Open heavy-flavour and quarkonia physics with ALICE

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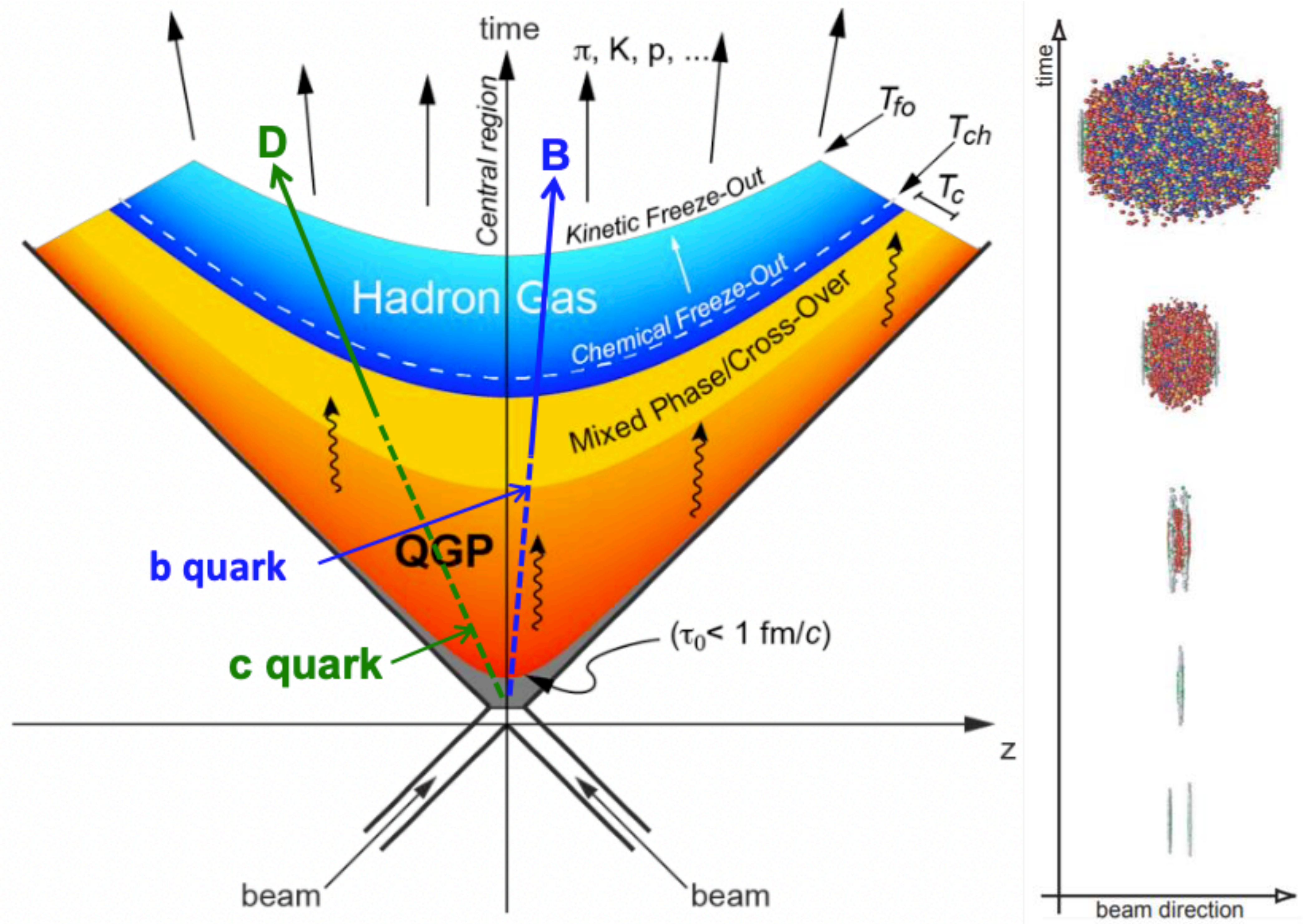
November 16, 2024

Why open heavy-flavour (HF)



- Charm:

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

- Beauty:

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

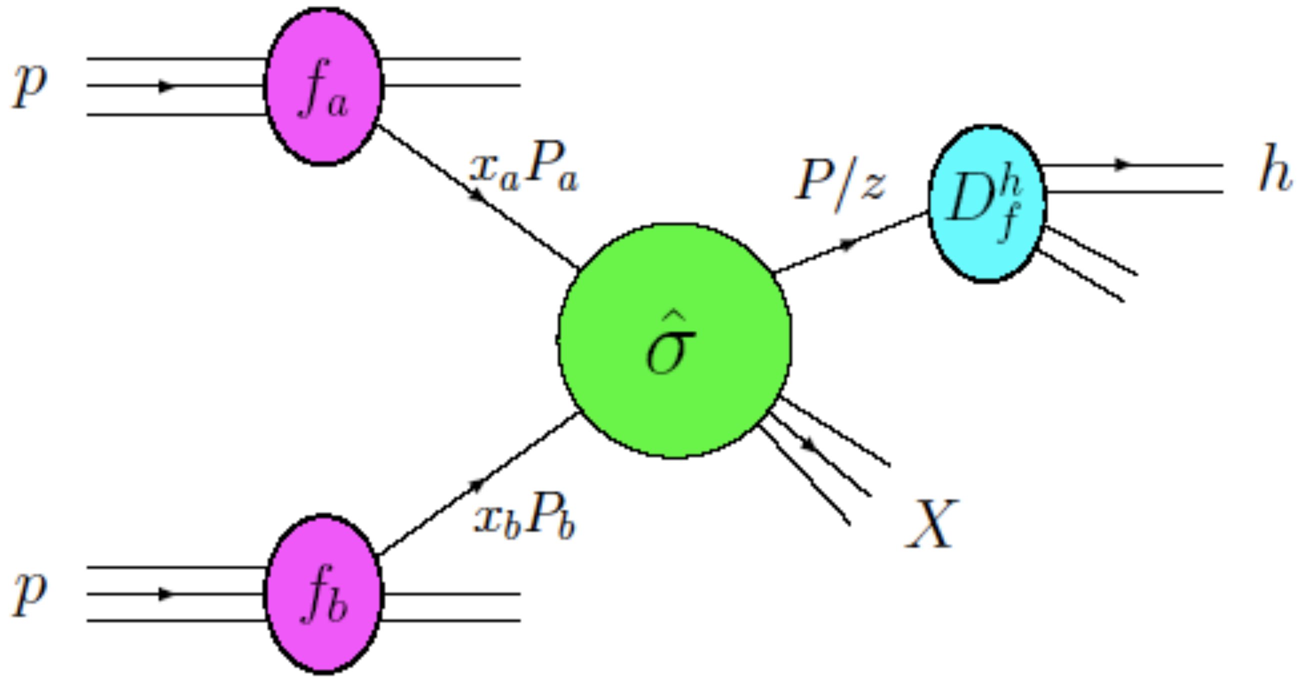
- $m_{\mathrm{Q}} \gg \Lambda_{\mathrm{QCD}}$
  - Enable the evaluation of their production cross sections within pQCD
- $m_{\mathrm{Q}} \gg T_{\mathrm{QGP}}$
  - Produced mainly in initial hard scatterings (high Q^2) at early stage of heavy-ion collisions
- $\tau_{\mathrm{prob}} \approx \dfrac{1}{2m_{\mathrm{q}}}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

- Hadroproduction described by factorisation approach:

$$\frac{\mathrm{d}\sigma^{\mathrm{D}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{D}}}(p_{\mathrm{T}};\mu_{\mathrm{F}};\mu_{\mathrm{R}}) = PDF(x_{\mathrm{a}},\mu_{\mathrm{F}})PDF(x_{\mathrm{b}},\mu_{\mathrm{F}}) \otimes \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_{\mathrm{a}},x_{\mathrm{b}},\mu_{\mathrm{R}},\mu_{\mathrm{F}}) \otimes D_{\mathrm{c}\to\mathrm{D}}(z=p_{\mathrm{D}}/p_{\mathrm{c}},\mu_{\mathrm{F}})$$

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

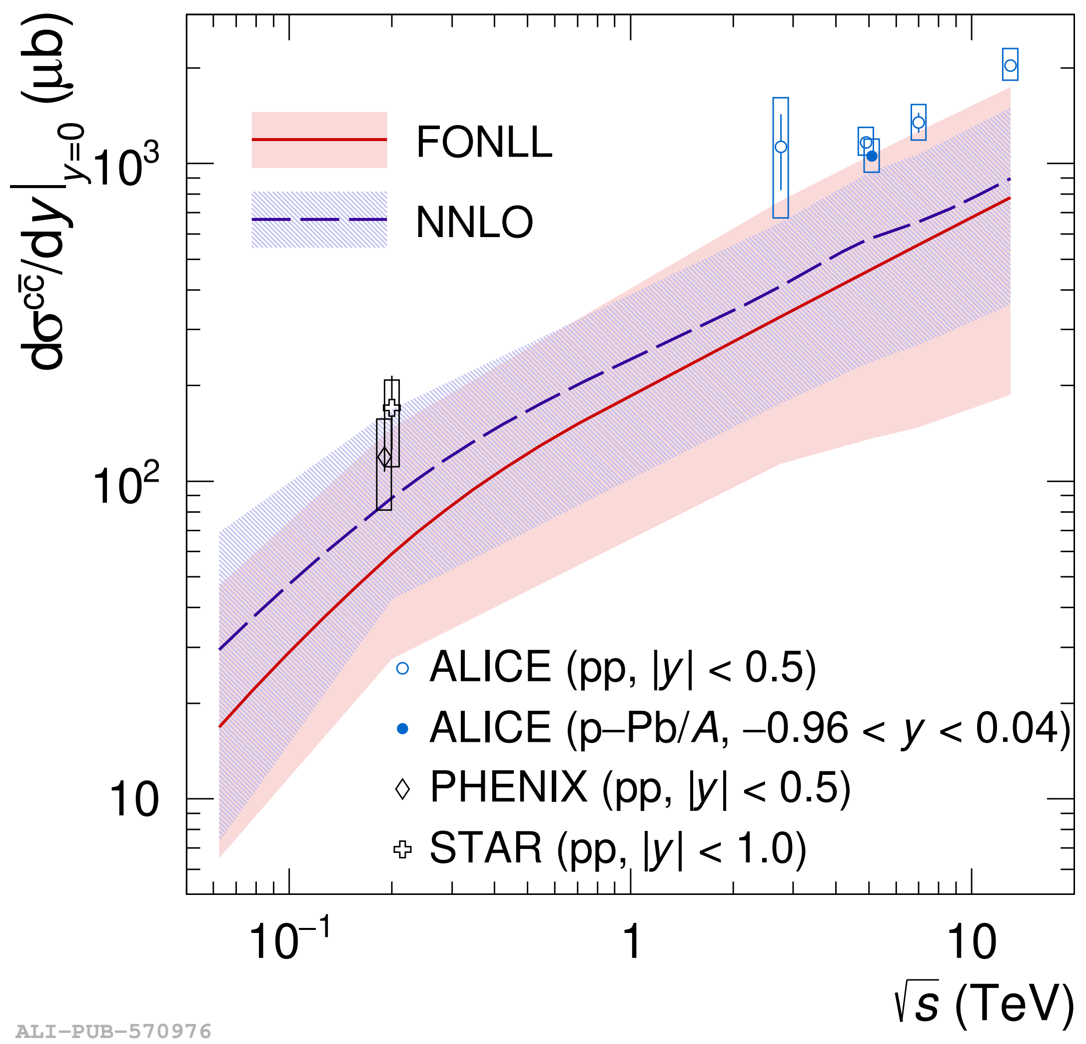
Fragmentation functions assumed to be universal

