ALICE open heavy-flavor overview

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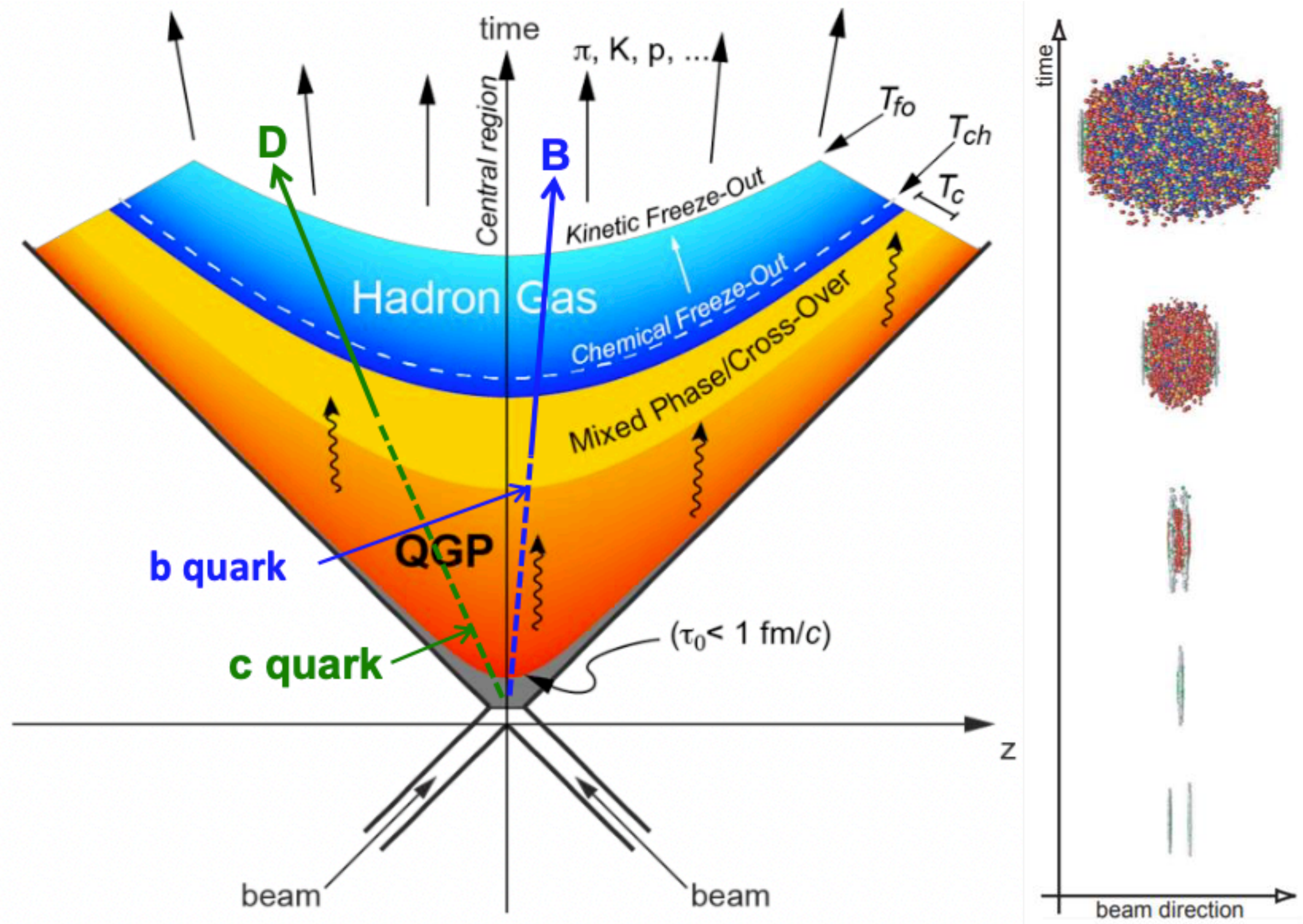
on behalf of the ALICE Collaboration

9th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions
Guangzhou, Guangdong, China
December 07, 2024

Why open heavy-flavour (HF)



- Charm:

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

- Beauty:

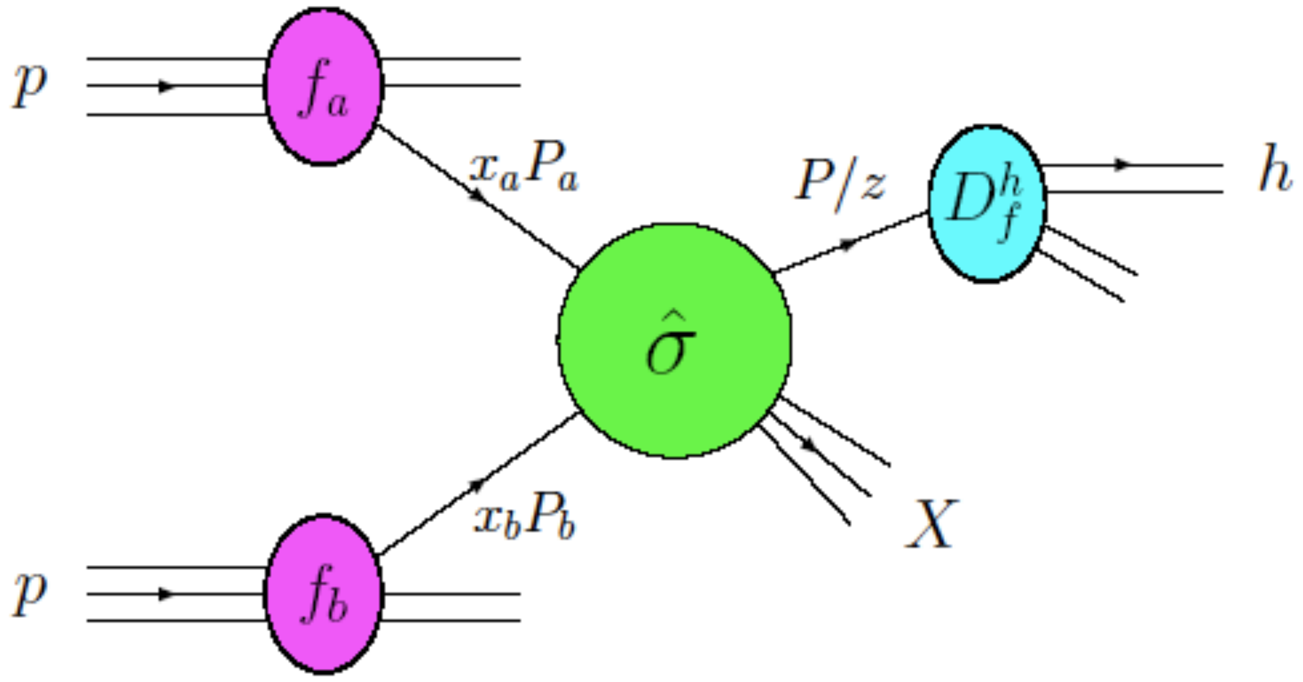
  $m_b \approx 4.2\ \text{GeV}/c^2$

- $m_Q \gg \Lambda_{QCD}$
  - 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
- $\tau_{prob} \approx \dfrac{1}{2m_q} \approx 0.1_{q=c}(0.03)_{q=b}\ \text{fm}/c\ < \tau_{QGP}(\approx 0.3 - 1.5\ \text{fm}/c)$
  - Experience the full evolution of the QGP

- Hadroproduction described by factorisation approach:

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

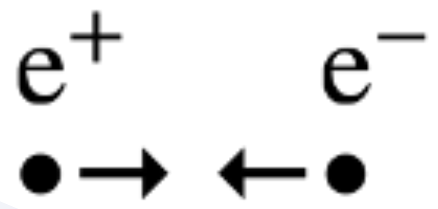
parton distribution function (PDF) (non-perturbative) | partonic cross section (perturbative) | hadronisation by fragmentation (non-perturbative)



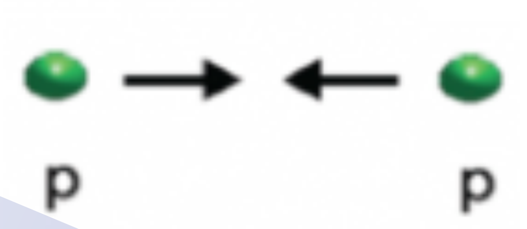
Fragmentation functions assumed to be universal

HF hadronisation

- Ratios of particle species sensitive to hadronisation

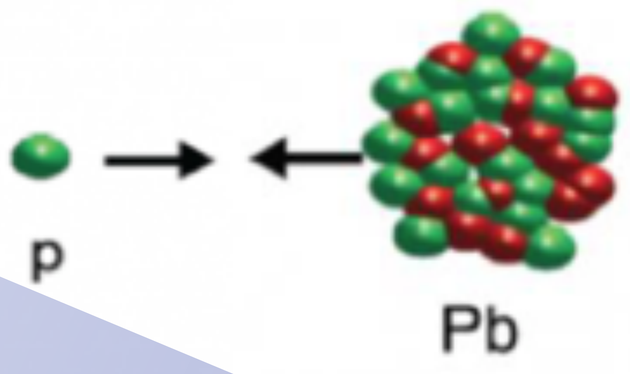


Vacuum

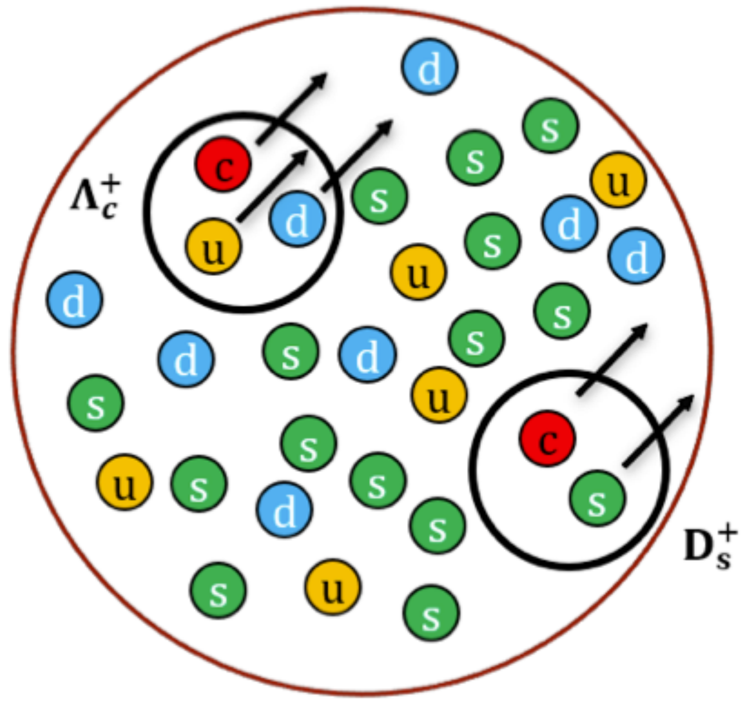


Not far from vacuum?

Or dense enough to alter hadronization?

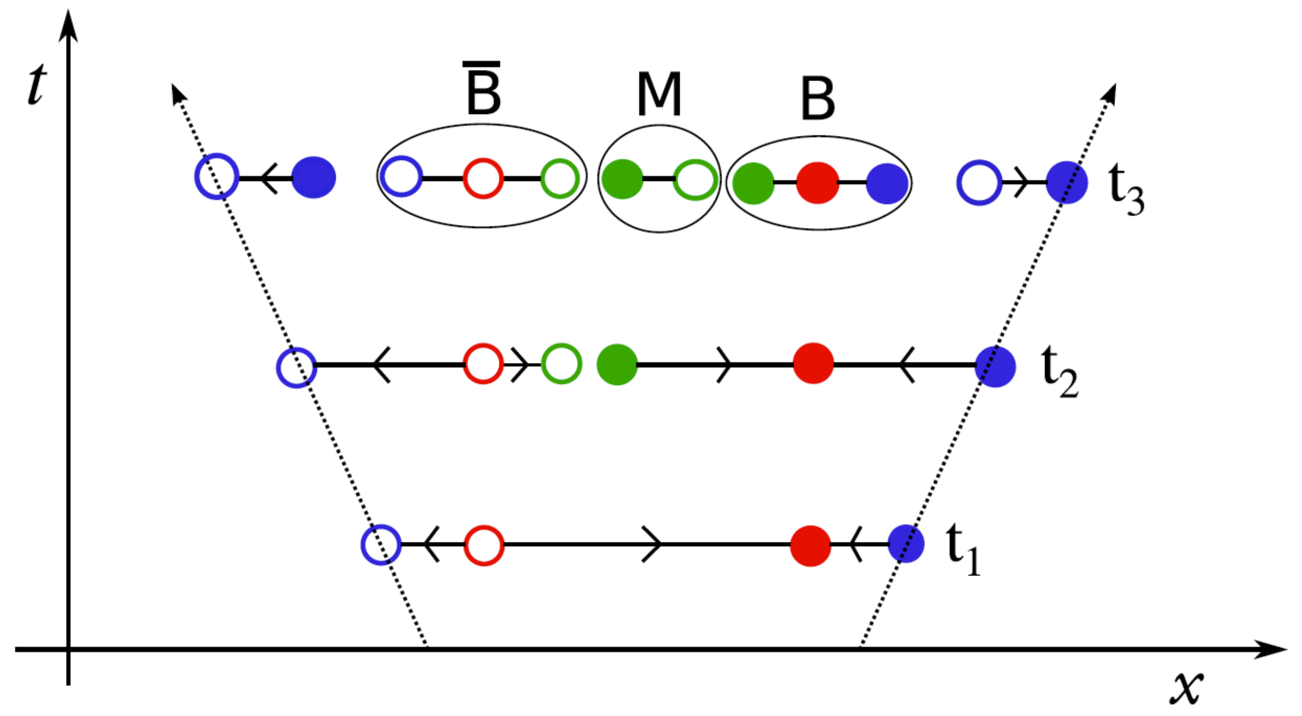


System size



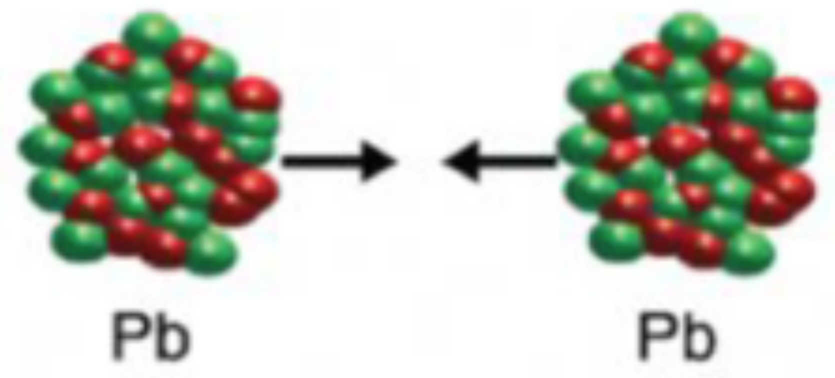
Fragmentation

- 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

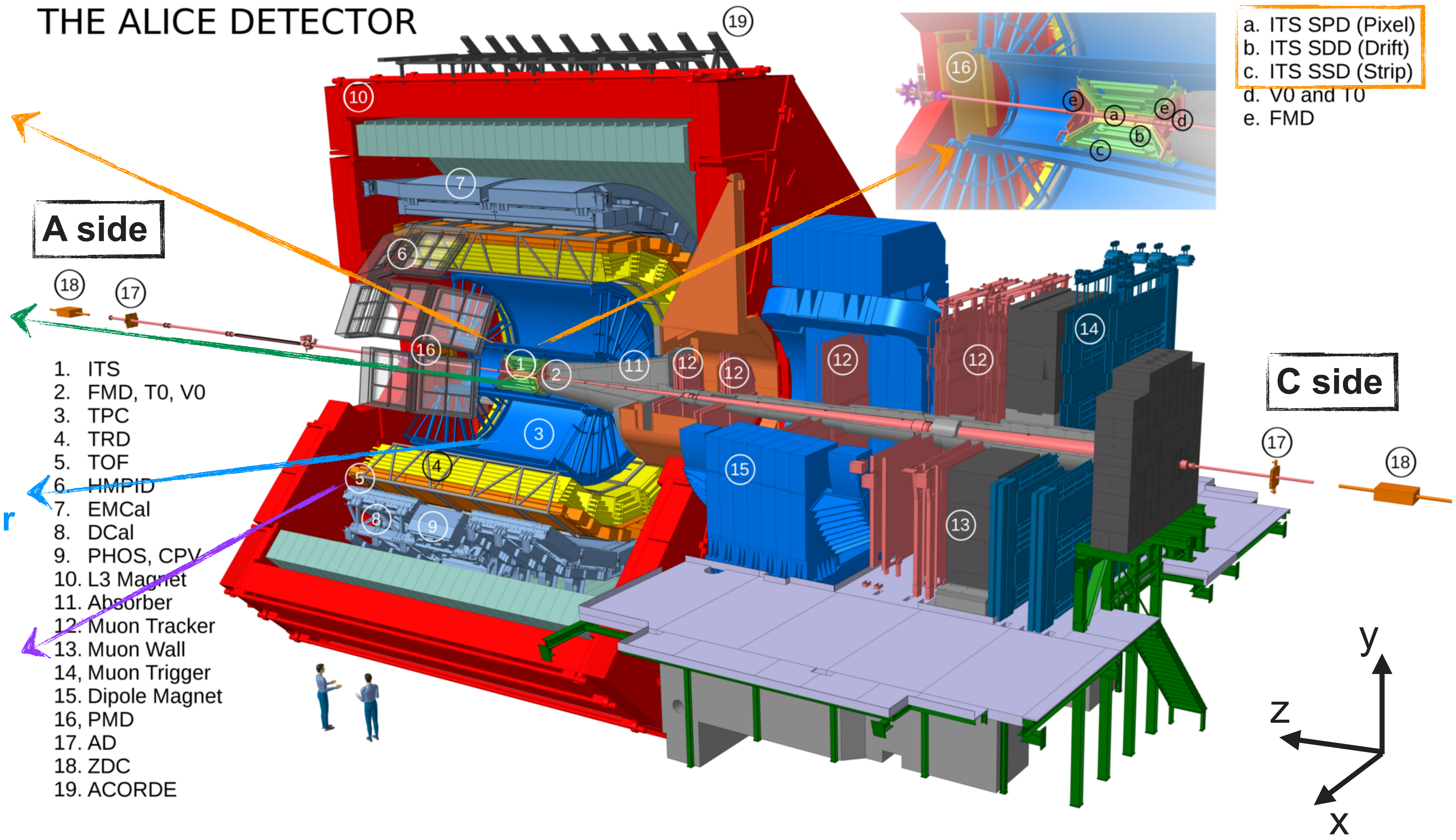


Dense, extended-size system

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

ALICE detector

- Inner Tracking System
  - $|\eta| < 0.9$
  - Tracking, vertexing, multiplicity
- V0
  - V0-A: $2.8 < \eta < 5.1$
  - V0-C: $-3.7 < \eta < -1.7$
  - Triggering, luminosity, multiplicity
- Time Projection Chamber
  - $|\eta| < 0.9$
  - Tracking, PID
- Time-Of-Flight
  - $|\eta| < 0.9$
  - Tracking, PID



Charm-hadron reconstruction

Hadronic decays

- $D^0(\bar{u}c) \to K^-\pi^+$, BR $\approx 3.95\,\%$
- $D^+(\bar{d}c) \to K^-\pi^+\pi^+$, BR $\approx 9.38\,\%$
- $D^{*+}(\bar{d}c) \to D^0\pi^+$, BR $\approx 67.7\,\%$
- $D_s^+(\bar{s}c) \to \phi\pi^+ \to K^+K^-\pi^+$, BR $\approx 2.22\,\%$
- $D_{s1}^+(\bar{s}c) \to D^{*+}K_s^0$, BR unknown
- $D_{s2}^{*+}(\bar{s}c) \to D^+K_s^0$, BR unknown
- $\Lambda_c^+(udc) \to pK^-\pi^+$, BR $\approx 6.28\,\%$
- $\Lambda_c^+(udc) \to pK_s^0$, BR $\approx 1.59\,\%$
- $\Sigma_c^0(ddc) \to \Lambda_c^+\pi^-$, BR $\approx 100\,\%$
- $\Sigma_c^{++}(uuc) \to \Lambda_c^+\pi^+$, BR $\approx 100\,\%$
- $\Xi_c^+(usc) \to \Xi^-\pi^+\pi^+$, BR $\approx 2.9\,\%$
- $\Xi_c^0(dsc) \to \Xi^-\pi^+$, BR $\approx 1.43\,\%$
- $\Omega_c^0(ssc) \to \Omega^-\pi^+$, BR unknown

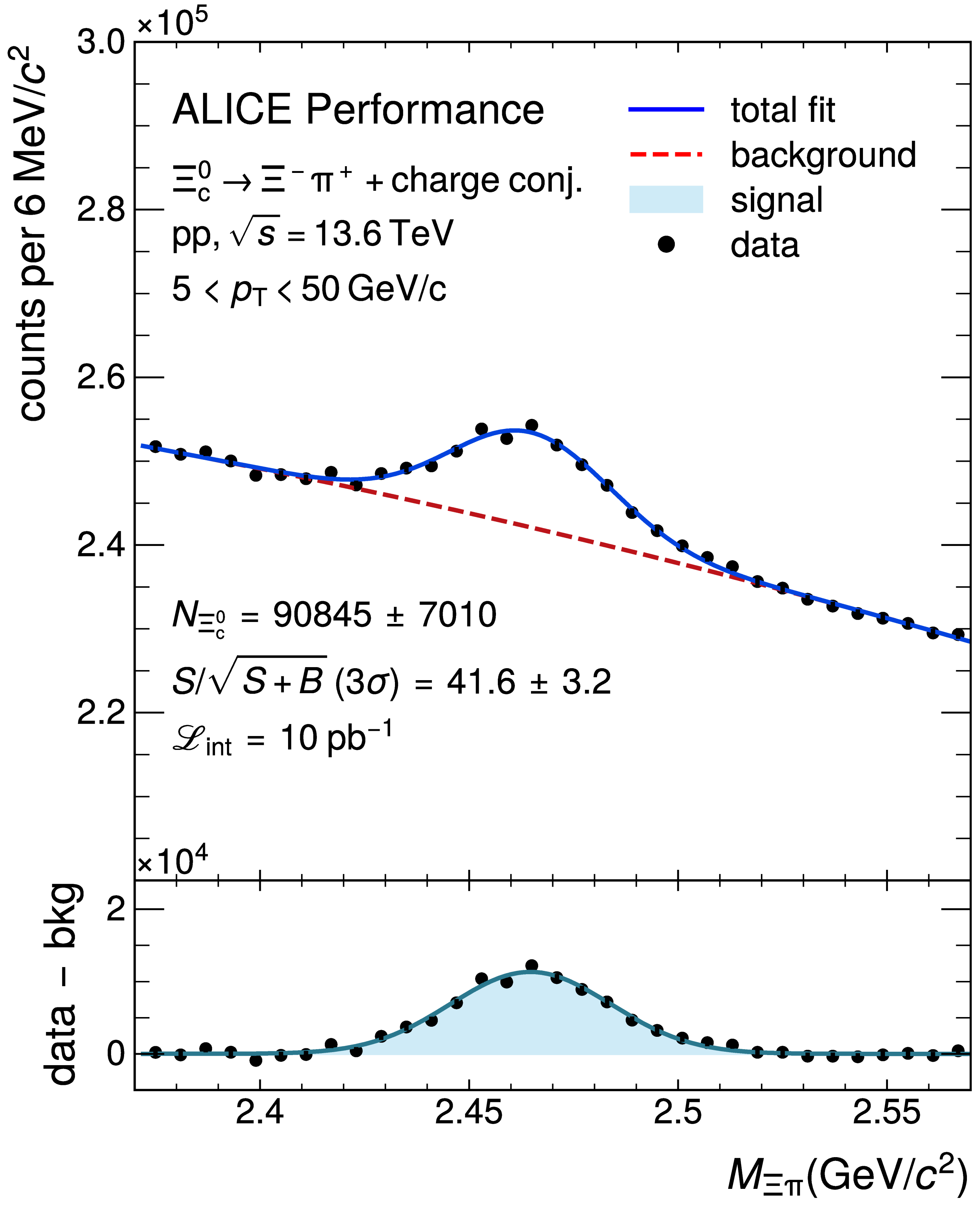
Semileptonic decays

- $\Lambda_c^+(udc) \to \Lambda e^+\nu_e$, BR $\approx 3.6\,\%$
- $\Xi_c^0(dsc) \to \Xi^- e^+\nu_e$, BR $\approx 1.04\,\%$
- $\Omega_c^0(ssc) \to \Omega^- e^+\nu_e$, BR unknown

Charge conjugates are included

Prompt

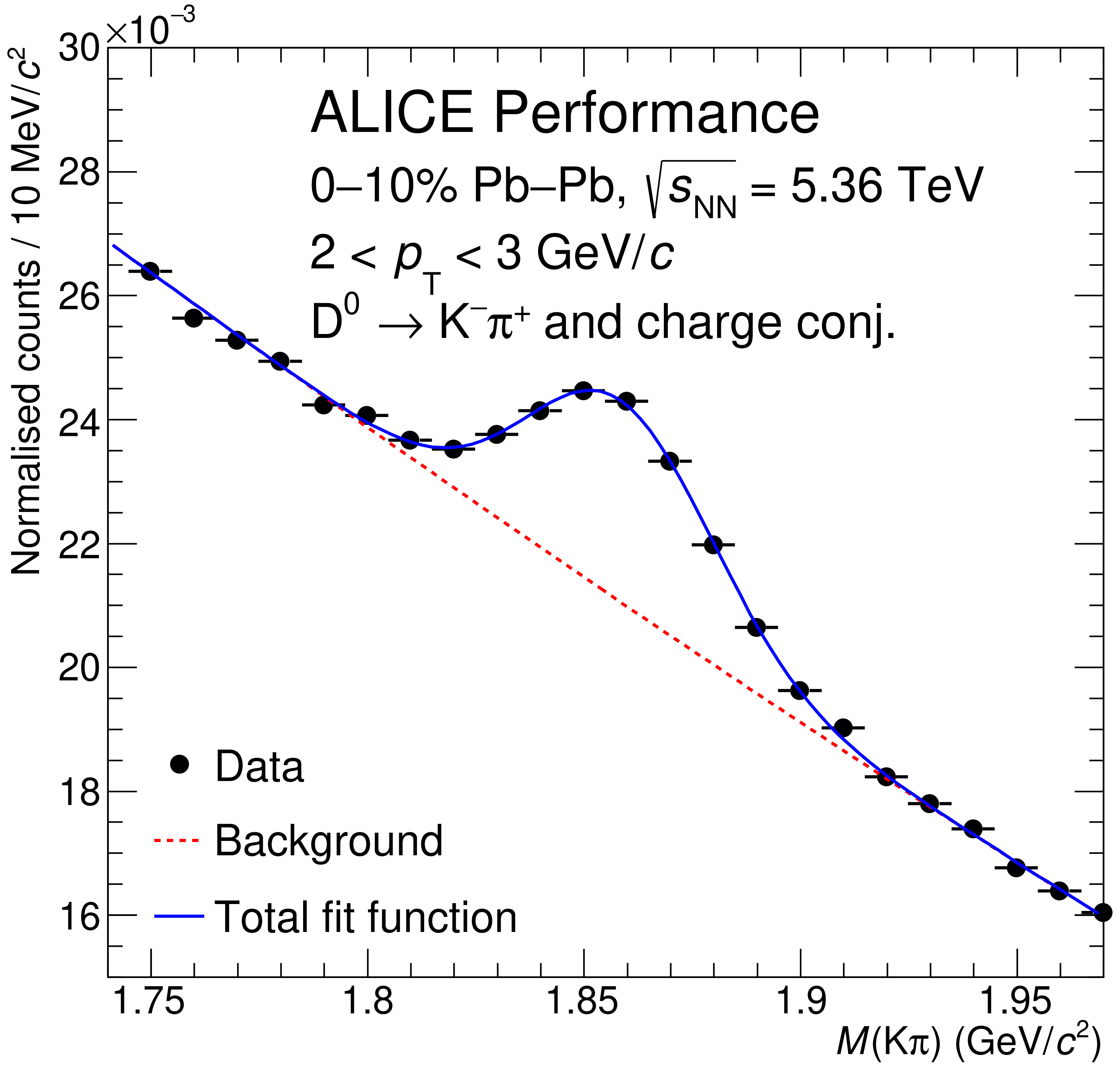
- $c \to$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$



