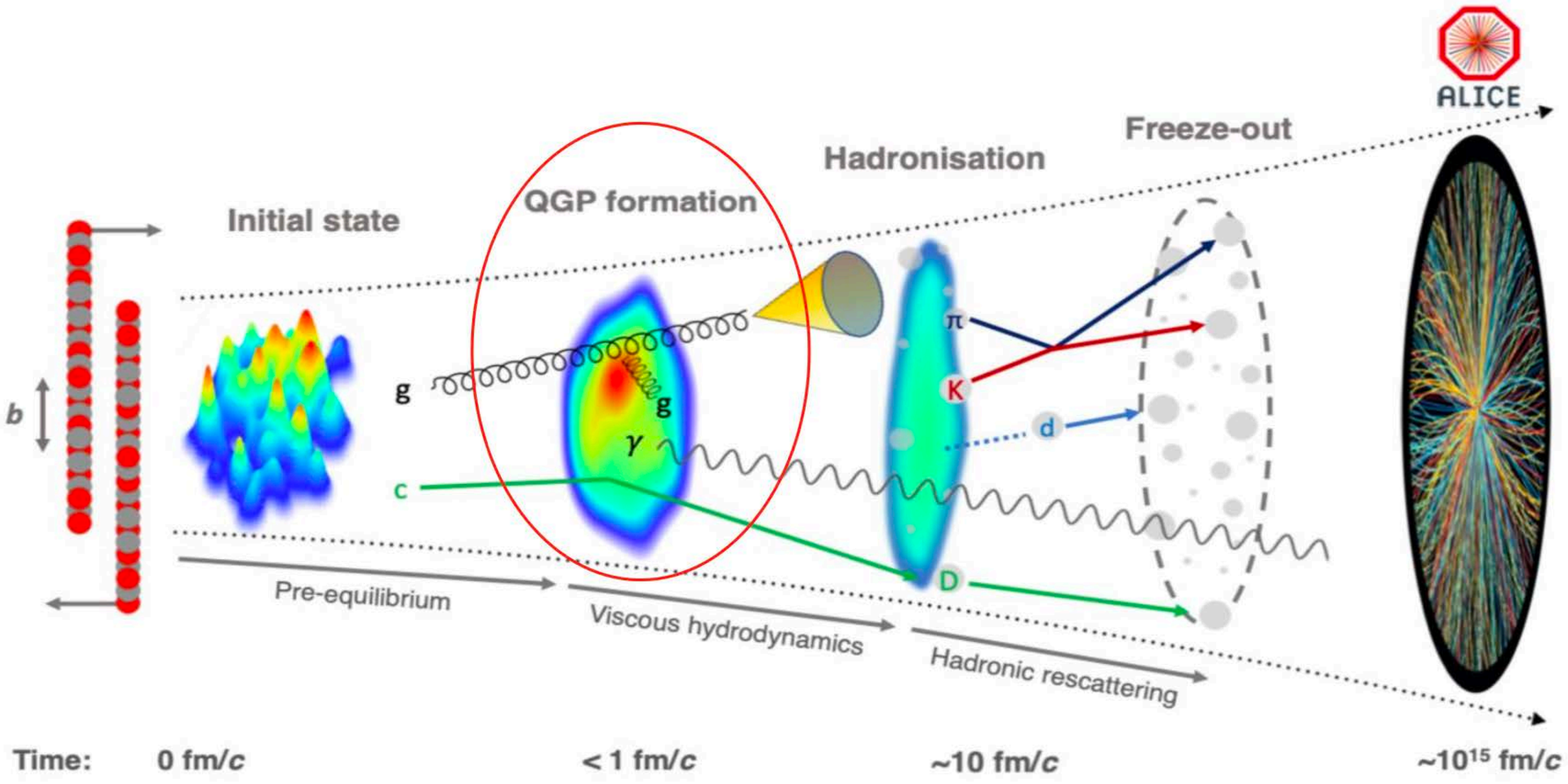
Heavy flavor measurements in ALICE and future prospects

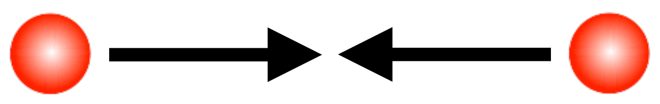
2nd TCHoU research center, member meeting, 18 Dec 2023

Jonghan Park

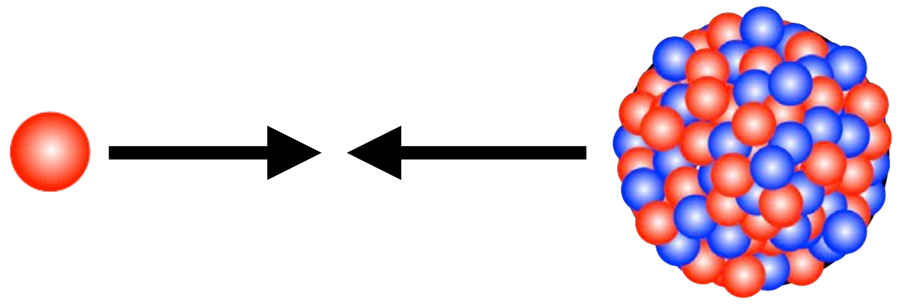
Physics Motivation

A Large Ion Collider Experiment aims at investigating a strongly coupled color-deconfined medium, known as ***quark-gluon plasma (QGP)***, created in ultrarelativistic heavy-ion collisions



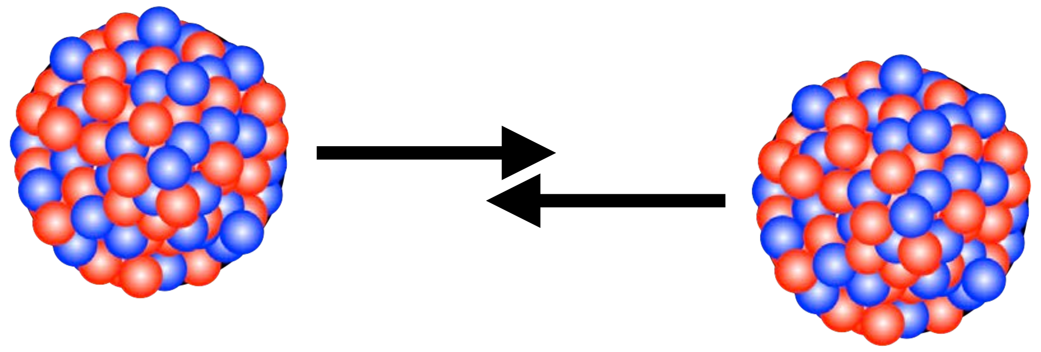


Test for pQCD calculations,
Reference for p–Pb and Pb–Pb



Cold Nuclear Matter (CNM) effects

Characterization of high multiplicity events and search for collectivity in small systems



Energy loss, collectivity, and hadronization modified in QGP

Why heavy quarks?

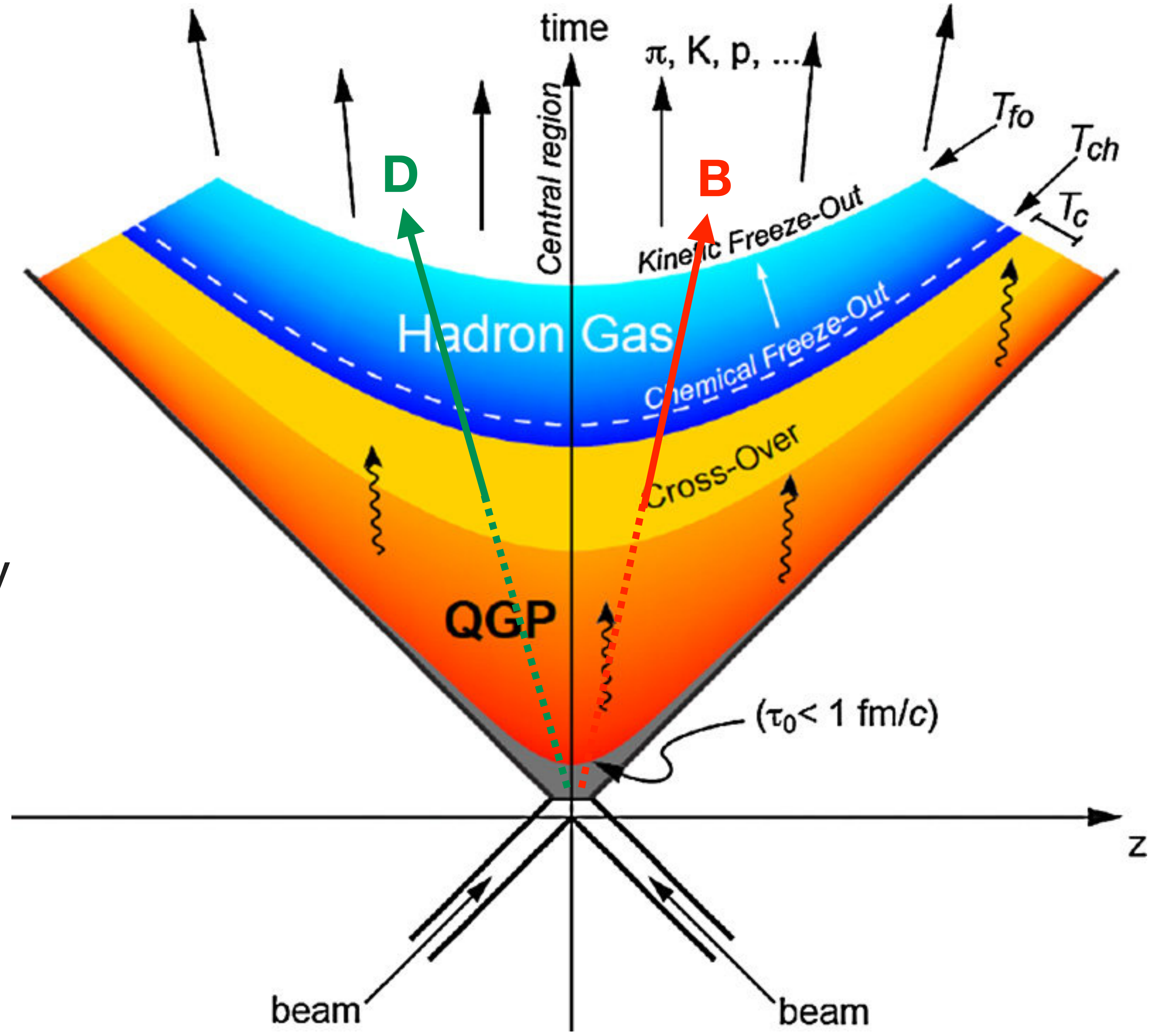
- Experience the full system evolution
  - ✓ Produced in initial hard scattering process
  - ✓ Not created and destroyed while traversing the medium
    - ➡ Flavor conserved

$$m_c \sim 1.3\,\mathrm{GeV}/c^2;\ m_b \sim 4.5\,\mathrm{GeV}/c^2;\ m_Q \gg \Lambda_{QCD}$$
$$\tau_{prod} = \hbar/4m_{c(b)} \simeq 0.1(0.02)\,\mathrm{fm}/c < \tau_{QGP} \simeq 0.3\,\mathrm{fm}/c \text{ at LHC}$$

- Interact with medium constituents and lose their energy via collisional and radiative processes
  - ✓ Color charge and quark mass dependence

$$Casimir\ color\ factor: C_F = \frac{4}{3}\ for\ quark;\ C_A = 3\ for\ gluon$$

- Participation in the collective expansion, thermalization in the medium



ALICE detector (Run 2)

