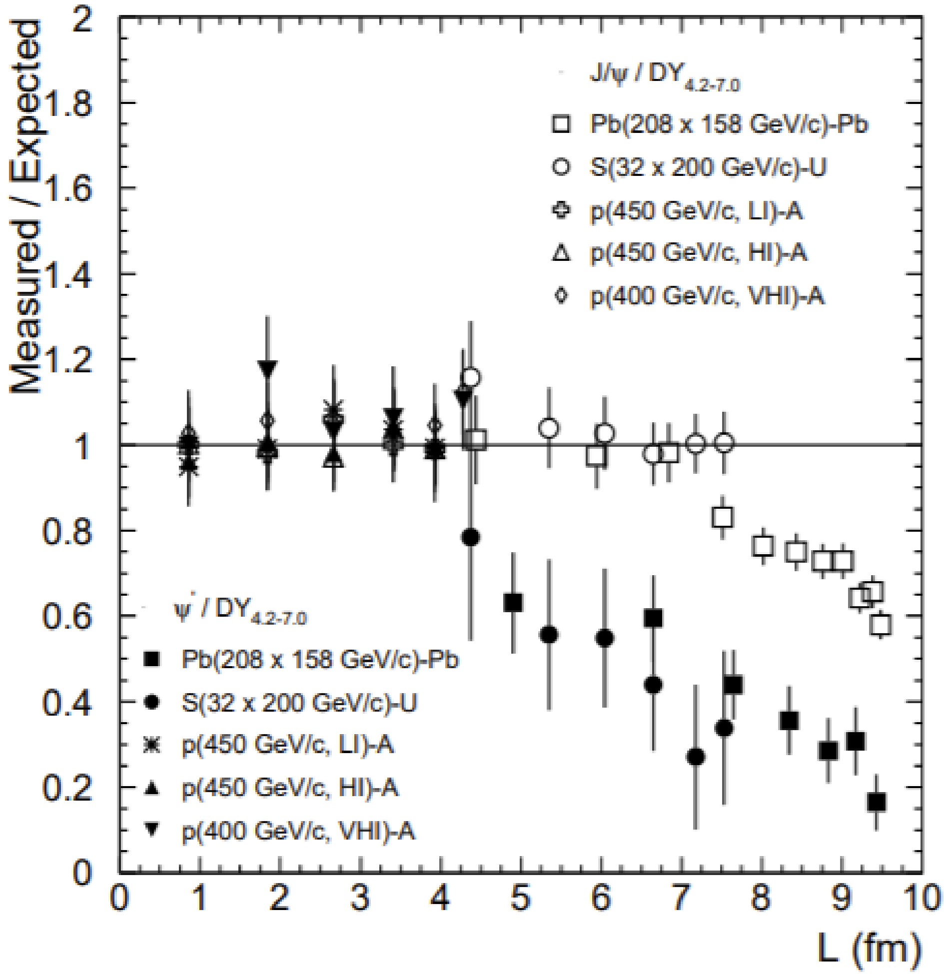
NA50: anomalous J/ψ suppression



📖 **NA50, PLB 450 (1999) 456**

- First evidence of **J/ψ anomalous suppression**
  - ⇨ Peripheral Pb-Pb collisions agree with the expected "ordinary" nuclear absorption from p-A (and S-U) collisions
  - ⇨ Suppression **beyond CNM effects** in **central Pb-Pb collisions**
  - ⇨ J/ψ suppression magnitude (~ 30%) quantitatively consistent with **melting of ψ(2S) and χ_c** (more loosely bound)

J/ψ and ψ(2S) at NA50

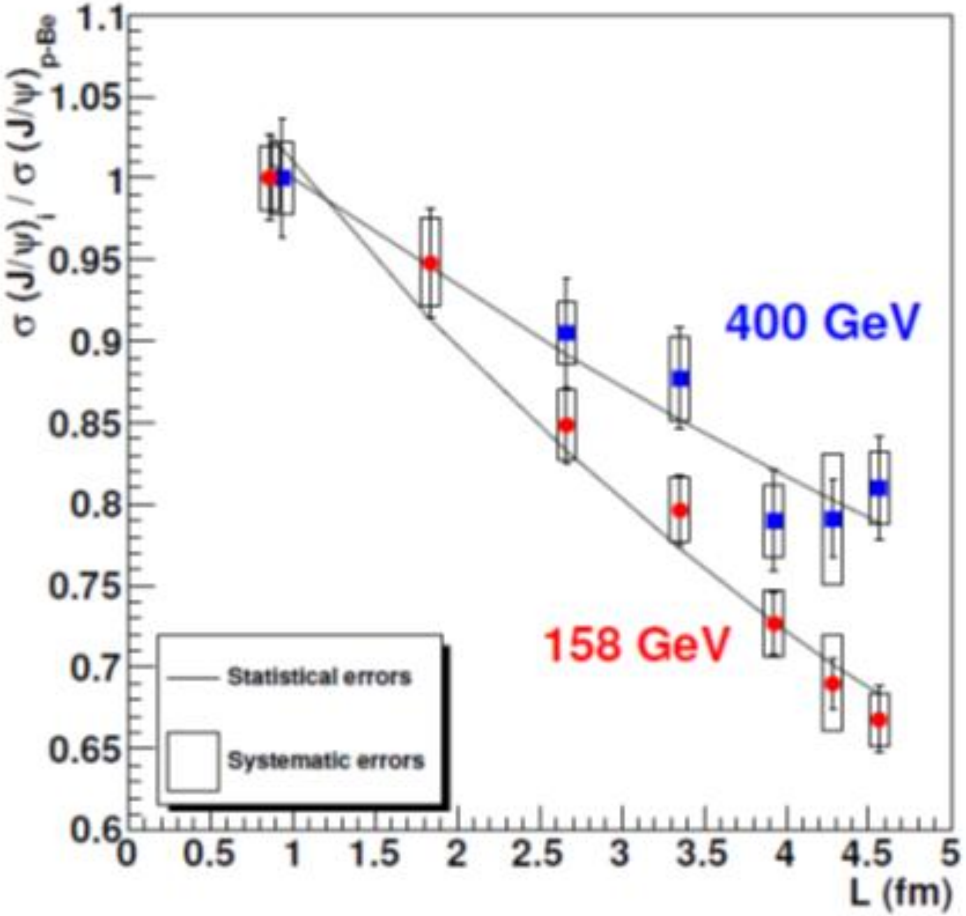


📖 NA50, EPJC 49 (2007) 559

- First evidence of **charmonium sequential suppression**
  - ⇨ **Stronger suppression of ψ(2S)** w.r.t. J/ψ at given centrality (expressed in terms of L)
  - ⇨ ψ(2S) suppression sets in for more peripheral events (smaller L) for a given collision system
- Note:
  - ⇨ “Ordinary” nuclear absorption (due to CNM effects) estimated from p-A data collected at different √s, under the assumption that the J/ψ absorption cross section does not depend on √s

CNM effects revisited by NA60

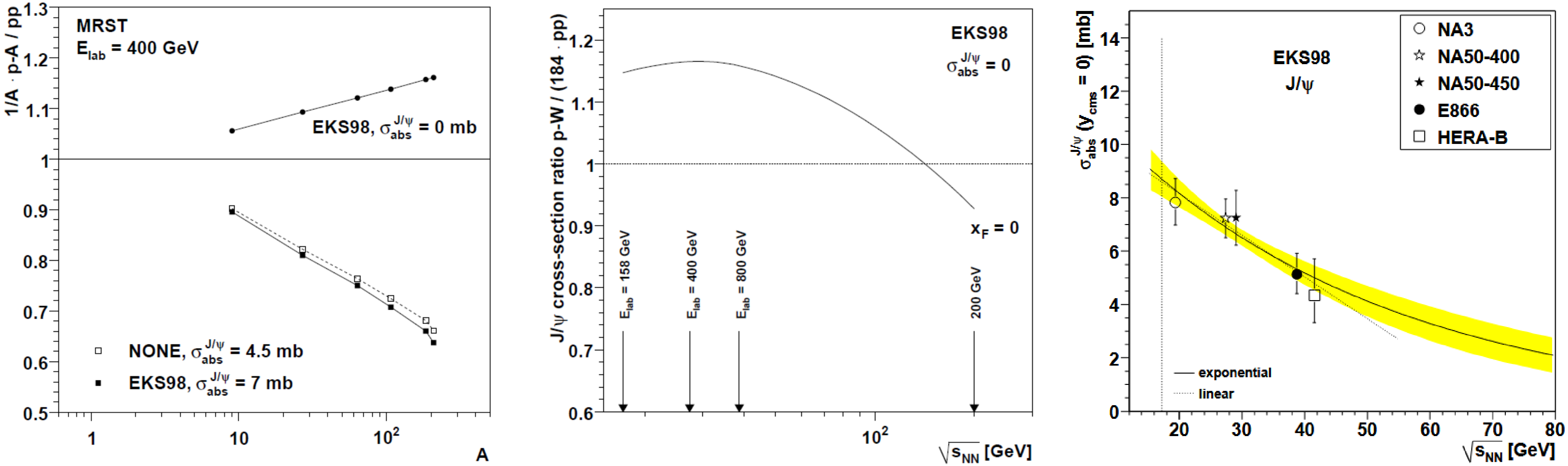
- Significant dependence of J/ψ suppression due to CNM effects on √s
  - ⇨ Stronger suppression (larger $\sigma_{abs}^{J/\psi}$) at lower √s
- Note:
  - ⇨ $\sigma_{abs}^{J/\psi}$ is an effective parameter which results from the interplay of several effects
- Proper reference for Pb-Pb collisions should be taken from p-A collisions at the same √s



NA60, PLB 706 (2012) 263

CNM effects vs √s

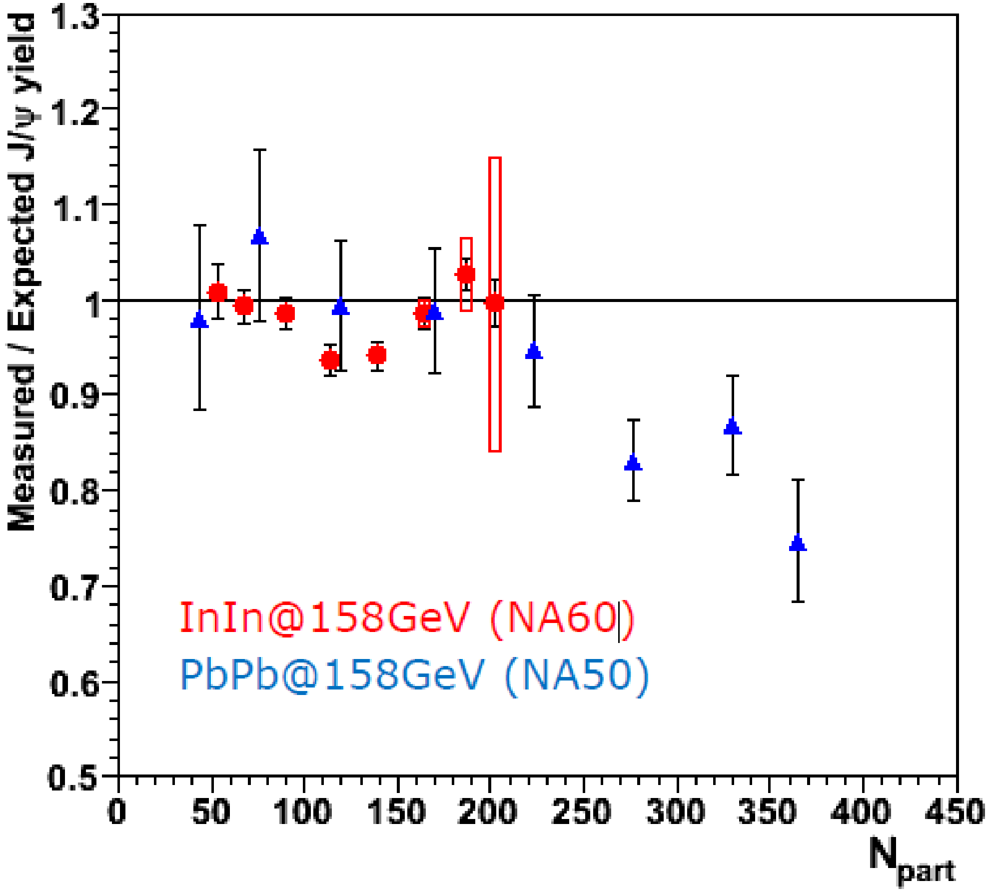
📖 Lourenco et al., JHEP 02 (2009) 014



- $\sigma_{abs}^{J/\psi}$ is an effective parameter which results from the interplay of several effects
- At low energies:
  - ⇨ Antishadowing in PDF
  - ⇨ Nuclear absorption (due to interactions with nucleons)

Legacy of NA38 + NA50 + NA60

NA60, Nucl. Phys. A830 (2009) 345



- Measured J/ψ yield, normalized CNM effects, evaluated from p-A results at the same energy
  - ⇨ Suppression by ~30% beyond CNM effects in central Pb-Pb collisions
  - ⇨ Qualitatively consistent with suppression of feed-down from ψ(2S) (measured) and χ_c (not measured)
  - ⇨ The “direct” J/ψ’s (more tightly bound) may persist in the deconfined medium created at SPS energies
- In-In results shows small or no suppression, with the origin of “wiggle” at intermediate centrality unclear
  - ⇨ Coupling to X(3872) via DD* proposed

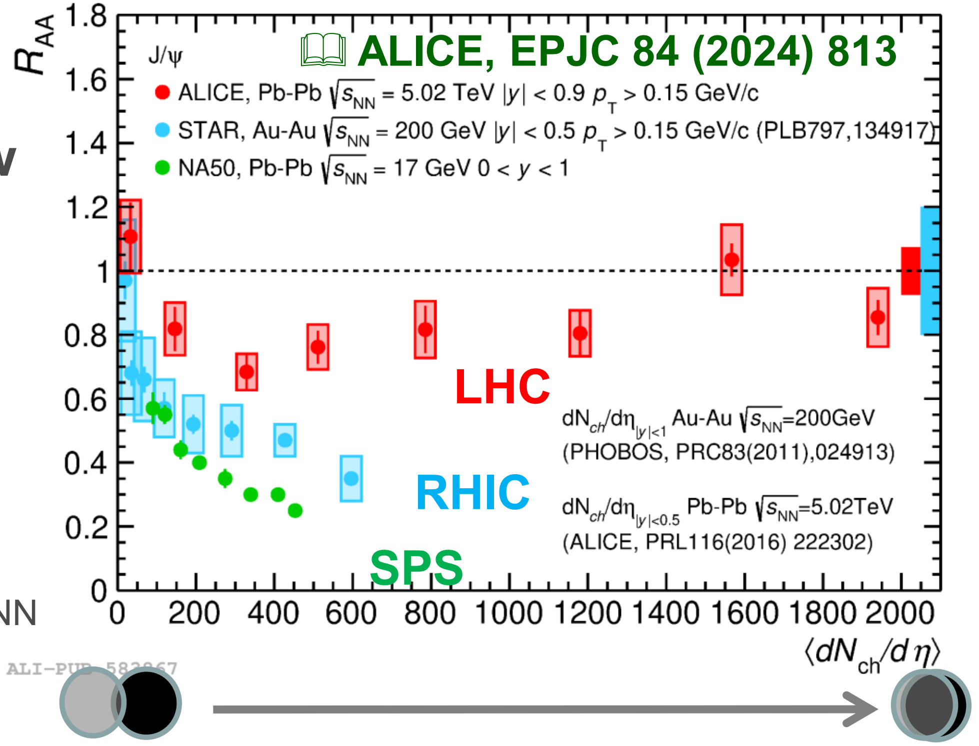
Blaschke et al., NPA 927 (2014) 1

Charmonia: what have we learned at collider energies (μ_B=0) ?

Low-p_T charmonium: recombination

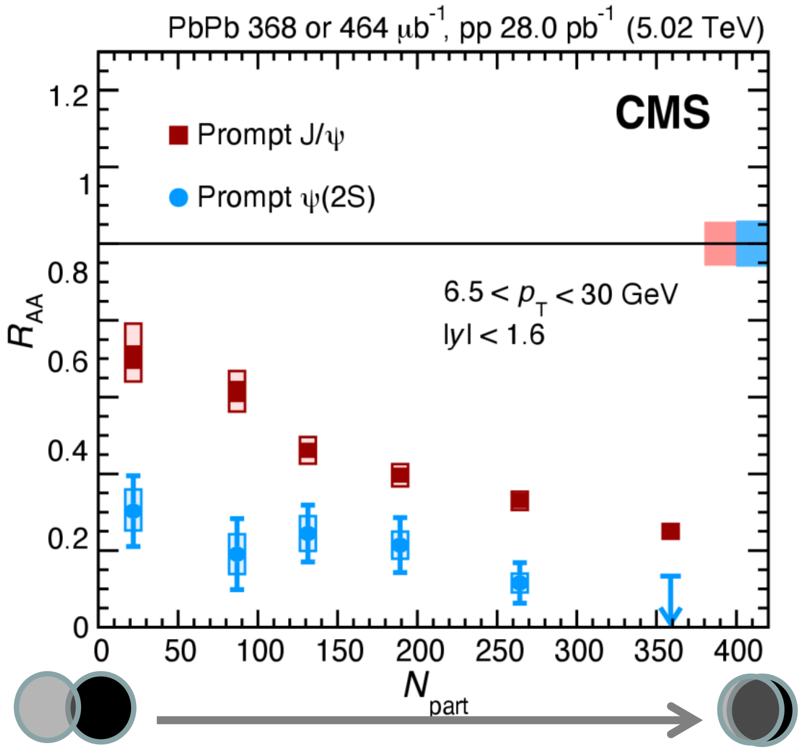
- If QGP is formed, charmonium production can occur also via $c\bar{c}$ **recombination** during the QGP expansion or at the phase boundary
  - ⇨ Charmonia from recombination mainly produced with **low momentum**

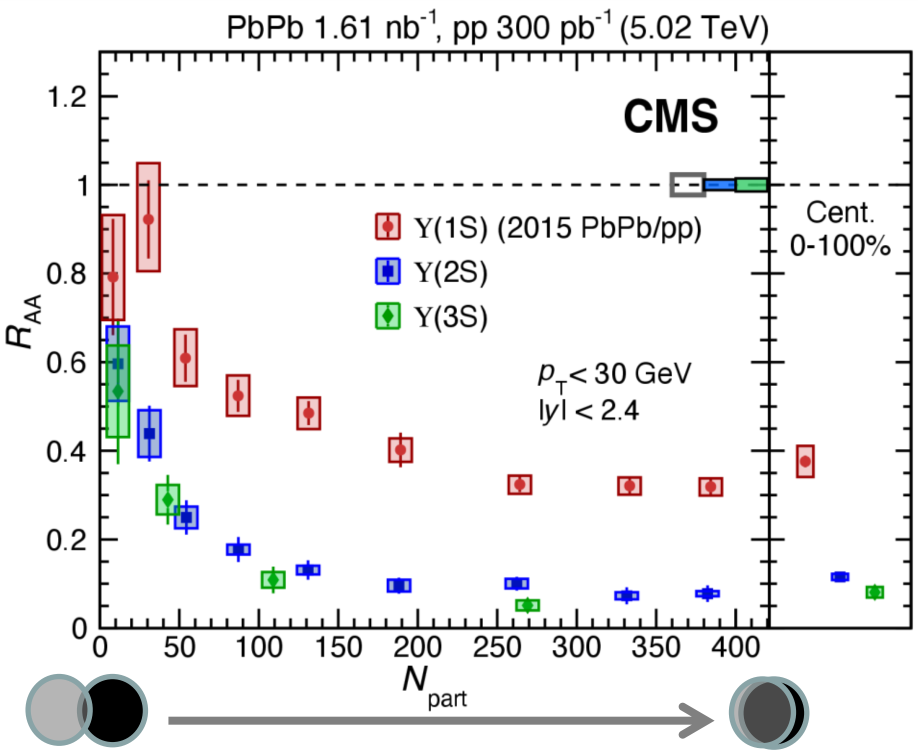
    📖 **Braun-Munzinger, Stachel, PLB 490 (2000) 196**
    📖 **Thews et al., PRC 63 (2001) 054905**



- Tested by measuring J/ψ yield in A-A collisions at different $\sqrt{s_{NN}}$
  - ⇨ Charm quark production cross section increases with $\sqrt{s_{NN}}$
  - ⇨ Probability of $c\bar{c}$ recombination increases with $\sqrt{s_{NN}}$
- J/ψ yield enhanced in A-A collisions at higher $\sqrt{s_{NN}}$
  - ⇨ Strong **evidence of J/ψ formation via $c\bar{c}$ recombination**

