Overview of recent results on open heavy flavour production (mainly) with ALICE at the LHC

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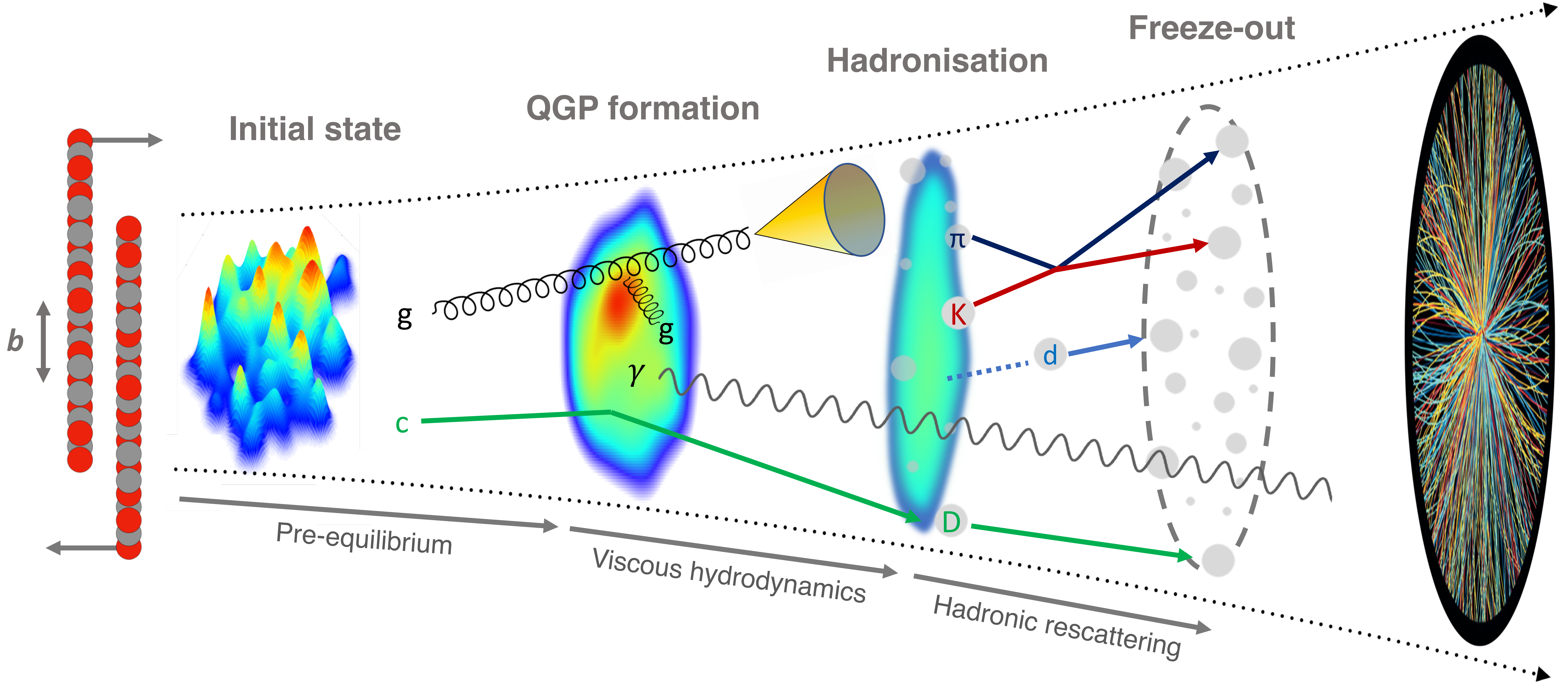
原子核结构与相对论重离子碰撞前沿交叉研讨会

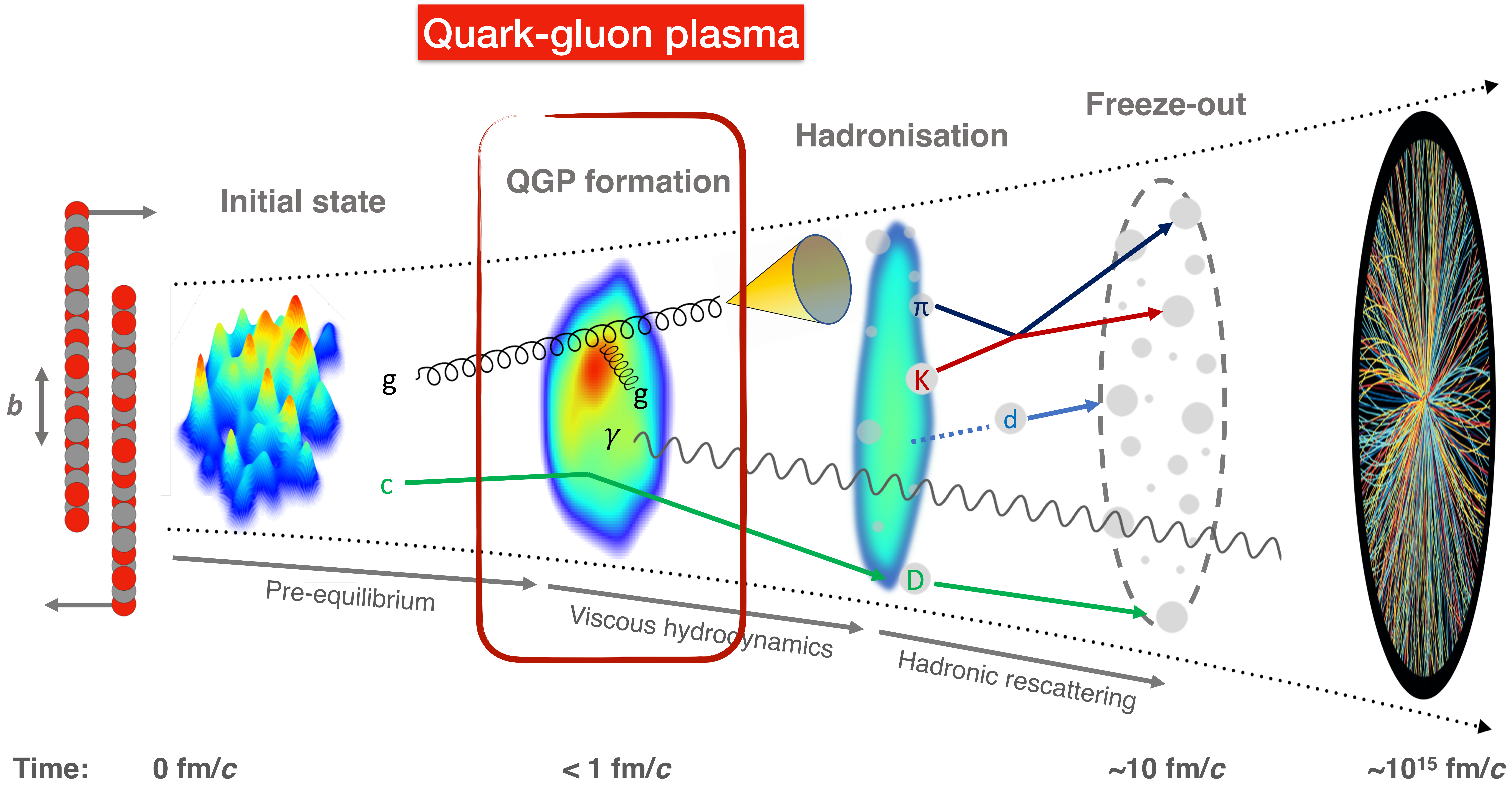
31 July – 6 Aug 2023, Dalian, China

Heavy-ion collisions

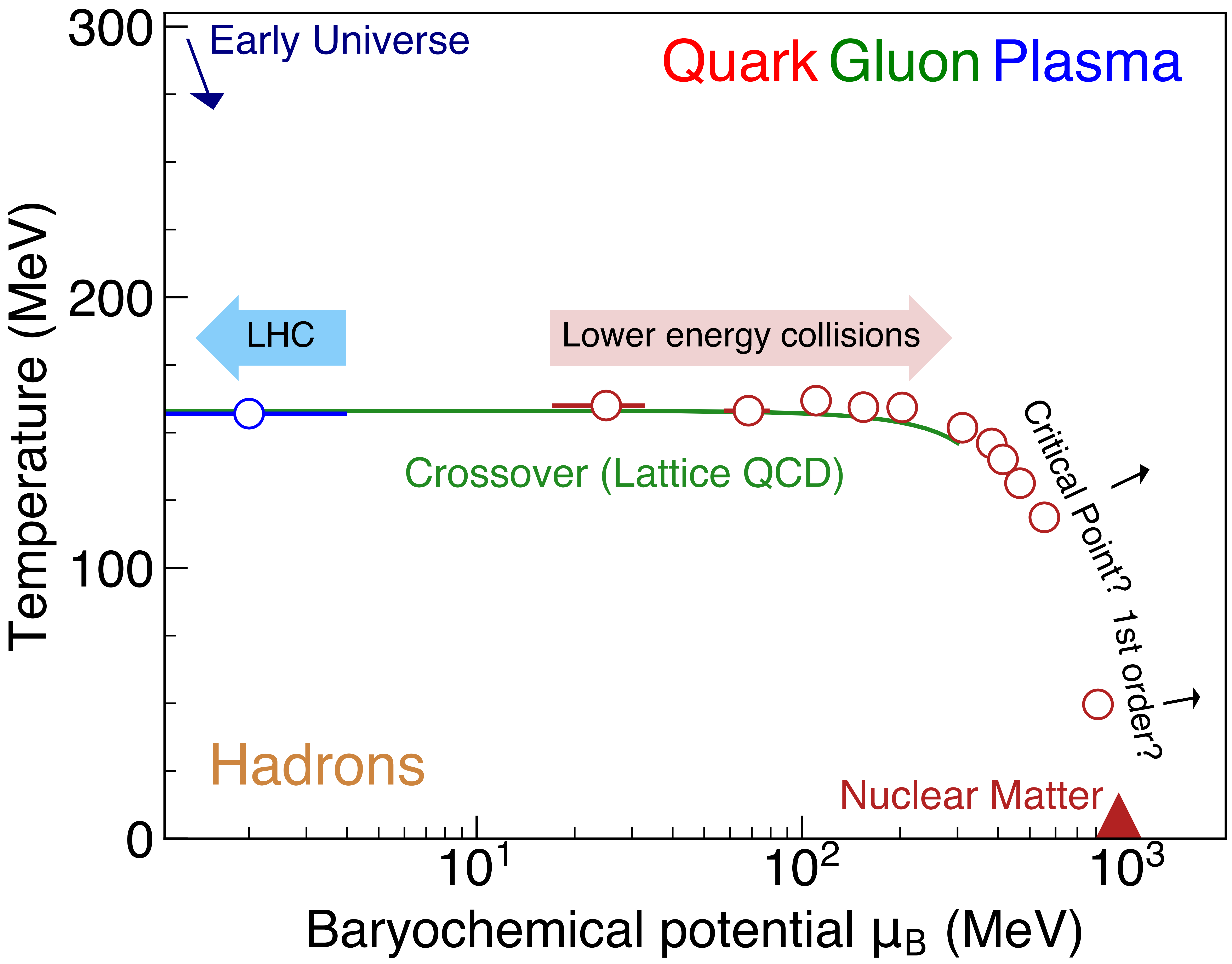


Time: 0 fm/c < 1 fm/c ~10 fm/c ~10^{15} fm/c

Heavy-ion collisions



QCD phase diagram



Signatures of the QGP

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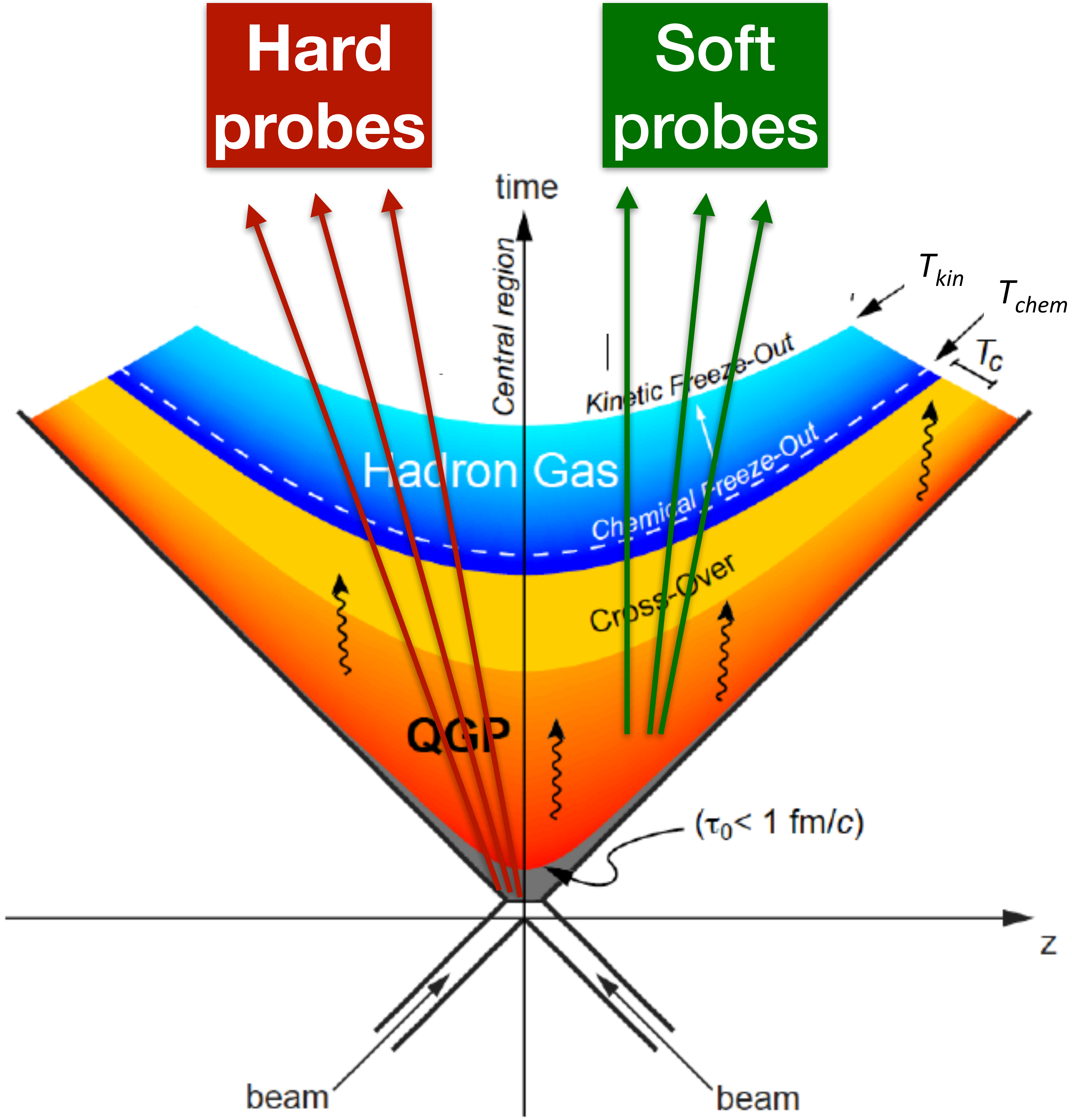


Heavy-ion collisions probe the strongly-interacting matter — the quark-gluon plasma (QGP) under extreme conditions of high temperature and energy density

Hard probes created at initial stage of the collision

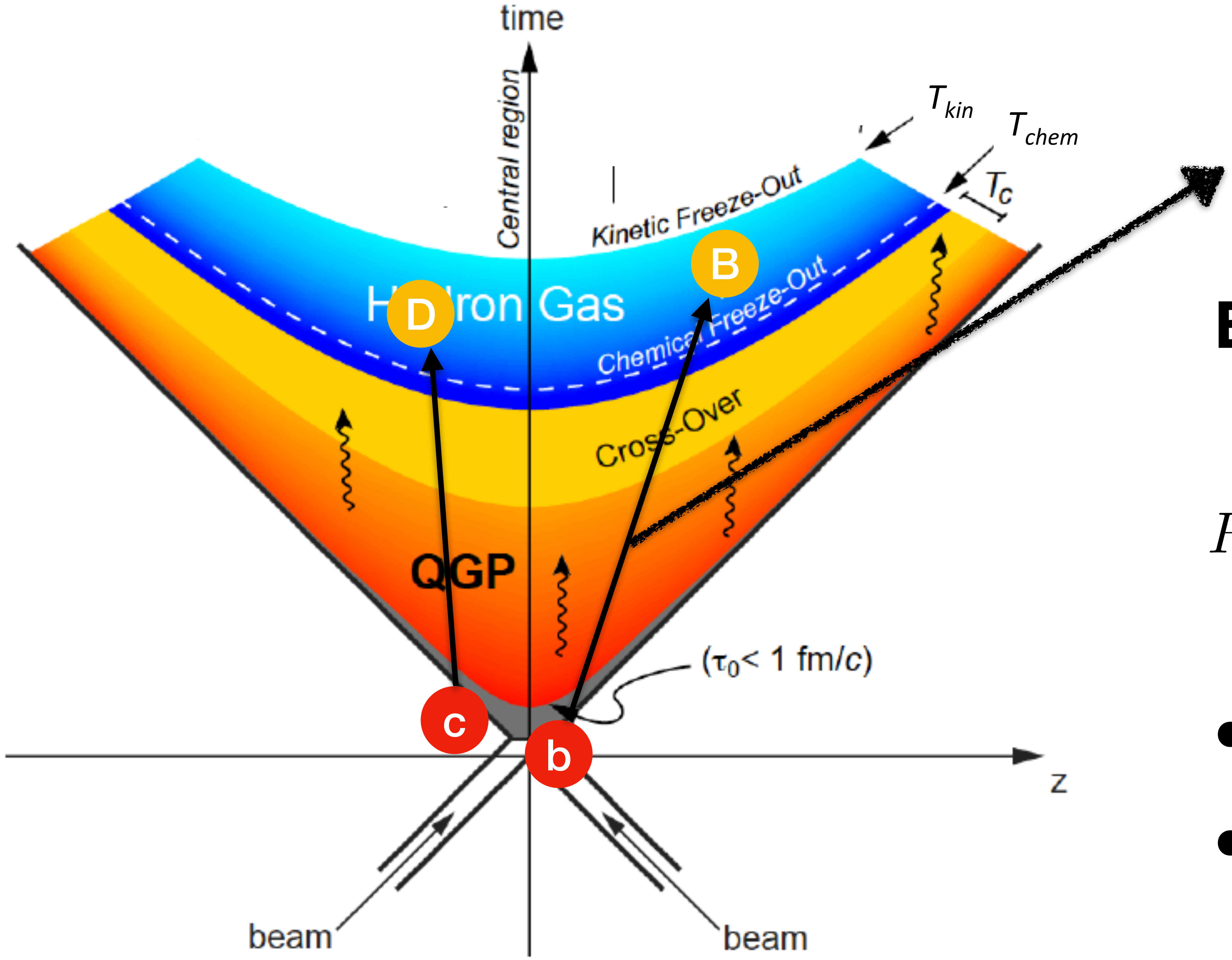
➡ QGP tomography

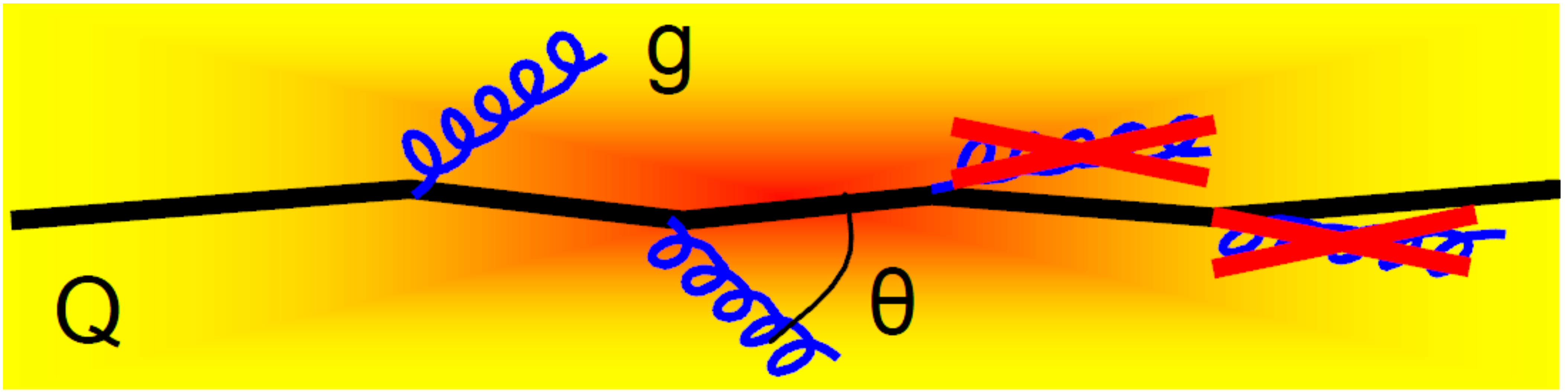
Soft probes created in the "fireball"

➡ 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





Energy loss in QGP medium

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{< T_{AA} > d\sigma_{pp}/dp_T}$$

QCD medium

QCD vacuum

- R_{AA} = 1 if no medium effect
- Radiative vs. collisional energy loss

Heavy quarks: QGP tomography

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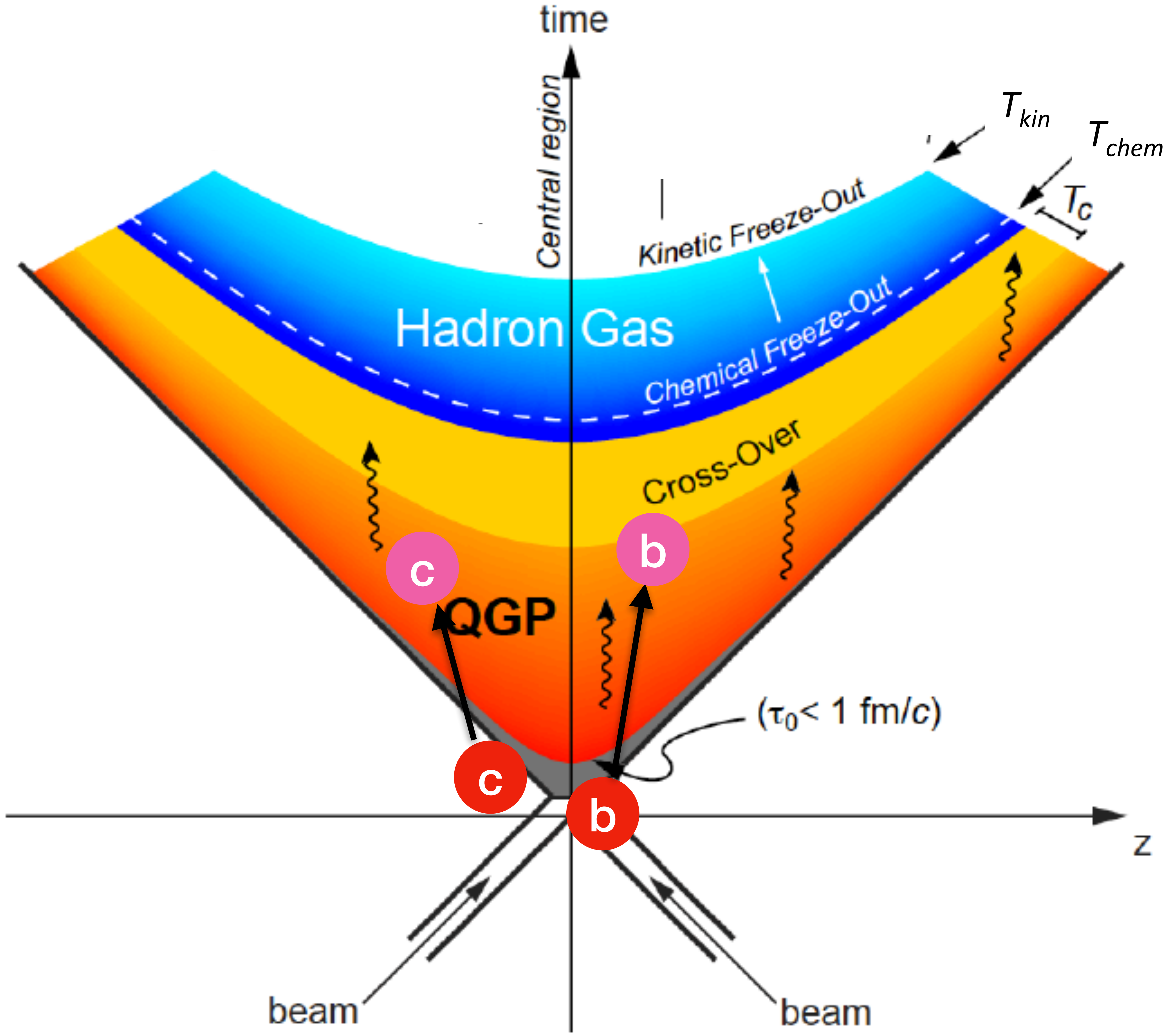
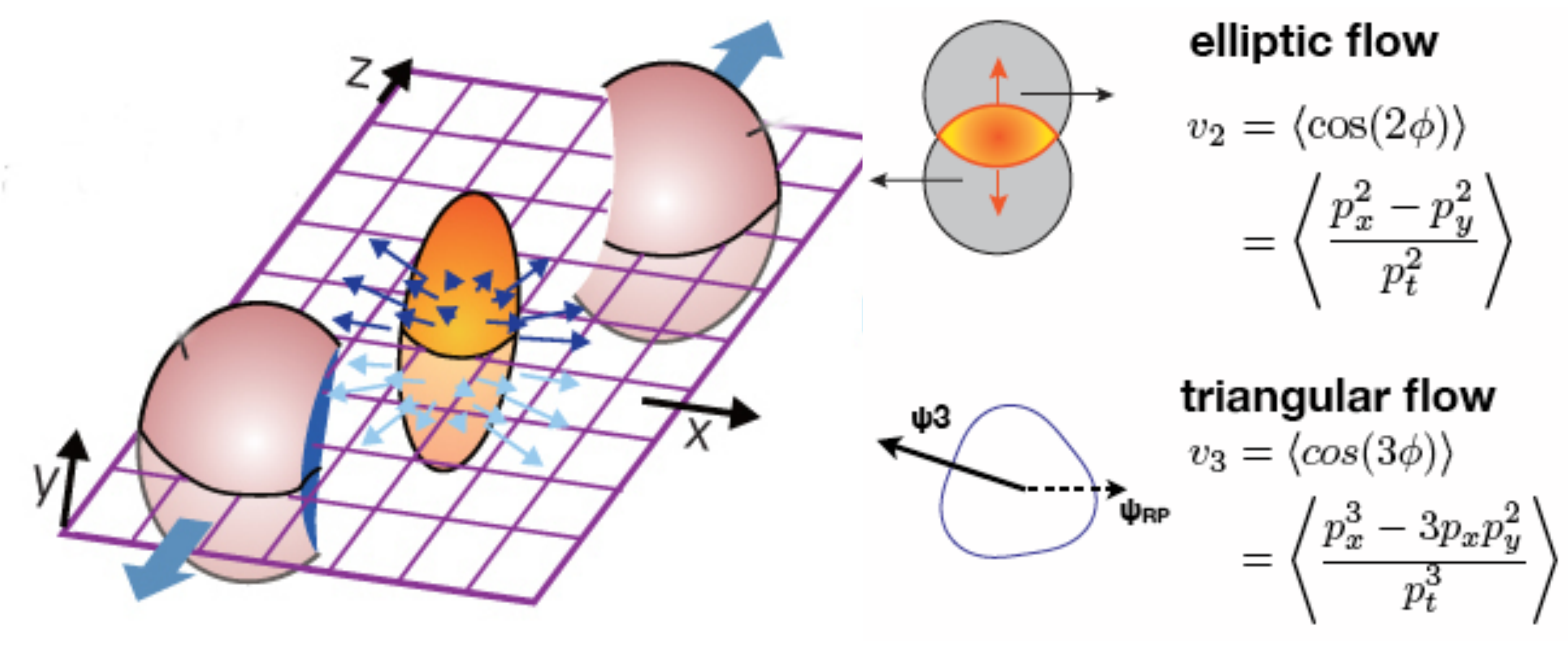