ALI-PERF-578571

Non-Prompt

- $b \to c \to$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$

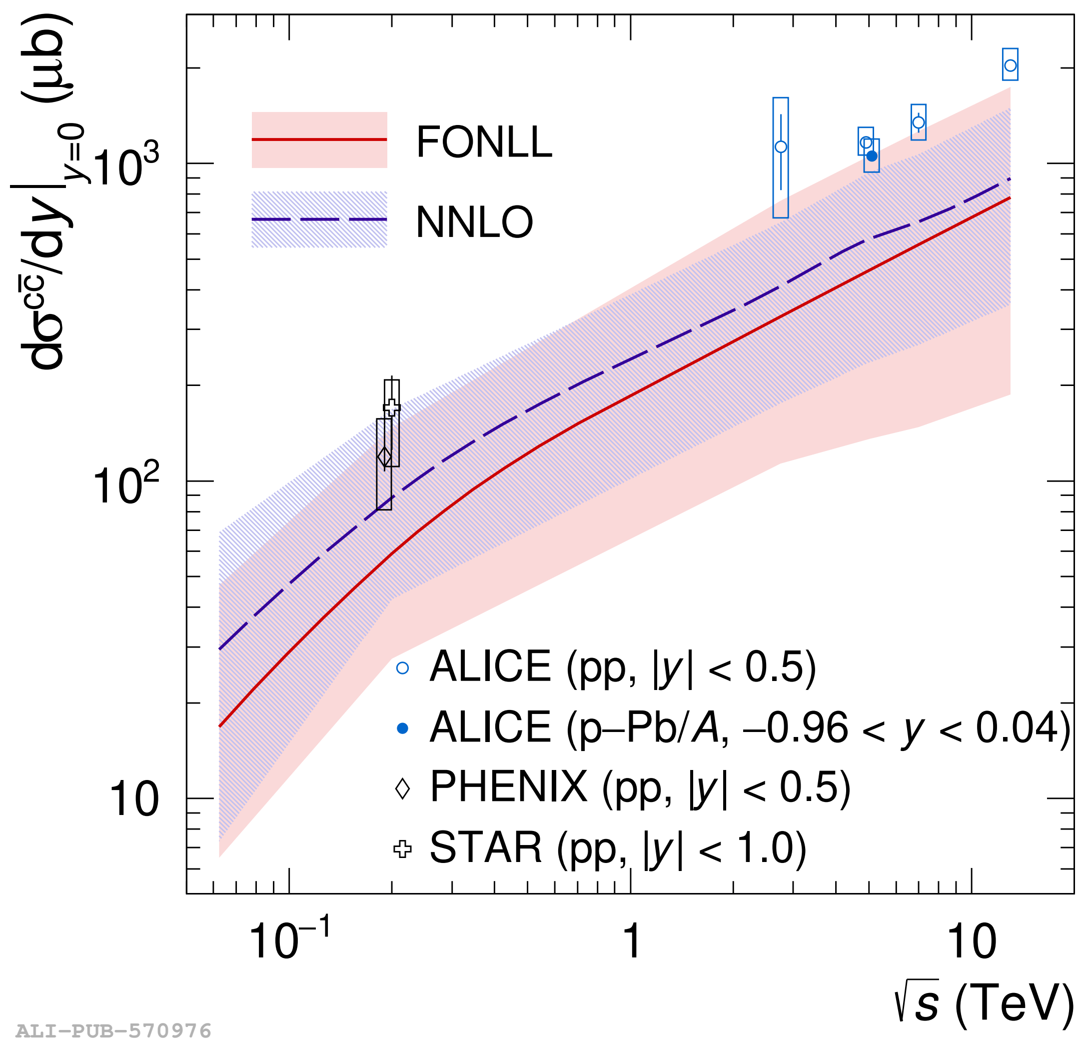


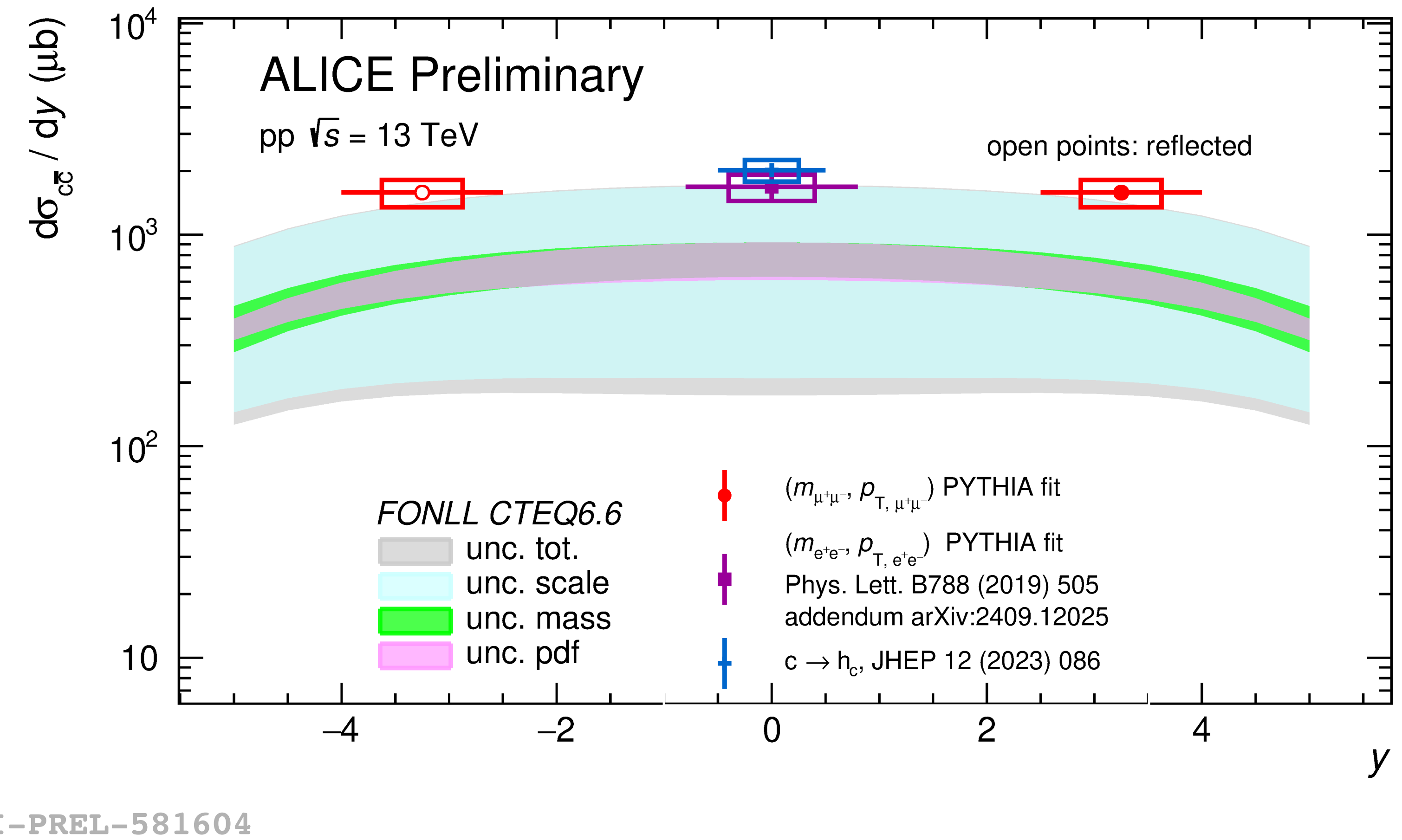
ALI-PERF-568645

HF production in small system

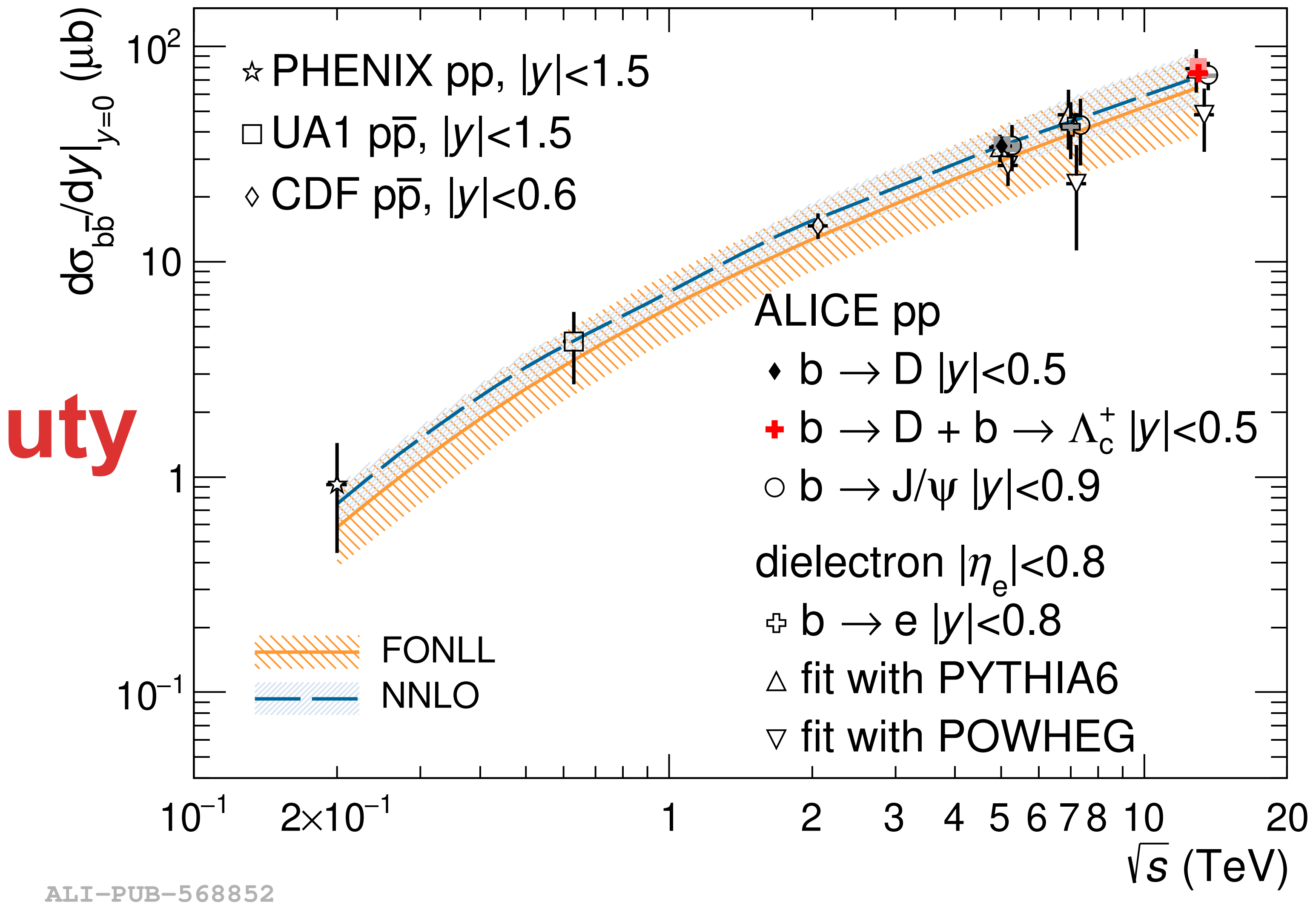
arXiv:2405.14571 (accepted by EPJC)

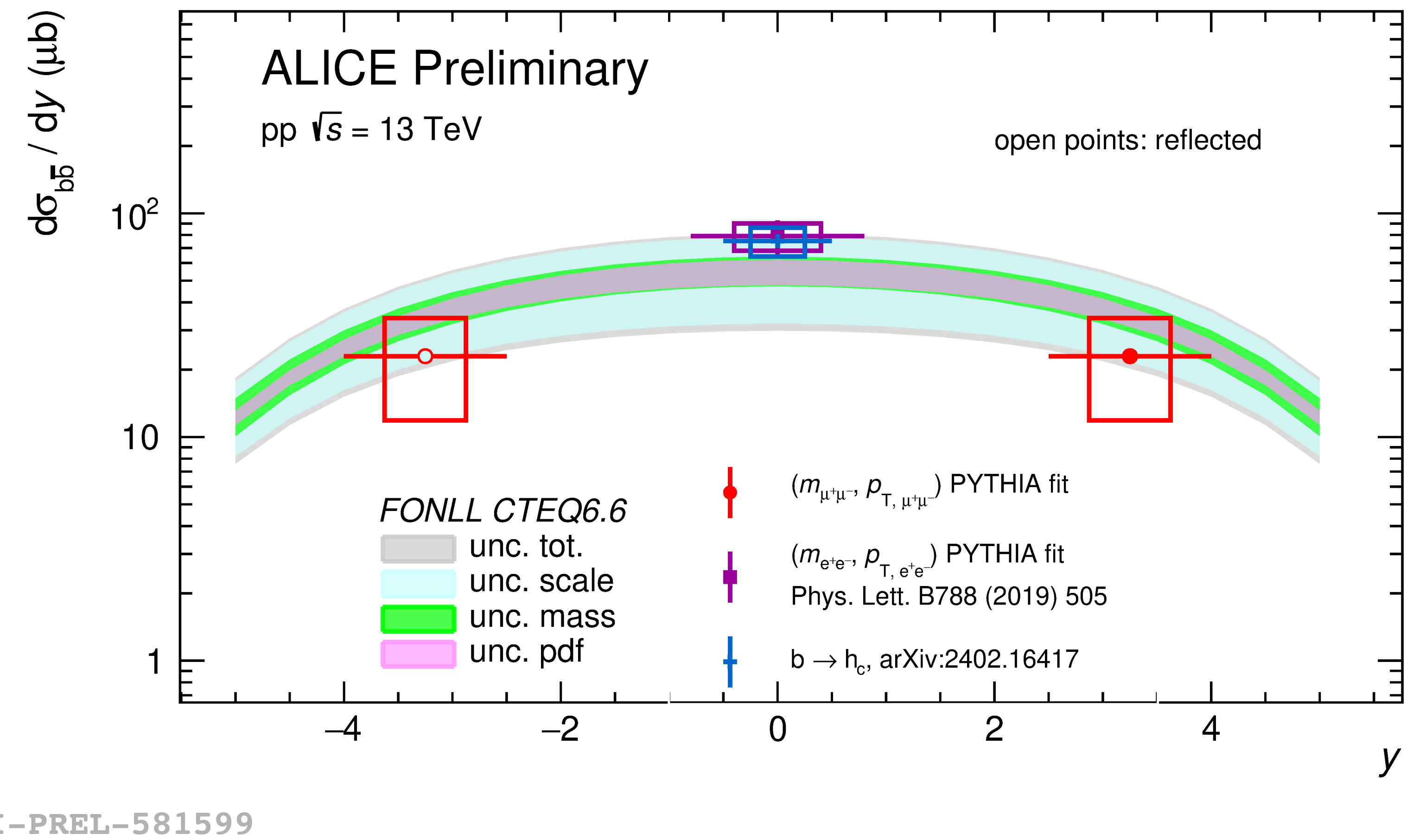
Charm



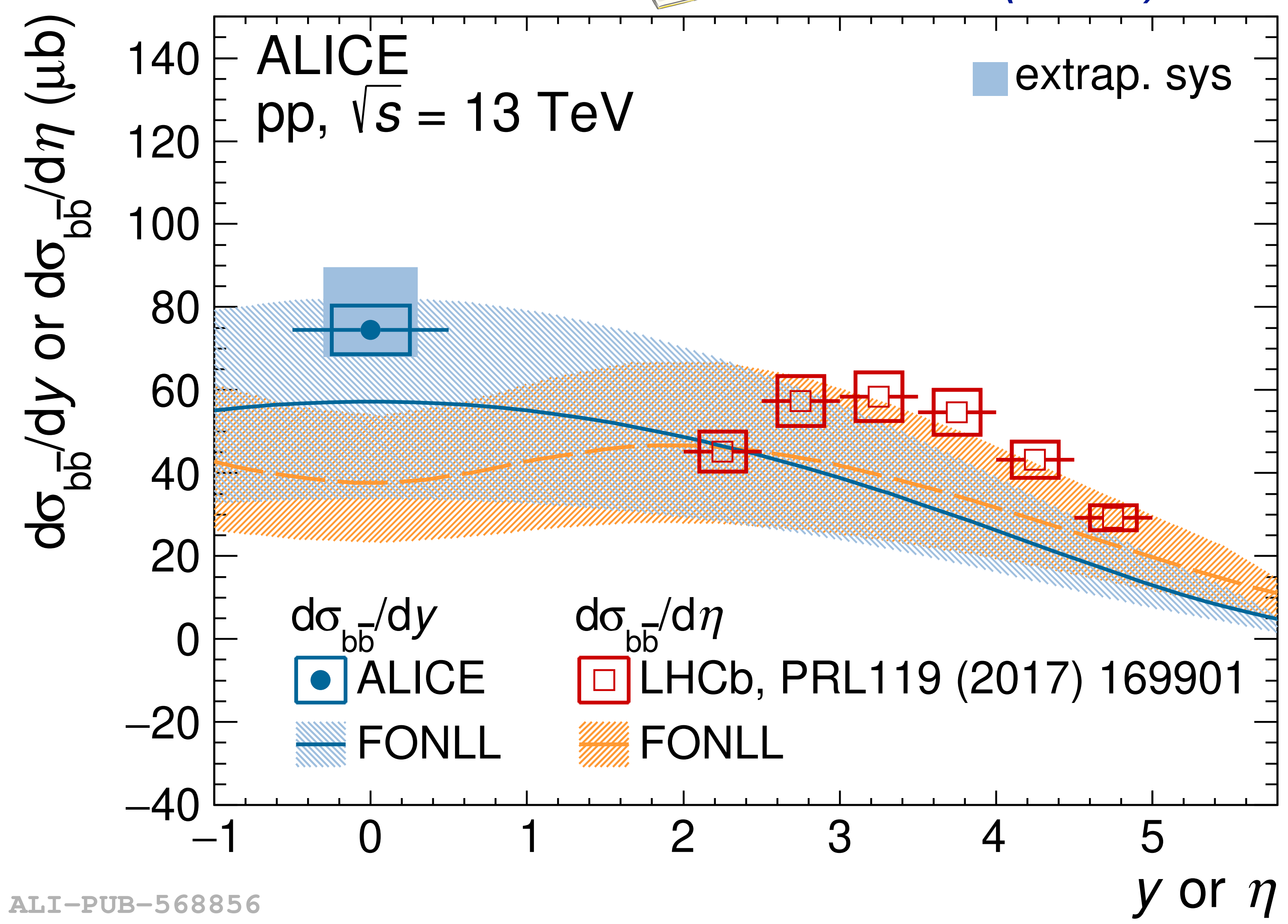


Beauty



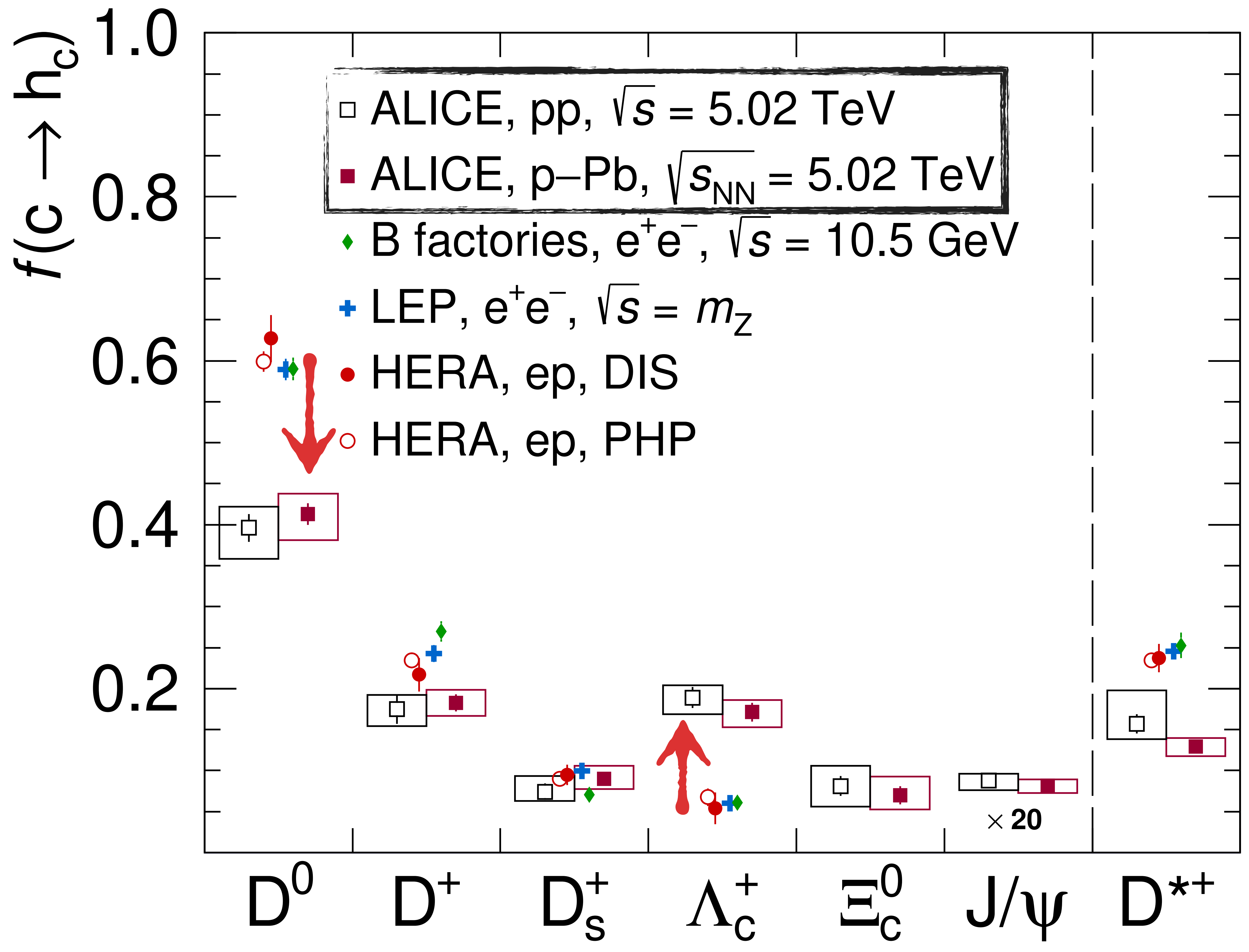


JHEP 10 (2024) 110



- $\sigma(c\bar{c})$ 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



ALI-PUB-570972

arXiv:2405.14571 (accepted by EPJC)

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

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

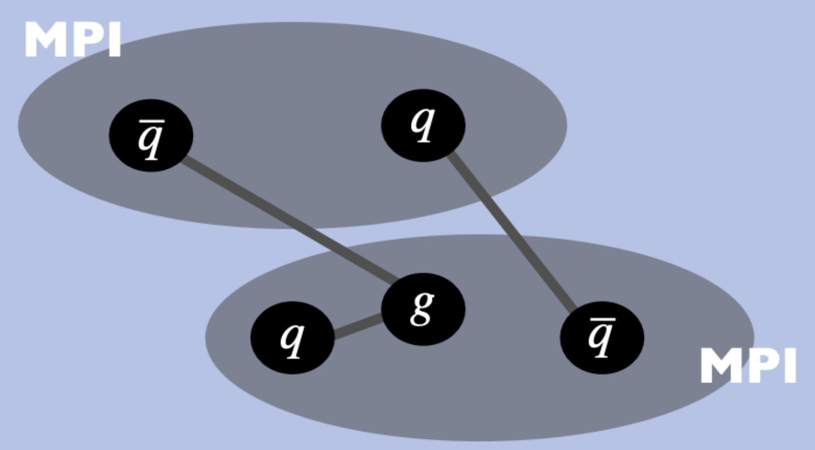
Fragmentation fractions universality is challenged

- 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

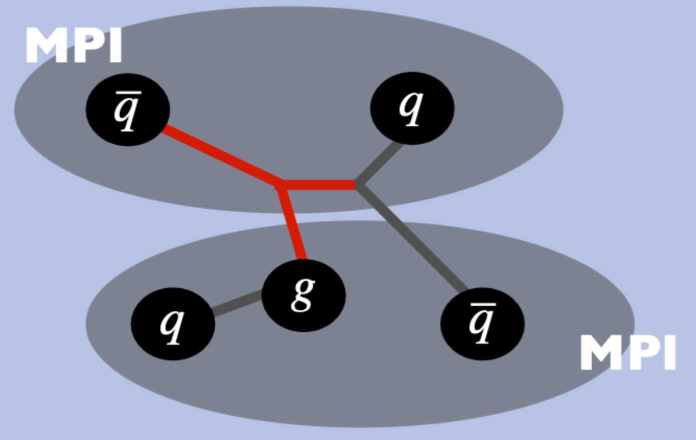
Modeling hadronization

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

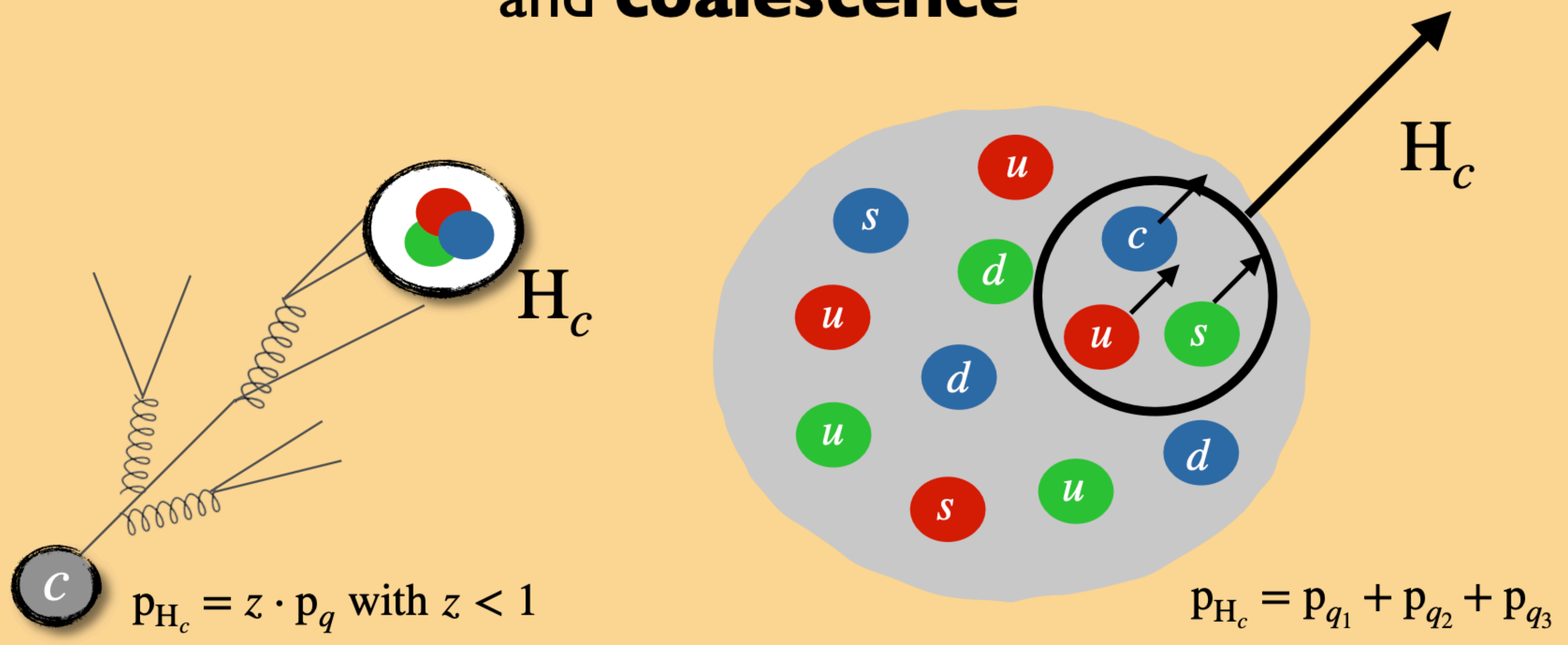


Mode 2
the **junction** topology leads to an increase of baryon production
JHEP 08 (2015) 003

CATANIA

Phys.Lett.B 821 (2021) 136622

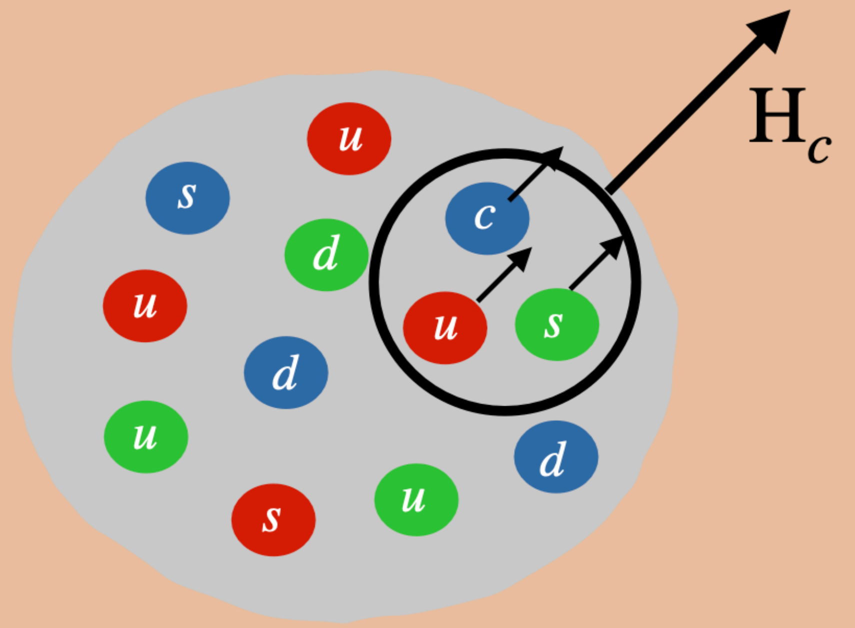
Hadronization via both **fragmentation** and **coalescence**



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

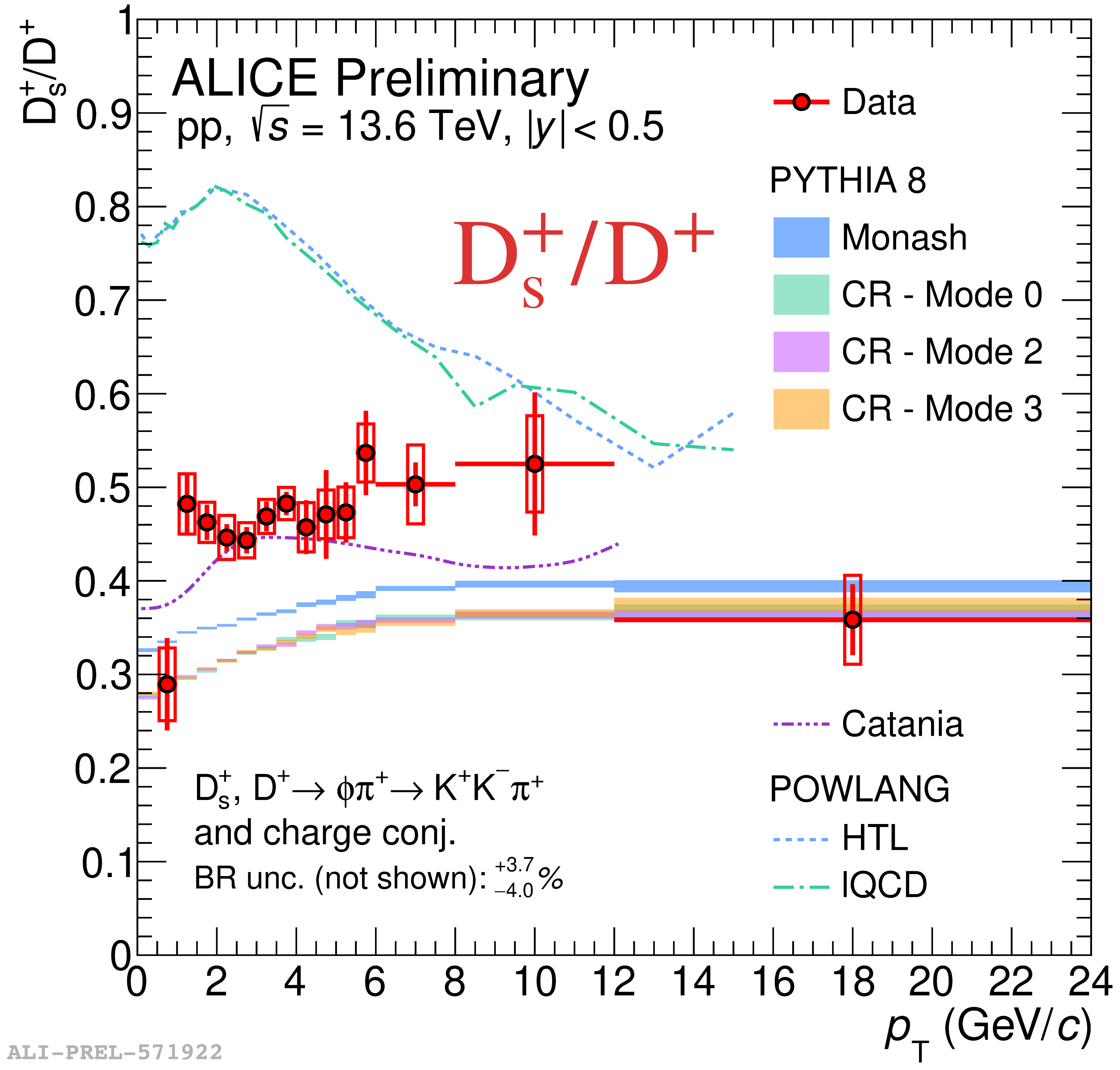
Phys.Lett.B 795 (2019) 117-121
Phys.Rev.D. 84 (2011) 014025

