Recent heavy-flavour highlights from ALICE

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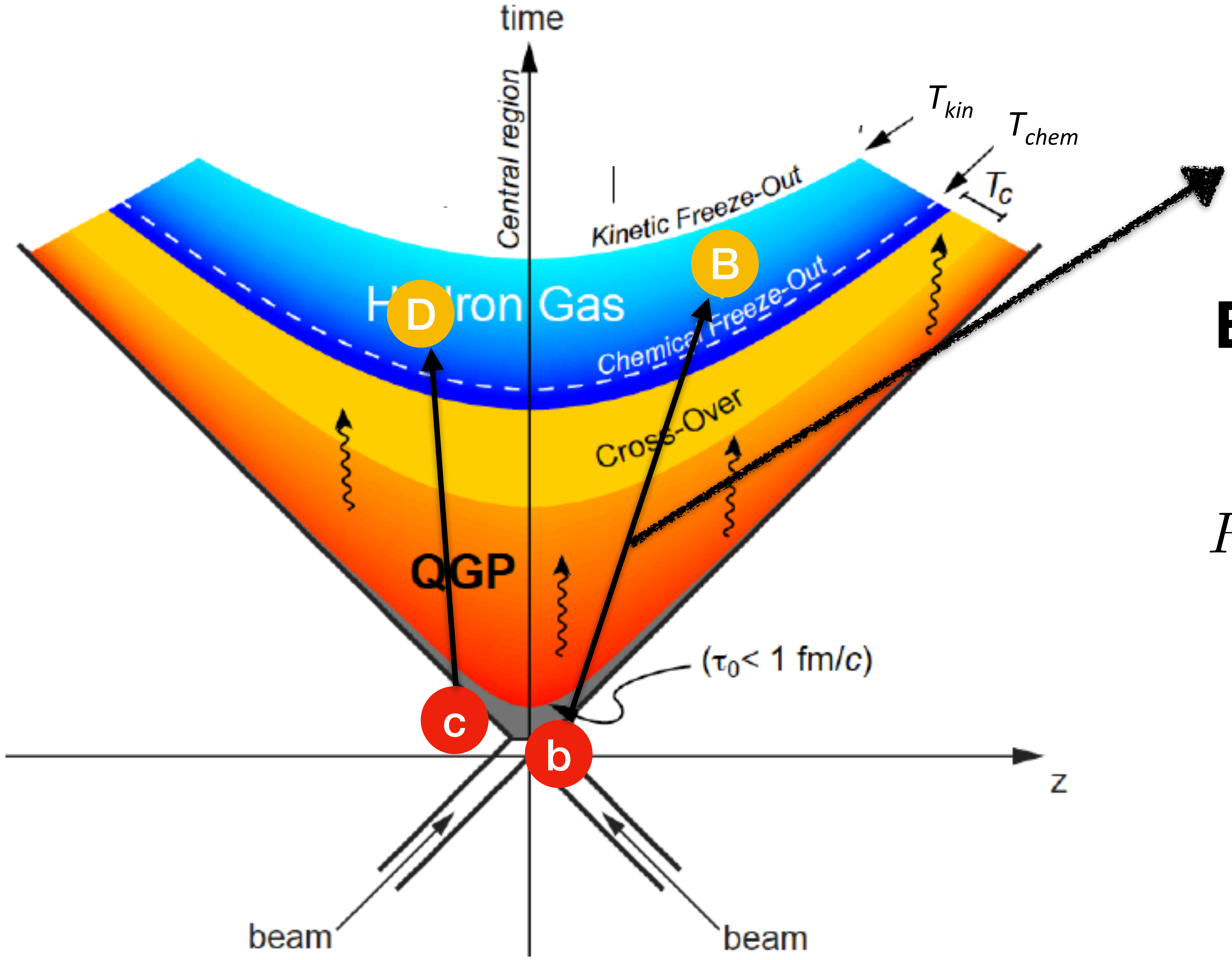
Central China Normal University

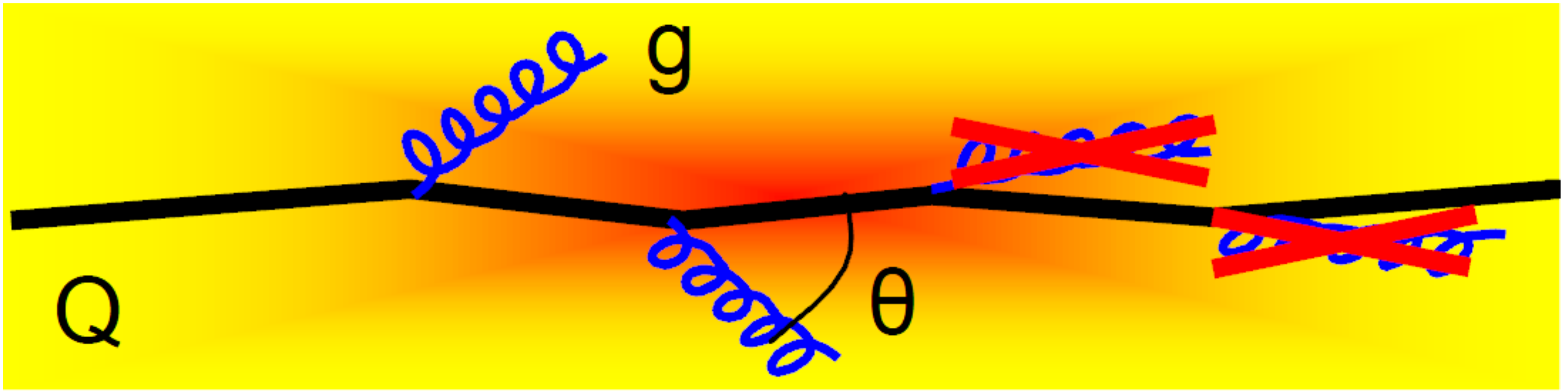
22nd conference on flavour physics and CP violation

27–31 May 2024, Bangkok, Thailand

Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of heavy-ion collisions before the QGP creation





Energy loss in QGP medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

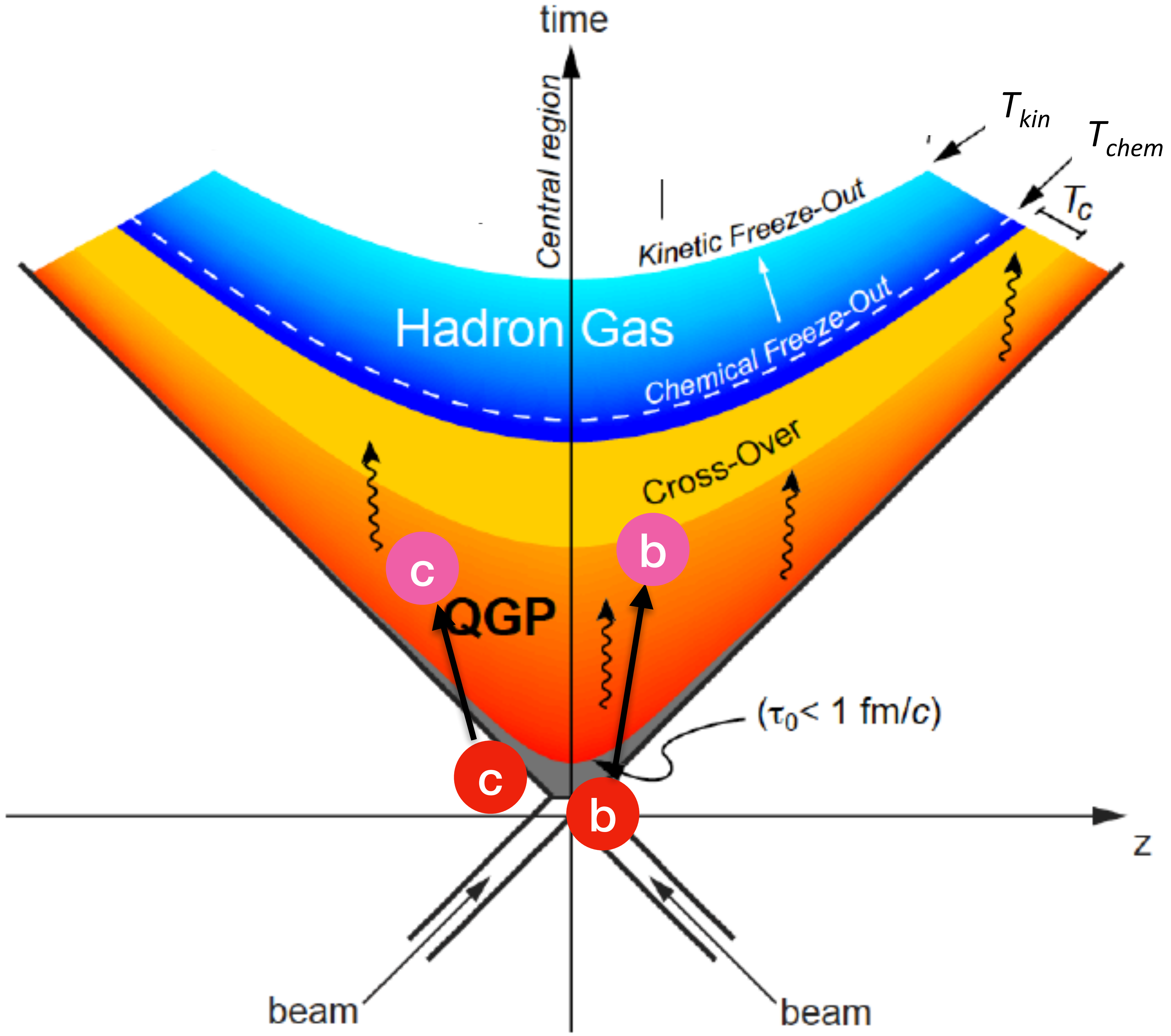
QCD medium

QCD vacuum

- R_{AA} = 1 if no medium effect and/or initial state effects
- Radiative vs. collisional energy loss

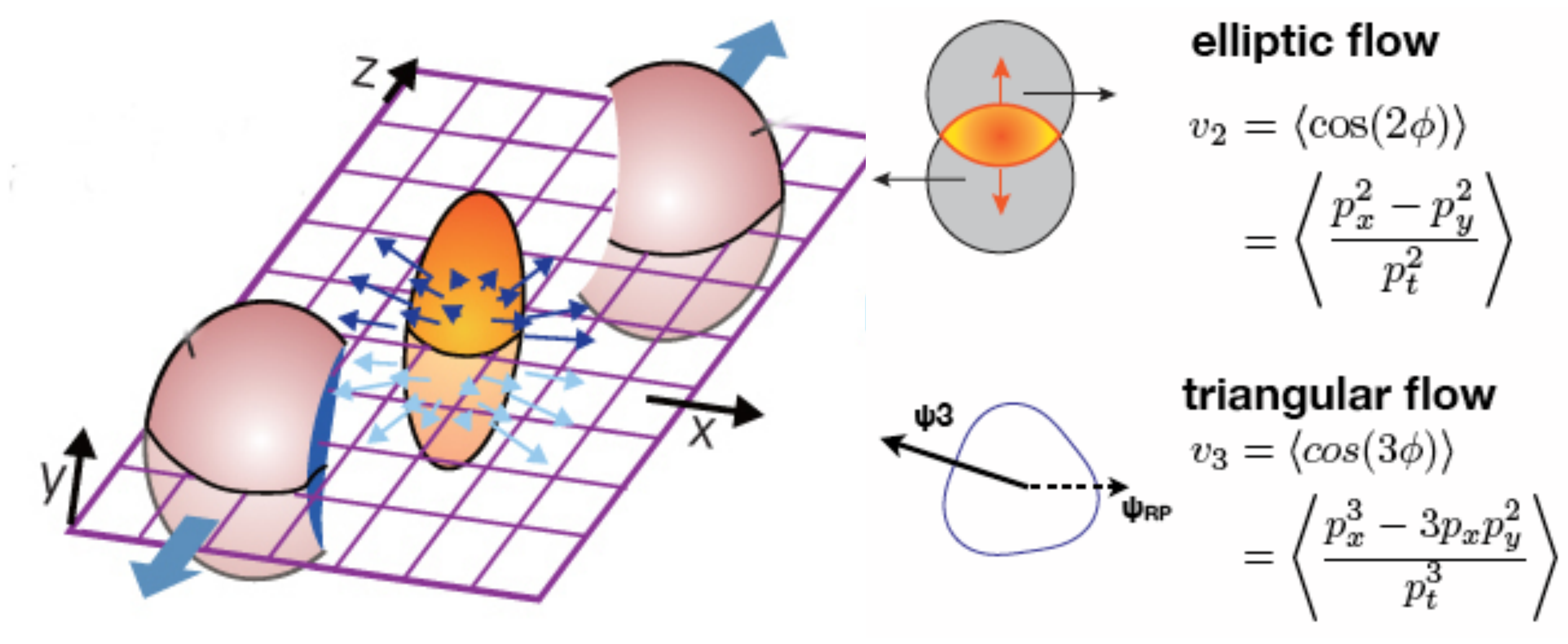
Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of heavy-ion collisions before the QGP creation



Collective expansion

➡ Anisotropic flow



➡ Results in complex azimuthal structure of final-state particles

Heavy quarks in small systems

$$\frac{d\sigma^{H_Q}}{dp_T}(\mu_F, \mu_R) = \boxed{\mathrm{PDF}(x_1, \mu_F)\mathrm{PDF}(x_2, \mu_F)} \otimes \boxed{\frac{d\sigma^{Q}}{dp_T}(x_1, x_2, \mu_F, \mu_R)} \otimes \boxed{D_{Q\to H_Q}(z = p_{H_Q}/p_Q, \mu_F)}$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

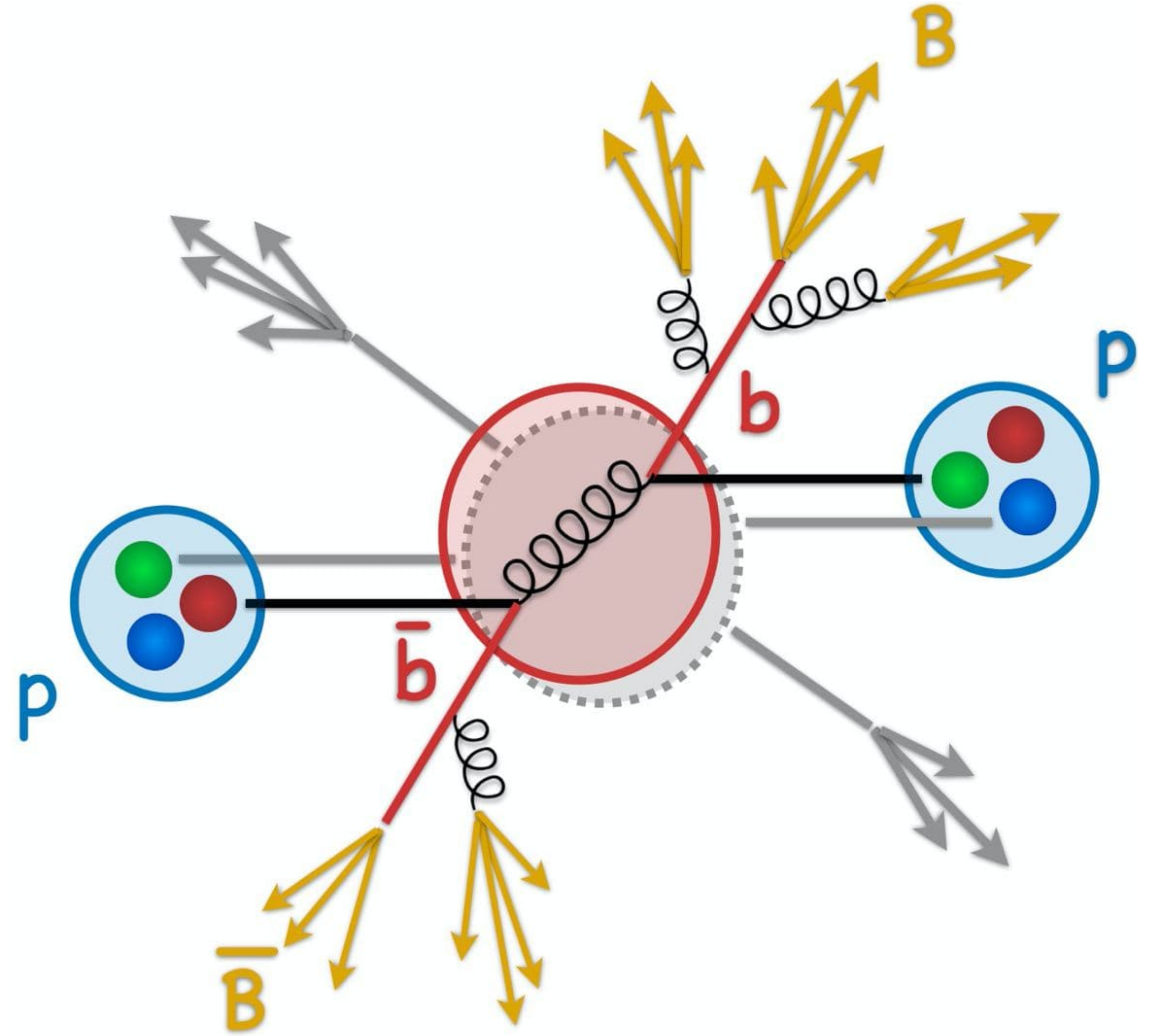
Fragmentation function (hadronization)

pp collisions

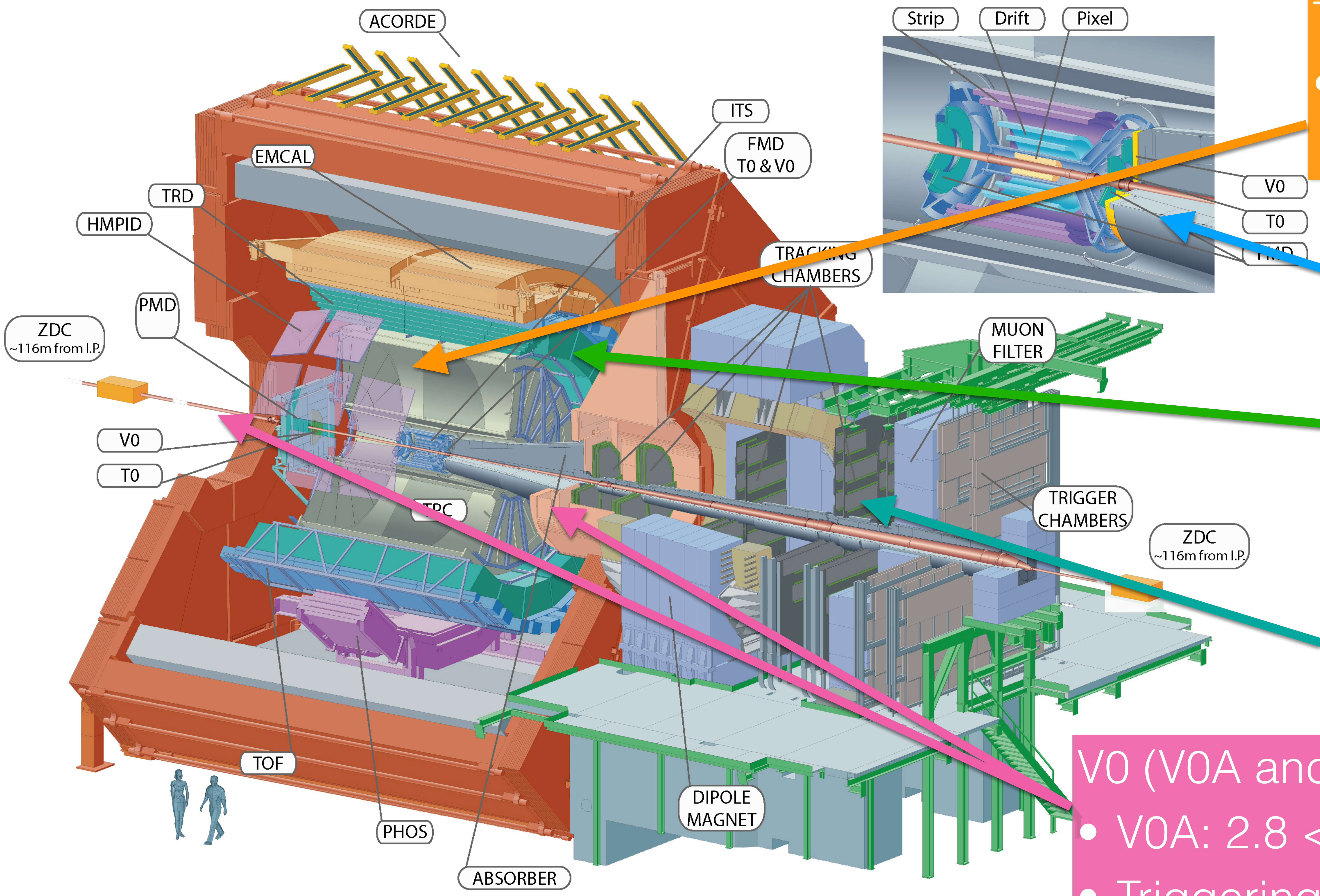
- Reference for pA and AA collisions
- Test pQCD factorization theorem
  ➡ Assume universal fragmentation and constrained from e⁻e⁺/ep collisions

p–Pb collisions

- Inspect cold nuclear matter (CNM) effects
- Collectivity at high-multiplicity (?)



ALICE apparatus (till Run2)



Time Projection Chamber (TPC)

- $|\eta| < 0.9$, charged-particle tracking and identification (PID)

Inner Tracking System (ITS)

- $|\eta| < 0.9$, vertexing

Time of Flight (TOF)

- $|\eta| < 0.9$, triggering, pileup rejection, PID

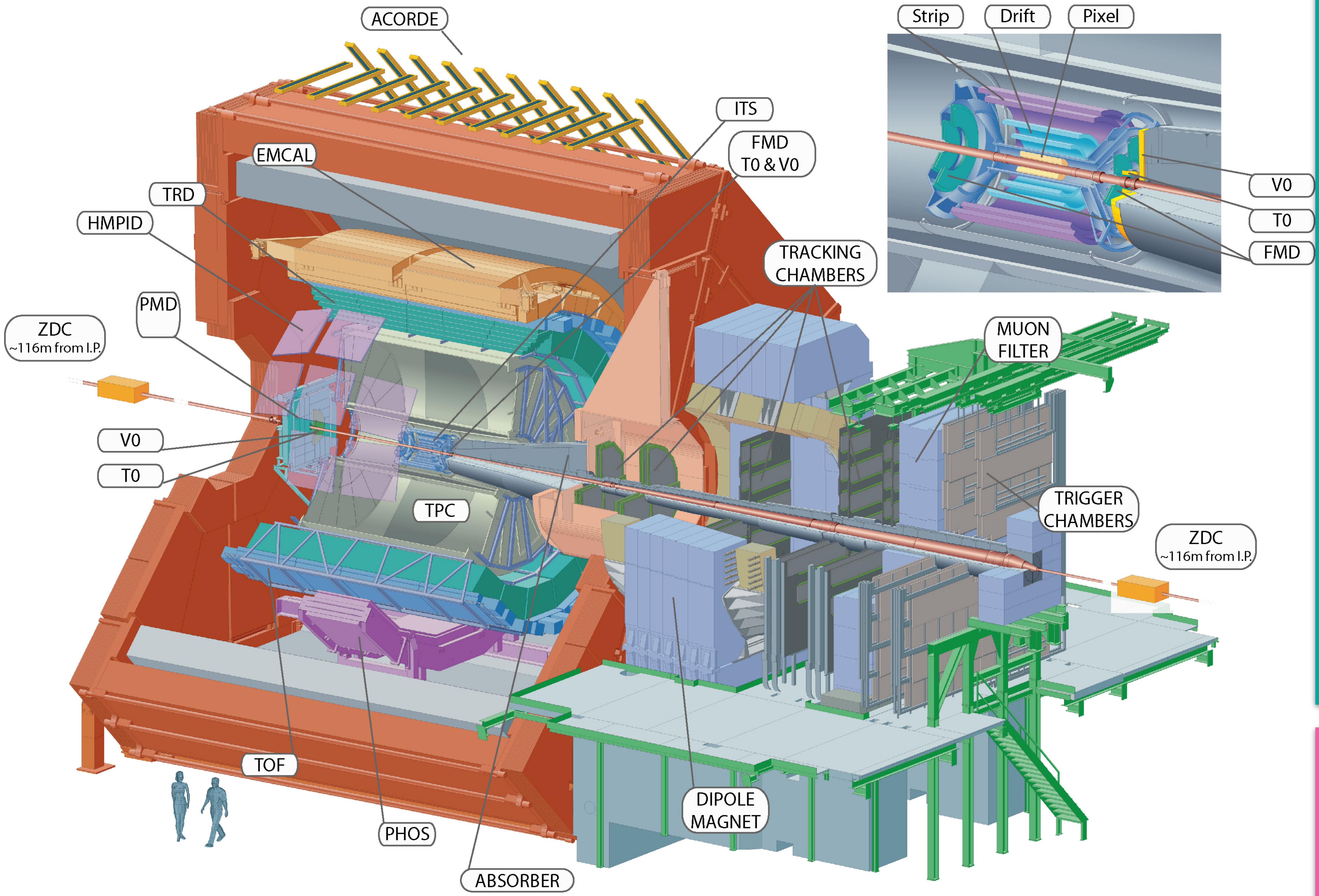
Muon spectrometer

- $2.5 < |\eta| < 4$, $\mu \leftarrow c,b$, $\mu \leftarrow W^{\pm}/Z^{0}$

V0 (V0A and V0C)

- V0A: $2.8 < \eta < 5.1$, V0C: $-3.7 < \eta < -1.7$
- Triggering and multiplicity determination