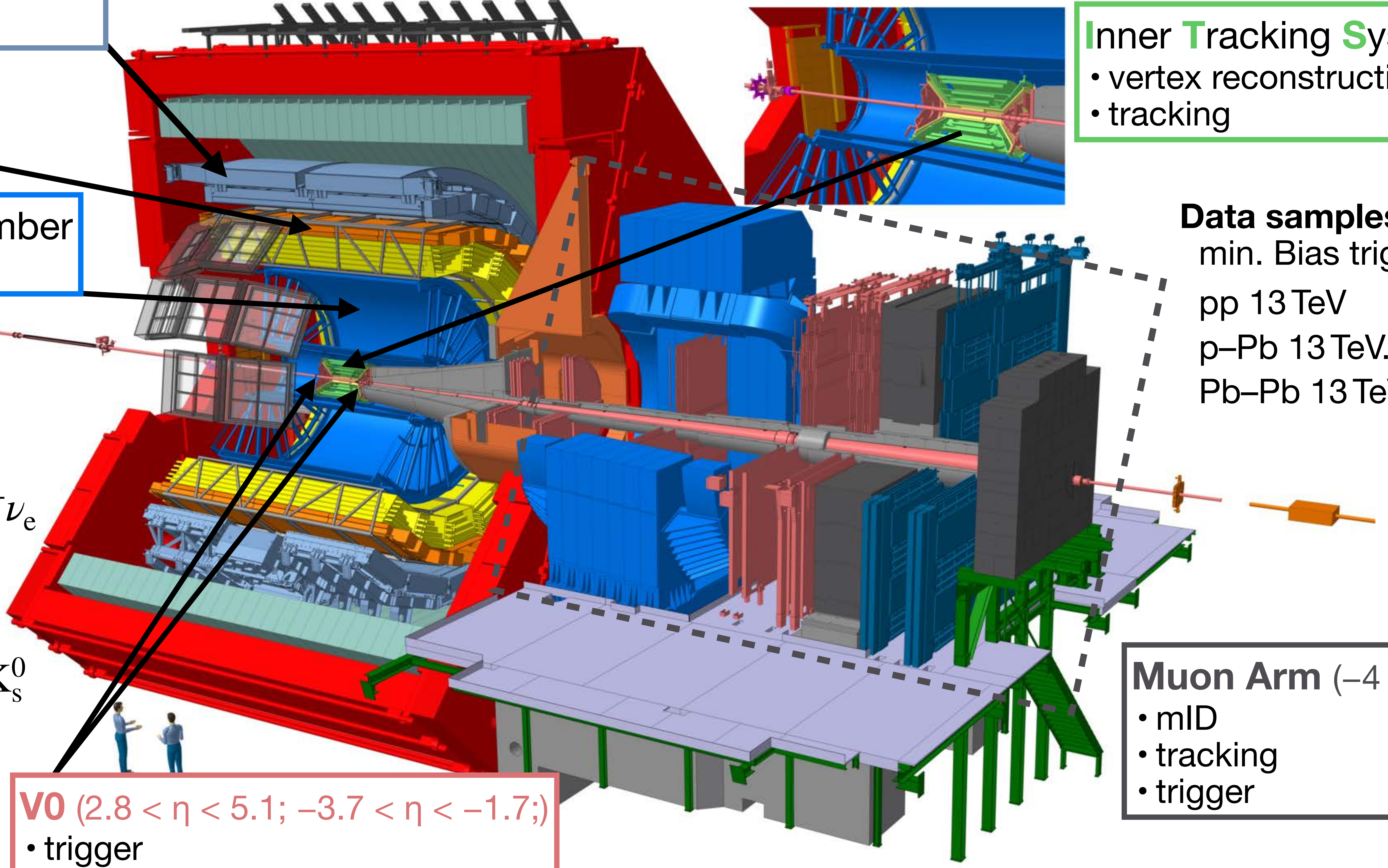
Central Barrel : |η| < 0.9

ElectroMagnetic Calorimeter
- eID

Time Of Fight
- PID

Time Projection Chamber
- tracking and PID

Inner Tracking System
- vertex reconstruction
- tracking



$D^0 \to K^- \pi^+$

$D^+ \to K^- \pi^+ \pi^+$

$D^{*+} \to D^0 \pi^+$

$\Xi_c^0 \to \Xi^- \pi^+,\ \Xi_c^0 \to \Xi^- e^+ \nu_e$

$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$

$\Omega_c^0 \to \Omega^- \pi^+$

$\Lambda_c^+ \to pK^- \pi^+,\ \Lambda_c^+ \to pK_s^0$

$\Sigma_c^{0,++} \to \Lambda_c^+ \pi^{-,+}$

$b, c \to e$

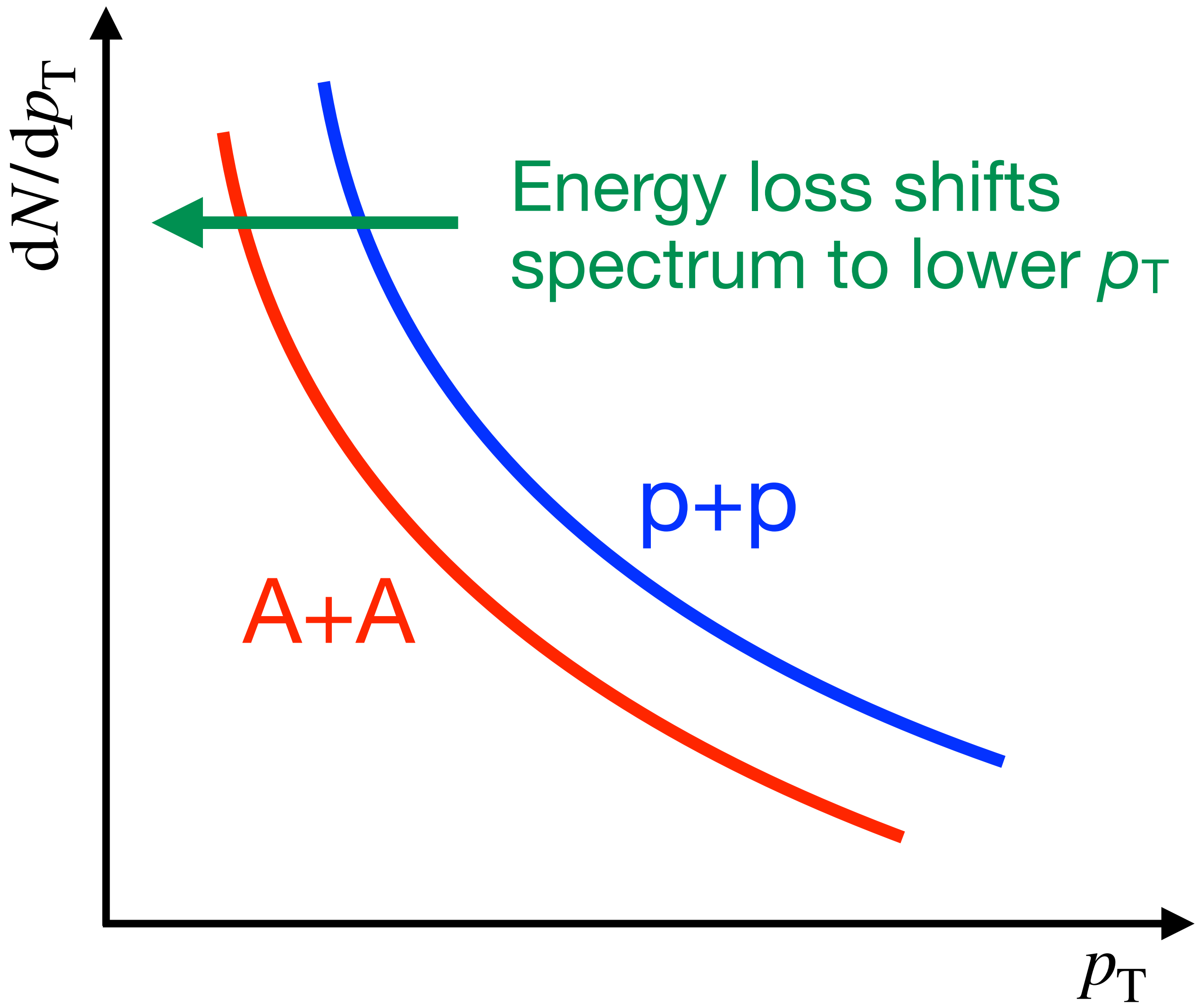
Data samples (Run2)
min. Bias trigger

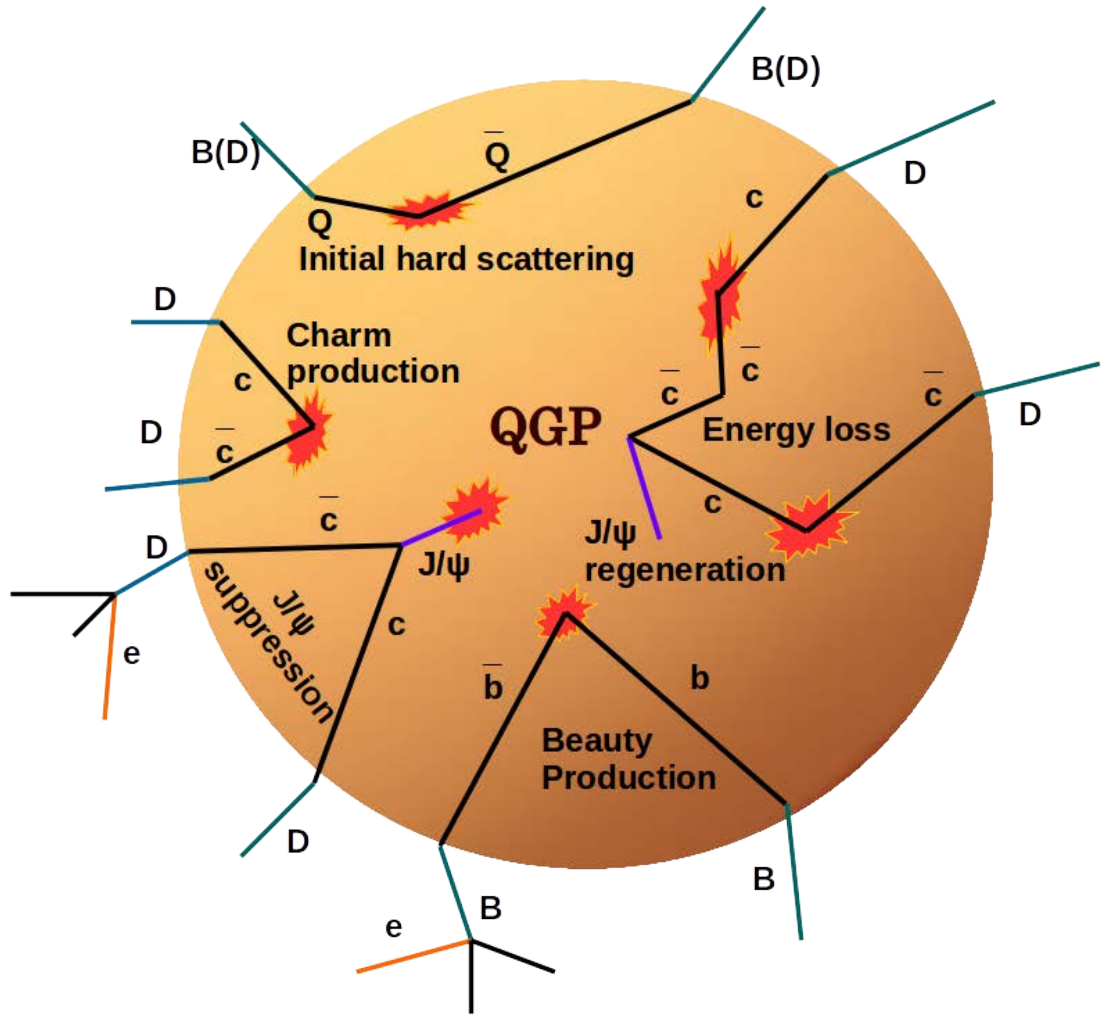
pp 13 TeV	~32 nb^{-1}
p–Pb 13 TeV.	~6 nb^{-1}
Pb–Pb 13 TeV	~114 μb^{-1}

Muon Arm (–4 < η < –2.5)
- mID
- tracking
- trigger

V0 (2.8 < η < 5.1; –3.7 < η < –1.7;)
- trigger
- centrality determination

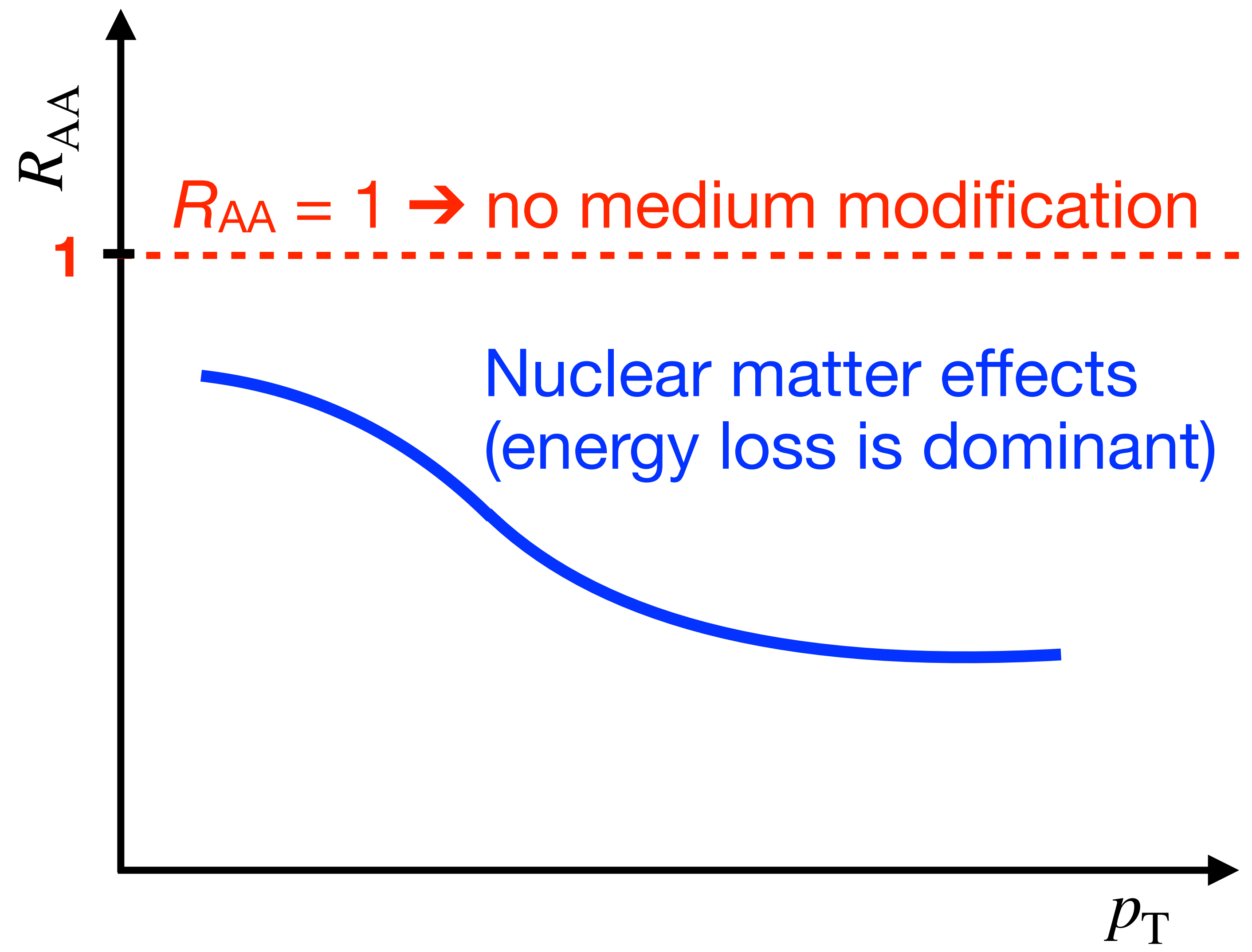
Nuclear modification factor (R_{AA})





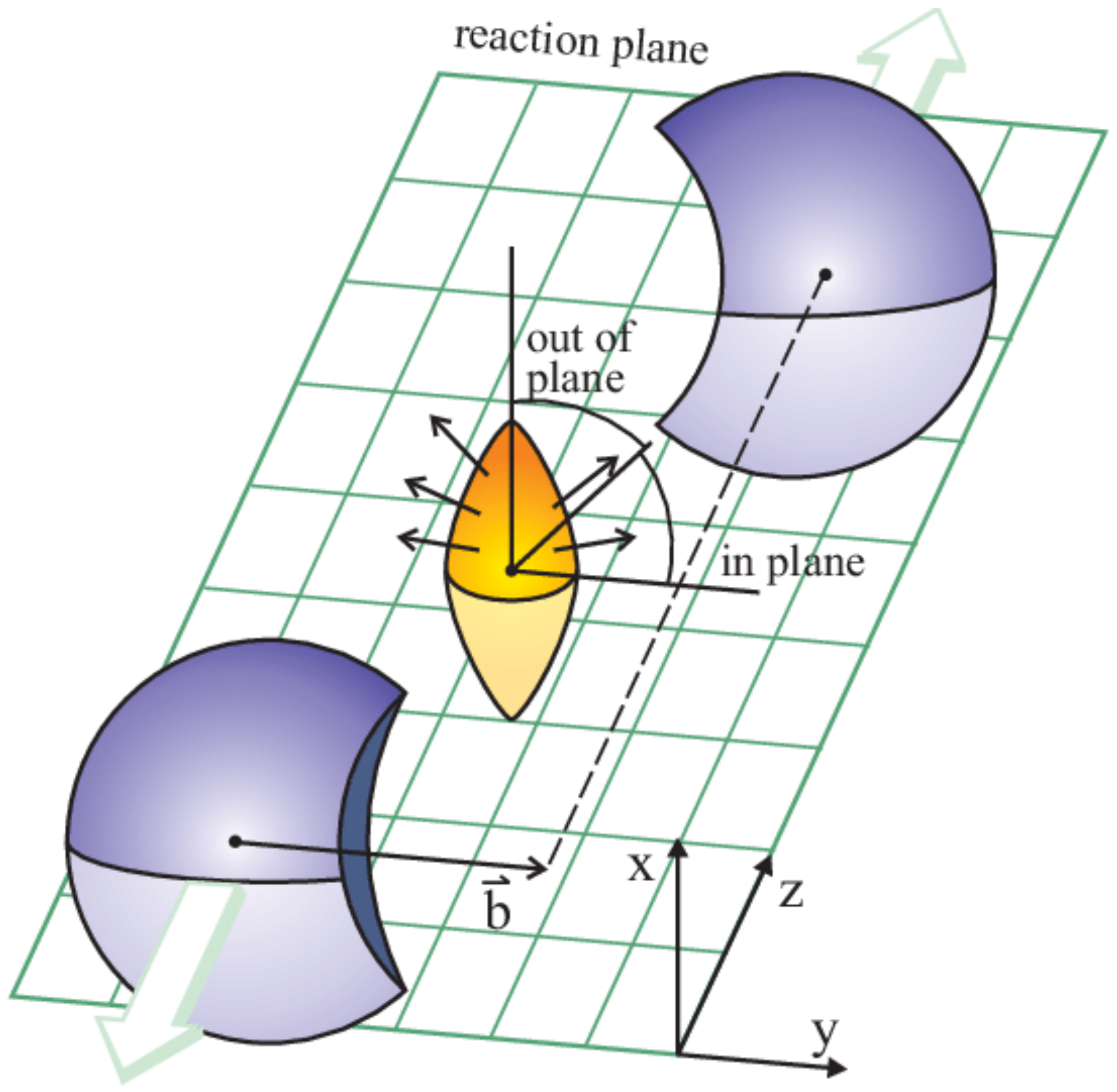
- Heavy quarks interact with medium constituents
  - ✓ Low p_T : elastic collisions with medium constituents (diffusion Brownian motion, possible thermalization in the medium)
  - ✓ High p_T : radiative energy loss (gluon emission) ➔ dead-cone effect