- 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

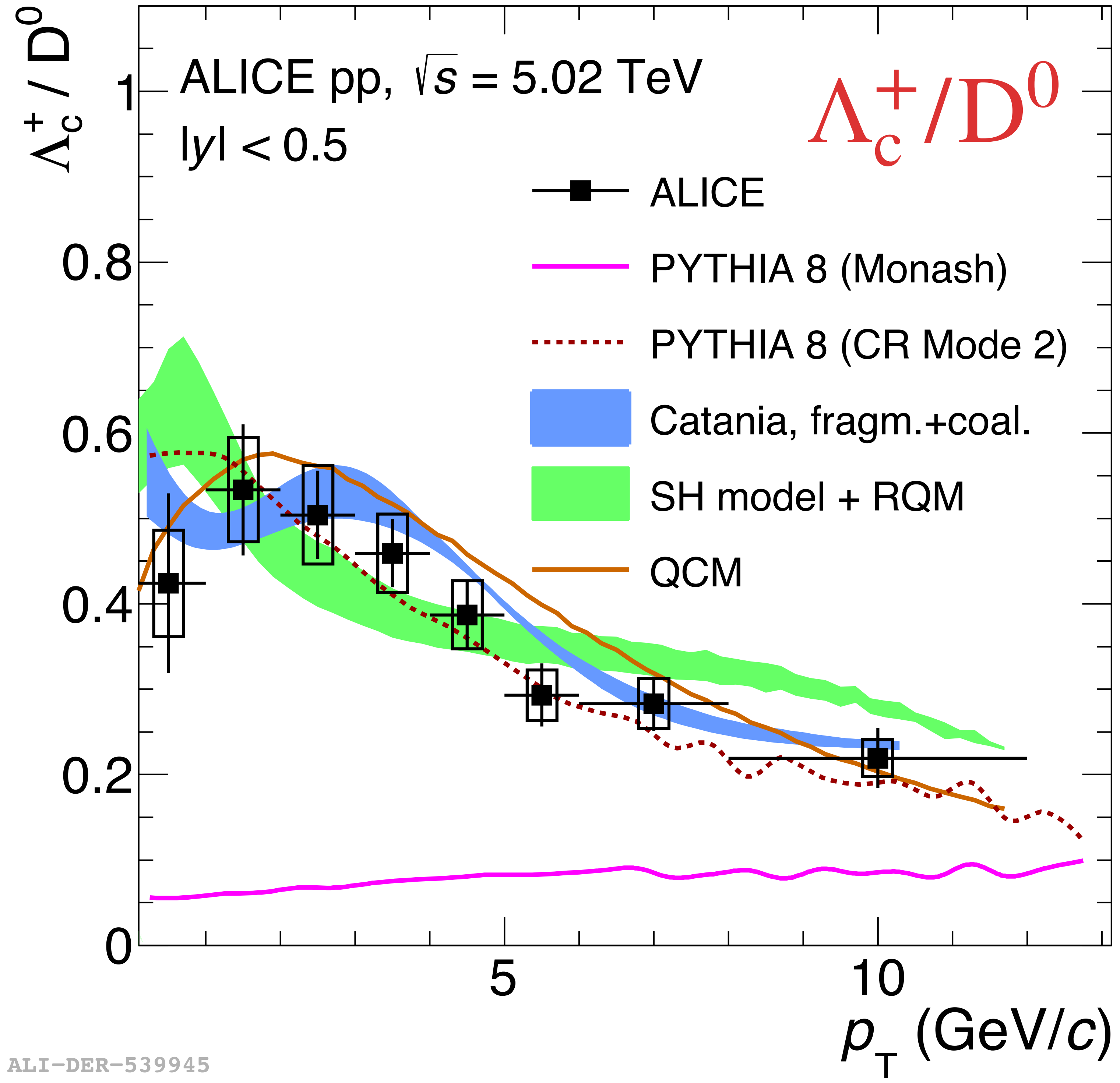
EPOS4HQ fragmentation + coalescence + resonance + UrQMD

Hadronisation: HF particle ratios in pp collisions

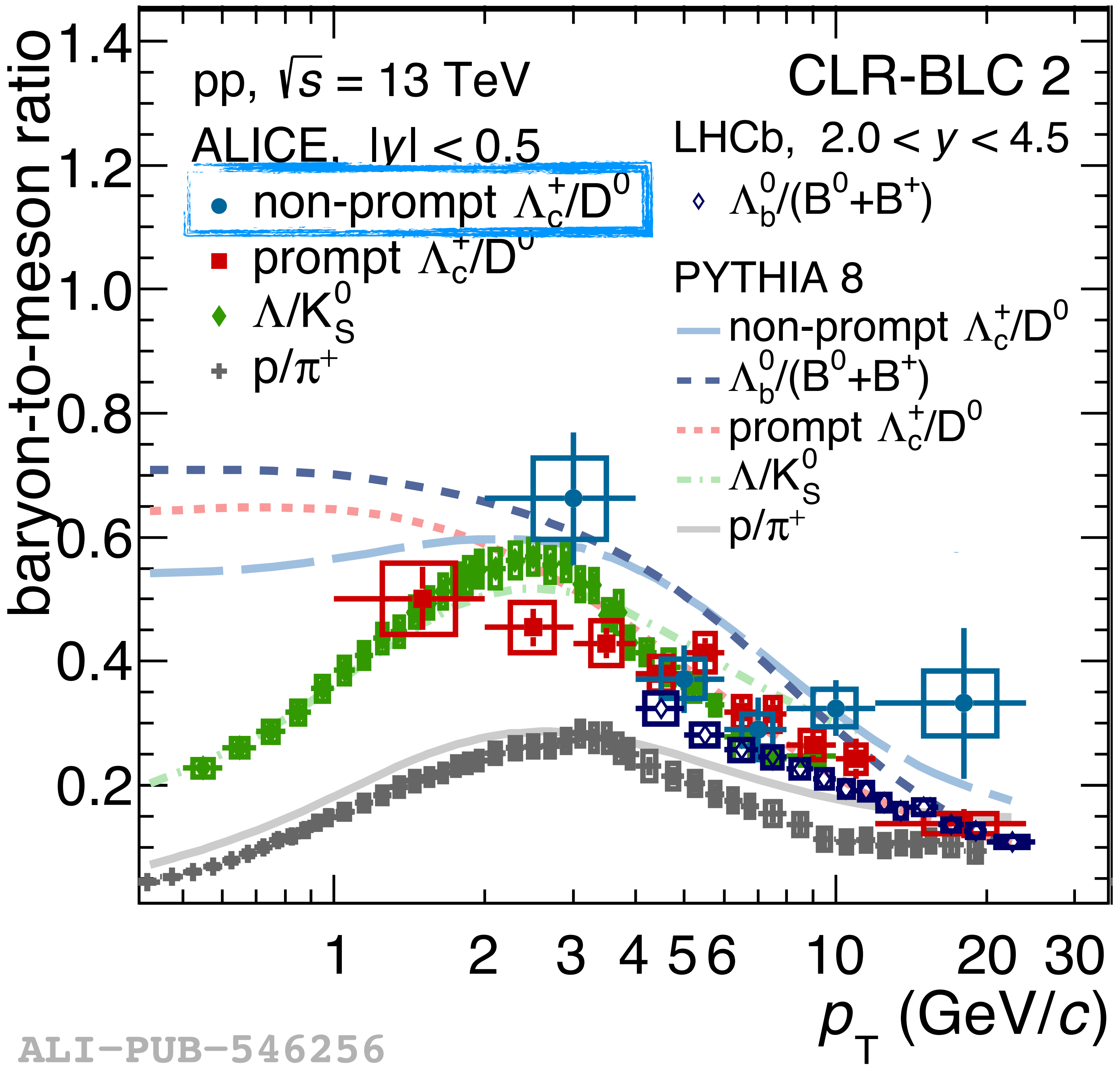
Run 3



Phys.Rev.C 107 (2023) 064901



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

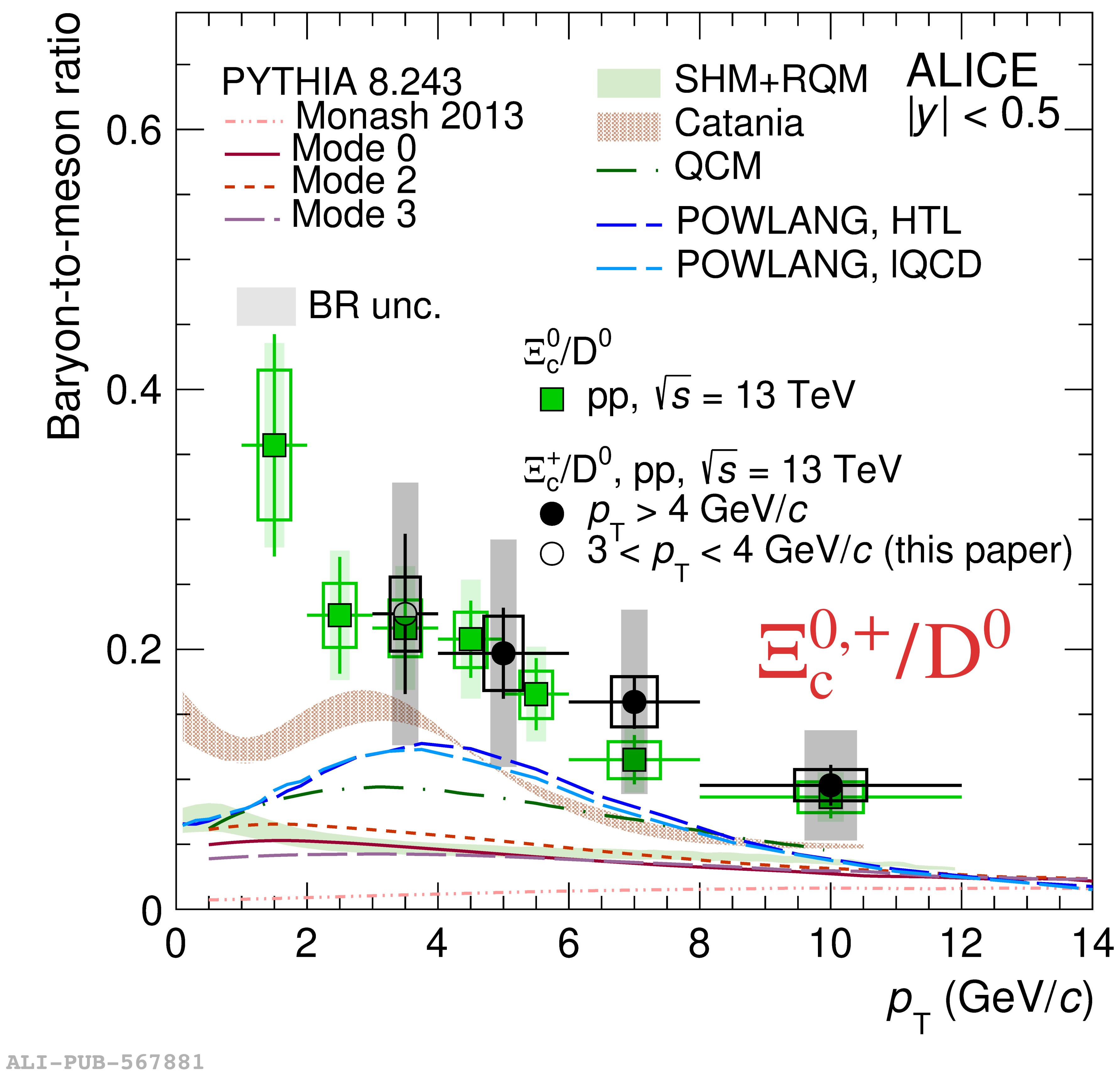
- Coalescence in pp collisions
- Assume a thermalised QGP-like system

Non-prompt Λ_c^+/D^0

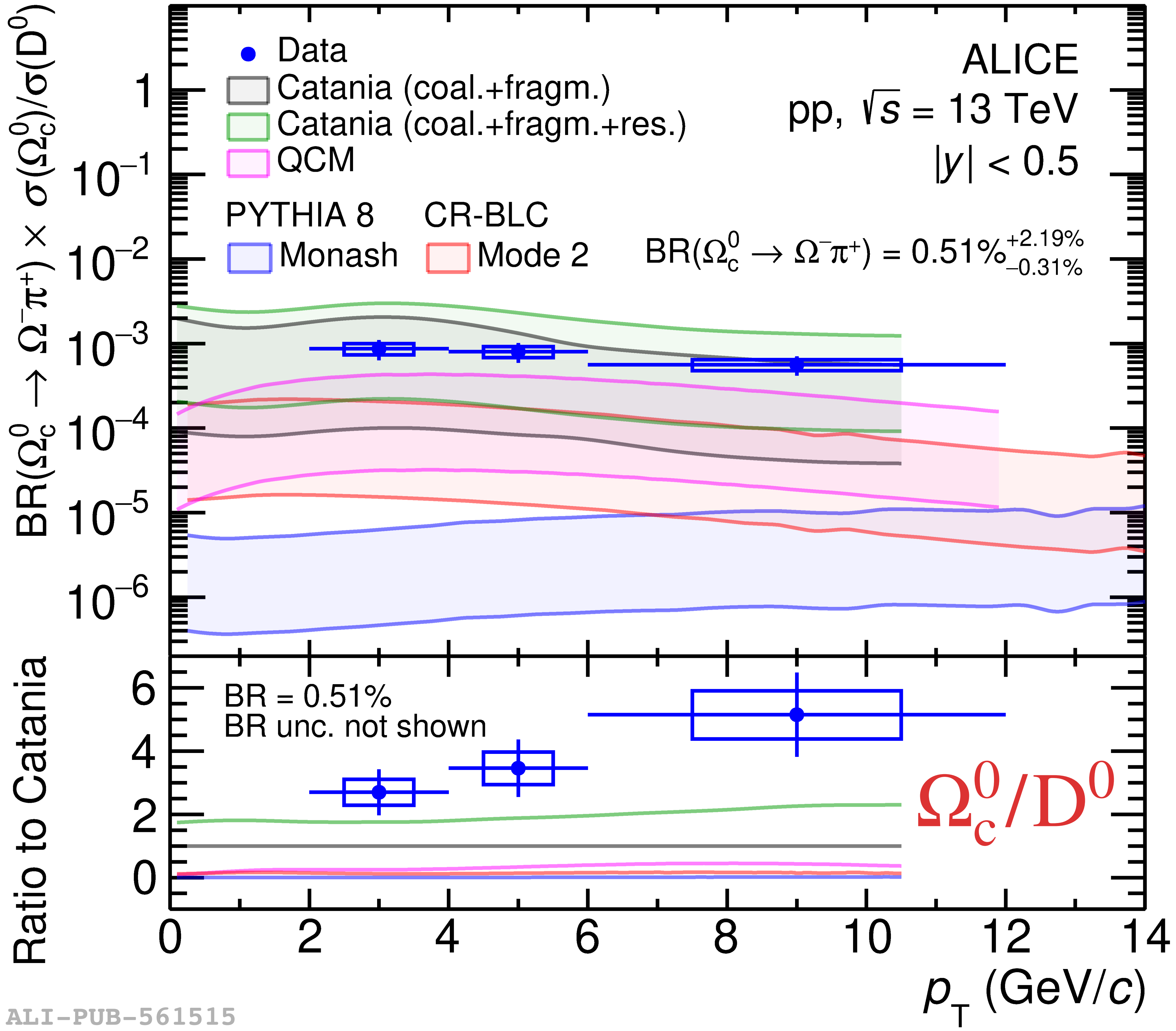
- Beauty, charm, and strange hadrons show a similar p_T trend

Hadronisation: HF particle ratios in pp collisions

JHEP 12 (2023) 086



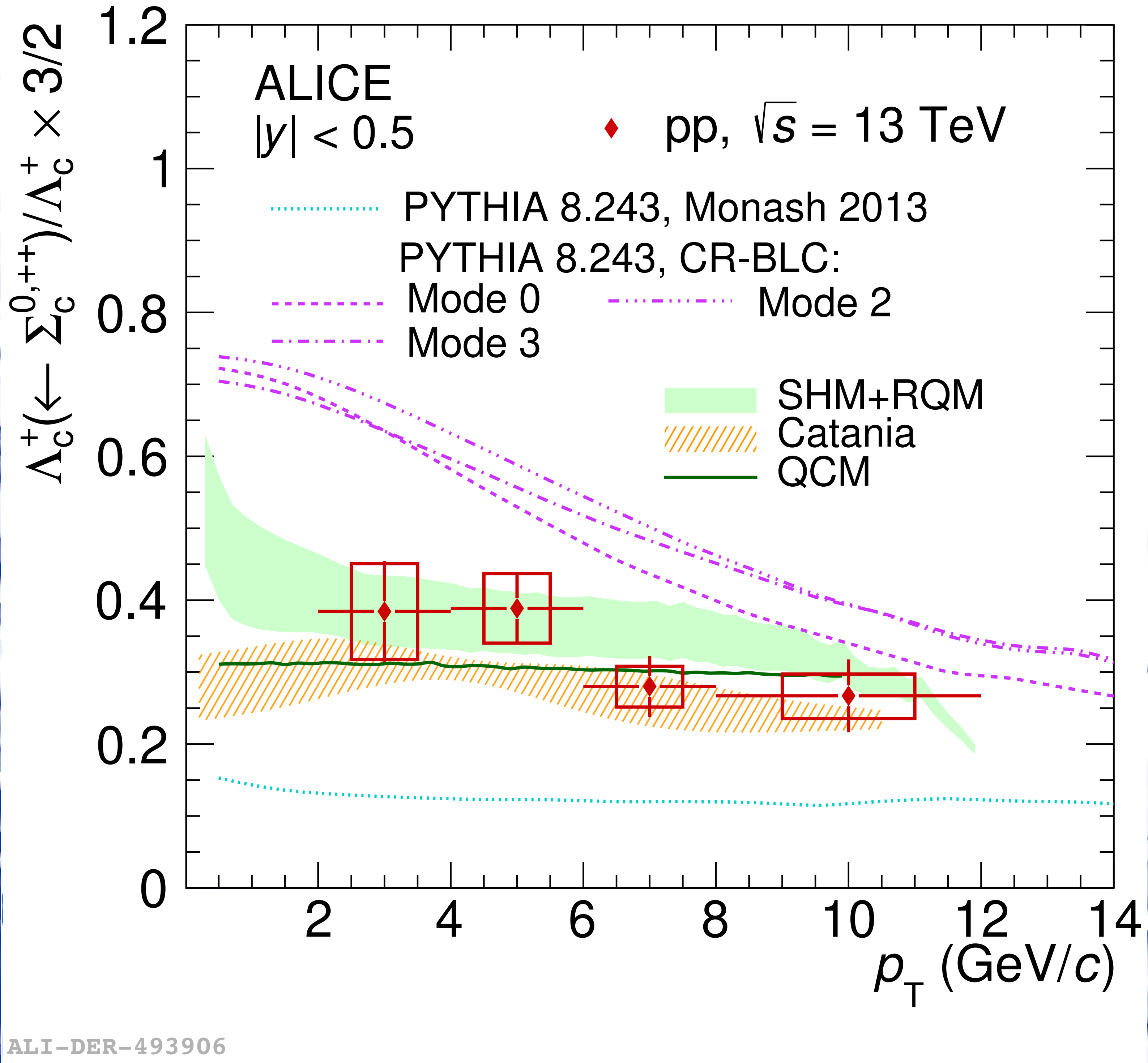
PLB 846 (2023) 137625



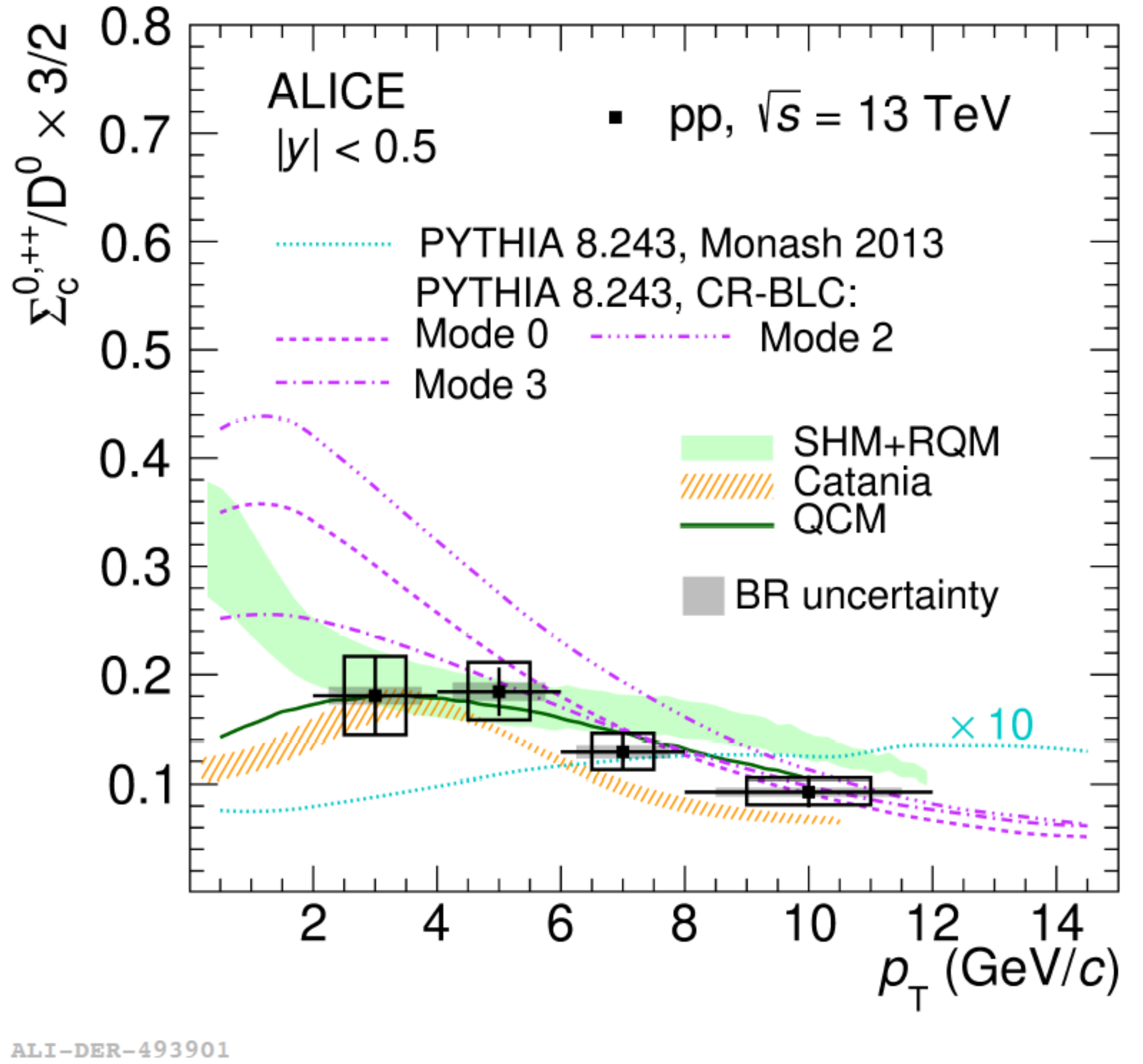
- Models cannot describe $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0
- The role of strangeness in HF hadronisation might be a challenge to theory

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*
QCM: *Eur.Phys.J.C 78 (2018) 344*

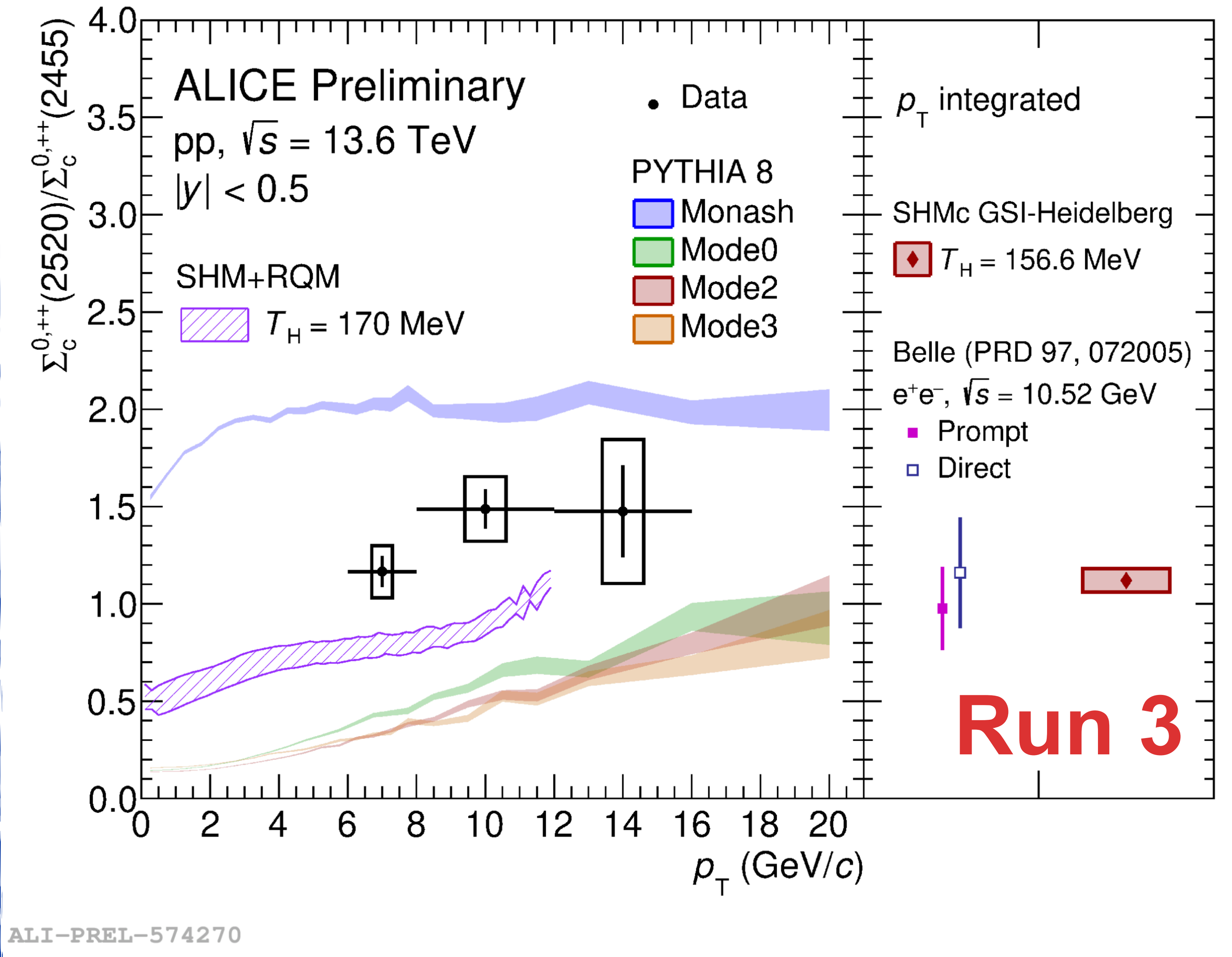
Hadronisation: higher mass particles decay



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



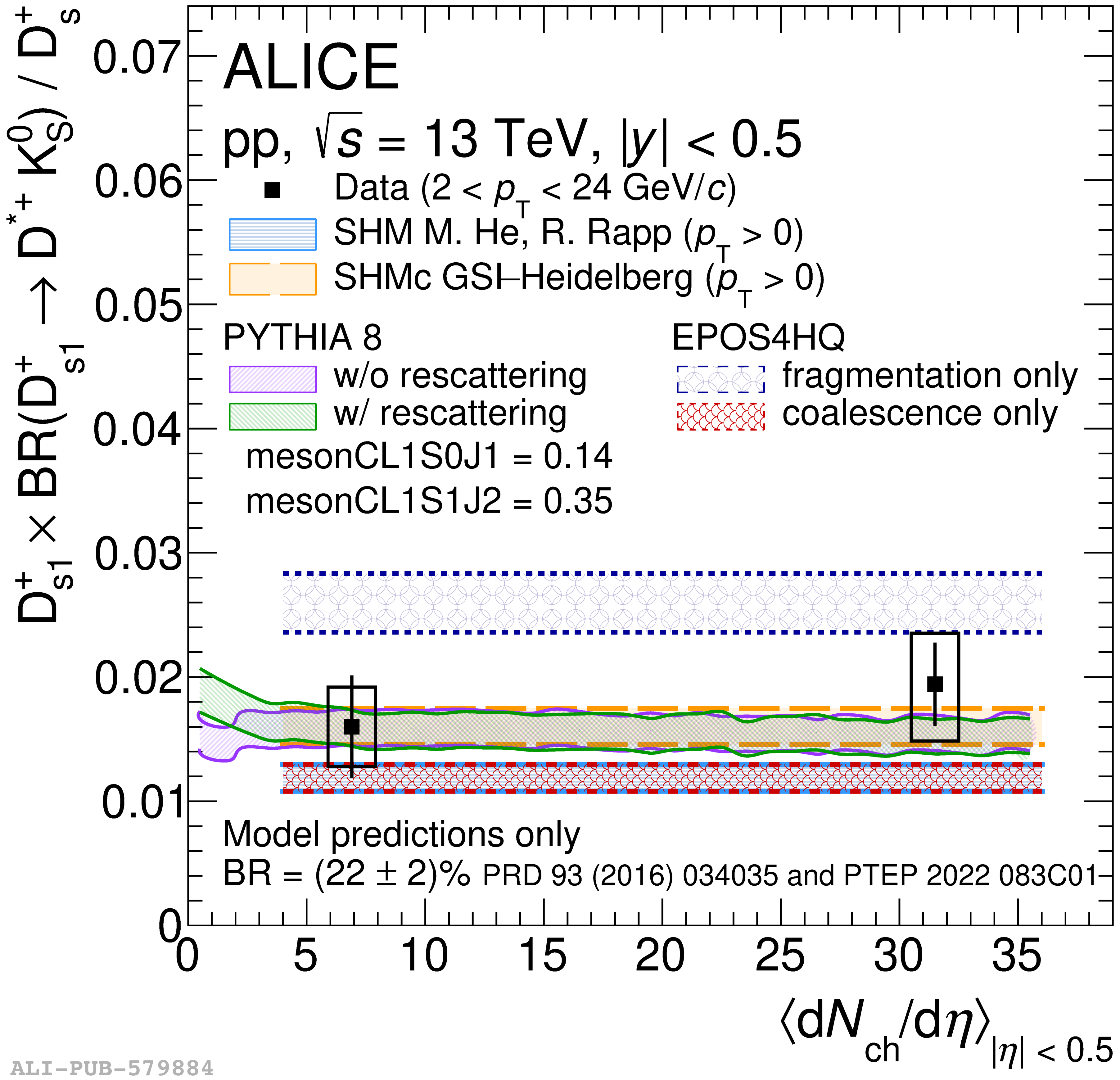
- Described by PYTHIA 8 CR, Catania, QCM and SHM+RQM