Collective expansion

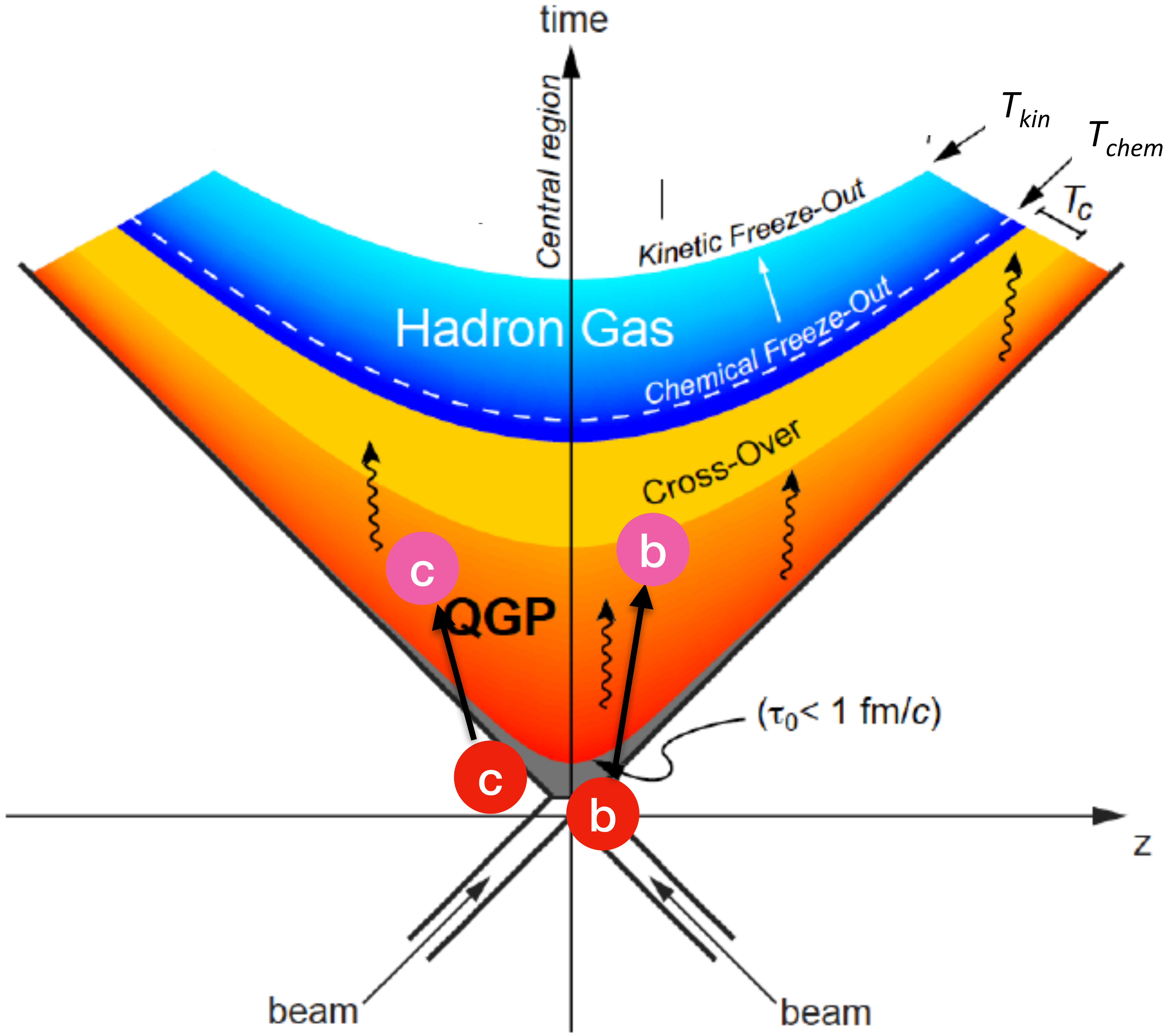
➡ Anisotropic flow



➡ Results in complex azimuthal structure of final state particles

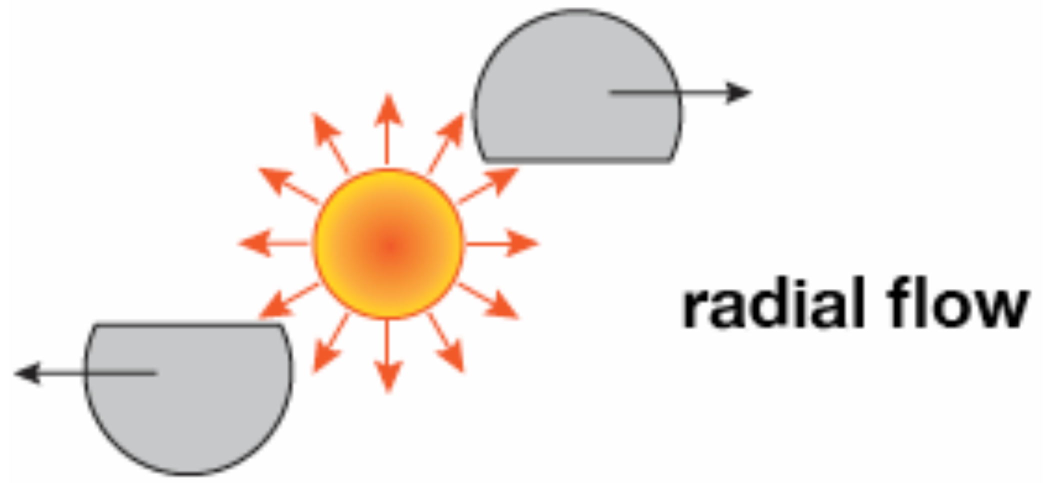
Heavy quarks: QGP tomography

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

$$p = p_0 + \beta m$$

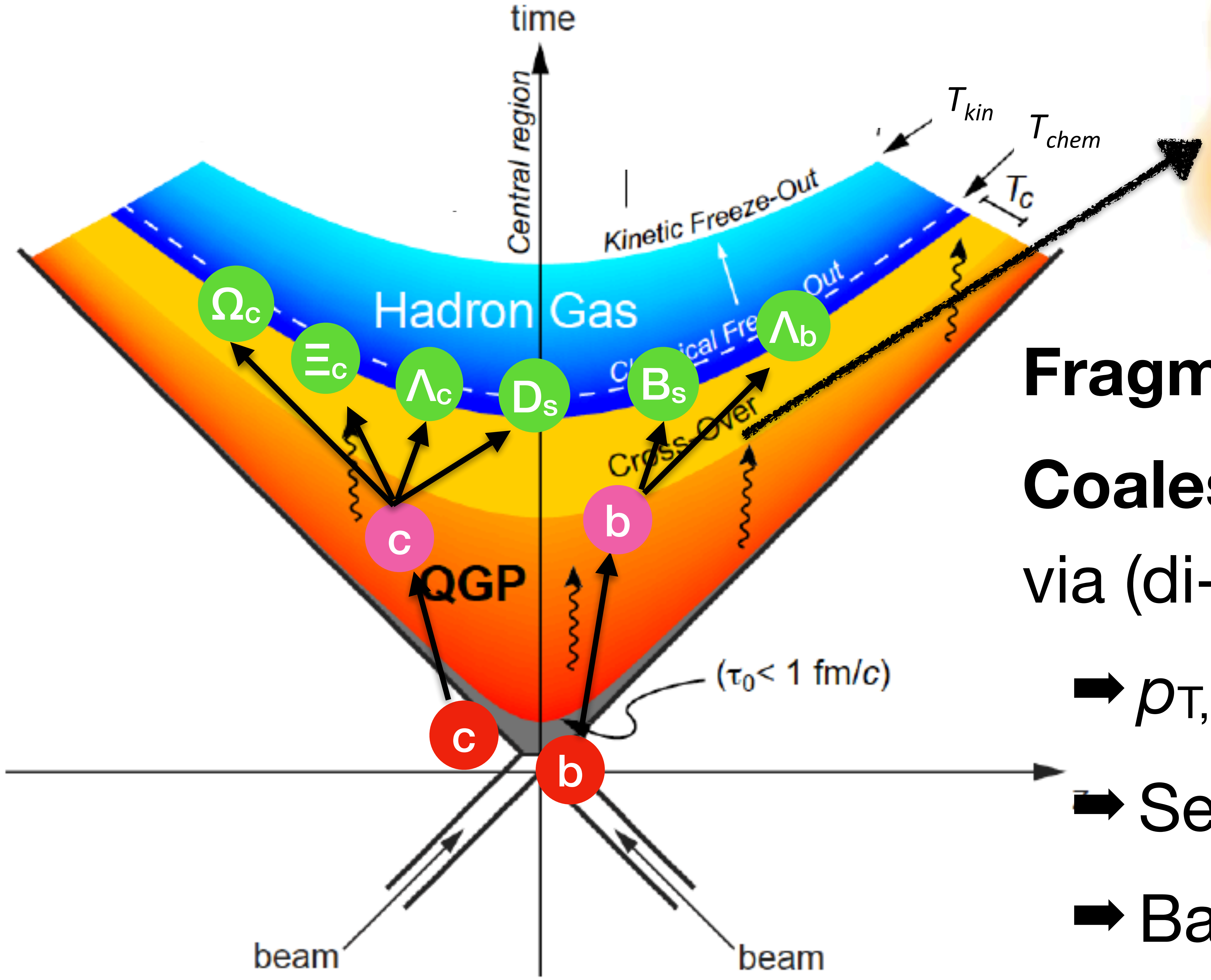
p_0: initial momentum
β: flow velocity
m: particle mass

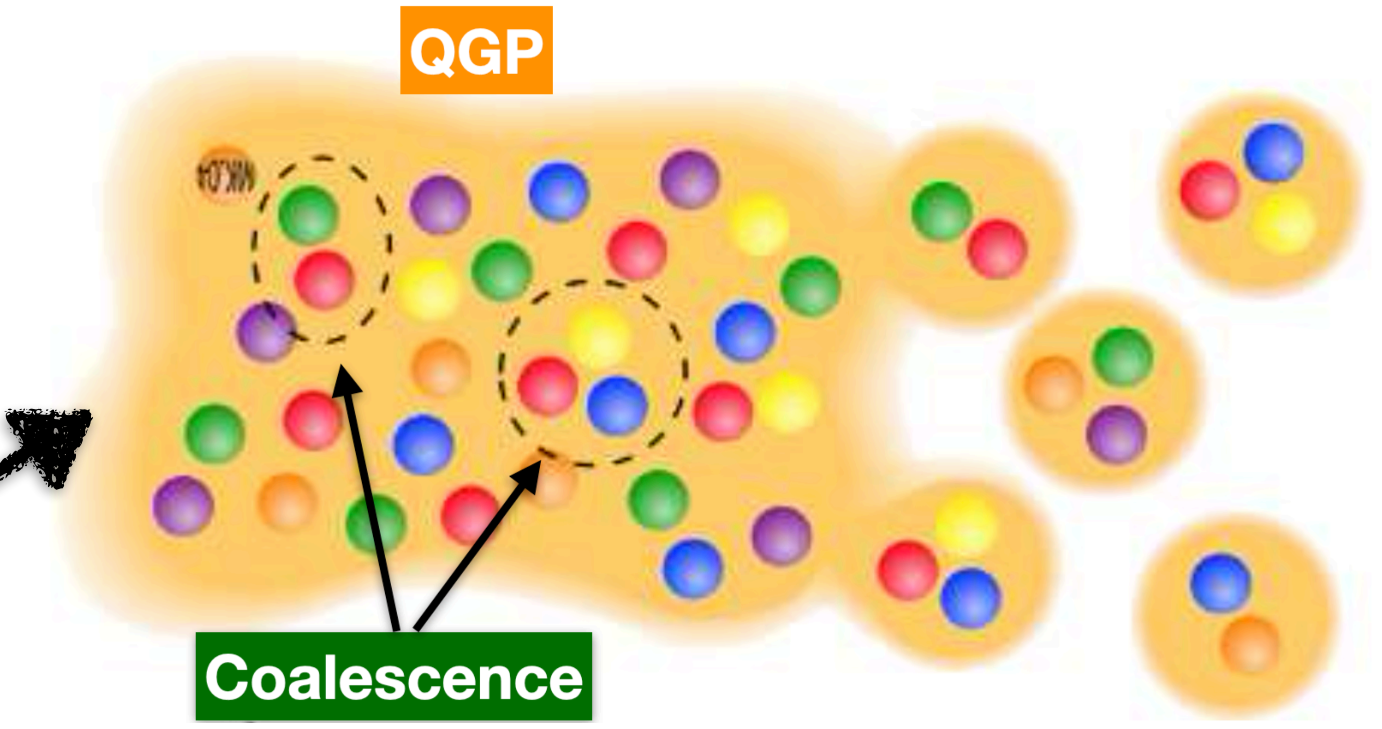
➡ More pronounced in central collisions

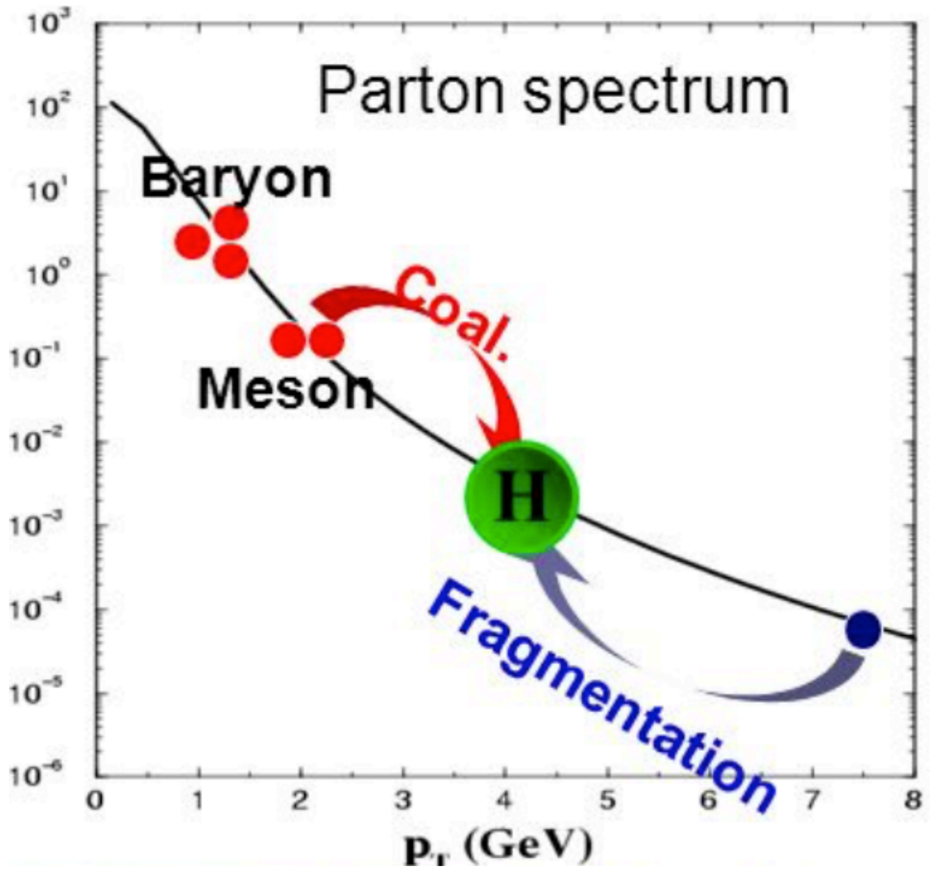
➡ Mass dependence

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

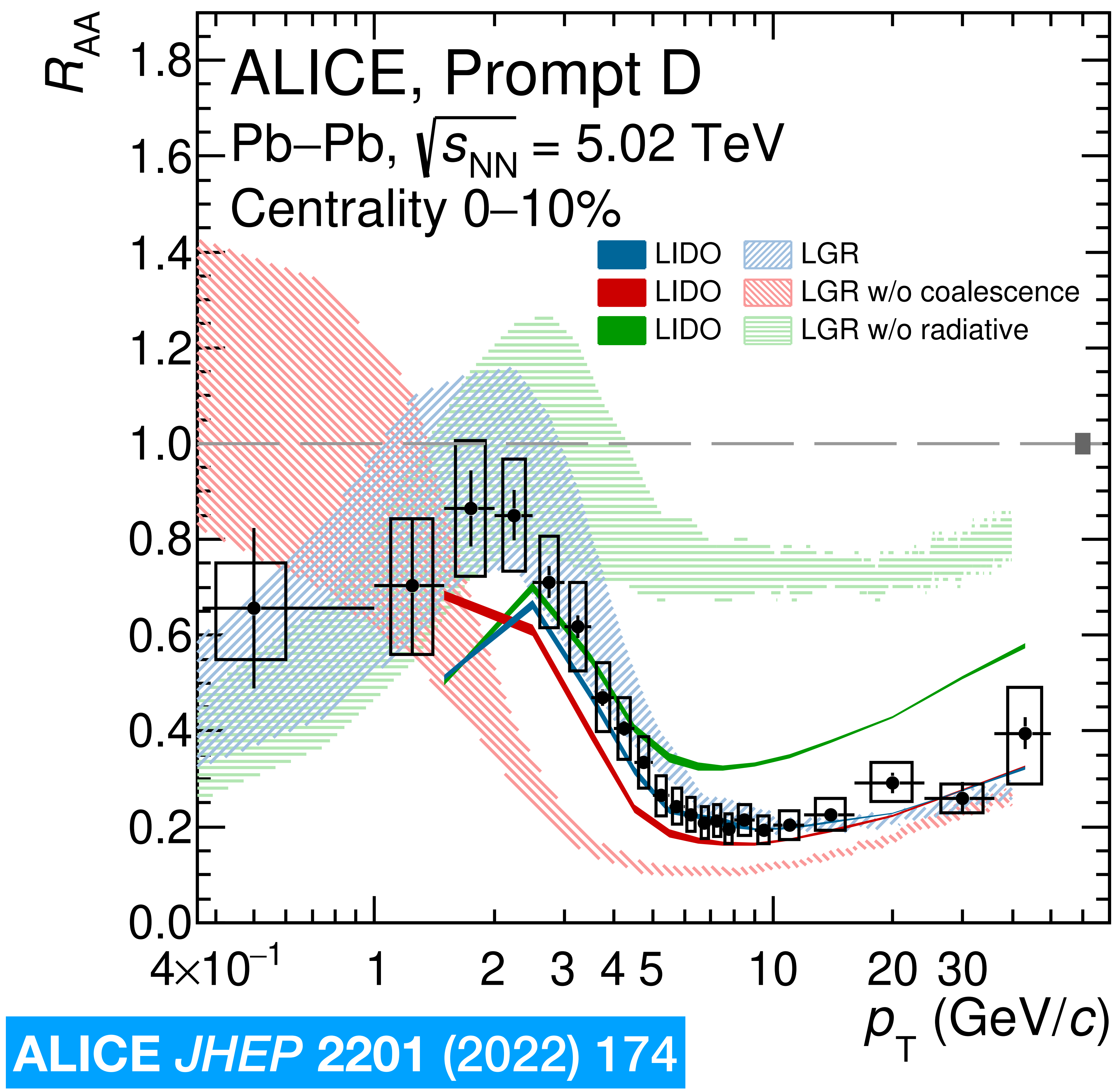
Coalescence/recombination — hadron formation via (di-)quark combination in the QGP medium

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

➡ Sensitive to baryon and meson species

➡ Baryons from lower momenta partons (denser)

Charm quark energy loss



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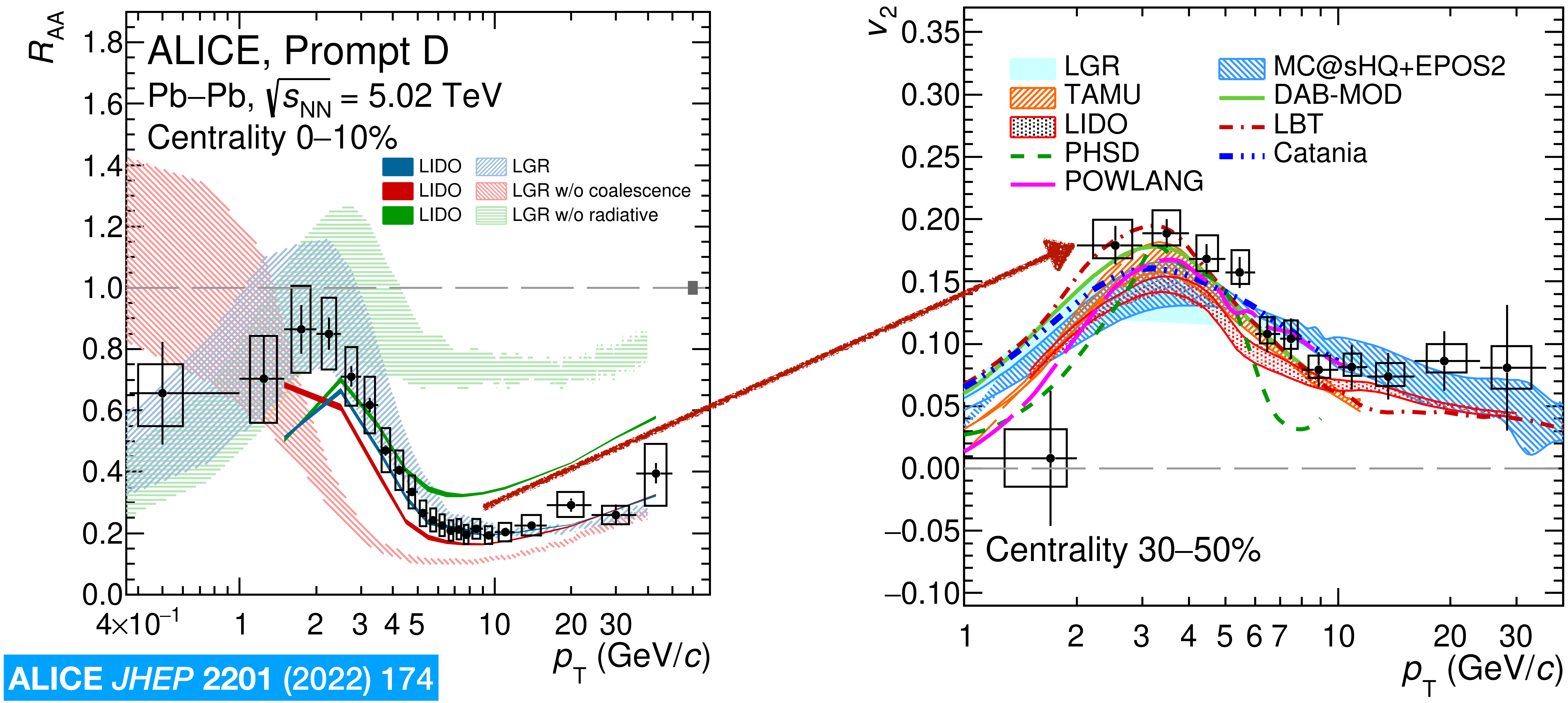
W/o coalescence Large deviation from data

➡ Hadronization via coalescence is important to interpret data

W/o radiative energy loss Reasonably describe data in $p_T < 5$ GeV/c, but largely overestimate data at high p_T

➡ Radiative energy loss is dominant at high p_T, while collisional energy loss is predominant at low and intermediate p_T

Charm quark transport



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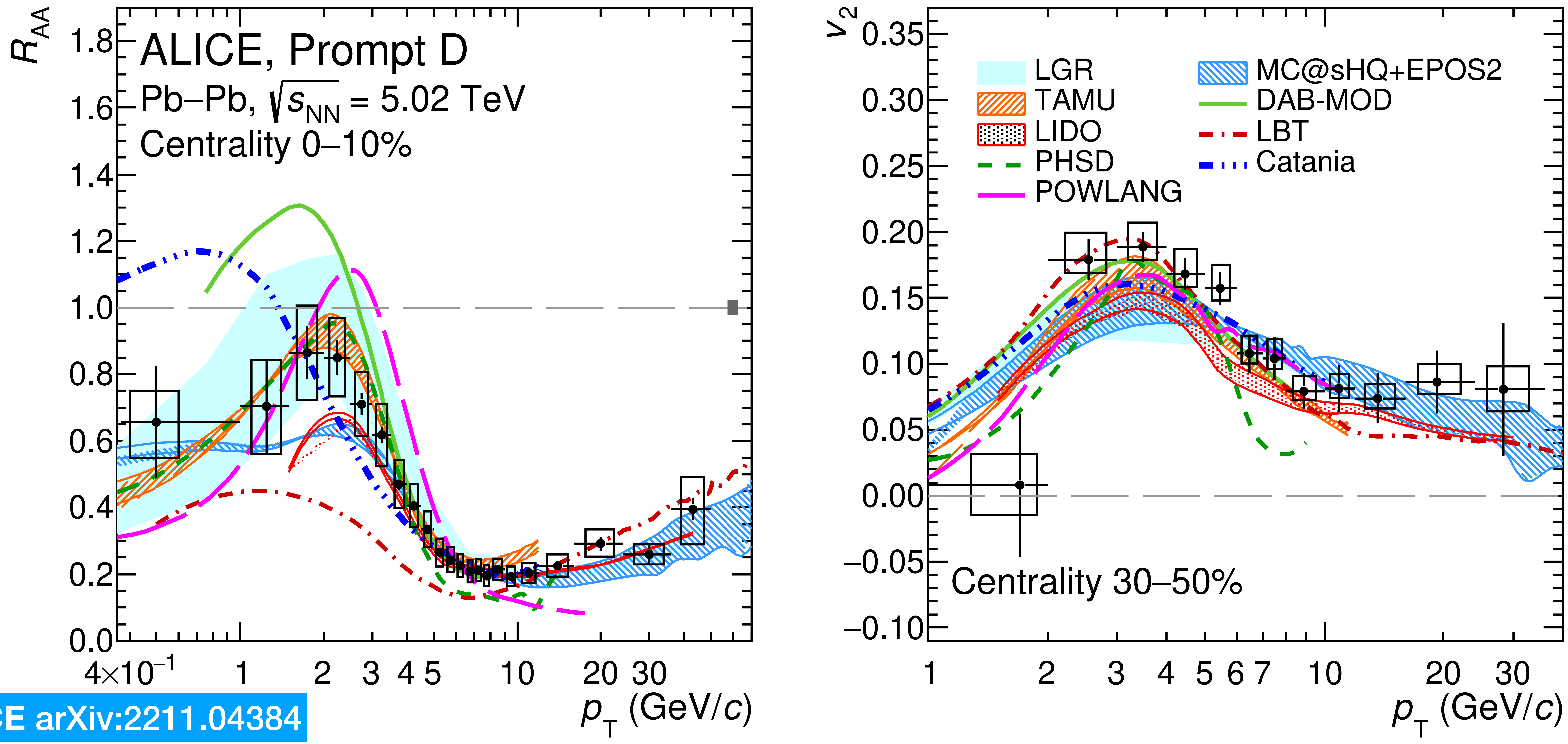
- Significant charmed hadron v_2 coefficient

➡ Consistent with strong suppression resulted by large energy loss

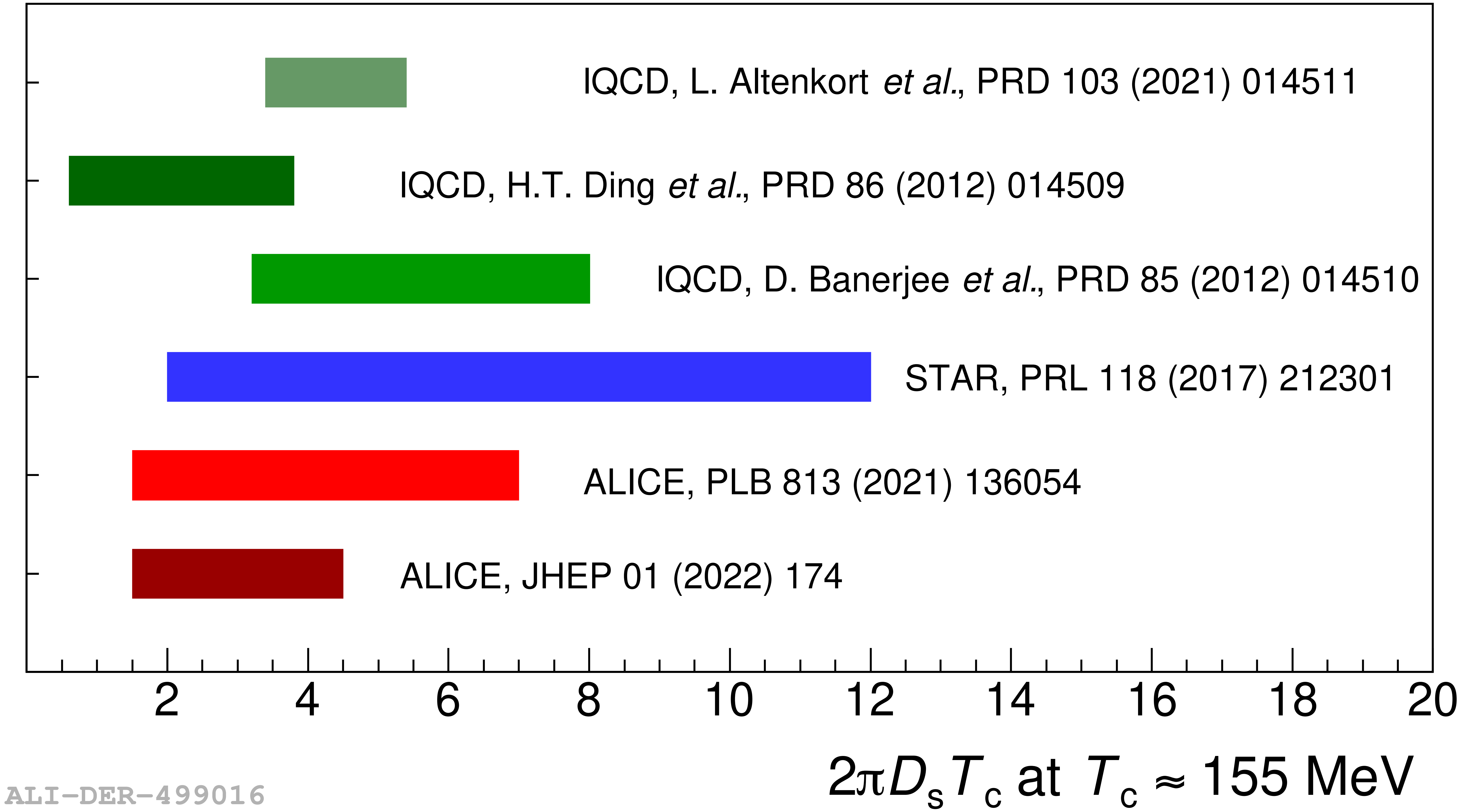
Charm quark transport



ALICE arXiv:2211.04384

- Most charm quark transport models able to describe both the R_{AA} and v_2
- Use to estimate the spatial diffusion coefficient *Ds*

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

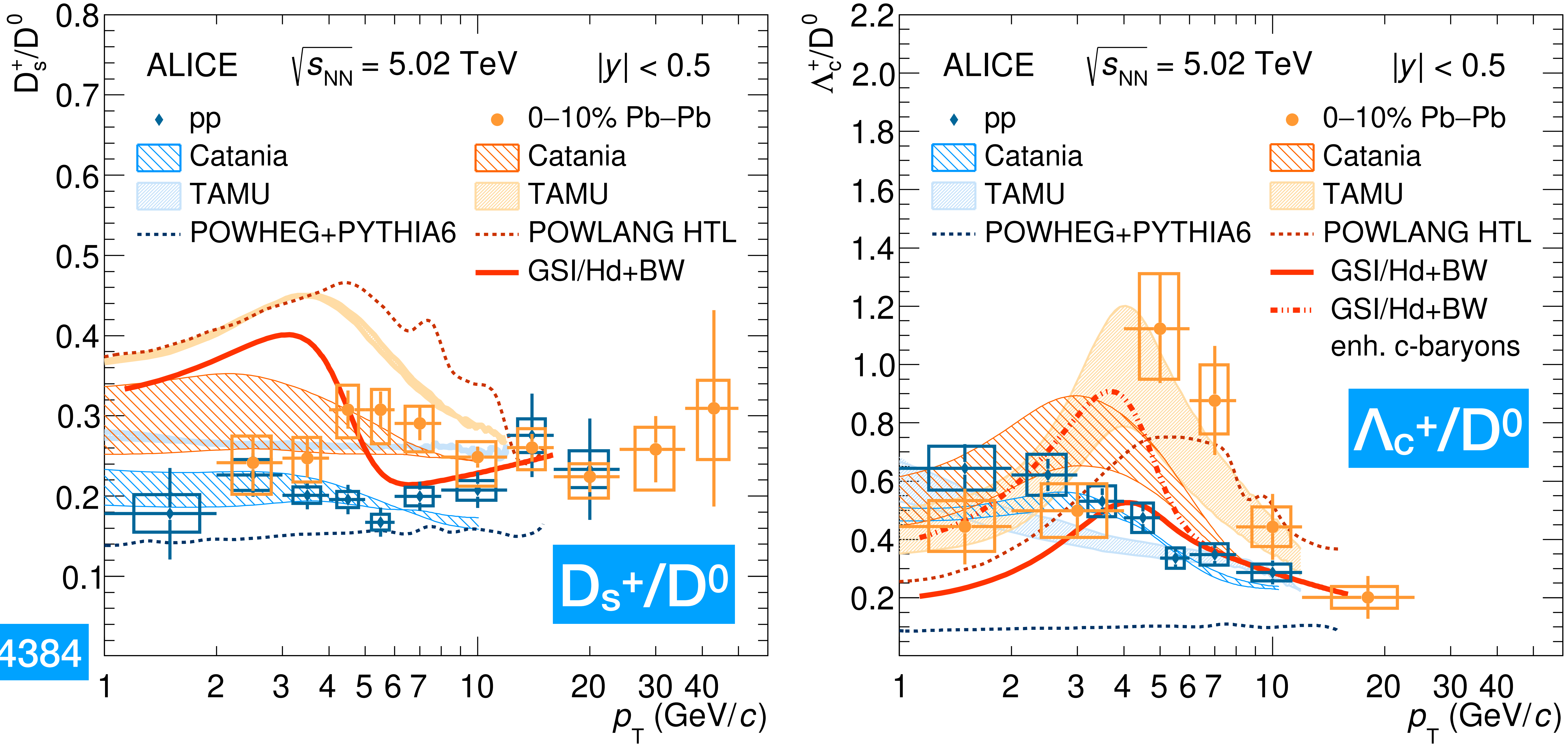
The newest constraints from ALICE by combining D meson R_{AA} and v_2