Bottomonium and high-p_T charmonium





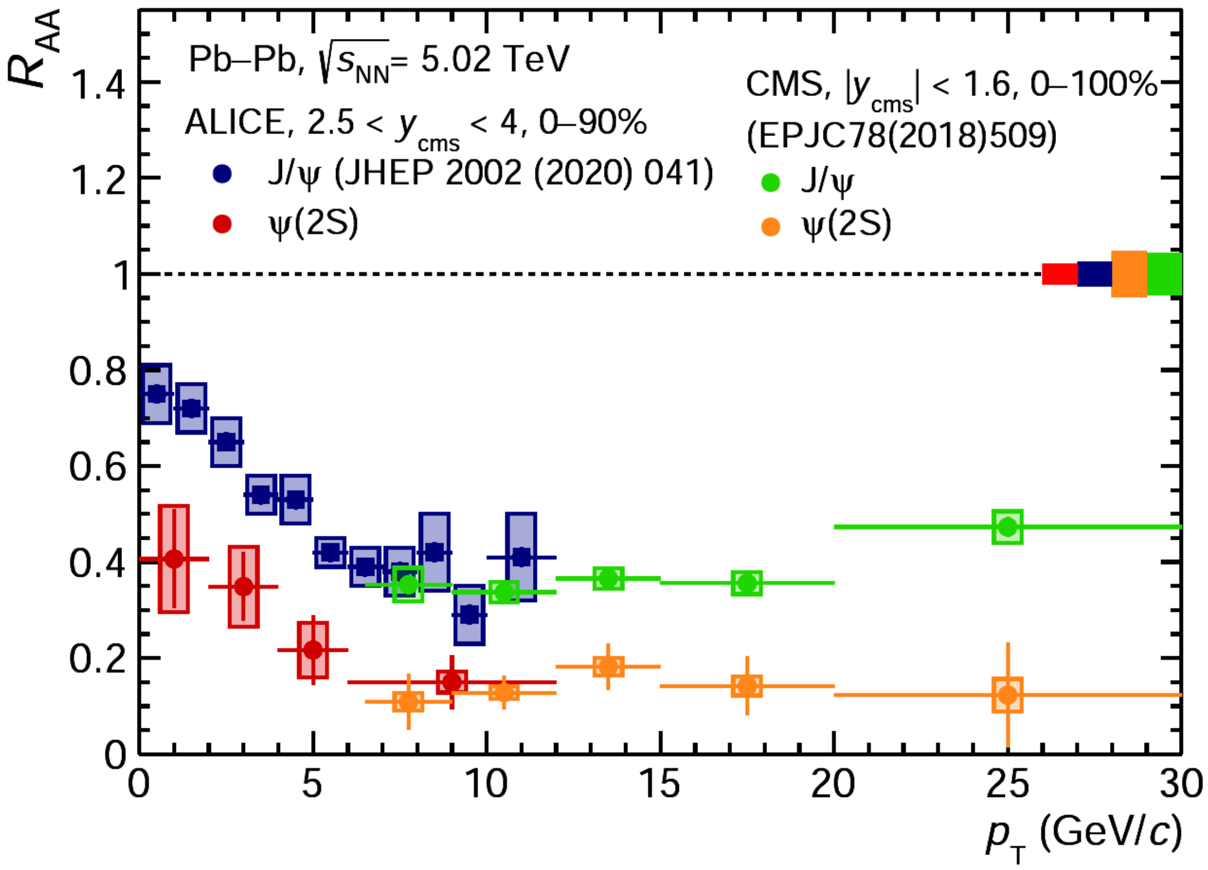
📖 **CMS, Phys.Rept. 1115 (2025) 219**

- High-p_T charmonia: $R_{AA}^{\psi(2S)} < R_{AA}^{J/\psi}$. Bottomonia: $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
  - ⇨ The more fragile states are the most suppressed
- Strong **indication of sequential suppression effects**, ordered by binding energy
  - ⇨ For a conclusive interpretation of quarkonia as a QGP thermometer, one needs to account for the feed-down from decays of excited S- and P-wave quarkonium states

Charmonium: sequential recombination

ALICE, PRL 132 (2024) 042301

- Clear hierarchy of suppression of J/ψ and ψ(2S) over a wide p_T range
- Increase of the J/ψ and ψ(2S) nuclear modification factors at low p_T
  - ⇨ Similar trend for the two charmonium sates
  - ⇨ Understood as a direct consequence of charmonium formation via recombination of charm quarks
  - ⇨ Recombination relevant at low p_T



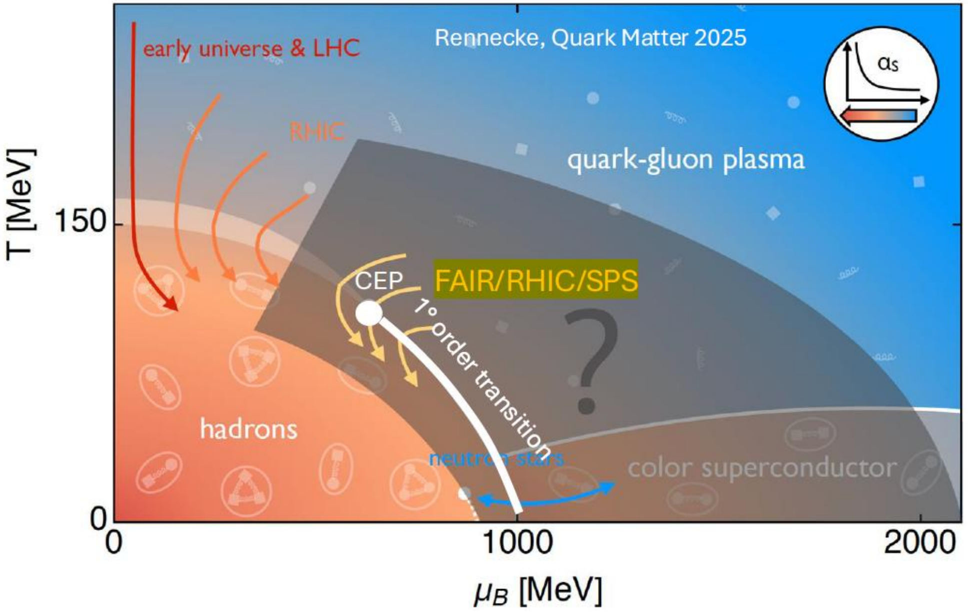
→ Sequential suppression and recombination in the charmonium sector

Charmonia: low vs. high $\sqrt{s_{NN}}$

- Nuclear PDFs:
  - ⇨ **SPS**: x ~ 10^{-1} (at y = 0) → **antishadowing**
  - ⇨ **LHC**: x ~ 10^{-3} (at y = 0) → **shadowing**
- Charmonium break-up in nuclear matter:
  - ⇨ **SPS**: **sizable**, because nuclei crossing time ($t_c \sim \mathrm{L}/\gamma_{\mathrm{cm}} \sim 0.5\ \mathrm{fm/c}$) is similar to $c\bar{c}$ formation time
  - ⇨ **LHC**: **negligible**, because nuclei crossing time is extremely short ($t_c \sim 10^{-3}\mathrm{fm/c}$)
- QGP effects:
  - ⇨ **SPS**: lower temperature, **suppression** of charmonia (if present) dominates
  - ⇨ **LHC**: higher temperature, initial suppression counterbalanced by $c\bar{c}$ **recombination** at later stages
- Recombination at SPS energies:
  - ⇨ On average 0.2 $c\bar{c}$ pairs created in central Pb-Pb collisions
  - ⇨ However, in a collision "with charm" (1 every 5 collisions) a c and a $\bar{c}$ are produced
  - ⇨ There is a non-zero probability to form charmonium (in the QGP or at the phase boundary) via recombination of these two quarks (so-called "endogamous" recombination)
  - ⇨ The so-called "exogamous" recombination (of c and $\bar{c}$ from different hard scatterings) is negligible

Going to lower $\sqrt{s_{NN}}$, why?

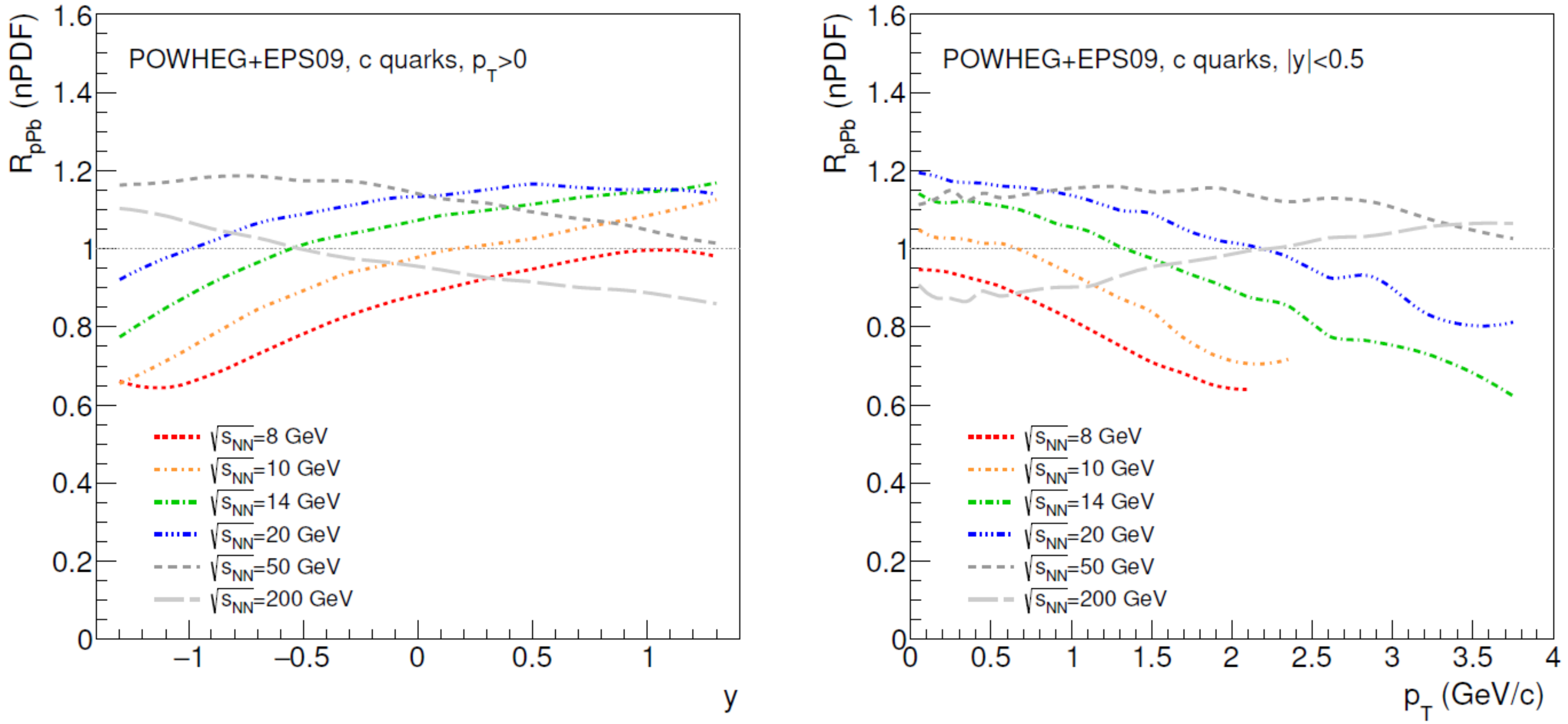
Charm: what can we still learn at low $\sqrt{s}$?



- Open charm: 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?**

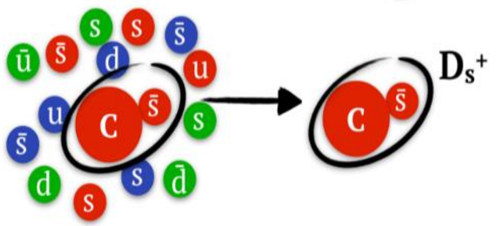
Nuclear PDFs

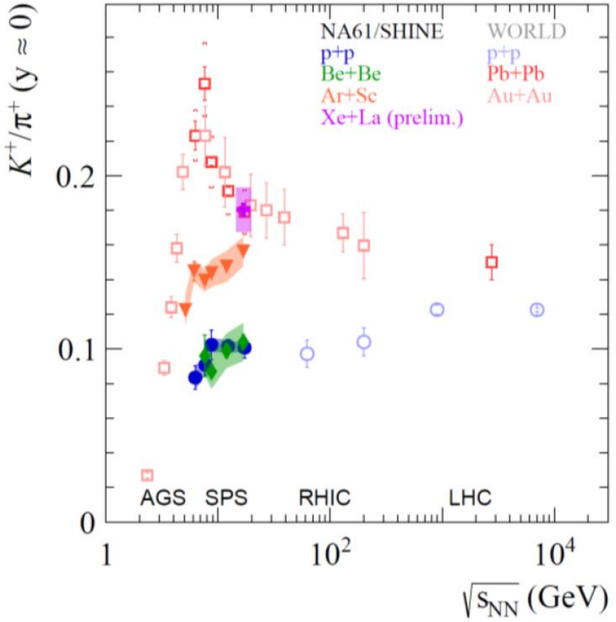
- Sensitivity to **nuclear PDFs in p-A** collisions at SPS ($\sqrt{s_{NN}}$ ~ 10-20 GeV)
  - ⇨ Unique opportunity to investigate the large x_{Bj} region: $0.1<x_{Bj}<0.3$ at Q^2~10-40 GeV^2
    - ✓ Probe EMC and anti-shadowing regions
  - ⇨ Perform measurements with various nuclear targets to access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

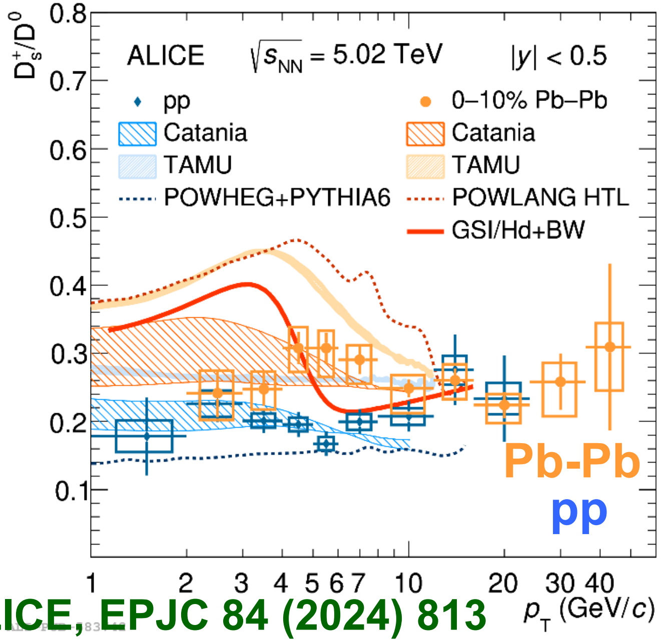


Open charm hadrochemistry

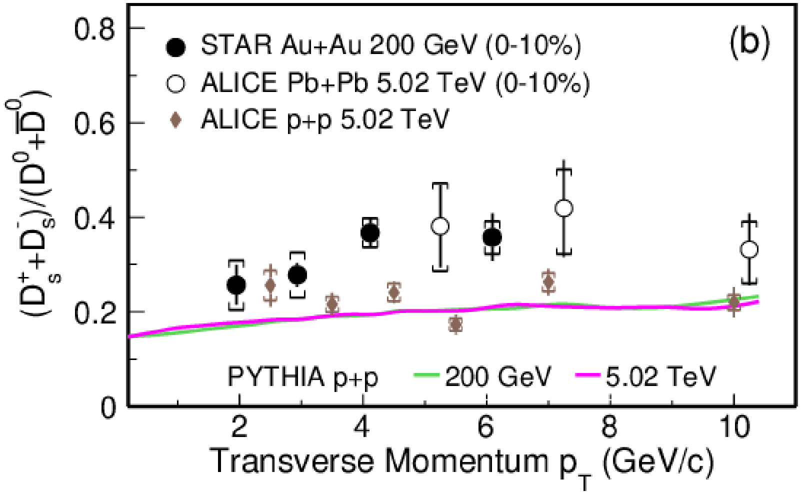
- Reconstruct different charm hadron species to get insight into **hadronization mechanism**
- **Strange/non-strange** meson ratio (D_s/D):
  - ⇨ D_s/D enhancement expected in A-A collisions due to hadronisation via **recombination** in the strangeness rich QGP
  - ⇨ Complement studies of strangeness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







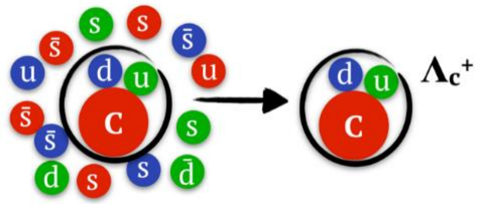
📖 ALICE, EPJC 84 (2024) 813

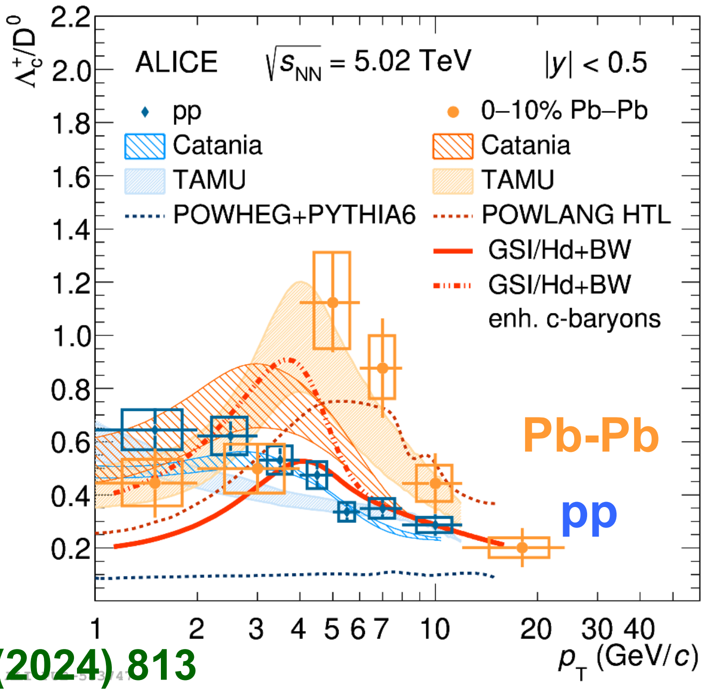


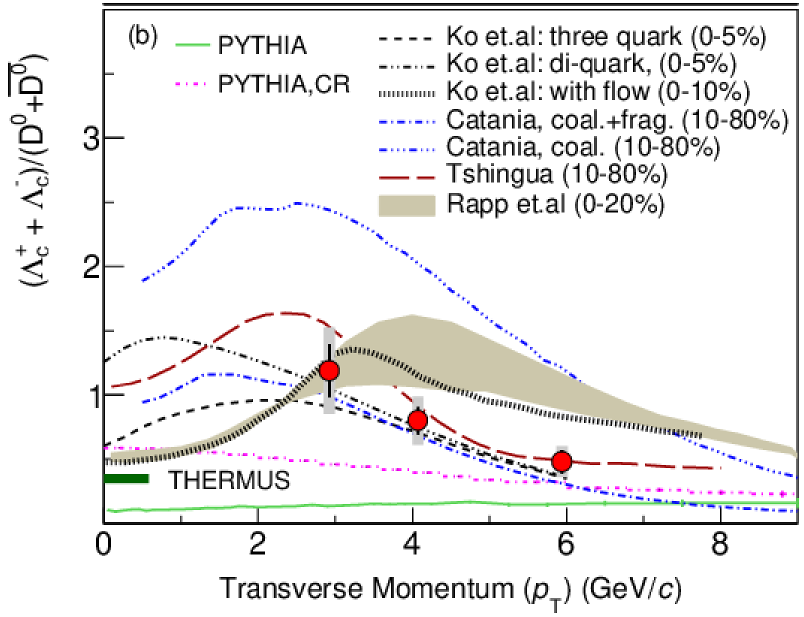
📖 STAR, PRL 127 (2021) 092301

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 recombination
  - ⇨ Interesting also in p-A since Λ_c/D^0 in pp (p-Pb) at LHC is higher than in e^+e^-





