Recent highlights on open heavy-flavor production with ALICE

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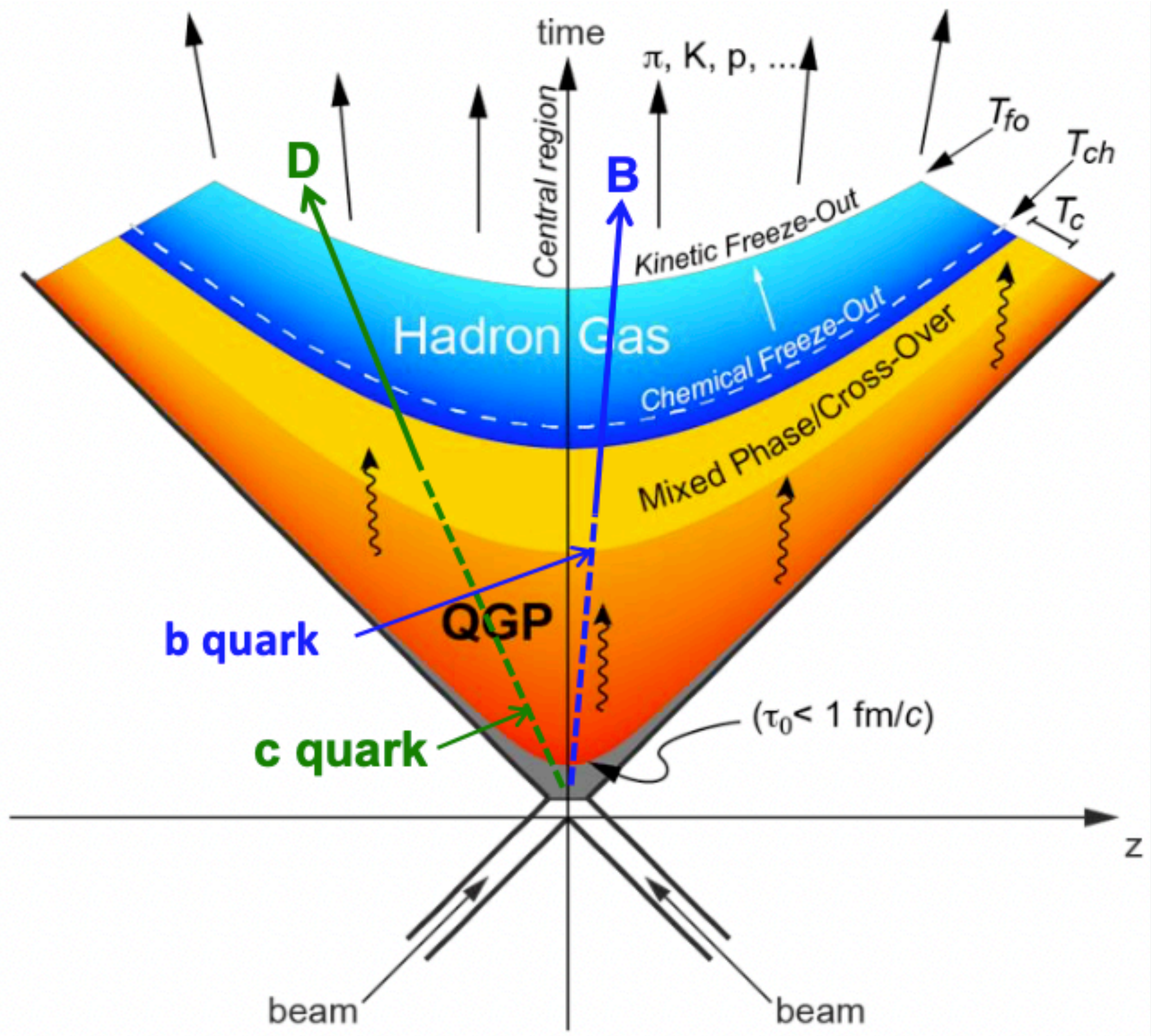
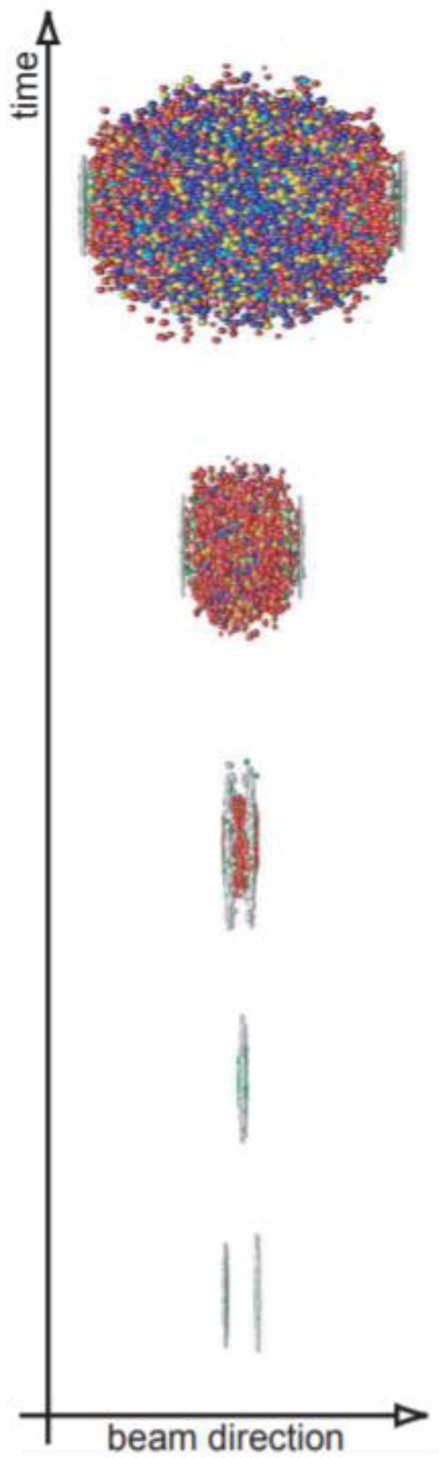
极端核物质前沿研讨会
湖北省宜昌市
2026年4月26日

Heavy quarks: a unique probe for high-density QCD





- Charm:

  $m_c \approx 1.3\ \mathrm{GeV}/c^2$

- Beauty:

  $m_b \approx 4.2\ \mathrm{GeV}/c^2$

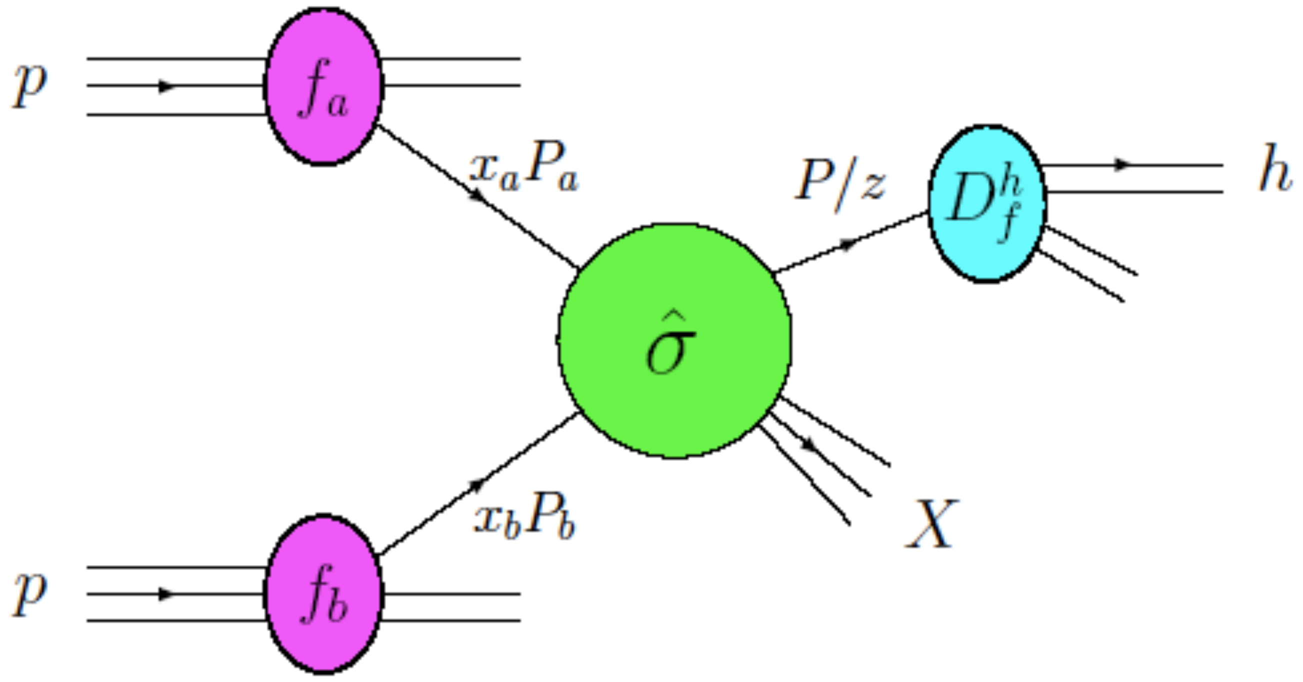
- $m_Q \gg \Lambda_{QCD}$
  - Enable the evaluation of their production cross sections within pQCD
- $m_Q \gg T_{QGP}$
  - Produced mainly in initial hard scatterings (high Q^2) at early stage of heavy-ion collisions
- $\tau_{prob} \approx \dfrac{1}{2m_q} \approx 0.1_{q=c}(0.03)_{q=b}\ \mathrm{fm}/c\ < \tau_{QGP}(\approx 0.3 - 1.5\ \mathrm{fm}/c)$
  - Experience the full evolution of the QGP

- Hadroproduction described by factorisation approach:

$$\frac{d\sigma^D}{dp_T^D}(p_T;\mu_F;\mu_R) = PDF(x_a,\mu_F)PDF(x_b,\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_a,x_b,\mu_R,\mu_F) \otimes D_{c\to D}(z = p_D/p_c,\mu_F)$$

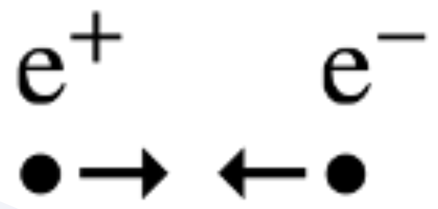
parton distribution function (PDF) (non-perturbative) — partonic cross section (perturbative) — hadronisation by fragmentation (non-perturbative)

Fragmentation functions assumed to be universal

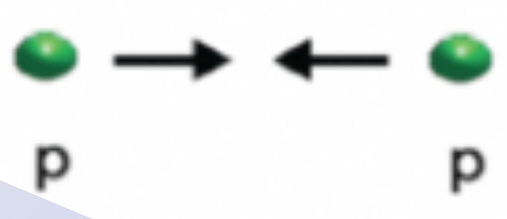


HF hadronisation

- Ratios of particle species sensitive to hadronisation

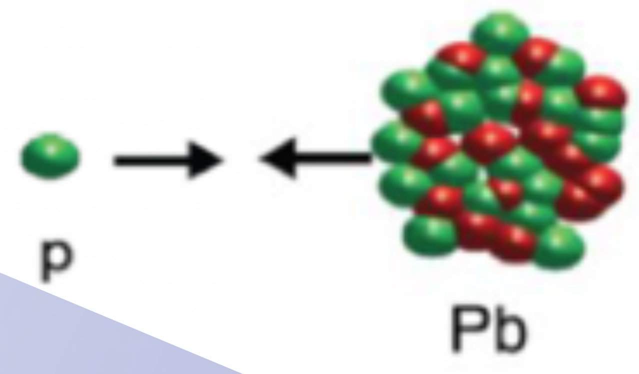


Vacuum

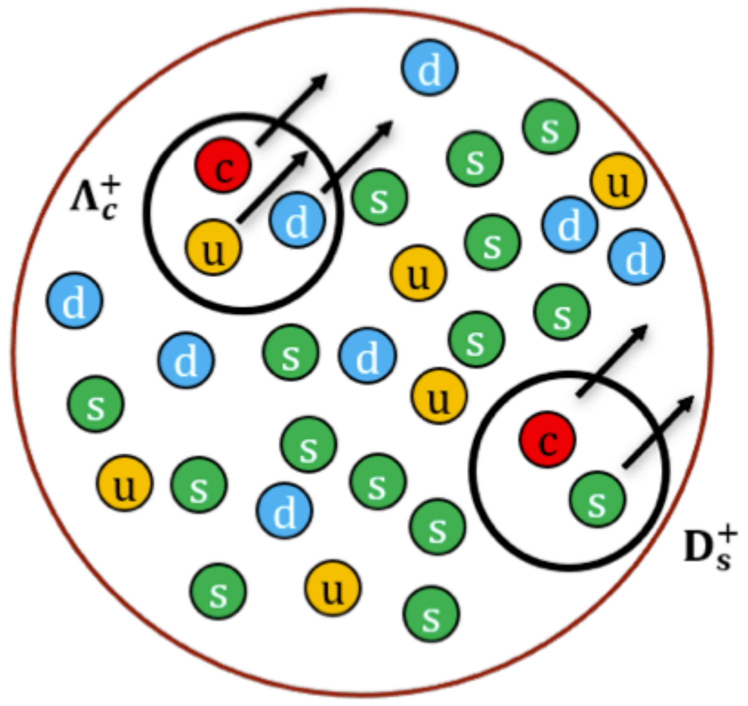


Not far from vacuum?

Or dense enough to alter hadronization?

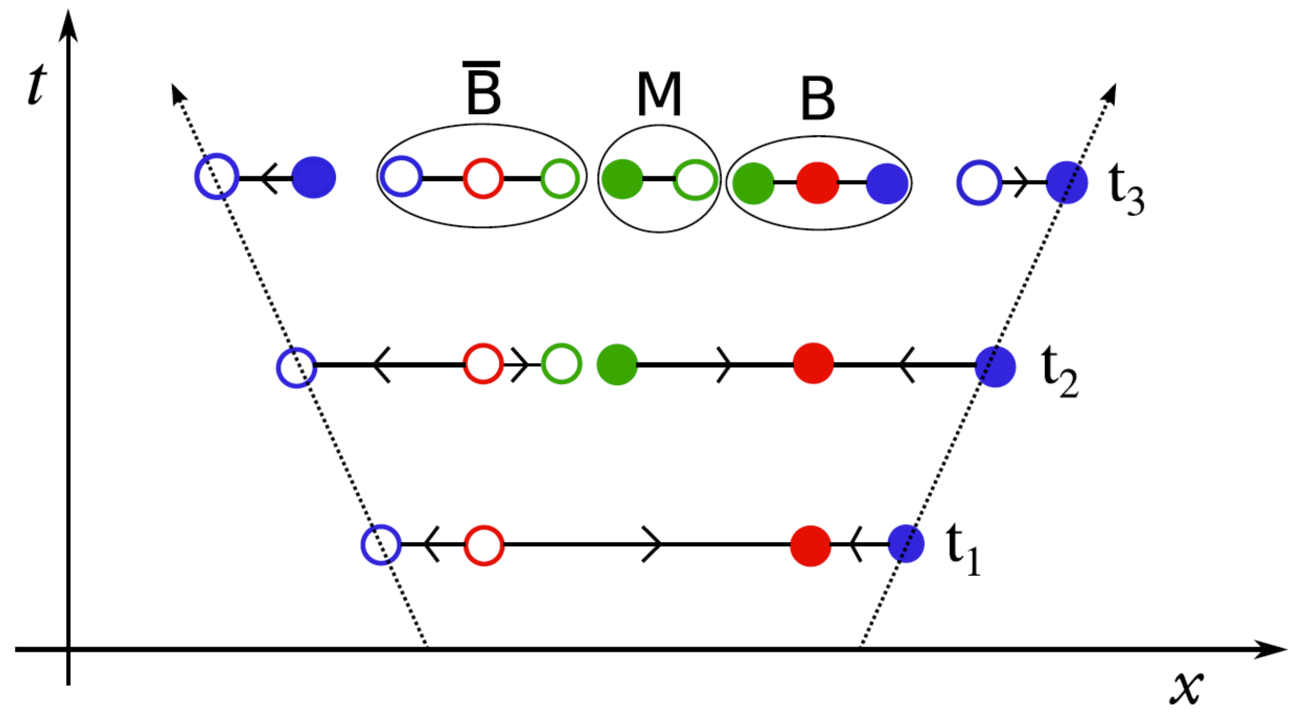


System size



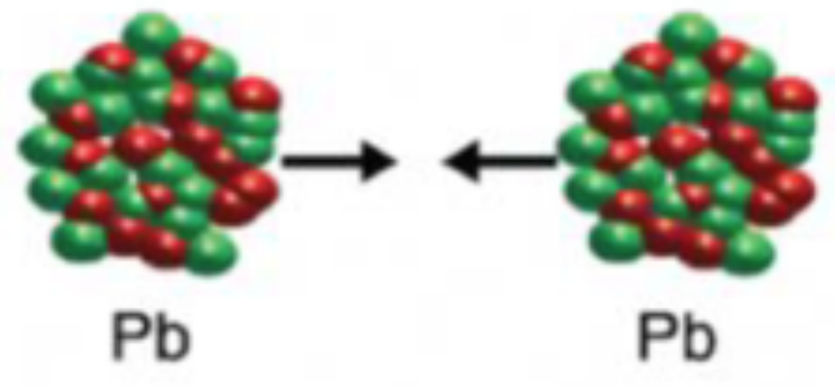
Fragmentation

- Hard scattering $e^+e^- \rightarrow q\bar{q}$
- Color-potential string between q and $\bar{q}$
- Hadronisation via multiple string breaking and formation of quark-antiquark pairs



Coalescence

- Heavy-quarks coalescence with light (di-)quarks from the system
- Expected to increase baryon production at low and intermediate p_T



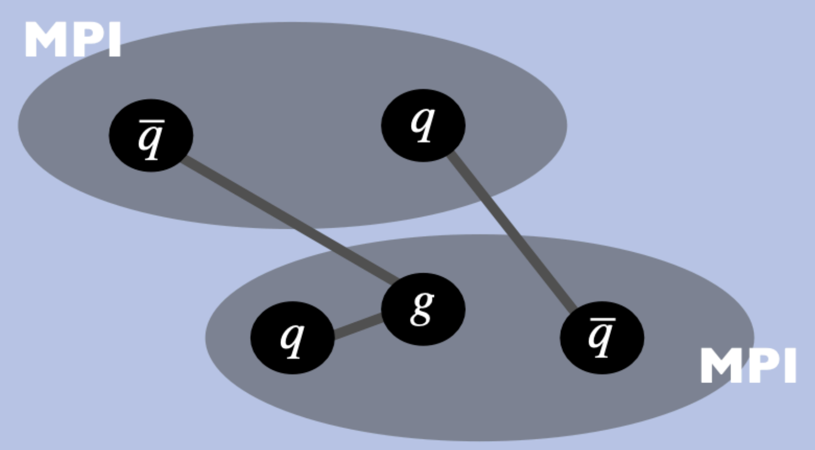
Dense, extended-size system

C. Bierlich, et al., *Eur.Phys.J.C 82 (2022) 228*

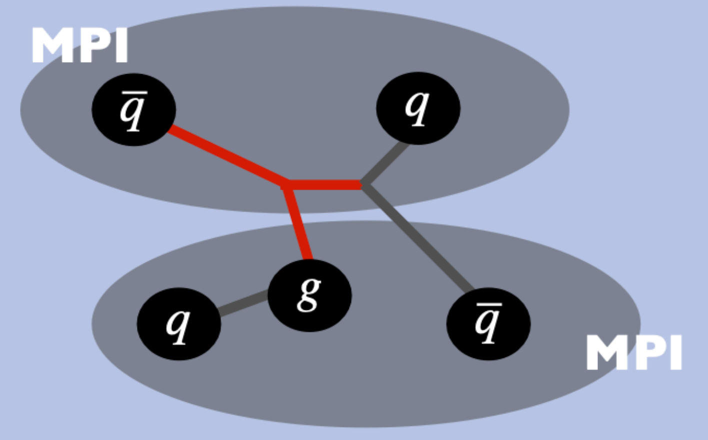
Modeling hadronization

PYTHIA 8

Hadronization via **fragmentation**, color reconnection between partons from different multiparton interactions



Monash tune
(tuned to e^+e^- measurements)
Eur.Phys.J. C 74 (2014) 3024

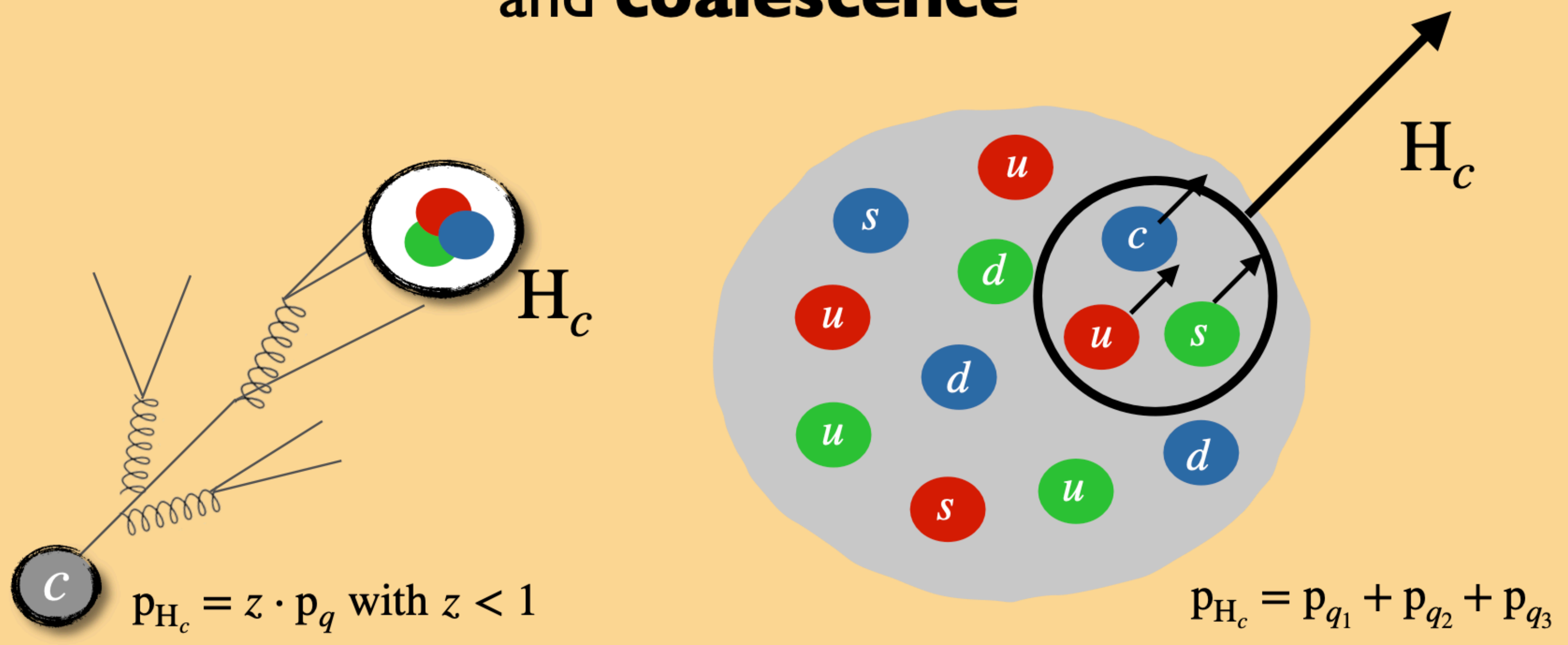


Mode 2
the **junction** topology leads to an increase of baryon production
JHEP 08 (2015) 003

CATANIA

Phys.Lett.B 821 (2021) 136622

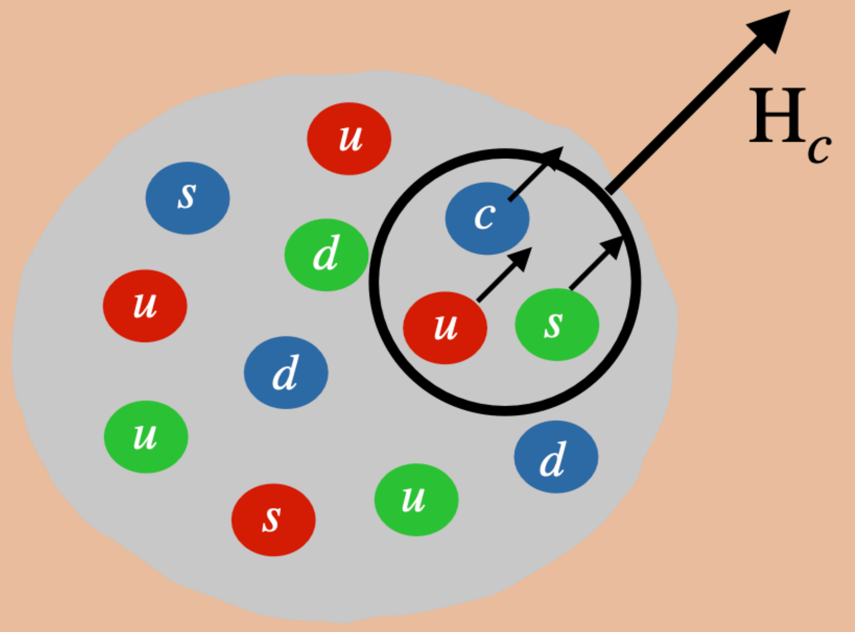
Hadronization via both **fragmentation** and **coalescence**



QCM

Eur.Phys.J.C 78 (2018) 344

Quark (re-)Combination Mechanism
equal-velocity combination of charm quark and light quarks (spatial properties neglected)



SHM + RQM

Phys.Lett.B 795 (2019) 117-121
Phys.Rev.D. 84 (2011) 014025

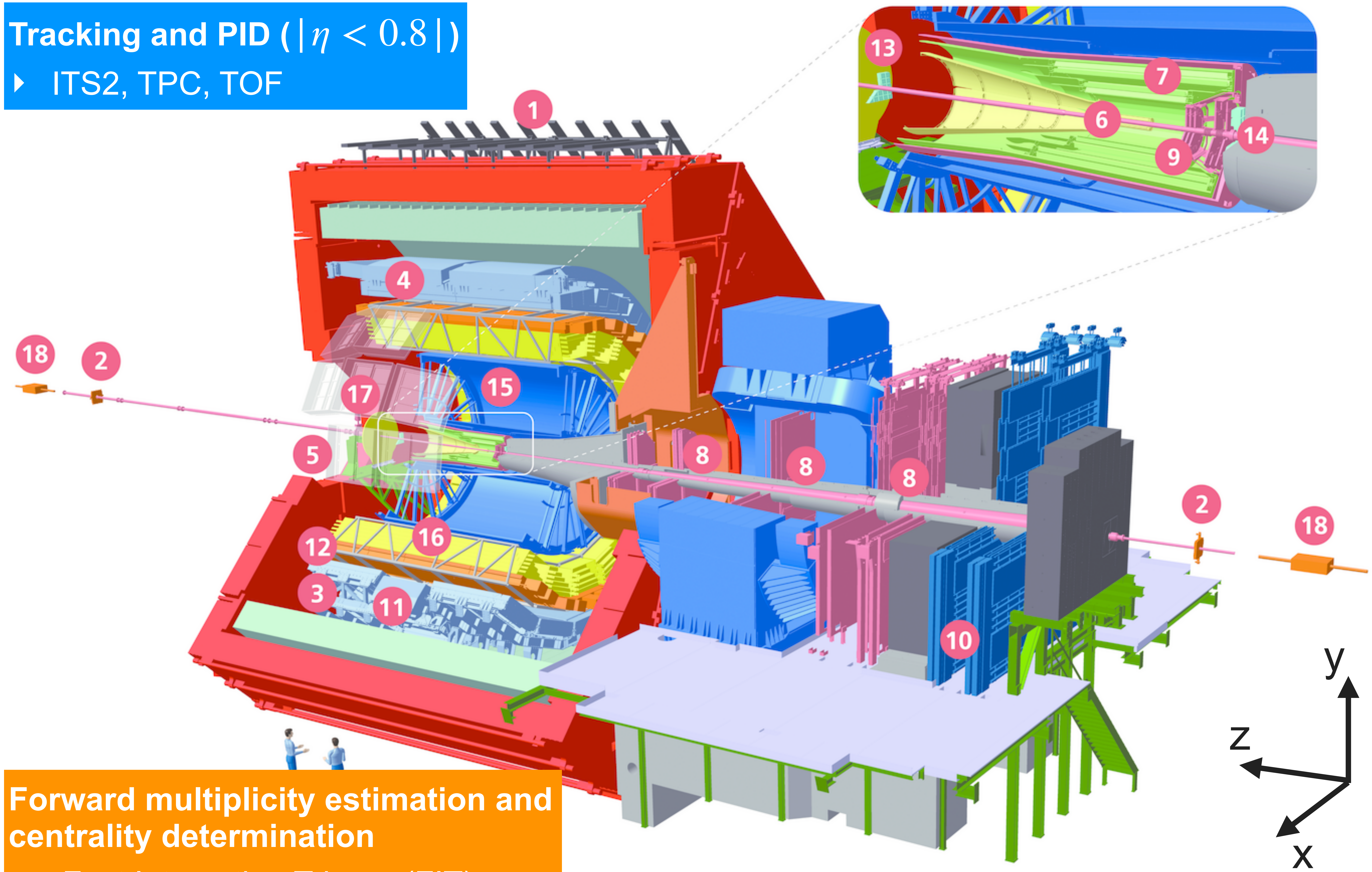
- Complexity of hadronization process replaced by **statistical weights** governed by hadron mass
- Feed-down from largely **augmented set of charm baryon stated** beyond the ones currently listed in the PDG, as predicted by Relativistic Quark Model

EPOS4HQ fragmentation + coalescence + resonance + UrQMD

ALICE detector in Run 3

Tracking and PID ($|\eta < 0.8|$)

- ITS2, TPC, TOF



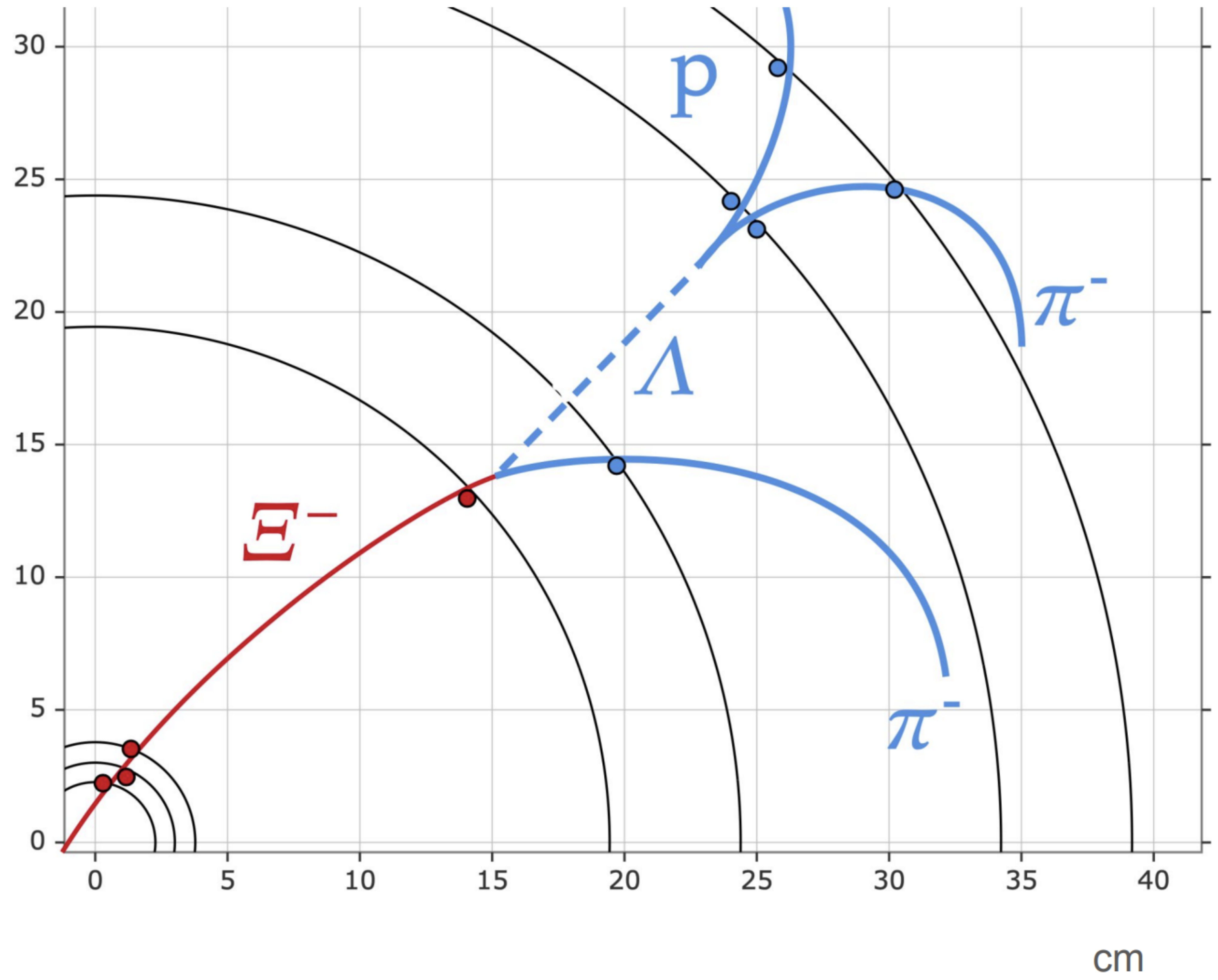
Forward multiplicity estimation and centrality determination