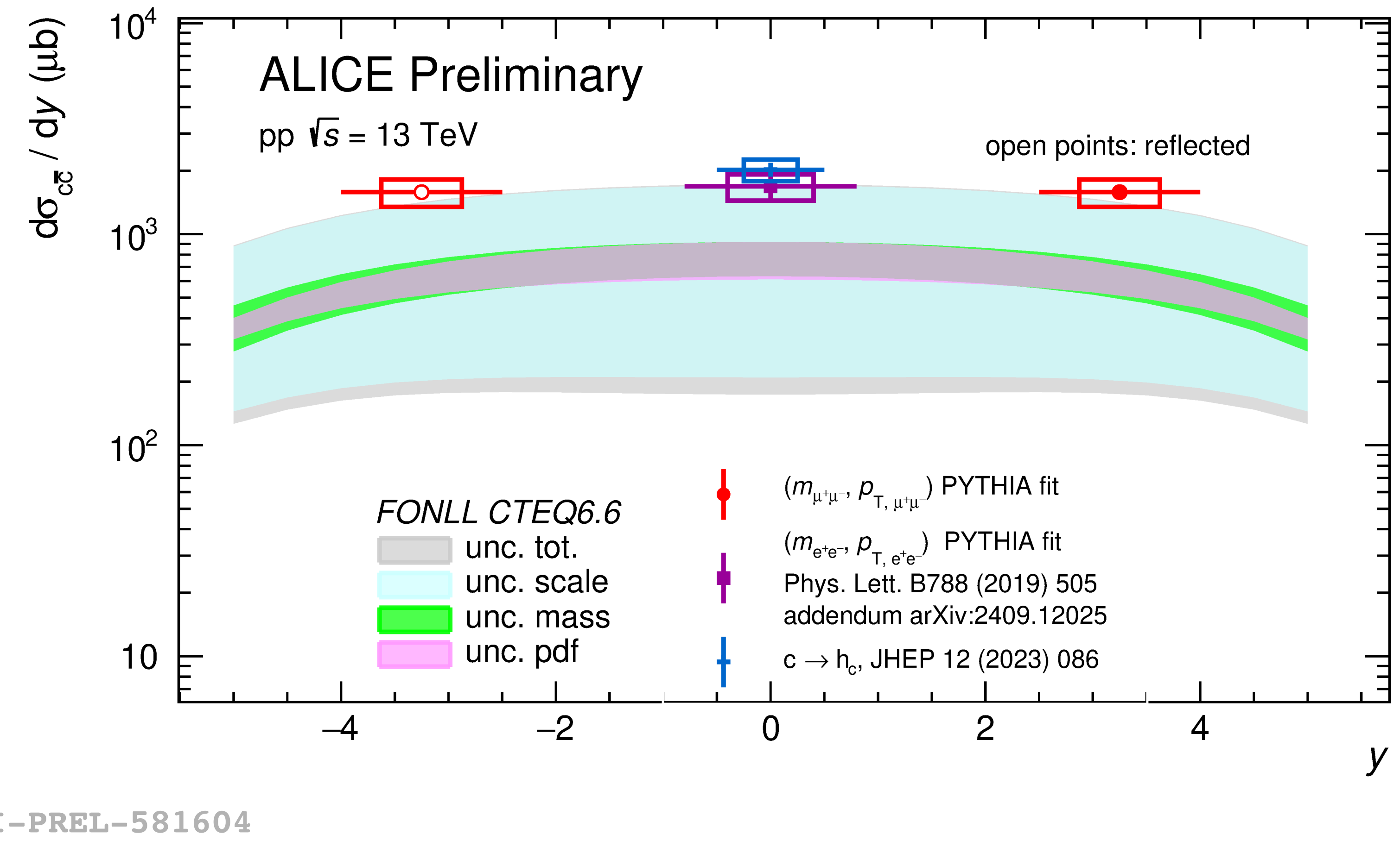


HF production in small system

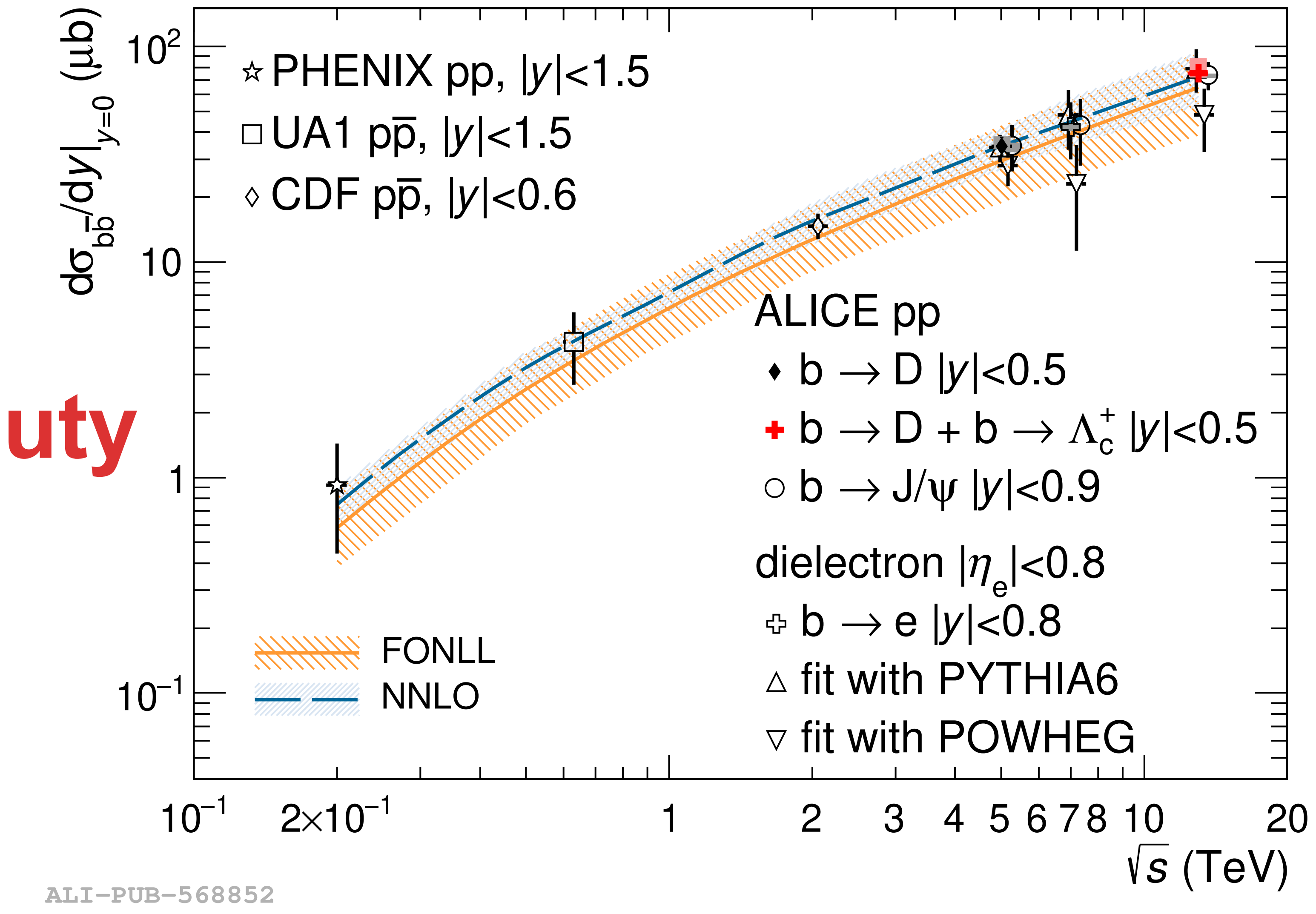
arXiv:2405.14571 (accepted by EPJC)