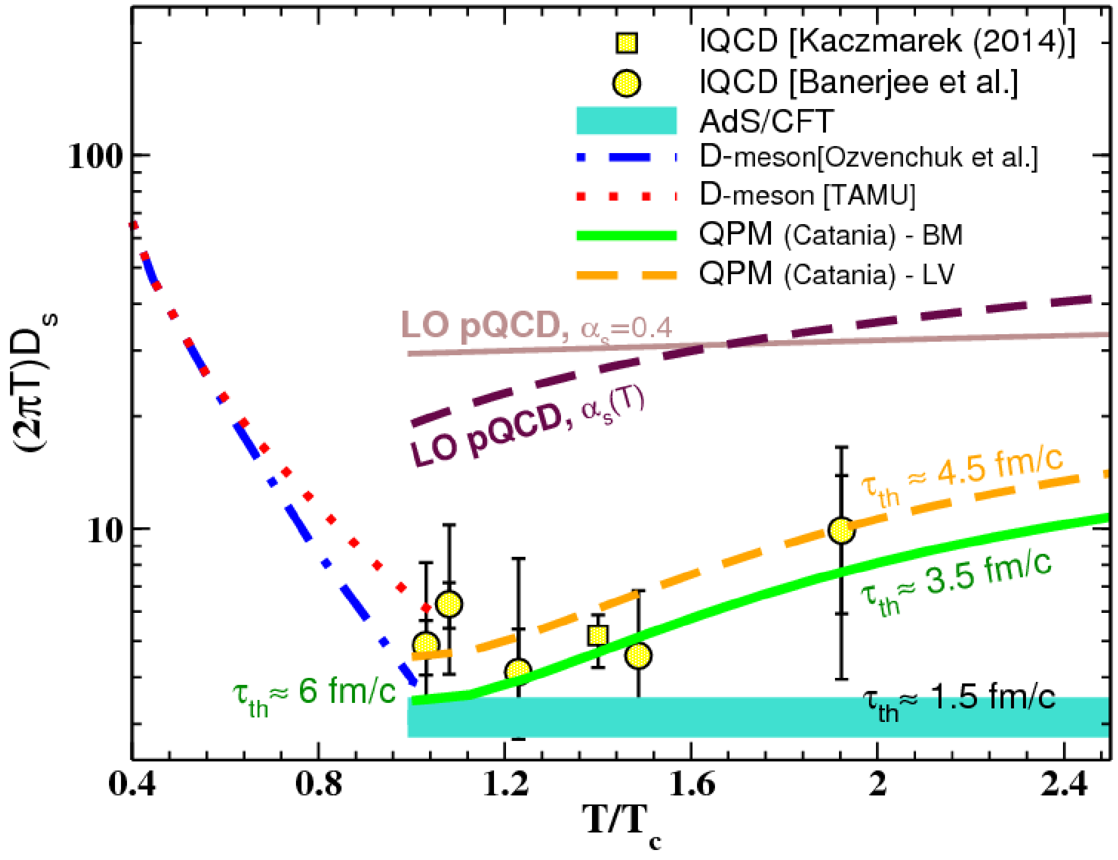


📖 ALICE, EPJC 84 (2024) 813

📖 STAR, PRL 124 (2020) 172301

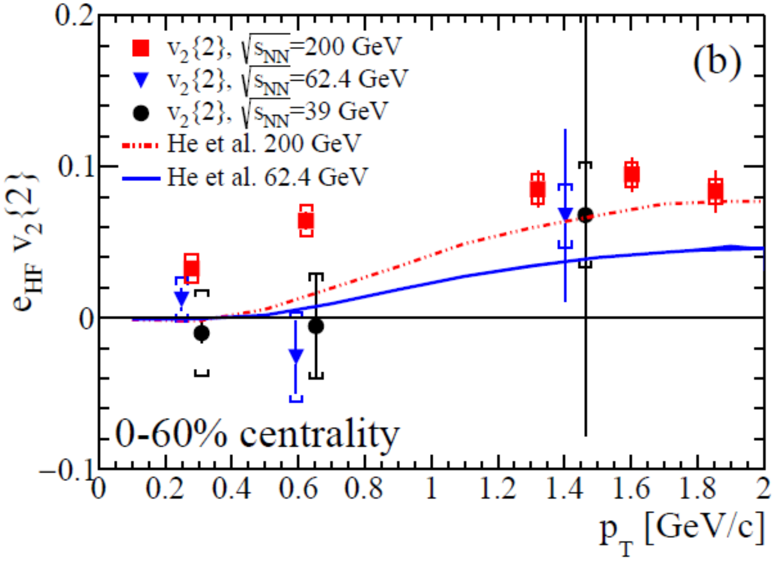
Charm in Pb-Pb: dN/dp_T and R_{AA}

- 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

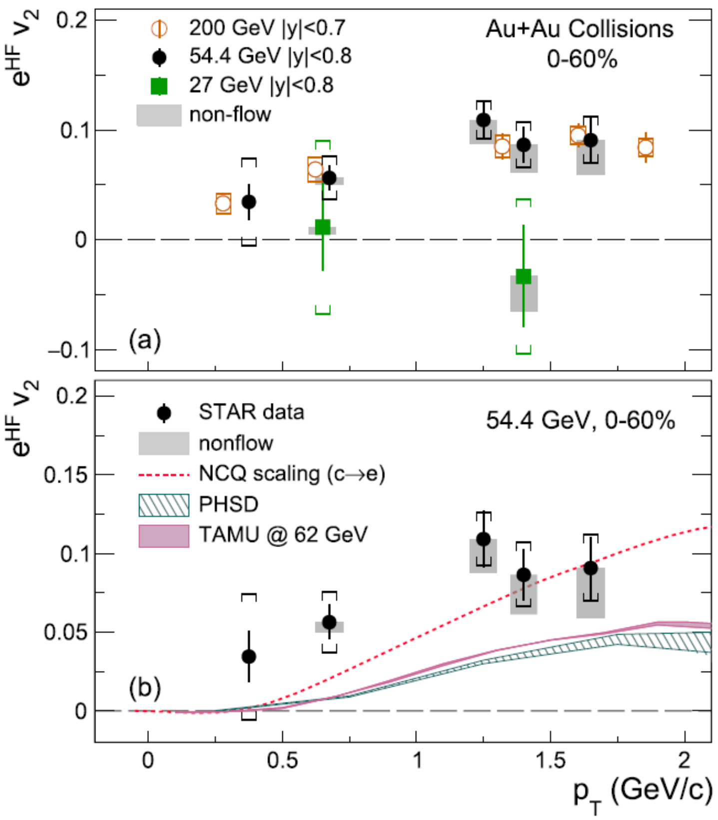


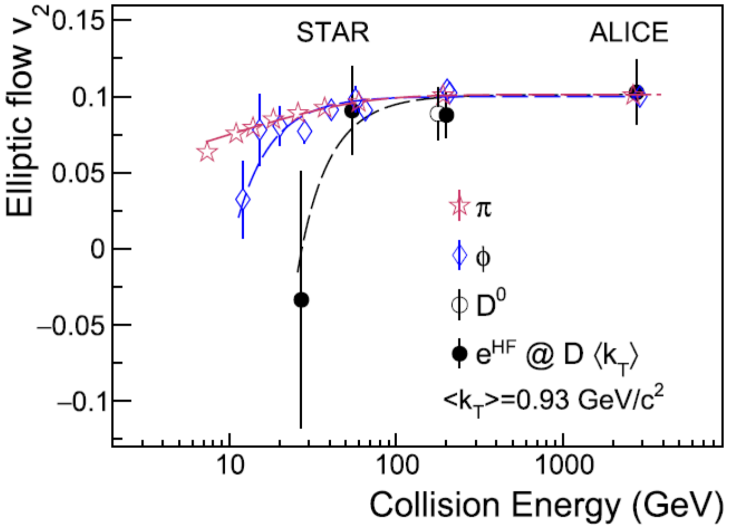
Charm in Pb-Pb: elliptic flow

- Study **charm thermalization** (hydrodynamization…) in the shorter-lived medium at lower collision energies
  - ➩ Current measurements of HF-decay electron v_2 at $\sqrt{s_{NN}}$=27 and 39 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



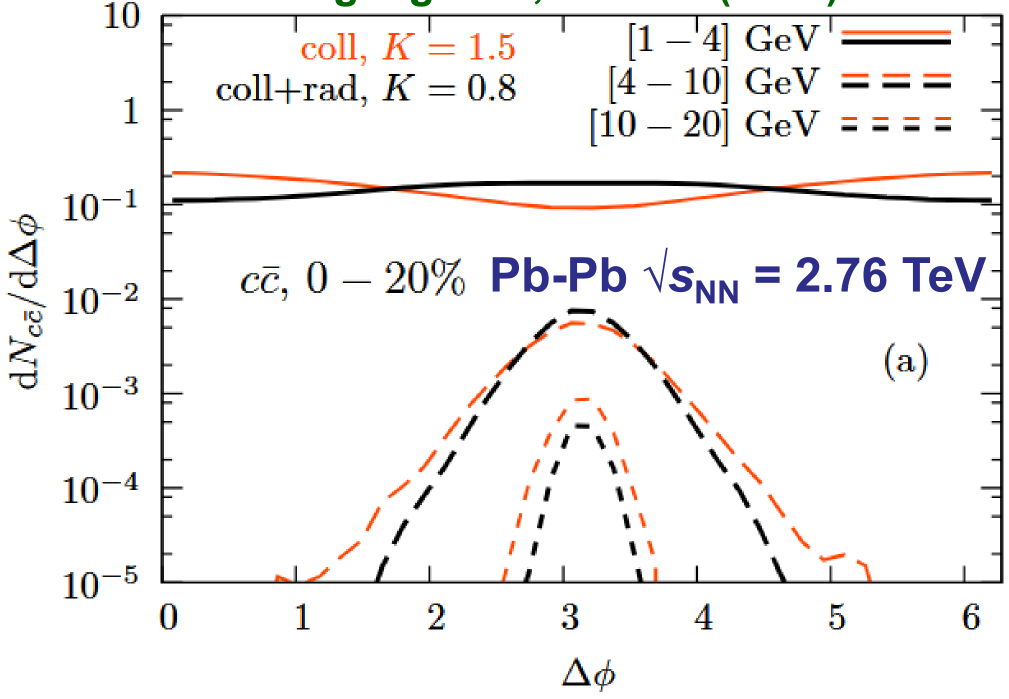


📖 STAR, PLB 844 (2023) 138071

$D\bar{D}$ angular correlations

- What can we learn from $\mathrm{D\bar{D}}$ correlations?
  - ⇨ At leading order, $\mathrm{c\bar{c}}$ 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 $\mathrm{D\bar{D}}$ 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

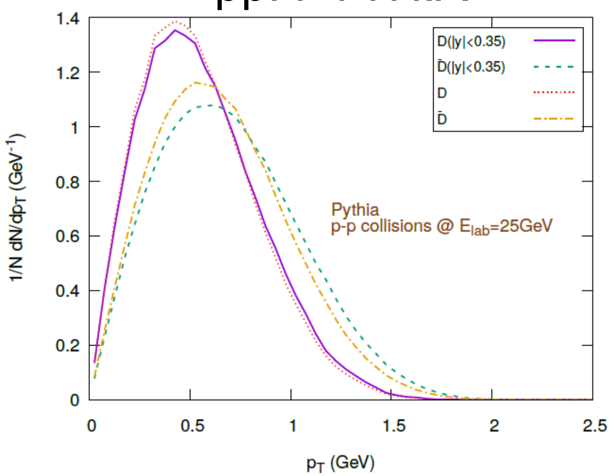
Nahrgang et al, PRC 90 (2014) 024907



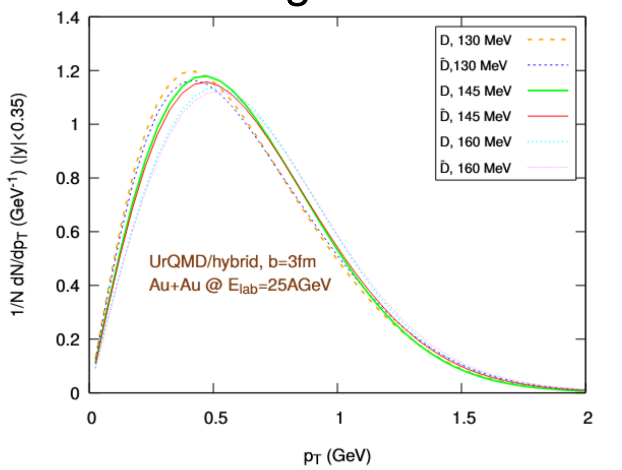
Diffusion at the production threshold

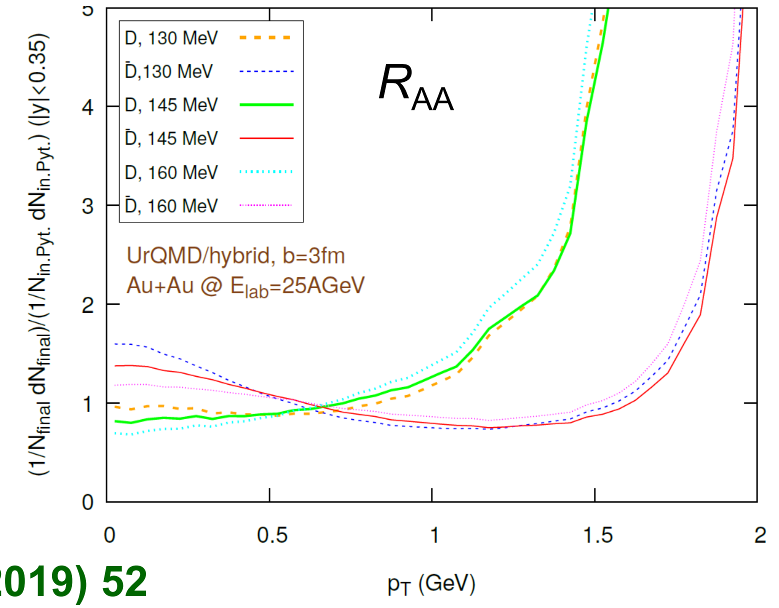
- Unique possibility at center-of-mass energies that are not too far above the charm production threshold
  - ⇨ Diffusion of charm particles (quark and/or hadrons) in the medium can drive them to higher momenta
  - ⇨ Could lead to an increase (even divergence) of the nuclear modification factor vs. p_T 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

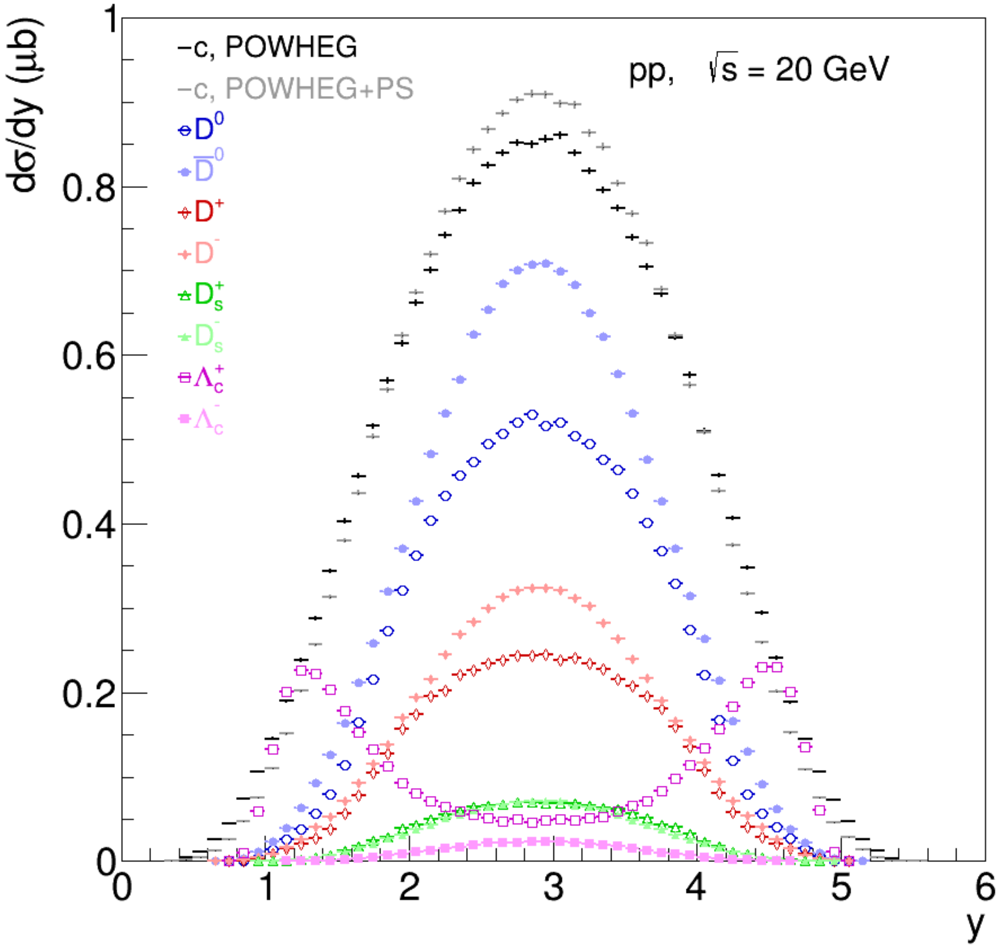




📖 **Inghirami et al, EPJC 79 (2019) 52**

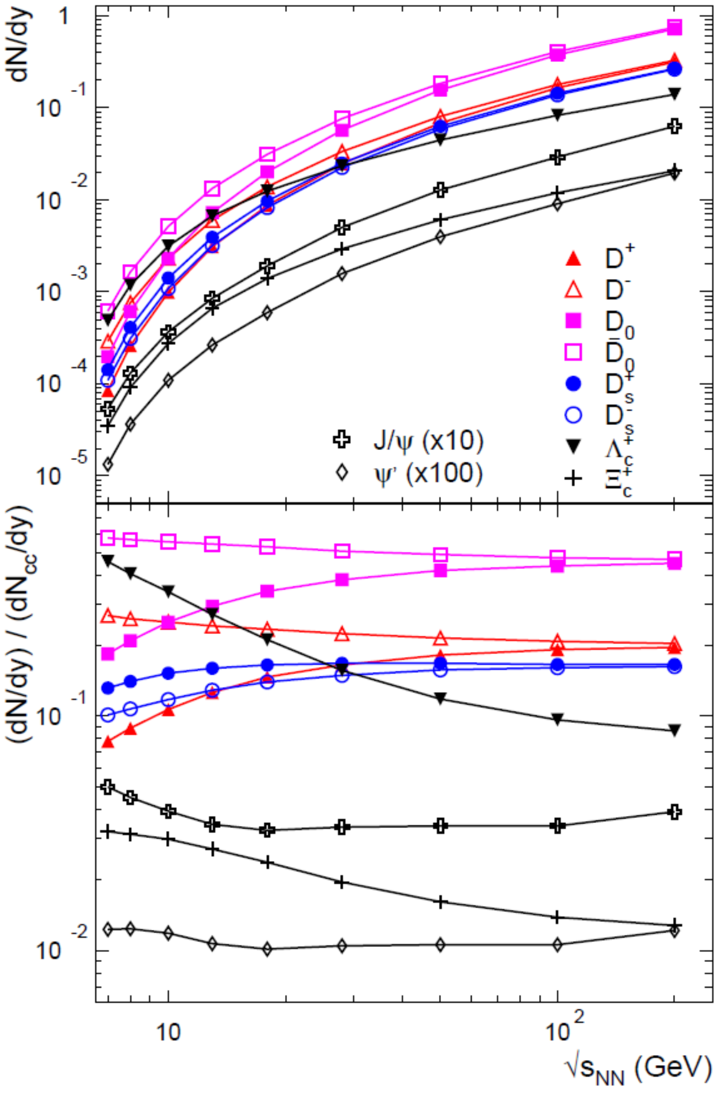
Open (and closed) charm hadrons

- 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 relative abundances affected by the medium produced in heavy-ion collisions?
  - ⇨ 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

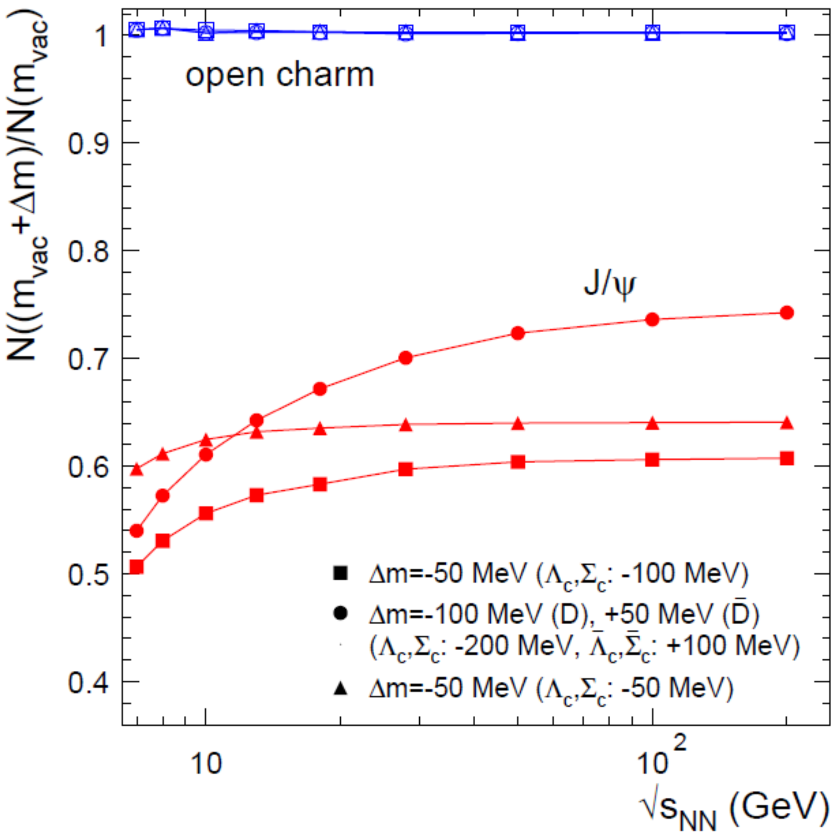
- Statistical hadronization model for charm
  - ⇨ Initial production of charm quarks in hard scatterings (pQCD+nPDF)
    - ✓ Charm yield determined by **charm cross section**, not by fireball temperature
  - ⇨ Charm conserved in the QGP
    - ✓ Accounted for by **charm balance equation** leading to a 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**

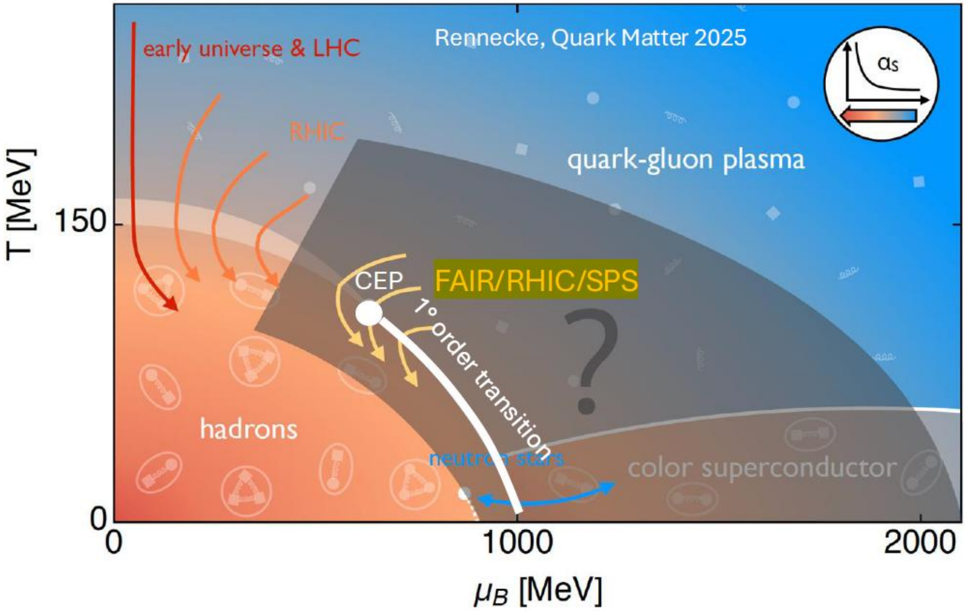
Open (and closed) charm hadrons

- 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



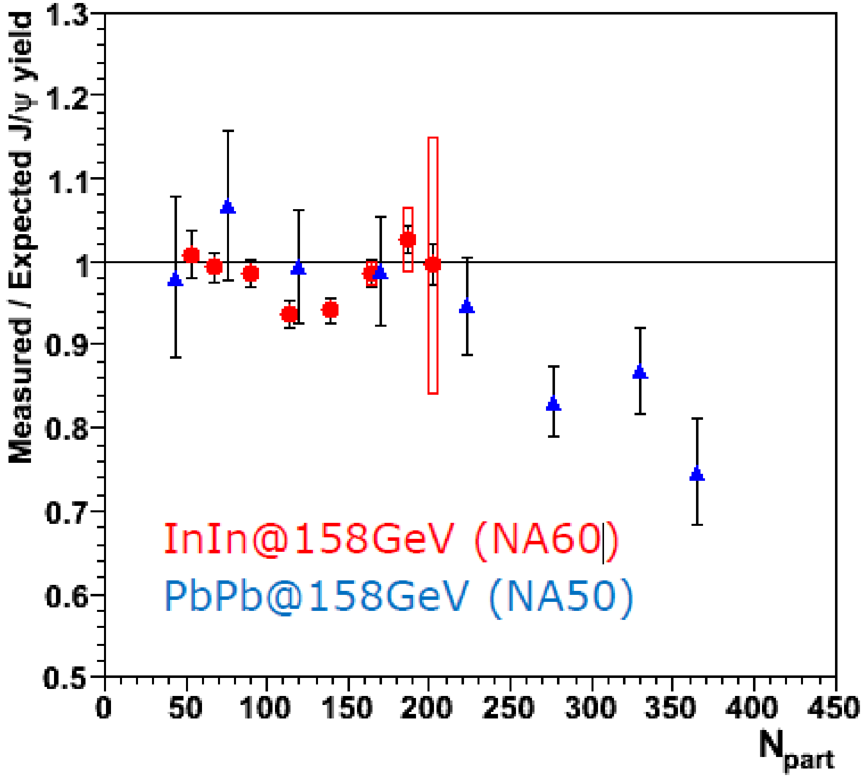
📖 **Andronic et al, PLB 659 (2008) 149**