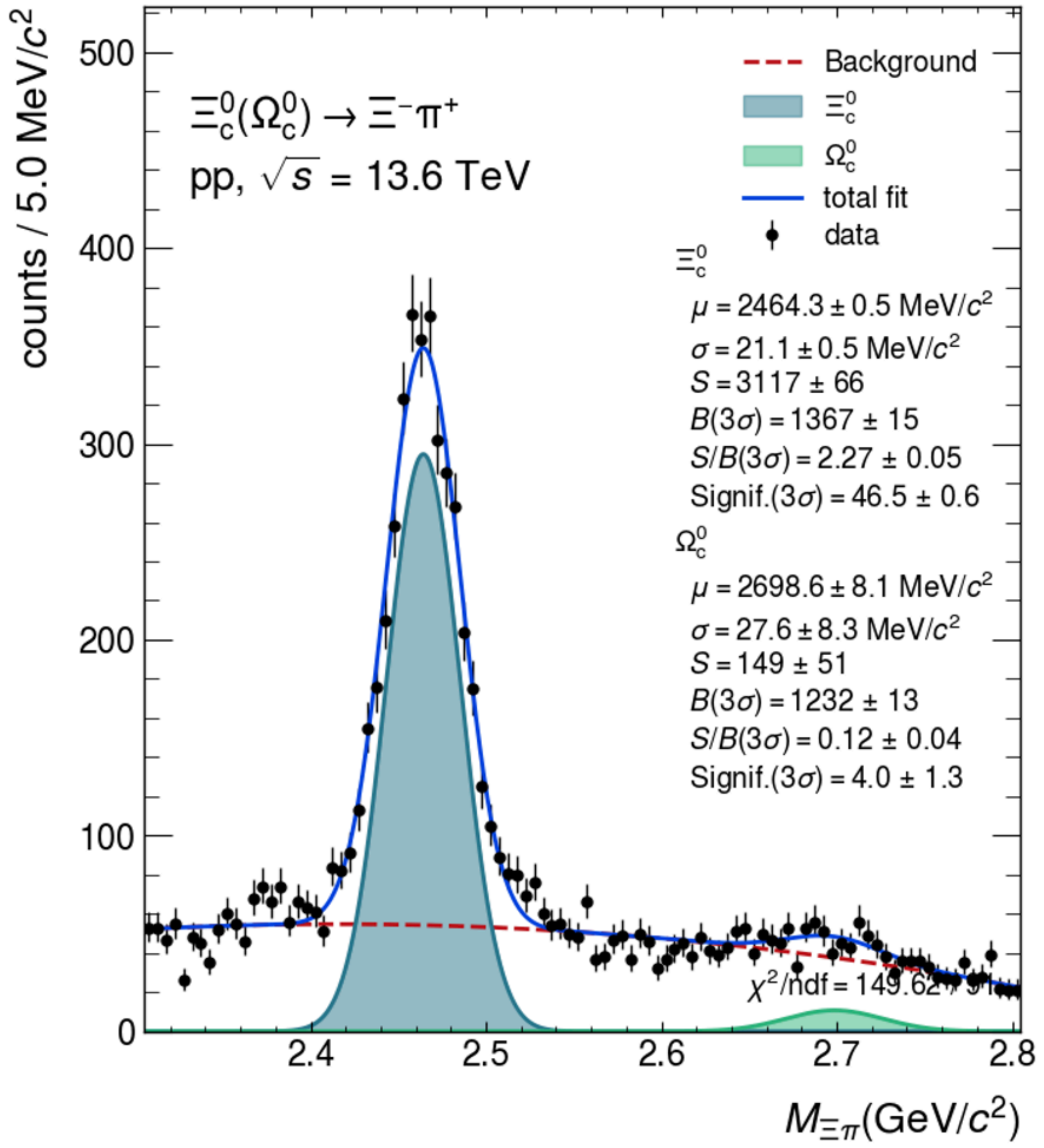
- Fast Interaction Trigger (FIT)

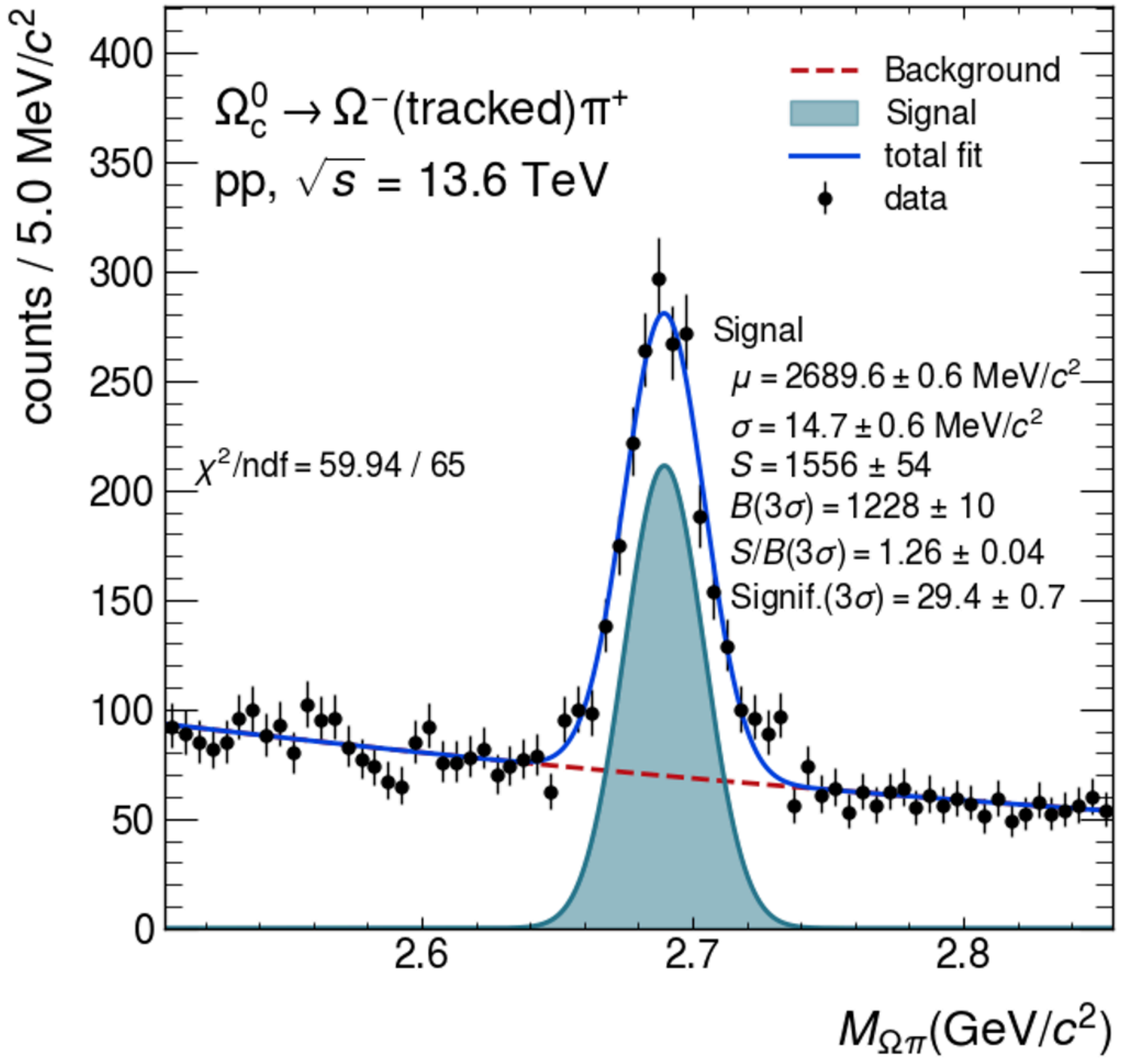
1 **ACORDE** | ALICE Cosmic Rays Detector
2 **AD** | ALICE Diffractive Detector
3 **DCal** | Di-jet Calorimeter
4 **EMCal** | Electromagnetic Calorimeter
5 **HMPID** | High Momentum Particle Identification Detector
6 **ITS-IB** | Inner Tracking System - Inner Barrel
7 **ITS-OB** | Inner Tracking System - Outer Barrel
8 **MCH** | Muon Tracking Chambers
9 **MFT** | Muon Forward Tracker
10 **MID** | Muon Identifier
11 **PHOS / CPV** | Photon Spectrometer
12 **TOF** | Time Of Flight
13 **T0+A** | Tzero + A
14 **T0+C** | Tzero + C
15 **TPC** | Time Projection Chamber
16 **TRD** | Transition Radiation Detector
17 **V0+** | Vzero + Detector
18 **ZDC** | Zero Degree Calorimeter

Strangeness tracking

- Directly track $\Xi^{\pm}$ and $\Omega^{\pm}$
- Improve vertex resolution, momentum resolution, S/B
- Important for multi-charm baryon measurements



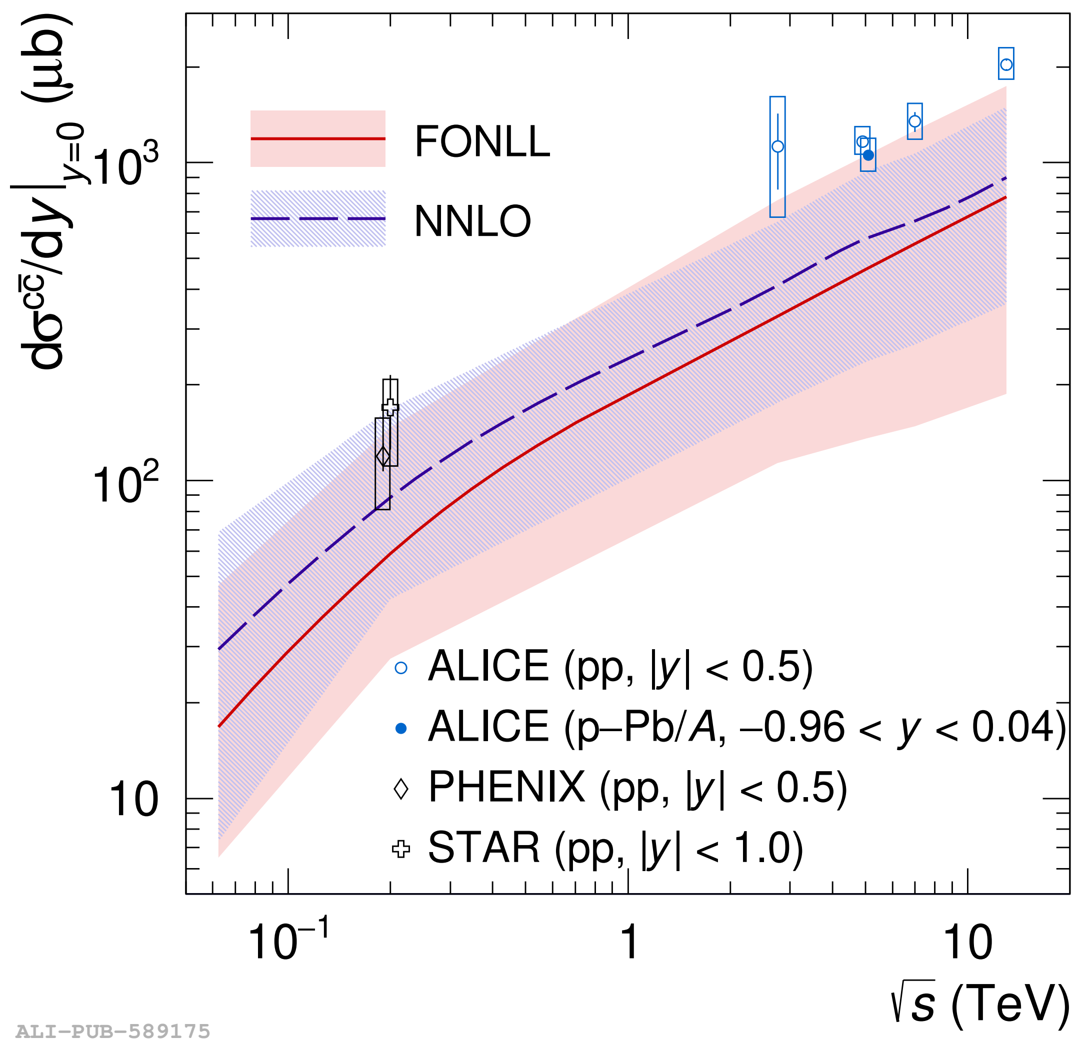


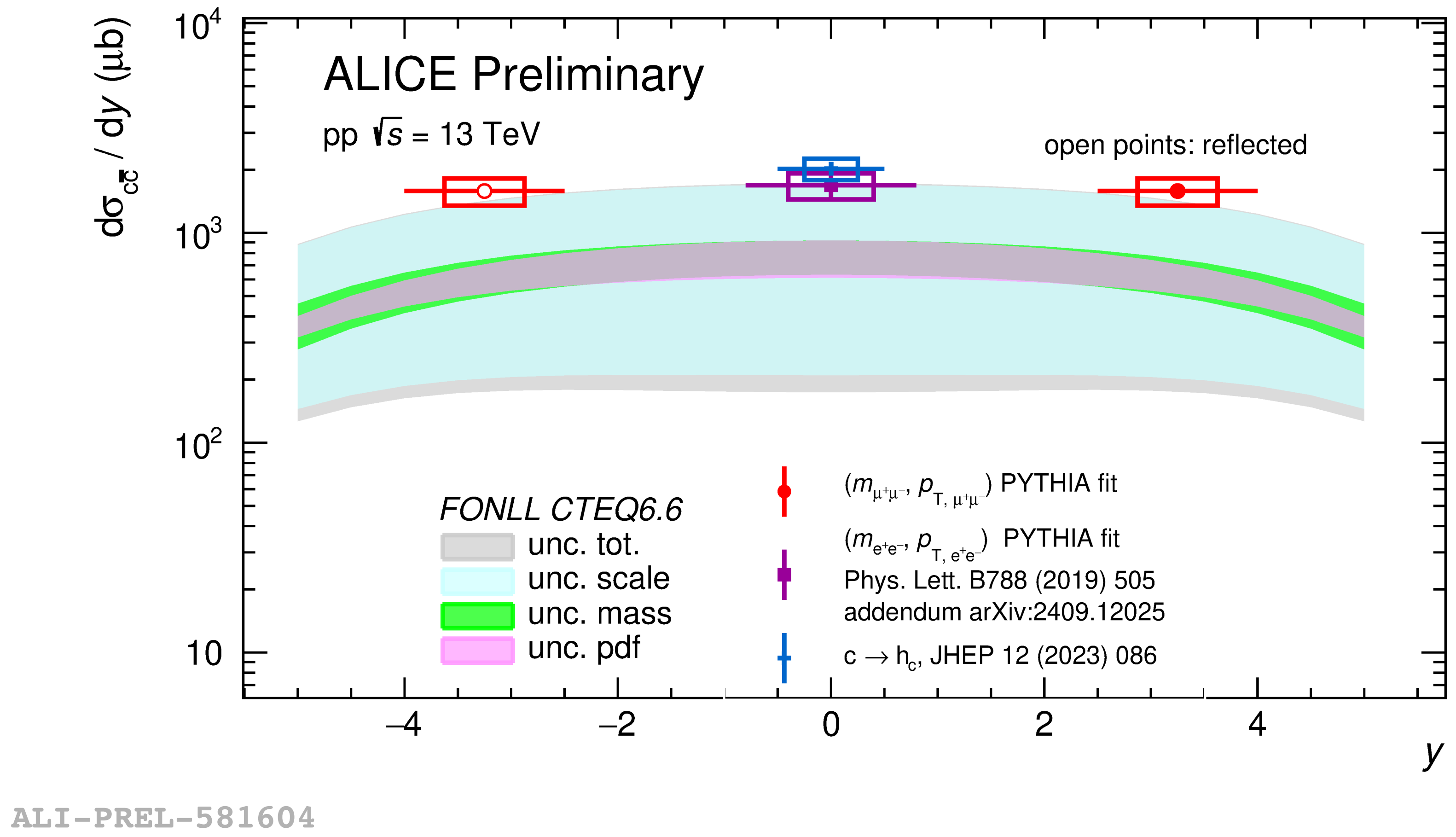


HF production in small system

EPJC 84 (2024) 1286

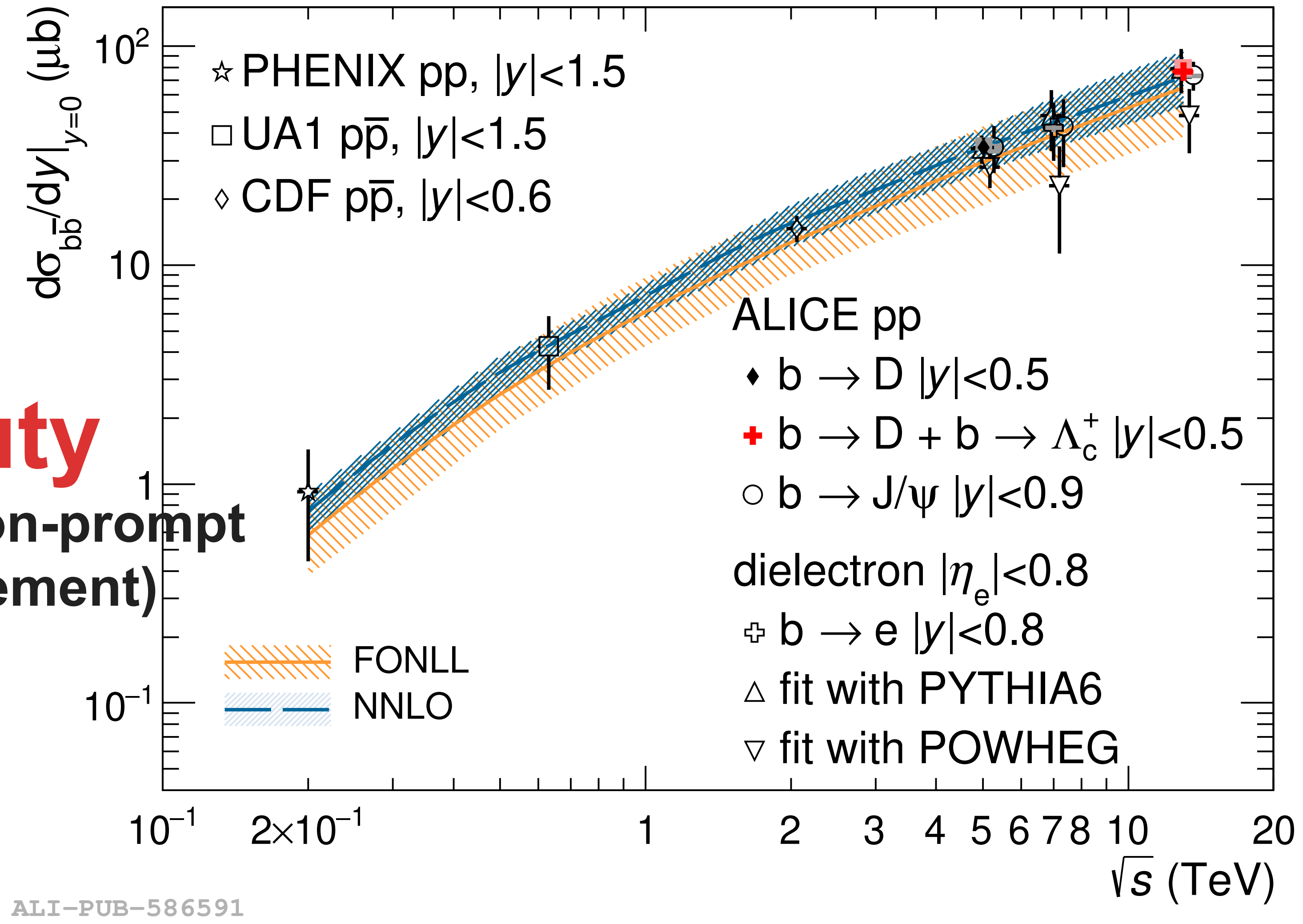
Charm

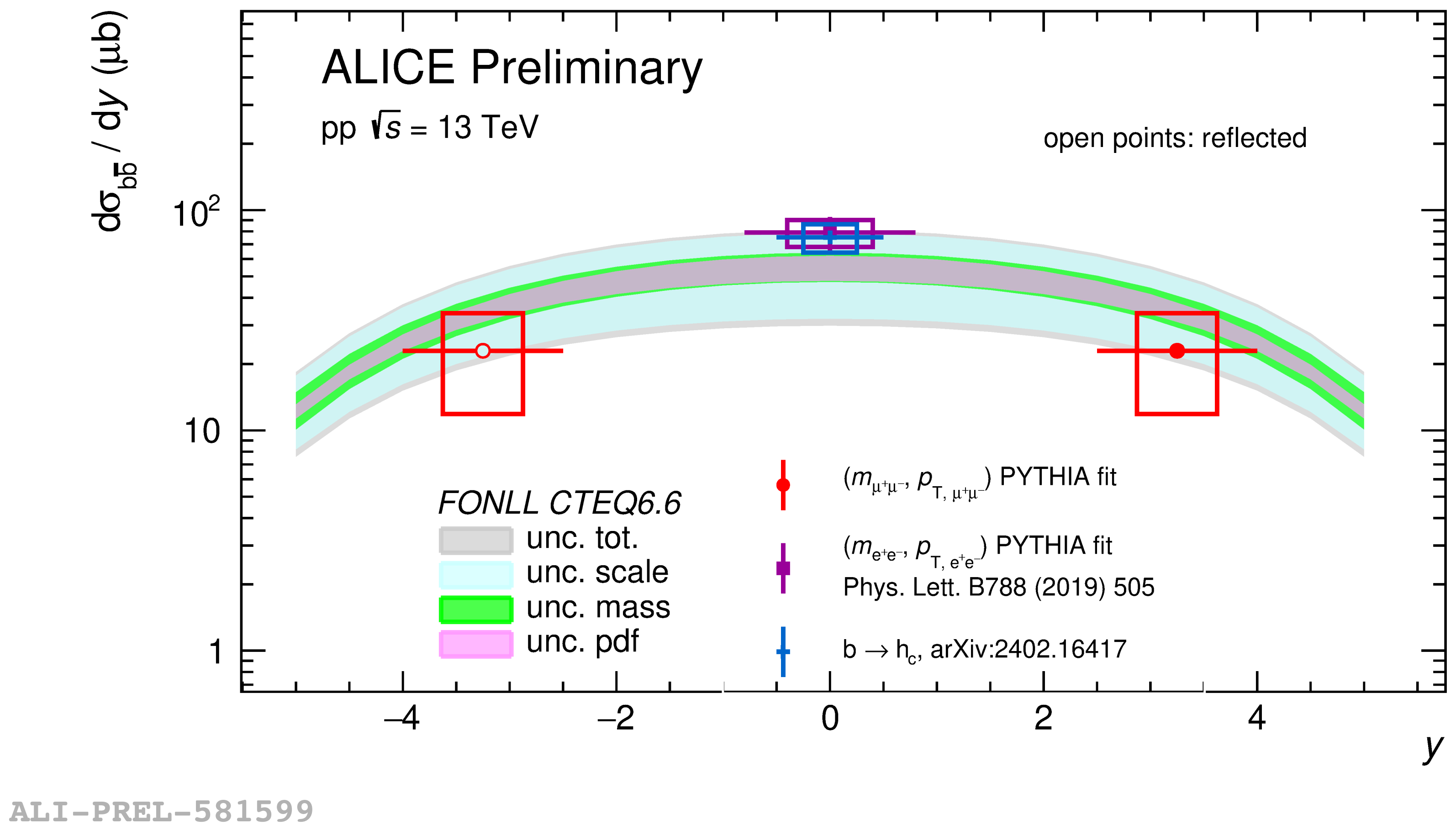




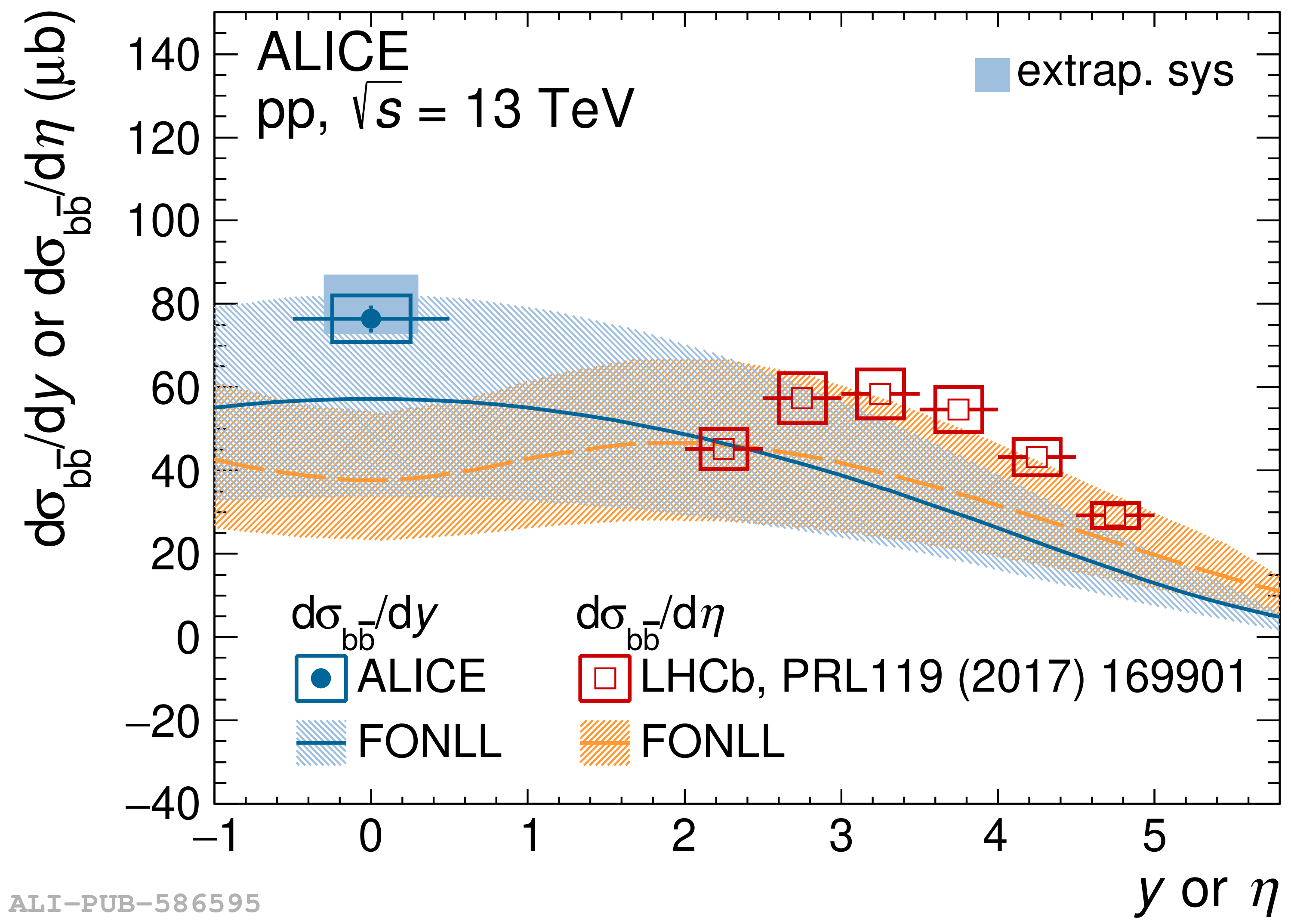
Beauty

(from non-prompt measurement)



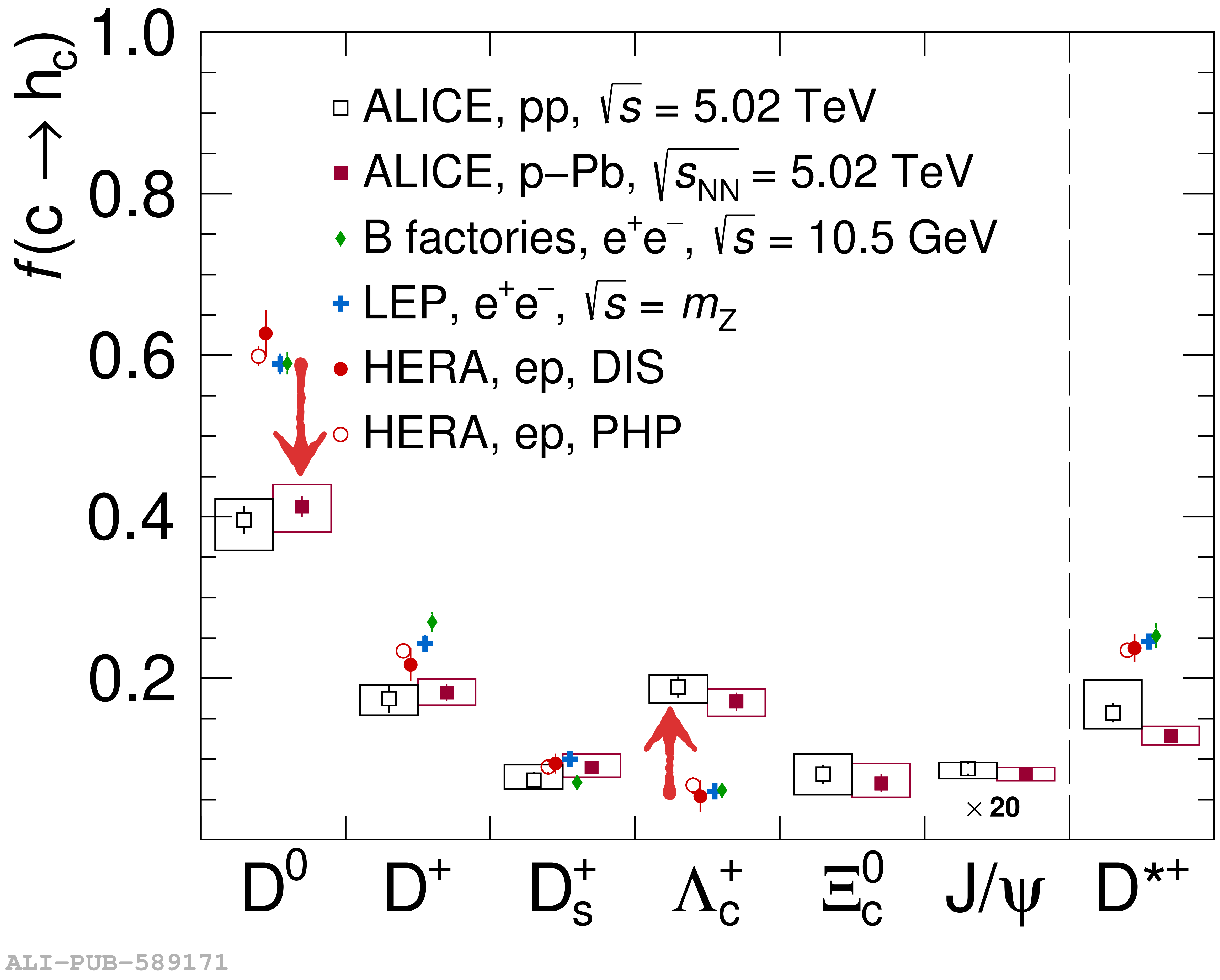


JHEP 10 (2024) 110



- $\sigma(c\bar{c})$ and $\sigma(b\bar{b})$ at the upper bound of state-of-the-art pQCD calculations
- Constrain recombination contribution to quarkonia

Charm fragmentation fractions in small system



EPJC 84 (2024) 1286

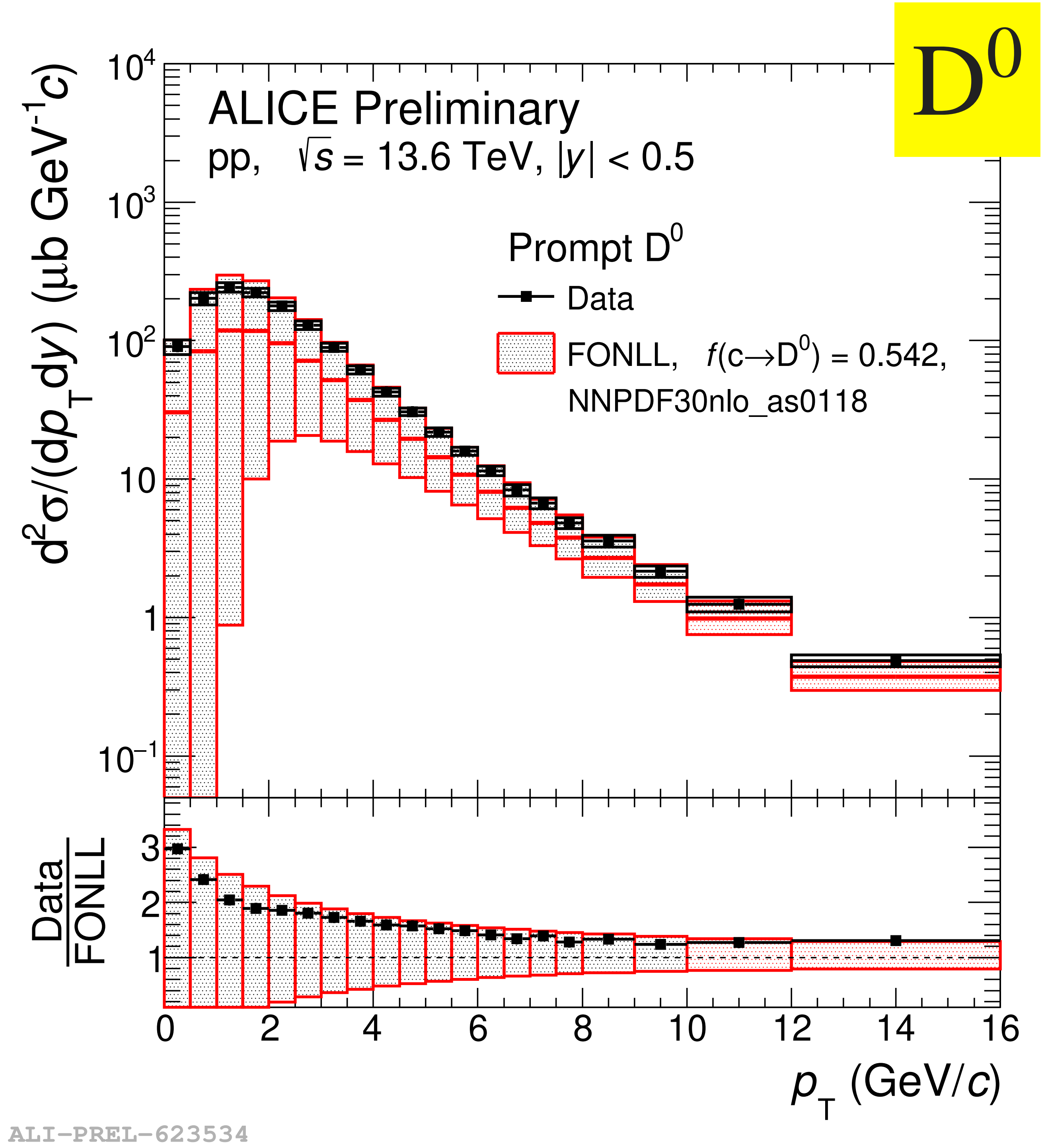
- Charm fragmentation fractions (FF)
  - $f(c \to H_c) = \sigma(H_c)/\sigma(c) = \sigma(H_c)/\sum_{\text{w.d.}} \sigma(H_c)$