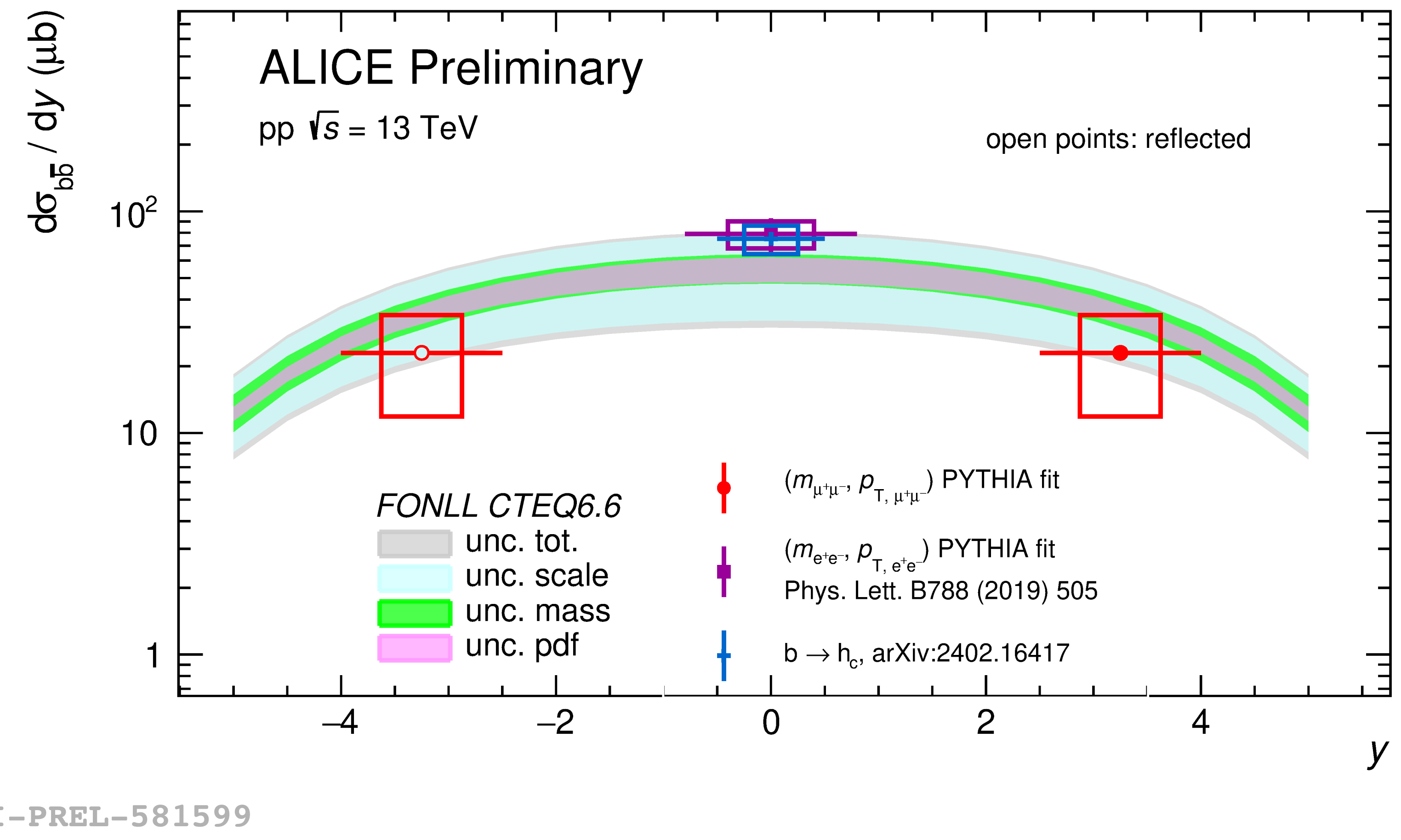
Charm



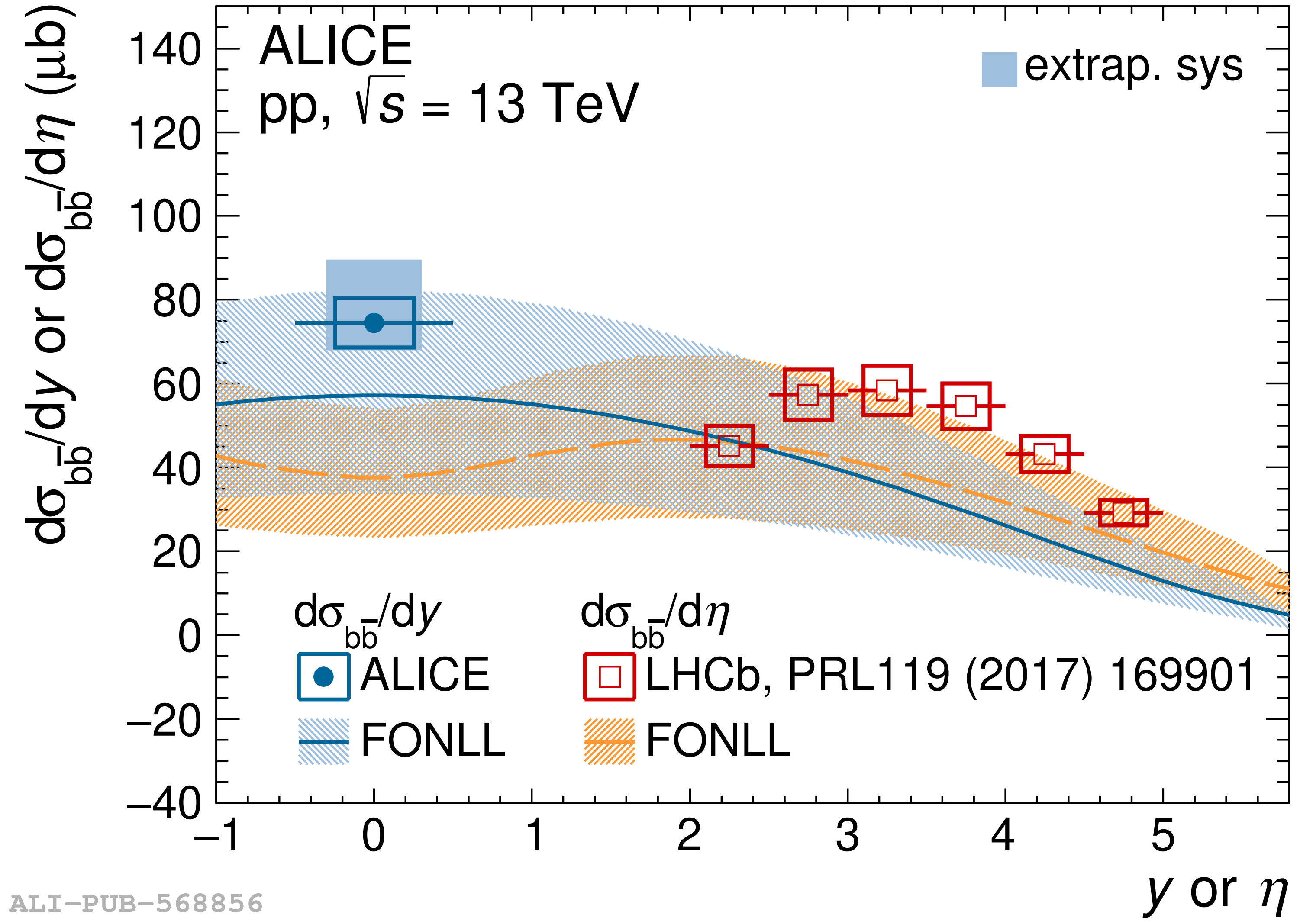


Beauty



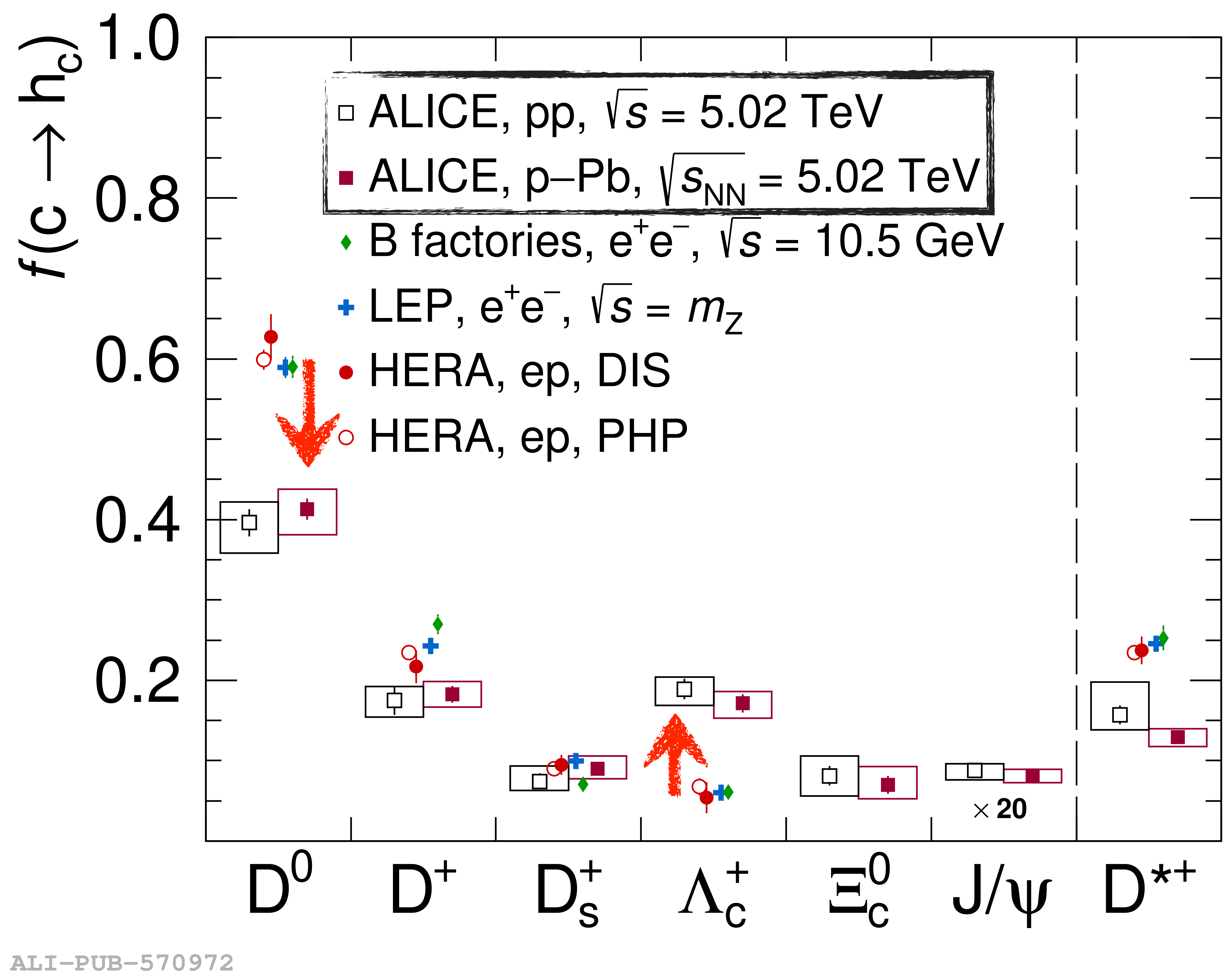


JHEP 10 (2024) 110



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



arXiv:2405.14571 (accepted by EPJC)