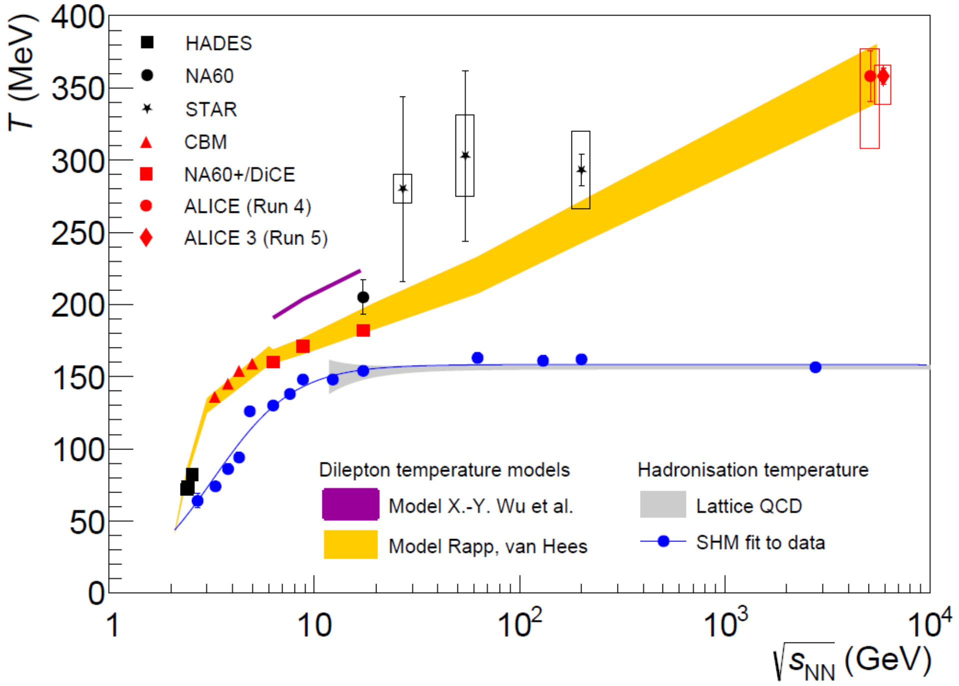
Charmonia: what can we still learn at low √s



- Charmonia
  - ⇨ Basically, no data available below top SPS energy
- J/ψ production in heavy-ion collisions
  - ⇨ Search for the **onset of deconfinement**
    - ✓ Can a threshold for hot matter effects be observed when lowering collision energy?
    - ✓ Can such thresholds be correlated with temperature measurements from an independent observable?
  - ⇨ Are there specific **μ_B-related effects**, with a quark excess influencing the dissociation process ?
- Study Cold Nuclear Matter effects
  - ⇨ Can comover vs QGP effects be separated when studying the √s-dependence of the suppression ?
  - ⇨ Can we understand the mechanisms at play for dissociation in CNM ?

Onset of charmonium suppression

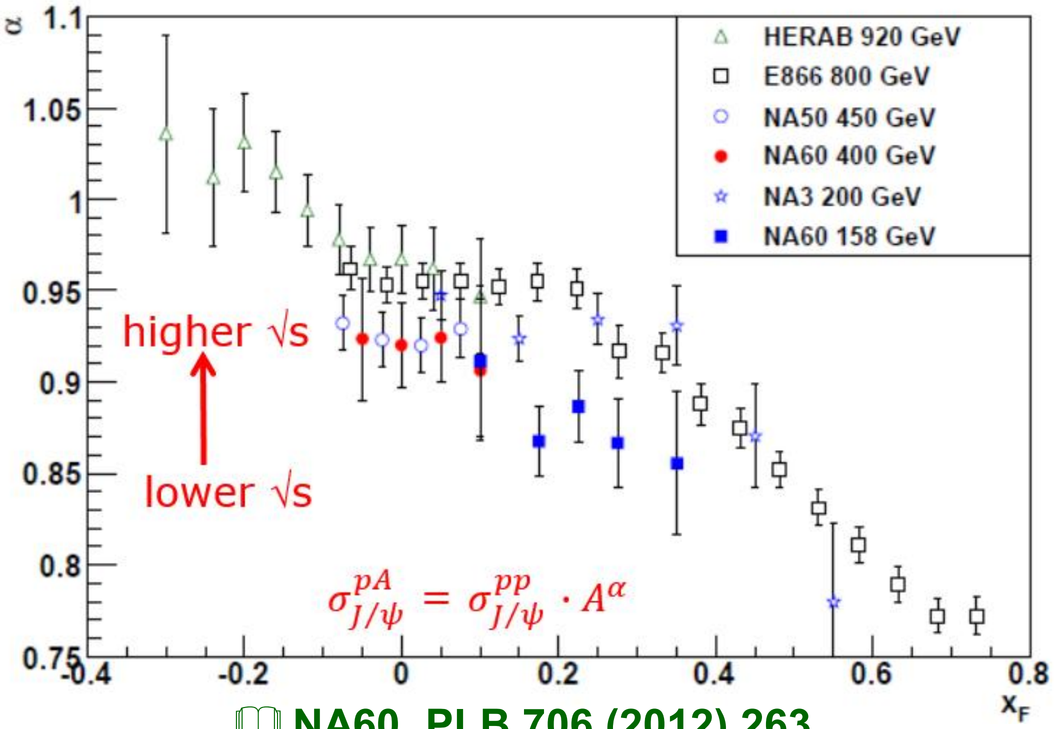




- Accessible via energy scan
- Evaluate the threshold temperature of the charmonium melting correlating the onset of suppression with T measured via thermal dimuons
  - ⇨ Dilepton T_{slope} reflects the (average) temperature of the early stage of the system
  - ⇨ T can be extracted by NA60+/DiCE with few MeV uncertainty

New insights into CNM effects

- CNM effects on J/ψ production observed to increase at low √s
- Measurements of CNM effects at different √s important because:
  - ⇨ Precise assessment of CNM effects (at the same √s as AA) is mandatory for the evaluation of hot matter effects
  - ⇨ Help to disentangle the various contributions (nPDFs, nuclear breakup…)

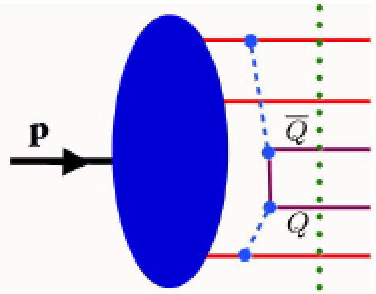


NA60, PLB 706 (2012) 263

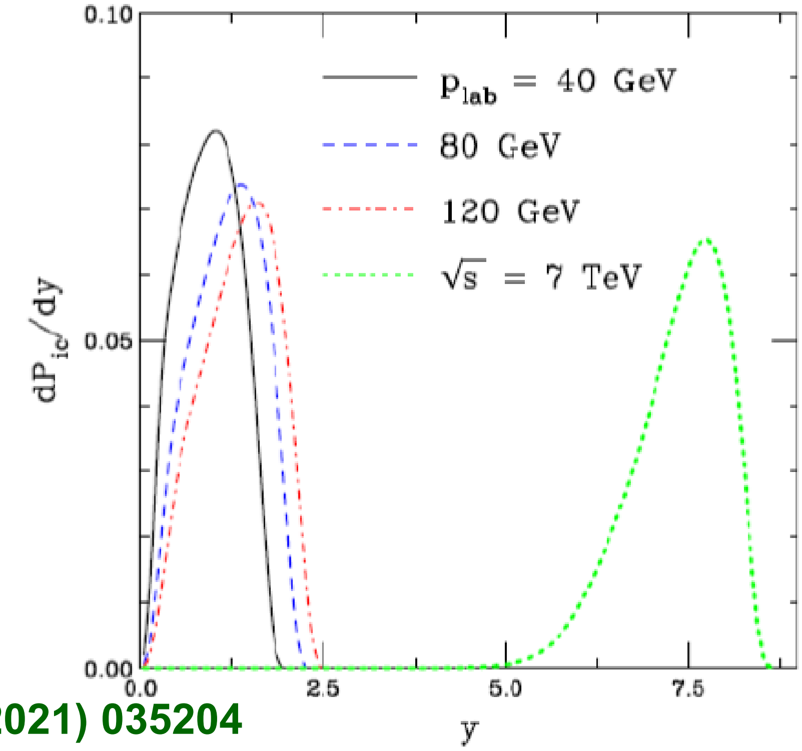
Intrinsic charm?

- Existence of a nonperturbative intrinsic heavy quark component in the nucleon wave function is a rigorous QCD prediction
  - ⇨ E.g. 5-quark Fock state |uudcc>
  - ⇨ When the proton scatters in a target, the coherence of the Fock components is broken and the fluctuations can hadronize

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



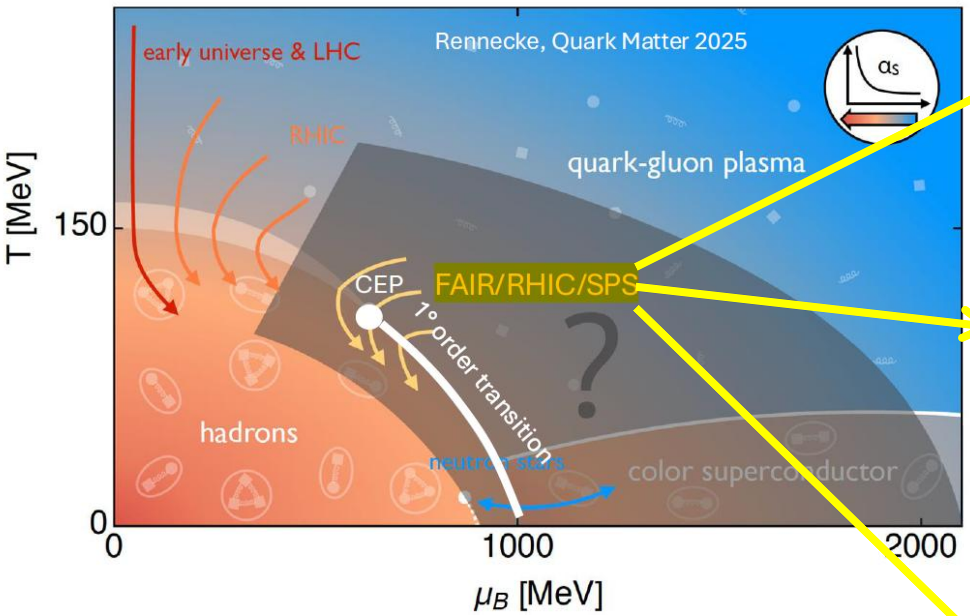
- Unambiguous experimental confirmation still missing
- Expected enhanced charm and charmonium production at large x_F
  - ⇨ Fixed target is the ideal configuration because enhancement expected closer to mid-y
  - ⇨ NA60+/DiCE at the SPS can provide an ideal experimental setup for these studies

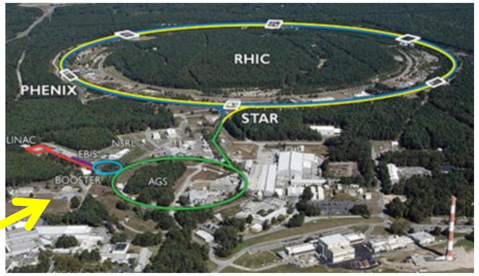


📖 **R. Vogt, PRC 103 (2021) 035204**

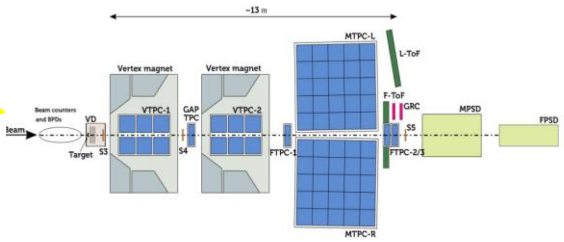
Prospects with NA60+/DiCE

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

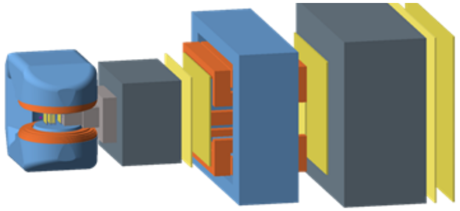




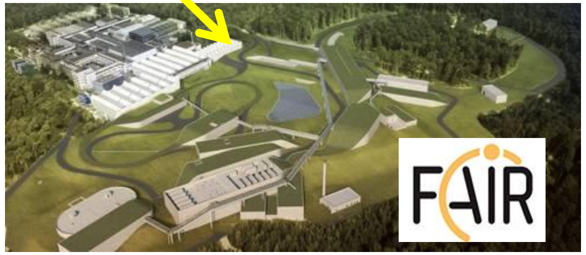
- **RHIC** Beam Energy scan
  - ⇨ Covers $\sqrt{s_{NN}}$ = 3-200 GeV
  - ⇨ Hadronic (soft) observables



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



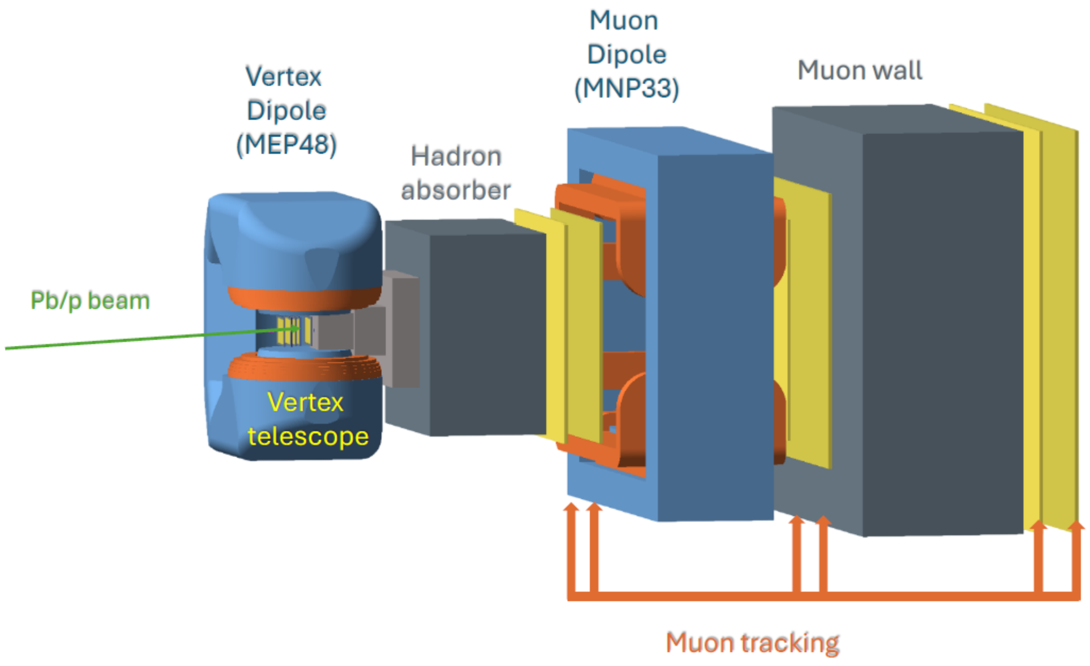
- New proposed experiment @ **SPS**: NA60+/DiCE
  - ⇨ Hard and electromagnetic probes



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

NA60+/DiCE at the low √s frontier

- NA60+ proposed experiment at CERN SPS
- **Goal**: study of hard and electromagnetic processes at CERN-SPS energies and investigation of the high-μ_B region of the QCD phase diagram QGP

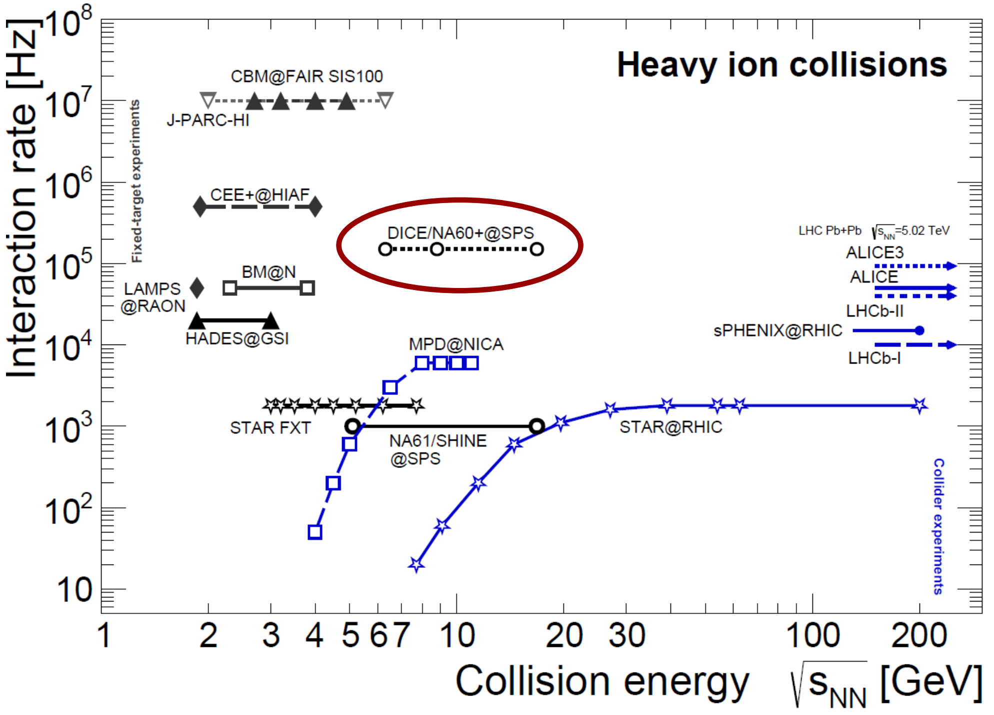


- **Hard** processes:
  - ⇨ Probe the Quark-Gluon Plasma and study its transport properties
- **Electromagnetic** processes
  - ⇨ Information on the temperature of the system (QGP and/or hadronic)
  - ⇨ Information on the nature of the phase transition
  - ⇨ Insight into the approach to chiral symmetry restoration

📖 **NA60+/DiCE proposal, CERN-SPSC-2025-023**

NA60+/DiCE at CERN SPS

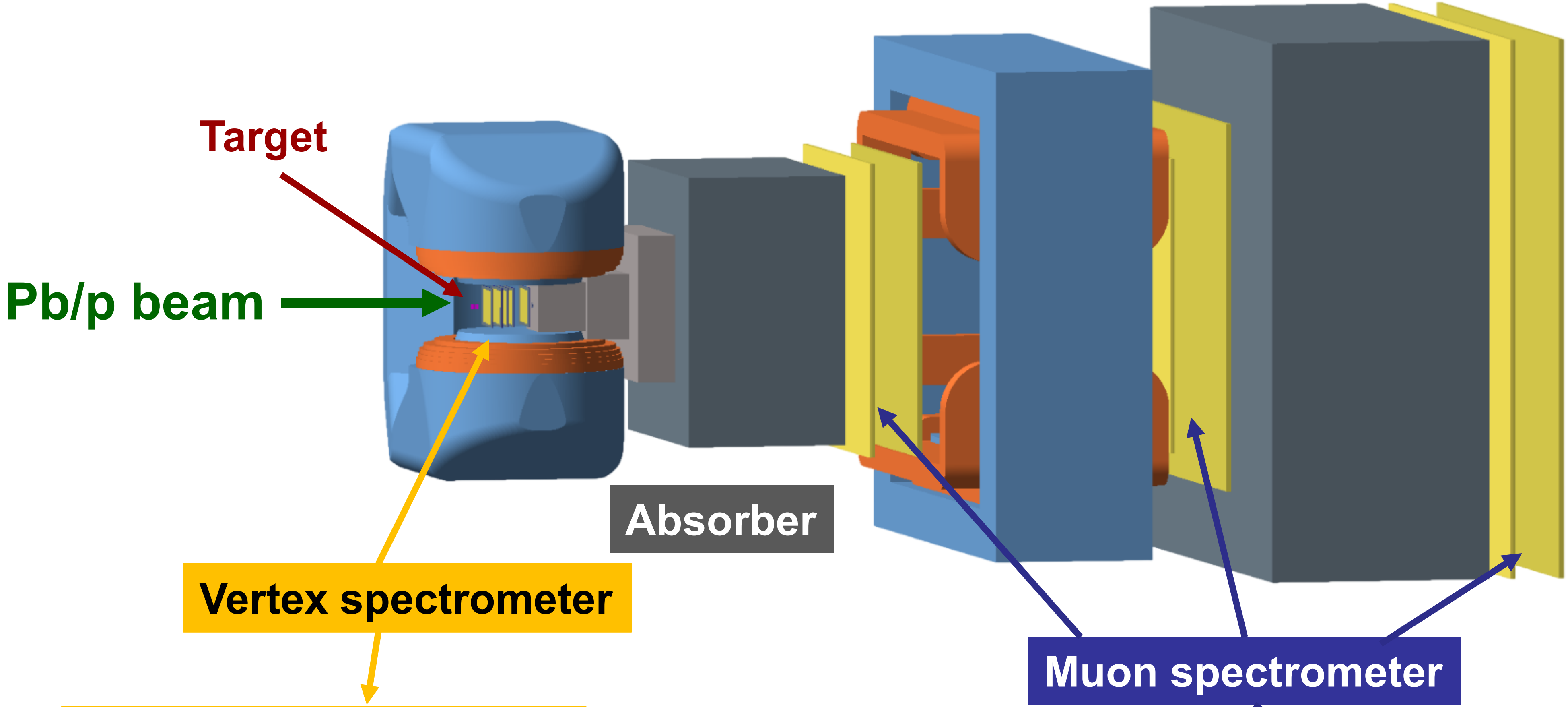
- Focus on particles from hard and electromagnetic processes, which are **rare processes**
  - ⇨ High precision measurements of these observables require **large interaction rates**
  - ⇨ Operation in **fixed target** mode
- Access a **wide μ_B interval**
  - ⇨ CERN SPS allows a **beam energy scan** in the range $6<\sqrt{s_{NN}}<17$ GeV corresponding to $200<\mu_B<450$ MeV
- Complementarity with experiments accessing:
  - ⇨ Different (hadronic) observables in the same energy range (RHIC BES, NA61/SHINE)
  - ⇨ Similar observables in a lower energy range (CBM at FAIR)



📖 Galatyuk, NPA 982 (2019), update May2025

→ Unique experiment in terms of energy coverage and interaction rate in the HI landscape!