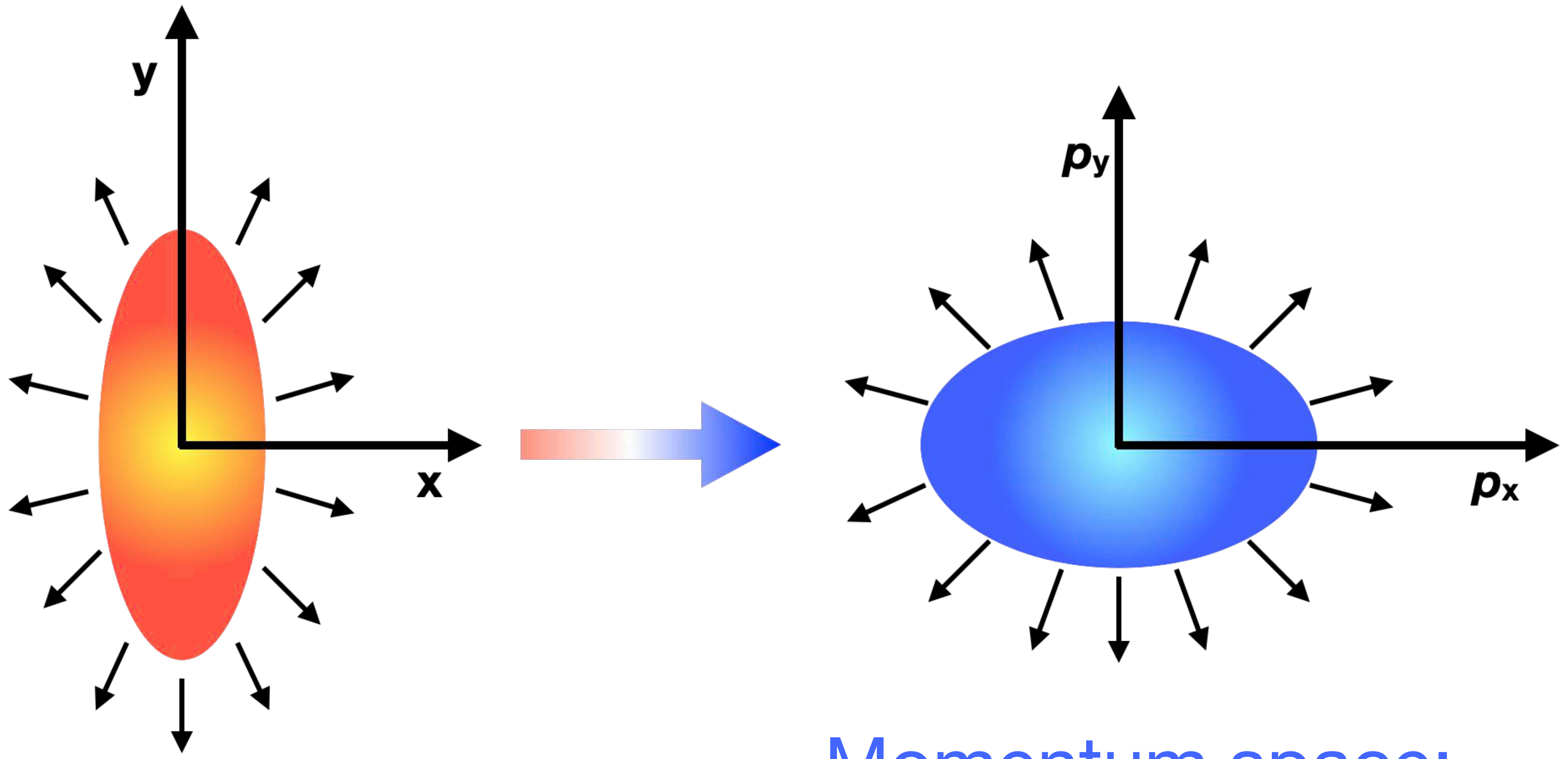
Gluonstrahlung probability $\propto \dfrac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$



$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Anisotropic flow





Coordinate space:
Initial asymmetry

Momentum space:
Final anisotropy

- Interaction among medium constituents converts the initial geometrical anisotropy of the fireball into momentum anisotropy of final-state
- Quantified by the Fourier decomposition of the azimuthal distribution of particles:

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \qquad v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

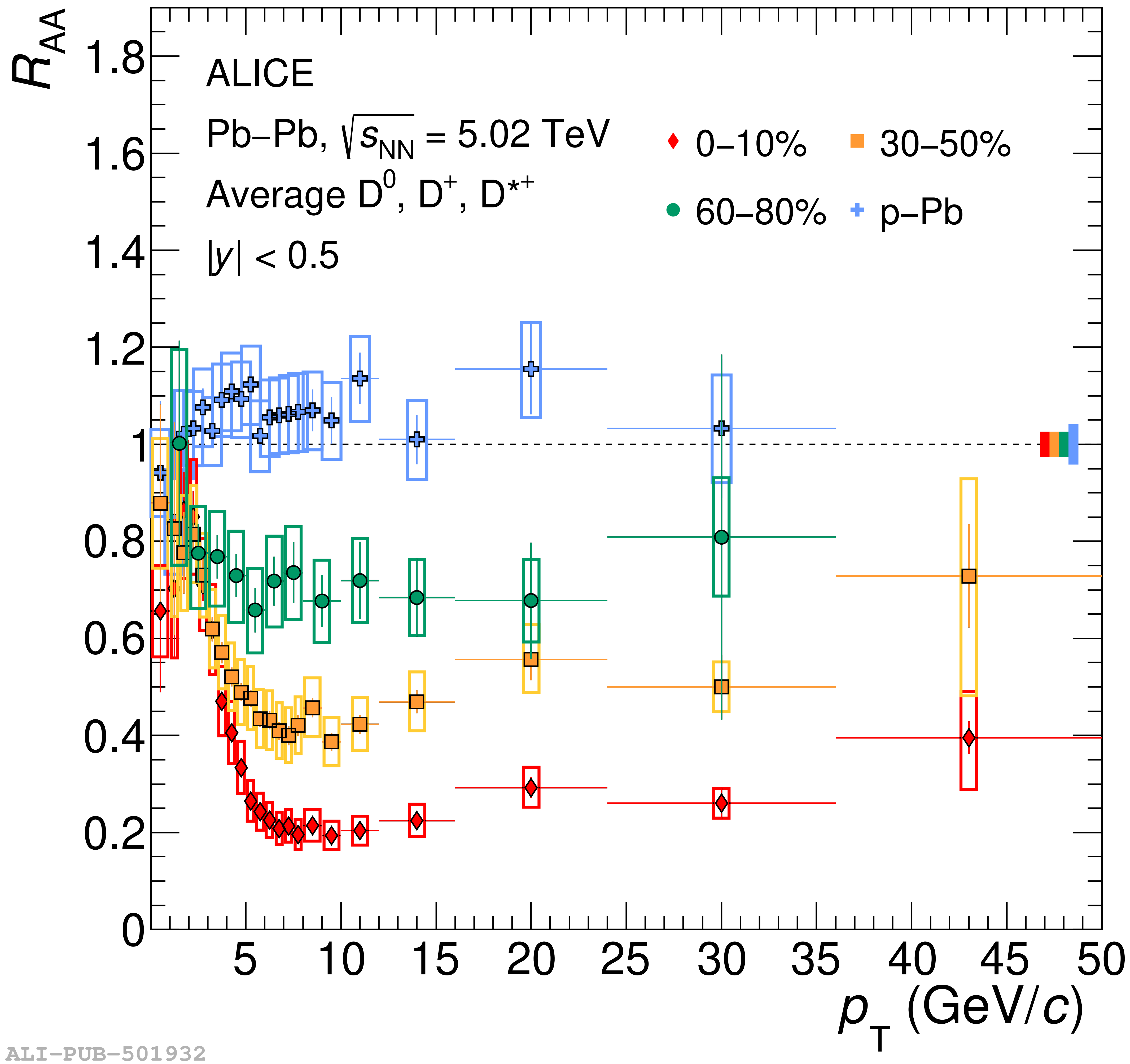
✓ Direct flow (v_1) : probes the early electromagnetic field in medium

✓ Elliptic flow (v_2) :
  - ➡ low p_T : sensitive to the participation in the collective motion and in the thermalization of heavy quarks
  - ➡ high p_T : sensitive to path-length dependence of energy loss

✓ Triangular flow (v_3) : originate from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region

Nuclear modification factor : prompt D mesons

JHEP 01 (2022) 174 : Pb–Pb 0–10%, 30–50%
JHEP 10 (2018) 174 : Pb–Pb 60–80%
JHEP 12 (2019) 092 : p–Pb



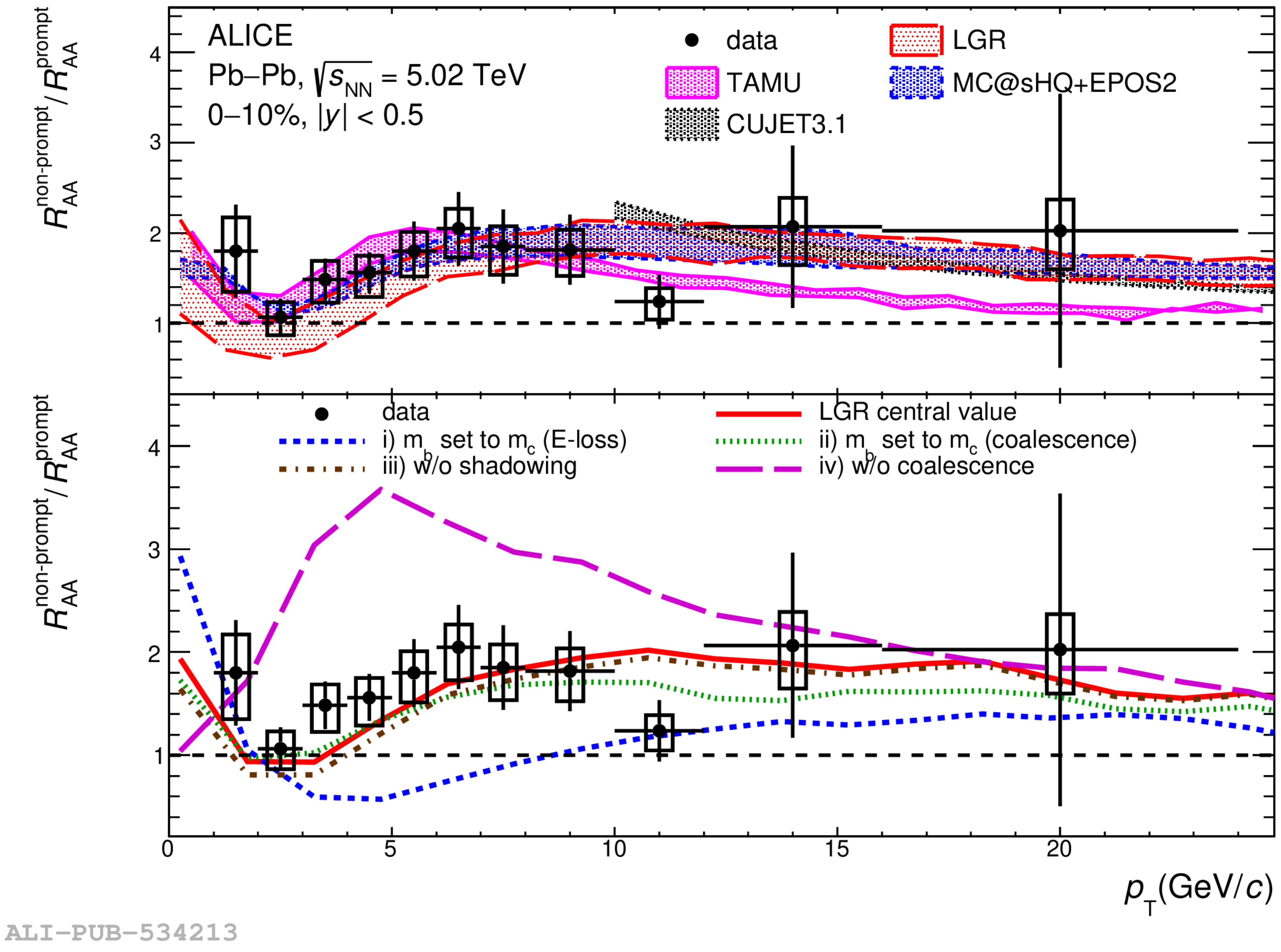
ALI-PUB-501932

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- Prompt D meson average nuclear modification factors in different centrality classes in Pb–Pb collisions and p–Pb collisions
- Observed suppression at intermediate and high p_T
  - ✓ Suppression increases from peripheral to central collisions in Pb–Pb collisions
  - ✓ Increasing medium density, size, and lifetime of the fireball
- R_{AA} in p–Pb collisions is compatible with unity within uncertainty
  - ✓ Suppression in PbPb collisions is due to final-state effects induced by the formation of a hot and dense QGP medium