ALICE heavy-flavour programme



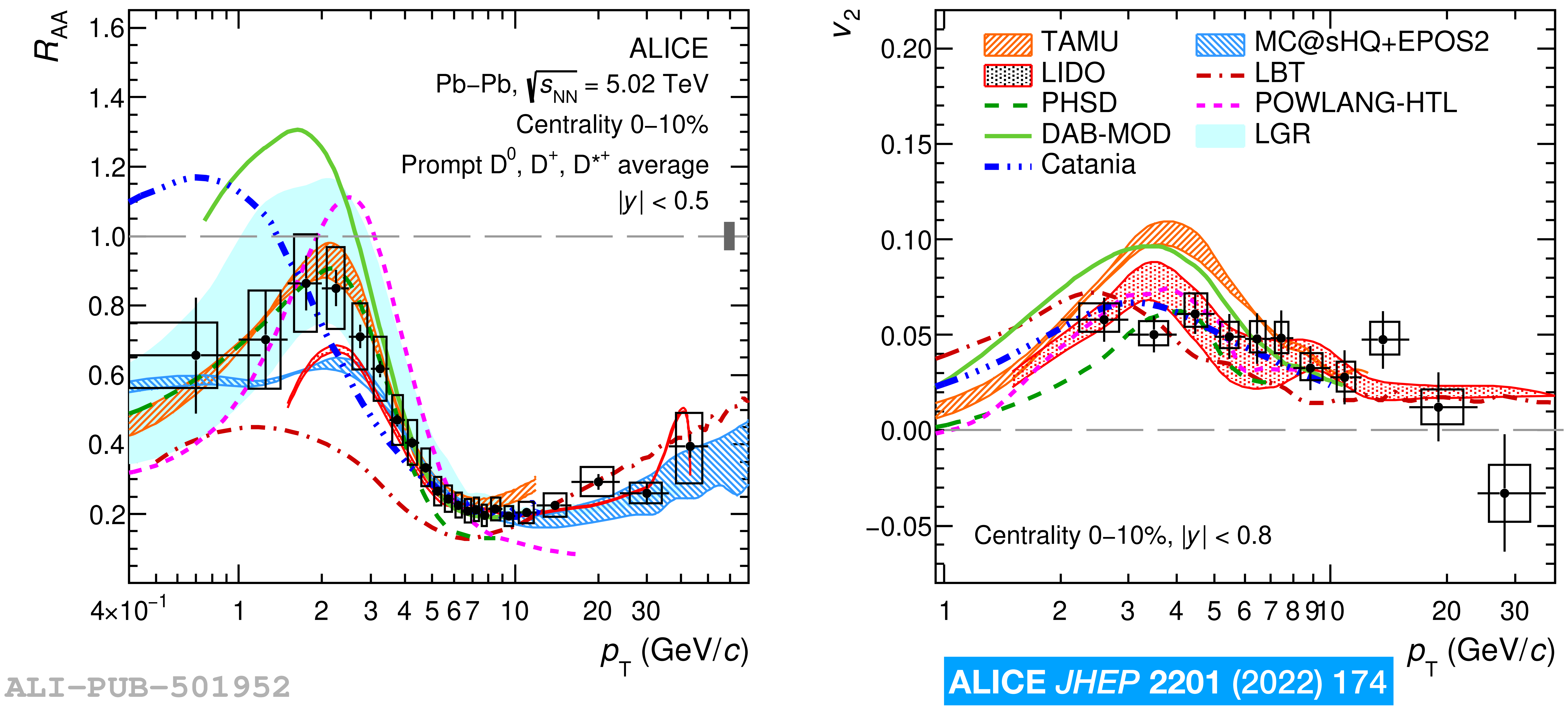
Hadronic decays ($|y| < 0.8$)

- $D^0 \rightarrow K^-\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$, $K^+K^-\pi^+$
- $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- $D_{s1}^+ \rightarrow D^{*+}K_S^0$
- $D_{s2}^{*+} \rightarrow D^+K_S^0$
- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$
- $\Lambda_c^+ \rightarrow pK^-\pi^+$, pK_S^0
- $\Sigma_c^{0,++}(2520), \Sigma_c^{0,++}(2544) \rightarrow \Lambda_c^+\pi^\mp$
- $\Xi_c^{0(+)} \rightarrow \Xi^-\pi^+(\pi^+)$, $\Xi^-e\nu_e$
- $\Omega_c^0 \rightarrow \Omega^-\pi^+$, $\Omega^-e^+\nu_e$

Semi-leptonic decays

- $c, b \rightarrow e^\pm$ ($|y| < 0.8$ or 0.6)
- $c, b \rightarrow \mu^\pm$ ($2.5 < y < 4$)

Charm-quark transport



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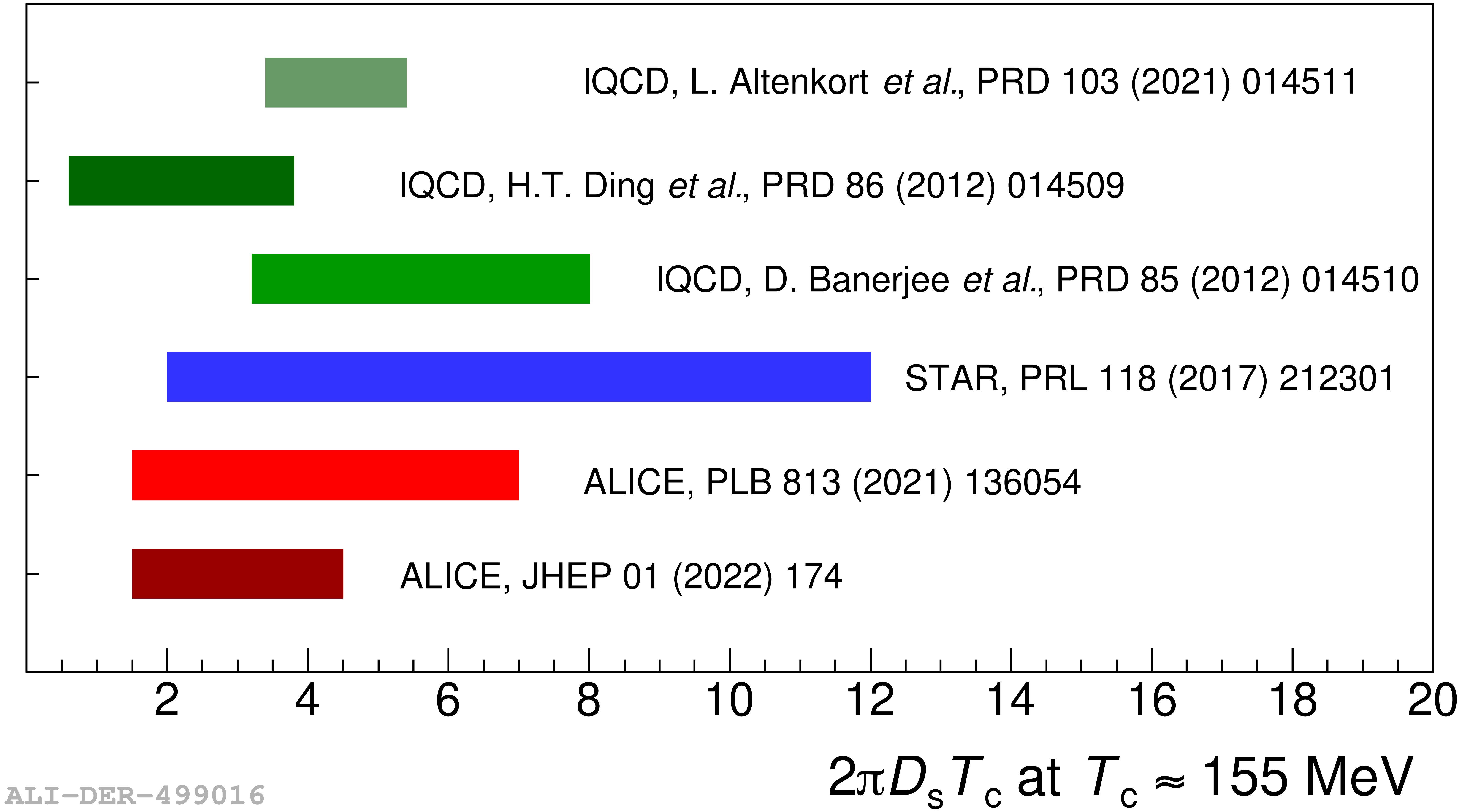
- Strong suppression and significant v_2 at intermediate p_T

  ➡ Hint that charm participates to the medium collective motion

- Most charm quark transport models able to describe both the R_{AA} and v_2

Charm-quark transport



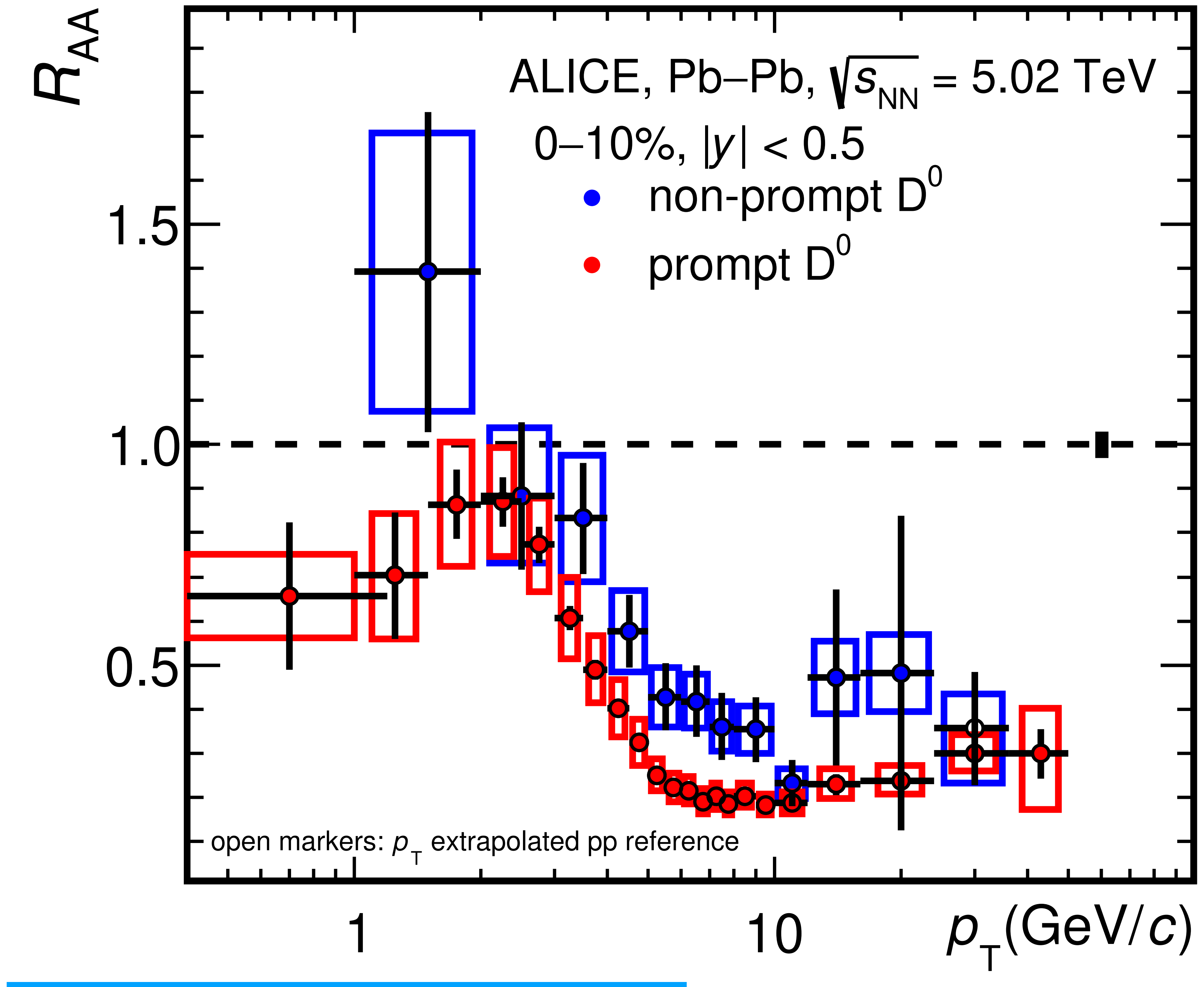
Diffusion coefficient D_s

- Almost independent of quark mass
- Characterization of the transport properties of the medium
- Constrains the specific shear viscosity η/s

Newest constraints from ALICE by combining D meson R_{AA} and v_2

- $1.5 < 2\pi D_s(T) < 4.5$, $\tau_{charm} = (m_{charm} / T)\, D_s(T) = 3–9$ fm/c $< \tau_{medium} \approx 10$ fm/c
- Indicate charm may thermalize in the medium

Beauty-quark energy loss



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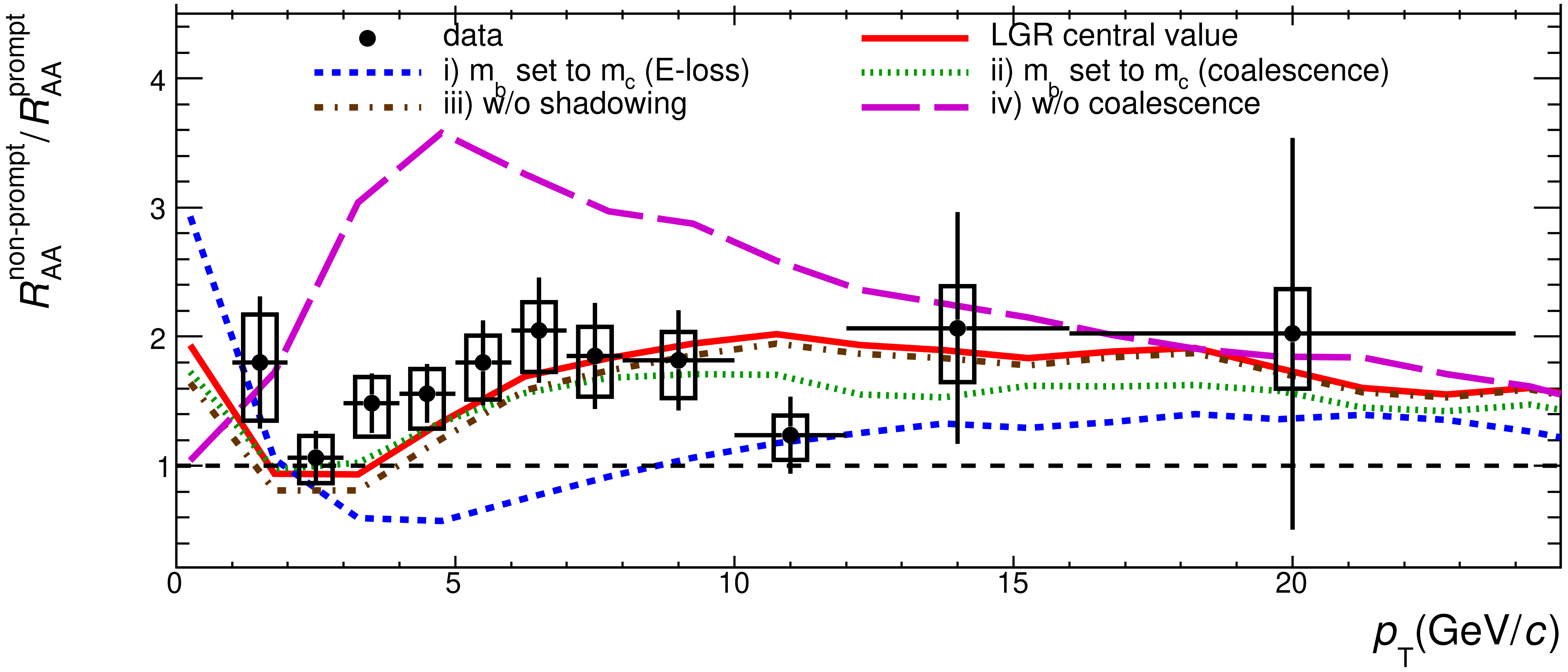

- Mass effects are important to describe data
- Coalescence plays a relevant role at intermediate p_T

Non-prompt D mesons are less suppressed than prompt D mesons

$$R_{AA}(\text{beauty}) > R_{AA}(\text{charm}) \Rightarrow \Delta E_{beauty} < \Delta E_{charm}$$

Beauty-quark elliptic flow

- $v_2(b \rightarrow D^0) > 0$

2.7σ significant effect

No strong p_T dependence

- $v_2(b \rightarrow D^0) < v_2(D)$

3.2σ significant effect

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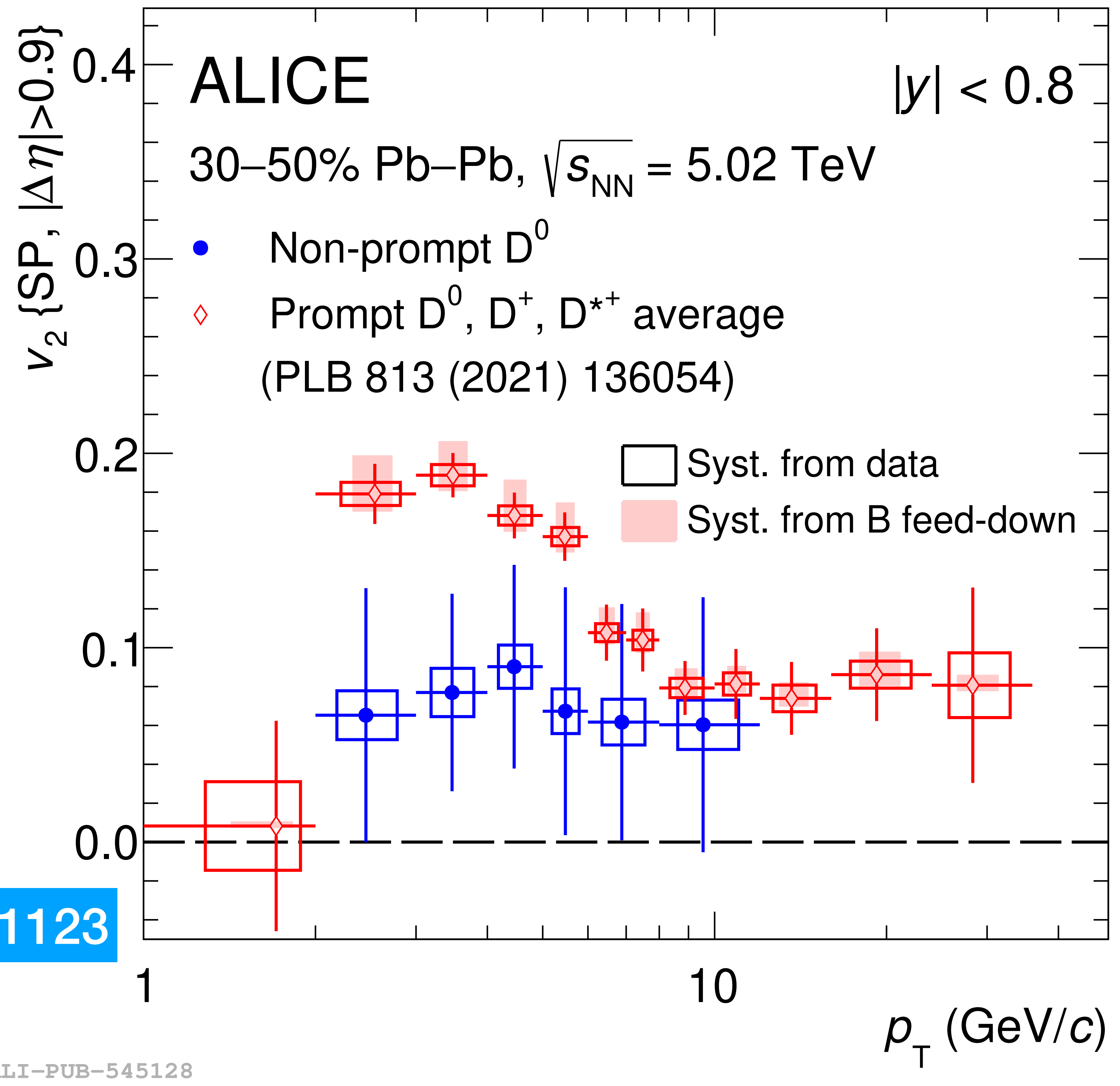
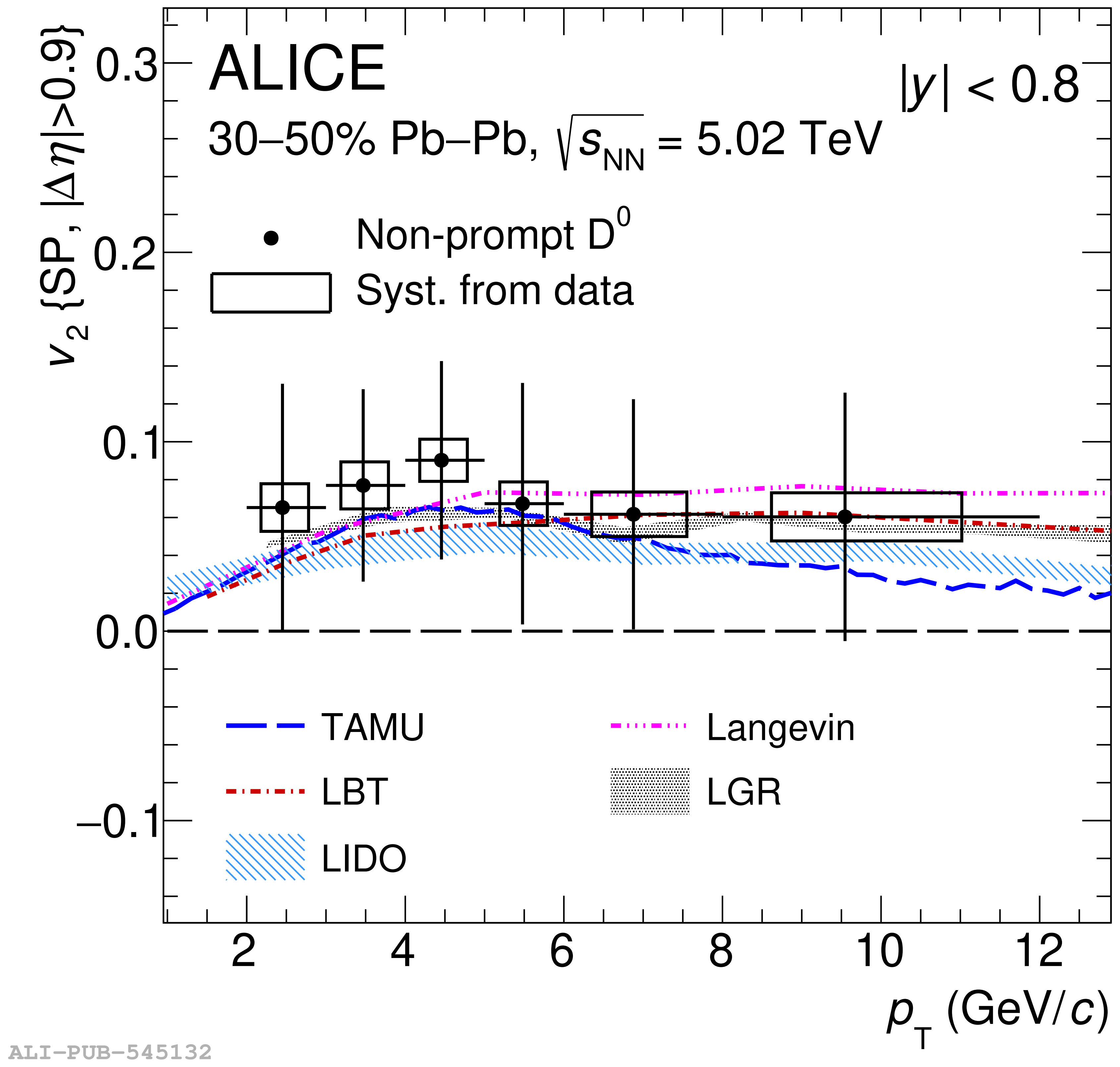
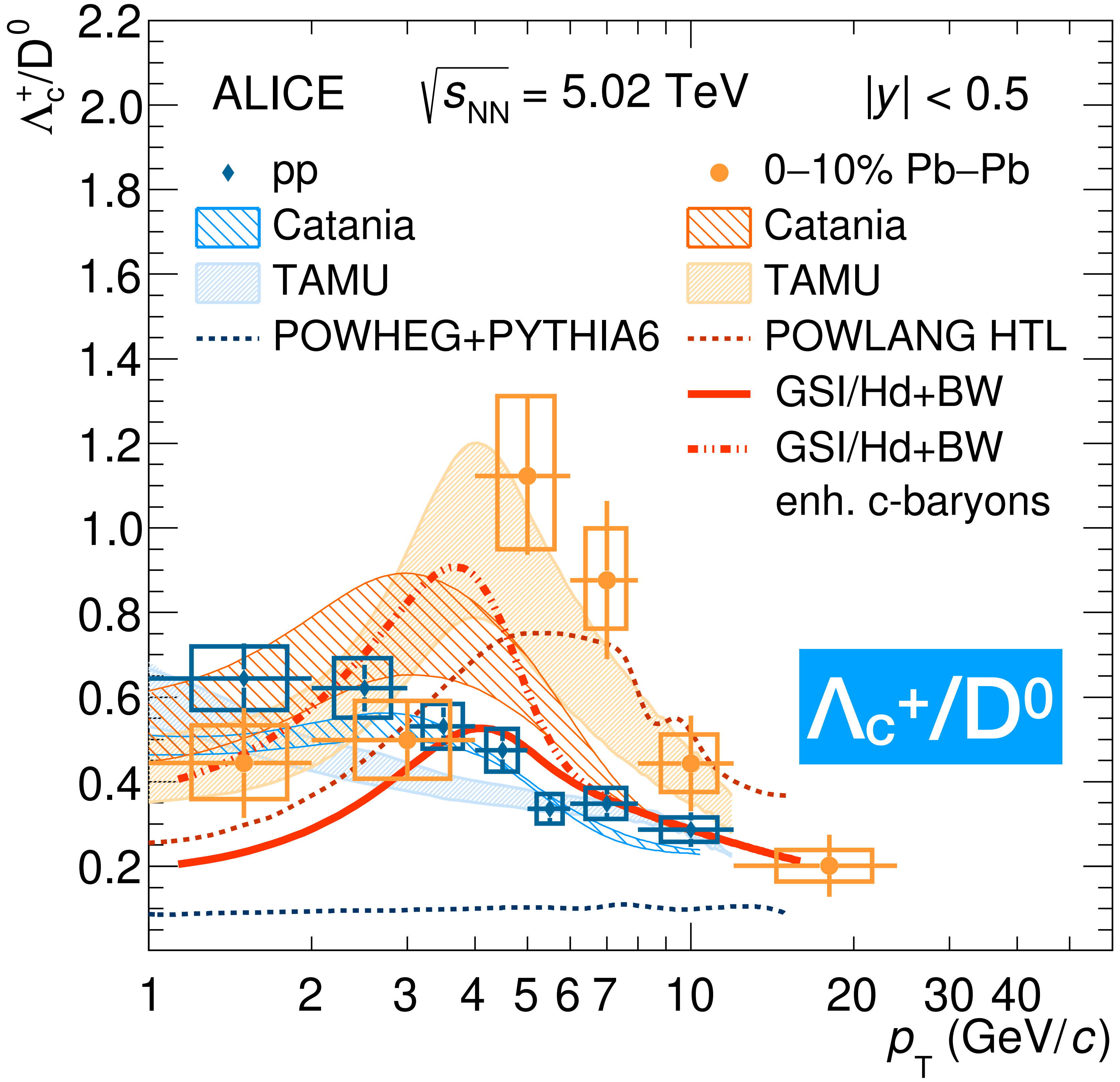
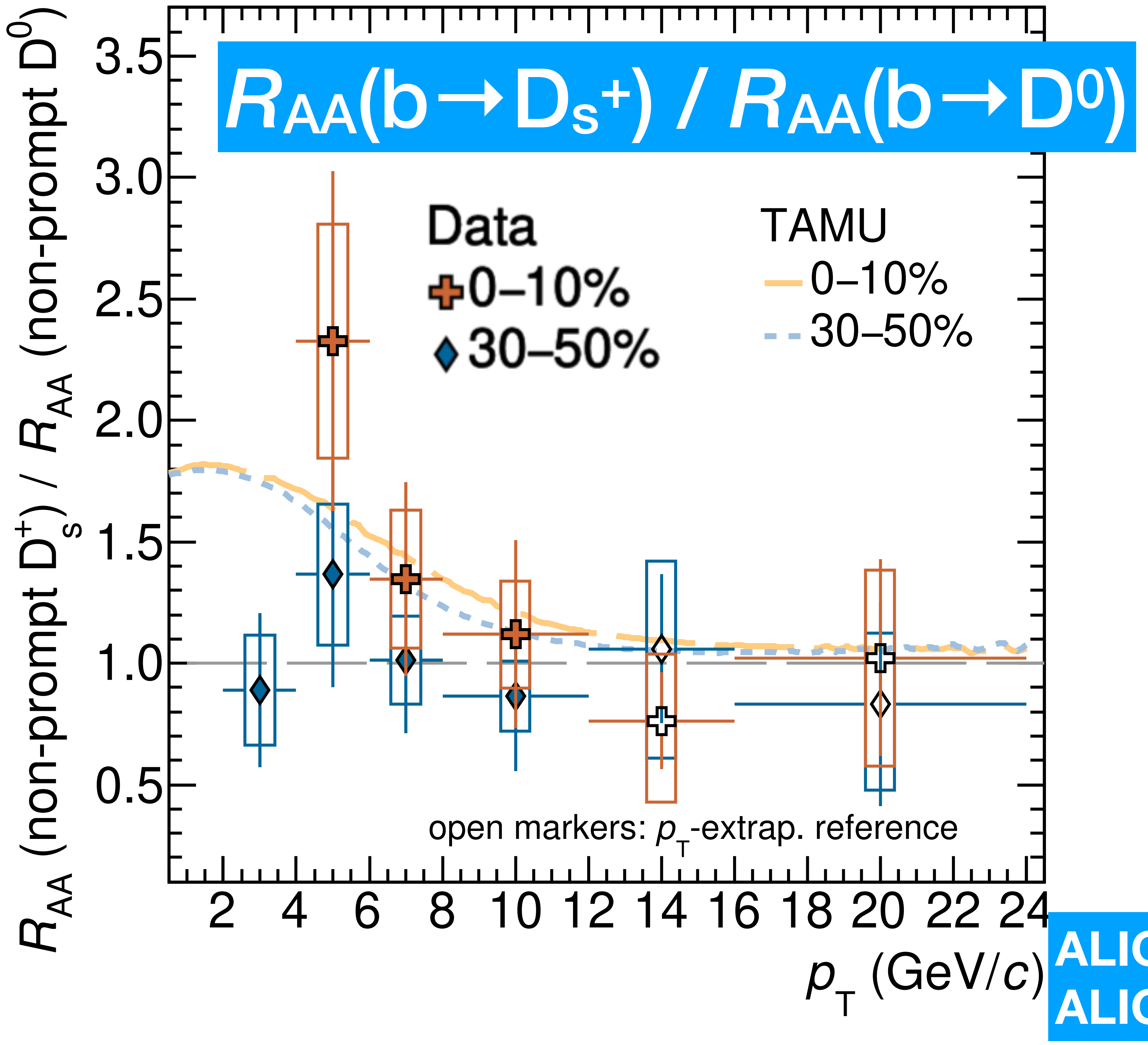