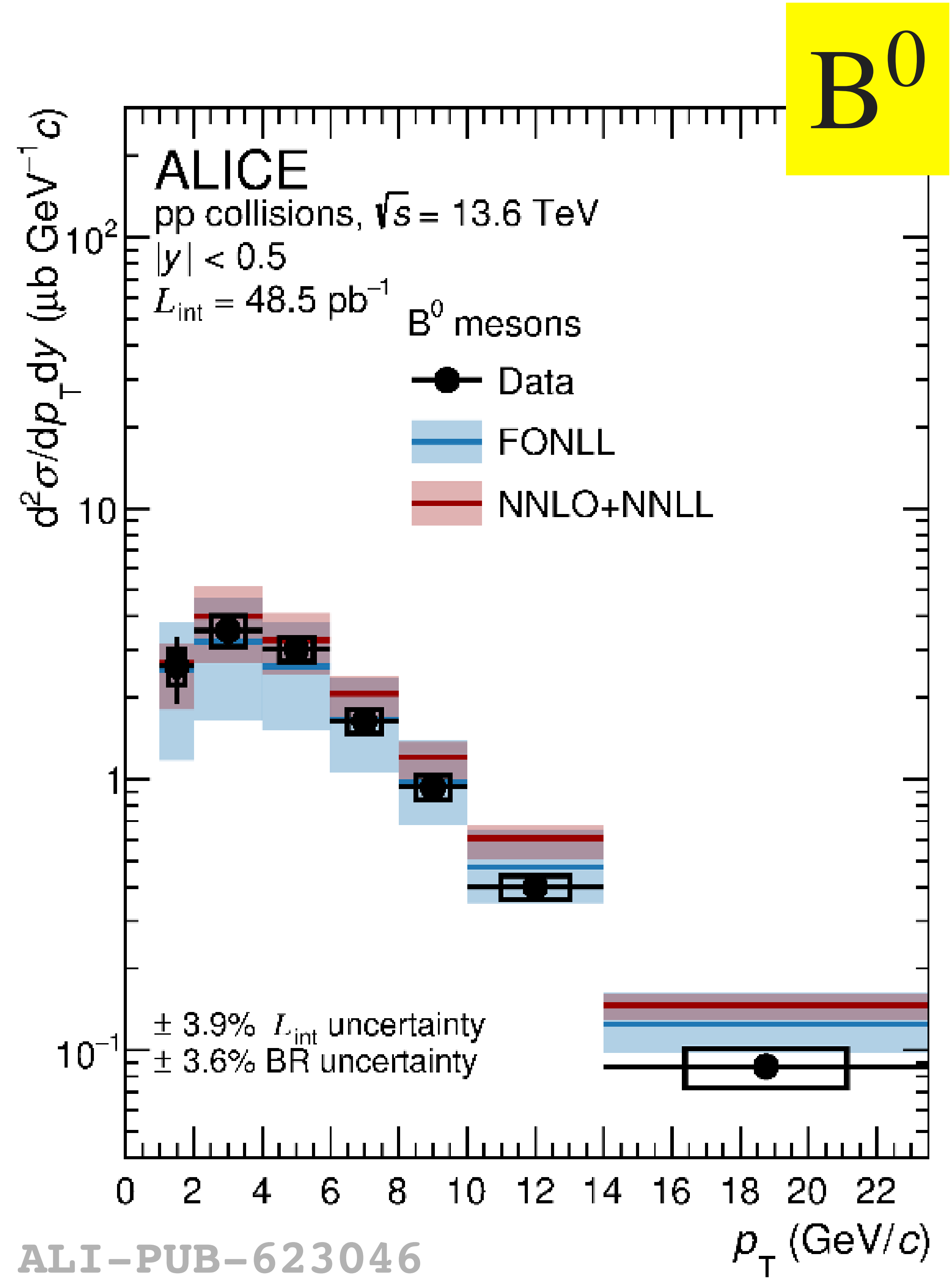
    (w.d.: weakly decaying)
  - Inputs used in a standard factorisation approach

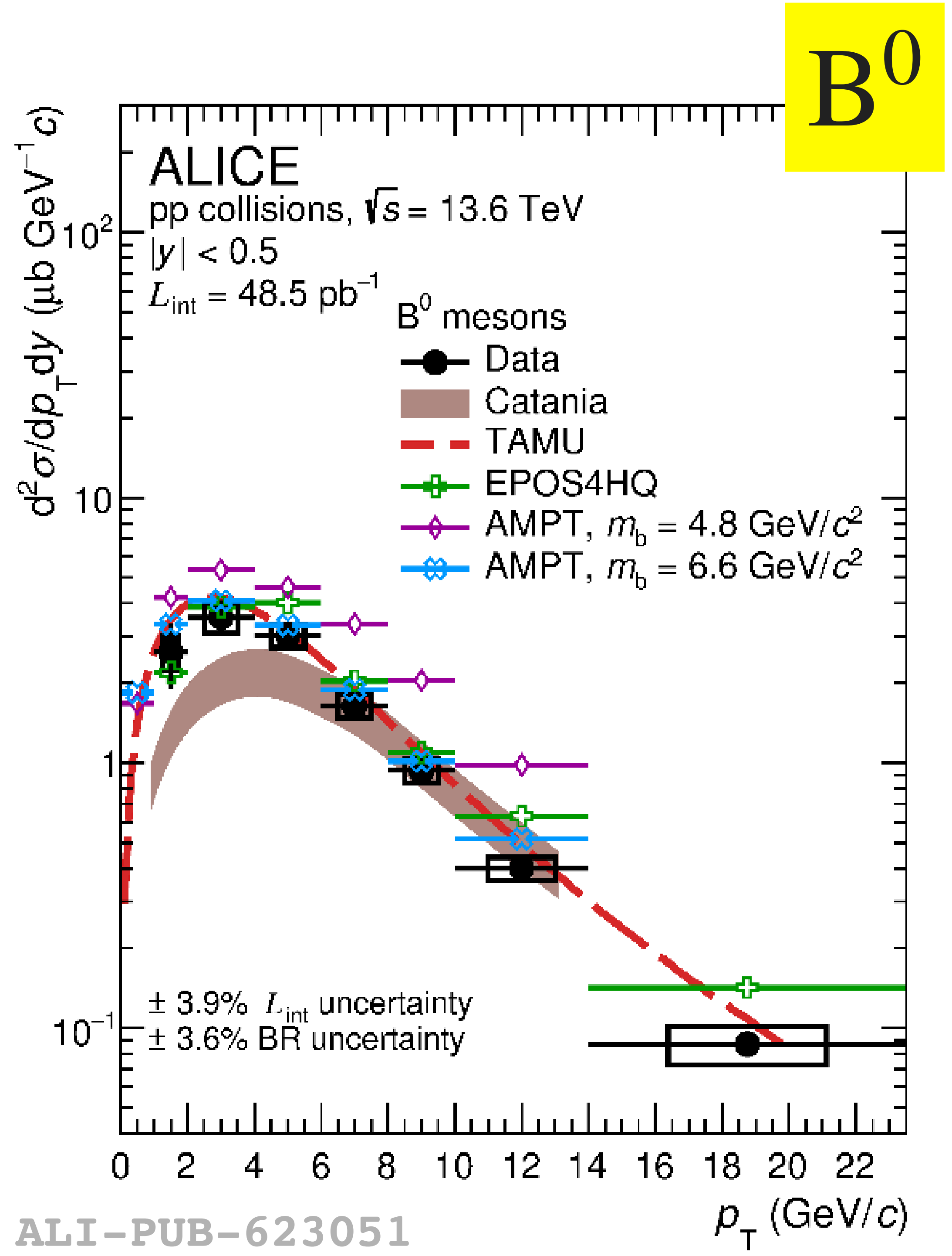
FF might be affected by possible medium effects

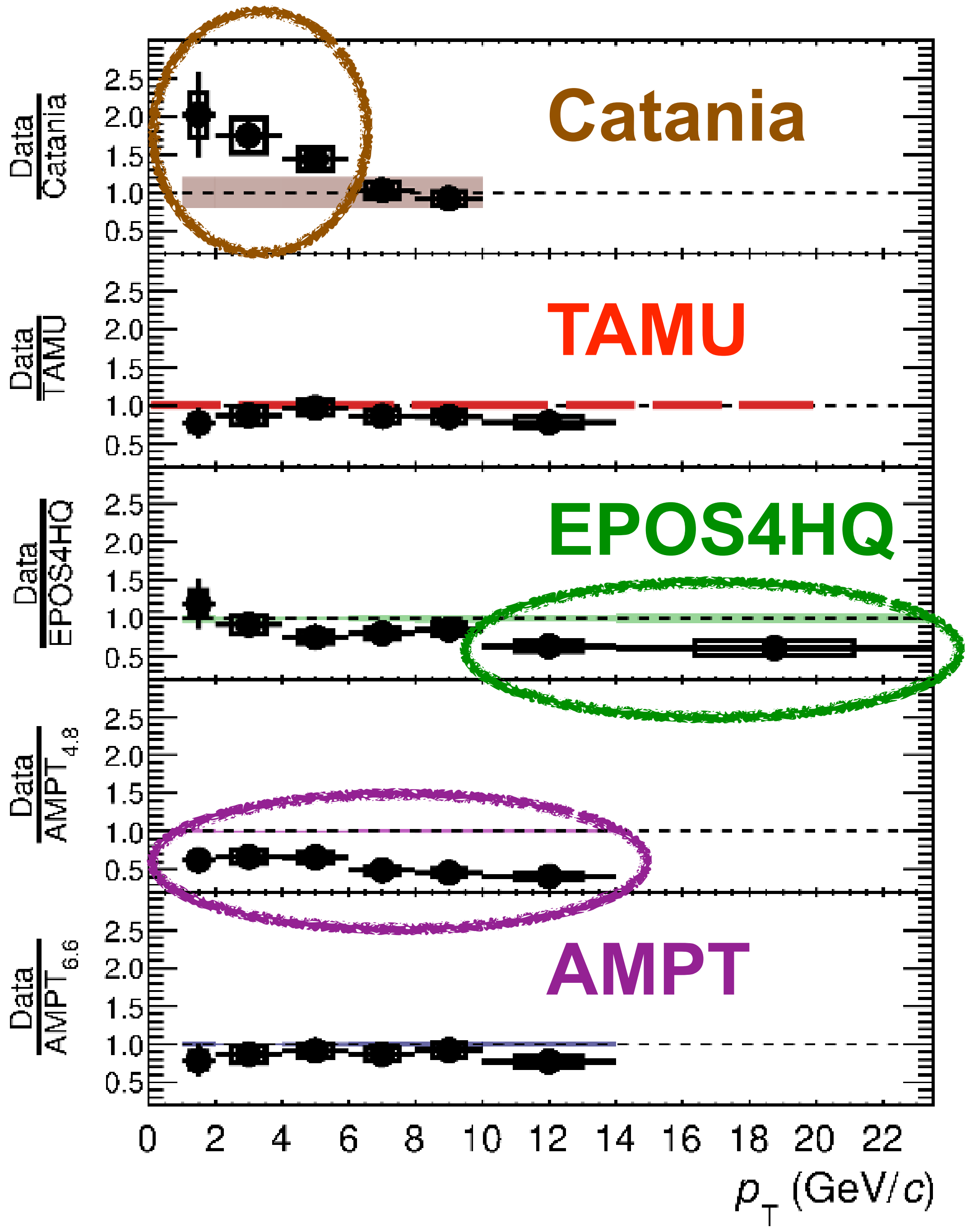
- Consistent with system size: pp and p–Pb collisions
- Significant enhancement for charm baryons in pp and p–Pb w.r.t. e^+e^- and e^-p collisions

D and B mesons production in small system









arXiv:2603.18904

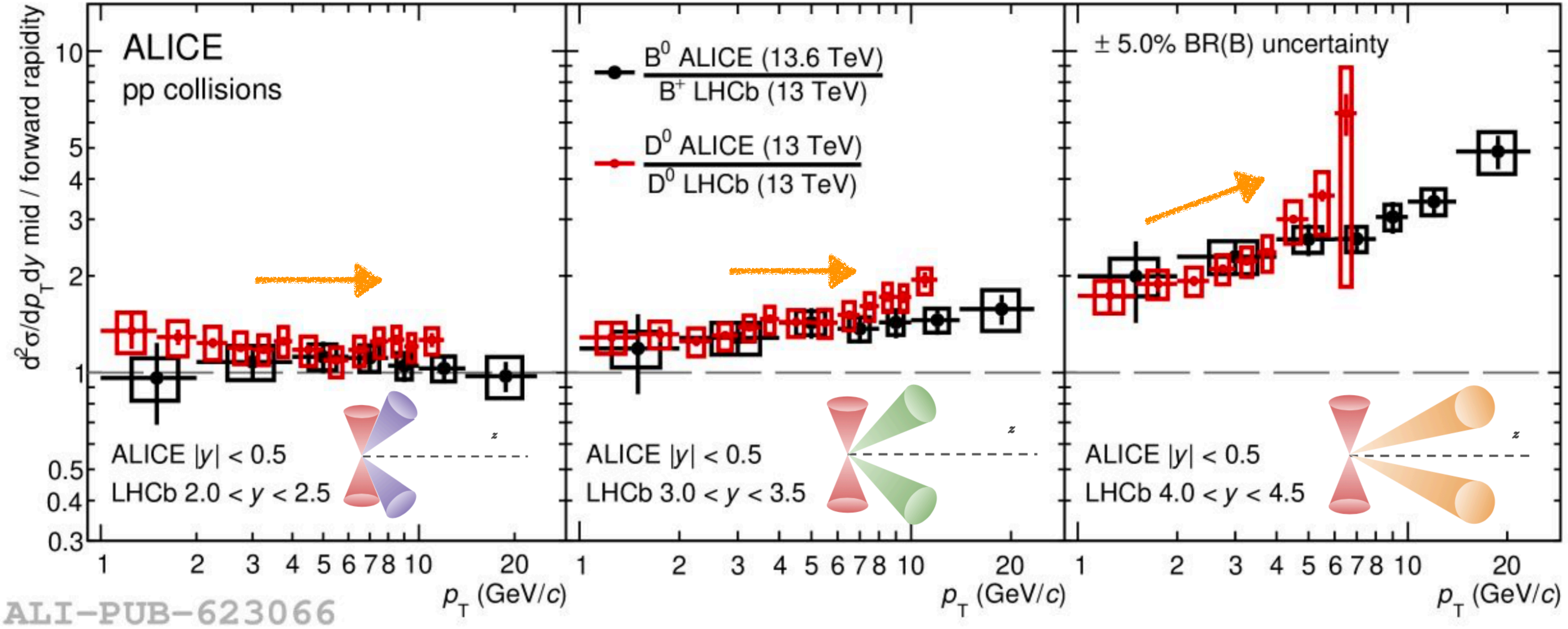
- Data can be described by **pQCD calculations** both for D^0 and B^0 mesons
- B^0 meson production comparing with **phenomenological models**
  - Catania: underestimate data for $p_{\mathrm{T}} < 6$ GeV/c
  - TAMU: describe data within uncertainties
  - EPOS4HQ: overestimate data for $p_{\mathrm{T}} > 10$ GeV/c
  - AMPT: overestimate data for $m_{\mathrm{b}} = 4.8$ GeV/c, reproduce data for $m_{\mathrm{b}} = 6.6$ GeV/c

D and B mesons mid-to-forward-rapidity ratio

arXiv:2603.18904

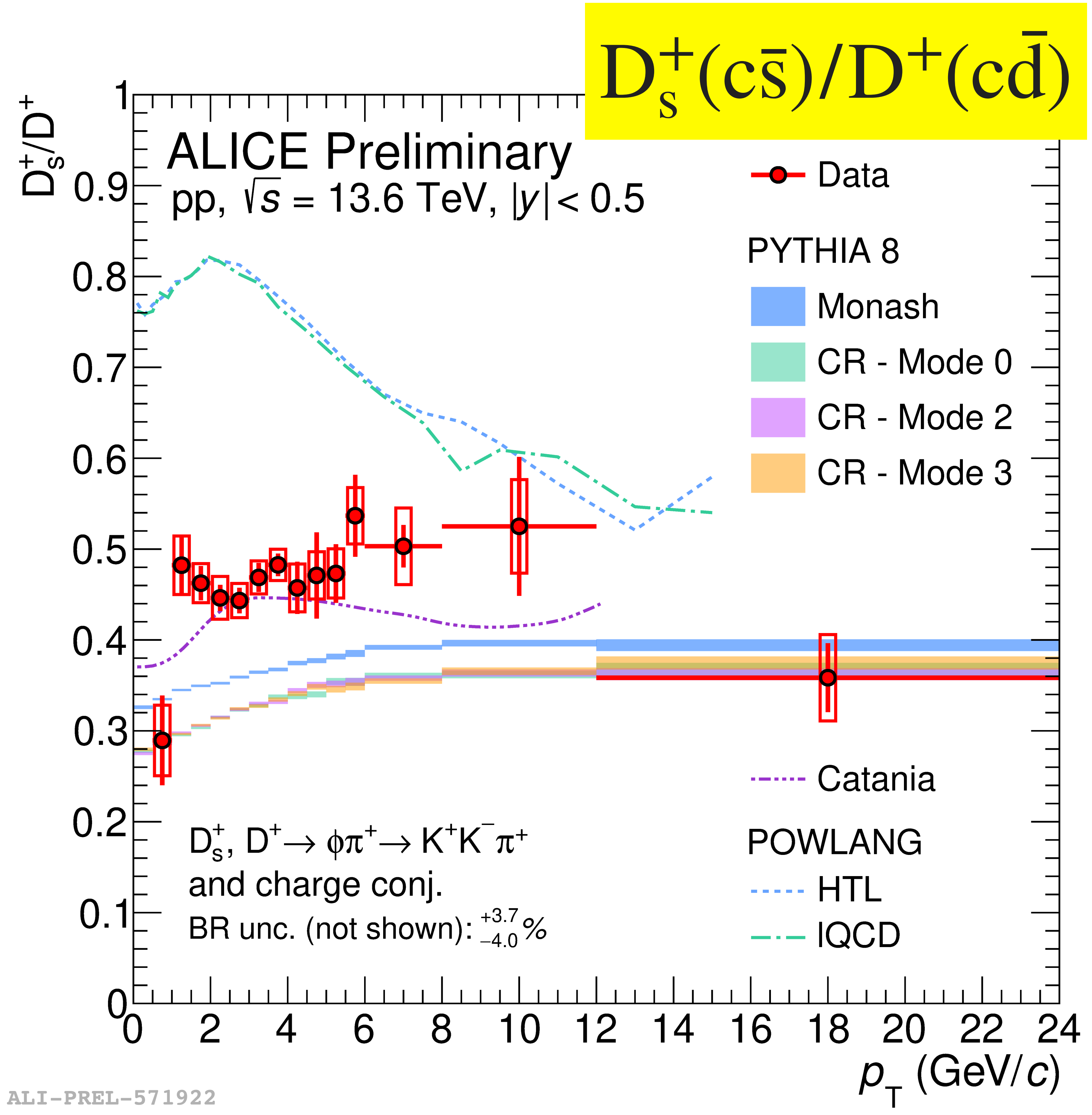
Beauty

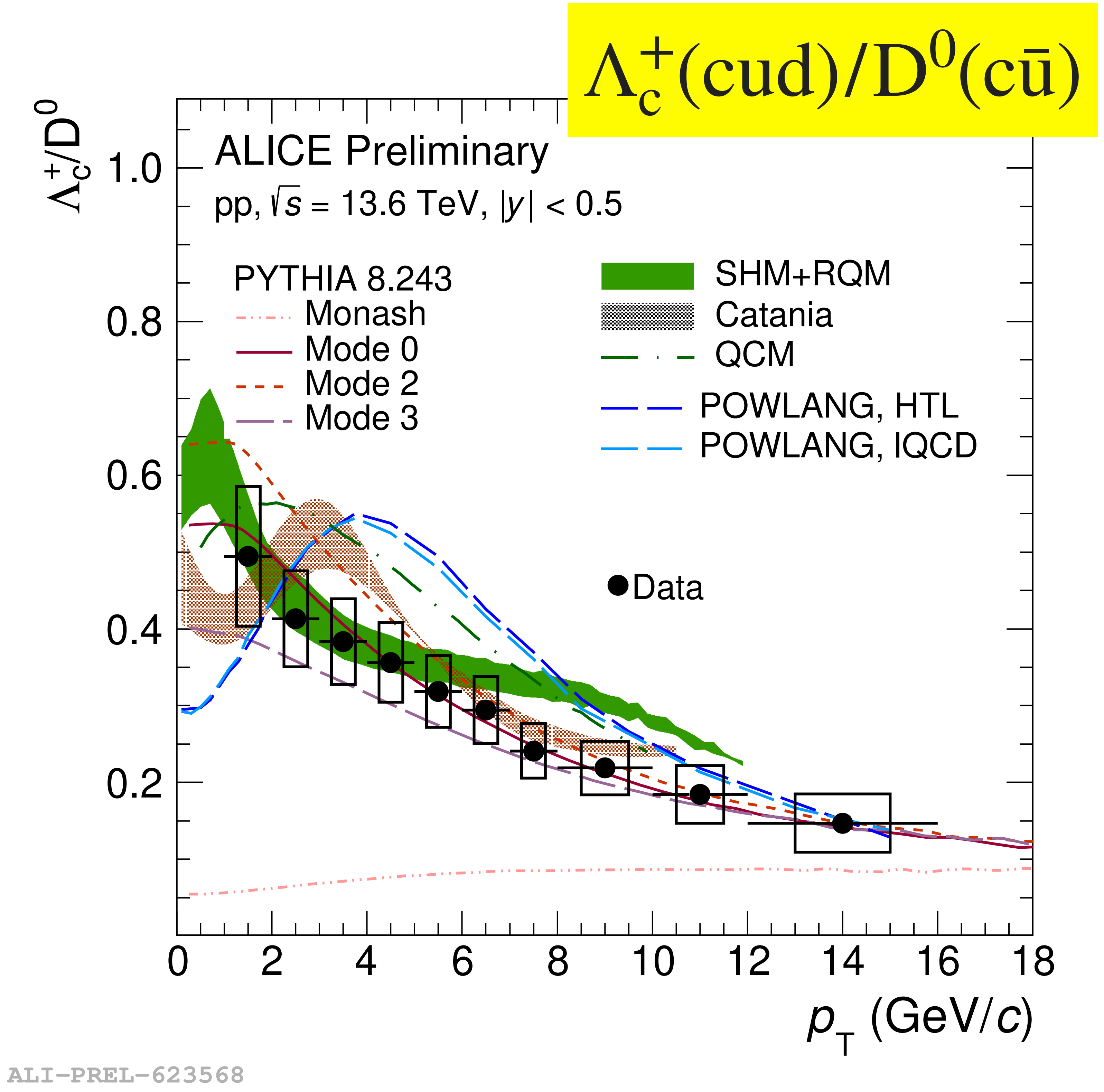
Charm

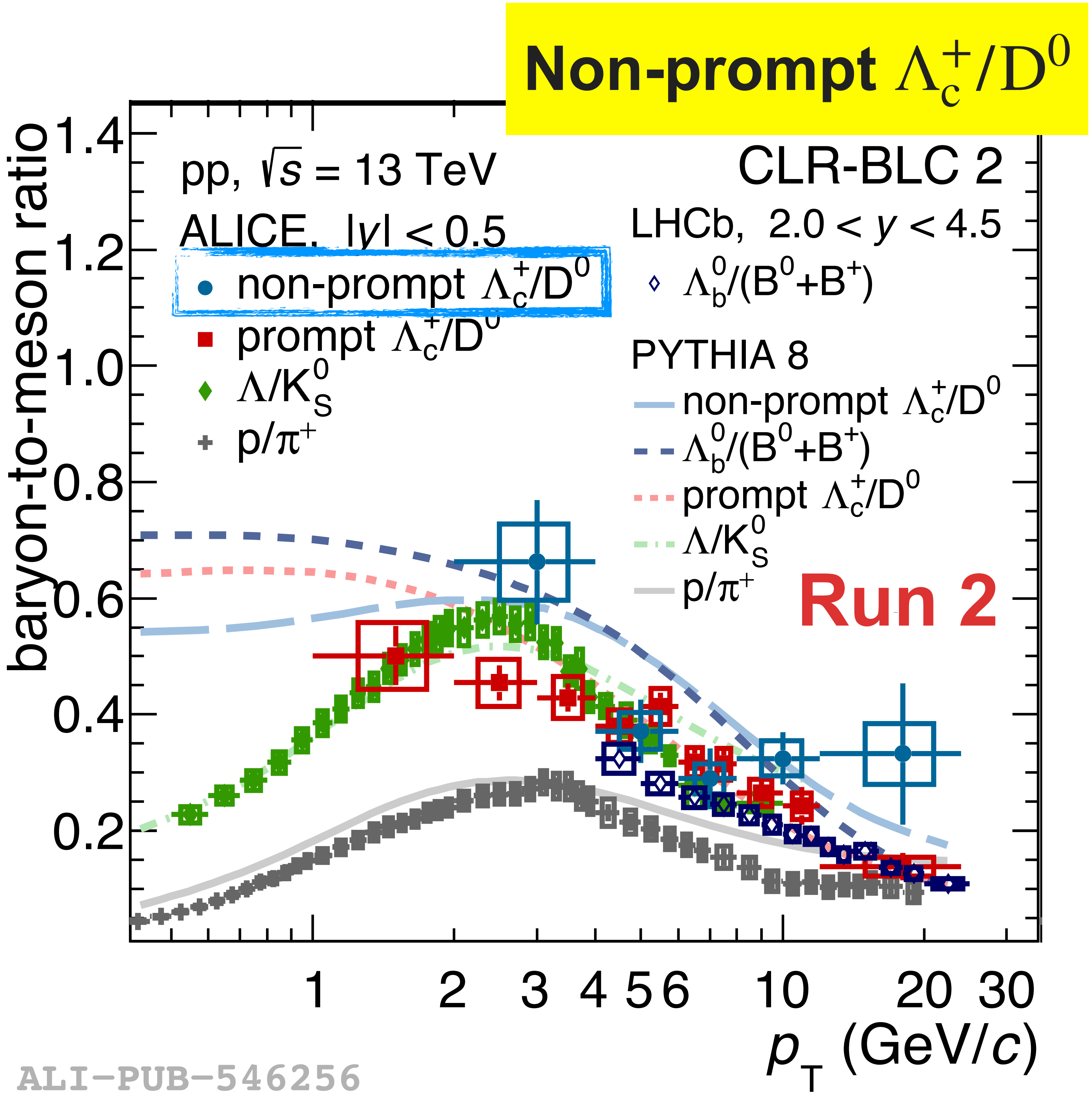


- Similar rapidity dependence of charm and beauty, independent of mass

Hadronisation: HF particle ratios in pp collisions







Phys.Rev.D 108 (2023) 112003

- PYTHIA 8 Monash: *Eur.Phys.J.C 74 (2014) 3024*
- PYTHIA 8 CR Mode: *JHEP 08 (2015) 003*
- Catania: *Phys.Lett.B 821 (2021) 136622*
- SHM: *Phys.Lett.B 795 (2019) 117-121*
- RQM: *Phys.Rev.D 84 (2011) 014025*
- QCM: *Eur.Phys.J.C 78 (2018) 344*

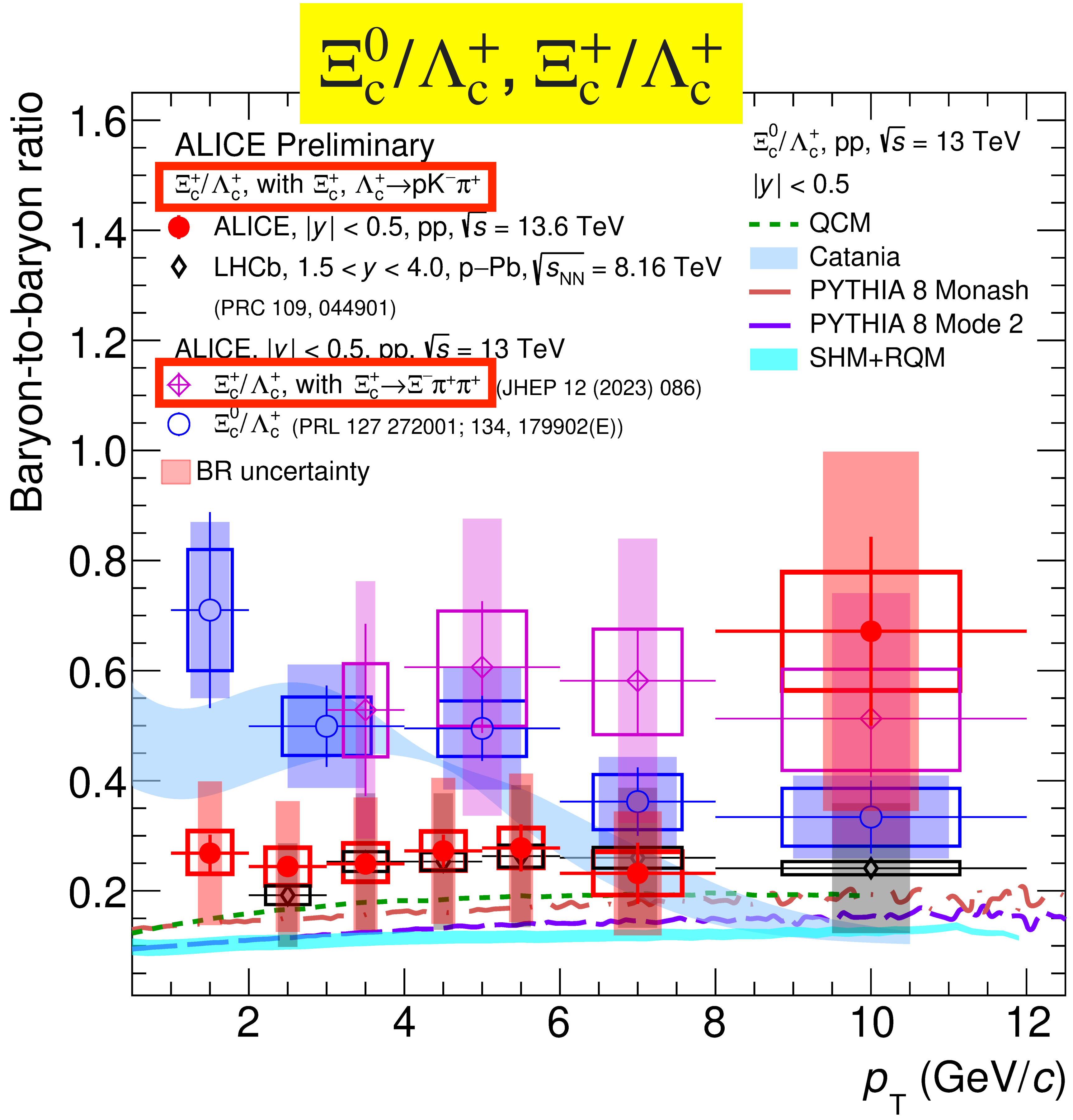
Catania works better

- Coalescence in pp collisions
- Assume a thermalised QGP-like system

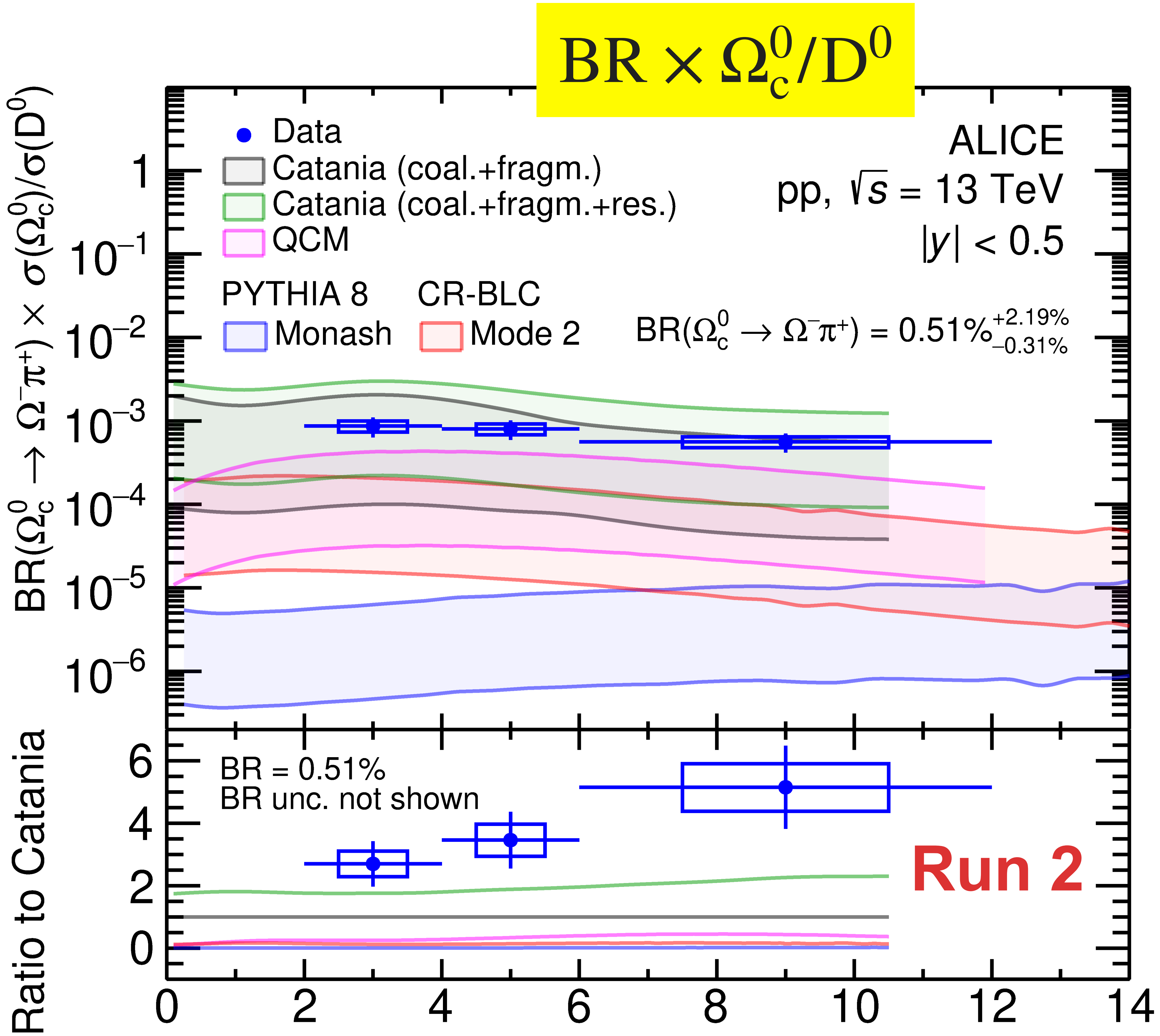
Non-prompt Λ_c^+/D^0

- Beauty, charm, and strange hadrons show a similar p_T trend

Hadronisation: HF particle ratios in pp collisions



ALI-PREL-621326



ALI-PUB-561515

PLB 846 (2023) 137625

- Ξ_c^0/Λ_c^+ consistent with Ξ_c^+/Λ_c^+ within large BR uncertainties
- The role of strangeness in HF hadronisation might be a challenge to theory

