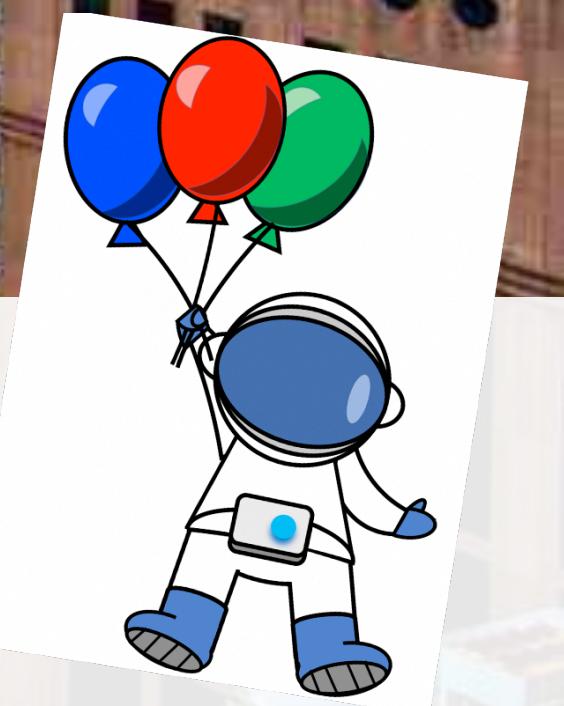


# Experimental overview on open-heavy flavours



Fabrizio Grosa  
CERN

Quark Matter 2023  
Houston | 08/09/2023



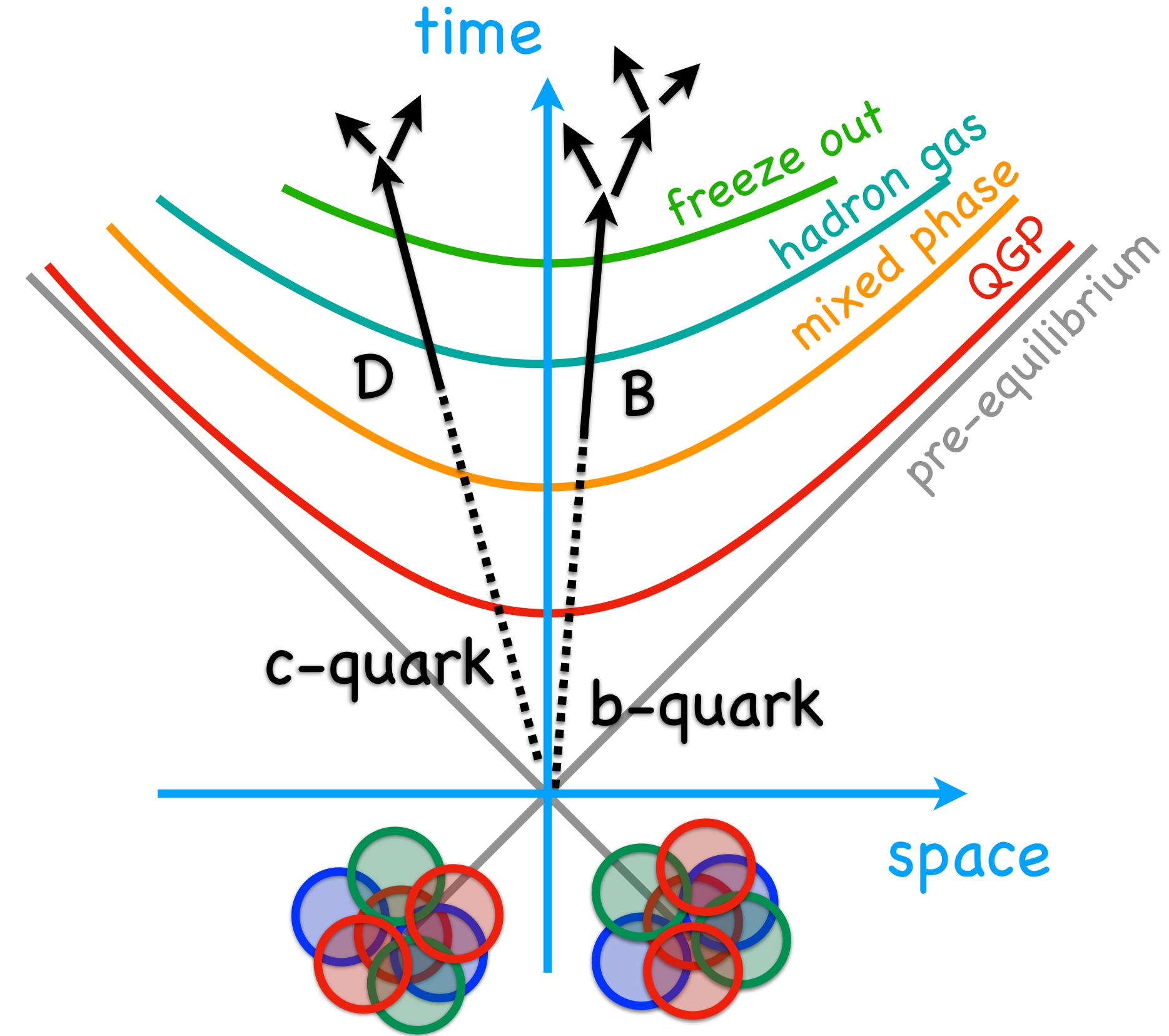
# Heavy quarks in the quark–gluon plasma

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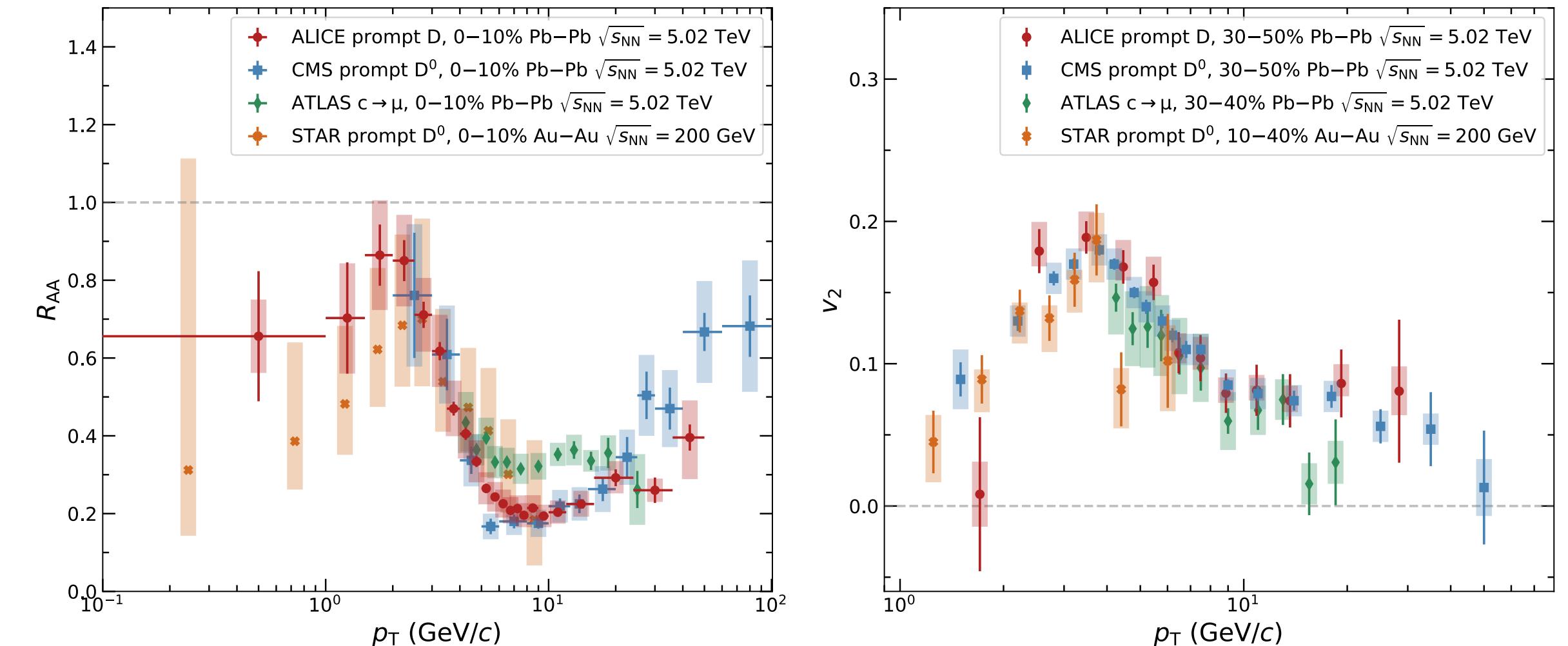
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- Heavy quarks: produced in shorter time scales than the quark–gluon plasma formation (QGP)
  - $\tau_{\text{HF}} \lesssim \hbar/m \approx 0.05\text{--}0.1 \text{ fm}/c$  depending on  $p_T$
  - $\tau_{\text{QGP form}}(\text{LHC}) \approx 0.3 \text{ fm}/c$

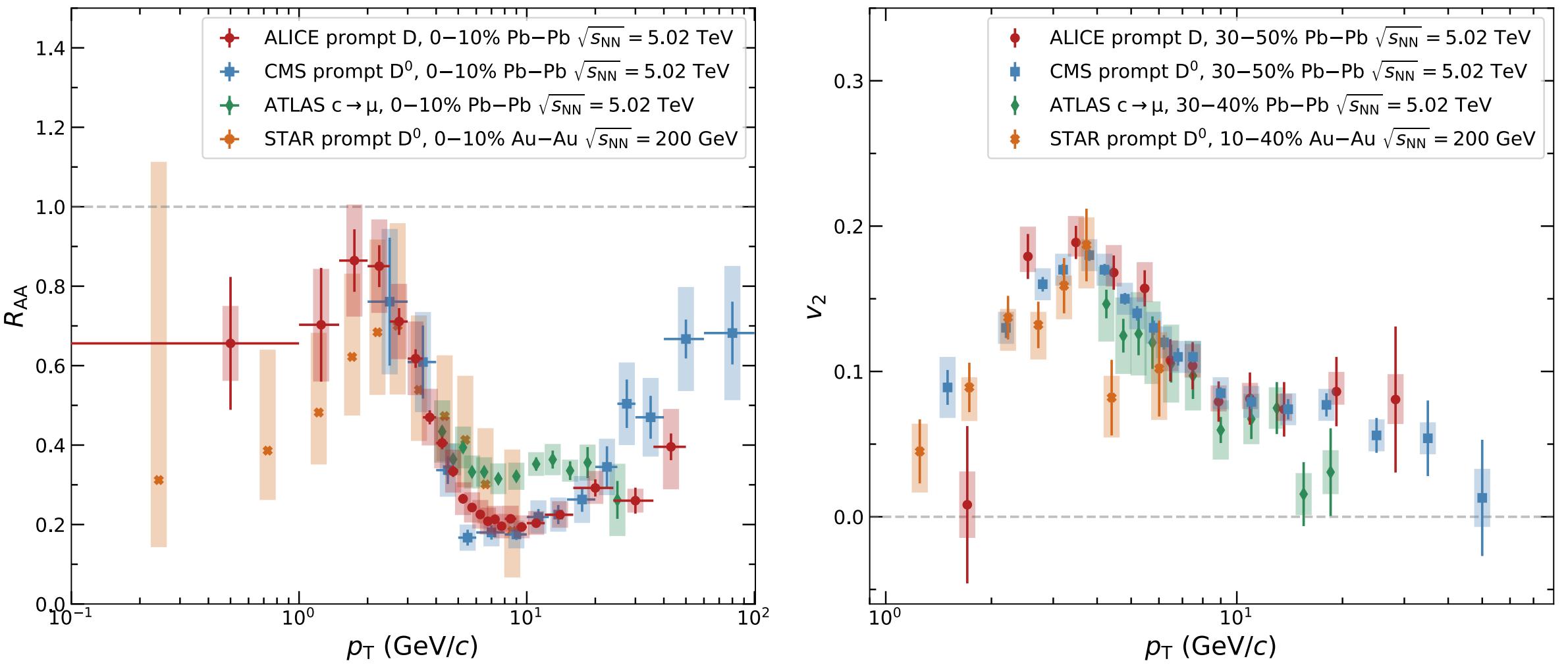
PRC 89 (2014) 034906



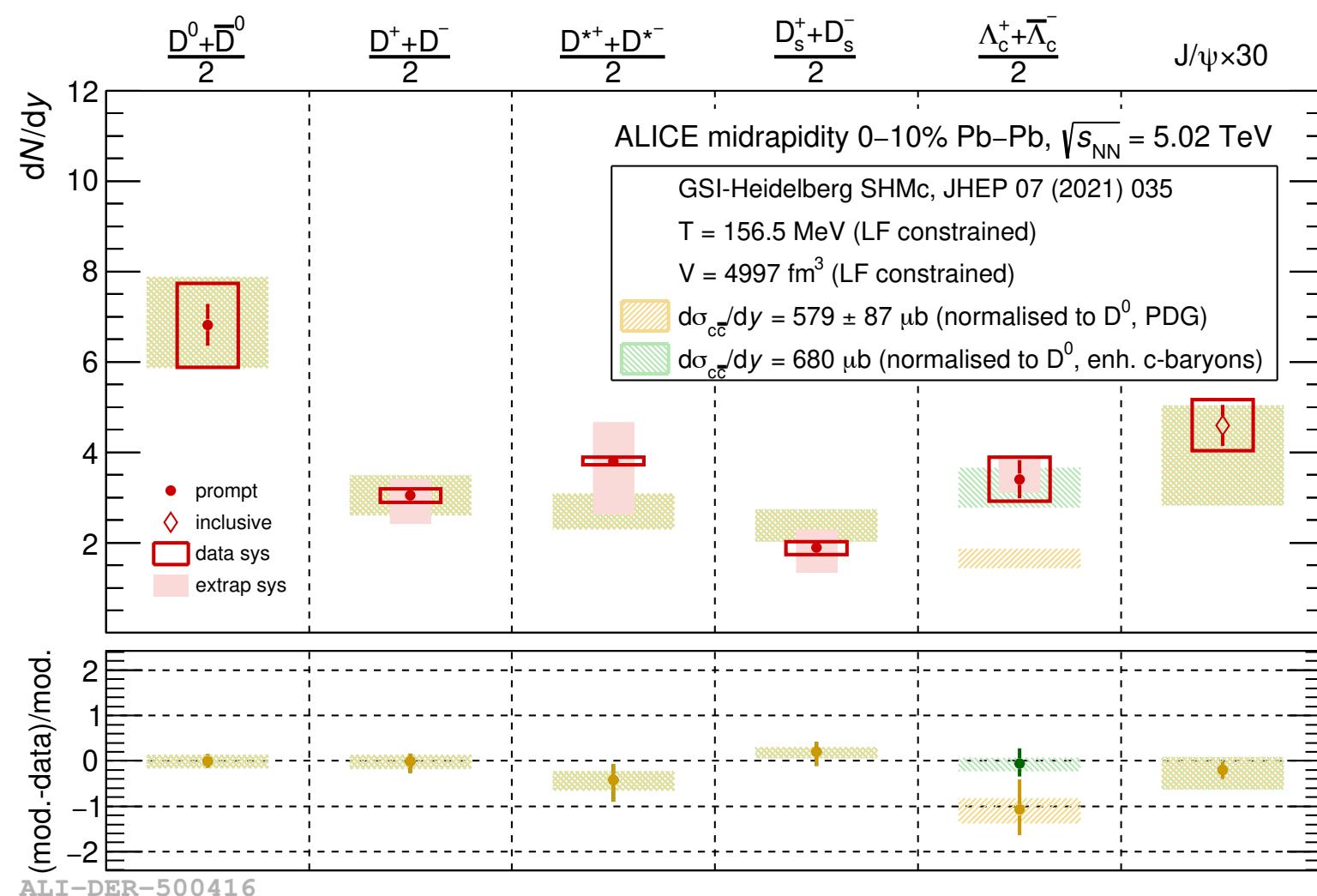
- Low- $p_T$ : multiple elastic collisions with the medium constituents
  - Diffusion motion and possible (partial) thermalisation in the medium
- High- $p_T$ : radiative energy loss (gluon emission)
  - Study properties of in-medium energy loss
- Momentum and angular distributions of HF hadrons
  - Study interactions of heavy-quarks with the medium
- Hydrochemistry: baryons and strange hadrons
  - Study hadronisation from the medium
- Vector meson polarisation:
  - Study initial strong magnetic fields
- Strong interaction of heavy-flavour hadrons with light hadrons:
  - Study the impact of hadronic phase on heavy-ion observables
- Small systems: heavy-ion like effects
  - Flow, baryons-to-meson ratio modification

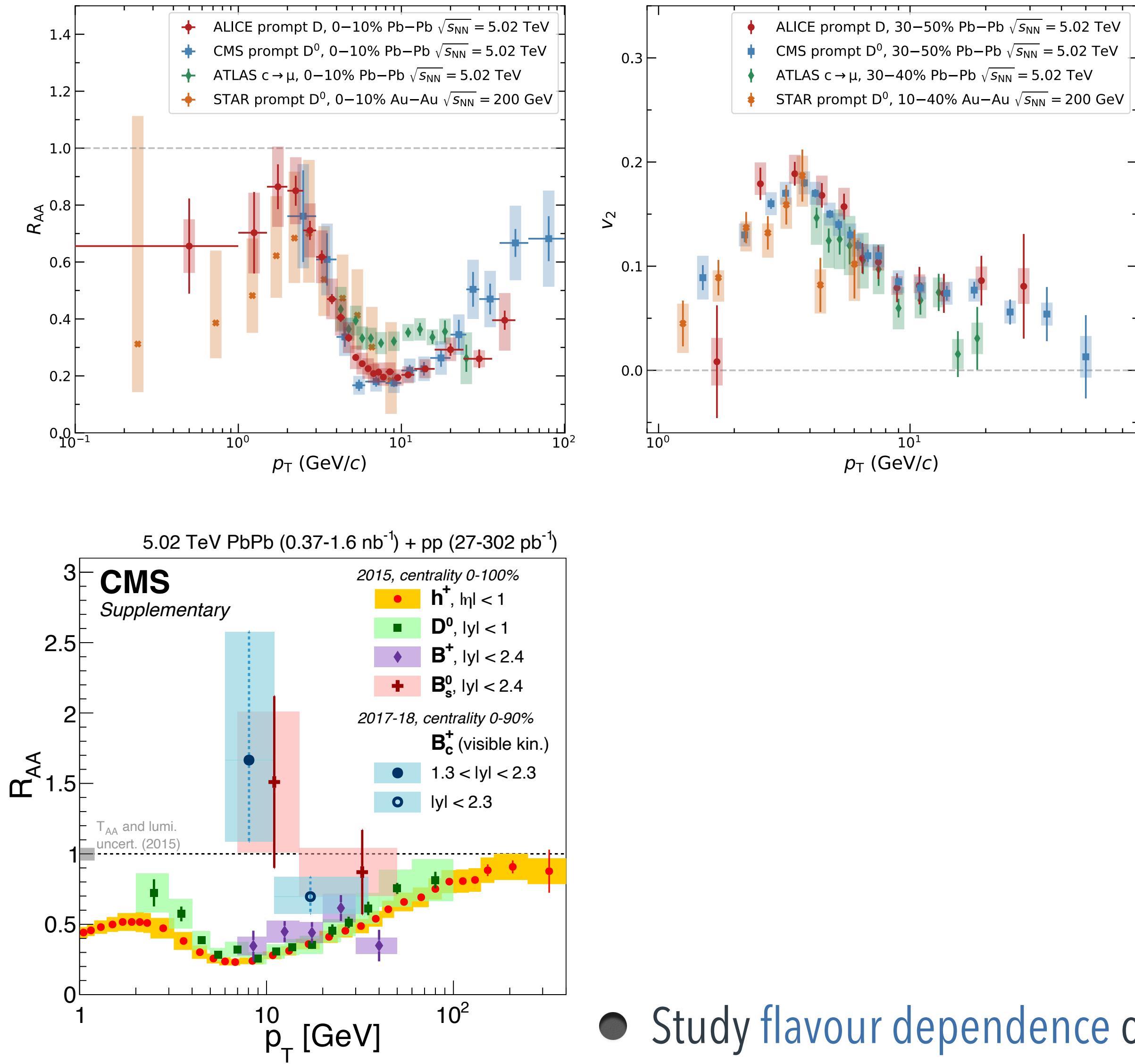


- Charm hadron production and azimuthal anisotropy
  - Constrain spatial diffusion coefficient  $1.5 < 2\pi D_s T_c < 4.5$
  - corresponding to a charm-quark relaxation time of  $3-8 \text{ fm}/c$

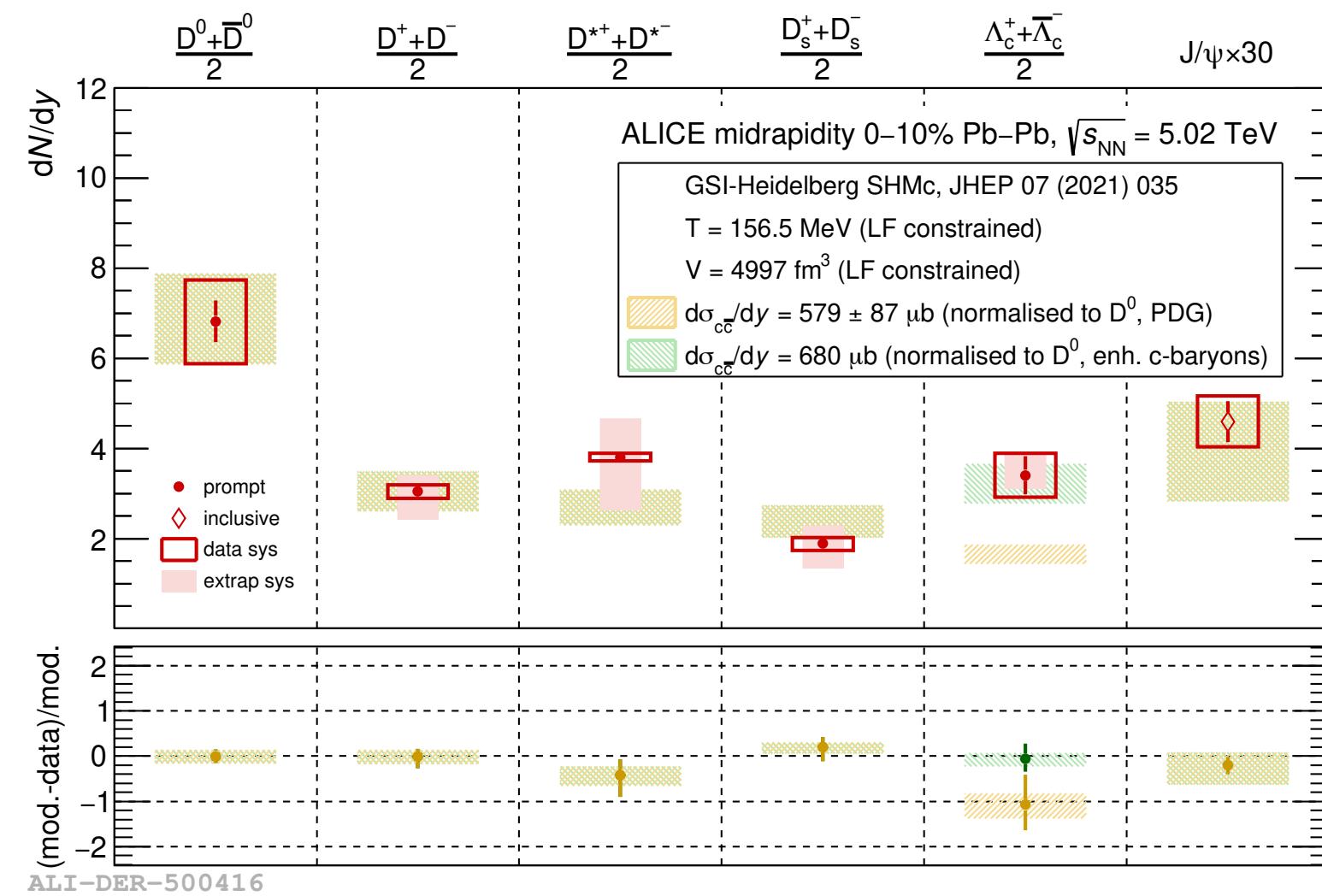


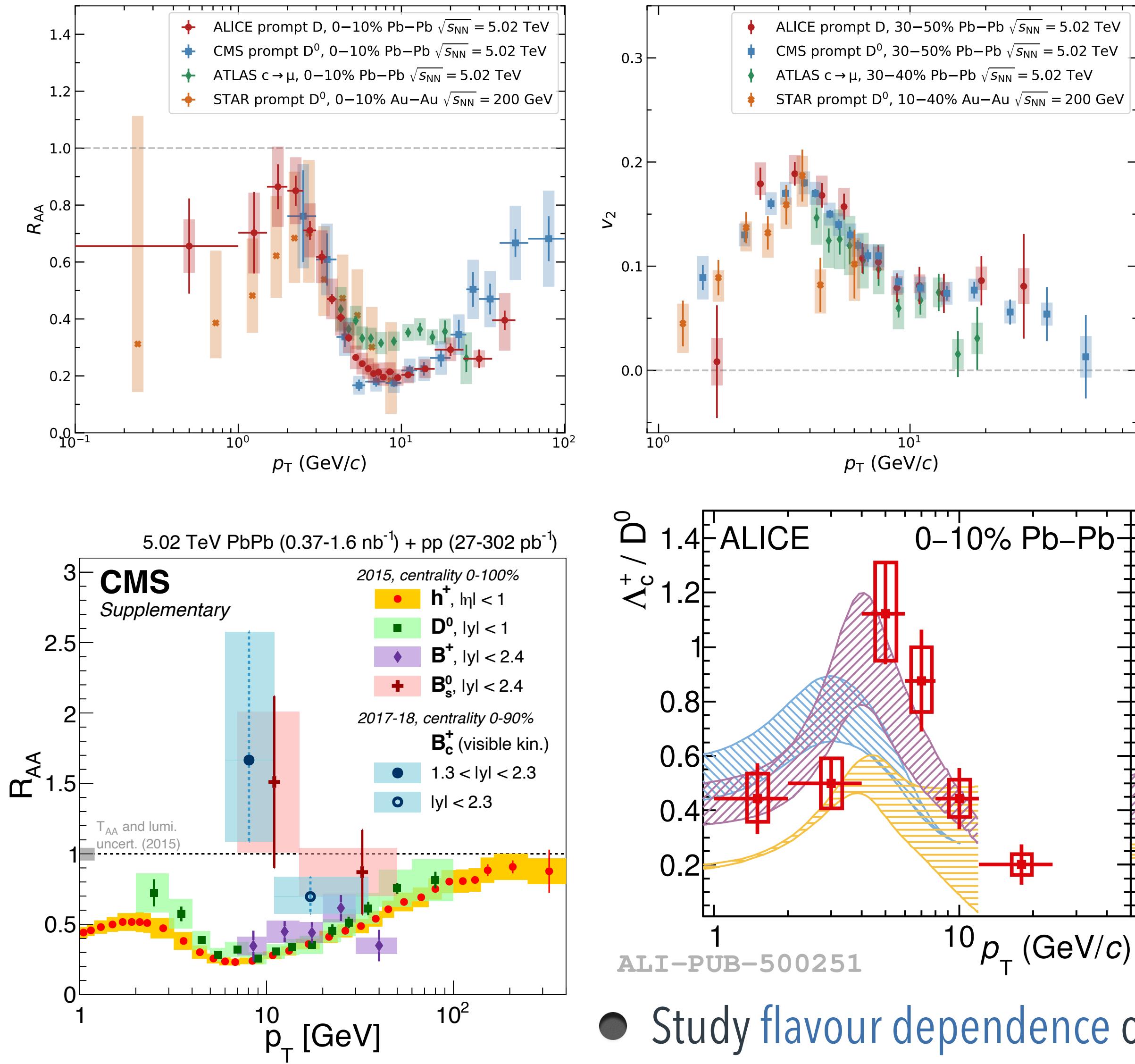
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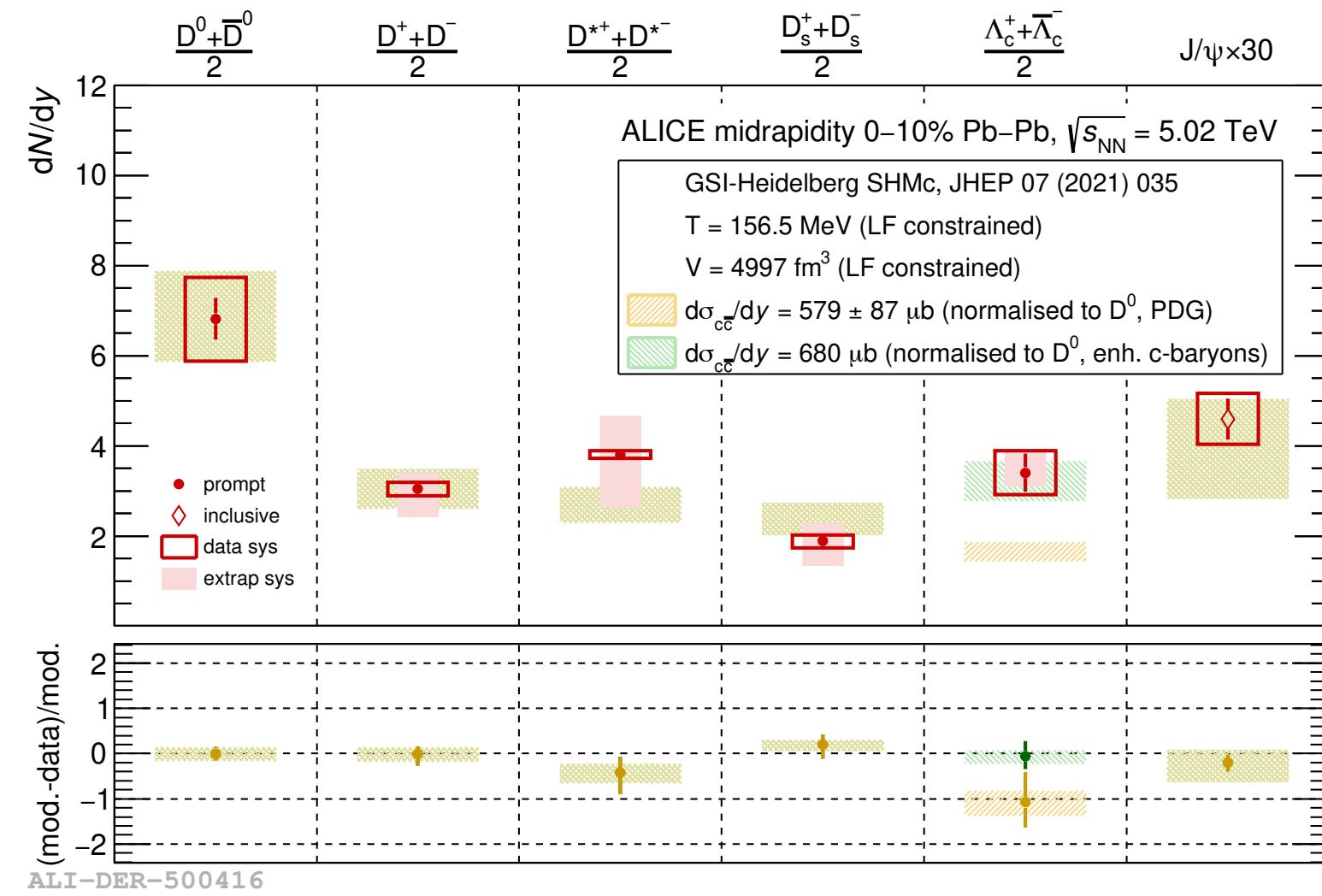


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- Study flavour dependence of in-medium energy loss

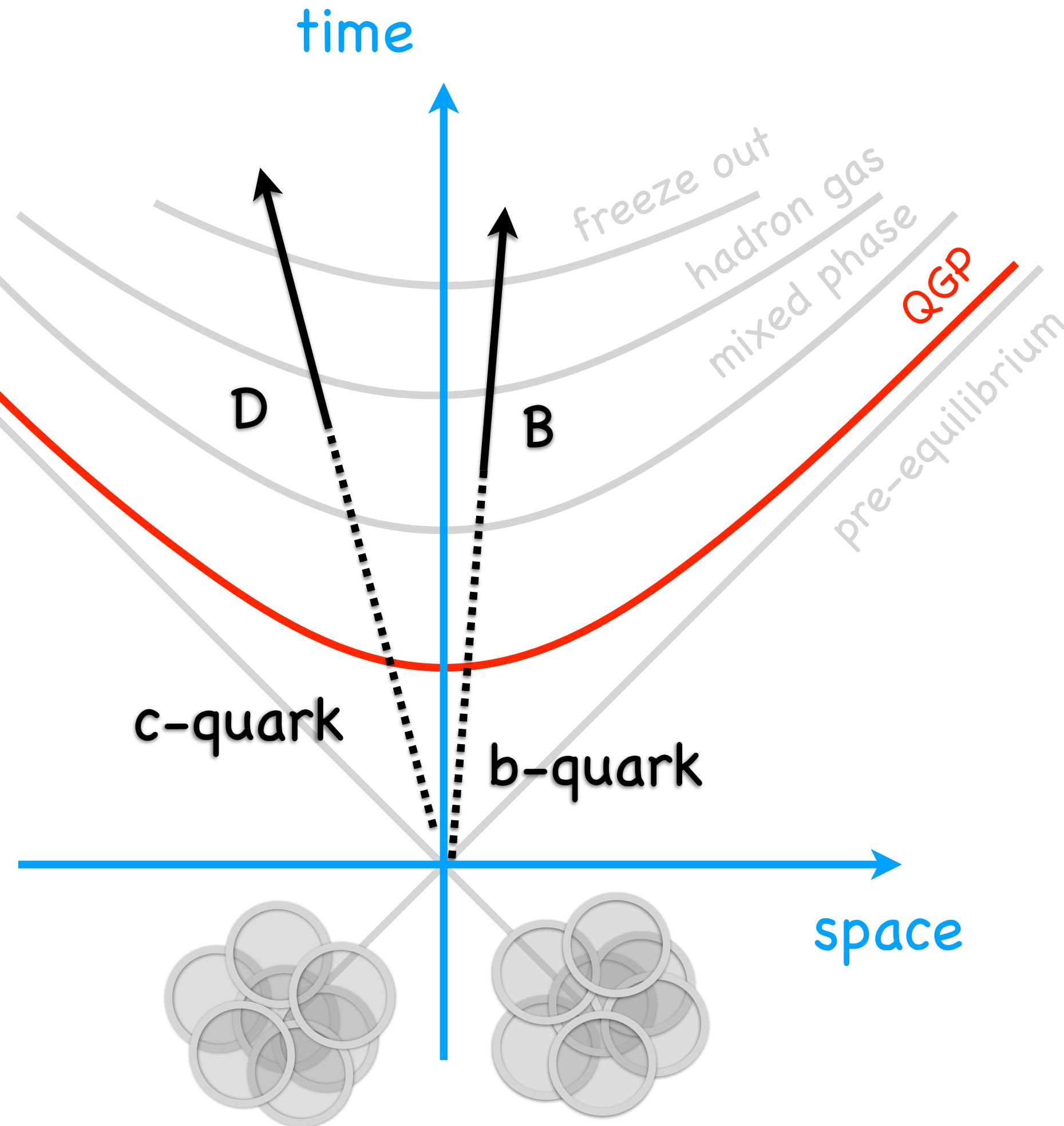




- Charm hadron production and azimuthal anisotropy
  - Constrain spatial diffusion coefficient  $1.5 < 2\pi D_s T_c < 4.5$  corresponding to a charm-quark relaxation time of  $3-8$  fm/ $c$
- Charm-hadron production yields comparable with statistical hadronisation model predictions
- Charm baryon enhancement in heavy-ion collisions
- Study flavour dependence of in-medium energy loss
- And many more results: [C. Terrevoli - experimental overview on open and hidden heavy-flavour measurements - QM2022](#)



- Heavy quarks interact with the QGP exchanging energy and momentum with the medium constituents



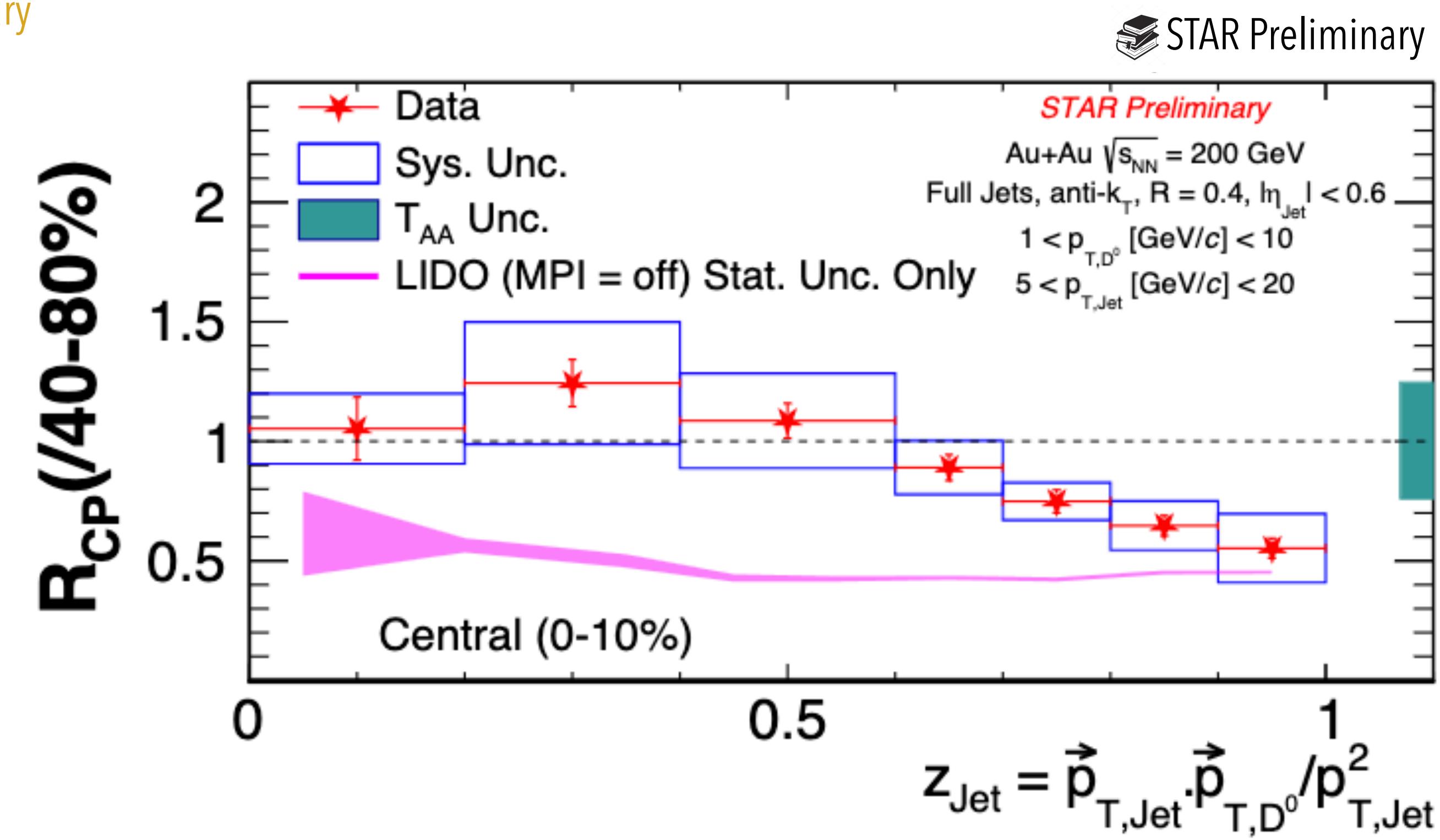
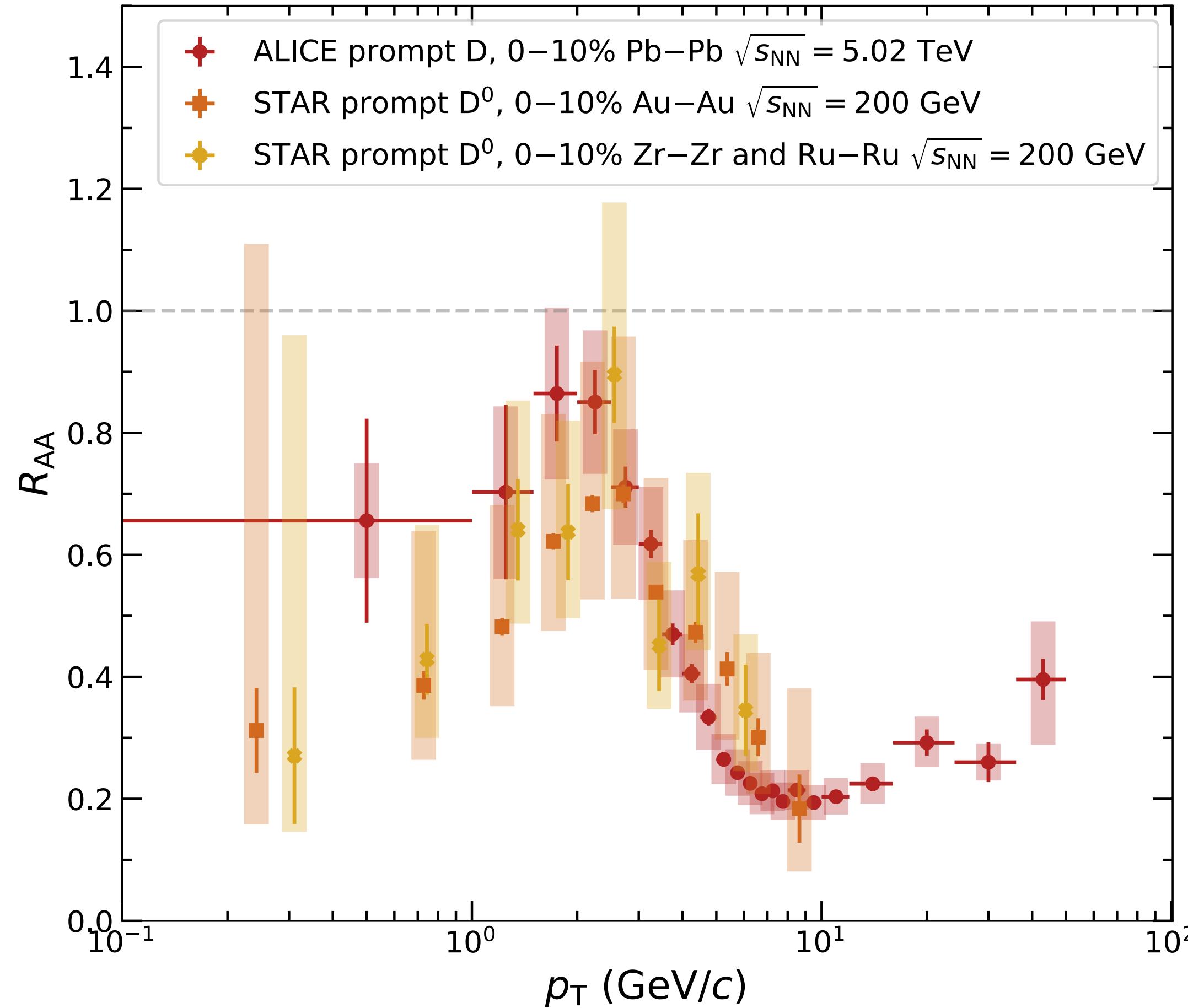
- Low- $p_T$ 
  - Diffusion of heavy-quarks in the thermal bath
  - Described via Boltzmann, Fokker-Planck or Langevin equations
  - Possible thermalisation of heavy-quarks in the medium
  - Participation to collective motions
- High- $p_T$ 
  - Energy loss of charm and beauty quarks in the medium
  - Study the colour-charge and quark-mass dependence of the in-medium energy loss
  - Study jet quenching and jet properties

# Charm-production as a function of energy and colliding system

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ALICE, JHEP 01 (2022) 174   STAR, PRC 99 (2019) 34908   STAR Preliminary



- $R_{AA}$  of  $D^0$  mesons measured in isobar collisions ( $Zr-Zr$  and  $Ru-Ru$ ) compatible with that measured in  $Au-Au$  collisions and at the LHC

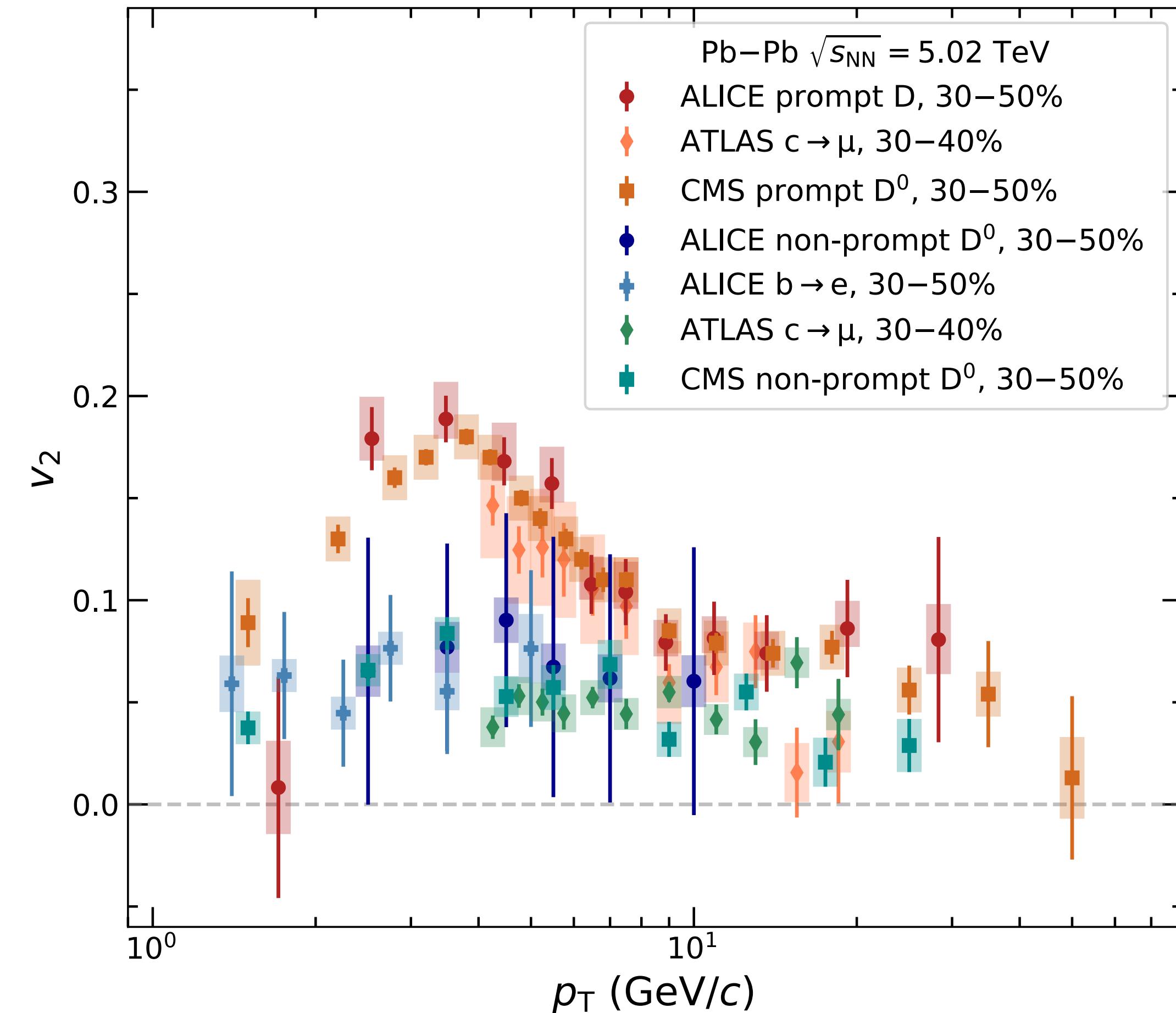
- $R_{CP}$  of  $D^0$ -tagged jets
  - not suppressed for small  $z$  values (soft fragmentation)
  - suppressed for large  $z$  values (hard fragmentation)

# Beauty-hadron azimuthal anisotropies

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09  
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R. Singh – Tue 05 Sept   M. Stojanovic – Wed 06 Sept



- Positive elliptic flow of open-beauty hadrons
  - Participation in the collective motions of the system
  - Lower than the one of charm hadrons for  $p_T < 10 \text{ GeV}/c$
  - Possible partial thermalisation of beauty quark in the QGP

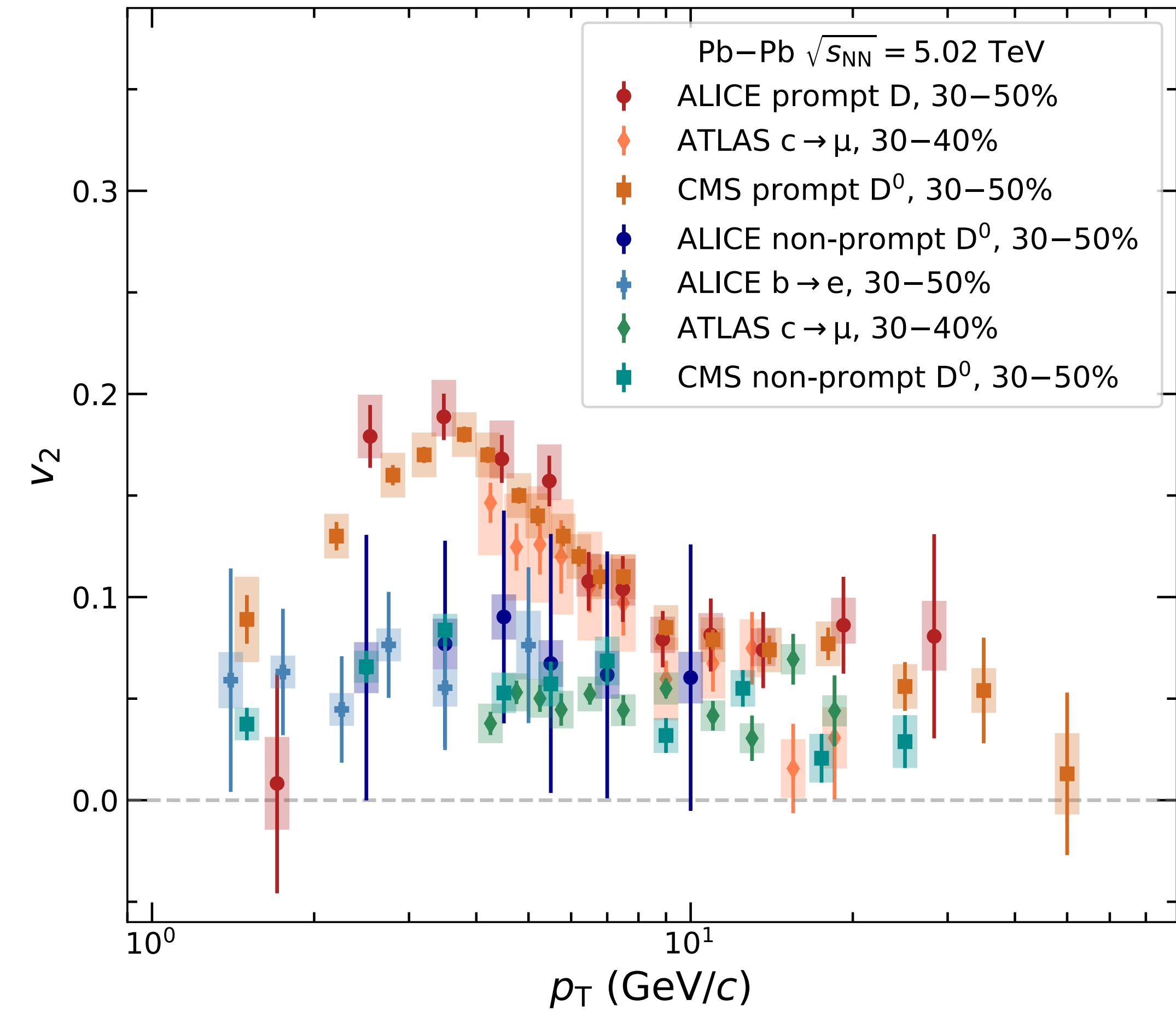
- ALICE, PLB 813 (2021) 136054
- ATLAS, PLB 807 (2020) 135595
- CMS, PLB 816 (2021) 136253
- ALICE, arXiv:2307.14084
- ALICE, PRL 126 (2021) 162001
- ATLAS, PLB 807 (2020) 135595
- CMS, arXiv:2212.01636

# Beauty-hadron azimuthal anisotropies

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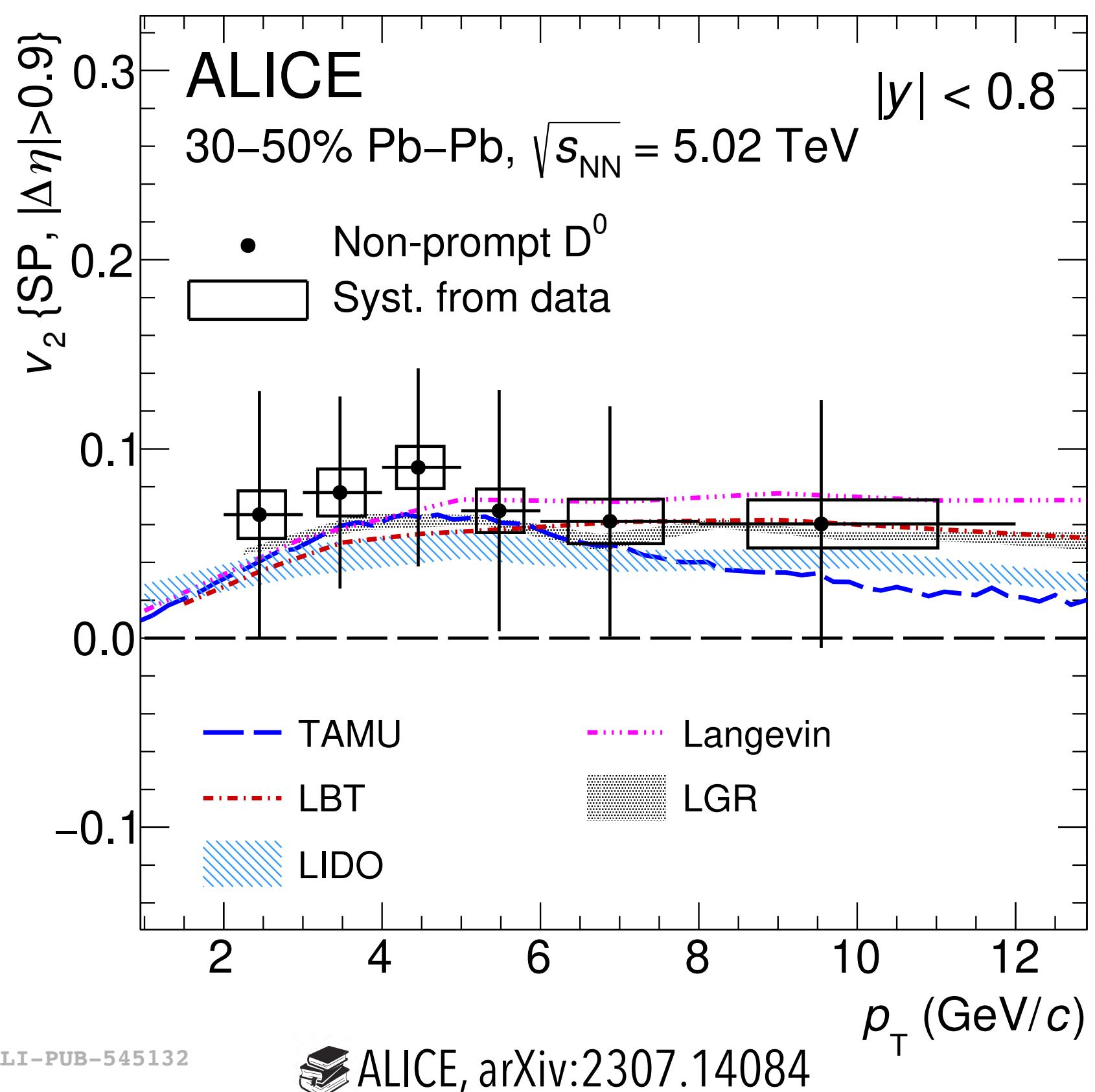
$\frac{10}{45}$

R. Singh – Tue 05 Sept    M. Stojanovic – Wed 06 Sept



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- ALICE, PLB 813 (2021) 136054
- ATLAS, PLB 807 (2020) 135595
- CMS, PLB 816 (2021) 136253
- ALICE, arXiv:2307.14084
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- CMS, arXiv:2212.01636