- Beauty-quark transport models give reasonable description to data
- Except TAMU (collisional only), both collisional interactions and radiative processes, and hadronisation via coalescence are considered in models

Heavy quark hadronization





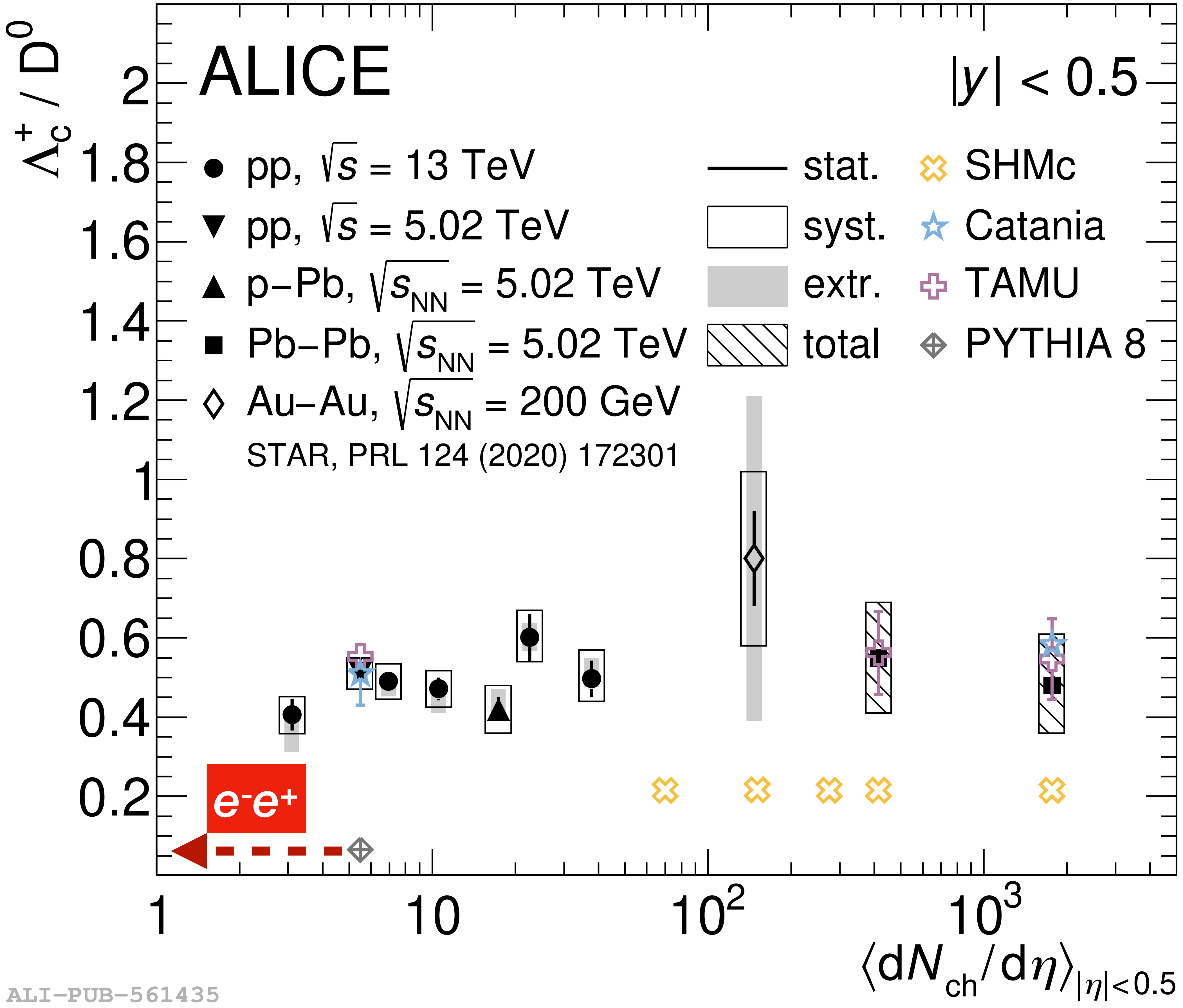
ALICE *Phys. Lett.* **B846** (2023) 137561
ALICE *Phys. Lett.* **B839** (2023) 137796

- Enhanced Λ_c/D^0 ratio in Pb–Pb w.r.t. pp at intermediate p_T

  ➡ Suggest interplay between hadronization via recombination and radial flow

- Suggest $R_{AA}(b\to D_s^+) > R_{AA}(b\to D^0)$ at $p_T \approx 5$ GeV/c: recombination with strange quarks in a strangeness-rich environment

Λ_c^+/D^0 ratio in small systems

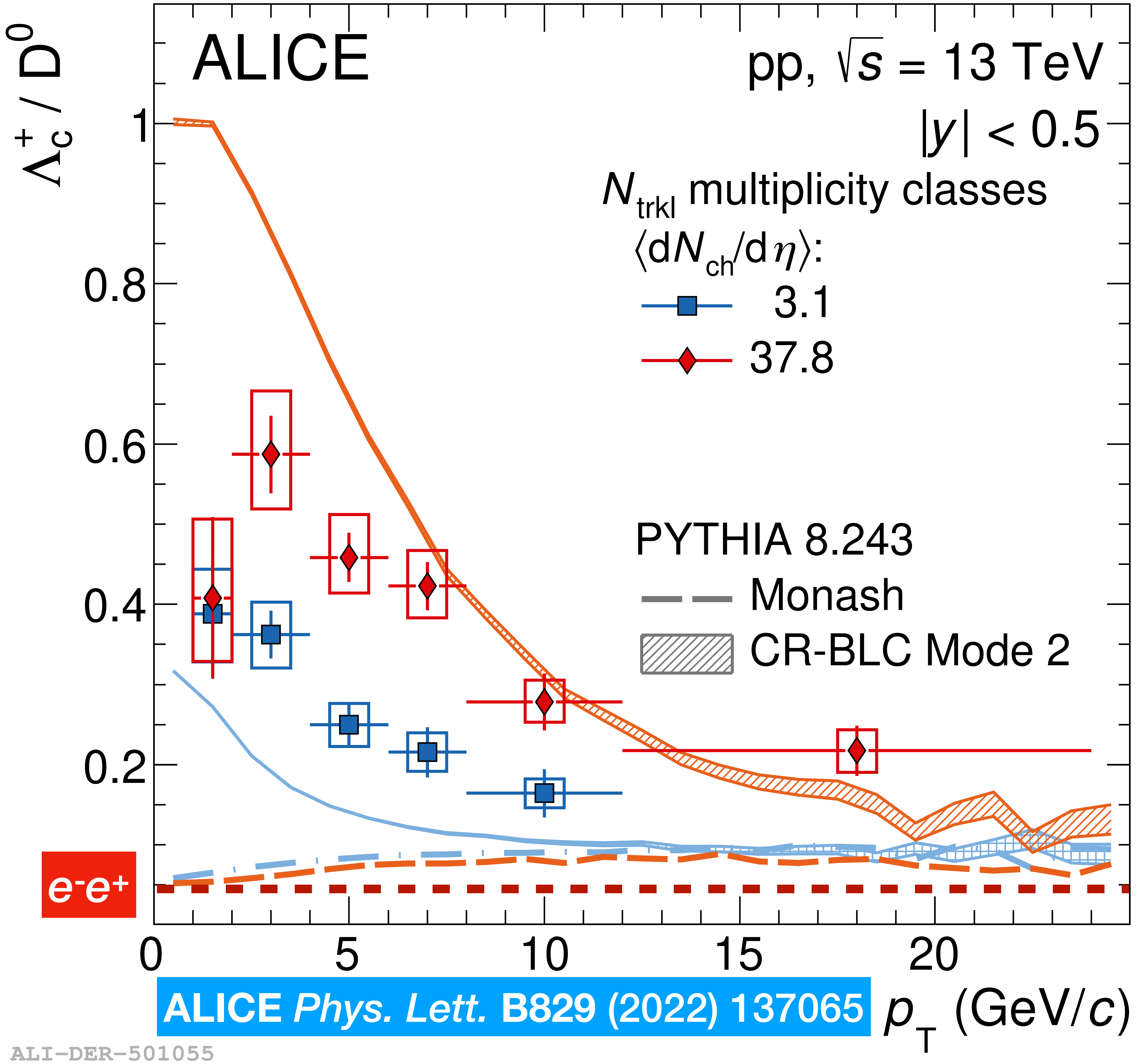


ALICE *Phys. Lett.* B839 (2023) 137796

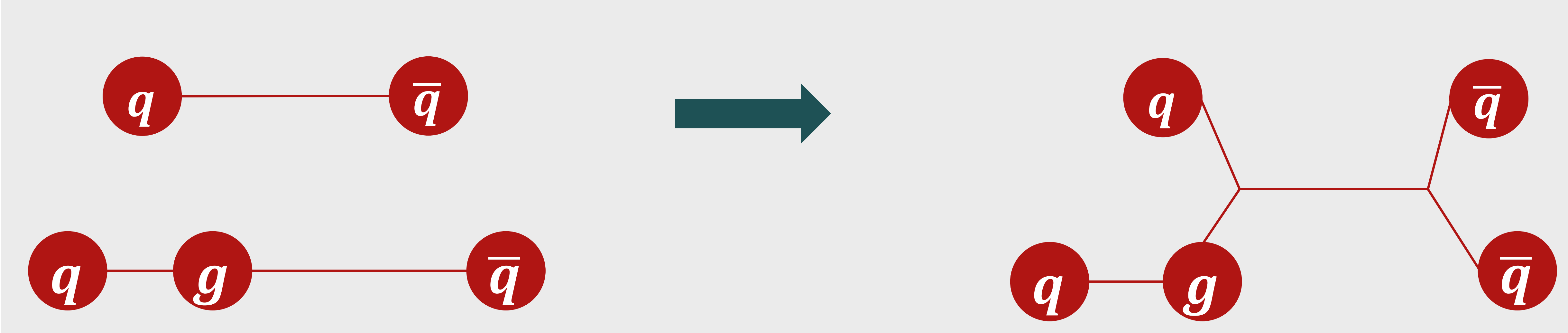
- p_T-integrated Λ_c^+/D^0 ratio vs multiplicity from pp, p–Pb to Pb–Pb collisions
  - ➡ No multiplicity dependence observed
  - ➡ Significantly higher than e^-e^+ and *ep* collisions (PYTHIA 8)
  - ➡ Suggest a modified hadronization mechanism in hadronic collisions w.r.t. e^-e^+ and e-p collisions

- Catania and TAMU which contain hadronization via coalescence describe data, while Statistic Hadronization Model (SHMc) underestimates data

Λ_c^+/D^0 ratio in pp collisions

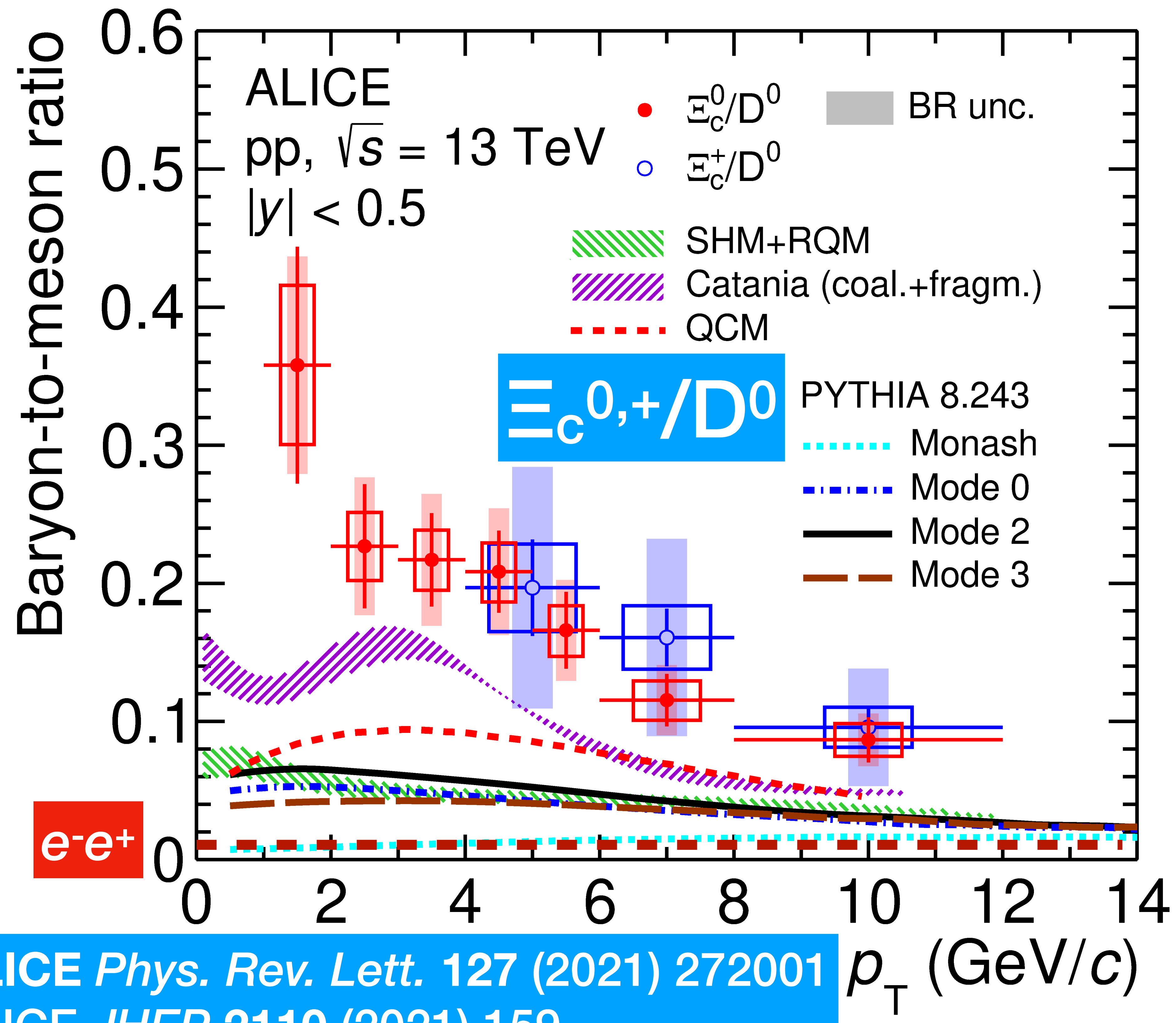


- p_T-differential Λ_c^+/D^0 ratio measured in pp collisions shows a substantial increase for increasing multiplicity
- Largely underestimated when comparing to the default PYTHIA tune (Monash)
- Good agreement including color-reconnection processes beyond leading color (CR-BLC), e.g., "junctions", between partons created in different MPIs



Strange charmed baryons in pp

ALICE



ALICE *Phys. Rev. Lett.* 127 (2021) 272001
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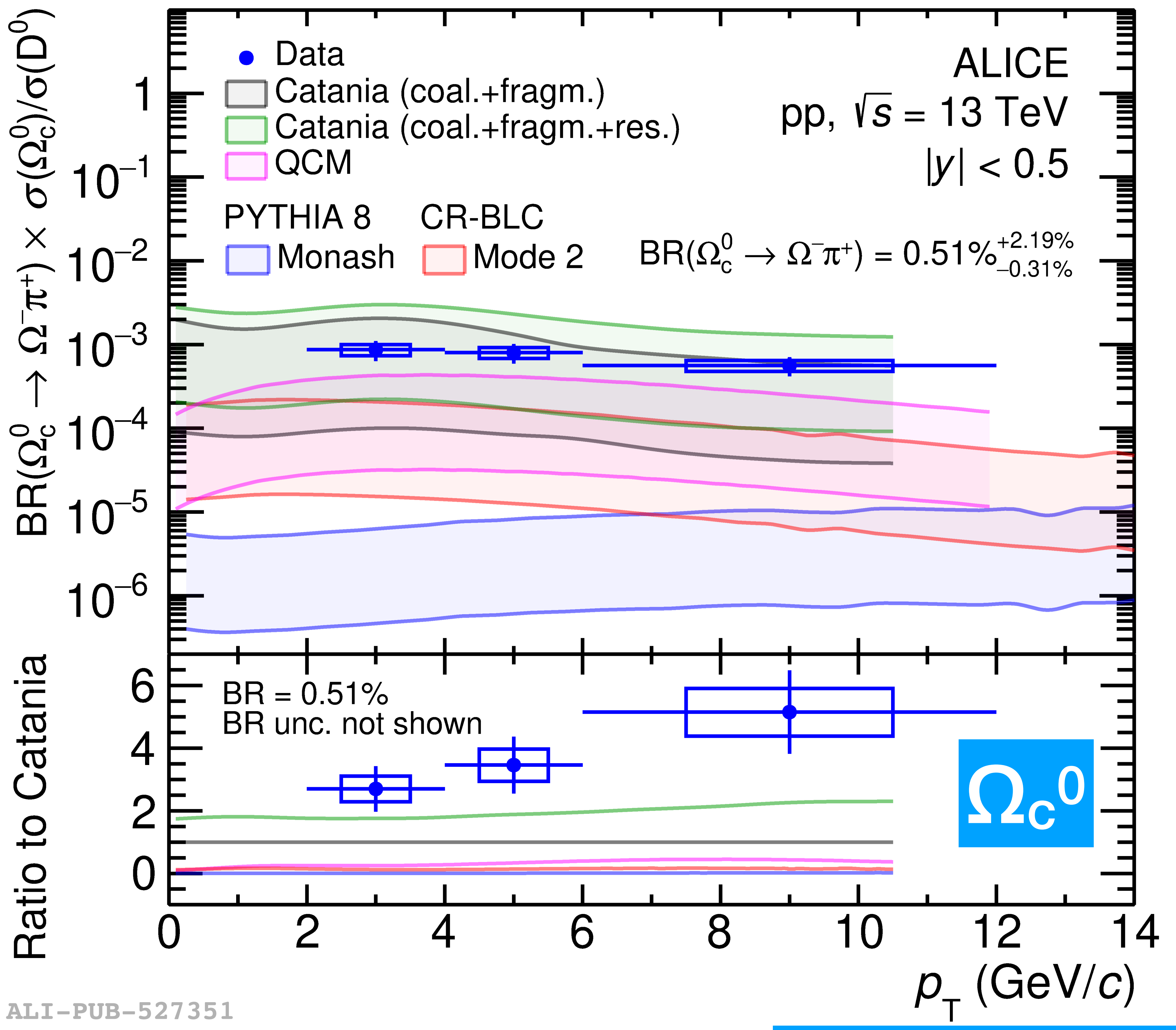
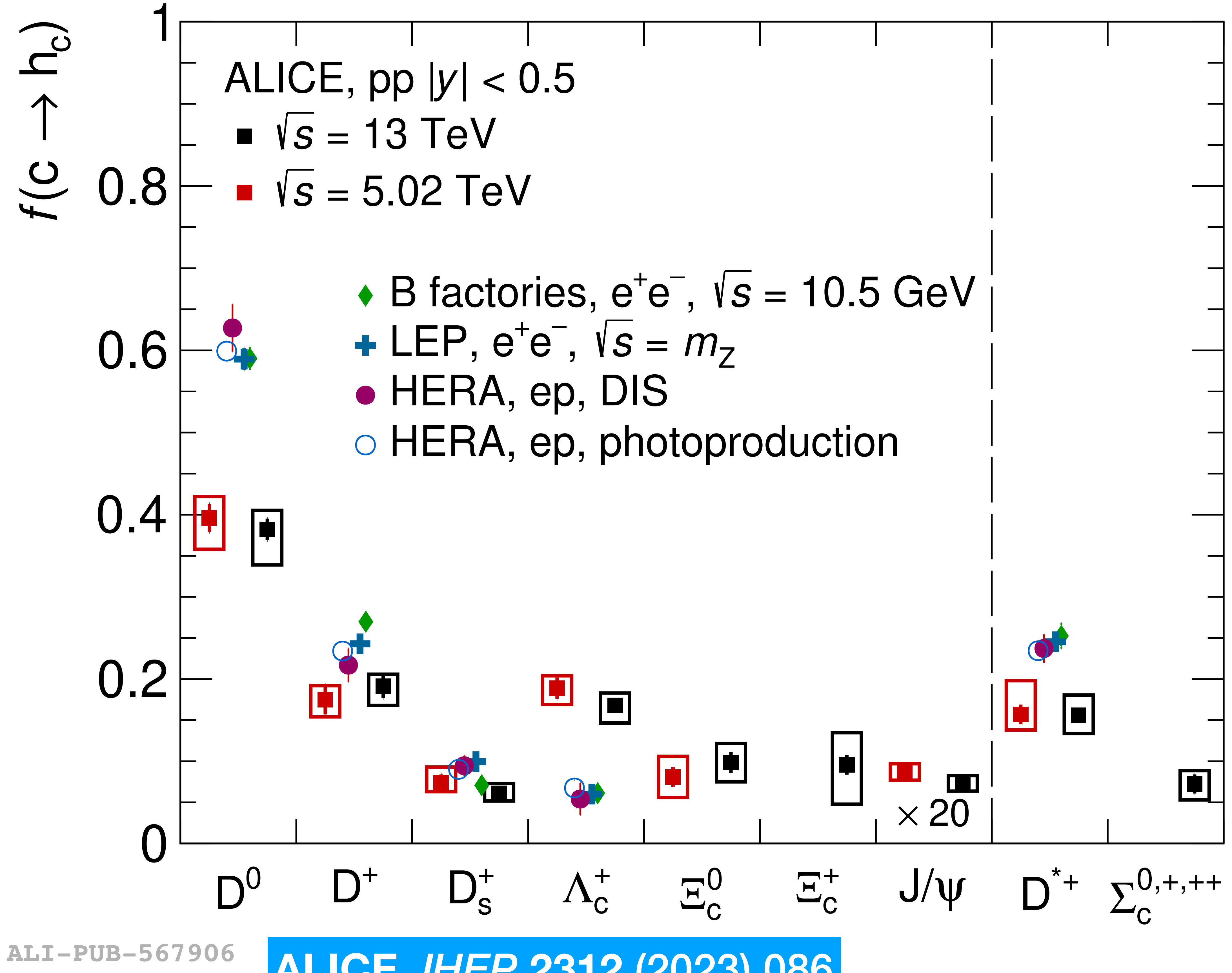