PYTHIA 8 Monash: *Eur.Phys.J.C 74 (2014) 3024*
PYTHIA 8 CR Mode: *JHEP 08 (2015) 003*
Catania: *Phys.Lett.B 821 (2021) 136622*
SHM: *Phys.Lett.B 795 (2019) 117-121*
RQM: *Phys.Rev.D 84 (2011) 014025*
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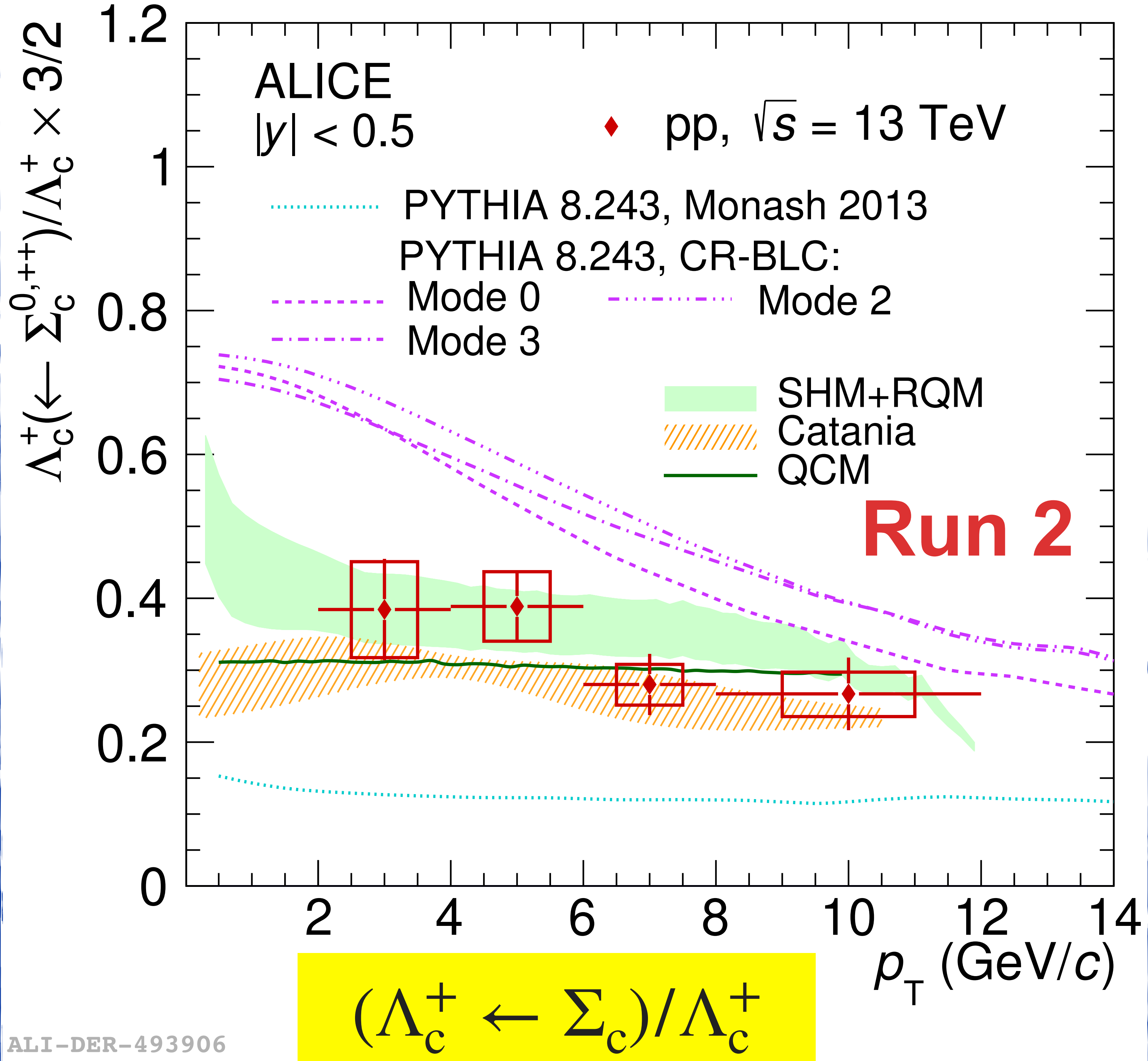
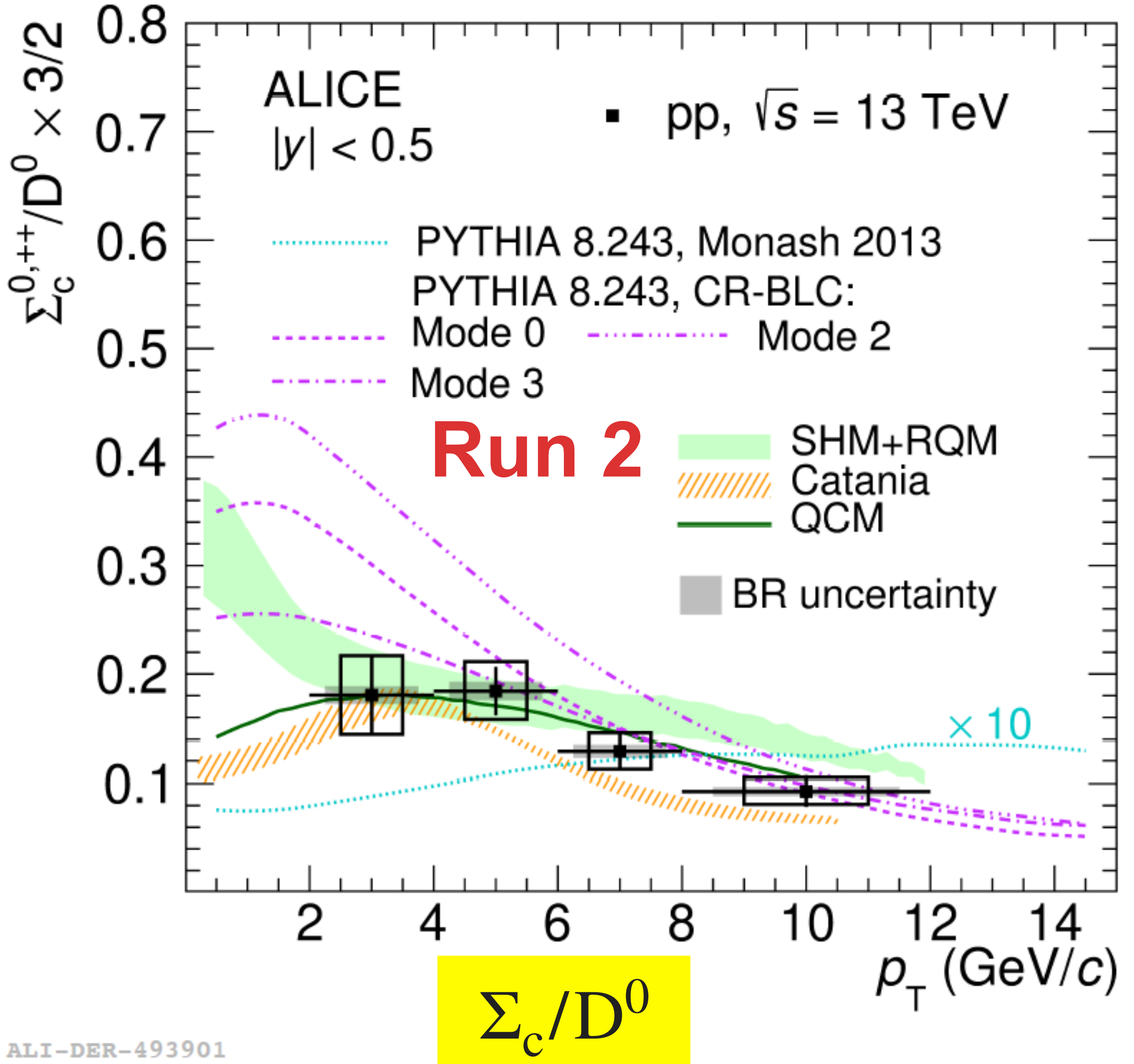
Hadronisation: higher mass particles decay



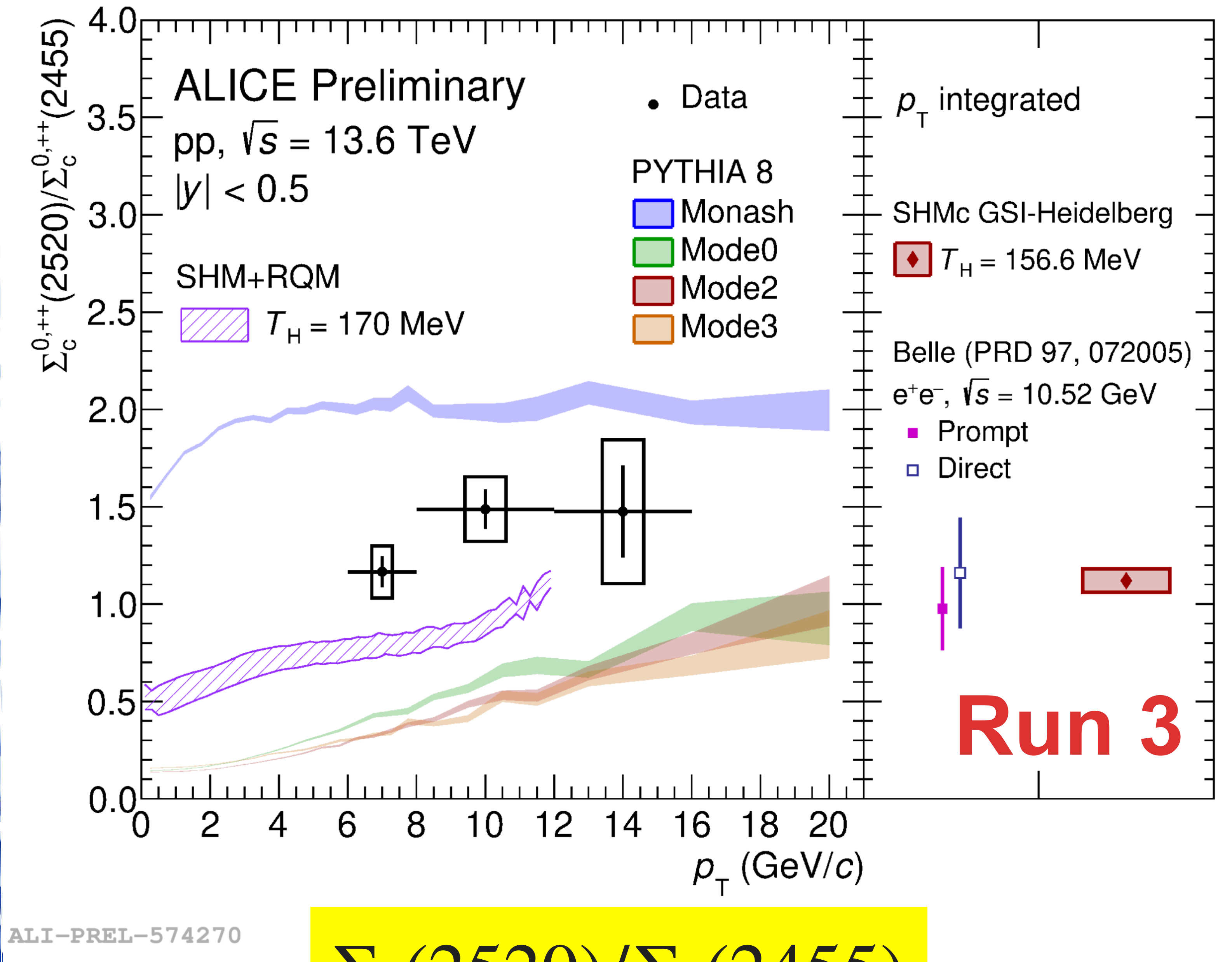
$(\Lambda_c^+ \leftarrow \Sigma_c)/\Lambda_c^+$

- ~40% Λ_c^+ from $\Sigma_c^{0,+,++}$ decays contribution, only partially explain Λ_c^+/D^0 enhancement



Σ_c/D^0

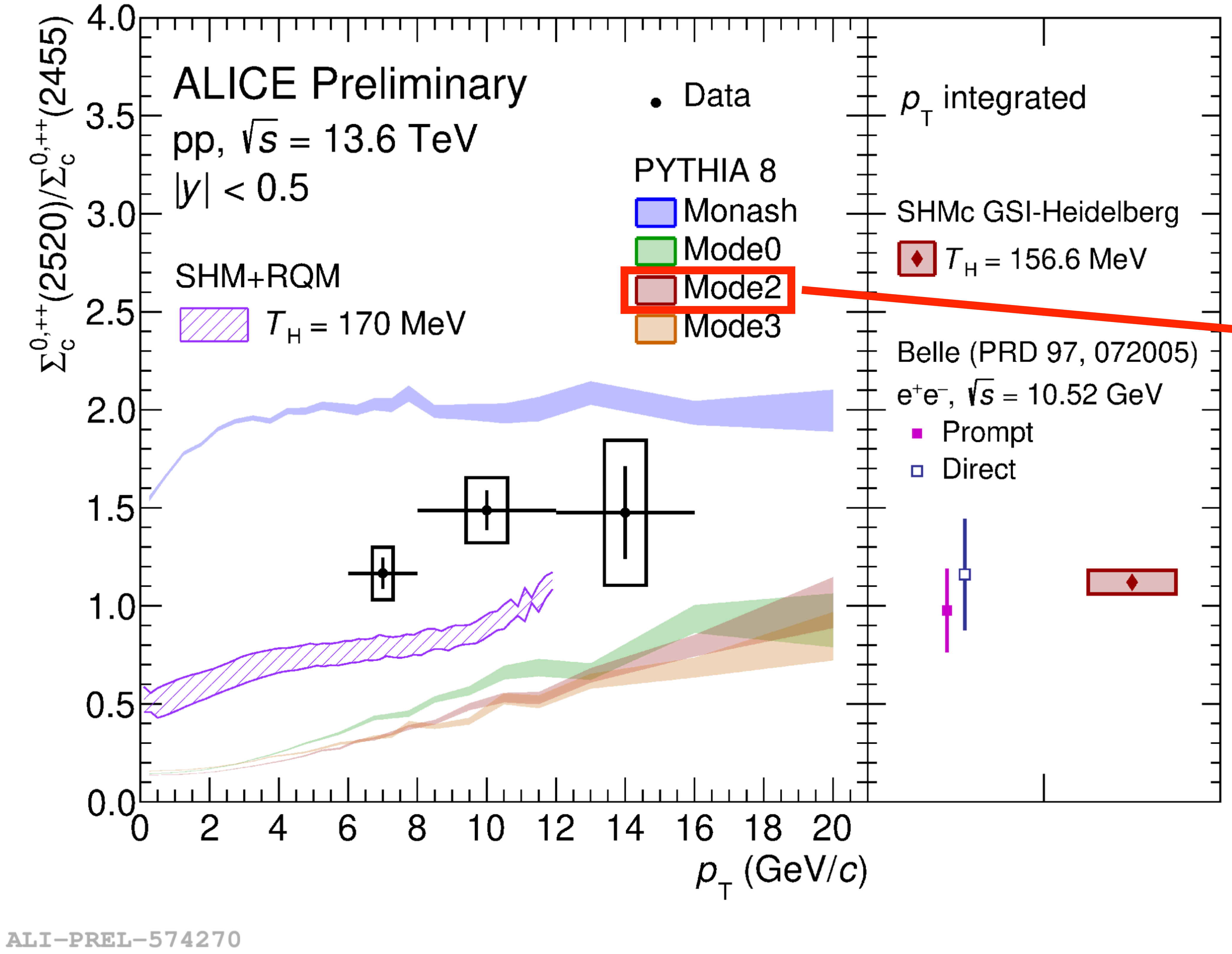
- Described by PYTHIA 8 CR, Catania, QCM and SHM+RQM



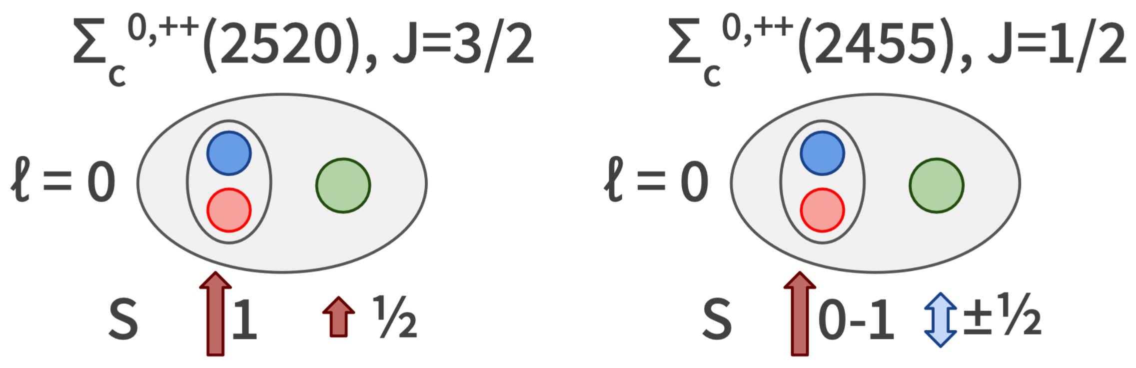
$\Sigma_c(2520)/\Sigma_c(2455)$

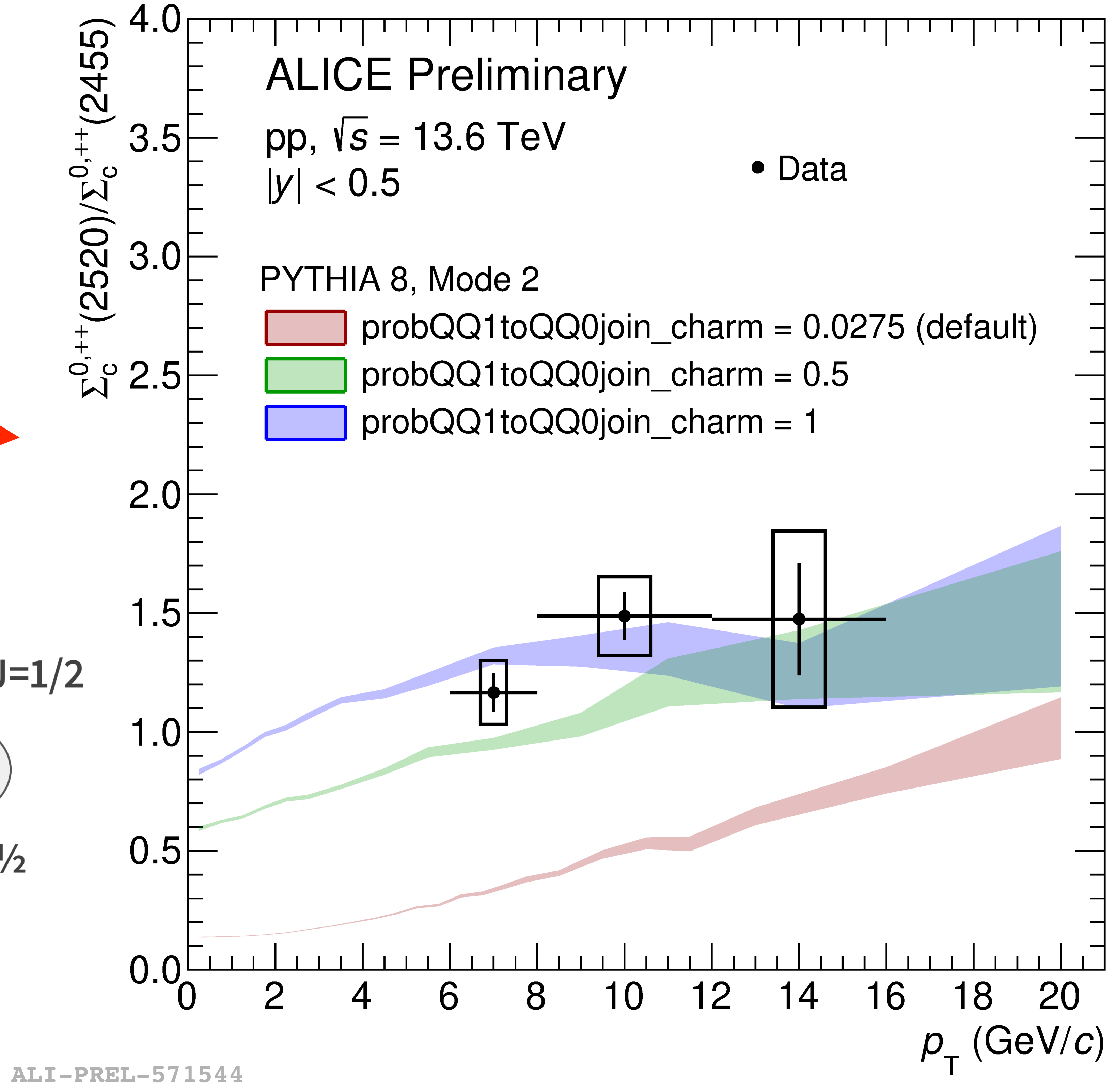
- Ratios between two $\Sigma_c^{0,++}$ states consistent with p_T integrated result from e^+e^- collisions
- Overestimated by PYTHIA 8 Monash, underestimated by CR and SHM+RQM

Hadronisation: higher mass particles decay



tune diquark spin component

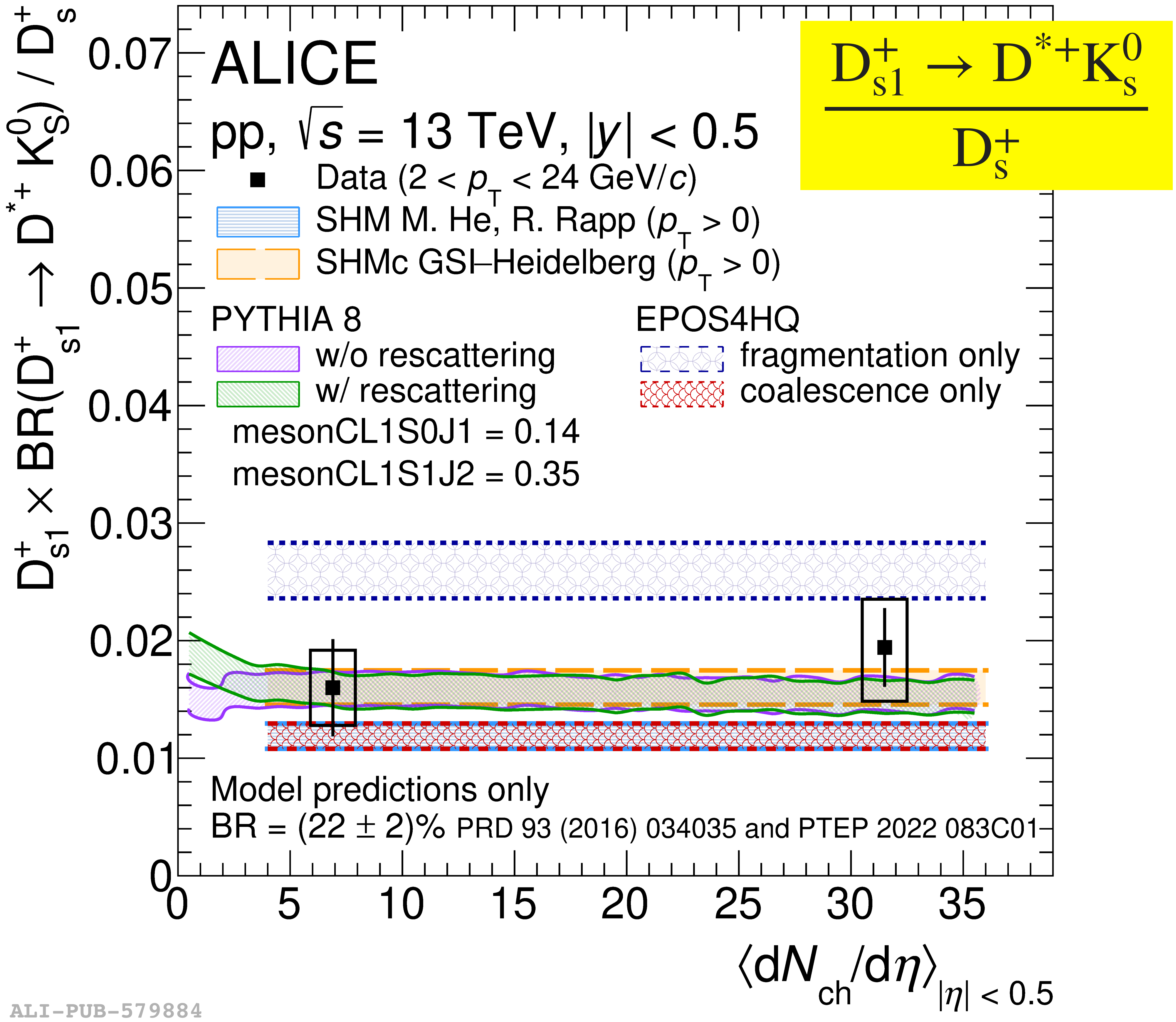


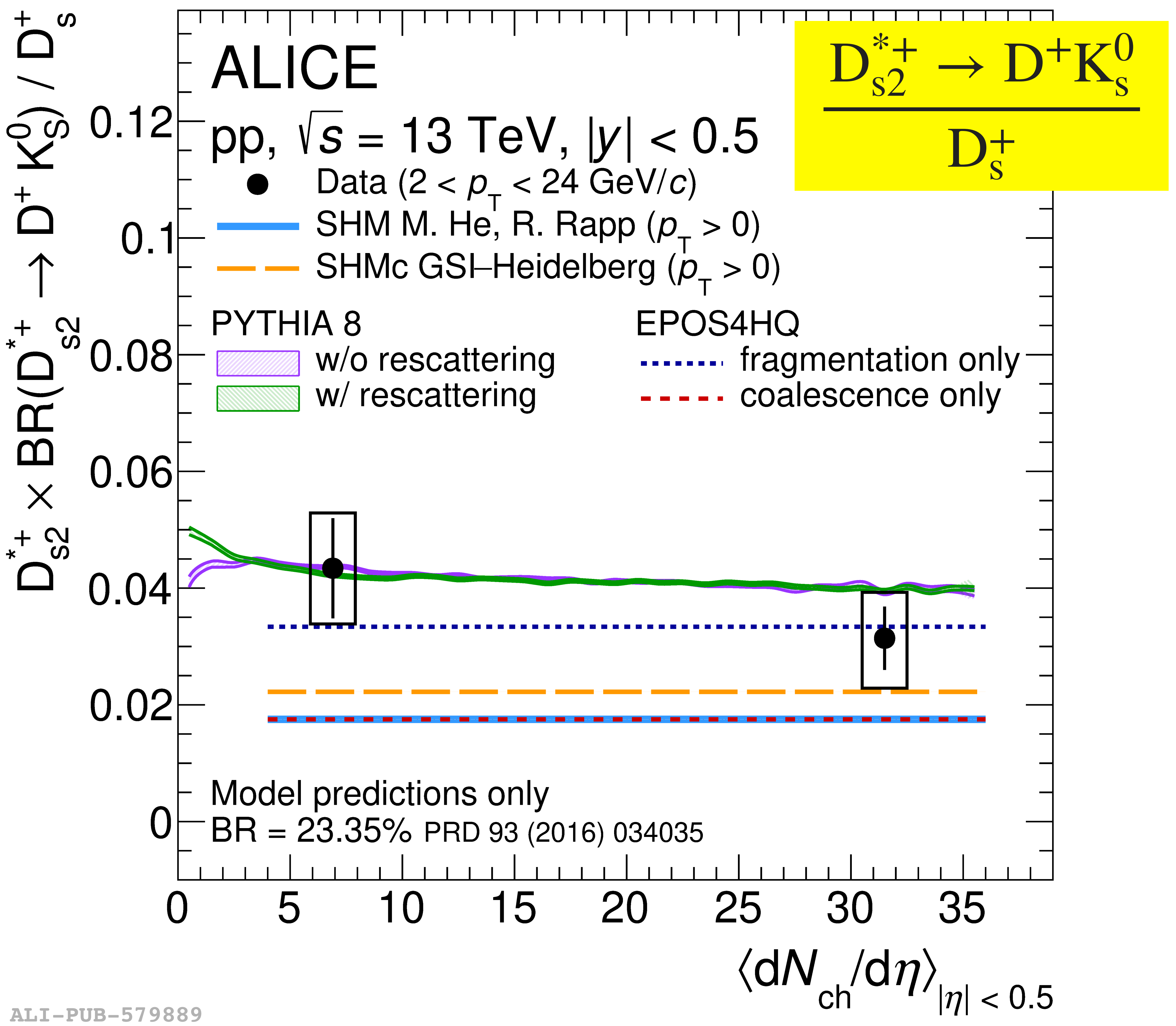


- PYTHIA: baryons are formed mainly via diquarks binding with other quarks
- probQQ1toQQ0join: probability produce spin 1 diquarks relative to spin 0 in junctions
- $\Sigma_c^{0,++}(2520)/\Sigma_c^{0,++}(2455)$ ratio can constrain model parameters