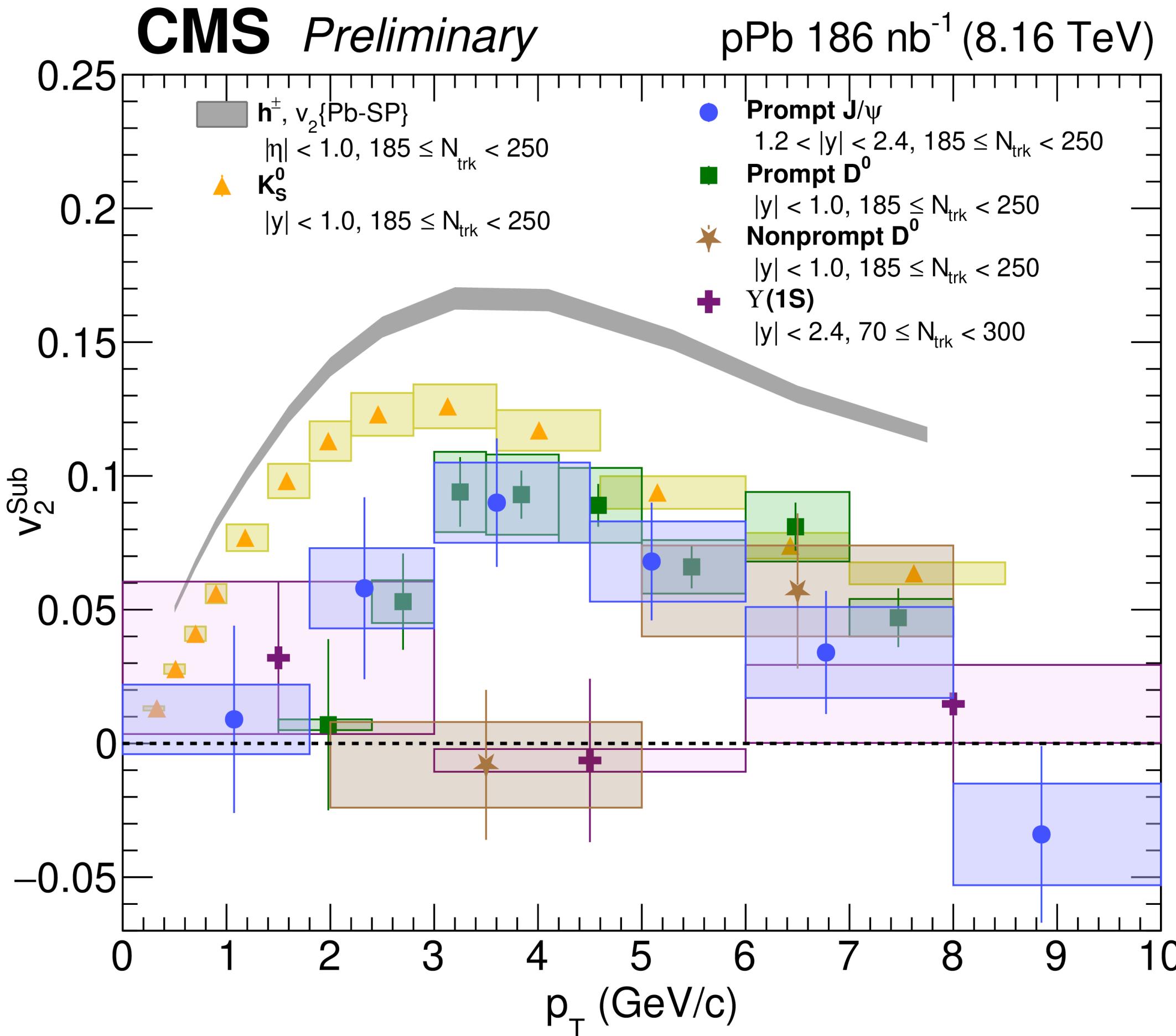
- Measurements described by models based on beauty-quark transport in a hydrodynamical expanding QGP that include collisional energy loss and hadronisation via coalescence

# Beauty-hadron azimuthal anisotropies in p-Pb collisions

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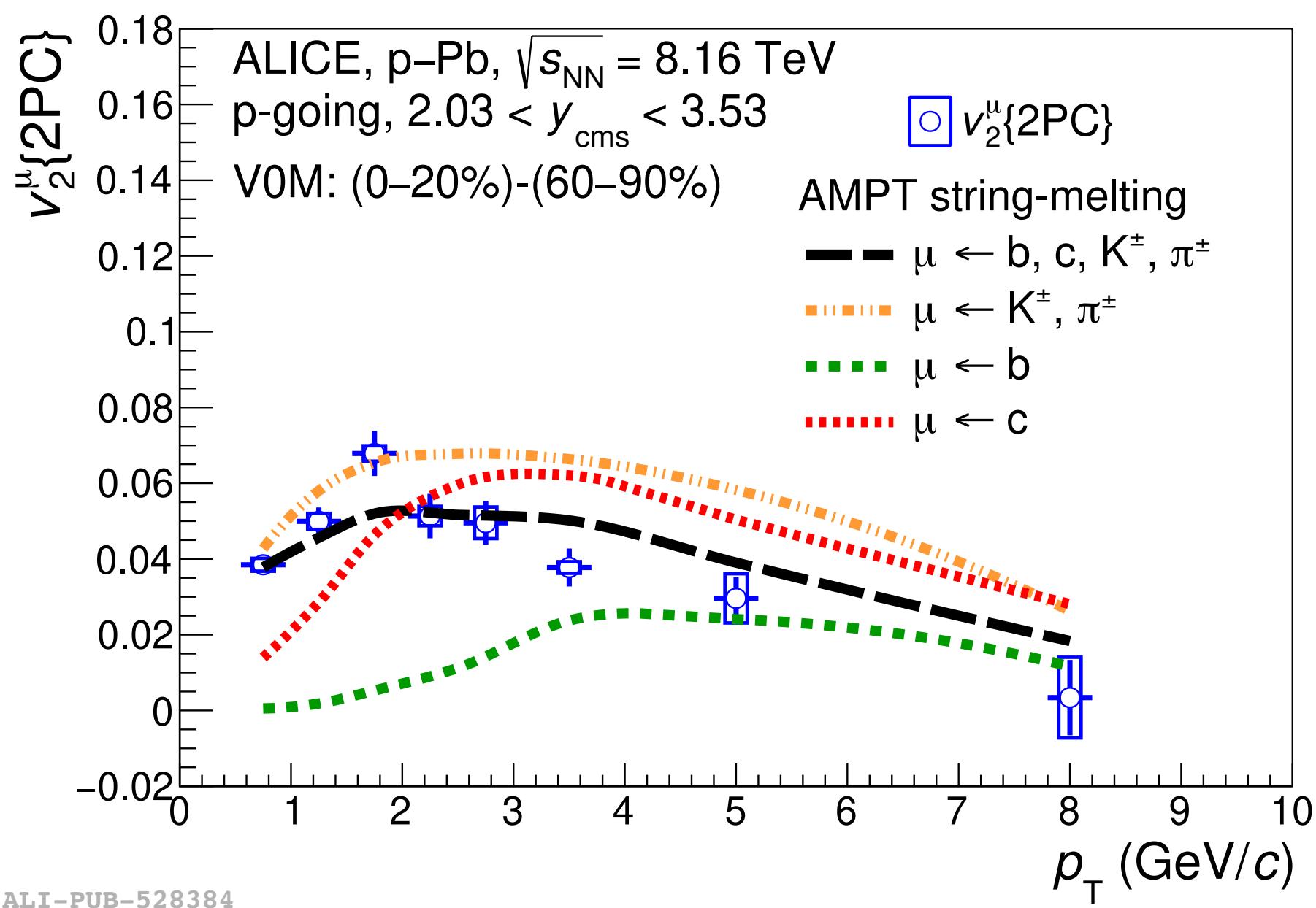
R. Singh – Tue 05 Sept    M. Stojanovic – Wed 06 Sept



- Positive elliptic flow of inclusive muons in p-Pb collisions  
→ In beauty dominated region ( $p_T > 6 \text{ GeV}/c$ )  $v_2$  close to zero

- Positive elliptic flow of prompt  $D^0$  in p-Pb collisions
- Indication of lower elliptic flow of non-prompt  $D^0$  also in p-Pb collisions
- Larger data samples needed to draw firm conclusions

- CMS Preliminary, CMS-PAS-HIN-21-001
- CMS, PRL 121 (2018) 082301
- CMS, PLB 791 (2019) 172
- CMS, PRL 121 (2018) 082301
- CMS, PLB 813 (2021) 136036



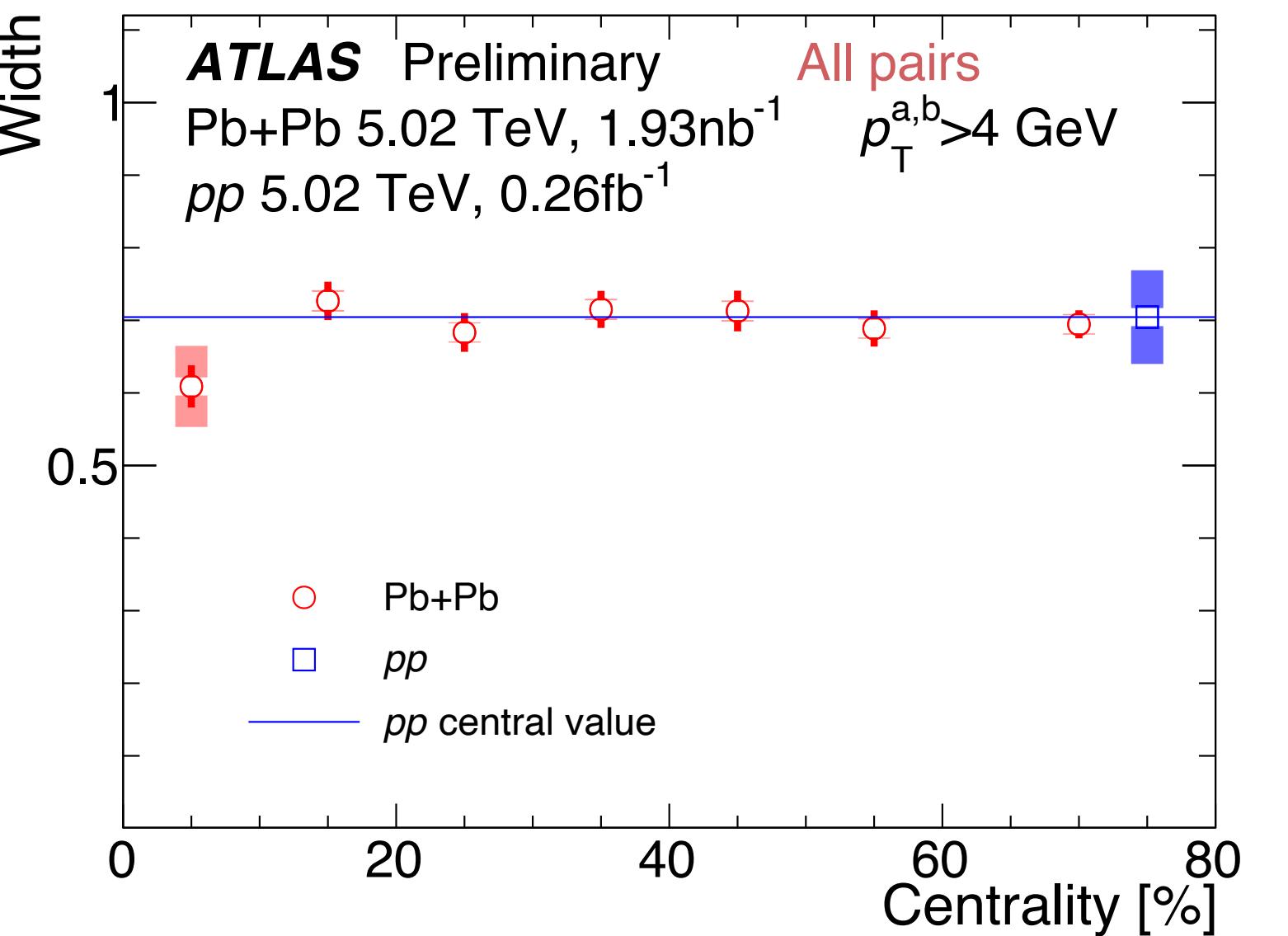
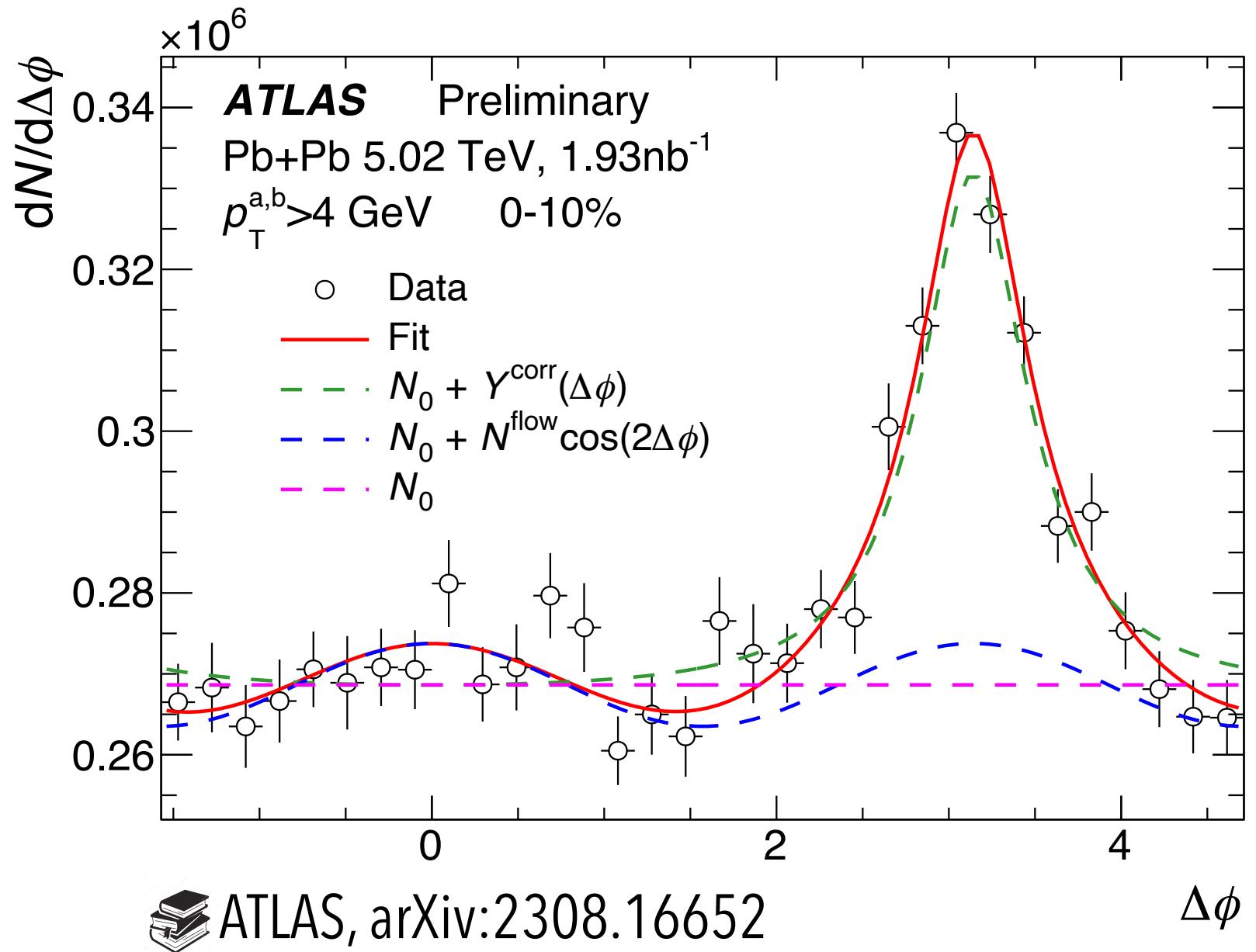
# Studying jet-quenching via azimuthal correlations

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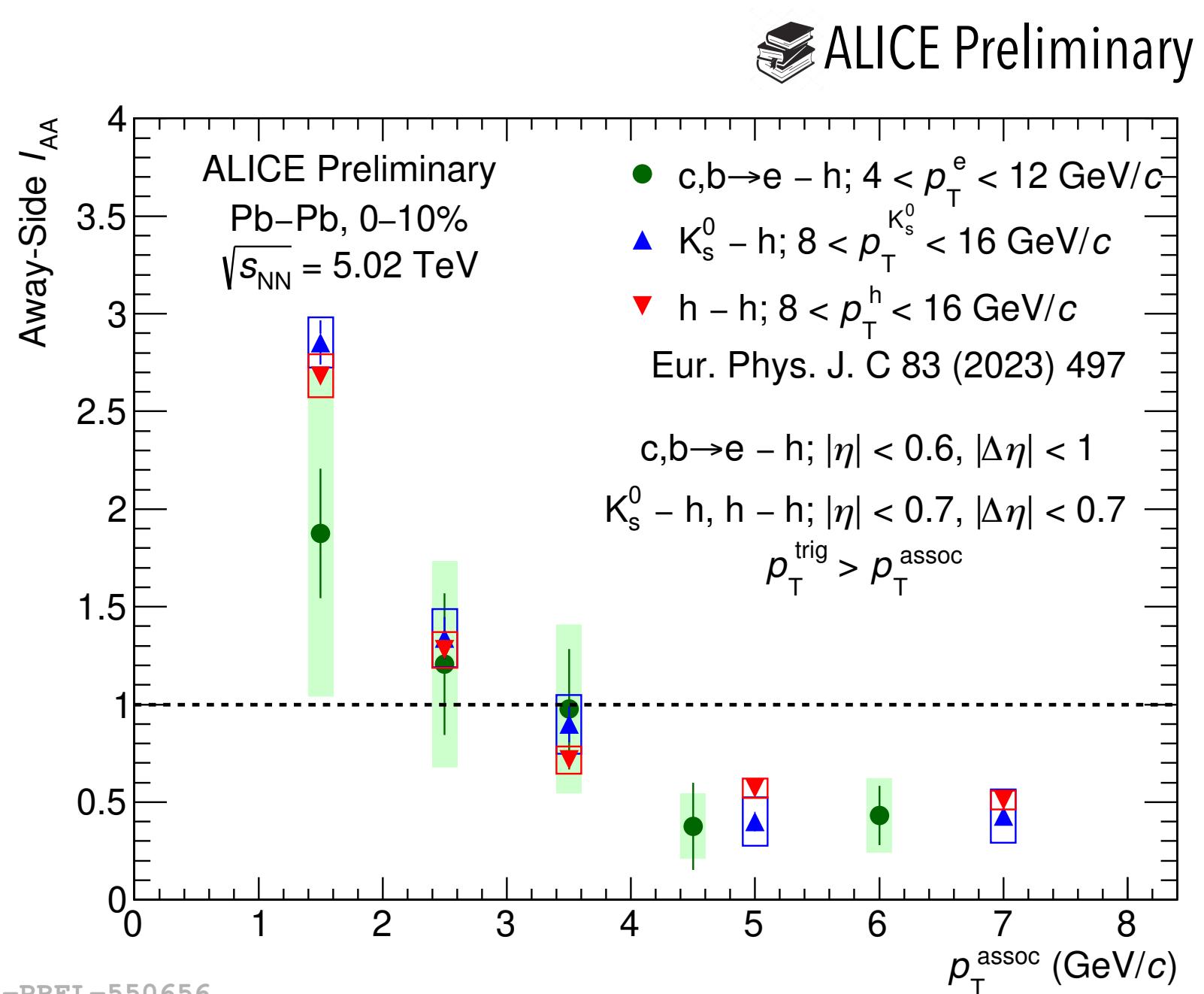
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A.M. Sickles – Tue 05 Sept R. Singh – Tue 05 Sept

- Measurements of angular correlations between HF hadrons can be used to study the **in-medium energy loss**
  - Goal: **search broadening of the away-side peak** in the azimuthal correlation due to deflection of energetic quarks in the QGP



- No evidence of modification of the away-side peak width in HF muon correlations as a function of centrality

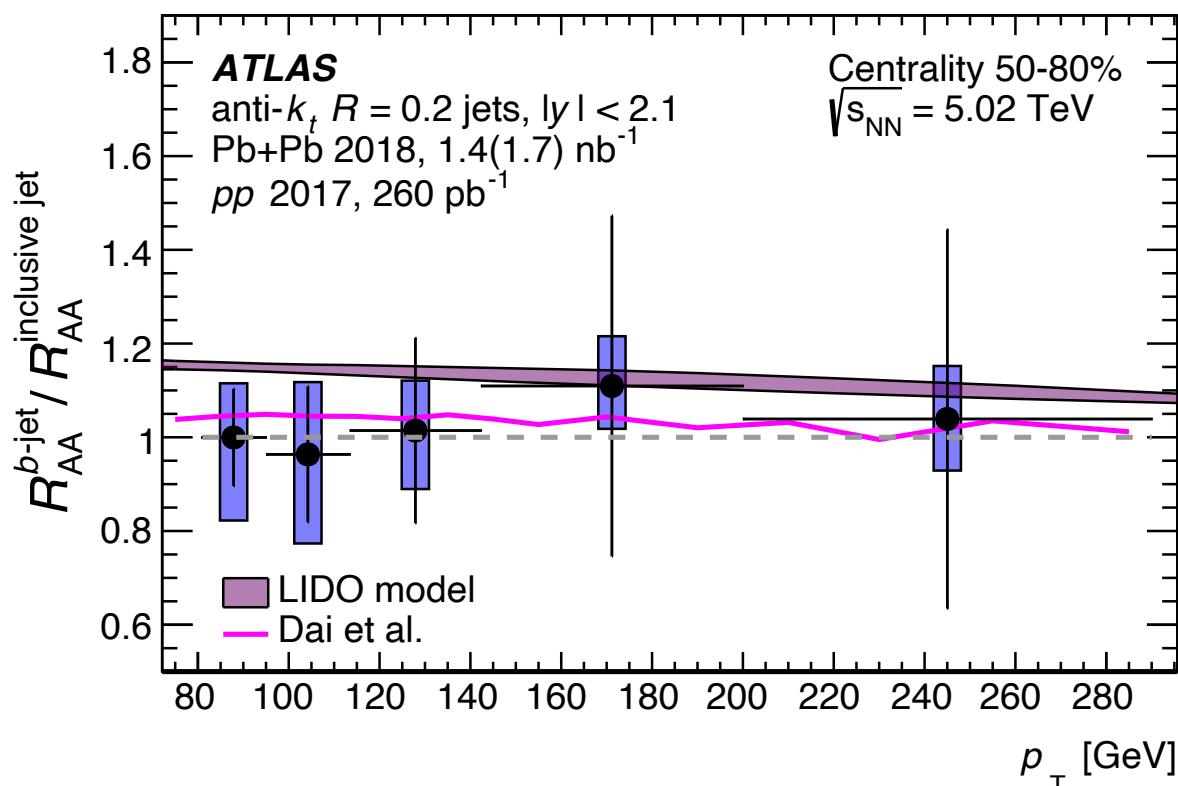
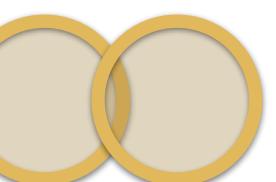
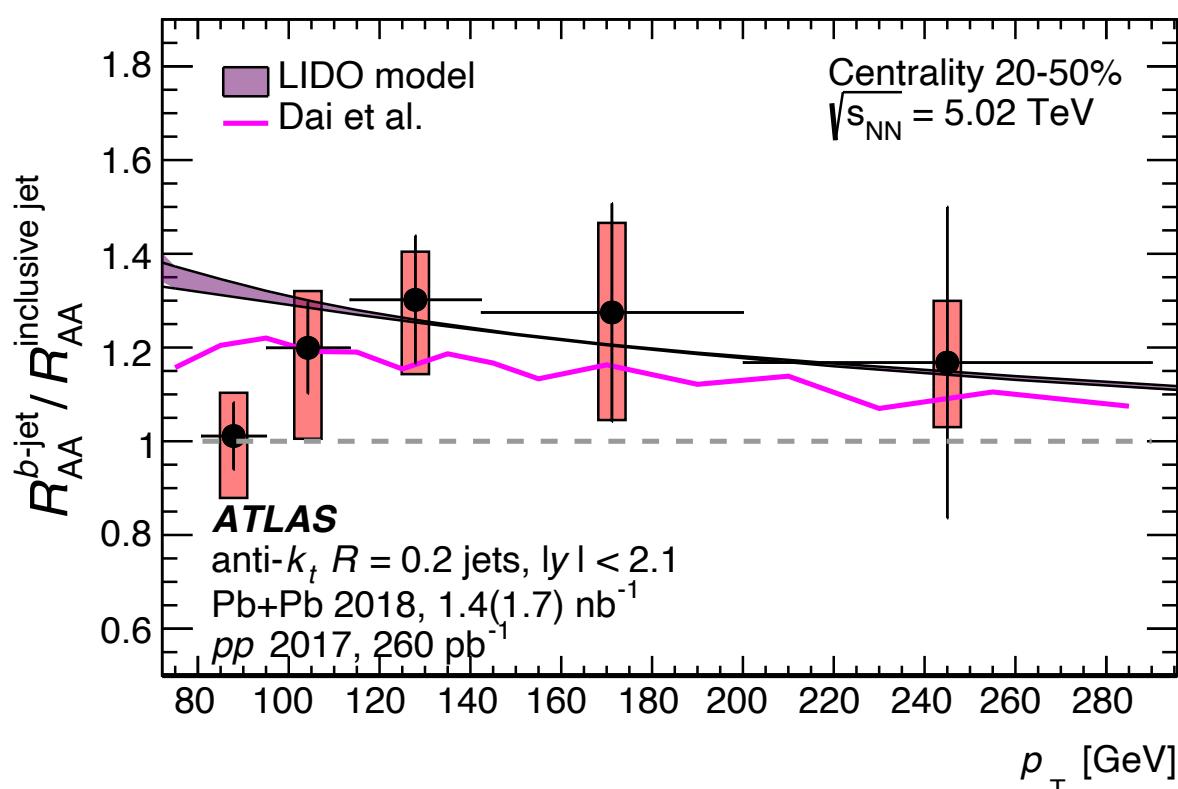
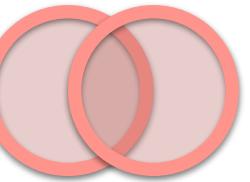
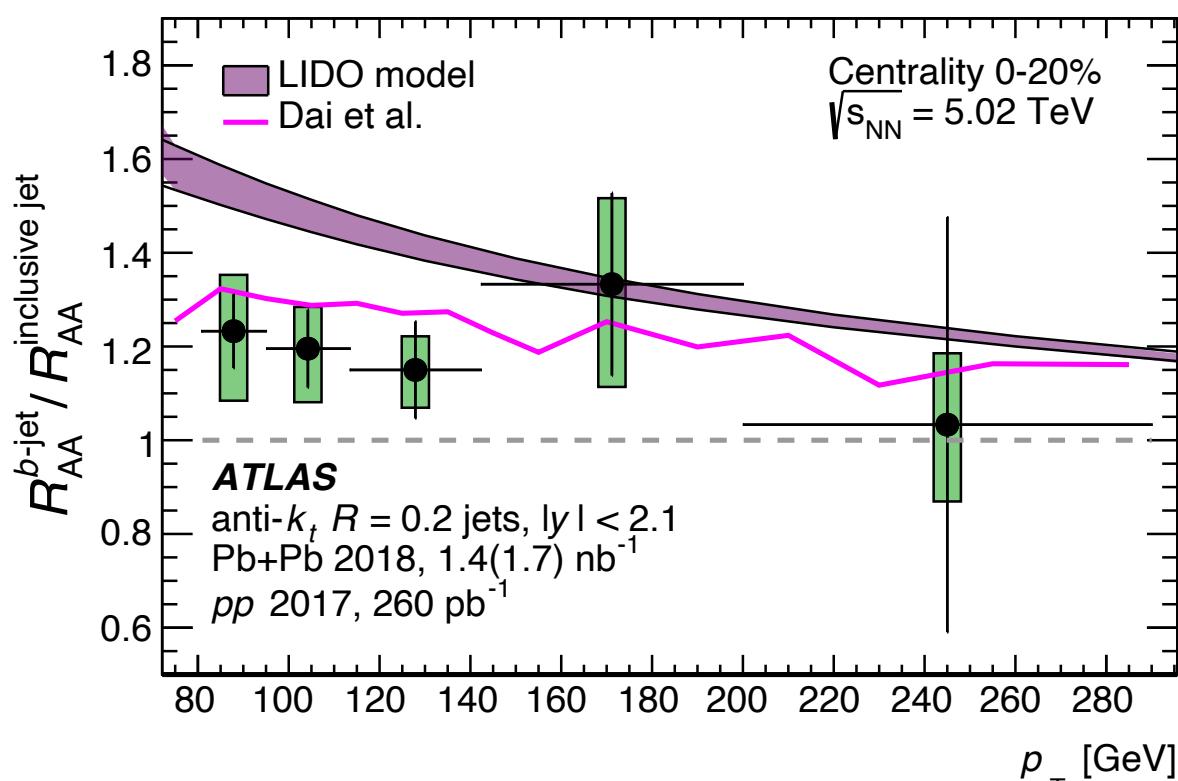


- Suppression of yield of high- $p_T$  associated particles in the away-side peak indicate suppression due to jet quenching
  - Quantified by the  $I_{AA} = Y_{AA} / Y_{pp}$
  - Similar for light hadrons (gluon initiated jets) and electrons from heavy-flavour hadron decays

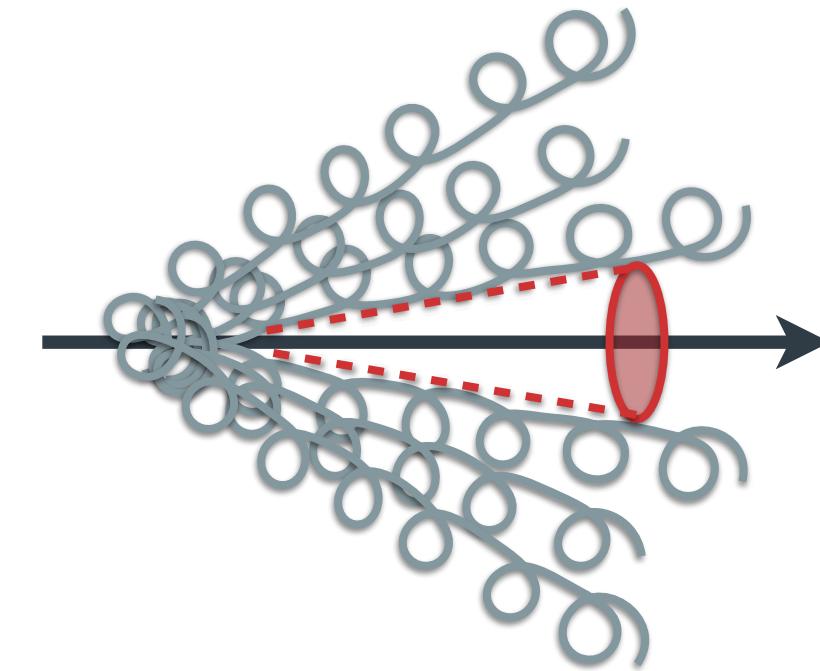
# Modification of b-tagged jets in heavy-ion collisions

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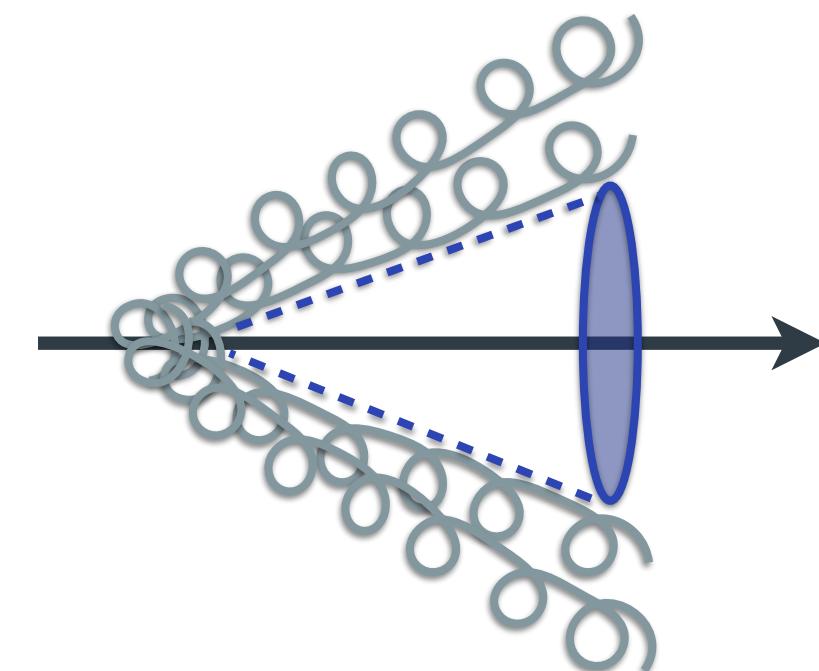
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small parton mass



large parton mass



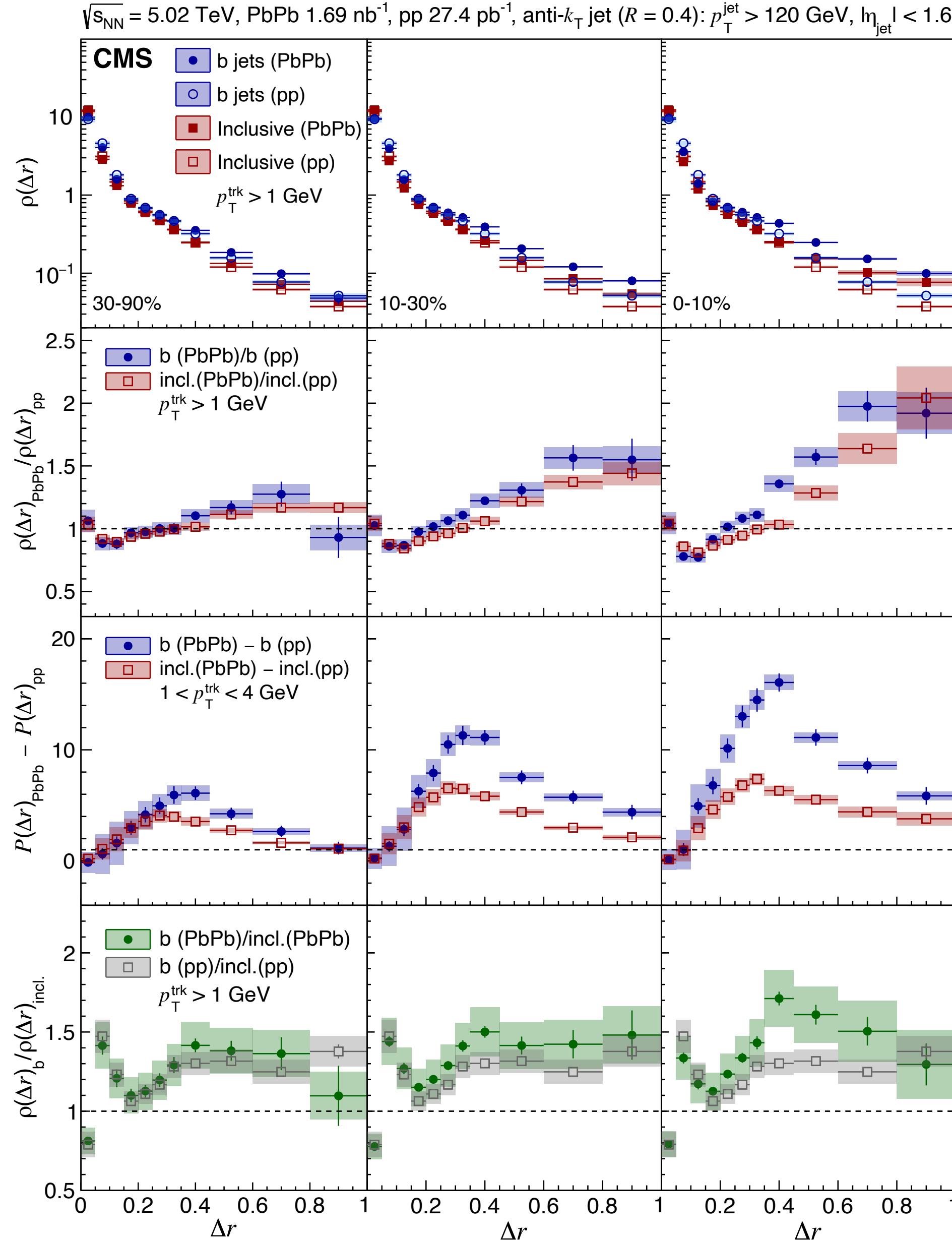
Dead cone effect: gluon radiation suppressed at angles smaller than  $\vartheta < m/E$

- b-tagged jets less suppressed than inclusive jets in central and mid central Pb–Pb collisions
  - b-quarks loose less energy in the QGP due to the dead cone effect
  - Models also include colour-charge dependence (quark vs. gluons)

# Modification of b-tagged jets in heavy-ion collisions

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$$\rho(\Delta r) = \frac{P(\Delta r)}{\sum_{\text{jets}} \sum_{\text{trk} \in (\Delta r < 1)} p_T^{\text{trk}}}$$

where  $P(\Delta r) = \frac{1}{\Delta r_b - \Delta r_b} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_a)} p_T^{\text{trk}}$

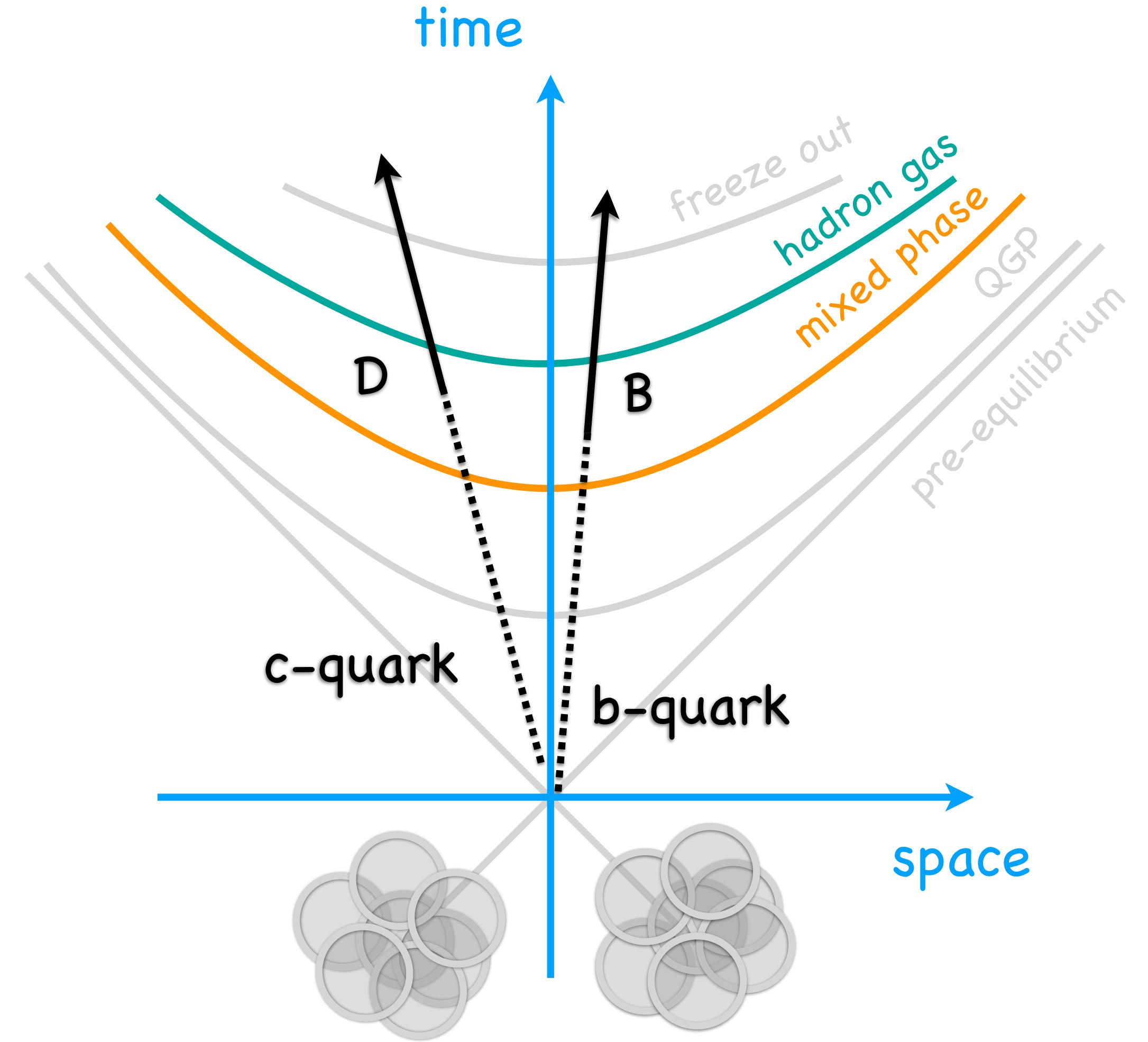
- Jet shape of b-tagged jets different from the one of inclusive jets
  - depletion of transverse momenta at small radial distances ( $\Delta r$ ) from the jet axis compared to inclusive jet shapes already present in pp collisions
  - Enhancement at intermediate-large  $\Delta r$  which increases with centrality

# Heavy-quark hadronisation from the medium

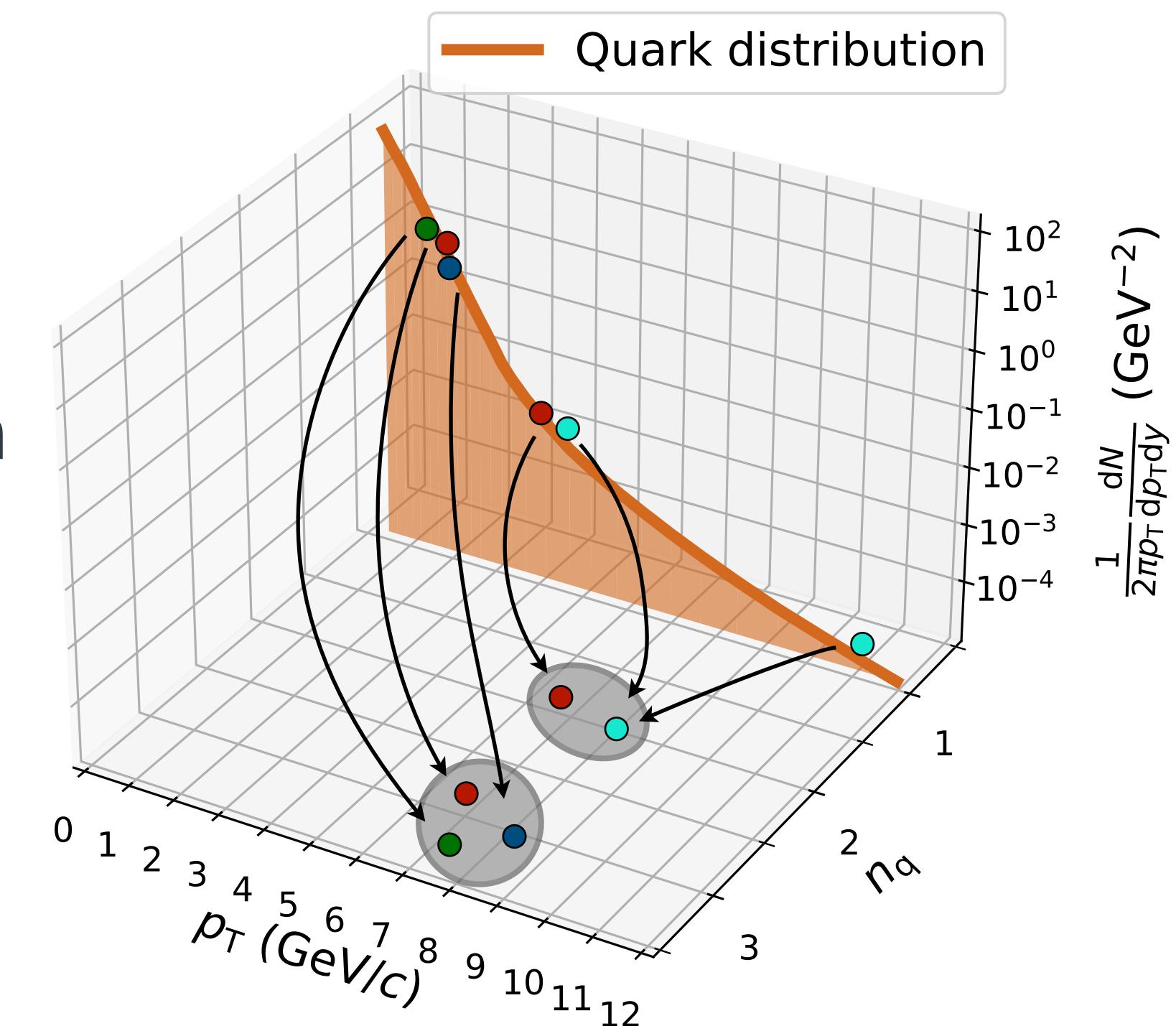
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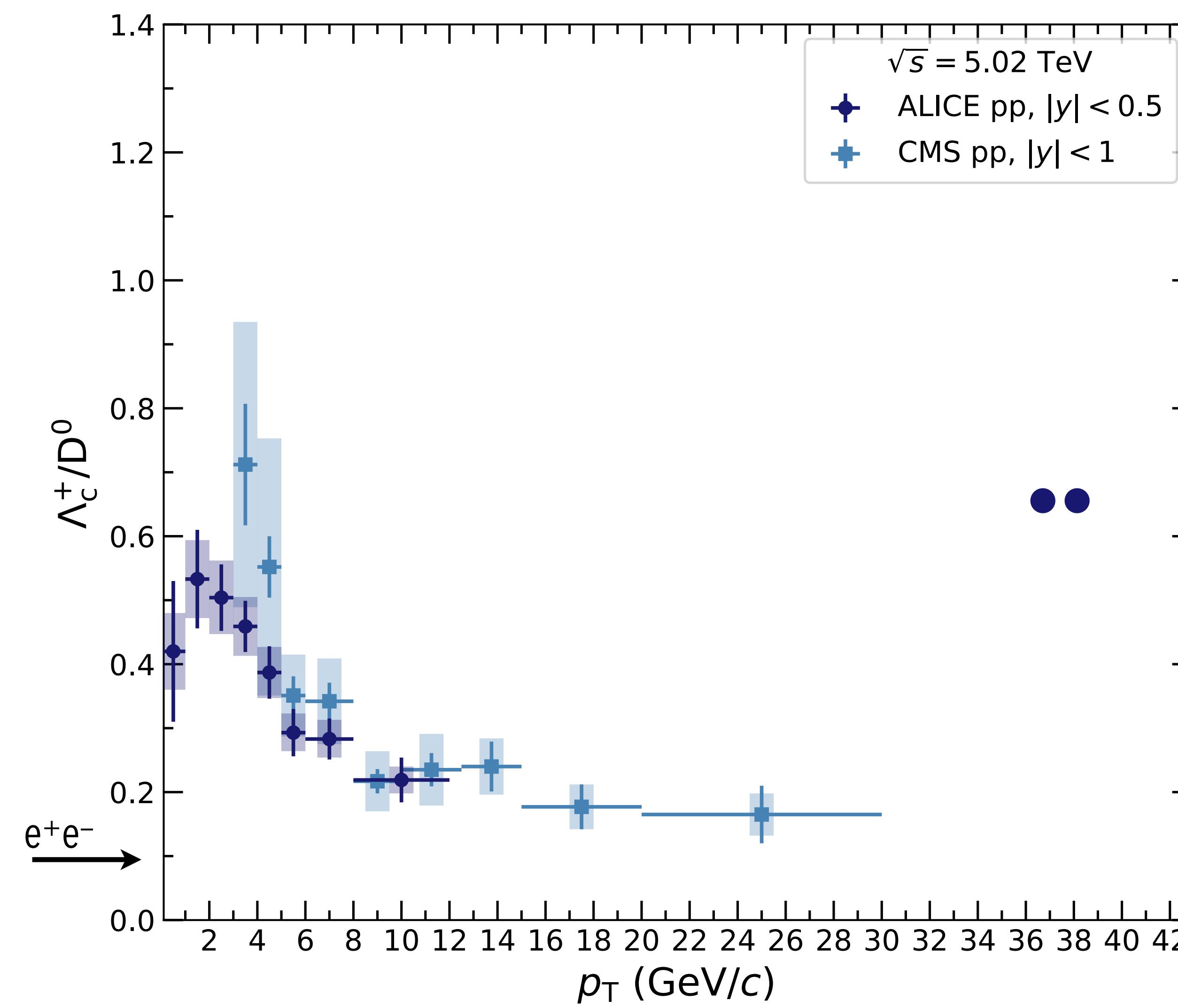
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- Hadronisation expected to be modified in presence of the colour-deconfined medium



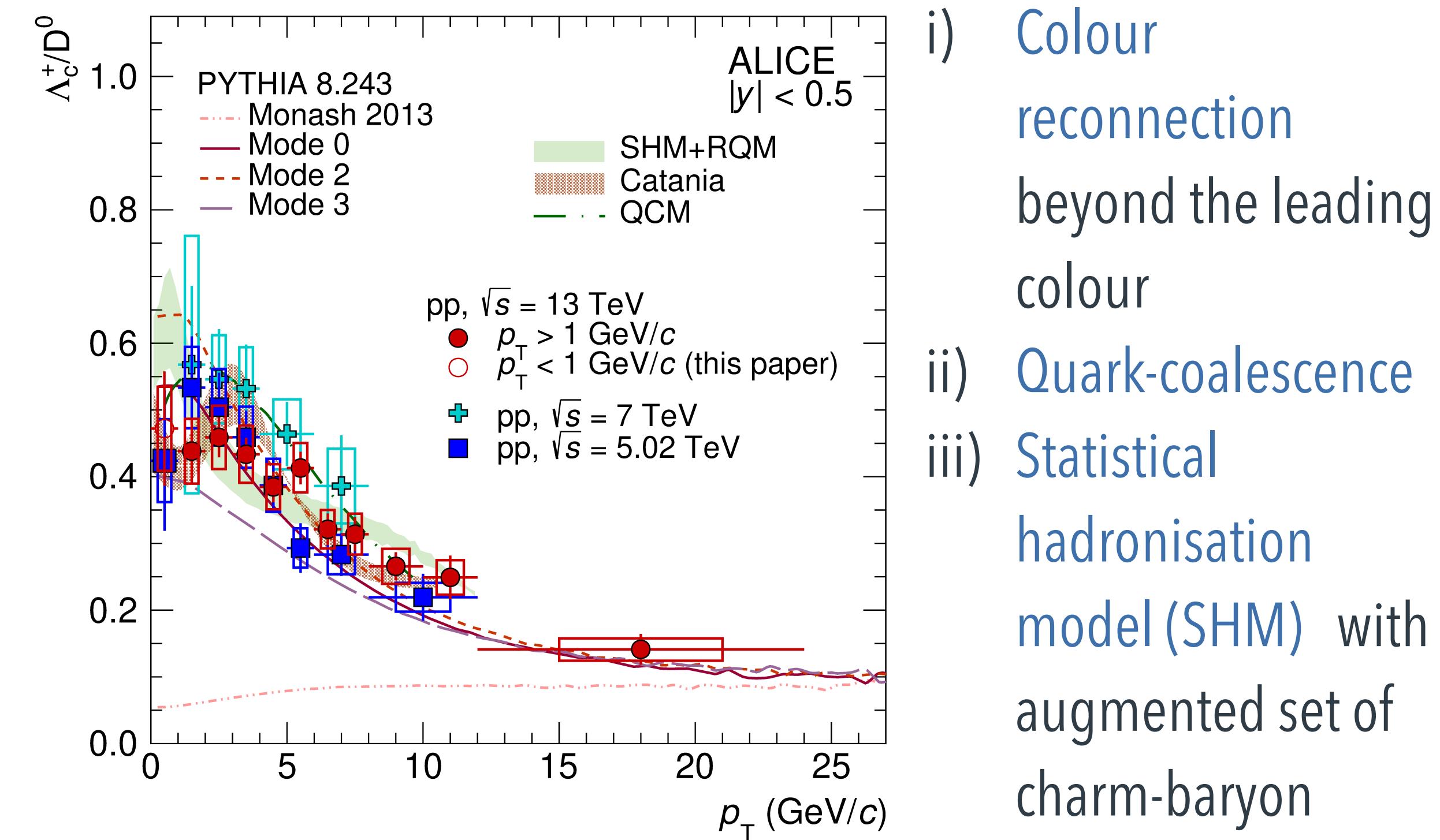
- (i) **Fragmentation  $D_{q \rightarrow h}(z_q, Q^2)$** 
  - A fraction of the parton momentum  $z_q$  is taken by the hadron
  - Can be modified by energy loss in the QGP
- (ii) **Recombination/coalescence**
  - Partons close in phase space can recombine
  - Enhances baryon-to-meson ratio at intermediate  $p_T$



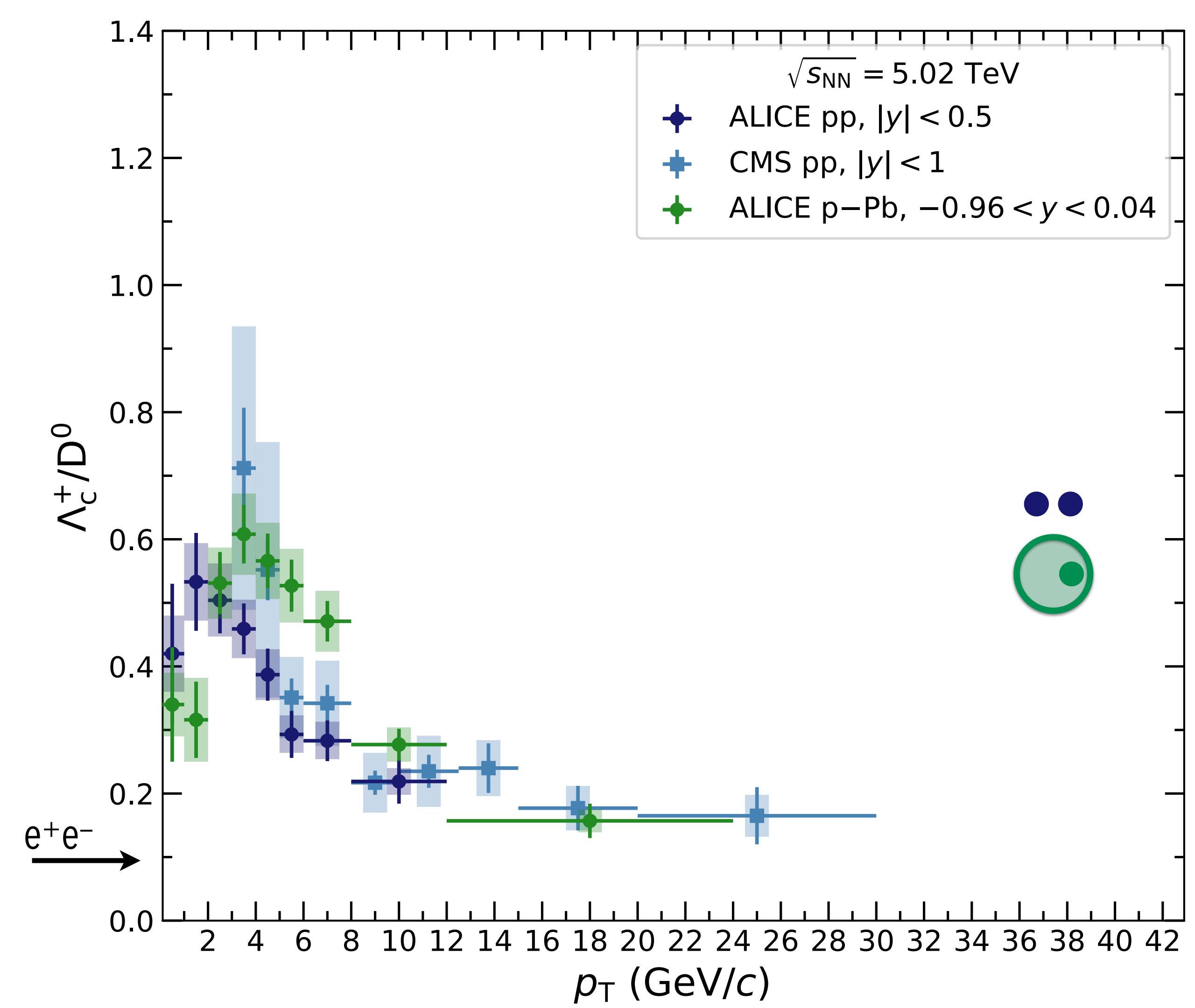


S. Chandra – Wed 06 Sept   J. Zhu – Wed 06 Sept

- Strong enhancement of charm baryon-to-meson ratio in  $pp$  collisions compared to  $e^+e^-$  collisions
  - Good agreement between ALICE and CMS data
  - Described by models based on