ALICE *Phys. Lett.* B846 (2023) 137625

- Enhancement of strange charmed baryon-to-meson ratio w.r.t. e^-e^+ is stronger than Λ_c^+/D^0
- All models are challenged by the data

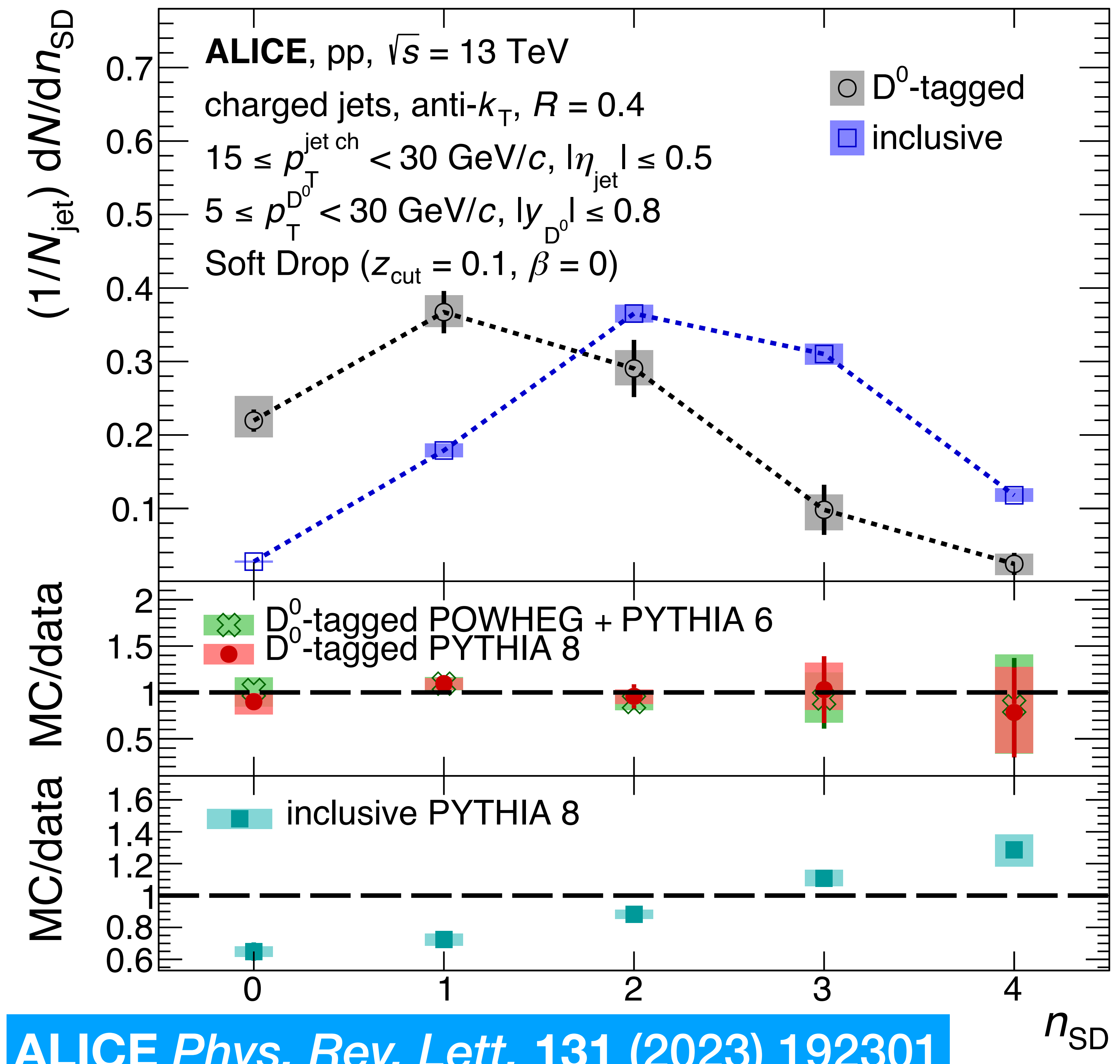
Charm quark hadronization



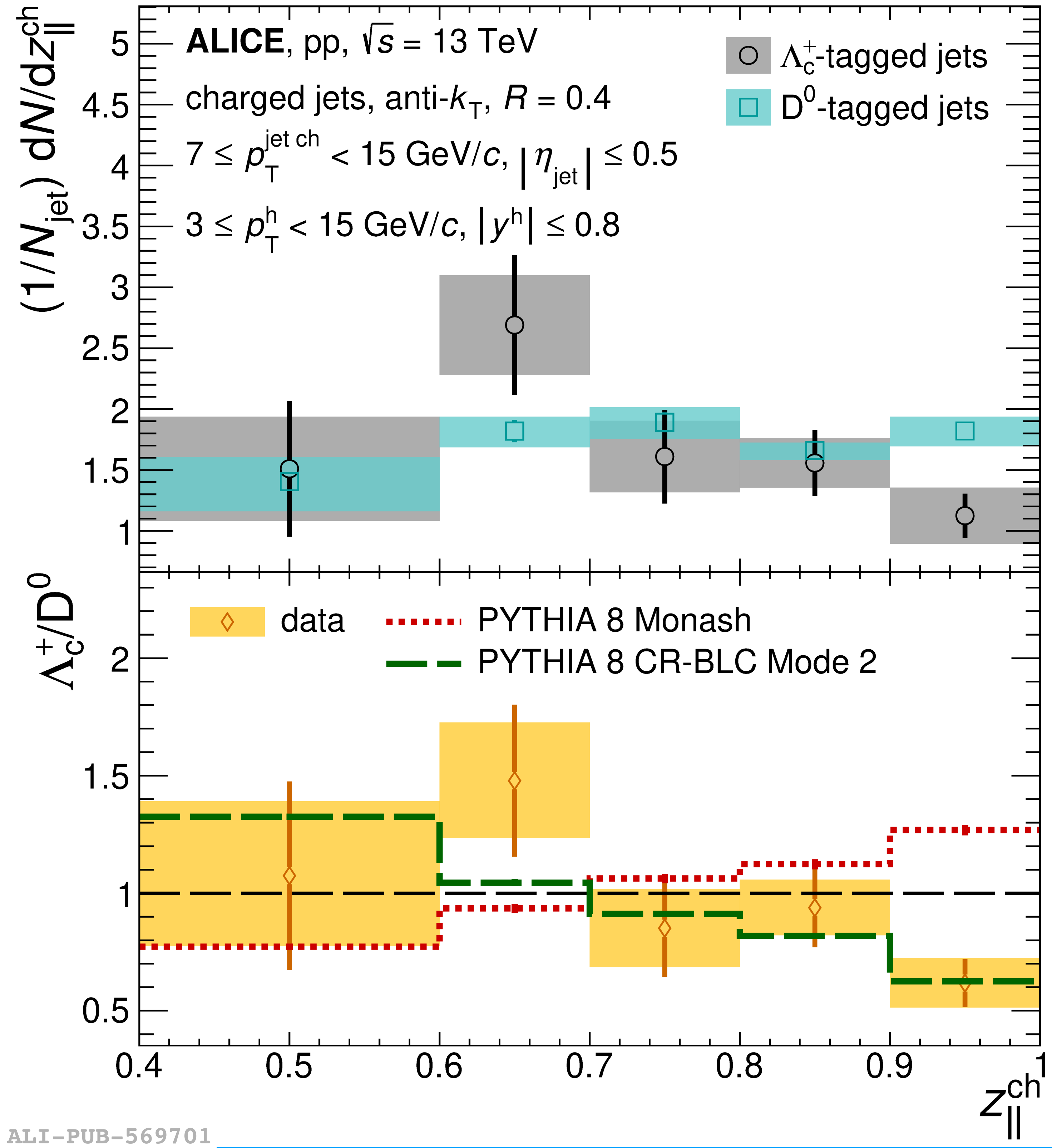
ALICE *JHEP* 2312 (2023) 086

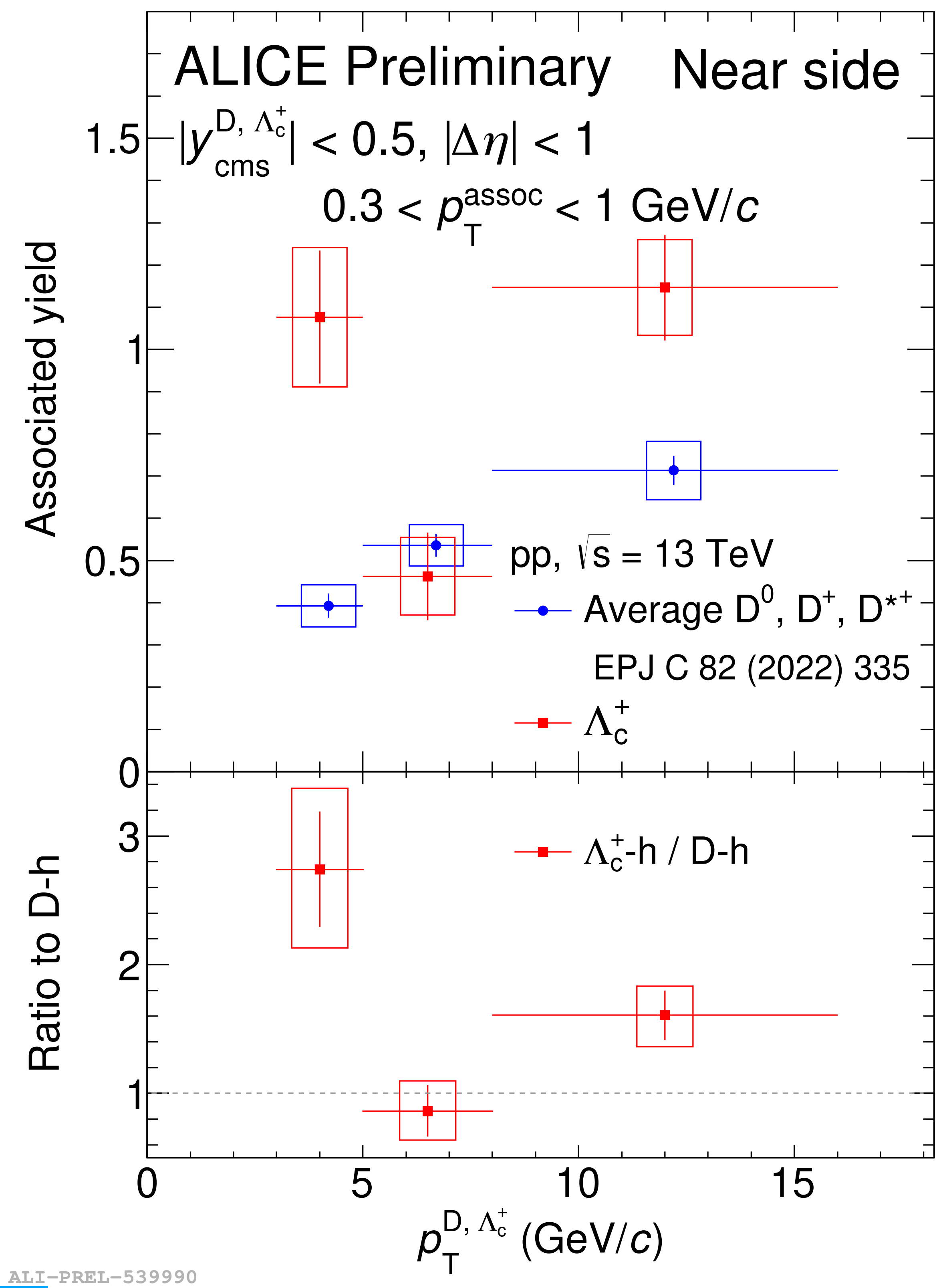
- Charm-quark fragmentation fractions to different hadrons $f(c \rightarrow H_c)$ at the LHC compared with LEP and HERA results
- Enhancement of baryon — overall reduction of relative D-meson abundance by a factor of 1.5 w.r.t e^-e^+ and ep collisions
- No significant energy dependence at the LHC

Charmed-hadron tagged jets



ALICE *Phys. Rev. Lett.* **131** (2023) 192301

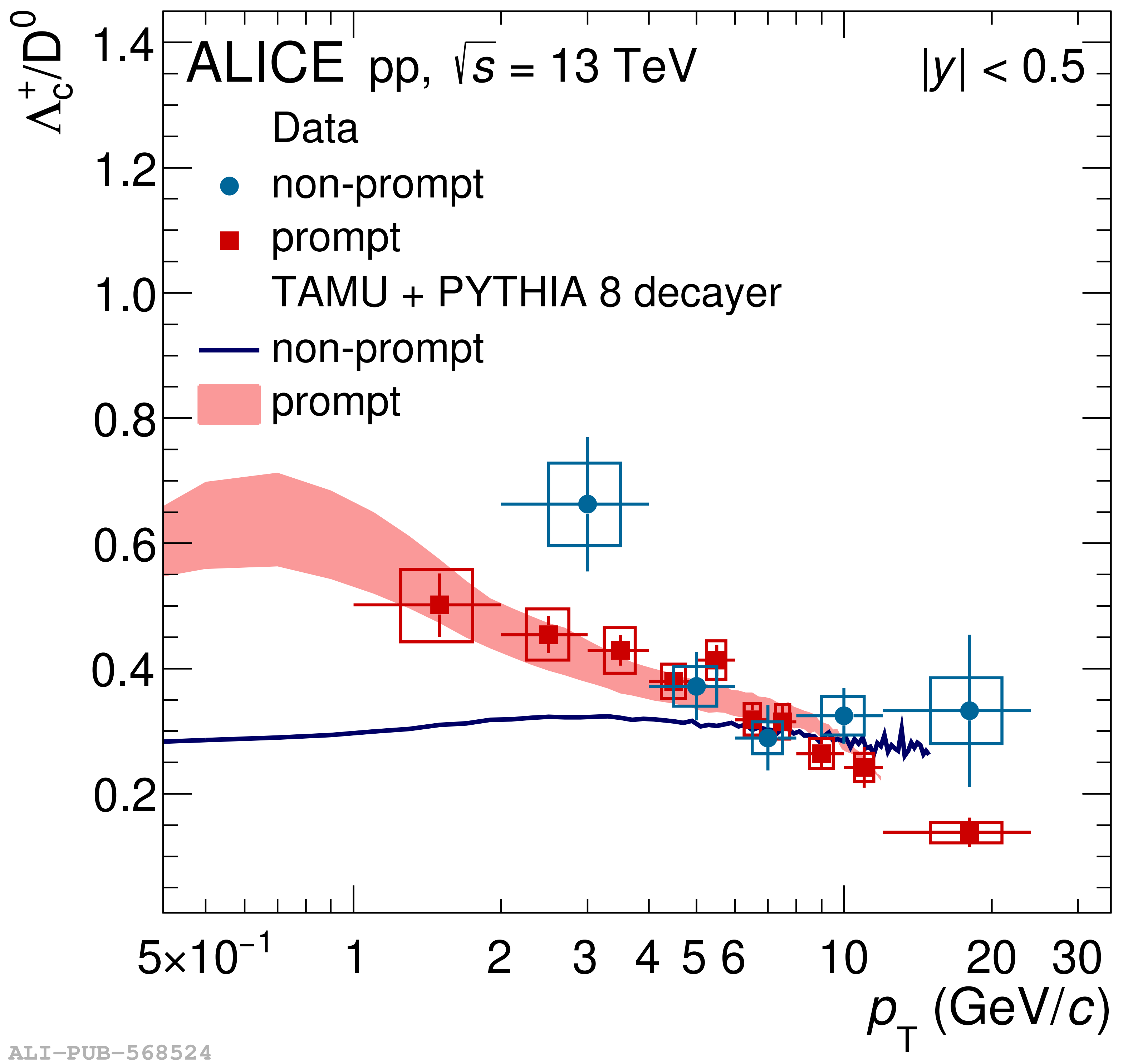


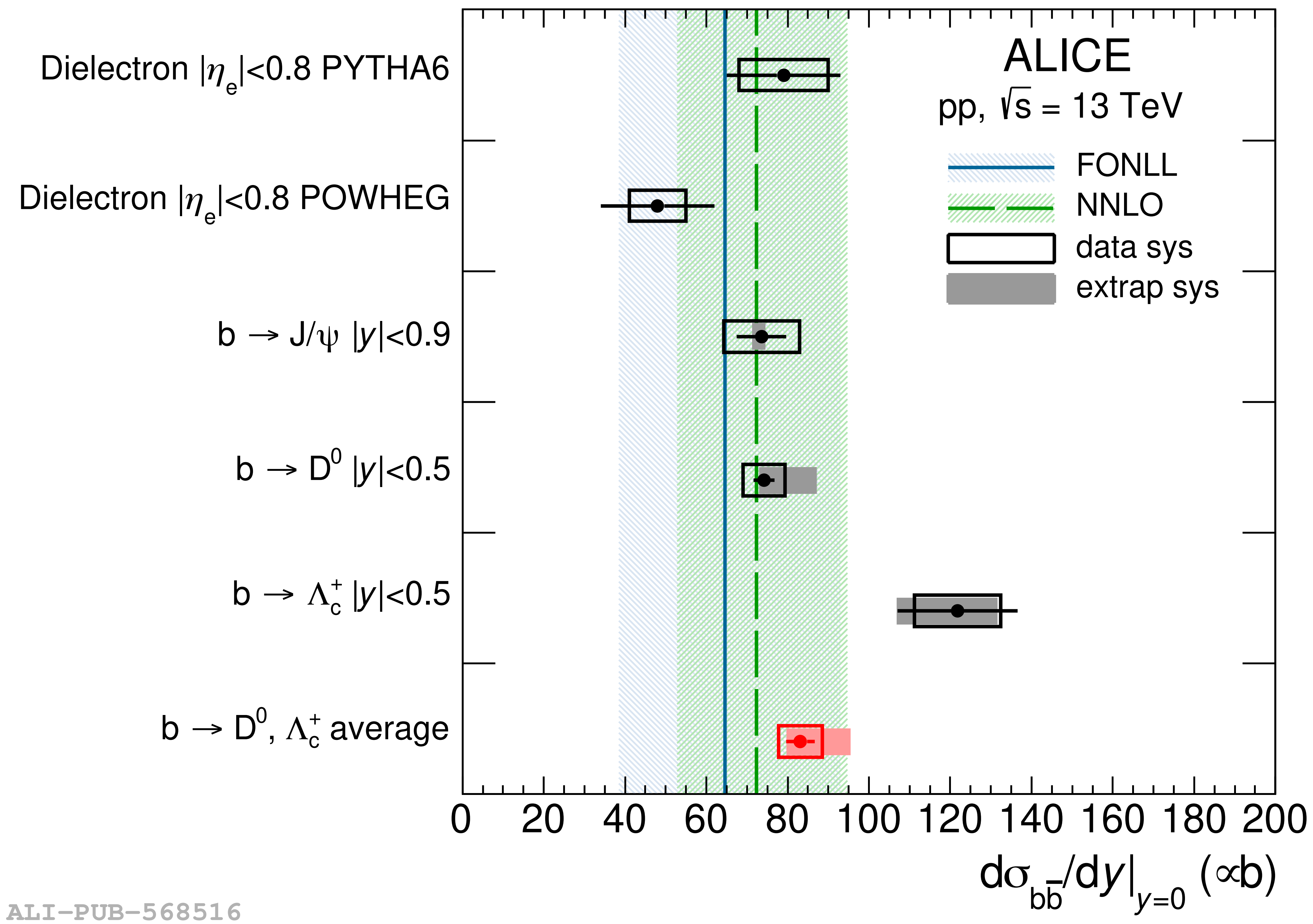


ALICE *Phys. Rev.* **D109** (2024) 072005

- D^0 tagged jets have less splitting than the inclusive ones — consistent with the harder fragmentation and dead-cone effect [**ALICE** *Nature* **605** (2022) 440]
- Indication that charm fragmentation into Λ_c^+ is softer and produces more collinear-associated particles compared to fragmentation into D^0

Beauty production in pp

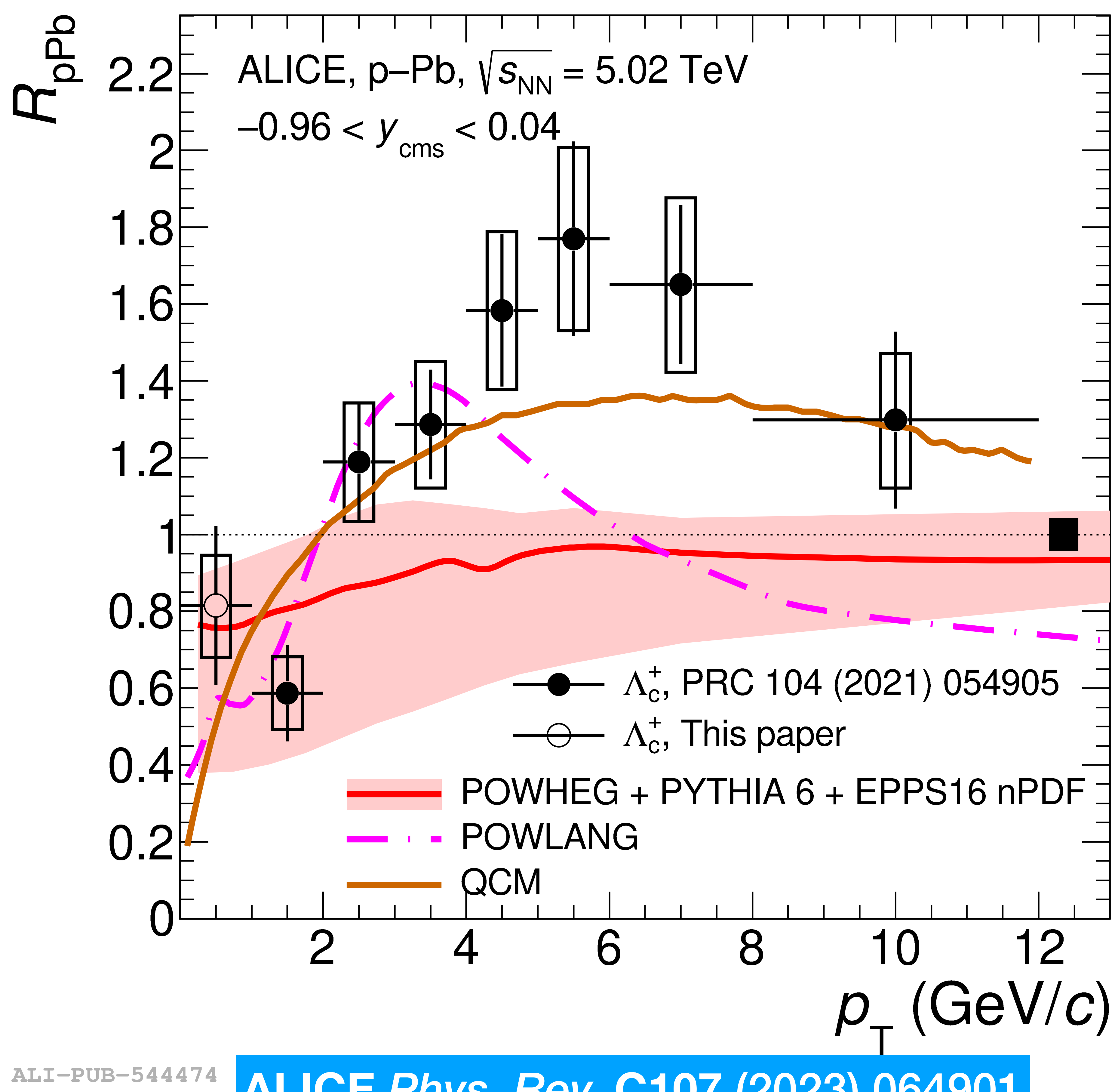




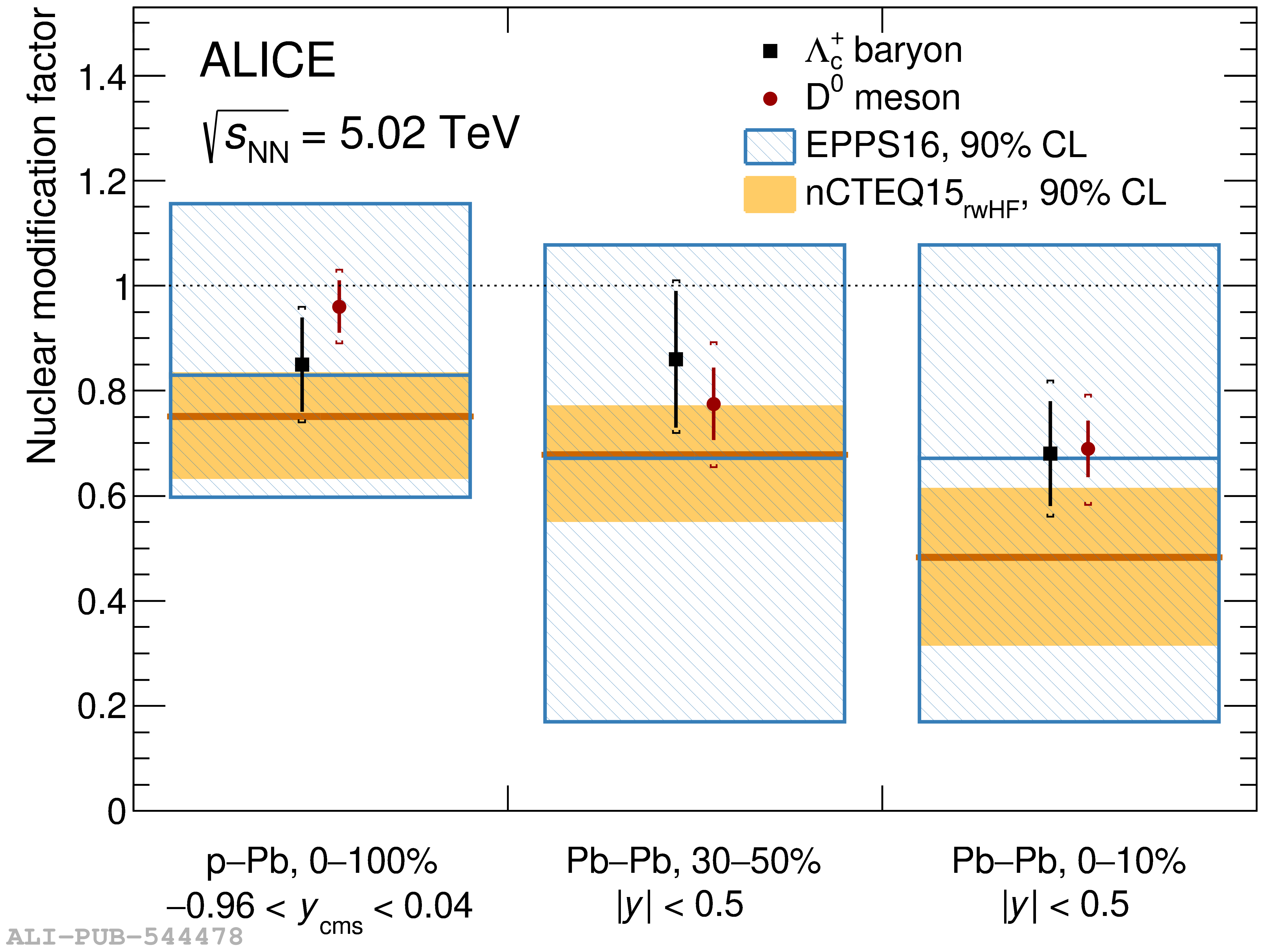
ALICE *Phys. Rev.* D108 (2023) 112003

- Λ_c^+/D^0 ratio: similar values and p_T dependence between prompt and non-prompt
- Total beauty cross section compatible with other measurements and pQCD calculations