Nuclear modification factor : non-prompt D^0

JHEP 12 (2022) 126

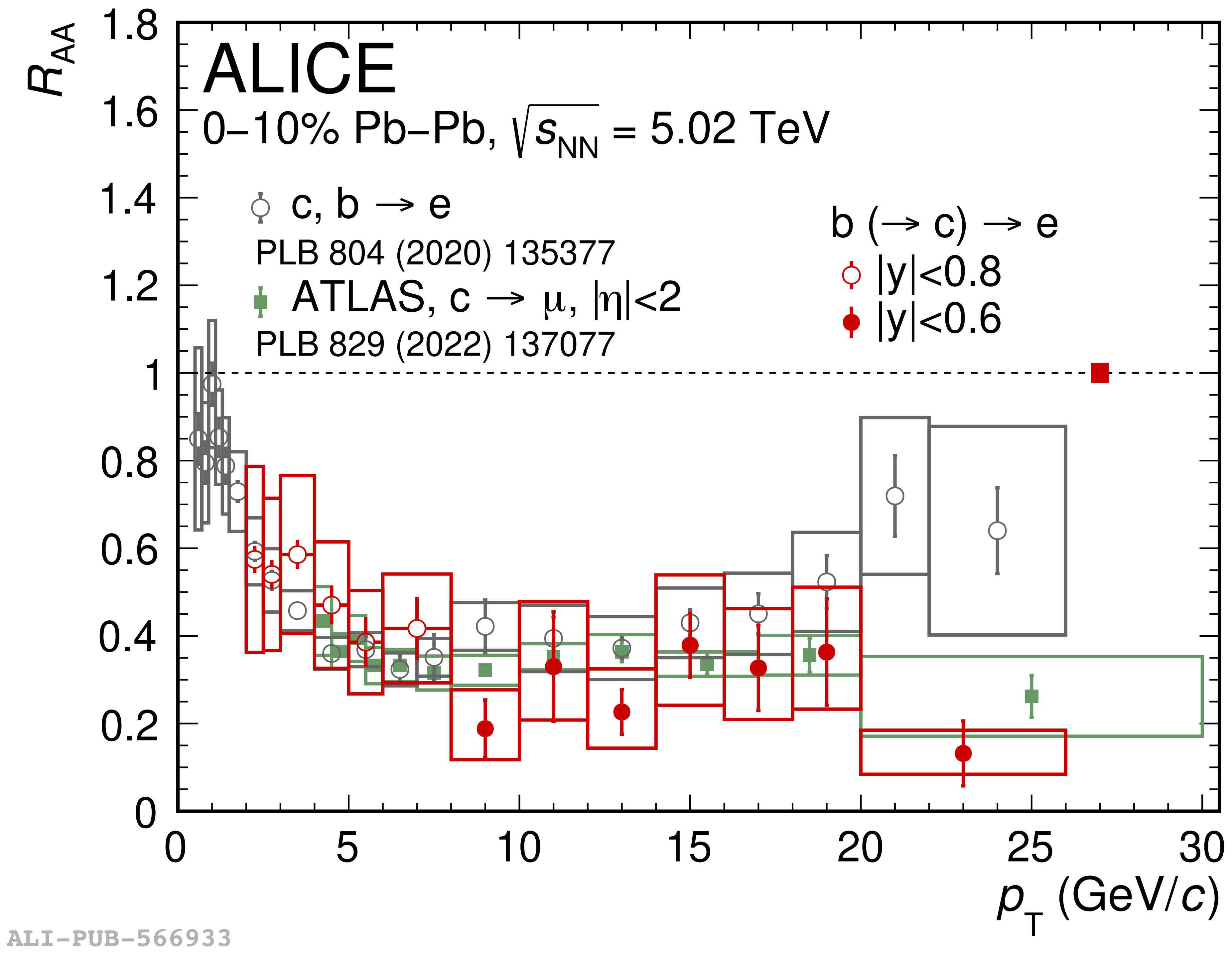


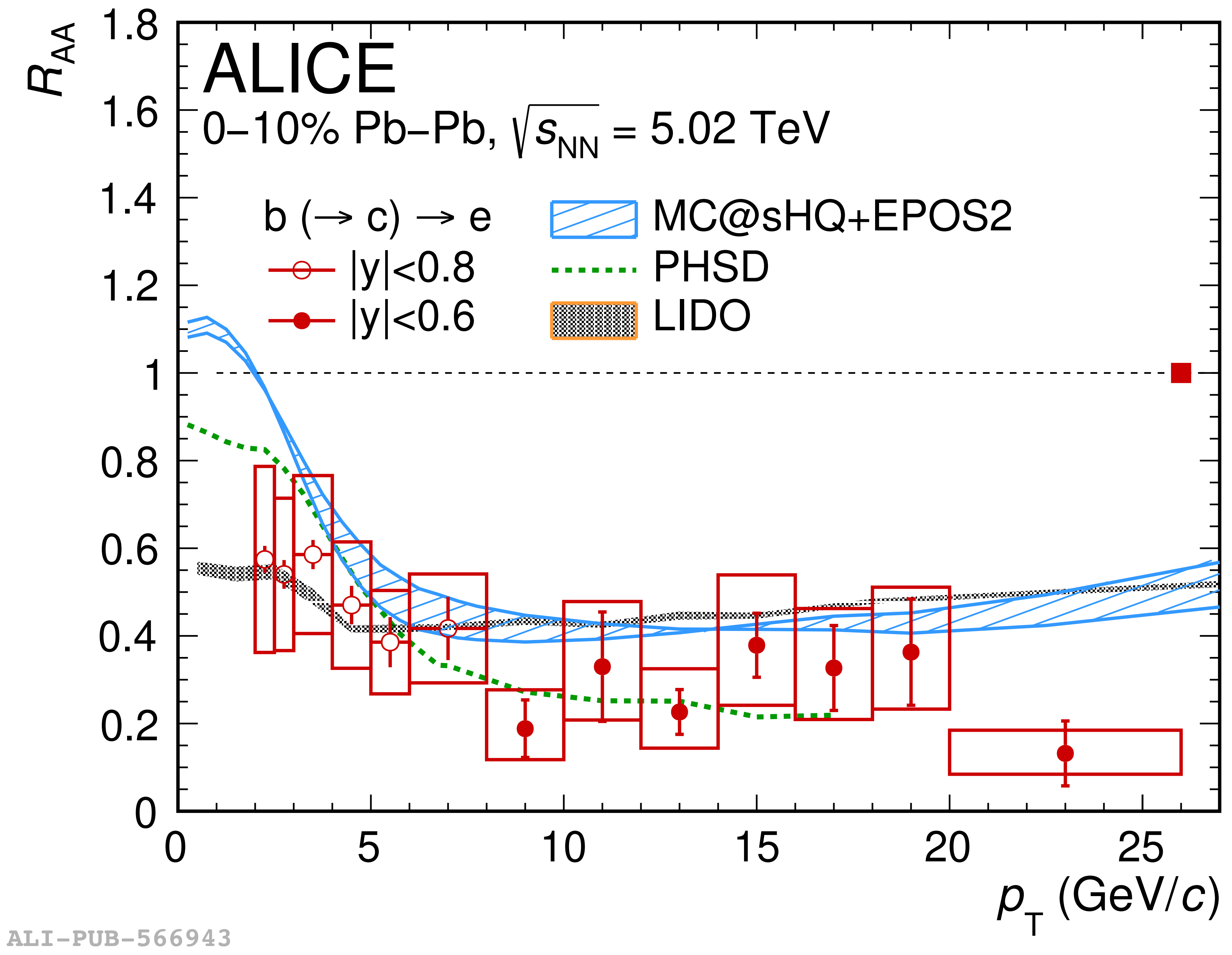
- Observed larger suppression for prompt D^0 compared to non-prompt D^0
  - ✓ Mass dependence of in-medium energy loss $\Delta E_c > \Delta E_b$
  - ✓ Well described by **TAMU**, **CUJET3.1**, **LGR** and **MC@sHQ+EPOS2** model predictions within uncertainties → all models include both collisional and radiative energy loss mechanisms
- **Coalescence** can explain the intermediate p_T trend: prompt D^0 acquire a higher momentum than the parent charm quark → hardening of the p_T spectra

Nuclear modification factor : heavy flavor electrons

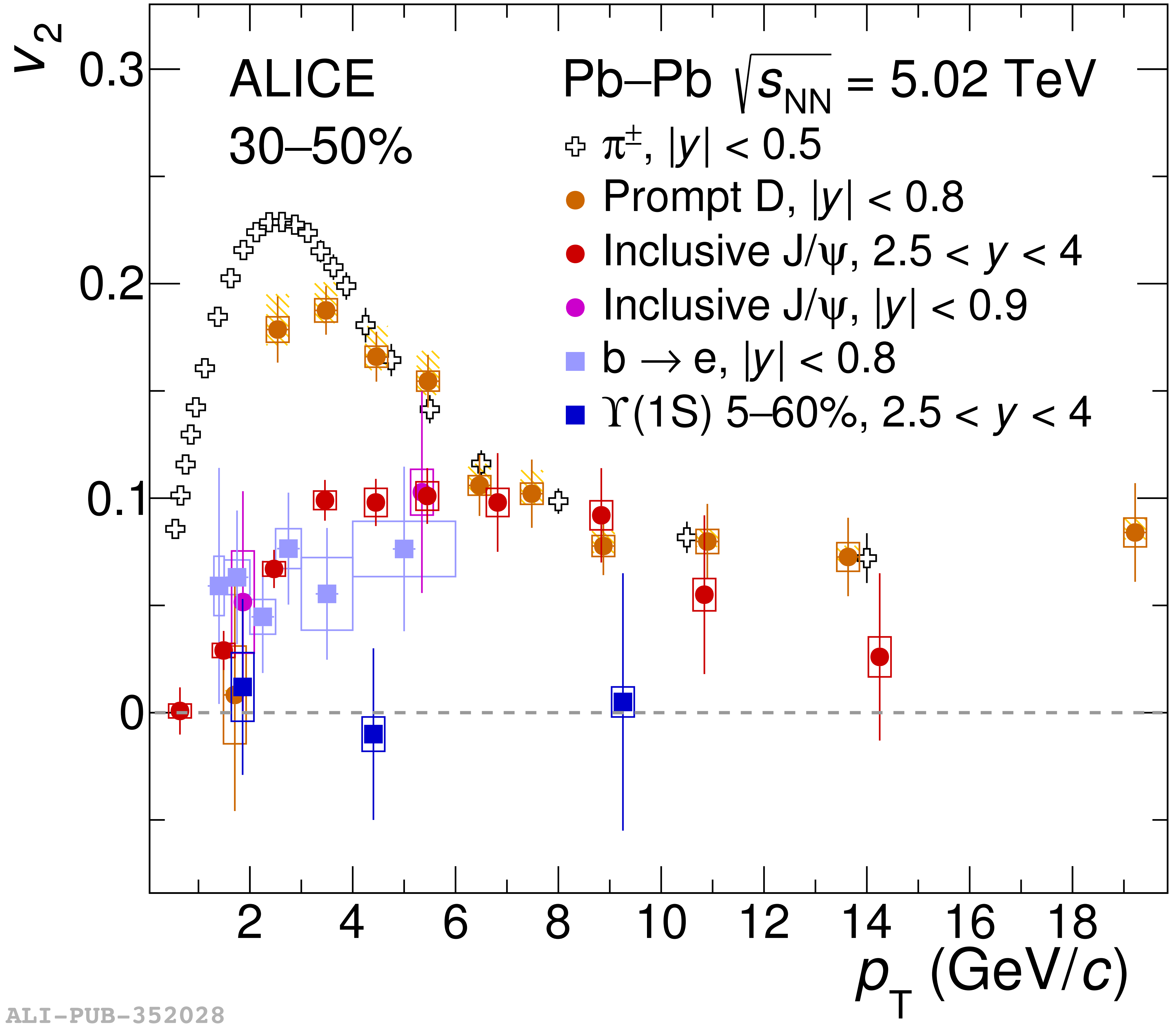
- Large suppression in the intermediate and high p_T region
  - ✓ R_{AA}(b(→c)→e) ≈ R_{AA}(b(→c)→μ) → no dependence on decay channel
  - ✓ No significant p_T dependence for p_T > 8 GeV/c
  - ✓ R_{AA} of b(→c)→e is slightly higher than that of b,c→e while both are merged at high p_T
    → beauty contribution is dominant
- Comparable with various models within uncertainties

Phys. Rev. C 108 (2023) 034906





Elliptic flow (v_2) : heavy flavor hadrons



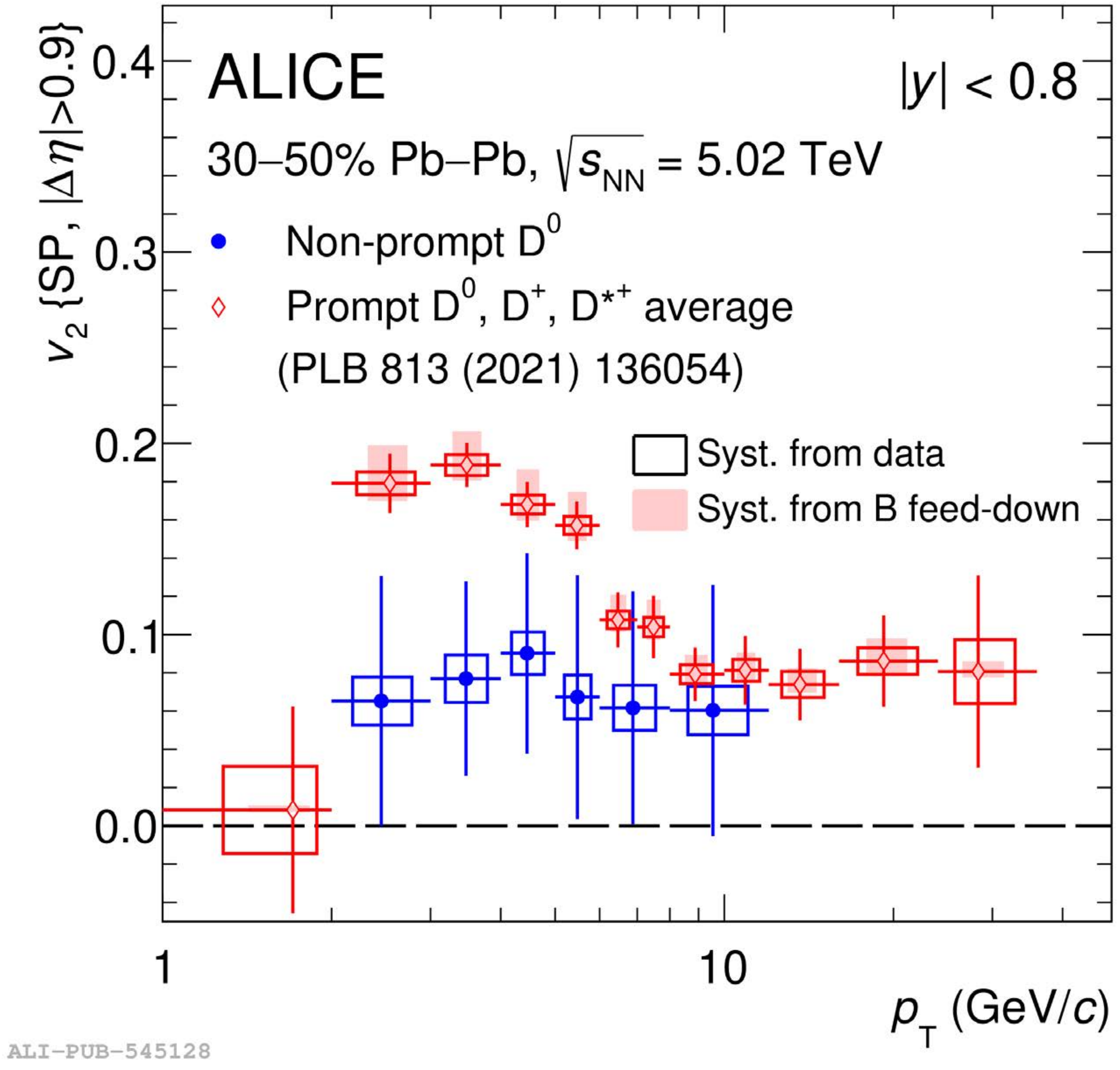
ALI-PUB-352028

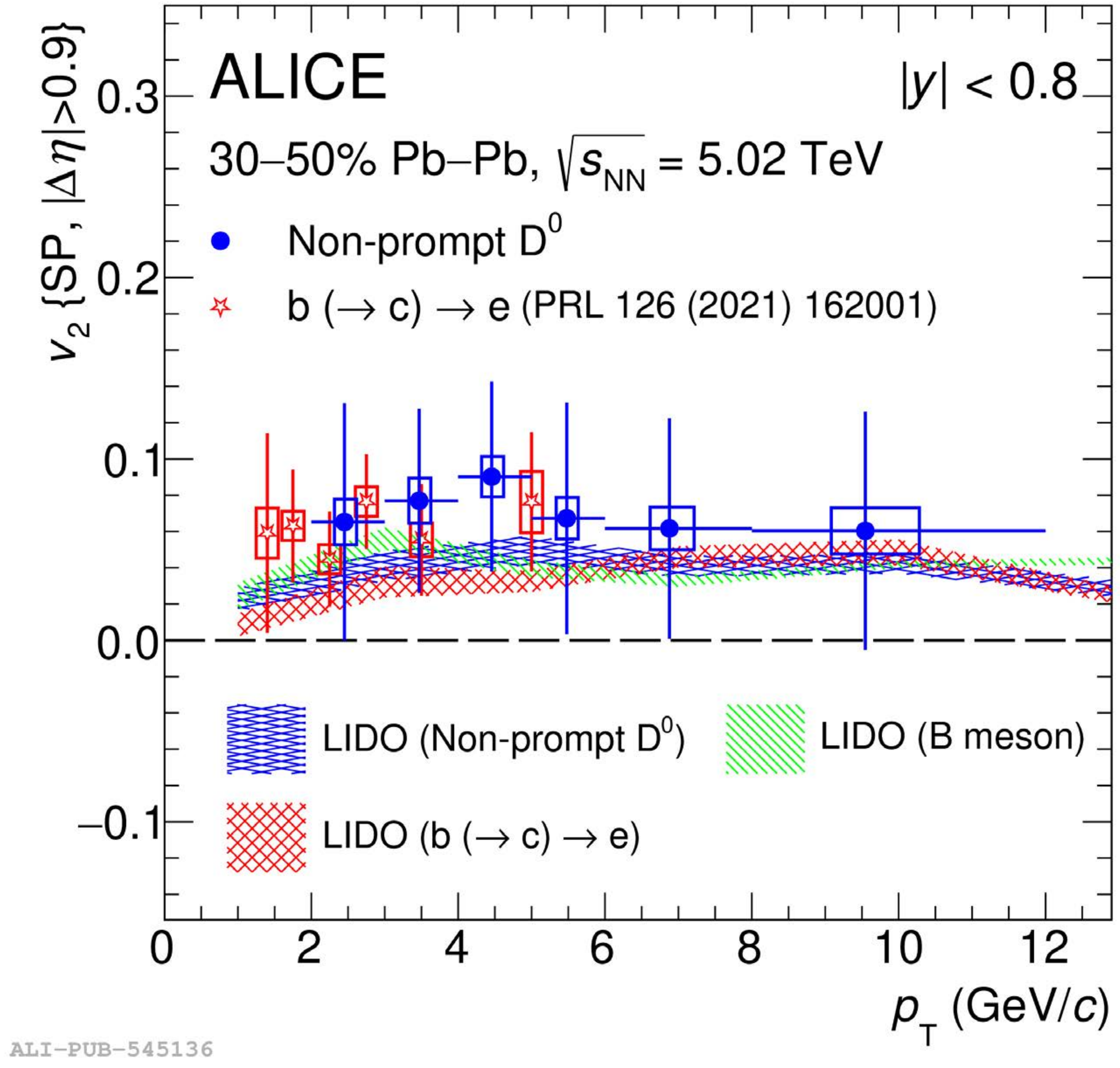
JHEP 09 (2018) 006 : pions
PLB 813 (2021) 136054 : prompt D
JHEP 10 (2020) 141 : include J/ψ
PRL 126, 162001 (2021) : b→e
PRL 123, 192301 (2019) : Υ(1S)