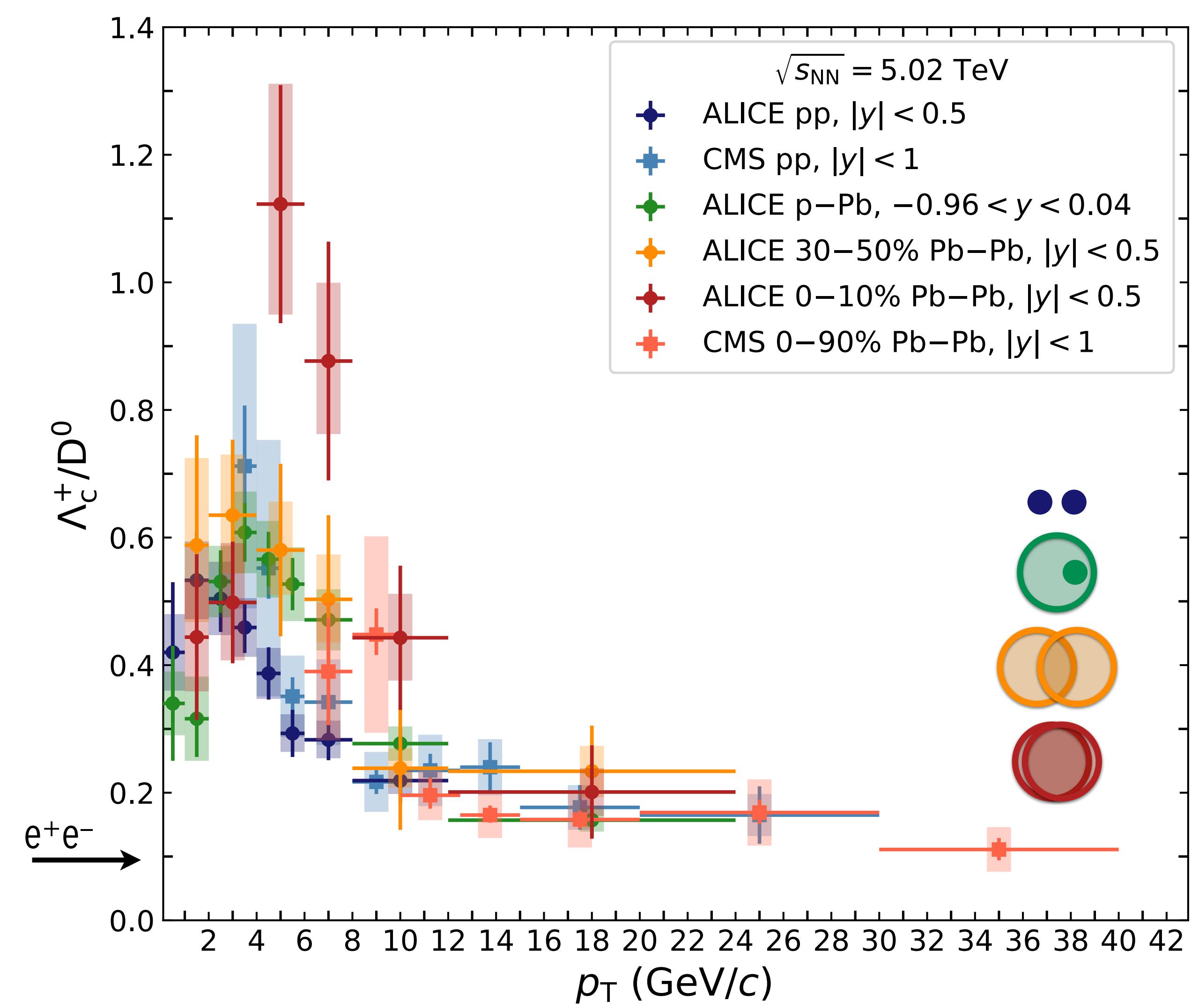


- i) Colour reconnection beyond the leading colour
- ii) Quark-coalescence
- iii) Statistical hadronisation model (SHM) with augmented set of charm-baryon excited states



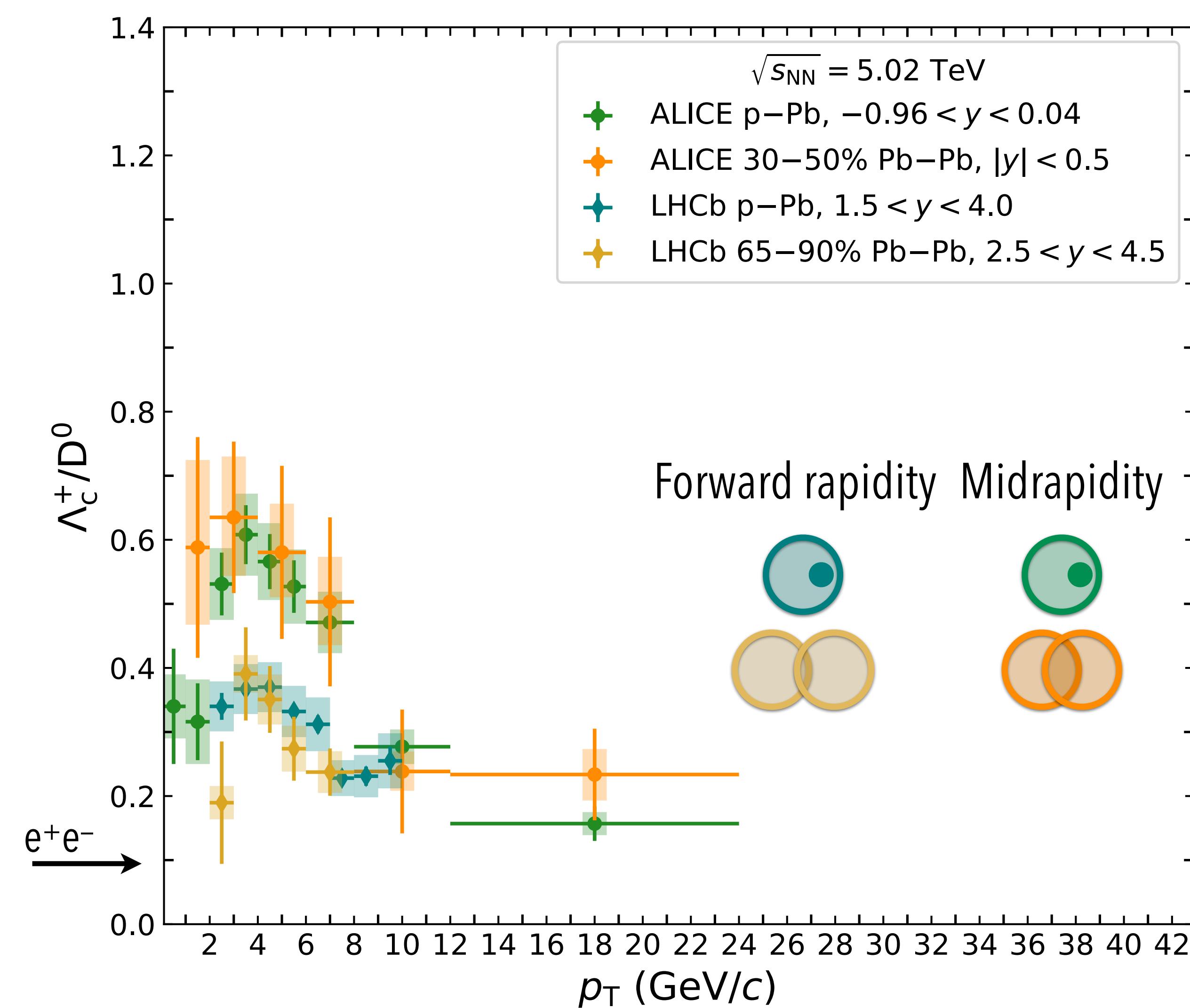
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  - Radial-flow like effect or quark recombination



S. Chandra – Wed 06 Sept   J. Zhu – Wed 06 Sept

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- Similar modification in Pb–Pb collisions, increasing with centrality



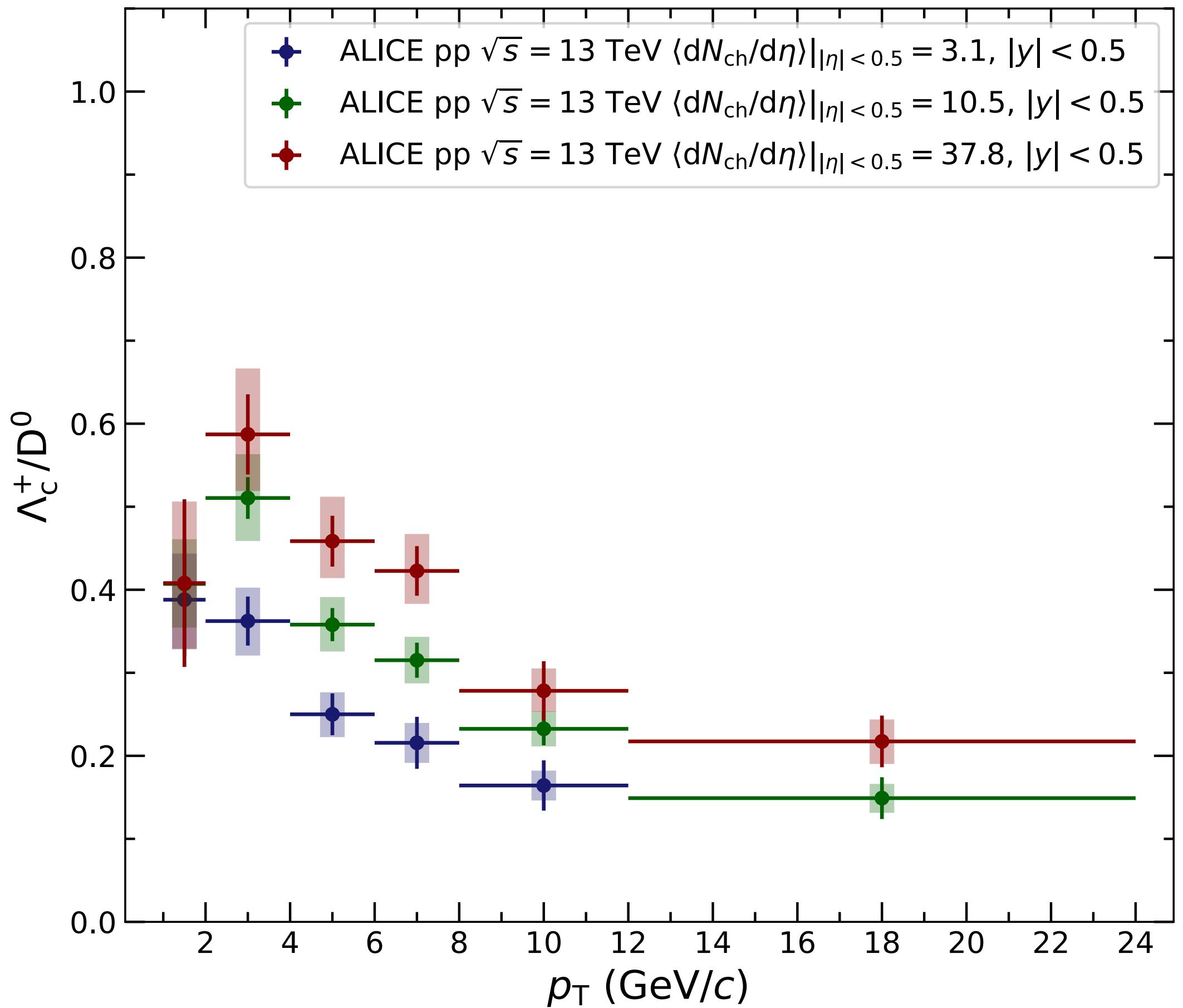
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  - Radial-flow like effect or quark recombination
- Similar modification in Pb-Pb collisions, increasing with centrality
- Similar behaviour at forward rapidity, but lower in absolute value
  - Rapidity dependence?

# Charm–baryon enhancement vs multiplicity

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ALICE, PLB 829 (2022) 137065

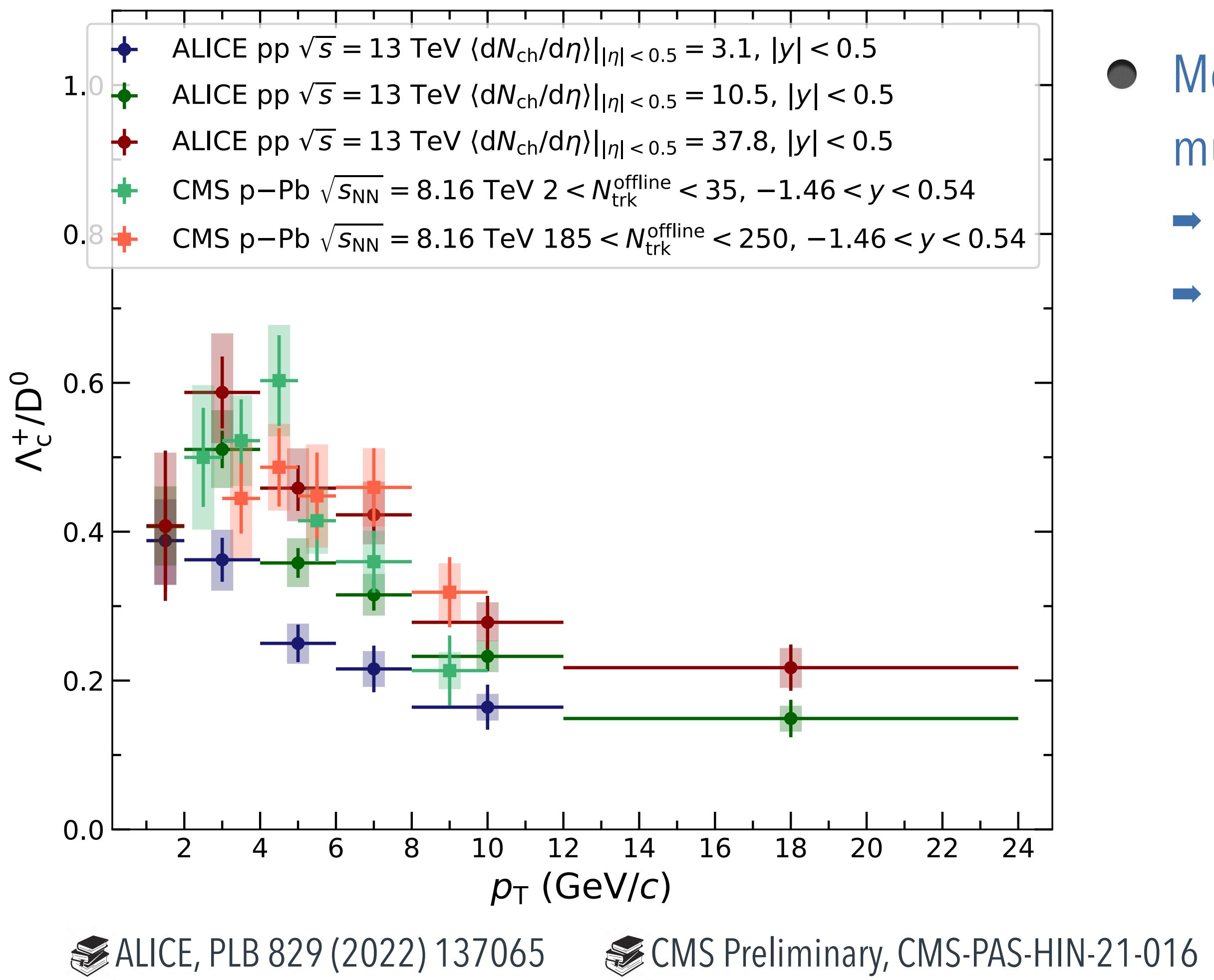
S. Chandra – Wed 06 Sept   J. Zhu – Wed 06 Sept

- Modification of  $\Lambda_c^+ / D^0$  ratio observed by ALICE as a function of multiplicity in pp collisions
  - Mostly in low multiplicity collisions

# Charm–baryon enhancement vs multiplicity

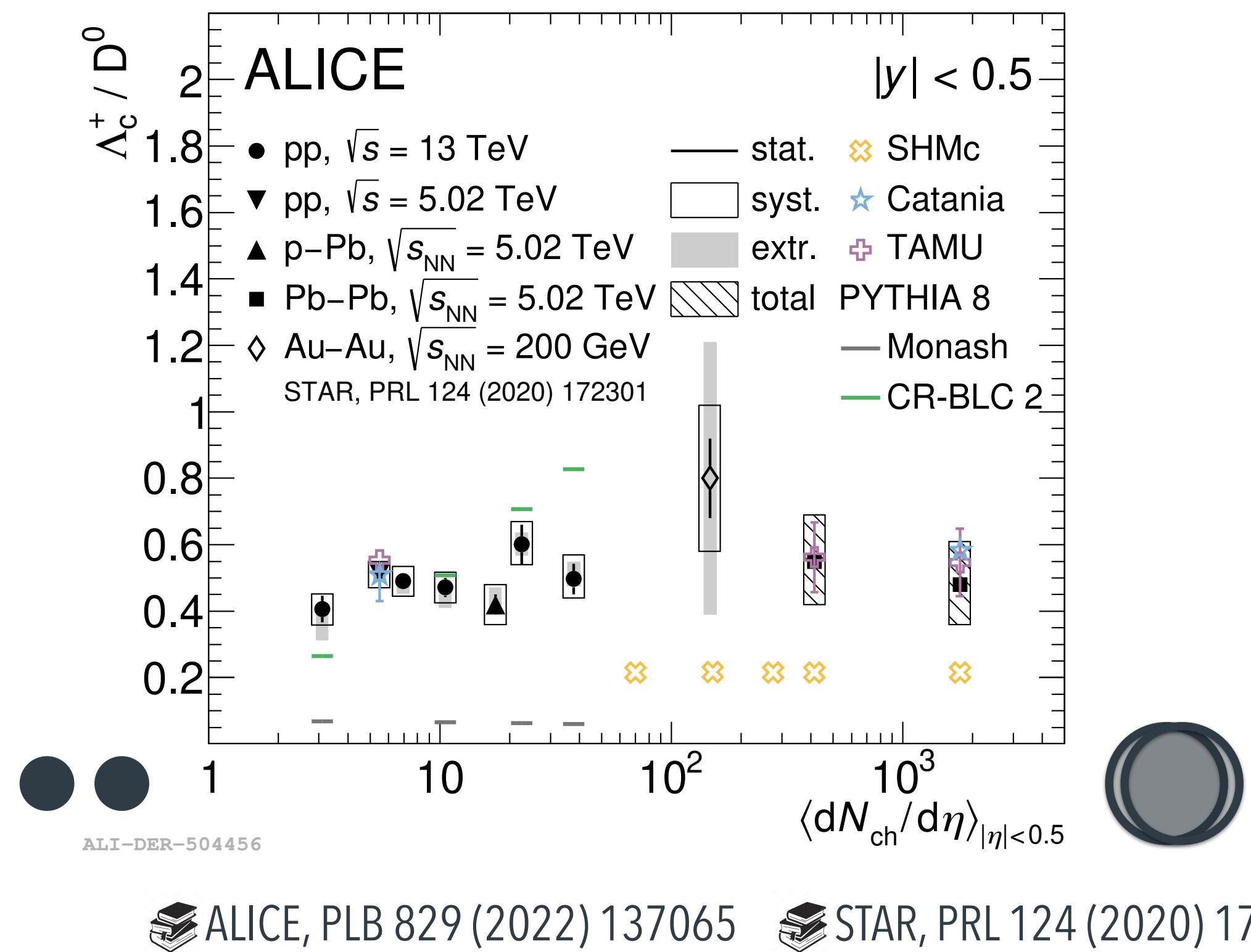
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- No evidence of  $p_T$ -integrated  $\Lambda_c^+ / D^0$  production ratio dependence on multiplicity from pp to AA collisions

- Modification of  $\Lambda_c^+ / D^0$  ratio observed by ALICE as a function of multiplicity in pp collisions
  - Mostly in low multiplicity collisions
  - No evidence of modification in p–Pb collisions by CMS, but compatible with ALICE results



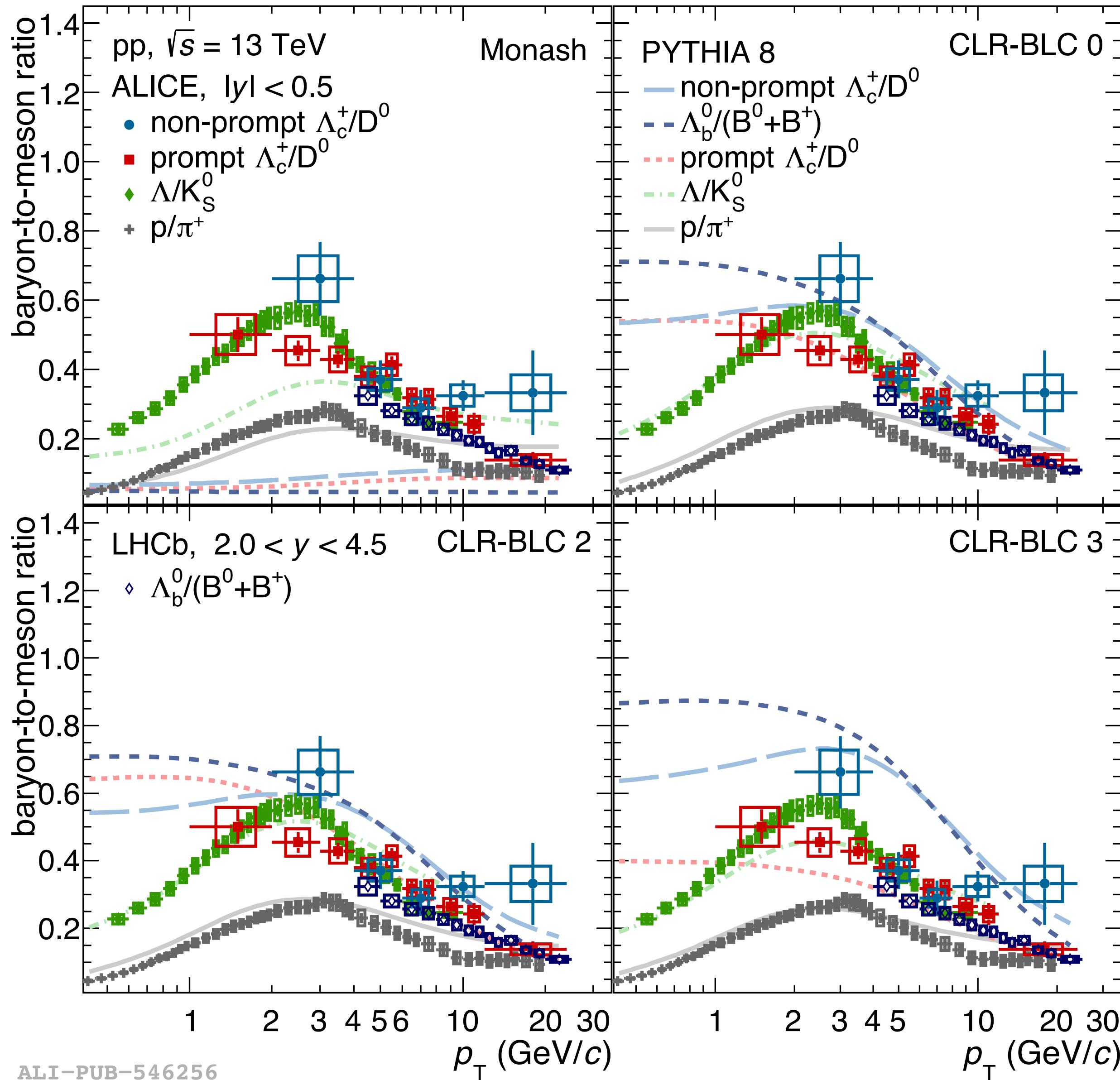
ALI-DER-504456

ALICE, PLB 829 (2022) 137065 STAR, PRL 124 (2020) 172301

# Beauty–baryon enhancement in pp collisions

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J. Zhu – Wed 06 Sept

- Non-prompt  $\Lambda_c^+ / D^0$  ratio and  $\Lambda_b^0 / B$  ratios show also large enhancement compared to pp collisions
  - Similar pattern of baryon-to-meson ratio for all the flavours
  - All flavours needed to properly constrain models and MC parameters

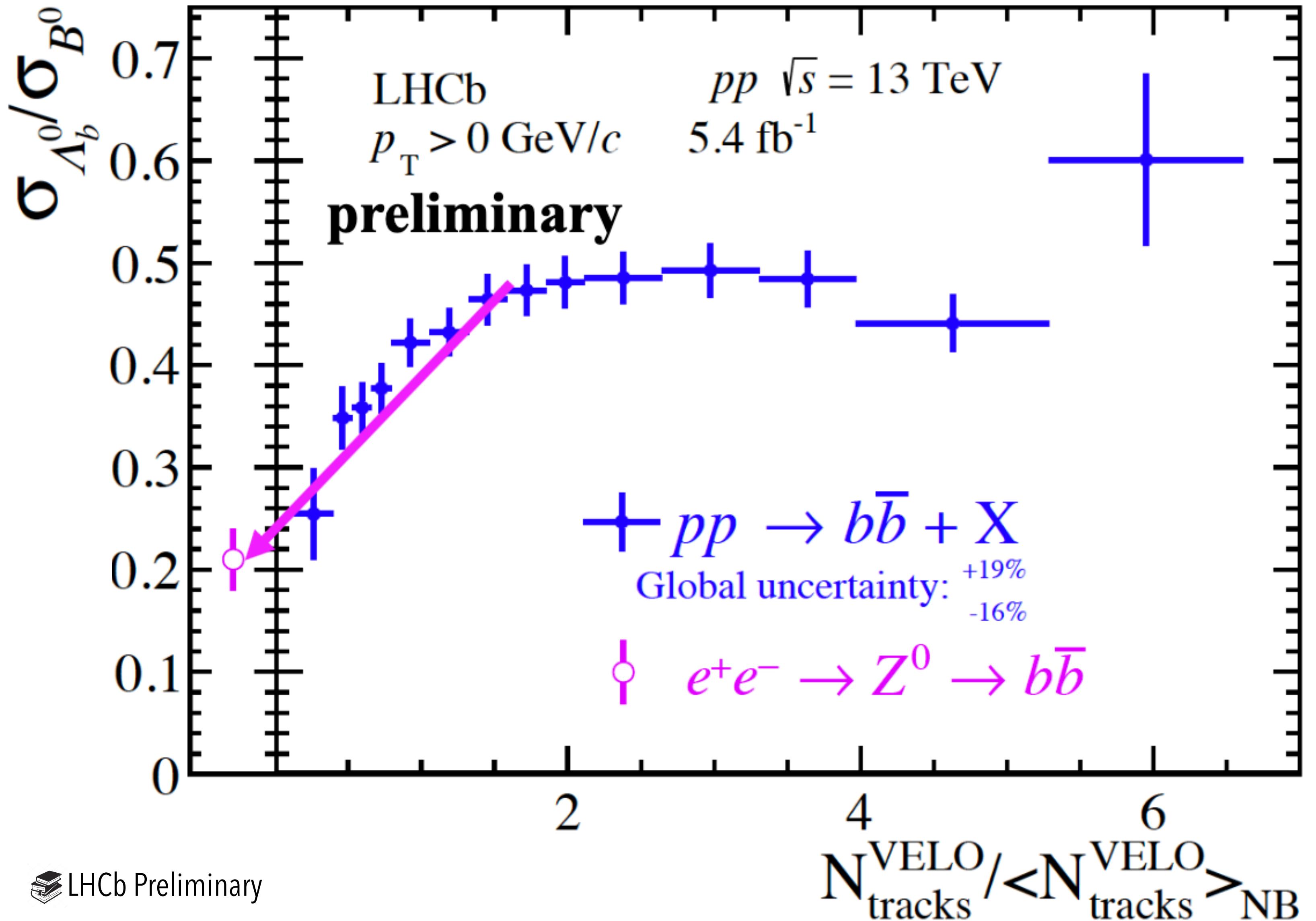
- ALICE, arXiv:2308.04873
- LHCb, PRD 100 (2019) 031102
- ALICE, PRL 128 (2022) 012001
- ALICE, EPJC 81 (2021) 256

# Beauty–baryon enhancement vs multiplicity

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C. Gu – Tue 05 Sept

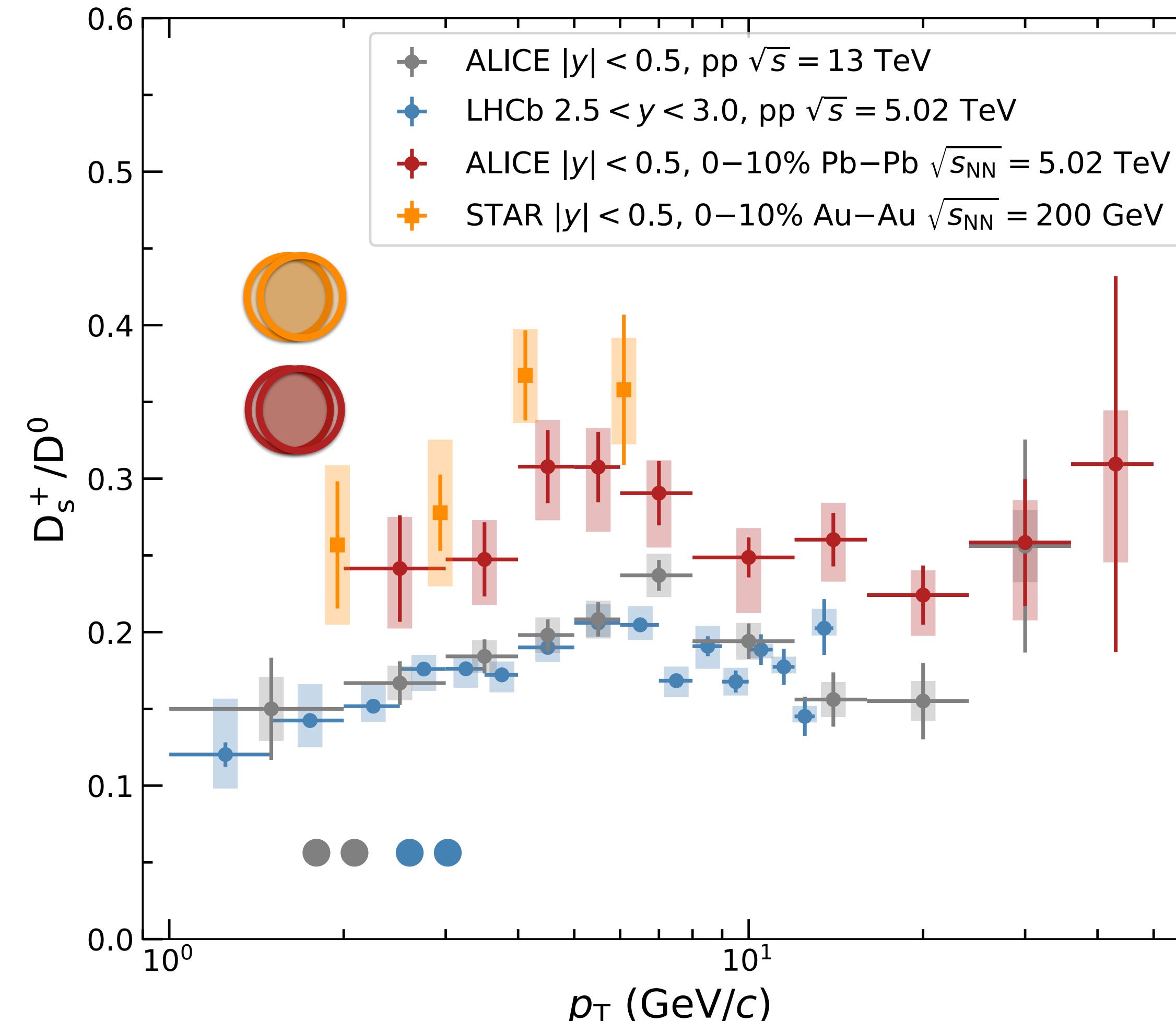


- $\Lambda_b^0 / B^0$  modified as a function of multiplicity in pp collisions
  - Approaches  $e^+e^-$  value at very low multiplicity
  - Saturates at high multiplicity

# Charm-quark hadronisation and strangeness enhancement

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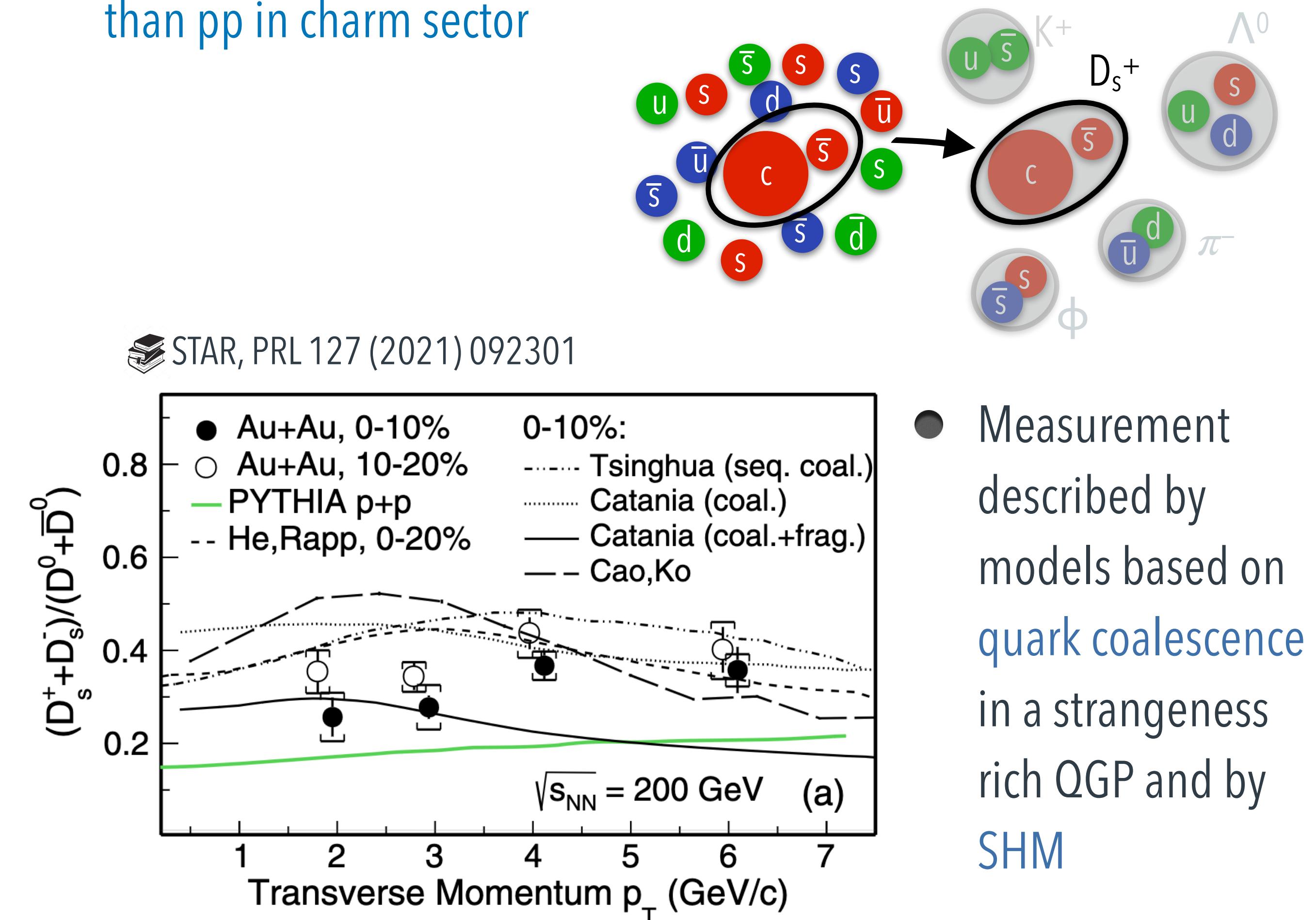
ALICE, PLB 827 (2022) 136986

STAR, PRL 127 (2021) 092301

ALICE, arXiv:2308.04877

LHCb, JHEP 03 (2016) 159

- Abundant production of strange quarks in the QGP
- Recombination → strange hadrons expected to be enhanced
- Strange-to-nonstrange ratio higher in Pb–Pb than pp in charm sector

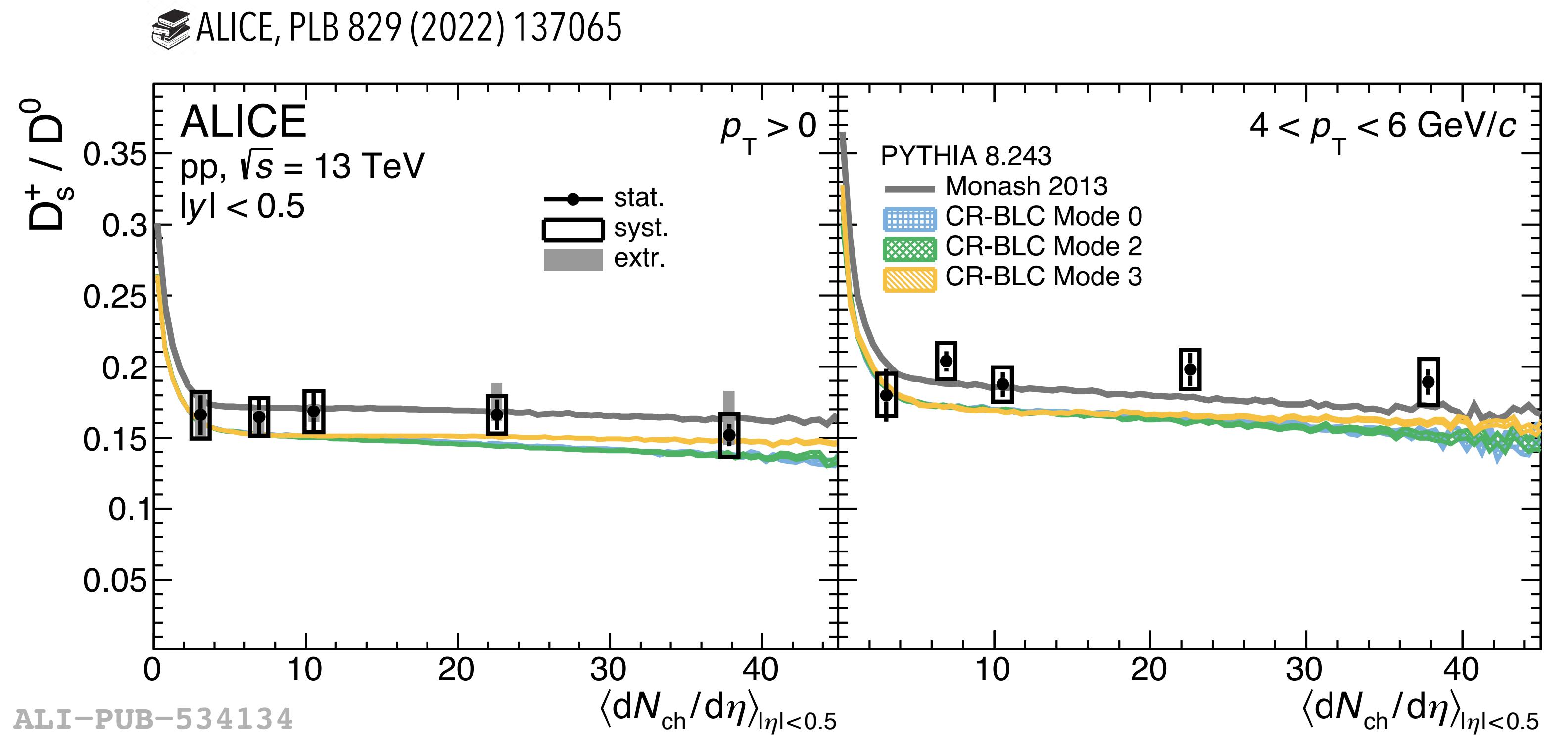


- Measurement described by models based on quark coalescence in a strangeness rich QGP and by SHM

# $D_s^+$ meson in pp collisions vs multiplicity

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25  
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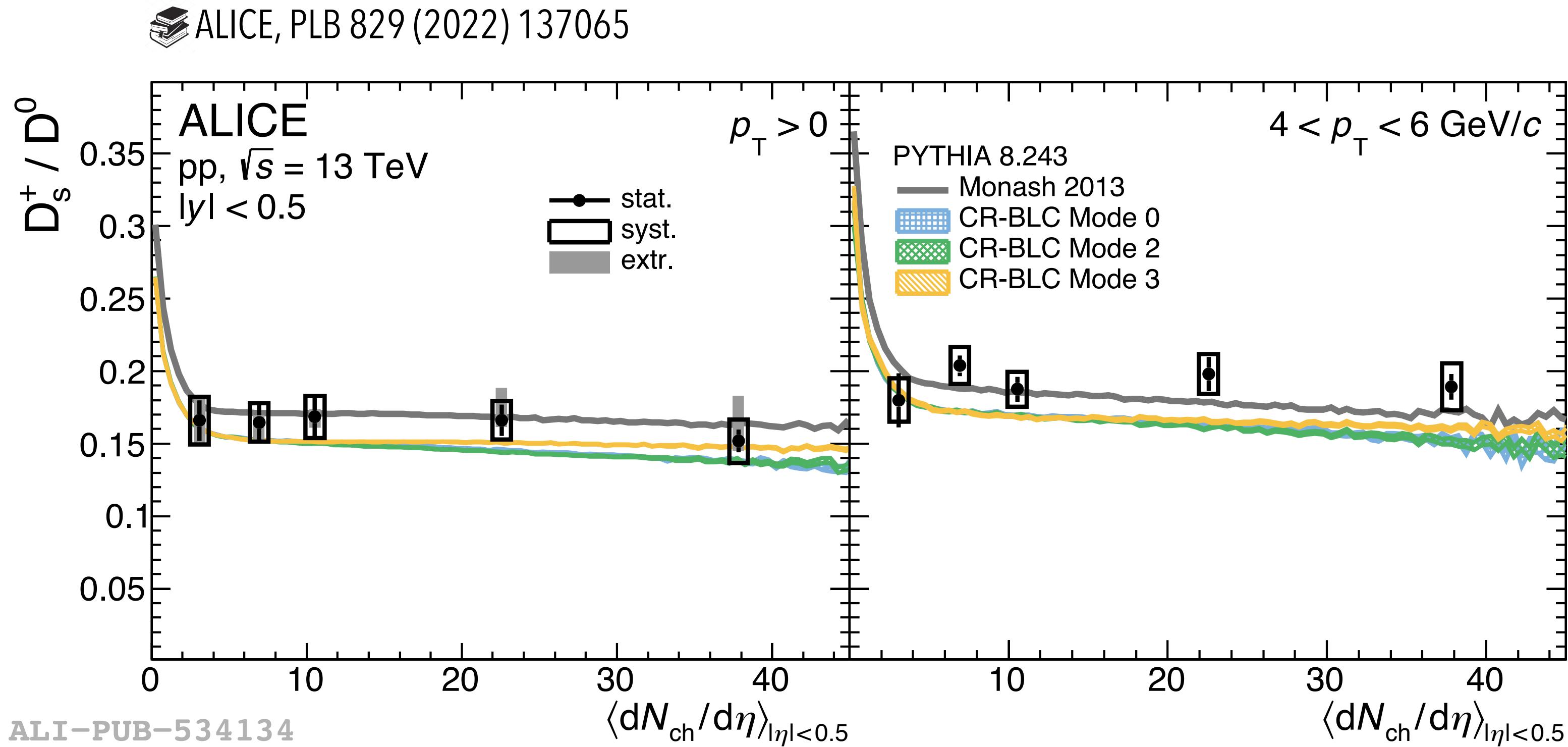
- No evidence of multiplicity dependence of  $D_s^+/D^0$  ratio in pp collisions
  - Up to  $\sim 2$  times the average p-Pb charged particle multiplicity
- $$\langle dN_{ch} / d\eta \rangle_{|\eta|_{lab} < 0.5}^{p-Pb} = 17.35 \pm 0.67$$

ALICE, PRL 110 (2013) 032301

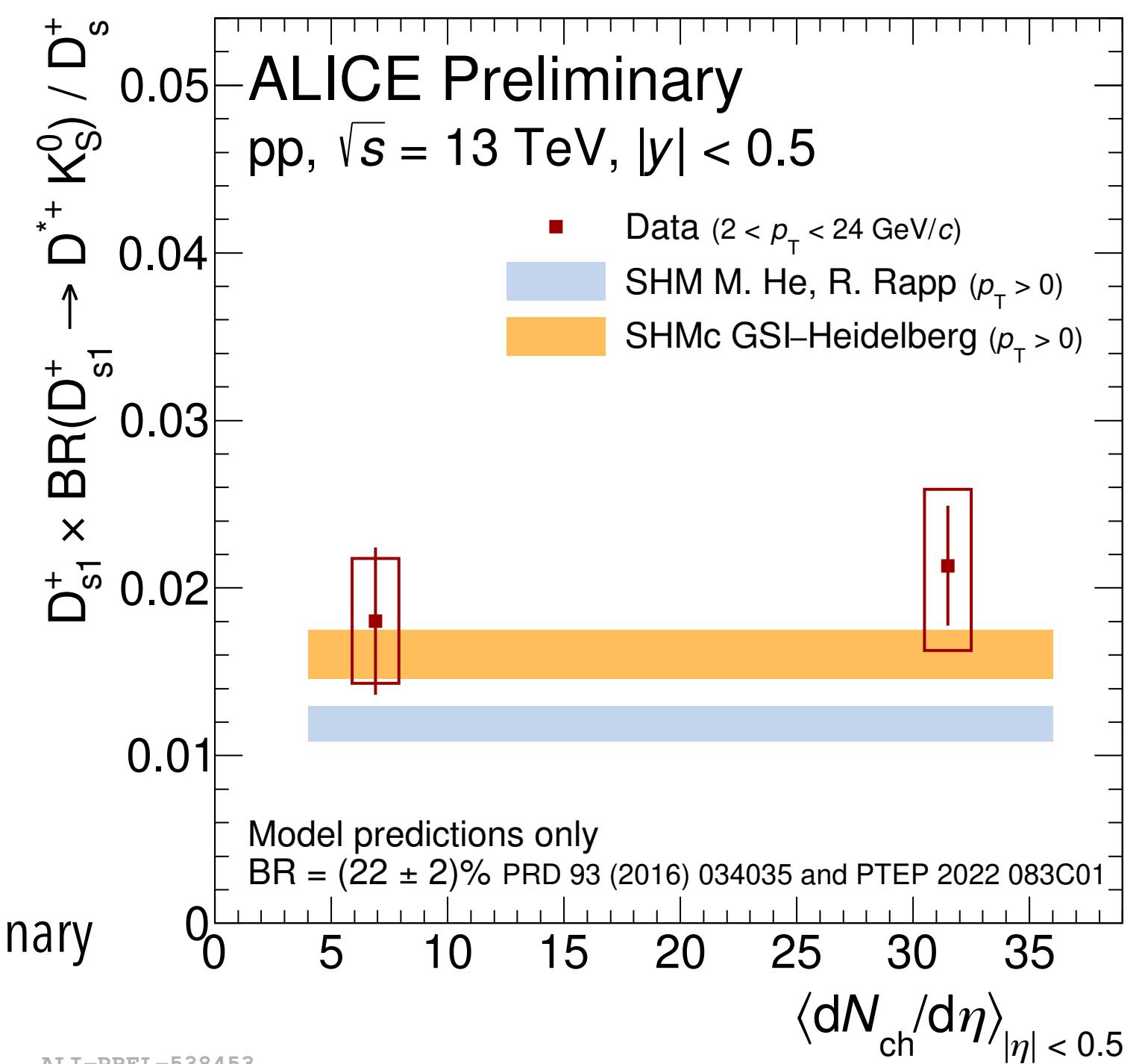
# $D_s^+$ meson in pp collisions vs multiplicity

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- No evidence of multiplicity dependence of  $D_s^+/D^0$  ratio in pp collisions
    - Up to  $\sim 2$  times the average p-Pb charged particle multiplicity
- $$\langle dN_{ch}/d\eta \rangle_{|\eta|_{lab} < 0.5}^{p-Pb} = 17.35 \pm 0.67$$
- ALICE, PRL 110 (2013) 032301



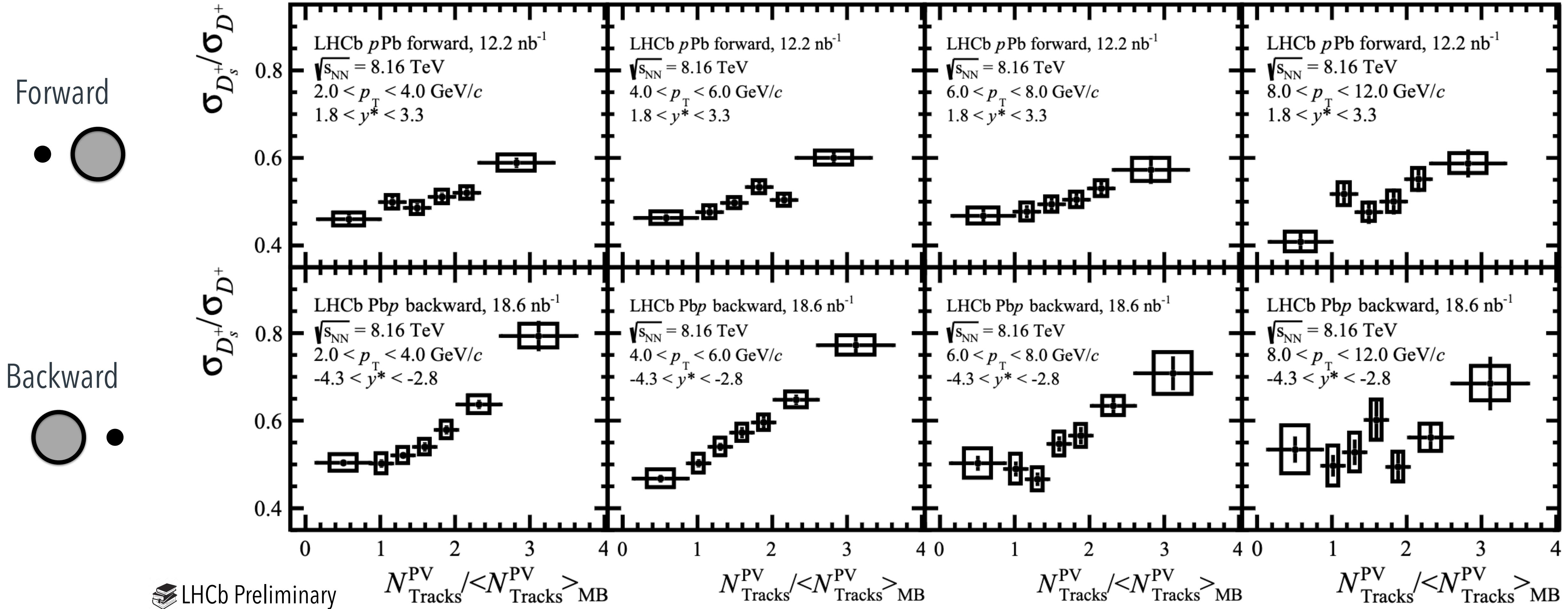
- First measurement of excited  $D_s$  production as a function of multiplicity
  - Ratio to the ground state does not show multiplicity dependence
  - Larger data samples needed

# $D_s^+$ meson in p–Pb collisions vs multiplicity

F. Gerosa (CERN)  
fgrosa@cern.ch

27  
45

C. Gu – Tue 05 Sept

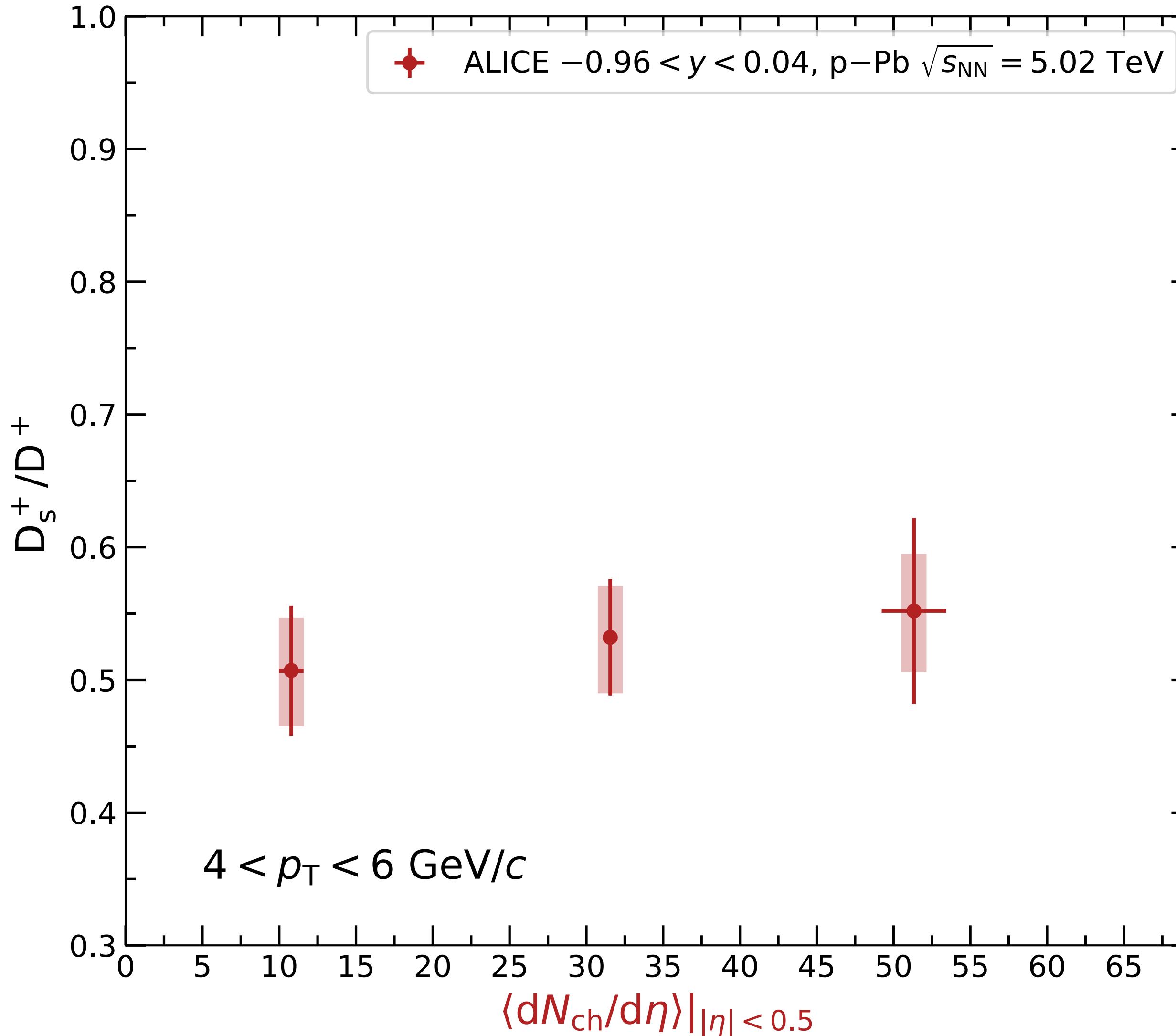


- First observation of  $D_s^+/\bar{D}^+$  increase as a function of multiplicity in p–Pb collisions at forward and backward rapidities
  - Steeper increase at backward compared to forward rapidity → because of higher average multiplicity?