Charm modification in p–Pb

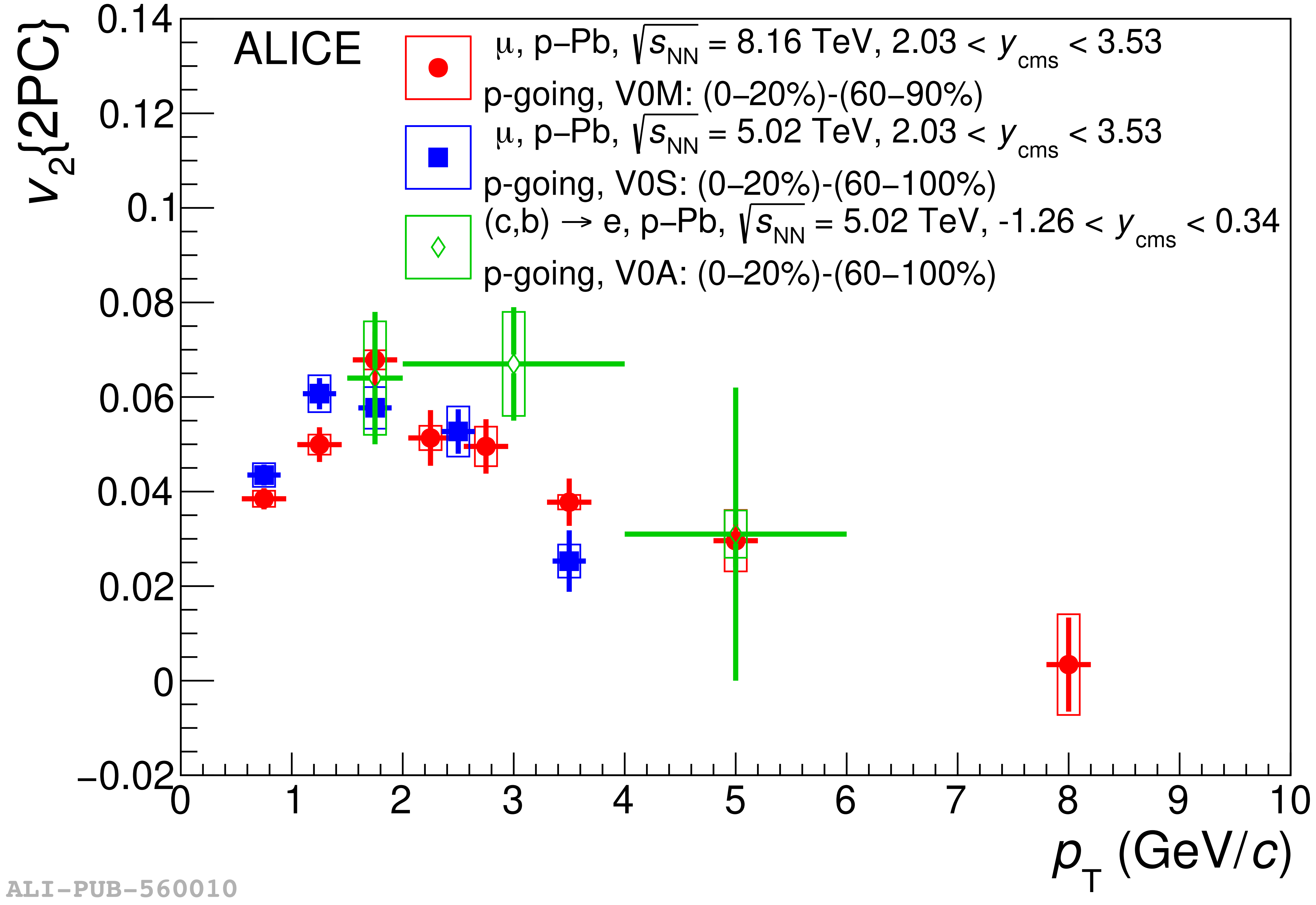


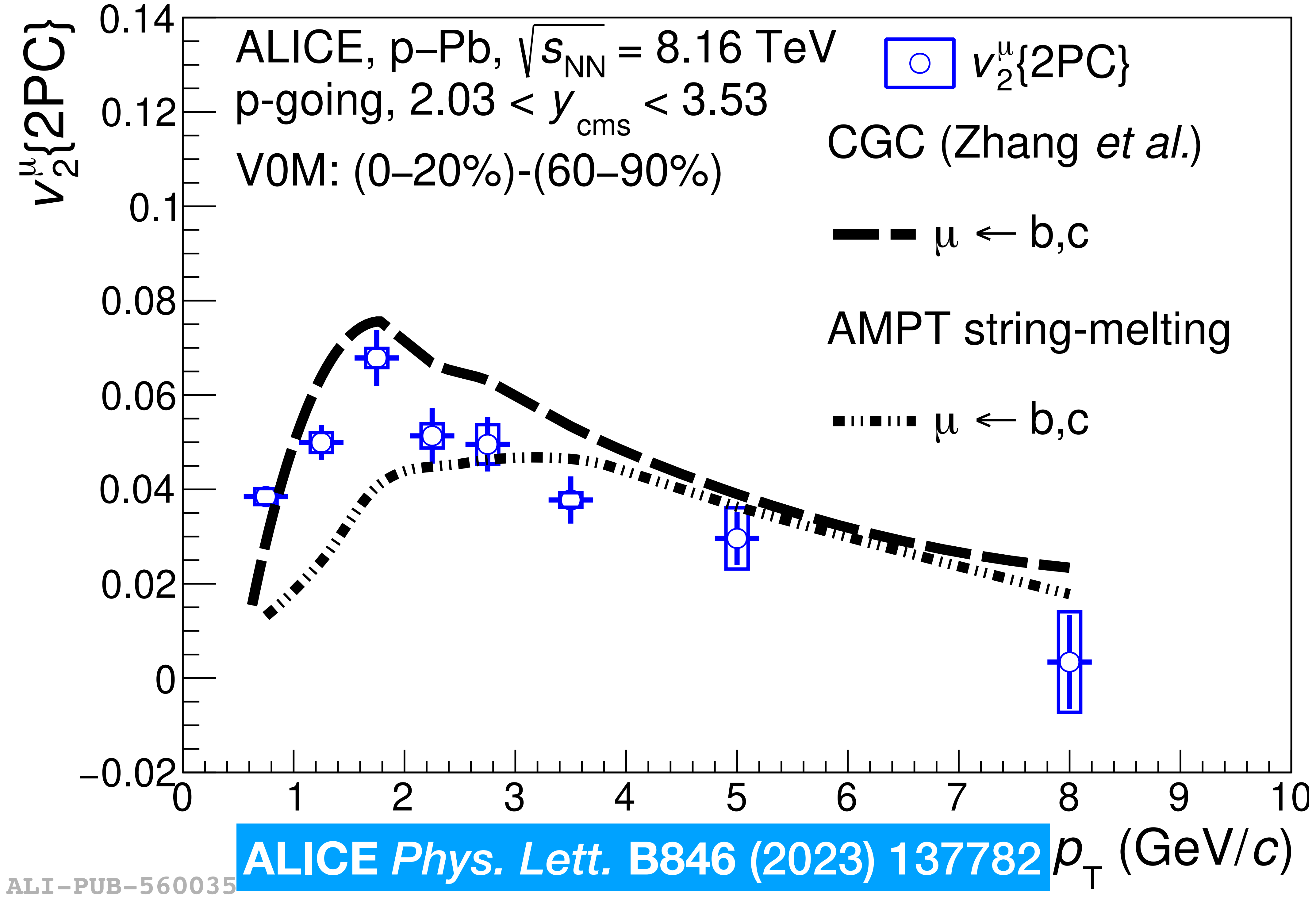
ALICE *Phys. Rev.* C107 (2023) 064901



- $R_{pPb}(\Lambda_c^+)$ > 1 at intermediate p_T: possible CMN effects + coalescence
- p_T-integrated nuclear modification factor is consistent with 1: constrains on nPDFs

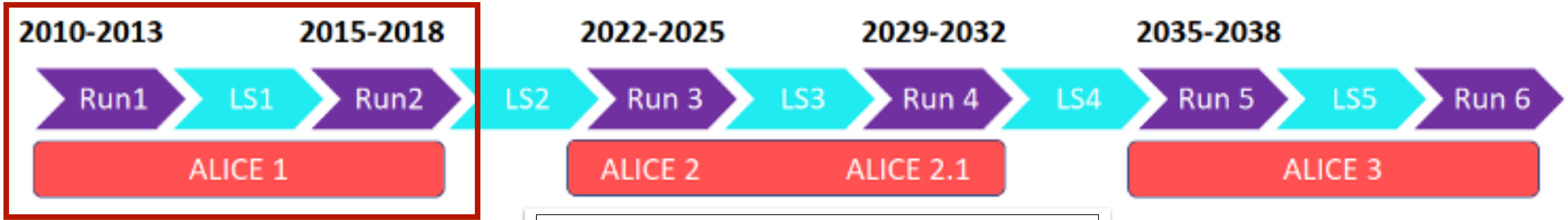
Azimuthal anisotropy in p–Pb

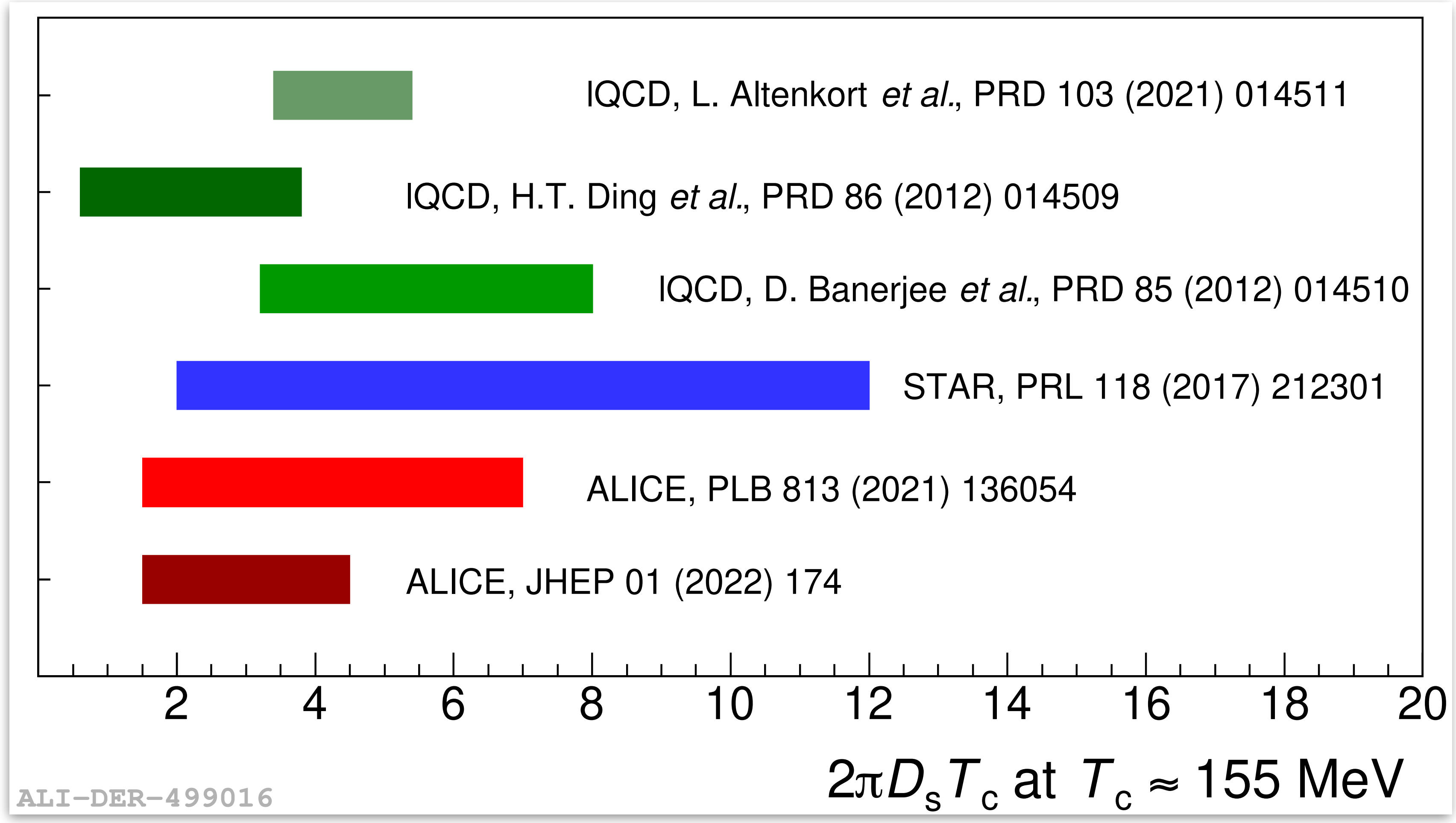


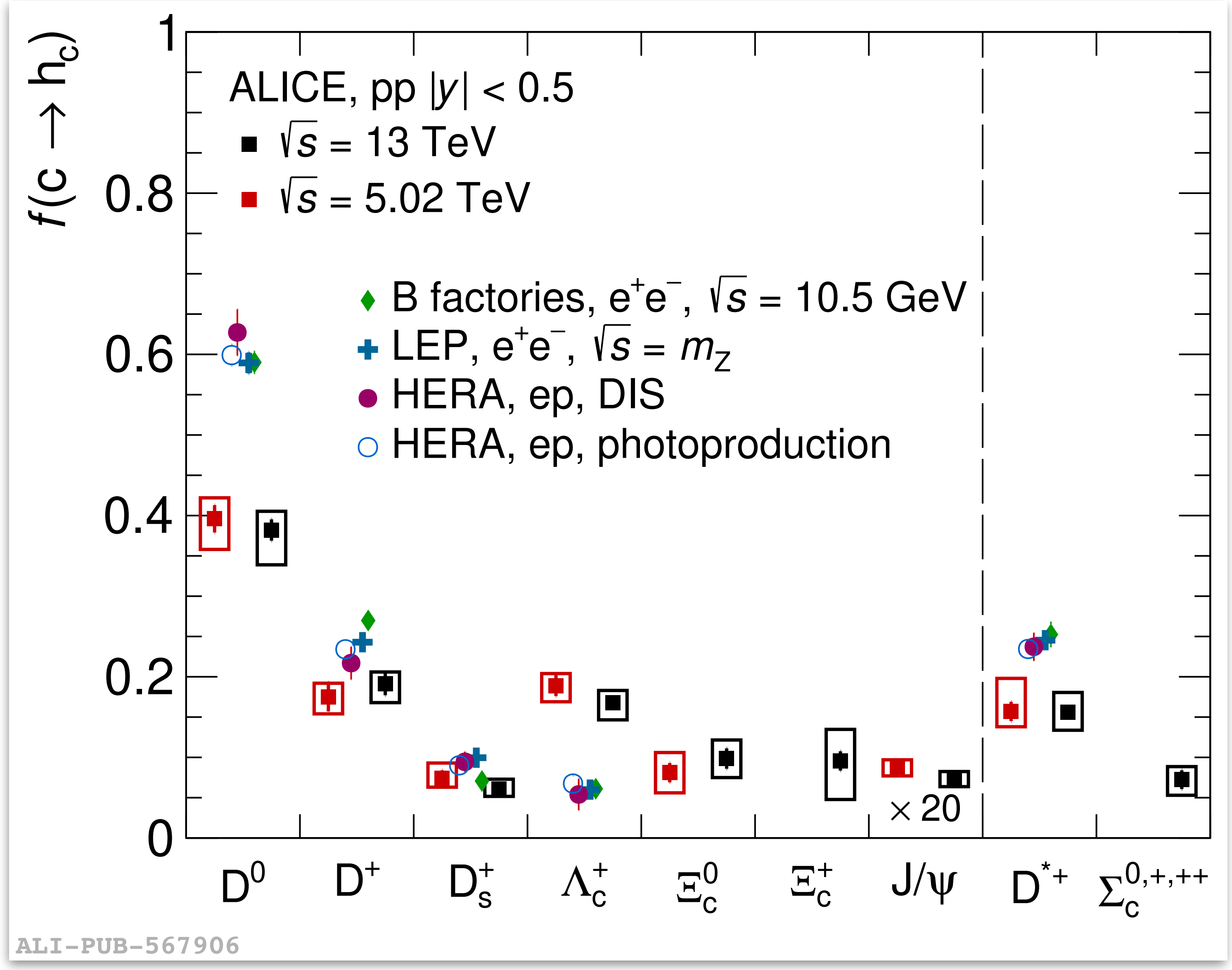


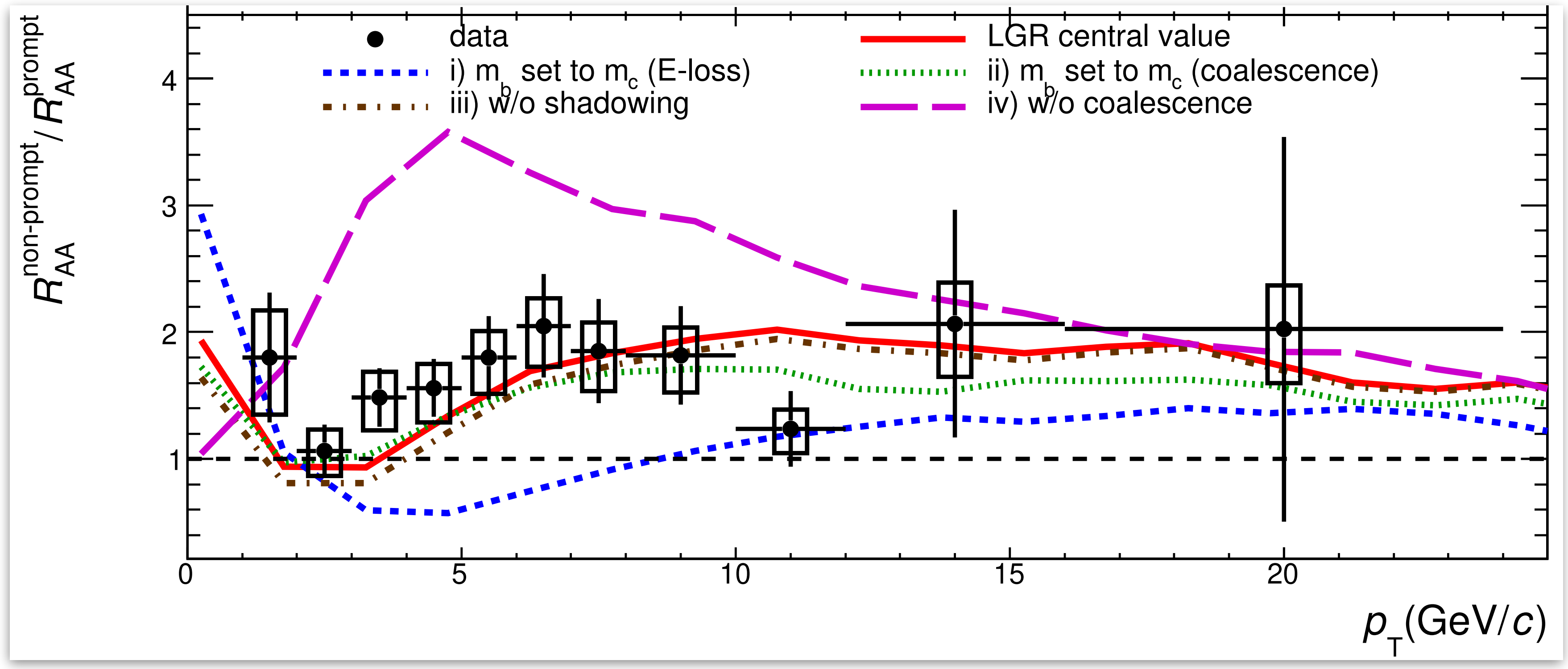
- Positive v_2 of inclusive muons at forward rapidity (dominated by HF decays in p_T > 2 GeV/c)
  - ➡ Good agreement with c,b→e at mid-rapidity within uncertainties
  - ➡ Described by both parton escape (AMPT) and initial stages partons correlations (CGC) mechanisms