NA60+/DiCE detector concept

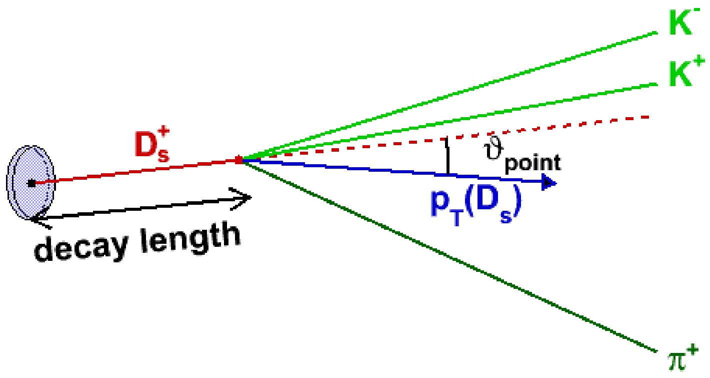


Precise tracking close to the interaction point

Measure dimuons downstream of absorber.
Absorber length will be varied with $\sqrt{s}$

Charm hadron reconstruction

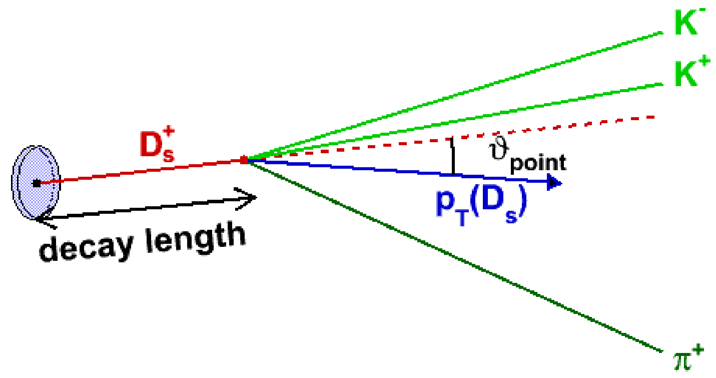
- Charmed mesons and baryons can be reconstructed from their decays into 2 or 3 charged hadrons
- Small production cross section + small(ish) BRs
  - ⇨Require large samples of minimum-bias collisions
- Mean proper decay lengths $c\tau$ ~60-300 μm
  - ⇨High precision on tracking and vertexing required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



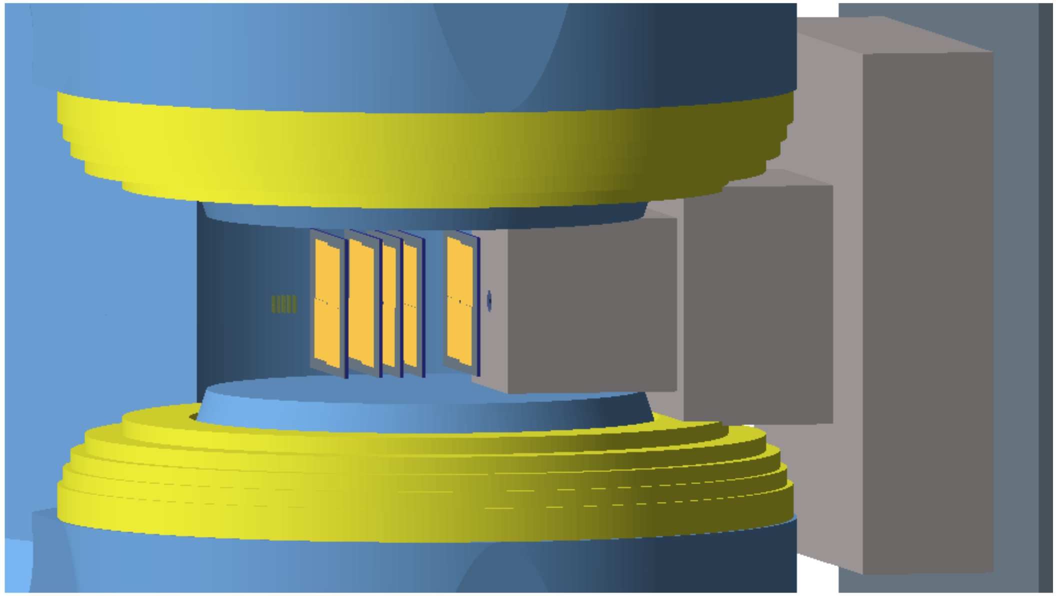
Hadron	Mass (MeV/c²)	$c\tau$ (μm)	Decay	BR
D^0	1865	123	$\rightarrow K^-\pi^+$	3.945%
D^+	1869	312	$\rightarrow K^-\pi^+\pi^+$	9.38%
D_s^+	1968	147	$\rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$	2.25%
Λ_c^+	2285	60	$\rightarrow pK^-\pi^+$ $\rightarrow pK^0_s$ $\rightarrow \Lambda\pi^+$	6.35% 1.61% 1.31%

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)

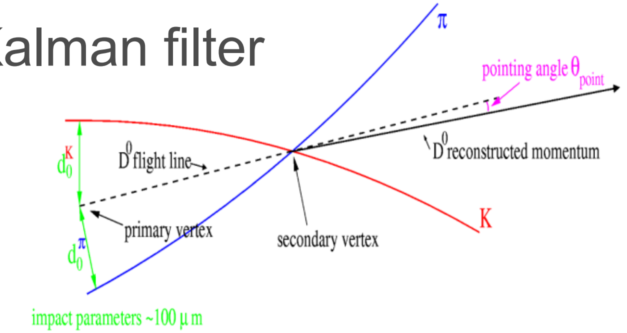


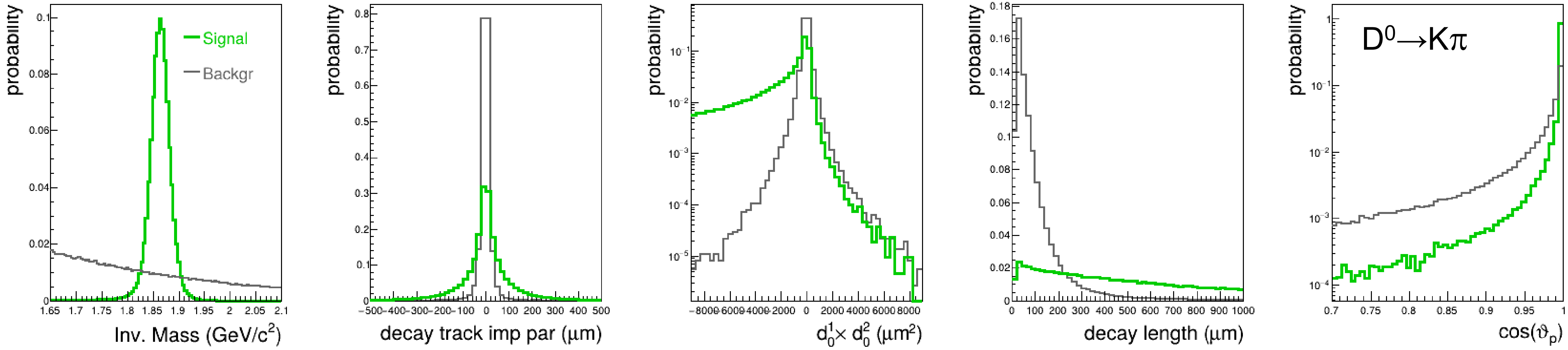
- Detector requirements:
  - ⇨High precision on track and vertex reconstruction
  - ⇨Low material budget



D-meson performance studies

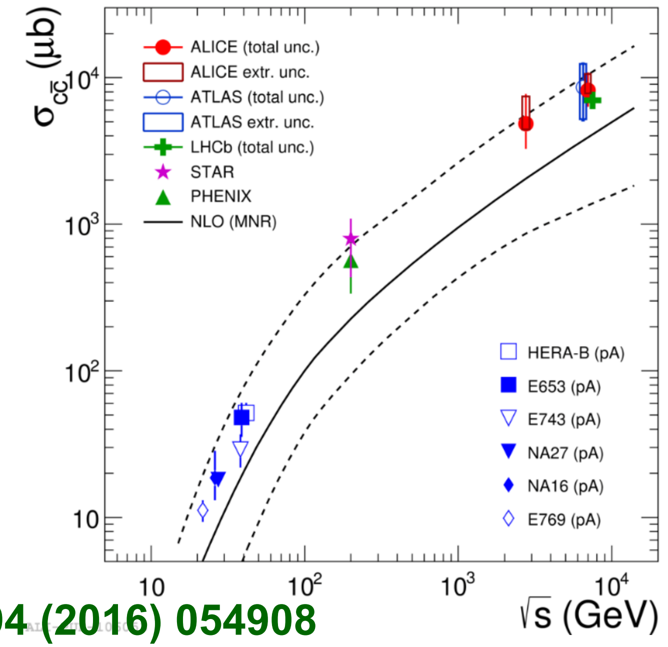
- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA
  - ⇨ Combinatorial background: dN/dp_T and dN/dy of π, K and p from NA49
  - ⇨ Parametrized simulation of VT resolution + track reconstruction with Kalman filter
  - ⇨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



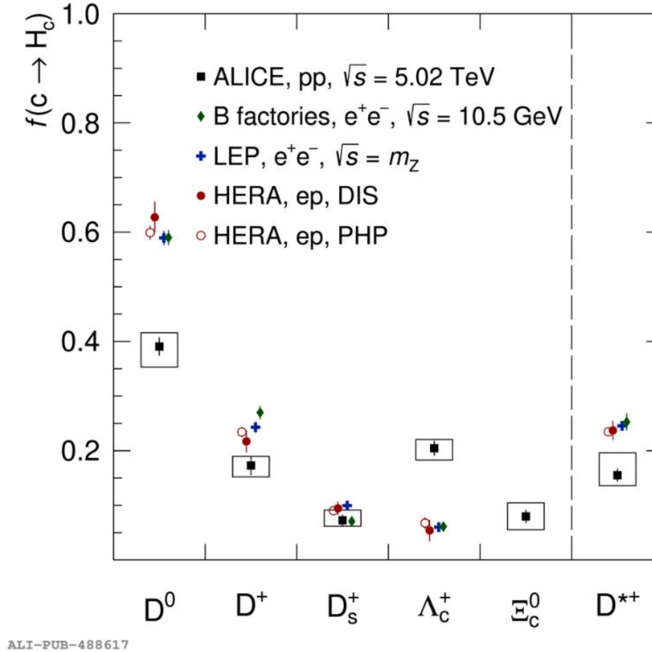


Normalization of signal

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



📖 ALICE, PRC94 (2016) 054908

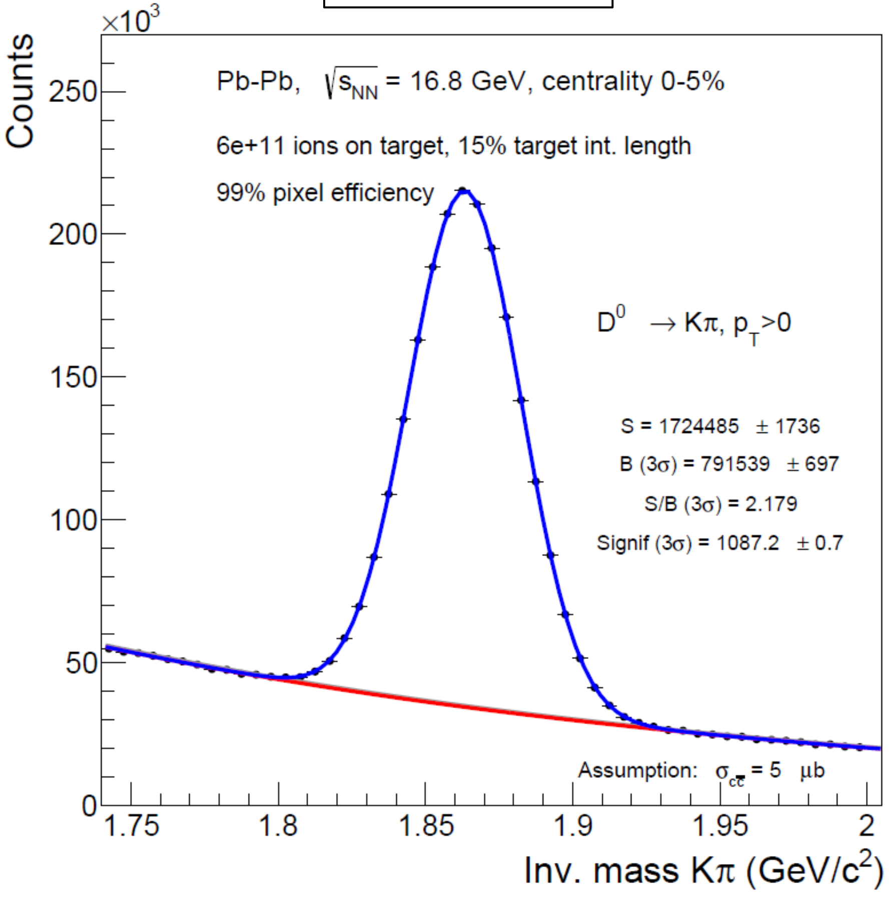


📖 ALICE, arXiv:2105.06335

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
- 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

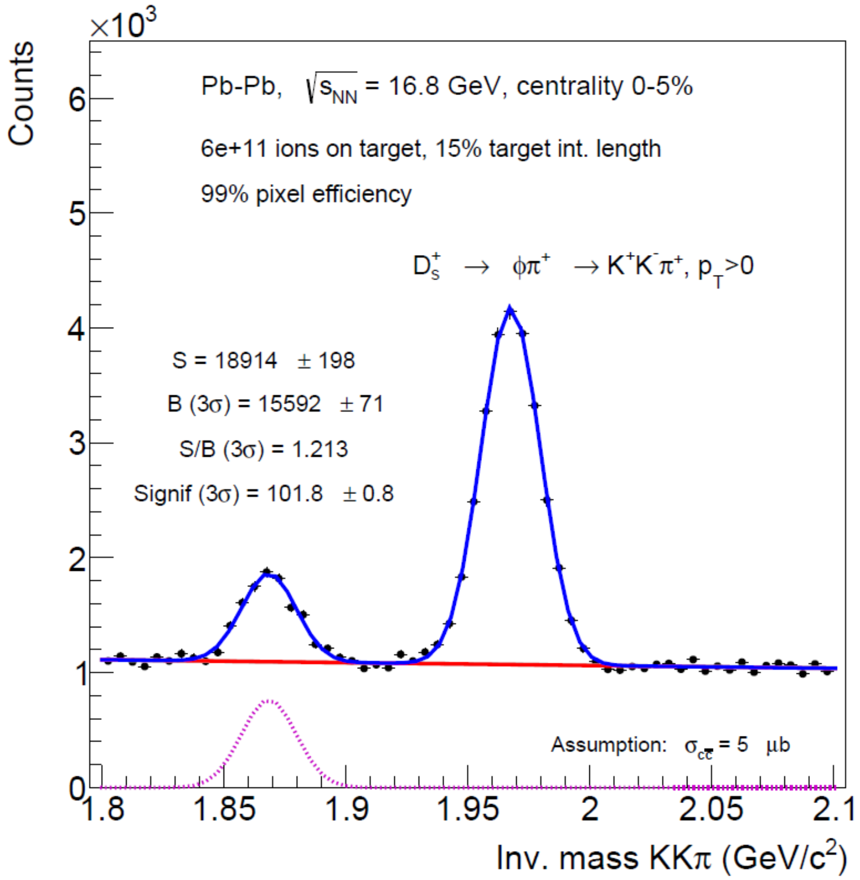
$D^0 \rightarrow K\pi$



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
- 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
- $D^+ \rightarrow KK\pi$ peak visible near the D_s^+ one, but D^+ performance will be better in the $K\pi\pi$ channel (with 10 times higher BR)

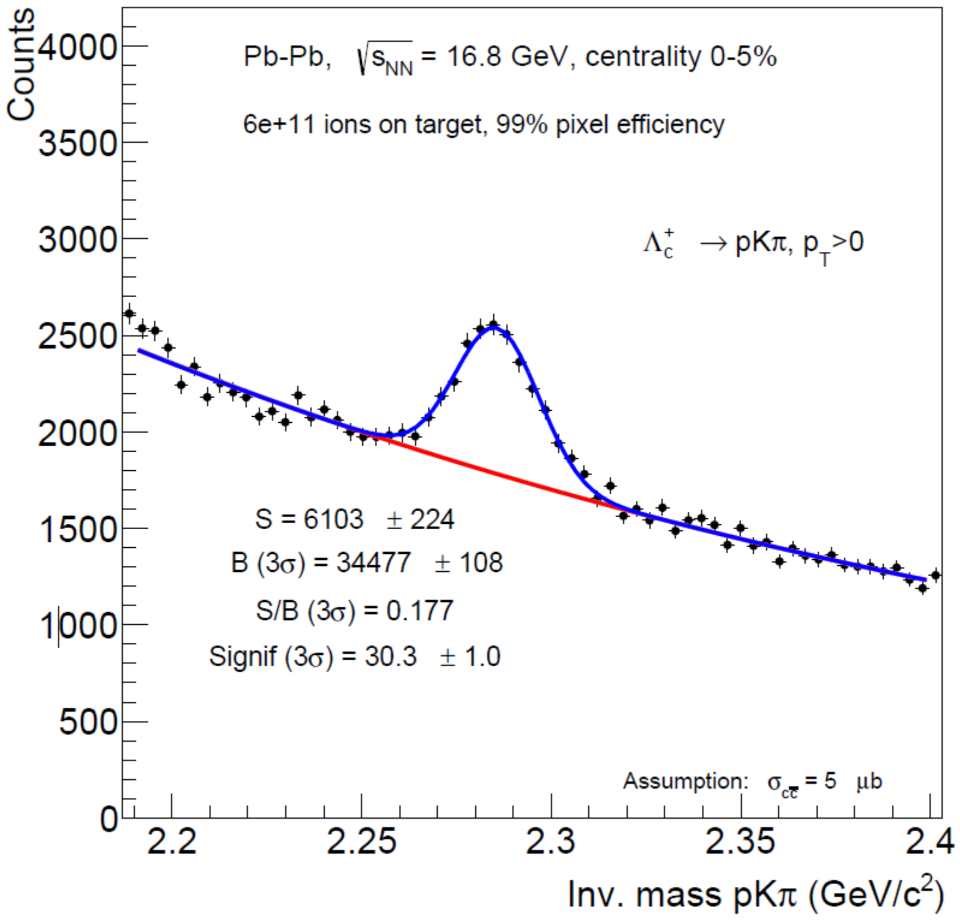
$D_s^+ \rightarrow \phi\pi \rightarrow KK\pi$



NA60+ physics performance : Λ_c^+

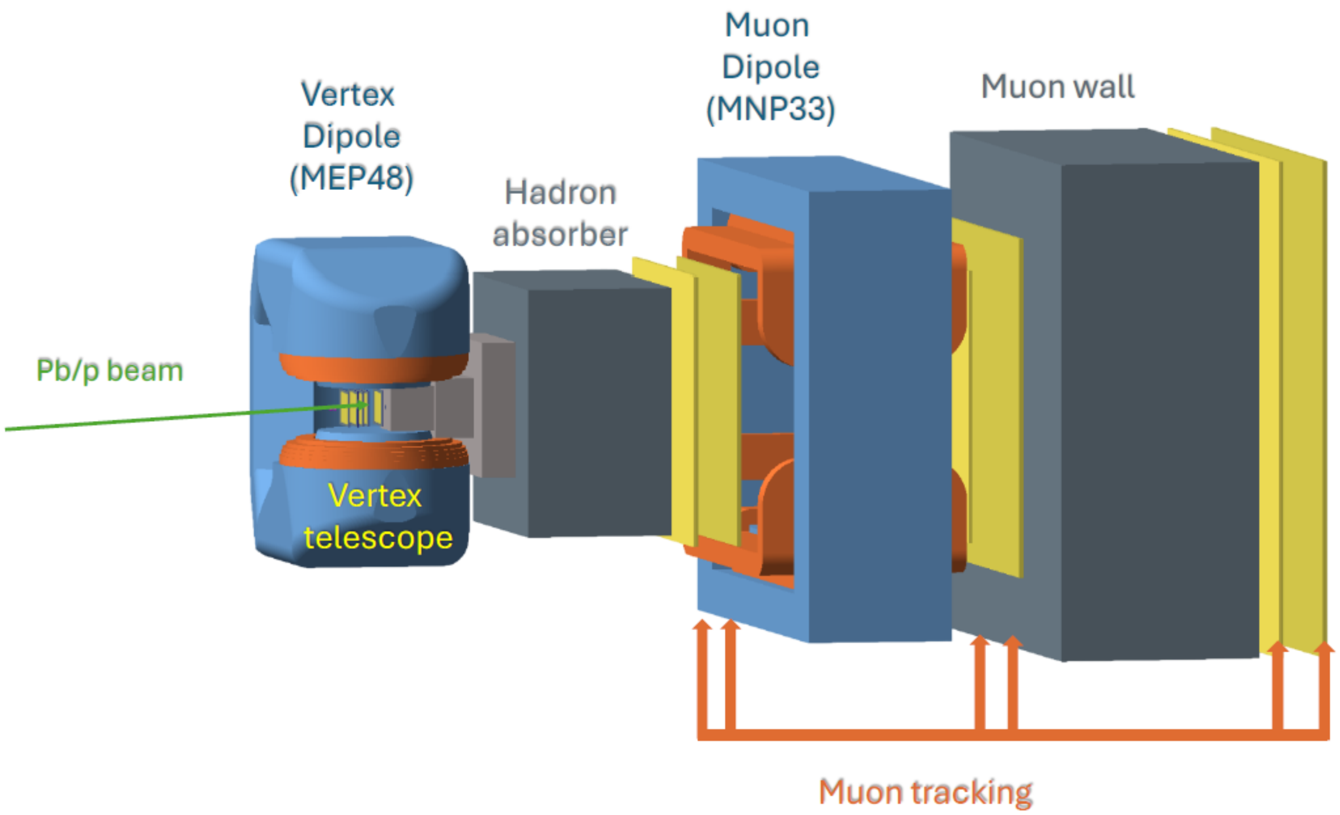
- Selections on **displaced decay vertex topology**
  - ⇨ Initial S/B ~ 10^{-9} (assuming f(c $\rightarrow \Lambda_c$)=10%) → after selections (based on BDT): S/B ~ 0.1 with 2% selection efficiency
- With 6×10^{11} Pb ions on target at E_{beam} = 150 GeV and 15% target interaction length (1 month of 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