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

Charm quark hadronization

Pb–Pb

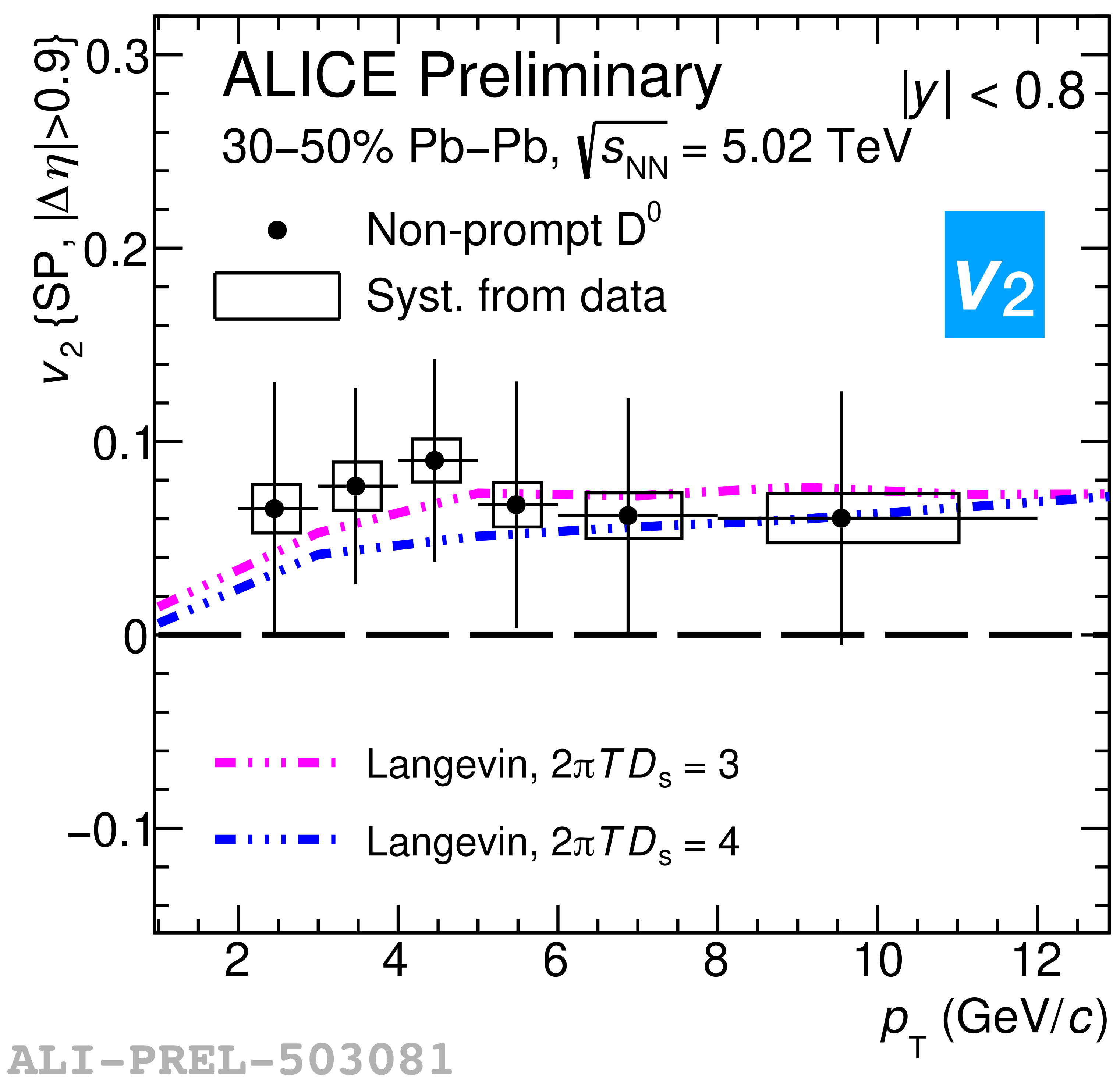
pp

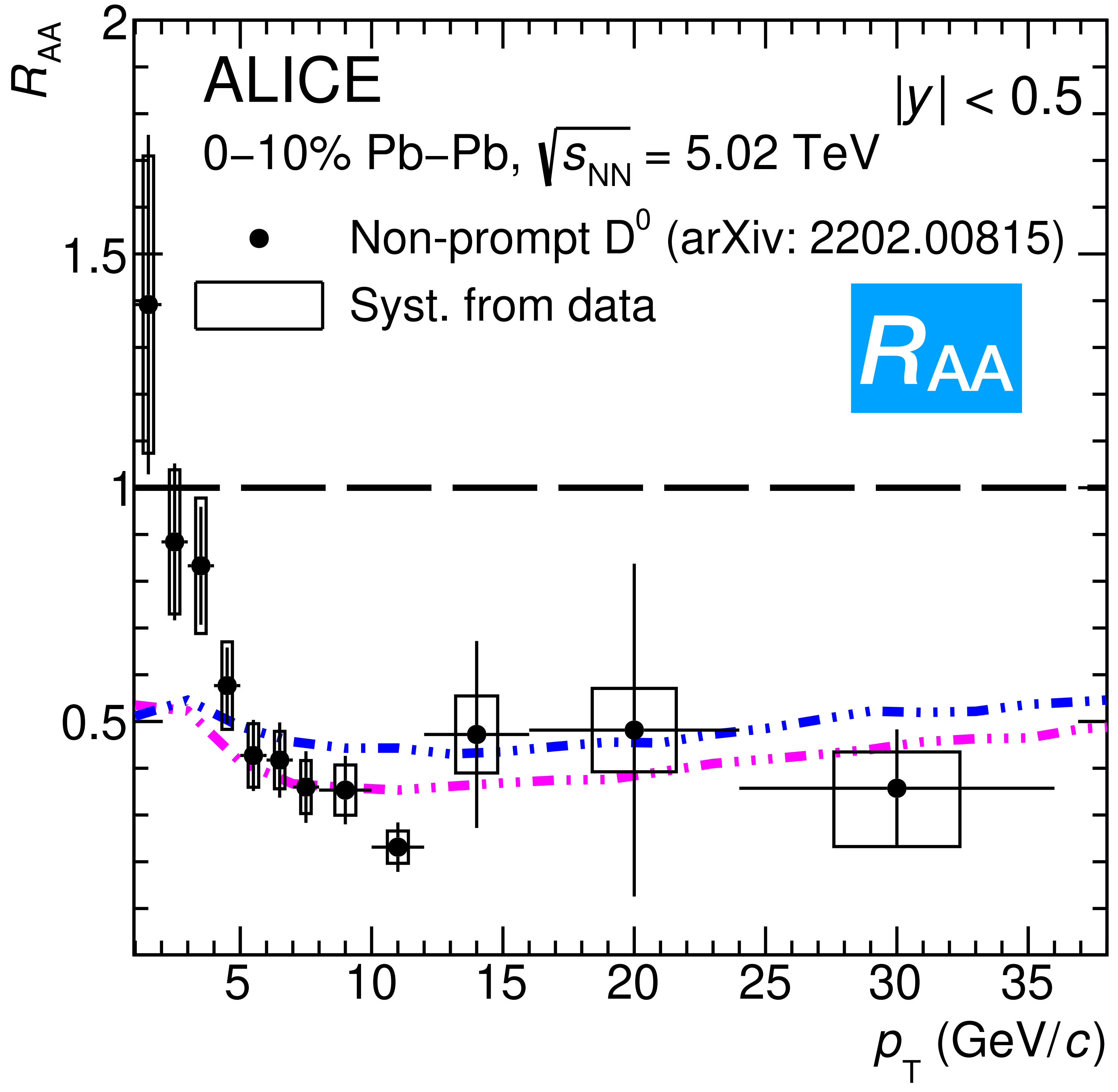


ALICE arXiv:2211.04384

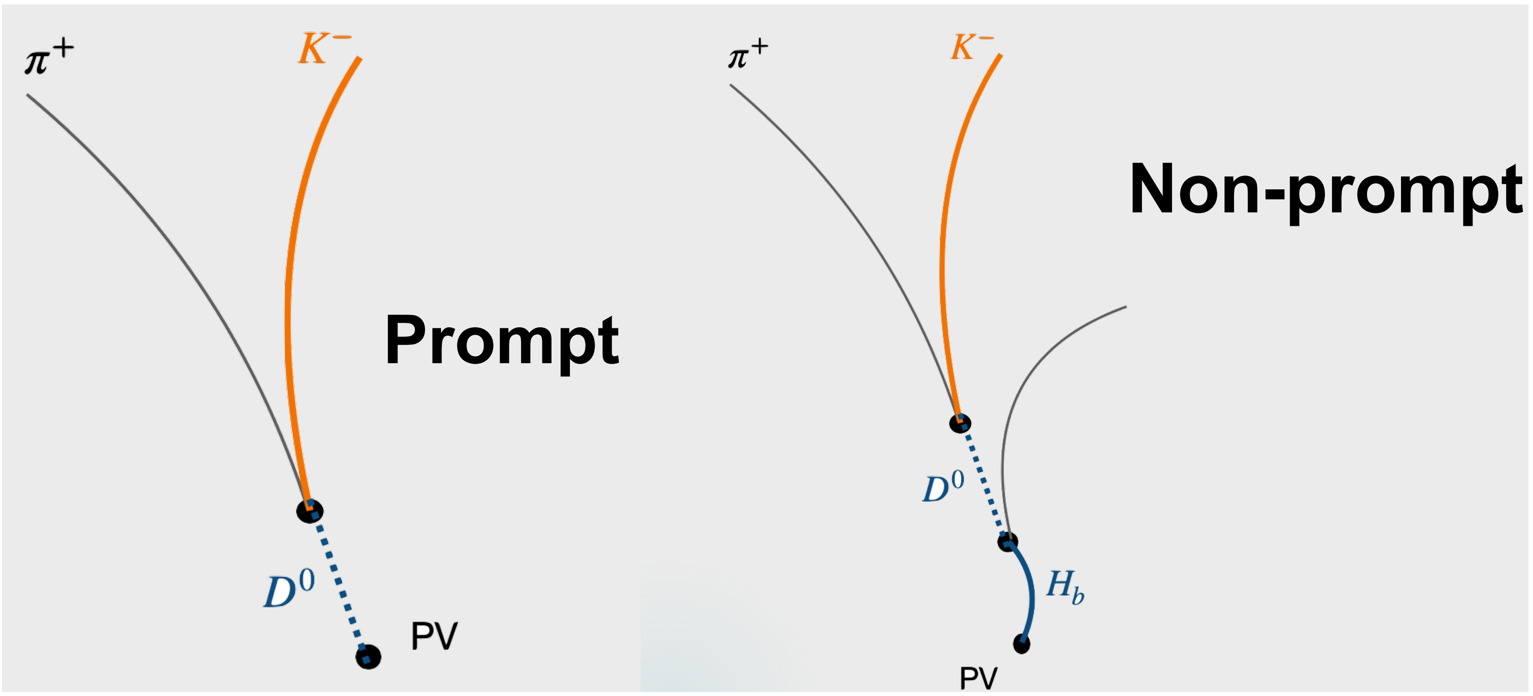
- Hints of enhanced D_s^+/D^0 ratio at intermediate p_T in Pb–Pb w.r.t. pp — support charm hadronization via recombination
- Enhanced Λ_c/D^0 ratio in Pb–Pb w.r.t. pp — suggest interplay between recombination and radial flow

Beauty quark transport





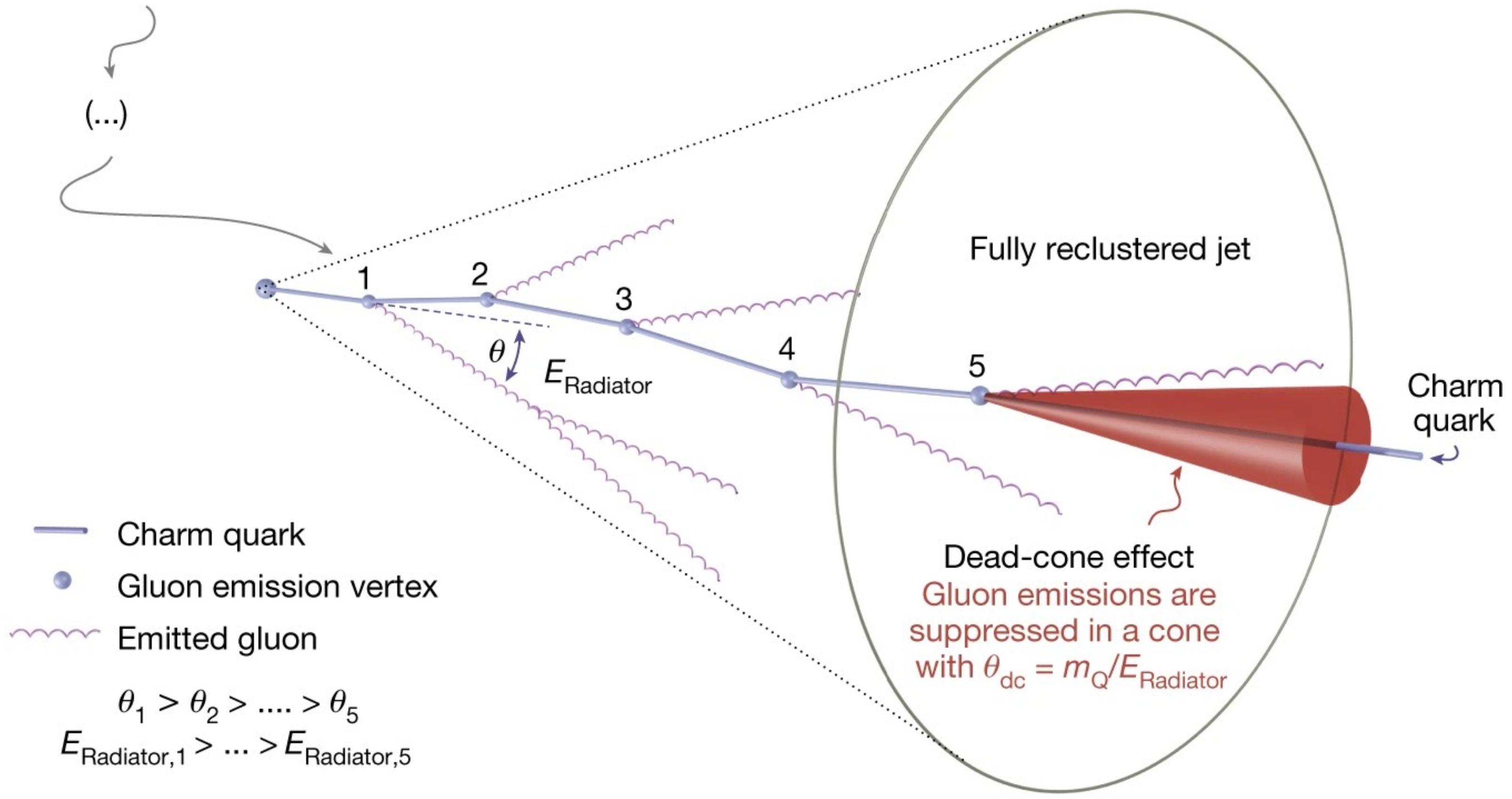
- Beauty particle R_{AA} and v_2 measured via non-prompt D^0 by ALICE
- Conclusion is similar to the measurements of B mesons, non-prompt J/Ψ and B meson semileptonic decays by ATLAS and CMS



- D_s obtained in beauty sector is similar to that in charm sector ($2\pi D_s \approx$ 1.5–4.5 for charm)
- Indicate $\tau_{beauty} \propto m_{beauty} D_s \gtrsim \tau_{medium}$ ($m_{beauty} \approx 3\, m_{charm}$)

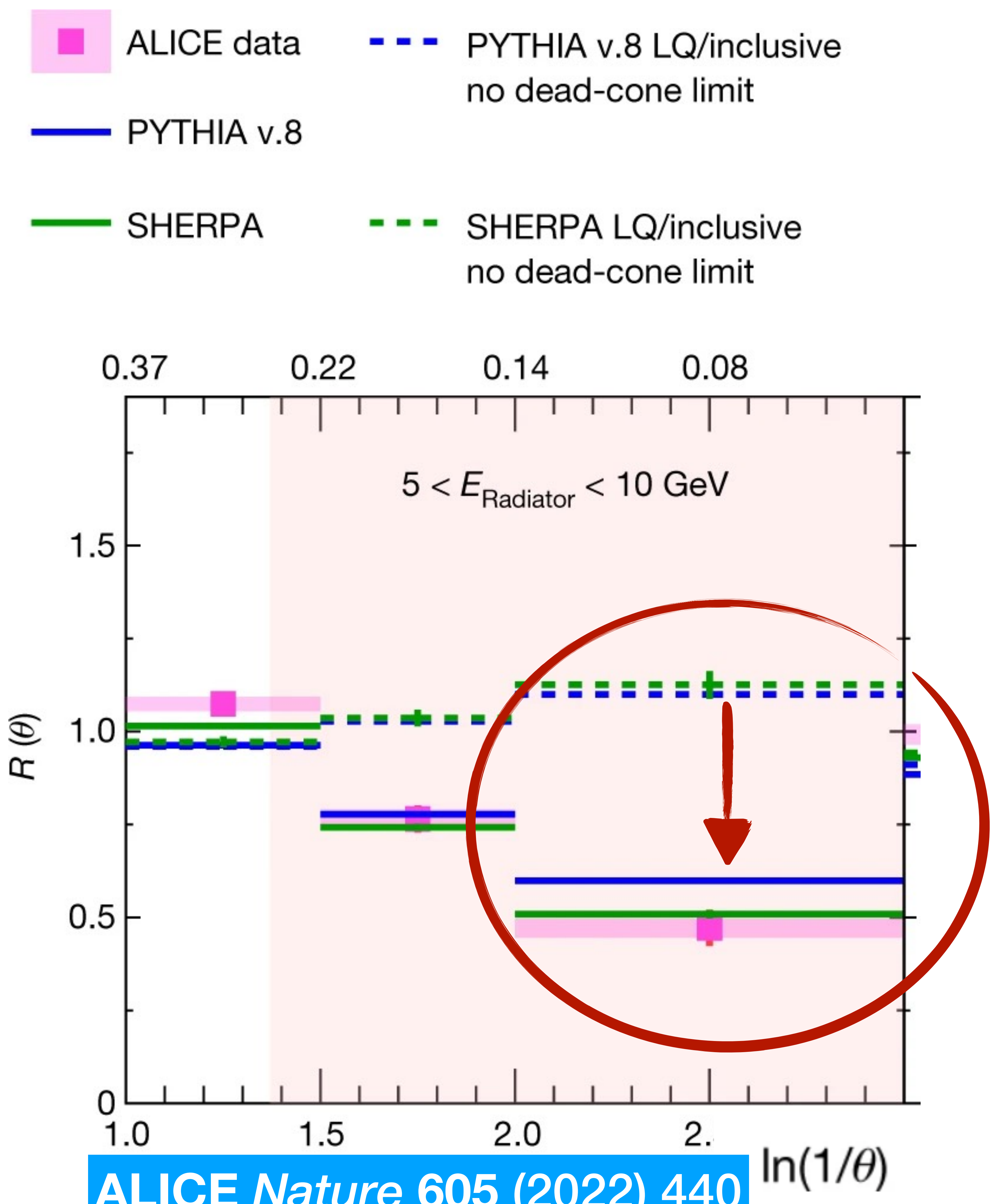
➡ What is thermalization DOF of beauty in the QGP medium?

Charm quark radiation in vacuum



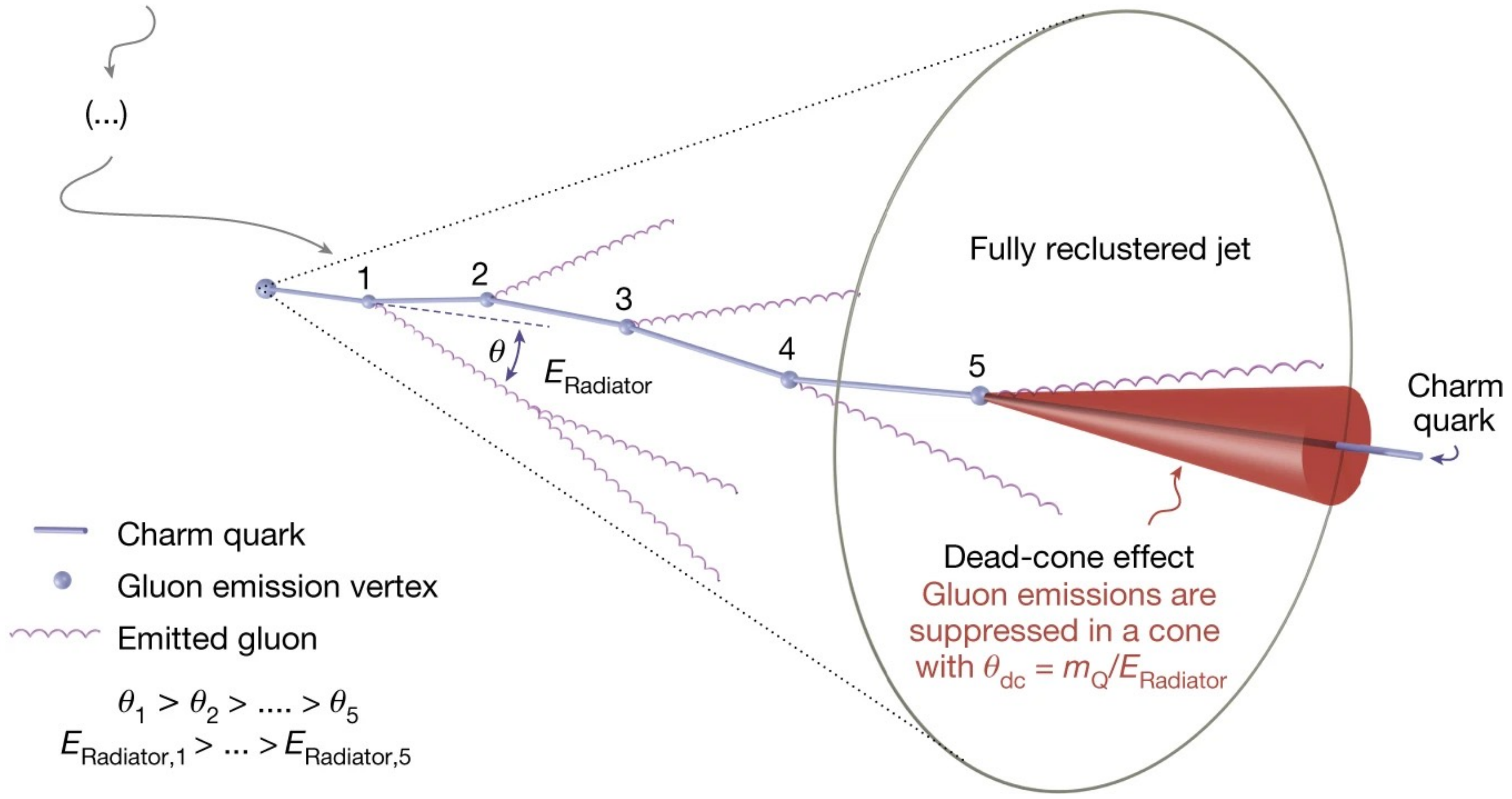
One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

- Direct observation for charm quarks in pp — QCD vacuum

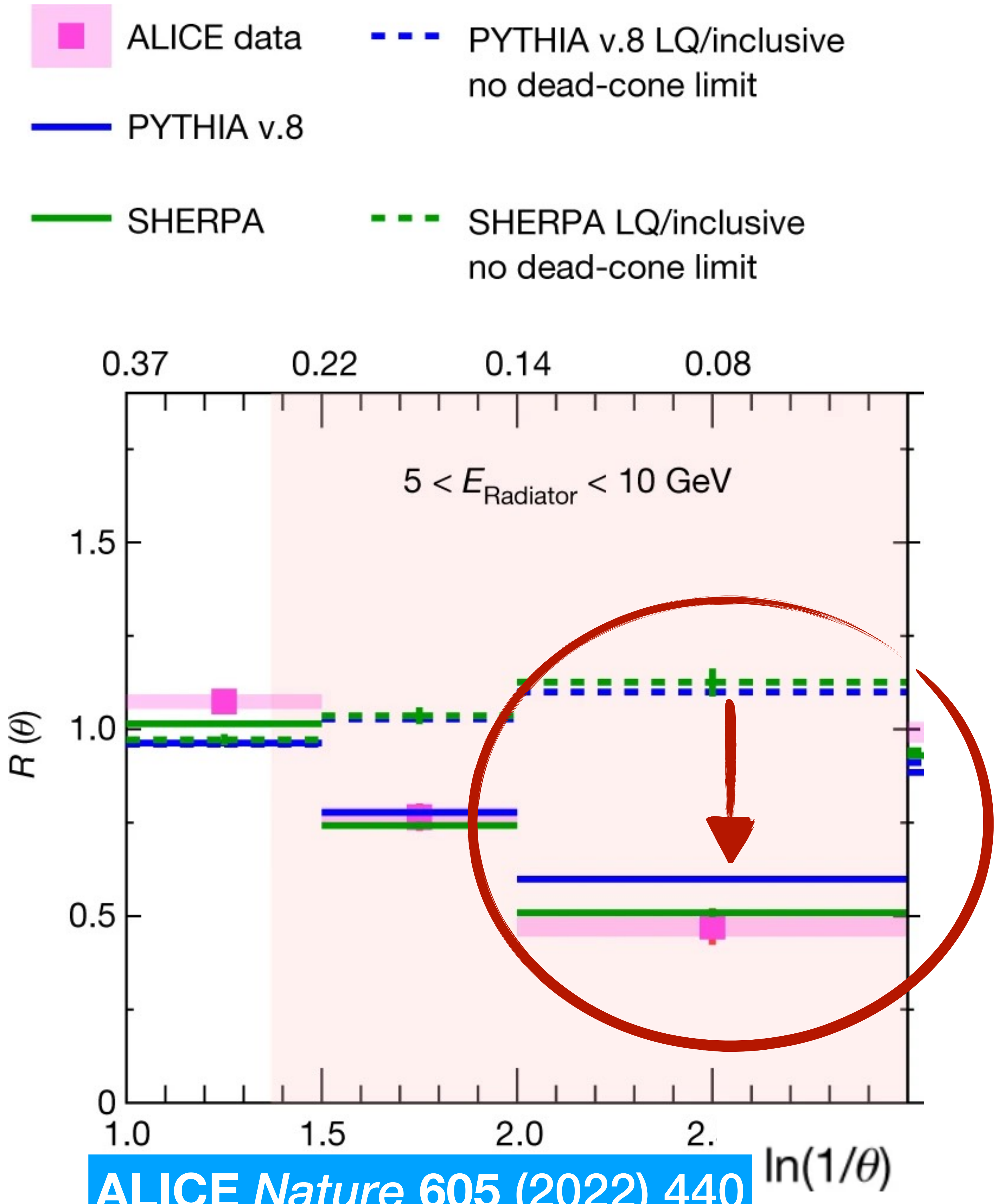


ALICE *Nature* 605 (2022) 440

Charm quark radiation in vacuum



One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect



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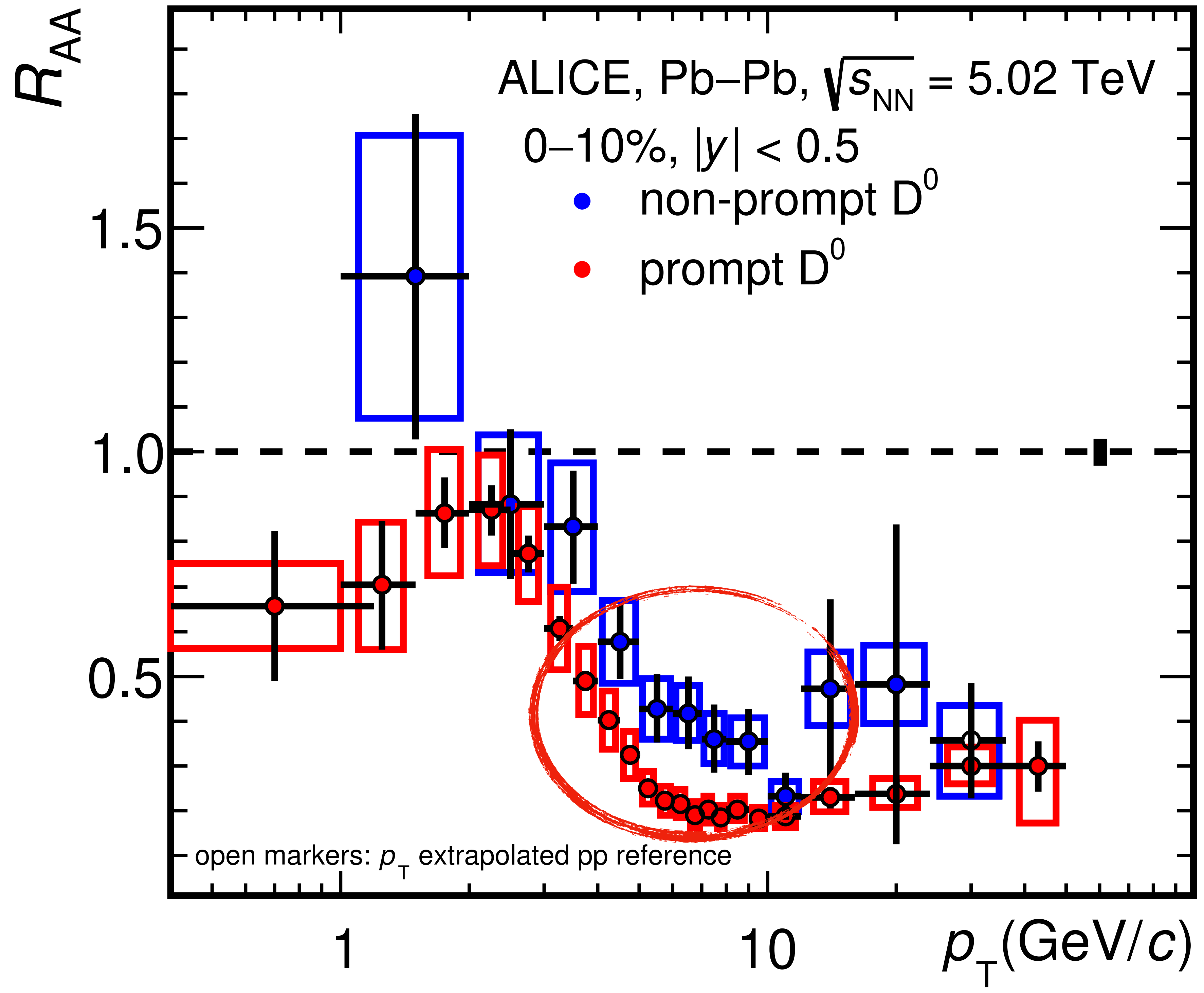
- Direct observation for charm quarks in pp — QCD vacuum

- Whether is it still validated in QCD medium?