- 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

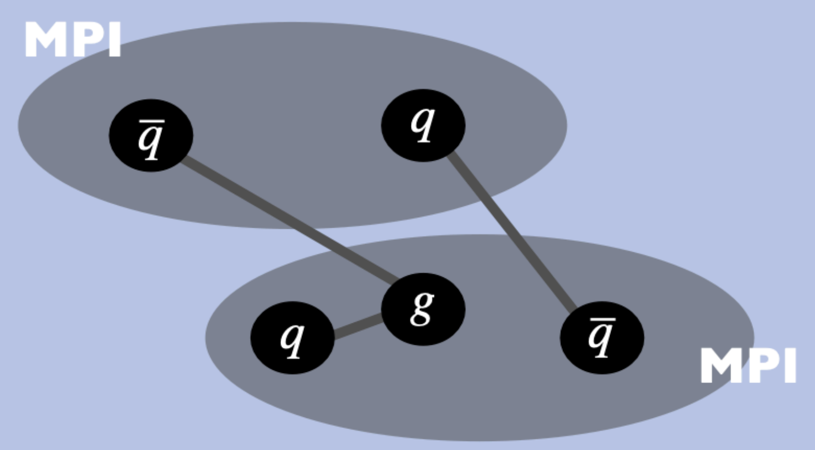
Fragmentation fractions universality is challenged

- 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

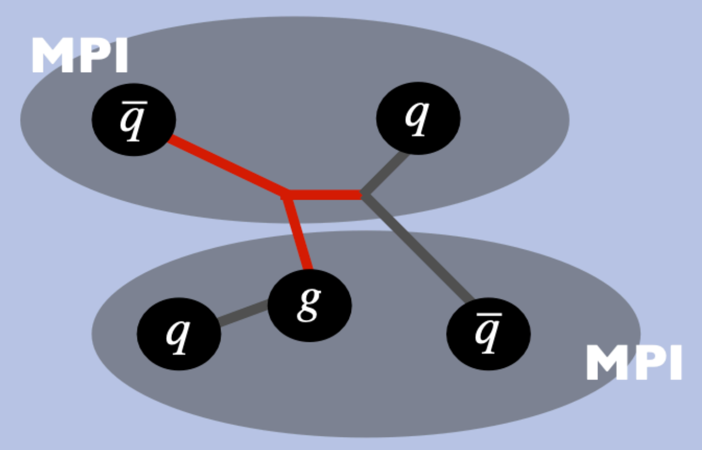
Modeling hadronization

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

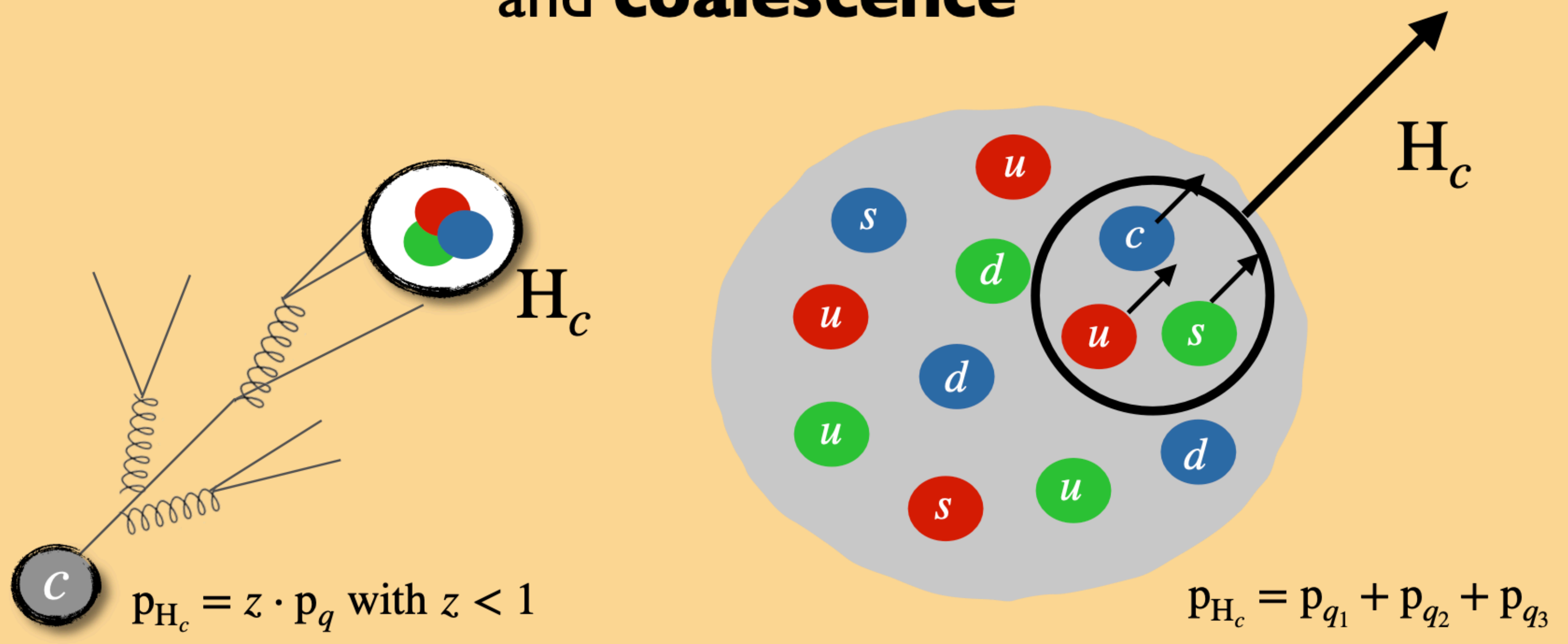


Mode 2
the **junction** topology leads to an increase of baryon production
JHEP 08 (2015) 003

CATANIA

Phys.Lett.B 821 (2021) 136622

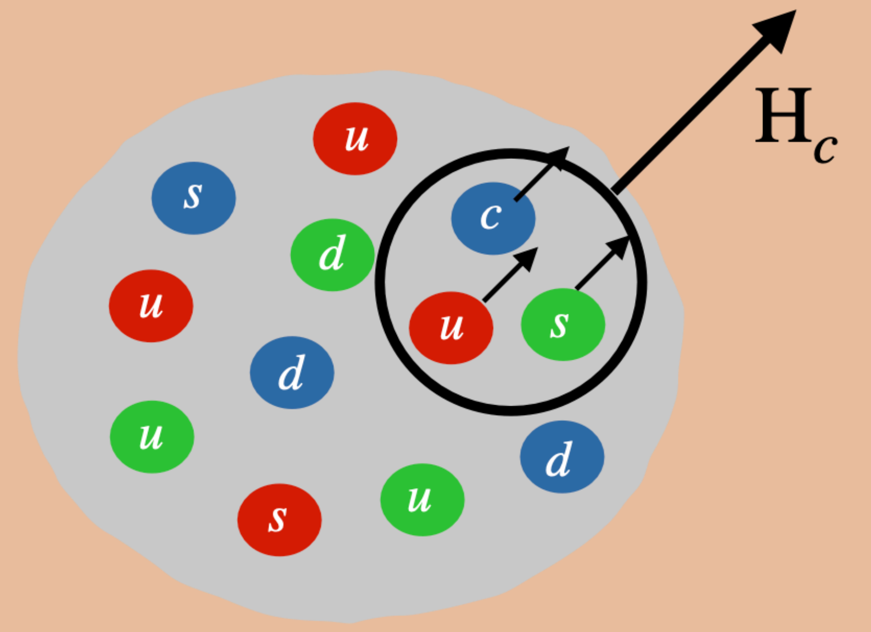
Hadronization via both **fragmentation** and **coalescence**