- Elliptic flow (v_2) of heavy flavor hadrons
  - ✓ Positive v_2 for prompt non-strange D mesons
  - ✓ Positive v_2 for J/ψ
  - ✓ Positive v_2 for b→e
- Υ(1S) v_2 compatible with zero
- Looking more in details at different p_T regions:
  - ✓ For $p_T < 3$ GeV/c → quark-mass ordering
    - ➡ v_2(Υ(1S)) ≲ v_2(b→e) ~ v_2(J/ψ) < v_2(D) < v_2(π)
  - ✓ For $3 < p_T < 6$ GeV/c → effects of coalescence for D mesons (c quark + light quarks)
    - ➡ v_2(J/ψ) < v_2(D) ~ v_2(π)
  - ✓ For $p_T > 6$ GeV/c → consistent with similar path-length dependence of the energy loss for light and heavy quarks
    - ➡ v_2(J/ψ) ~ v_2(D) ~ v_2(π)

Elliptic flow (v_2) : non-prompt D^0

- Observed lower non-prompt D^0 v_2 than prompt D meson v_2 in $2 < p_T < 8$ GeV/c and compatible with b→e elliptic flow
  - ✓ Different degree of participation to the collective motion of the medium between charm and beauty quarks
- Comparable with models including hadronization via coalescence in addition to fragmentation





EPJC 83 (2023) 1123

Heavy flavor hadrons in small systems

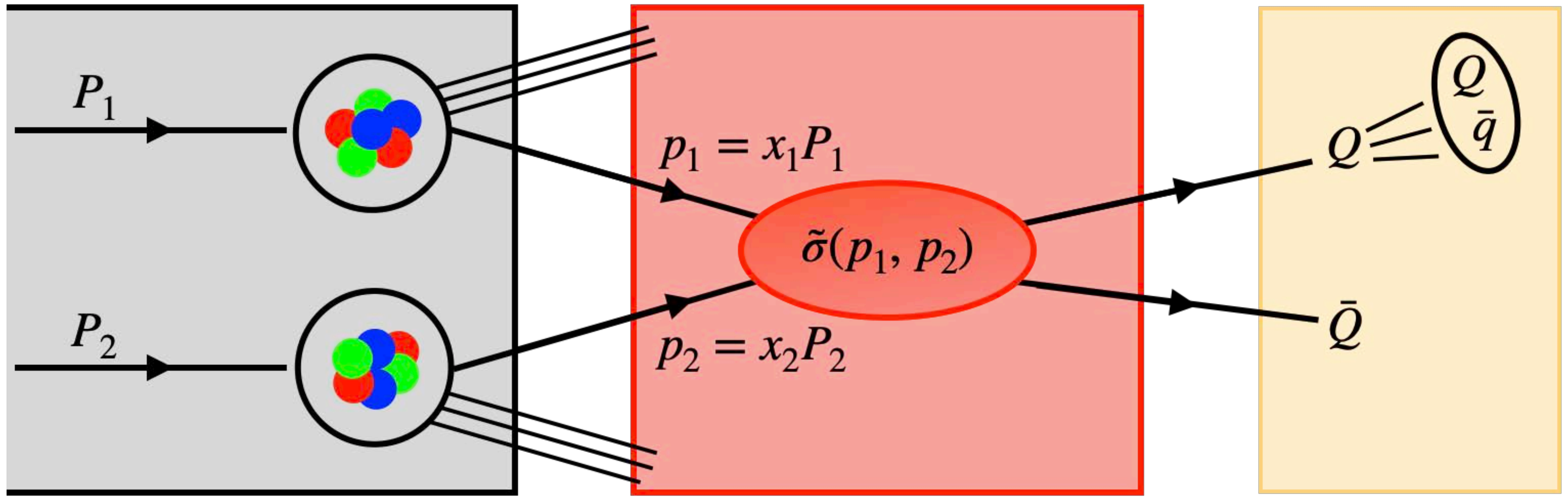
- Production cross section of heavy flavor hadrons can be described by the factorization approach: parton distribution functions (PDFs), partonic cross section, and fragmentation fuctions (FFs)

$$\sigma^{\mathrm{hard}}_{AB\to h} = \boxed{\mathrm{PDF}(x_a, Q^2)\mathrm{PDF}(x_b, Q^2)} \otimes \boxed{\sigma^{\mathrm{hard}}_{ab\to c}(x_a, x_b, Q^2)} \otimes \boxed{D_{c\to h}(z = p_h/p_c, Q^2)}$$

parton distribution function (PDFs)

hard scattering cross section (pQCD)

fragmentation function (hadronization)

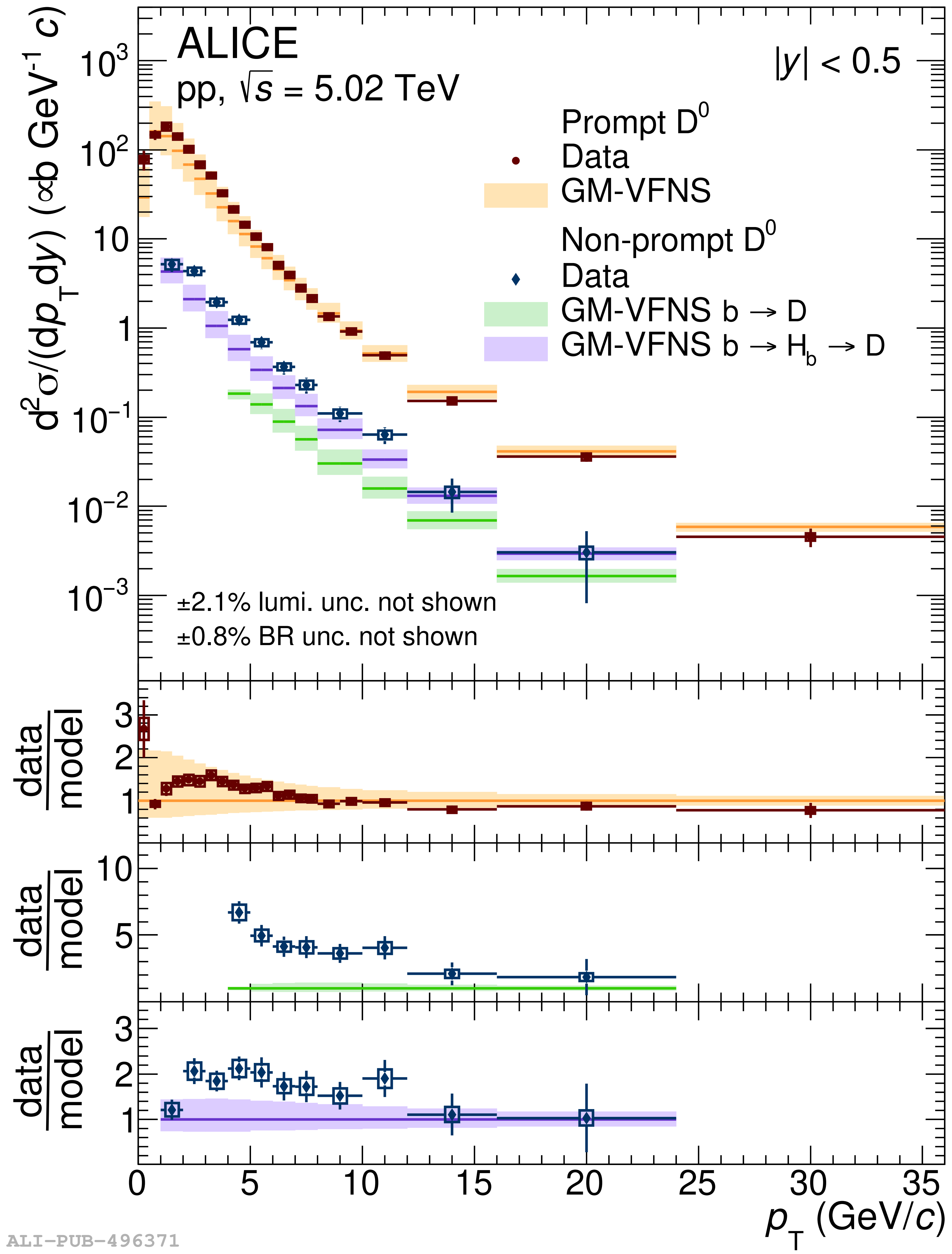


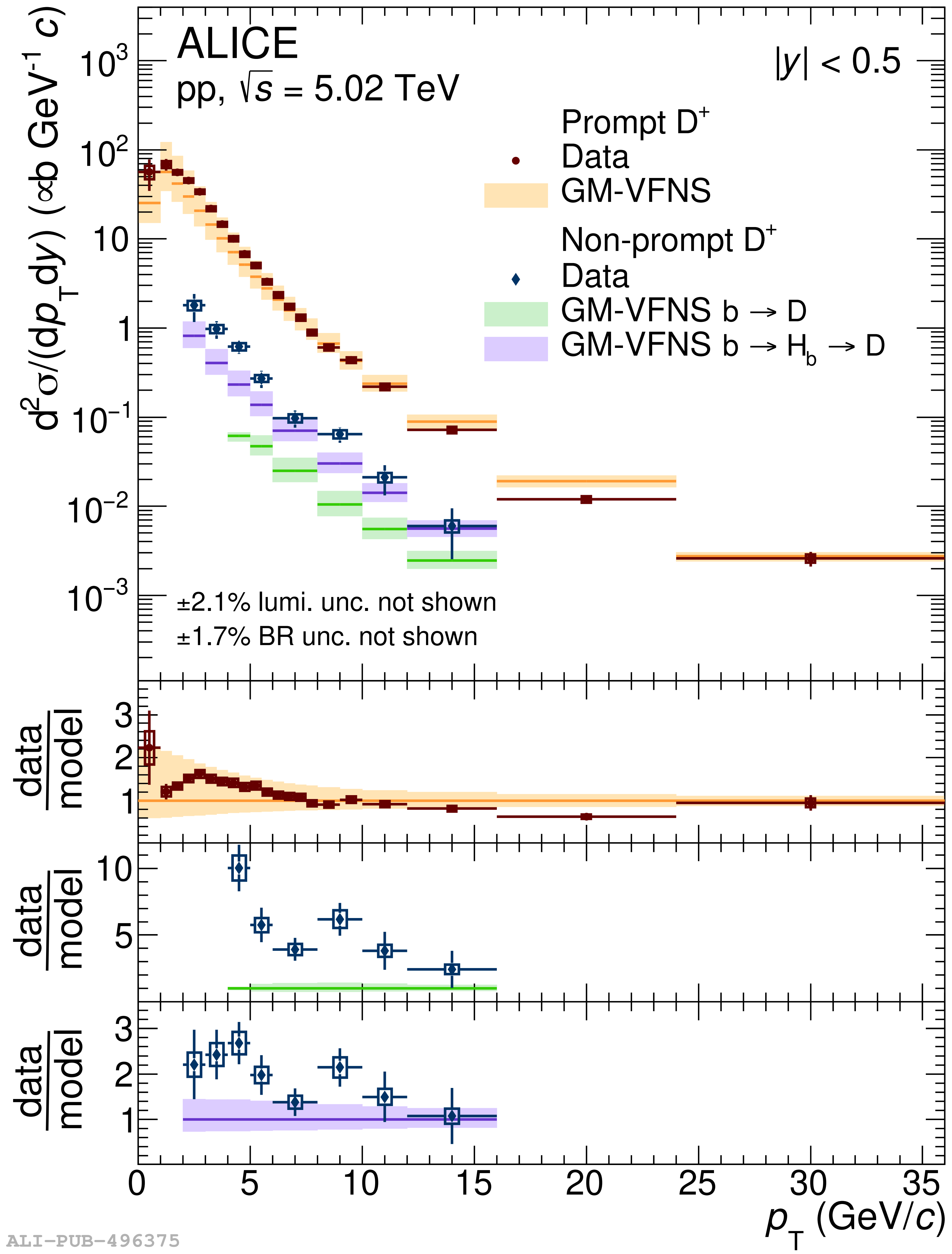
Fragmentation functions (non perturbative) are assumed to be universal among collision systems and constrained from measurements in e+e− and e−p collisions