Hadronisation: resonances decay

Phys.Rev.D 111 (2025) 112005



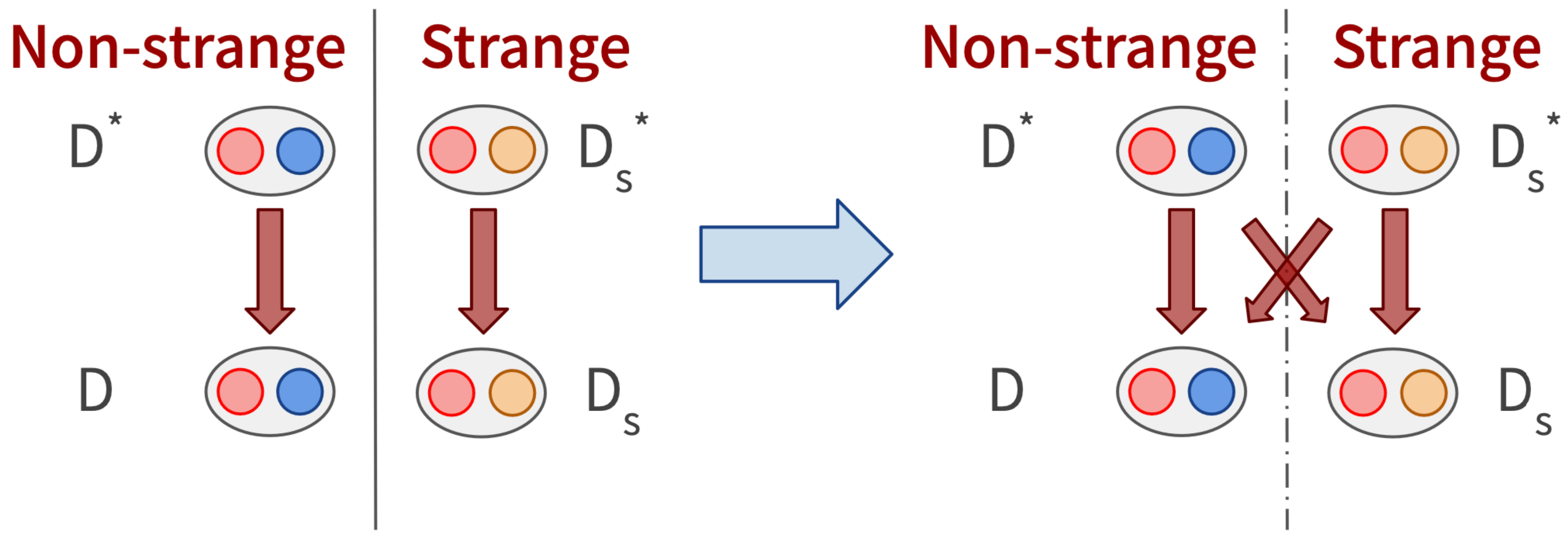


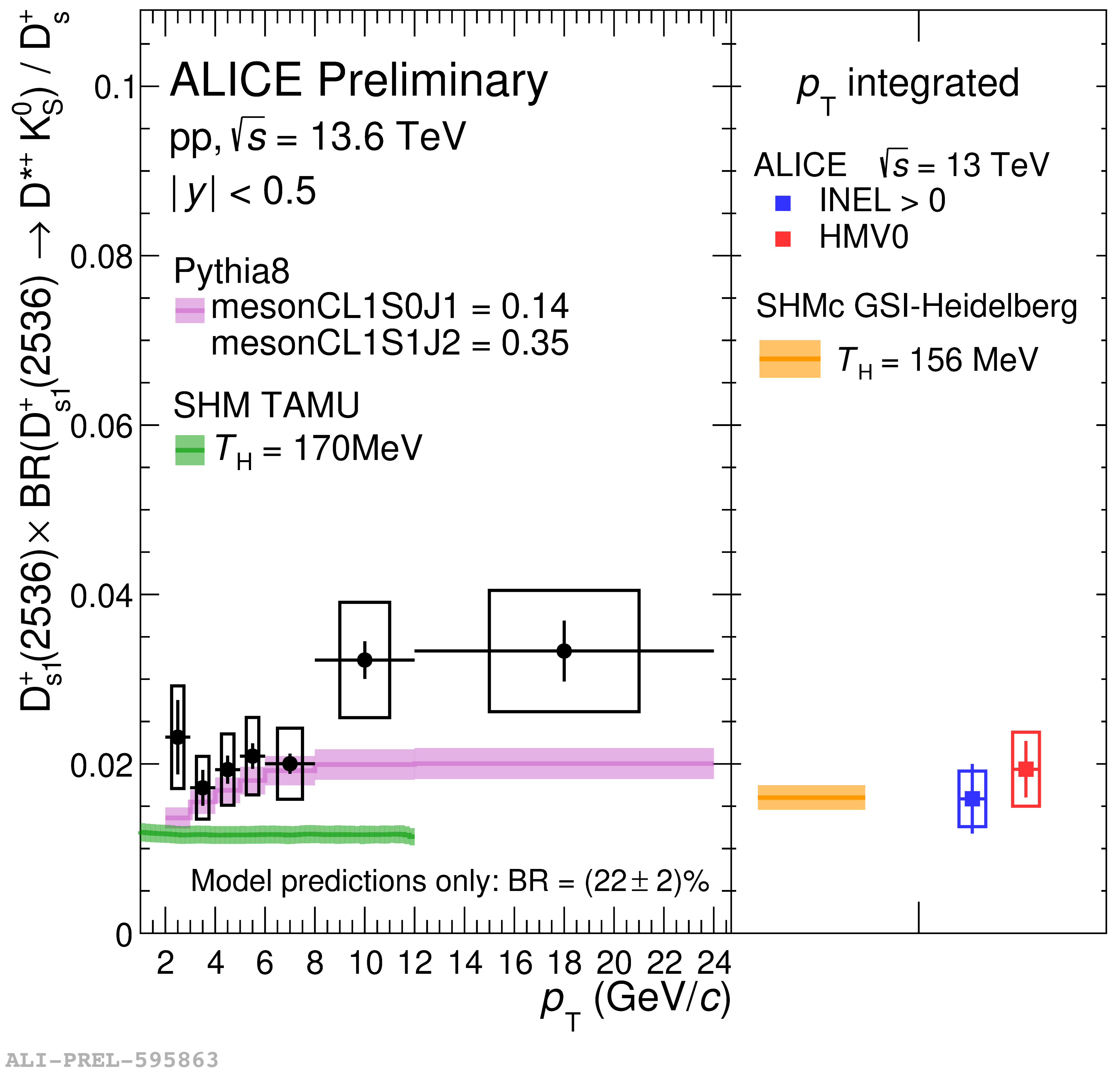
- D_{s1}^{+}/D_{s}^{+} and D_{s2}^{*+}/D_{s}^{+} ratios flat vs. charged-particle multiplicity, as ground-state D-meson ratios
- Multiplicity trend described by SHM, SHMc, EPOS4HQ models and by PYTHIA 8 calculations

Hadronisation: resonances decay

- $D_{s1}^{+}(2536) \rightarrow D^{*+}K_{s}^{0}$, $D_{s2}^{*+}(2573) \rightarrow D^{+}K_{s}^{0}$
  - Strange excited states decaying to non-strange ground state
- Inclusion of these states in model prediction can effectively "dilute" the D_{s}^{+}/D^{+} ratio
  - Could flatten models where excited strange D mesons only decay to D_{s}^{+} mesons

- High-mass resonance states could play important role in the description of ground state heavy flavor



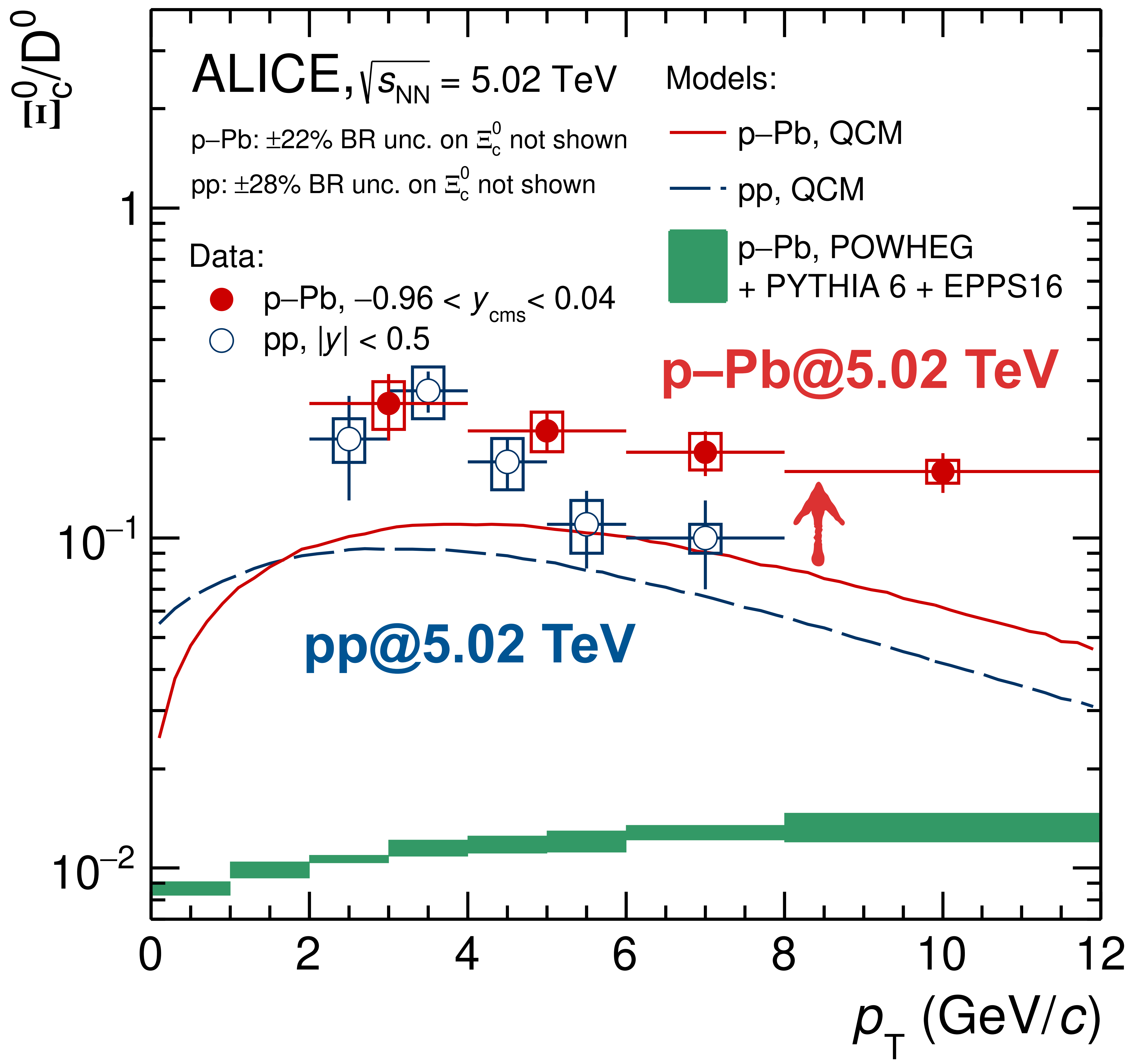


CR-BLC JHEP 08 (2015) 003

TAMU Phys.Lett.B 795 (2019) 117-121

GSI-Heidelberg JHEP 07 (2021) 035

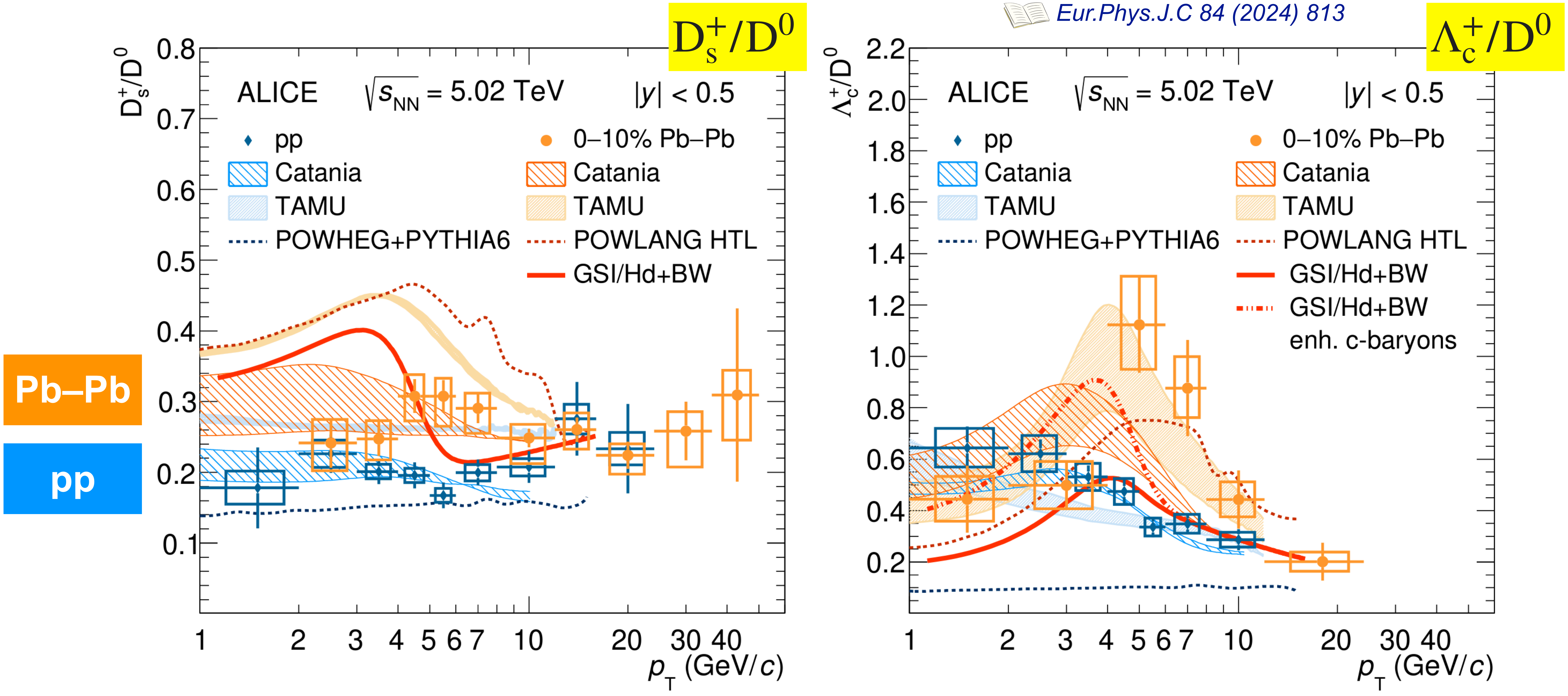
Hadronisation: Ξ_c^0/D^0 in p–Pb collisions



EPJC85(2025)86

- Hint of enhancement at high p_T in p–Pb w.r.t. pp collisions
- Underestimated by QCM for both pp and p–Pb collisions

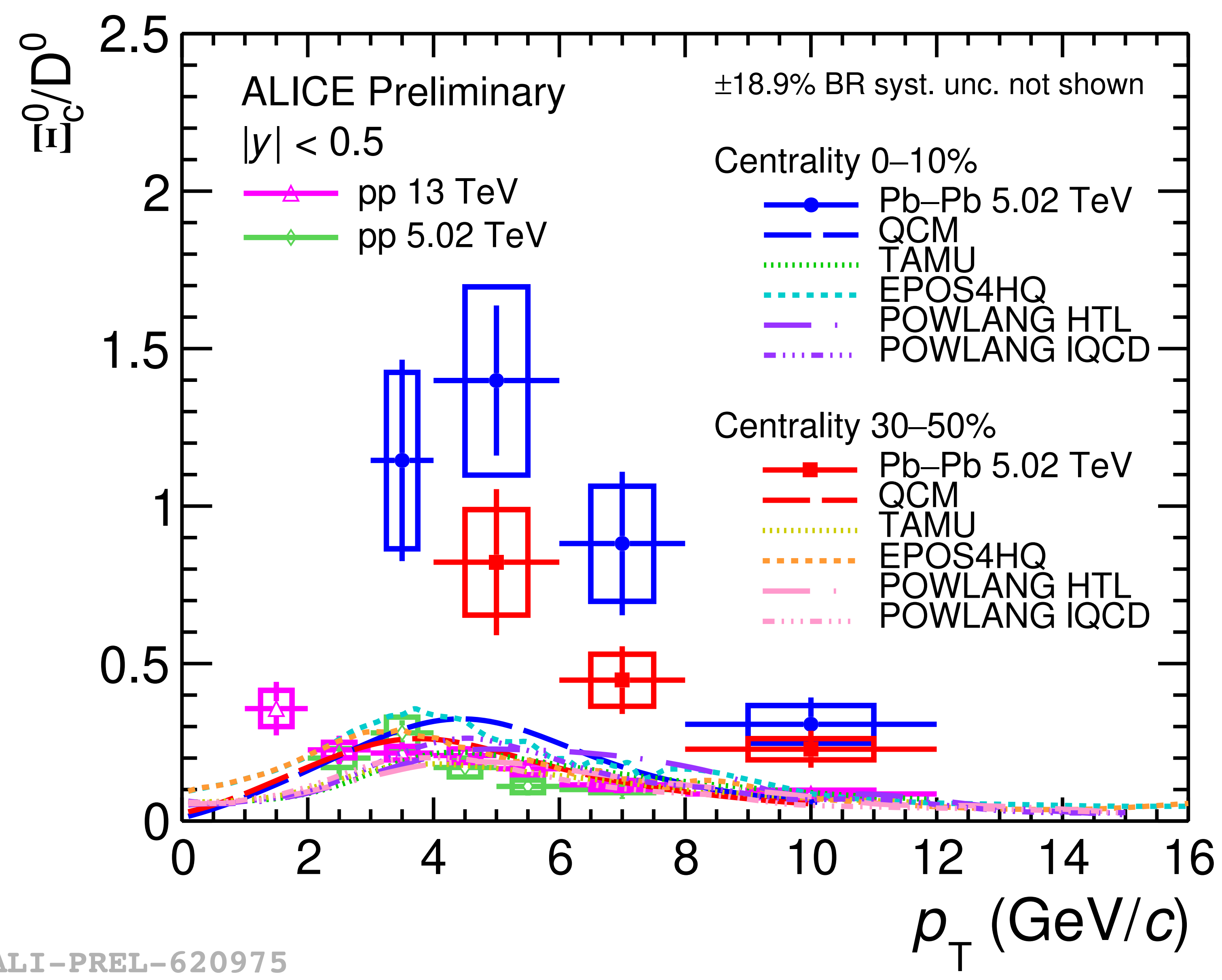
Hadronisation: large system



- D_s^+/D^0 and Λ_c^+/D^0 ratios enhanced at intermediate p_T in Pb–Pb w.r.t pp collisions
  - Described by models based on coalescence and radial flow mechanisms

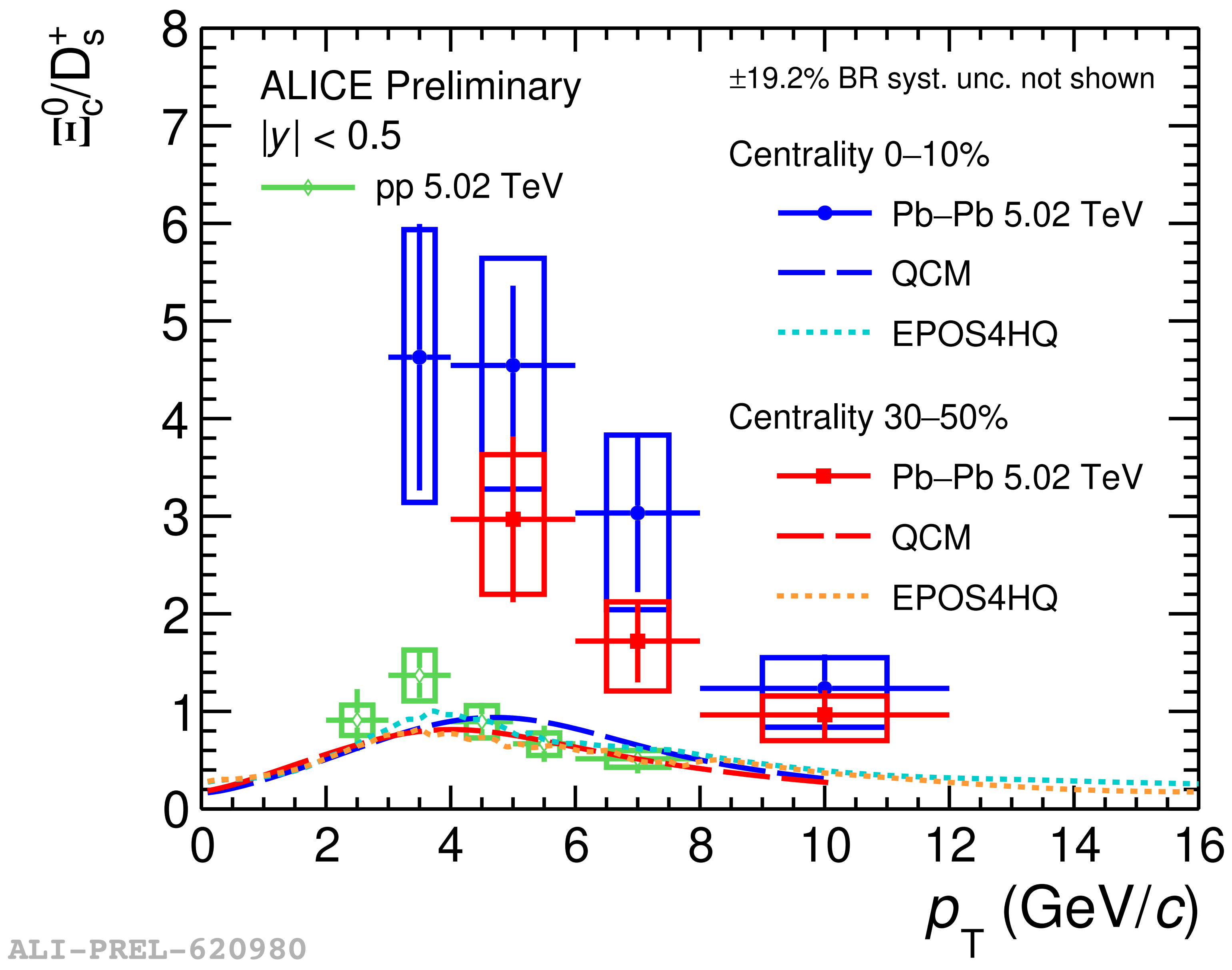
Hadronisation: large system

$\Xi_c^0(\mathrm{csd})/\mathrm{D}^0(\mathrm{c\bar{u}})$



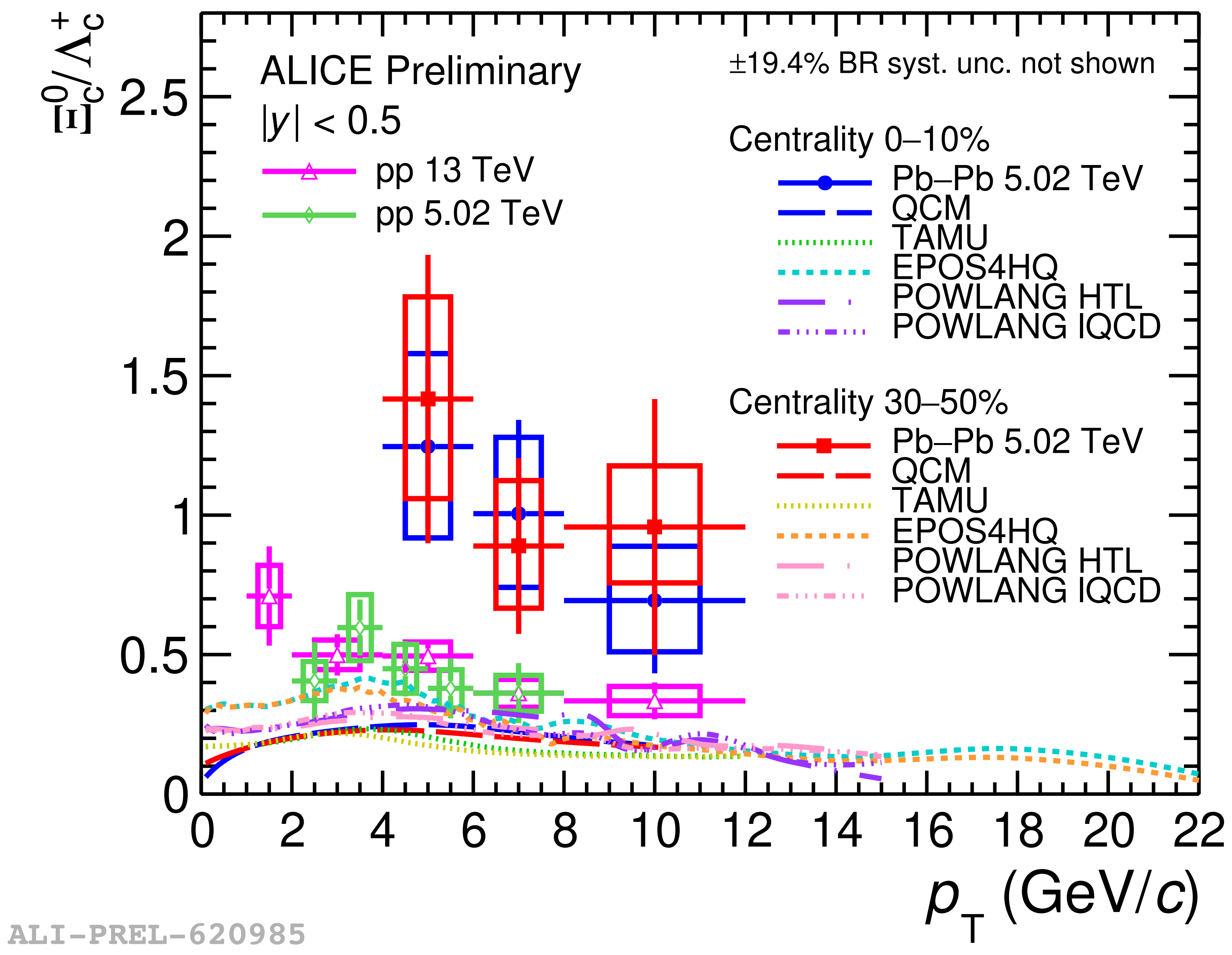
Baryon + Strangeness enhancement

$\Xi_c^0(\mathrm{csd})/\mathrm{D_s^+}(\mathrm{c\bar{s}})$



Baryon enhancement

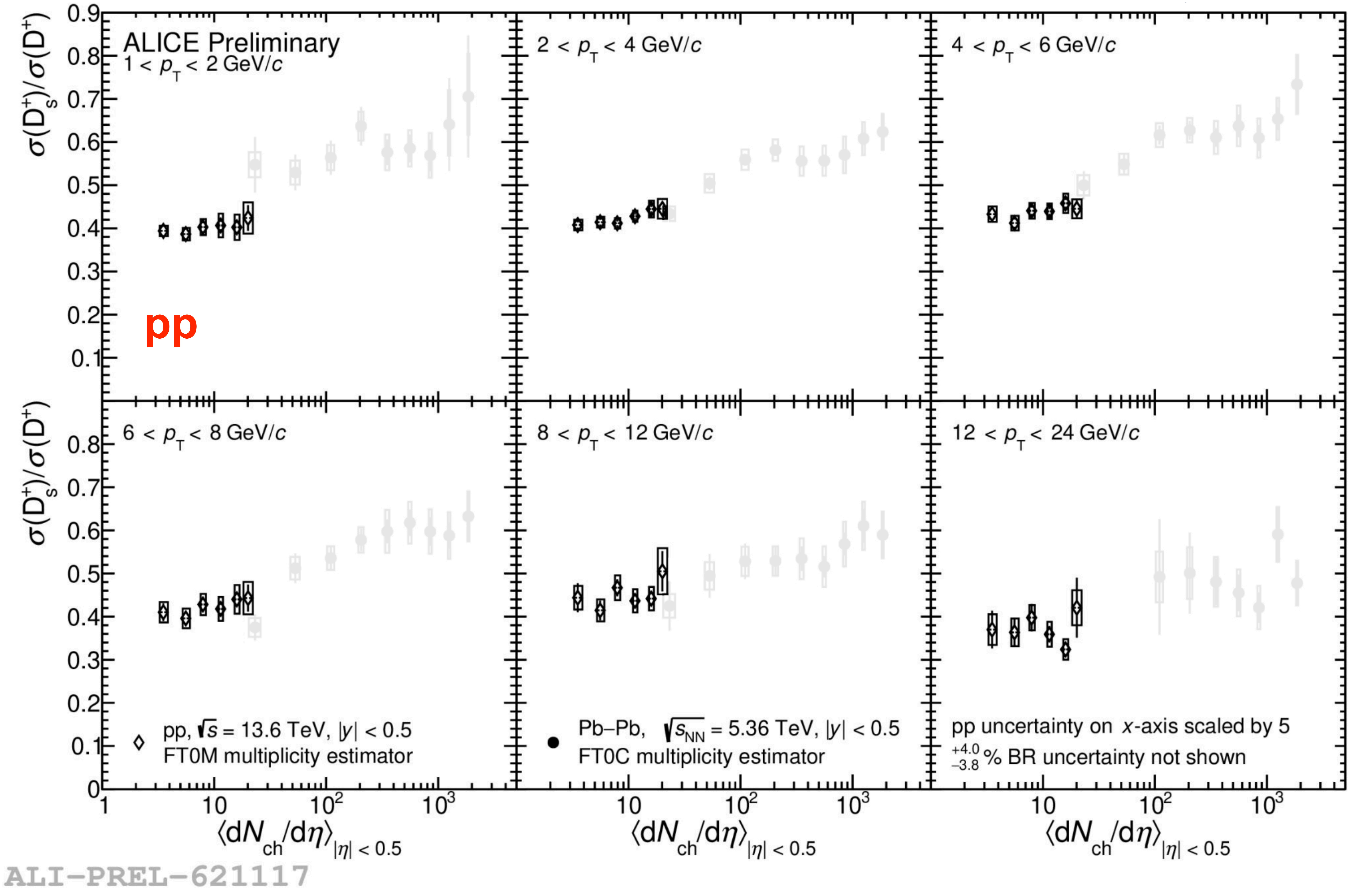
$\Xi_c^0(\mathrm{csd})/\Lambda_c^+(\mathrm{cdu})$



Strangeness enhancement

- Ξ_c^0/D^0, $\Xi_c^0/\mathrm{D_s^+}$ and Ξ_c^0/Λ_c^+ ratios enhanced at intermediate p_T in Pb–Pb w.r.t pp collisions
  - Underestimated by models based on coalescence and radial flow mechanisms

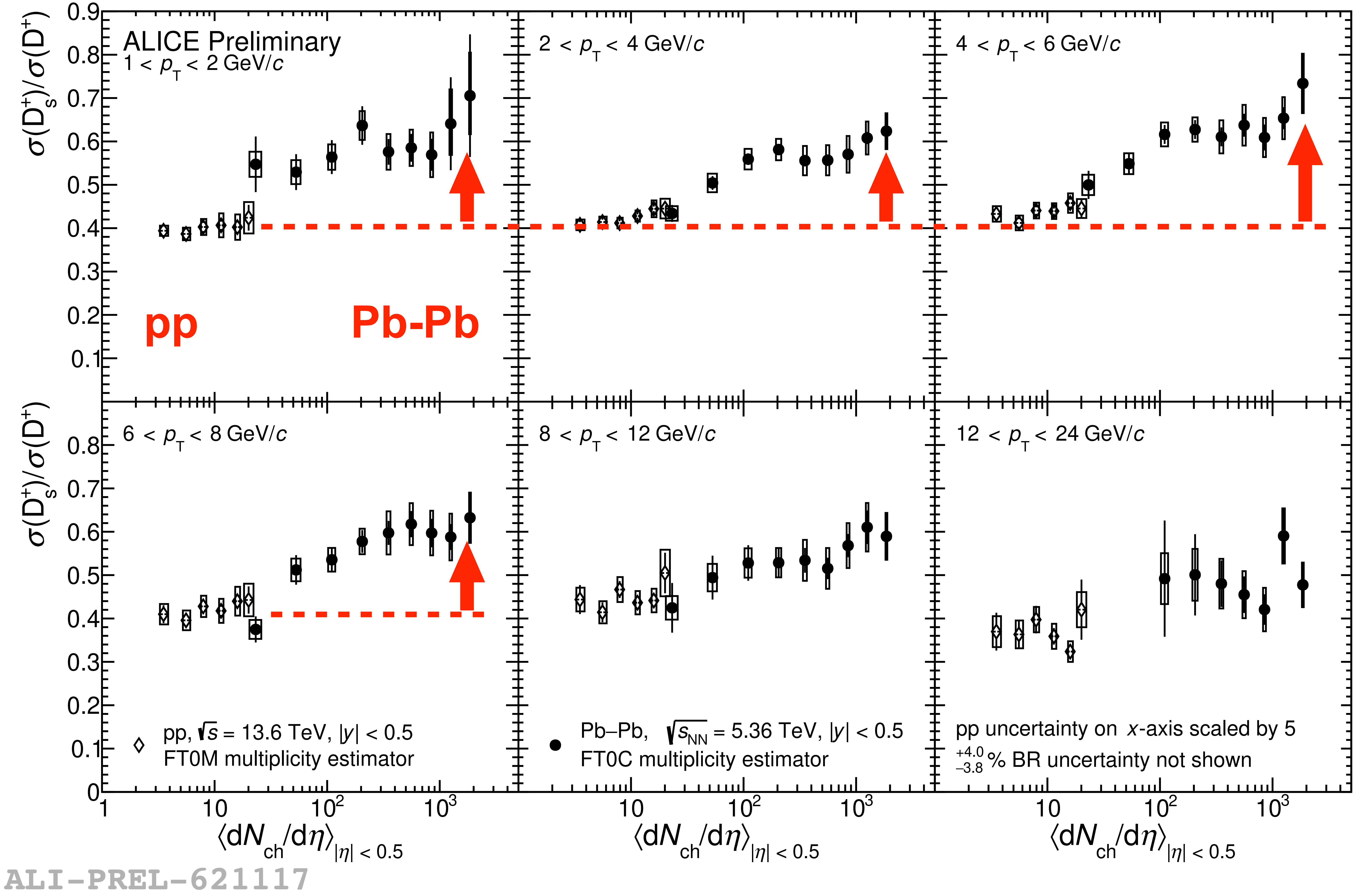
Hadronisation: system scan (by multiplicity)



D_s^+/D^+ in pp:

- No dependence on multiplicity
- No dependence on p_T
- As expected from hadronization via fragmentation

Hadronisation: system scan (by multiplicity)



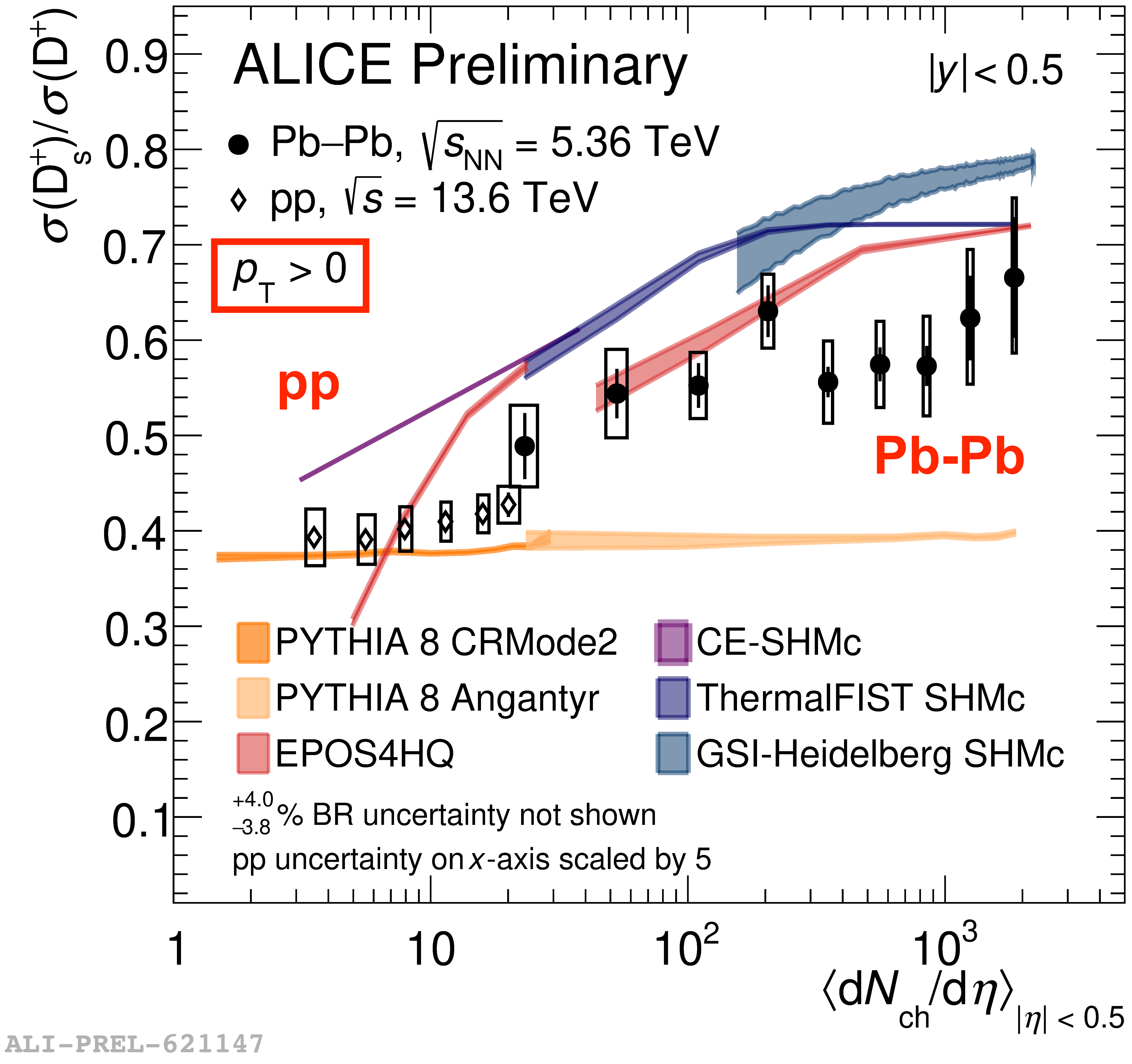
D_s^+/D^+ in pp:

- No dependence on multiplicity
- No dependence on p_T
- As expected from hadronization via fragmentation

D_s^+/D^+ in Pb-Pb:

- Increasing trend with multiplicity up to 8 GeV/c
- Similar to pp at high p_T
- Coalescence + strangeness enhancement?