QCM

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

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



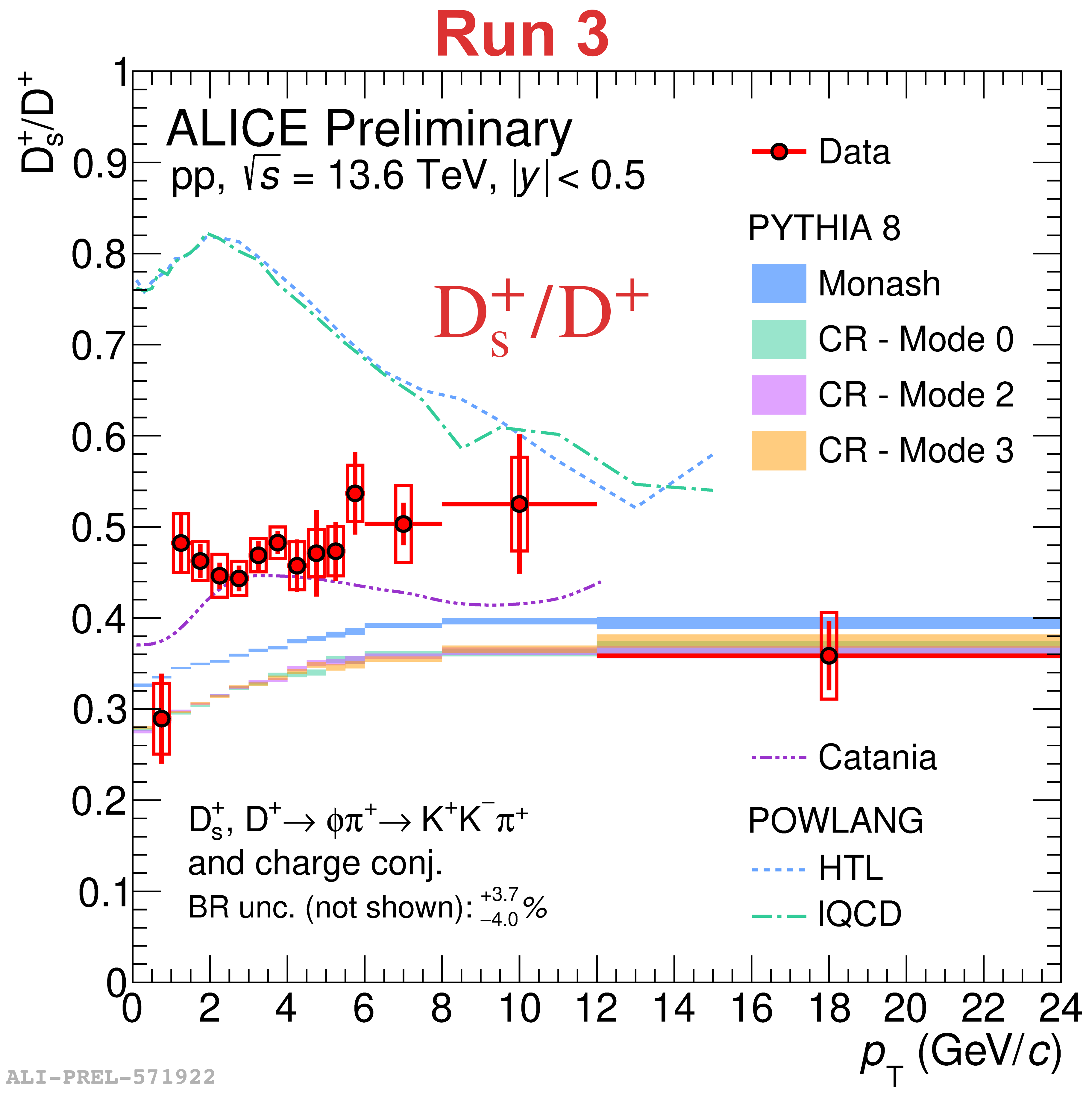
SHM + RQM

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

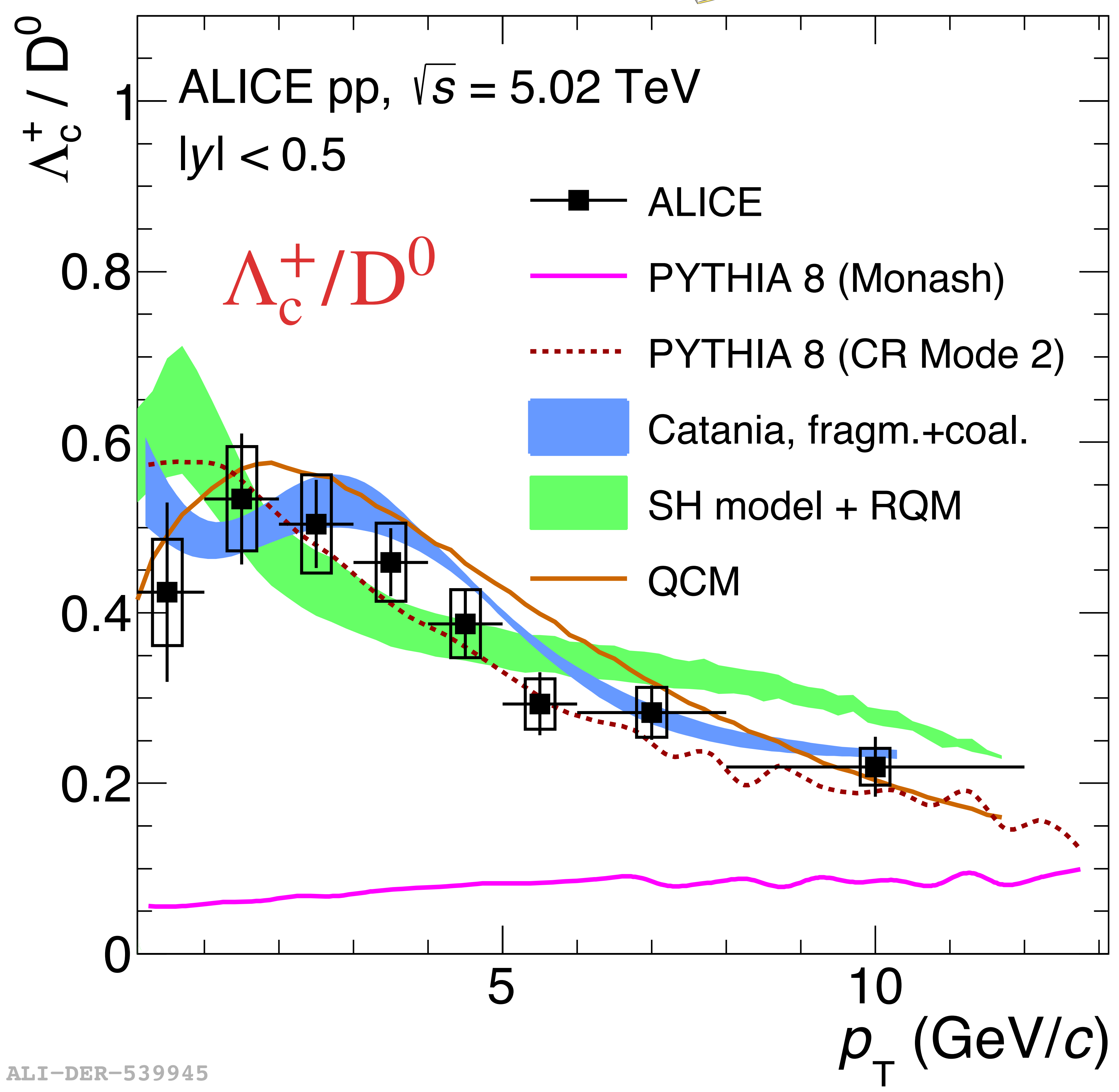
- Complexity of hadronization process replaced by **statistical weights** governed by hadron mass
- Feed-down from largely **augmented set of charm baryon stated** beyond the ones currently listed in the PDG, as predicted by Relativistic Quark Model

EPOS4HQ fragmentation + coalescence + resonance + UrQMD

Hadronisation: HF particle ratios in small system



Phys.Rev.C 107 (2023) 064901

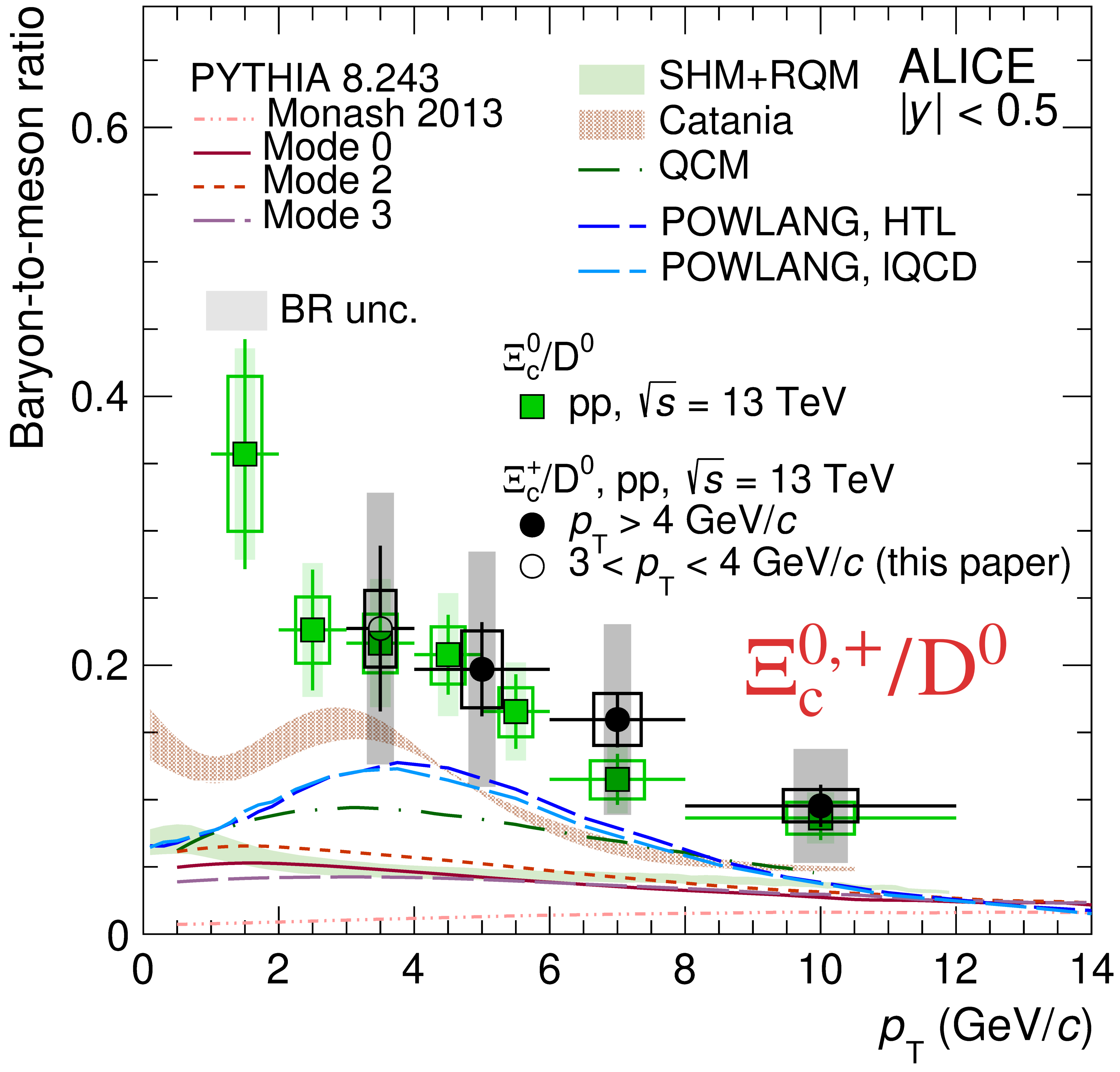


- Catania works better
  - Coalescence in pp collisions
  - Assume a thermalised QGP-like system