Ratios of particle species are sensitive to heavy quark hadronization

Production cross section : prompt/non-prompt D^0/D^+

JHEP 05 (2021) 220

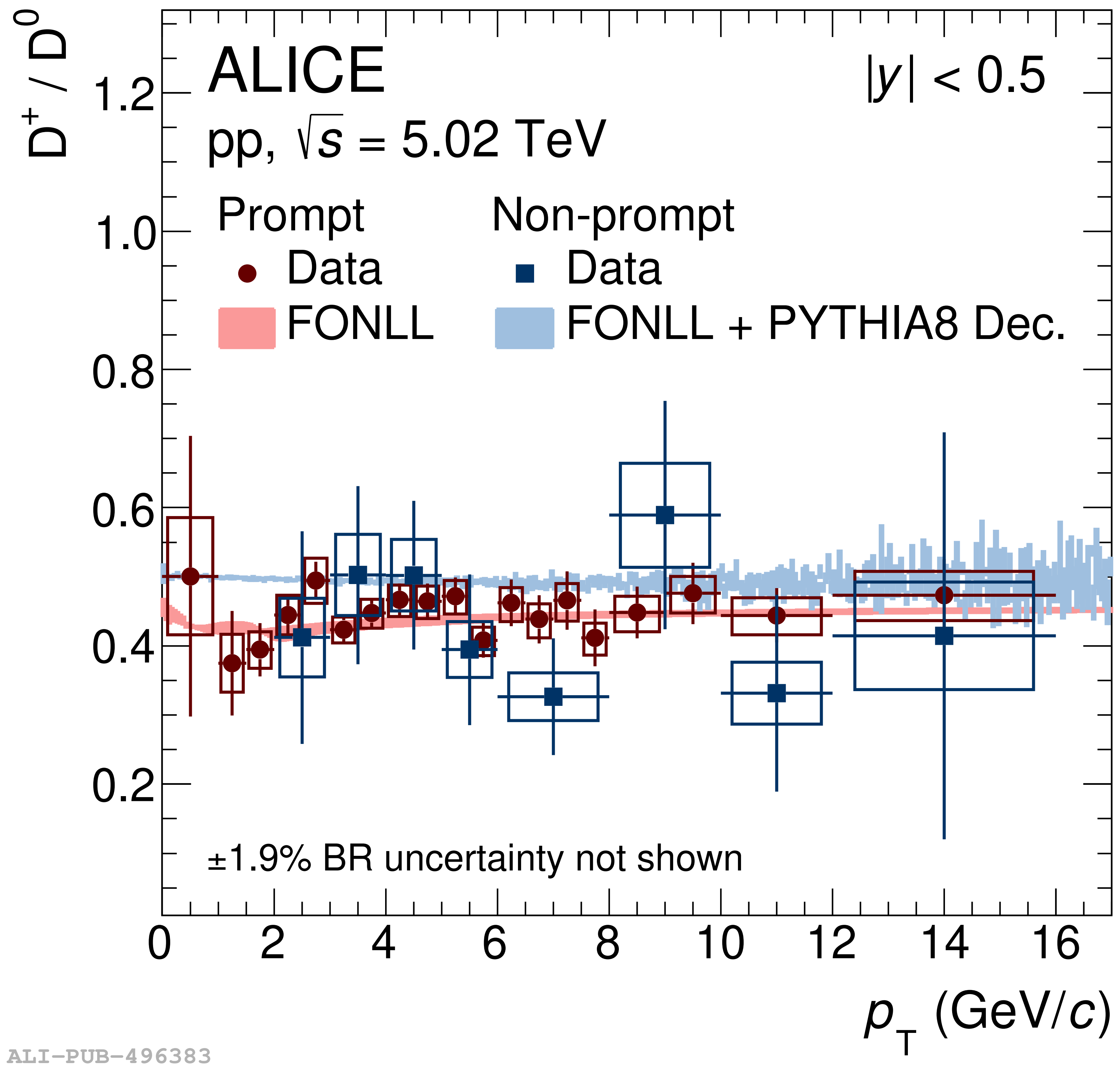


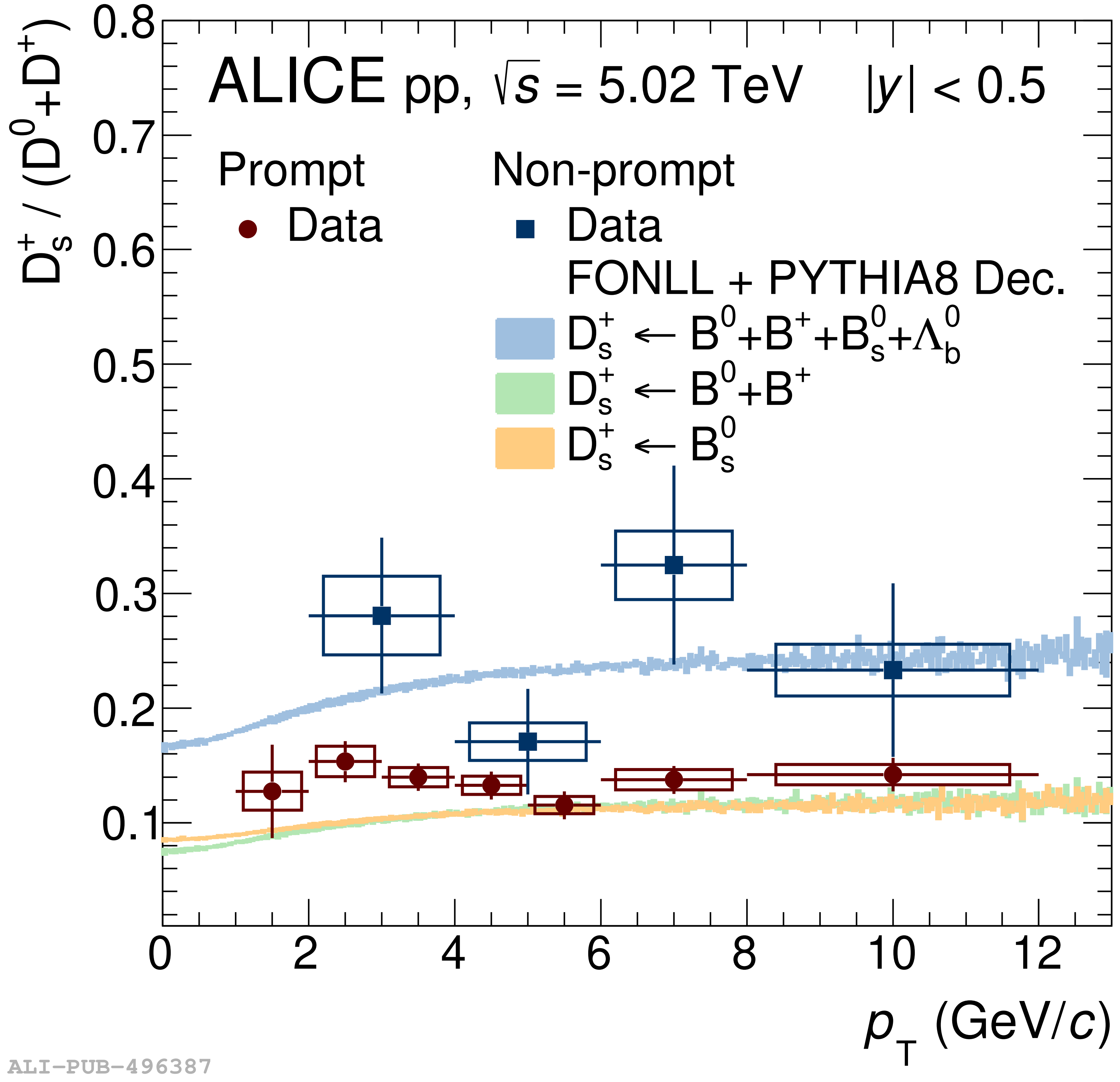


- Precise measurements of prompt and non-prompt D meson production cross sections over wide p_T range
  - ✓ Described within uncertainties by pQCD model calculations
  - ✓ GM-VFNS predictions underestimate non-prompt D meson cross section
  - ✓ Data provides good constraints for models (experimental uncertainties are smaller than that of theoretical ones)

Charm meson production in pp collisions

- Independent meson-to-meson ratios in transverse momentum p_T
- FONLL calculations (pQCD) correctly describe the data
  - ✓ Using fragmentation functions from e^+e^-, e^-p measurements
- Higher D_s/D^0+D^+ ratios for non-prompt D mesons, due to relevant contribution to D_s from B^0, B^+ decays

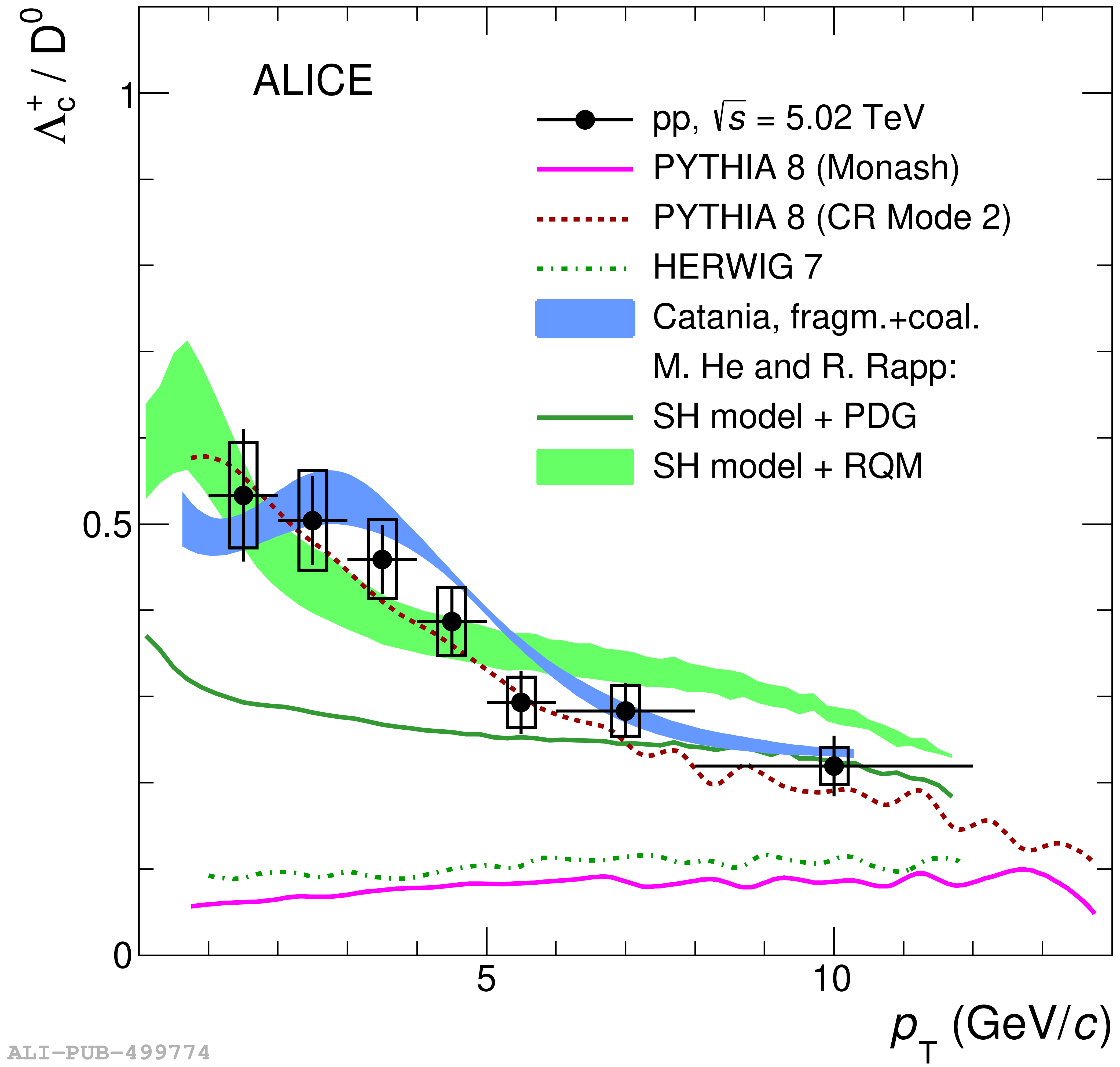




JHEP 05 (2021) 220

Charm baryon production in pp collisions

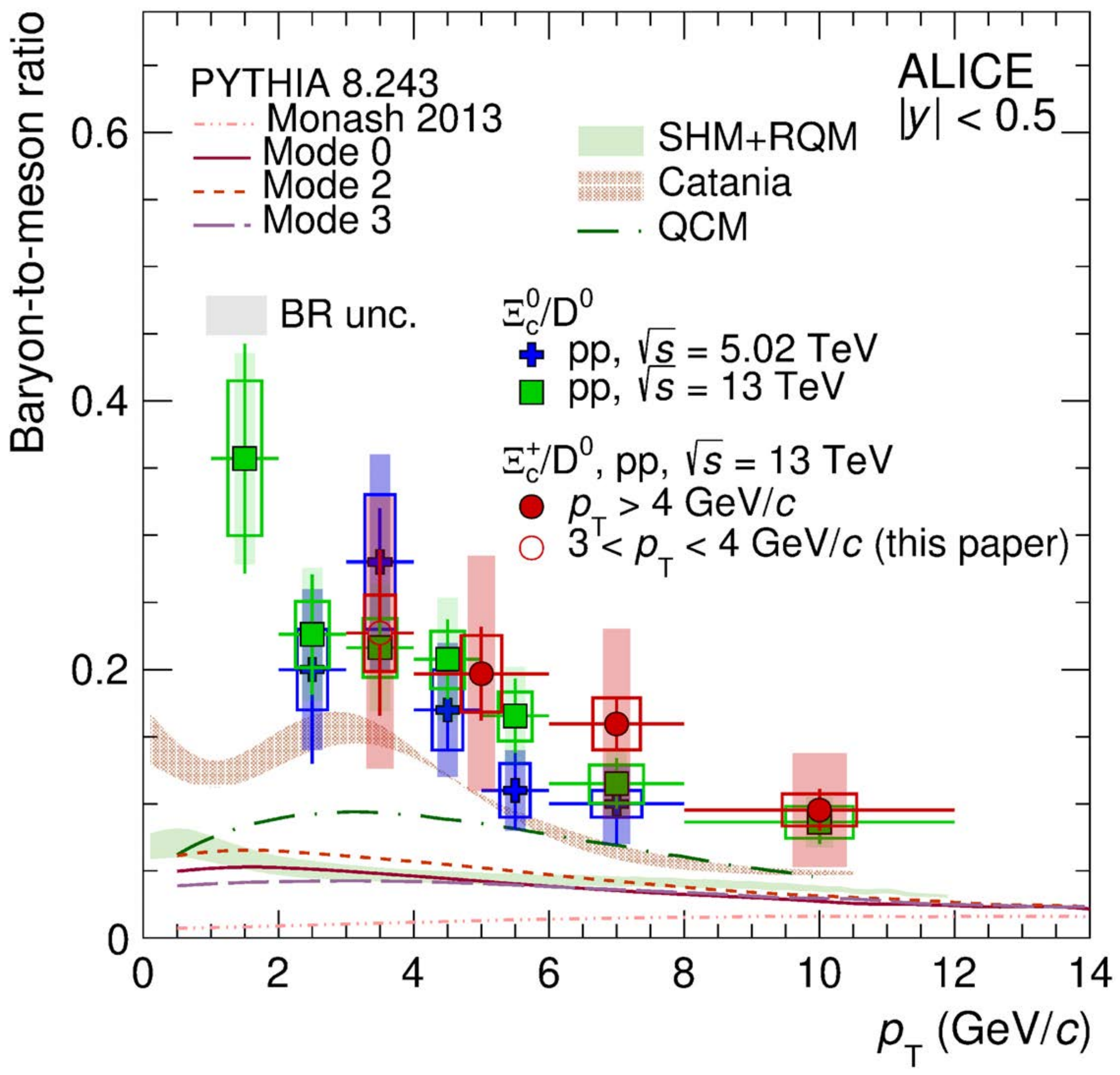
PRL 127, 202301 (2021)

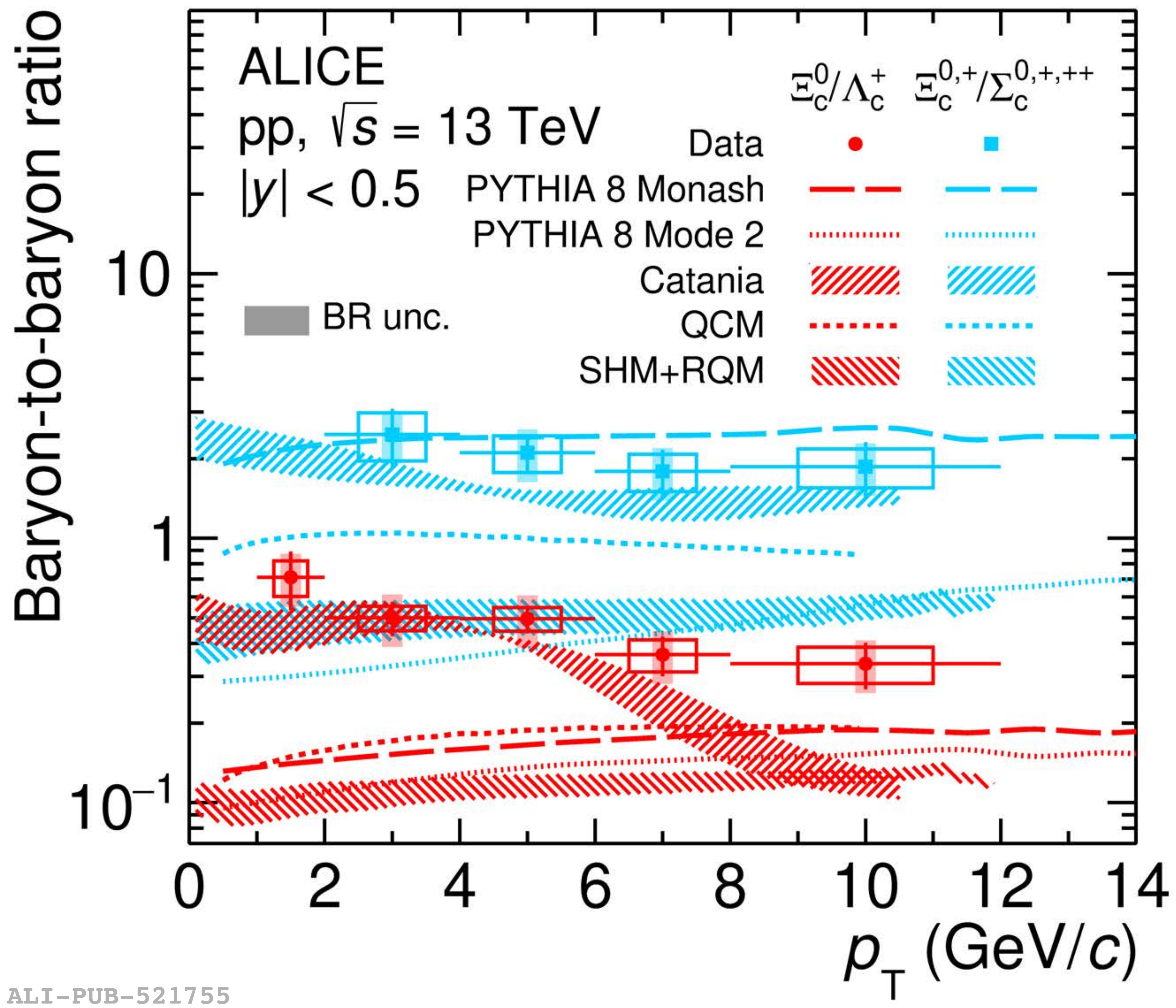


- First measurement of Λ_c production down to $p_T = 0$ in small system
  - Enhancement of prompt Λ_c/D^0 ratio at low and intermediate p_T w.r.t e^+e^- results
- Described by :
  - ✓ Significantly underestimated by PYTHIA 8 Monash tune (which incorporates fragmentation parameters from e^+e^- data)
  - ✓ PYTHIA 8 with color-reconnection beyond leading color (CR-BLC) → "junction" topology enhances charm baryon production
  - ✓ Catania model → thermalized system of u, d, s and gluons; hadronization via coalescence in addition to fragmentation
  - ✓ Statistical Hadronization Model and Relativistic Quark Model → strong feed-down from augmented set of excited charm baryons
    - ➡ PDG : $5\Lambda_c$, $3\Sigma_c$, $8\Xi_c$, $2\Omega_c$
    - ➡ RQM : $18\Lambda_c$, $42\Sigma_c$, $62\Xi_c$, $34\Omega_c$