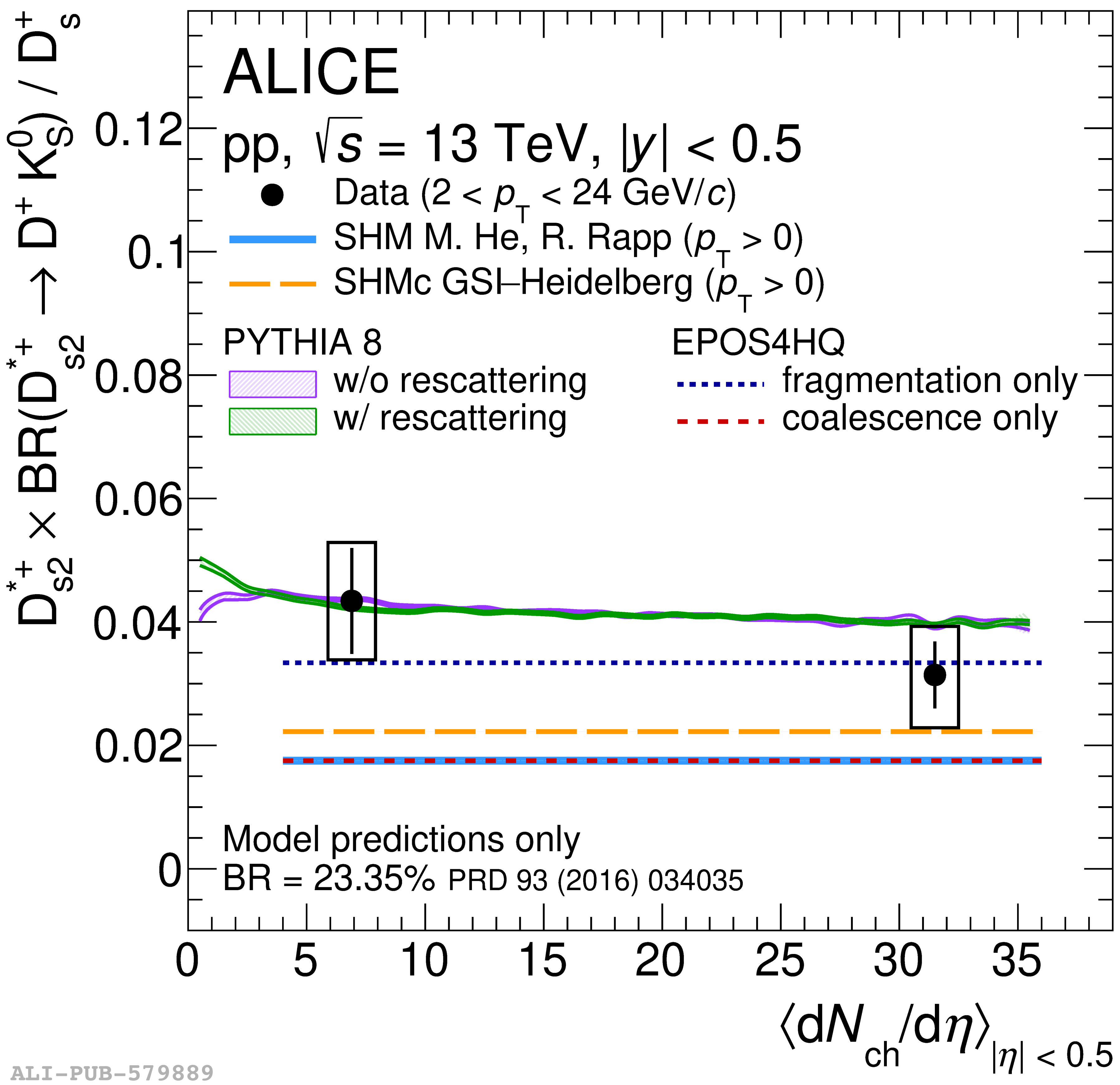


- Ratios between two $\Sigma_c^{0,++}$ states consistent with p_T integrated result from e^+e^- collisions
- Overestimated by PYTHIA 8 Monash, underestimated by CR and SHM+RQM

Hadronisation: resonances decay

arXiv:2409.11938

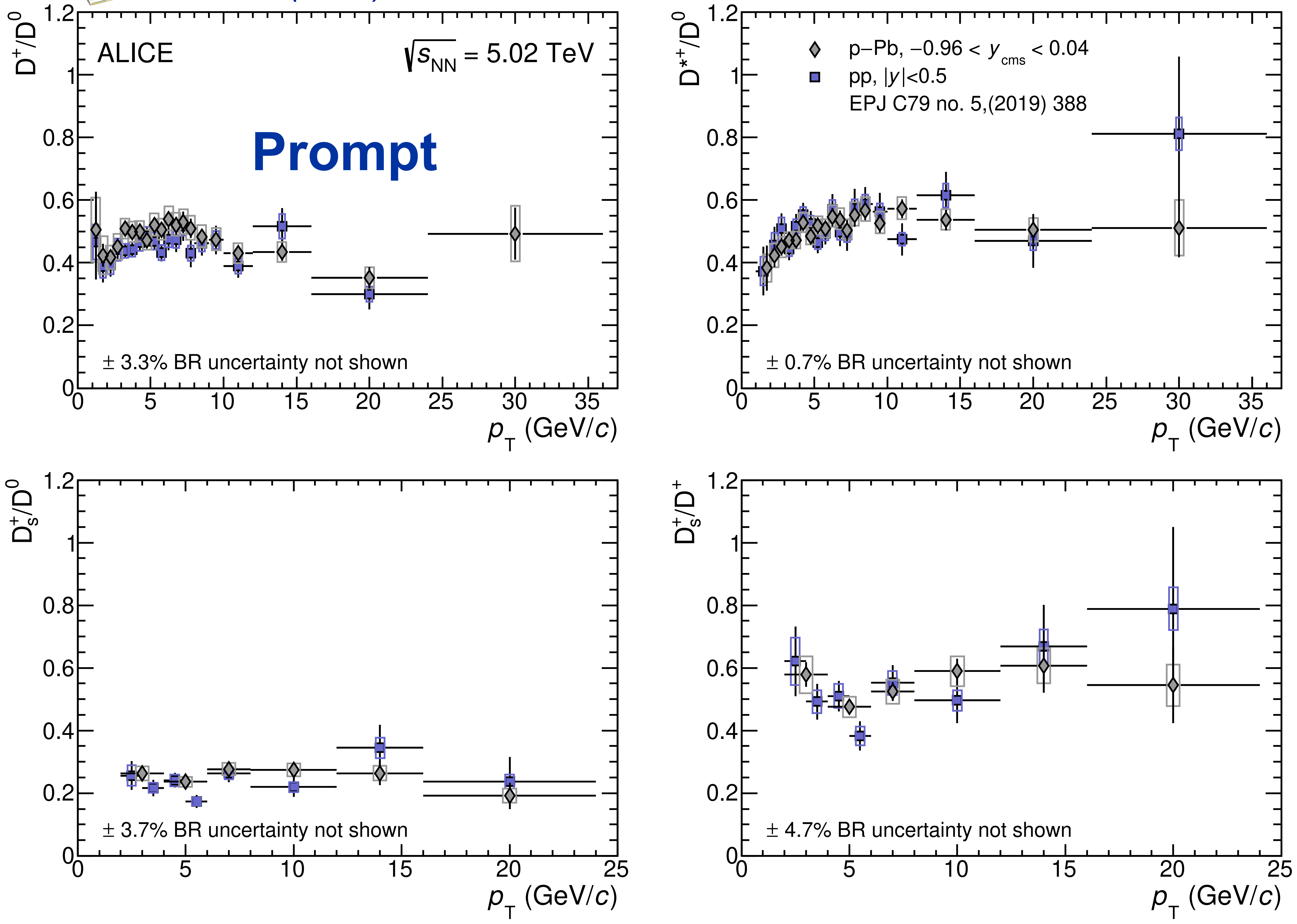




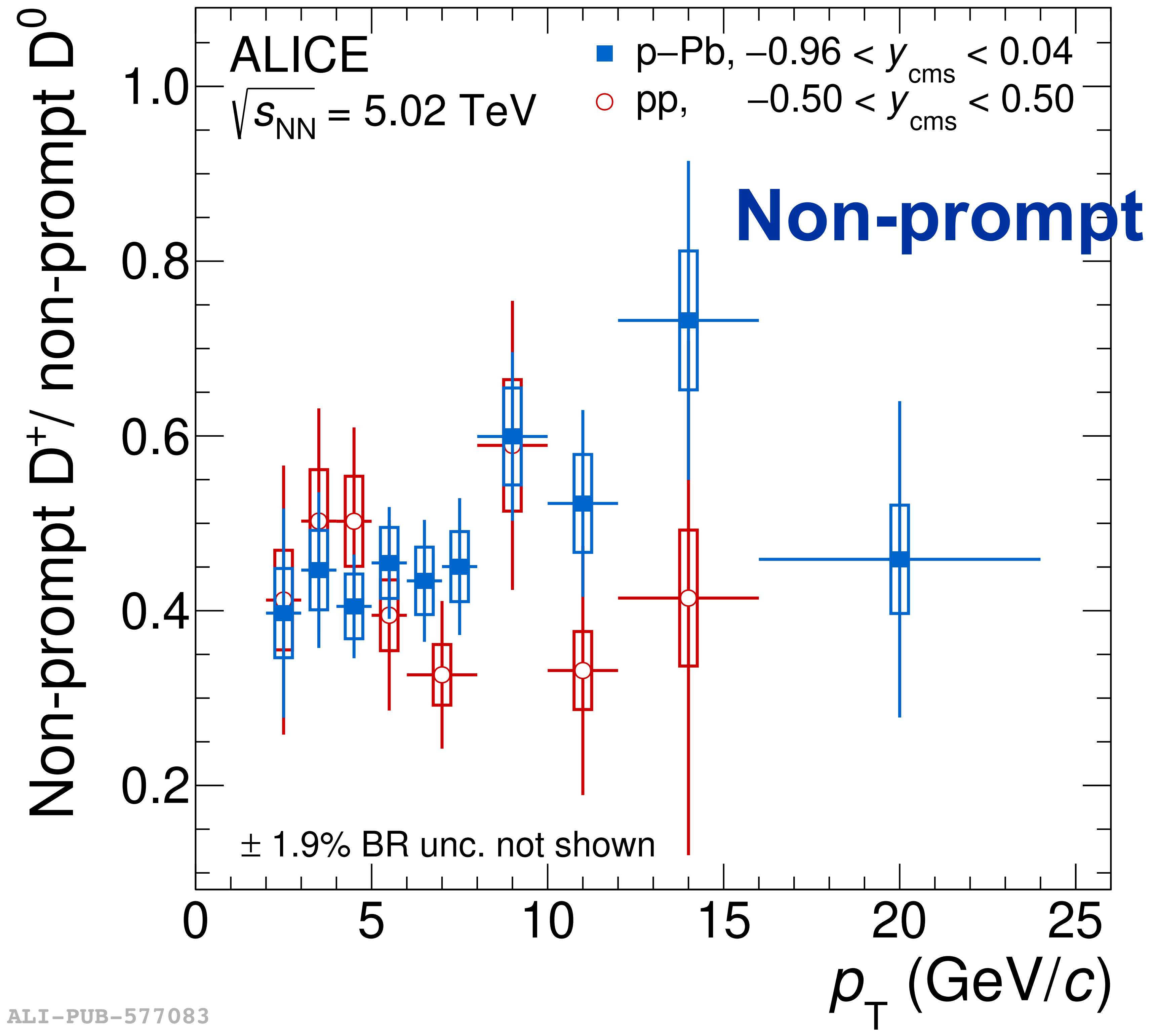
- D_{s1}^{+}/D_{s}^{+} and D_{s2}^{*+}/D_{s}^{+} ratios flat vs. charged-particle multiplicity, as ground-state D-meson ratios
- Multiplicity trend described by SHM, SHMc, EPOS4HQ models and by PYTHIA 8 calculations

Hadronisation: D-meson ratios in p–Pb collisions

JHEP 12 (2019) 092



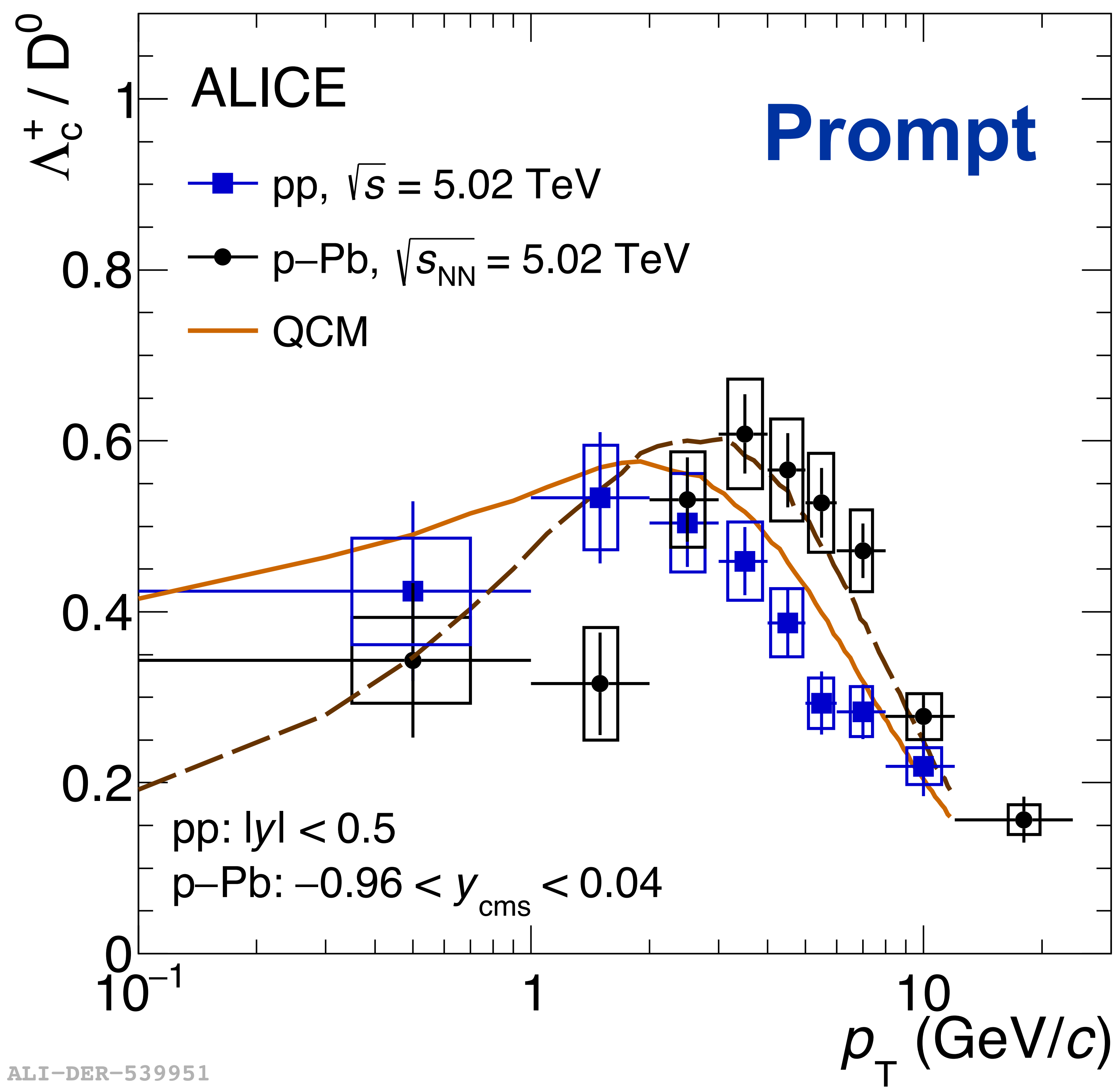
arXiv:2407.10593



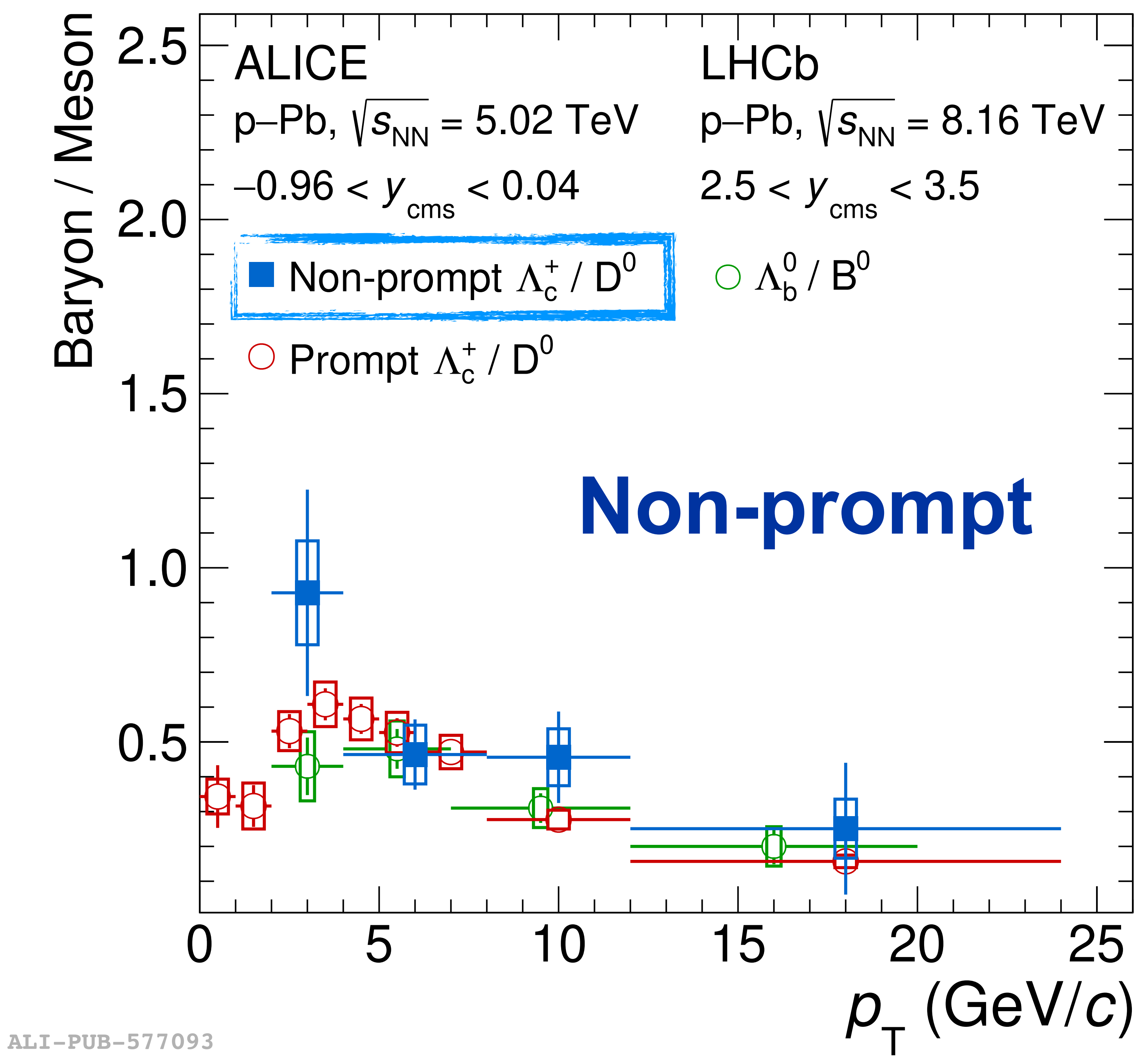
- (Prompt D^+ or $\mathrm{D_s^+}$) / (prompt D^0) in p–Pb is compatible with pp results
- (Non-prompt D^+) / (non-prompt D^0) in p–Pb is compatible with pp results

Hadronisation: Λ_c^+/D^0 in p–Pb collisions

Phys.Rev.C 107 (2023) 064901



arXiv:2407.10593



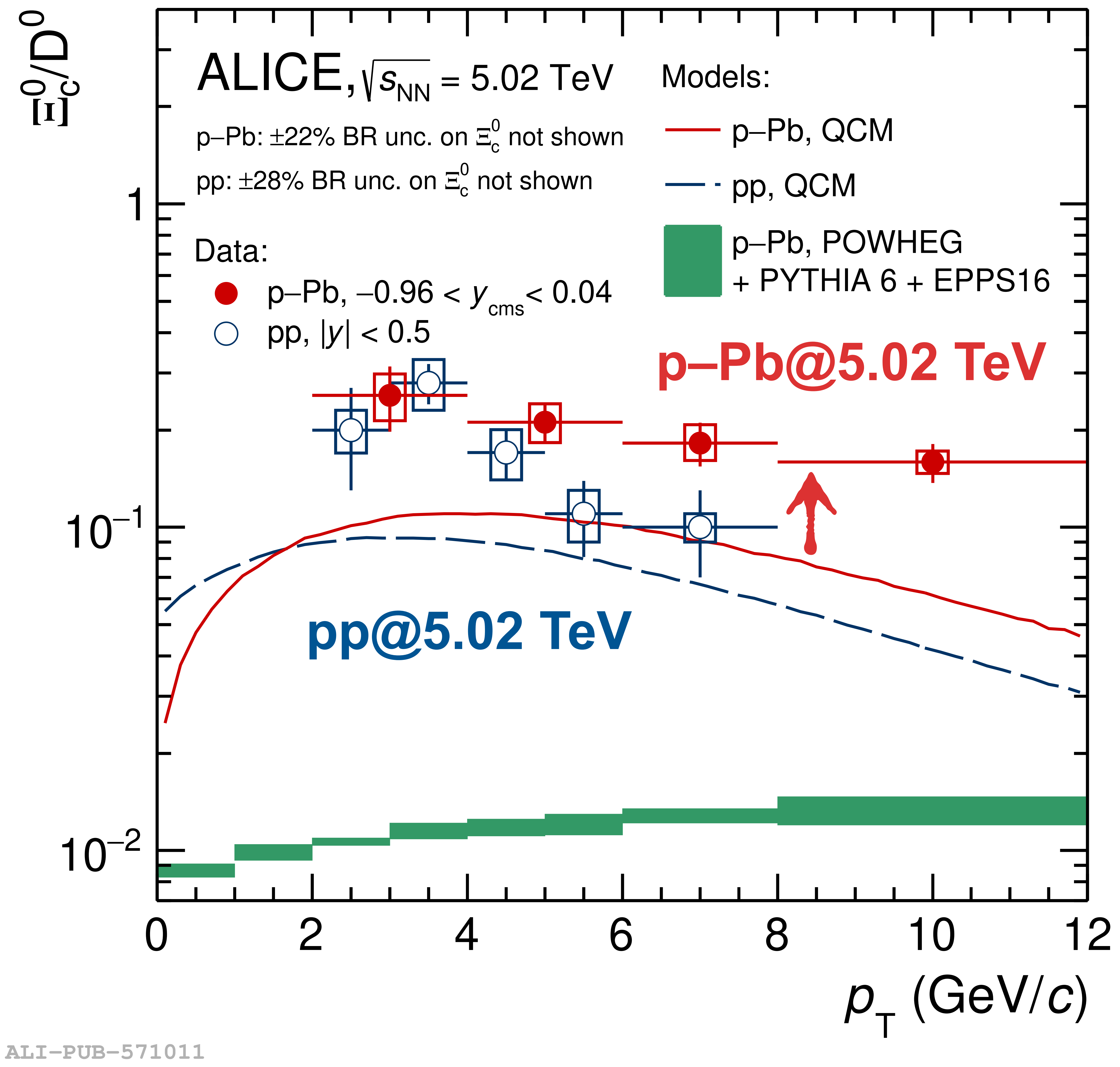
Prompt Λ_c^+/D^0 in p–Pb collisions

- First measurement down to $p_T = 0$
- Shift of peak towards higher p_T could be due to quark recombination or collective effects (e.g. radial flow)
- Well described by quark (re)combination model (QCM)

Non-prompt Λ_c^+/D^0 in p–Pb collisions

- Similarity between prompt and non-prompt Λ_c^+/D^0 within uncertainties

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



arXiv:2405.14538

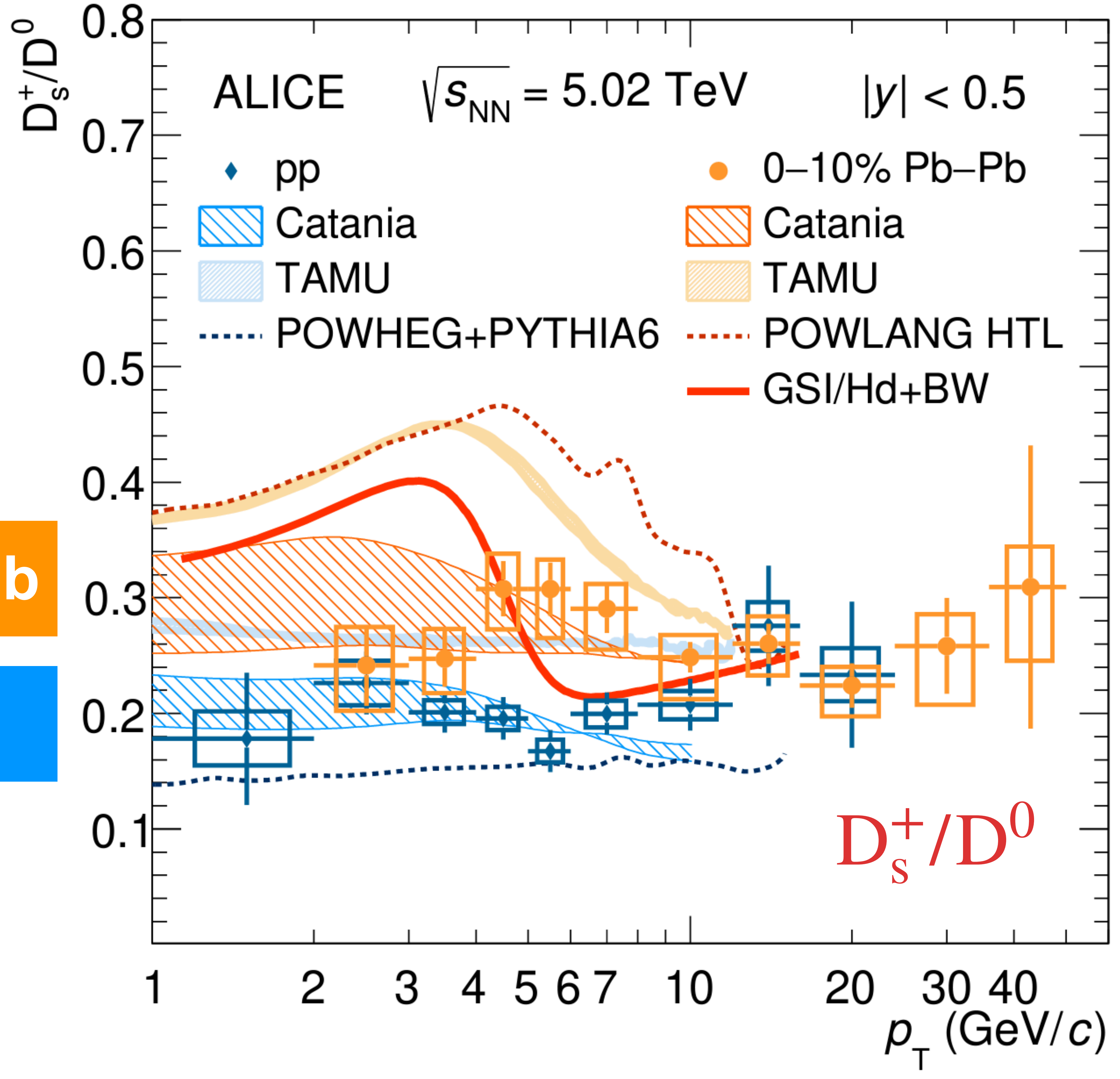
- Hint of enhancement at high p_T in p–Pb w.r.t. pp collisions
- Underestimated by QCM for both pp and p–Pb collisions