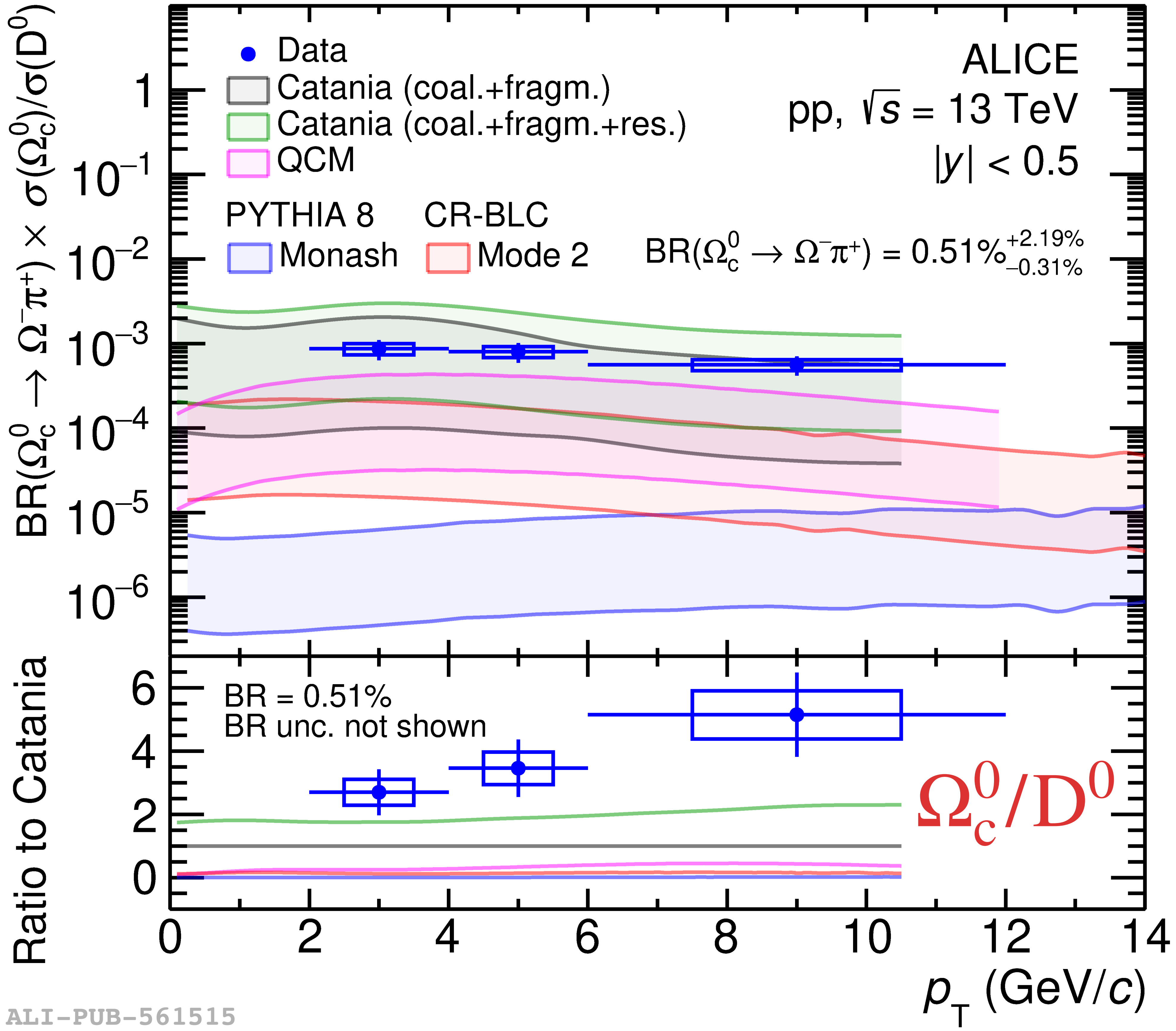
PYTHIA 8 Monash: *Eur.Phys.J.C 74 (2014) 3024*
PYTHIA 8 CR Mode: *JHEP 08 (2015) 003*
Catania: *Phys.Lett.B 821 (2021) 136622*
SHM: *Phys.Lett.B 795 (2019) 117-121*
RQM: *Phys.Rev.D 84 (2011) 014025*
QCM: *Eur.Phys.J.C 78 (2018) 344*

Hadronisation: HF particle ratios in small system

JHEP 12 (2023) 086



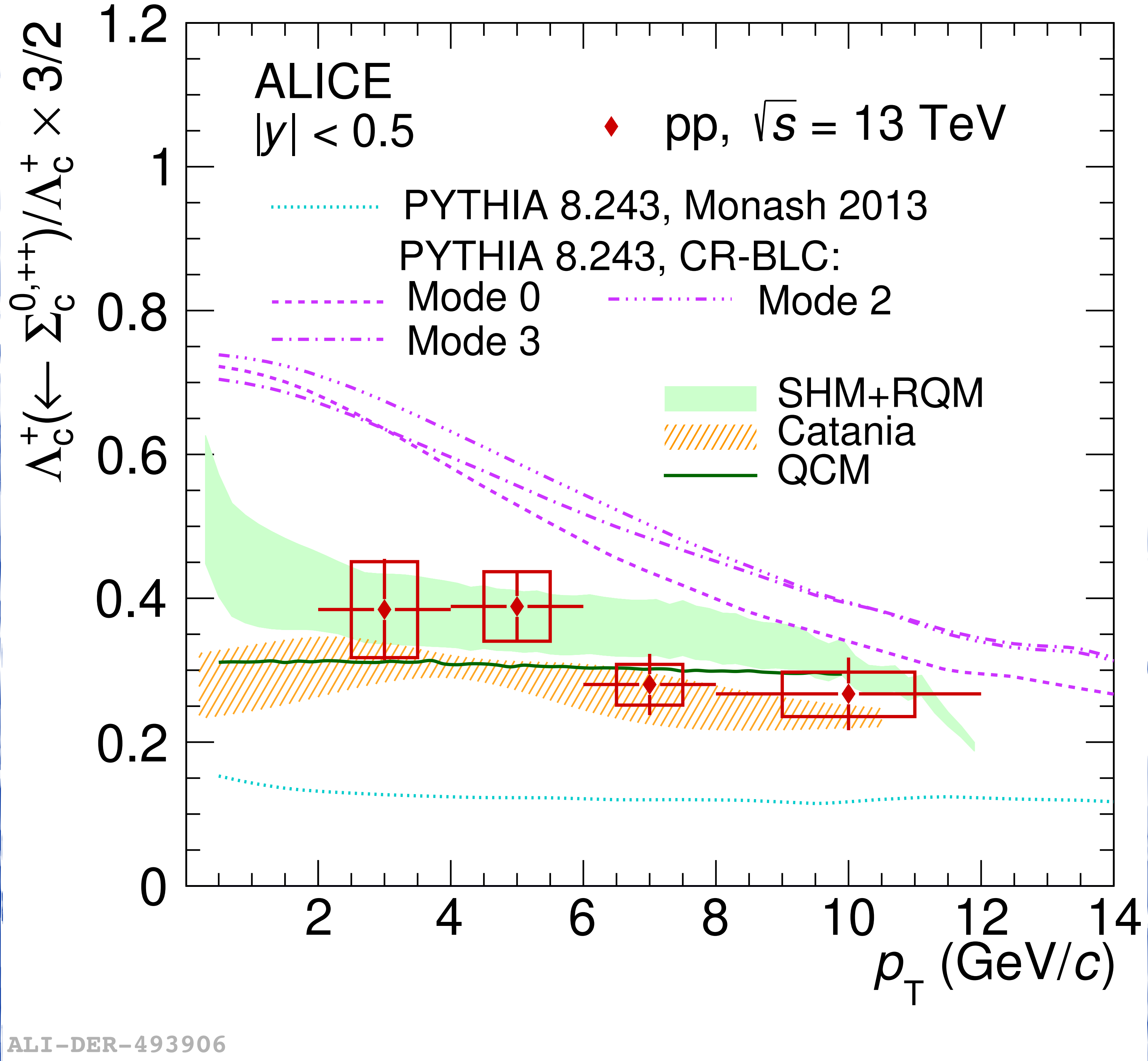
PLB 846 (2023) 137625



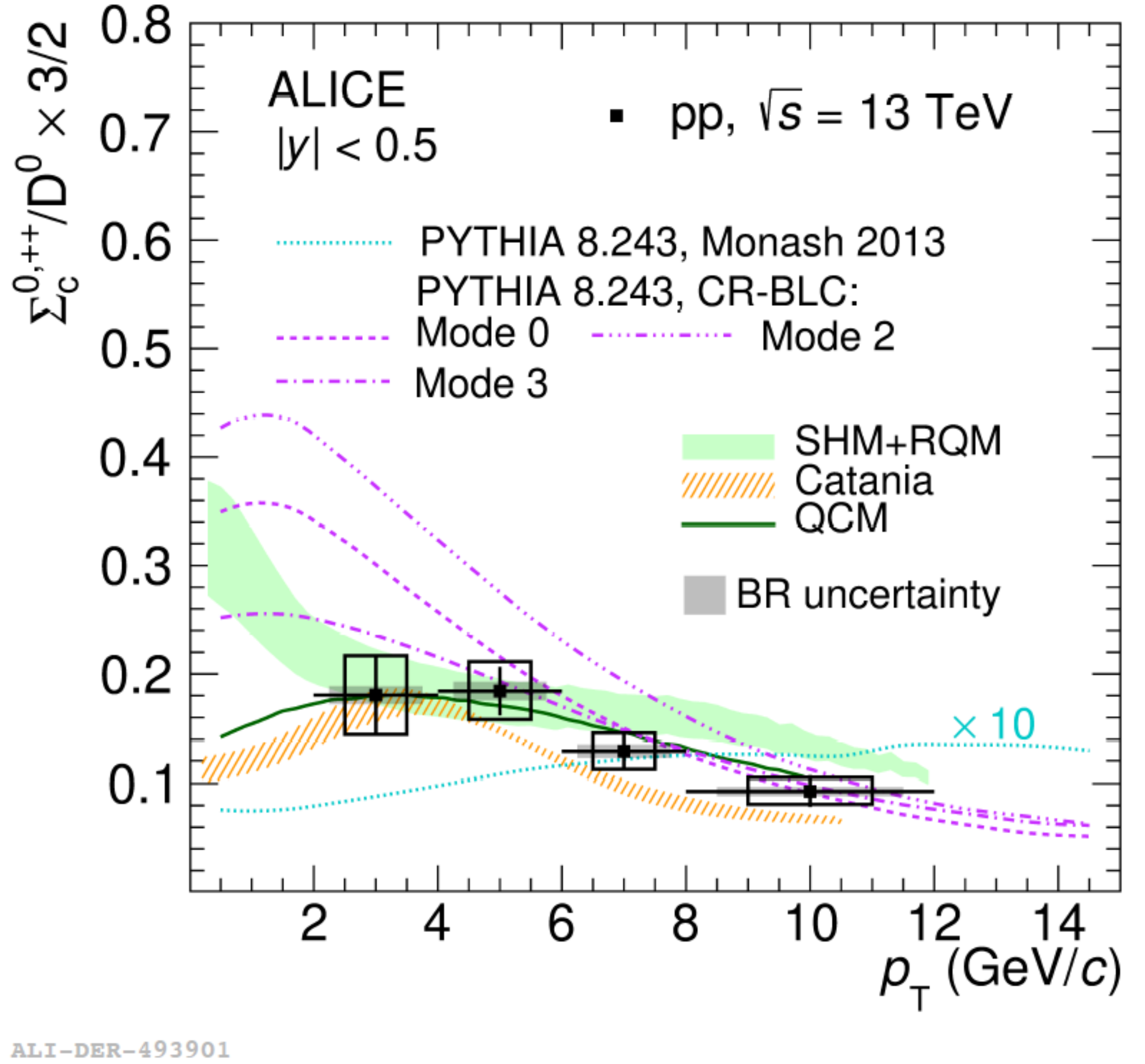
- Models cannot describe $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0
- The role of strangeness in HF hadronisation might be a challenge to theory