A journey through QCD







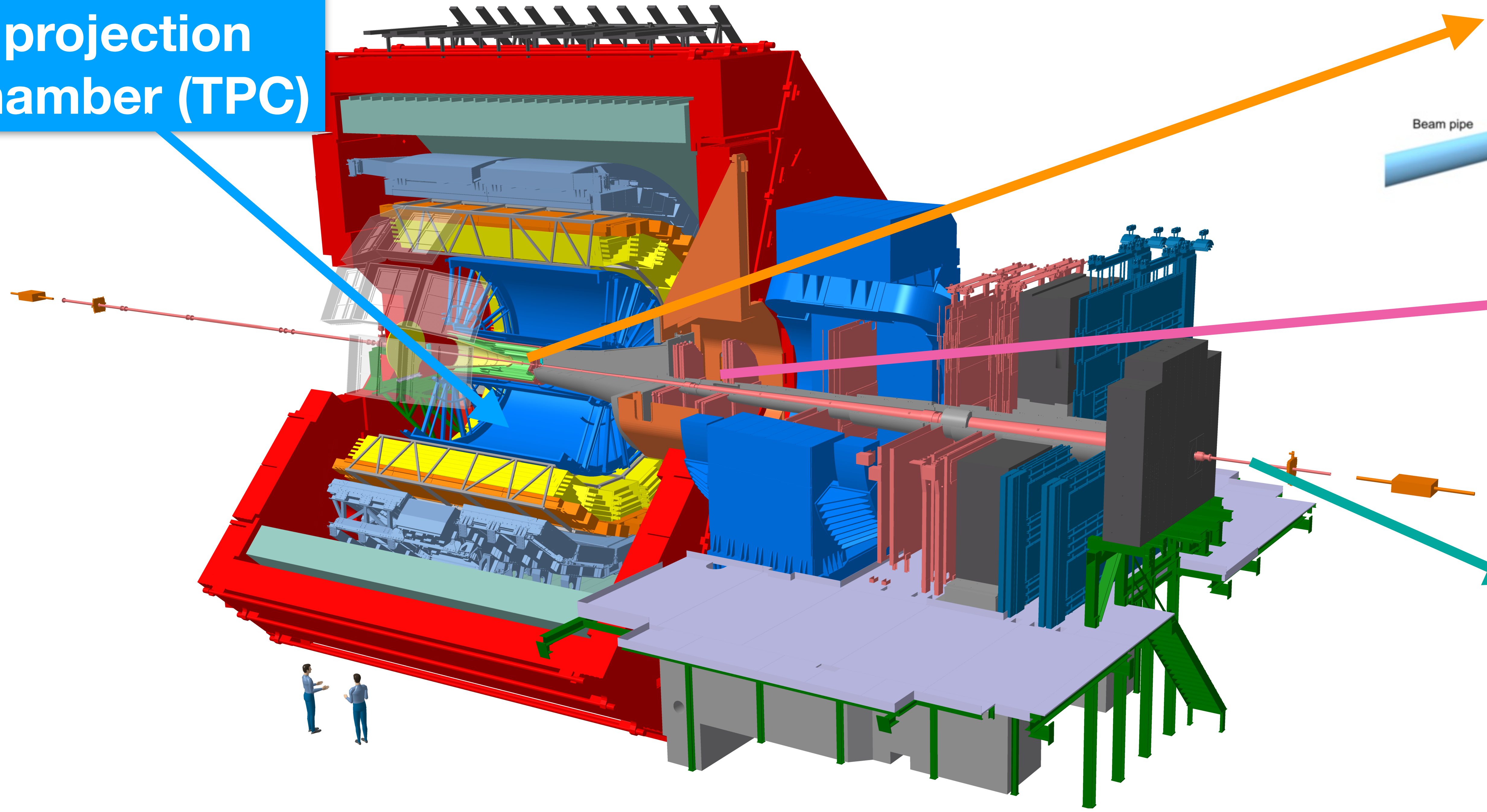


More than a QGP factory

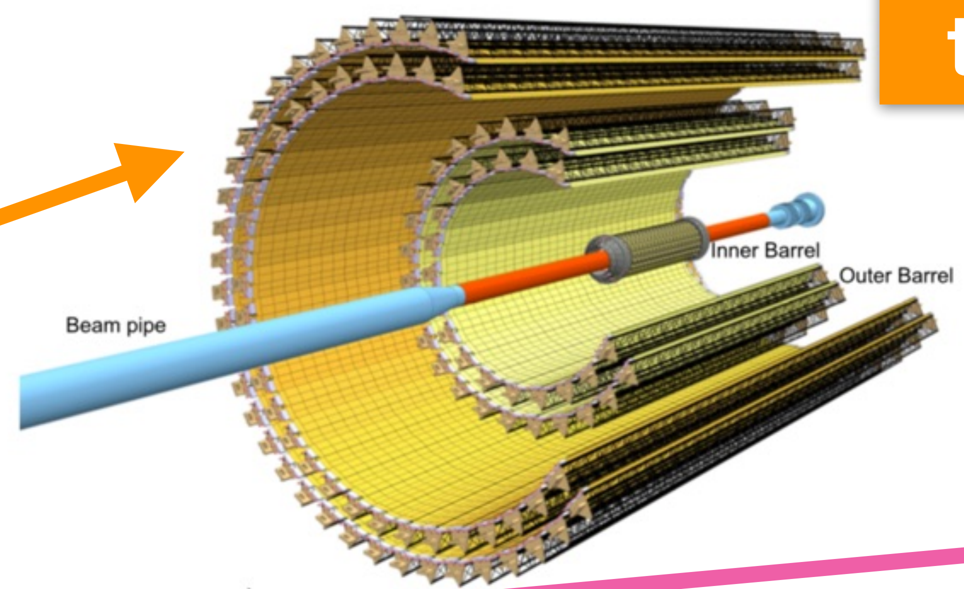
A journey through QCD

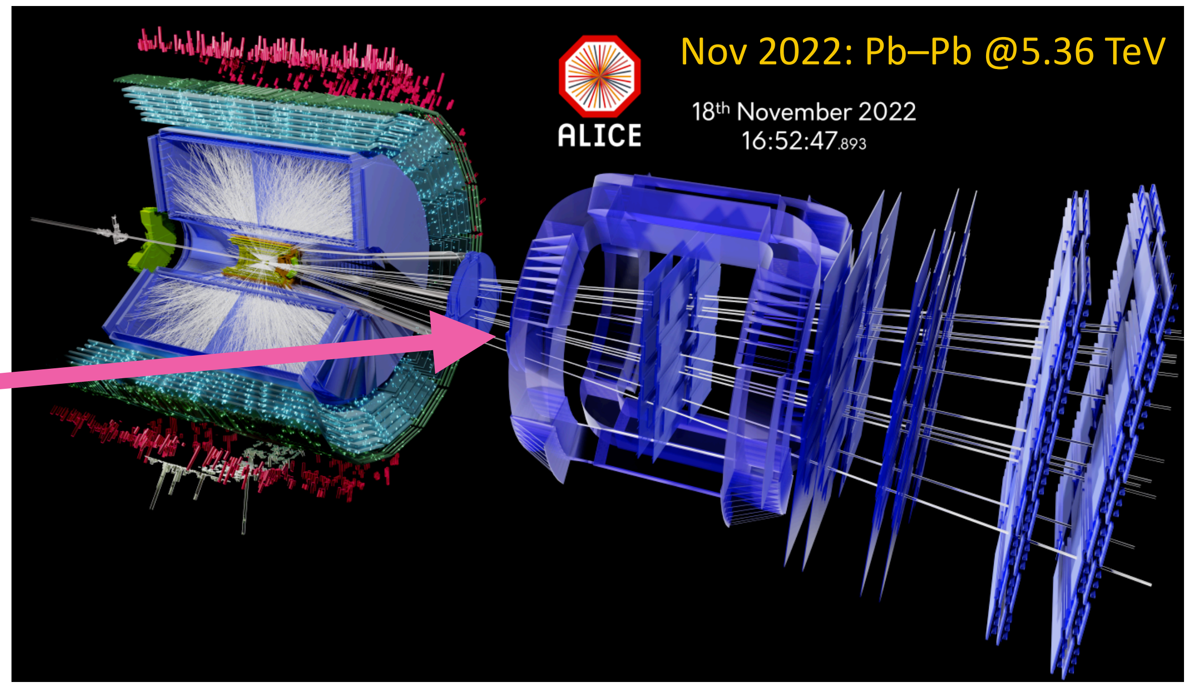
2010-2013		2015-2018		2022-2025		2029-2032		2035-2038		
Run1	LS1	Run2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
ALICE 1				ALICE 2		ALICE 2.1		ALICE 3		

Upgraded readout of time projection chamber (TPC)

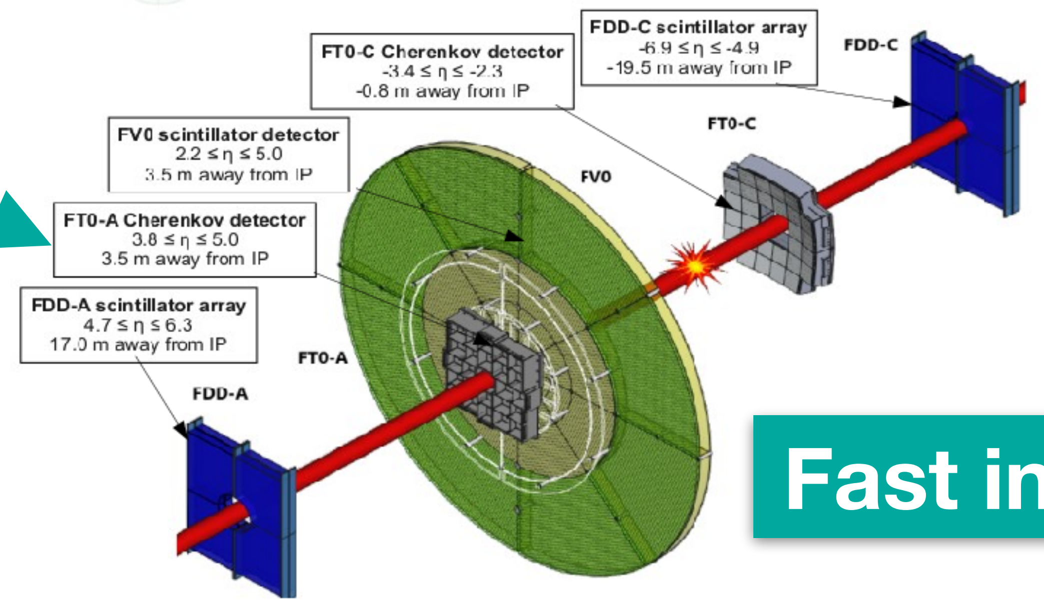


The 2nd generation inner tracking system (ITS2)



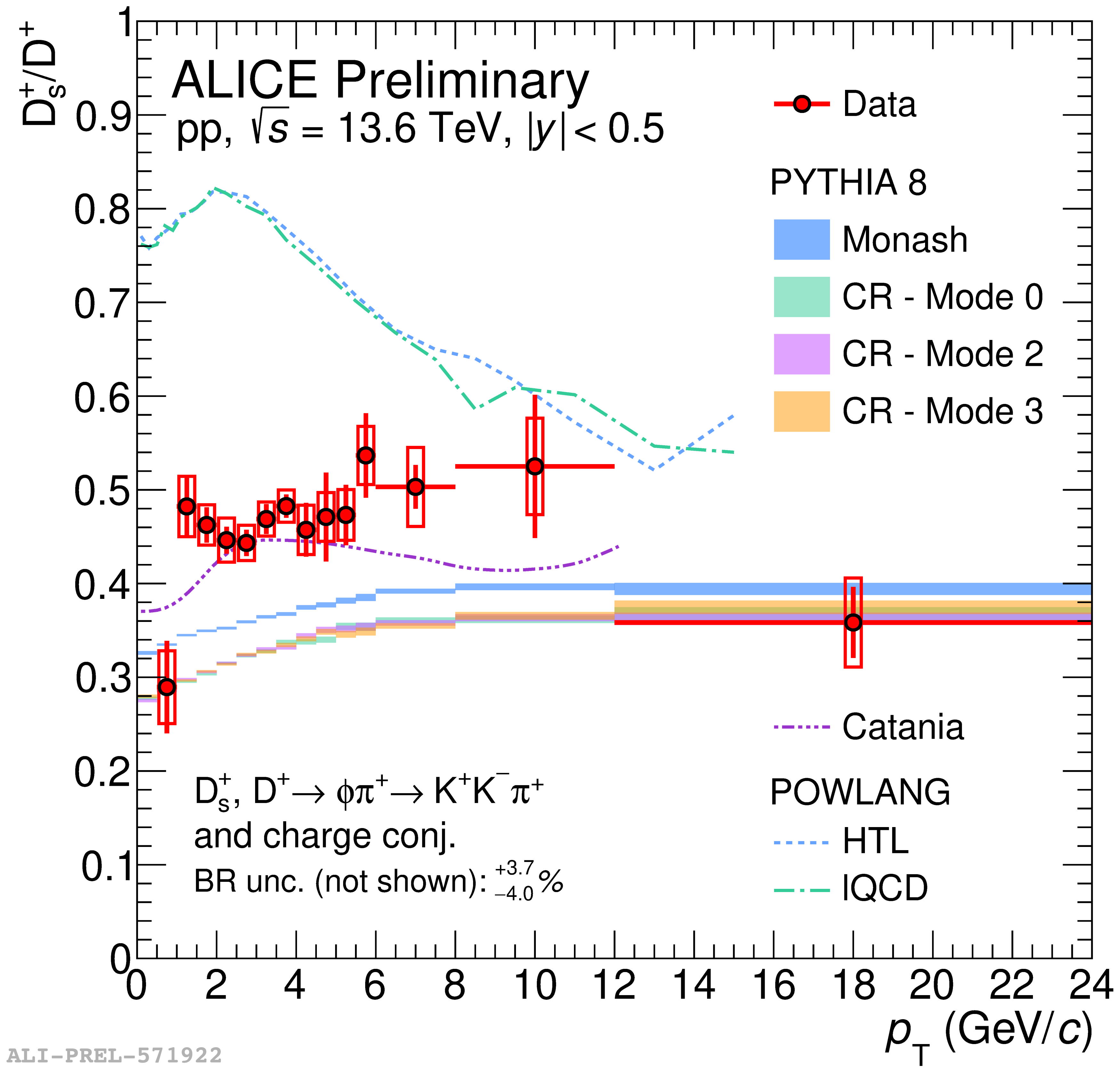


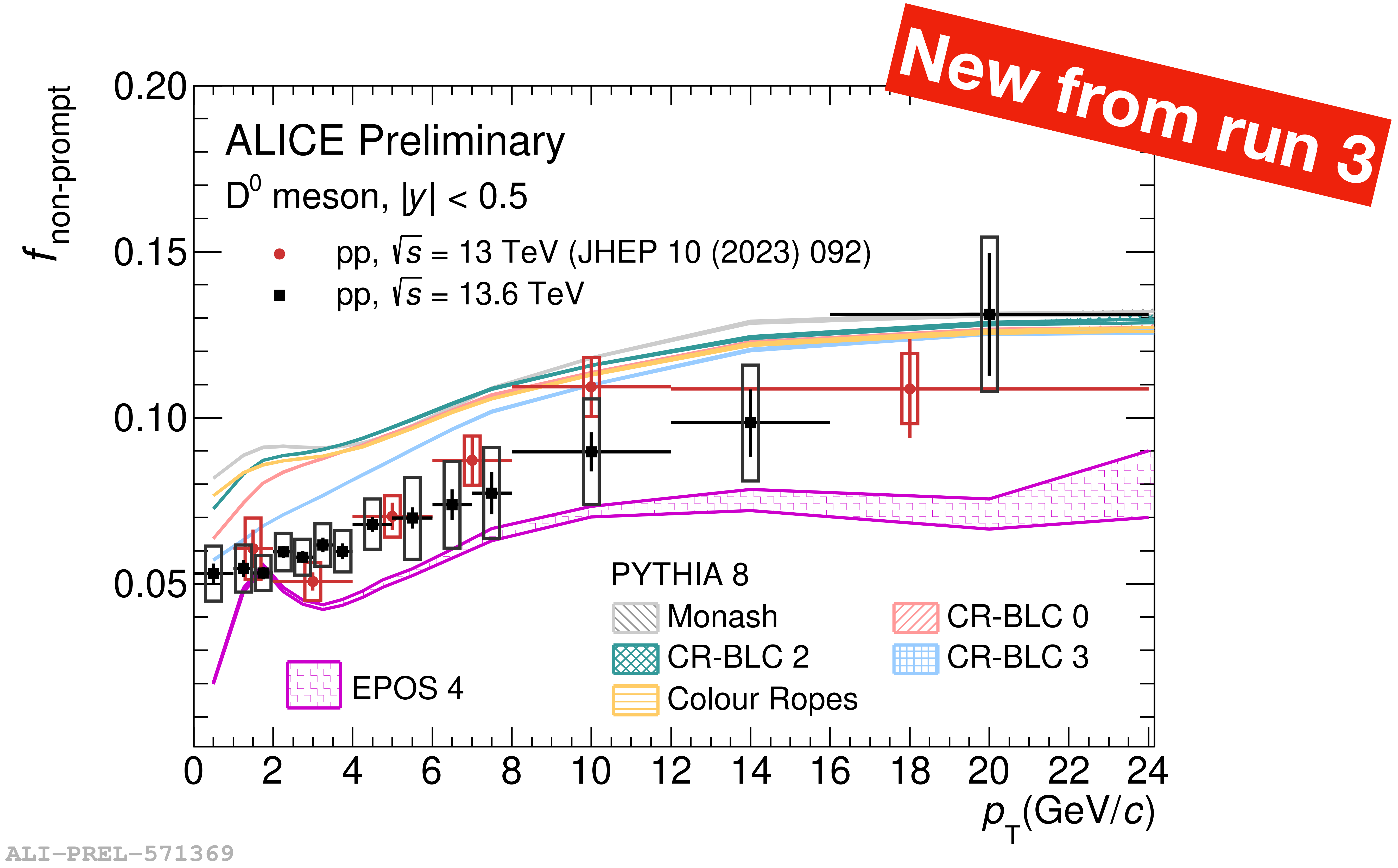
Muon forward tracker (MFT)



Fast integrated trigger (FIT)

D_s^+ and $b \to D^0$ production





- Measurements are extended to lower p_T and more granular w. r. t. run 2

➡ Stronger constraints on the modelling of charm-quark hadronization

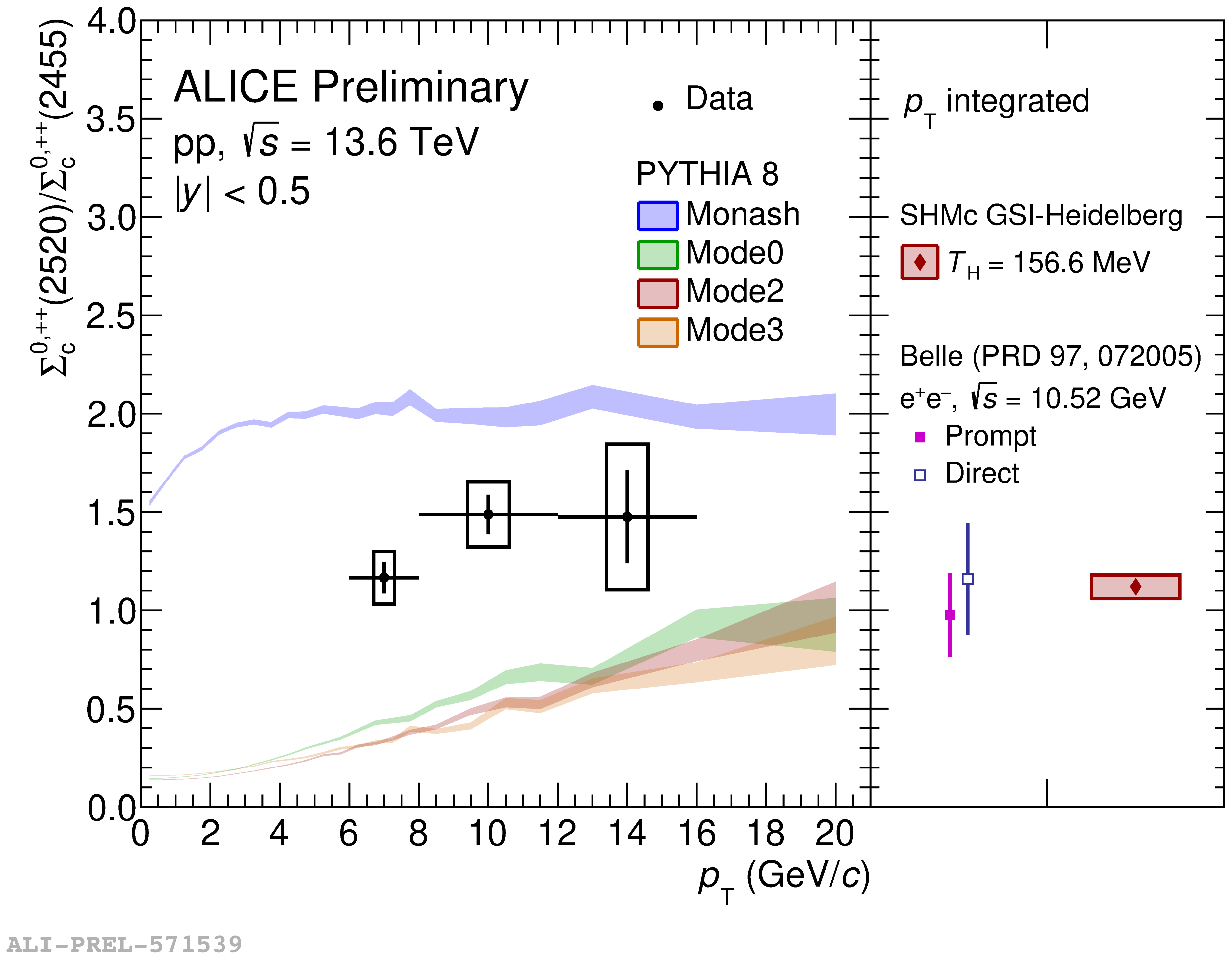
$\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$