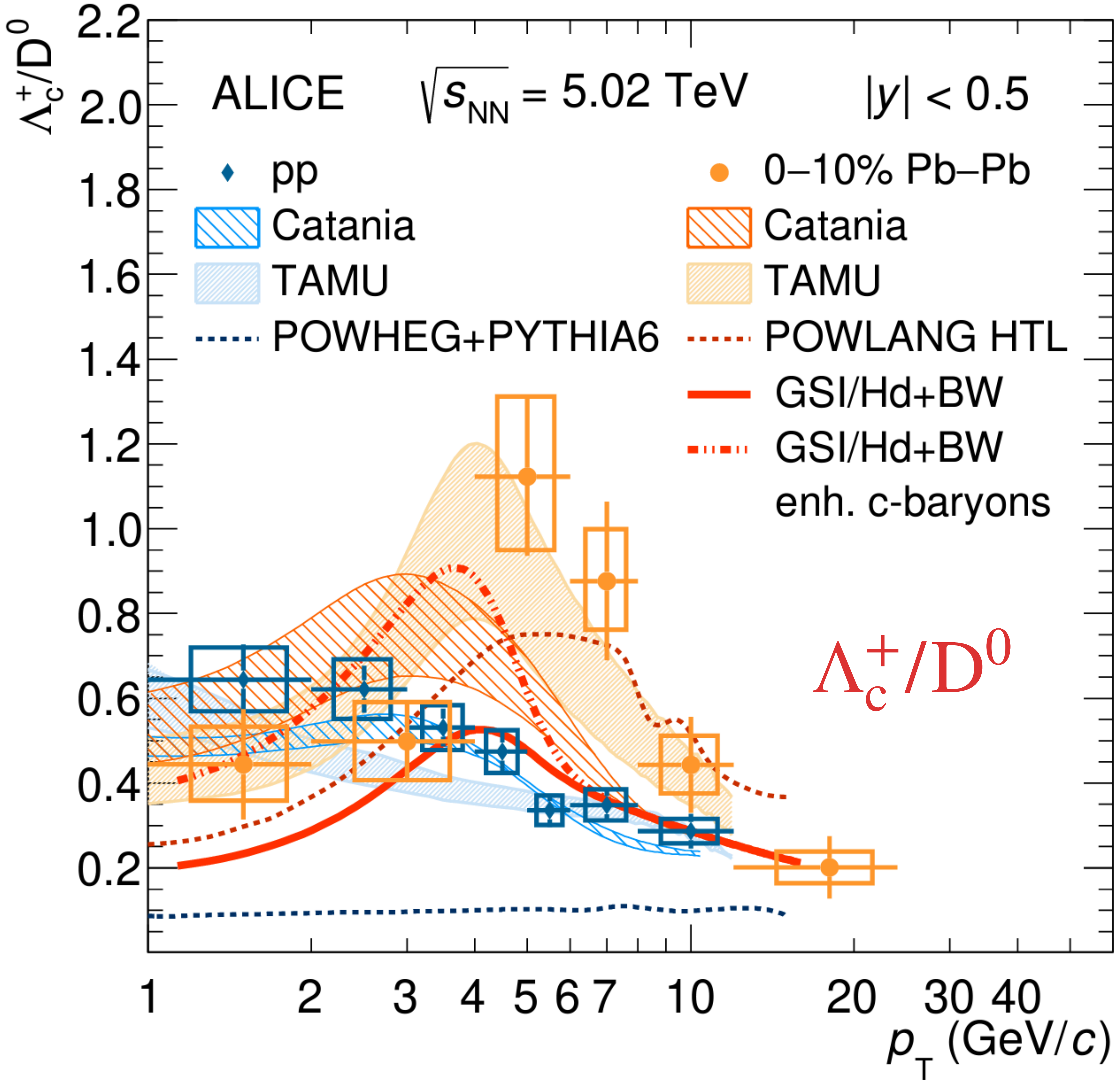
Hadronisation: large system

Eur.Phys.J.C 84 (2024) 813

Pb–Pb

pp

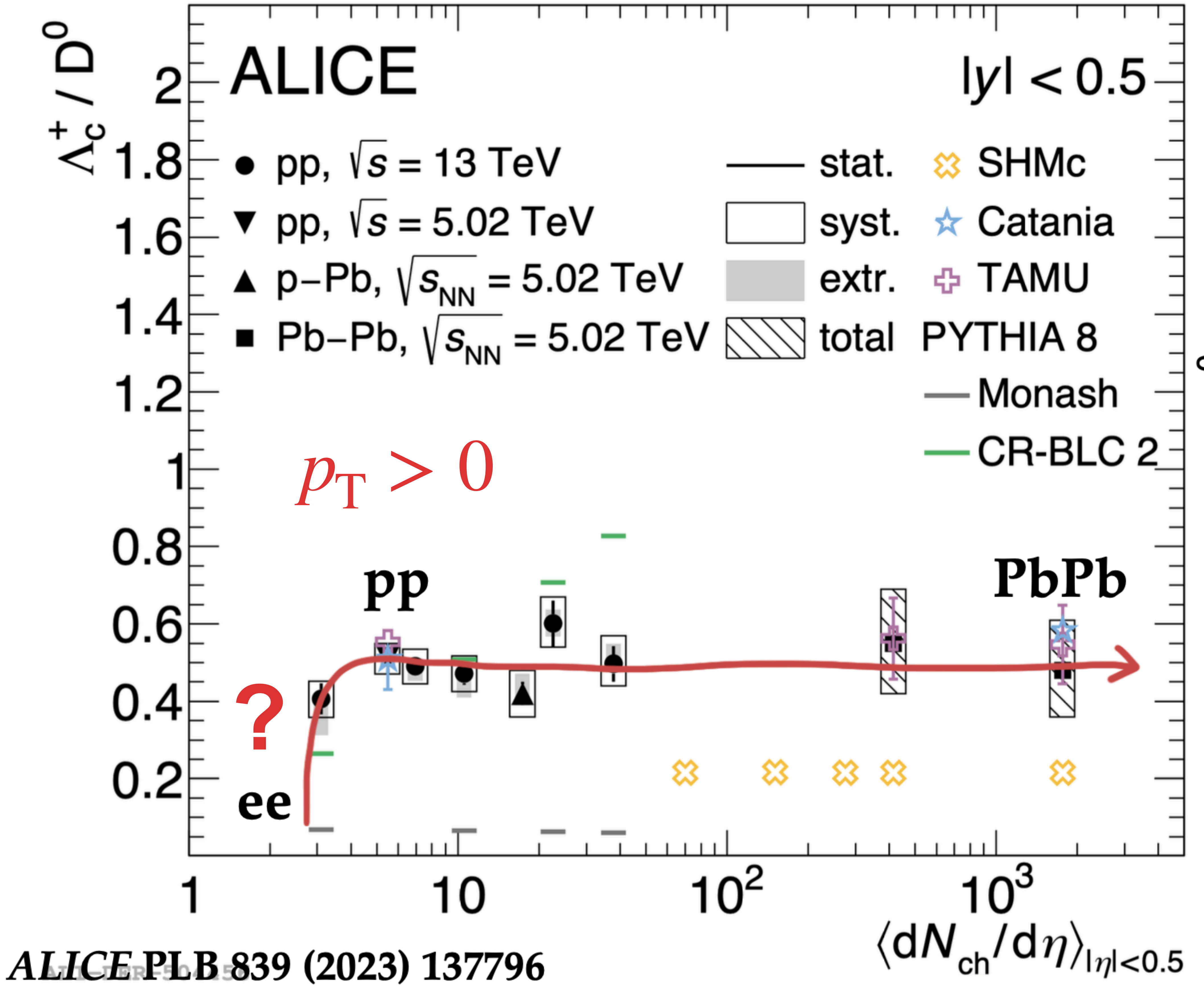




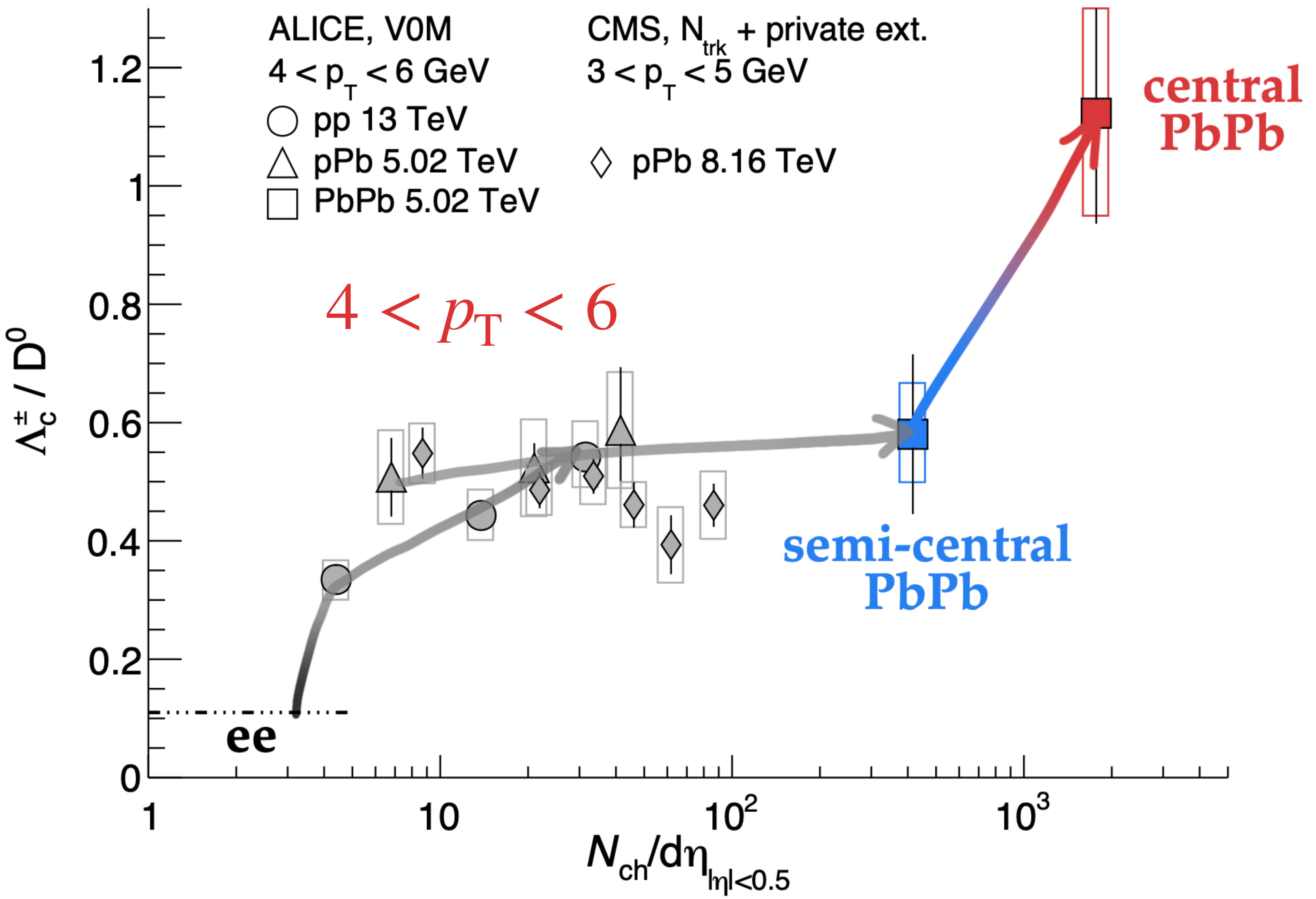
Ξ_c^0/D^0 in preparation, larger enhancement expected

- 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: system scan (by multiplicity)

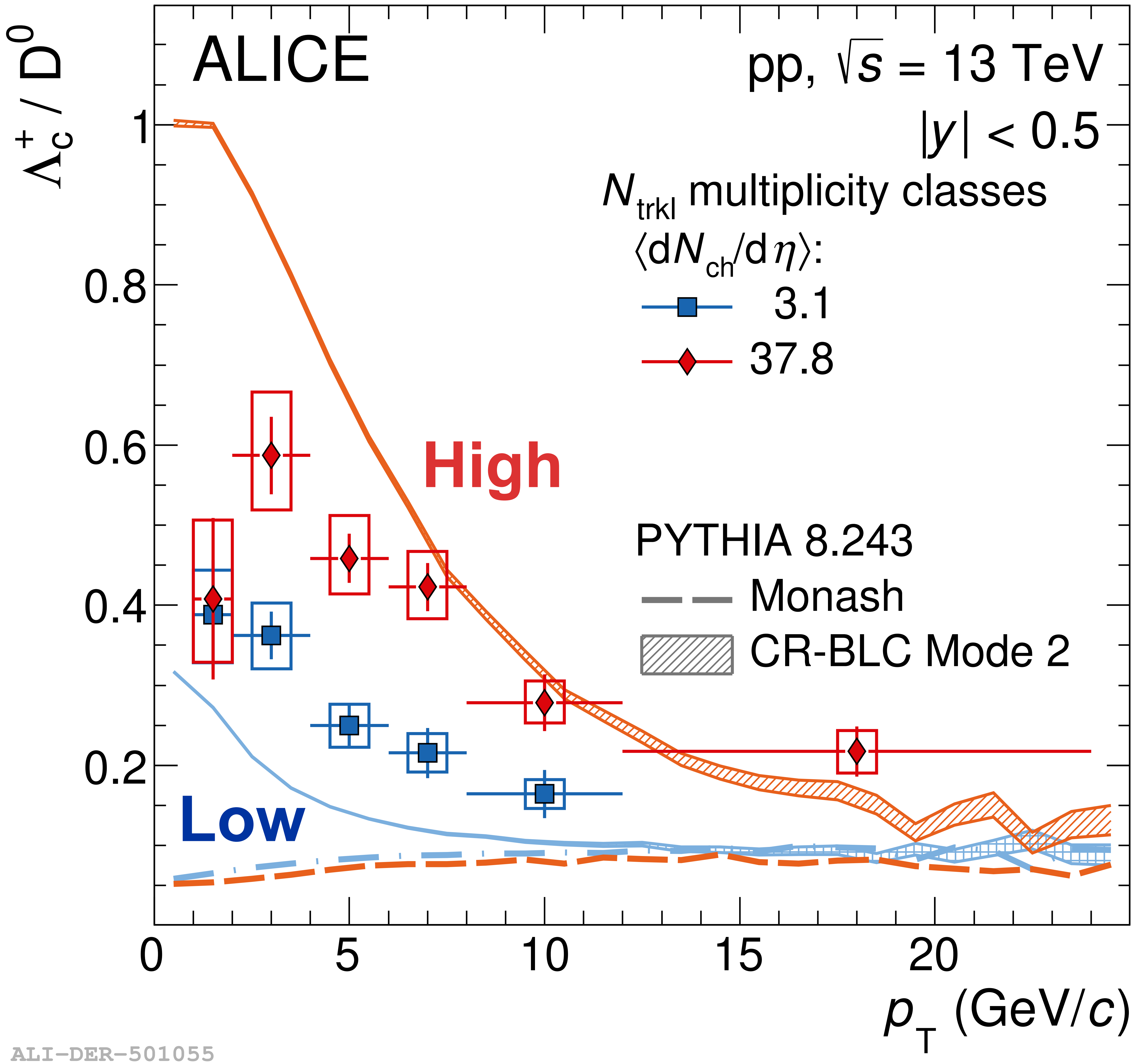


ALICE PLB 839 (2023) 137796



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

Hadronisation: vs. p_T in different multiplicity

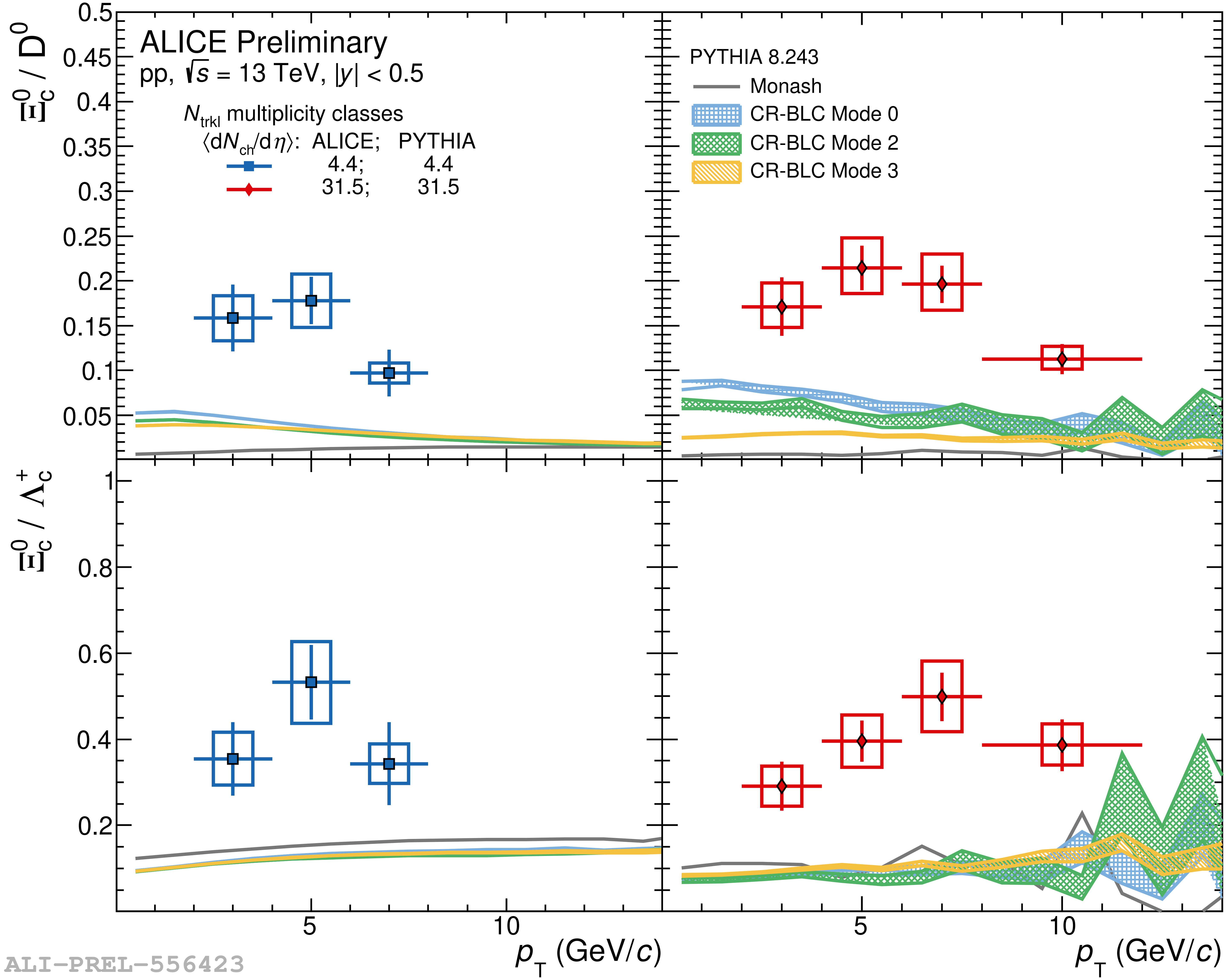


ALI-DER-501055

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

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

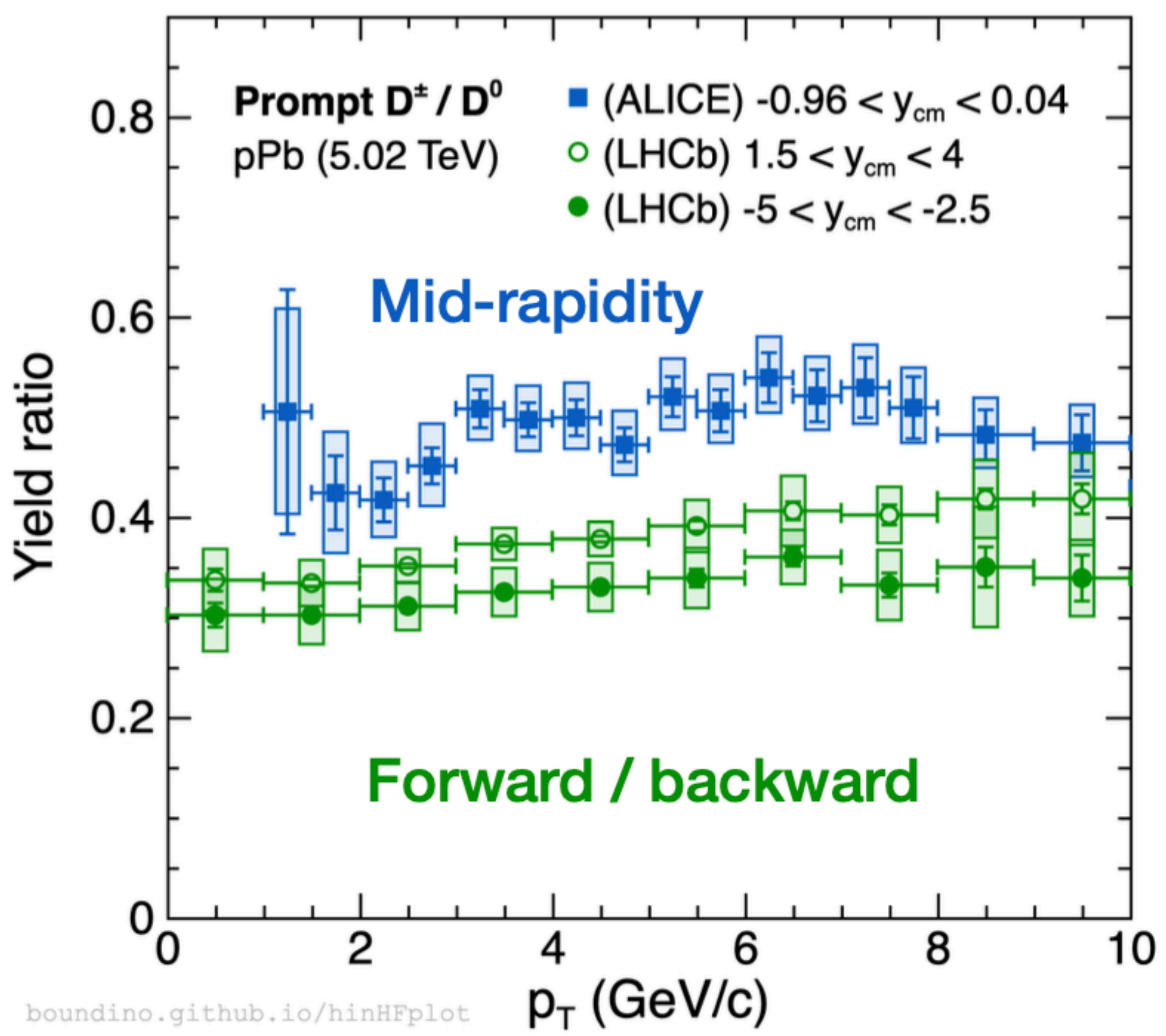
Hadronisation: vs. p_T in different multiplicity



- 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

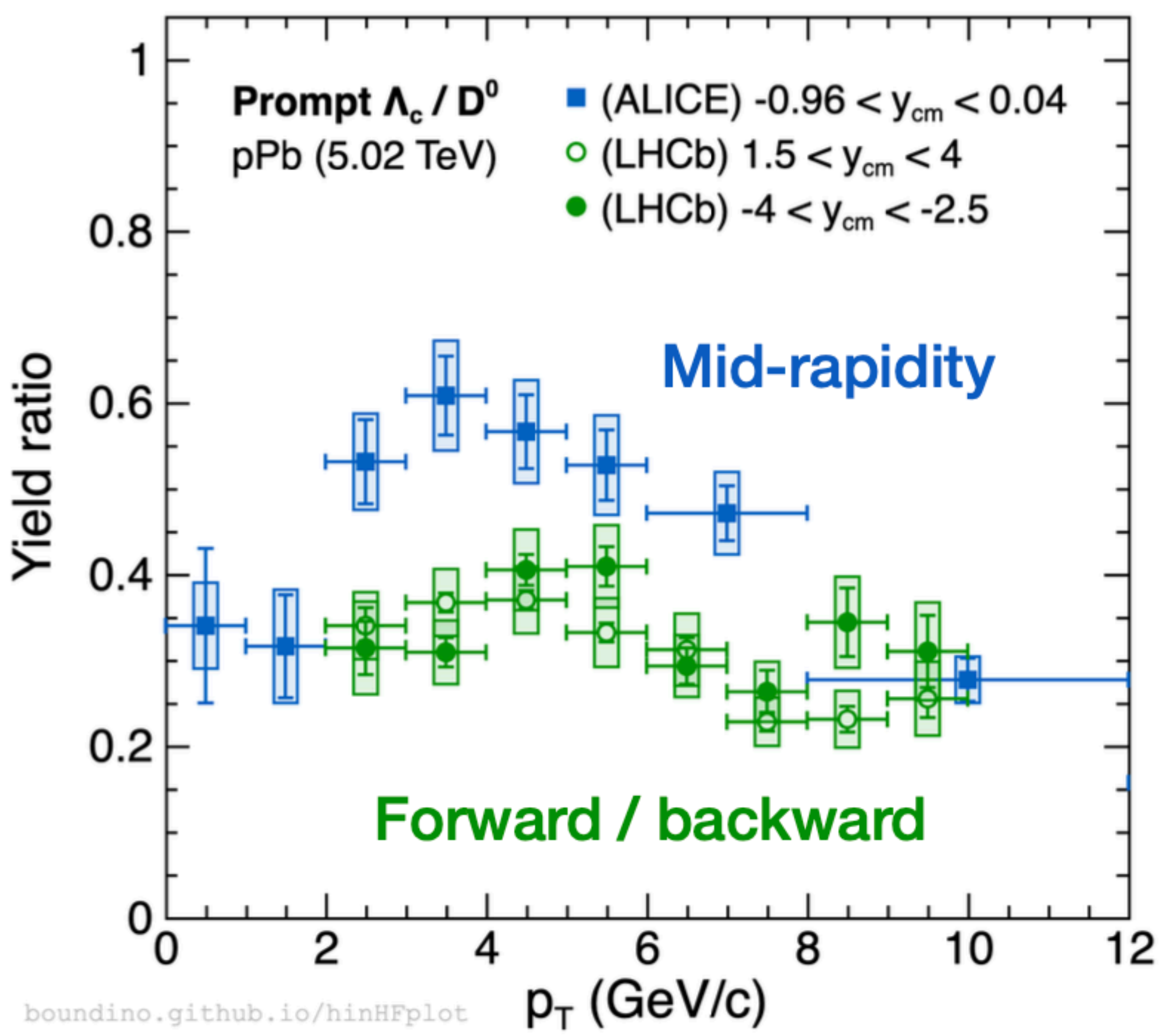
Hadronisation: rapidity dependence (more challenges)

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



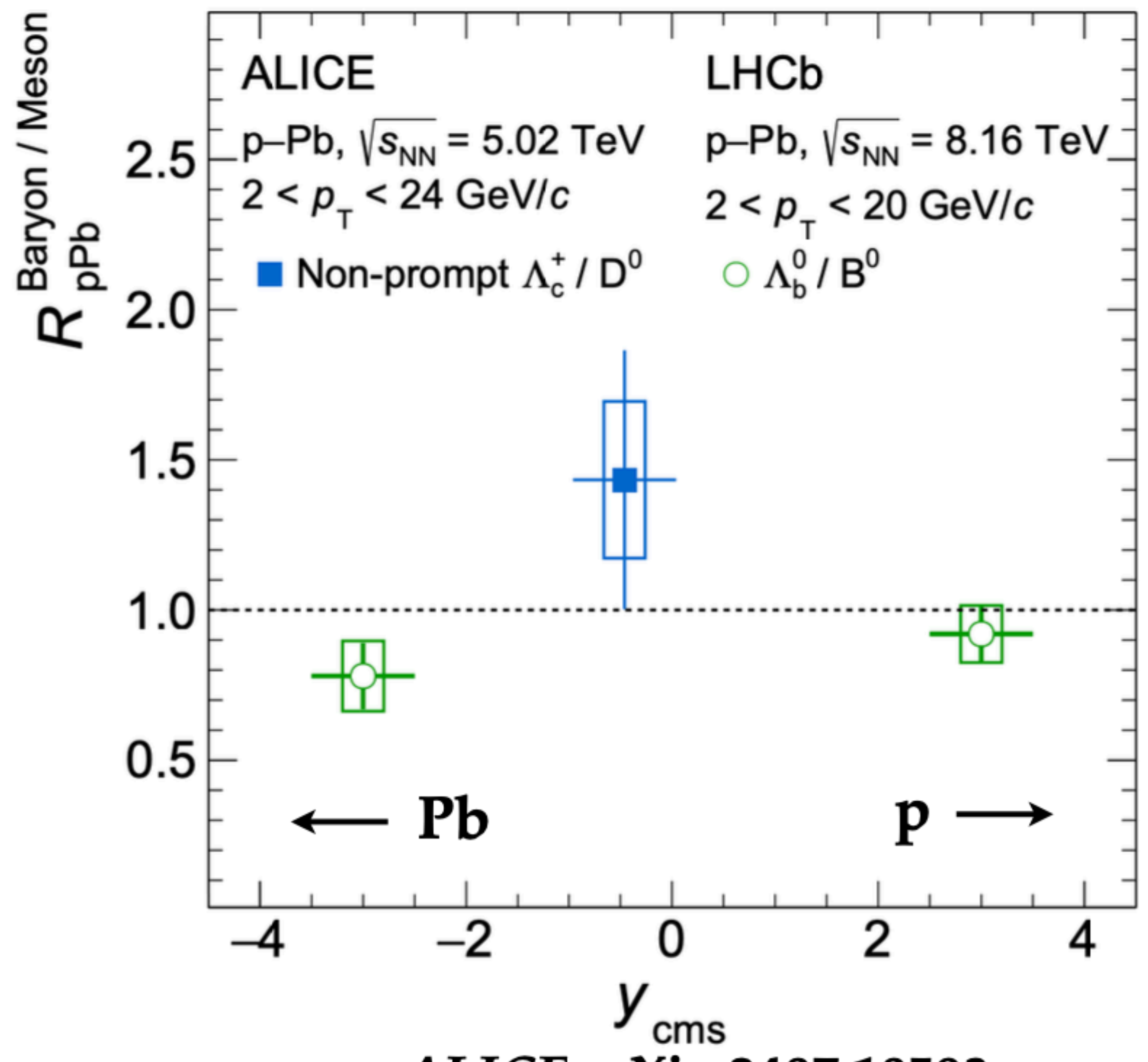
ALICE JHEP 12 (2019) 092
LHCb JHEP 01 (2024) 070

$\Lambda_c (cud)$ / $D^0 (c\bar{u})$



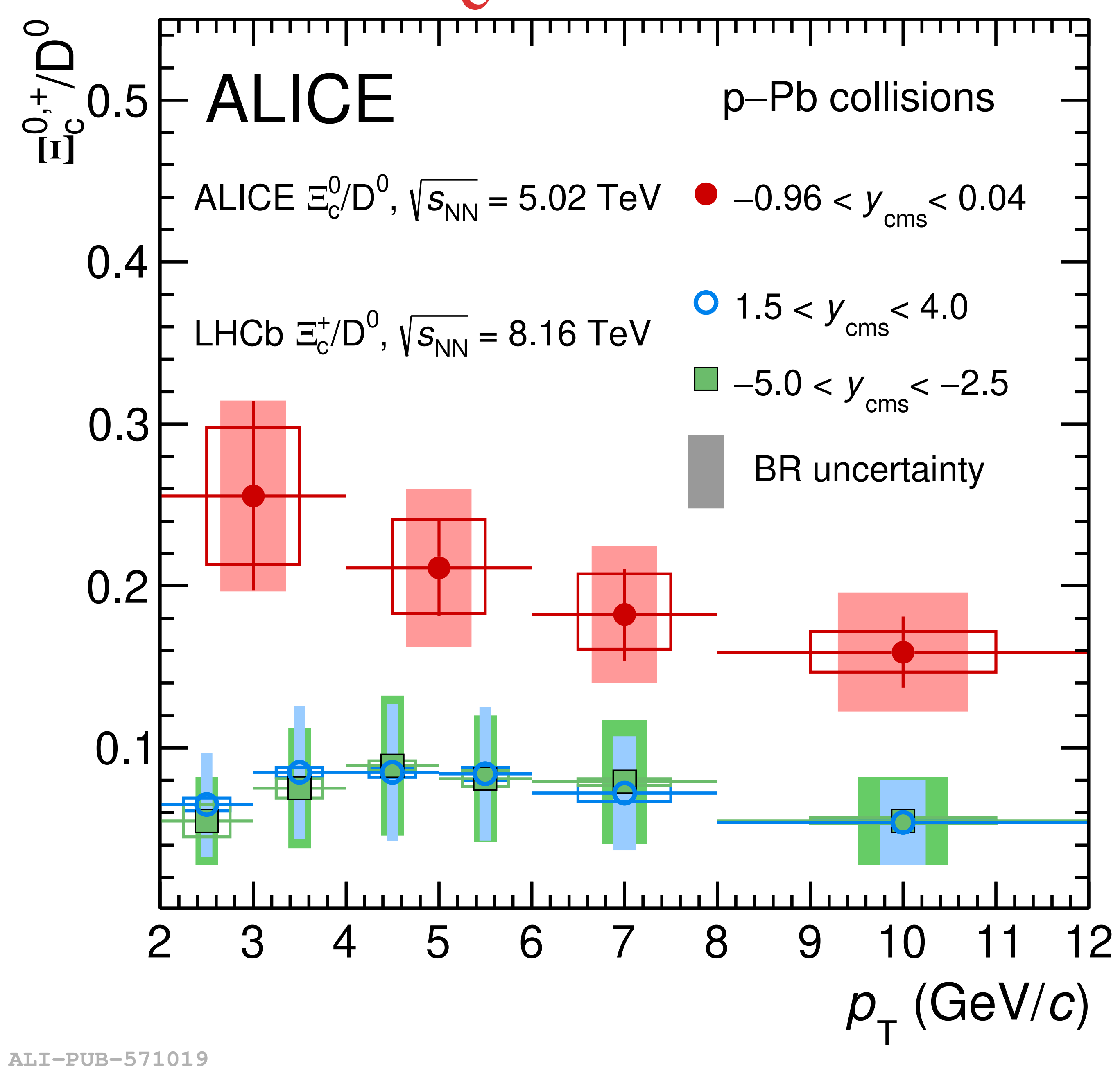
ALICE PRC 107 (2023) 064901
LHCb JHEP 02 (2019) 102