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*

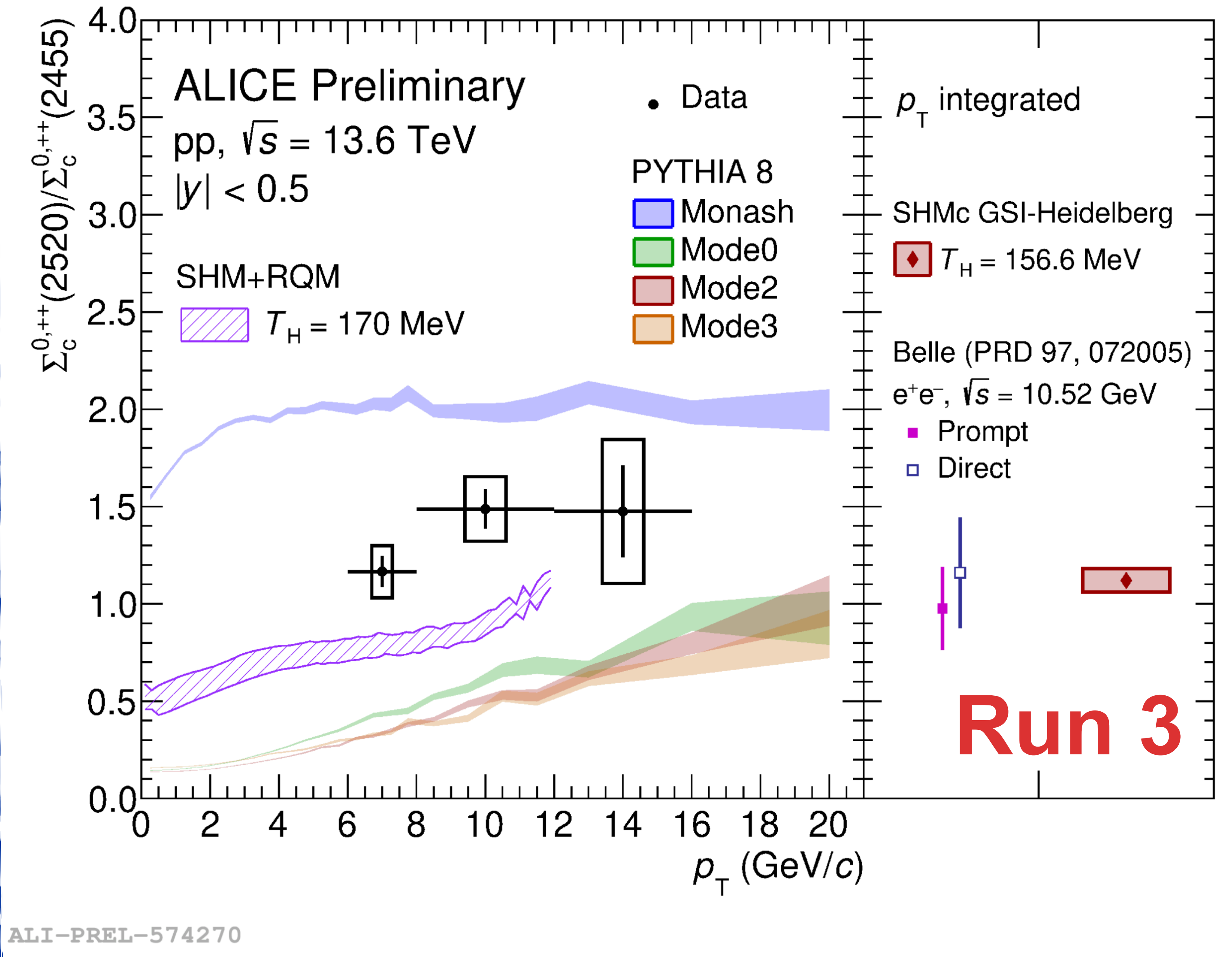
Hadronisation: higher mass particles decay



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



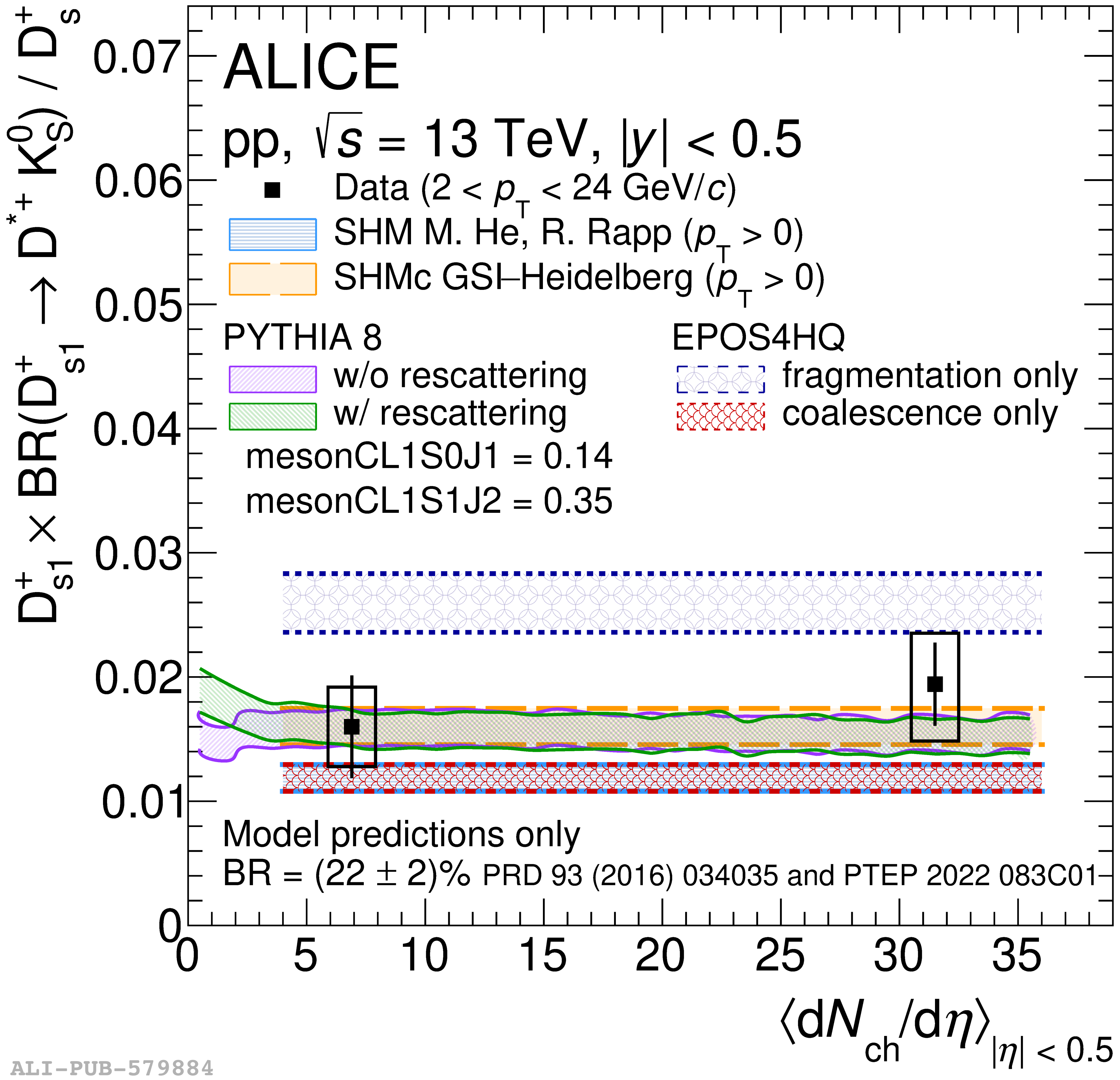
- Described by PYTHIA 8 CR, Catania, QCM and SHM+RQM