➡ Mass dependent heavy quark radiative energy loss

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

Mass dependent R_{AA}



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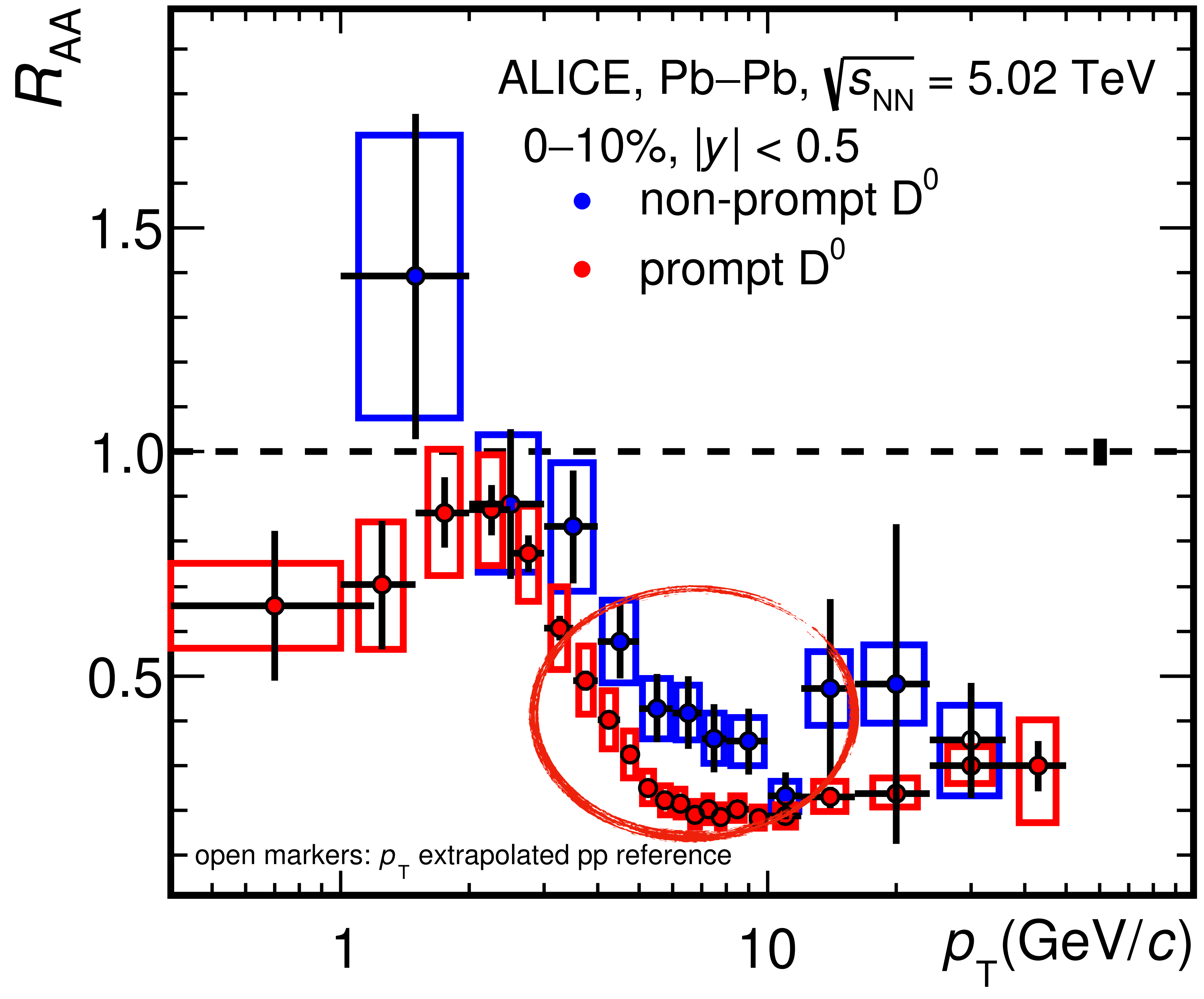
Non-prompt D mesons are less suppressed than prompt D mesons

R_{AA}(beauty) > R_{AA} (charm) ⇒ $\Delta E_{beauty} < \Delta E_{charm}$ (?)

Mass dependent R_{AA}



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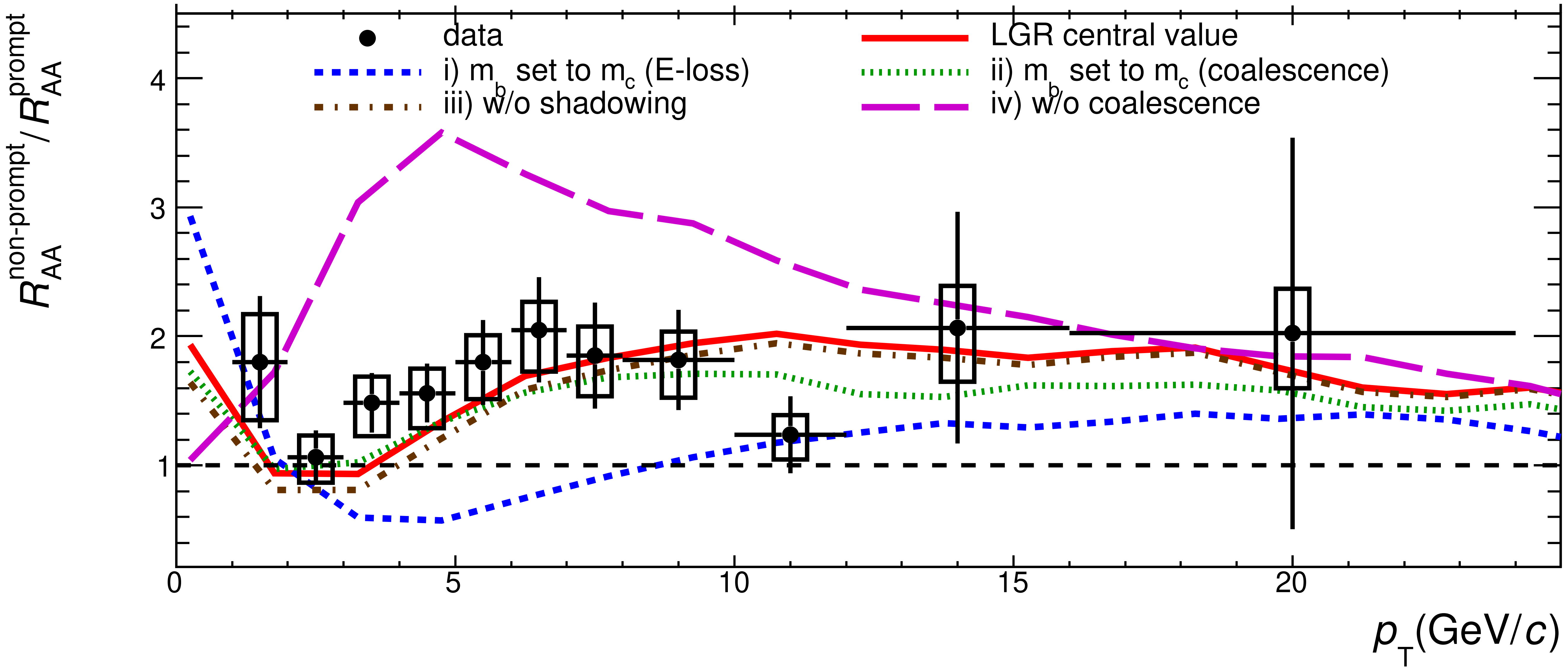
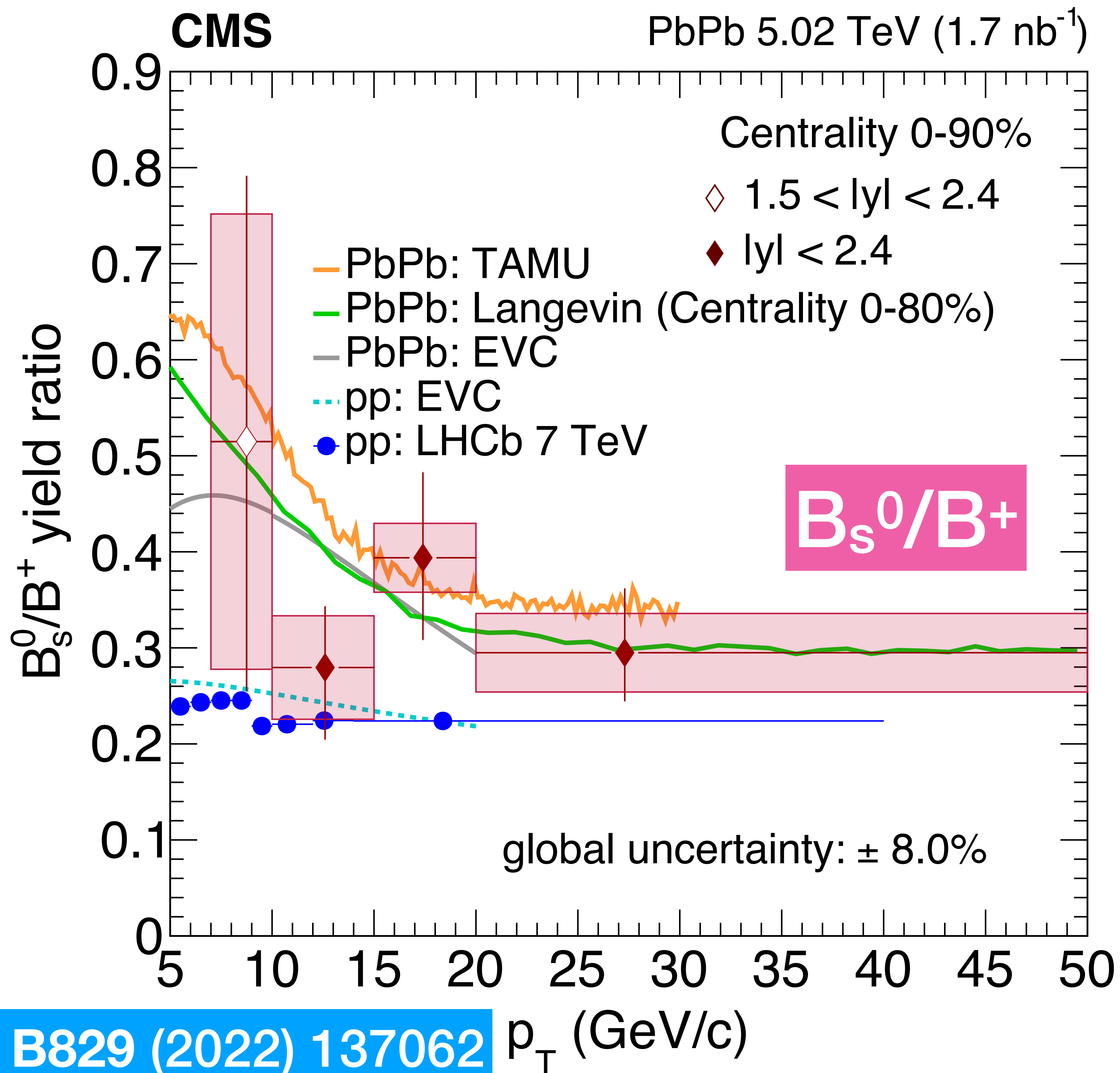


- Mass effect is important to describe data
- However, coalescence is more critical

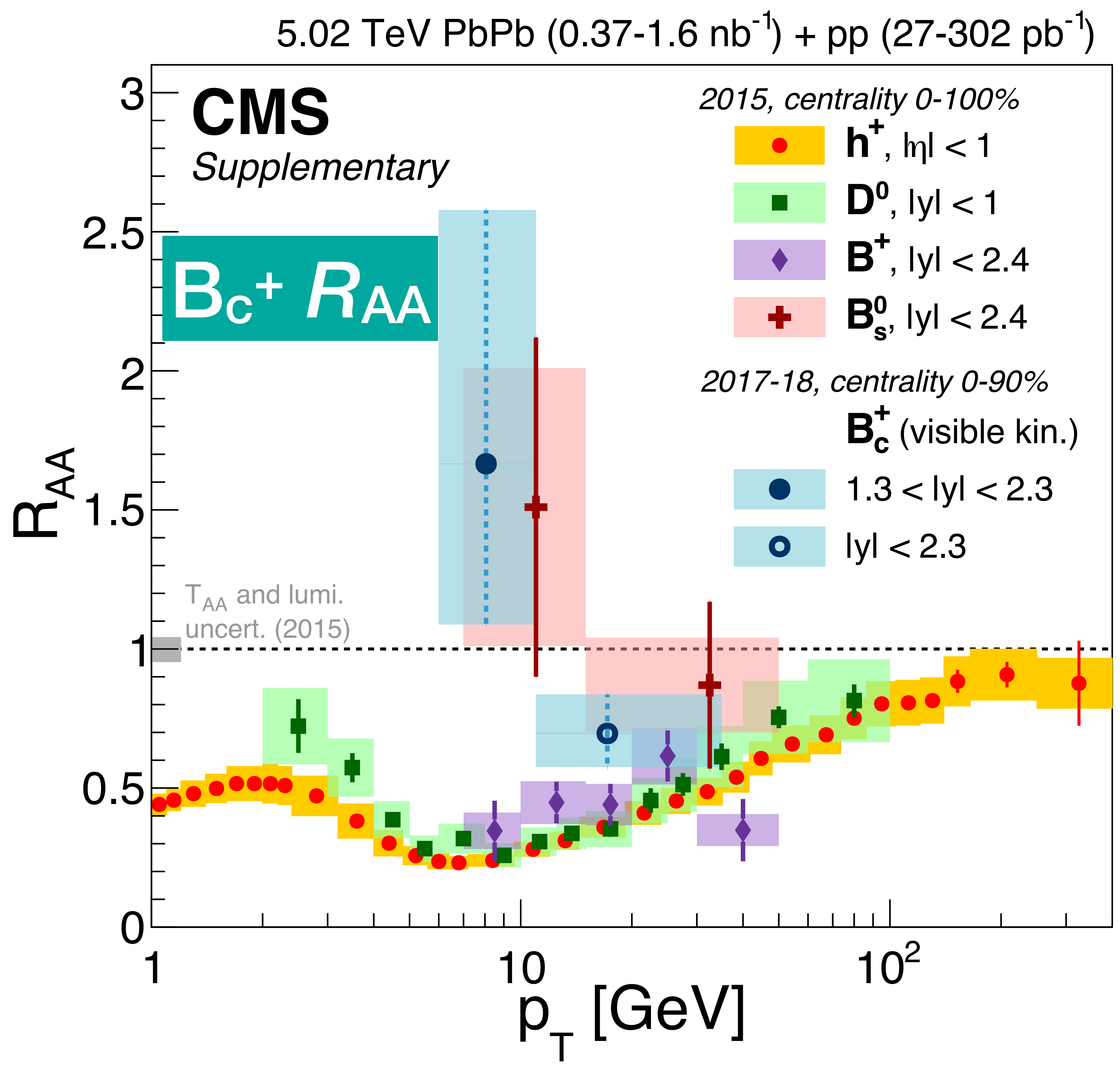
Non-prompt D mesons are less suppressed than prompt D mesons

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

Beauty quark hadronization



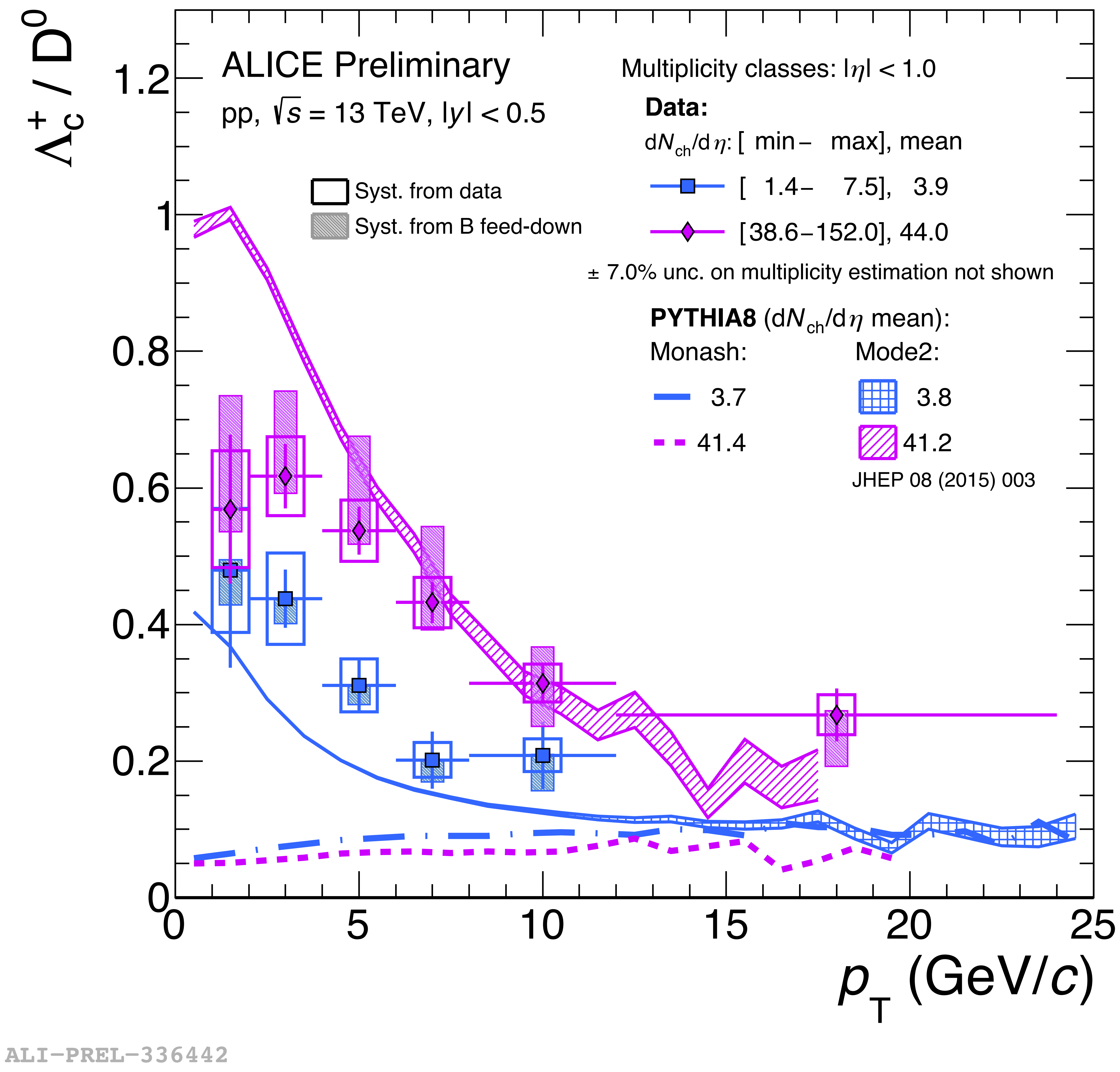
CMS *Phys. Lett.* B829 (2022) 137062



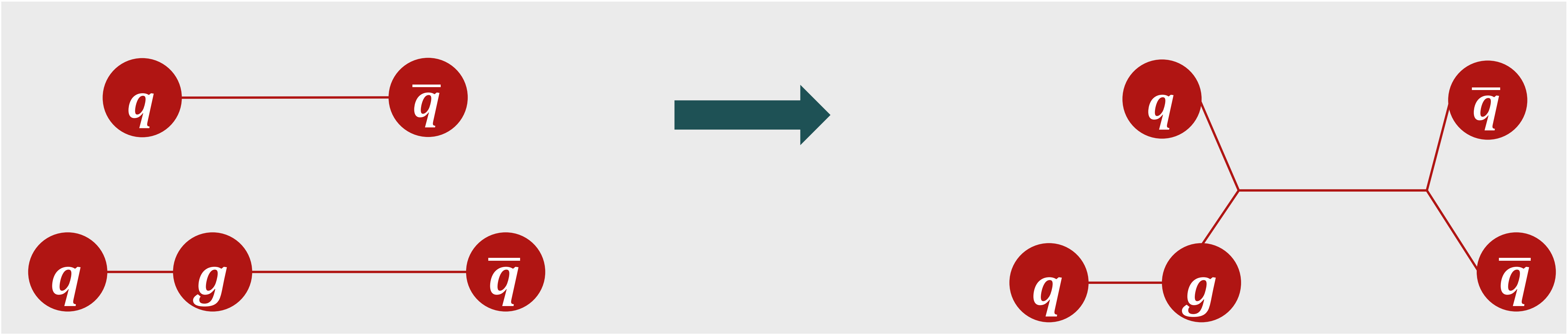
CMS *Phys. Rev. Lett.* 128 (2022) 252301

- Hints of B_s^0 and B_c^+ enhancement in Pb–Pb collisions
- Indicate recombination during beauty quark hadronization

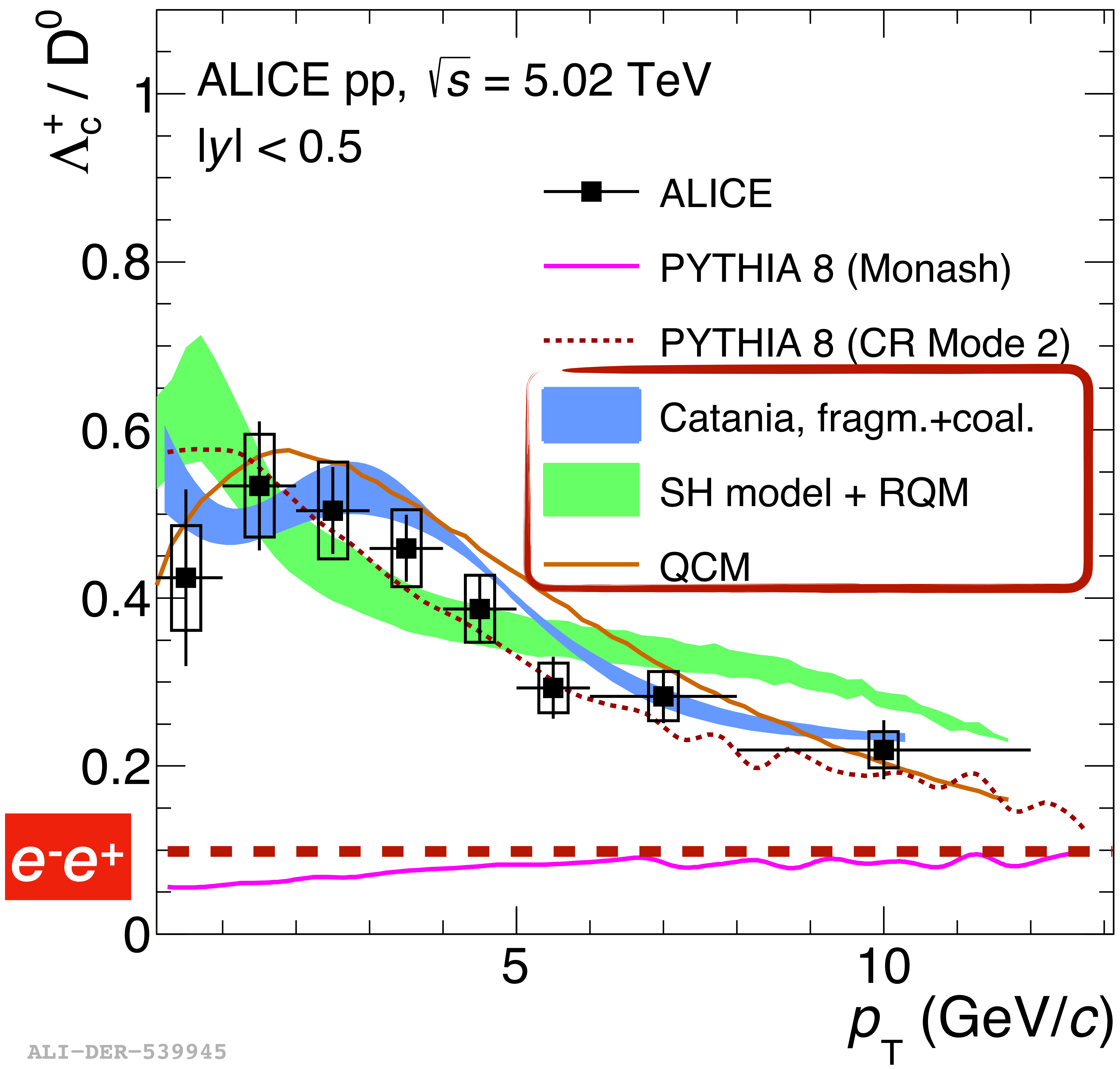
Λ_c^+/D^0 ratio in pp collisions



- Λ_c / D^0 ratio shows a more substantial increase for increasing multiplicity
- Largely underestimated when comparing to the default PYTHIA tune (Monash)
- Good agreement including color-reconnection processes (eg “junctions") between partons created in different MPIs



Λ_c^+/D^0 ratio in pp collisions



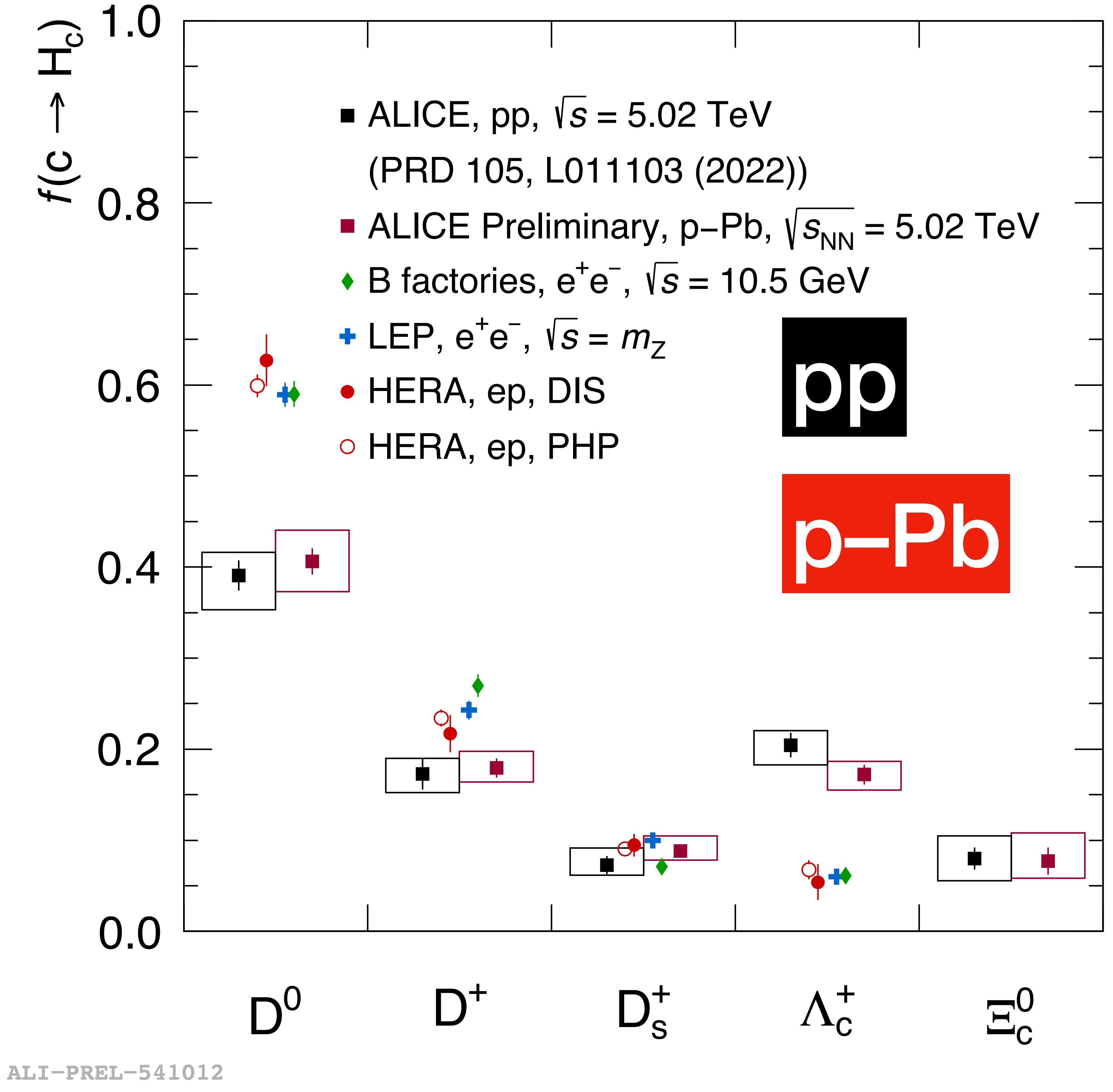
- Catania Thermalised system of gluons, light quarks and antiquarks (QGP), hadronisation via coalescence and fragmentation
- SH model + RQM Hadronisation driven by statistical weights govern by hadron masses, feed-down from excited baryon states predicted by RQM
- QCM Pure coalescence model, charm is combined with co-moving light antiquark or two quarks

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

Heavy flavour production

- Production cross section of heavy-flavour hadrons is typically described by a factorization framework

- Fragmentation functions are constrained from e^-e^+ and ep measurements, assuming they are applicable universally in hadronic collisions