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



ALICE arXiv:2407.10593
LHCb PRD 99 (2019) 052011

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

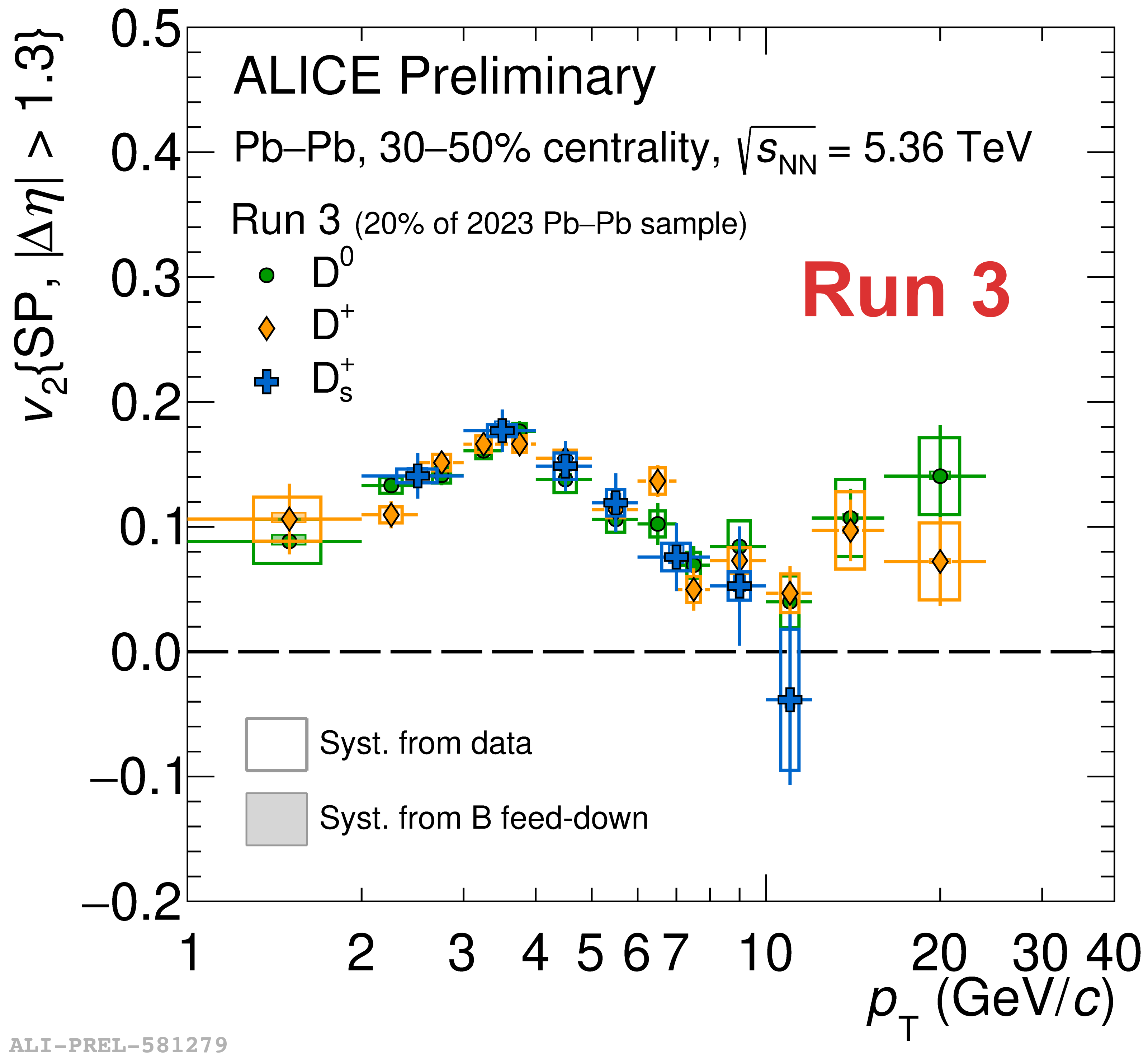


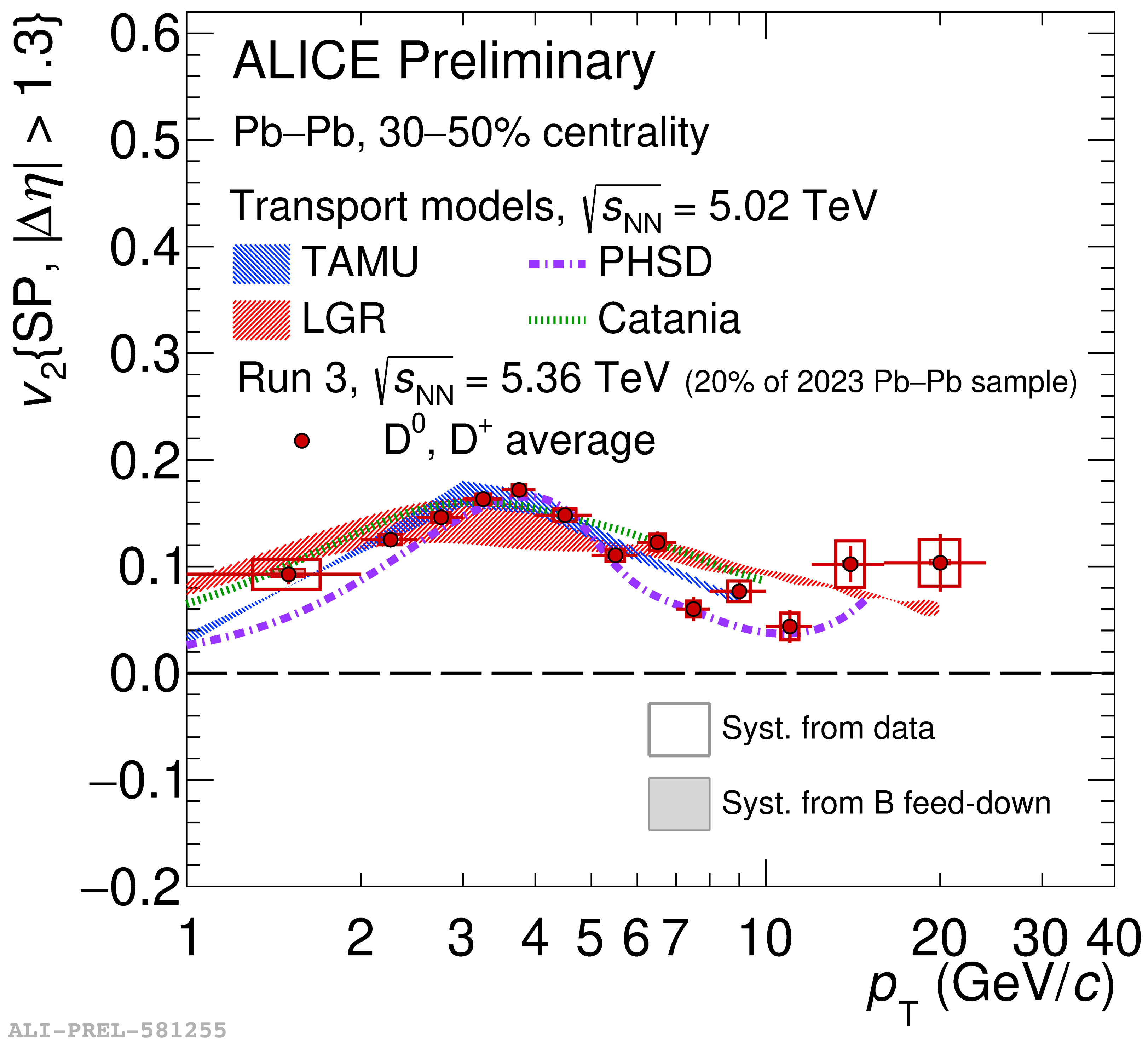
arXiv:2405.14538

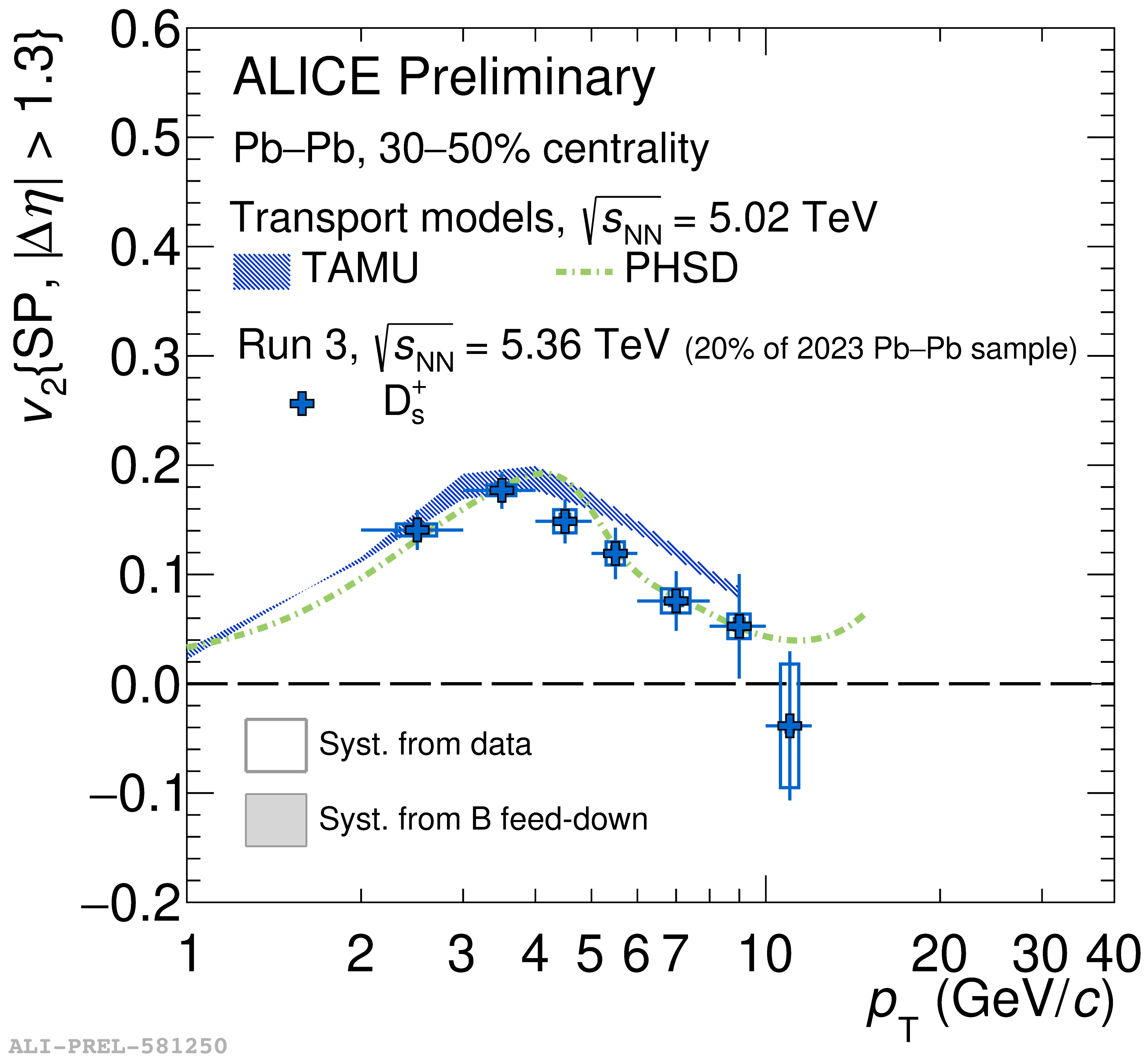
- Rapidity dependence in both meson and baryon, in both charm and beauty sectors
  - Models do not expect rapidity dependence

Xianglei Zhu's talk on Sunday at 09:25

Collectivity: strange and non-strange D-mesons elliptic flow







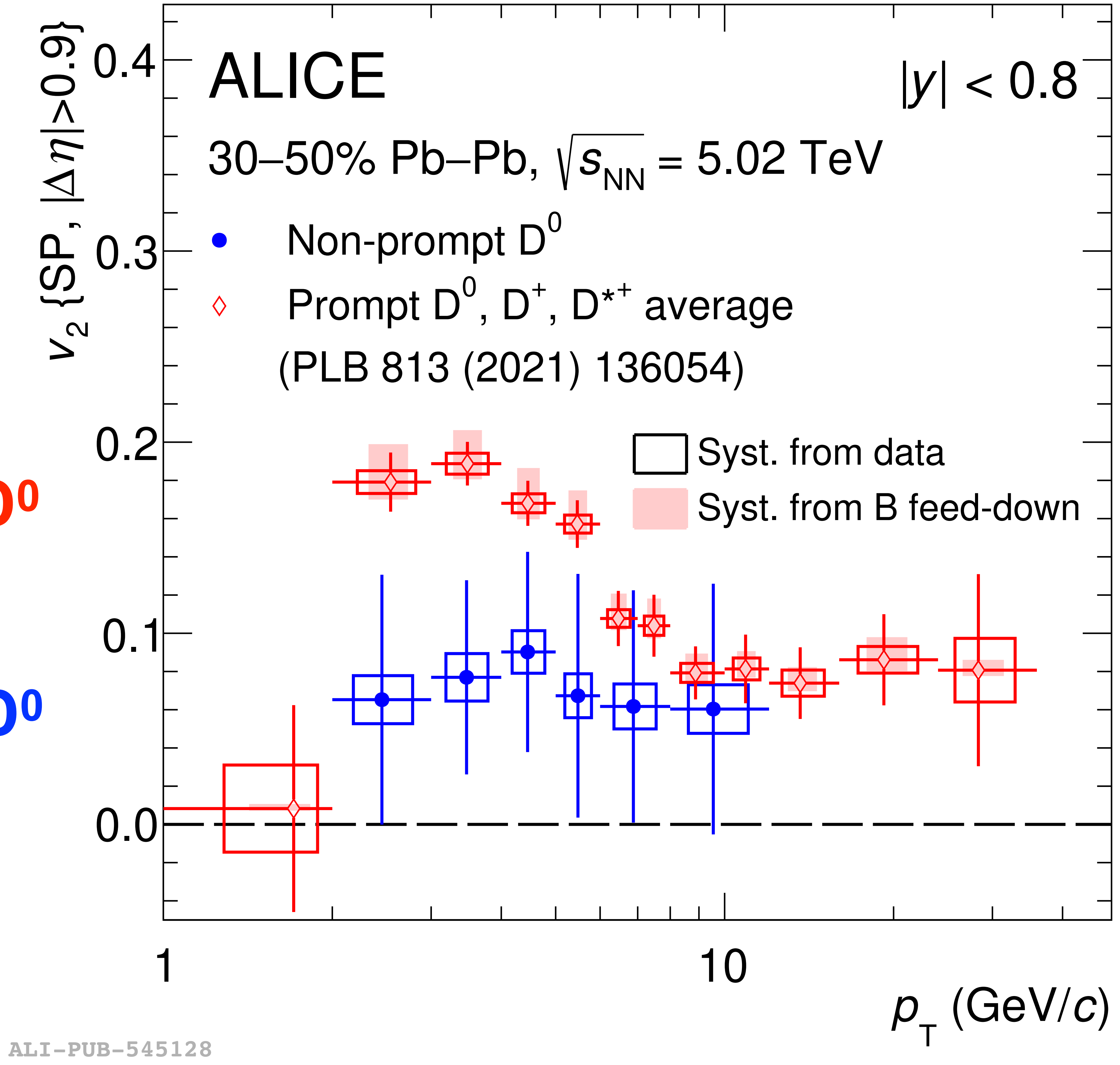
- About x4 larger statistics more than Run 2, x5 more statistics will come soon
- No significant difference between strange and non-strange D mesons
- Strange D-meson elliptic flow reproduced by transport models

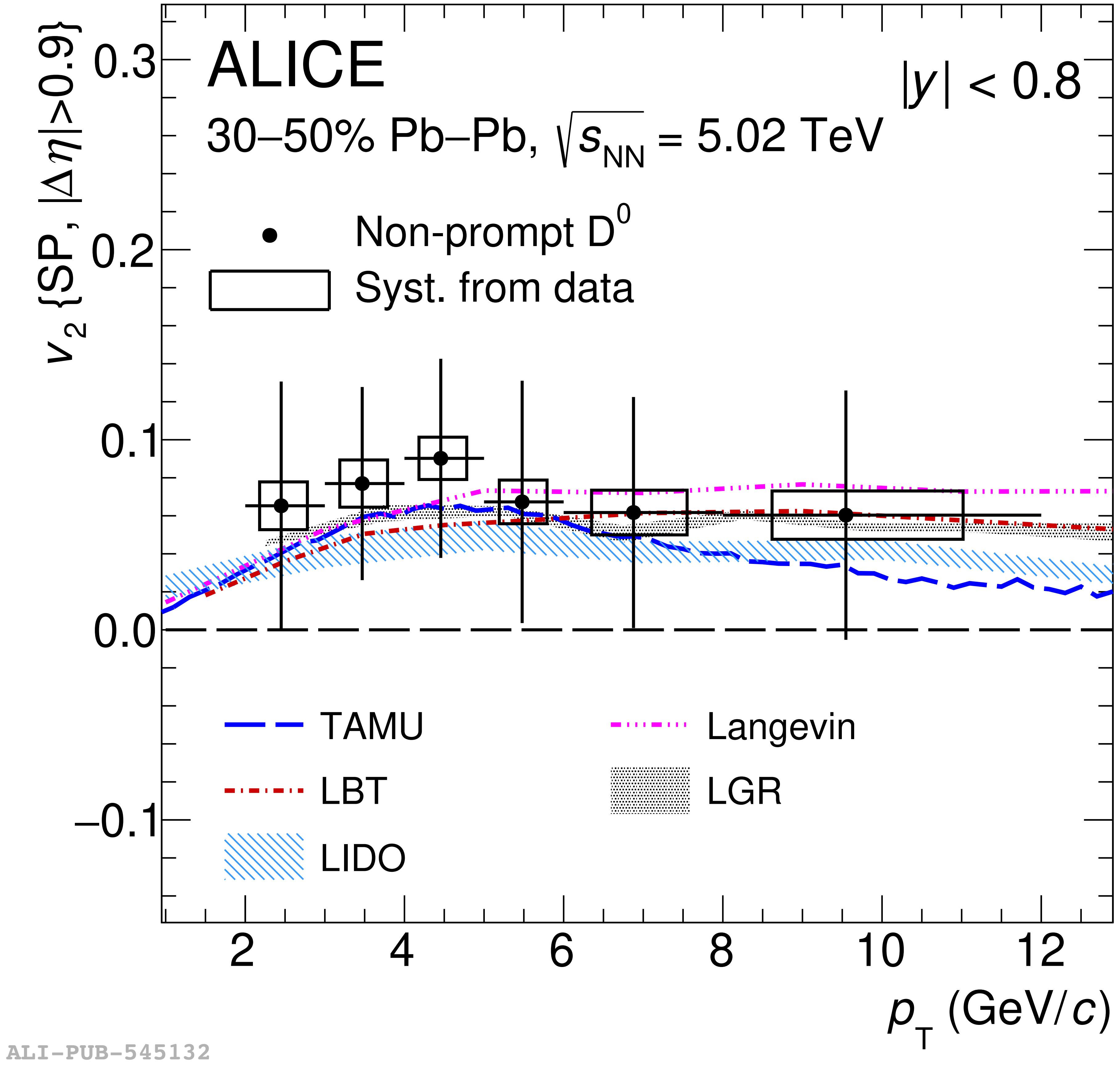
Collectivity: non-prompt D^0 elliptic flow

Eur.Phys.J.C 83 (2023) 1123

c → D^0

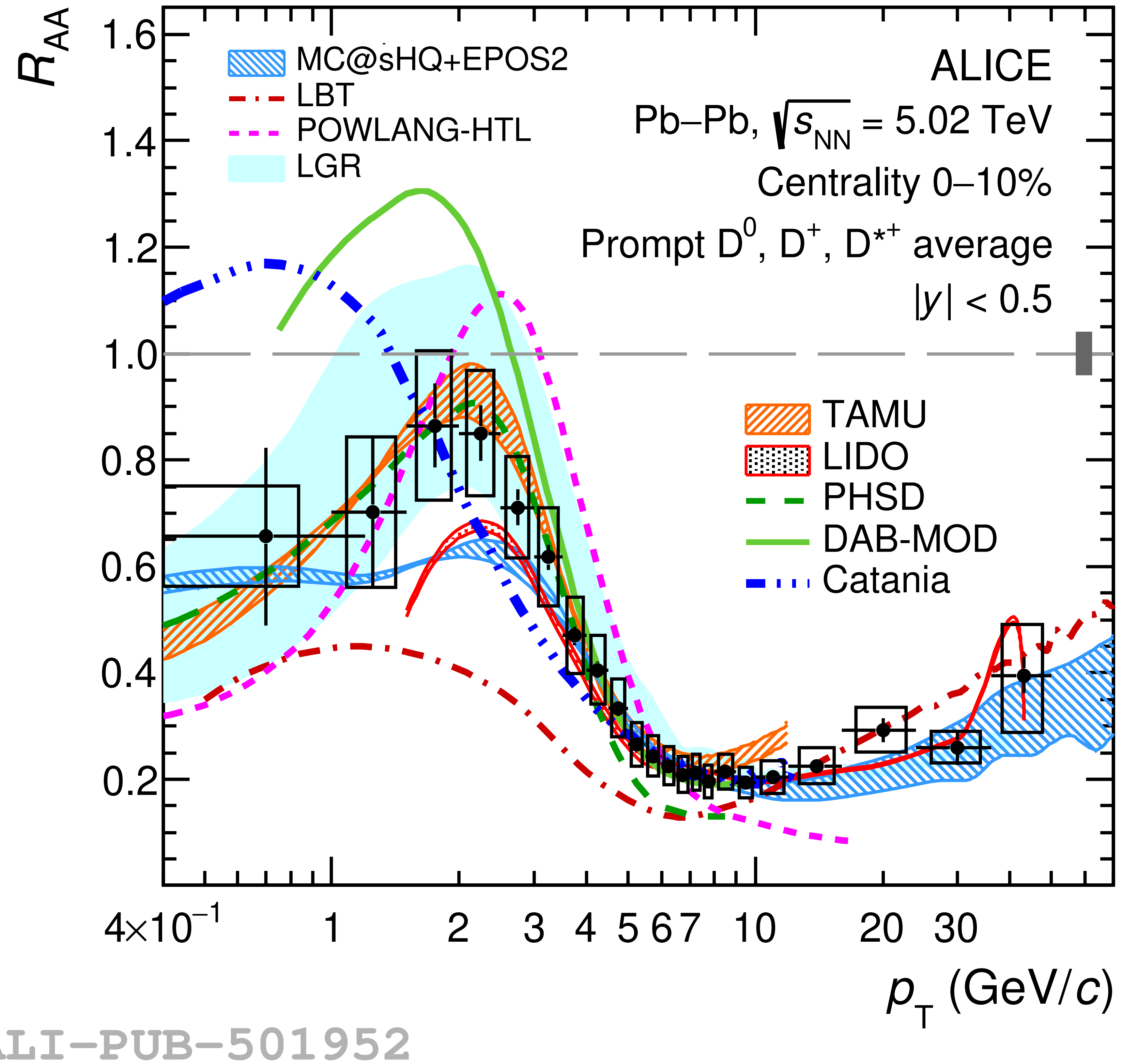
b → D^0





- Non-zero open beauty flow signal → possible partial thermalisation of beauty quark
- Described by models including collisional energy loss and hadronisation by coalescence

Energy loss: D⁰ R_{AA}

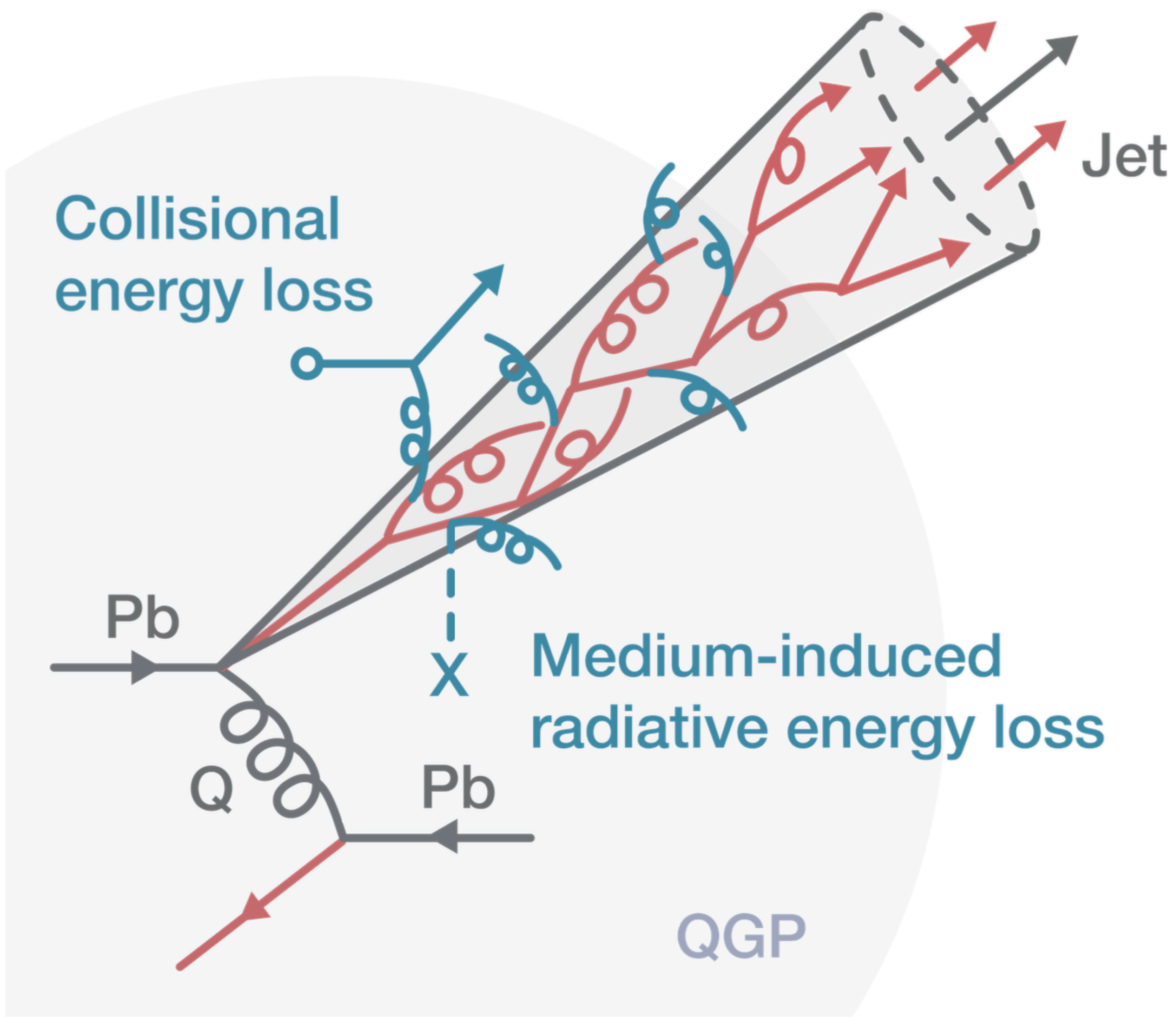


collective flow, hadronisation, nuclear PDF

collisional E loss

radiative E loss

JHEP 01 (2022) 174

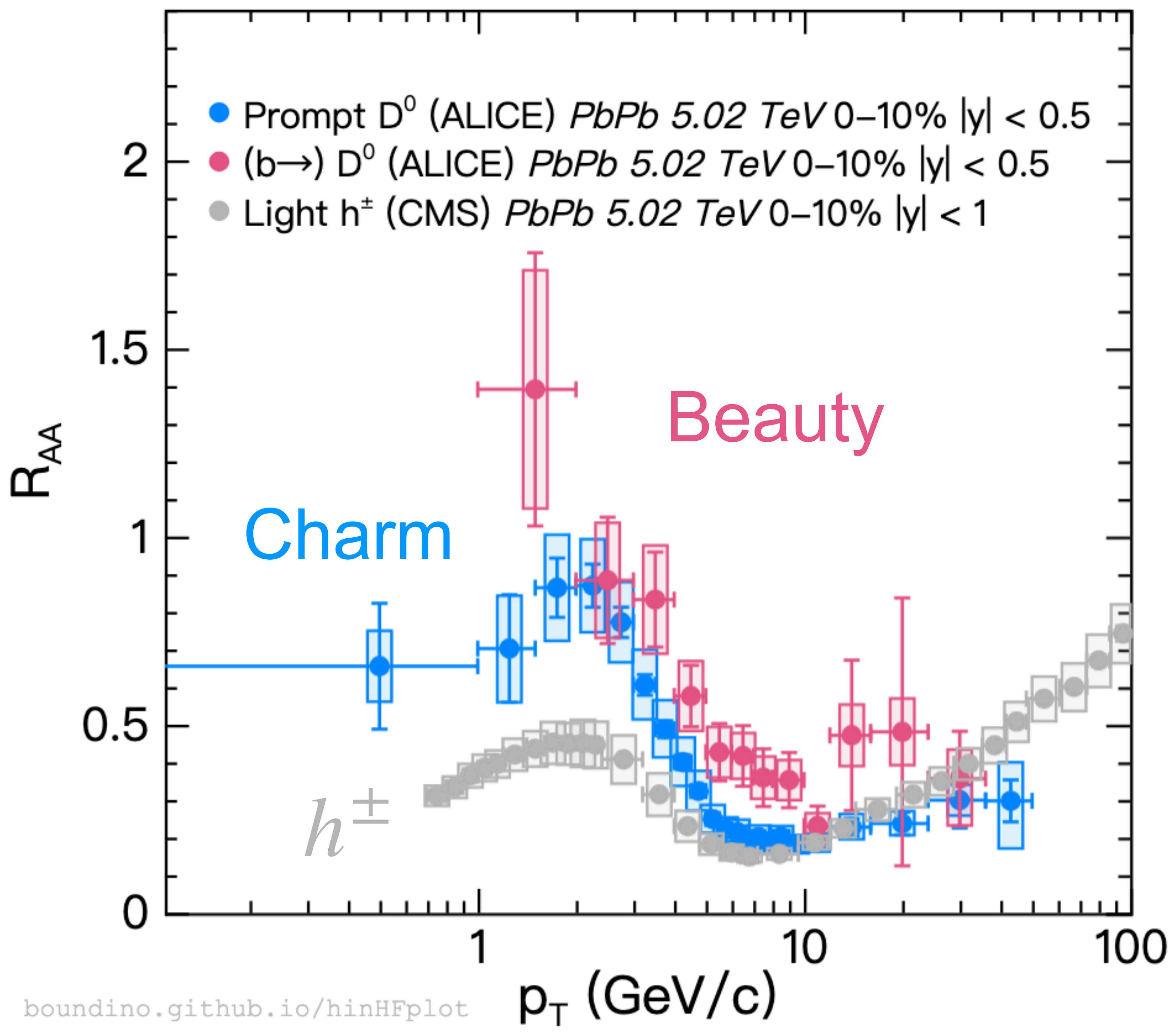


Energy loss of hard parton in QGP in pQCD picture

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}/dp_T}$$

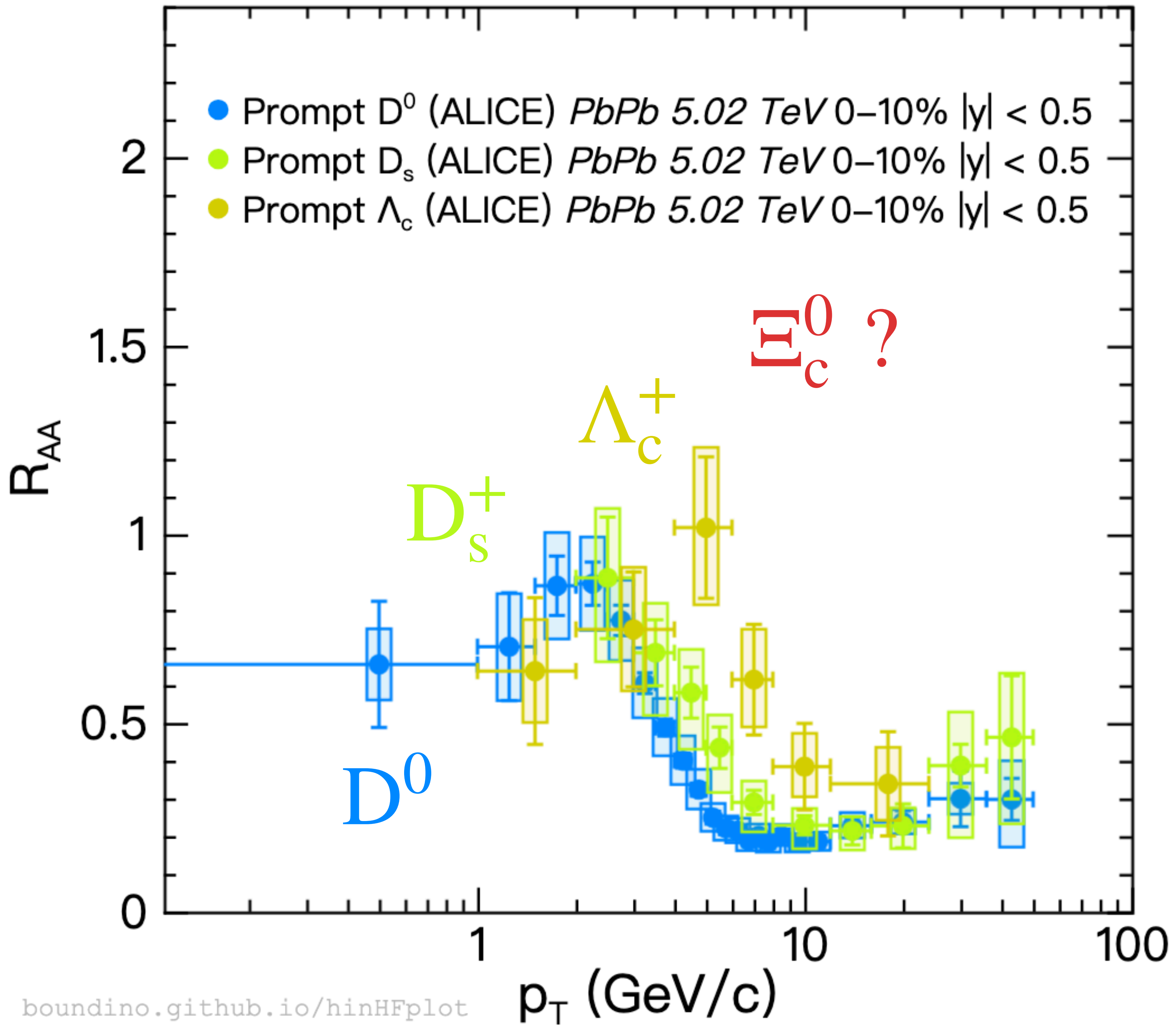
- Prompt D⁰ suppression in wide kinematics
  - Charm lose energy in QGP by collisions at low p_T and radiations at high p_T
- R_{AA} variable:
  - Advantage: BR unc. cancelled
  - Disadvantage: pp reference not well understood (QGP-like system in pp?)