$\Lambda_c^+ \rightarrow pK\pi$



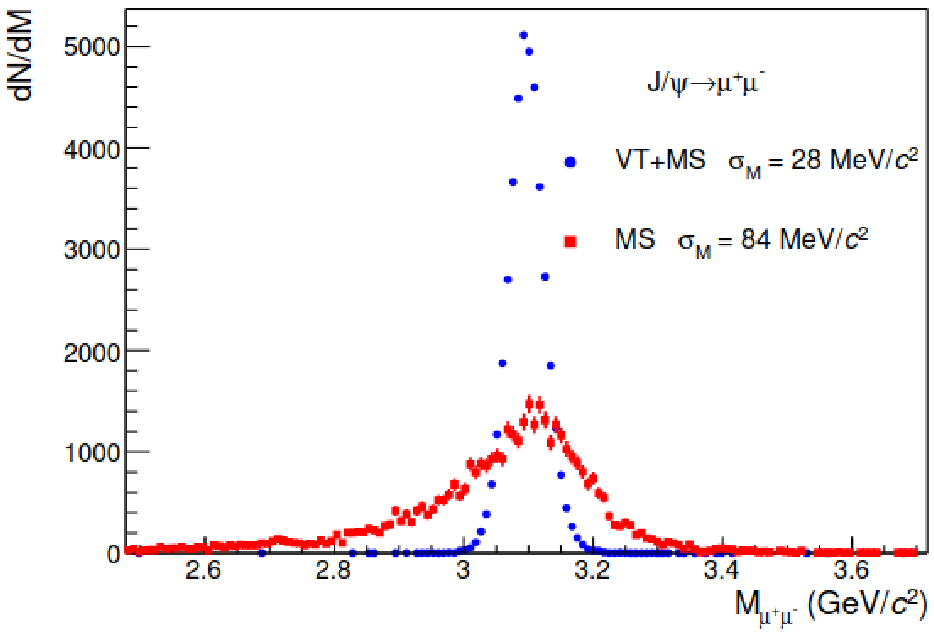
Charmonium reconstruction in NA60+/DiCE

- J/ψ and $\psi(2S)$ reconstructed from their dimuon decay
  - ⇨ $BR(J/\psi \rightarrow \mu^+\mu^-) = 5.96\%$
  - ⇨ $BR(\psi(2S) \rightarrow \mu^+\mu^-) = 0.8\%$
- Muon tracks reconstructed in the Muon Spectrometer and matched to the Vertex Telescope
- Under study: possibility of measuring $\chi_c \rightarrow J/\psi+\gamma$
  - ⇨ γ reconstructed via conversion in an e^+e^- pair in the vertex telescope

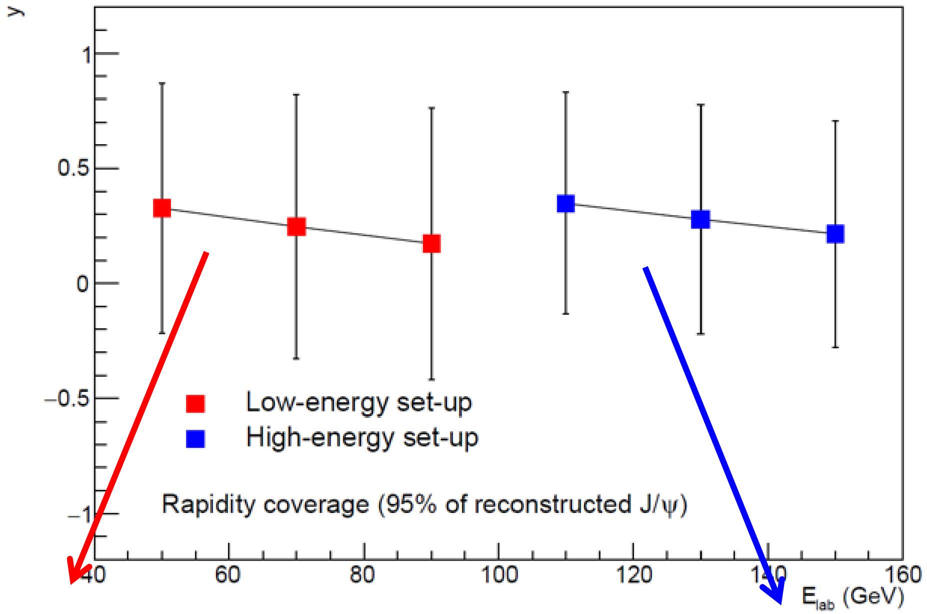


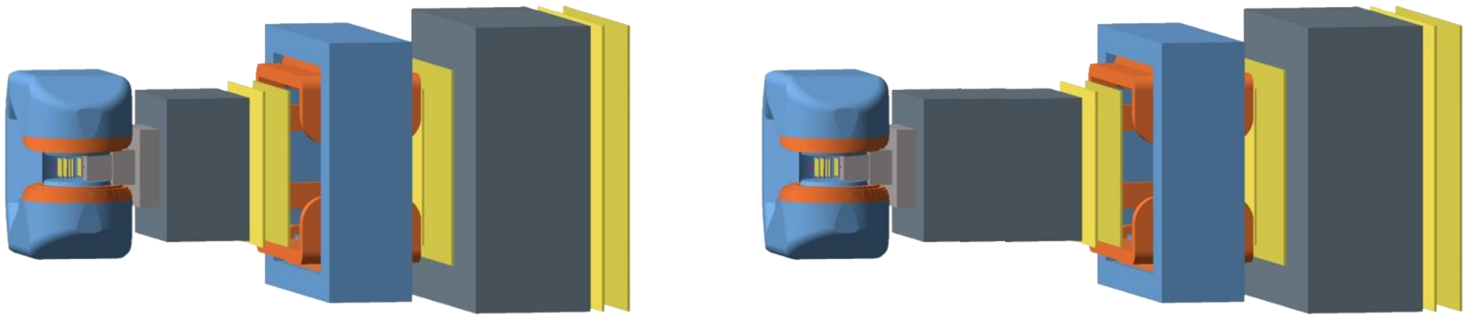
Charmonium reconstruction in NA60+/DiCE

- Very good mass resolution
  - ⇨ ~30 MeV/c^2 for J/ψ



- One-unit rapidity coverage, reaching mid-y at all energies (adapting the setup)

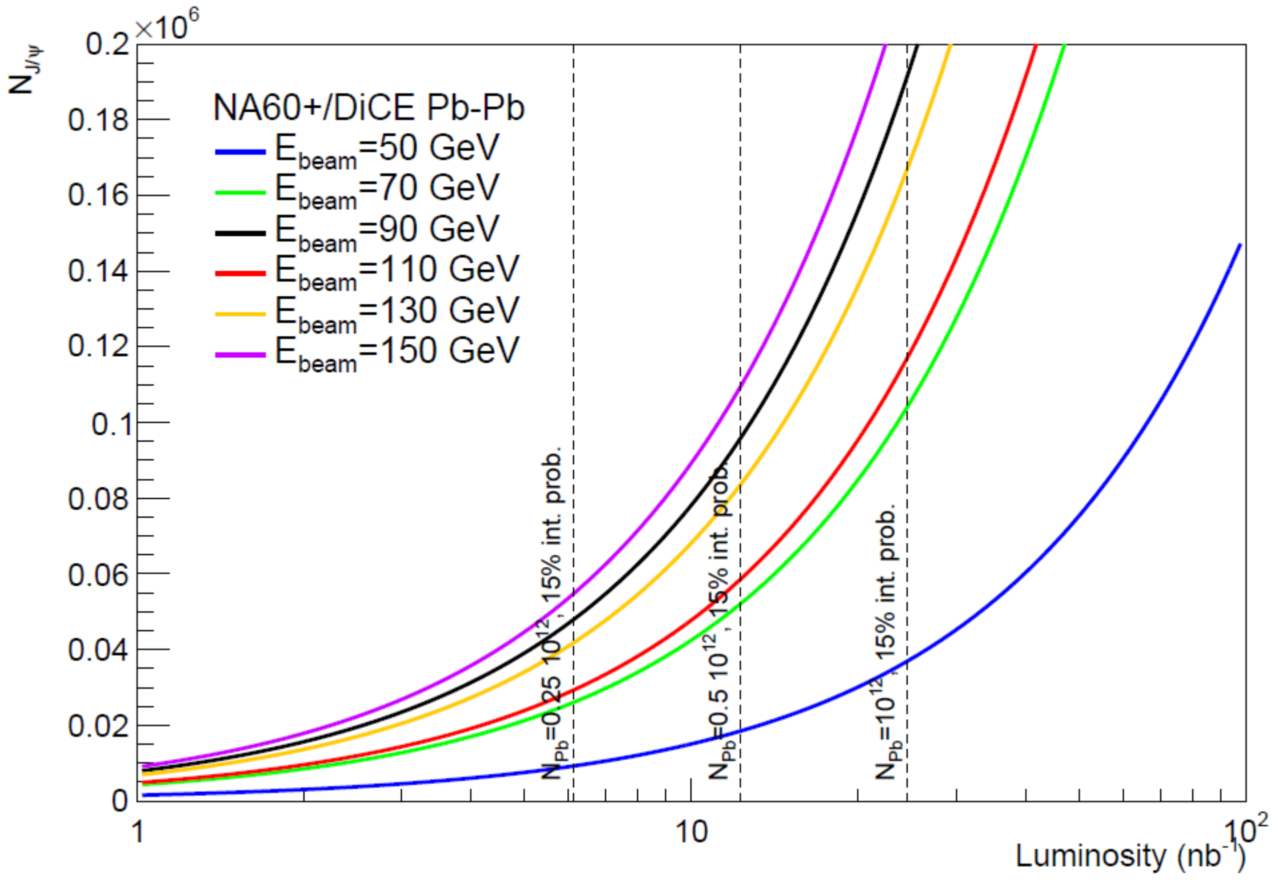




Estimation of expected yields

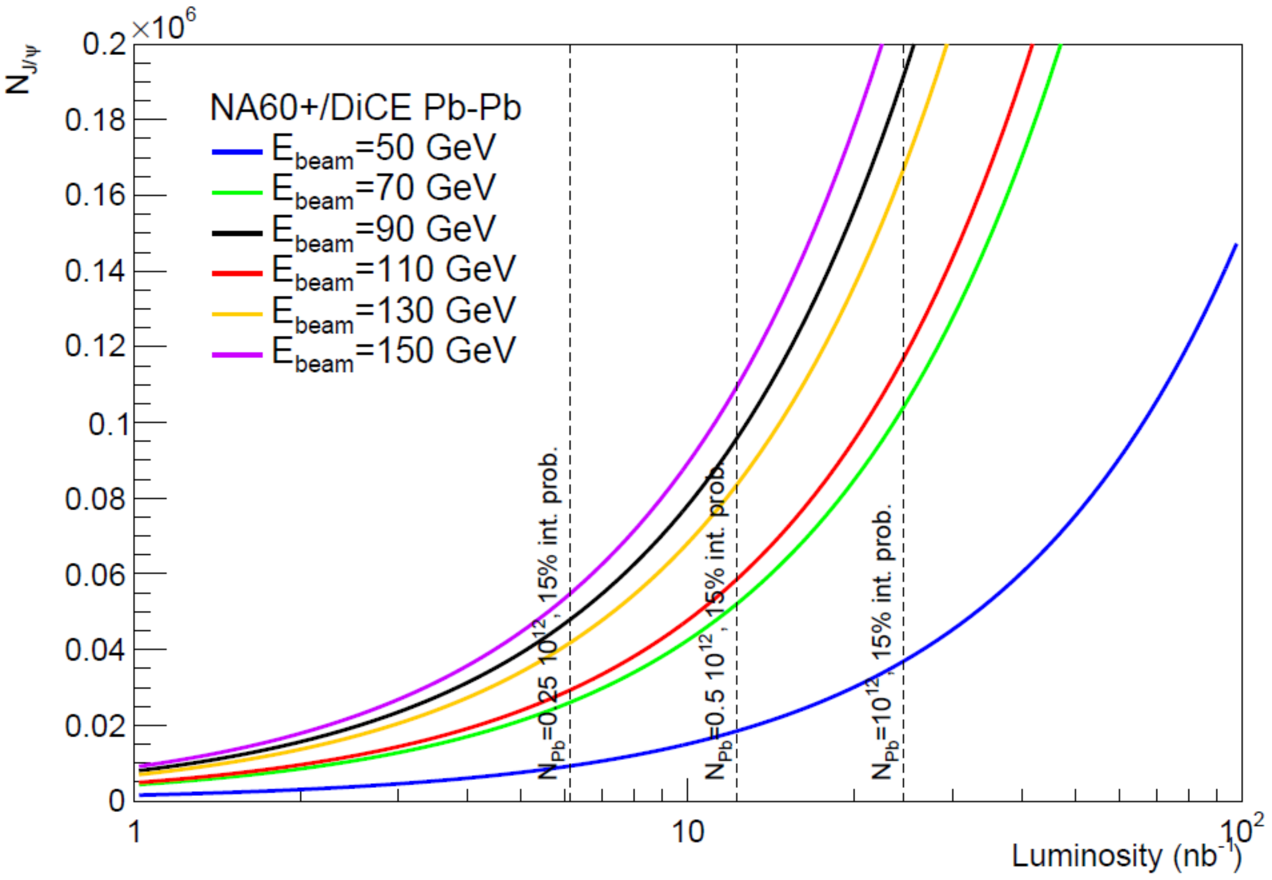
- Difficult to have precise estimates due to:
  - ⇨ Scarce knowledge of the elementary production cross section
  - ⇨ Unknown CNM and hot matter effects

- High luminosity needed to cope with the low production cross sections, especially at low √s
  - ⇨ Pb beam intensity: ~5×10^5 ions/s
  - ⇨ Pb-ions on target at each energy: 0.6×10^{12}
  - ⇨ Target interaction length = 15%
  - ⇨ Integrated luminosity ~ 15 nb^{-1} at each energy

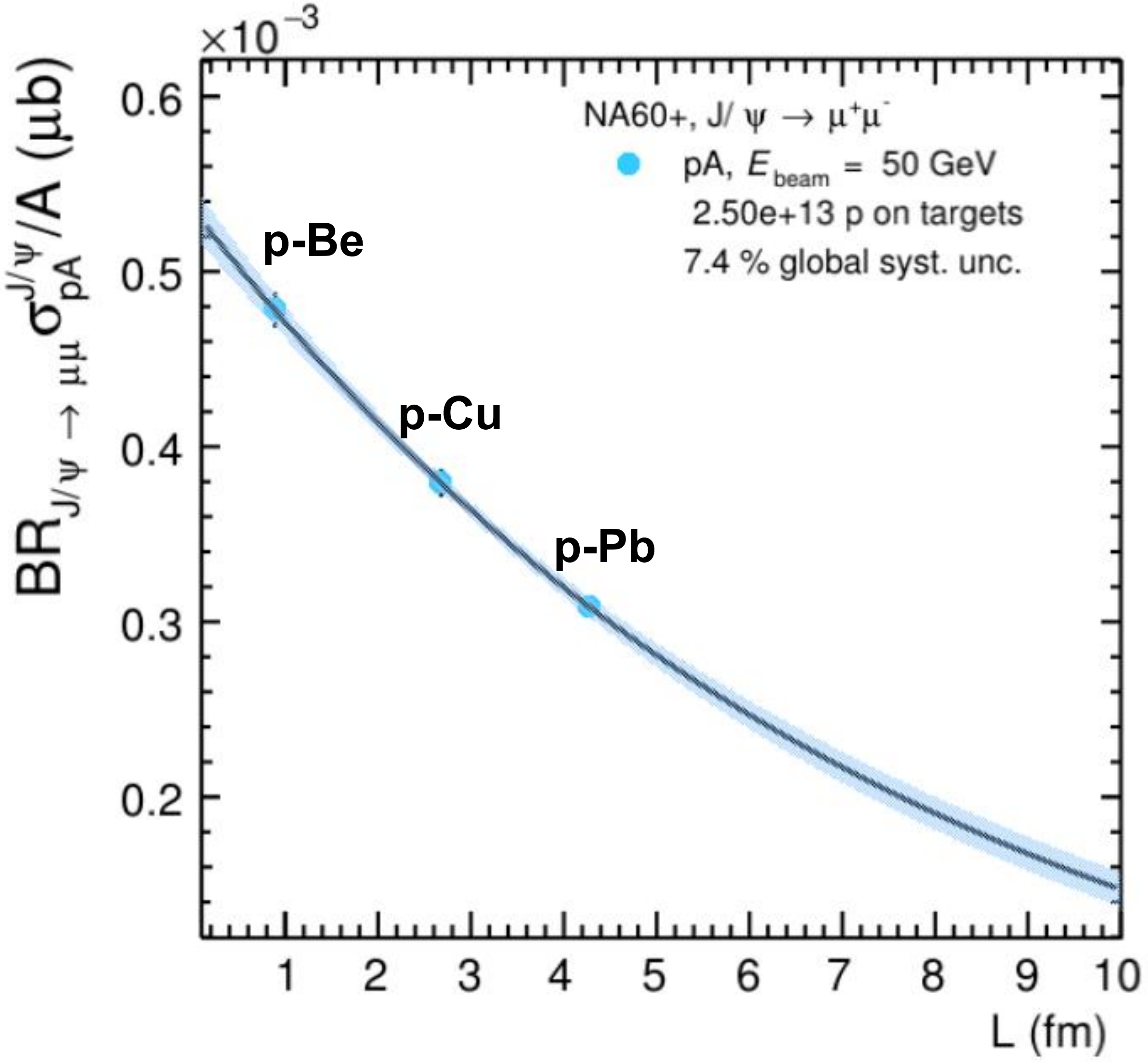


Estimation of expected yields

- Difficult to have precise estimates due to:
  - ⇨ Scarce knowledge of the elementary production cross section
  - ⇨ Unknown CNM and hot matter effects
- Assumptions:
  - ⇨ Empirical parametrization of J/ψ production in pp
    - 🕮 **Vogt, Phys. Rep. 310 (199) 197**
  - ⇨ CNM break-up: $\sigma_{abs}^{J/\psi}$ = 7.6 mb as measured by NA60 at √s = 17 GeV
  - ⇨ Extra 20% suppression due to QGP
- Expectations:
  - ⇨ ~O(10^4) J/ψ at E_{beam} = 50 GeV
  - ⇨ ~O(10^5) J/ψ at E_{beam} = 158 GeV



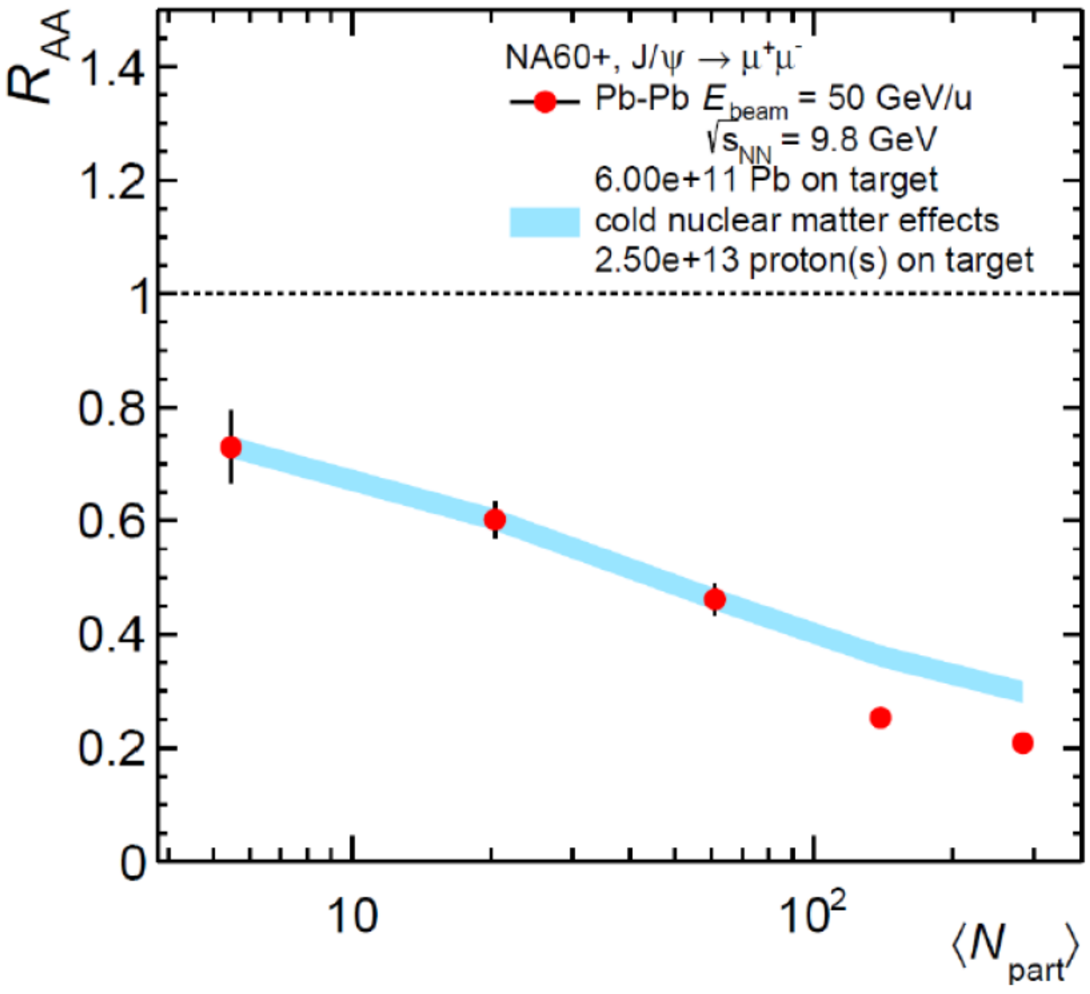
J/ψ in p-A: calibrate CNM effects



- Integrated luminosity per N-N collision: similar to the one for Pb-Pb
  - ⇨ Achievable by extracting primary low-energy p beams from the SPS
- Target: 3mm Pb + 3mm Cu + 12mm Be
  - ⇨ 15% interaction probability
- p-A data will allow to evaluate:
  - ⇨ Production cross-section in pp, $\boldsymbol{\sigma_{pp}}$, via extrapolation to A = 1
    - ✓ **To be used to calculate R_{AA}**
  - ⇨ $\sigma^{J/\psi}_{abs}$ to estimate CNM effects at each energy