# $D_s^+$ meson in p–Pb collisions vs multiplicity

F. Gerosa (CERN)  
fgrosa@cern.ch

28  
45



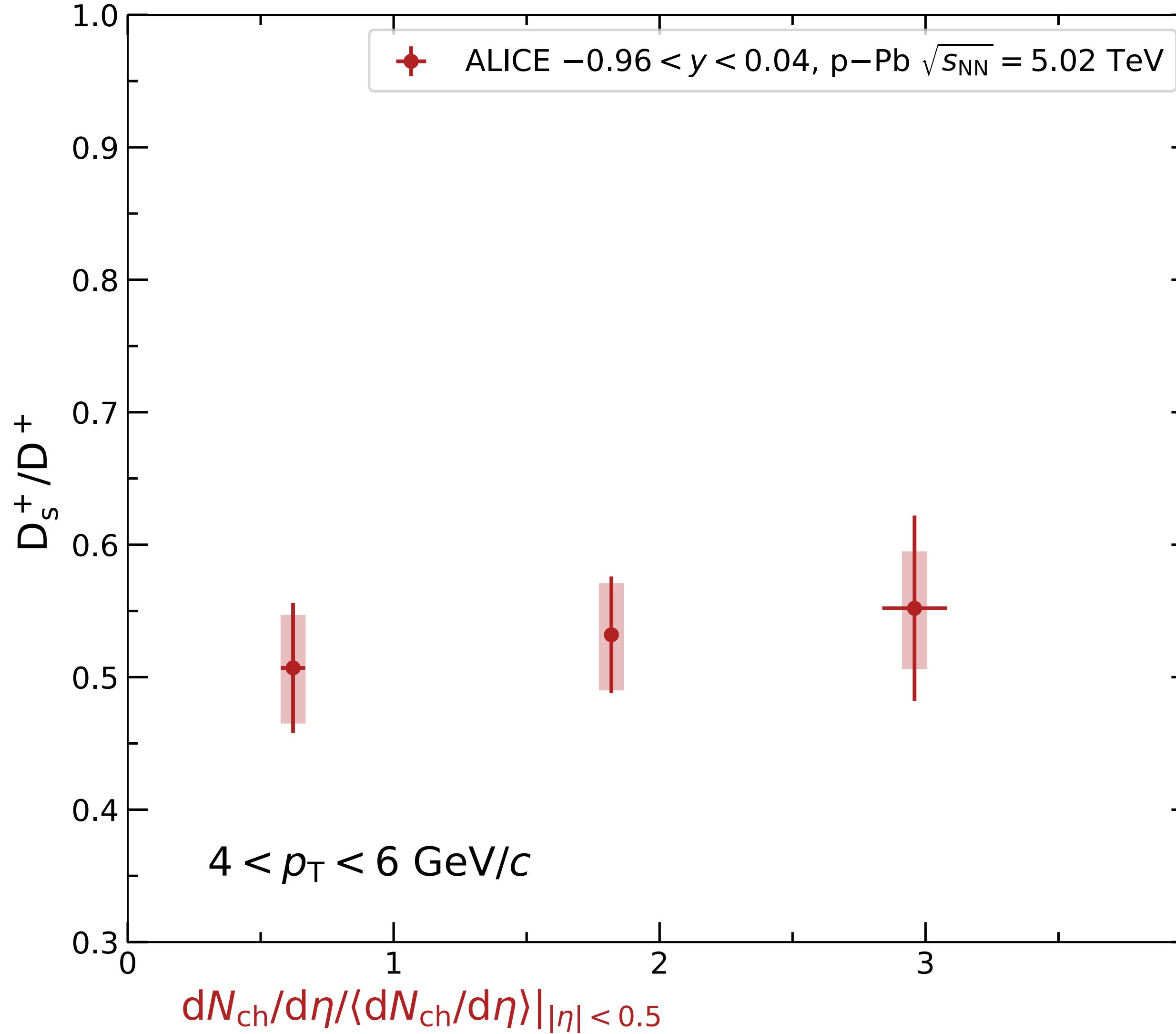
- No evidence of multiplicity dependence at midrapidity

ALICE, JHEP 12 (2019) 092  
LHCb Preliminary

# $D_s^+$ meson in p–Pb collisions vs multiplicity

F. Grossa (CERN)  
fgrosa@cern.ch

29  
45



- No evidence of multiplicity dependence at midrapidity

ALICE, JHEP 12 (2019) 092  
LHCb Preliminary

ALICE, PRL 110 (2013) 032301

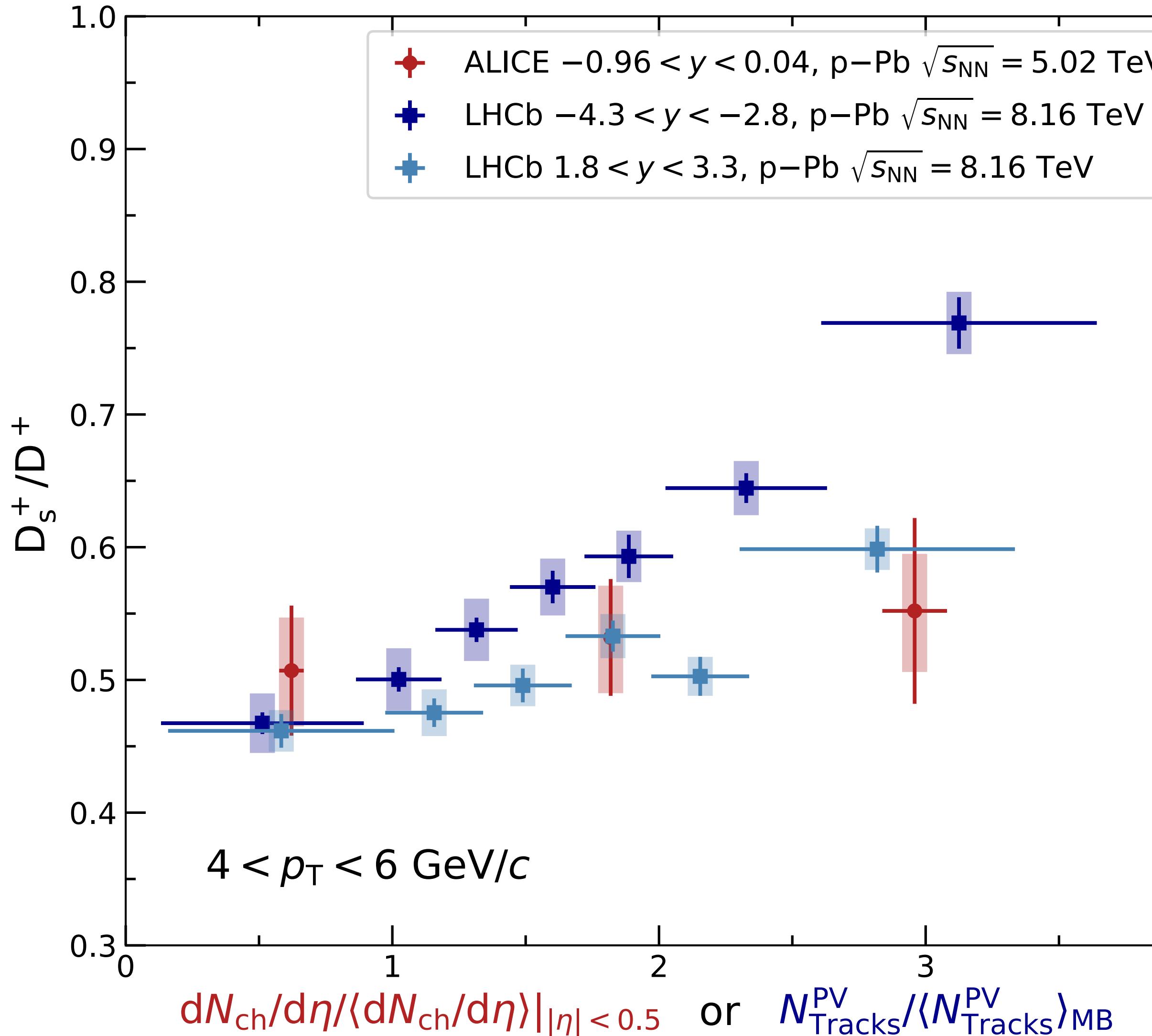
Self normalised to the average MB multiplicity  $\langle dN_{ch}/d\eta \rangle_{|\eta|_{lab} < 0.5}^{p-Pb} = 17.35 \pm 0.67$

# $D_s^+$ meson in p–Pb collisions vs multiplicity

F. Grossa (CERN)  
fgrosa@cern.ch

30  
45

C. Gu – Tue 05 Sept



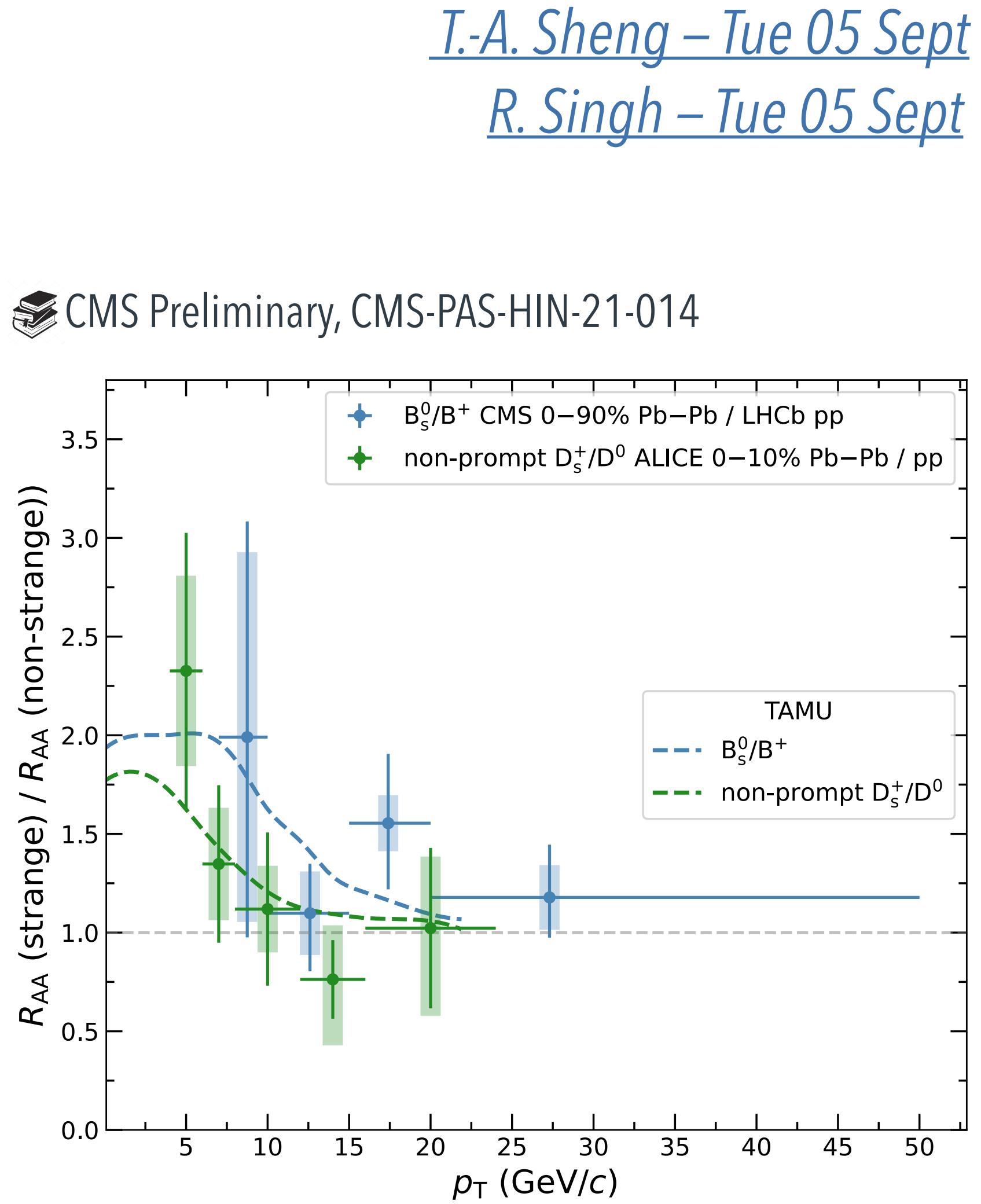
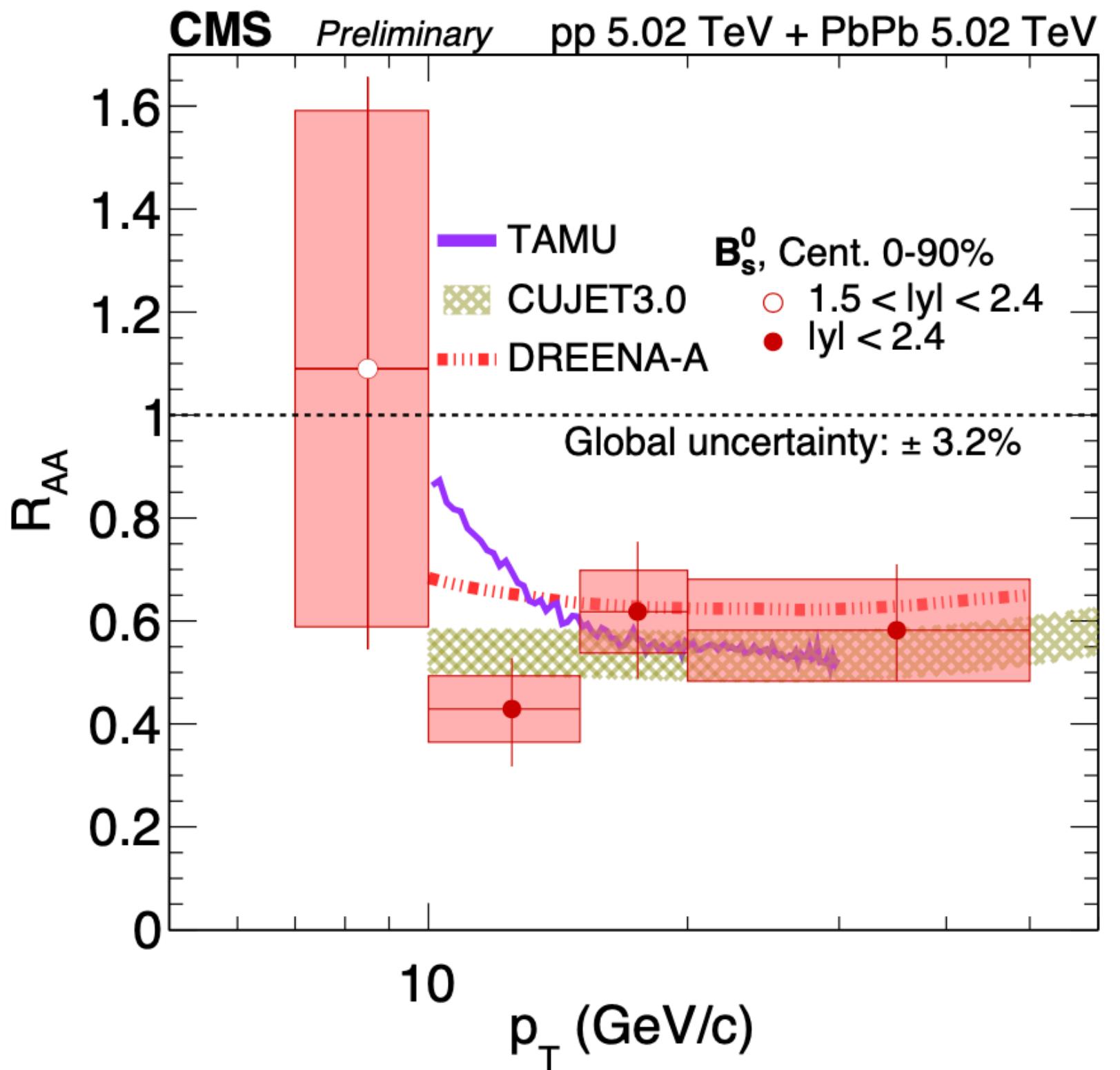
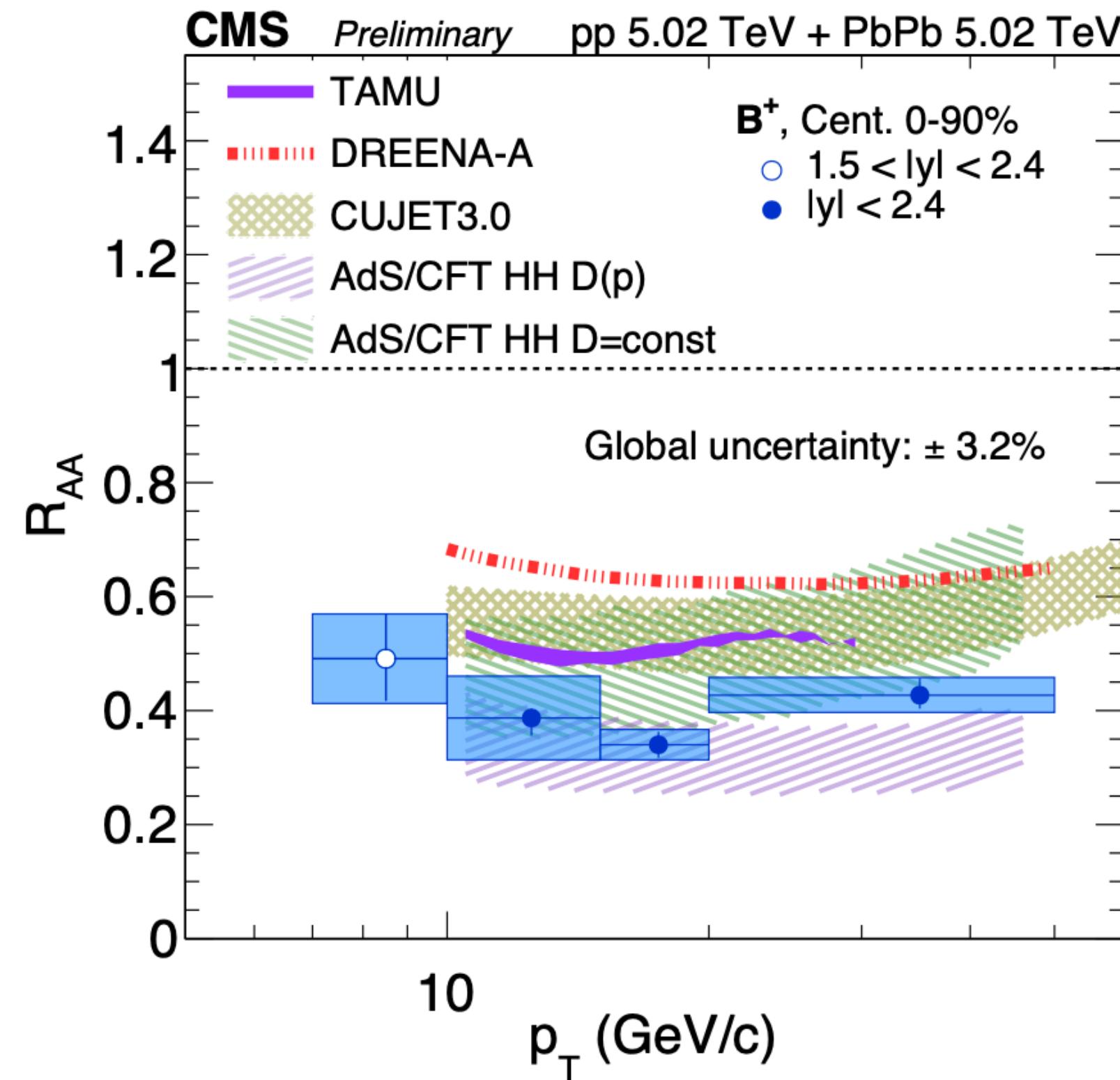
- No evidence of multiplicity dependence at midrapidity
- Compatible with forward rapidity measurement, tension with backward rapidity
  - Steeper slope for forward rapidity probably due to different absolute multiplicity in different rapidity regions not considered in self normalised multiplicity
  - Crucial to plot the  $D_s^+/D$  ratio as a function of the charged-particle density  $dN_{ch}/d\eta$

ALICE, JHEP 12 (2019) 092  
LHCb Preliminary

# Beauty-quark hadronisation and strangeness enhancement

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31  
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- Measurements in the beauty sector compatible with transport models implementing strangeness enhancement and hadronisation via recombination
  - Do beauty quarks reach (partial) thermalisation?
- Current data precision limited: also compatible with no enhancement scenario
  - LHC Run 3 and future upgrades/experiments crucial to study the beauty sector

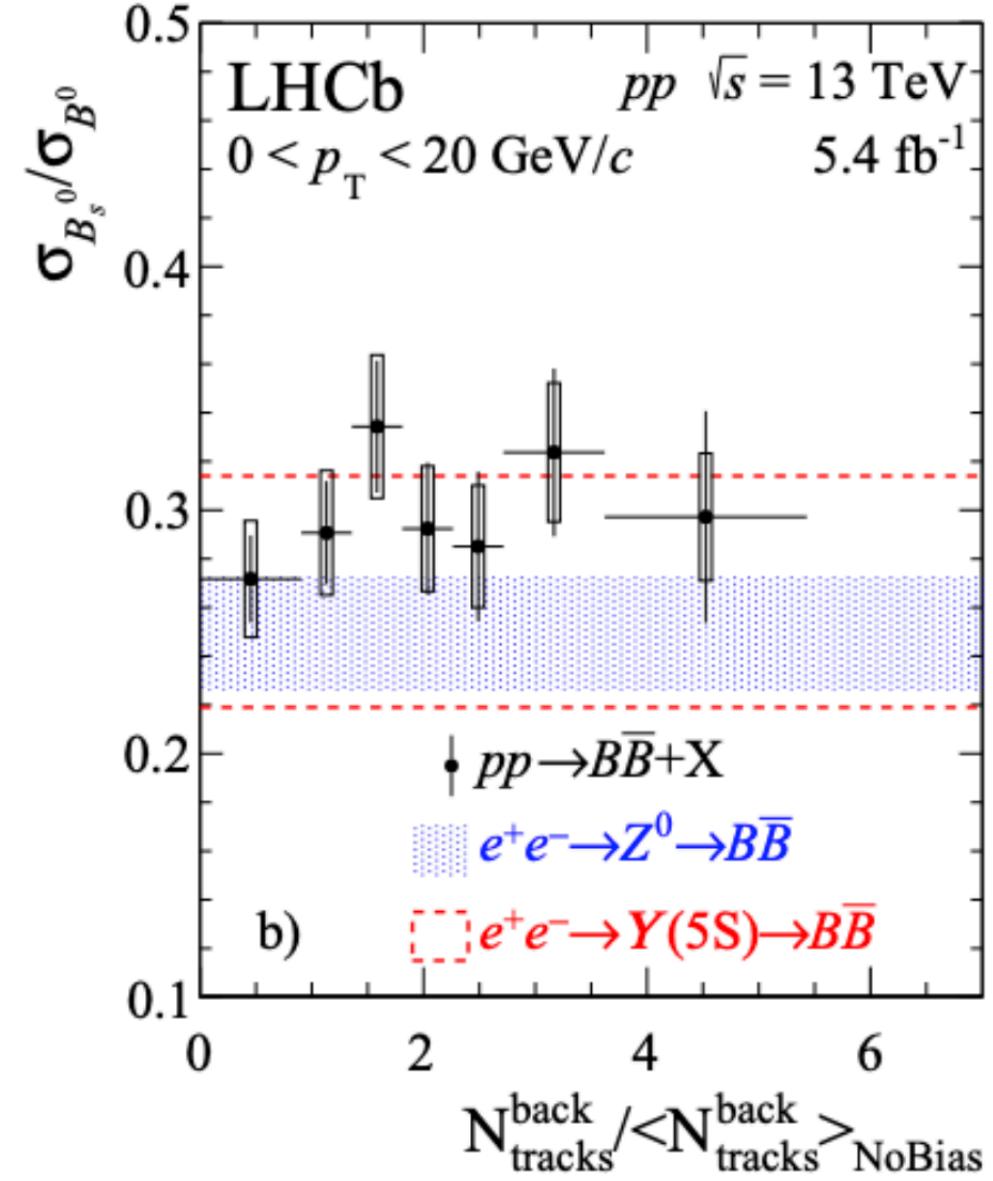
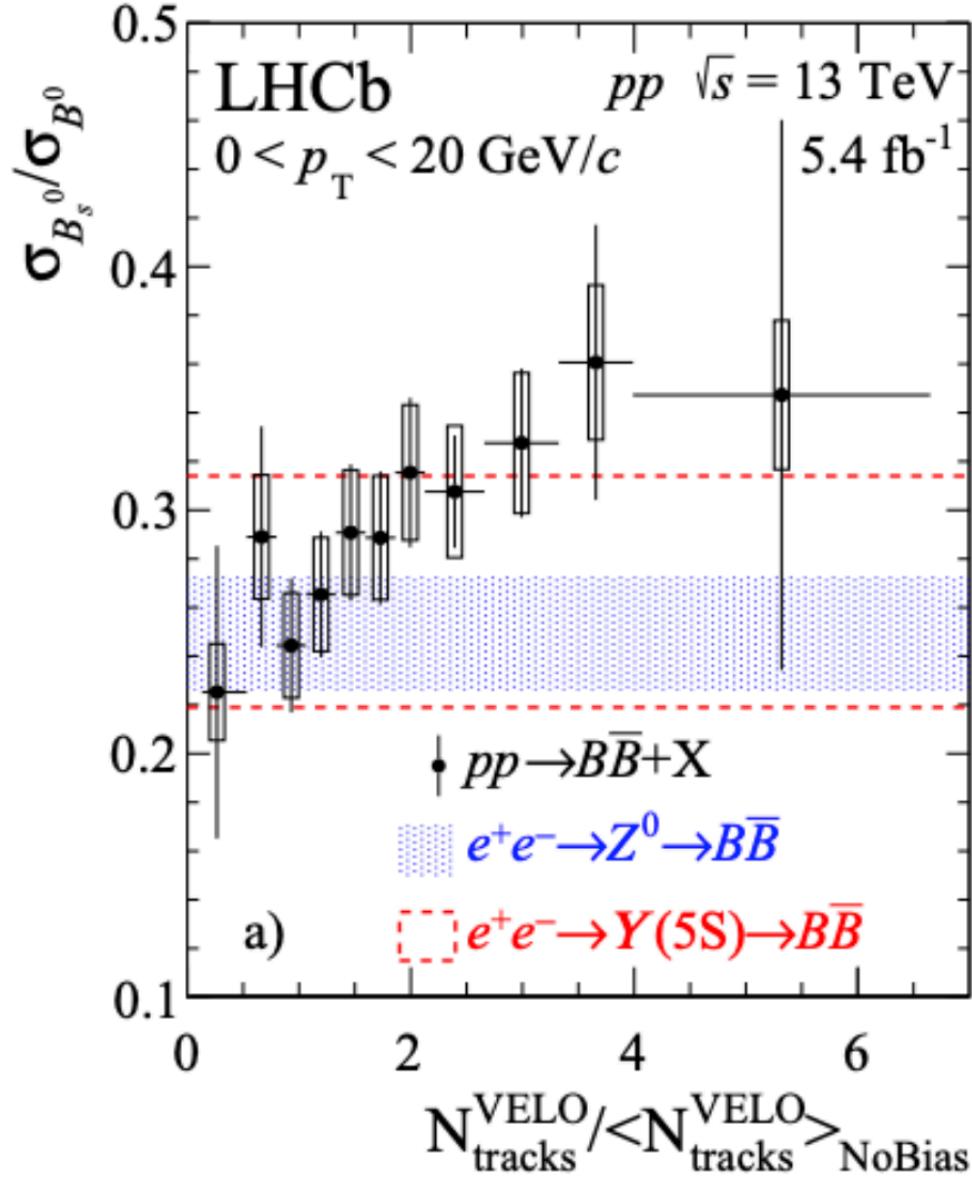
CMS, PLB 829 (2022) 137062  
 LHCb, PRD 100 (2019) 031102  
 ALICE, arXiv:2204.10386

T.-A. Sheng – Tue 05 Sept  
R. Singh – Tue 05 Sept

# $B_s^0/B^0$ in pp collisions as a function of multiplicity

F. Gerosa (CERN)  
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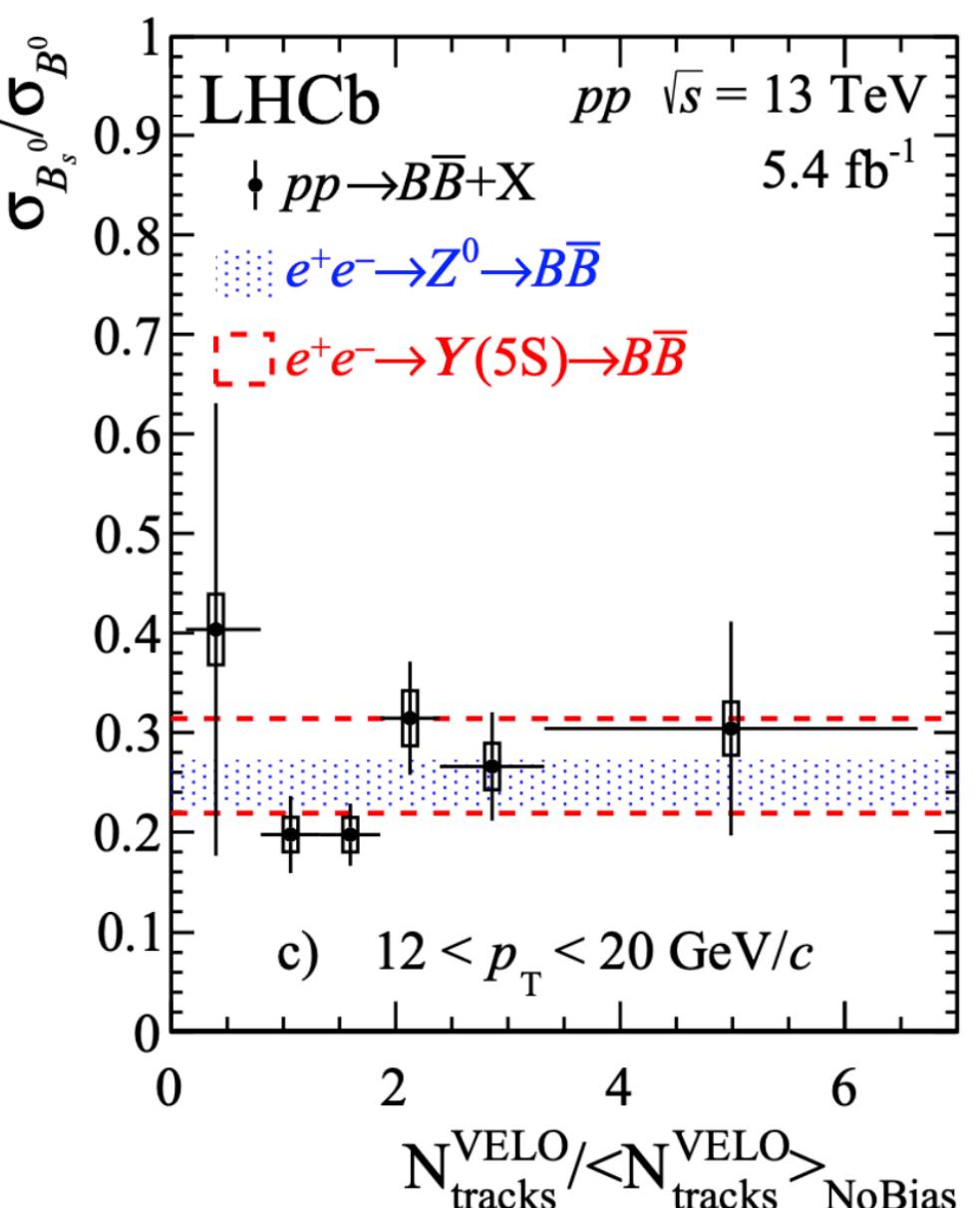
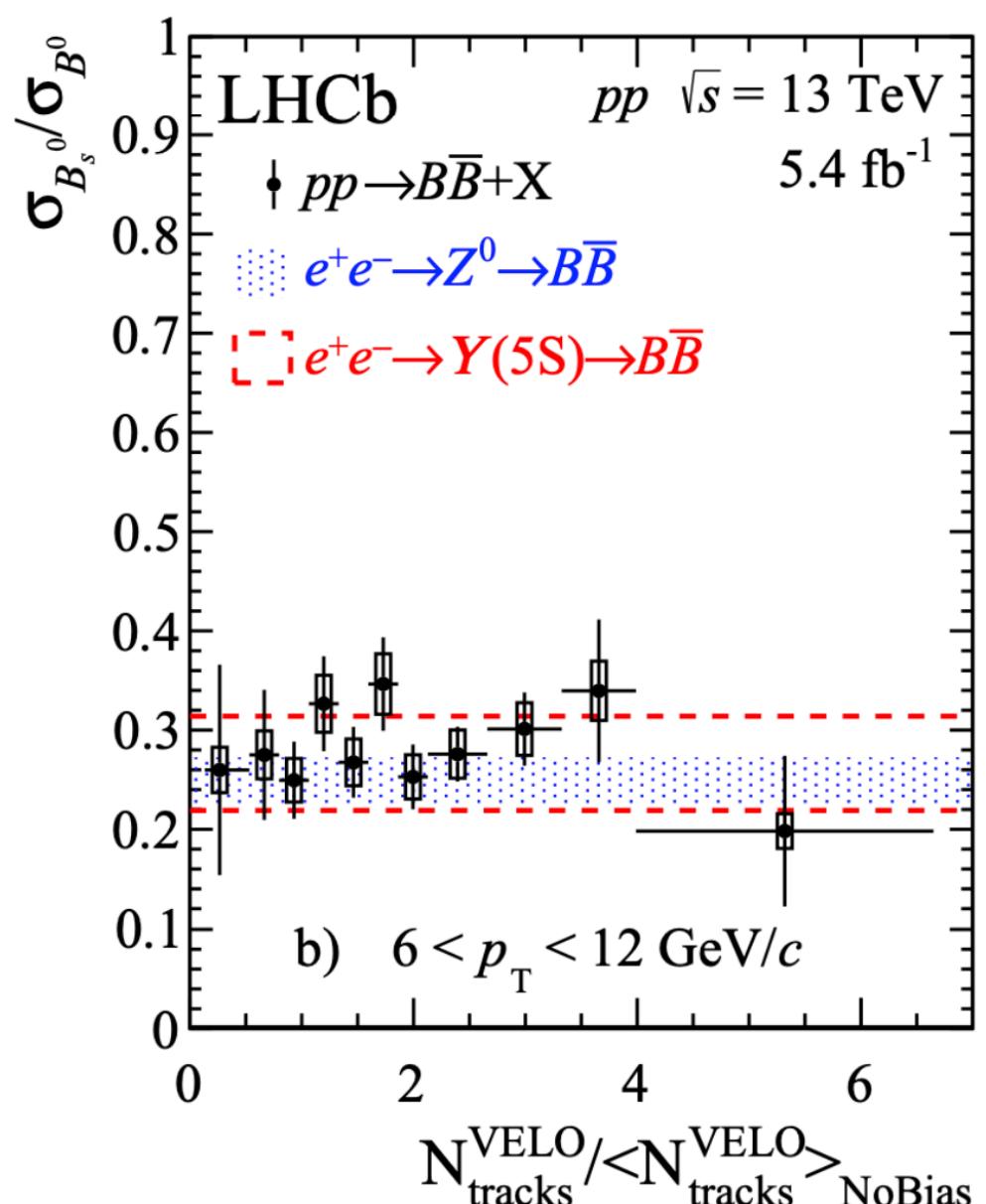
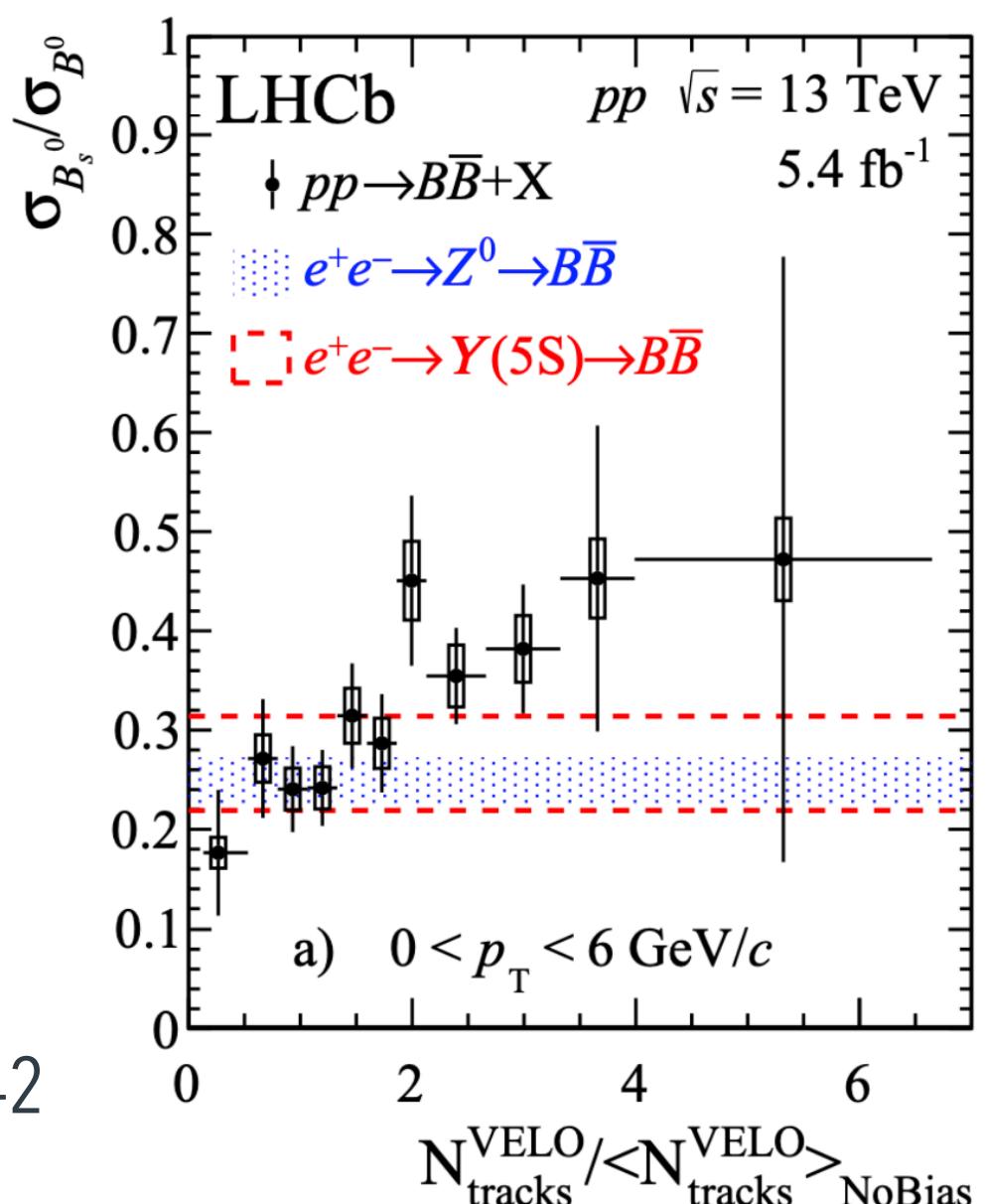
31  
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- Multiplicity dependence of  $B_s^0/B^0$  in pp collisions
  - Significant increase with multiplicity in case of charged-particle multiplicity measured in the same rapidity range of B mesons (higher multiplicity reached)
  - No evidence of multiplicity dependence if charged-particle multiplicity measured with large pseudorapidity gap with respect to B mesons (lower multiplicity reached)

C. Gu – Tue 05 Sept

- Multiplicity dependence at low  $p_T$  only

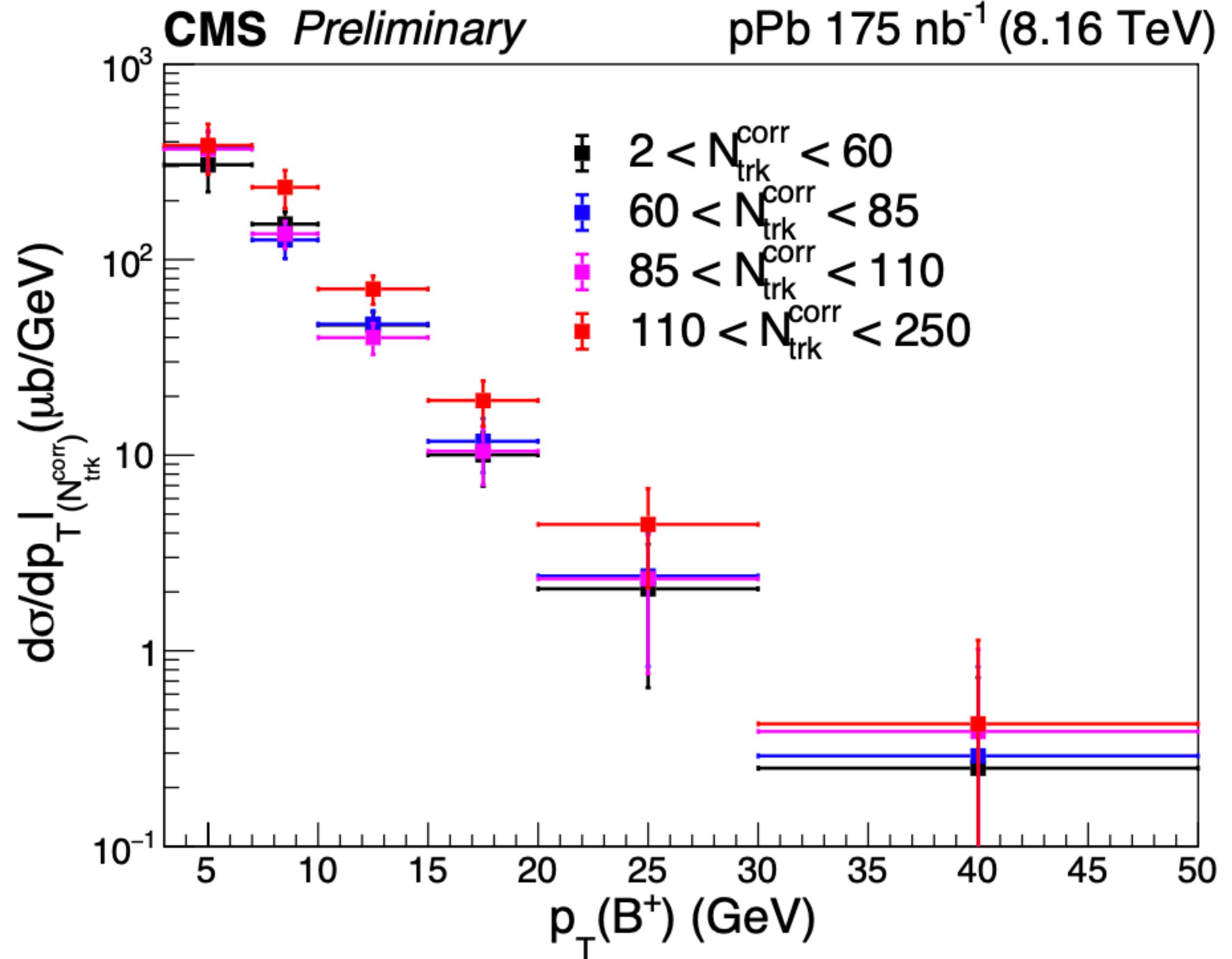
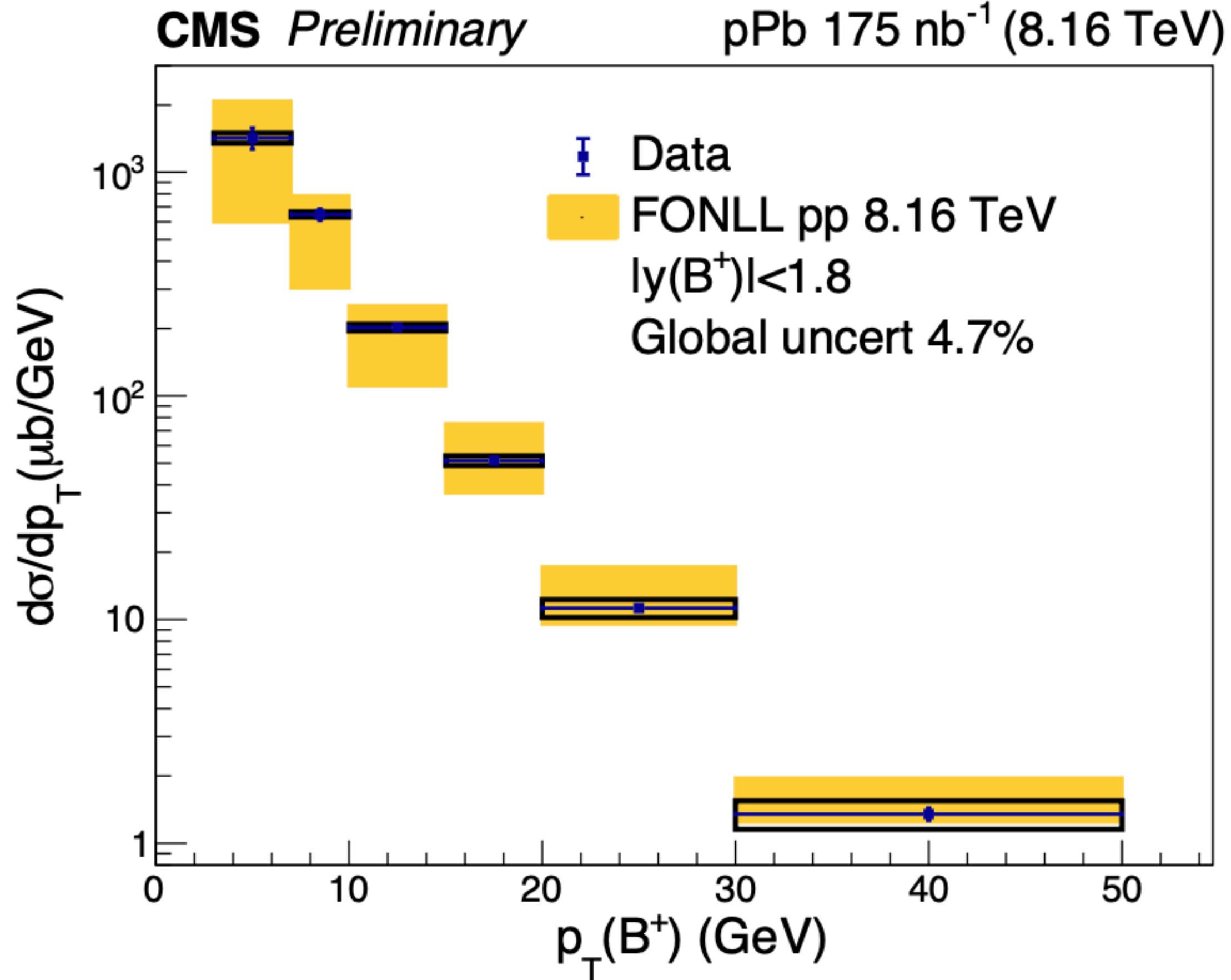


# B<sup>+</sup> production in p–Pb collisions as a function of multiplicity

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33  
45

T.-A. Sheng – Tue 05 Sept



- B<sup>+</sup> cross section in p–Pb collisions compatible with A-scaled FONLL prediction
- B<sup>+</sup> production measured as a function of the charged particle multiplicity at midrapidity
  - Promising prospects to measure B<sub>s</sub><sup>0</sup>/B as a function of multiplicity at midrapidity as well

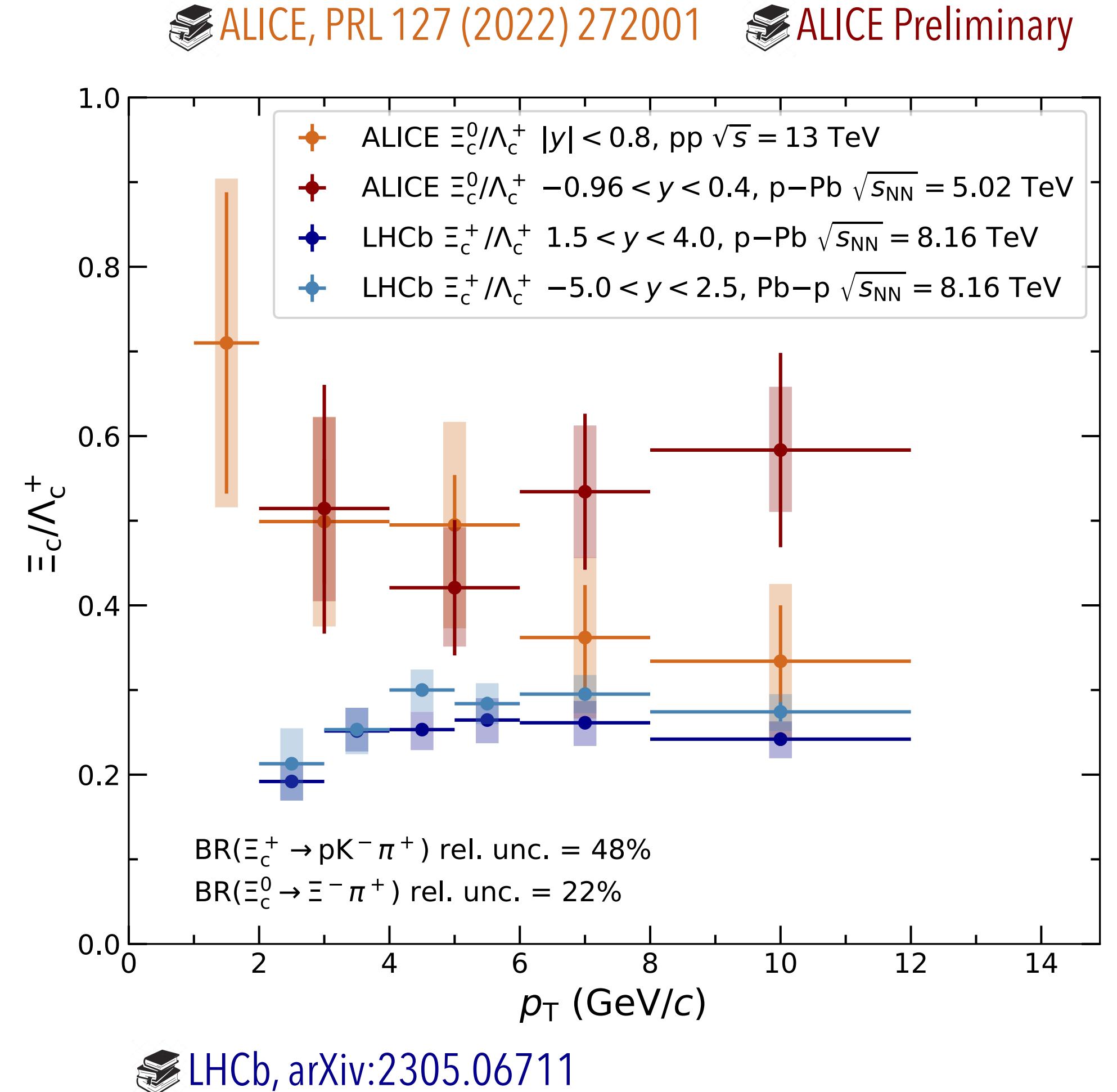
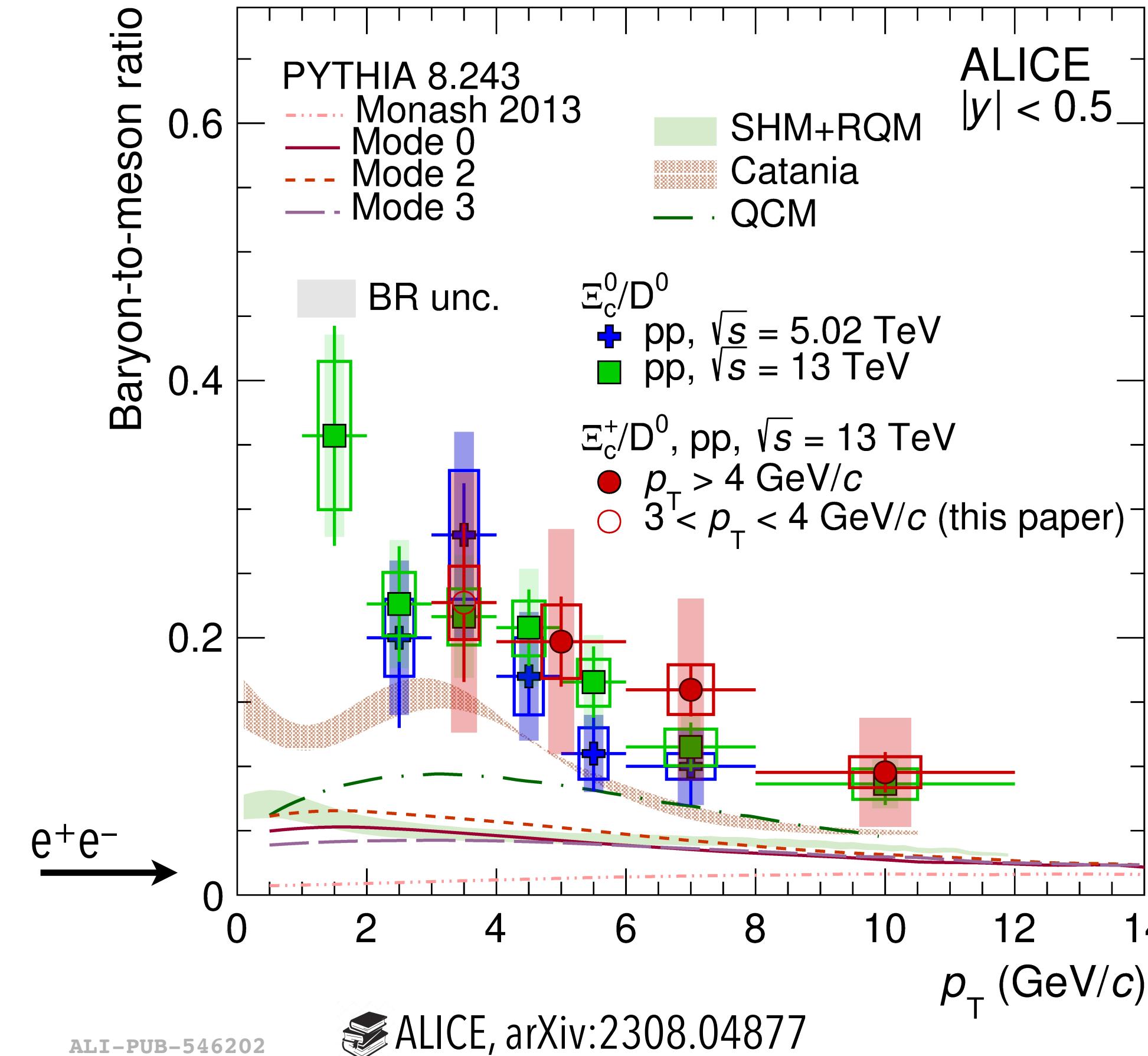
CMS Preliminary, CMS-PAS-HIN-22-001

# Heavy-flavour baryons with strange-quark content in small systems

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45

- Enhanced production of  $\Xi_c$  relative to  $D^0$  in pp collisions compared to  $e^+e^-$  collisions
  - Tension with models that describe the  $\Lambda_c^+$  production
    - Due to large strangeness content?