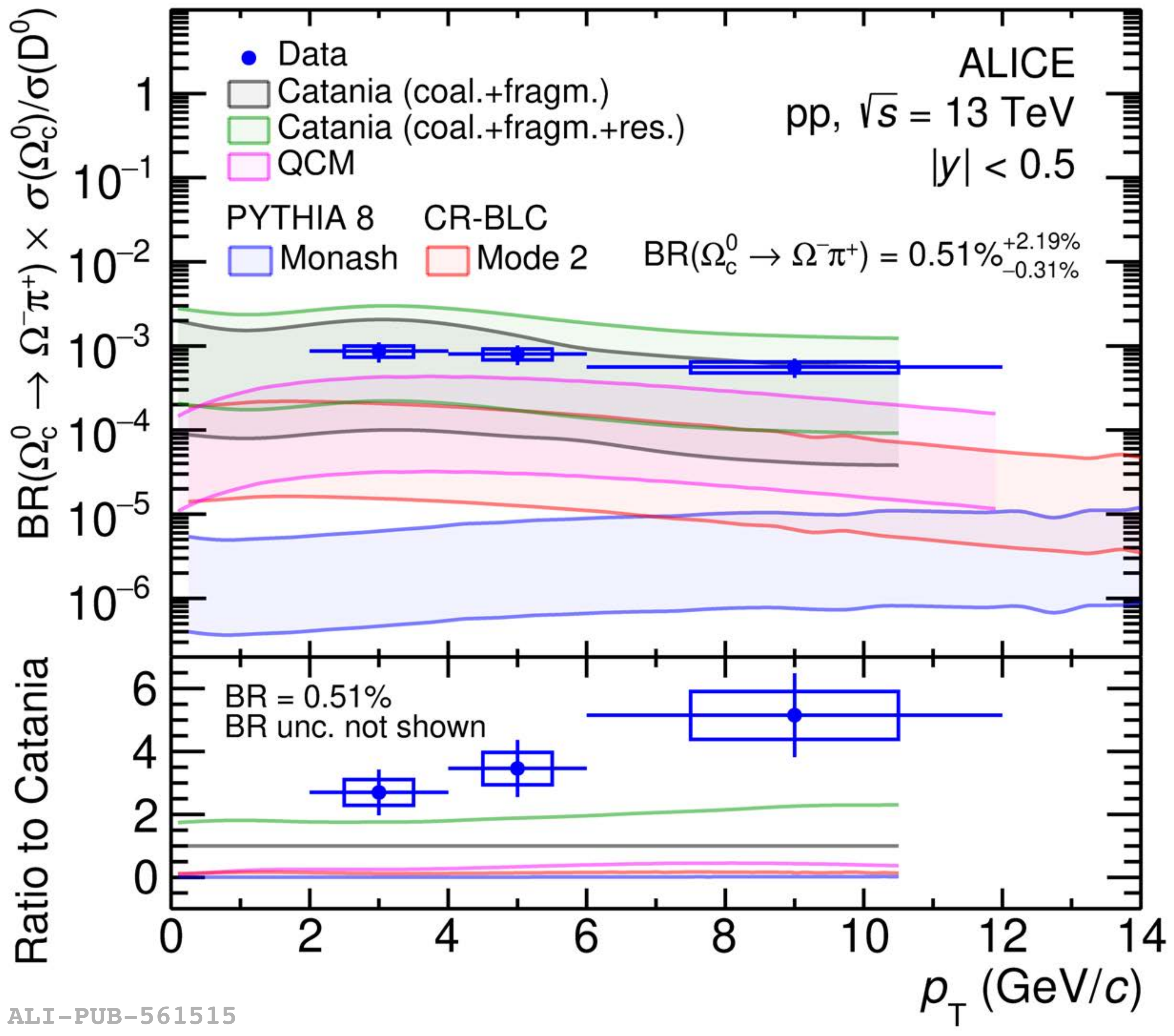
Charm baryon production in pp collisions

arXiv:2308.04877





PRL 127 (2021) 272001

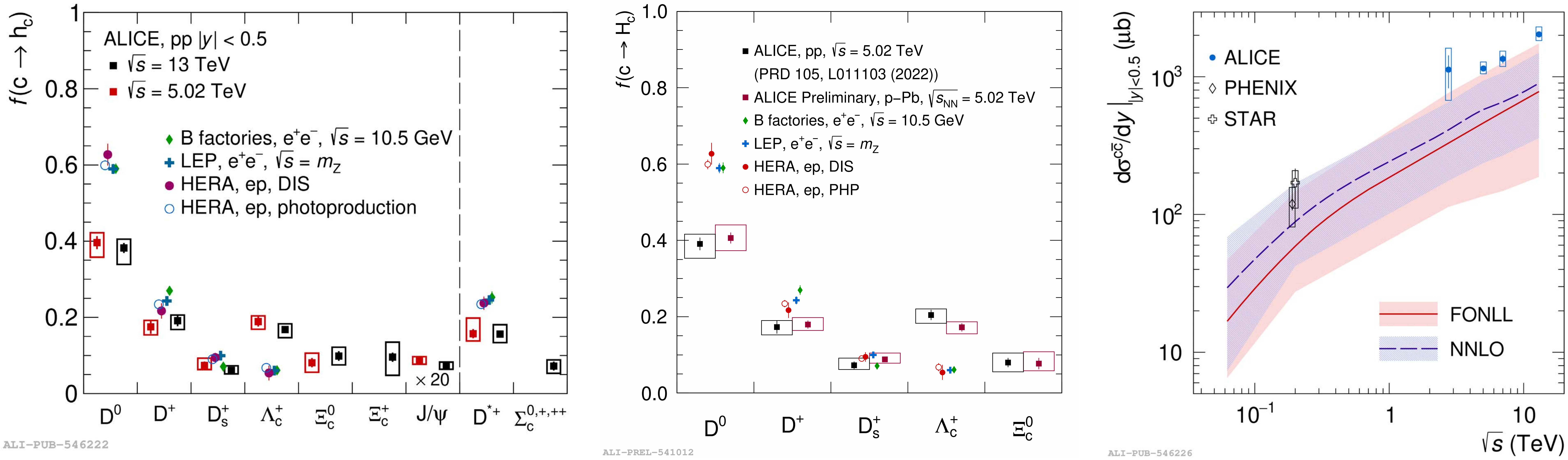


- Clear p_T dependence
- Significantly underestimated by models

- Agreement with PYTHIA 8 Monash tune
- Similar enhancement w.r.t e^+e^- for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$

- No p_T dependence
- Catania closer to the measurements when additional resonances are considered

Charm fragmentation fractions at LHC

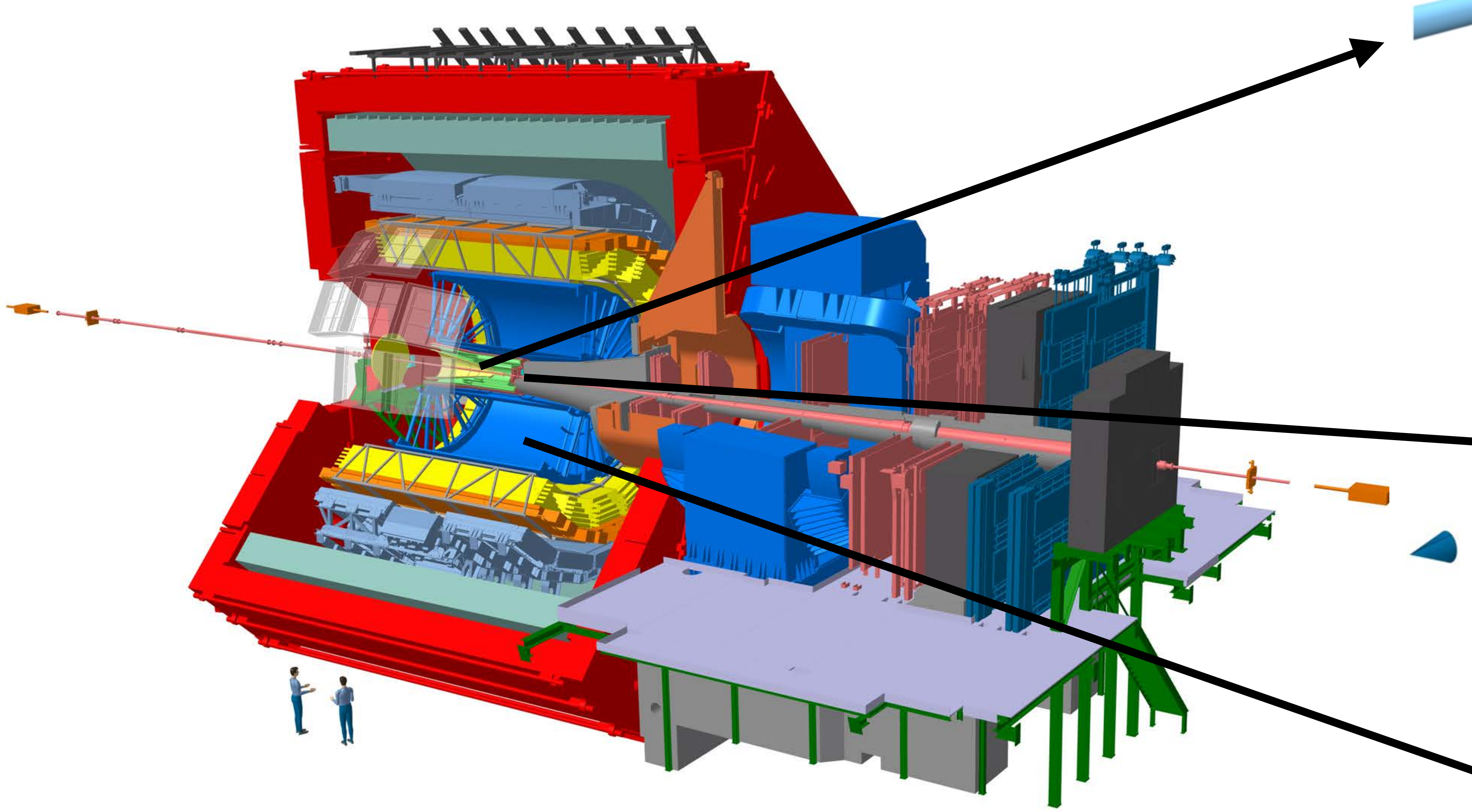


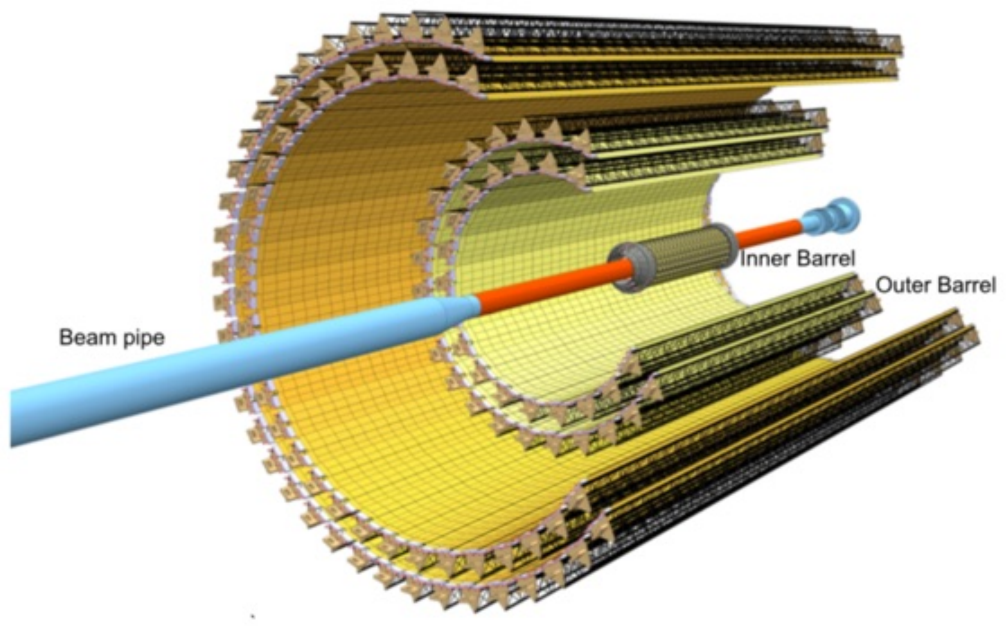
- Charm fragmentation fractions at LHC
  - ✓ Independent of center-of-mass energy and system size
  - ✓ Significant enhanced for charm baryons w.r.t dd and ep collisions
    - ➡ breaking of the universality of fragmentation functions
- Charm quark production cross section at midrapidity is at the upper boundary of state-of-the-art pQCD calculations

ALICE detector in Run 3

In Run 3 and Run 4

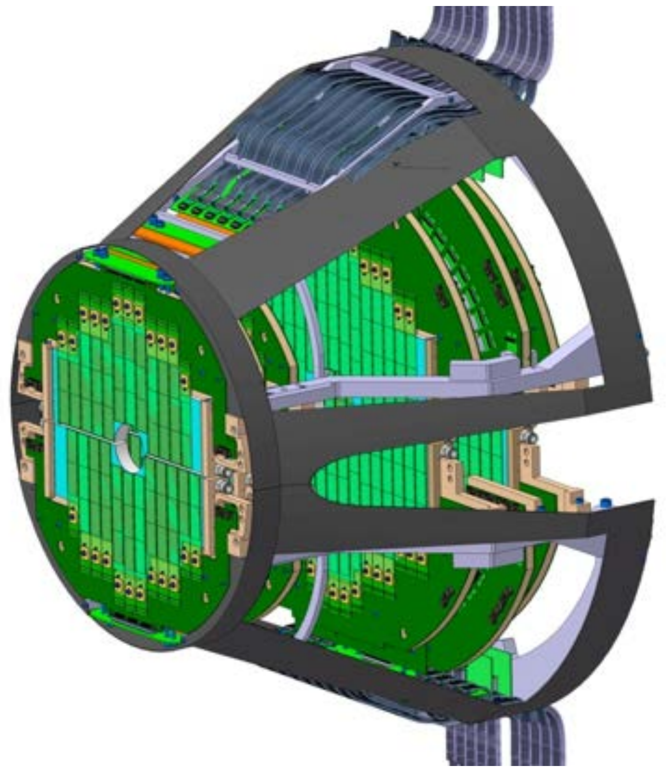
✓ 500 kHz in pp / up to 50 kHz in Pb–Pb
✓ 200 pb^{-1} in pp / 10 nb^{-1} in Pb–Pb





Inner Tracking System

- 7 pixel layers
- More granularity
- Closer to the beam pipe
- Reduce material budget
- Improved pointing resolution