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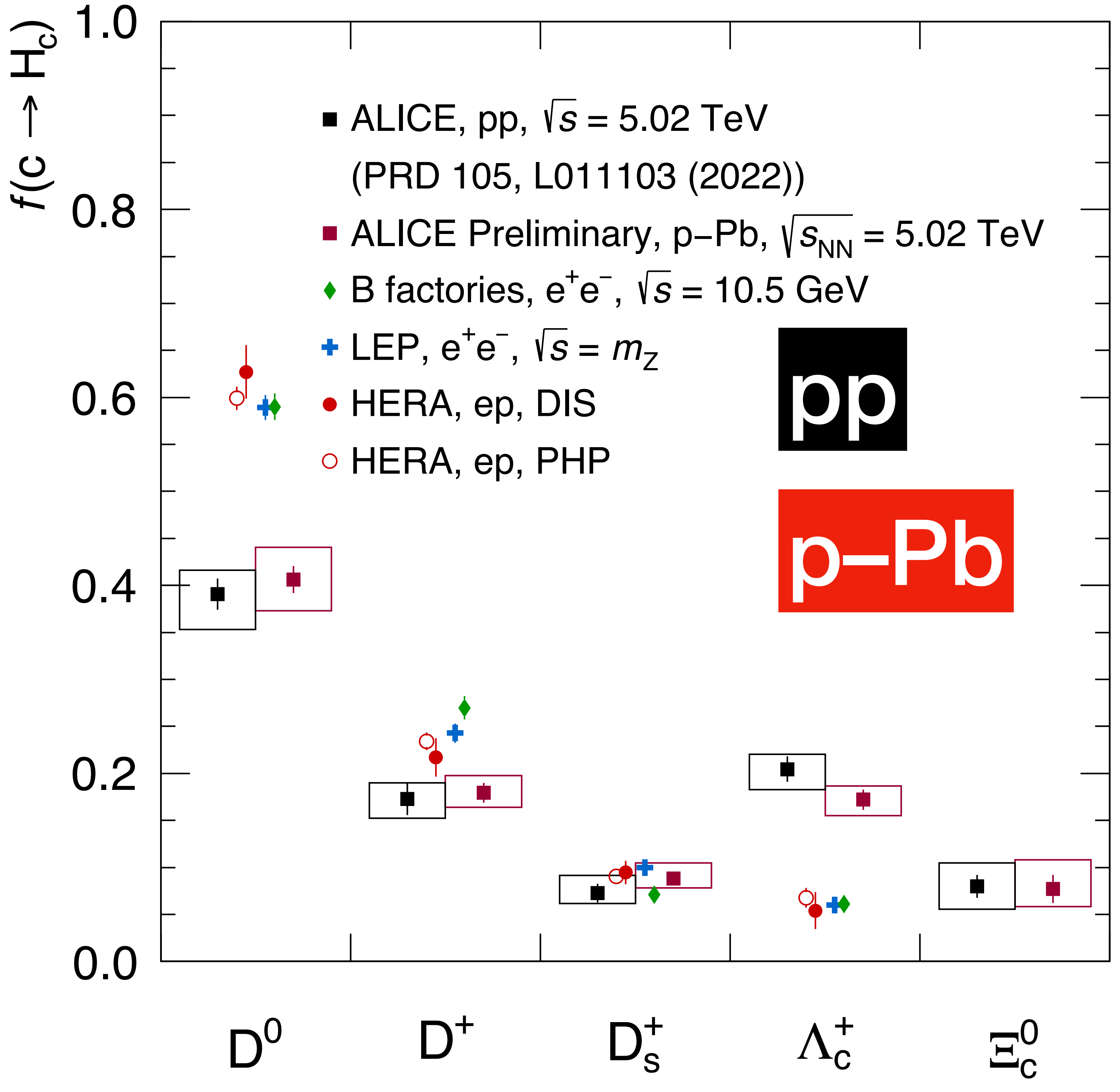
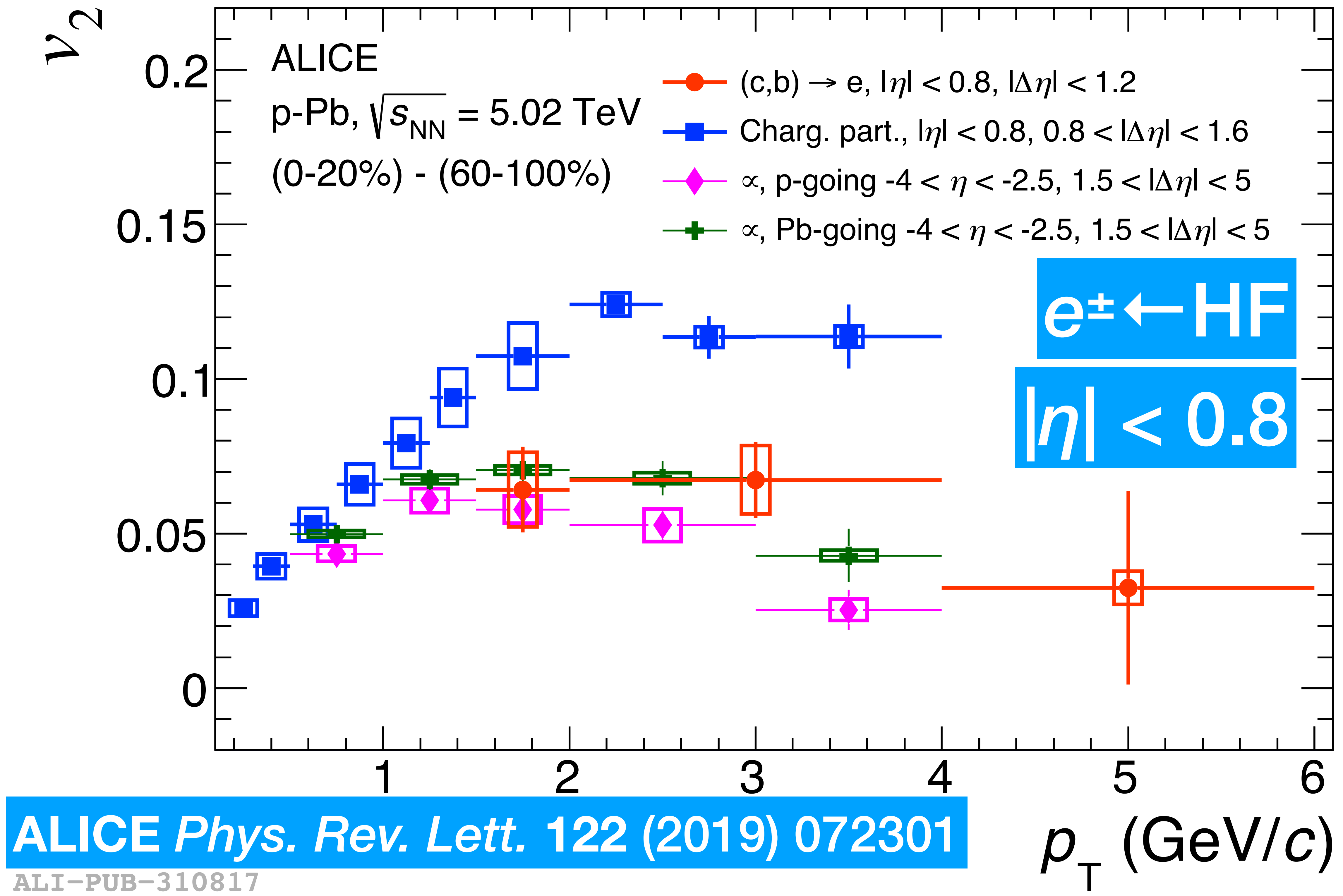


$$\frac{d\sigma^{pp\to H_Q}}{dp_T} = \sum_{ij} f_i(x_1,\mu_F) f_j(x_2,\mu_F) \oplus \frac{d\sigma^{ij\to Q}}{dp_T}(x_1 x_2,\mu_F,\mu_R) \oplus D_{Q\to H_Q}\left(z_Q = \frac{p_{H_Q}}{p_Q},\mu_F\right)$$

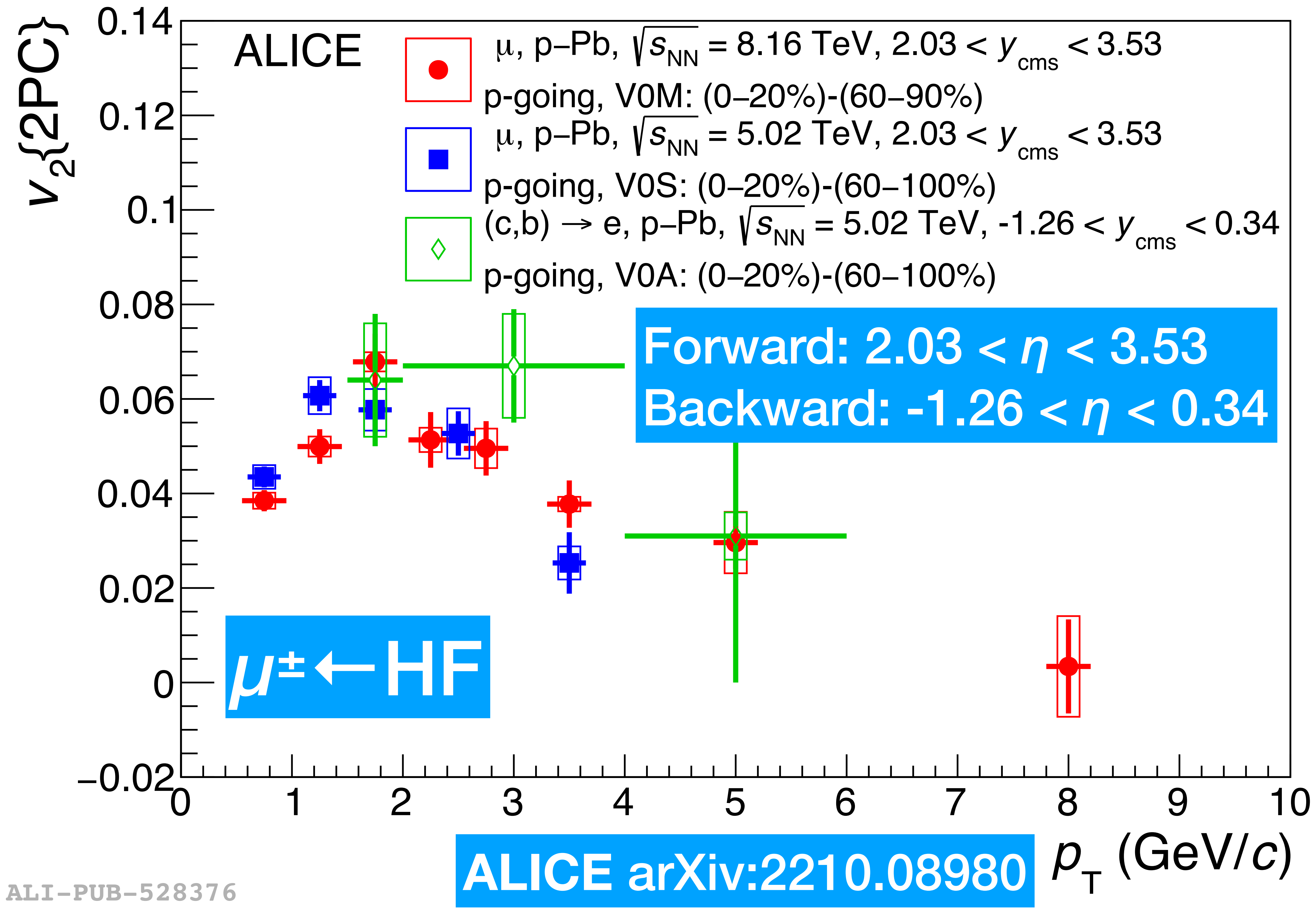
Parton distribution functions (PDF) | Hard scattering cross section (pQCD) | Fragmentation function (Hadronization)

v_2 of heavy quarks in p–Pb



ALICE *Phys. Rev. Lett.* 122 (2019) 072301

ALI-PUB-310817



ALI-PUB-528376

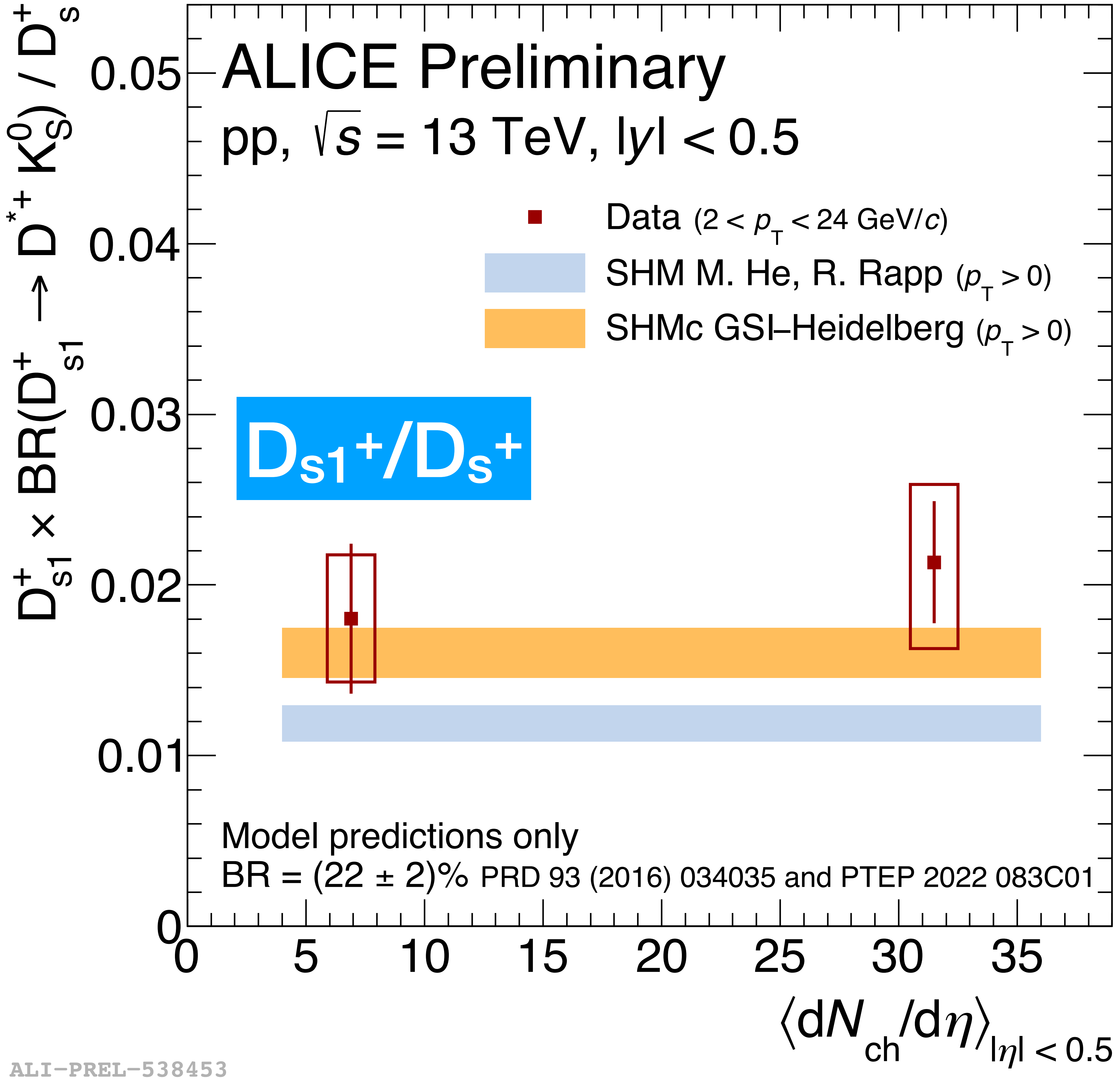
ALICE arXiv:2210.08980

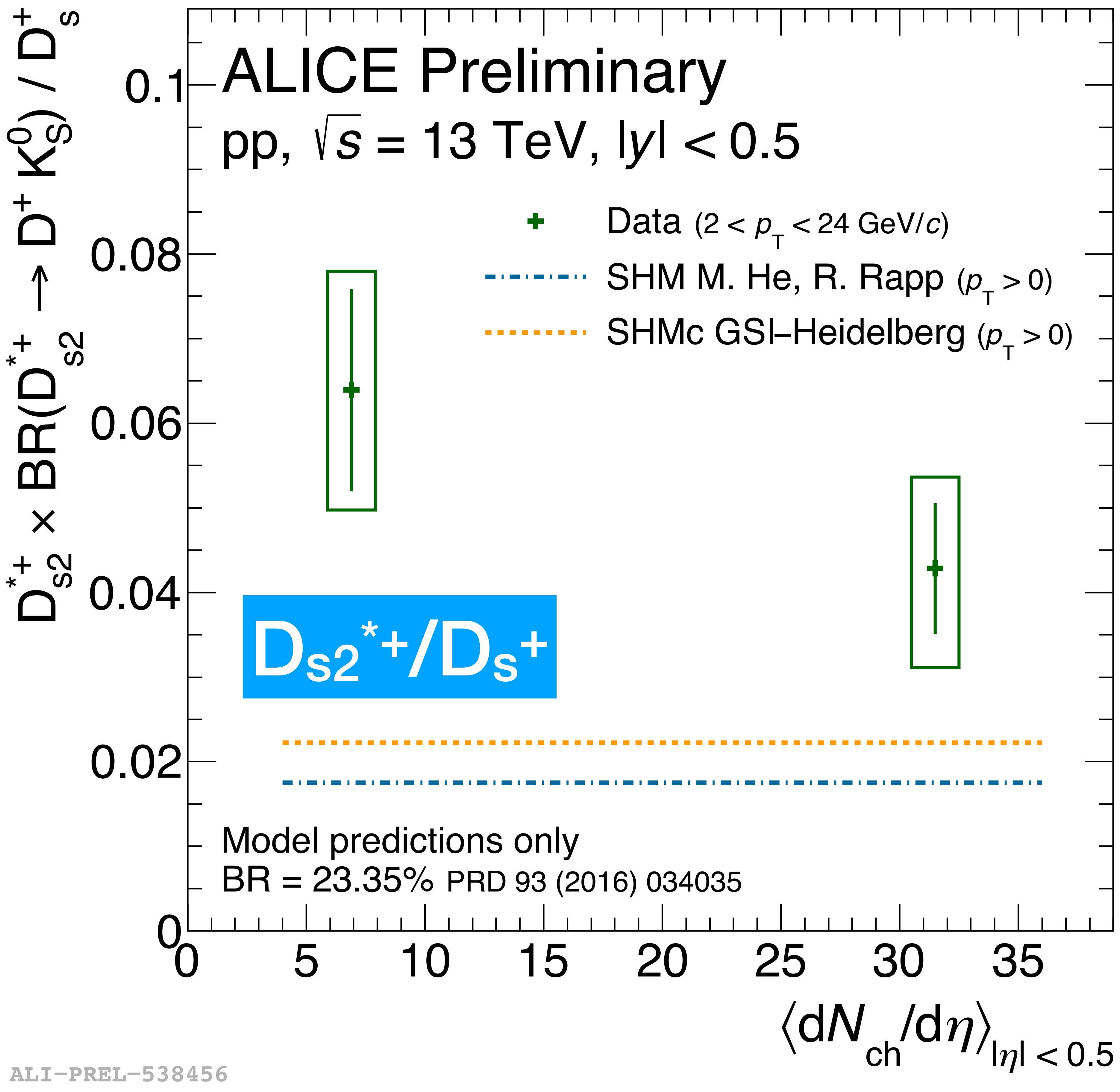
- Significant v_2 coefficient of heavy flavour particles is observed at both midrapidity and forward/backward rapidities in p–Pb collisions

➡ Do heavy quarks undergo hydro-like evolution in small collision systems?

➡ Is it correlated with the hadronization behaviors?

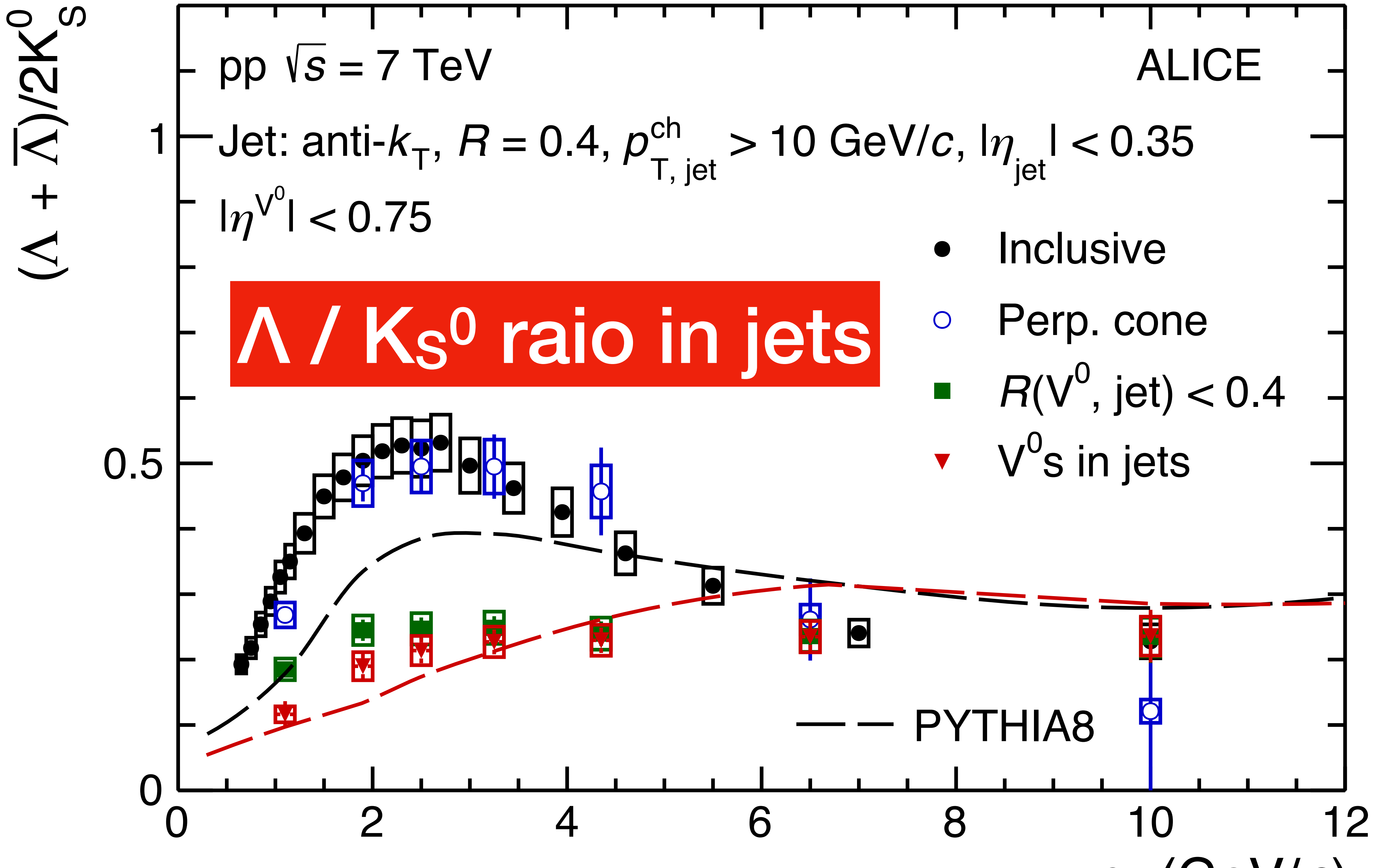
Next step – exited states (?)



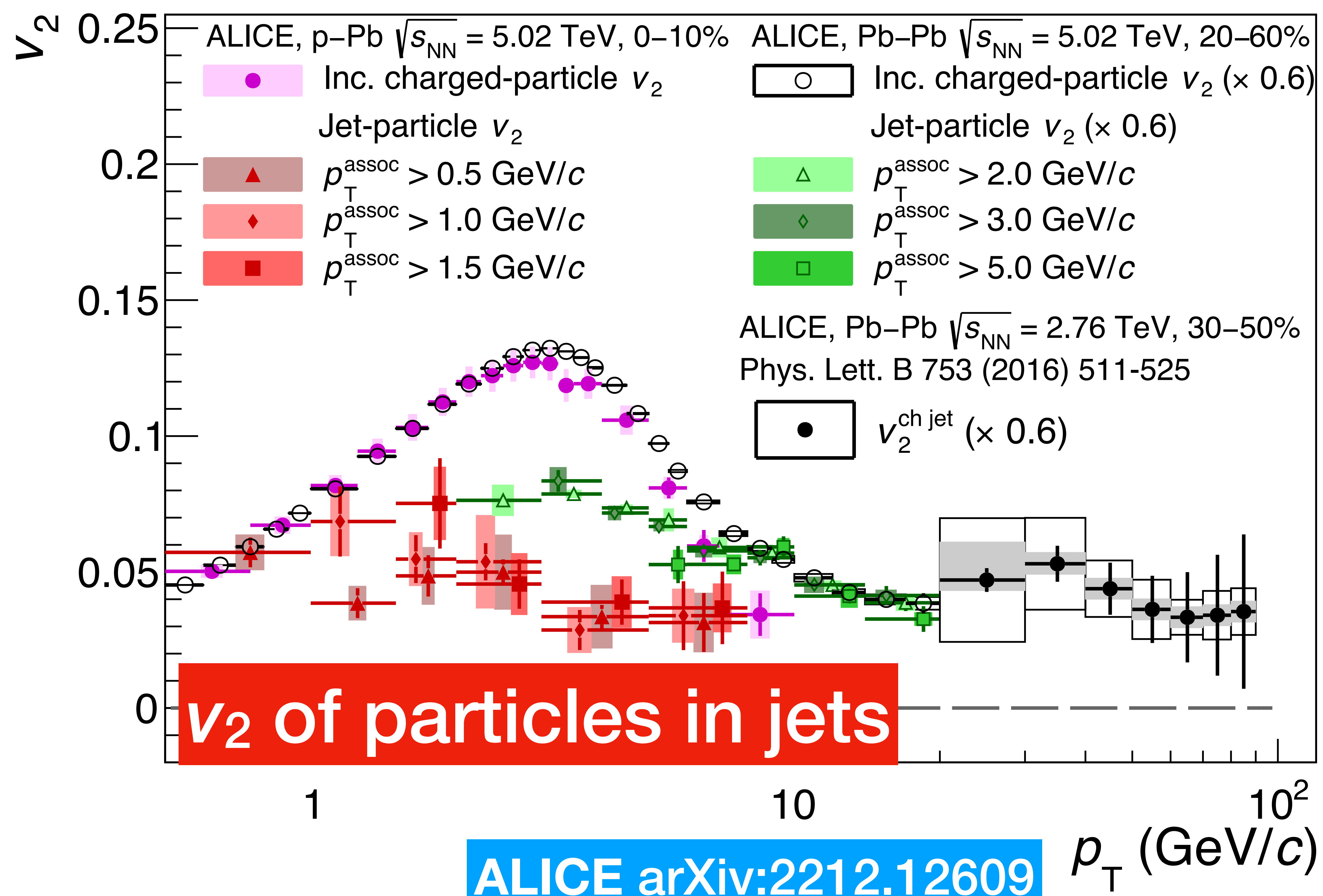


- No significant multiplicity dependence on D_{s1}^+/D_s^+ ratio, reproduced by SHM
- Hints of decreasing trend of D_{s2}^{*+}/D_s^+ ratio with multiplicity and prediction tension

Next step – jets (?)



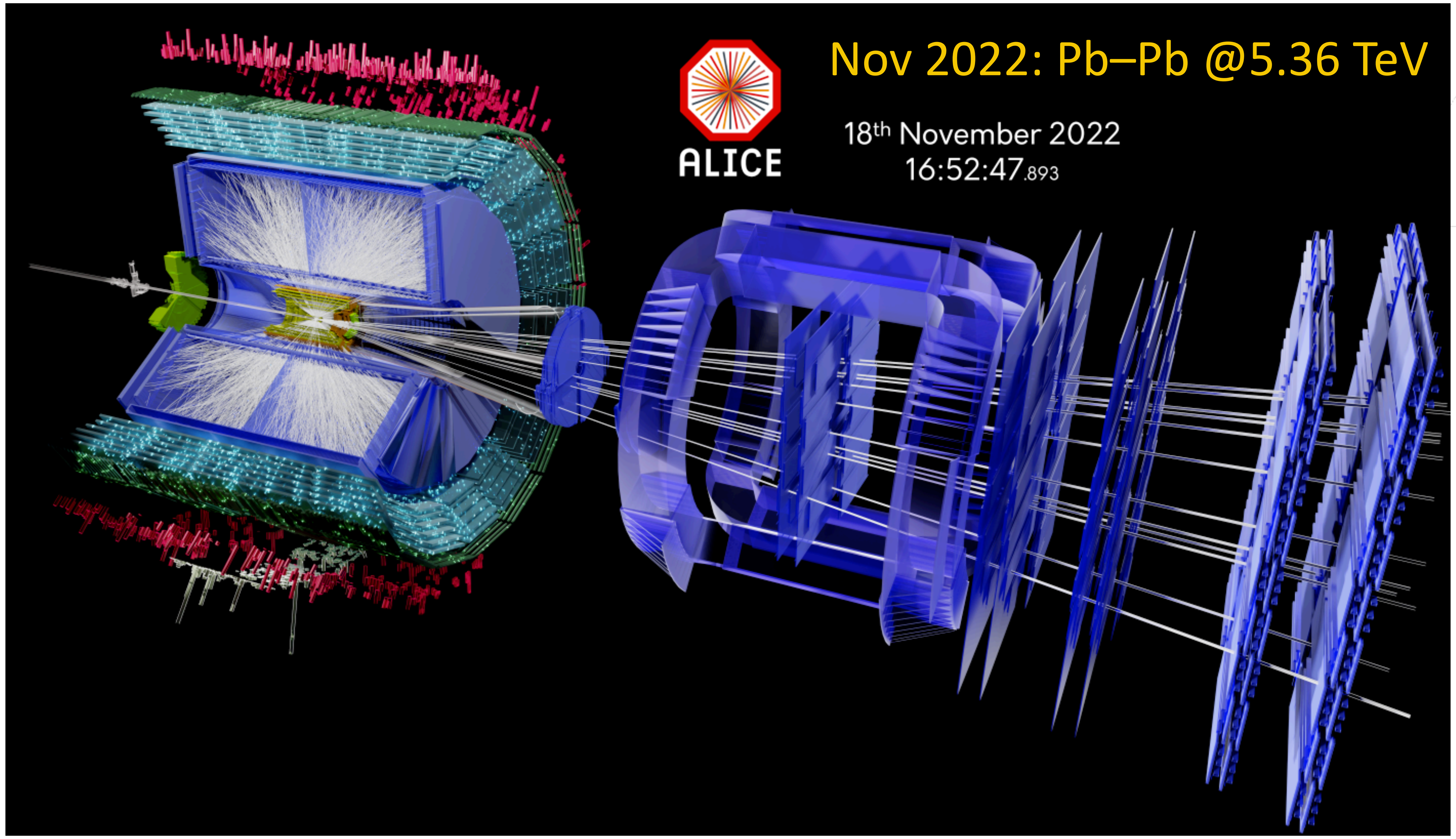
ALICE *Phys. Lett.* B827 (2022) 136984



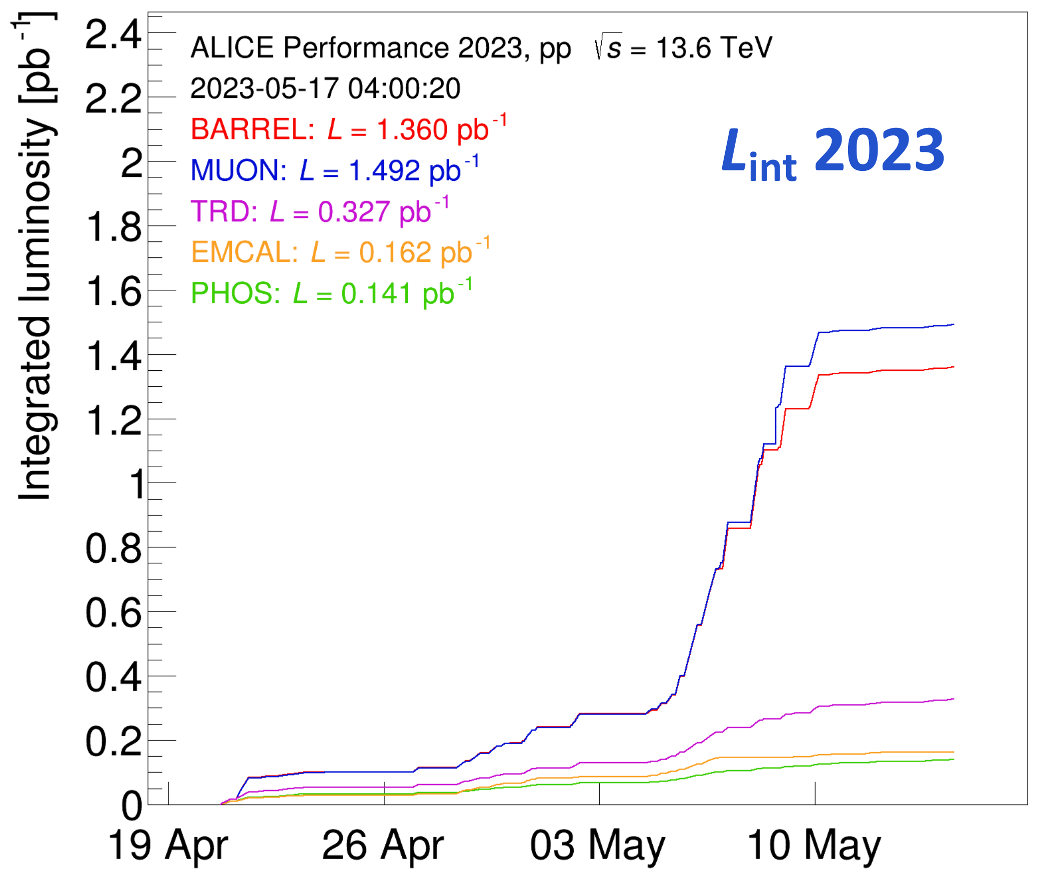
ALICE arXiv:2212.12609

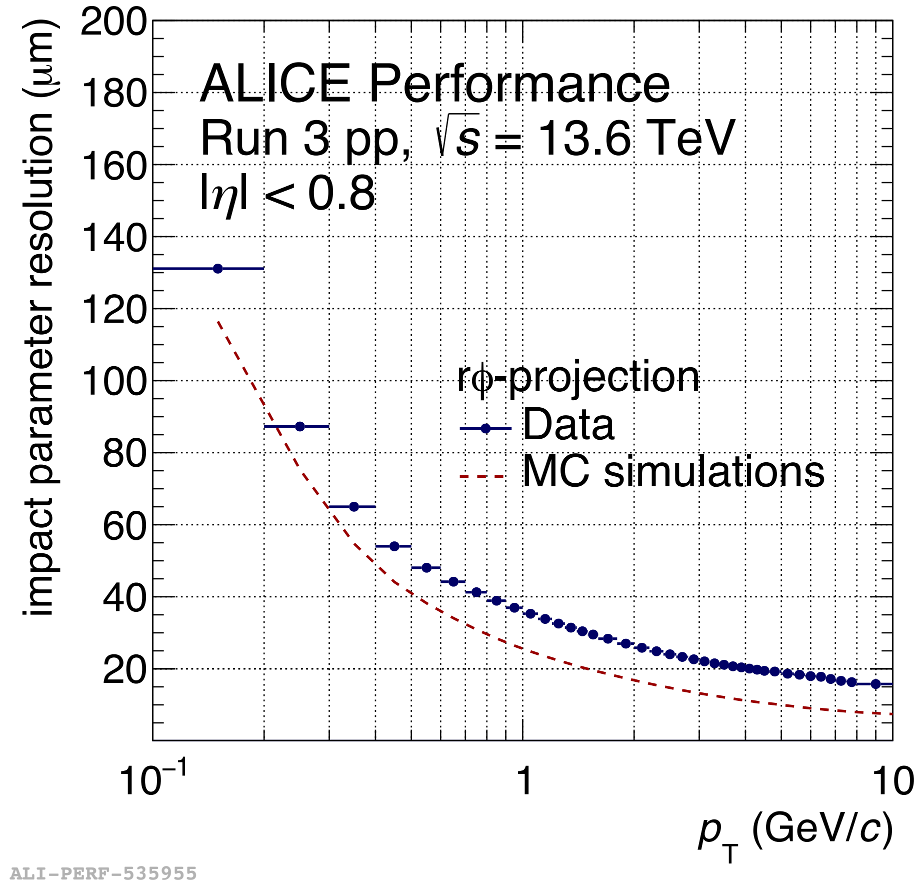
- Λ/K_S^0 ratio in jets does not show a maximum at intermediate p_T
- Non-zero v_2 of jet particles in both Pb–Pb and p–Pb collisions, amplitude differs from that of the inclusive particles