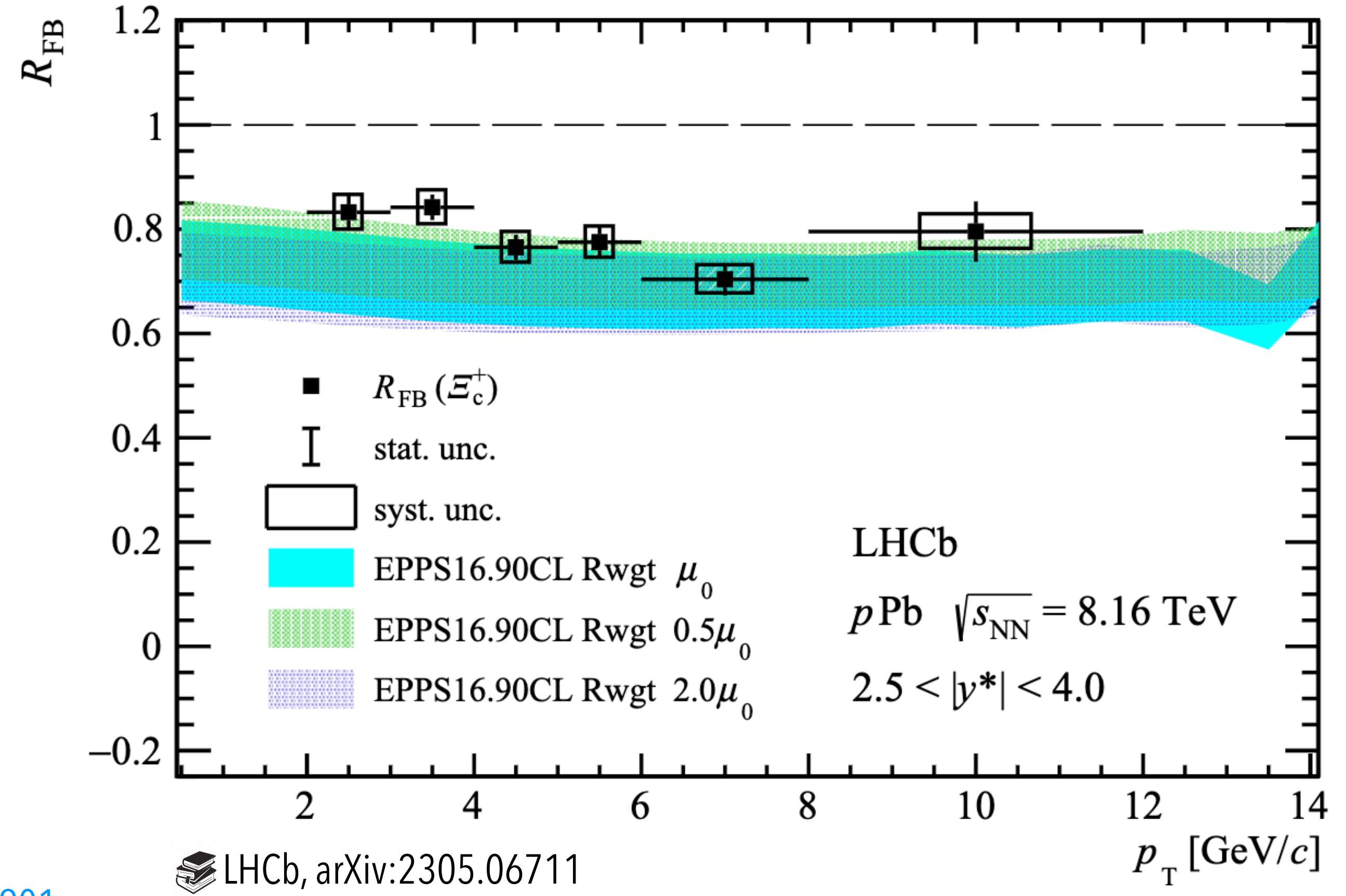
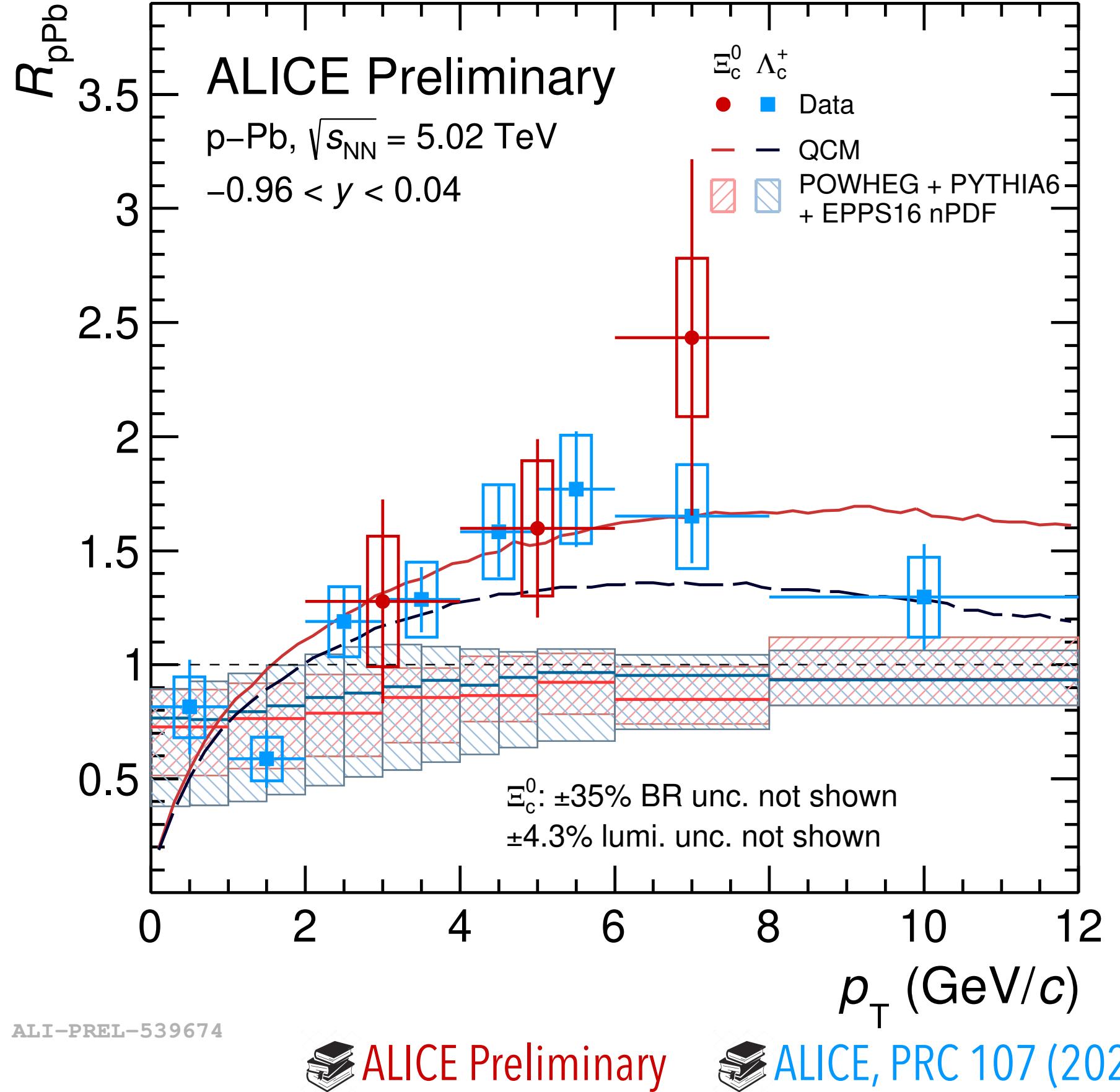
- No modification of  $\Xi_c^0/\Lambda_c^+$  between pp and p-Pb collisions at midrapidity
  - Hint of lower  $\Xi_c/\Lambda_c^+$  at forward rapidity compared to midrapidity
    - Large BR uncertainty of different channels does not allow for conclusions
- J. Zhu – Wed 06 Sept

# Heavy-flavour baryons with strange-quark content in p-Pb collisions

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45

C. Gu – Tue 05 Sept   J. Zhu – Wed 06 Sept



- $R_{pPb}$  of  $\Xi_c^0$  and  $\Lambda_c^+$  baryons compatible within uncertainties
  - At high  $p_T$  higher than prediction including nuclear PDFs
  - Well described by model based on quark-coalescence

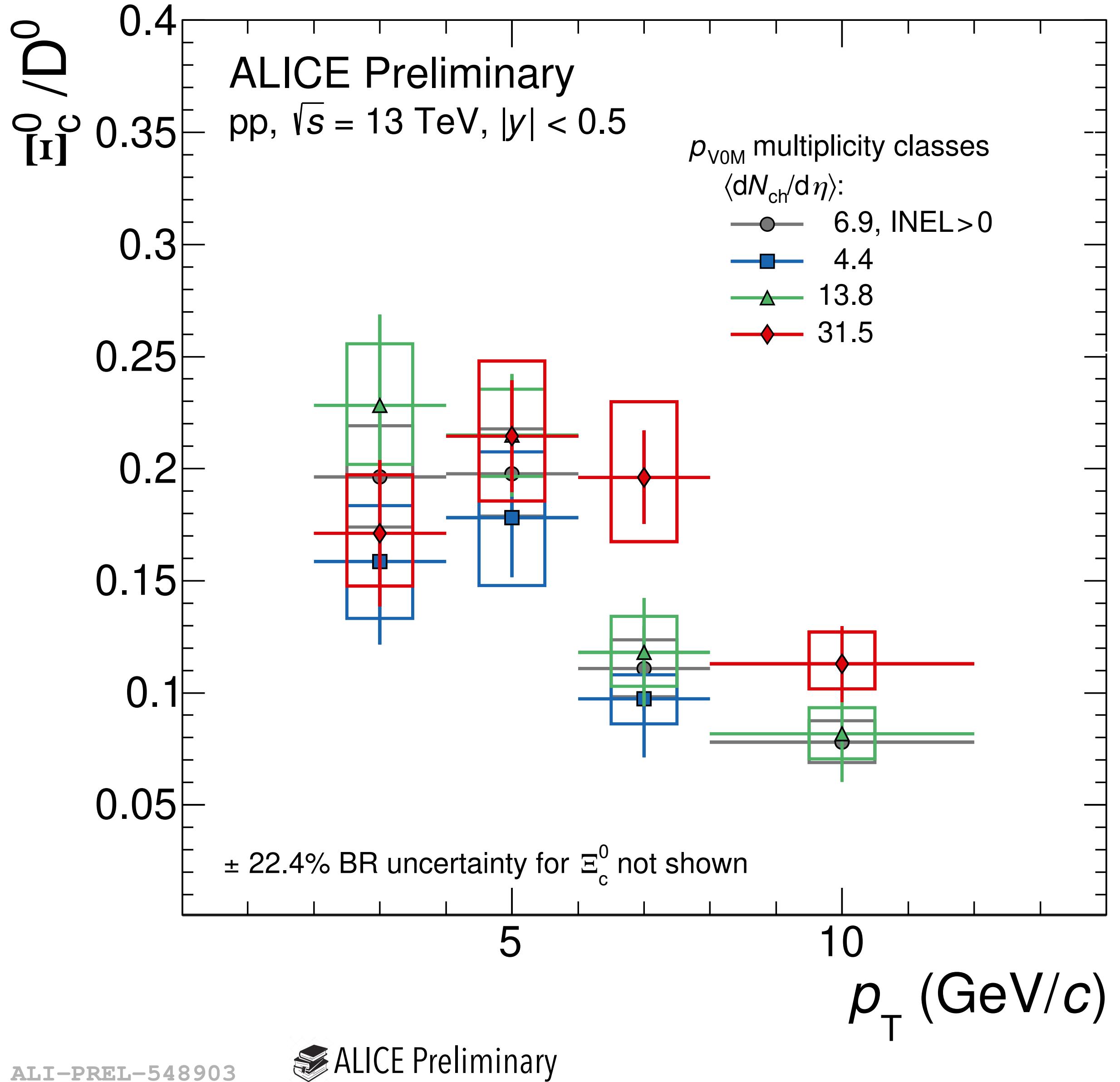
- $R_{FB}$  of  $\Xi_c^+$  baryons flat as a function of  $p_T$ 
  - Compatible with effect due to nuclear PDFs only

# Heavy-flavour baryons with strange-quark content vs. multiplicity

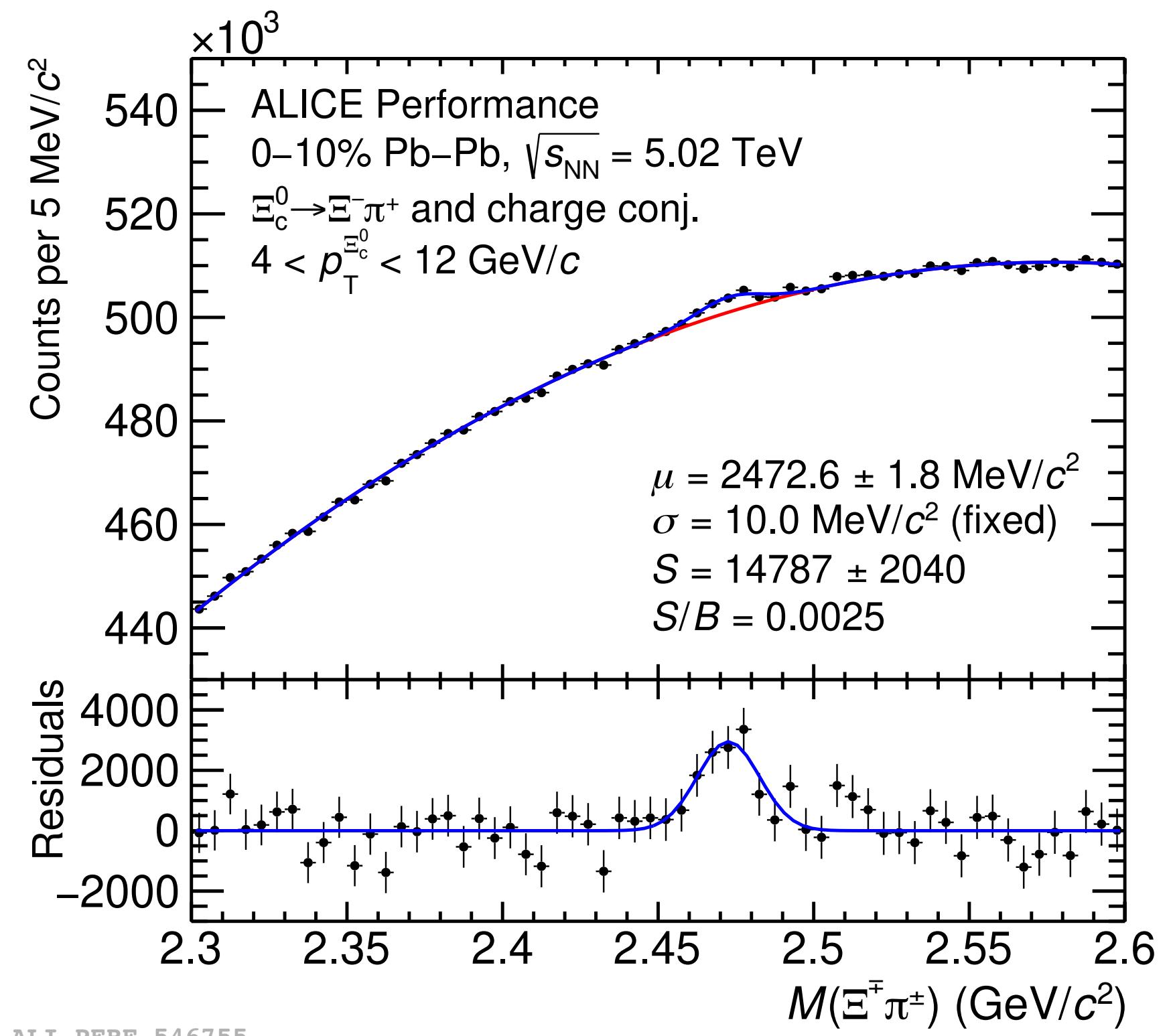
F. Gerosa (CERN)  
fgrosa@cern.ch

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J. Zhu – Wed 06 Sept

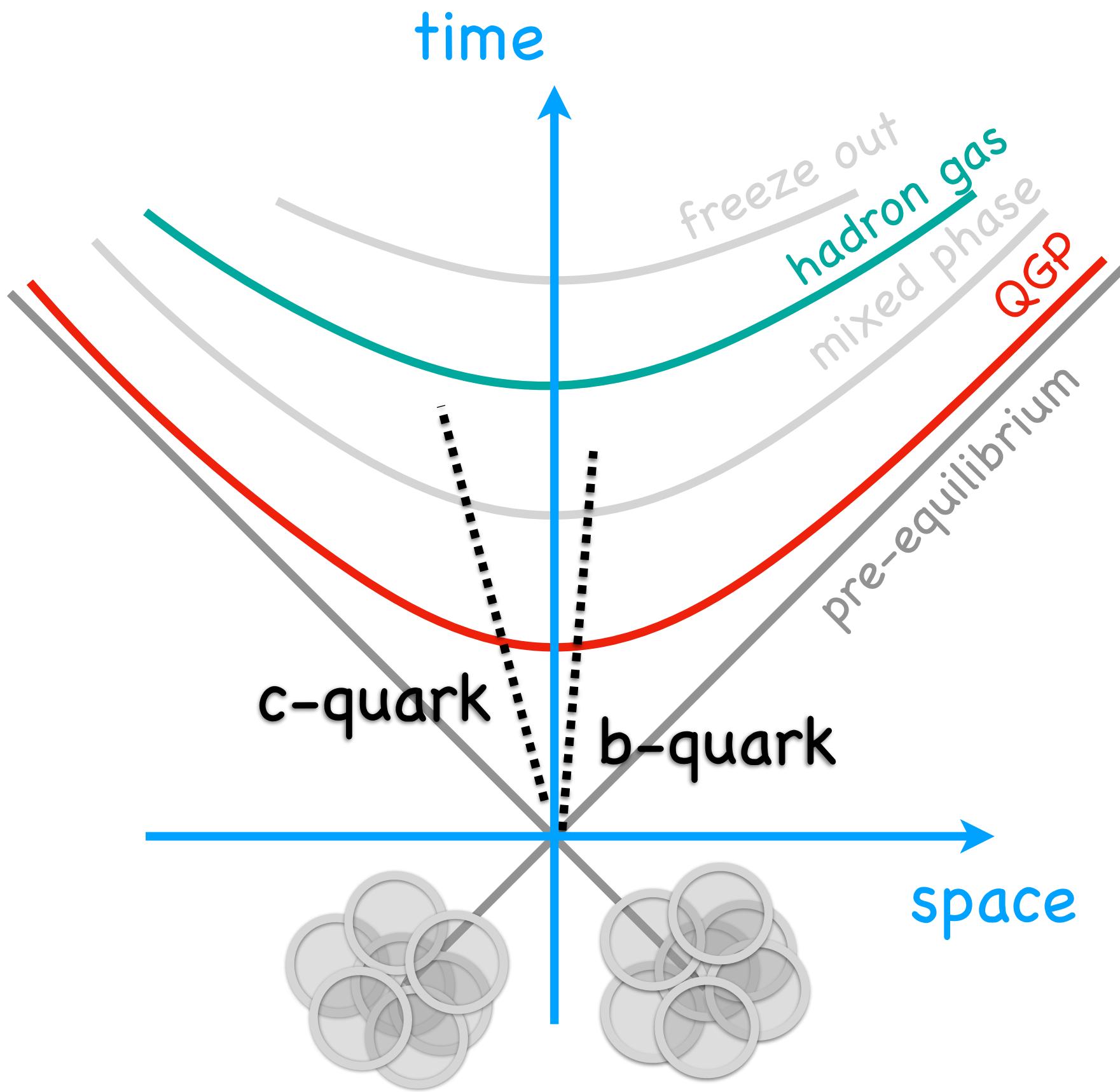


- No evidence of multiplicity dependence of  $\Xi_c/D^0$  ratio
  - Larger data samples needed to conclude
- More insights in production would be provided by measurements in heavy-ion collisions
  - first signal of  $\Xi_c$  in Pb–Pb collisions

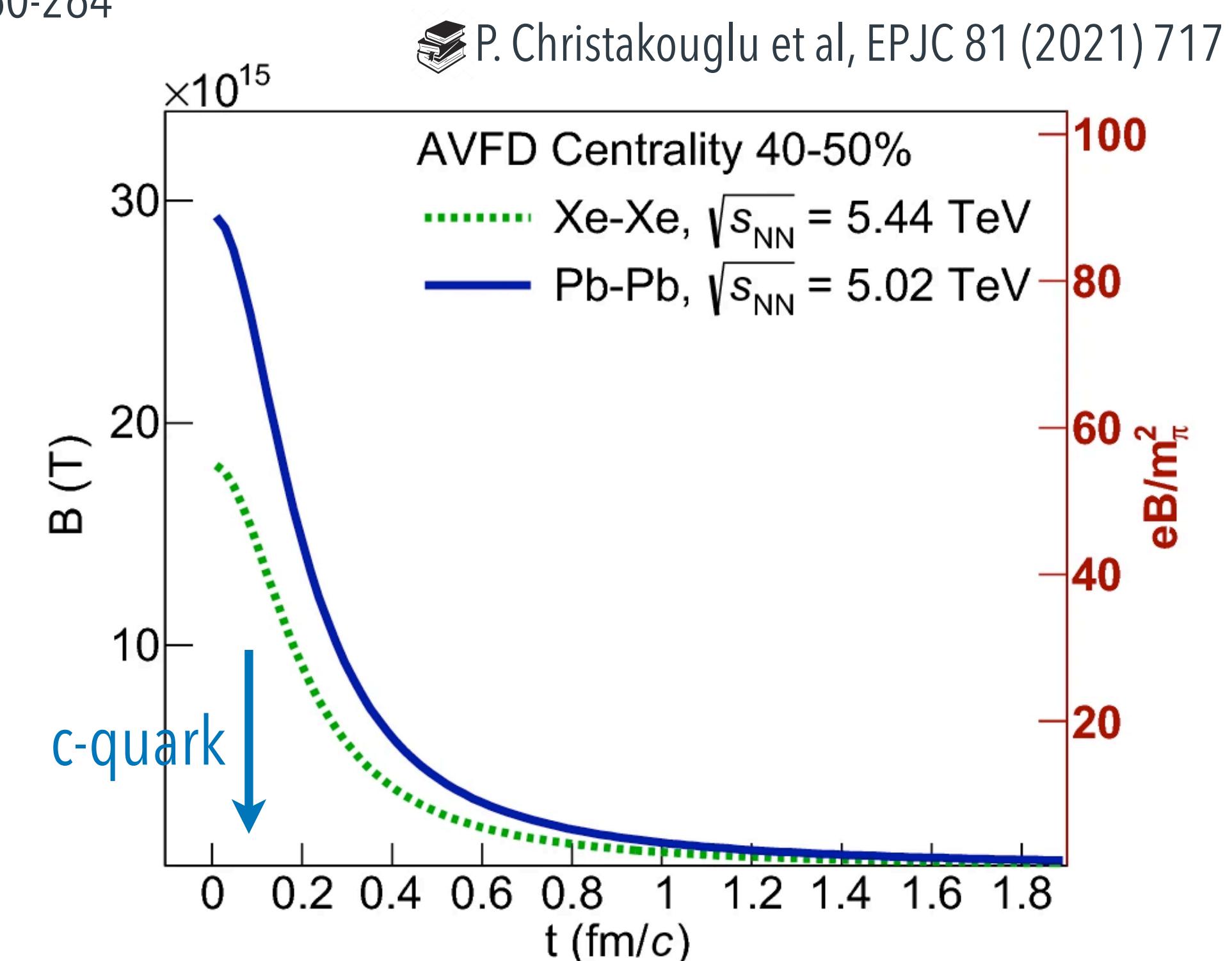


# Polarisation of vector charm mesons

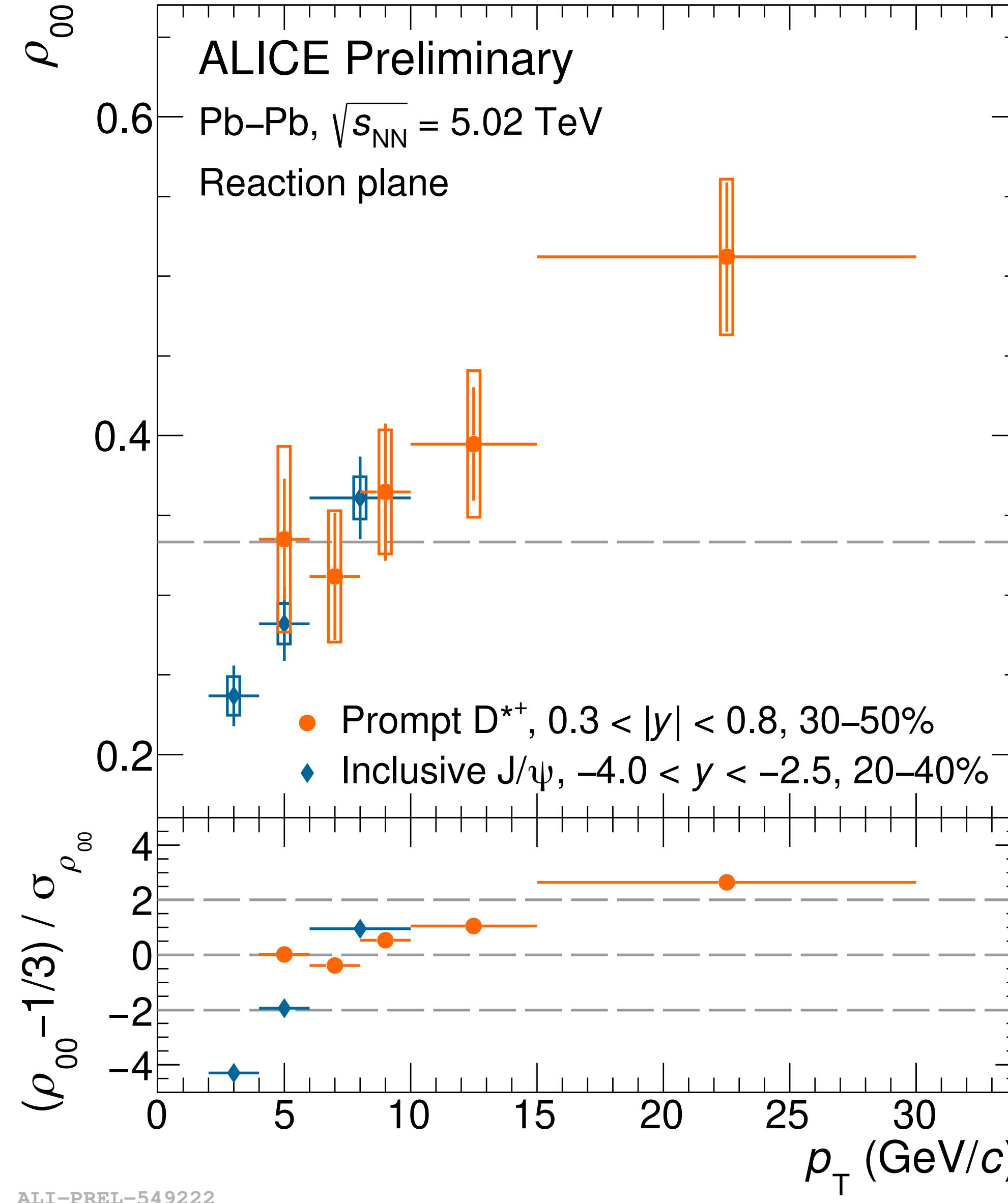
- Non-central heavy-ion collisions
  - Large angular momentum due to the medium rotation F. Becattini et al, PRC 77 (2008) 024906
  - Huge initial magnetic field ( $B \sim 10^{16}$  T) Kharzeev et al, NPA 803 (2008) 227-253
    - Lifetime expected to increase with rapidity S.K. Das et al, PLB 768 (2017) 260-264



- Charm quarks are produced in the initial stage of the collision and hence are expected to be more sensitive to the magnetic field



- Polarisation of charm quark transferred to hadrons through hadronisation process



1. Recombination of polarised quark-antiquark pairs in the QGP

$$\rho_{00}^{\text{rec}} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} \begin{cases} > 1/3 \text{ if } P_q \cdot P_{\bar{q}} < 0 \\ < 1/3 \text{ if } P_q \cdot P_{\bar{q}} > 0 \end{cases}$$

→ vorticity or B field  
if same-charge  
quark-antiquark

2. Fragmentation of polarised heavy quarks

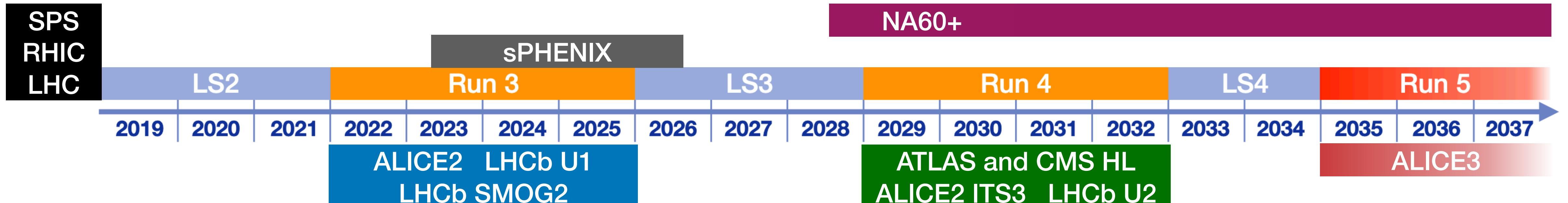
$$\rho_{00}^{\text{frag}} = \frac{1 + \beta \cdot P_q^2}{3 - \beta \cdot P_q^2} > 1/3$$

- $J/\psi$  measurement compatible with polarisation due to vorticity and hadronisation via recombination
- $D^{*+}$  measurement compatible with polarisation and hadronisation via fragmentation

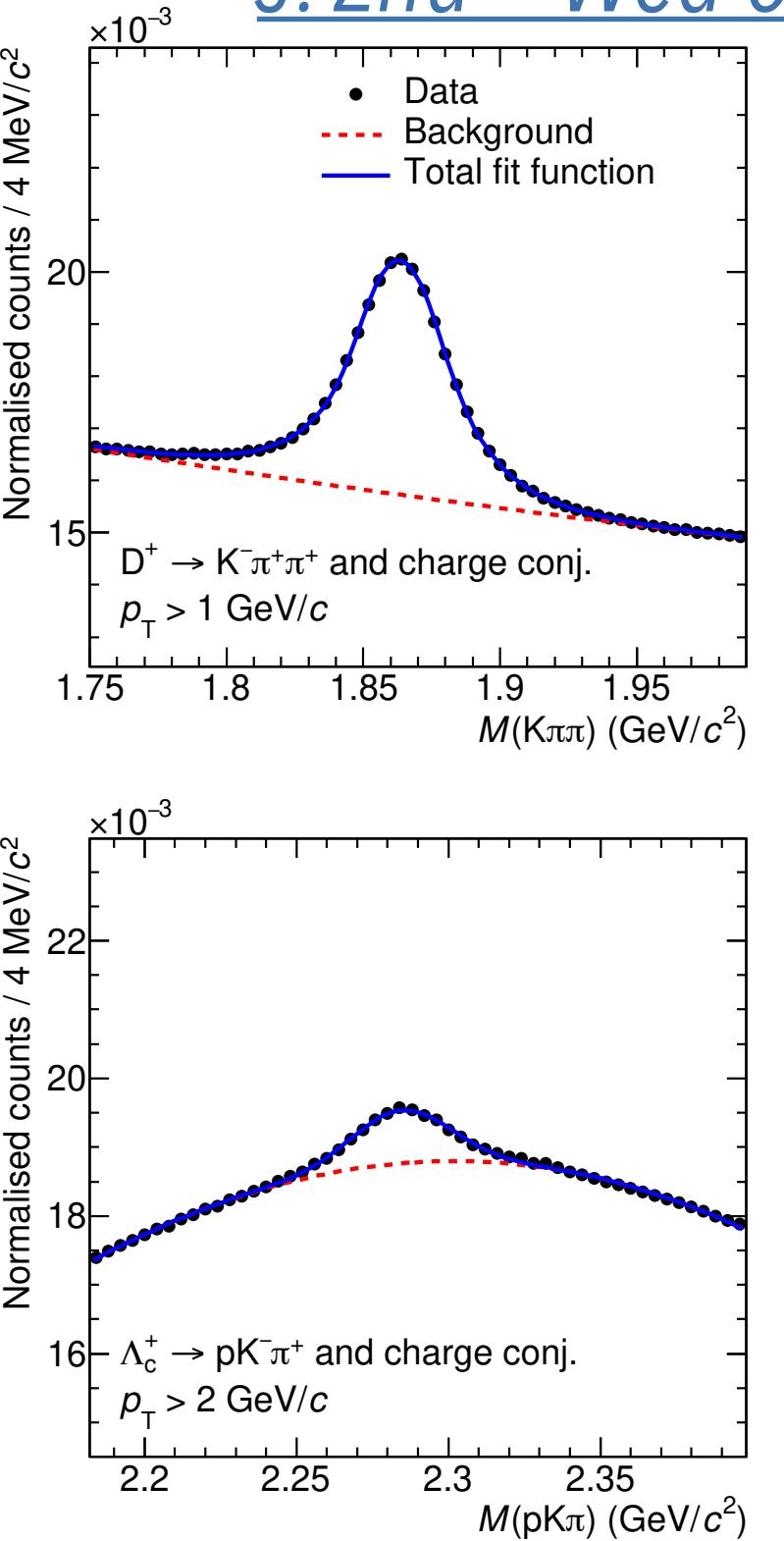
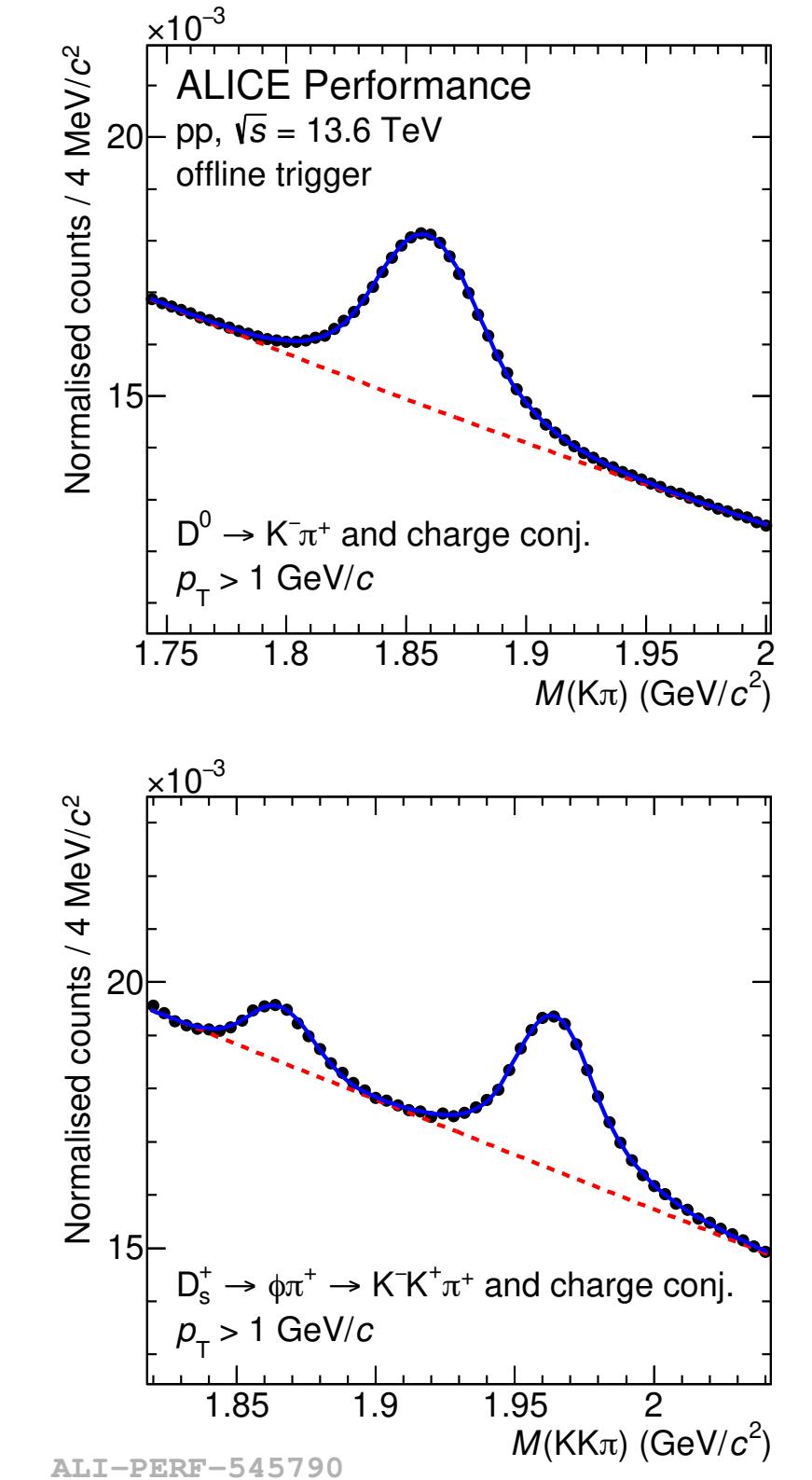
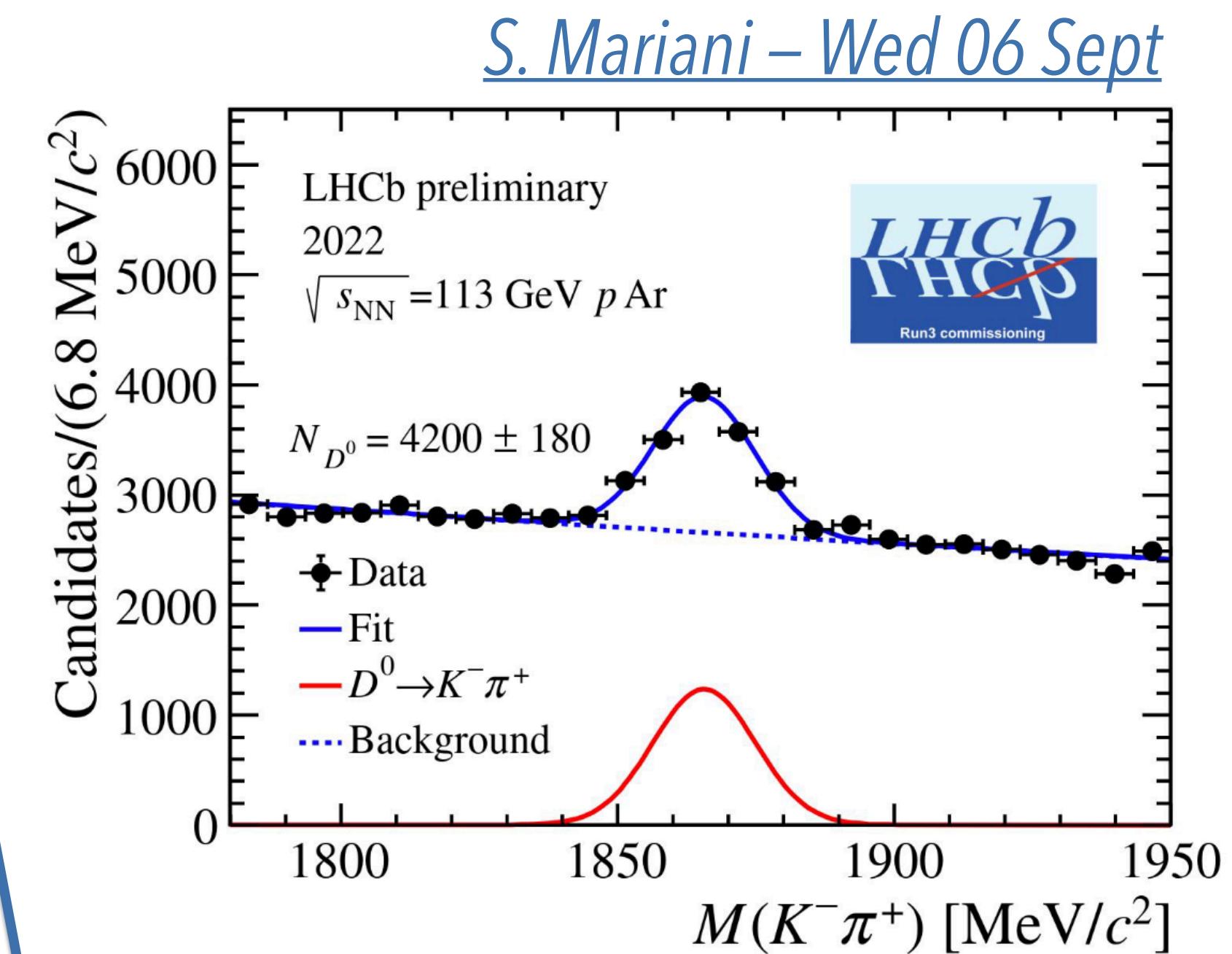


- Several new measurements in heavy flavour sector in small and large collision systems for QM2023
  - Insights in heavy-quark interactions in the QGP
  - Insights in heavy-quark hadronisation
  - Insights in heavy-quark polarisation
- Complementary of different experiments very important to draw stronger conclusions

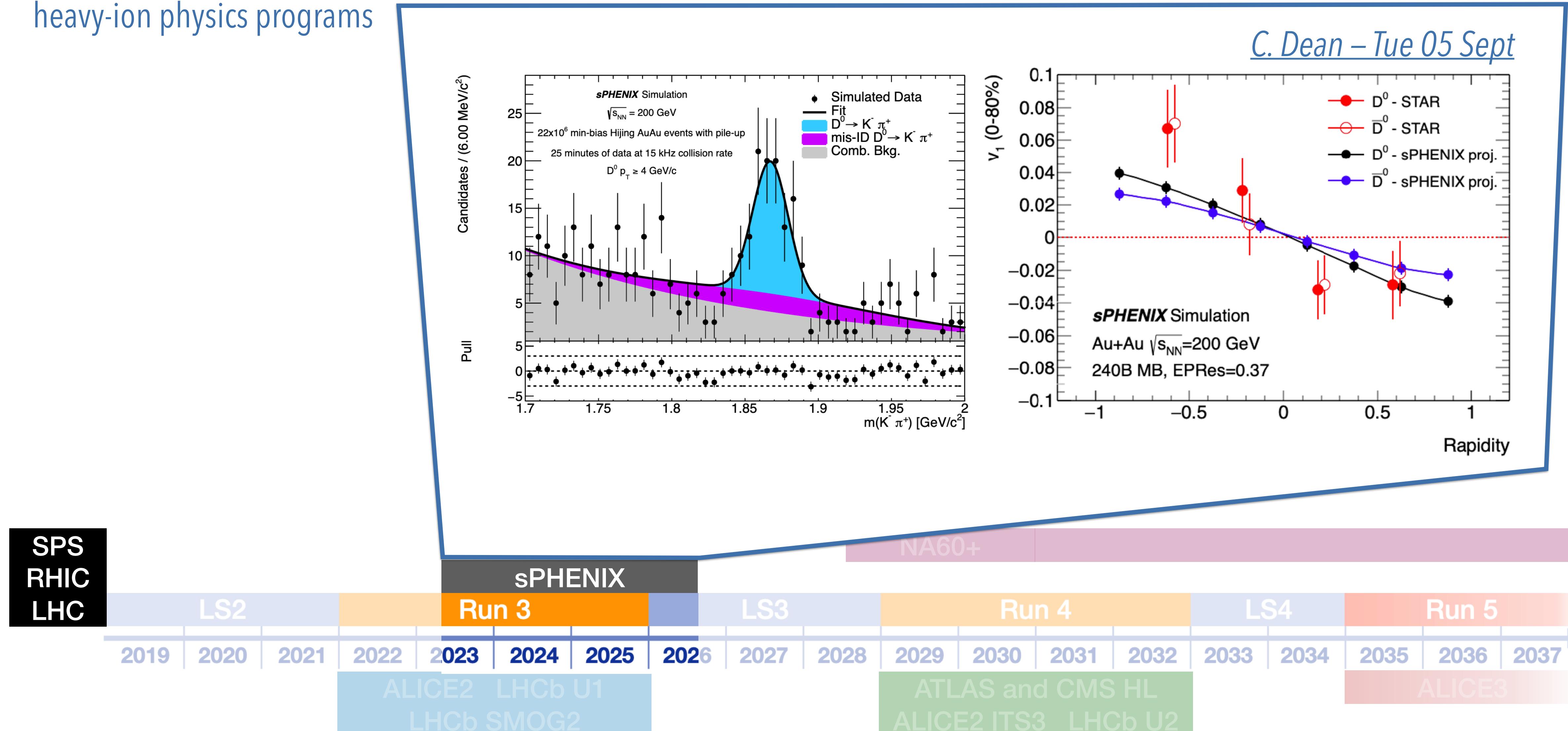
- Heavy-flavour physics pillar of current and future heavy-ion physics programs



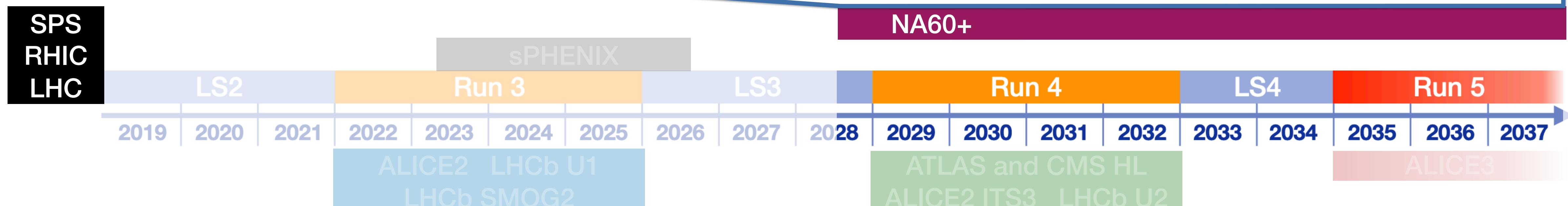
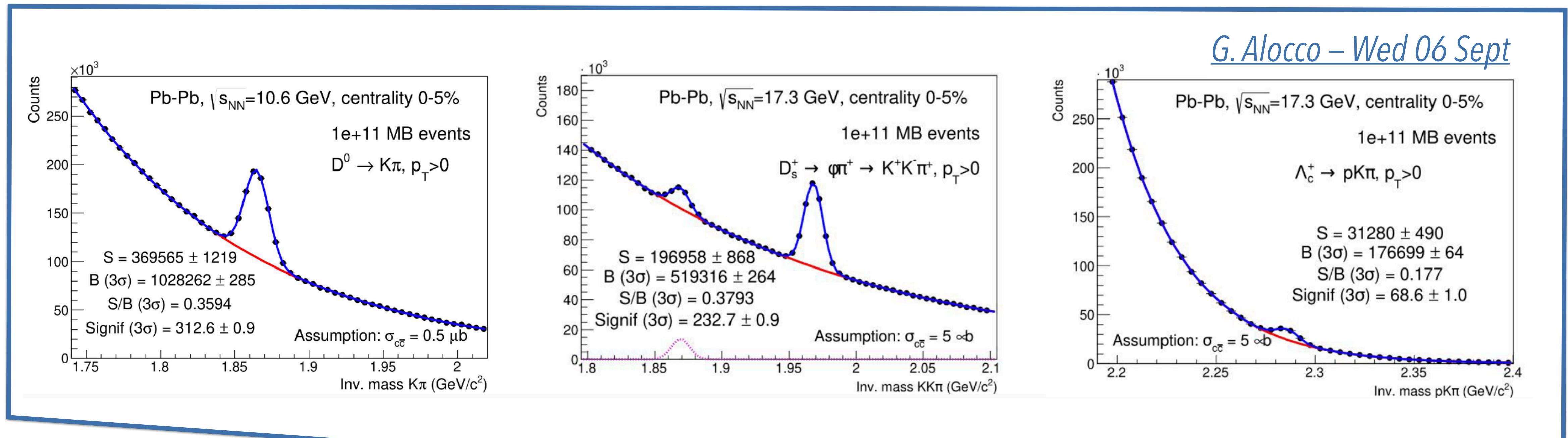
- Heavy-flavour physics pillar of current and future heavy-ion physics programs



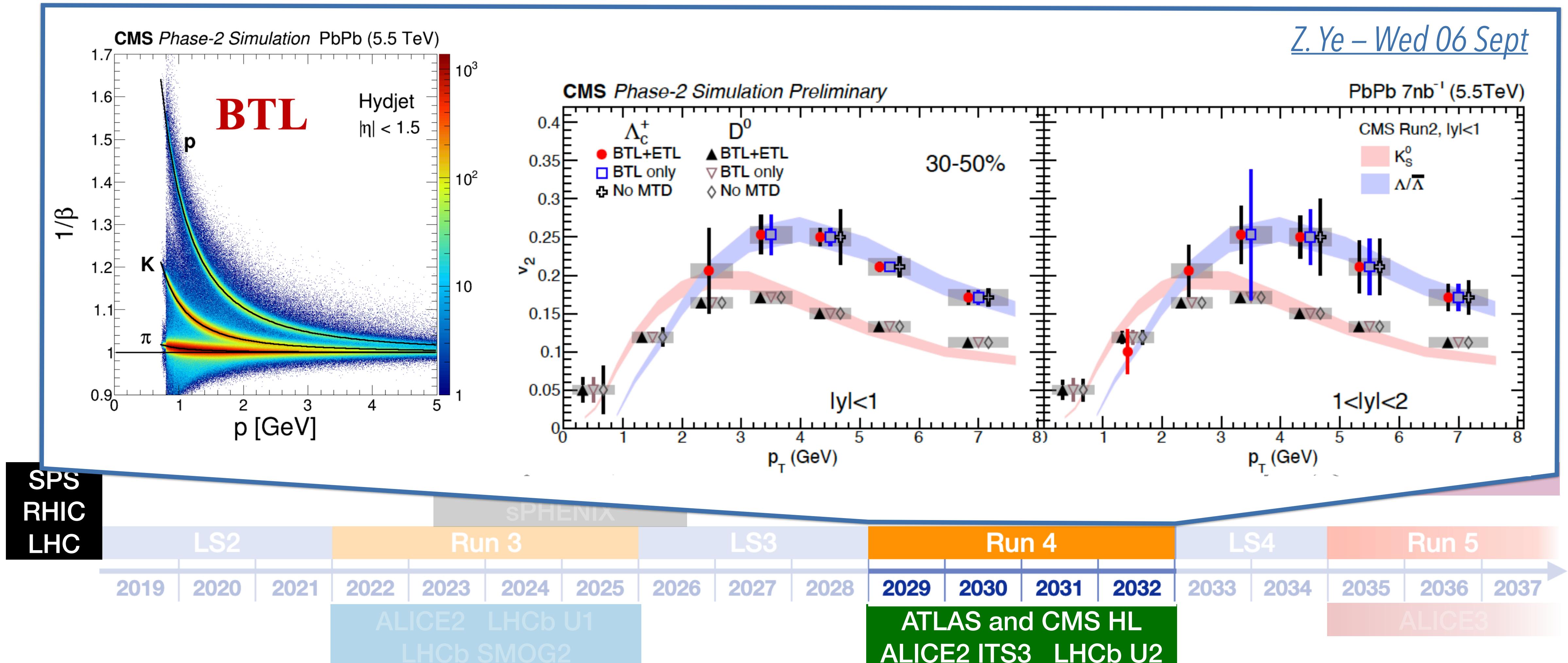
- Heavy-flavour physics pillar of current and future heavy-ion physics programs



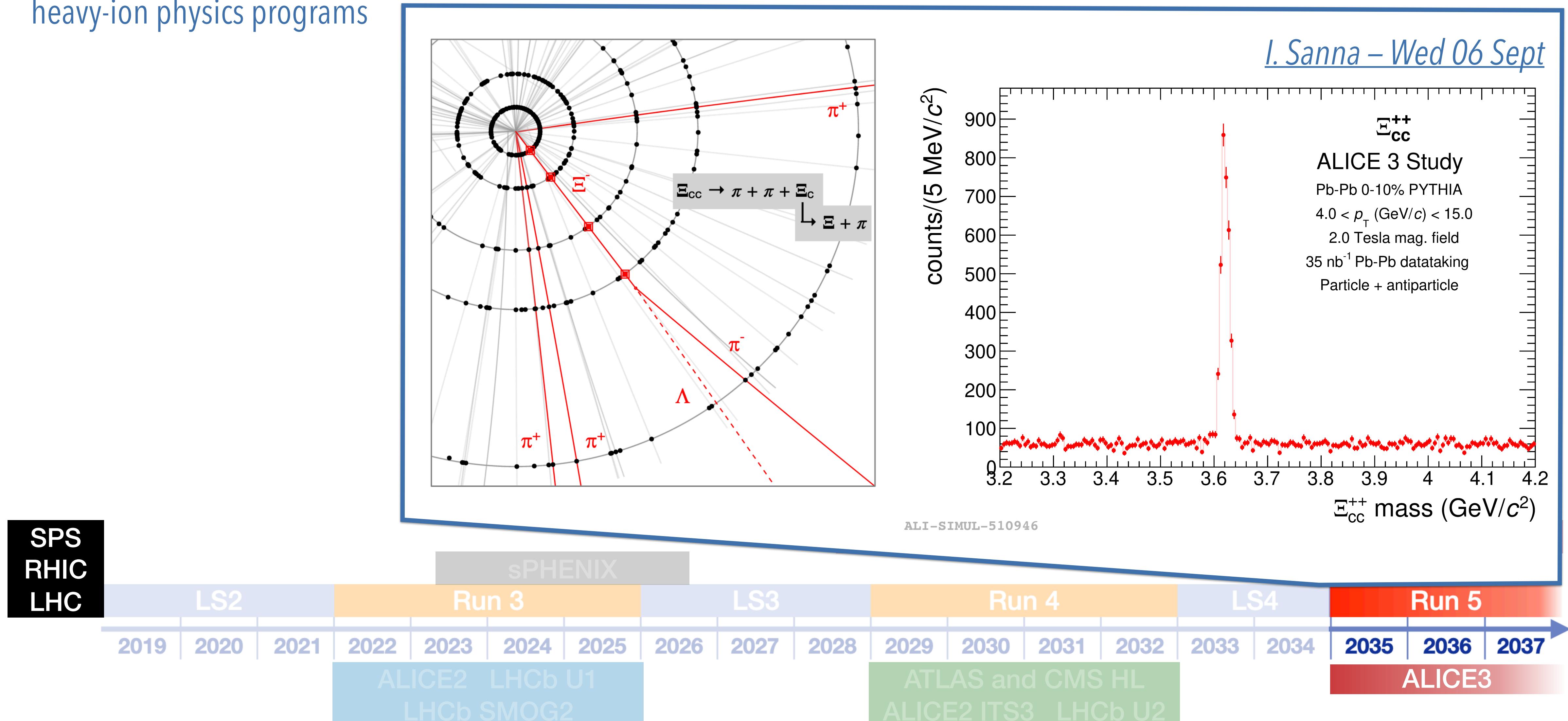
- Heavy-flavour physics pillar of current and future heavy-ion physics programs



- Heavy-flavour physics pillar of current and future heavy-ion physics programs



- Heavy-flavour physics pillar of current and future heavy-ion physics programs





Thanks!

In particular, for the discussions and inputs to: A. Angerami, I. Corredoira, A. Dainese, M. Durham, C. Gu, G. Krintiras, S. Kundu, L. Micheletti, S. Mariani, F. Prino, A. Rossi, M. Rybar, N. Sahoo, C. Terrevoli

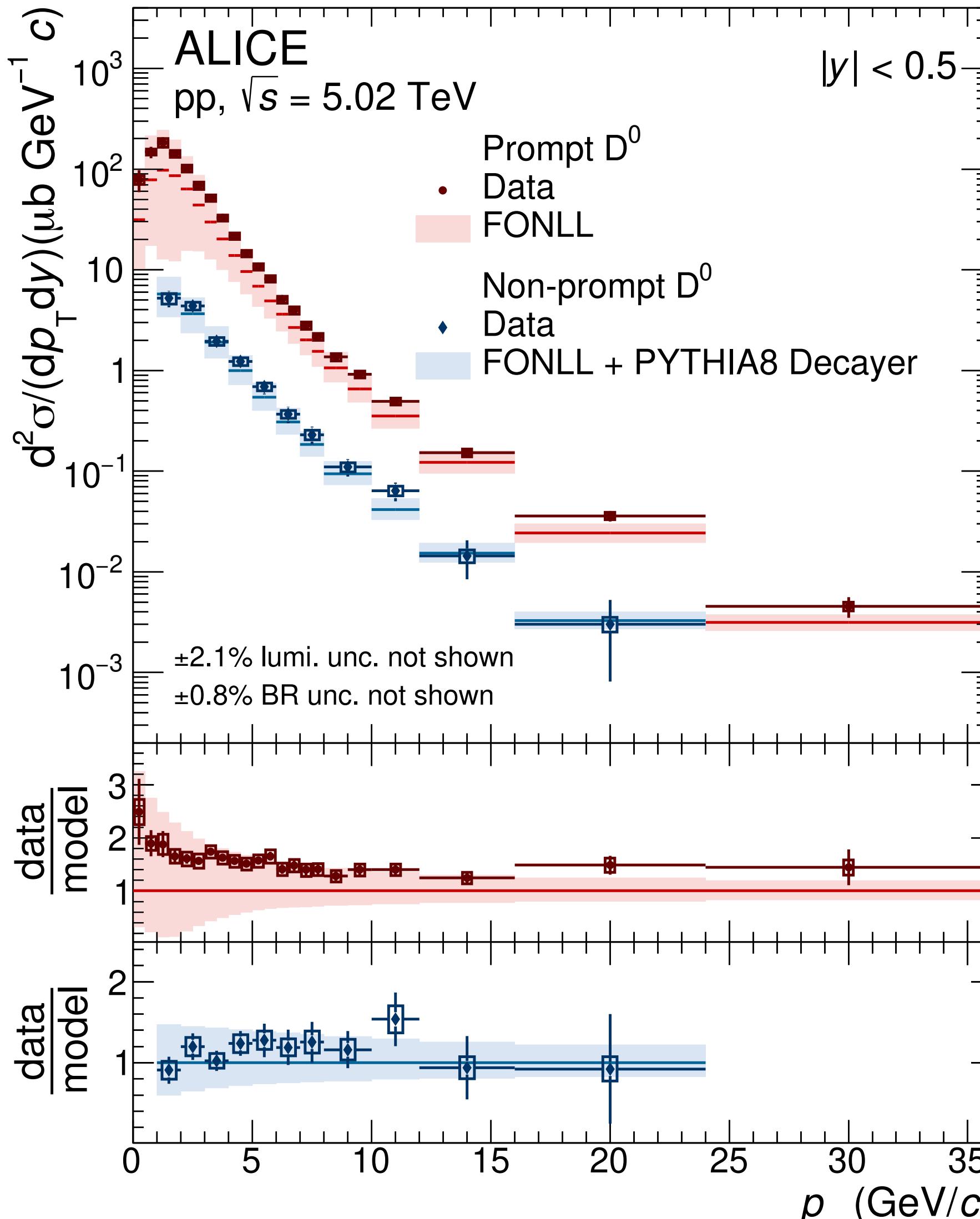
The background of the slide features a panoramic aerial view of a city skyline during the day. The sky is filled with large, white, fluffy clouds against a bright blue backdrop. In the foreground, there's a mix of architectural styles, including several modern skyscrapers with glass and steel facades, some older brick buildings, and a prominent building with a large, light-colored dome and red roof tiles. The overall scene is vibrant and captures the essence of a major urban center.