Muon Forward Tracker

- 5 planes of MAPS
- vertexing and tracking for muon

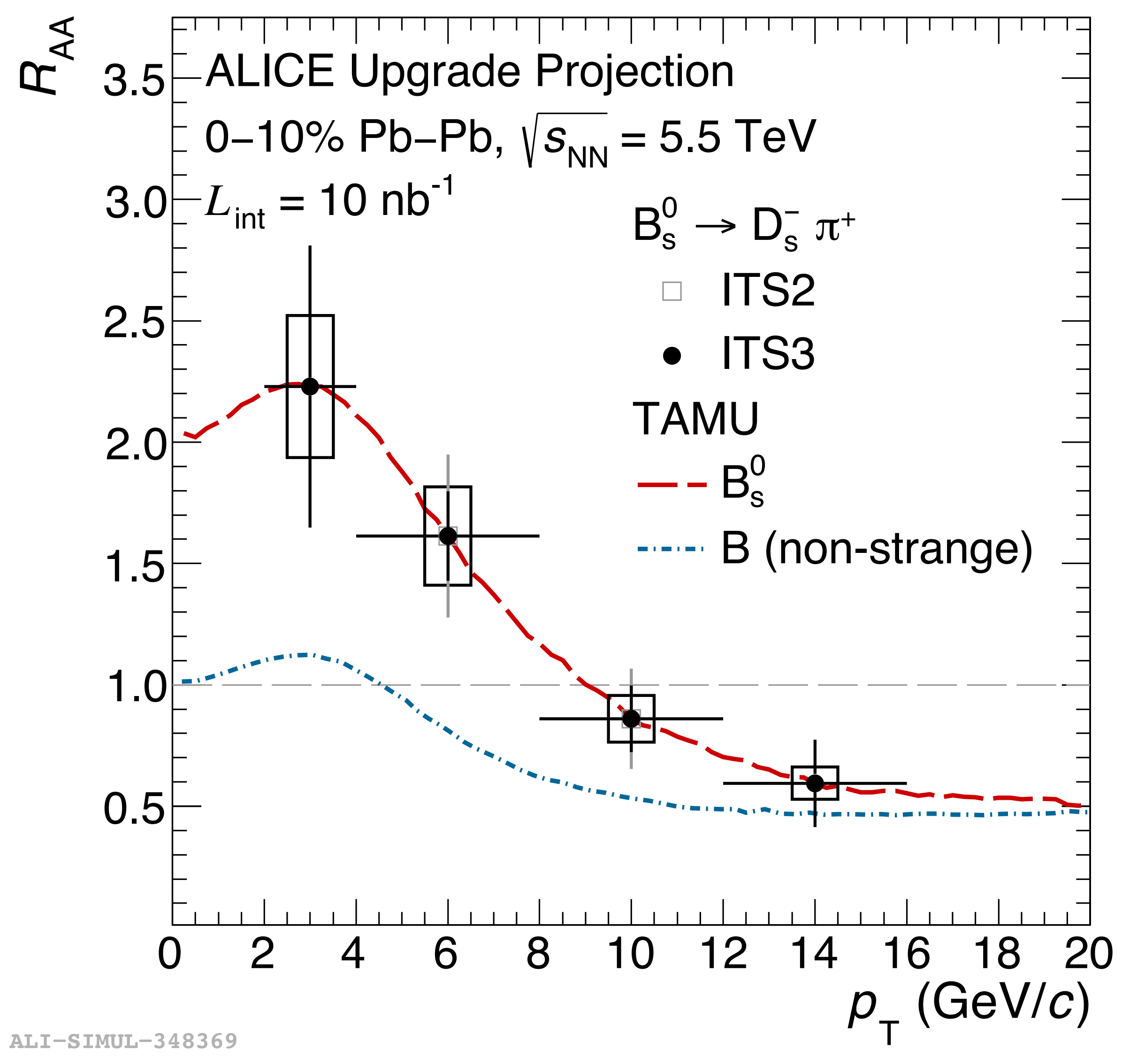
Time Projection Chamber

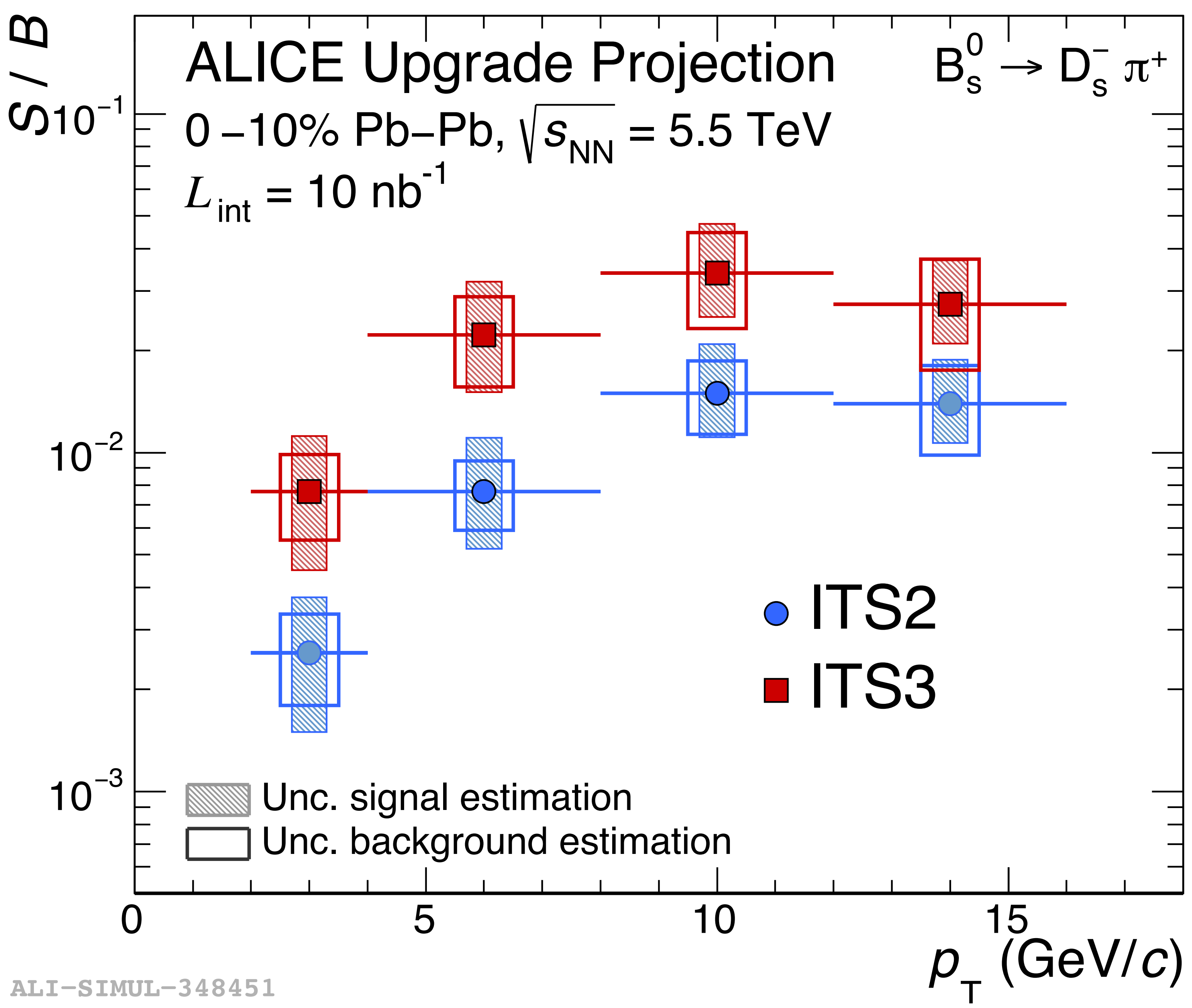
- New readout chambers with GEM
- Continuous readout

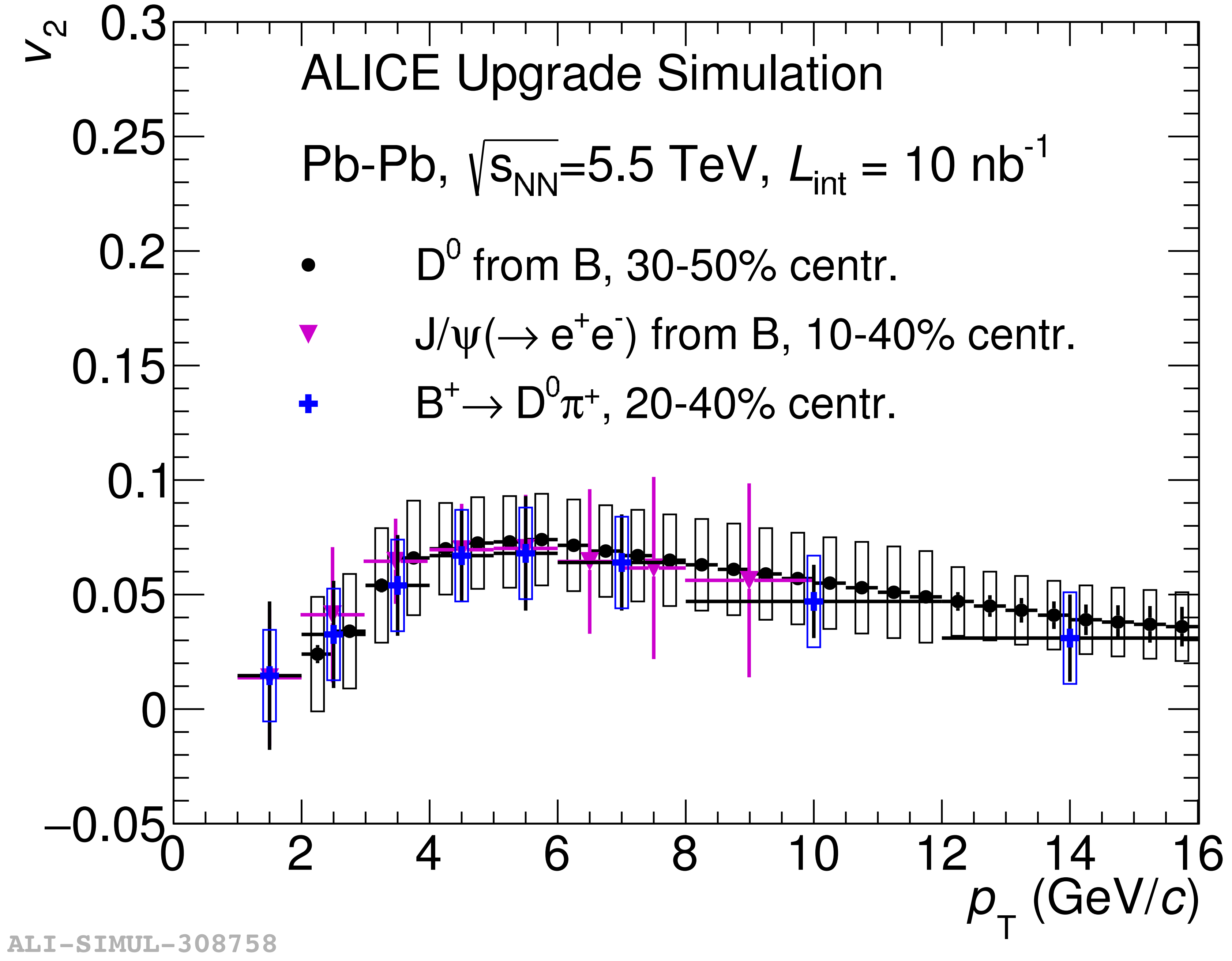
Improved impact parameter resolution, in particular for low p_T, in order to select more effectively decay vertices of heavy-flavor mesons and baryons

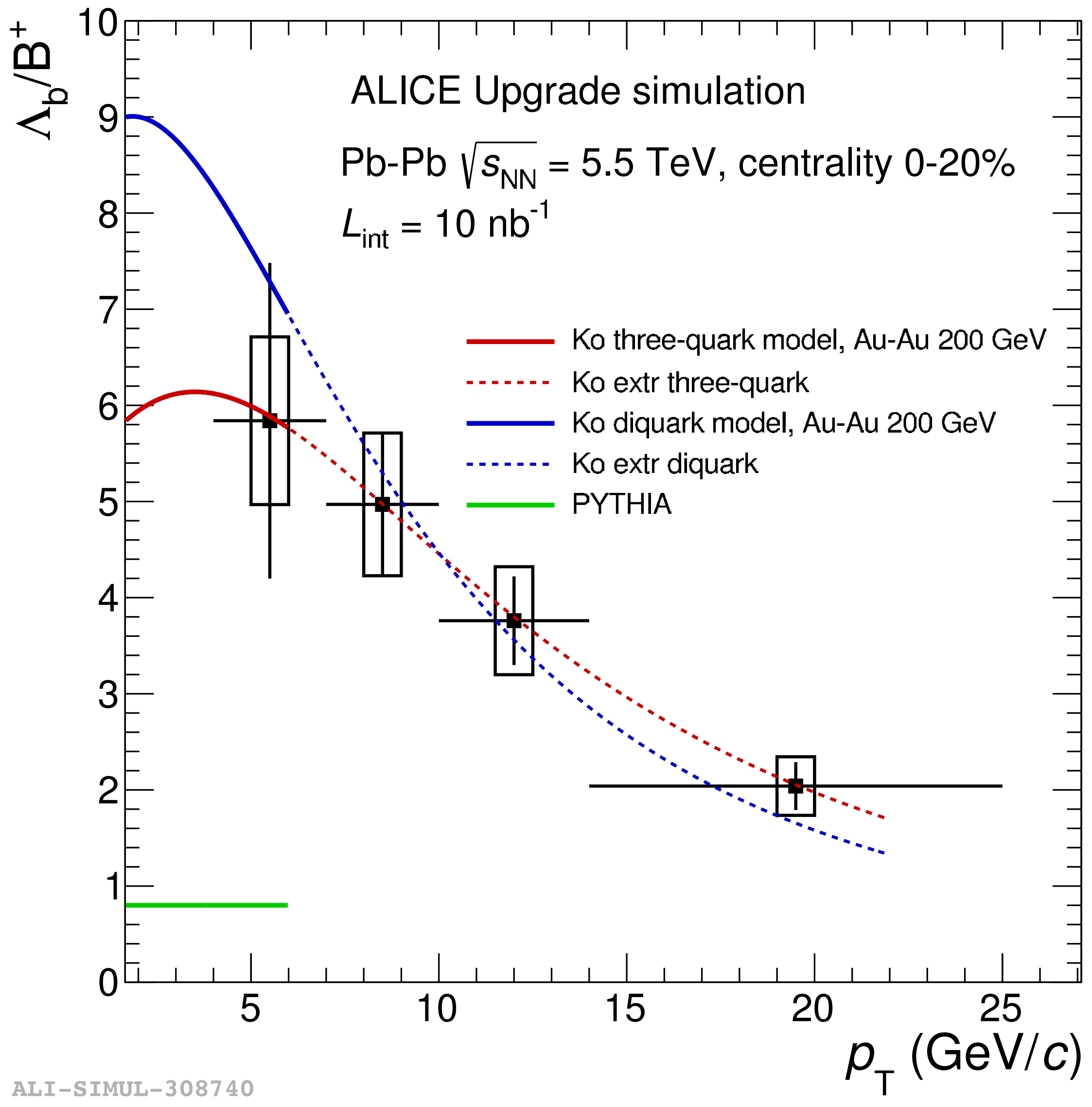
Performance in Run 3

- Ability to measure B hadrons via full reconstruction
  - ✓ Significant increase of signal to background ratio for B_s
- Understanding of in-medium energy loss, hadronization mechanism, thermalization in the medium via B hadrons









Summary and Outlook

- Heavy flavor measurements with ALICE detector in pp, p–Pb, Pb–Pb collisions
- Strong suppression of heavy-flavor production in central Pb–Pb collisions
  - ✓ Mass ordering of the R_{AA} at intermediate p_T
  - ✓ Compared with various model predictions implementing different energy loss and hadronization
- Strong coupling of charm quark with medium constituents at low p_T
  - ✓ Smaller v_2 for beauty → weaker thermalization than charm
- Charm baryon-to-meson ratios in pp collisions present significant differences to e^+e^-, ep collisions
  - ✓ Charm fragmentation fractions not universal across collision systems
- Upgraded ALICE detector during LS2
  - ✓ Better pointing/tracking resolution, higher statistics
  - ✓ Extend heavy flavor physics program with better precision

Thank you for your attention!

Backup