Energy loss: mass dependence

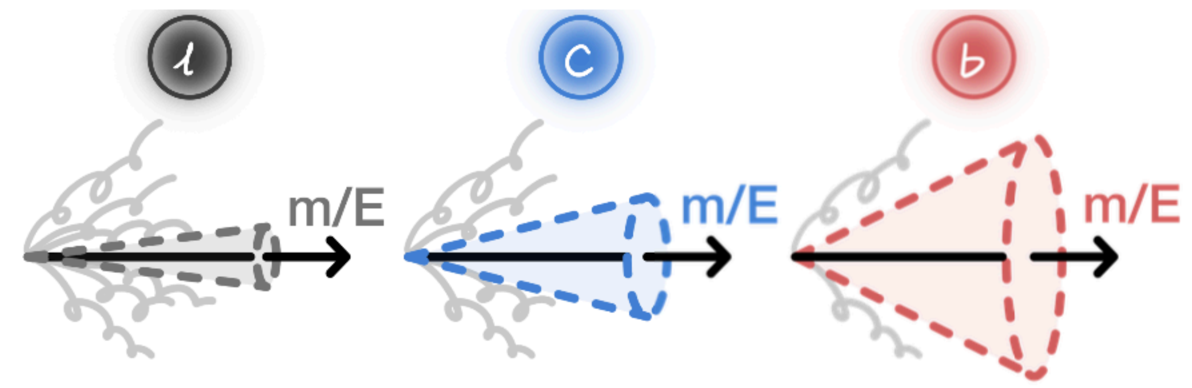


→ JHEP 01 (2022) 174 → JHEP 12 (2022) 126
→ JHEP 04 (2017) 039

Xiaoming Zhang's talk on Sunday at 09:00



→ JHEP 01 (2022) 174 → PLB 827 (2022) 136986
→ PLB 839 (2023) 137796



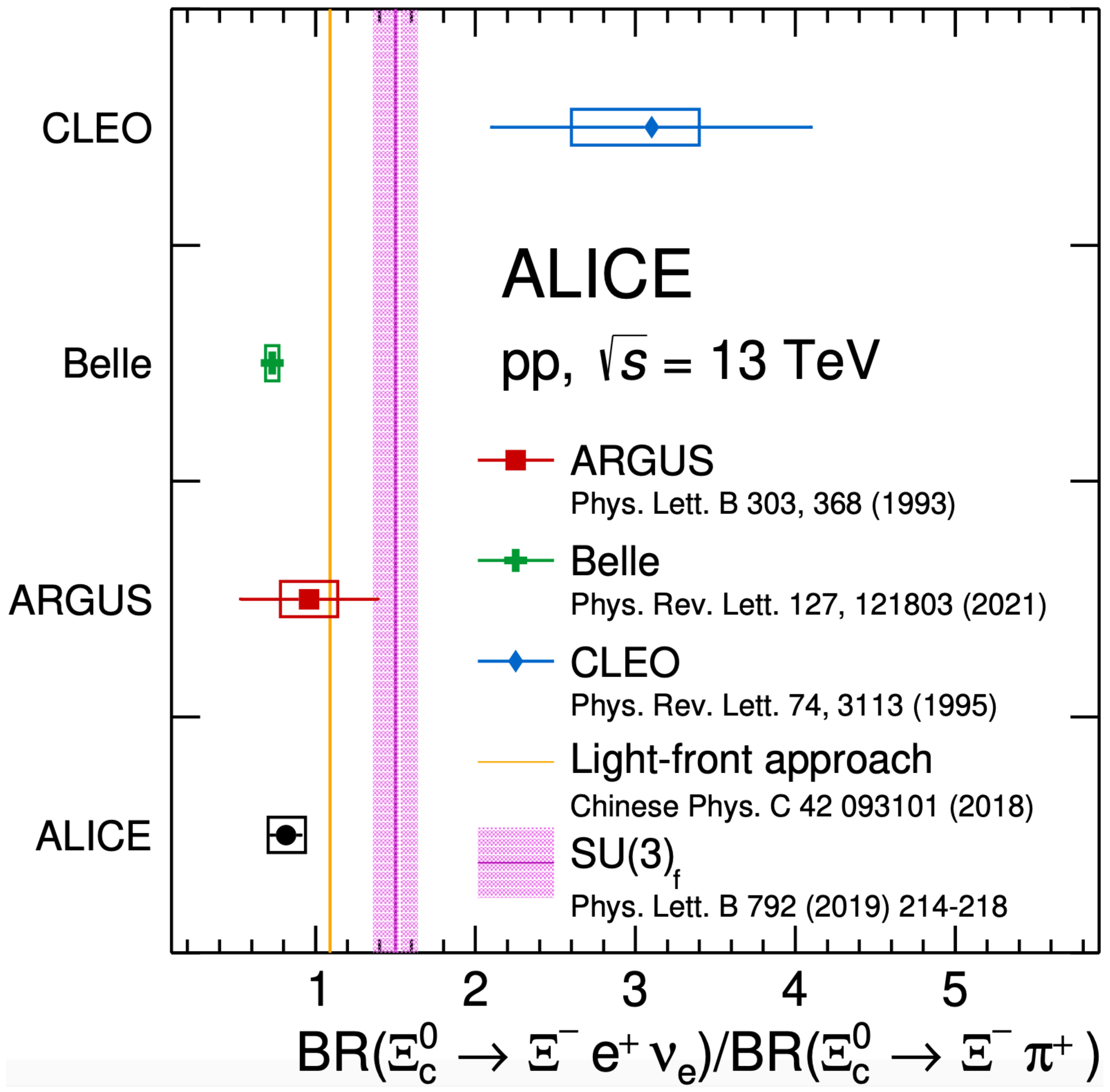
Dead cone effect

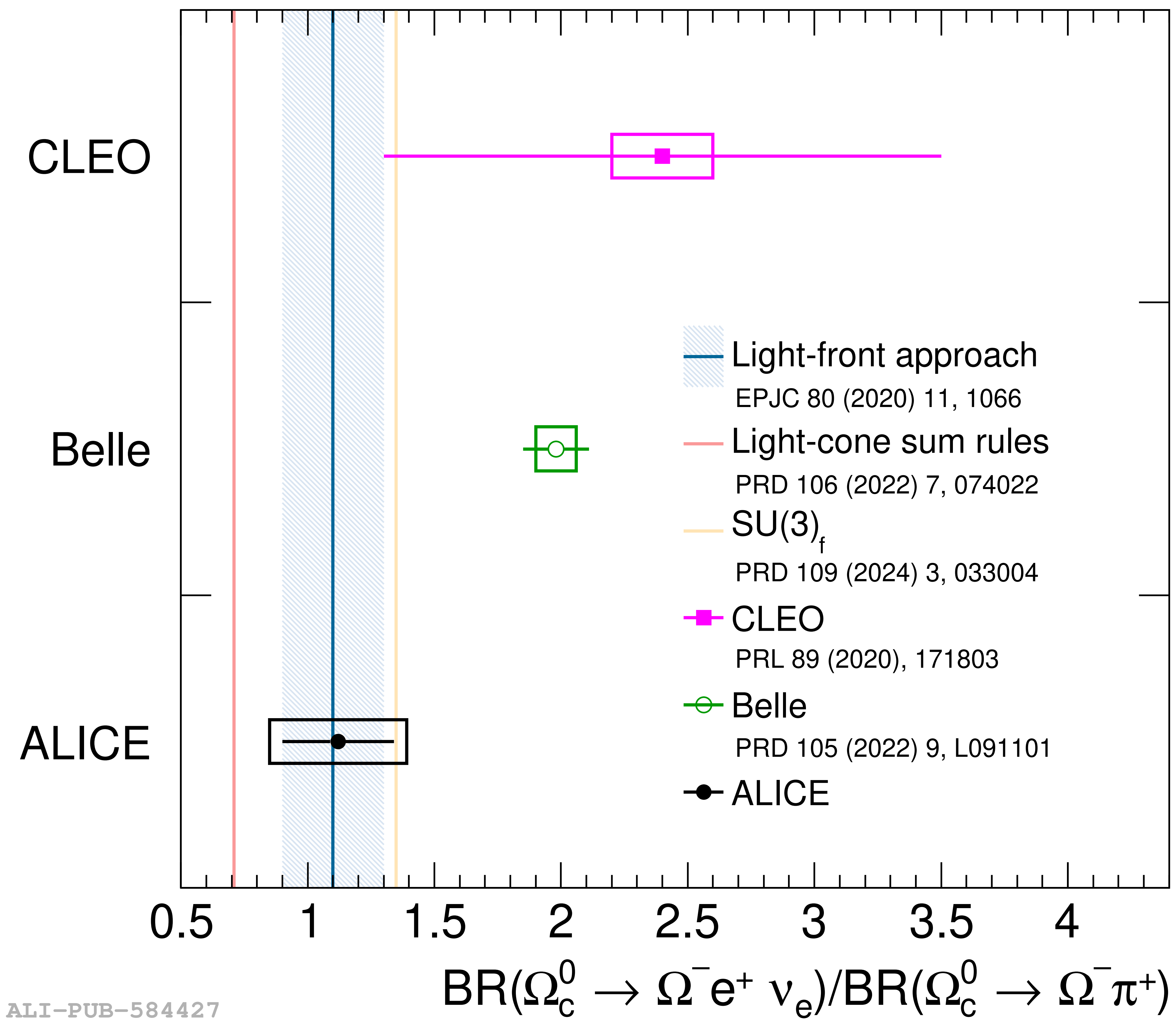
Radiation suppressed inside $\theta < m/E$

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

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

Branching-fraction ratio: Ξ_c^0 and Ω_c^0





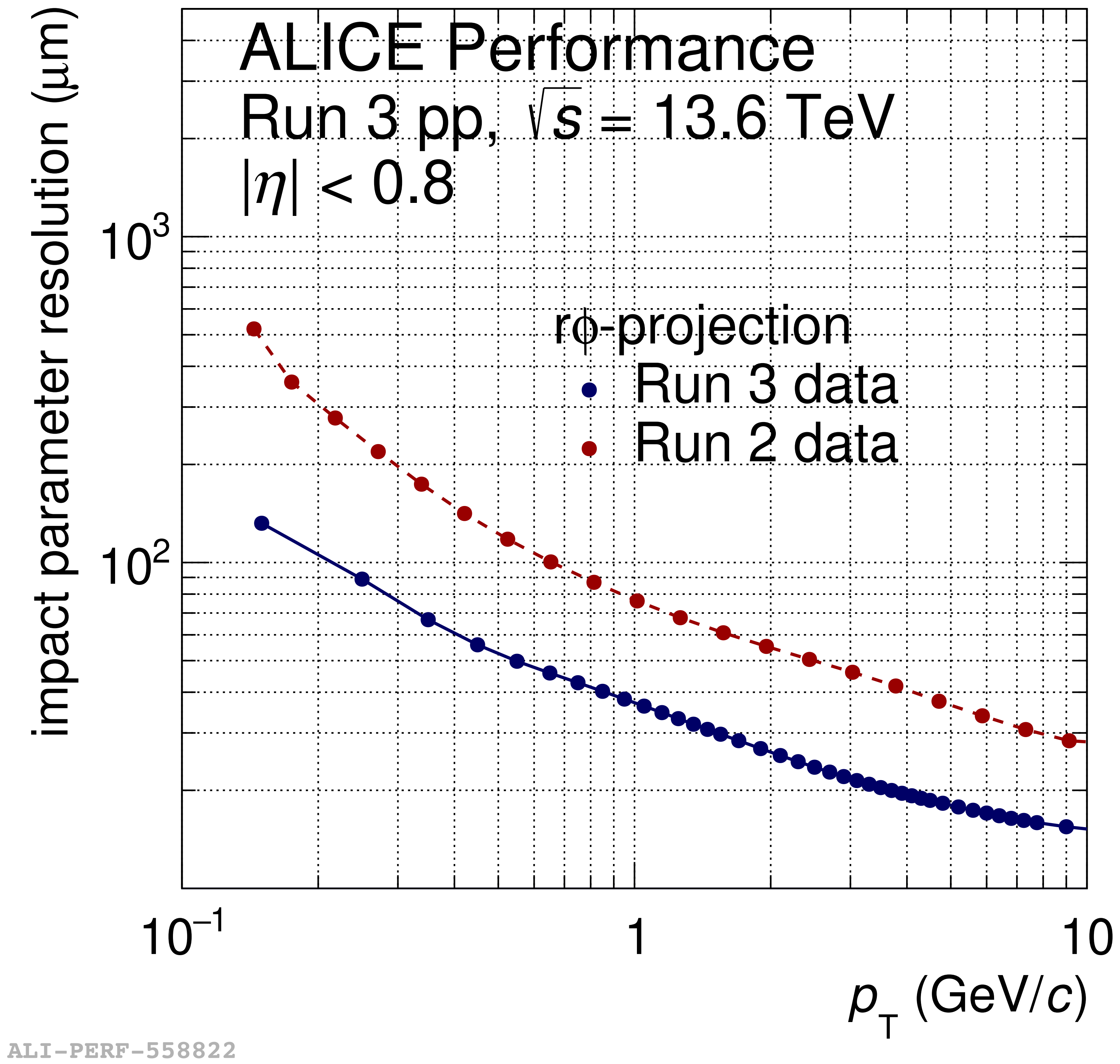
Phys. Rev. Lett. 127 (2021) 272001

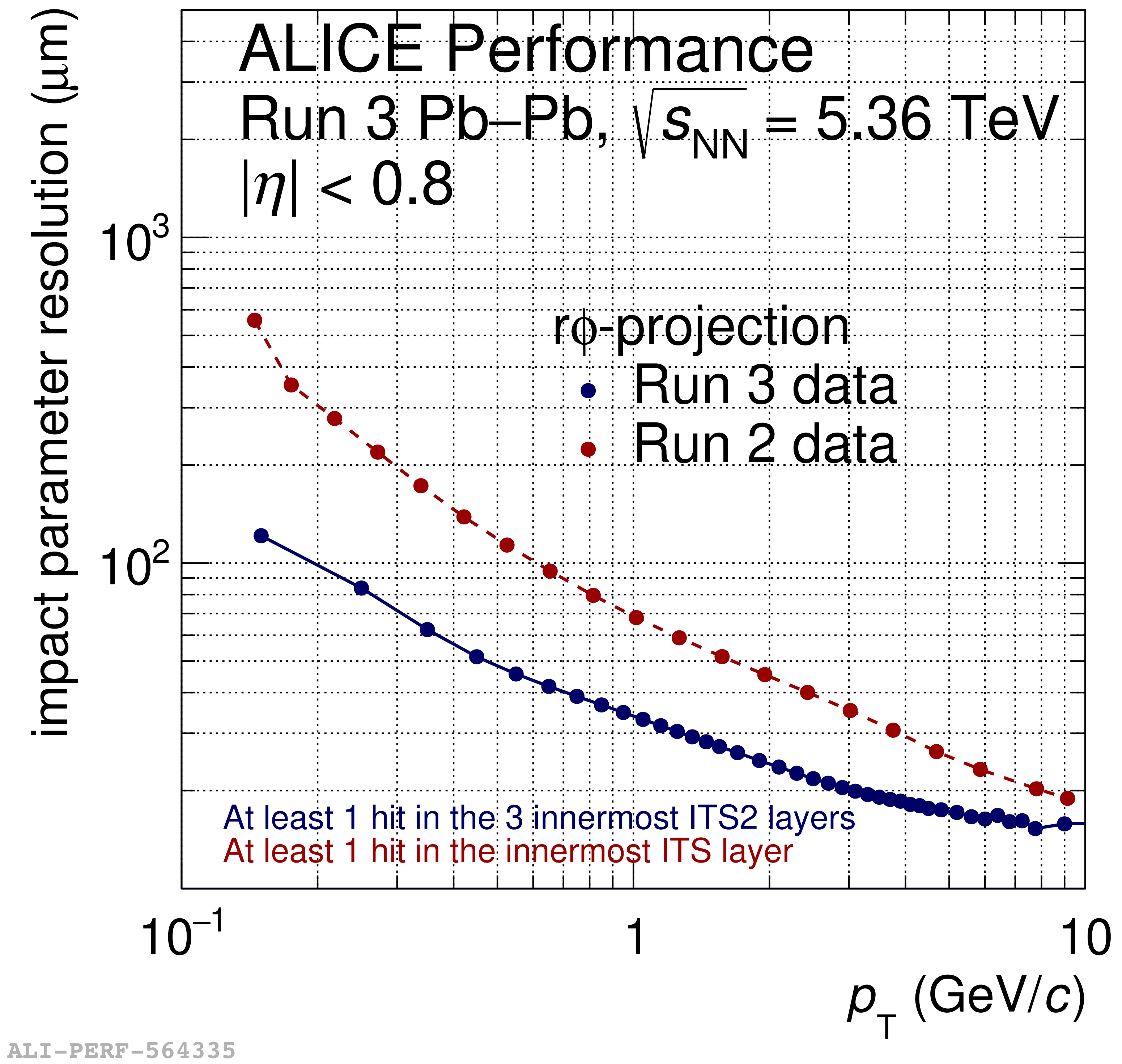
Phys.Rev.D 110 (2024) 032014

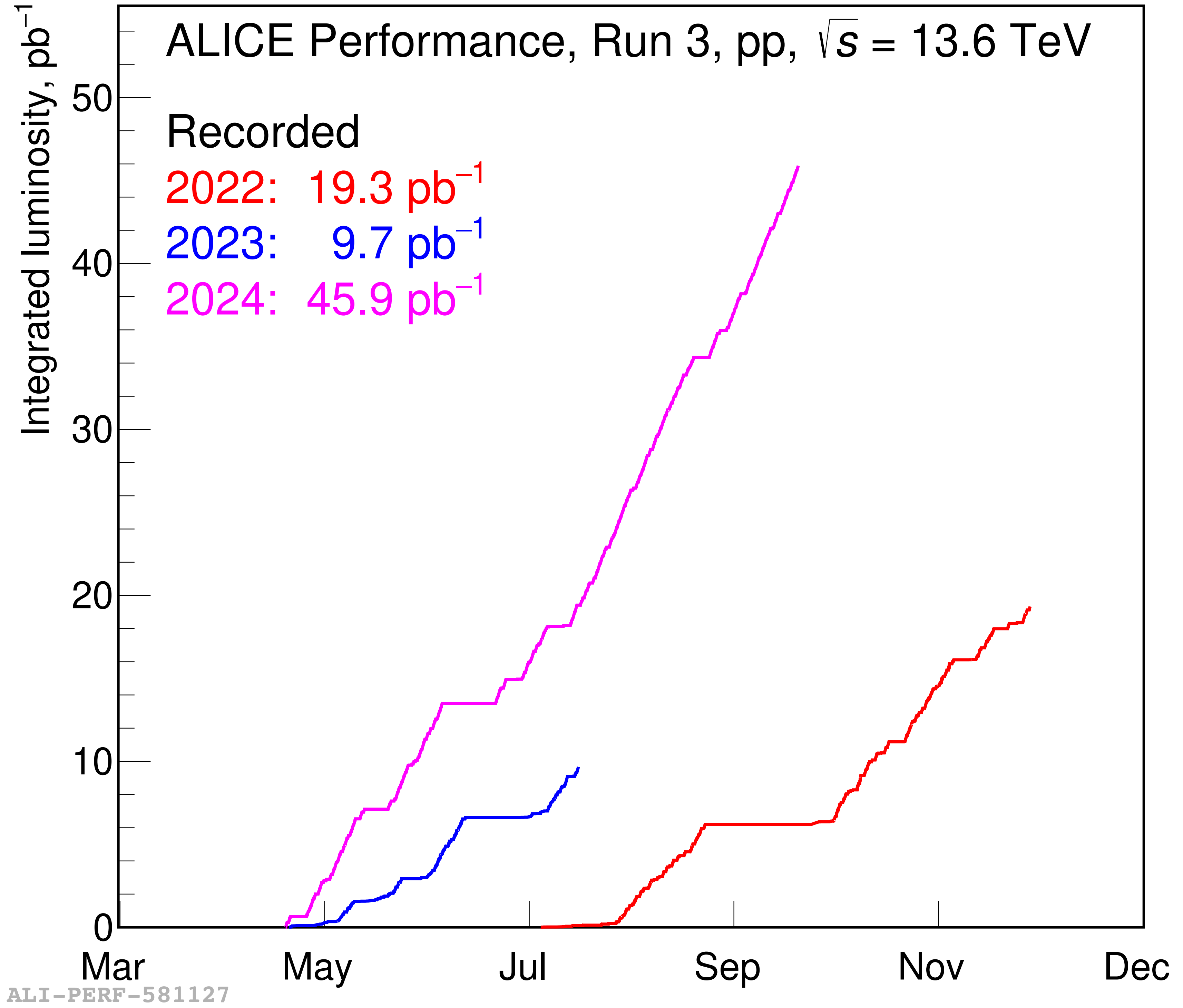
- Consistent with Belle result in 0.54σ
- Models overestimate ALICE and Belle results

- 2.3σ lower than Belle result
- Consistent with theory calculations

Outlook: more precise and more statistics in Run 3







- ITS upgrade improves pointing resolution (by a factor of 2)
- TPC continuous readout allows to collect much larger data sample

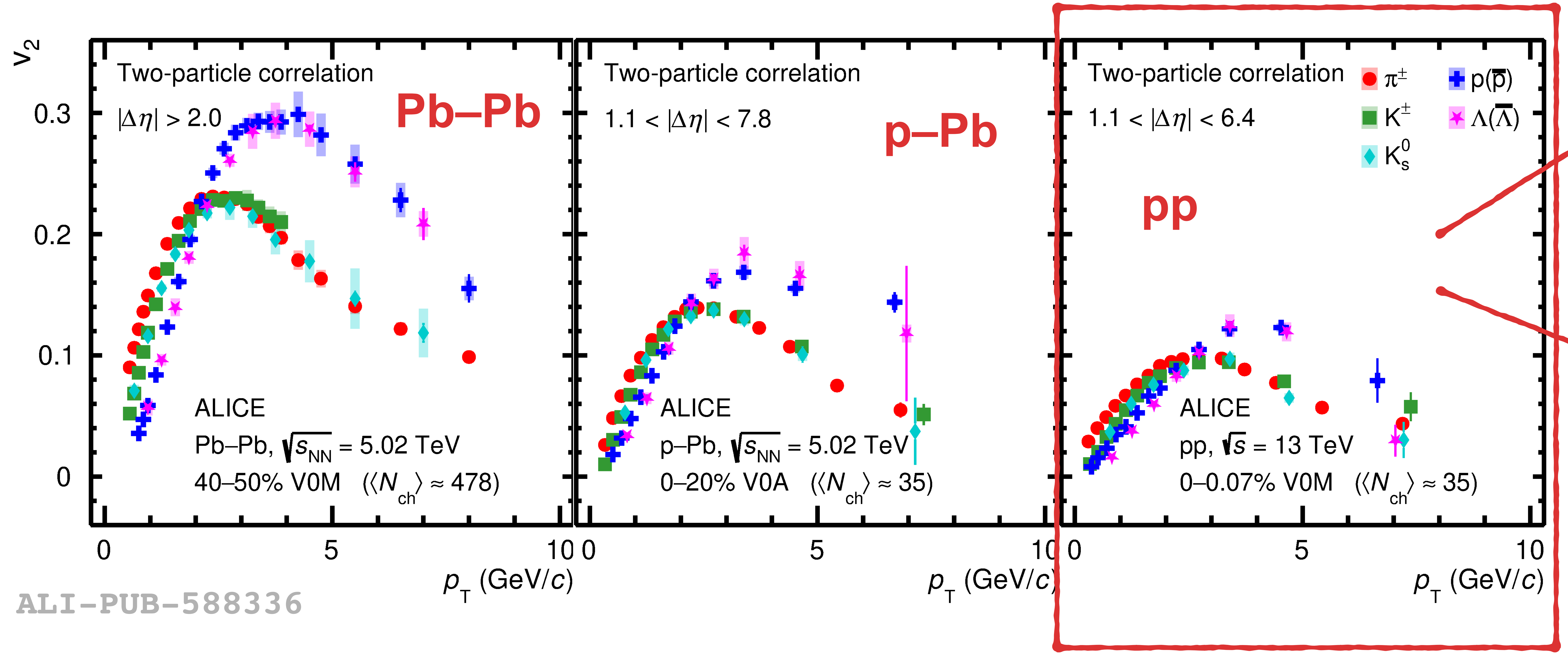
Summary

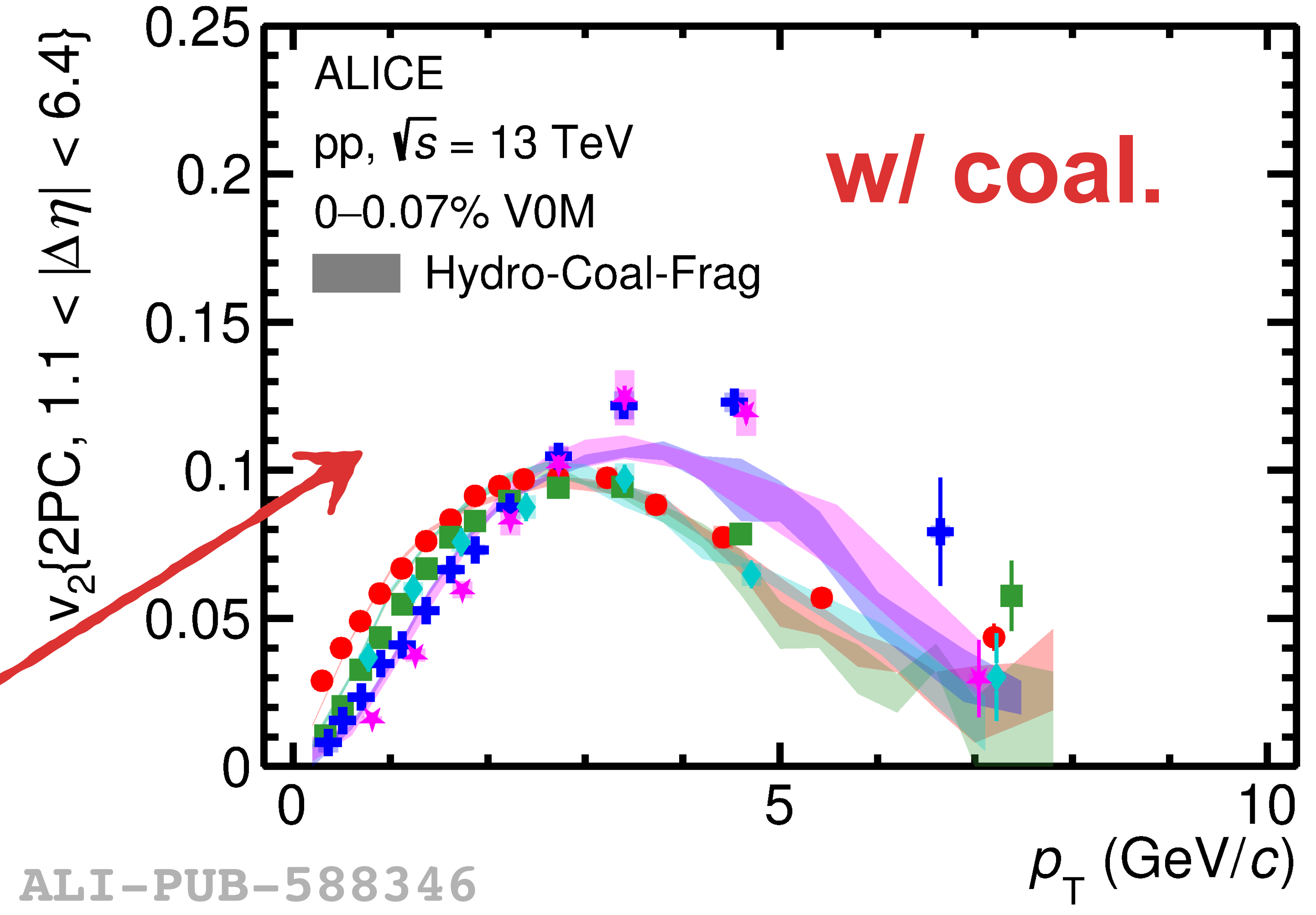
- Assumption of universal parton-to-hadron fragmentation fractions not valid at LHC energies
- HF hadronisation mechanisms in small collision systems at LHC need further investigations
  - Resonance decay? Coalescence? Radial flow?
- Heavy quarks are thermalised and have mass-dependent energy loss in large collisions systems