# ADDITIONAL SLIDES

# Production of heavy quarks in proton–proton collisions

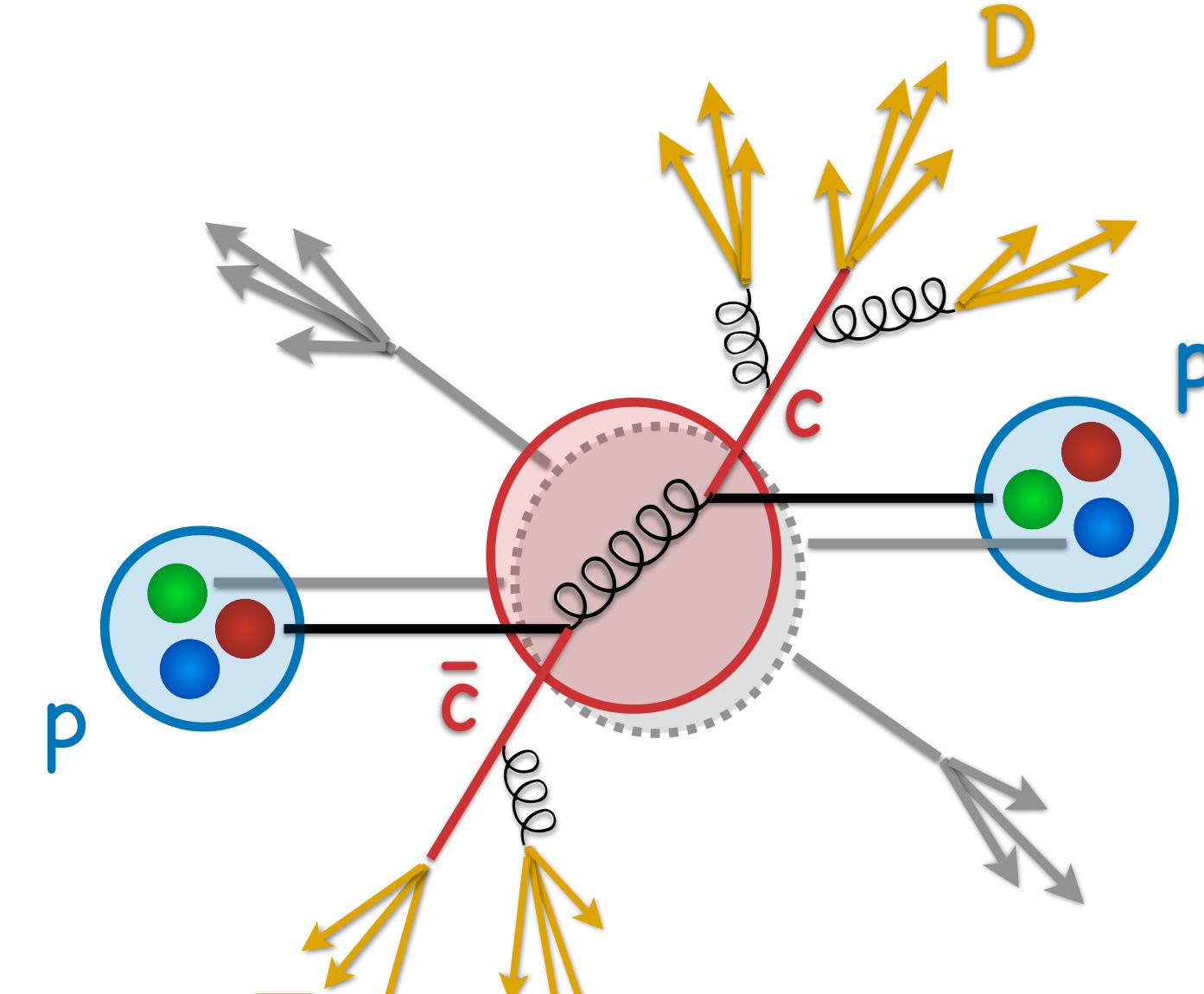
F. Grossa (CERN)  
fgrosa@cern.ch

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ALICE, JHEP 05 (2021) 220

- Charm and beauty quarks are produced in hard-scattering processes
- perturbative QCD calculations based on the factorisation theorem

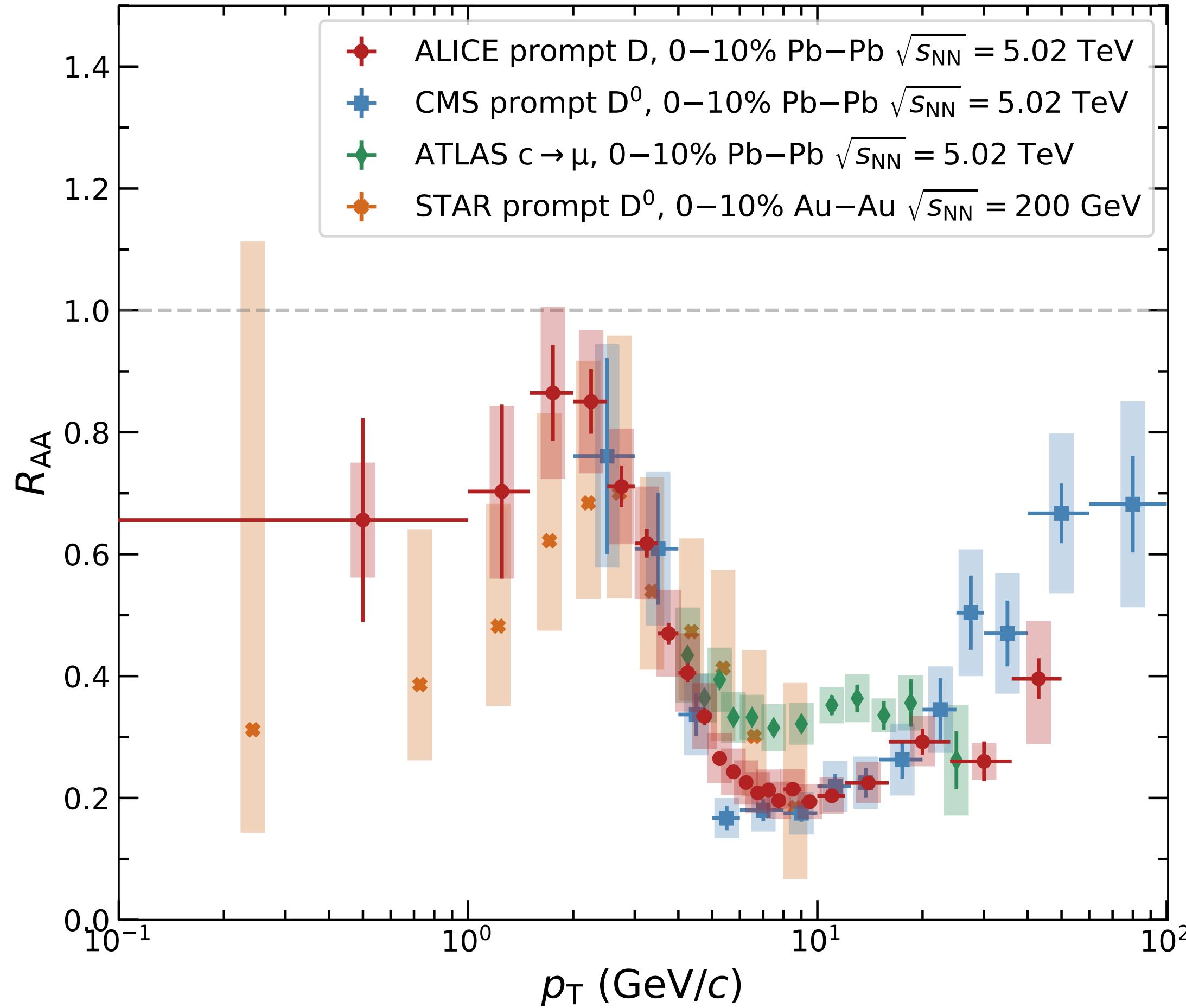


$$\sigma_{hh \rightarrow Hh} = \text{PDF}(x_a, Q^2) \text{ PDF}(x_b, Q^2) \otimes \sigma_{ab \rightarrow q\bar{q}} \otimes D_{q \rightarrow h}(z_q, Q^2)$$

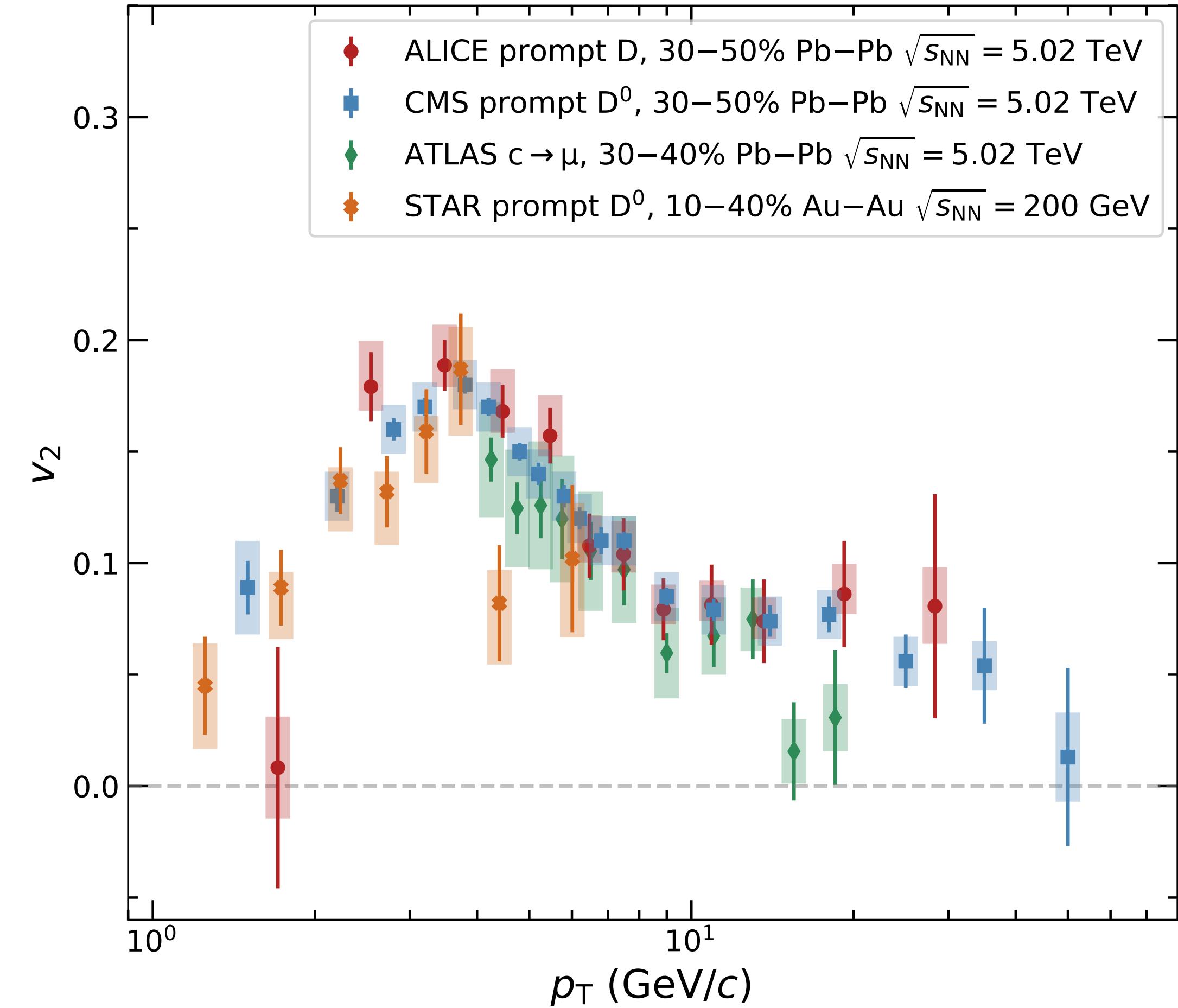
Parton distribution functions (non perturbative)      Partonic cross section (perturbative)      Fragmentation functions (non perturbative)

# The main observables

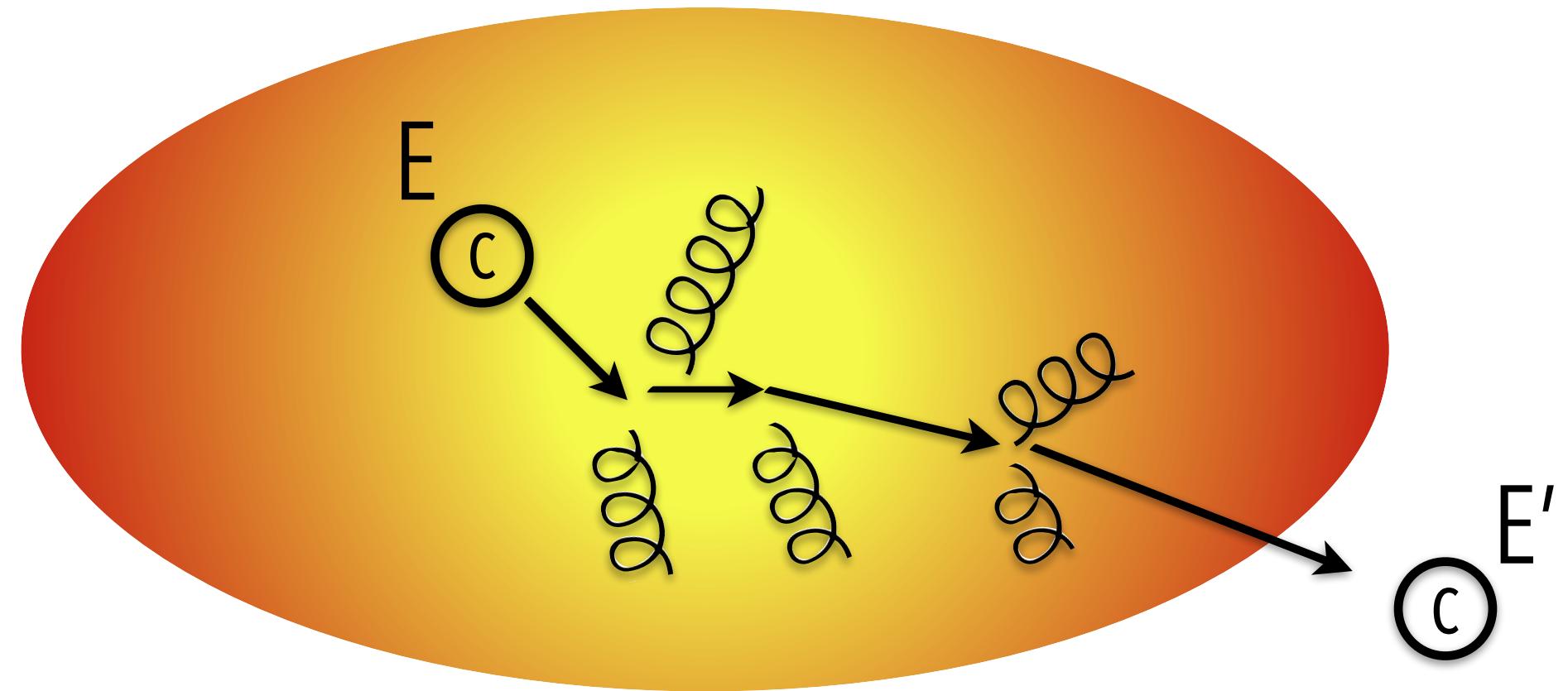
$$\text{Nuclear modification factor } R_{\text{AA}} = \frac{dN_{\text{AA}}/dp_T}{\langle N_{\text{coll}} \rangle \cdot dN_{\text{pp}}/dp_T}$$



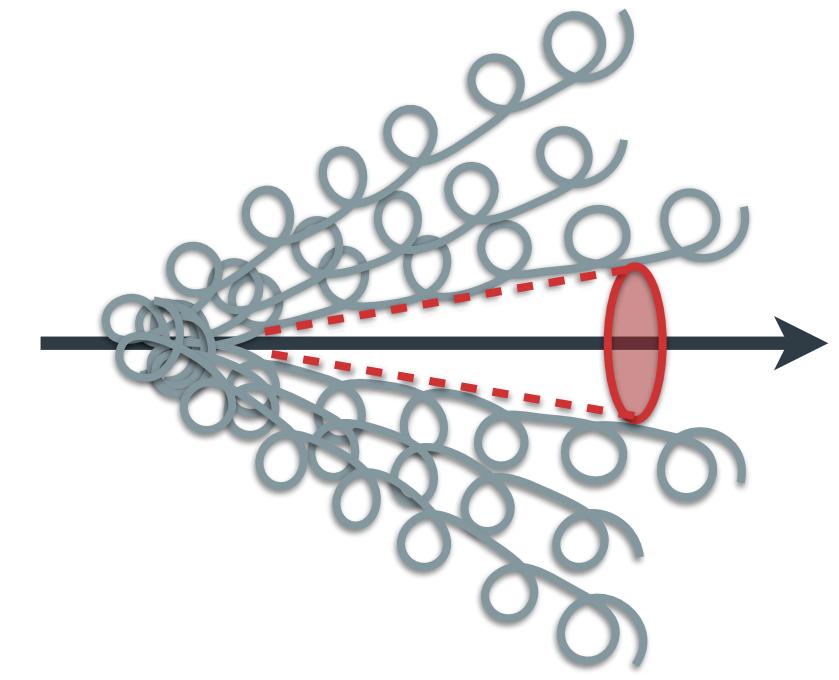
$$\text{Elliptic flow } v_2 = \langle \cos 2(\varphi - \Psi_{\text{RP}}) \rangle$$



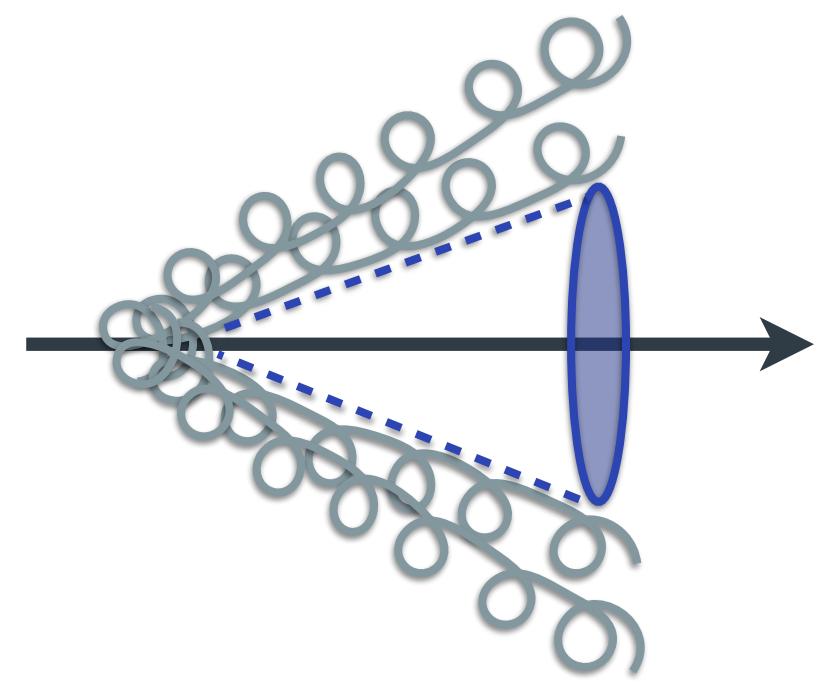
- Dominant effect: energy loss of charm and beauty quarks in the medium
- Goal: study the colour-charge and quark-mass dependence of the in-medium energy loss



small parton mass



large parton mass



$$\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$$

Path traversed in the medium

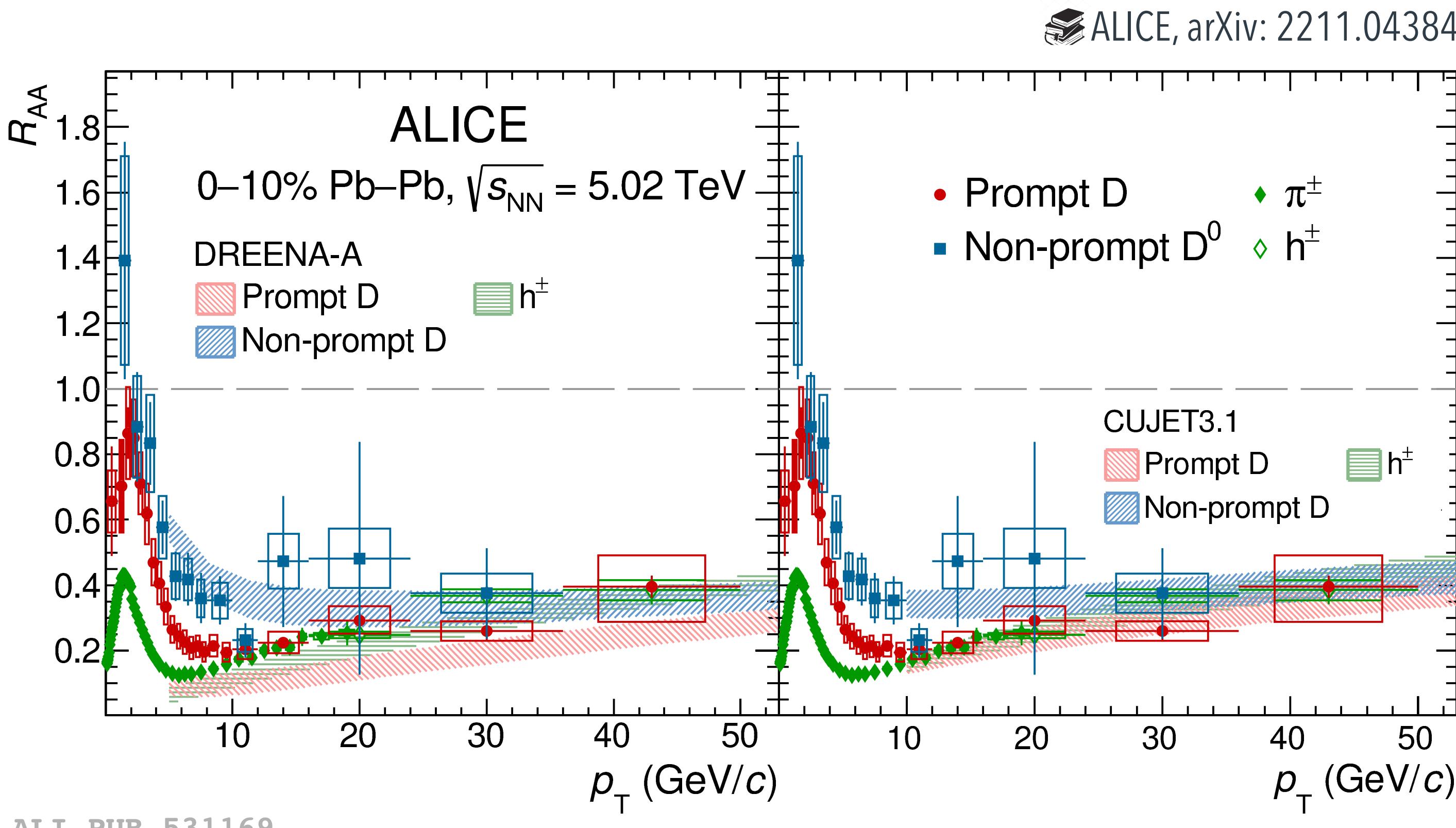
Strong coupling constant

Transport coefficient (average of the square of the transverse momentum exchanged with the QGP per unit mean free path)

Casimir factor = 3 for gluons and 4/3 for quarks

Dead cone effect: gluon radiation suppressed at angles smaller than  $\vartheta < m/E$

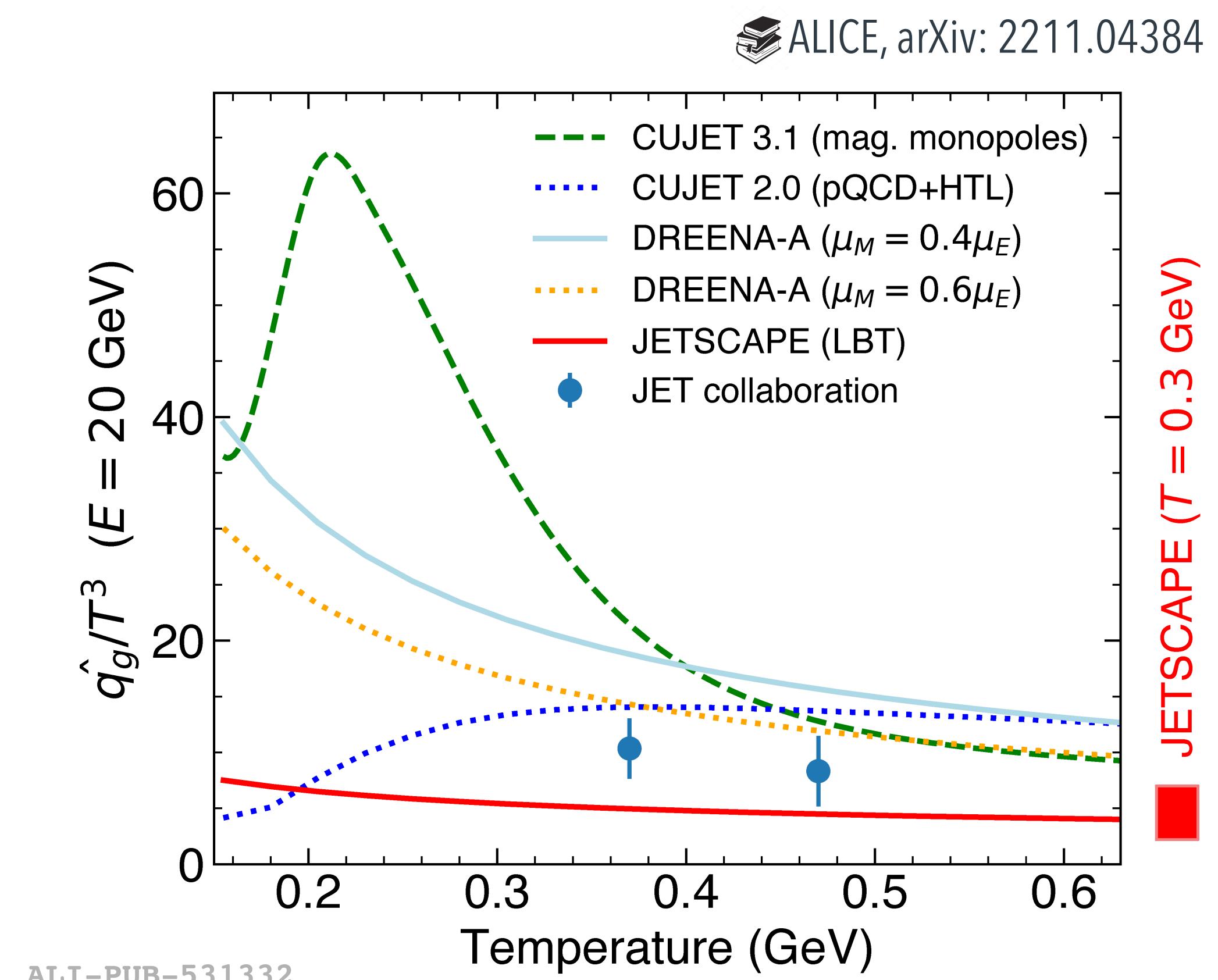
# The high- $p_T$ regime



- Data-to-model comparison seems to favour the scenario of weak coupling for high temperatures
- Less constraints for models at low temperatures
- Different observables needed

- Hierarchy of suppression as expected from dead cone effect

$$R_{AA}(b) > R_{AA}(c) \gtrsim R_{AA}(\text{light})$$



- Models based on the charm-quark transport on a hydrodynamically expanding QGP
  - Typical momentum transfers in scatterings between charm quarks and medium constituents (heat bath) are small
  - Charm quarks undergo soft and incoherent collisions → Brownian motion
  - Boltzmann equation can be reduced to a Langevin or Fokker-Plank equation

$$\frac{\partial}{\partial t} f_Q(t, \mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) \cdot f_Q(t, \mathbf{p}) + \frac{\partial}{\partial p^j} [B^{ij}(\mathbf{p}) \cdot f_Q(t, \mathbf{p})] \right\}$$

- In case of a medium in thermal equilibrium
  - $A^i(\mathbf{p}) = A(\mathbf{p})p_i$  friction
  - $B^{ij}(\mathbf{p}) = B_0(p) \cdot P_{ij}^\perp(\mathbf{p}) + B_1(p) \cdot P_{ij}^\parallel(\mathbf{p})$  momentum broadening

- Brownian motion of heavy quarks in QGP governed by the coupling of heavy quarks to the medium
  - Spatial diffusion coefficient

$$D_s = \frac{T}{m_{\text{charm}} A(p=0)}$$



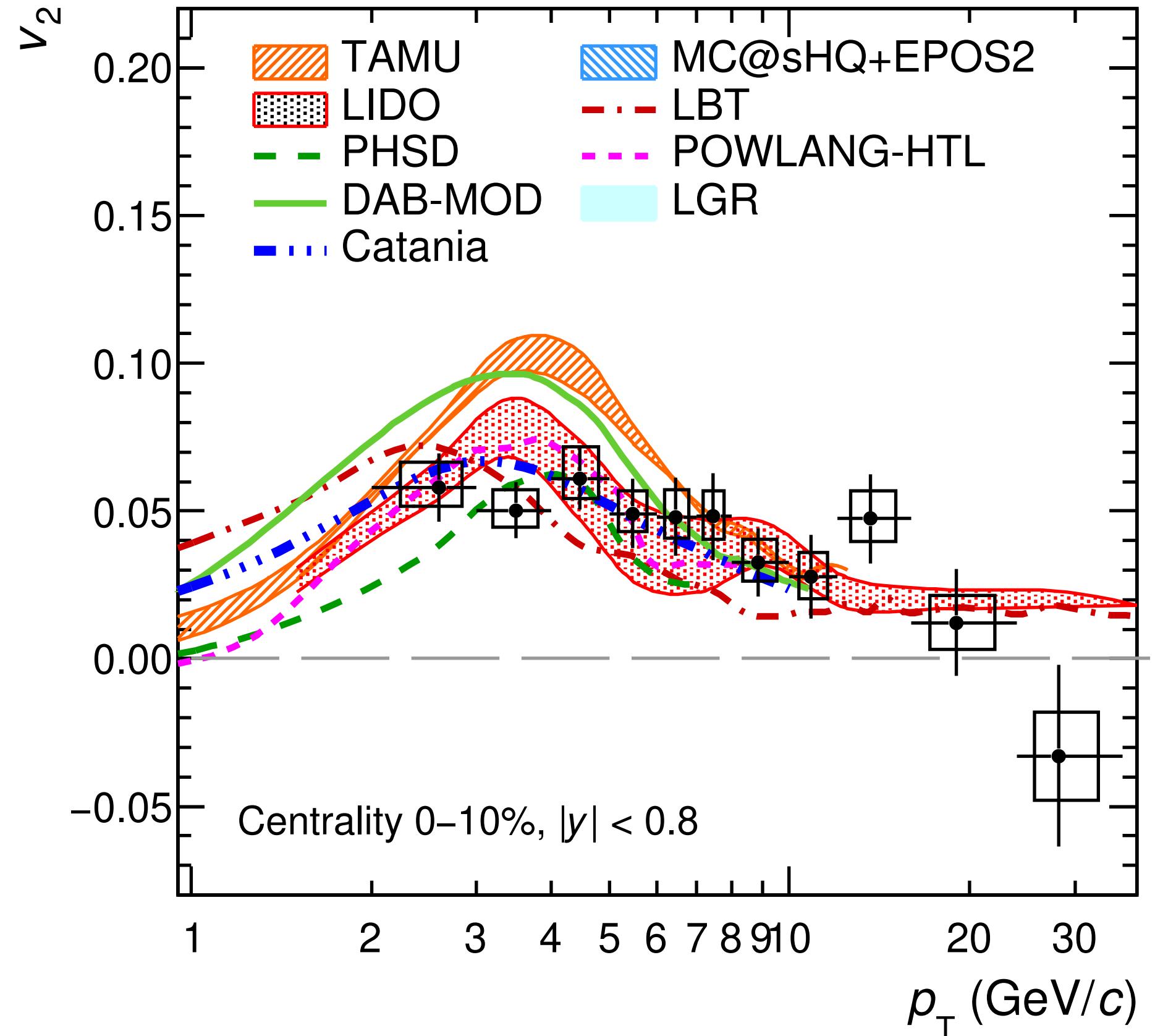
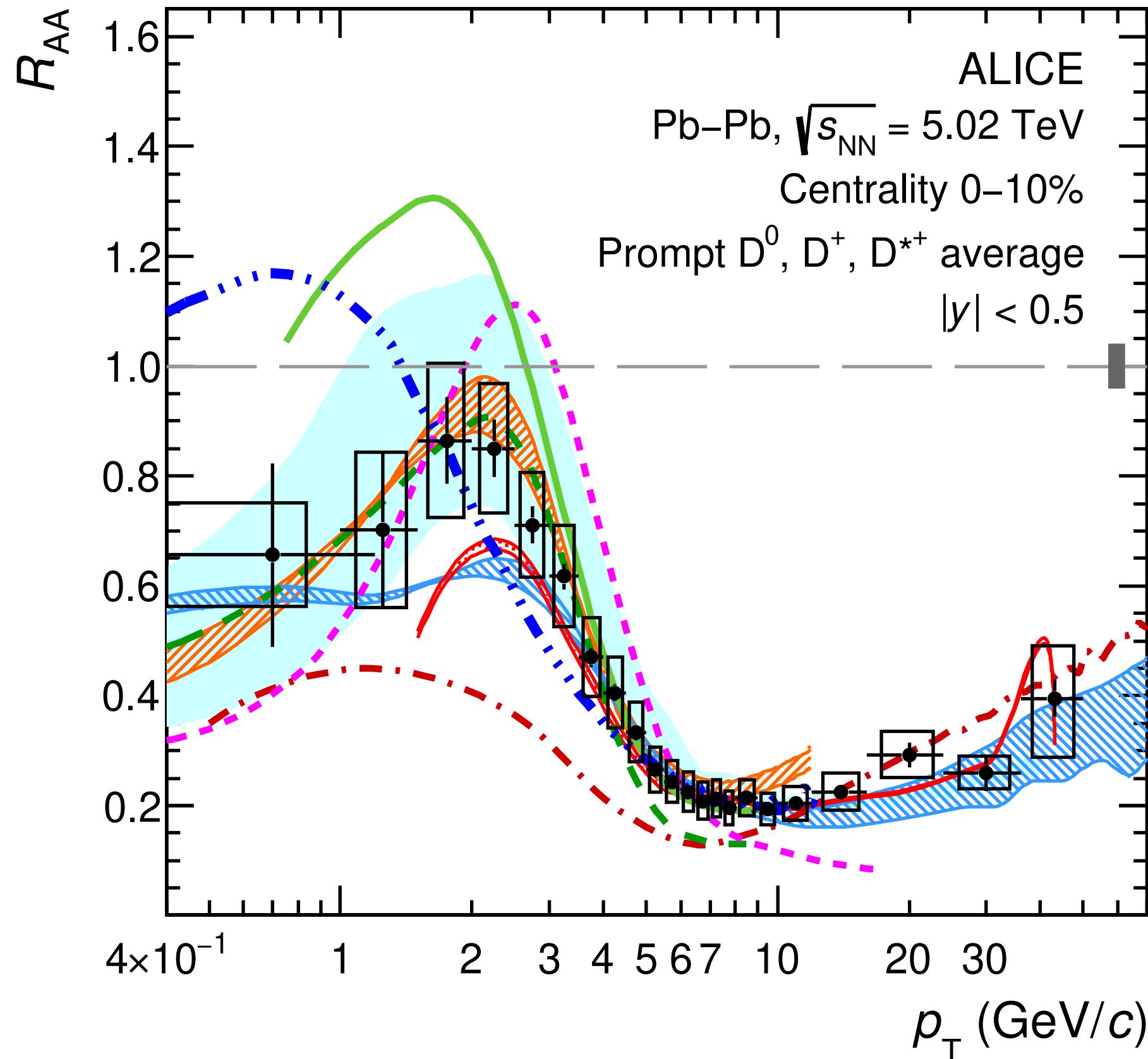
Related to the thermalisation time of the charm quark

Approximately  $A(p=0) \propto 1/m_{\text{charm}}$

$$\tau_{\text{charm}} = (m_{\text{charm}}/T) \cdot D_s$$

# Transport models for charm quarks

ALICE, JHEP 01 (2022) 174



- Additional model ingredients
- Initial state conditions
- Nuclear PDFs
- Hadronisation via different mechanisms
- Hadronic phase

TAMU: PRL 124 (2020) 042301  
MC@sHQ+EPOS2: PRC 89 (2014) 014905  
LGR: arXiv:1912.08965

LIDO: PRC 98 (2018) 064901  
PHSD: PRC 93 (2016) 034906  
Catania: PLB 805 (2020) 135460

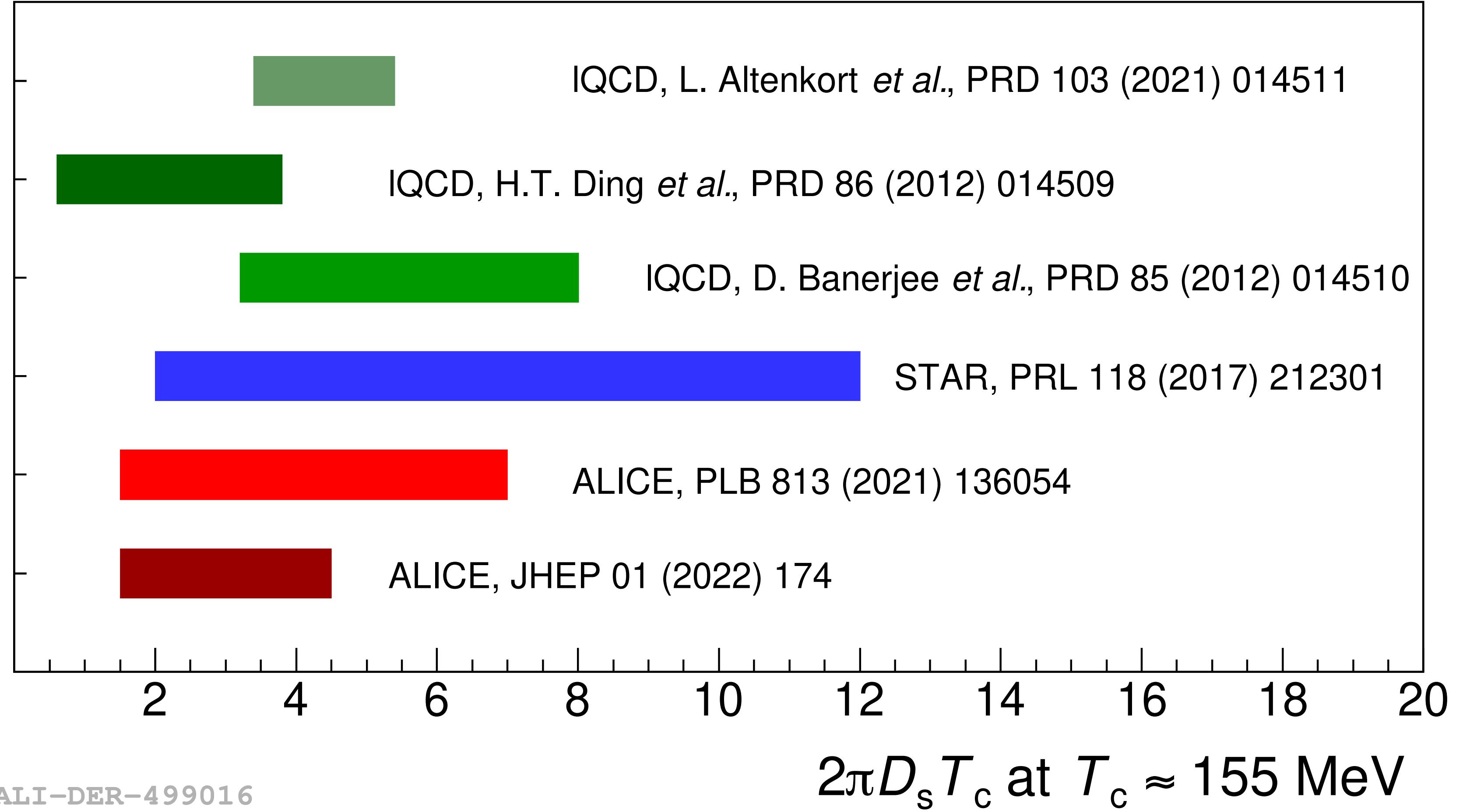
POWLANG: EPJC (2019) 79:494  
LBT: PRC 94 (2016) 014909  
DAB-MOD: arXiv:1906.10768

# Estimates of the spatial-diffusion coefficient

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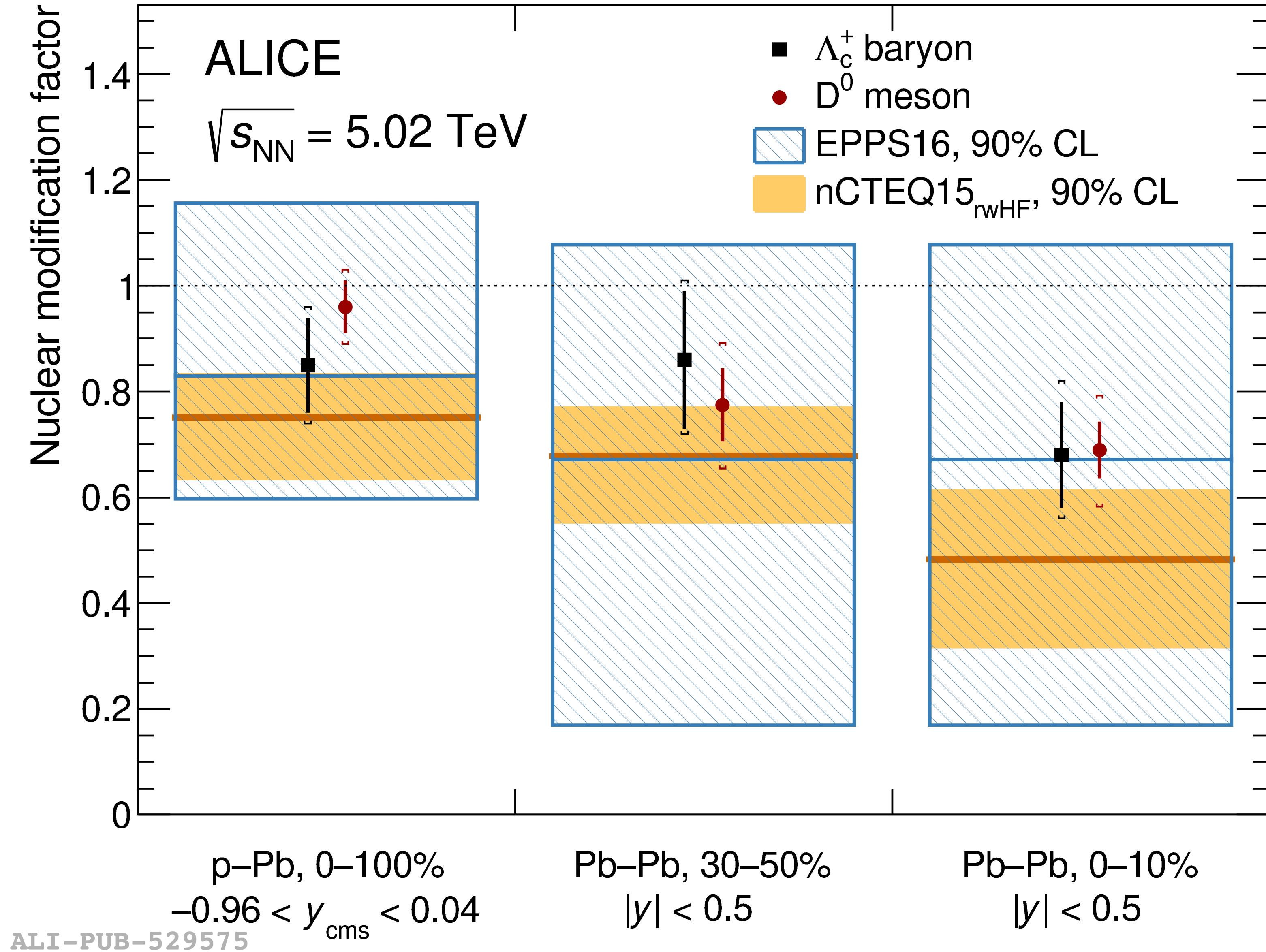
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ALICE, JHEP 01 (2022) 174



- Can we state that the transport coefficient in a model that describes the data is correct?

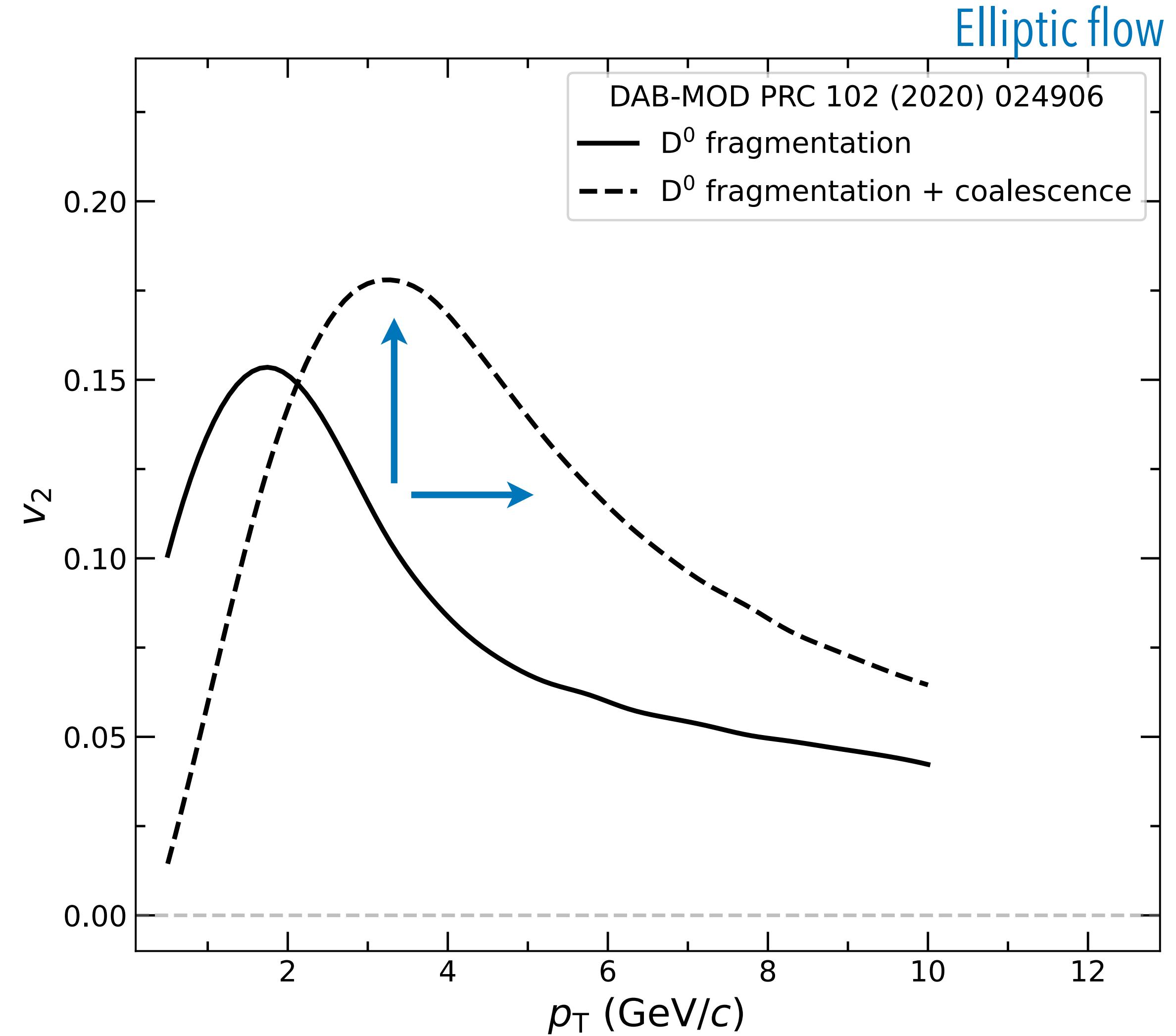
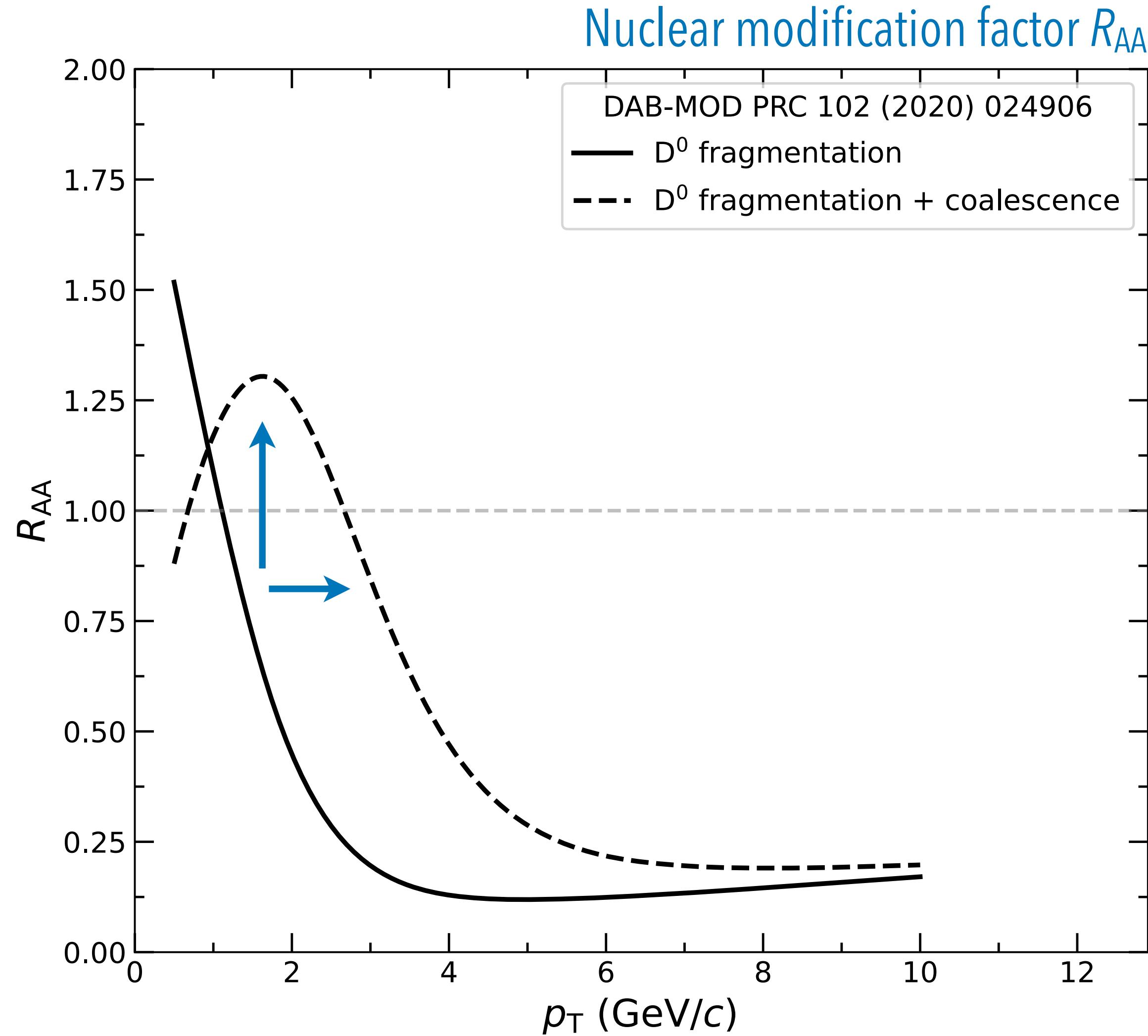
- Interval of spatial diffusion coefficient obtained by considering the values used in the transport models that reproduce the data
  - $2.5 < 2\pi D_s T_c < 4.5$  which corresponds to  $2 < \tau_{\text{charm}} < 6$  fm/c
  - Indicates a thermalisation time of the charm quark comparable with the QGP lifetime
  - Compatible with values obtained with QCD calculations on lattice



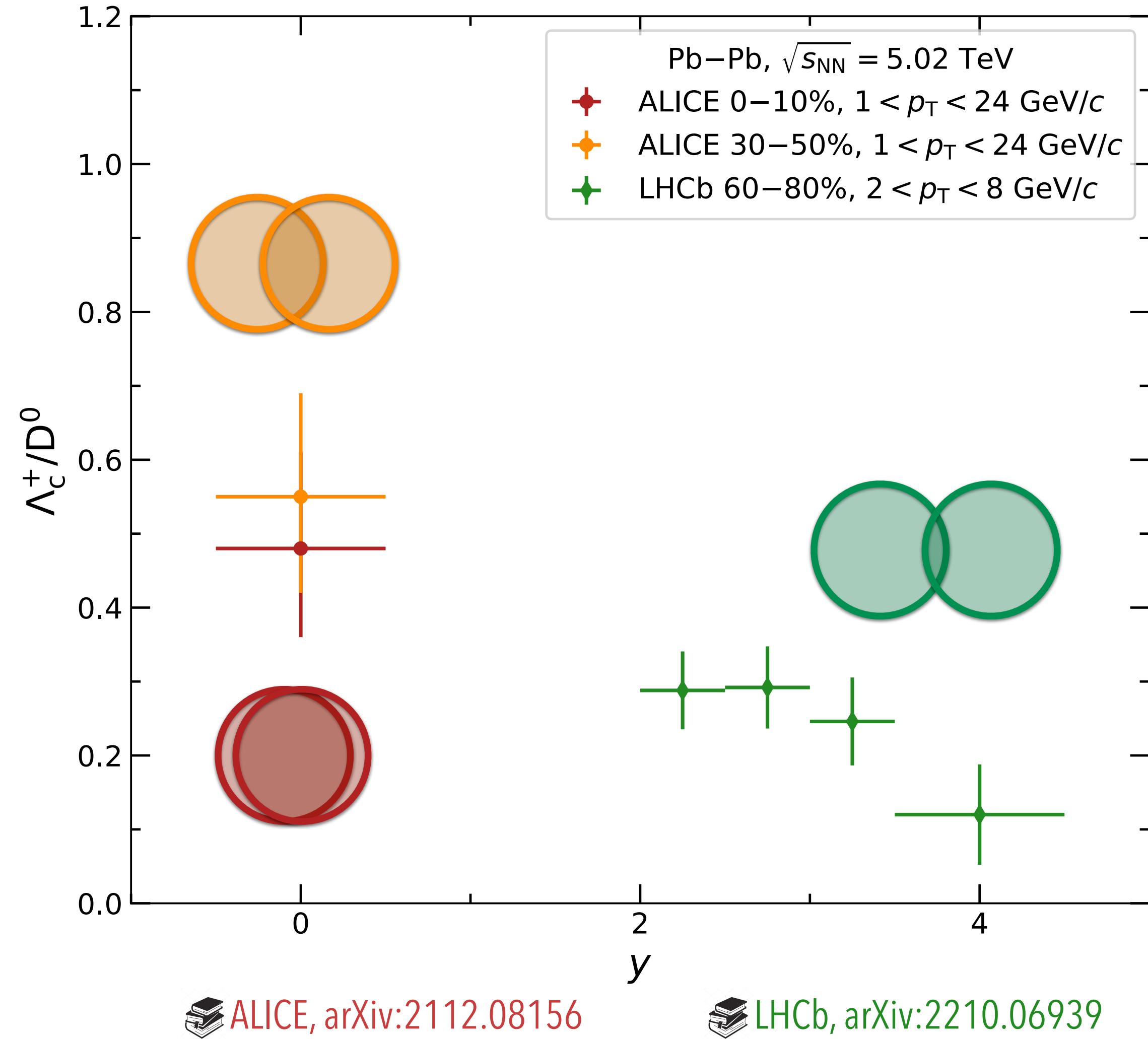
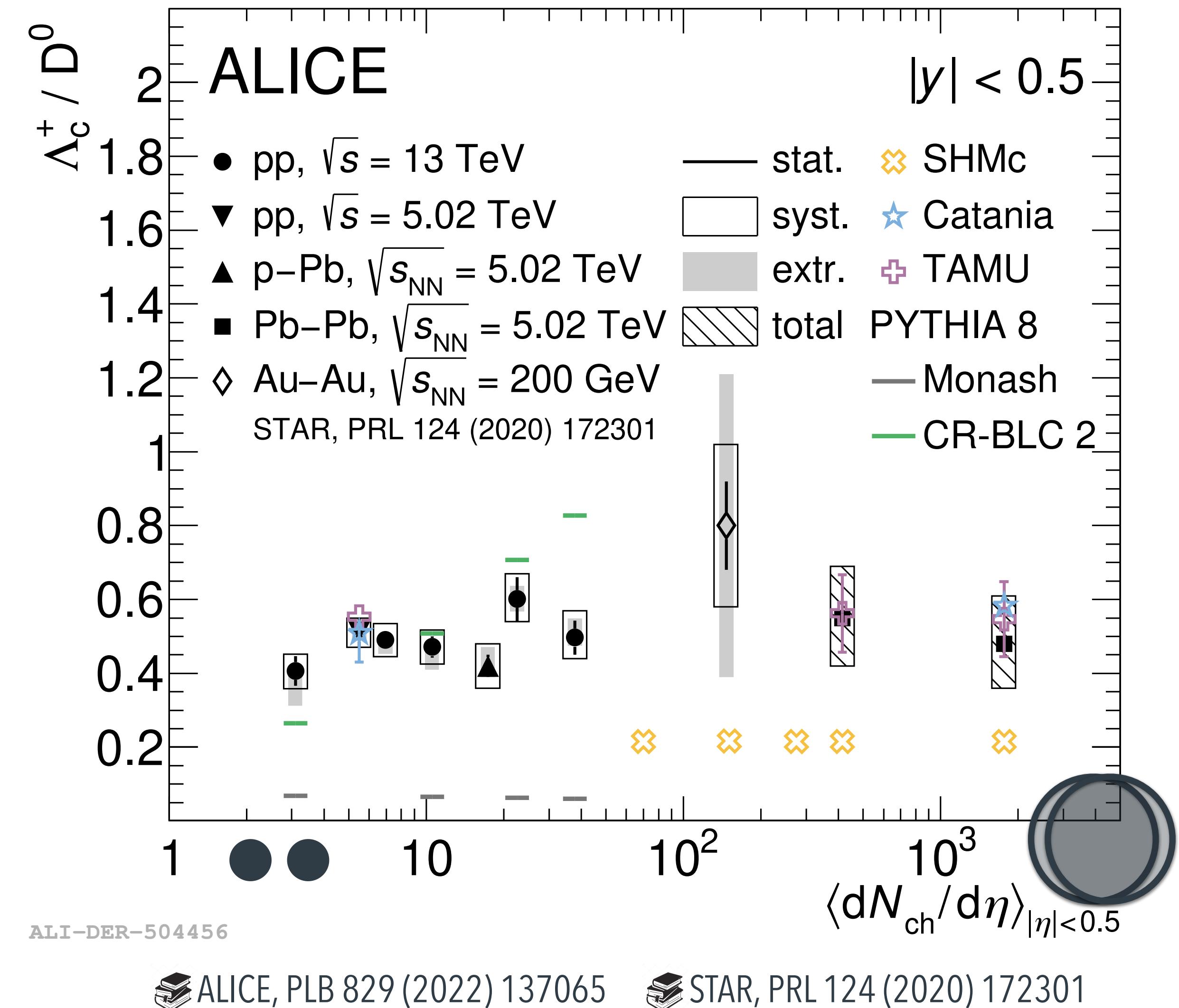
# Charm-quark hadronisation from the medium