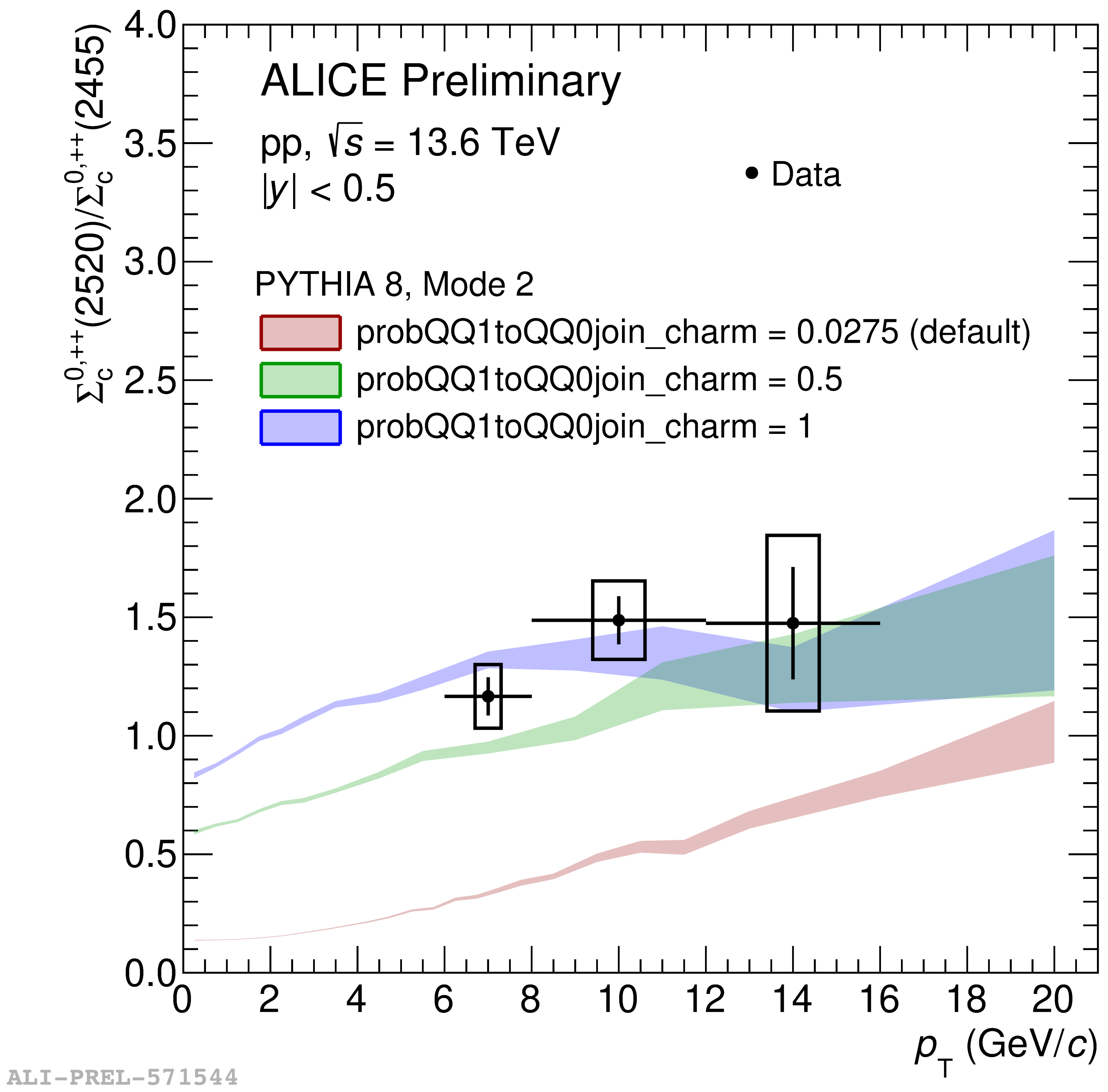
New from run 3

First $\Sigma_c^{0,++}(2520)$ measurement at the LHC

$\Sigma_c^{0,++}(2520)$, J = 3/2

$\Sigma_c^{0,++}(2455)$, J = 1/2

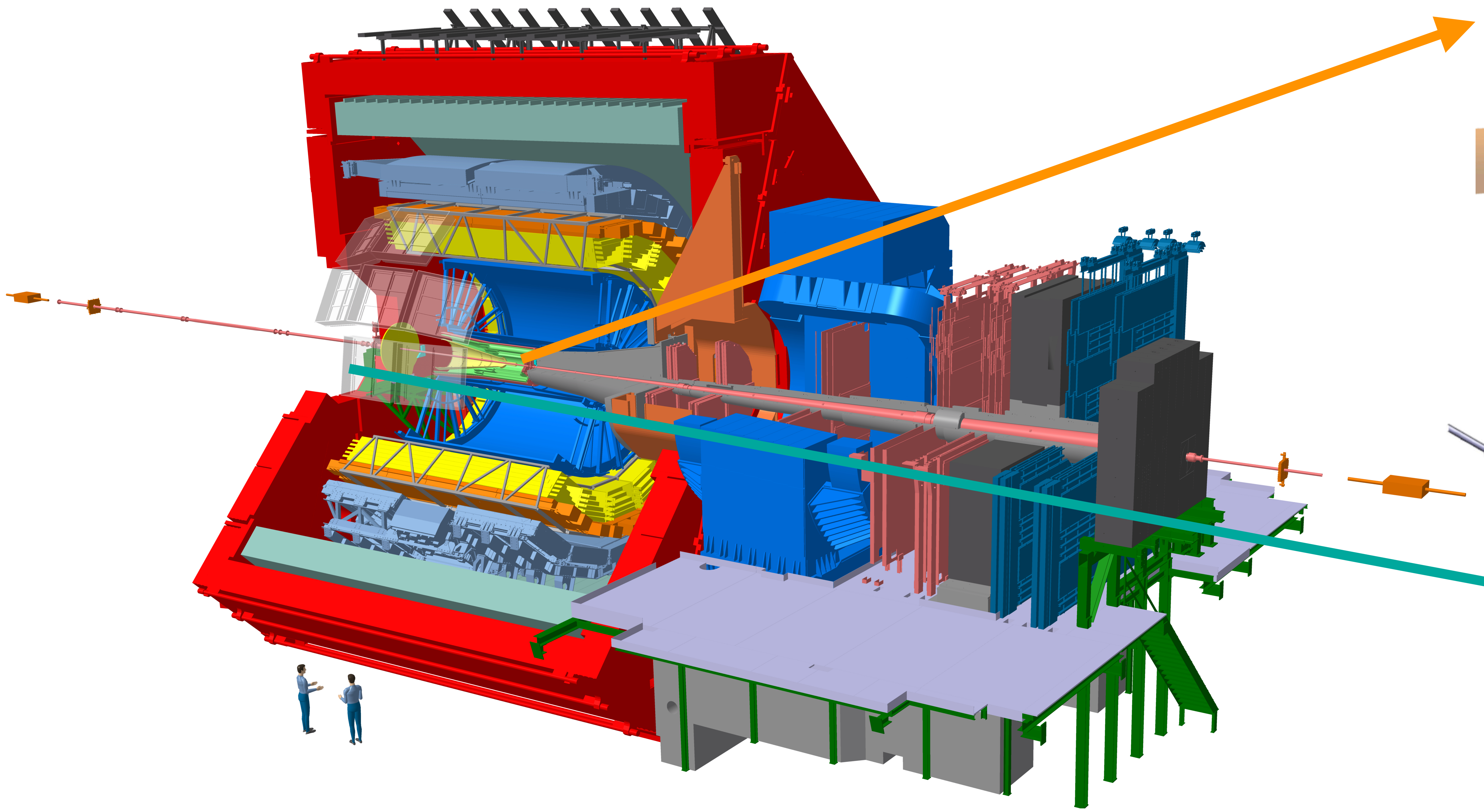




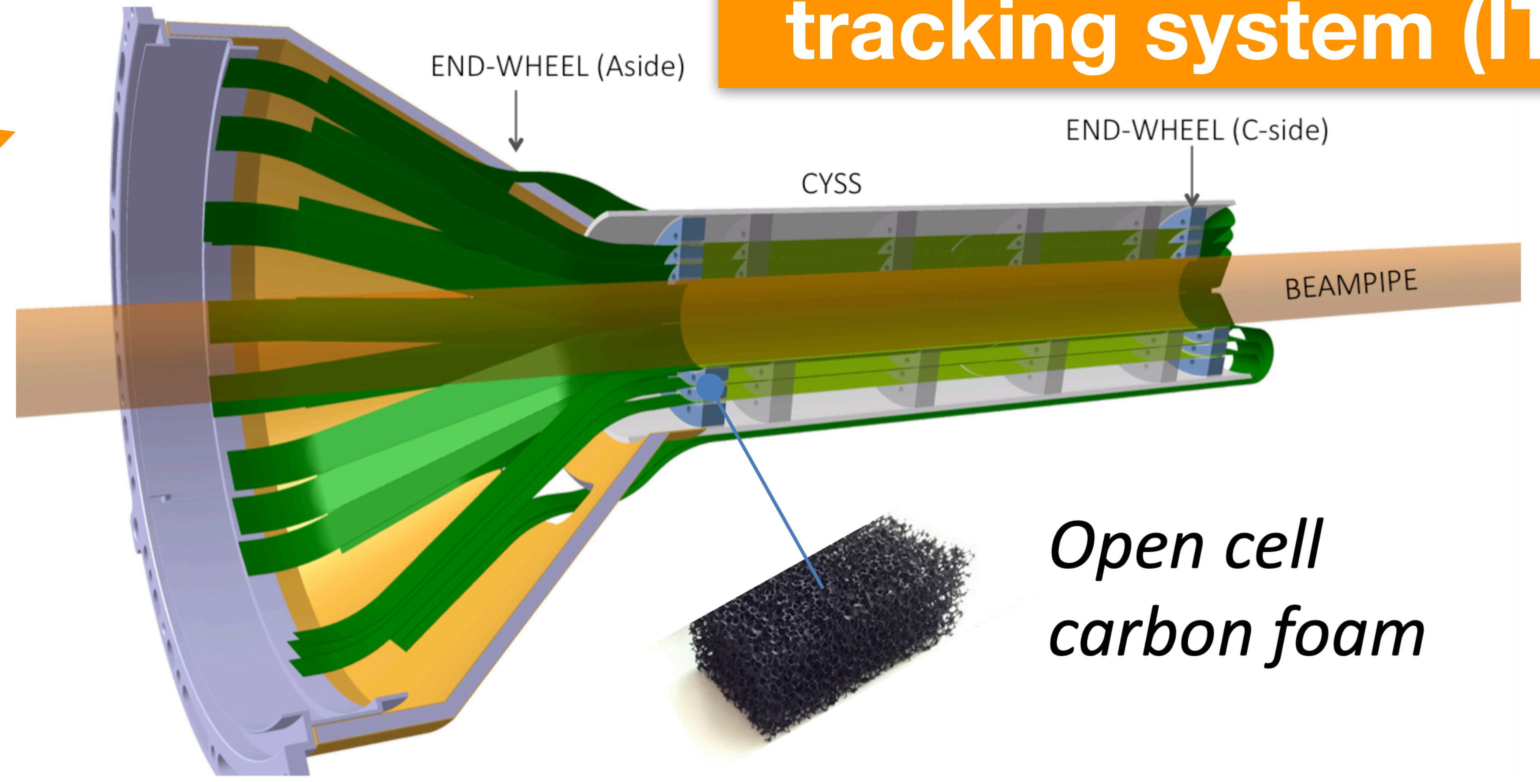
- SHM agrees with data within uncertainties
- PYTHIA with neither Monash nor CR-BLC reproduces data
- Ratio sensitive to c-diquark spin-1 to spin-0 suppression factor

Femtoscopy of the QCD

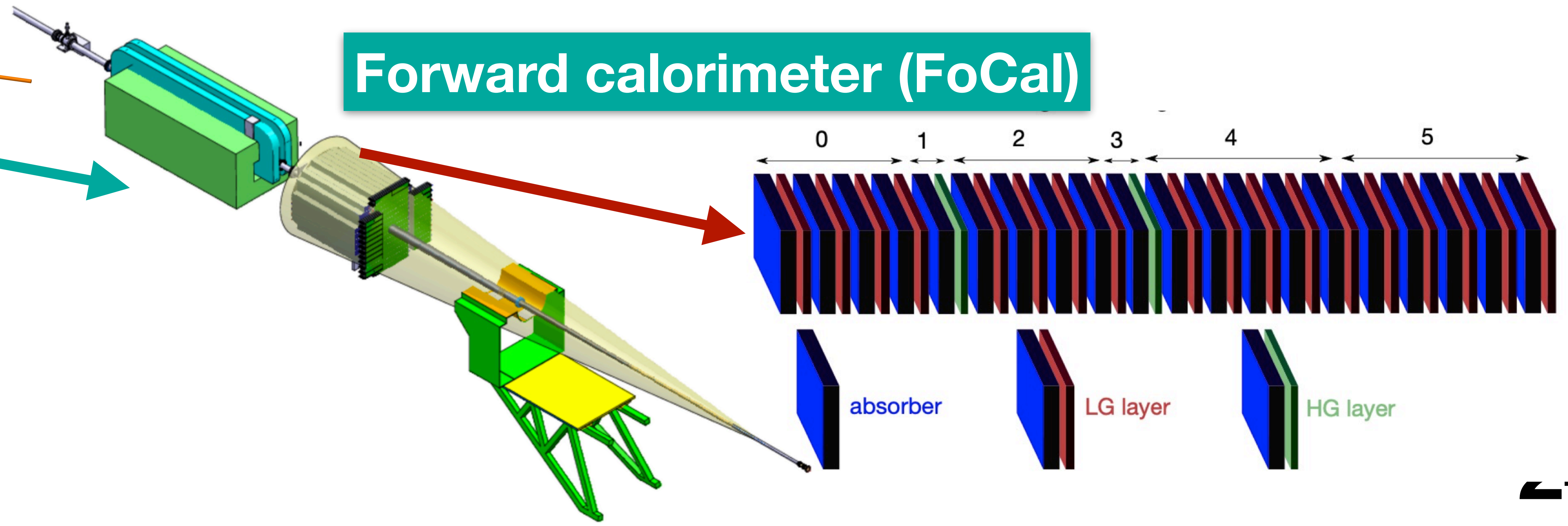
2010-2013		2015-2018		2022-2025		2029-2032		2035-2038		
Run1	LS1	Run2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
ALICE 1				ALICE 2		ALICE 2.1		ALICE 3		



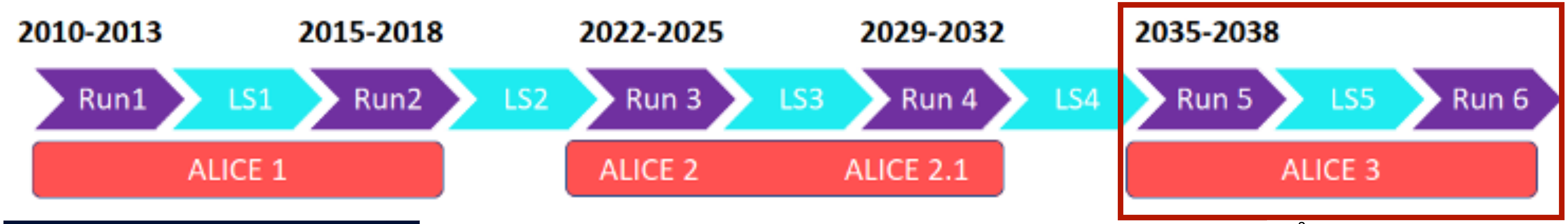
The 3rd generation inner tracking system (ITS3)

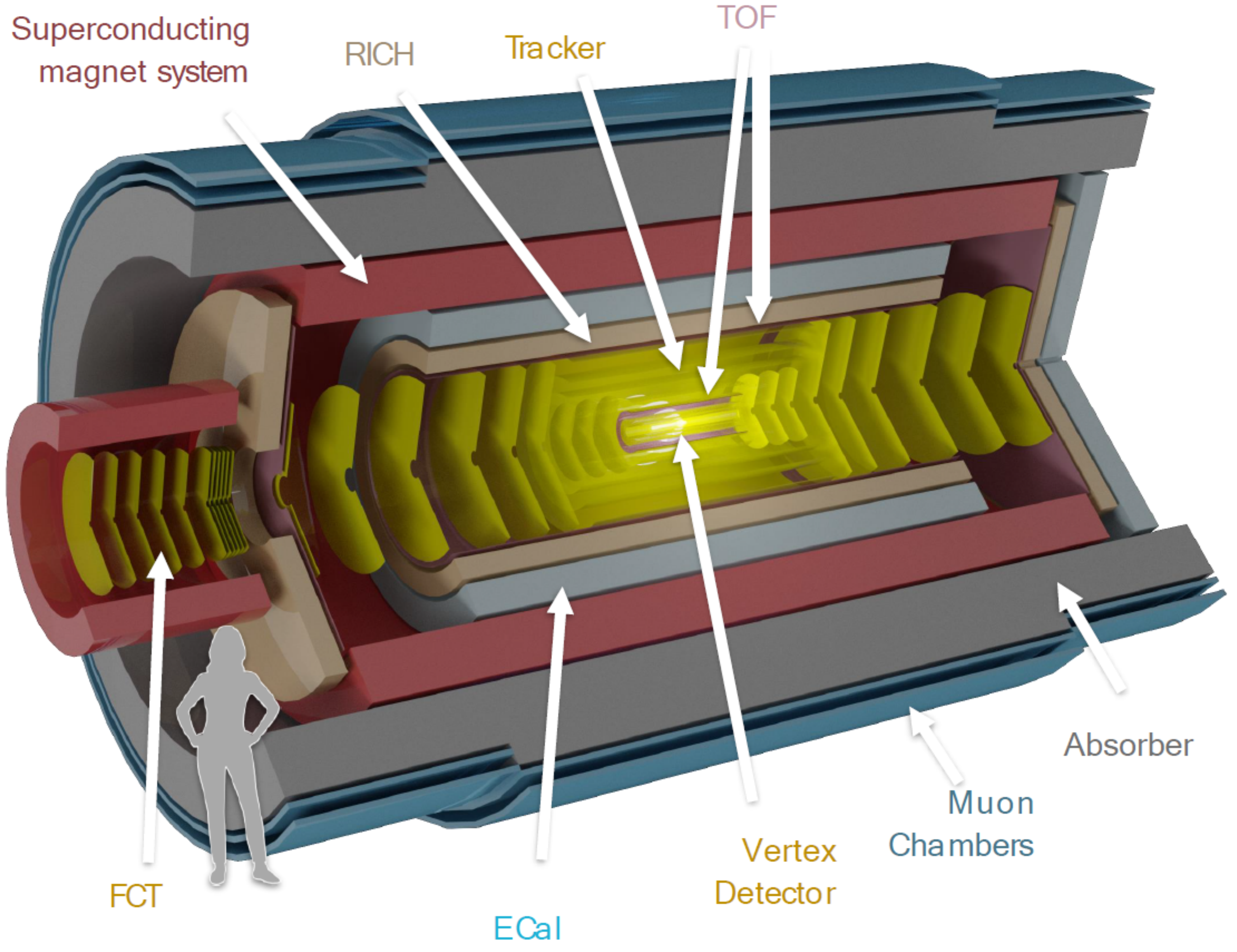


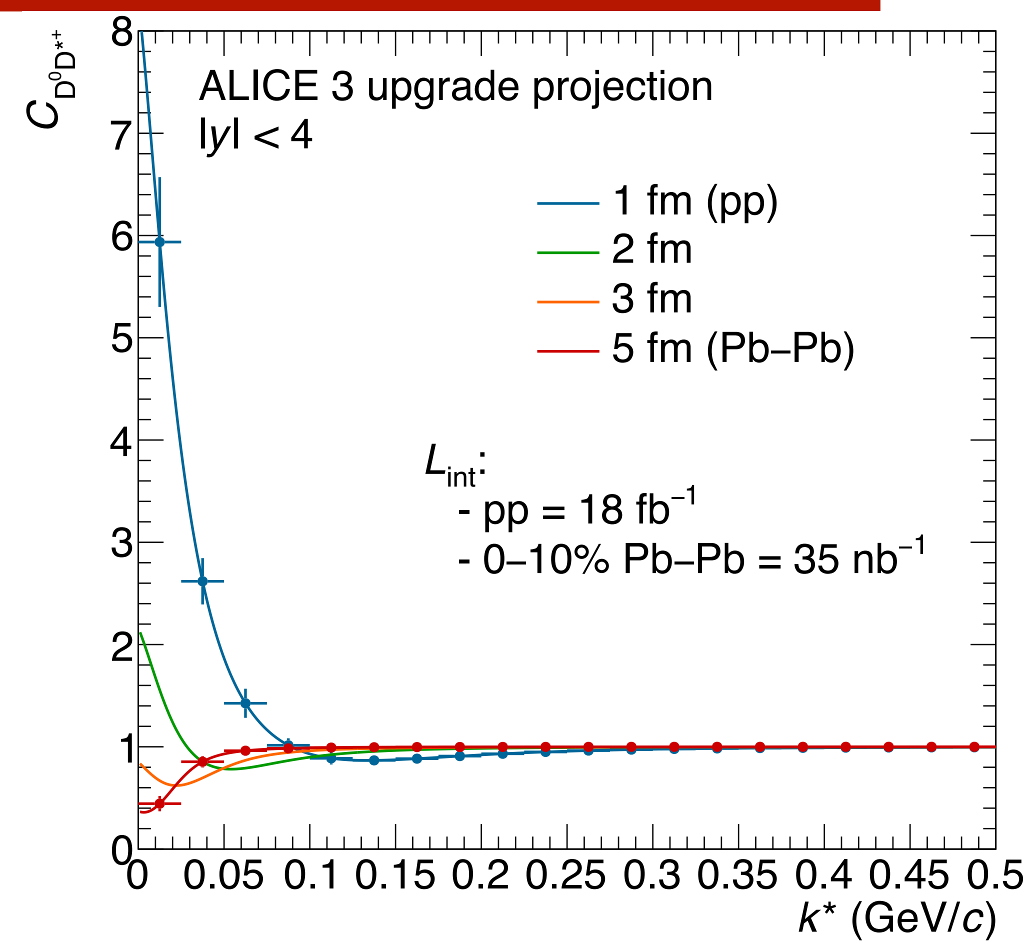
Forward calorimeter (FoCal)

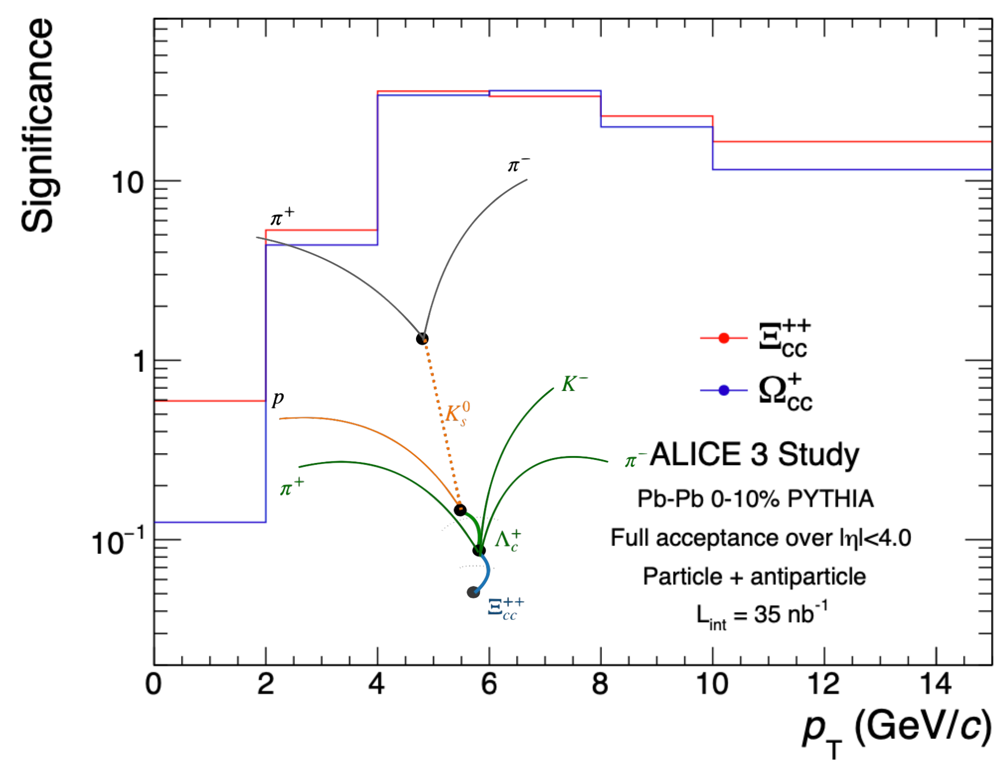


Next-generation experiment



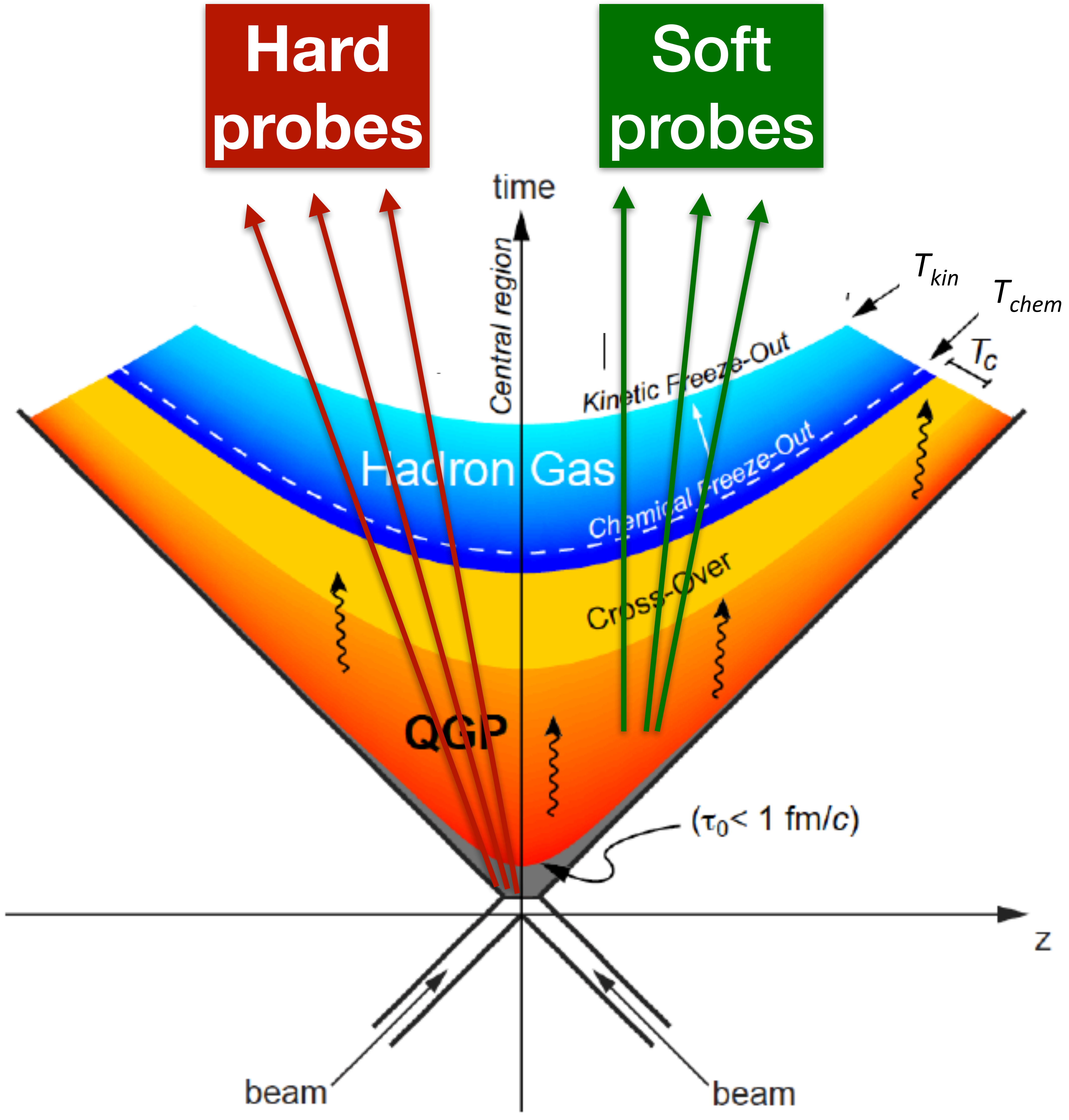






Backup

Signatures of the QGP



Heavy-ion collisions probe the strongly-interacting matter — the quark-gluon plasma (QGP) under extreme conditions of high temperature and energy density

Hard probes created at initial stage of the collision

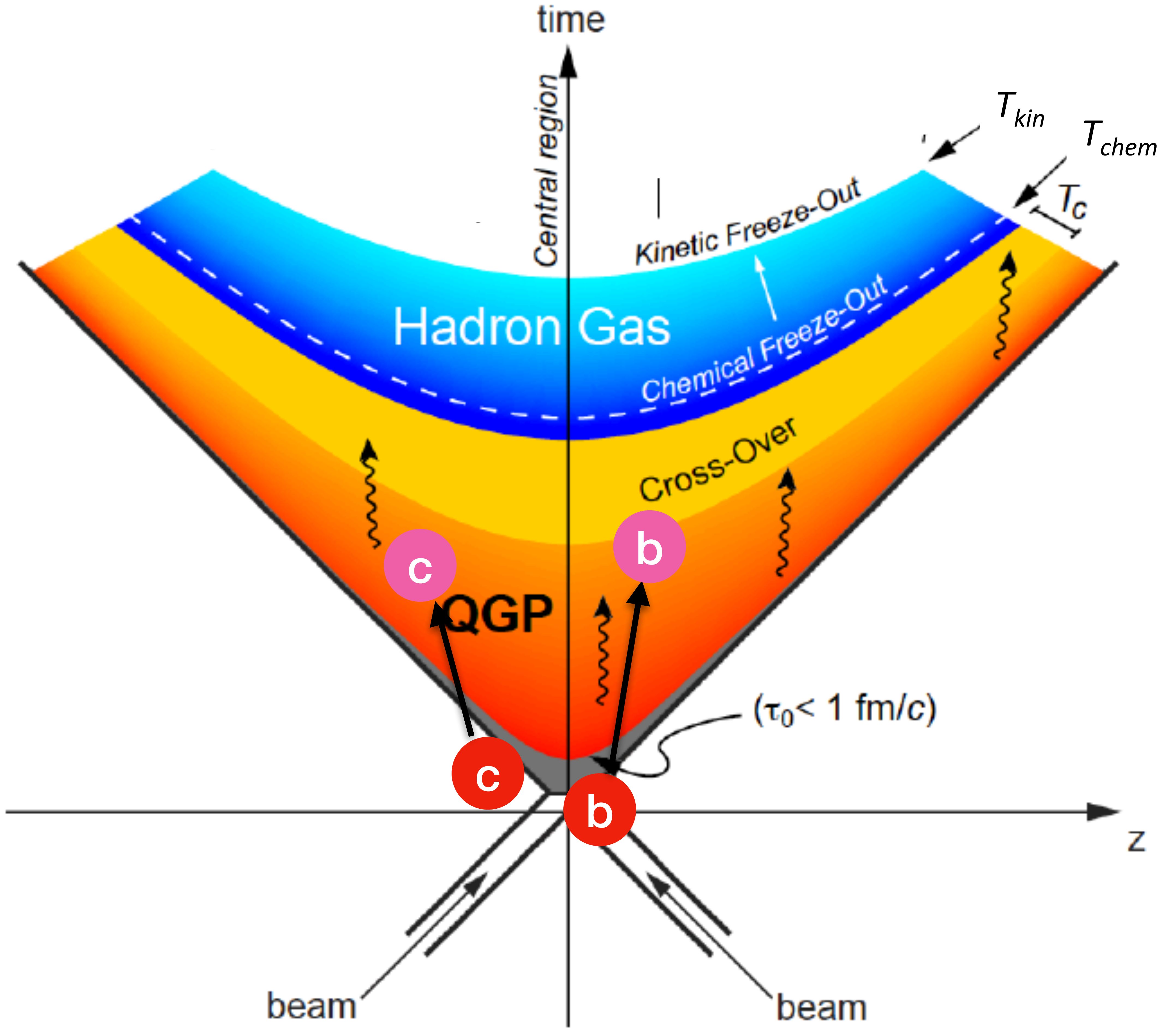
➡ QGP tomography

Soft probes created in the "fireball"

➡ Fingerprint of the QGP evolution

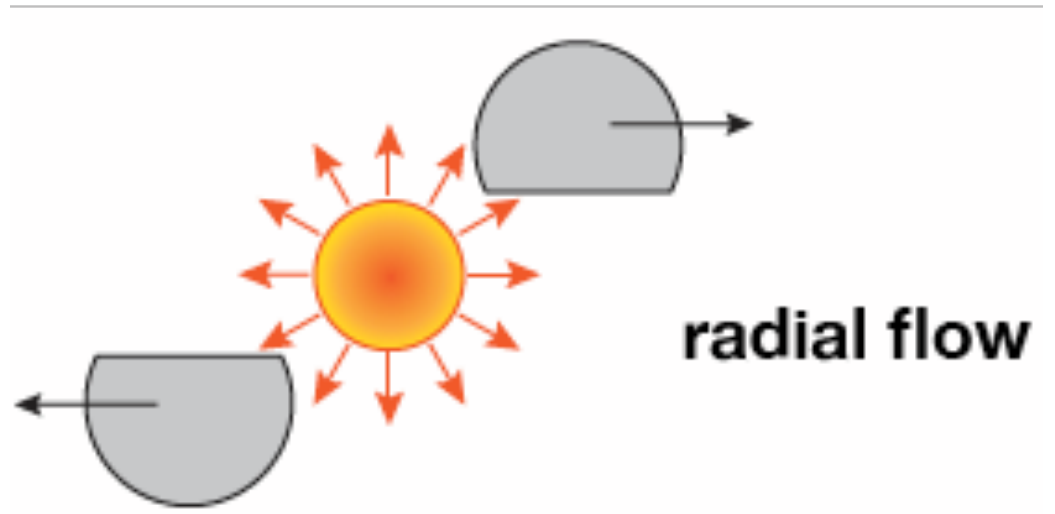
Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation