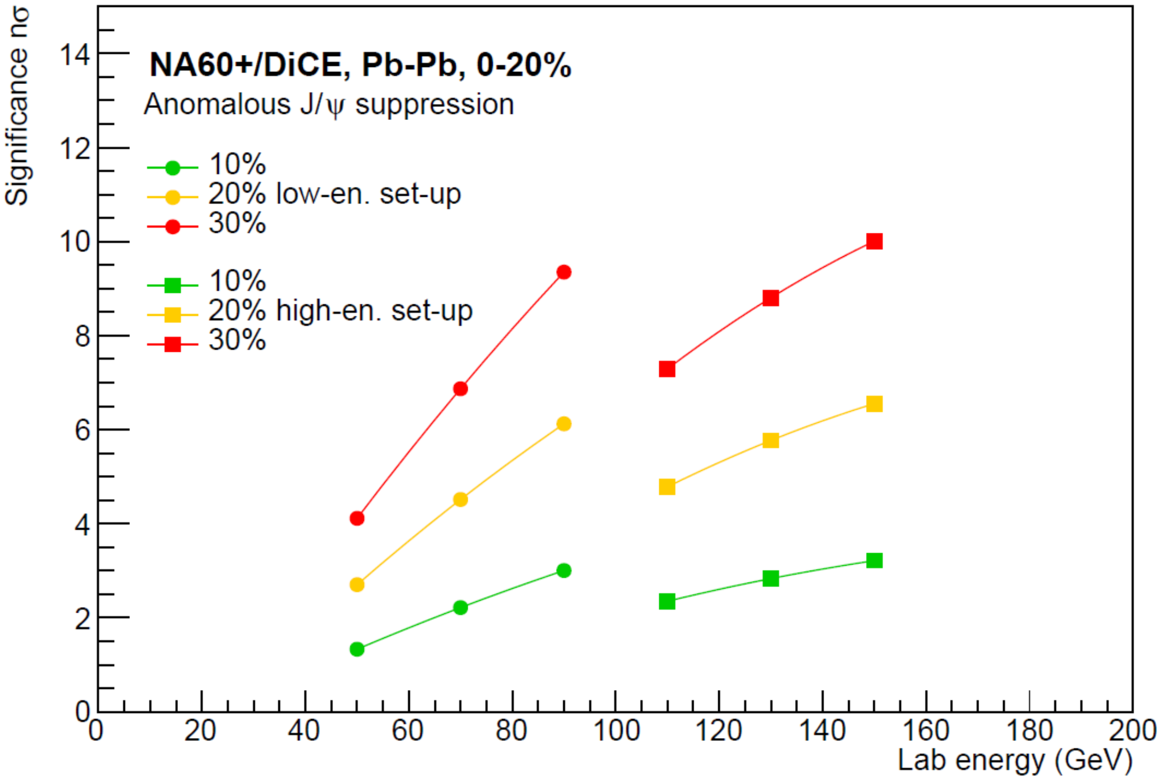
J/ψ in Pb-Pb: anomalous suppression

- Expected performance for J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 9.8 GeV (E_{beam} = 50 GeV/nucleon)
  - ⇨ Assumed 30% suppression, beyond CNM, for the two more central collision intervals



J/ψ in Pb-Pb: anomalous suppression

- Estimated significance for the observation of a suppression signal exceeding cold nuclear matter effects by 10%, 20% or 30% for the 20% most central Pb-Pb collisions
  - ⇨ Significance larger than ~ 3σ can be reached at all energies for a 20% anomalous suppression level
- Precise evaluation of anomalous suppression within reach even at low energy



Summary and prospects

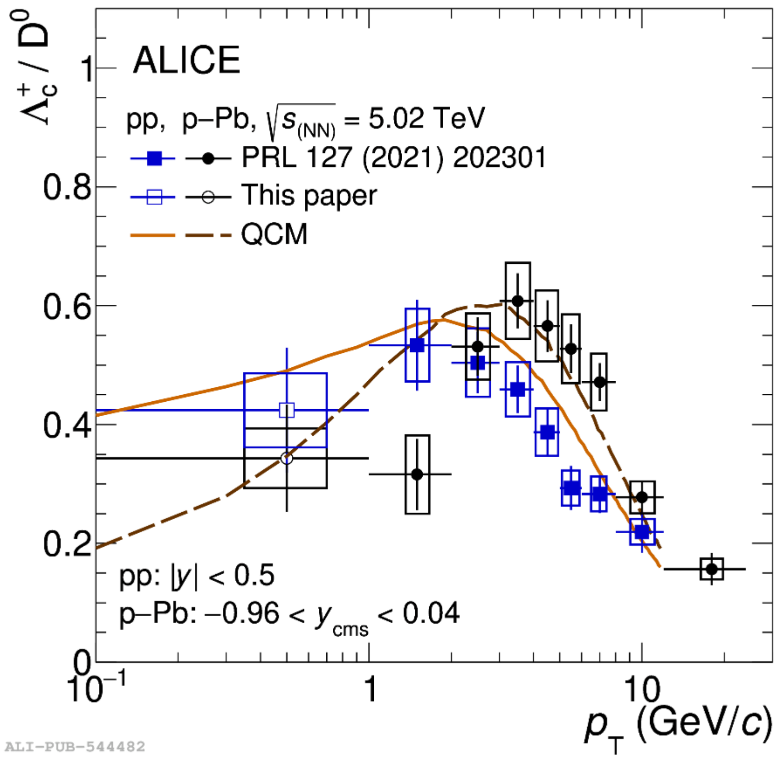
- Clear **physics case** for measurements of open charm hadrons and charmonia in heavy-ion (and p-A) collisions at SPS energies (and below)
  - ⇨ Probe the medium at lower temperatures as compared to LHC and RHIC top energy
  - ⇨ Sensitive to **nuclear PDFs** (antishadowing and EMC) and **Cold Nuclear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

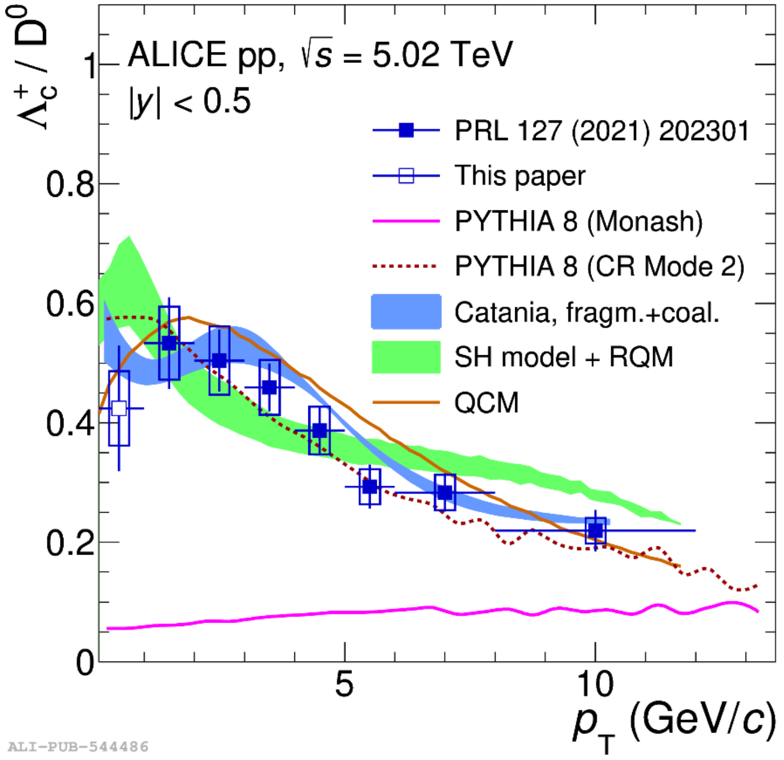
- Charming perspectives for **open charm and charmonium reconstruction** with NA60+/DiCE
  - ⇨ Measure production in an (almost) unexplored energy domain
  - ⇨ Characterize transport properties and hadronization of QGP at high μ_B by measuring **yield, v_2 and relative abundances** of different **charm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

Backup

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

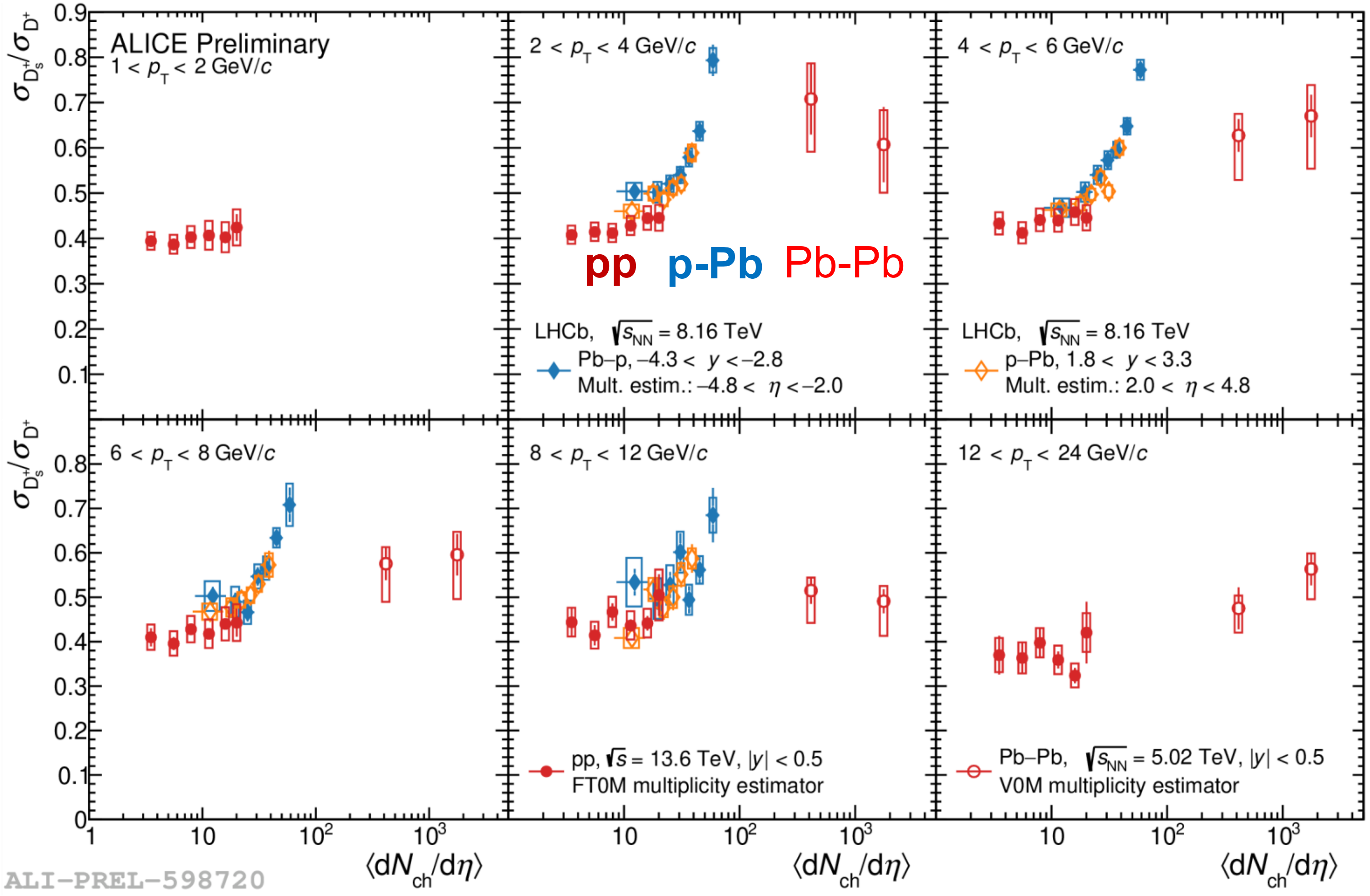




📖 **ALICE, PRC 107 (2023) 064901**

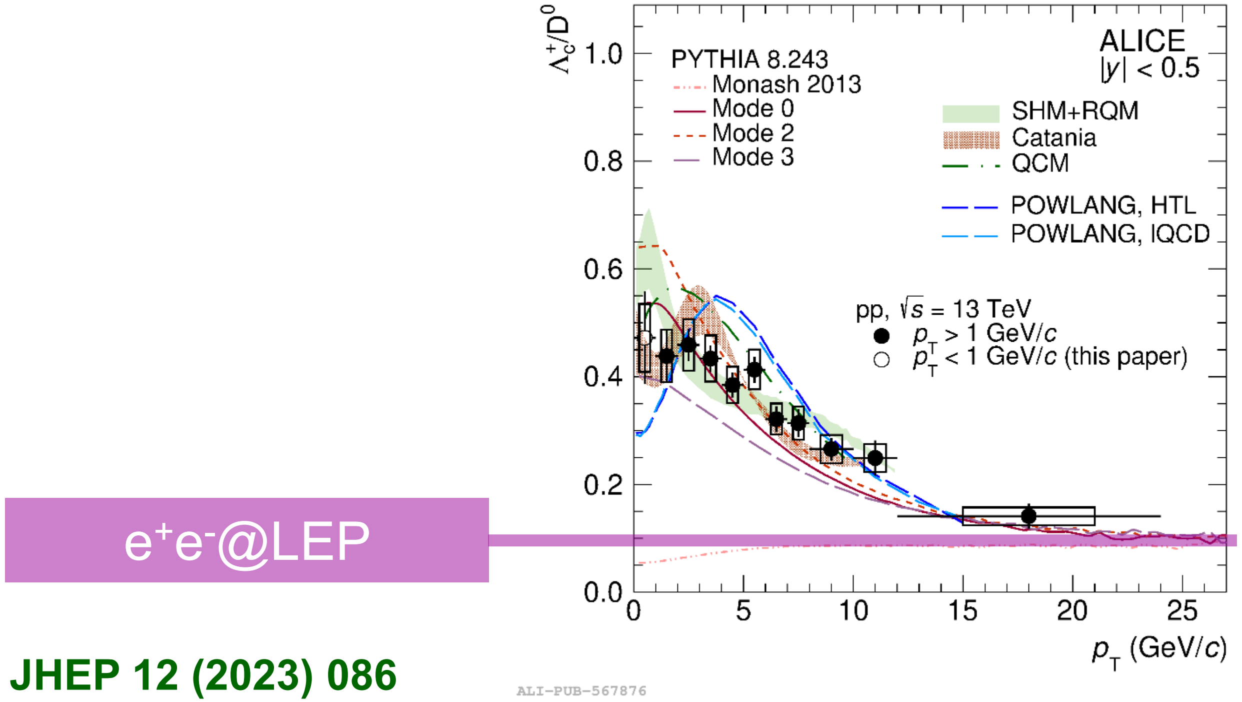
Charm-strange meson production

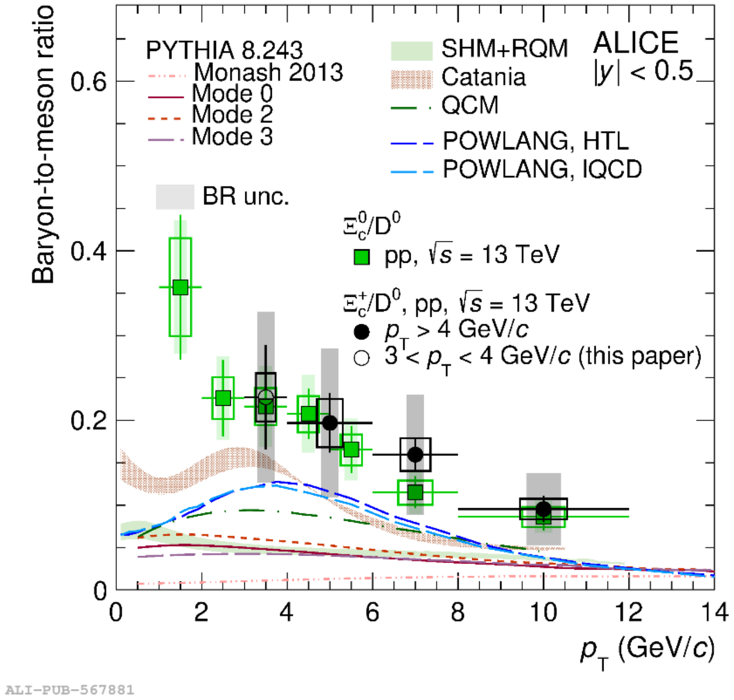
- Strange/non-strange ratio
  - ⇨ (Hint of) enhancement at low p_T in Pb-Pb compared to pp
    - ✓ Expected in case of QGP formation due to lifting of strangeness suppression + hadronization via recombination
  - ⇨ No multiplicity dependence in pp collisions at mid-rapidity
  - ⇨ Trend observed by LHCb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



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

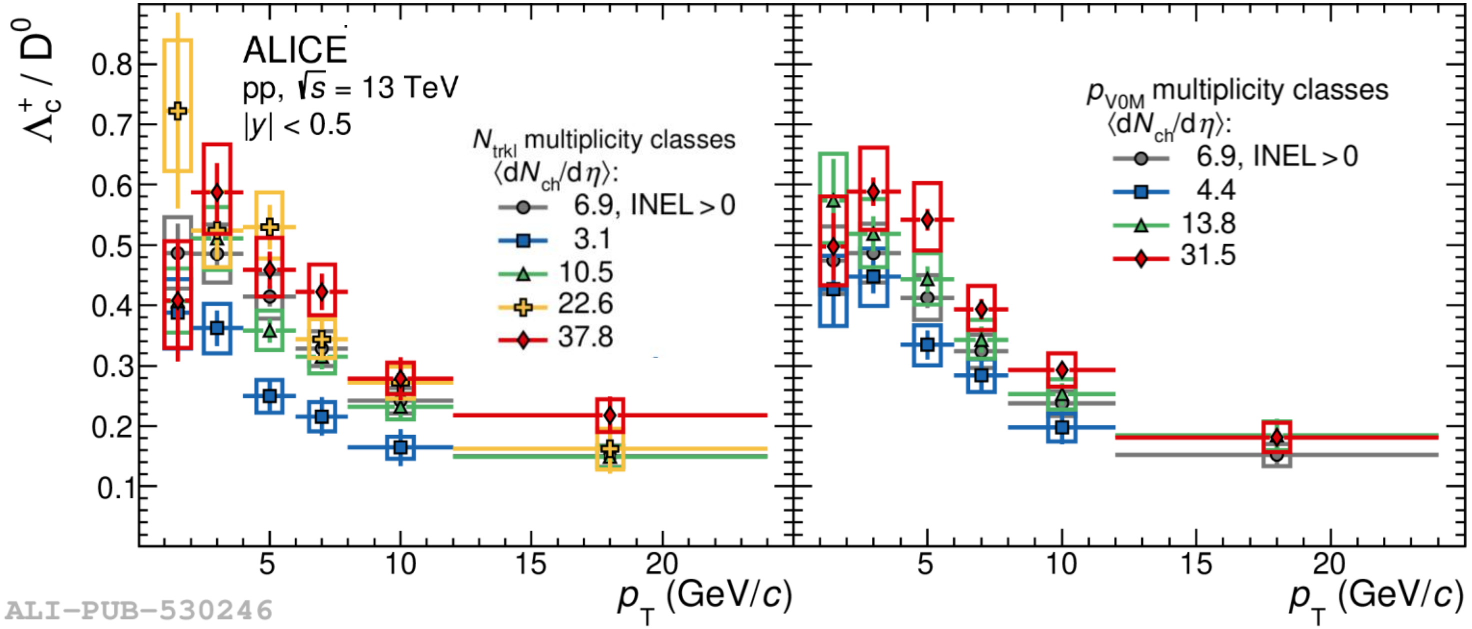




📖 **ALICE, JHEP 12 (2023) 086**

Charmed baryons vs. multiplicity

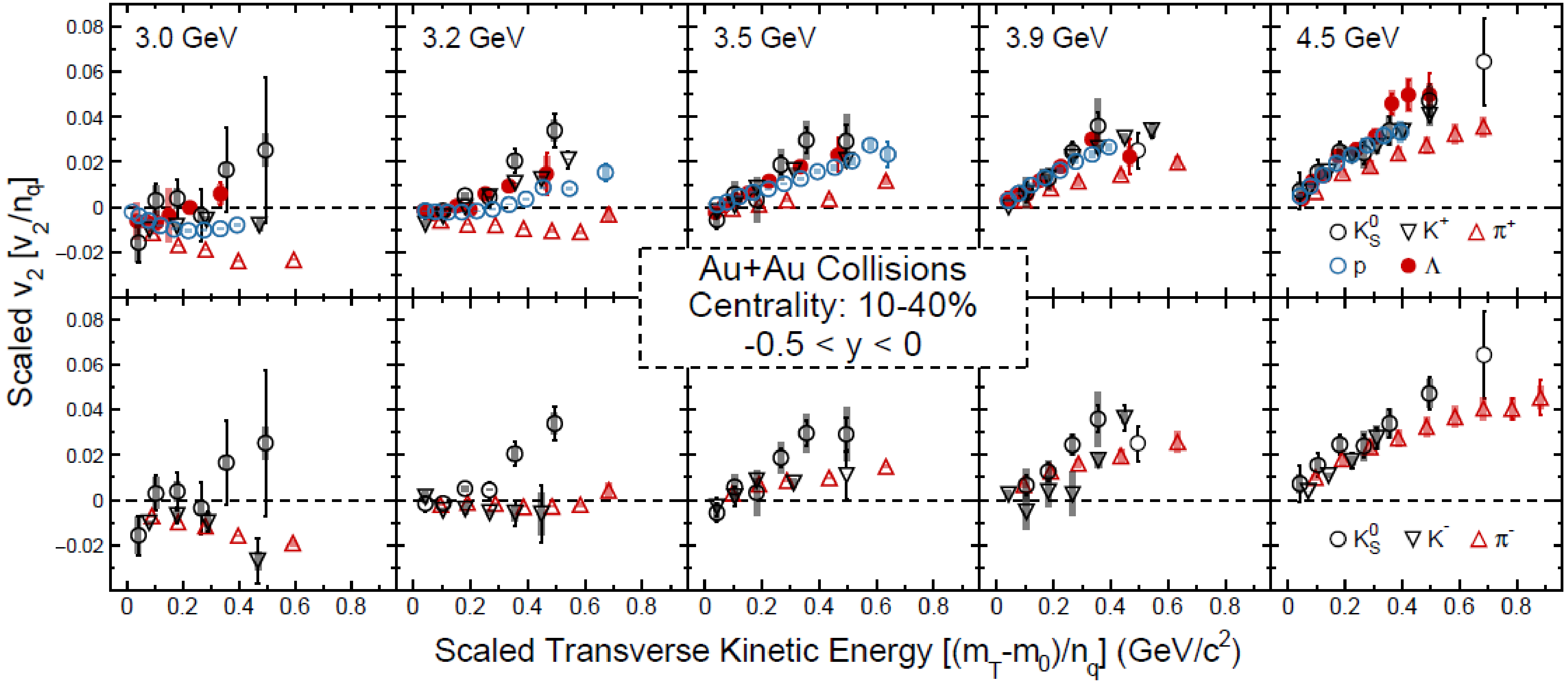
- Baryon/meson ratios vs. multiplicity
  - ⇨ Multiplicity-dependent enhancement for p_T<12 GeV/c
  - ⇨ Observed with both midrapidity and forward rapidity multiplicity estimators
    - ✓ Not a consequence of a possible bias arising from autocorrelations between the multiplicity estimator and charm jet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