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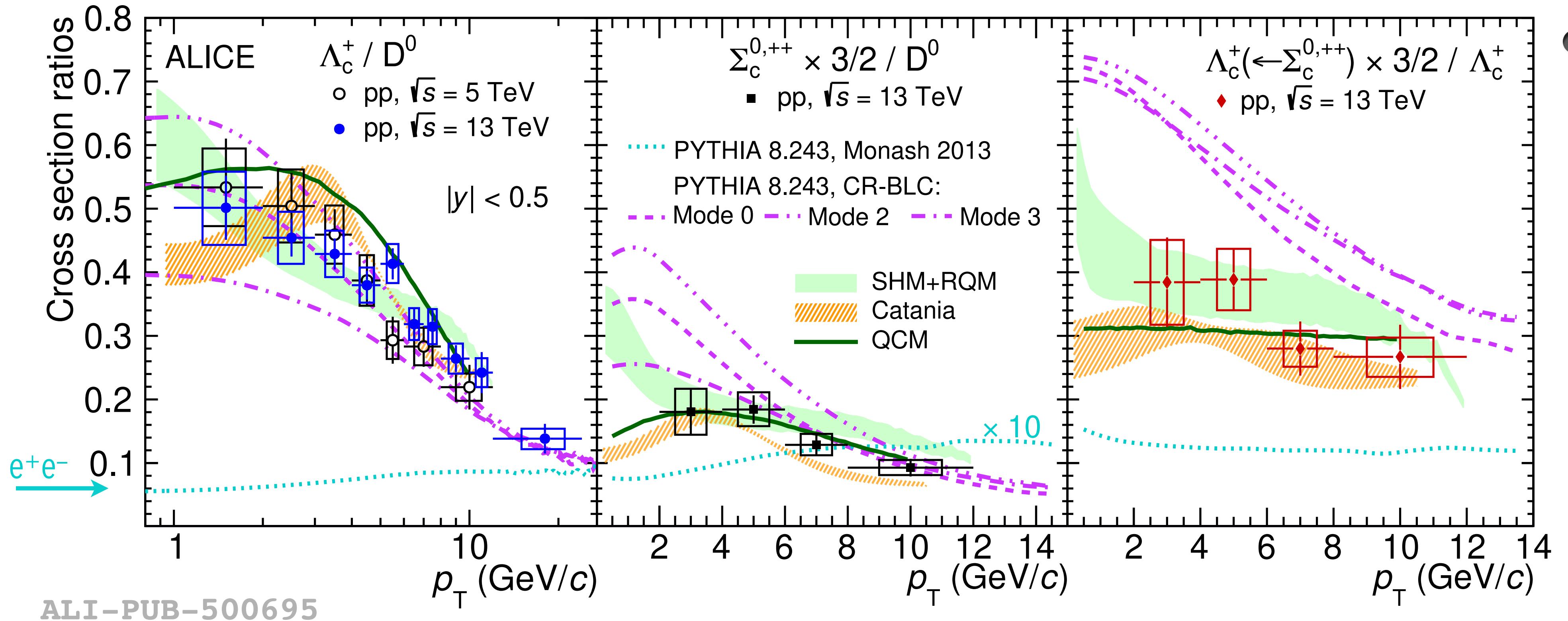


- Formation of a peak structure at intermediate  $p_T$



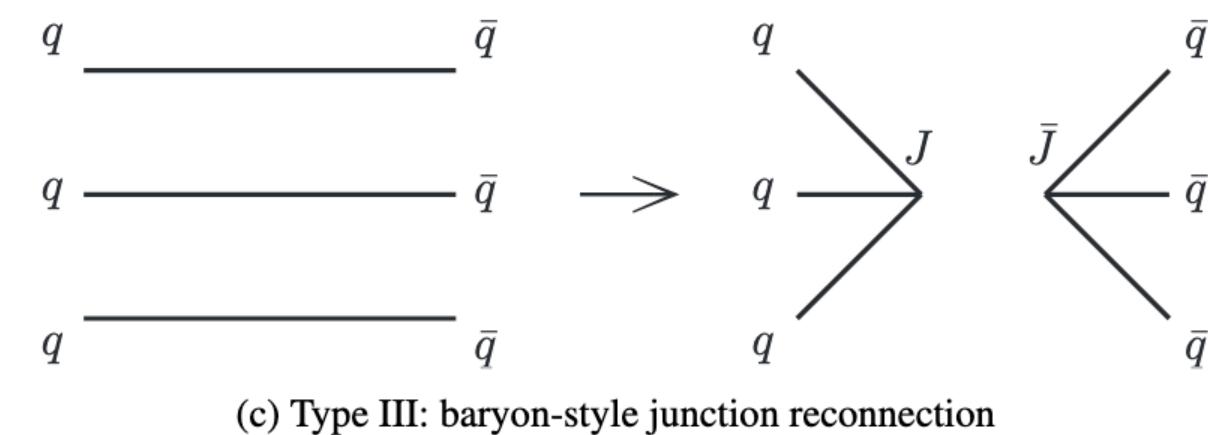
- No indication of modification of  $p_T$ -integrated  $\Lambda_c^+/D^0$  ratio from pp to Pb-Pb collisions
- Possible hint of rapidity dependence

# Charm baryon enhancement in pp collisions



- Color Reconnection (PYTHIA8)

J.P. Christiansen, P. Z. Skands, JHEP 08 (2015) 003



- Quark coalescence (+fragmentation)

V. Minissale, S. Plumari, V. Greco PLB 821 (2021) 136622  
 J. Song, H. Li, F.-I. Shao et al EPJC (2018) 78: 344

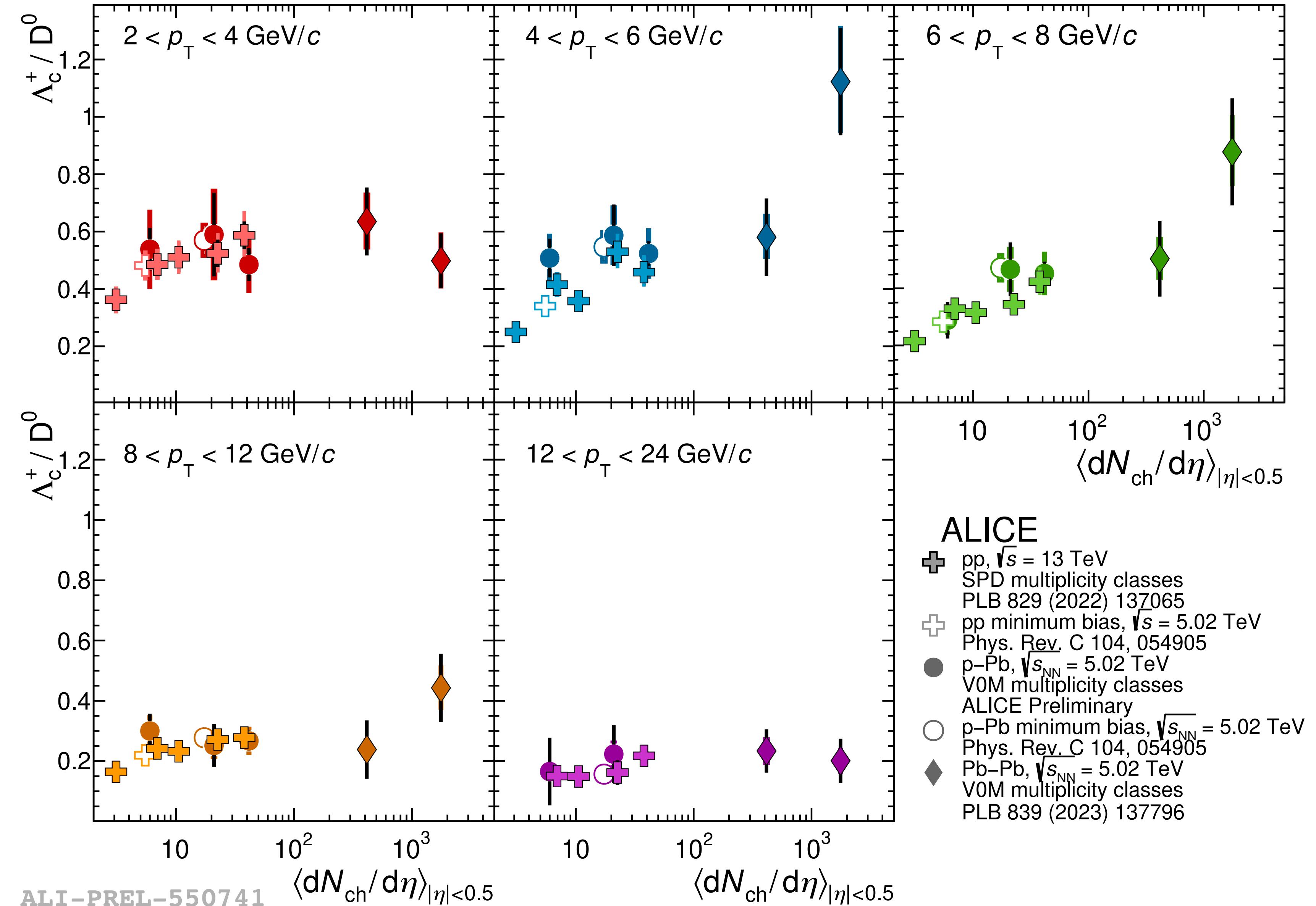
- Statistical hadronisation model with augmented set of charm-baryon excited states from lattice QCD

M. He, R. Rapp, PLB 795 (2019) 117-121

# Charm baryon enhancement in pp collisions vs multiplicity

F. Gerosa (CERN)  
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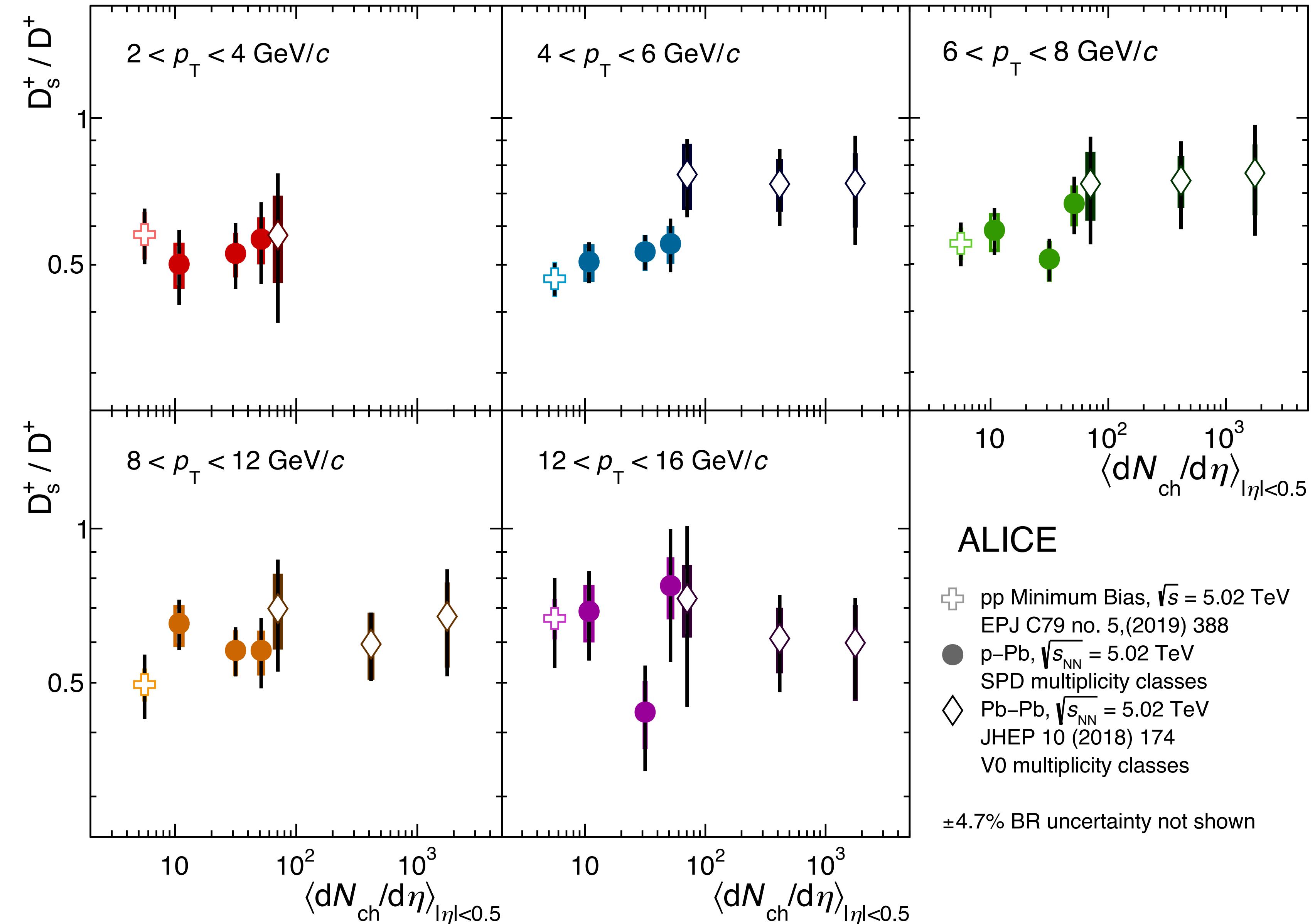
59  
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# $D_s^+$ meson in pp and p–Pb collisions vs multiplicity at midrapidity

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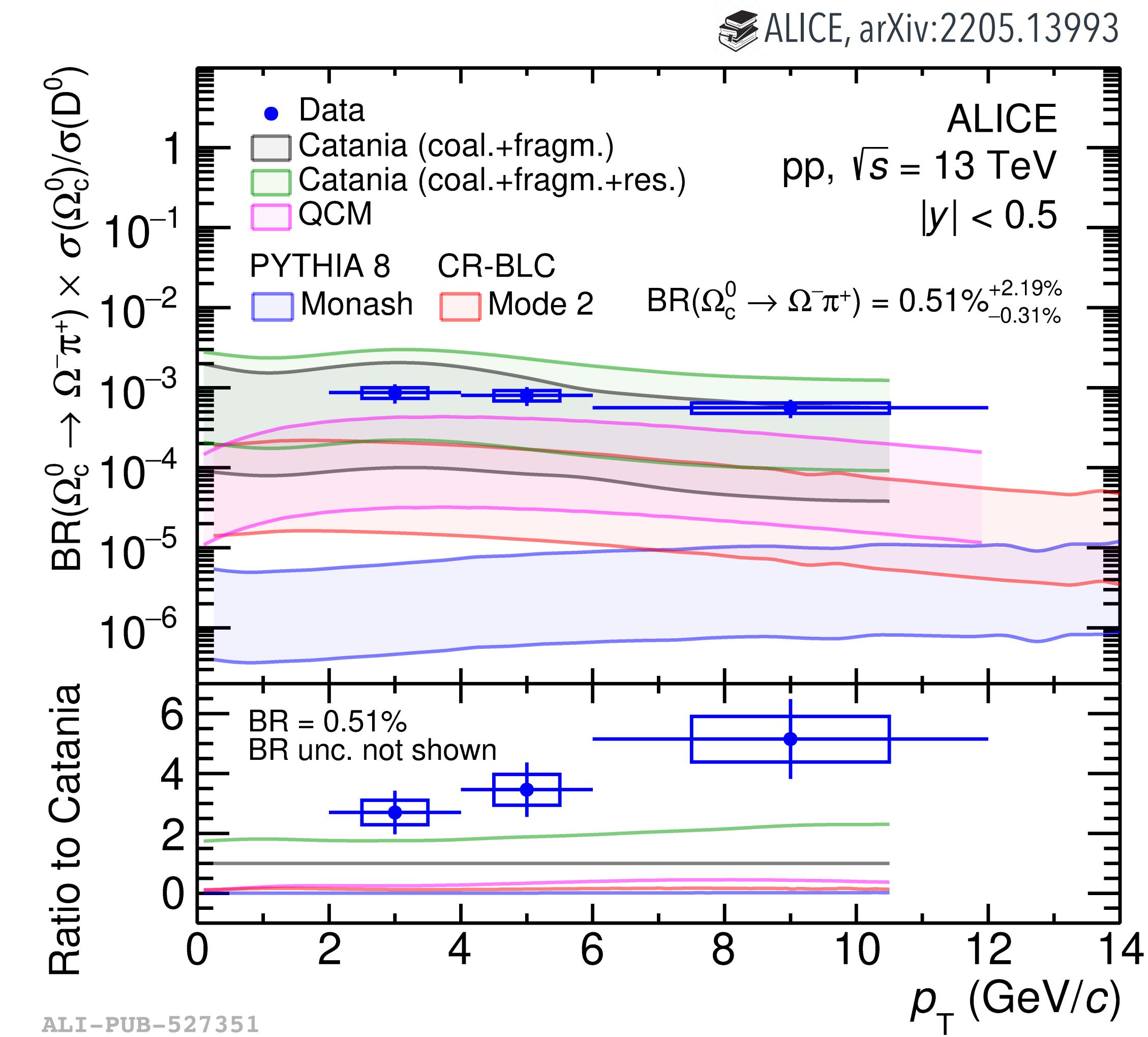
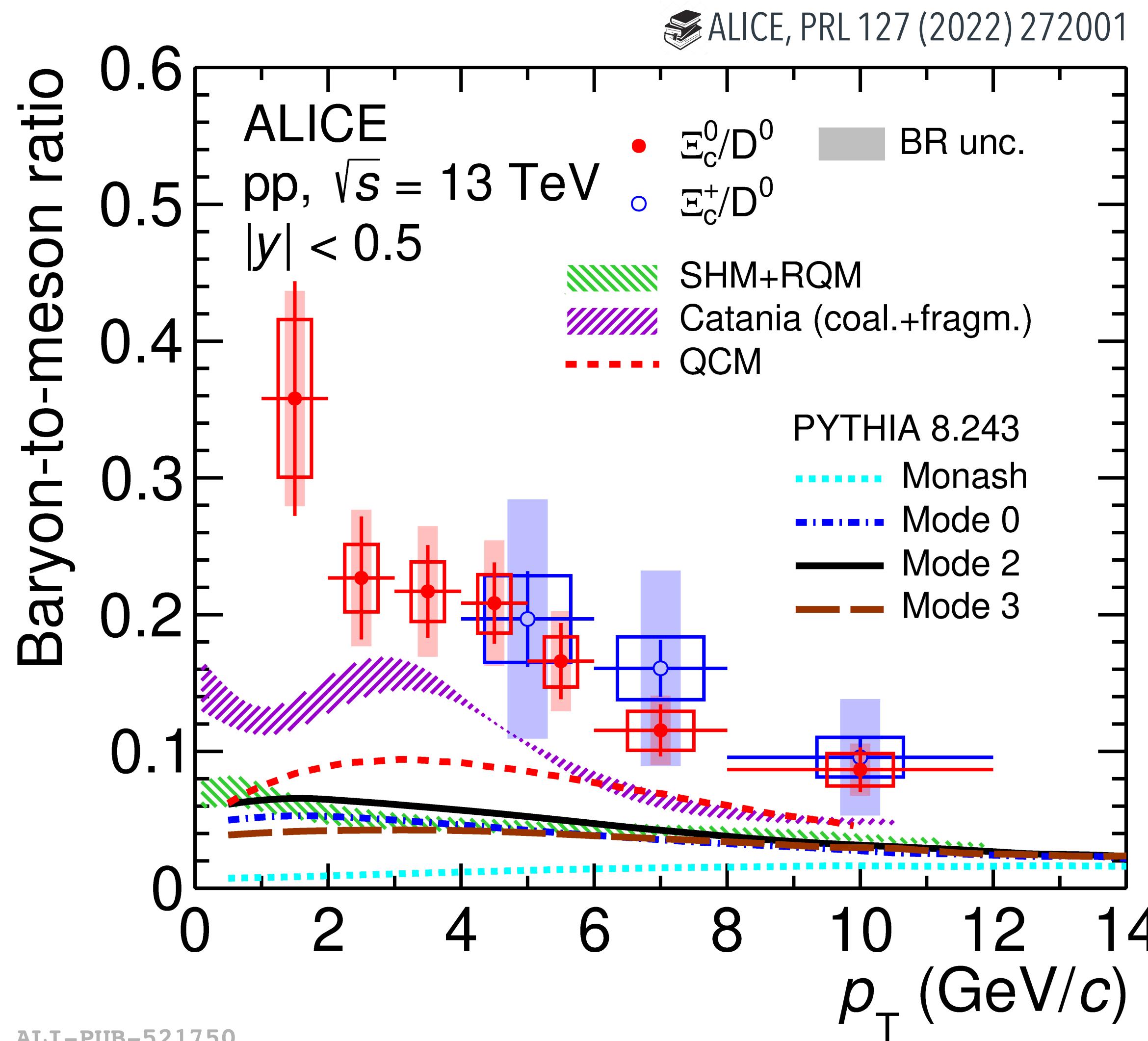
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# Charm-strange baryon enhancement in pp collisions

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61  
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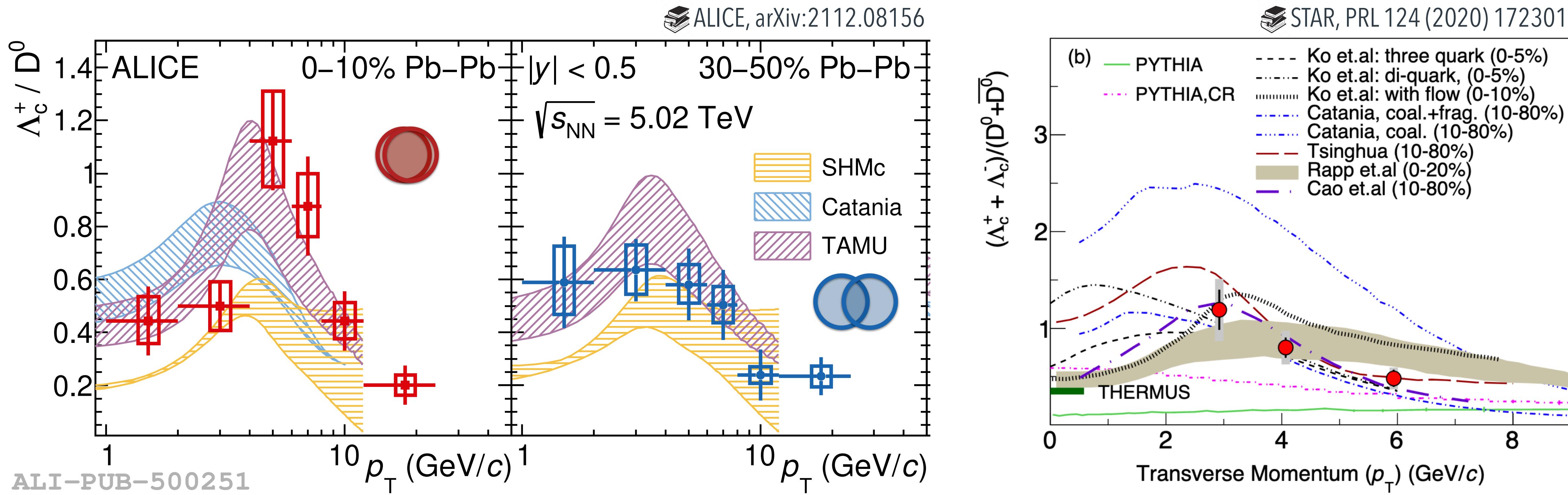


- Models do not reproduce charm-strange baryons

# Charm baryon enhancement in heavy-ion collisions

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62  
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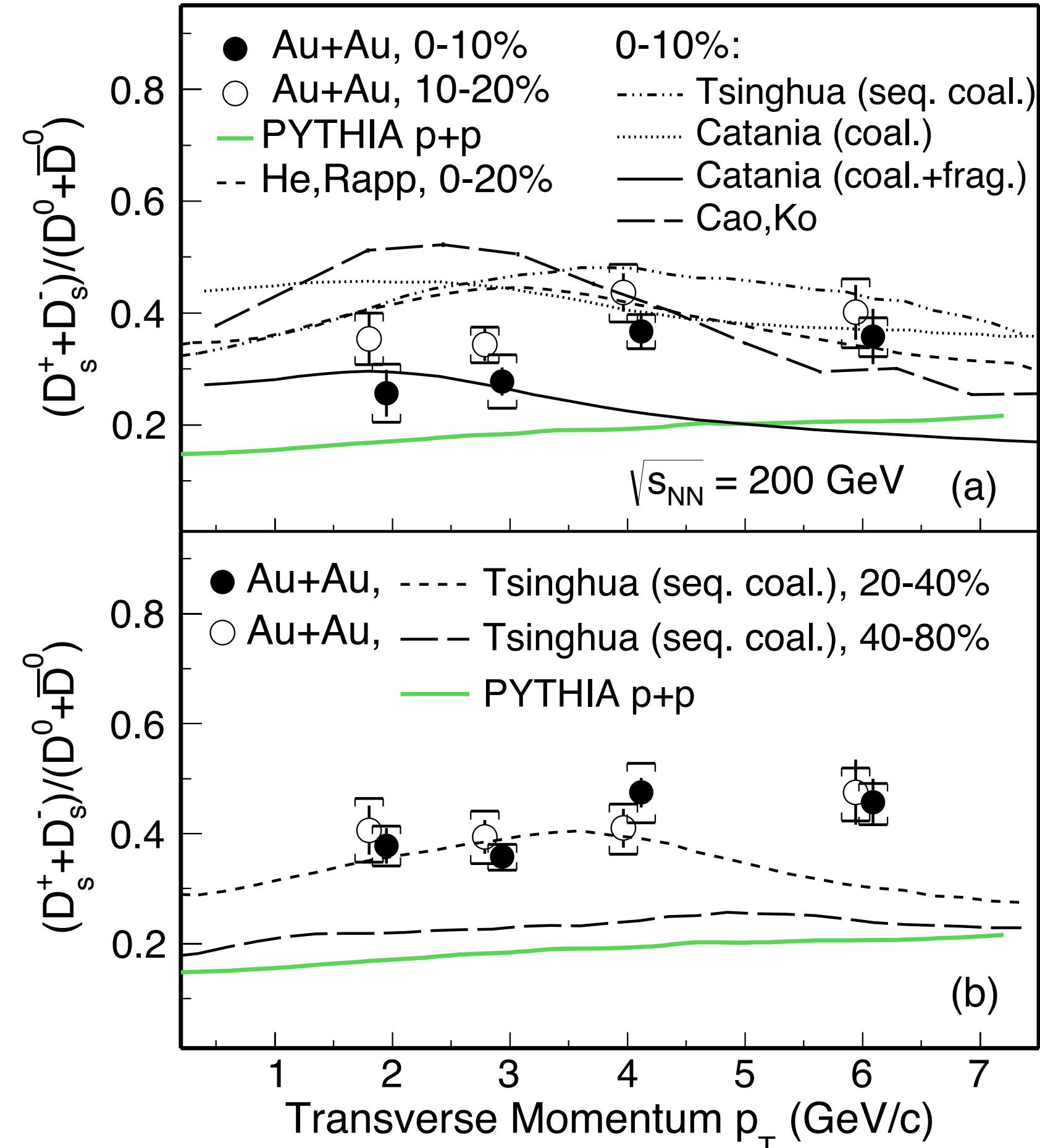
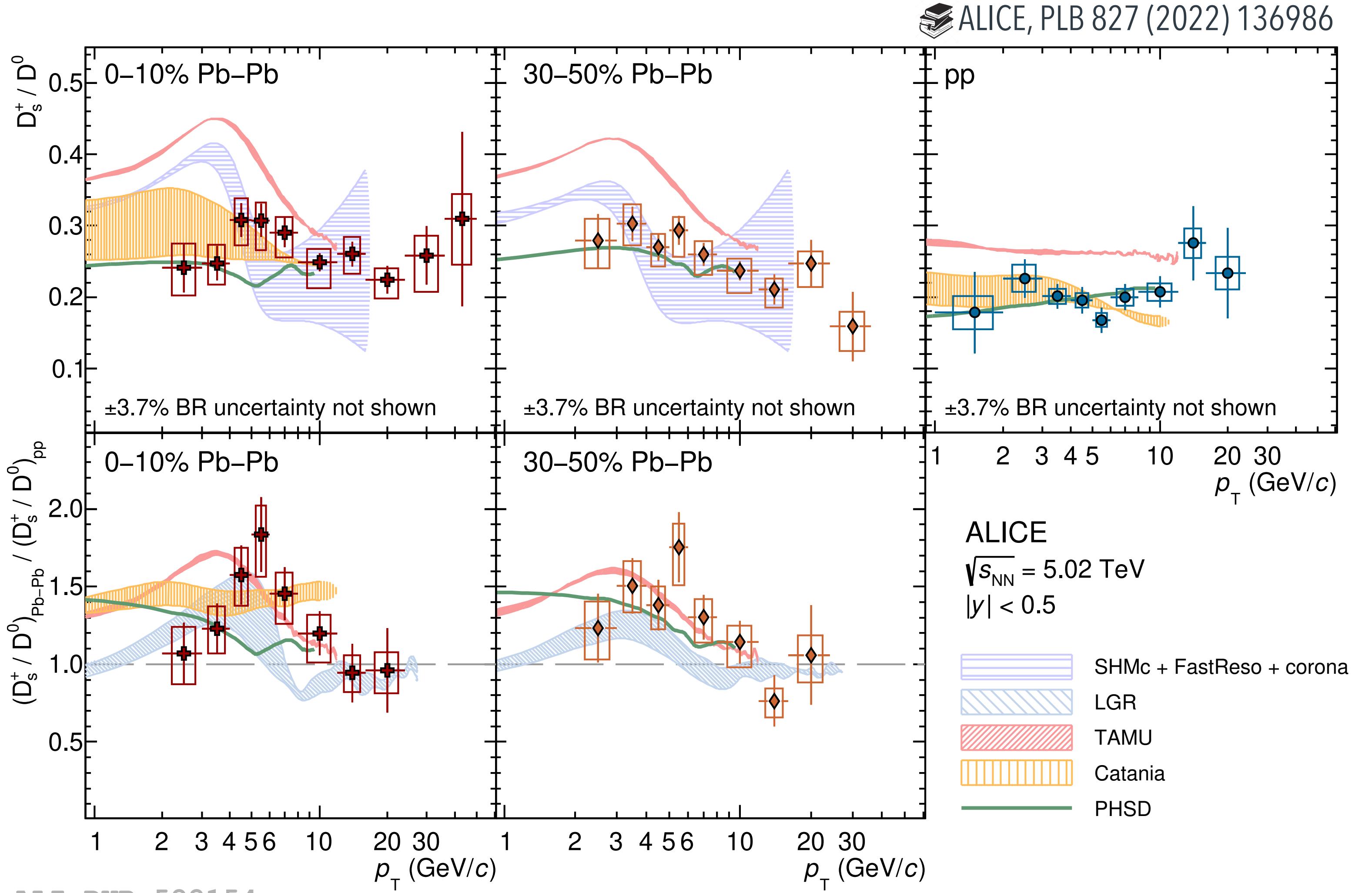


- Coalescence implementations:
  - Instantaneous Catania, EPJC (2018) 78:348
  - Cao et al, PLB 807 (2020) 135561 Ko et al, PRC 101 (2020) 024909
  - Resonance Recombination model TAMU, PRL 124 (2020) 042301
  - Sequential recombination Tsinghua, arXiv:1805.10858
- Statistical hadronisation (no enhanced baryon states):
  - Input charm cross section from pp measurements, hydro-based spectrum for core and a pp scaled spectrum for corona
  - SHMc, JHEP 07 (2021) 035
  - Alternative implementation THERMUS, CPC 180 (2009) 84

# $D_s^+ / D^0$ in Pb–Pb collisions compared with models

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63  
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ALI-PUB-522154

- Enhancement of strange-to-nonstrange production ratio in Pb–Pb collisions with respect to pp collisions typically well described by models, but absolute value still challenging to be reproduced

# Statistical hadronisation model for charm hadrons

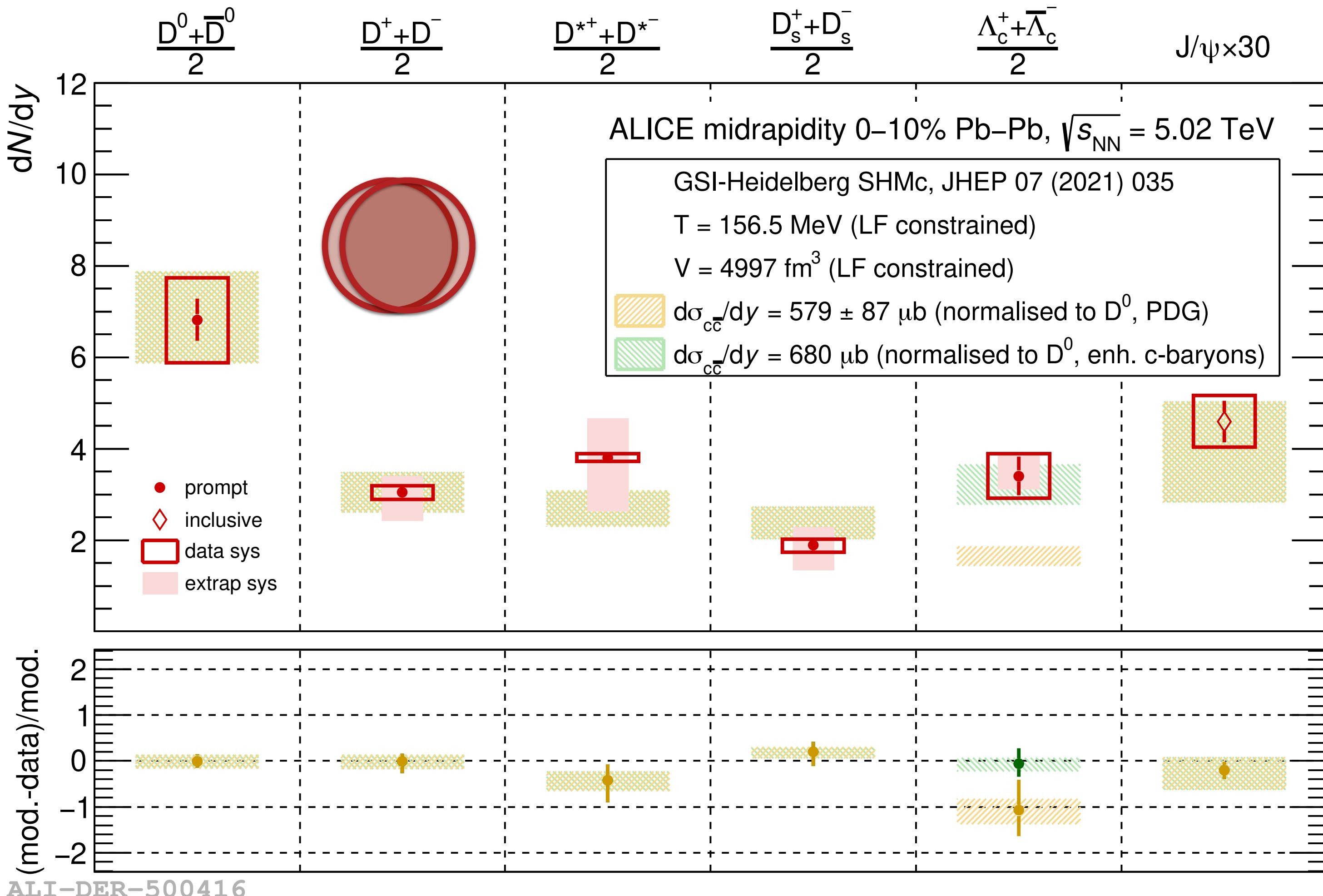
F. Gerosa (CERN)  
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64  
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- Assumptions:
  - Charm quarks created in initial hard scatterings (thermal production negligible) and survive the entire evolution
  - They reach thermal equilibrium and hadronise at the phase boundary

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} g_c V \left\{ \sum_i n_{D_i} + \dots \right\} + g_c^2 V \left\{ \sum_i n_{J/\psi_i} + \dots \right\}$$

Charm fugacity factor, constrained from measurements of charm production cross sections in pp collisions



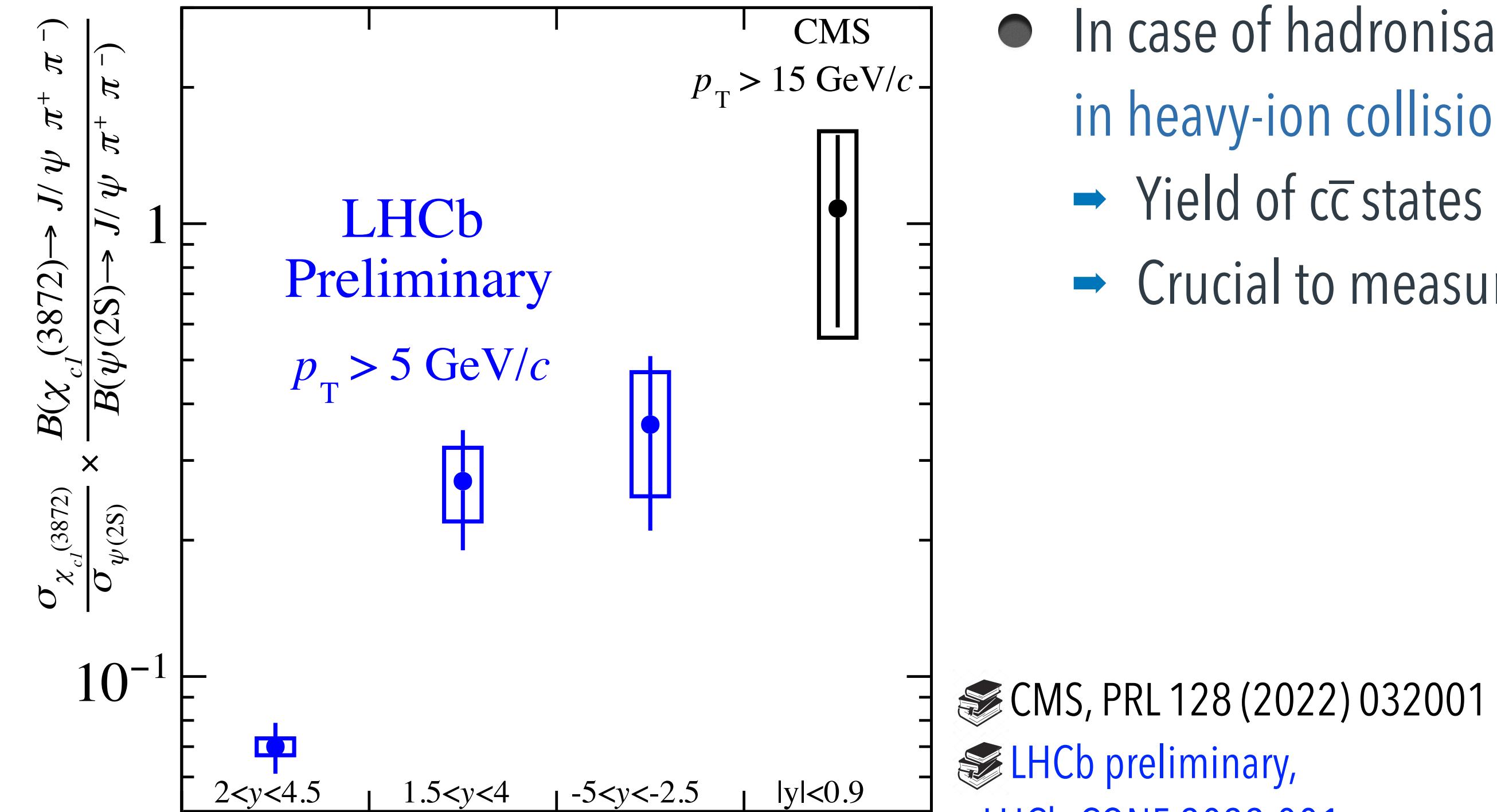
- Charm-hadron abundances described by SHM
  - $\Lambda_c^+$  underestimated if no enhanced set of excited baryon states
  - Indication of charm quark thermalisation in the QGP

SHMc, JHEP 07 (2021) 035

ALICE, JHEP 01 (2022) 174

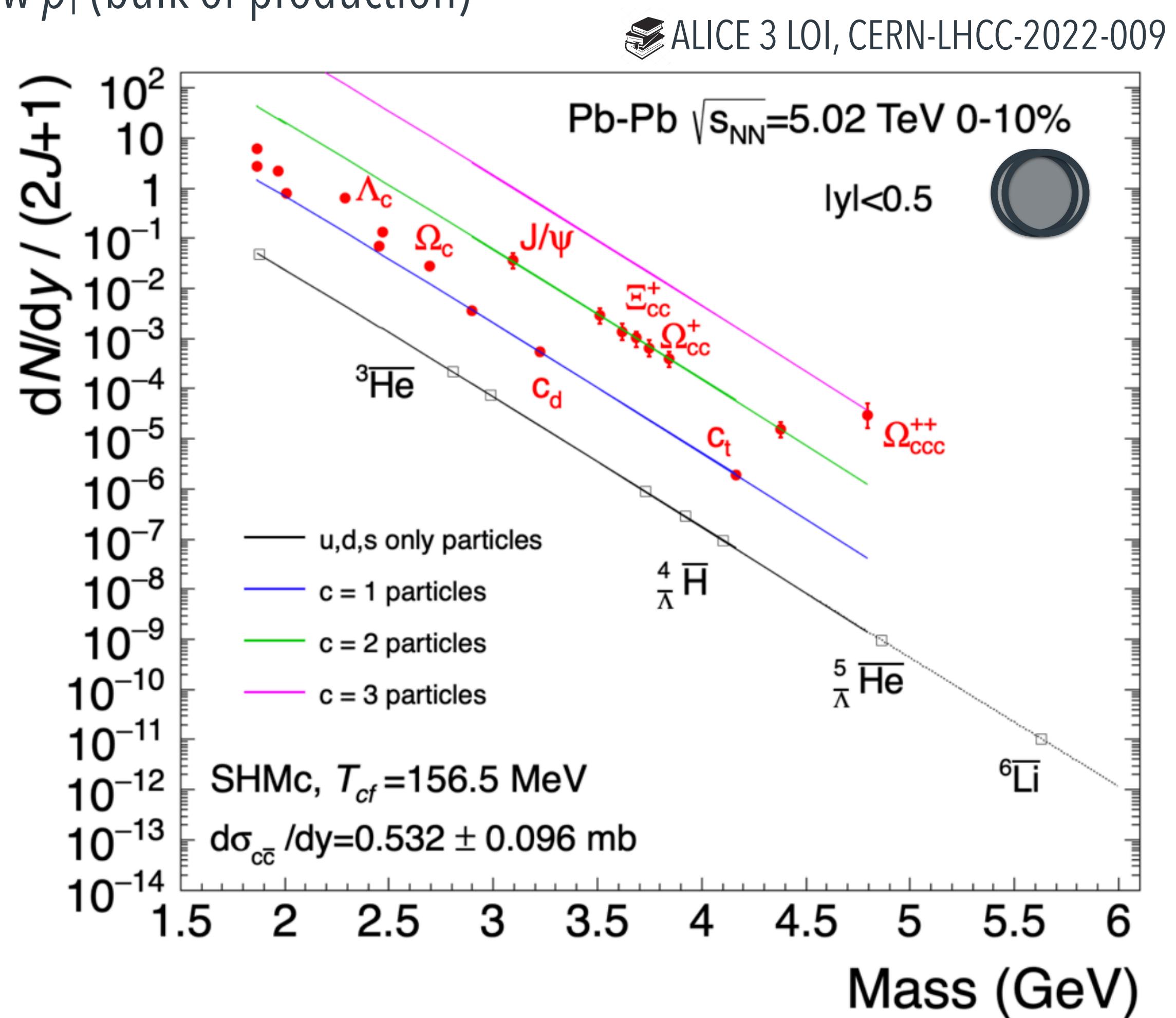
ALICE, PLB 827 (2022) 136986

ALICE, arXiv:2112.08156



- Multicharm states production in single-parton scattering strongly disfavoured compared to single-charm hadrons in pp collisions
  - Expected significant enhancement in heavy-ion collisions
- SHM: emergence of unique pattern due to  $g_c^n$  dependence

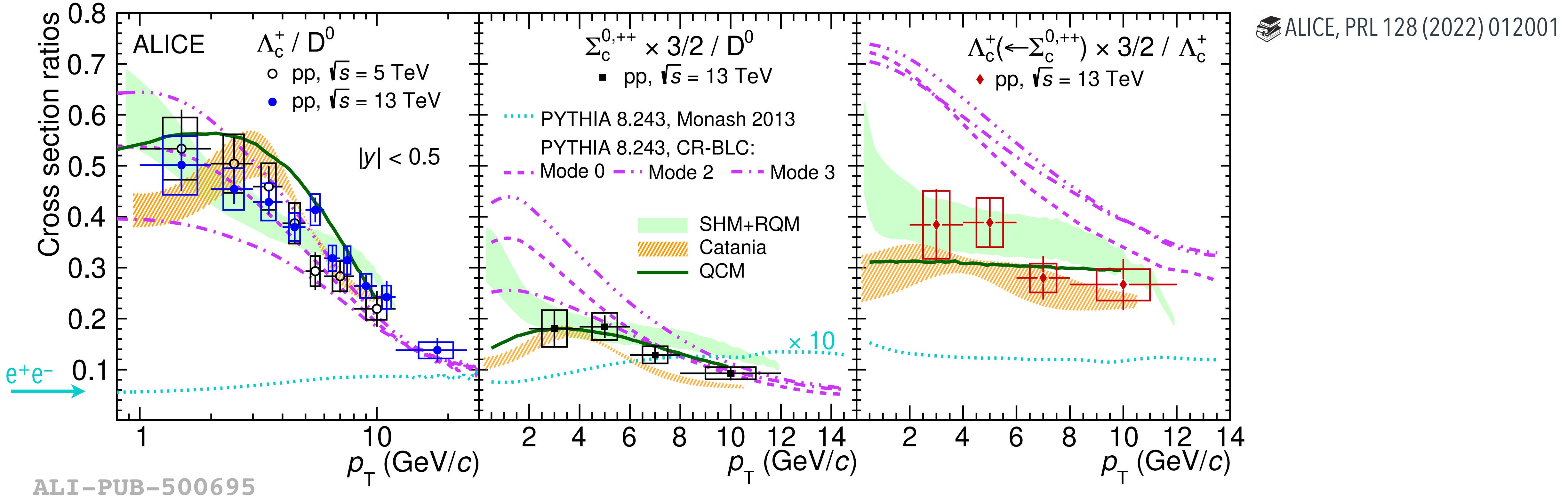
- In case of hadronisation via recombination exotic  $c\bar{c}$  states expected to be enhanced in heavy-ion collisions compared to pp collisions
  - Yield of  $c\bar{c}$  states depends on binding energy and size
  - Crucial to measure low  $p_T$  (bulk of production)



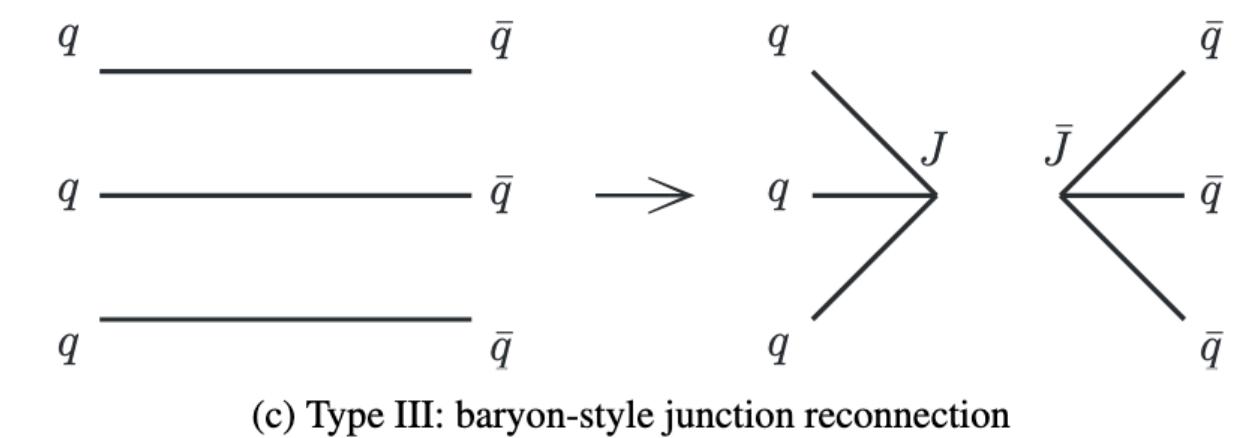
# Baryon enhancement in pp collisions

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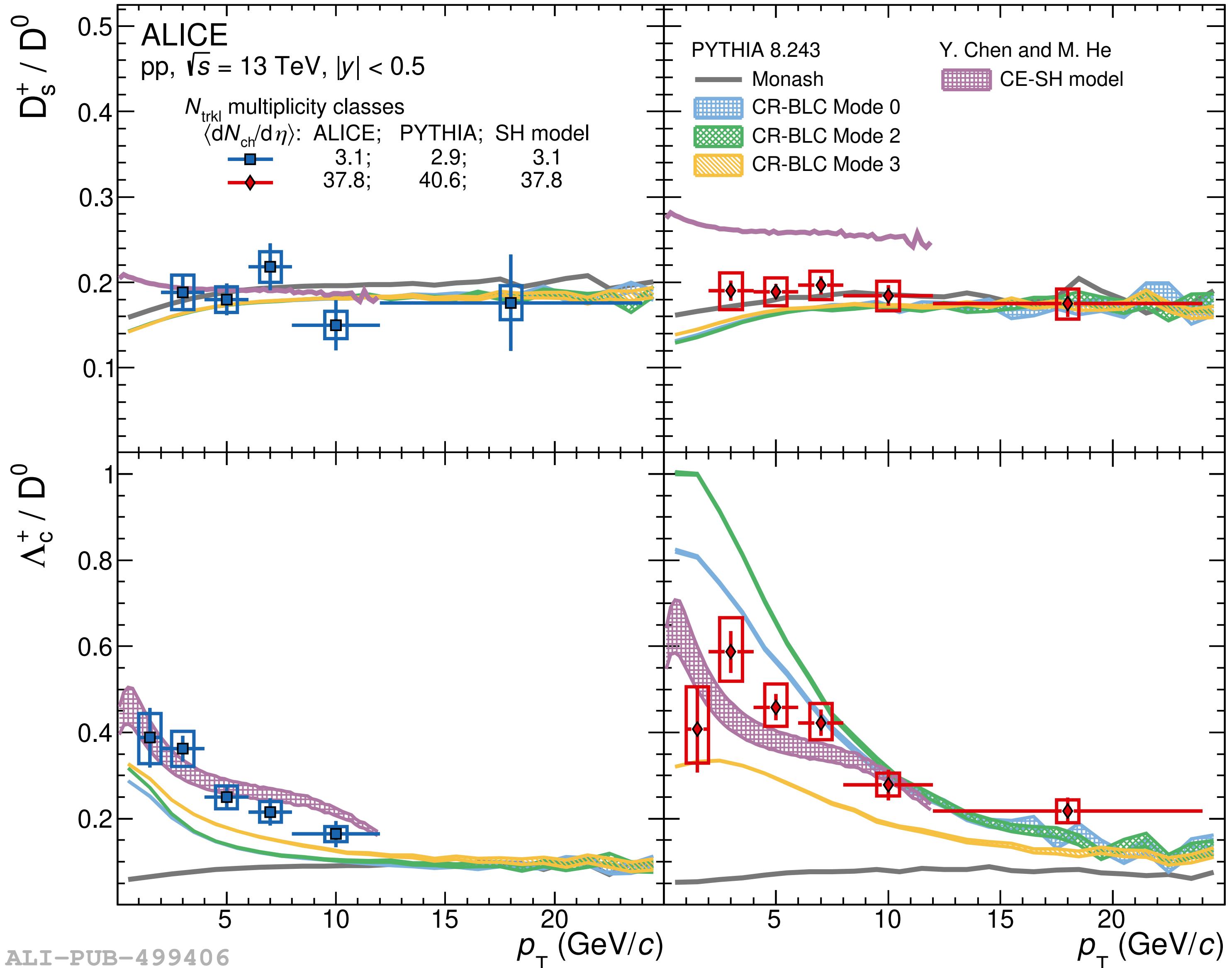
- Quark coalescence (+fragmentation)
  - ALICE, V. Minissale, S. Plumari, V. Greco PLB 821 (2021) 136622
  - J. Song, H. Li, F.-I. Shao et al EPJC (2018) 78: 344
- Color Reconnection (PYTHIA8)
  - ALICE, J.P. Christiansen, P.Z. Skands, JHEP 08 (2015) 003
- Statistical hadronisation model with augmented set of charm-baryon excited states from lattice QCD
  - ALICE, M. He, R. Rapp, PLB 795 (2019) 117-121