Hadronisation: system scan (by multiplicity)



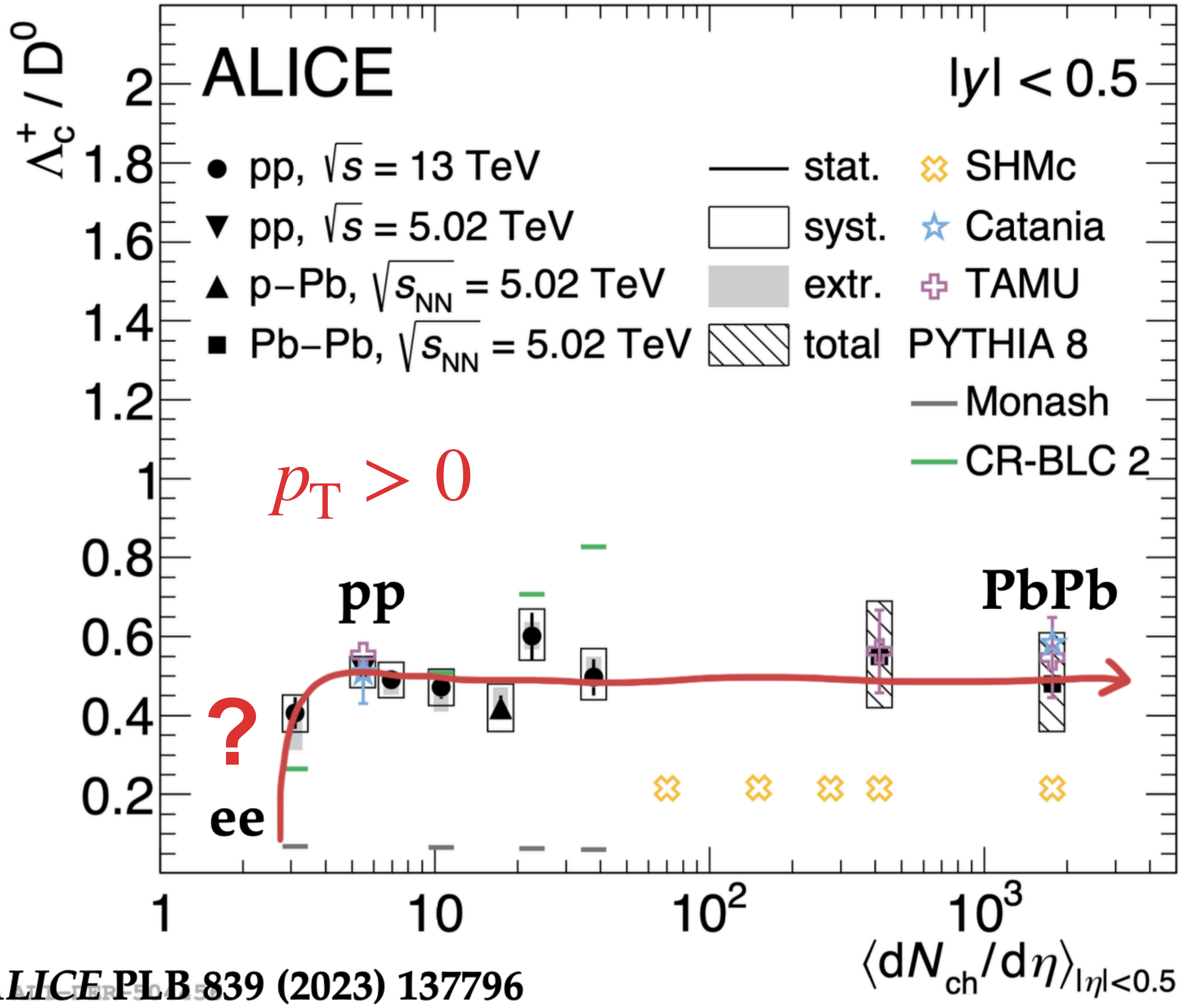
p_T integrated ratio increasing with multiplicity in Pb-Pb

- PYTHIA predicts a flat trend
  - Describe pp, not enough for Pb-Pb
- EPOS4HQ shows steep increase in pp, qualitatively describes increasing trend in Pb-Pb
- Statistical hadronization models expect increasing trend with multiplicity, but systematically overshoot measured ratios

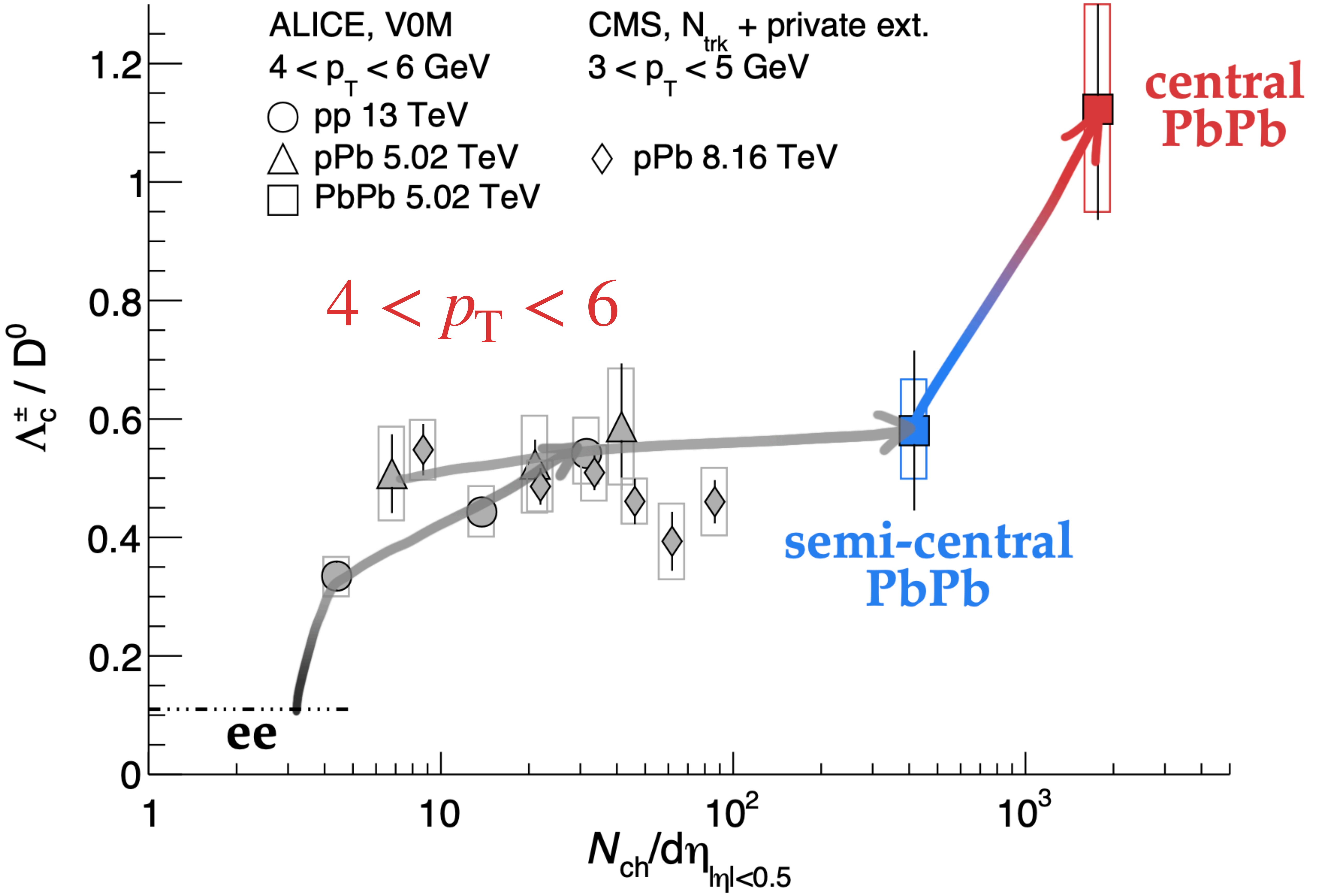
Missing piece in hadronization?

CR-BLC JHEP 08 (2015) 003
Angantyr JHEP 10 (2018) 134
EPOS4HQ PRC 110 (2024) 2, 024909
TAMU PLB 815 (2021) 136144
ThermalFIST PRC 100, 054906 (2019)
GSI-Heidelberg SHMc JHEP 07 (2021) 035

Hadronisation: system scan (by multiplicity)

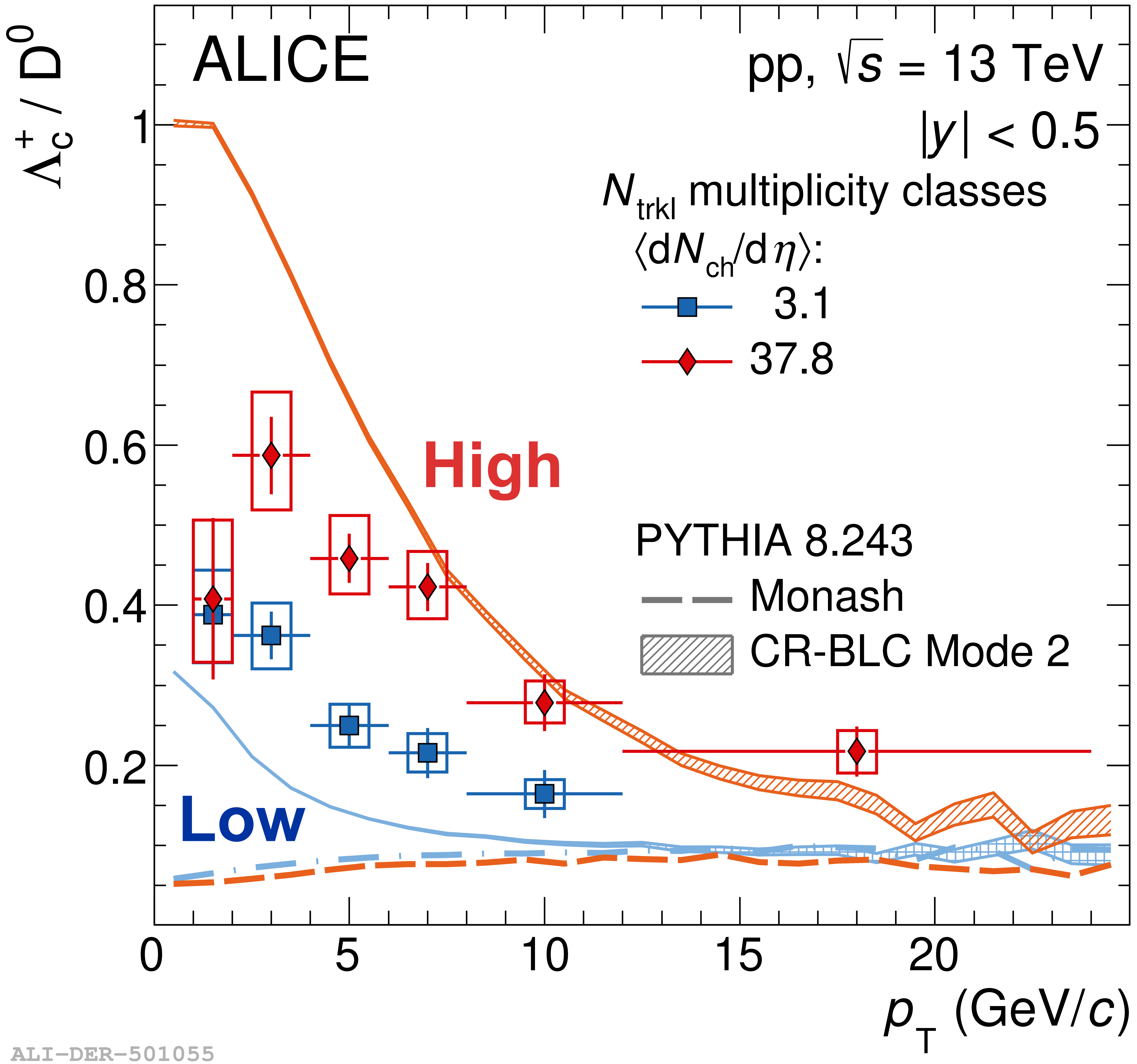


ALICE PLB 839 (2023) 137796



- No modification of overall production
- Difference between collision systems is due to momentum redistribution

Hadronisation: Λ_c^+ vs. p_T in different multiplicity

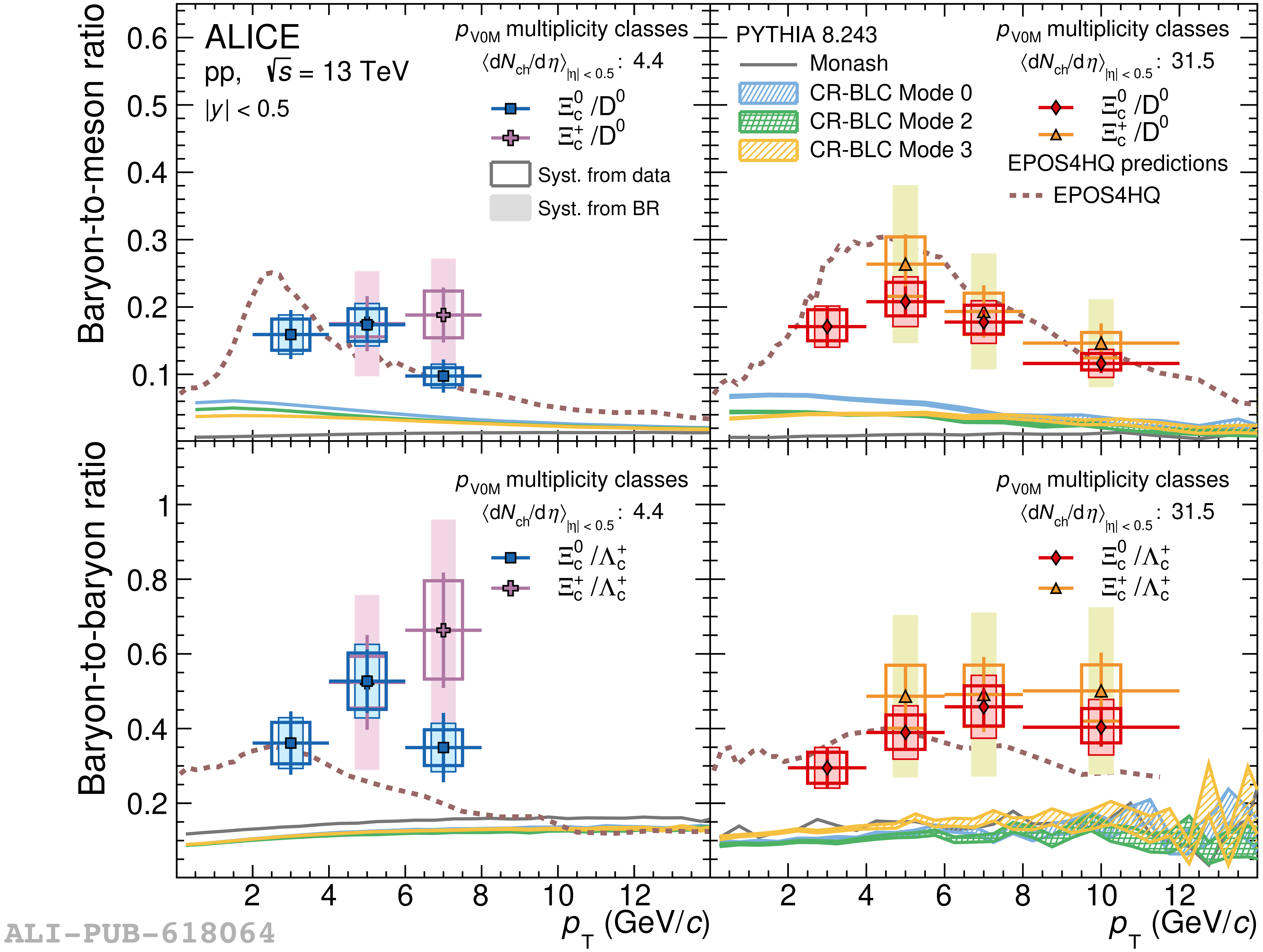


ALI-DER-501055

Λ_c^+/D^0 vs. p_T in different multiplicity

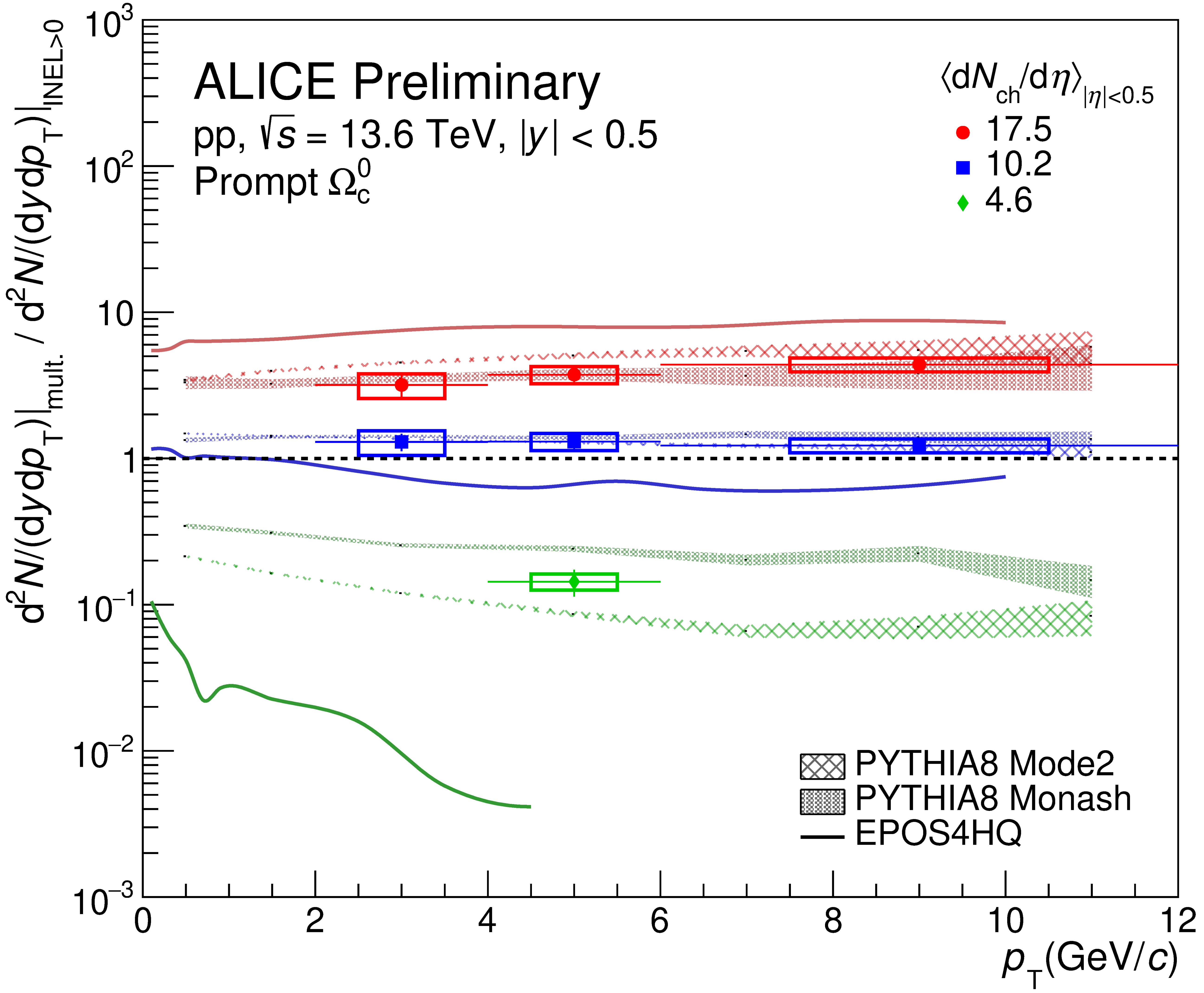
- Multiplicity-dependent enhancement with 5.3σ from lowest to highest multiplicity

Hadronisation: $\Xi_c^{0,+}$ vs. p_T in different multiplicity



- No significant multiplicity dependence for Ξ_c^0/D^0 and Ξ_c^0/Λ_c^+ within large uncertainties
- PYTHIA 8 CR largely underestimates the measurements

Hadronisation: Ω_c^0 vs. p_T in different multiplicity

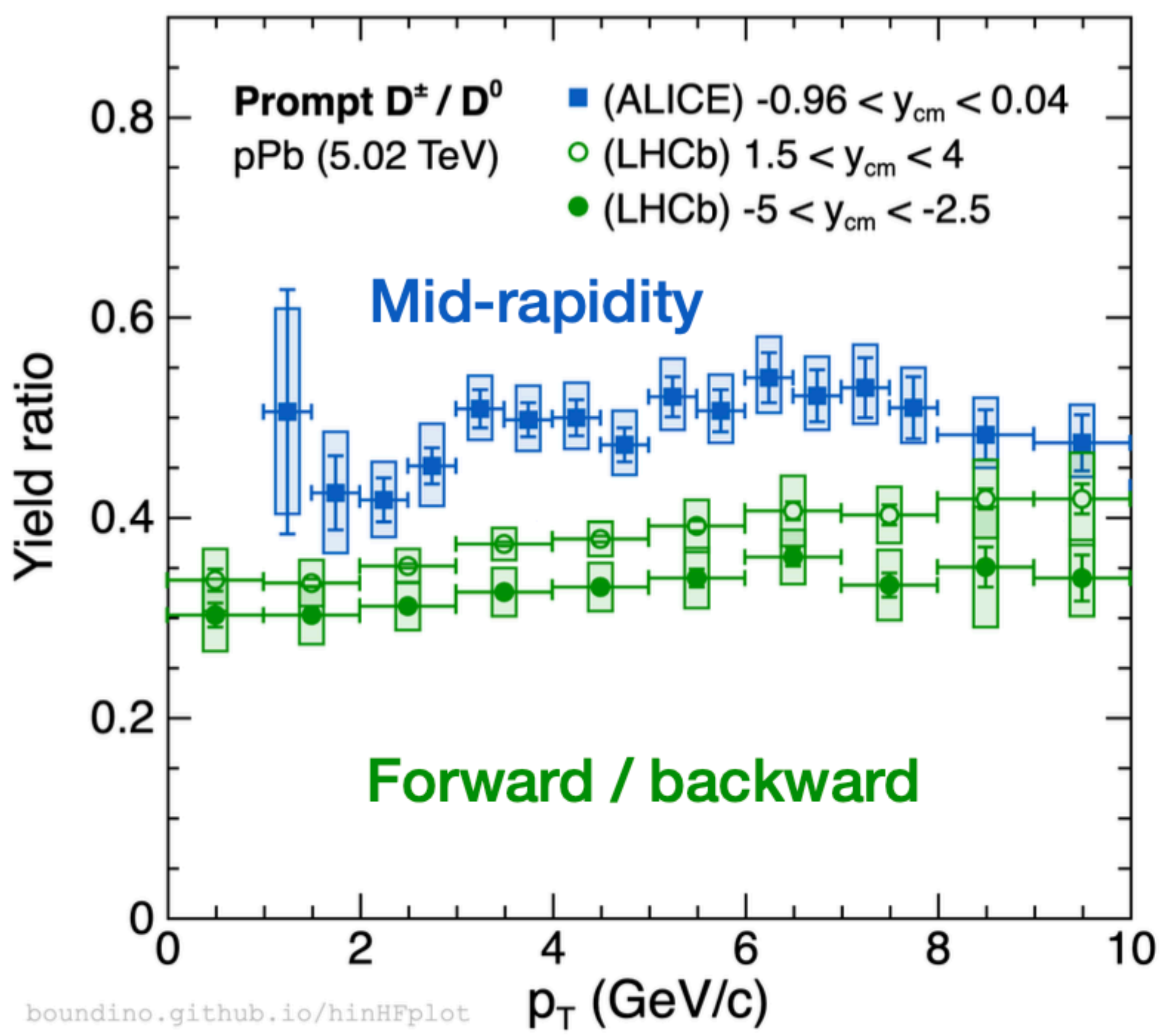


ALI-PREL-621365

- PYTHIA describe self-normalised ratios in high and intermediate mult., but some tension in the lowest mult.
- EPOS4HQ predicts a different trend of the Ω_c^0 production w.r.t. the measurement, in particular at low mult.

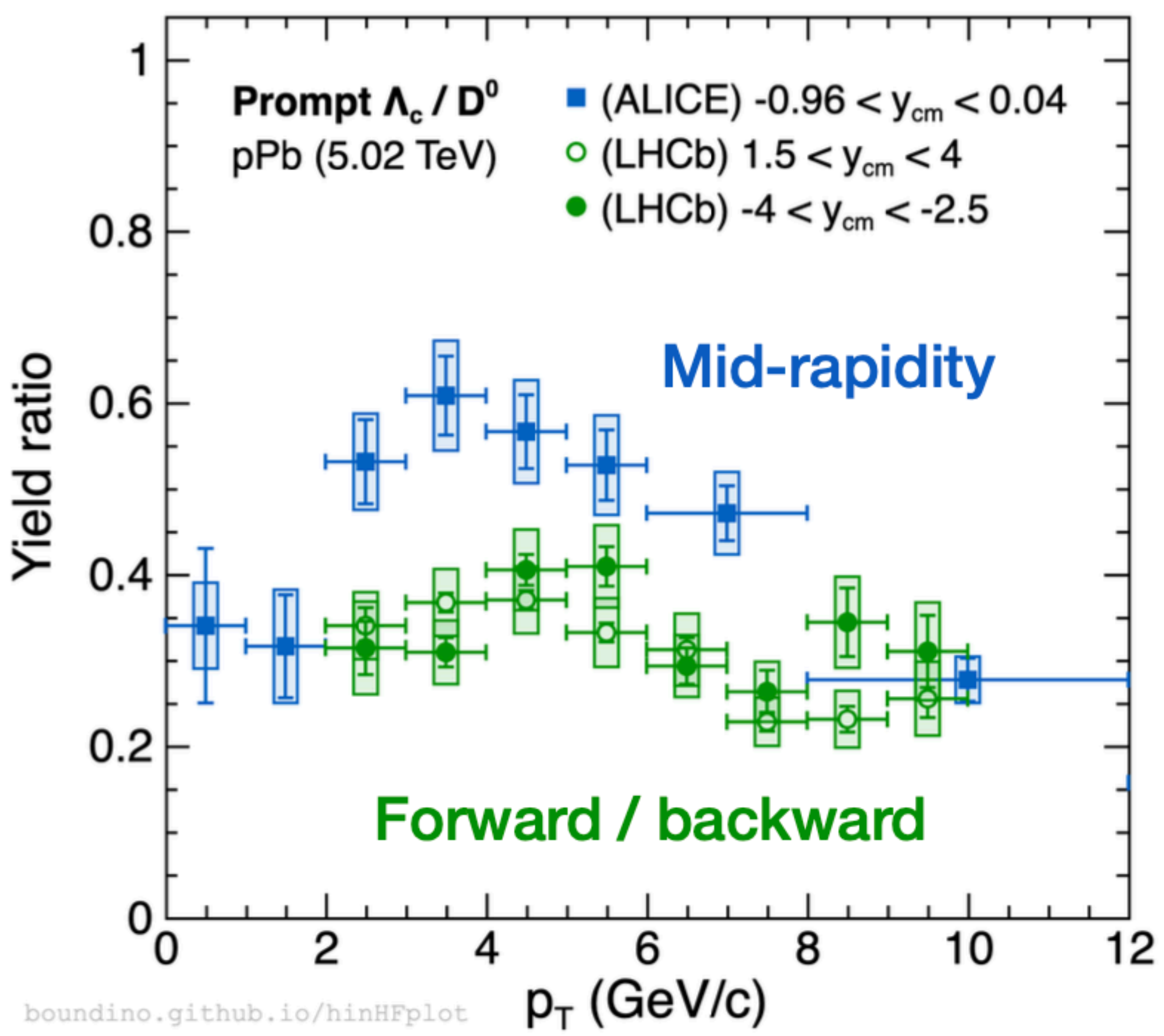
Hadronisation: rapidity dependence (more challenges)

D^+ ($c\bar{d}$) / D^0 ($c\bar{u}$)



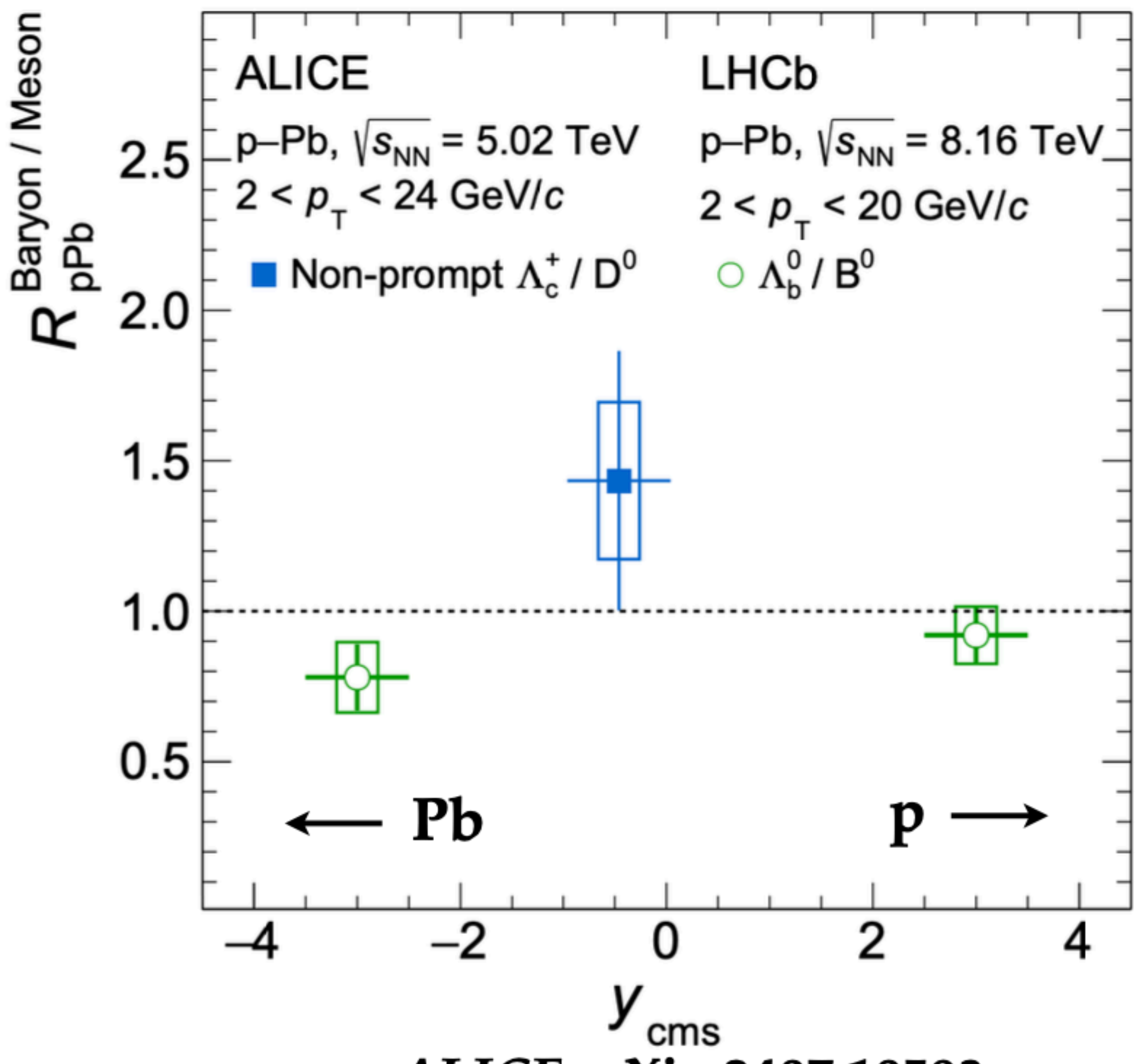
ALICE JHEP 12 (2019) 092
LHCb JHEP 01 (2024) 070

Λ_c (cud) / D^0 ($c\bar{u}$)