Collective expansion

➡ Radial flow



➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

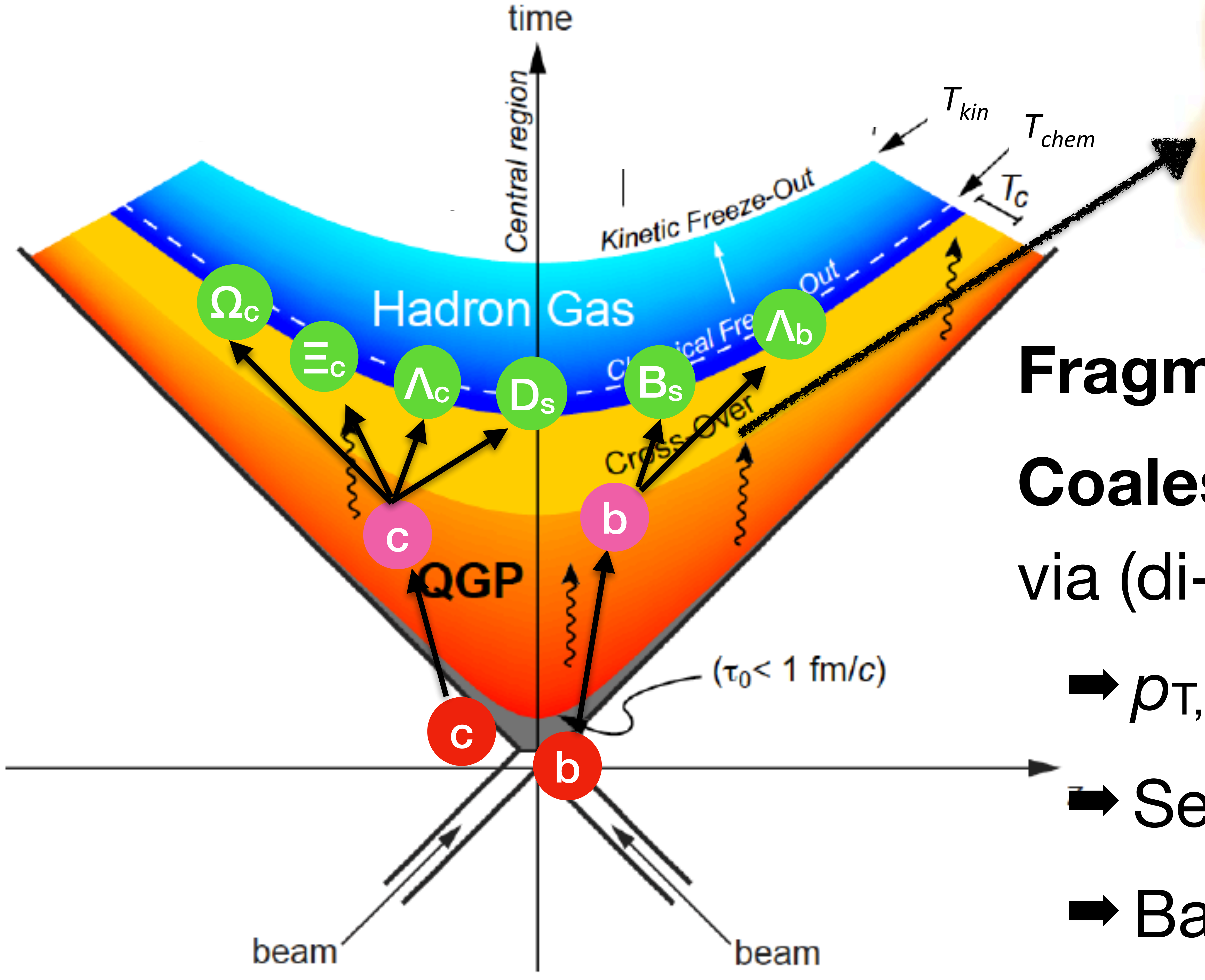
p_0: initial momentum
β: flow velocity
m: particle mass

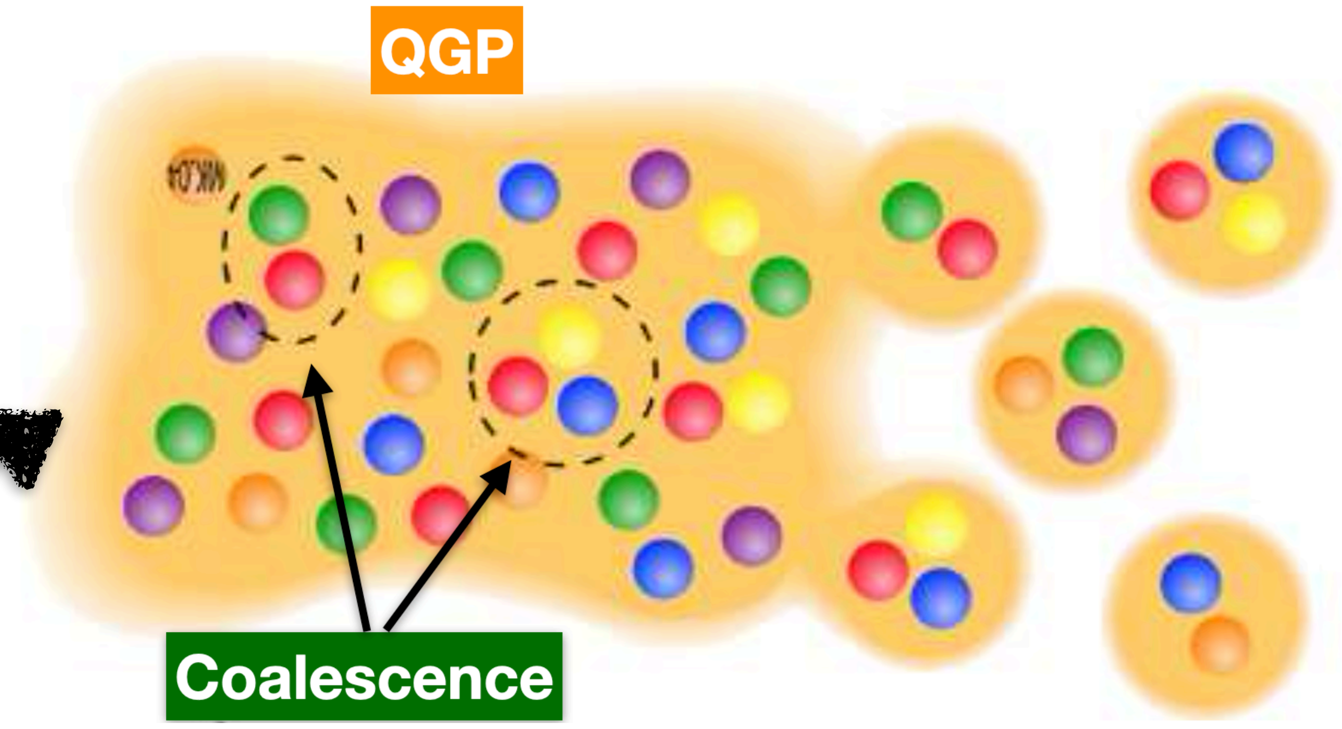
➡ More pronounced in central collisions

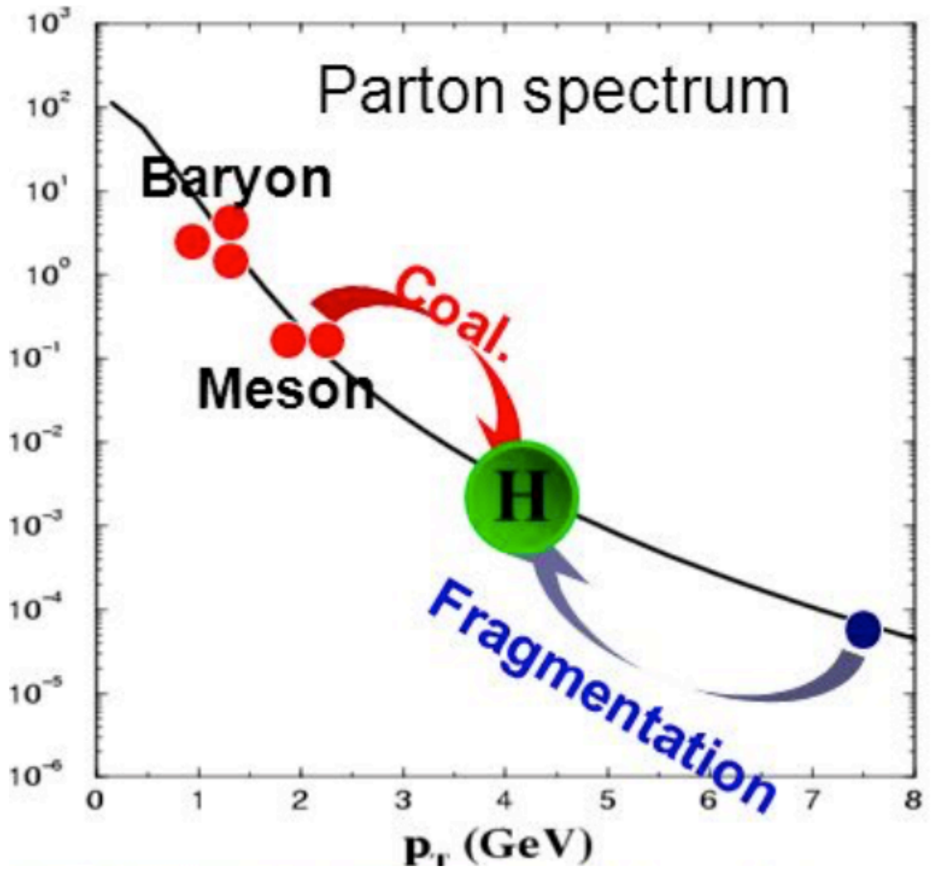
➡ Mass dependence

Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation







Fragmentation — hadrons from high p_T partons

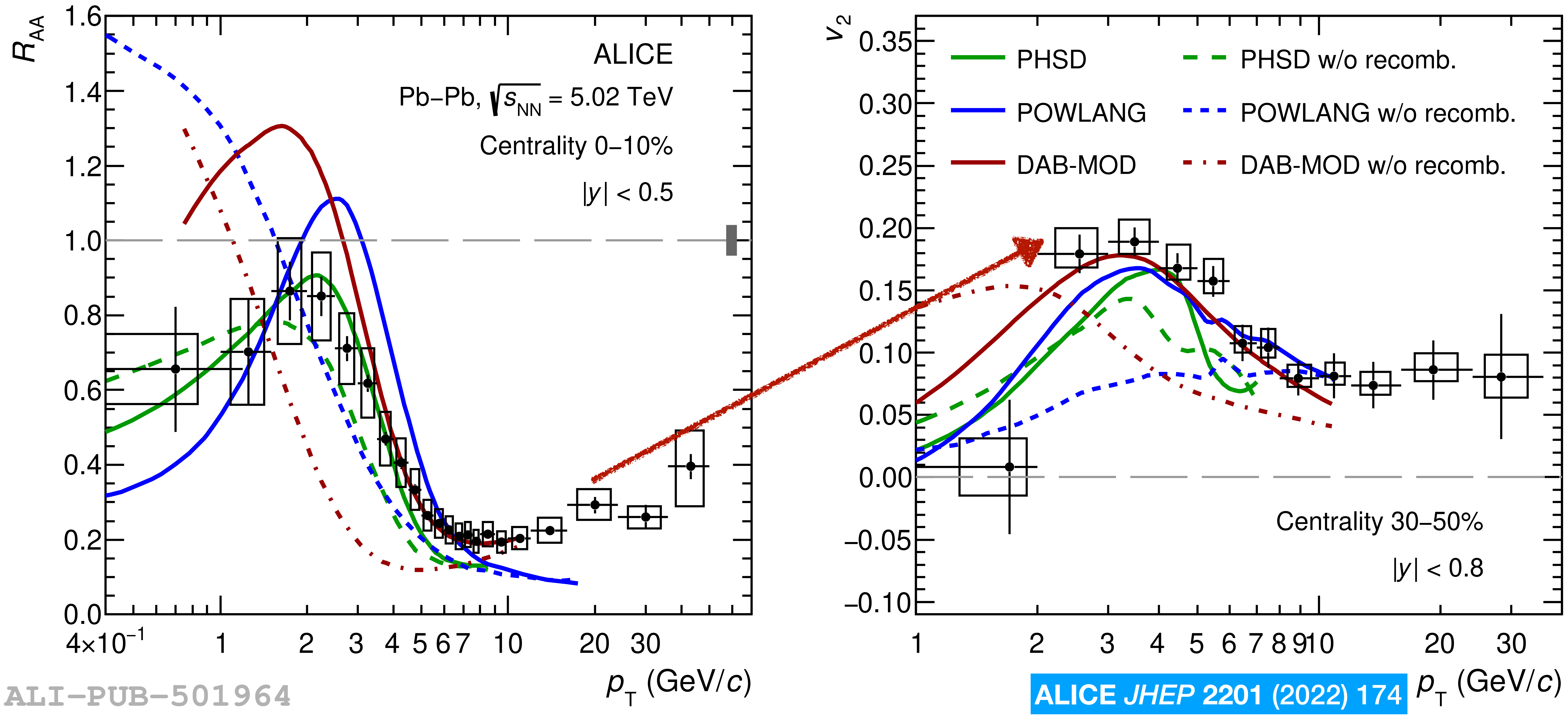
Coalescence/recombination — hadron formation via (di-)quark combination in the QGP medium

➡ $p_{T,hadron} \simeq n\, p_{T,parton}$, n = 2 (meson), 3 (baryon)

➡ Sensitive to baryon and meson species

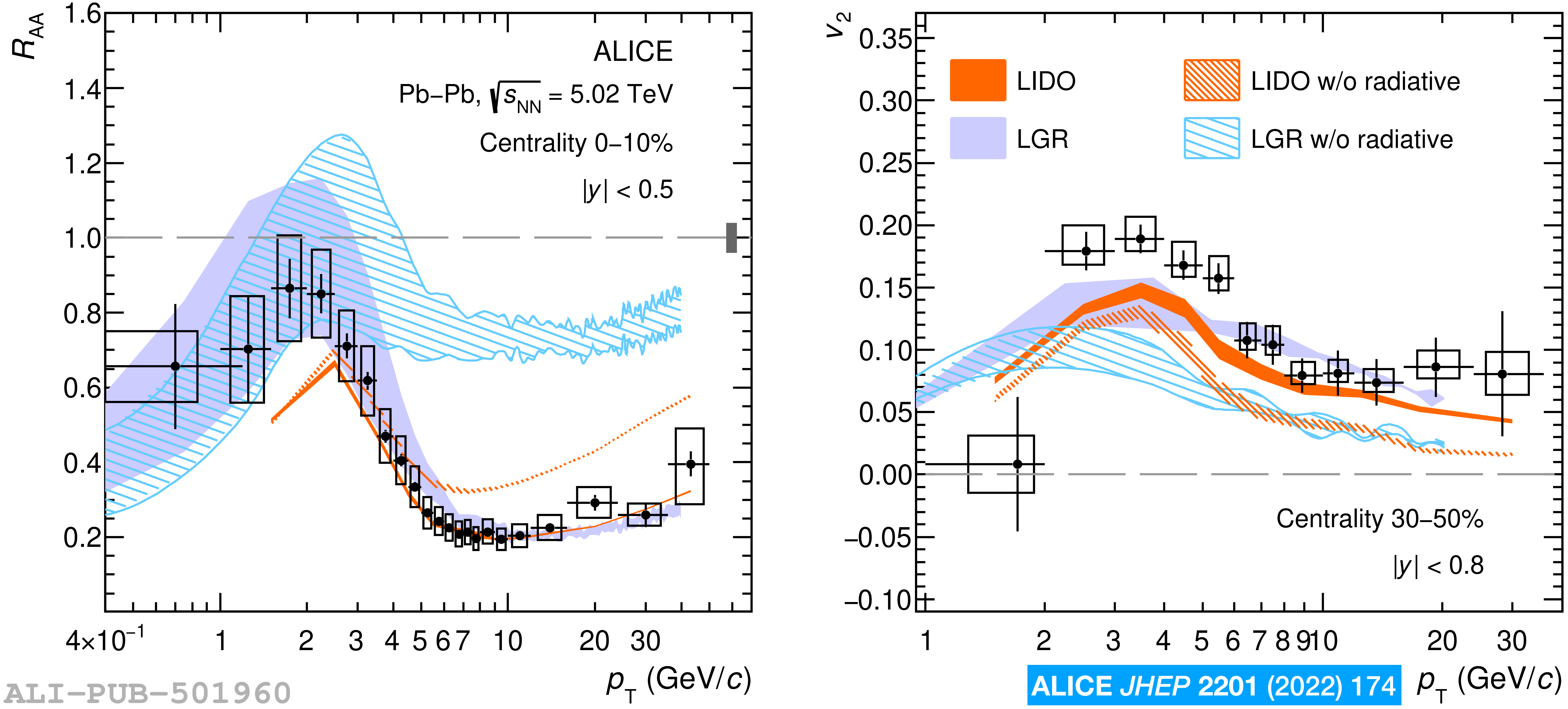
➡ Baryons from lower momenta partons (denser)

Charm quark transport



- Significant charmed hadron v_2 coefficient — consistent with strong suppression
- Hadronization via coalescence is important at low and intermediate p_T

Charm quark transport

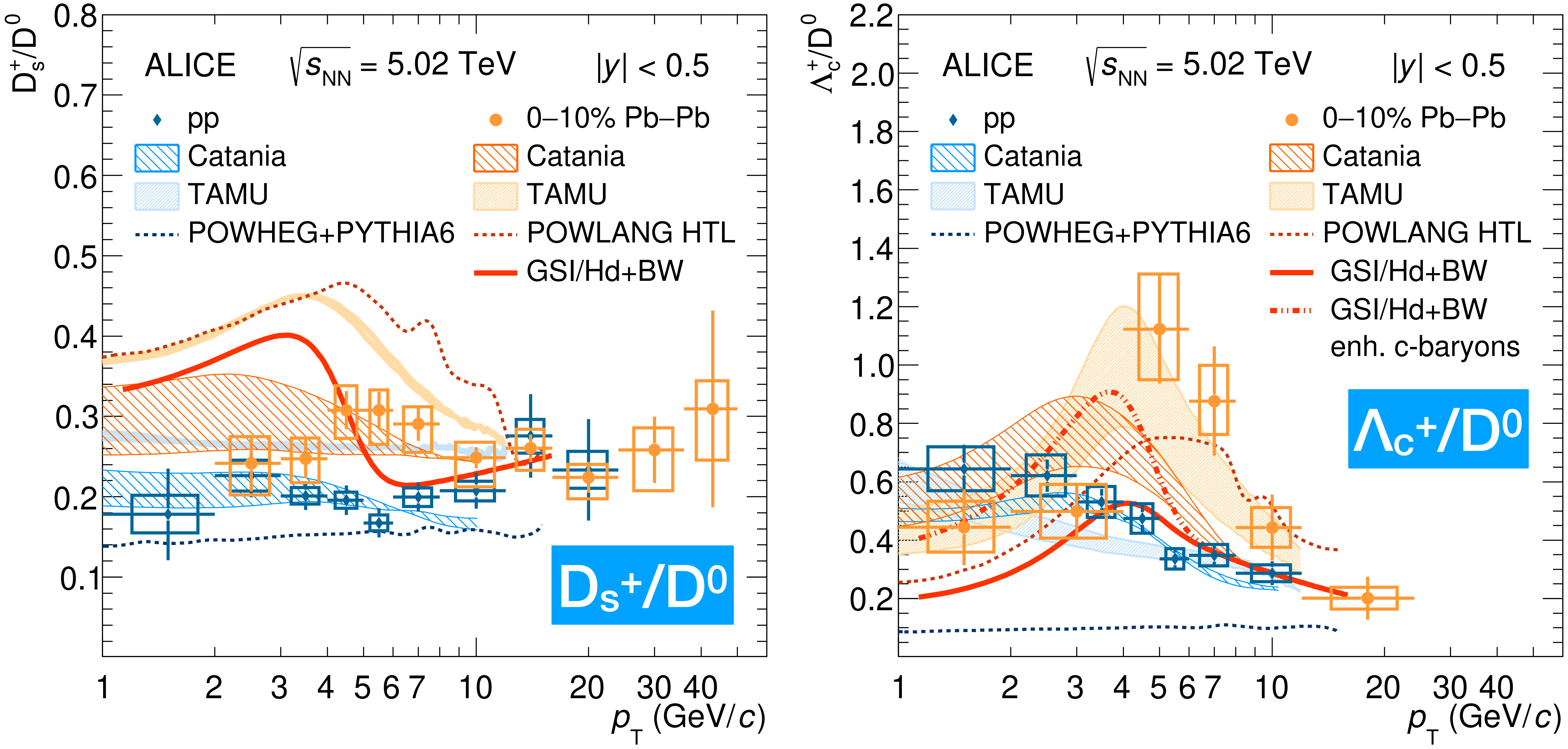


- Significant charmed hadron v_2 coefficient — consistent with strong suppression
- Radiative energy loss is important at intermediate and high p_T

Charm quark hadronization

Pb–Pb

pp



- Hints of enhanced D_s^+/D^0 ratio at intermediate p_T in Pb–Pb w.r.t. pp — support charm hadronization via recombination
- Enhanced Λ_c/D^0 ratio in Pb–Pb w.r.t. pp — suggest interplay between recombination and radial flow

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ALICE arXiv:2211.04384

Strange-beauty hadron R_{AA}

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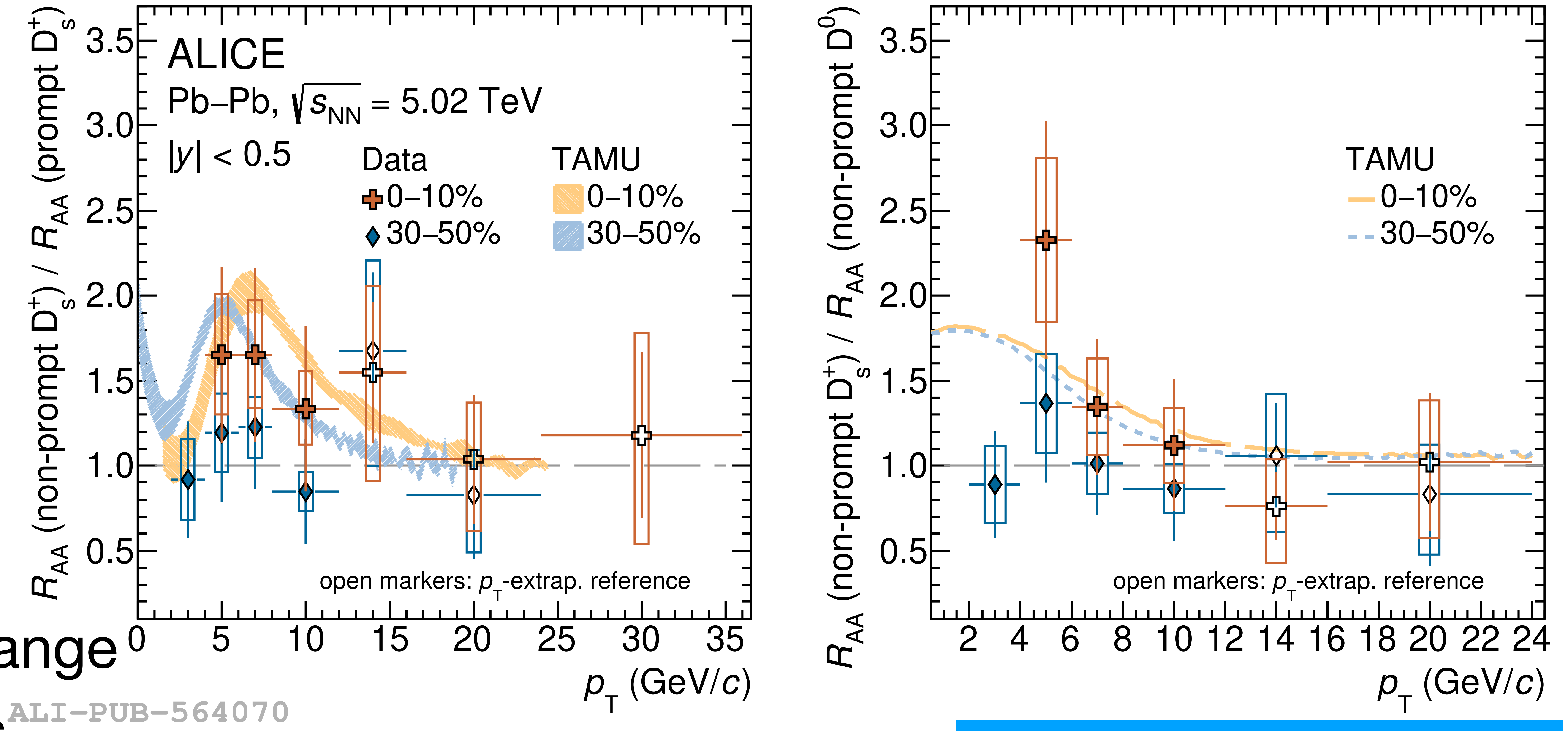
In p_T < 6 GeV/c

- $R_{AA}(b \to D_s^+) > R_{AA}(D_s^+)$
  ➡ Hint of quark mass dependent energy loss

- $R_{AA}(b \to D_s^+) > R_{AA}(b \to D^0)$
  ➡ Recombination with strange quarks in a strangeness-rich environment



ALICE *Phys. Lett.* B846 (2023) 137561

TAMU model: energy loss via collisional processes, and hadronisation via coalescence and fragmentation

➡ Qualitatively describes data