# $D_s^+/D^0$ and $\Lambda_c^+/D^0$ in pp collisions as a function of multiplicity

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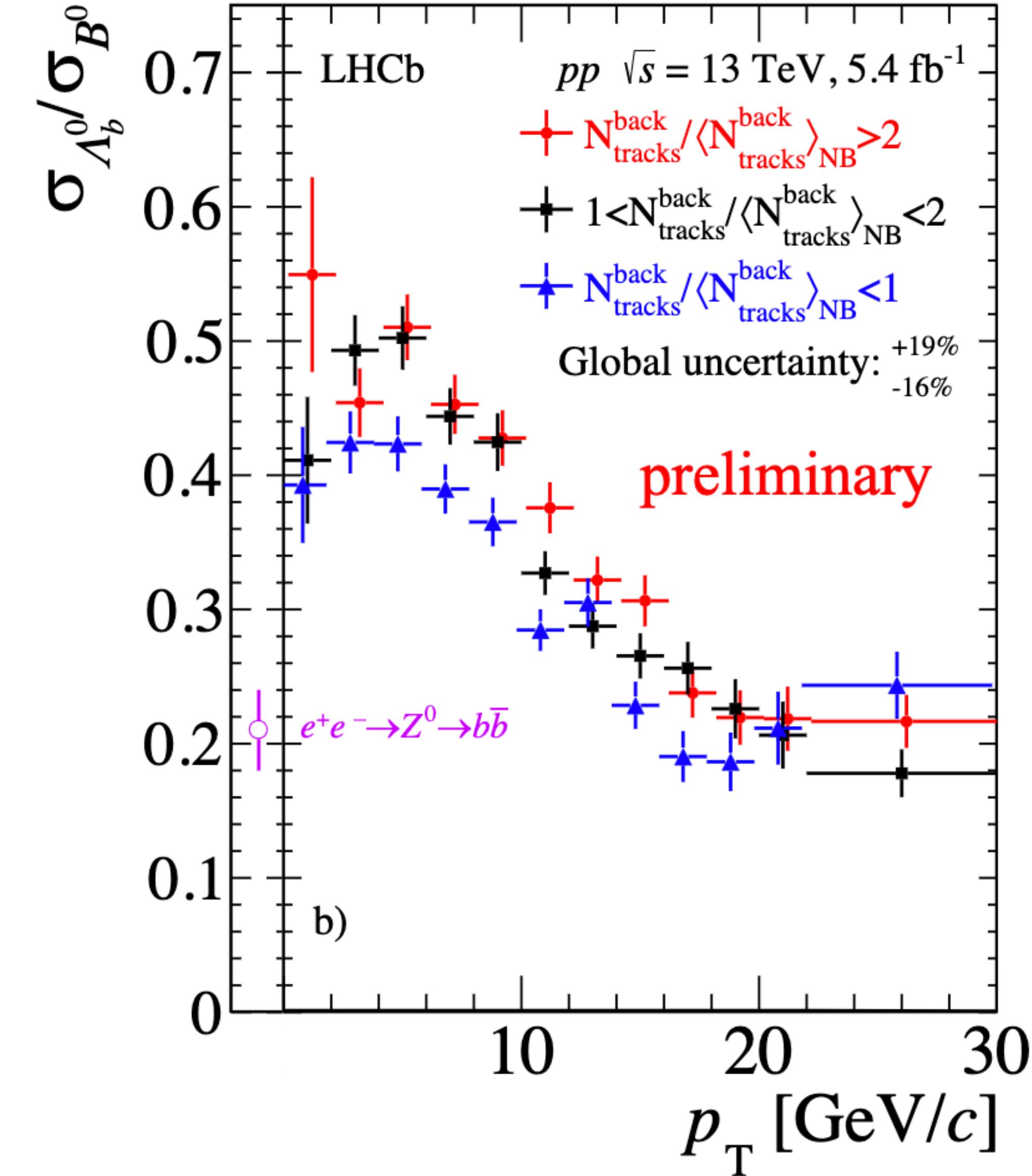
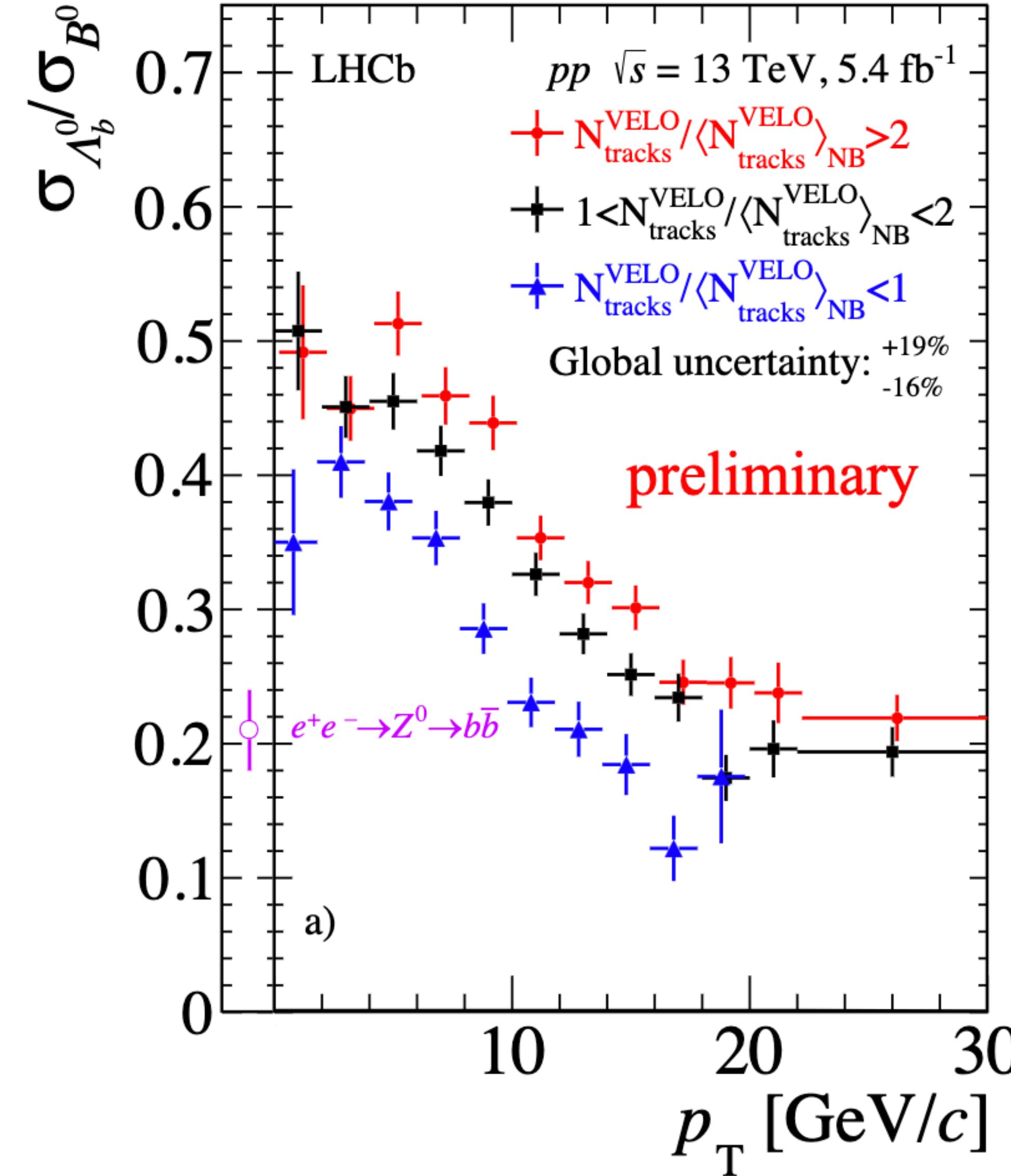


- Significant modification of the  $p_T$  dependence of the  $\Lambda_c^+/D^0$  ratio as a function of multiplicity in pp collisions
- No multiplicity dependence observed for  $D_s^+/D^0$  in pp collisions

# $\Lambda_b^0/B^0$ in pp collisions as a function of multiplicity

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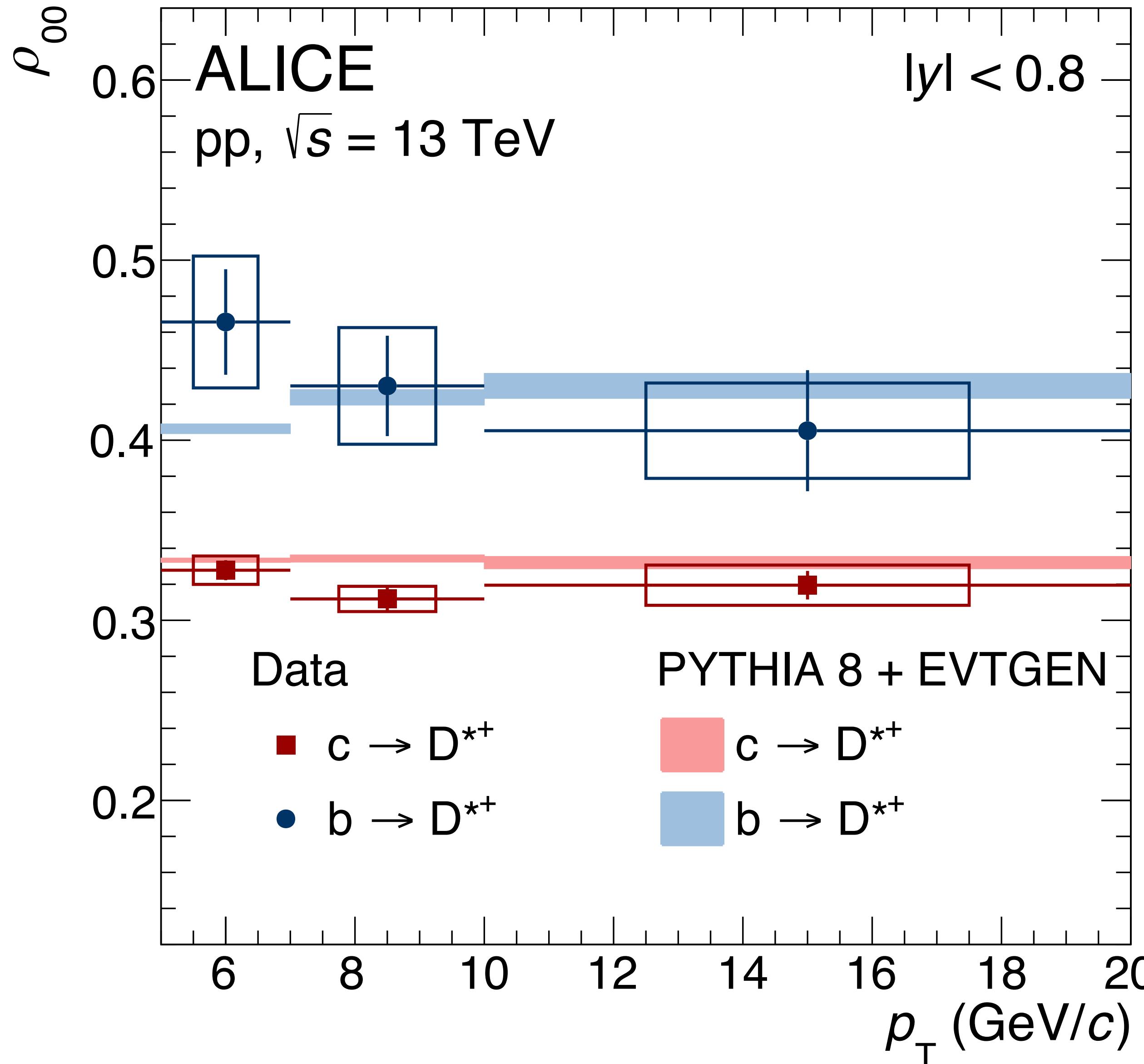
68  
45



# Spin alignment of $D^{*+}$ mesons in pp collisions

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$\frac{69}{45}$

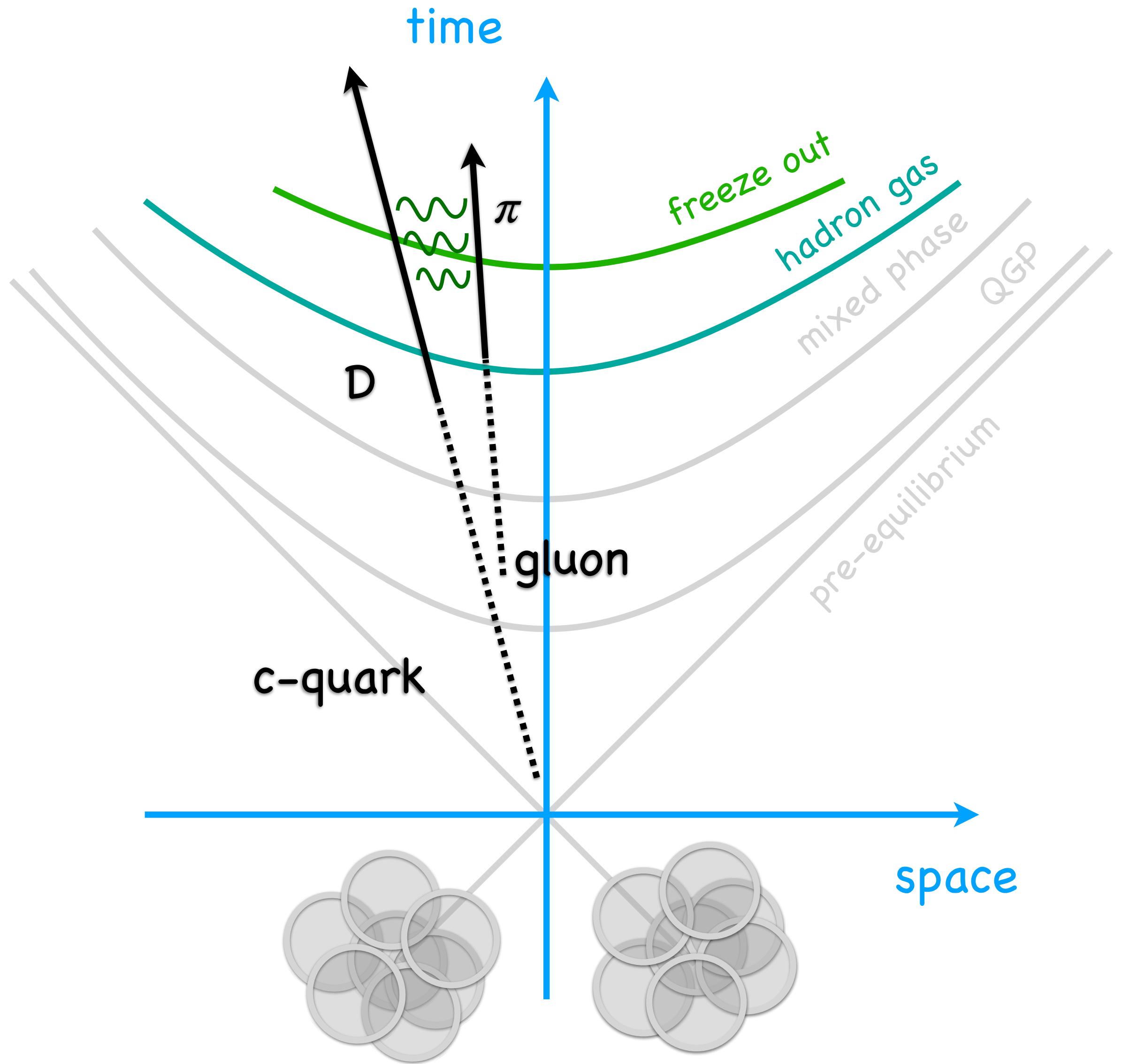


- Spin alignment of prompt and non-prompt charm vector mesons with respect to helicity axis in pp collisions
  - Prompt  $D^{*+}$  compatible with no polarisation
  - Non-prompt  $D^{*+}$   $\rho_{00} > 1/3$  (helicity conservation in  $B \rightarrow D^{*+}X$  decays)
- Measurement of  $D^{*+}$  vector mesons in heavy-ion collisions crucial to complete the picture for c-quark

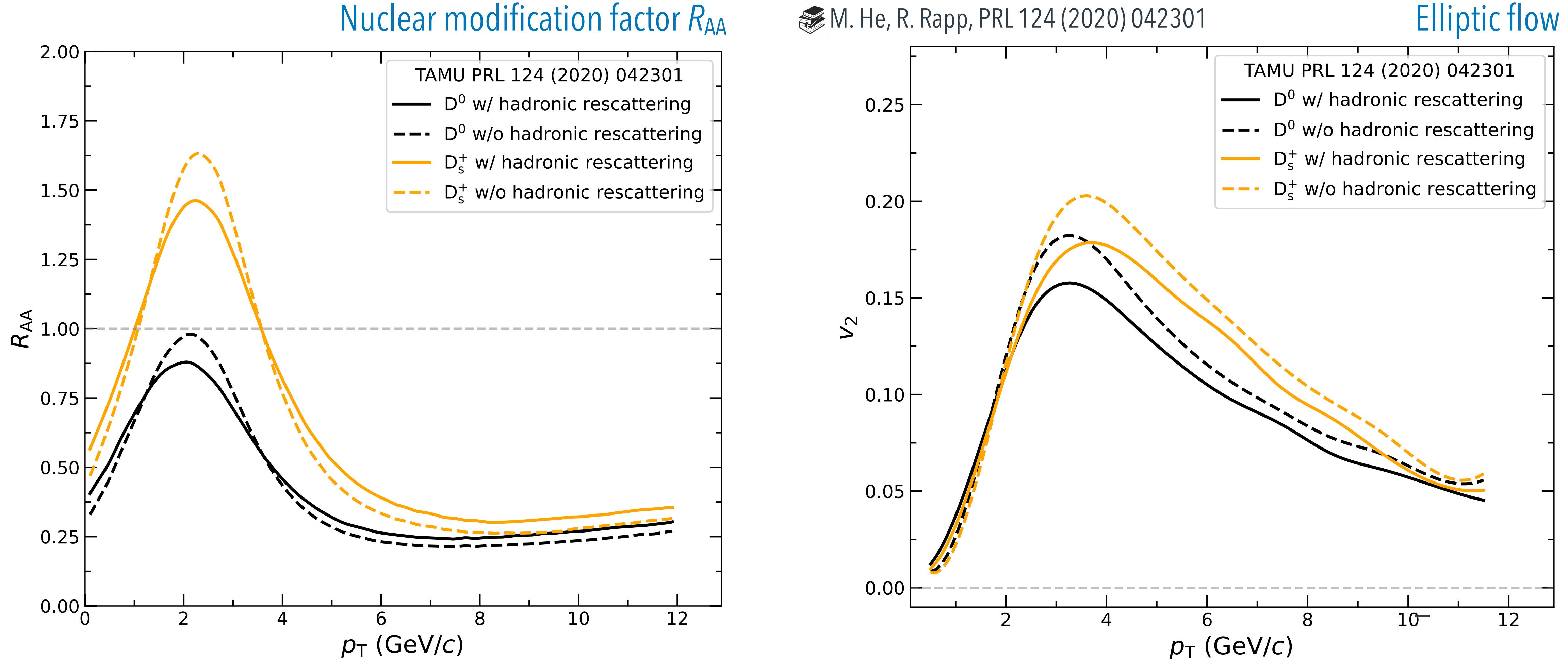
# Charm hadrons in the hadronic phase

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$\frac{70}{45}$



- After the hadronisation, charm quarks hadrons might still interact with the light hadrons produced  
→ How much does the hadronic phase influence the heavy-ion observables?



- In the TAMU model the scattering lengths used for  $\pi D$  and  $K D$  are:

→  $a_{\pi D}(l=3/2) = -0.10$  fm      M. He et al, PLB 701 (2011) 445–450

→  $a_{KD}(l=1) = -0.22$  fm

→ No experimental constraints!

# The study of the residual strong interactions

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$\frac{72}{45}$

- Femtoscopy technique: based on the correlation function (CF)

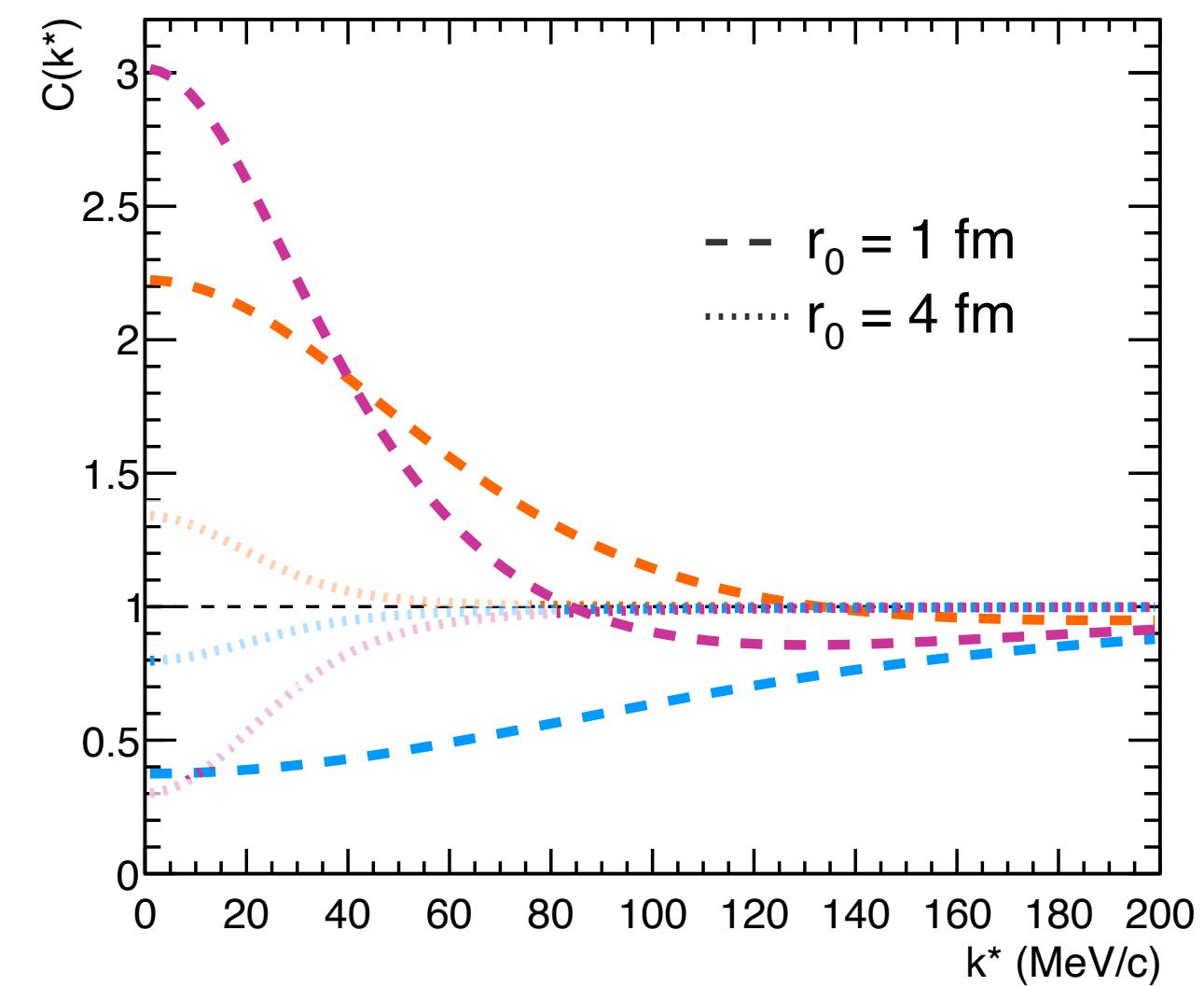
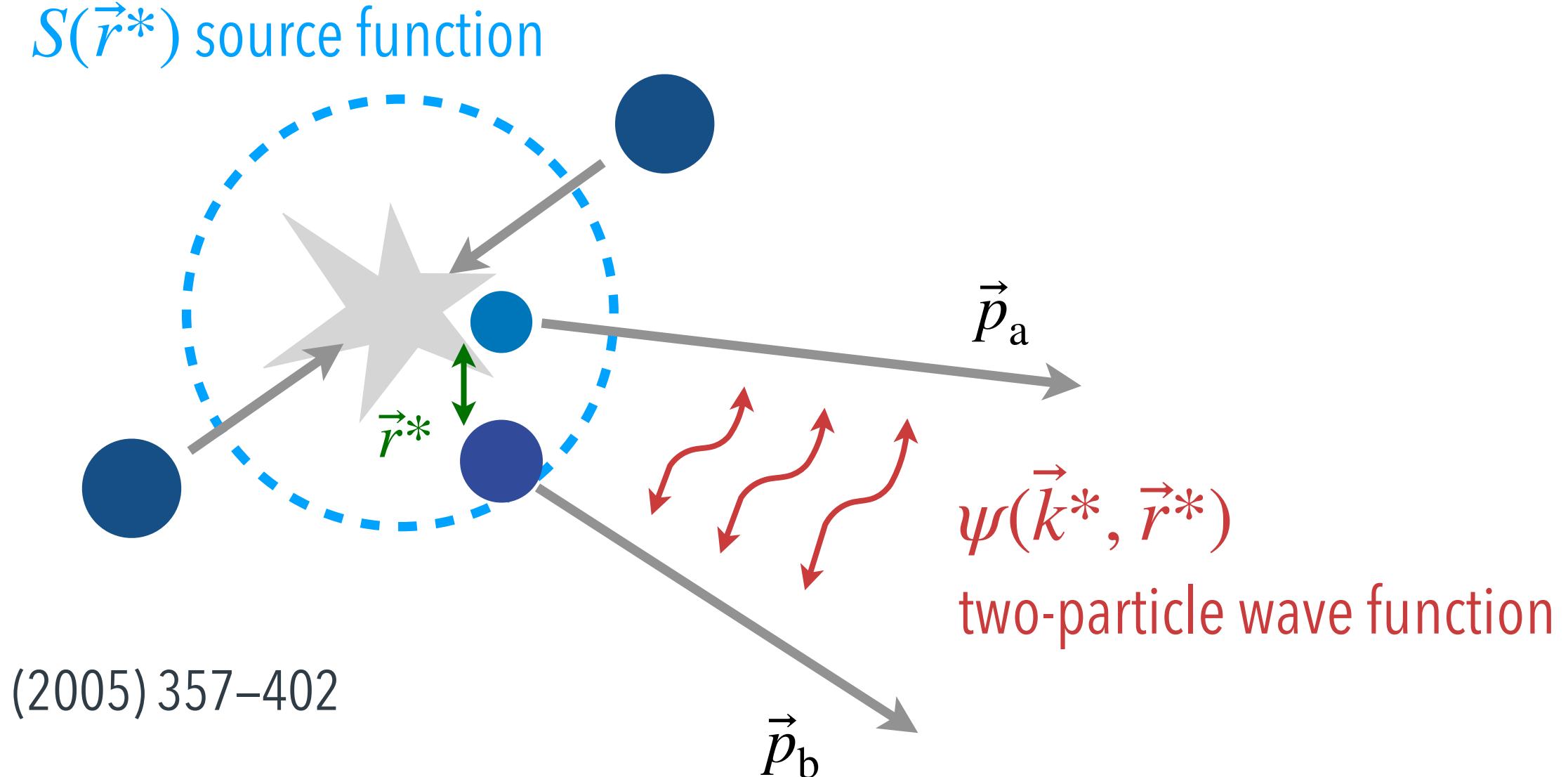
<b>Experiment</b>	<b>Theory</b>
$C(k^*) = \mathcal{N} \frac{N_{\text{pairs}}(\vec{k}^*)}{N_{\text{mixed}}(\vec{k}^*)}$	$\int S(\vec{r}^*)  \psi(\vec{k}^*, \vec{r}^*) ^2 d^3 r^*$

Koonin-Pratt equation

Book M. Lisa, S. Pratt et al, Ann. Rev. Nucl. Part. Sci. 55 (2005) 357–402

where  $\vec{k}^* = \frac{\vec{p}_a^* - \vec{p}_b^*}{2}$  is in the rest frame of the particle pair

- Relative wave function sensitive to interaction potential
- Emitting source: hypersurface at kinematic freeze out of final-state particles
- $C(k^*)$  most sensitive to strong interaction when the source size  $\sim 1$  fm



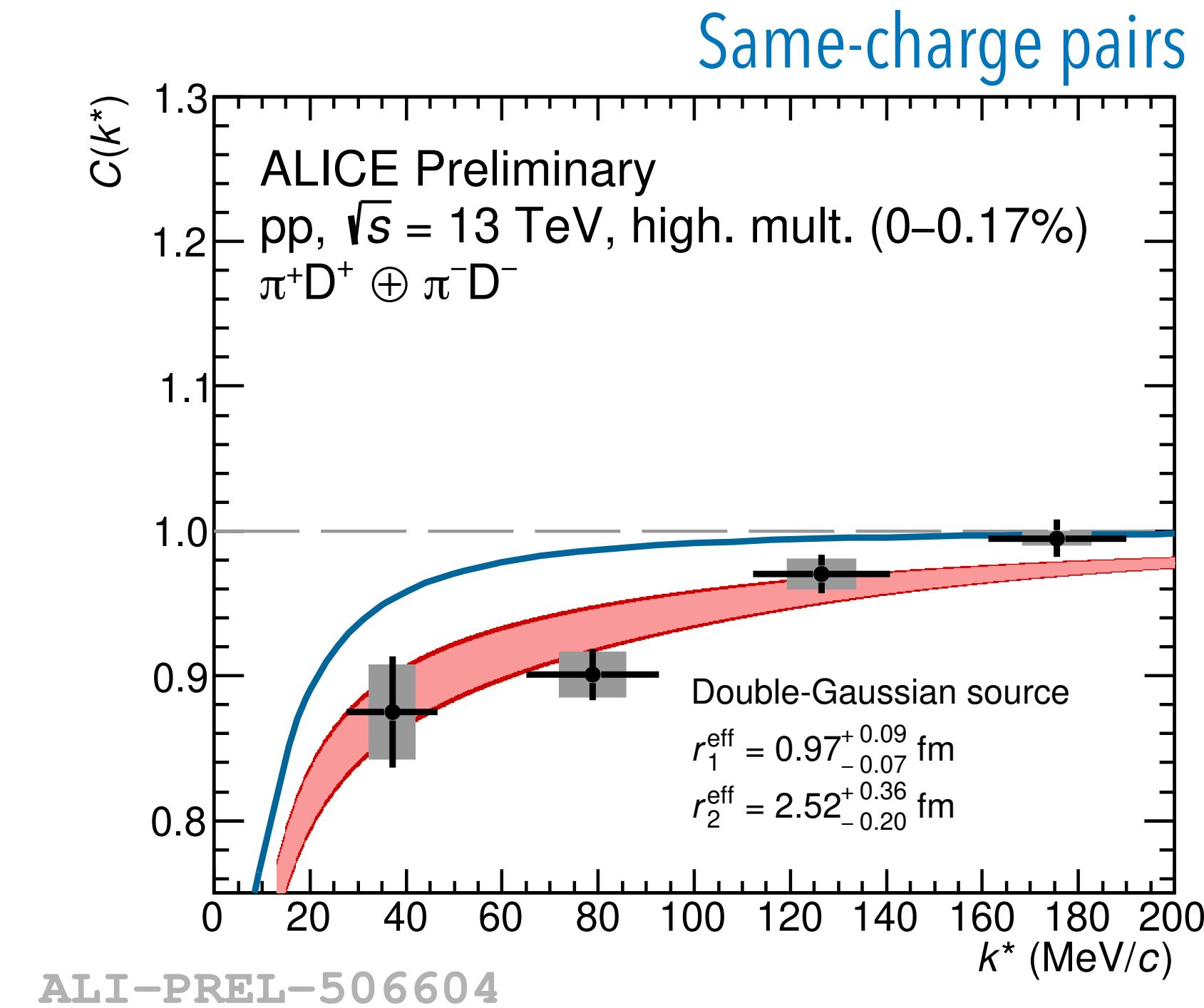
Absence of interaction  $C(k^*) = 1$   
 Attractive potential  $C(k^*) > 1$   
 Repulsive potential  $C(k^*) < 1$   
 Bound-state formation  $C(k^*) <> 1$



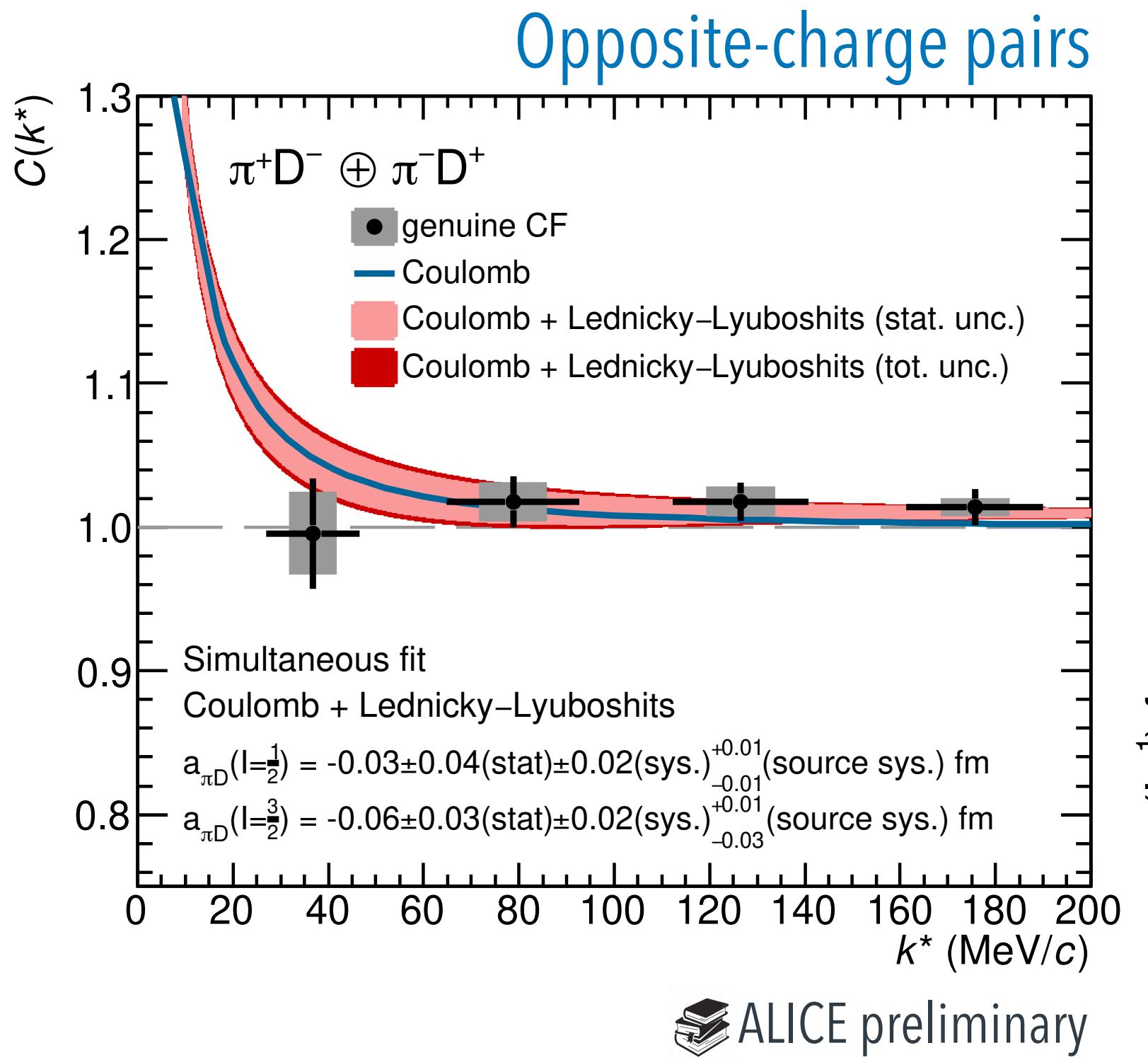
# $\pi D$ interaction: fit with Lednický-Lyuboshits formula

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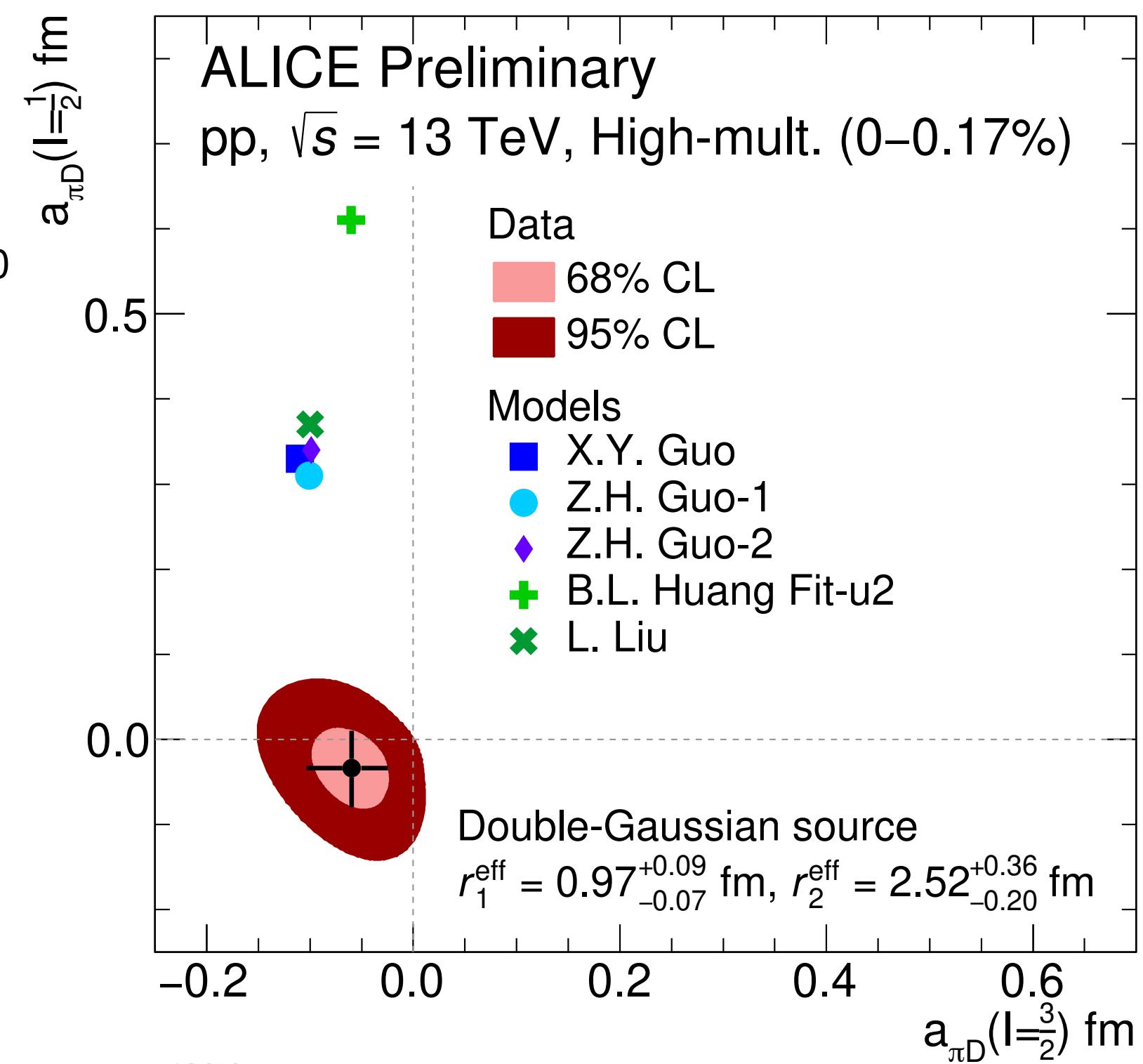
73  
45



- Scattering length for  $|l|=3/2$  in agreement with models
- Scattering length for  $|l|=1/2$  significantly smaller than models
- The values found indicate a **small rescattering of D mesons in the hadronic phase of heavy-ion collisions**

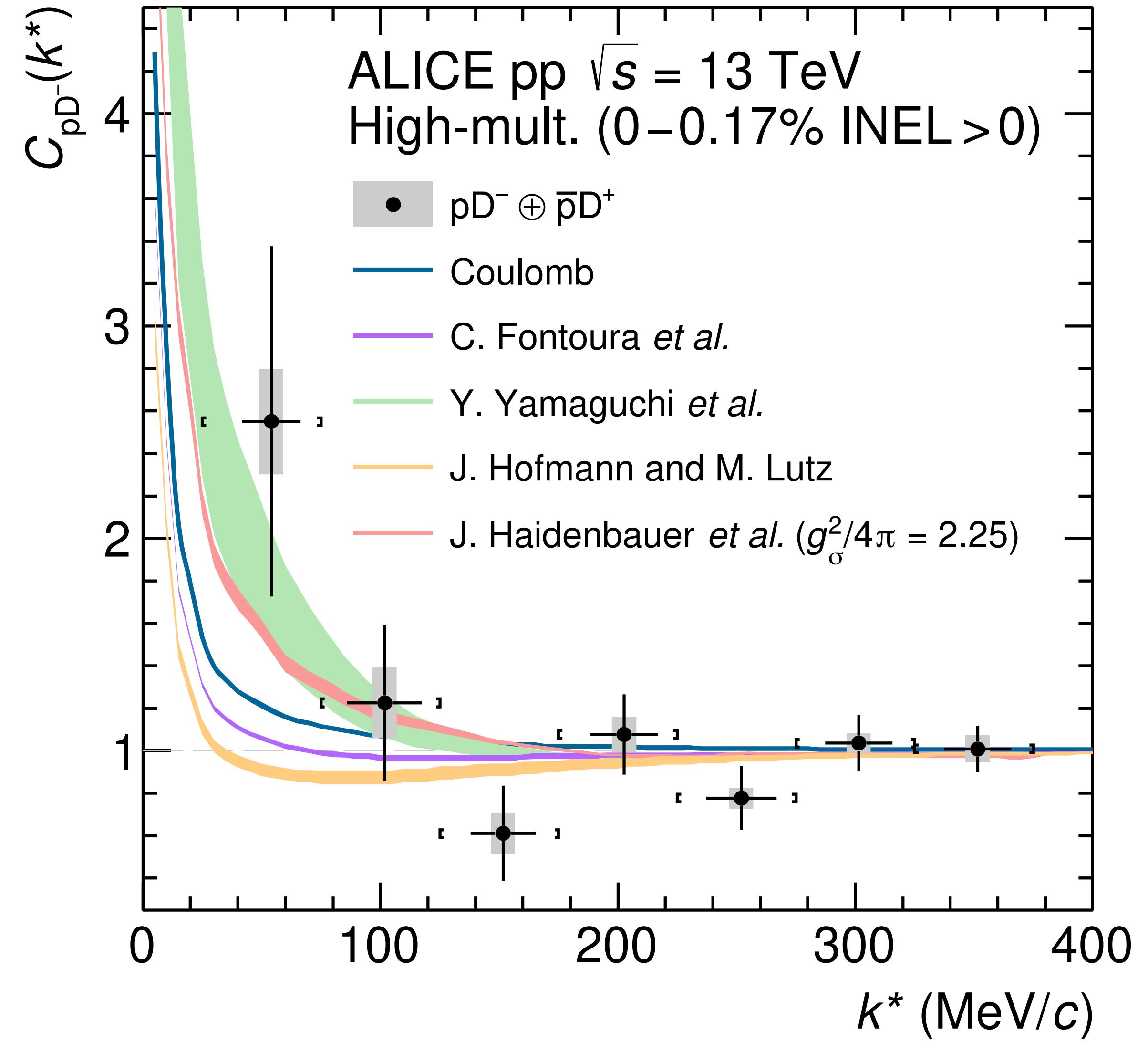


ALICE preliminary



ALI-PREL-513658

- pD<sup>-</sup>
  - Typically very small compared to other interactions (light-light  $\sim 7\text{-}8$  fm, light-strange  $\sim 1.5$  fm)
  - Most of the models predict repulsive interaction
  - Possible bound state formation (Yamaguchi et al)
- Data compatible with Coulomb only interaction, but comparison slightly improves when also **attractive strong interaction** is considered



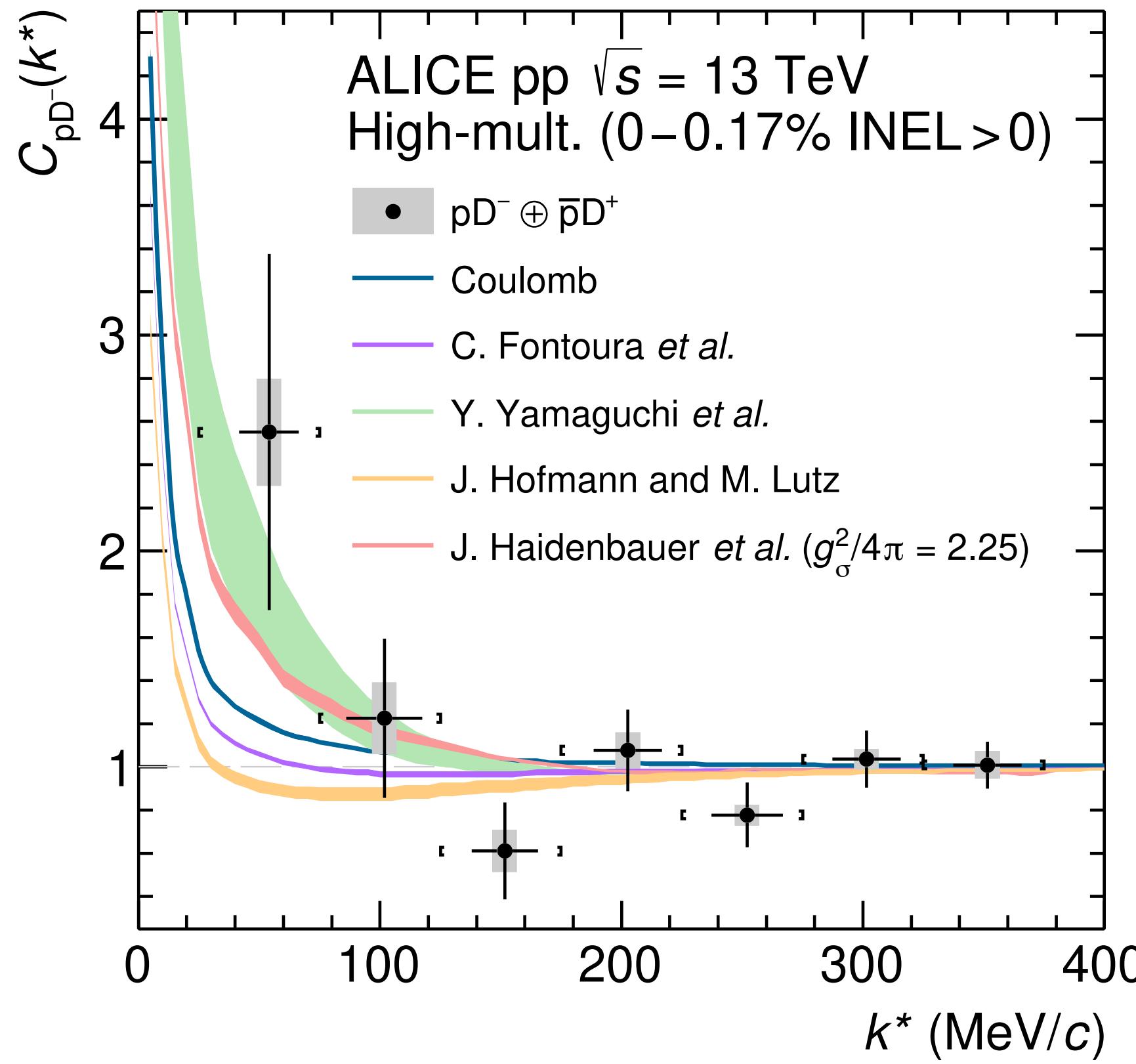
J. Haidenbauer et al, Eur. Phys. J. A34 (2007) 107–117

J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90–139

C. Fontoura et al, Phys. Rev. C 87 (2013) 025206

Yamaguchi et al, Phys. Rev. D84 (2011) 014032

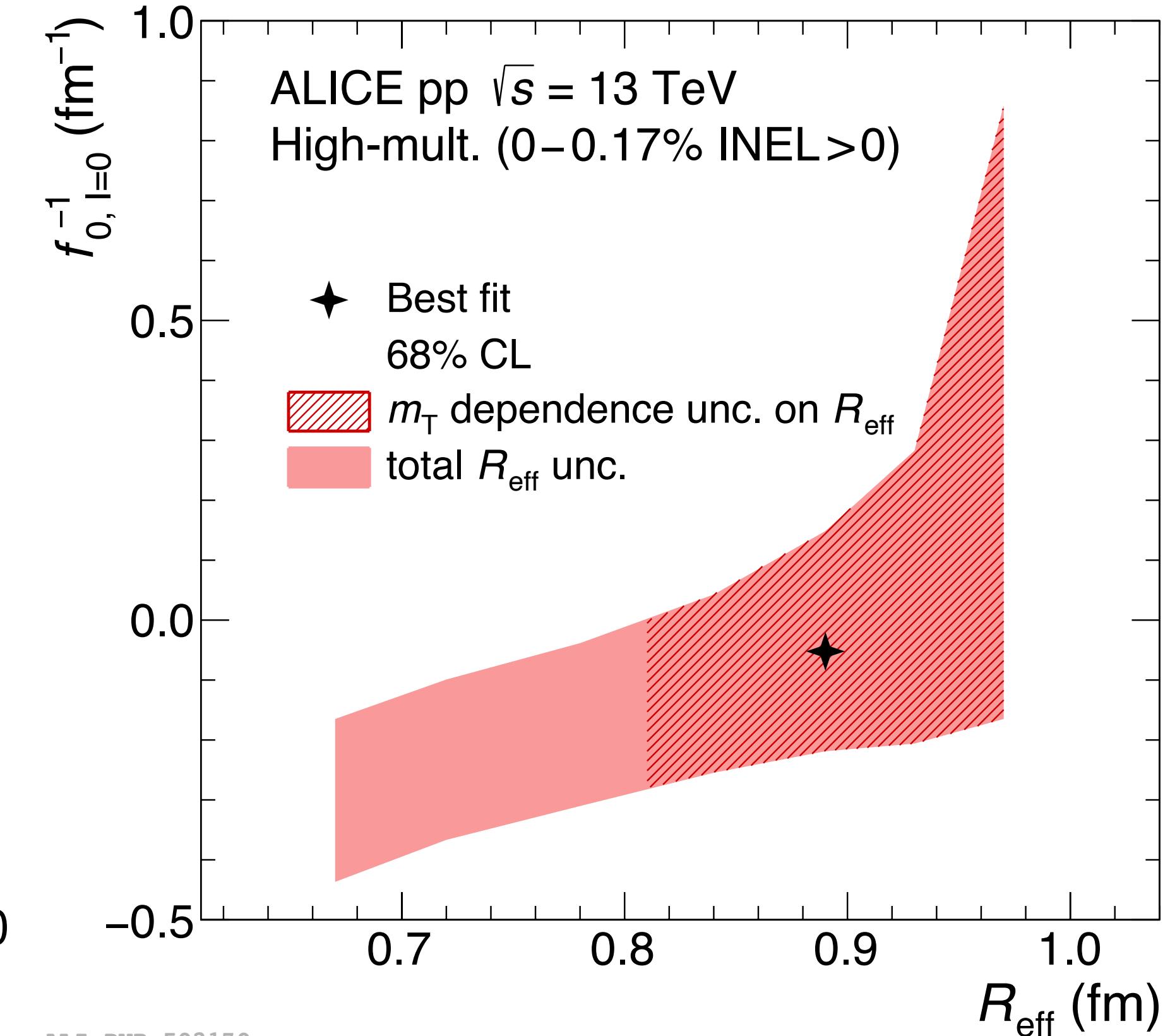
- Small compared to other interactions (scattering lengths light-light  $\sim 7\text{-}8 \text{ fm}$ , light-strange  $\sim 1.5 \text{ fm}$ )
- Most of the models predict repulsive interaction
- Possible bound state formation (Yamaguchi et al)



ALI-PUB-502166

J. Haidenbauer et al, EPJA 34 (2007) 107–117

J. Hofmann and M. Lutz, NPA 763 (2005) 90–139



ALI-PUB-502170

Fontura et al, PRC 87 (2013) 025206

Yamaguchi et al, PRD 84 (2011) 014032

ALICE, PRD 106 (2022) 052010

- Interval of scattering length for isospin  $I=0$  at 68% CL indicates either **attractive interaction** with or without the formation of a bound state

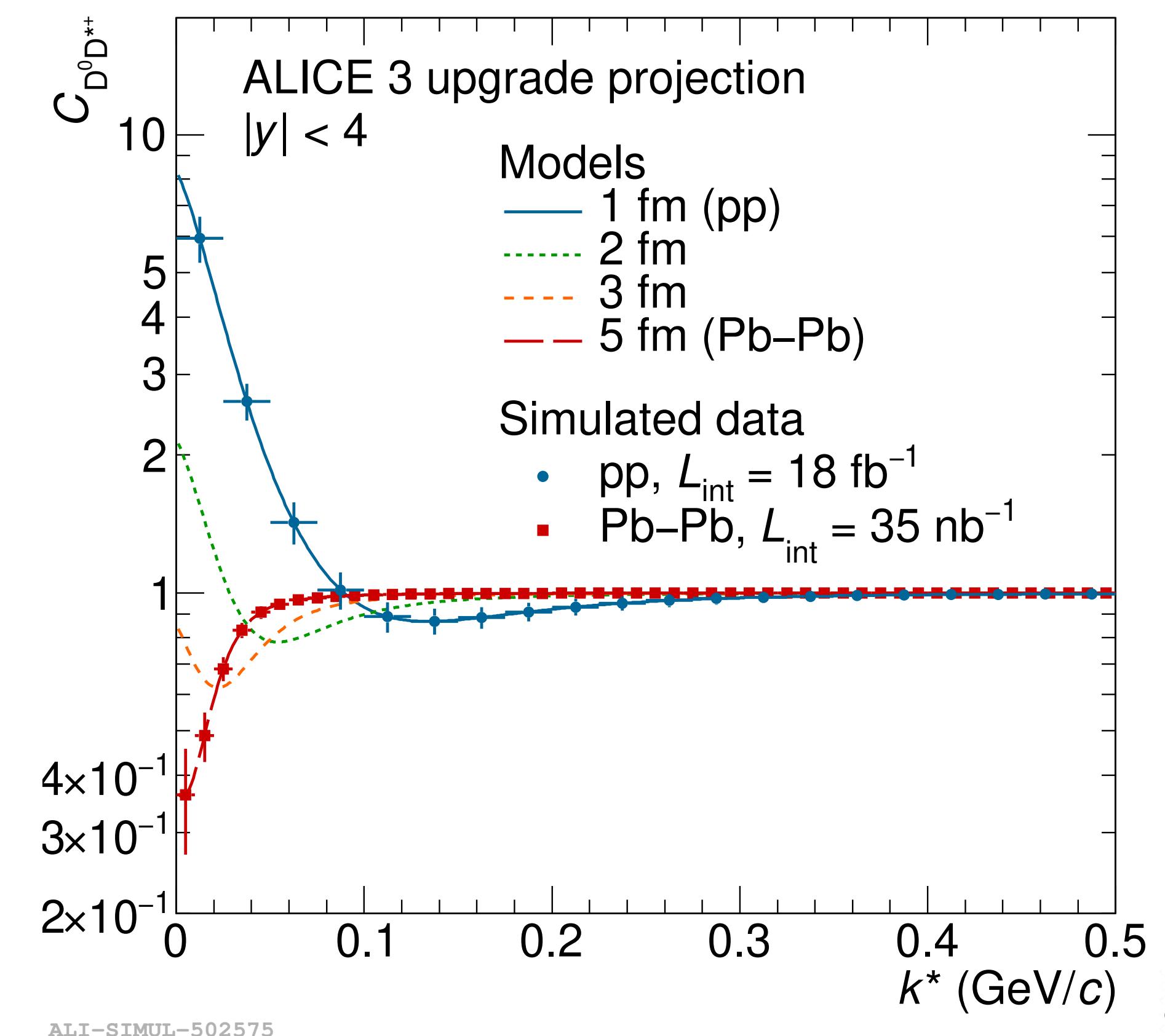
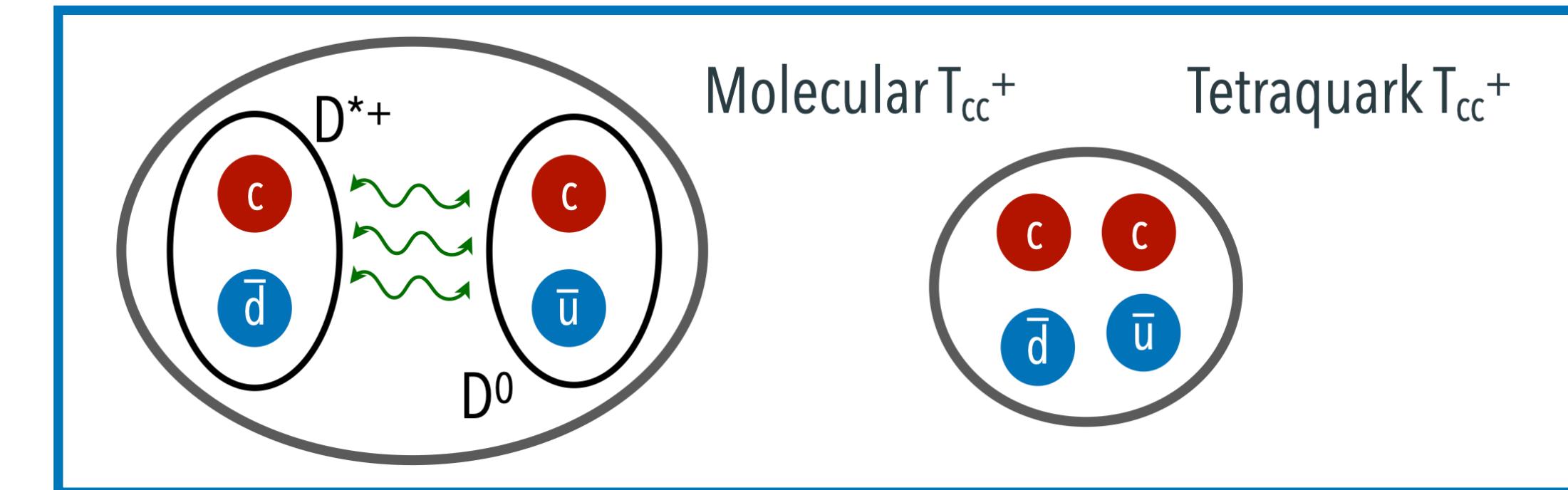
# Charm-charm hadron interaction: hadronic physics

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$\frac{76}{45}$

- Charm molecules?

System	I ( $J^P(C)$ )	Candidate
np	0 ( $1^+$ )	deuteron
ND	0 ( $1/2^-$ )	$\Lambda_c(2765)$
ND*	0 ( $3/2^-$ )	$\Lambda_c(2940)$
ND	0 ( $1/2^-$ )	$\Sigma_c(2800)$
$D^*\bar{D}$	0 ( $1^{++}$ )	$X(3872)$
$D^*D$	0 ( $1^+$ )	$T_{cc}$
$D_1\bar{D}$	0 ( $1^{--}$ )	$\Upsilon(4260)$
$D_1\bar{D}^*$	0 ( $1^{--}$ )	$\Upsilon(4360)$
$\Sigma\bar{D}$	1/2 ( $1/2^-$ )	$P_c(4312)$
$\Sigma\bar{D}^*$	1/2 ( $1/2^-$ )	$P_c(4457)$
$\Sigma\bar{D}^*$	1/2 ( $3/2^-$ )	$P_c(4440)$



- Interplay between system size and scattering length
  - Size-dependent modification of  $C(k^*)$  in presence of a molecular state