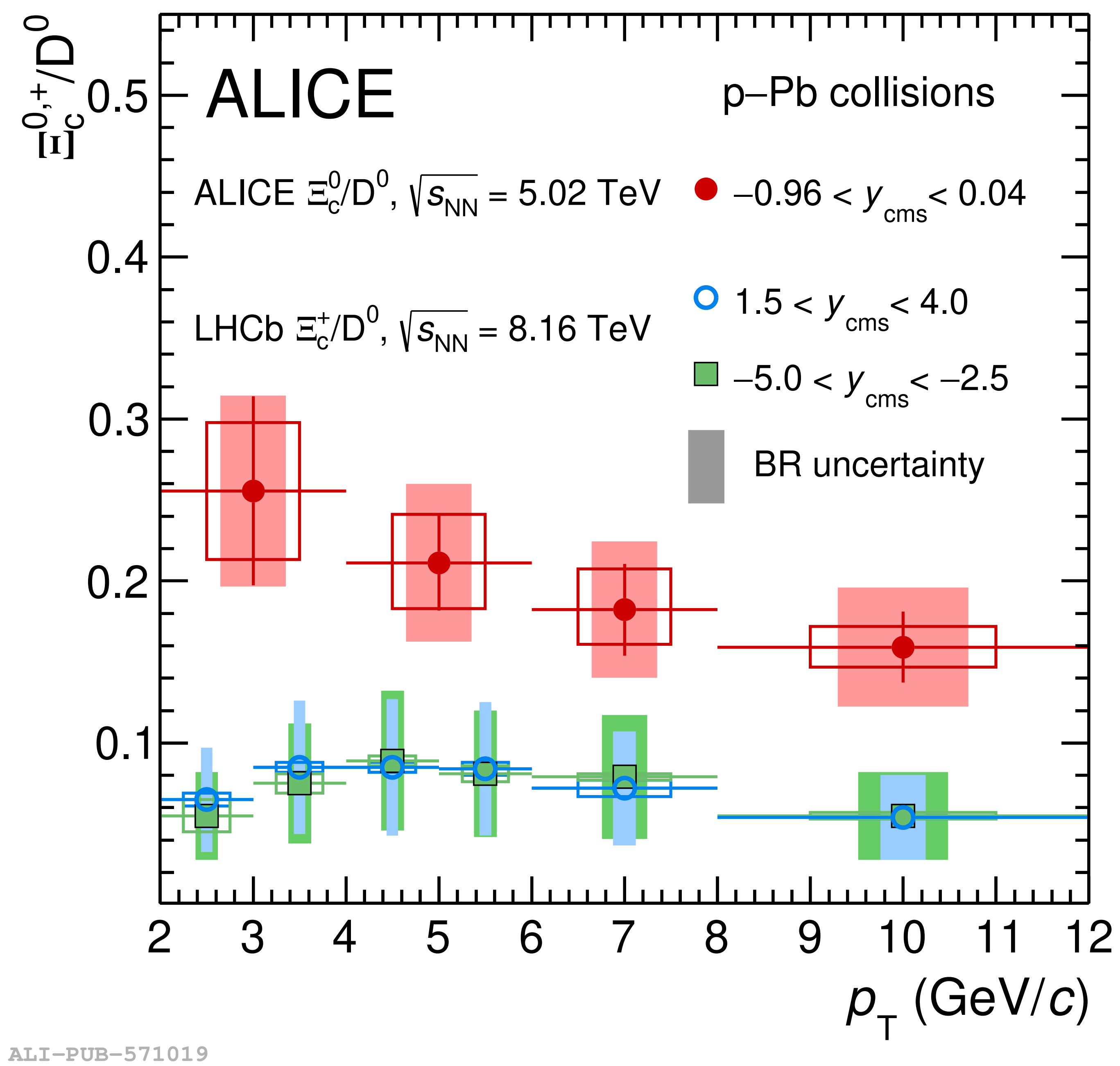
ALICE PRC 107 (2023) 064901
LHCb JHEP 02 (2019) 102

Λ_b (bud) / B^0 ($b\bar{d}$) double ratio



ALICE arXiv:2407.10593
LHCb PRD 99 (2019) 052011

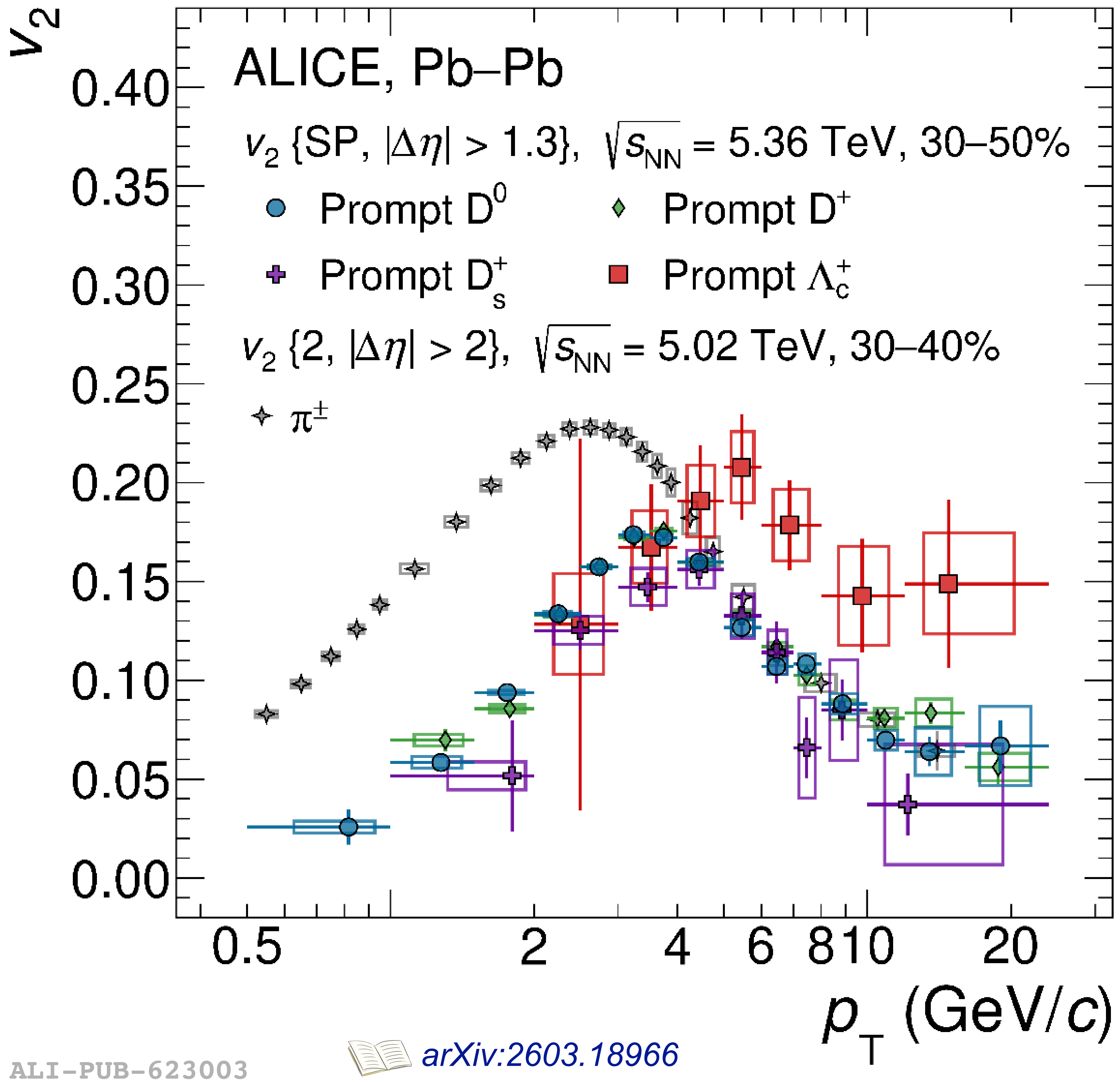
$\Xi_c^{0,+}/D^0$



EPJC85(2025)86

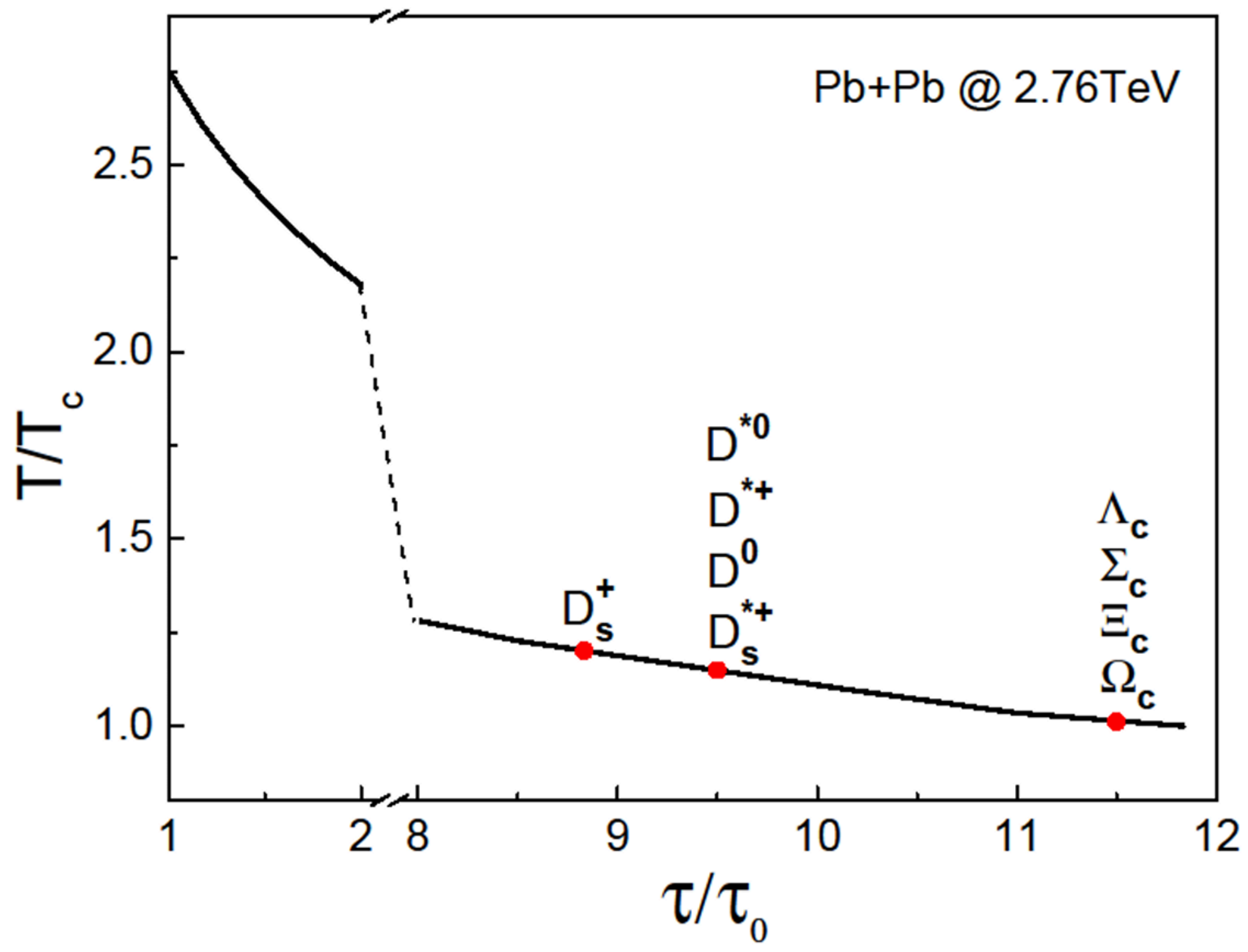
- Rapidity dependence in both meson and baryon, in both charm and beauty sectors
  - Models do not expect rapidity dependence

Collectivity: charm-hadron elliptic flow in Pb-Pb



arXiv:2603.18966

- Evidence of baryon-meson splitting in HF sector for $4 < p_T < 12$ GeV/c
- Effect of hadronization via coalescence + partonic origin of charm-hadron elliptic flow
- $v_2(D^0)$ and $v_2(D_s^+)$: 2.6σ deviation in $1 < p_T < 5$ GeV/c
  - Sequential coalescence ?



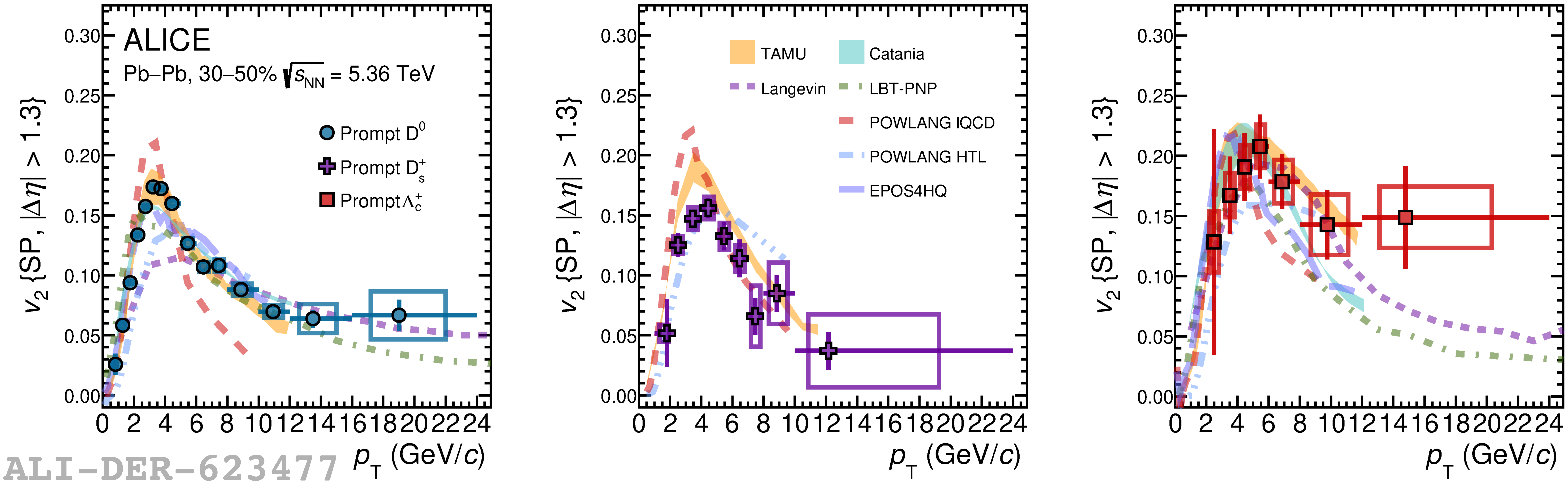
$\tau_{J/\psi} < \tau_{D_s} < \tau_{D^0} < \tau_{\Lambda_c} < \tau_{\pi,K,N}$

Pengfei Zhuang et al, Springer Proc.Phys. 250 (2020) 275-278

Collectivity: charm-hadron elliptic flow in Pb-Pb

TAMU: PRL 124 (2020) 042301
Catania: PRC 96 (2017) 045202
Langevin: EPJC 81 (2021) 1035

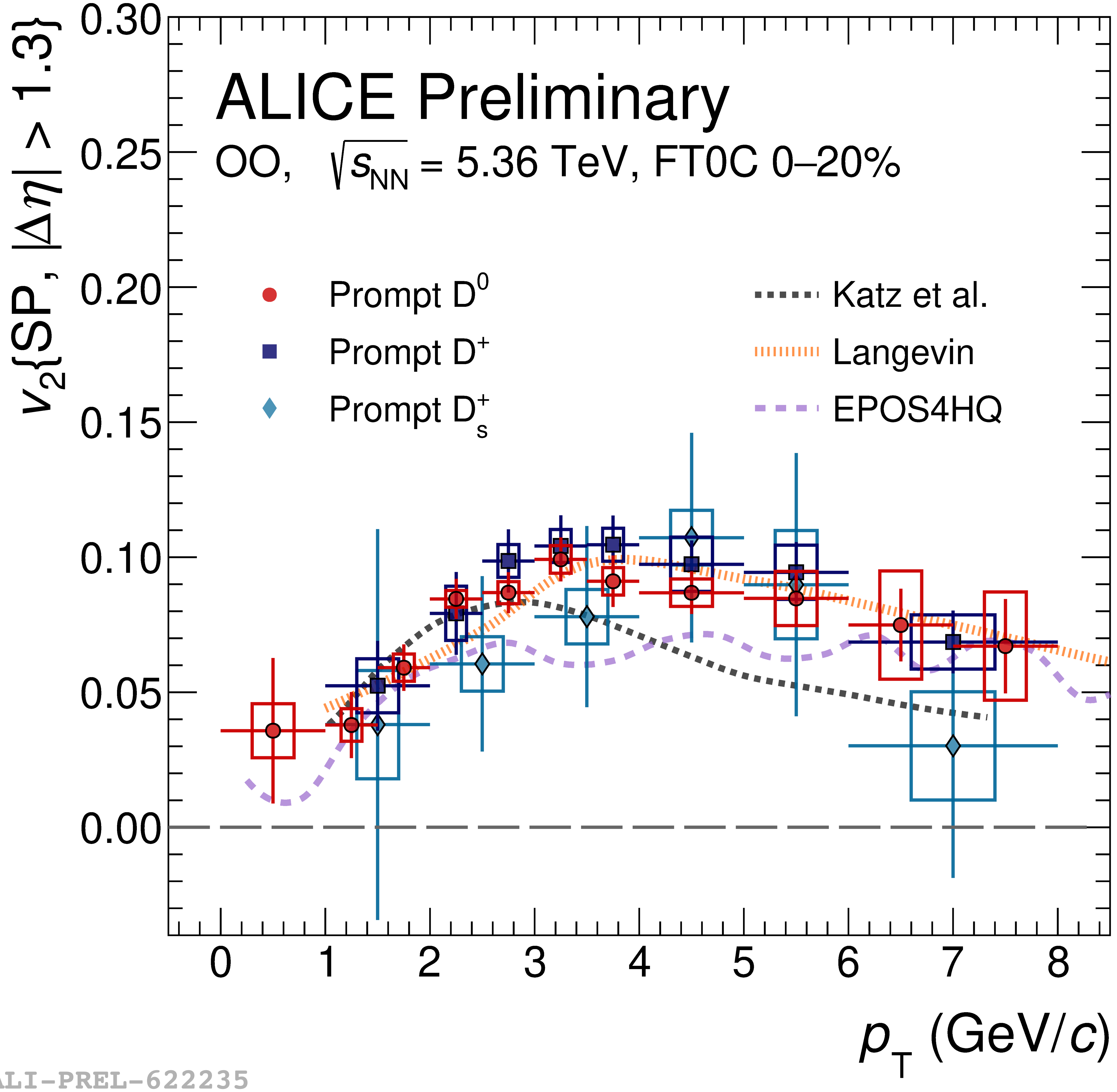
LBT-PNP: PLB 850 (2024) 138523
POWLANG: EPJC 82 (2022) 607
EPOS4HQ: J. Zhao et al. PRC 110 (2024) 024909



arXiv:2603.18966

- Precise charm-hadron elliptic-flow measurements challenge transport model predictions
  - TAMU provides the best quantitative description across the different charm-hadron species

Collectivity: D-meson elliptic flow in OO

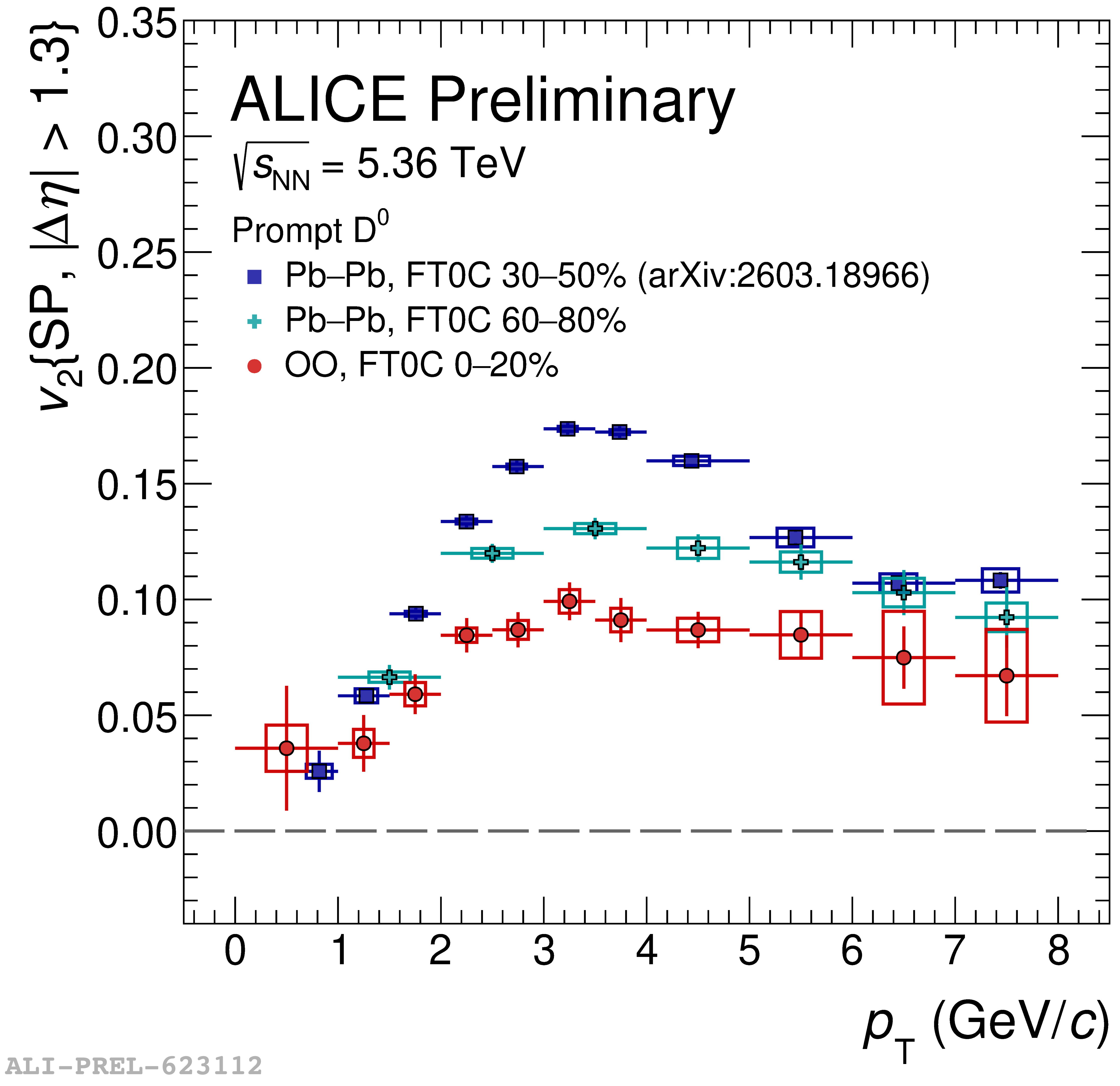


ALI-PREL-622235

- First observation of positive D-meson elliptic flow in central OO
  - originating from initial geometry
  - charm sensitive to the system collective motions
- Qualitatively described by transport models including QGP formation

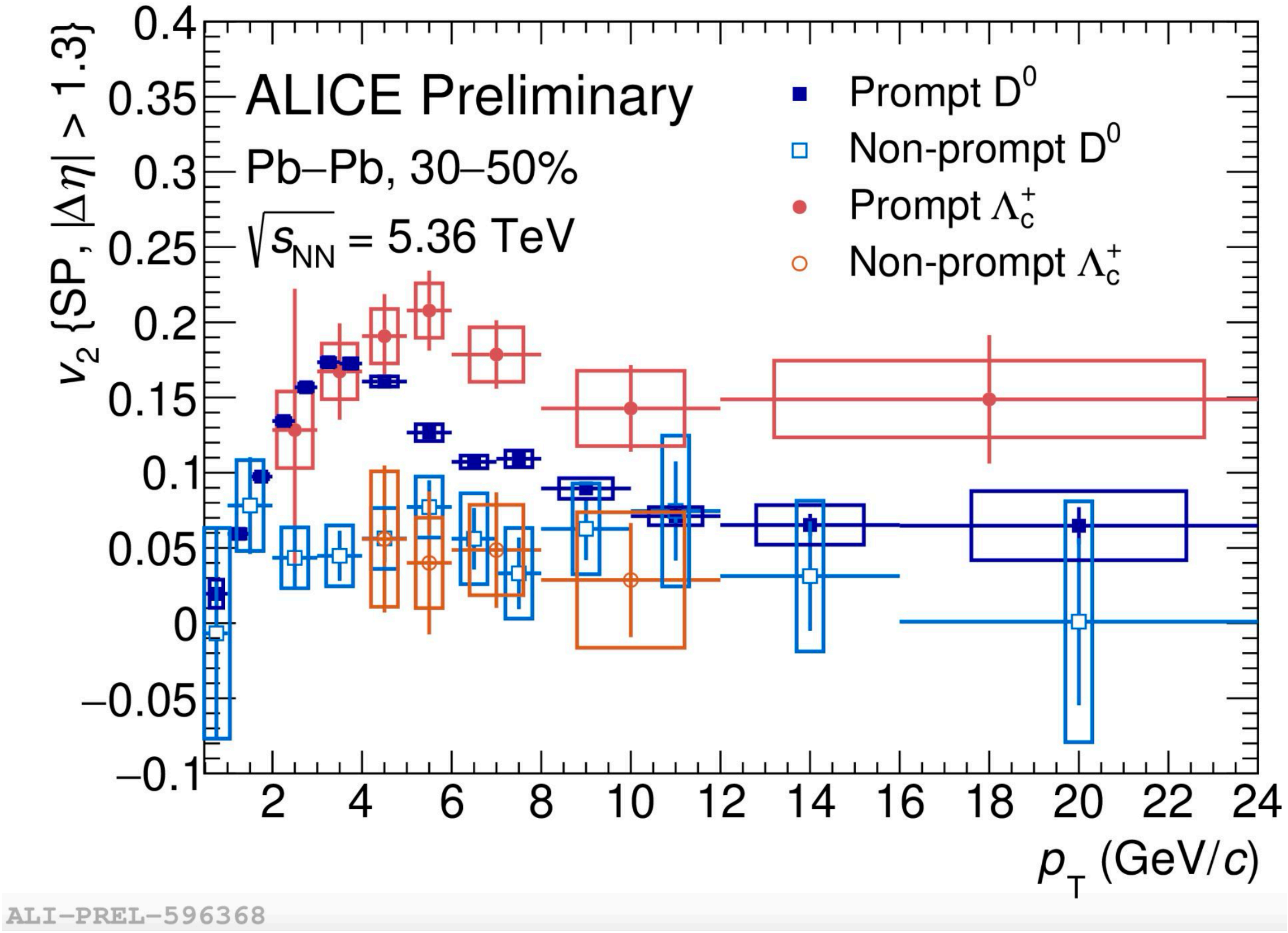
R. Katz et al. PRC 102 (2020) 041901
Langevin: EPJC 81 (2021) 1035
EPOS4HQ: J. Zhao et al. PRC 110 (2024) 024909

Collectivity: D-meson elliptic flow in OO



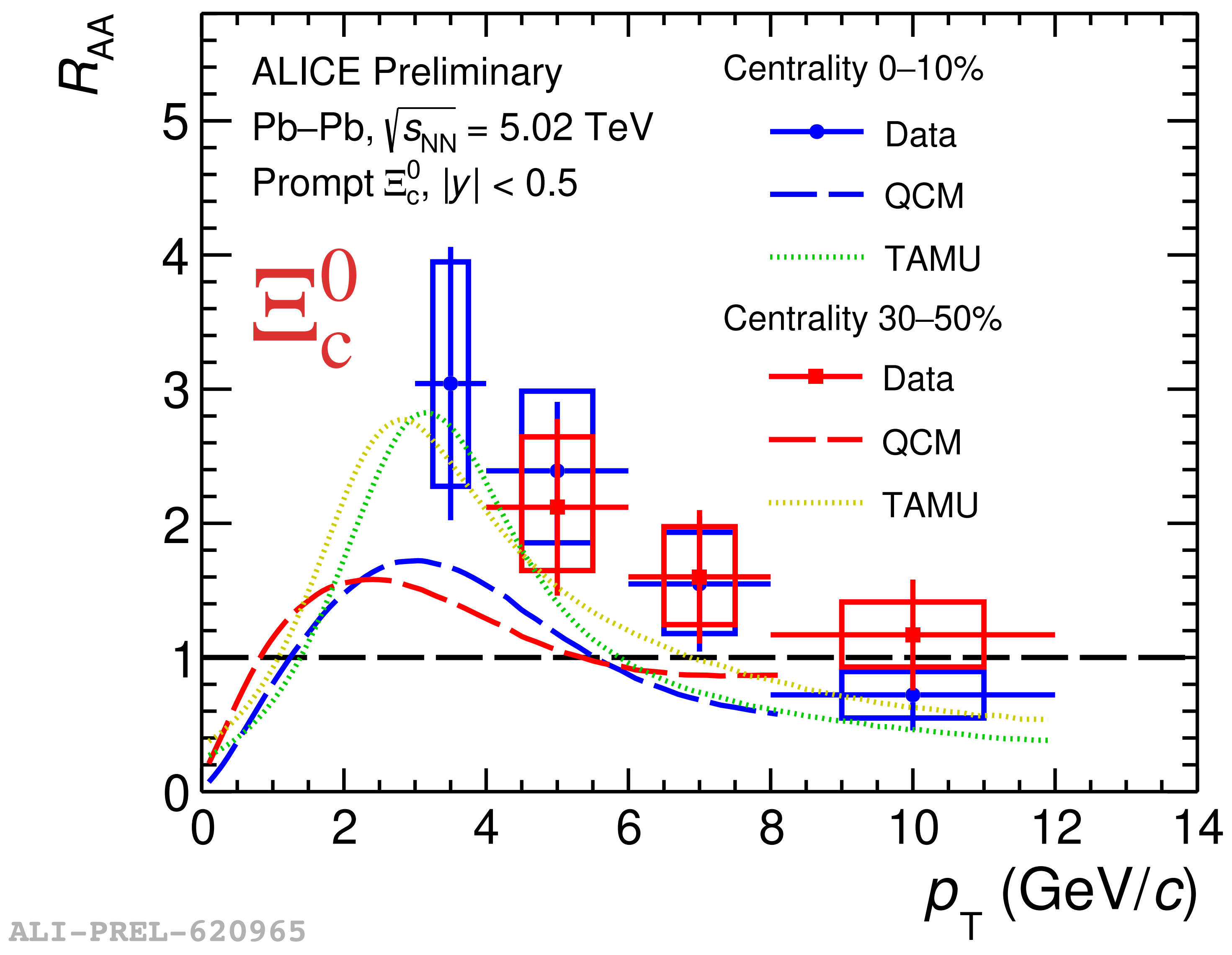
- Sizable differences between peripheral Pb–Pb and central OO
  - dN/dy in central OO ≈ peripheral Pb–Pb but reduced eccentricity
  - Sensitivity to different sources of charm v_2

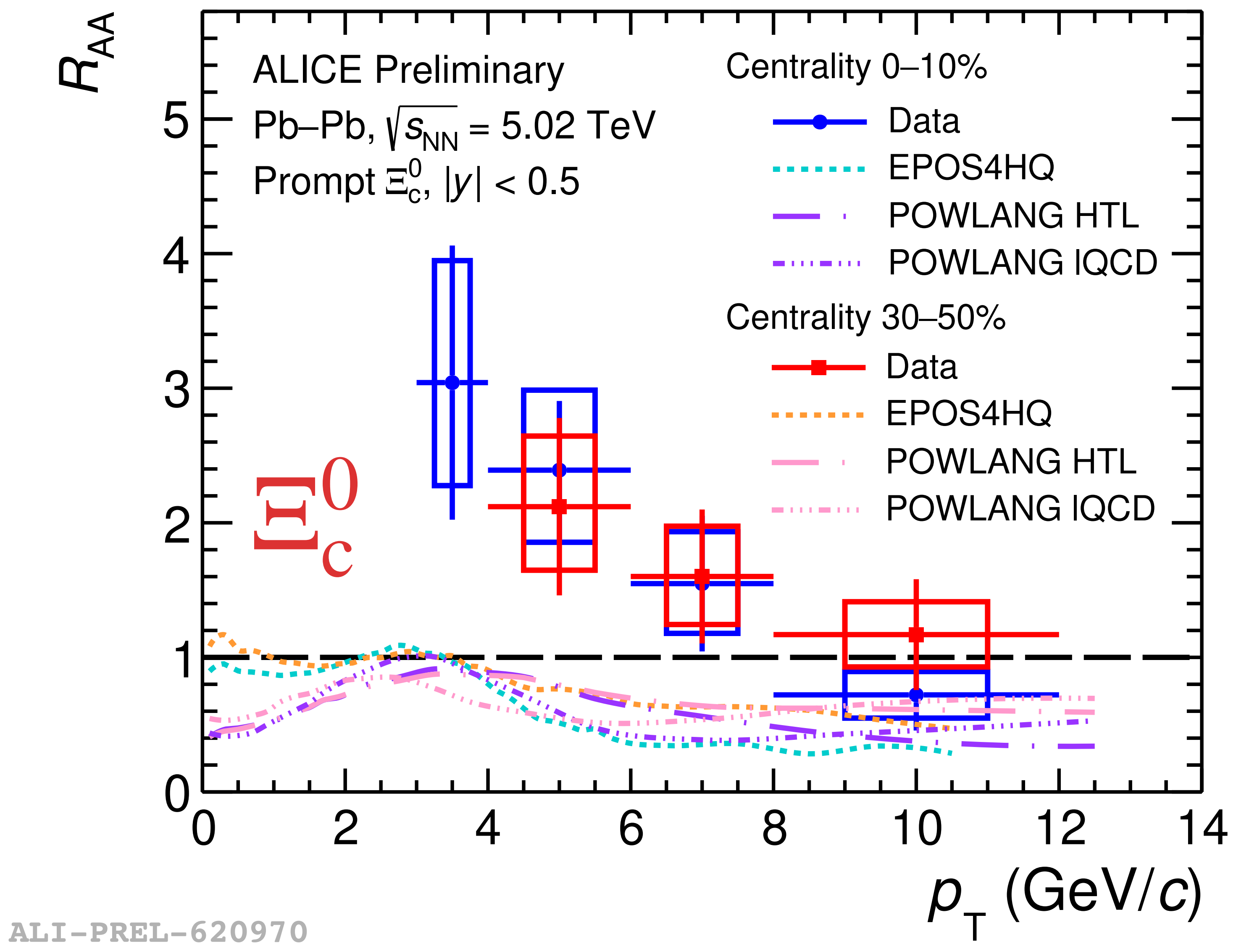
Collectivity: non-prompt charm hadron elliptic flow