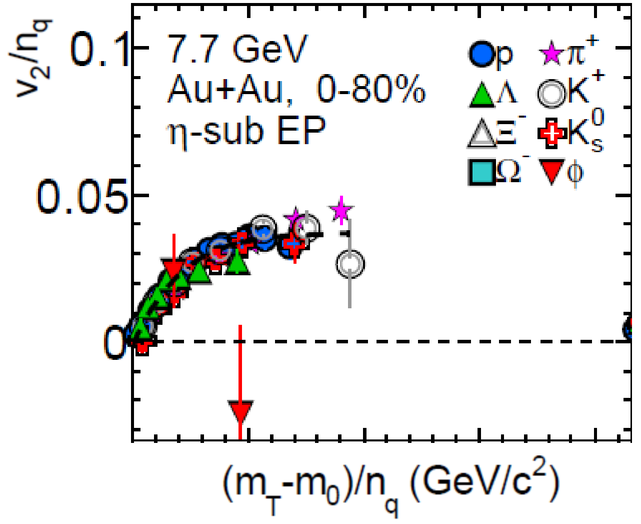


📖 **ALICE, PLB 829 (2022) 137065**

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**

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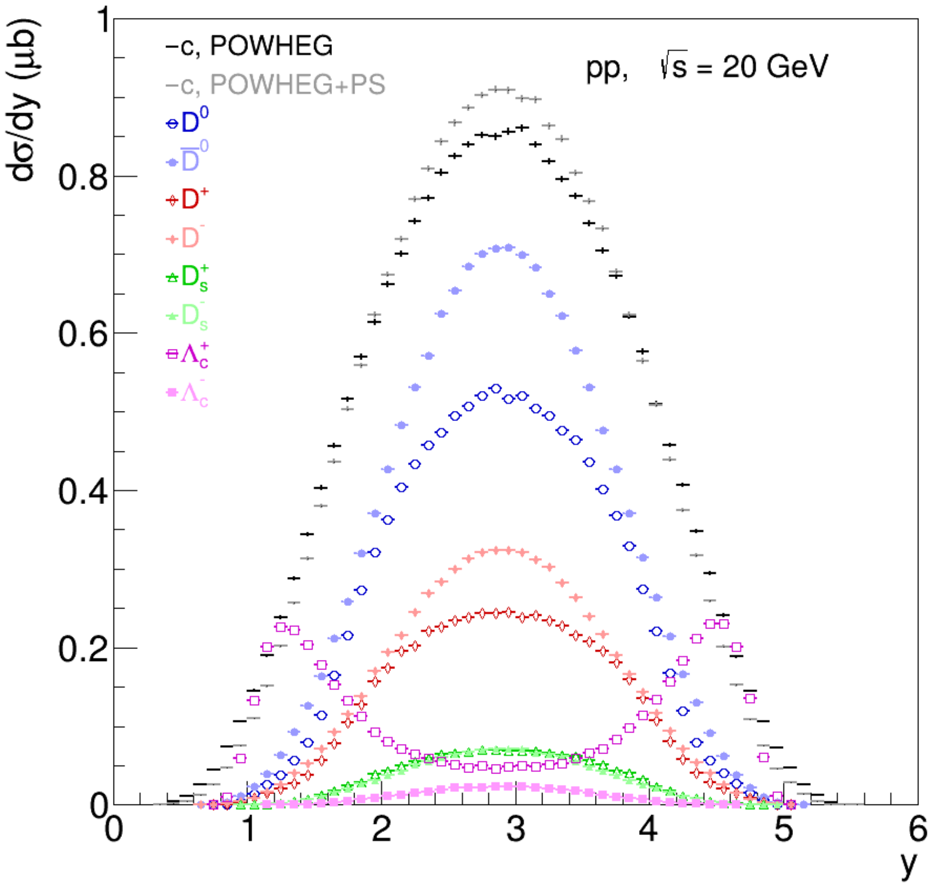
- **Fast simulations** for central Pb-Pb collisions:
  - ⇨ D-meson signal simulation: p_T and y distributions from POWHEG-BOX+PYTHIA



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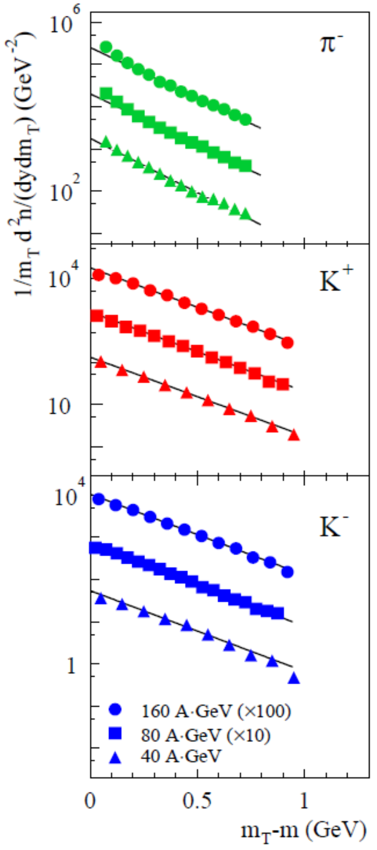
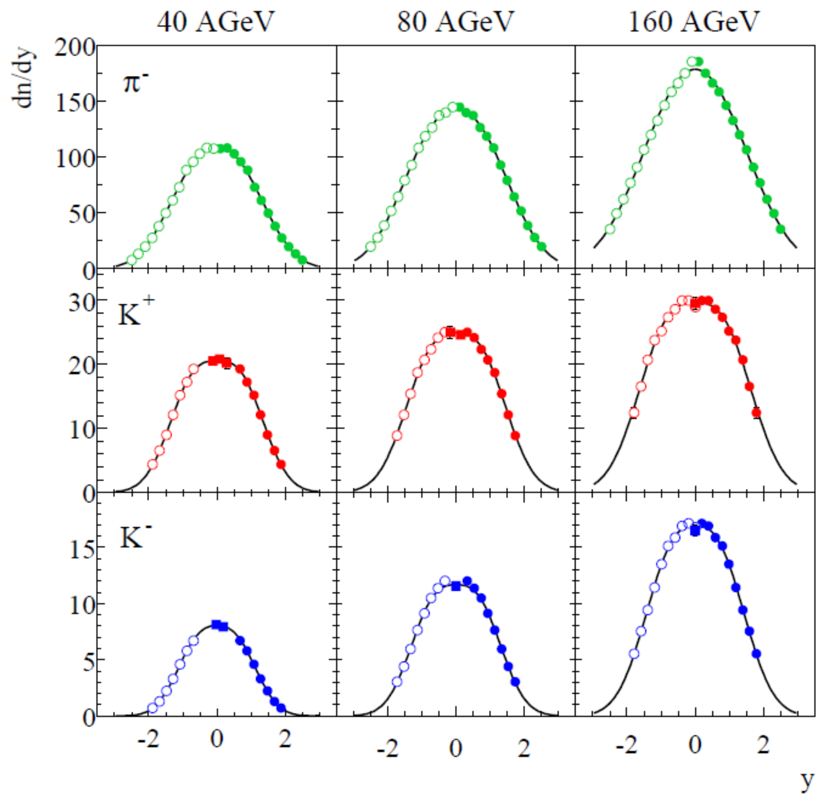
📖 **NA49, PRC 66 (2002) 054902**





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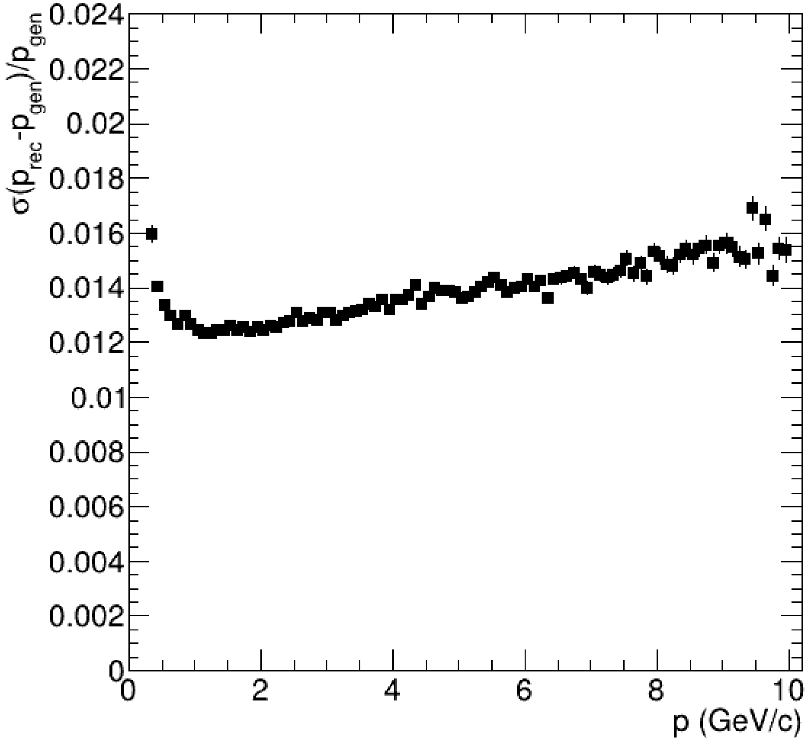

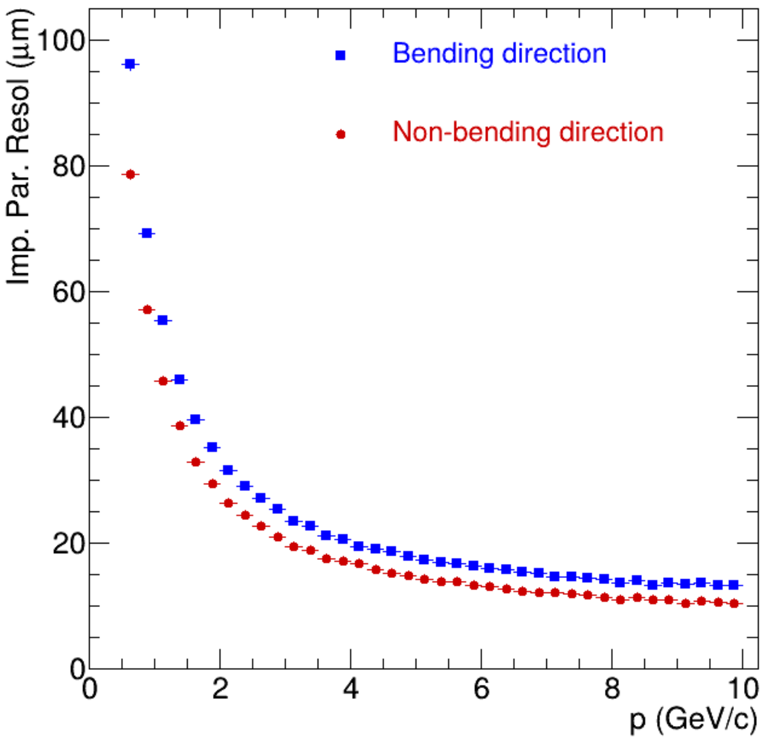

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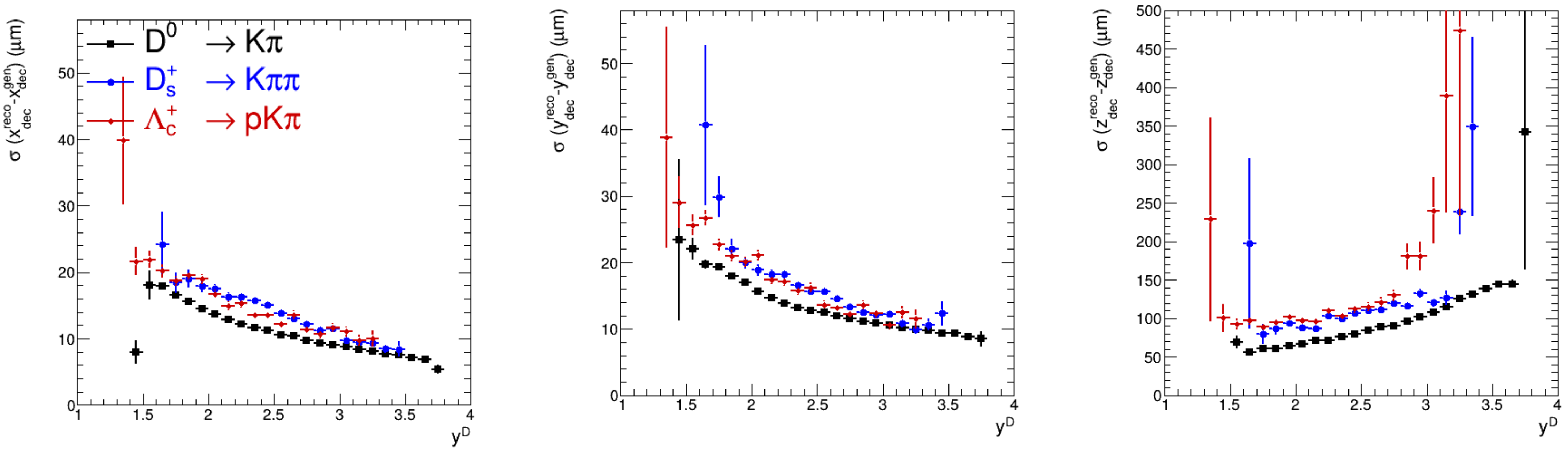

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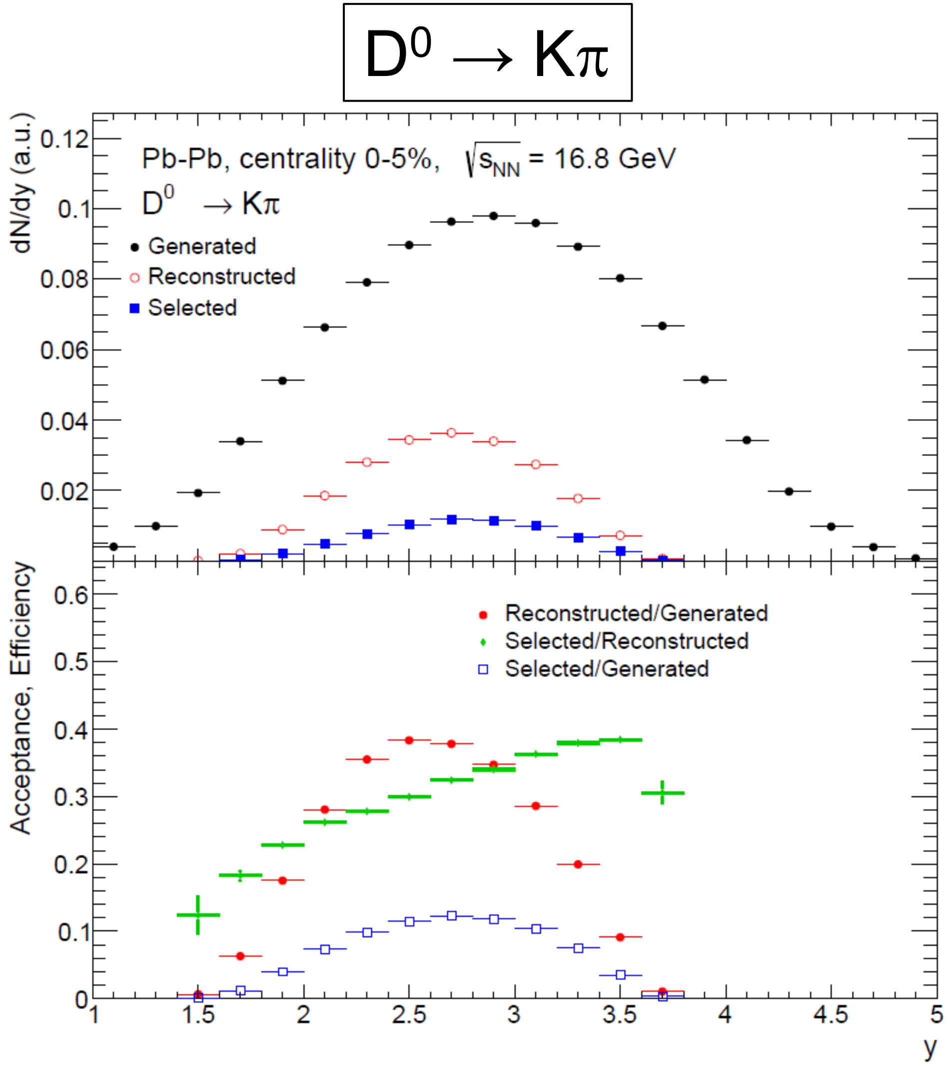
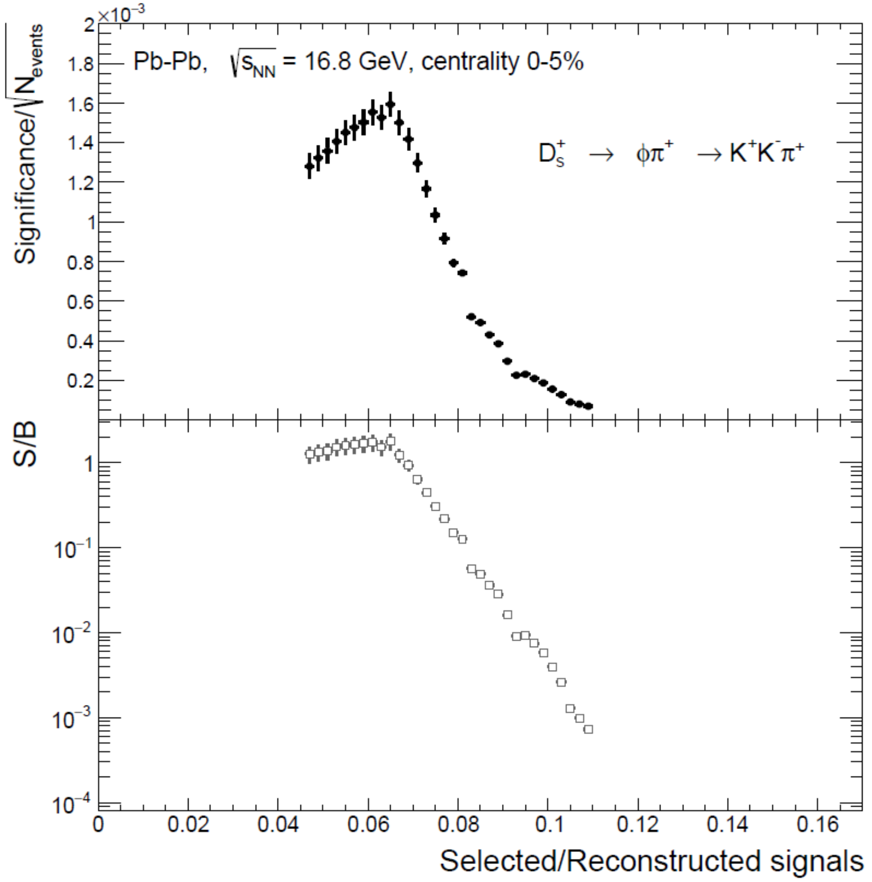
  - ⇨ Initial S/B ~ 10^{-7} → after selections S/B ~ 2



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

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



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 $\rightarrow \Lambda_c$)=10%) → after selections S/B ~ 0.1 with 2% selection efficiency

$\Lambda_c^+ \rightarrow pK\pi$