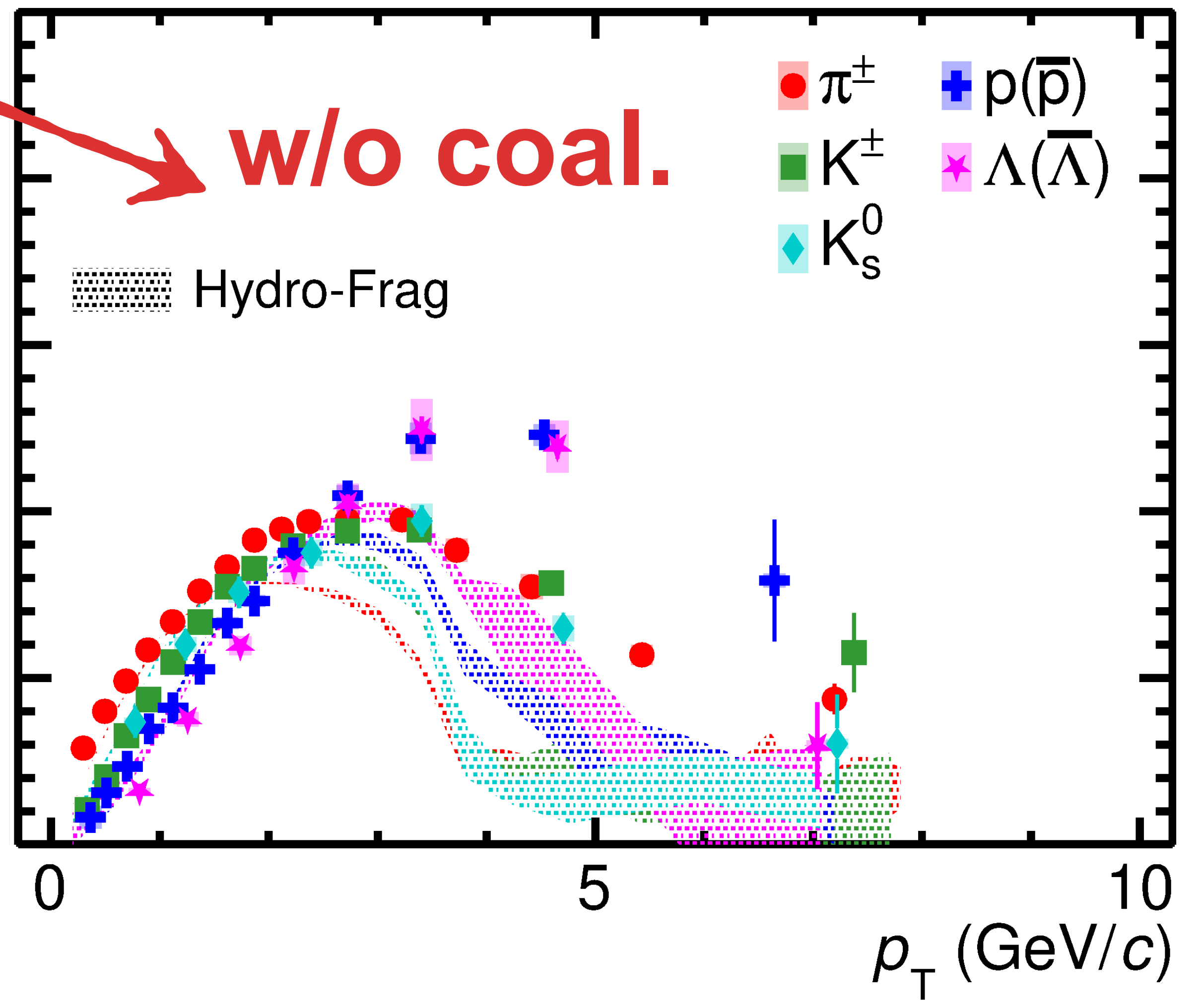
Backup

Partonic flow in small system

arXiv:2411.09323

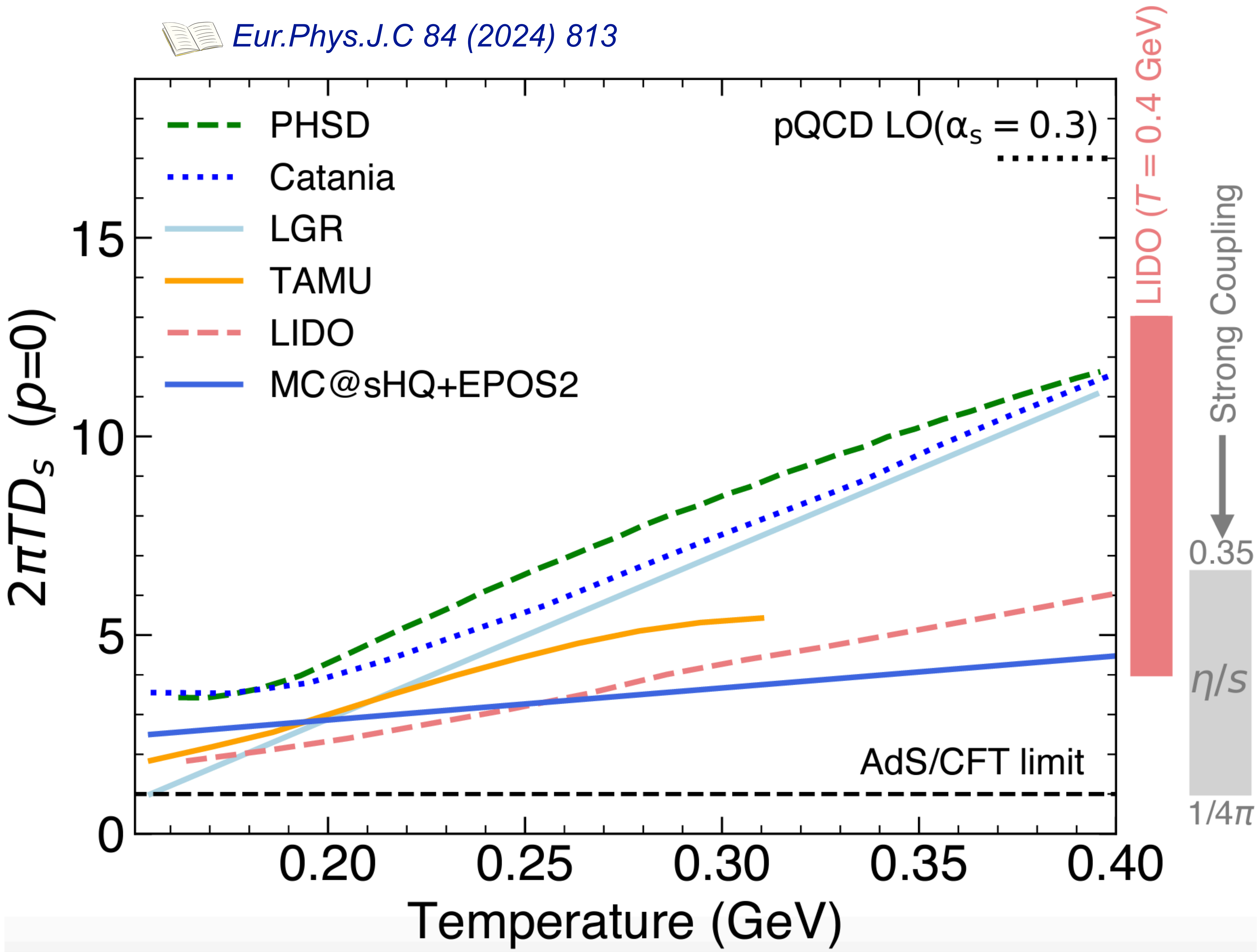




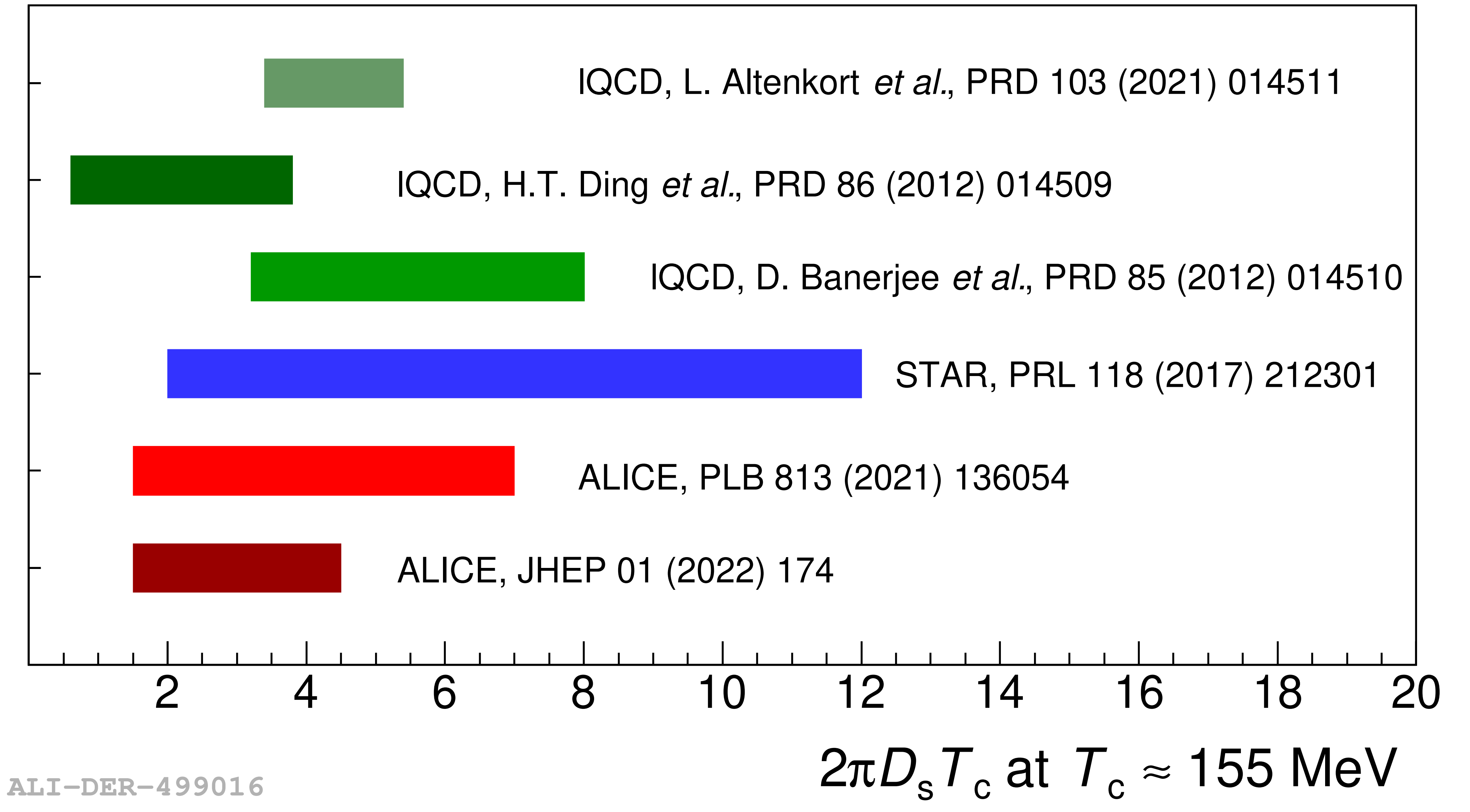


Charm spatial diffusion coefficient D_s

Eur.Phys.J.C 84 (2024) 813

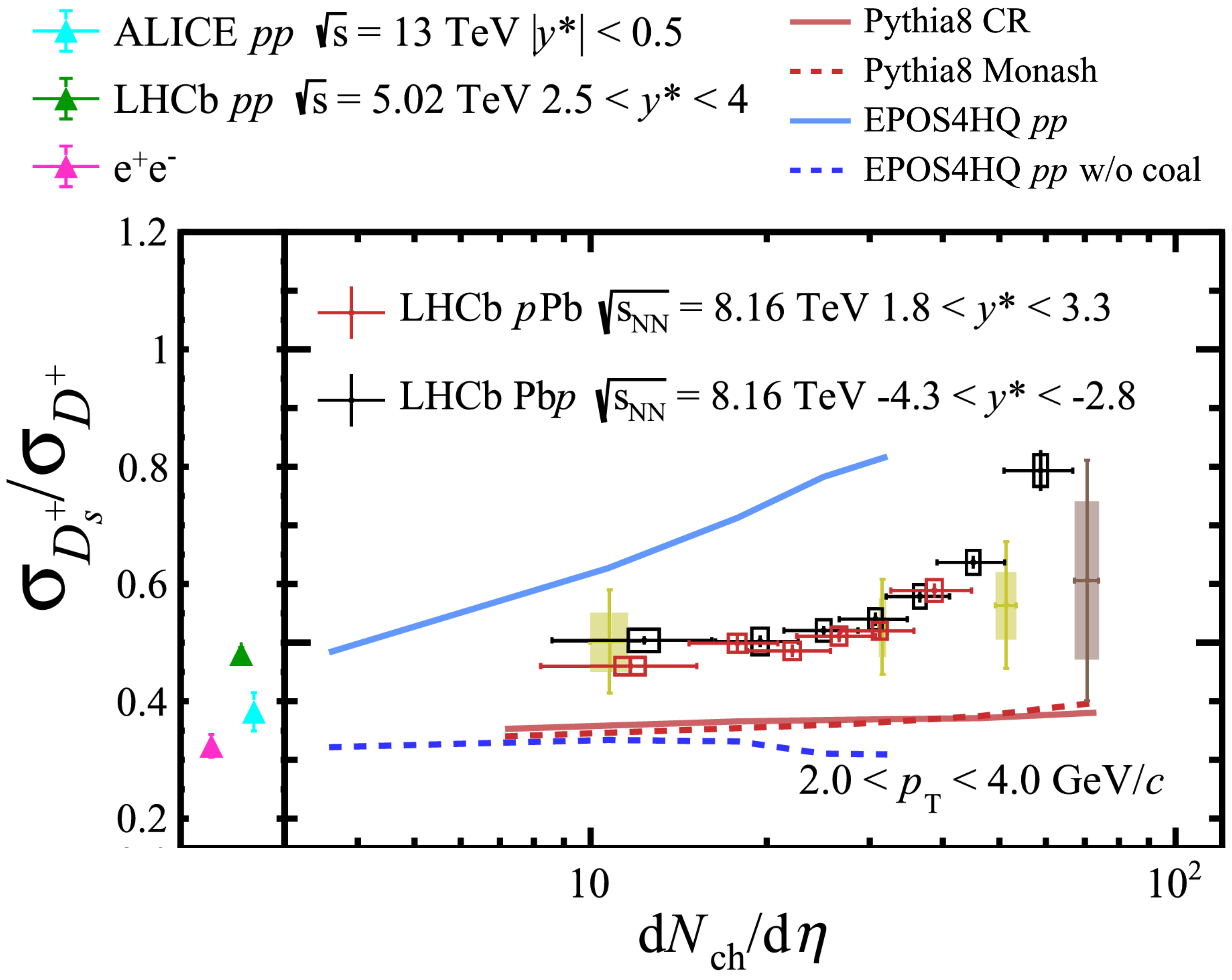


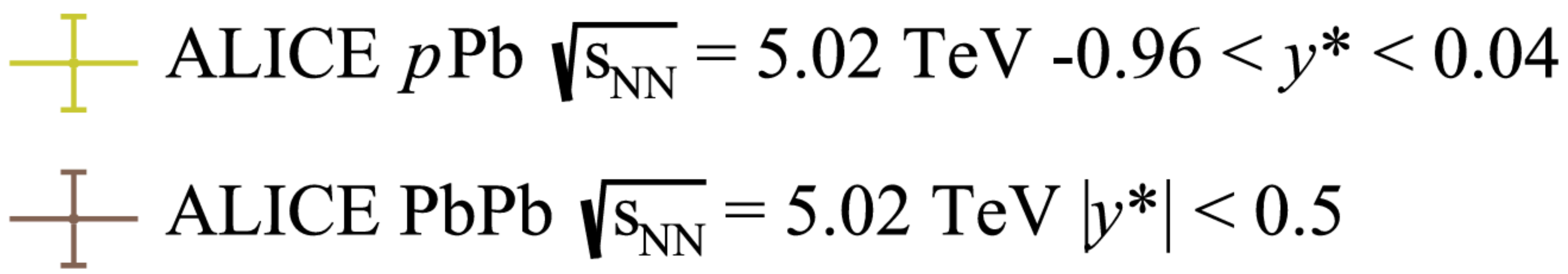
JHEP 01 (2022) 174



- Constraint by R_{AA} and flow of D mesons
  - $1.5 < 2\pi D_s T_c < 4.5$ at $T_{pc} = 155$ MeV
  - $D_s \propto$ relaxation time
  - $\tau_{relax} = (3-9)$ fm/$c \lesssim \tau_{QGP}$
- Charm readily participates in the collective motion of the QGP after production

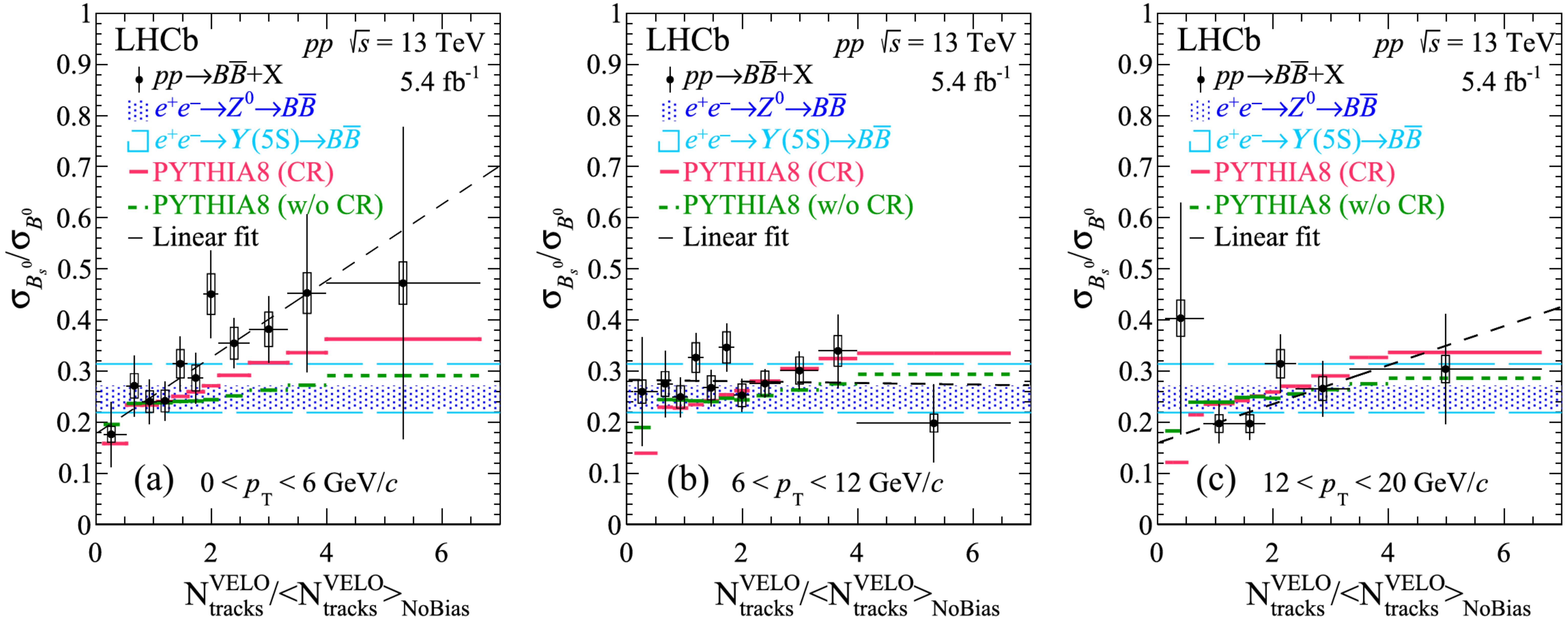
M-to-M event multiplicity dependence (LHCb)





Phys. Rev. D 110 (2024) L031105

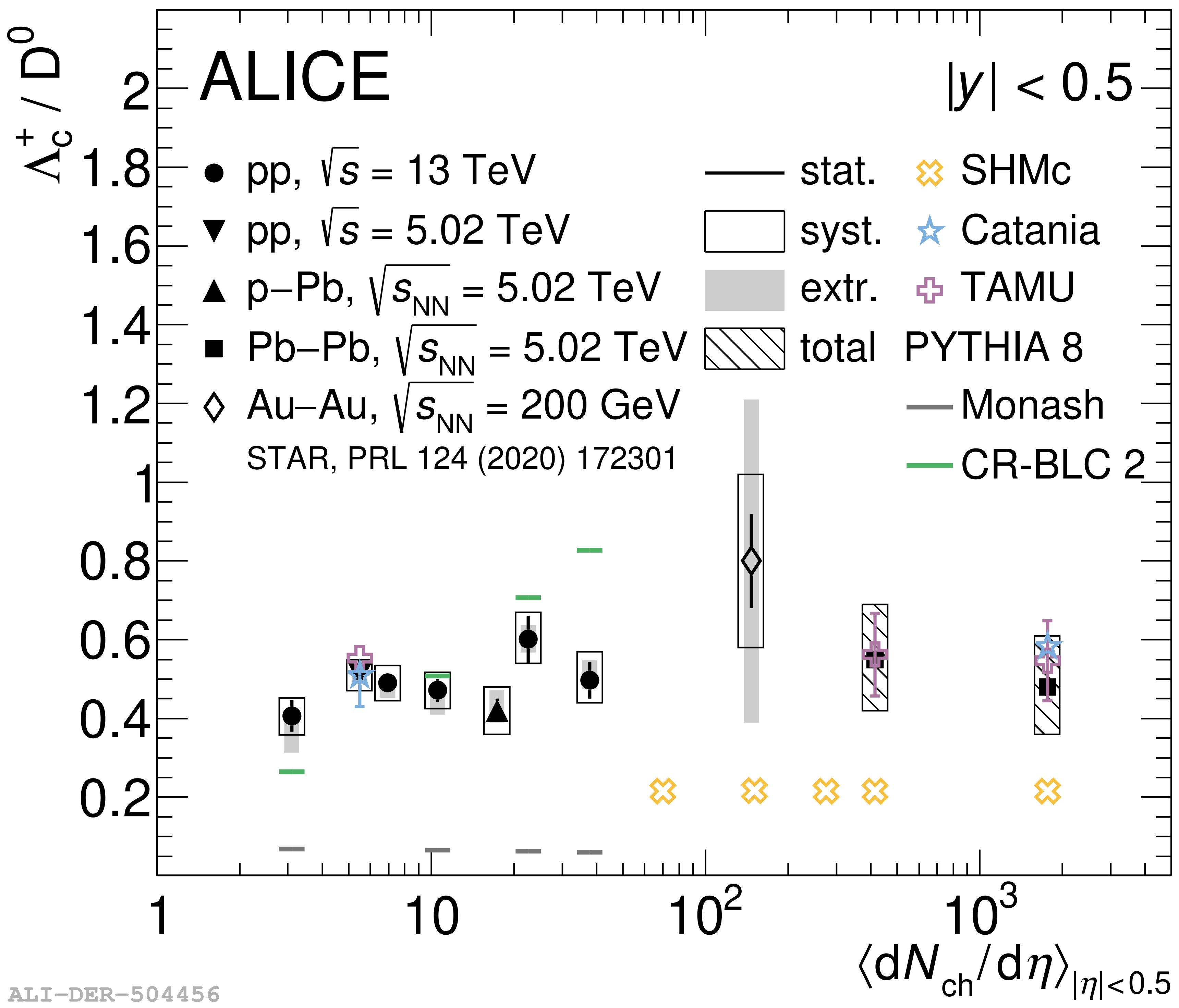
Phys.Rev.Lett. 131 (2023) 061901

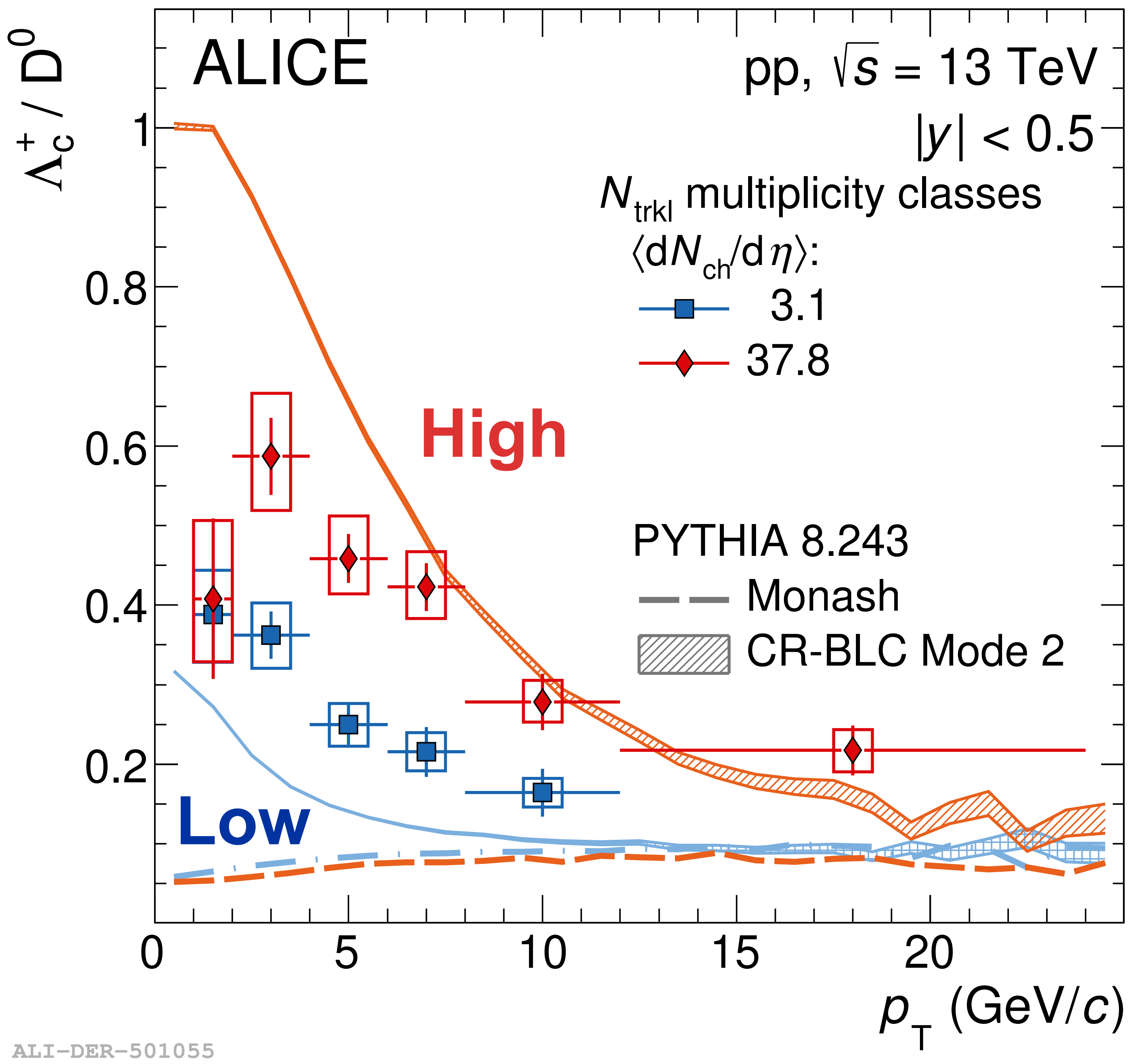


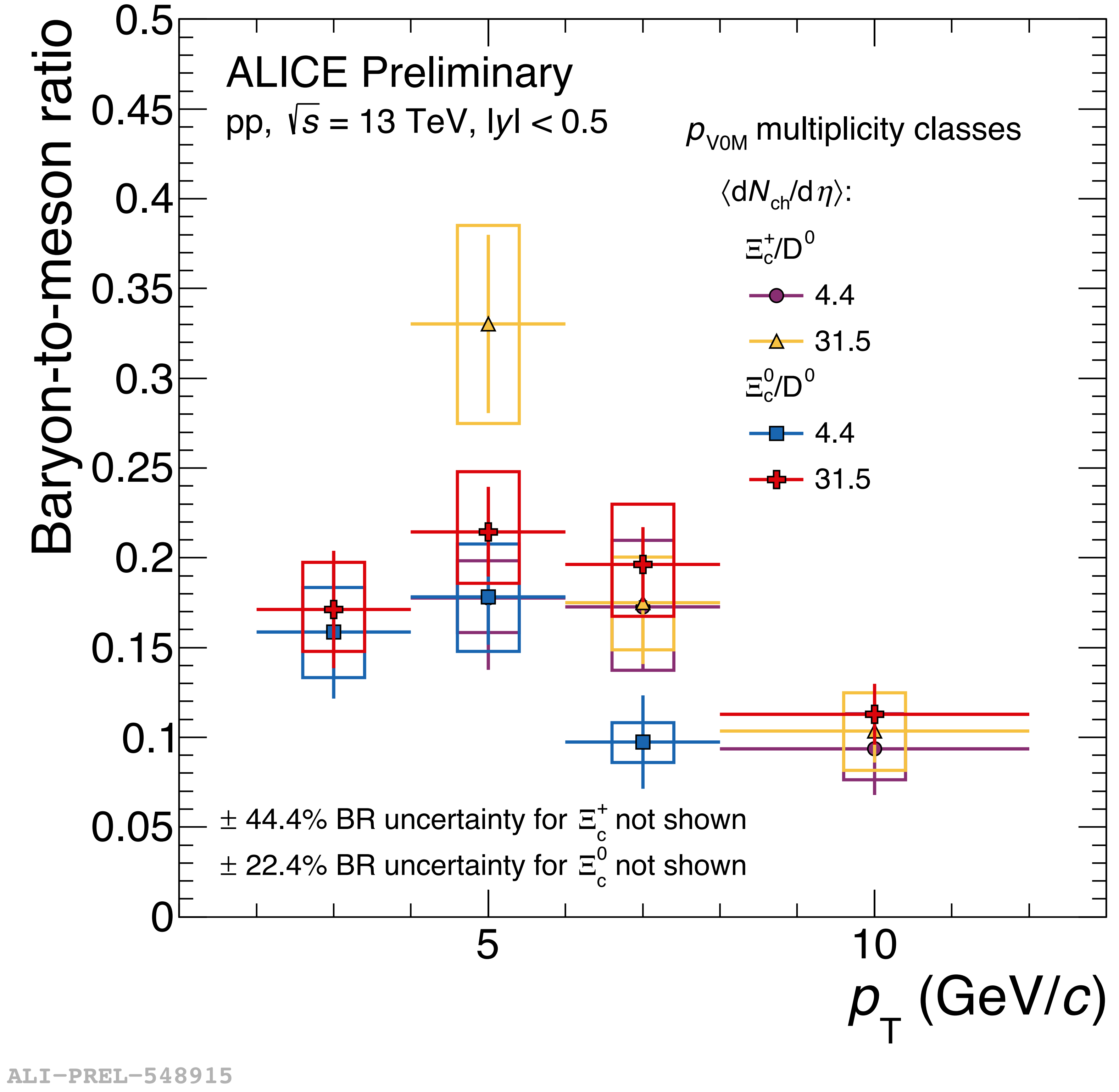
- Observed clear indications of strangeness enhancement in both charm and beauty sectors
- Final state effects such as coalescence are important at low p_T and high multiplicity

B-to-M event multiplicity dependence (ALICE)

Phys.Lett.B 829 (2022) 137065







p_T-integrated Λ_c^+/D^0 vs. multiplicity

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

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

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

$\Xi_c^{0,+}/D^0$ vs. p_T in different multiplicity

- No significant multiplicity dependence as a function of p_T within uncertainties

B-to-M event multiplicity dependence (CMS)

arXiv:2407.13615

B-to-M event multiplicity dependence (LHCb)

Phys.Rev.Lett. 132 (2024) 081901