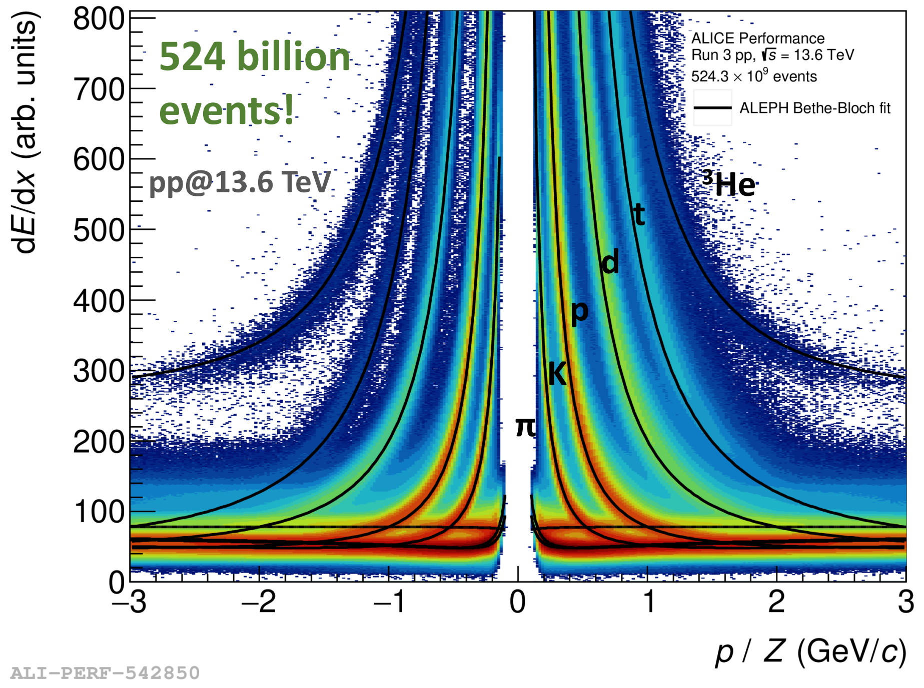
Outlook: ALICE run3/4

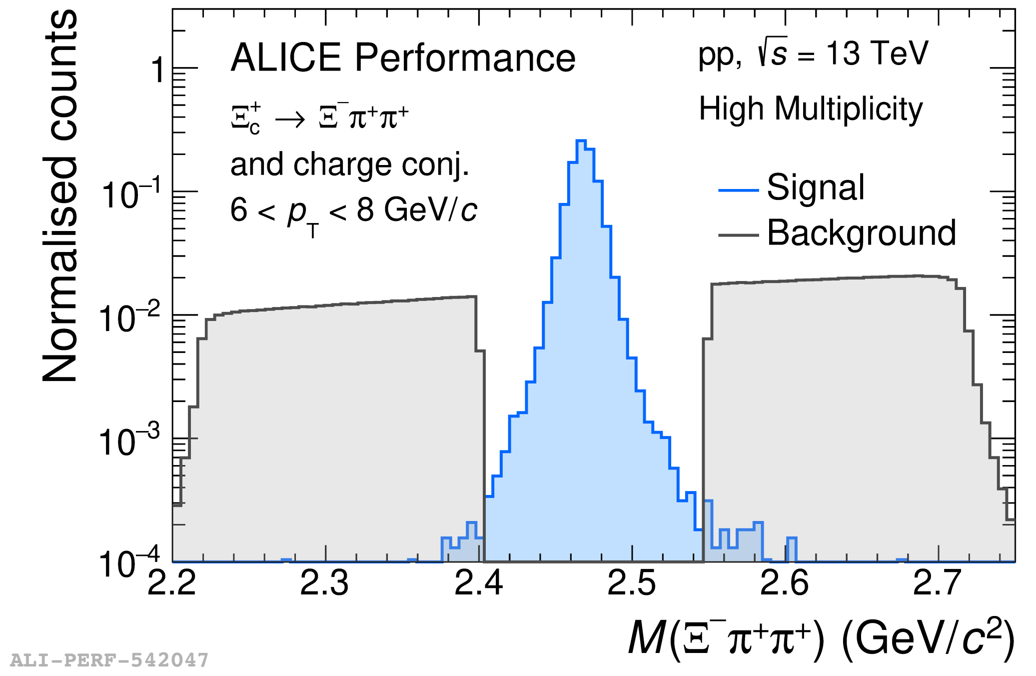


ALICE arXiv:2302.01238

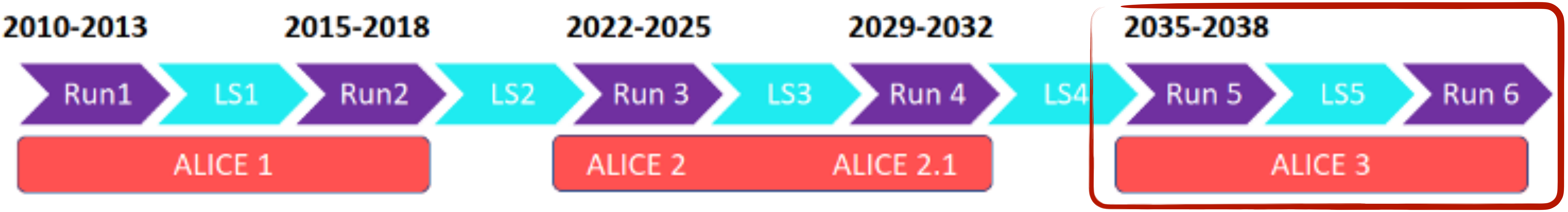


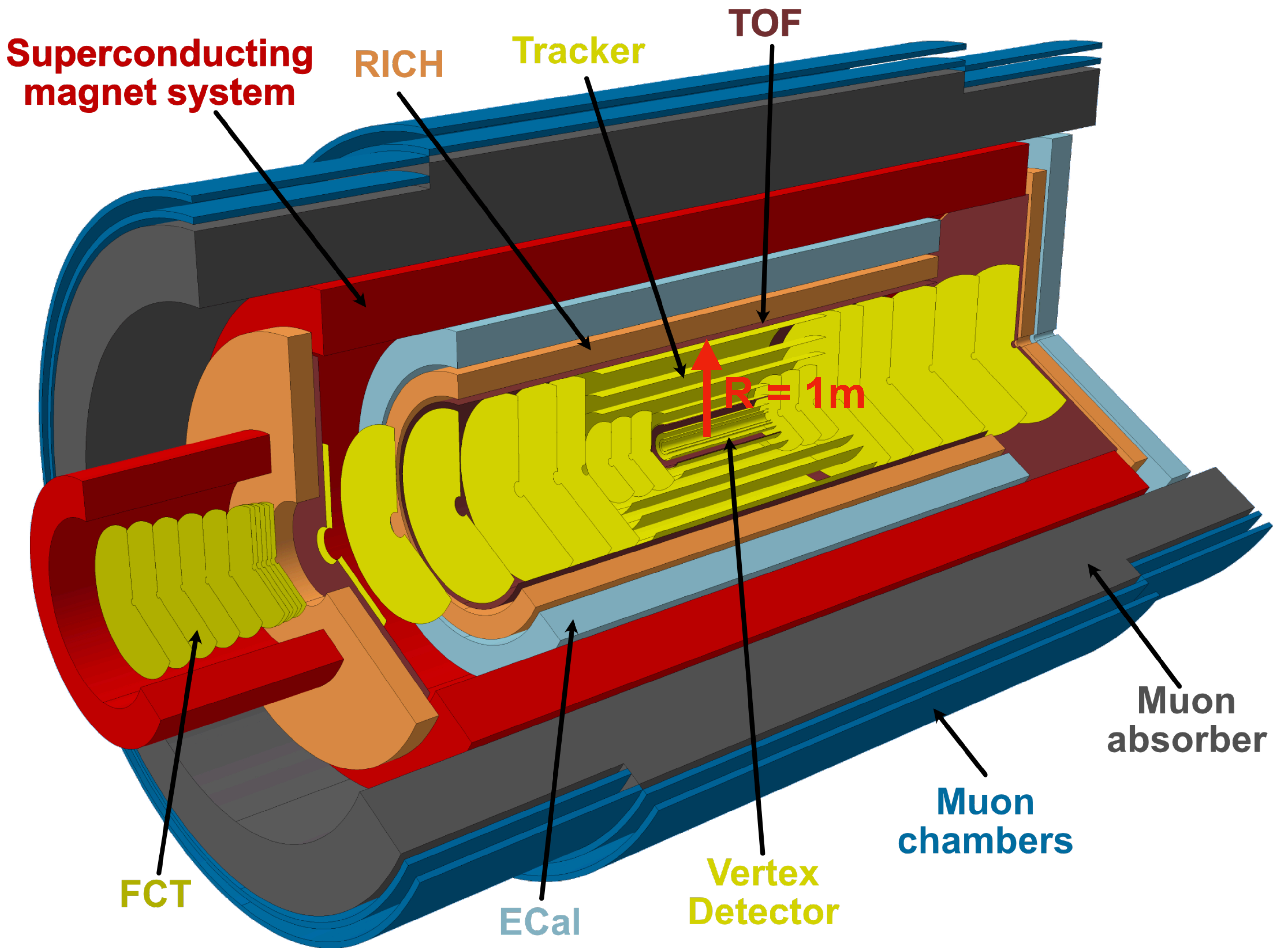


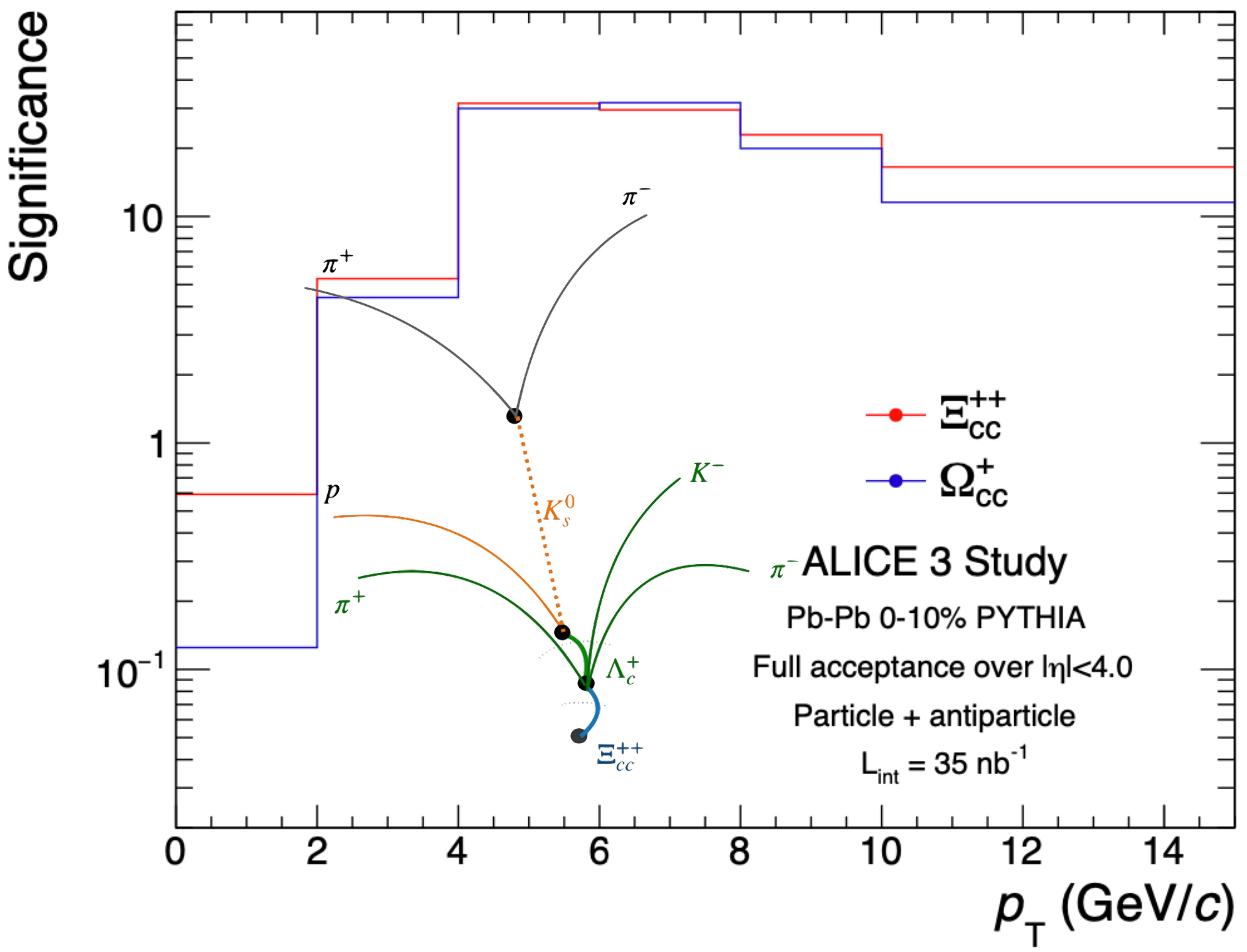




Outlook: ALICE run5 and beyond

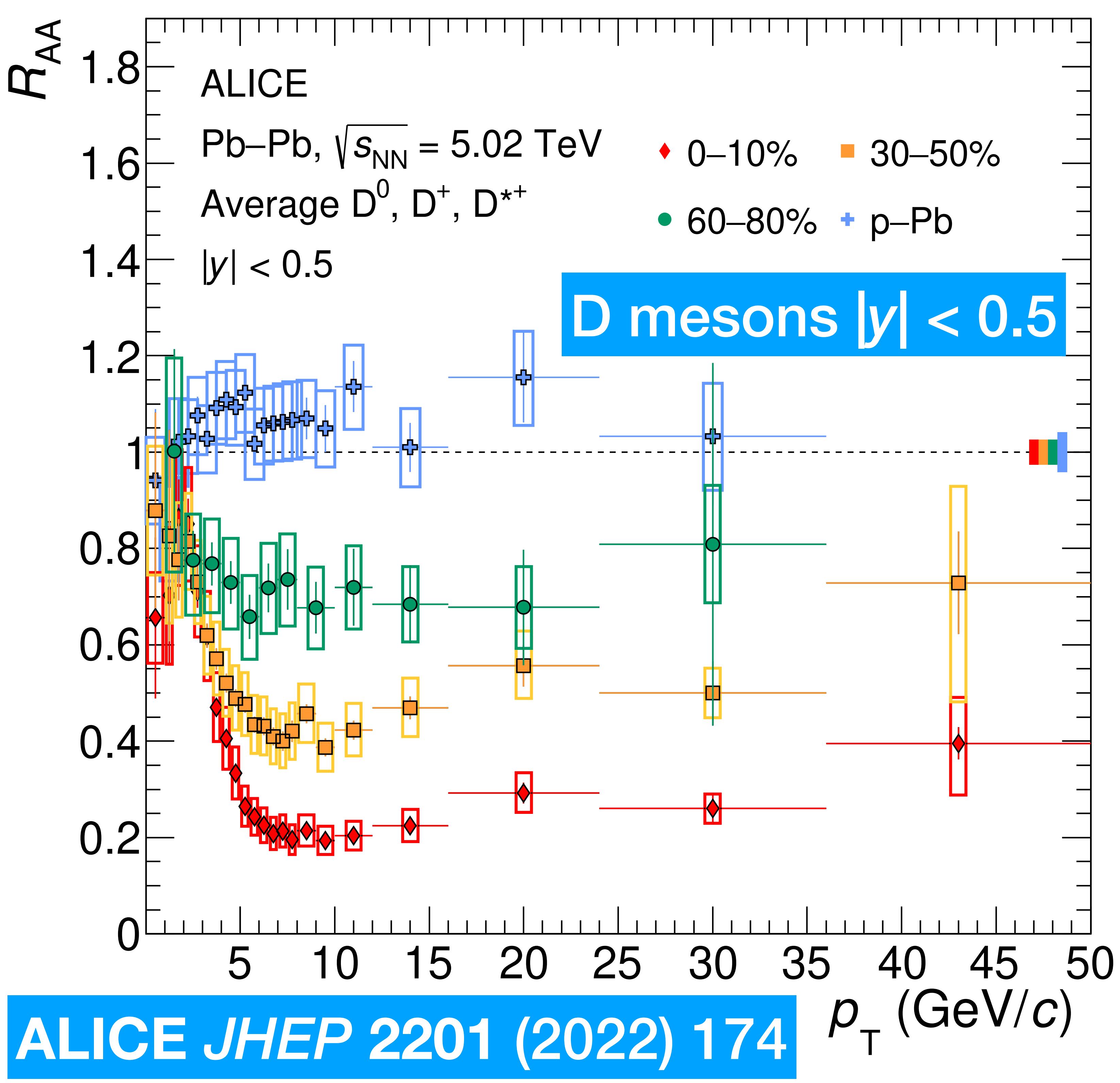






Backup

Charmed particle R_{AA}



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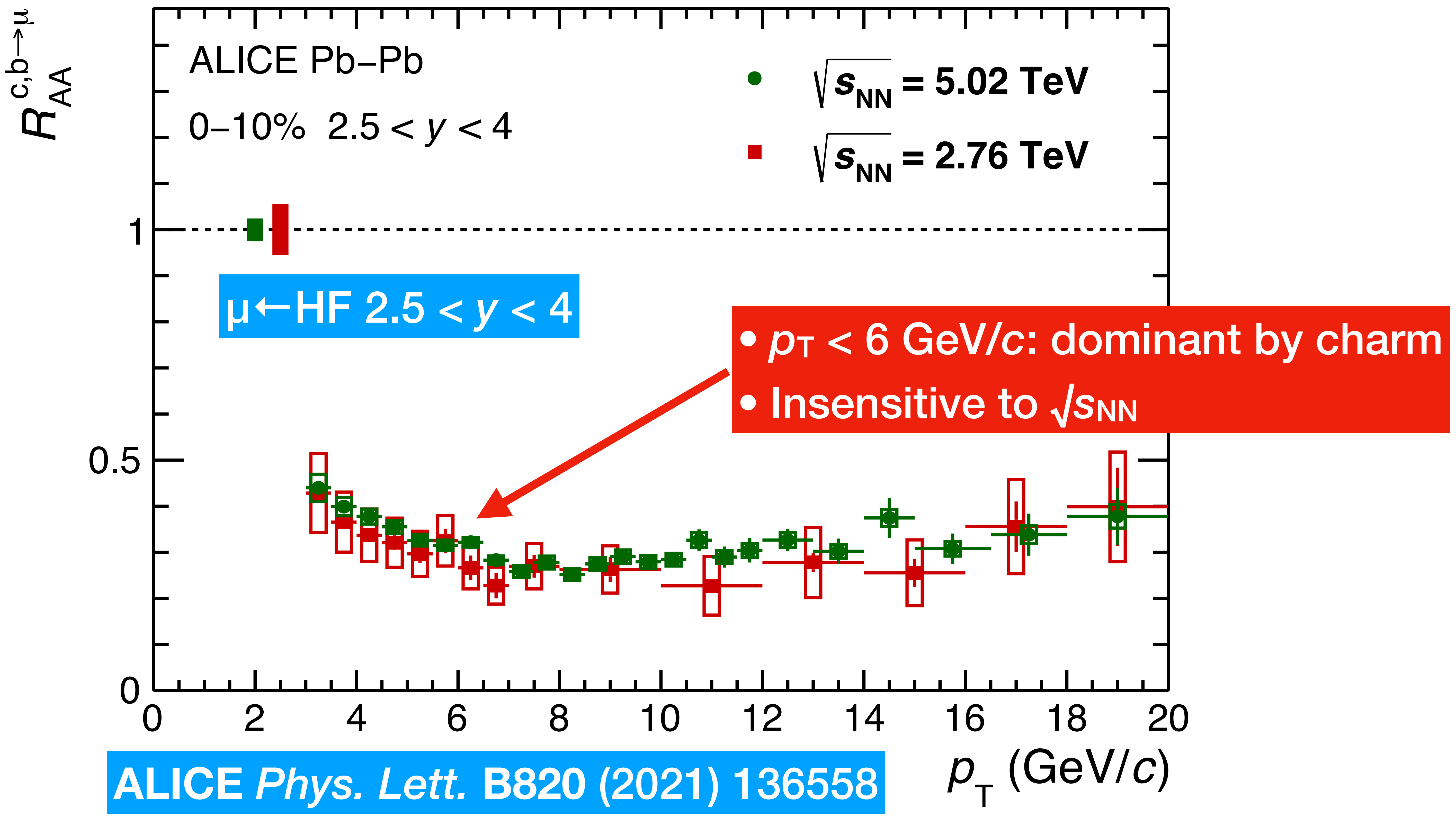
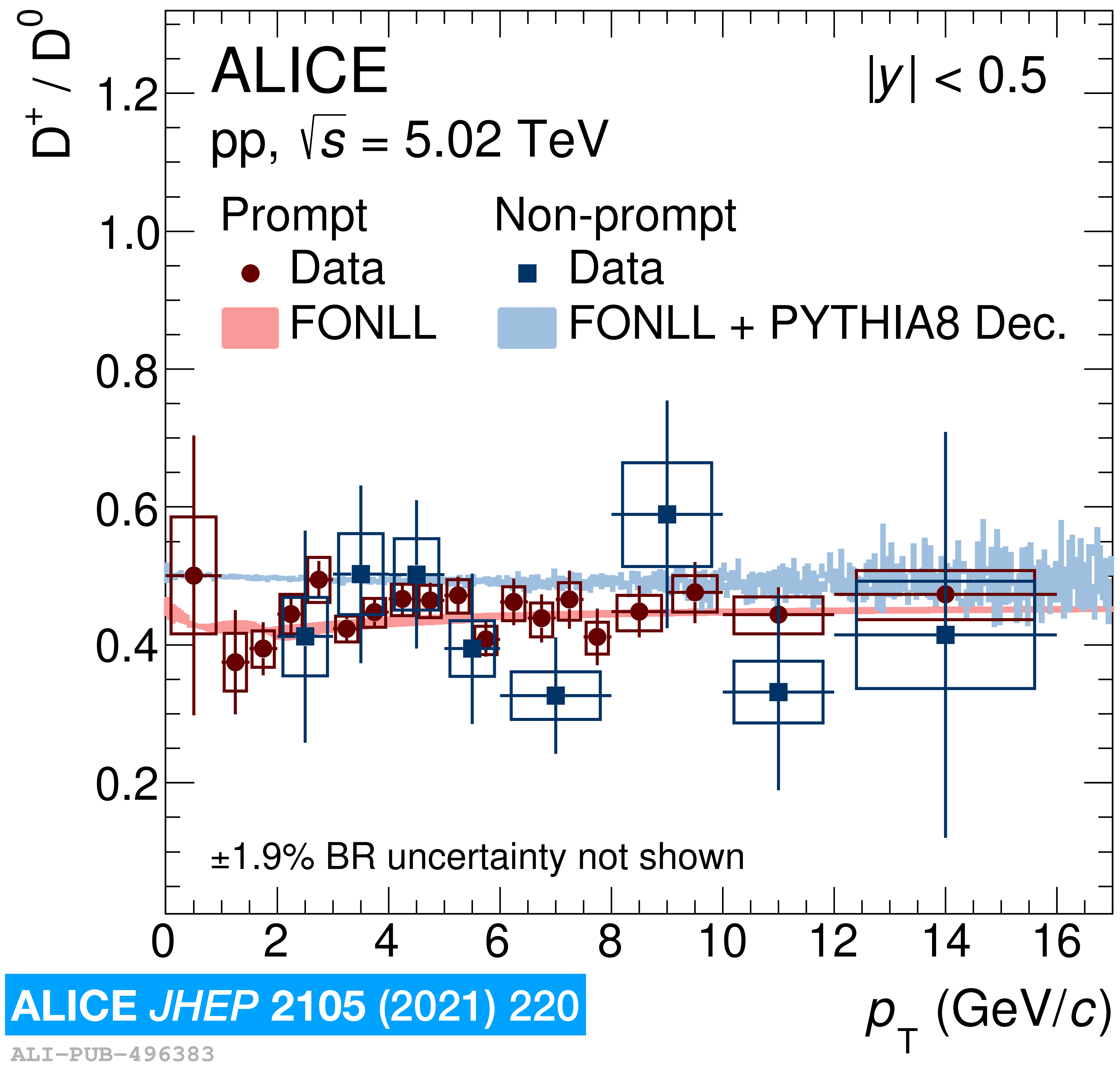


ALICE *Phys. Lett.* B820 (2021) 136558

- Suppression increases from peripheral to central collisions
- Similar suppression in the most central collisions between mid- and forward-rapidity