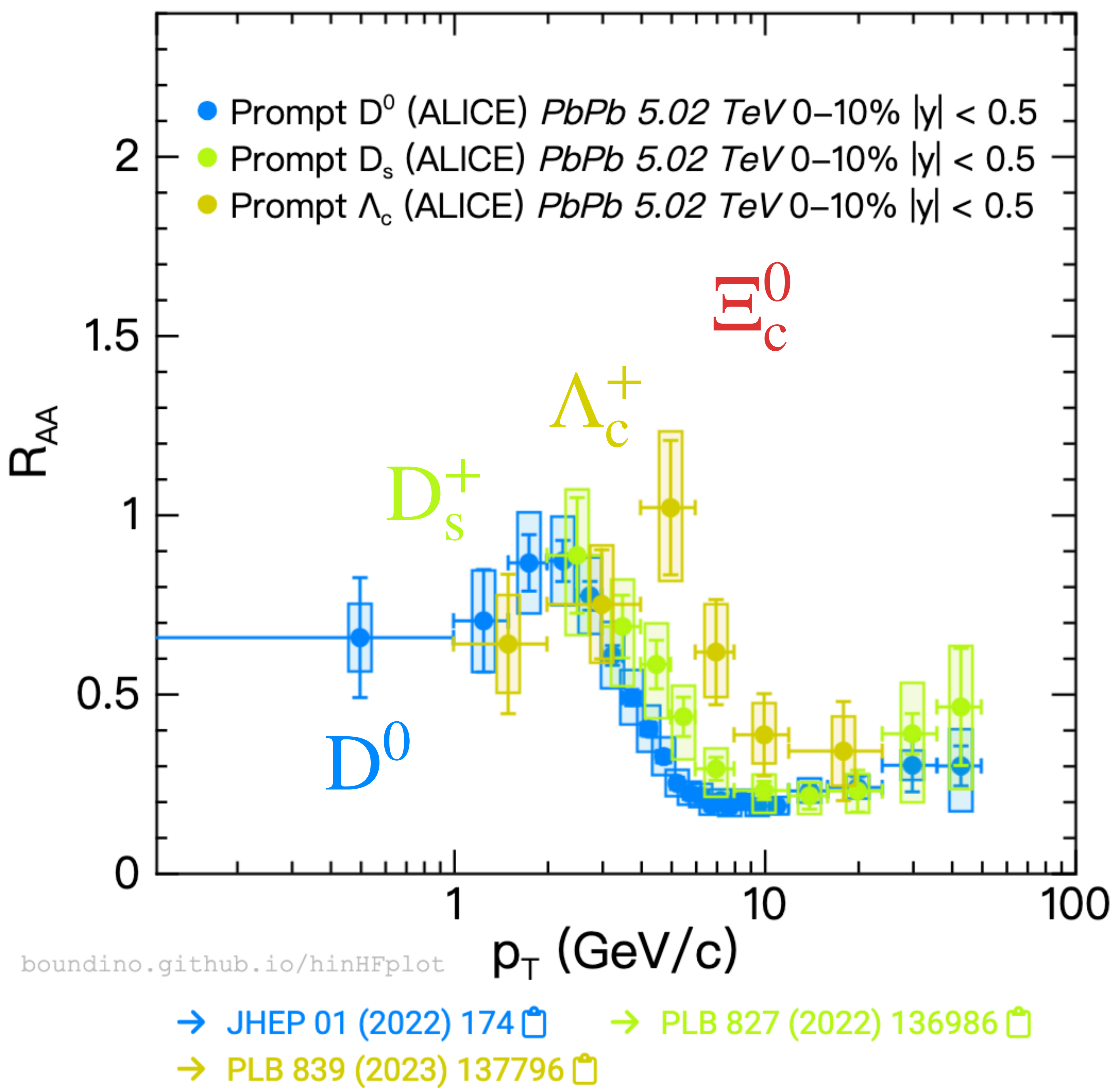


- Positive non-prompt v_2, lower than the prompt one $\rightarrow$ $m_b \gg m_c$, longer relaxation time
- Consistent D^0 and Λ_c^+ non-prompt v_2

Energy loss: mass dependence





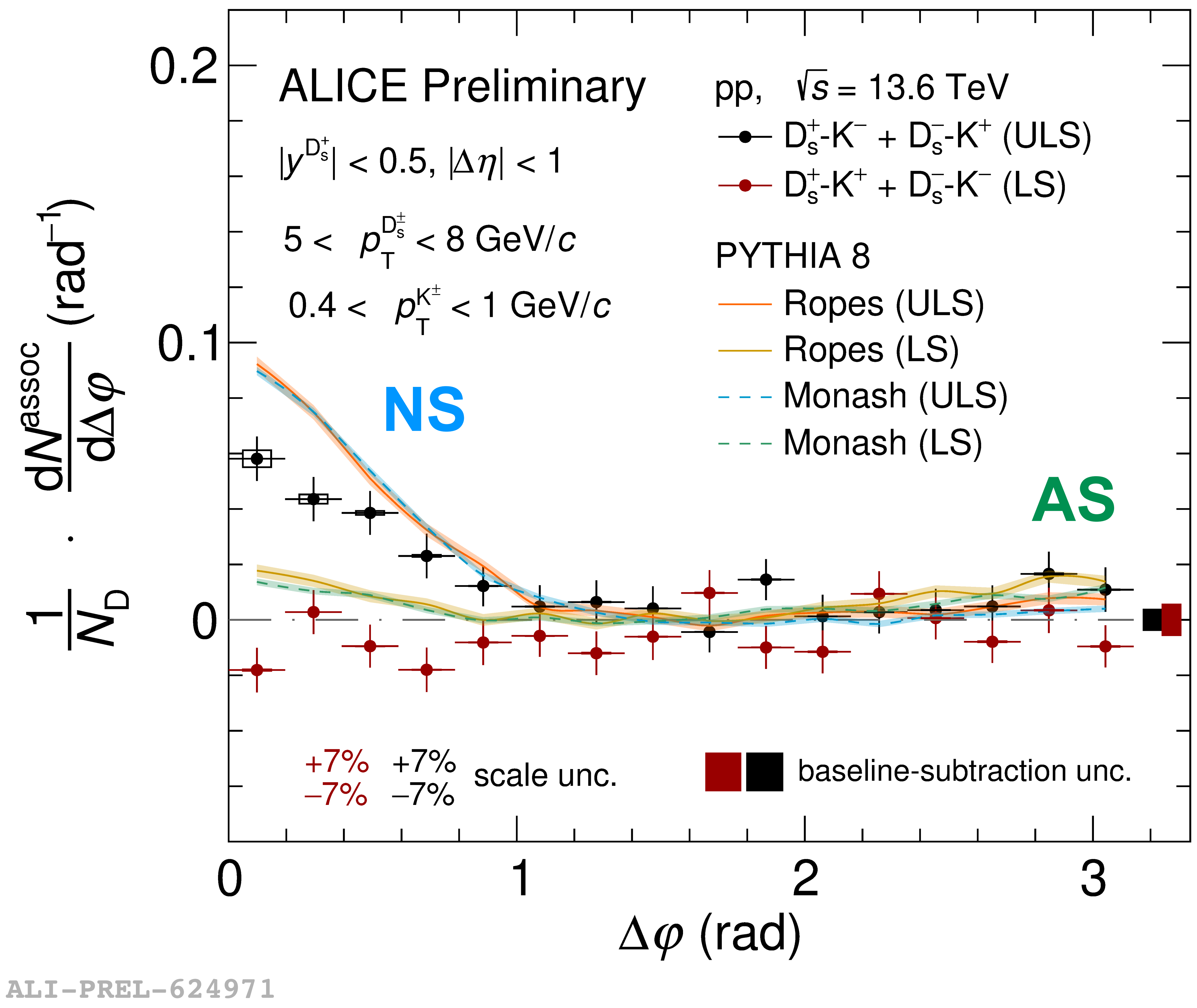


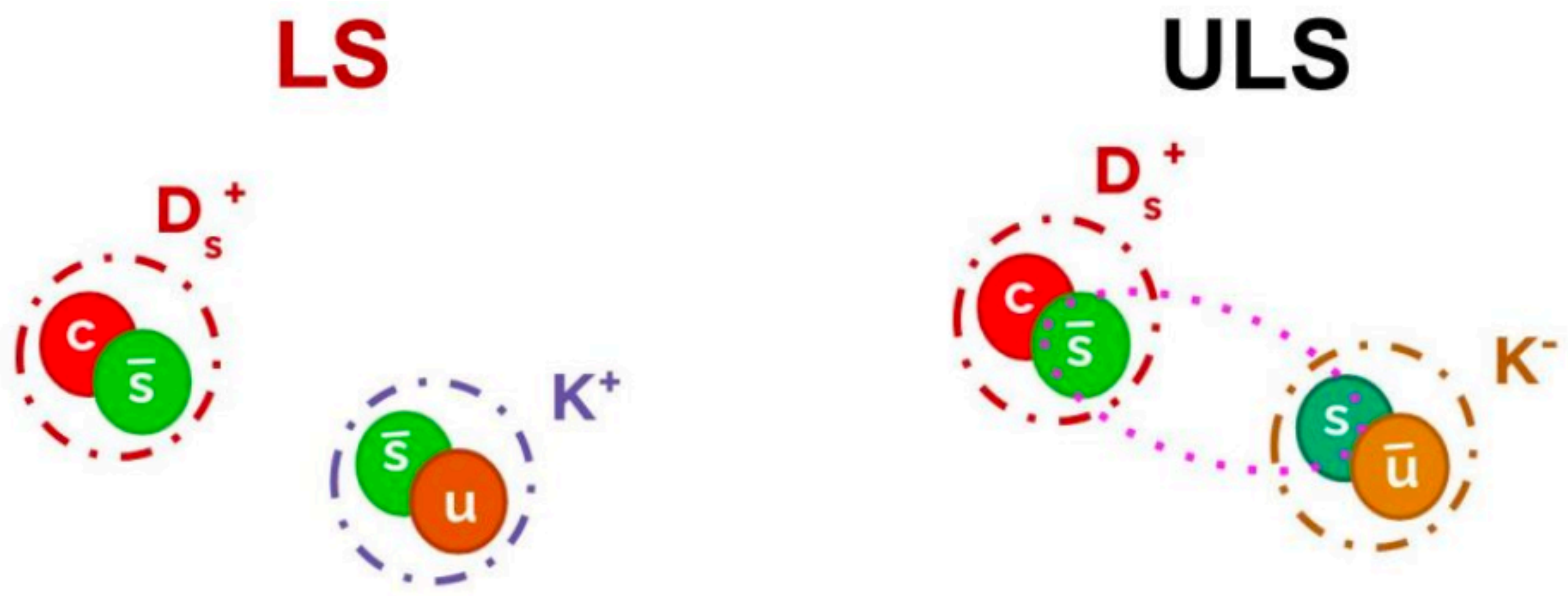
In central collisions at $4 < p_T < 8$ GeV/c

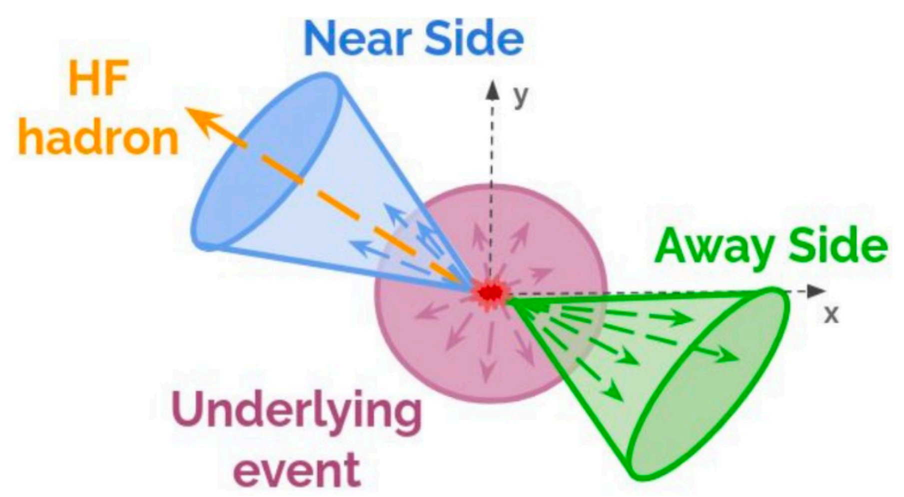
- A hint of hierarchy $R_{AA}(D) < R_{AA}(D_s^+) < R_{AA}(\Lambda_c^+) < R_{AA}(\Xi_c^0)$

Azimuthal correlation: Ds with identified particles

- Multi-differential investigation of fragmentation processes
  - explore local quantum-number conservation
- Enhanced unlike-sign (ULS) near-side peak is observed at $p_T > 5\ \mathrm{GeV}/c$ for Ds-K correlations
  - due to strange-antistrange pair production in hadronization
  - good compatibility with PYTHIA 8 preductions

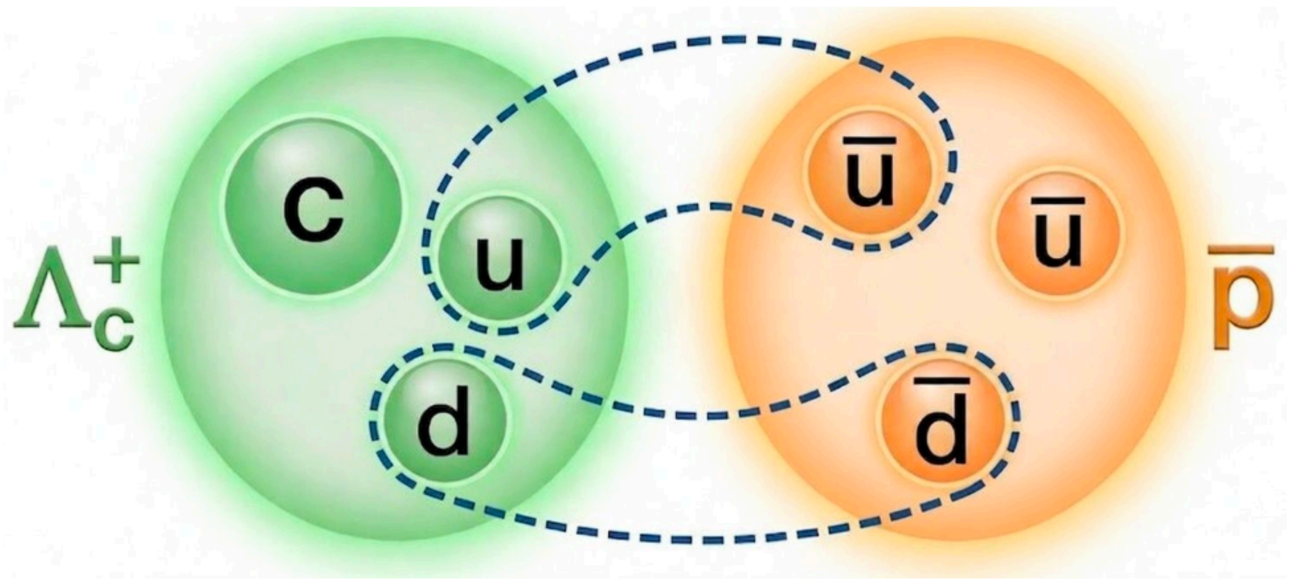


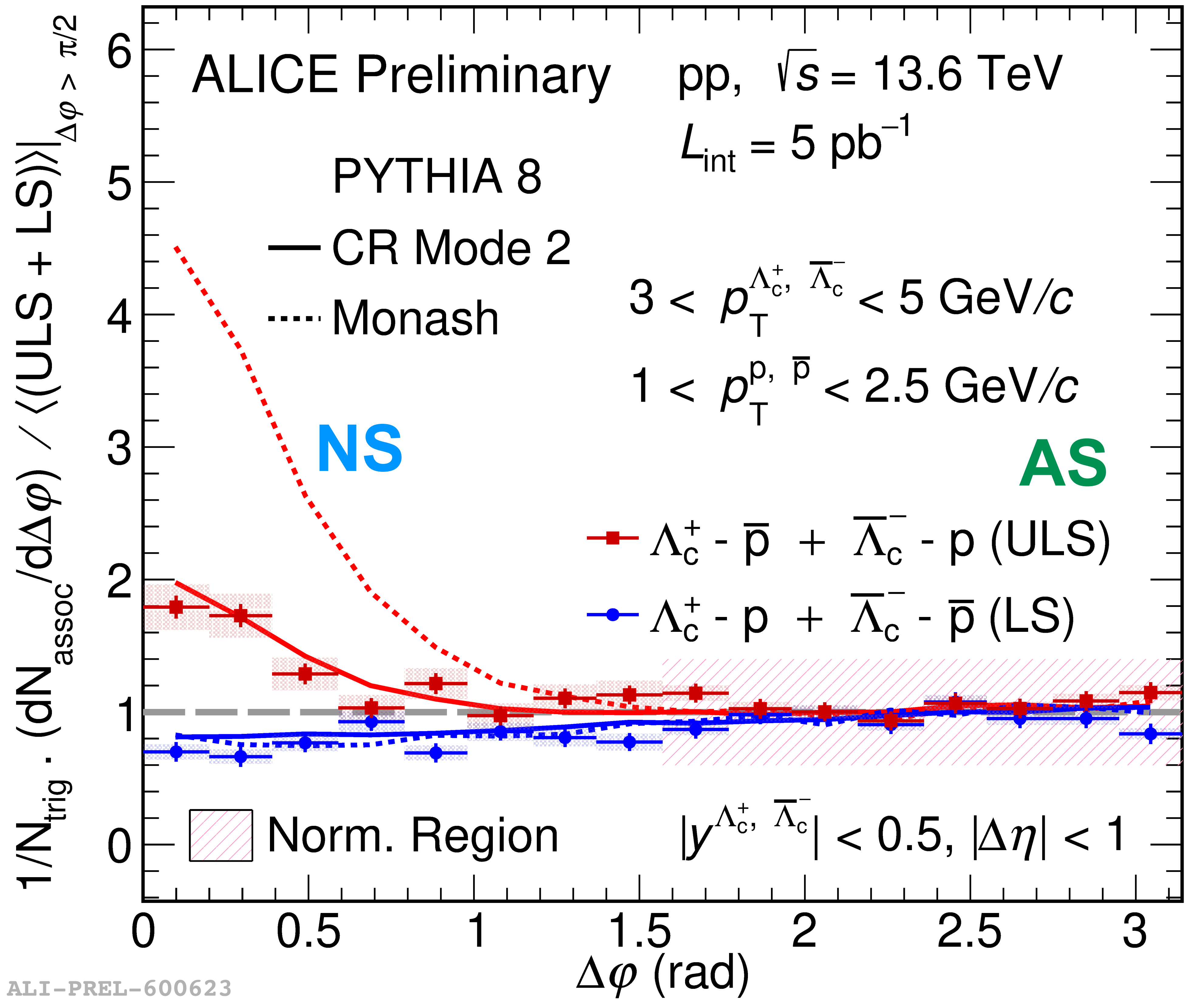


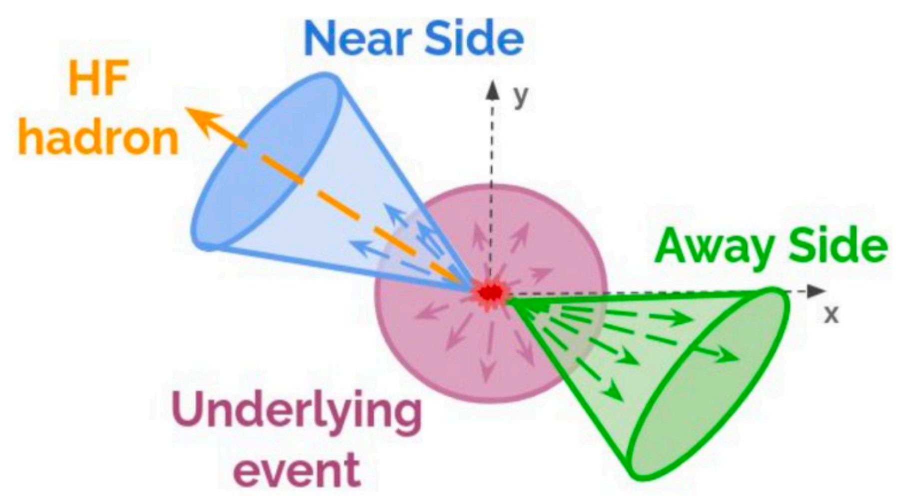


Azimuthal correlation: Λ_c^+ with identified particles

- NS unlike sign peak from baryon-number conservation in Λ_c^+-p correlations
  - explained by diquark-antidiquark production in PYTHIA string breaking
- Reduced NS peak in PYTHIA 8 CR-BLC Mode 2 due to baryon production in junctions
  - better description of the measurement







Femtoscopy: charm-hadron

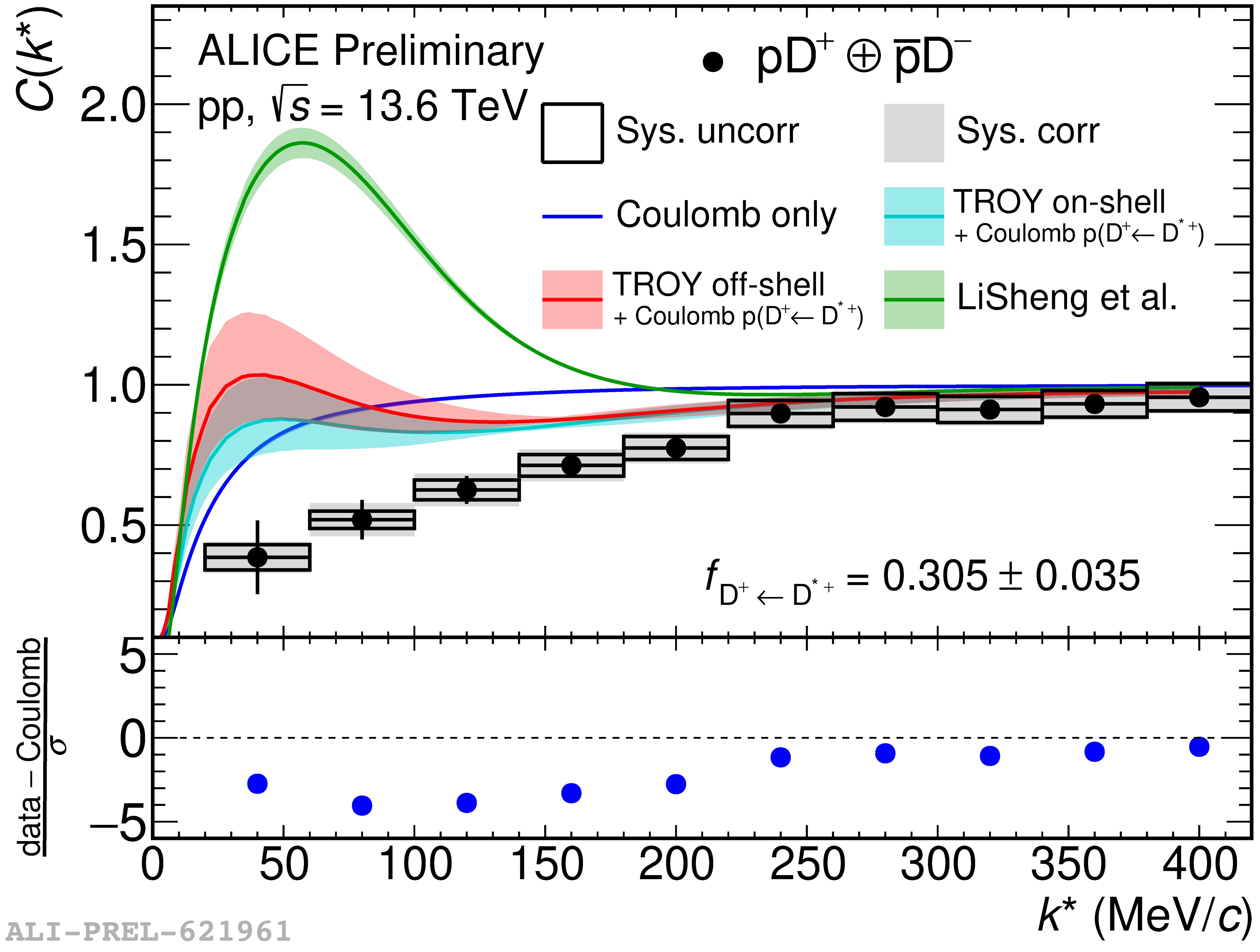
Experiment | Theory

$$C(k^*) = \mathcal{N}\frac{N^{\rm pairs}_{\rm same}(k^*)}{N^{\rm pairs}_{\rm mixed}(k^*)} = \int S(\vec{r^*})\left|\psi(\vec{k^*},\vec{r^*})\right|^2 d^3r^*$$

Relative momentum
$\vec{k}^* = \frac{1}{2}\mid \vec{p}_1^* - \vec{p}_2^* \mid$

Run 2 results: PRD 106 (2022) 052010
PRD 110 (2024) 032004

- Important to shed the light on hadron rescattering and on the existence/structure of exotic resonances
- First evidence of residual strong interaction in charm sector
  - formation of p-D+ exotic states disfavoured
- All models include the bound states $\Sigma_c(2800)$
  - A bump at k^* around 50 MeV

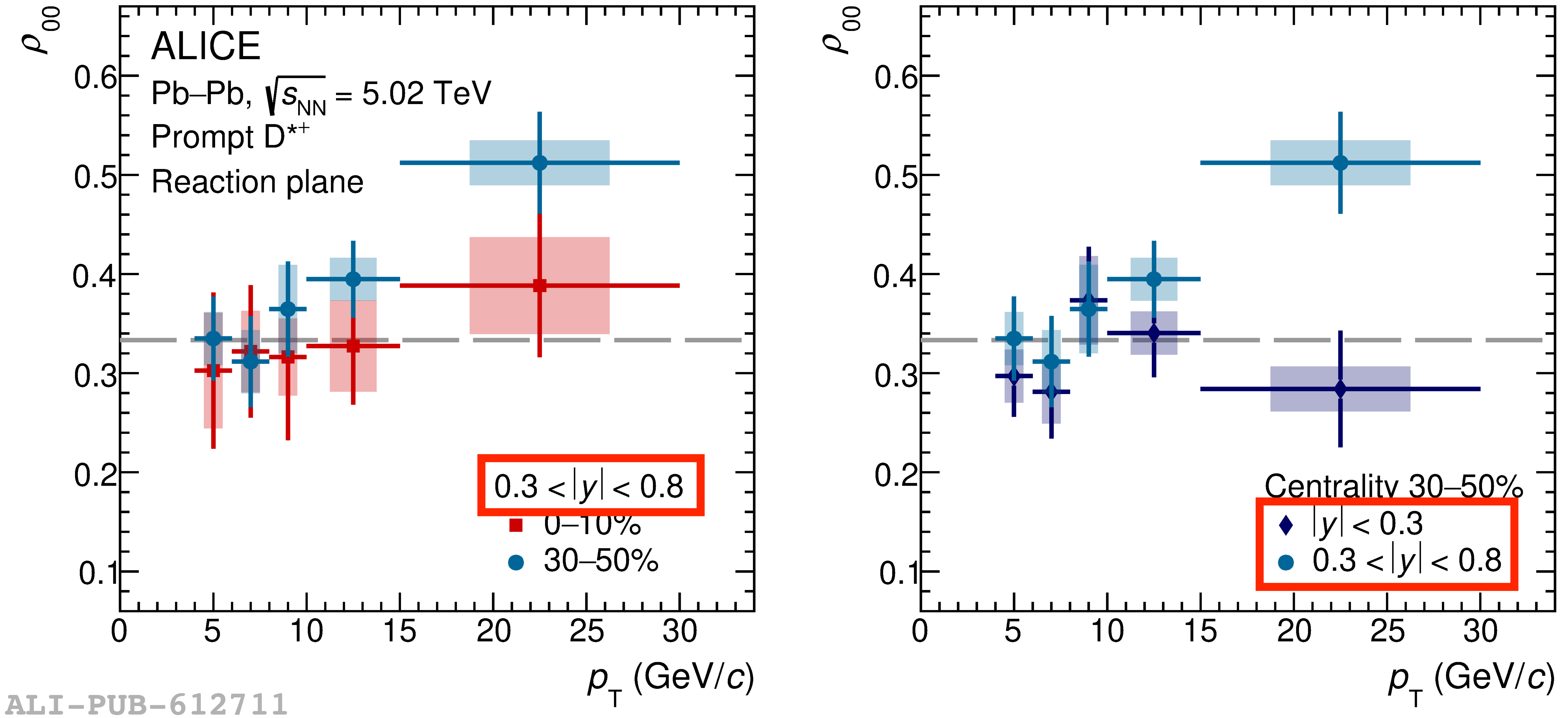


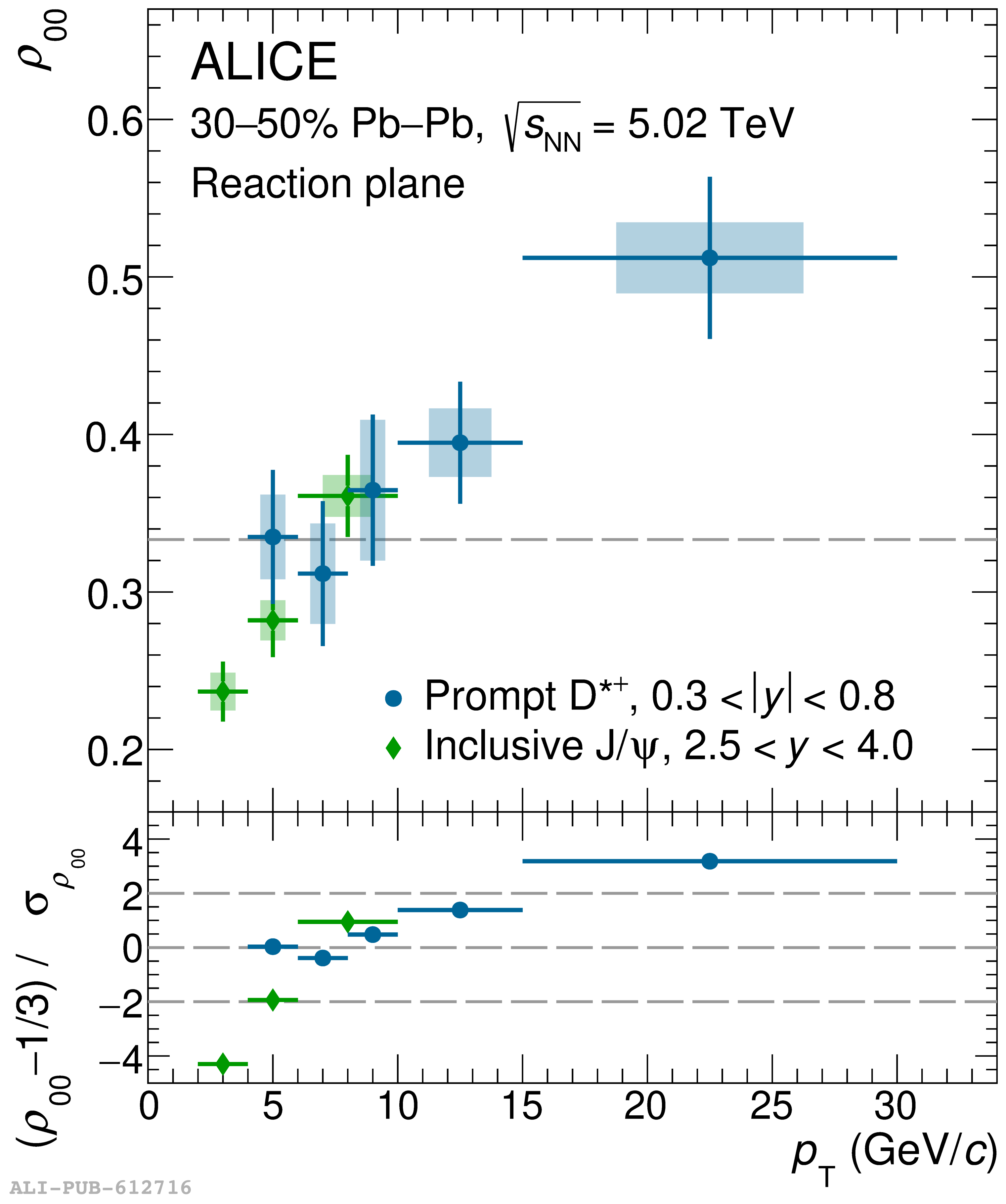
TROY(on/off shell): Coulomb + repulsive strong interaction
LiSheng: Coulomb + attractive strong interaction

TROY: M. Barbat et al. arXiv:2507.07864
LiSheng et al. PRD 89 (2014) 014026

Spin alignment: D^{*+}

JHEP10(2025)094





- Hint of centrality and p_T dependence
- Rapidity dependence at high p_T in semicentral collisions
  - Compatible with longer-lasting B at larger rapidity
- Hint of rising trend with p_T for prompt D^{*+} and inclusive J/ψ

Summary

- Parton-to-hadron fragmentation fractions might be affected by possible medium effects in small system
- HF hadronization mechanisms in small collision systems at LHC need further investigations
  - Resonance decay? Coalescence? Radial flow?
- Ξ_c^0 production in large system challenges current hadronization models
- Deviation between $v_2(\mathrm{D}^0)$ and $v_2(\mathrm{D_s^+})$ supports sequential coalescence?
- Azimuthal correlation, femtoscopy, polarization, …, can help us understand HF hadronization from different perspectives

Backup