➡ Charm quarks undergo strong energy loss in a wide rapidity range

Meson-to-meson ratios



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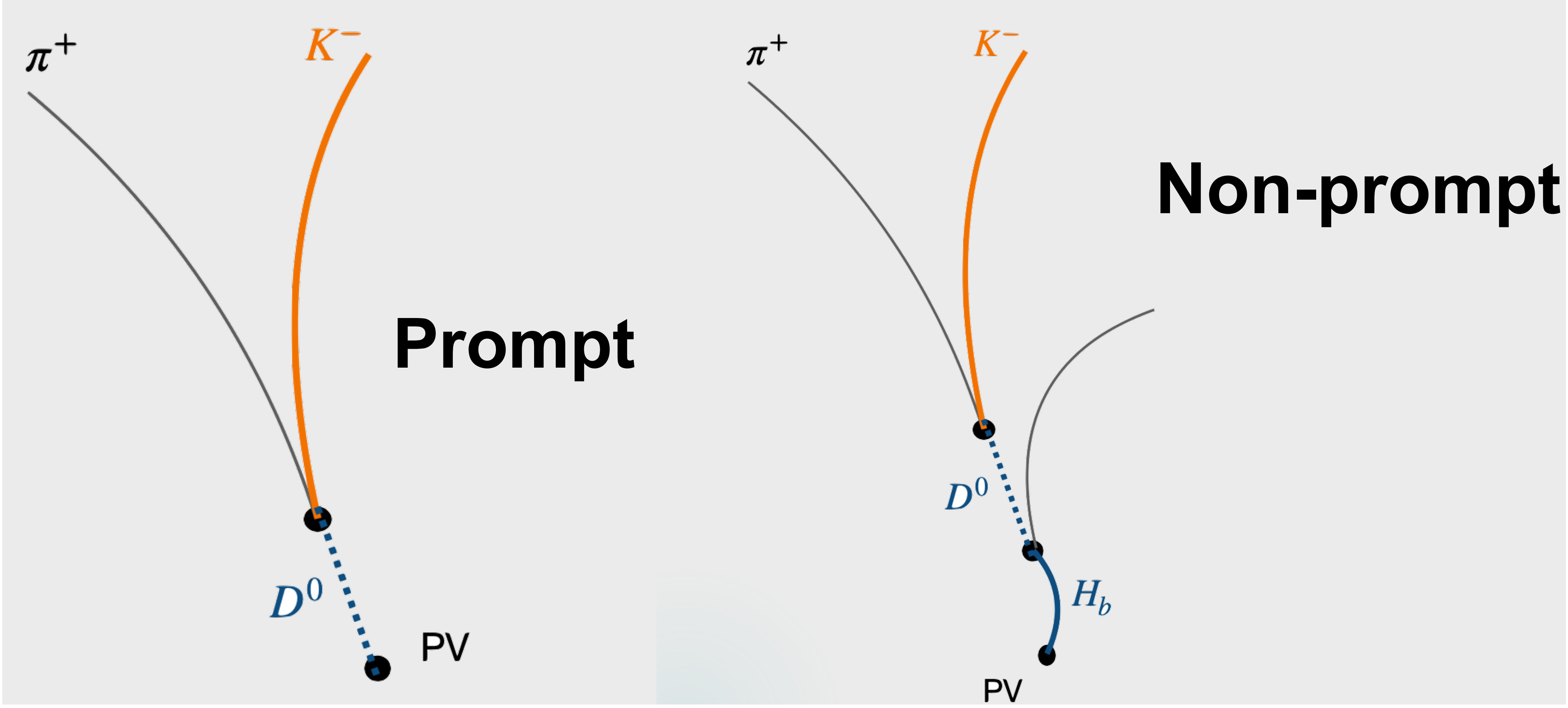
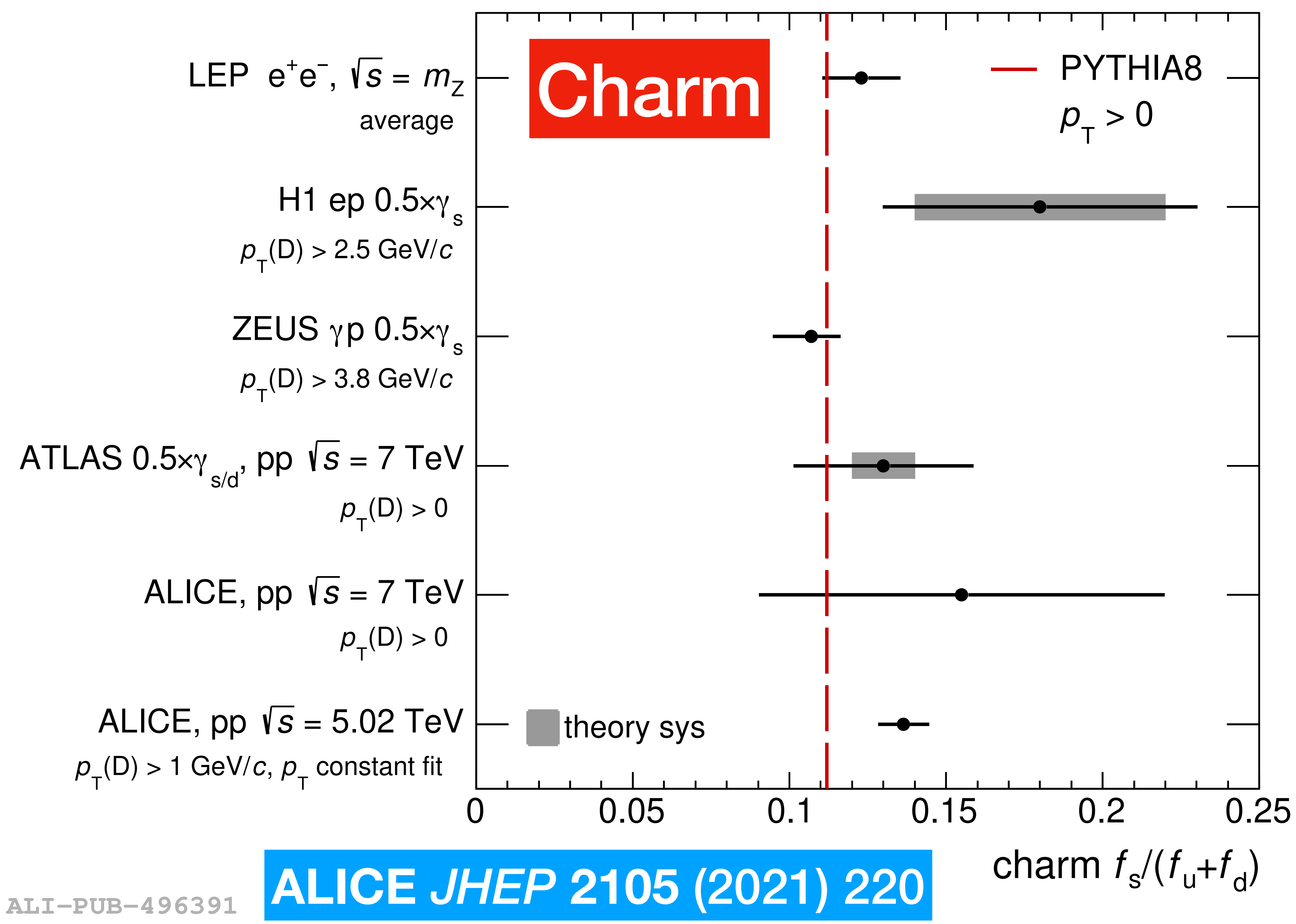
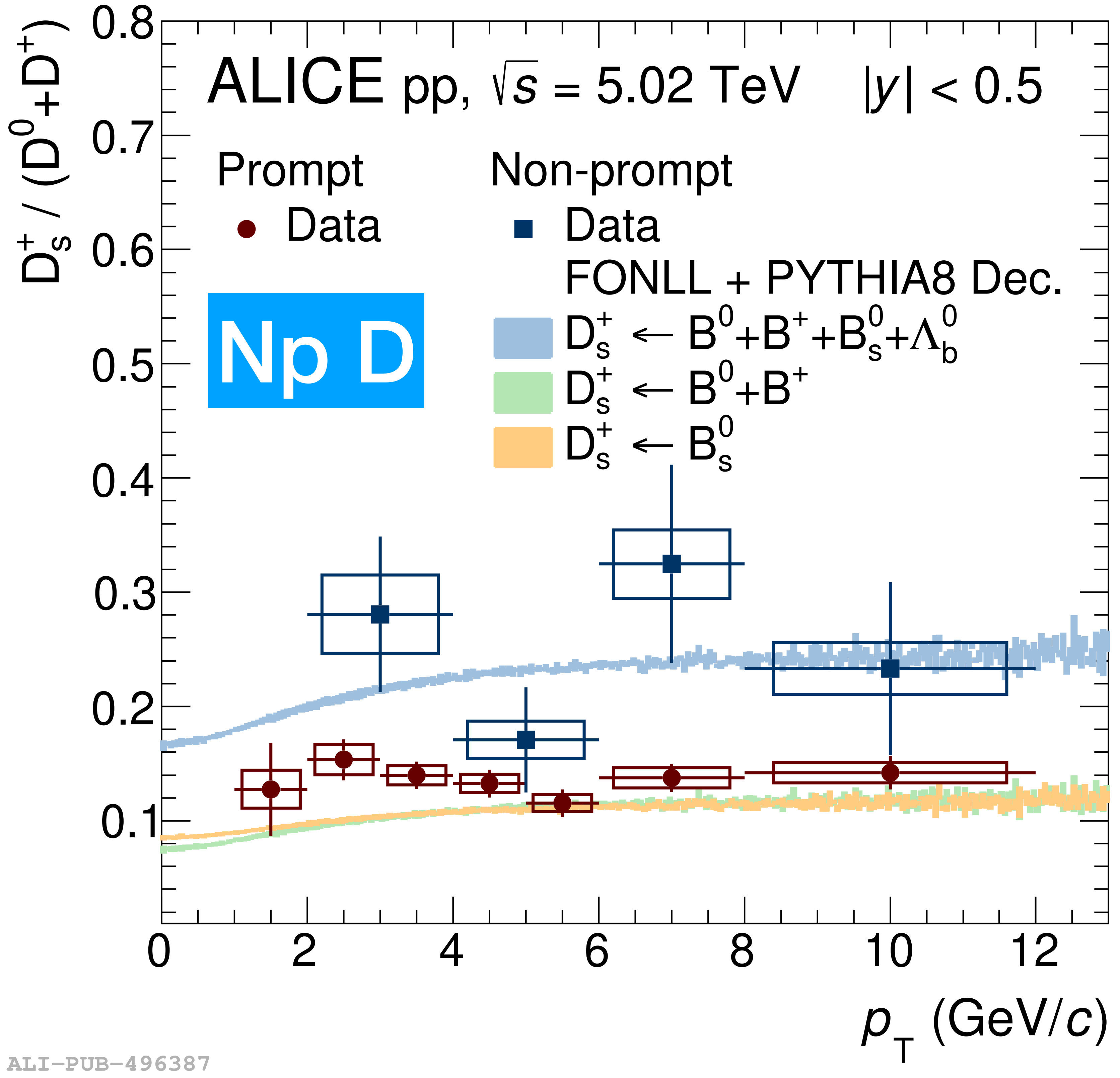
- No significant p_T-dependence for charm and beauty meson-to-meson ratios
- Good agreement with models that use fragmentation fraction tuned on leptonic collision measurements



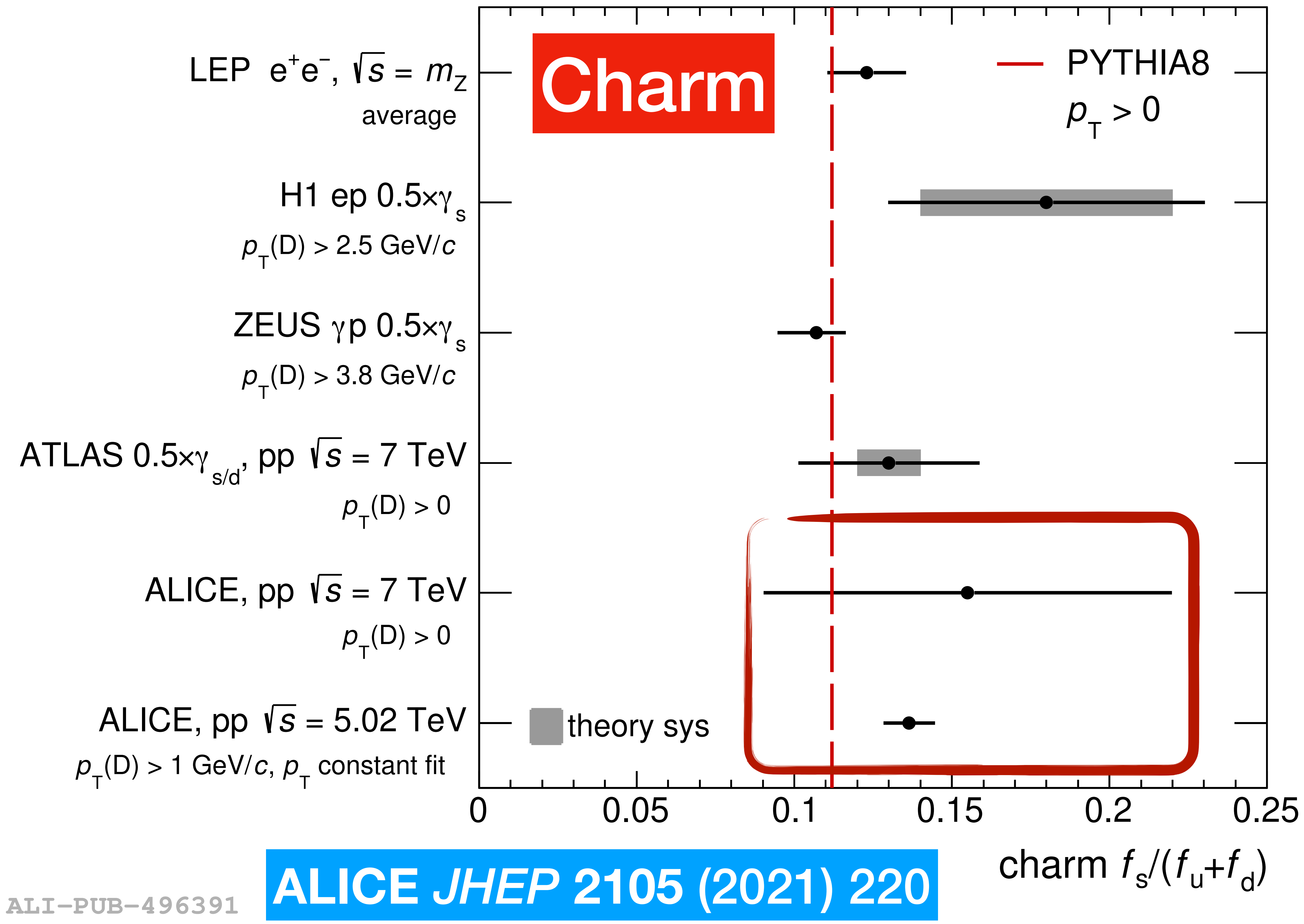
Strange-to-non-strange meson



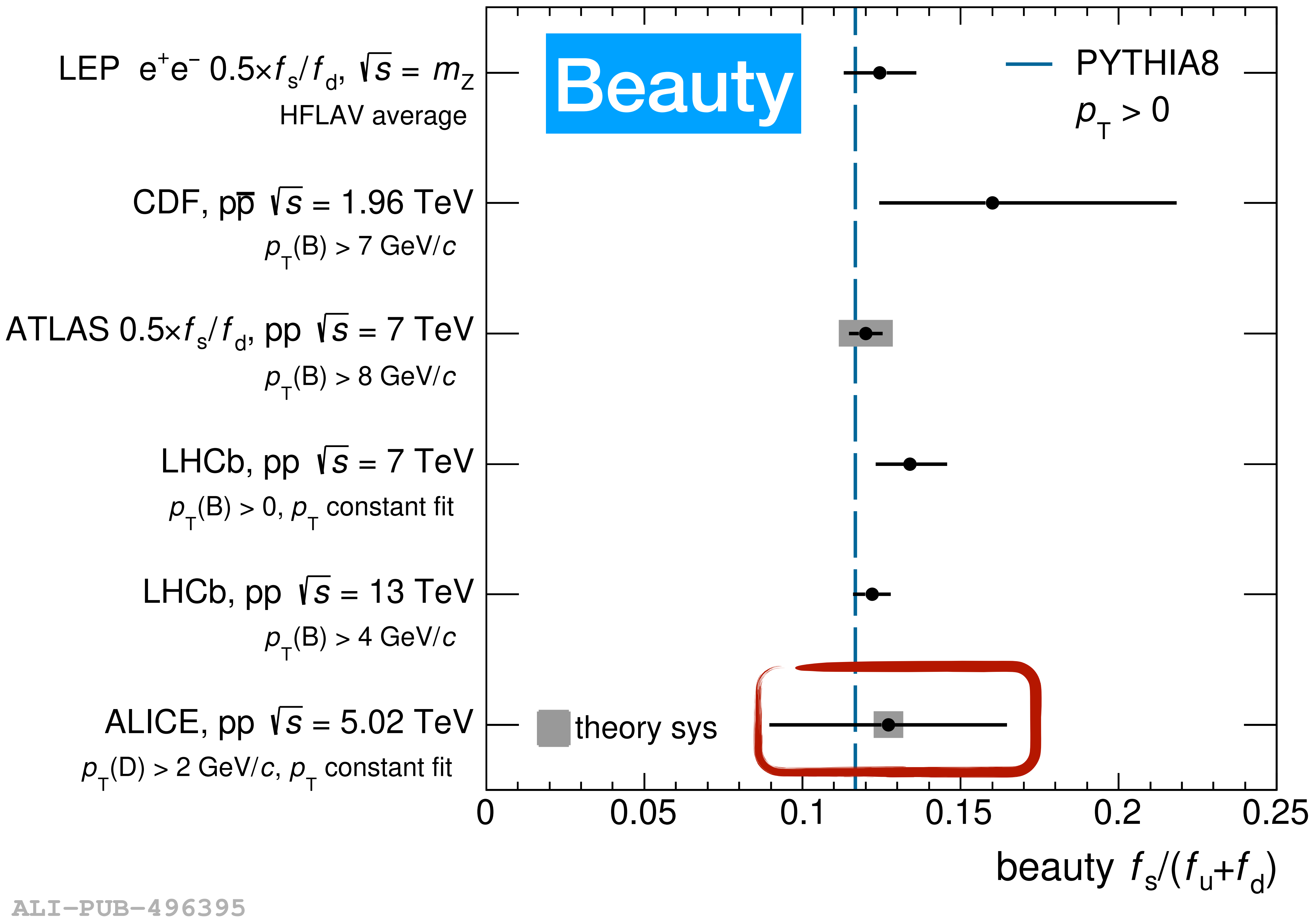
ALICE *JHEP* 2105 (2021) 220



Strange-to-non-strange meson

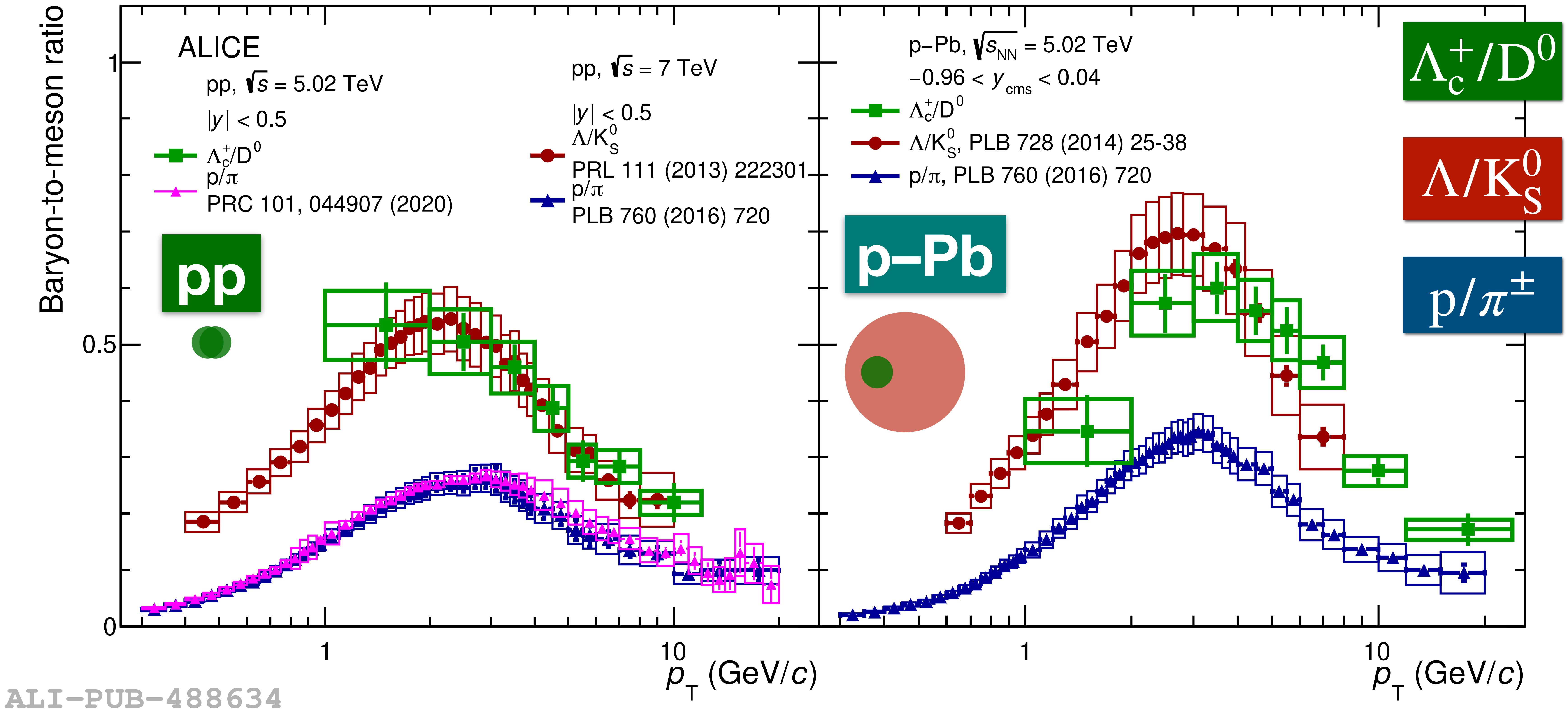


ALICE *JHEP* 2105 (2021) 220



- Fragmentation fraction ratios for charm and beauty mesons are well described by PYTHIA8 with fragmentation fraction tuned on e^-e^+
- No significant dependence on energy and collision systems

Λc/D0 ratio in pp and p–Pb



- Baryon-to-meson ratio enhancement is observed in p–Pb and pp collisions at high multiplicities in **charm sector**

➡ Similar as that in strange sector

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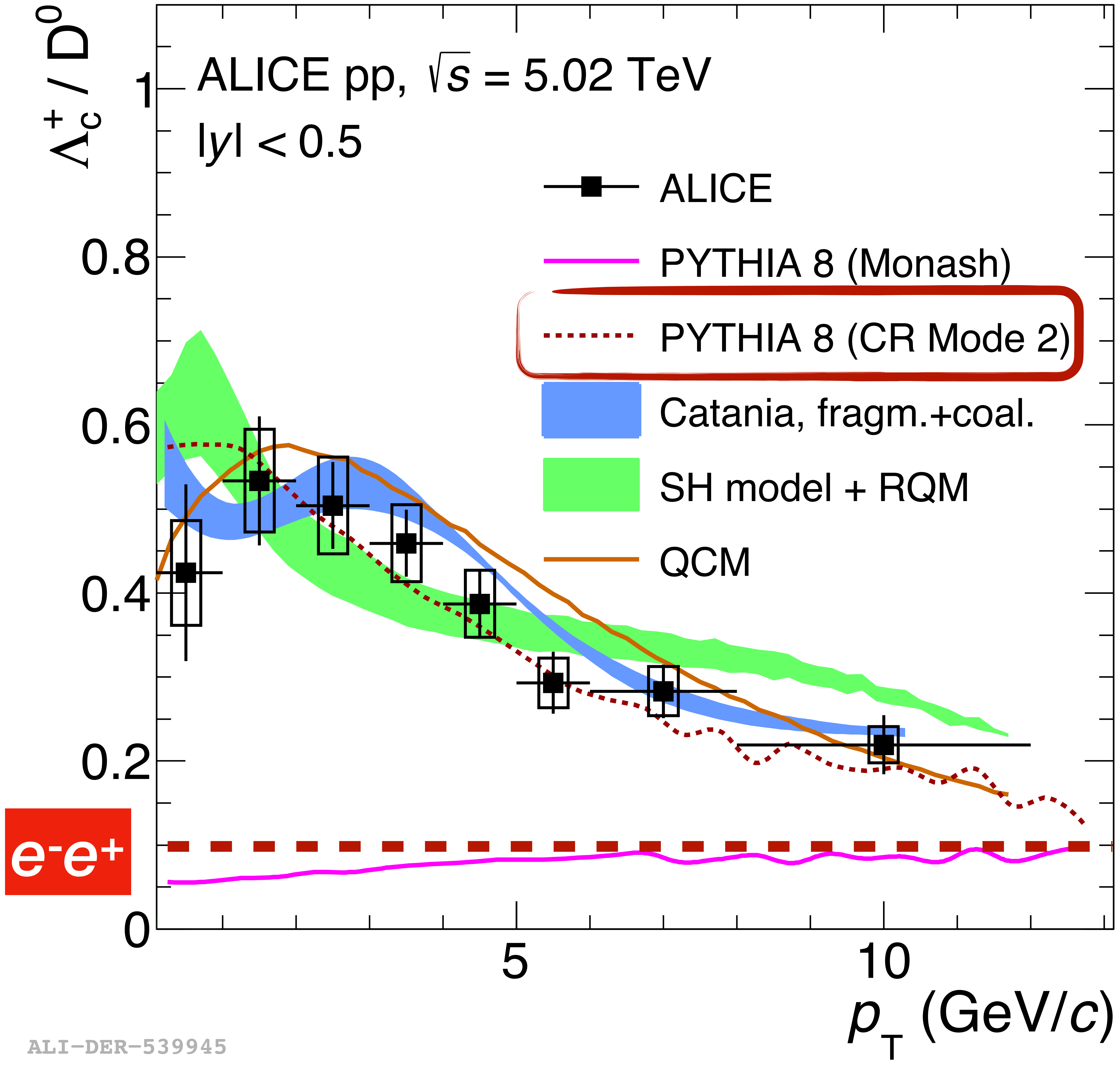
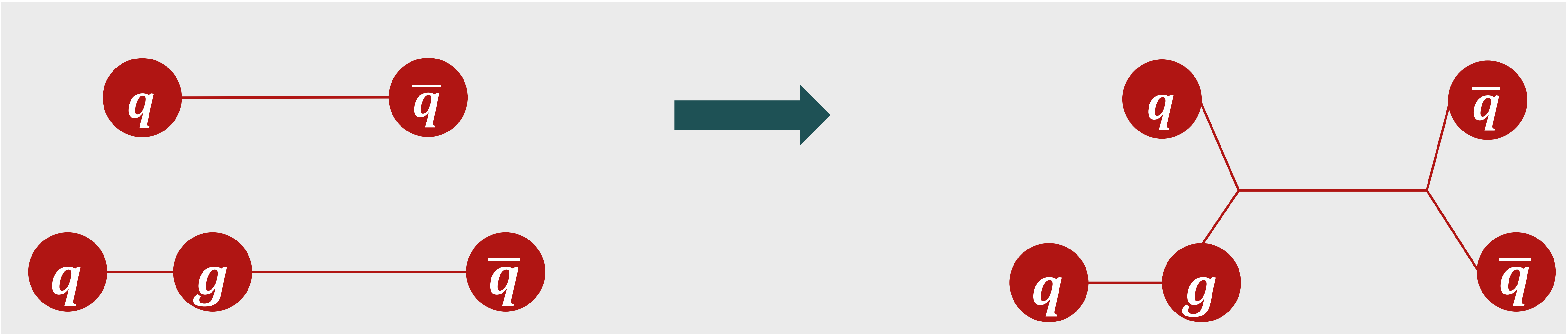
Λ_c^+/D^0 ratio in pp collisions



- Λ_c/D^0 ratios significantly higher than e^-e^+, p_T dependence observed
- PYTHIA8 color-reconnection Allowing “junction” topologies in multiparton interactions, which enhance the charm baryon production



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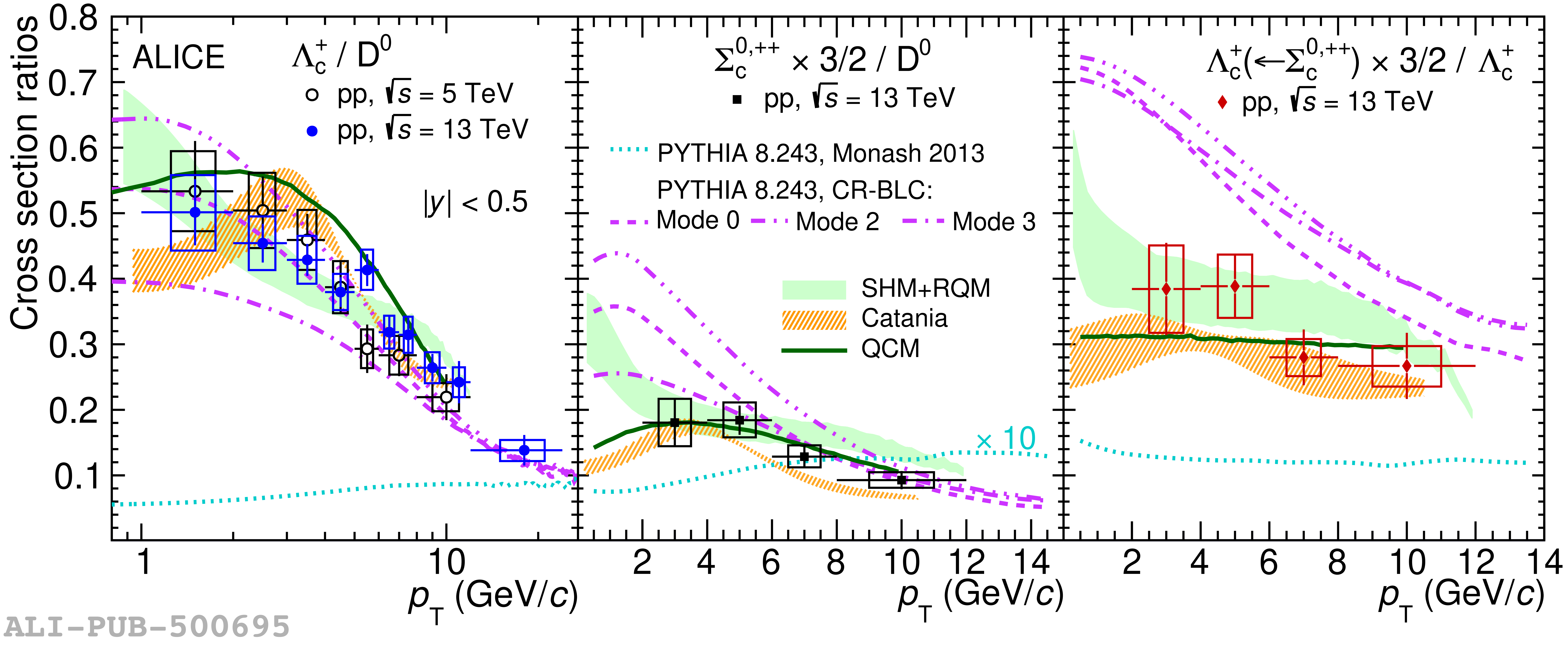
$\Sigma_c^{0,++}$ production in pp collisions



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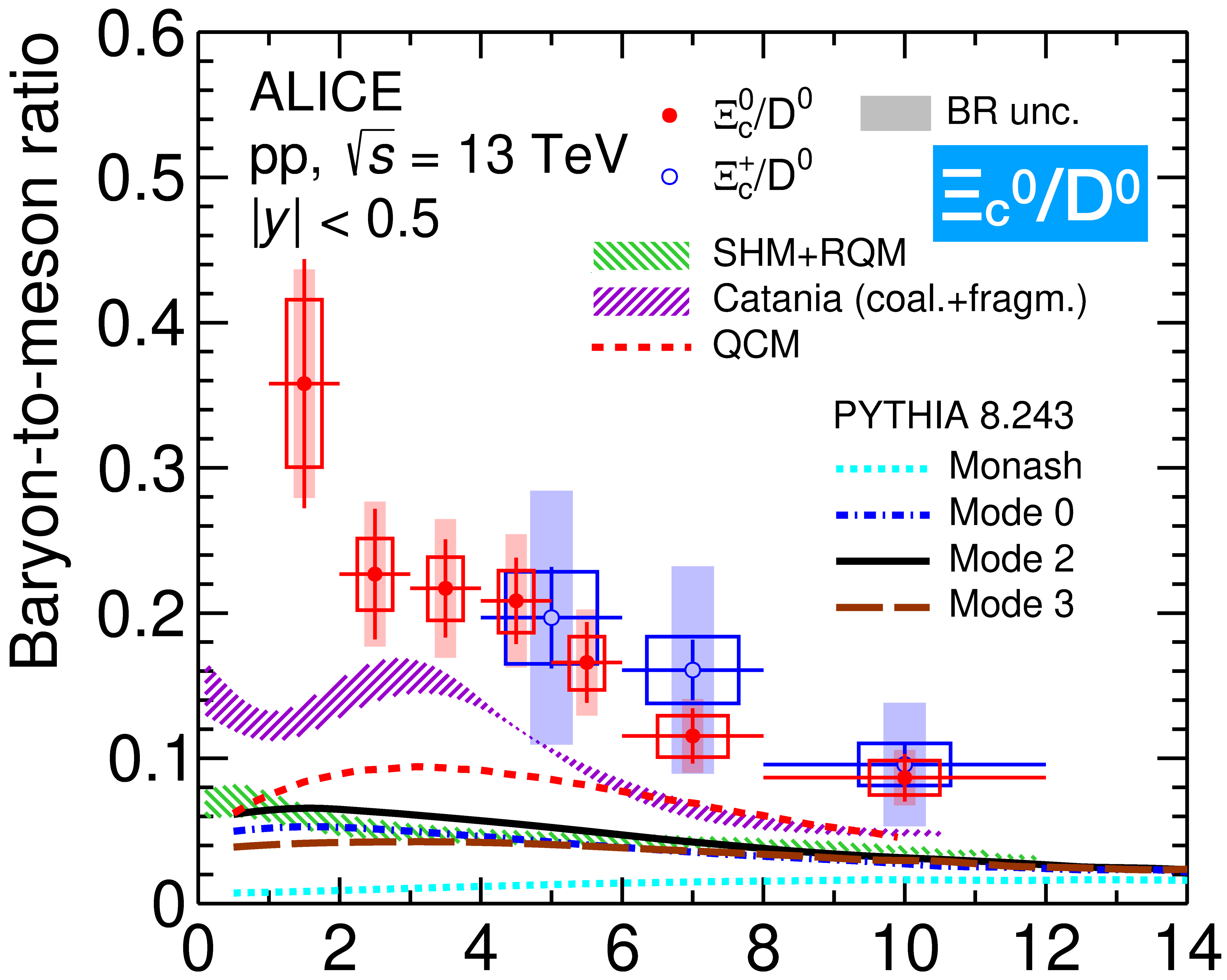
- SHM+RQM, Catania, and QCM describe the $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio while PYTHIA8 with CR-BLC overestimates the data

Strange charmed baryon in pp



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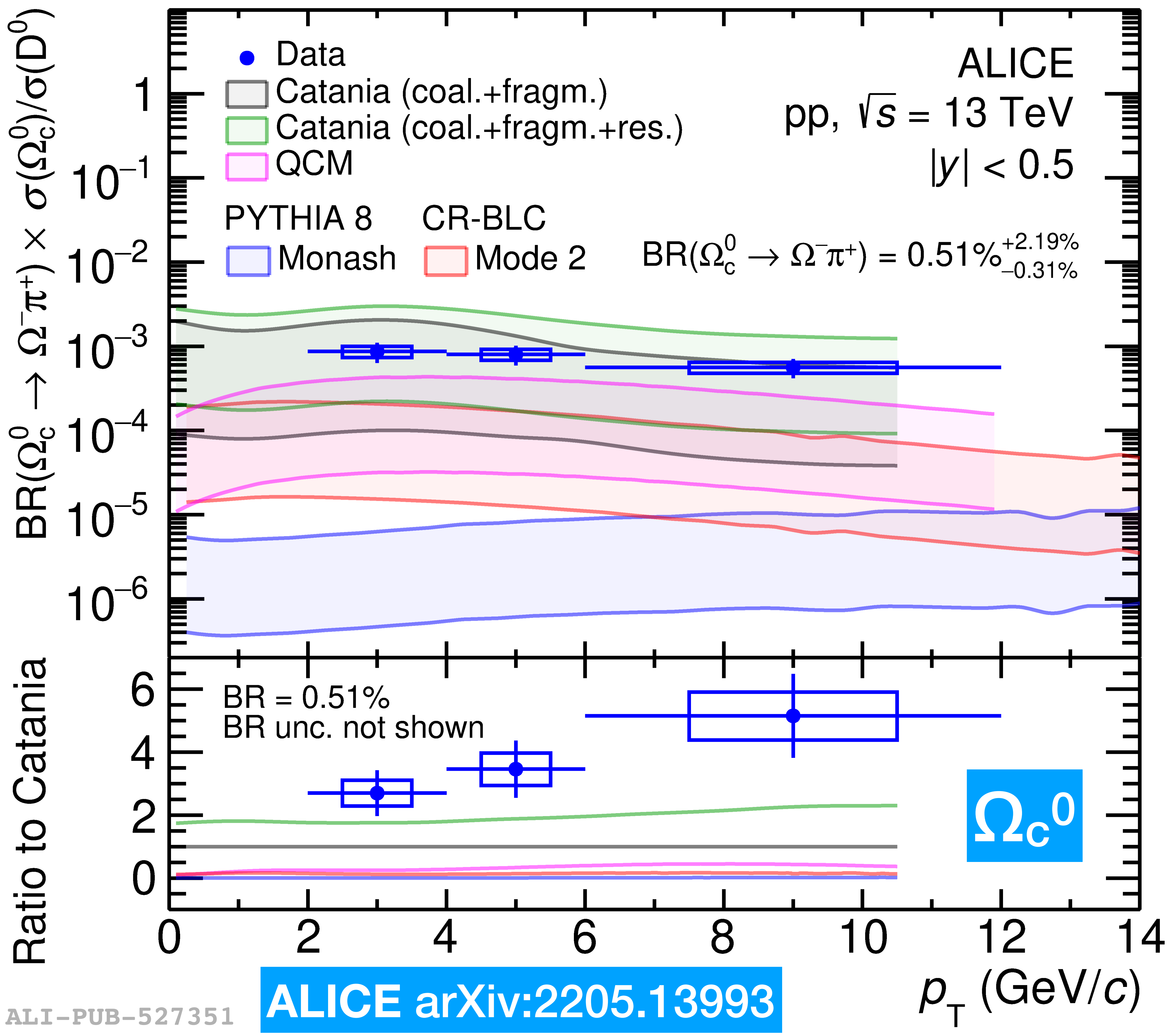
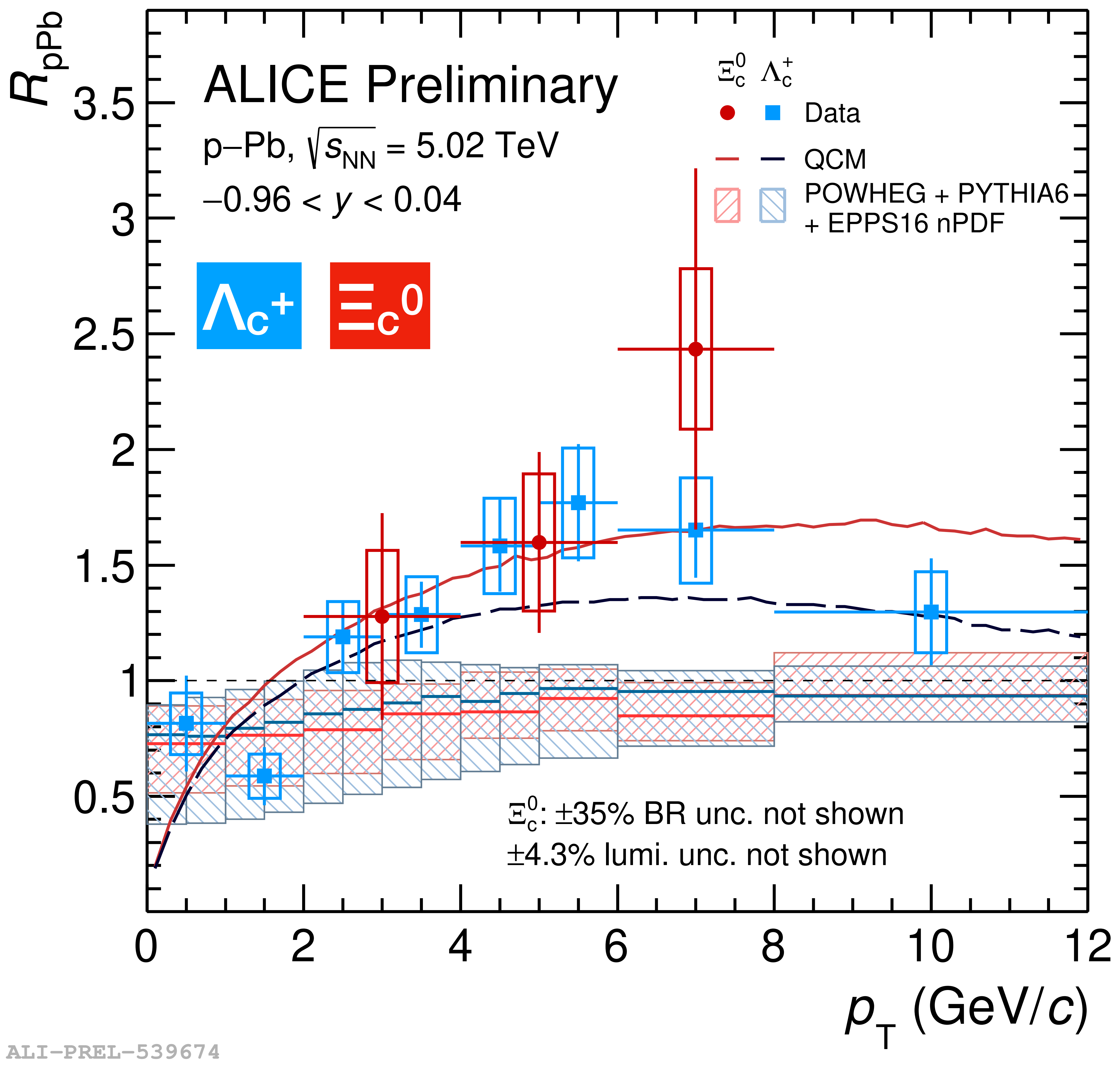
ALICE *JHEP* **2110** (2021) 159



- Catania model closer to the measurement when decays from additional higher-mass resonances are considered

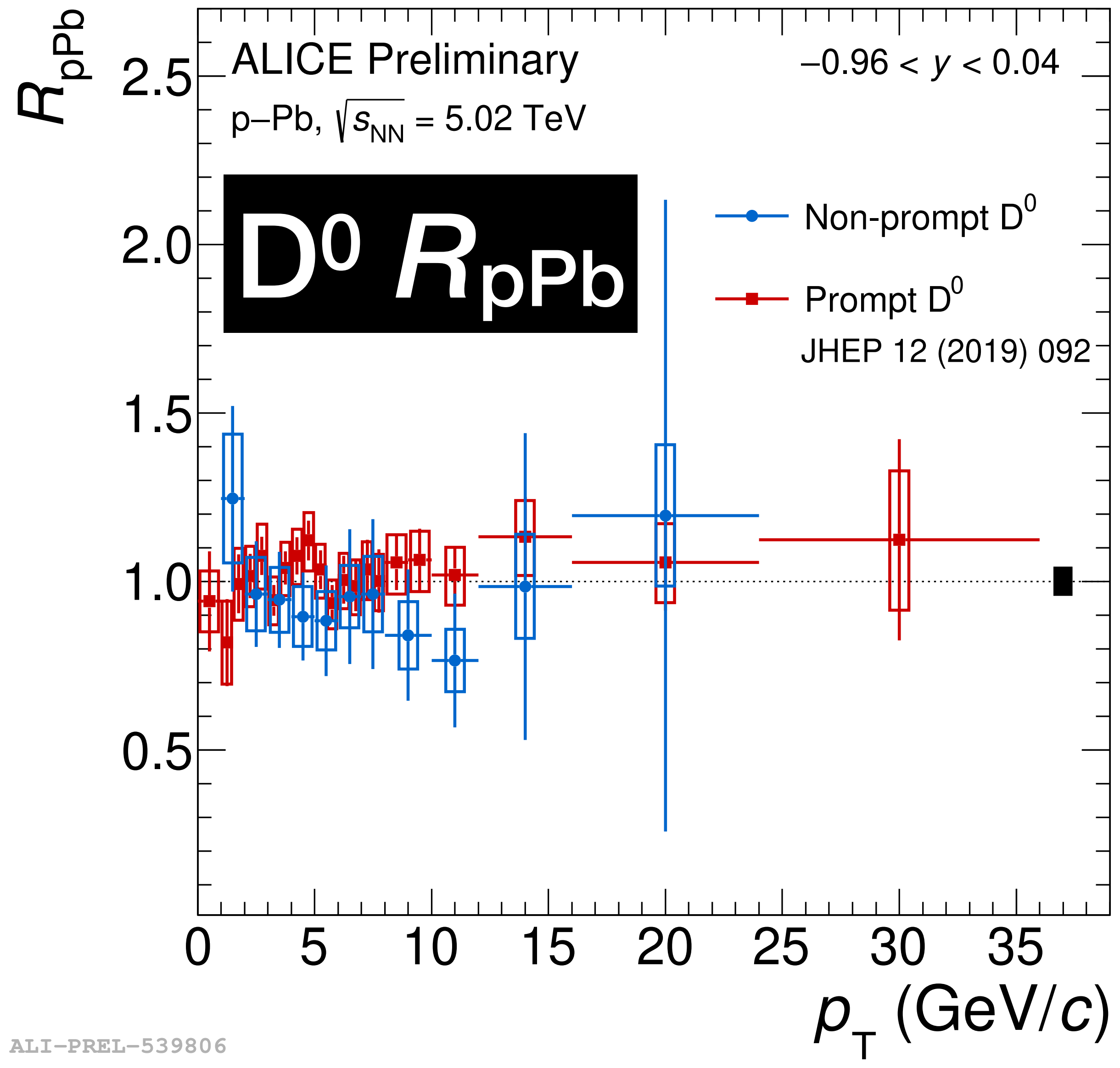
Heavy flavours in p–Pb

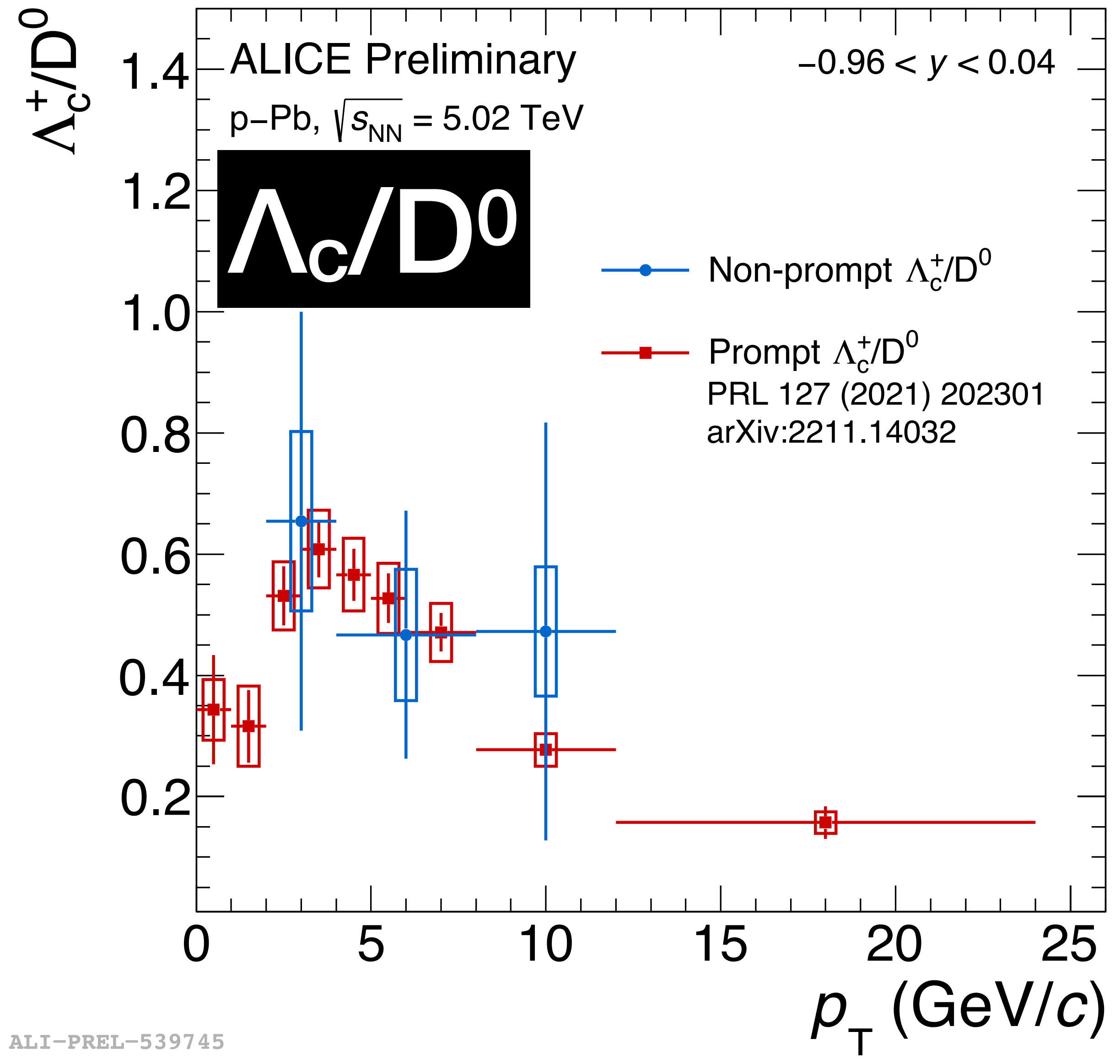


- R_{pPb} of Λ_c^+ and Ξ_c^0 are in agreement within the uncertainties
- QCM prediction agrees with measurement

Prompt

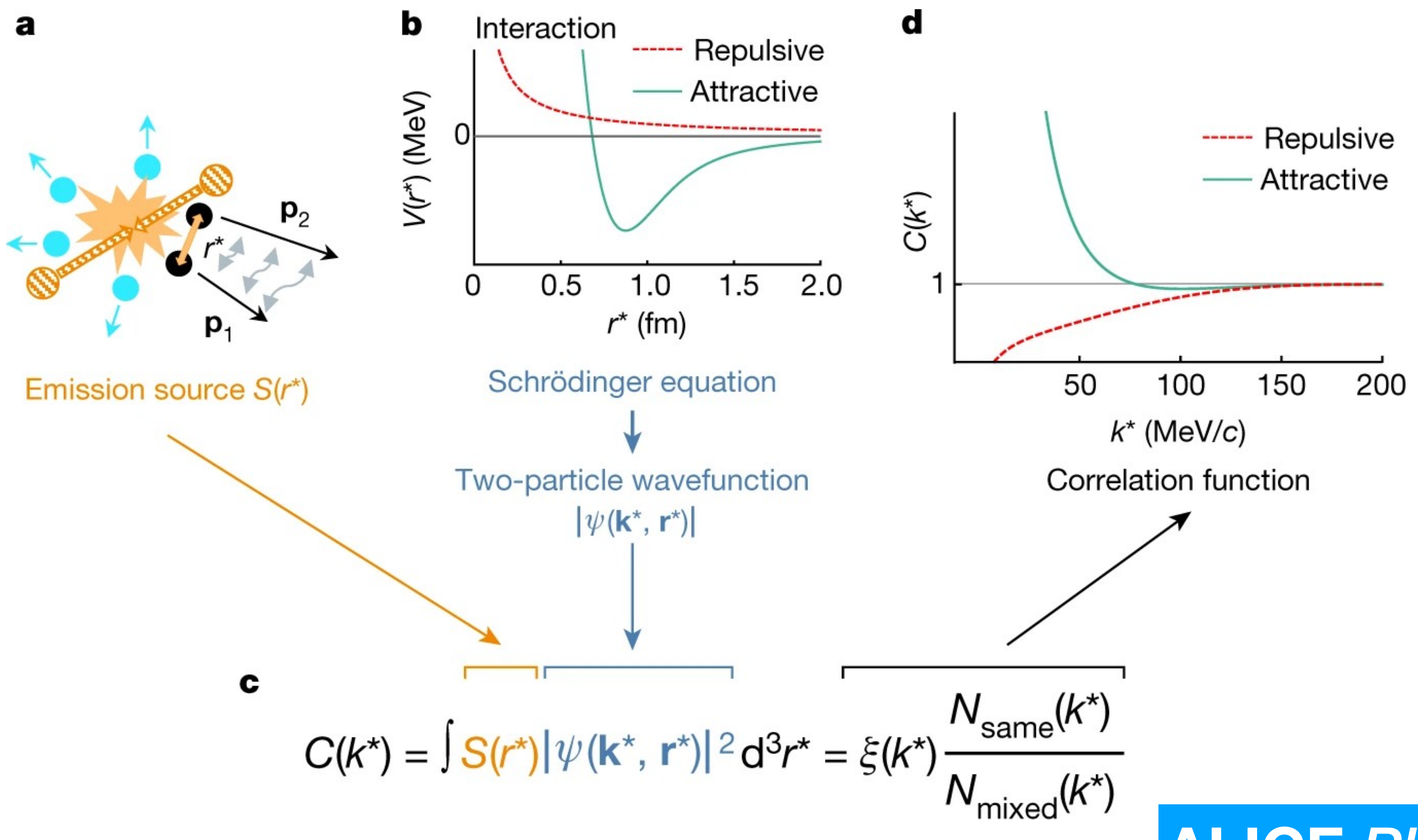
Non-prompt

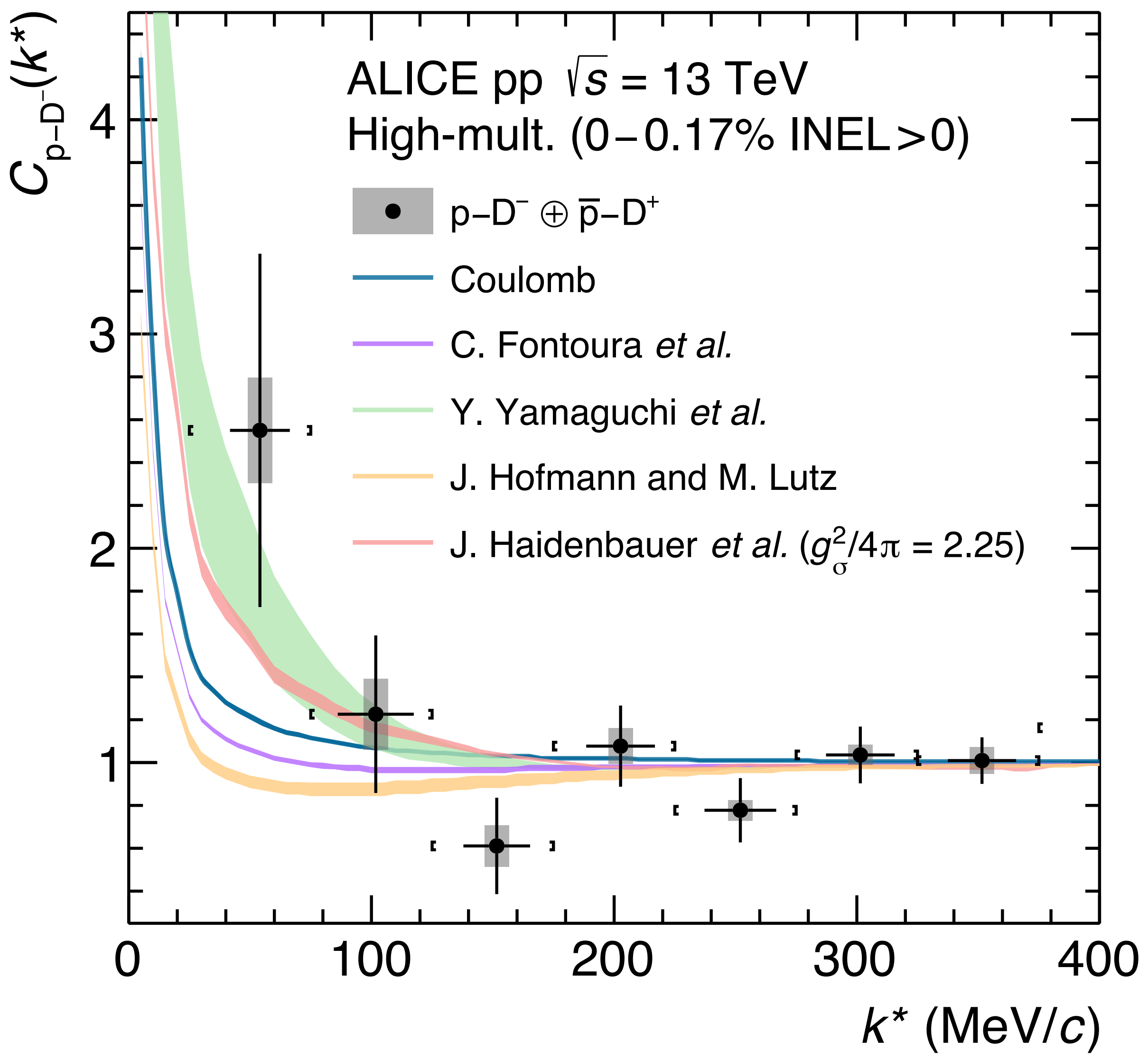




- Similar behavior between prompt and non-prompt charm baryons

Femtoscopy and polarization





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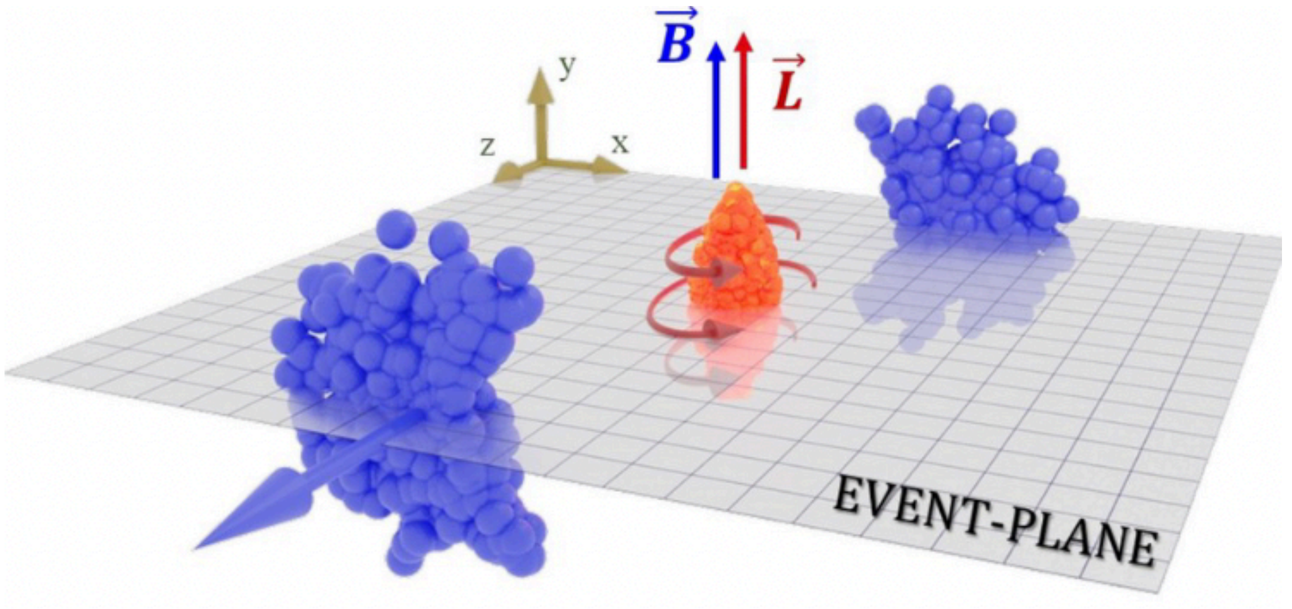

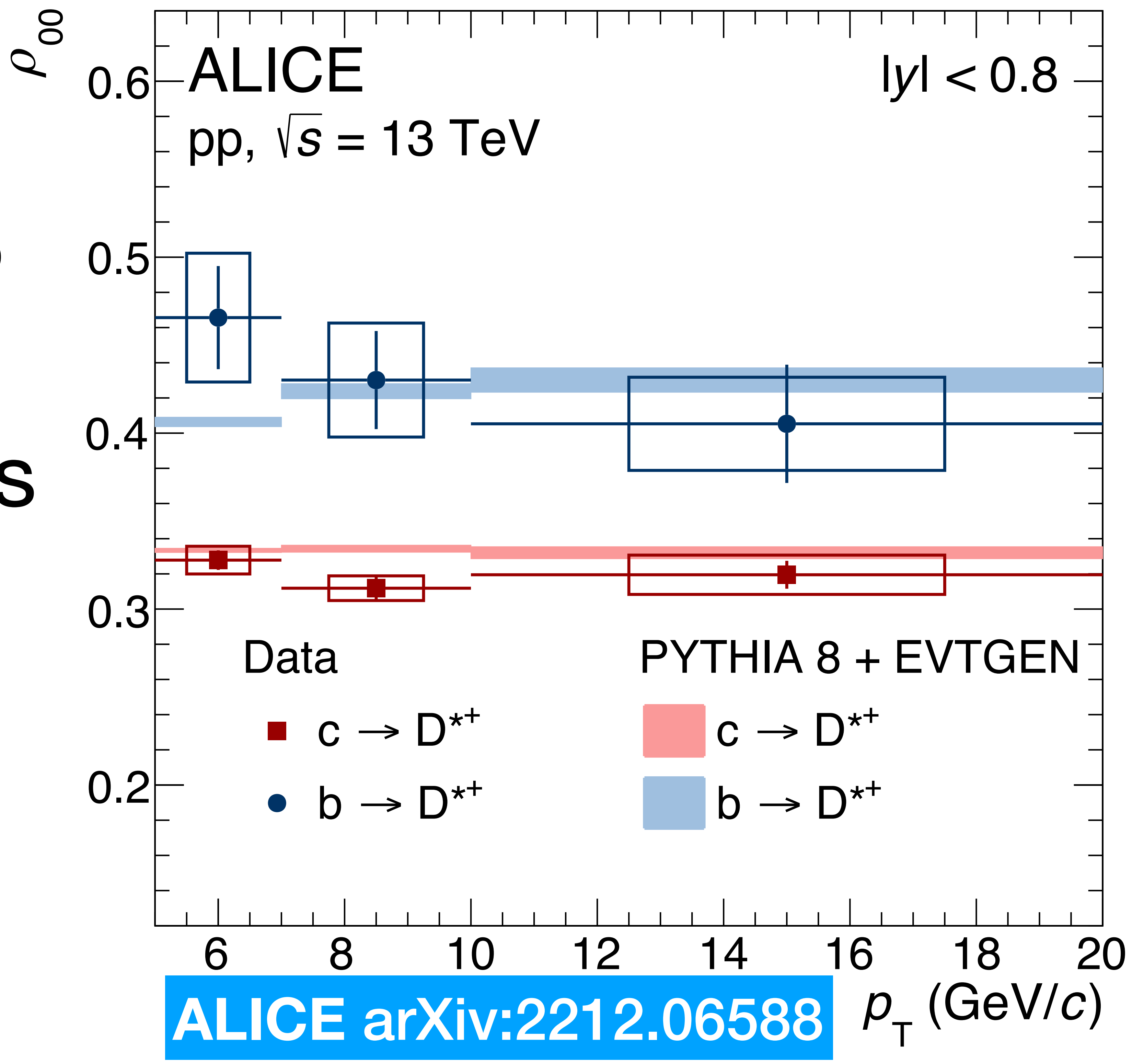

ALICE arXiv:2212.06588

- Unveiling strong-interaction potentials among hadrons via femtoscopy — test for lattice QCD, input for EOS of neutron stars
- No significant no spin alignment for prompt D*+, hint of spin alignment for non-prompt D*+ — baseline for heavy-ion collisions