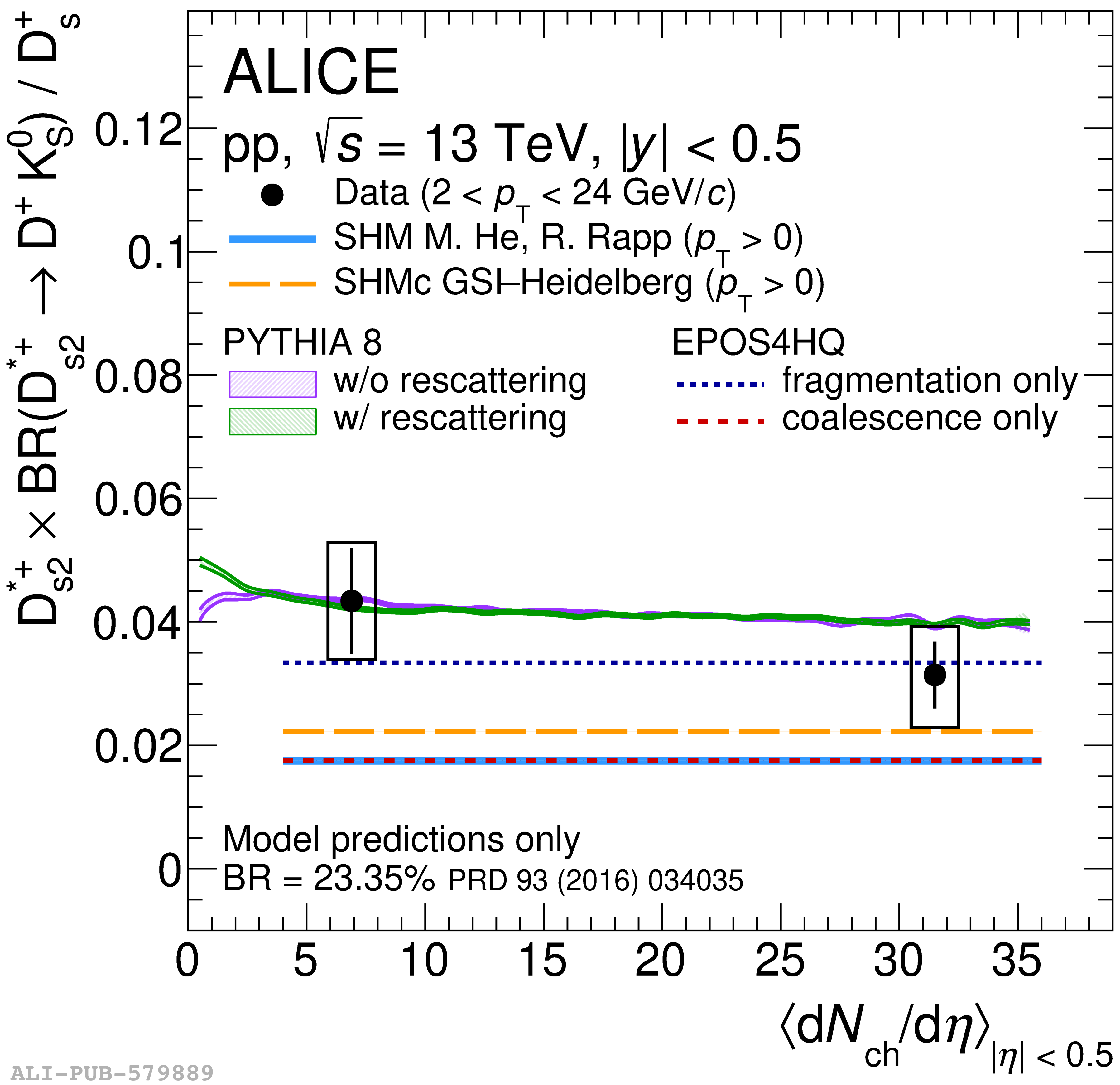


- Ratios between two $\Sigma_c^{0,++}$ states consistent with p_T integrated result from e^+e^- collisions
- Overestimated by PYTHIA 8 Monash, underestimated by CR and SHM+RQM

Hadronisation: resonances decay

arXiv:2409.11938





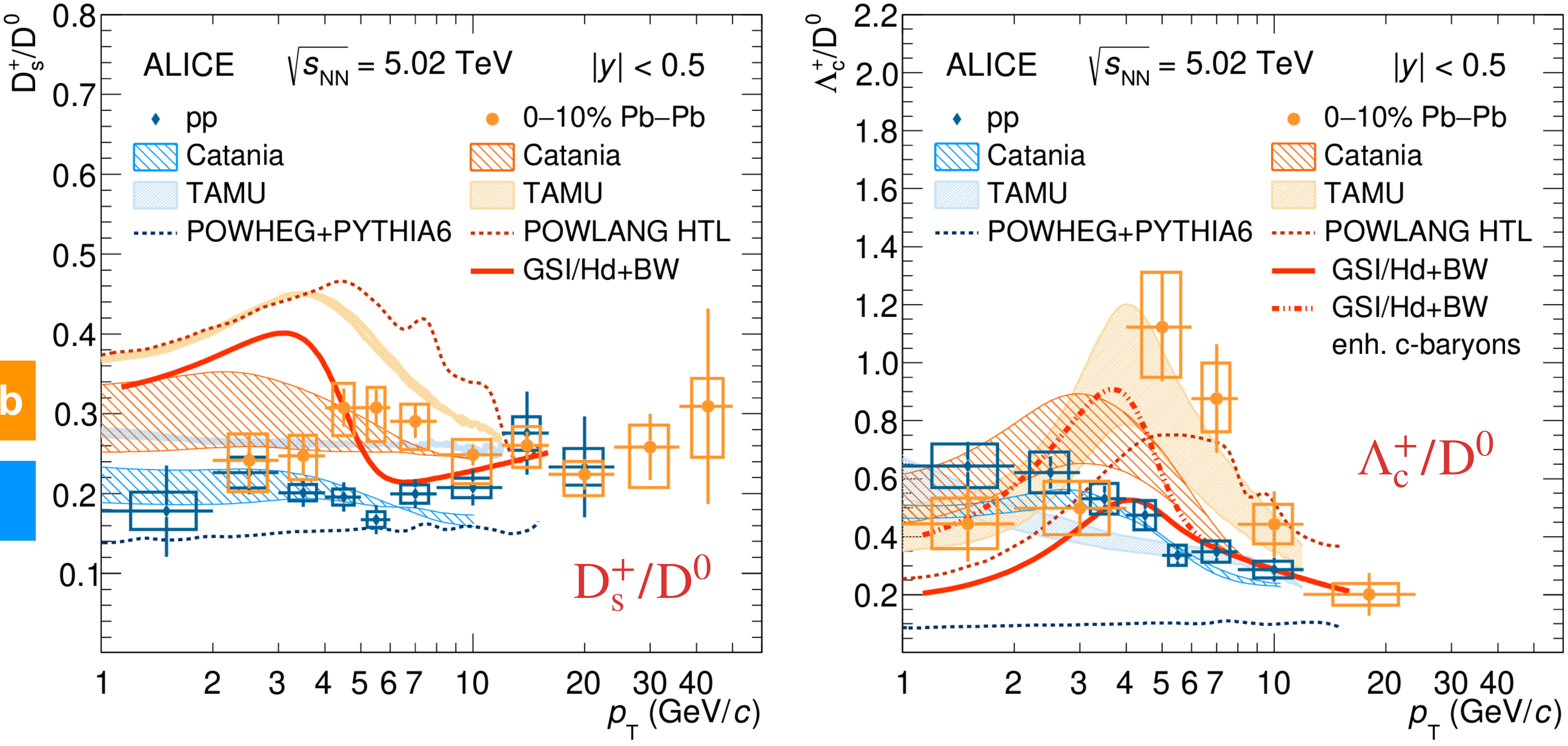
- D^+_{s1}/D^+_s and D^{*+}_{s2}/D^+_s ratios flat vs. charged-particle multiplicity, as ground-state D-meson ratios
- Multiplicity trend described by SHM, SHMc, EPOS4HQ models and by PYTHIA 8 calculations

Hadronisation: large system

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

Pb–Pb

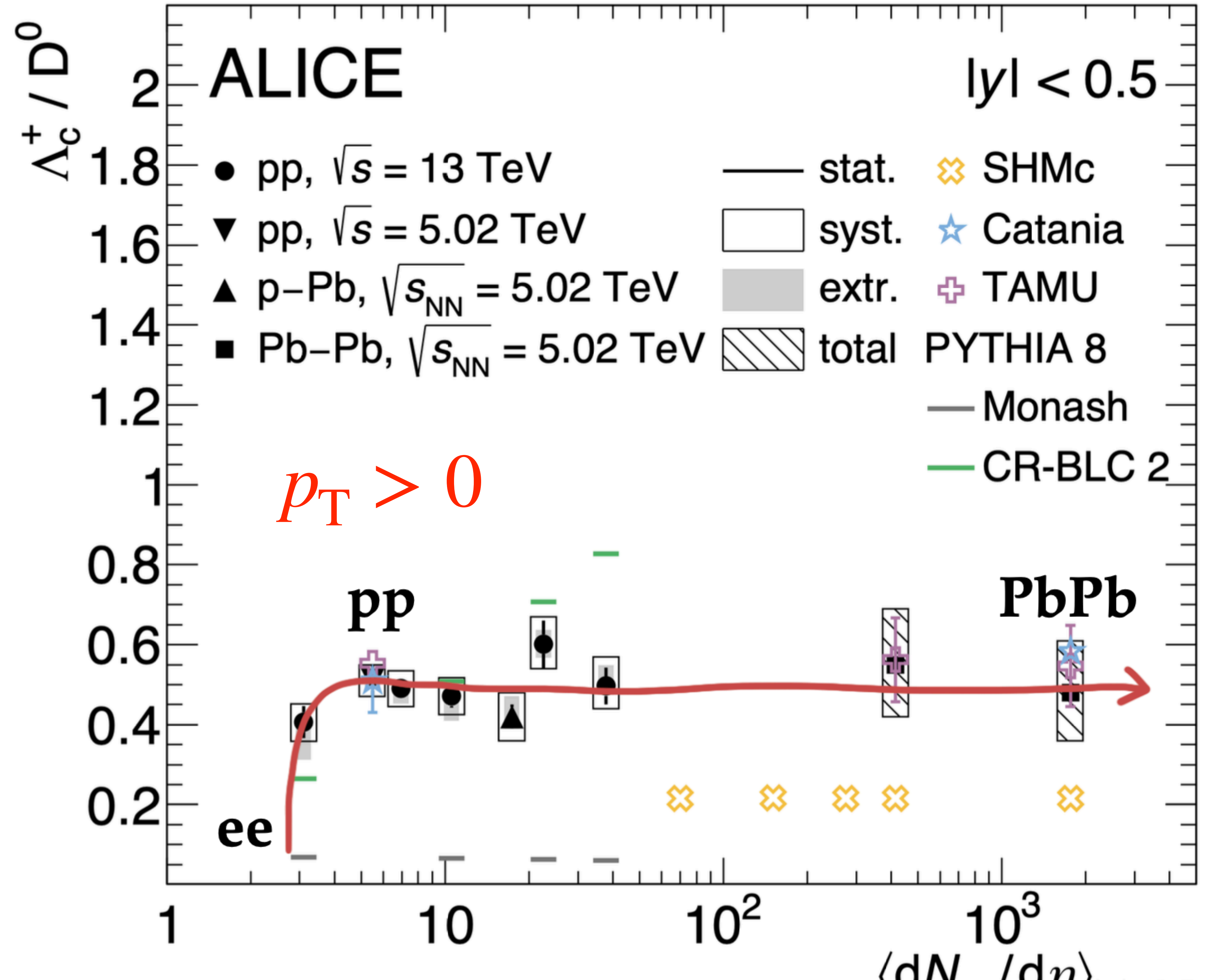
pp



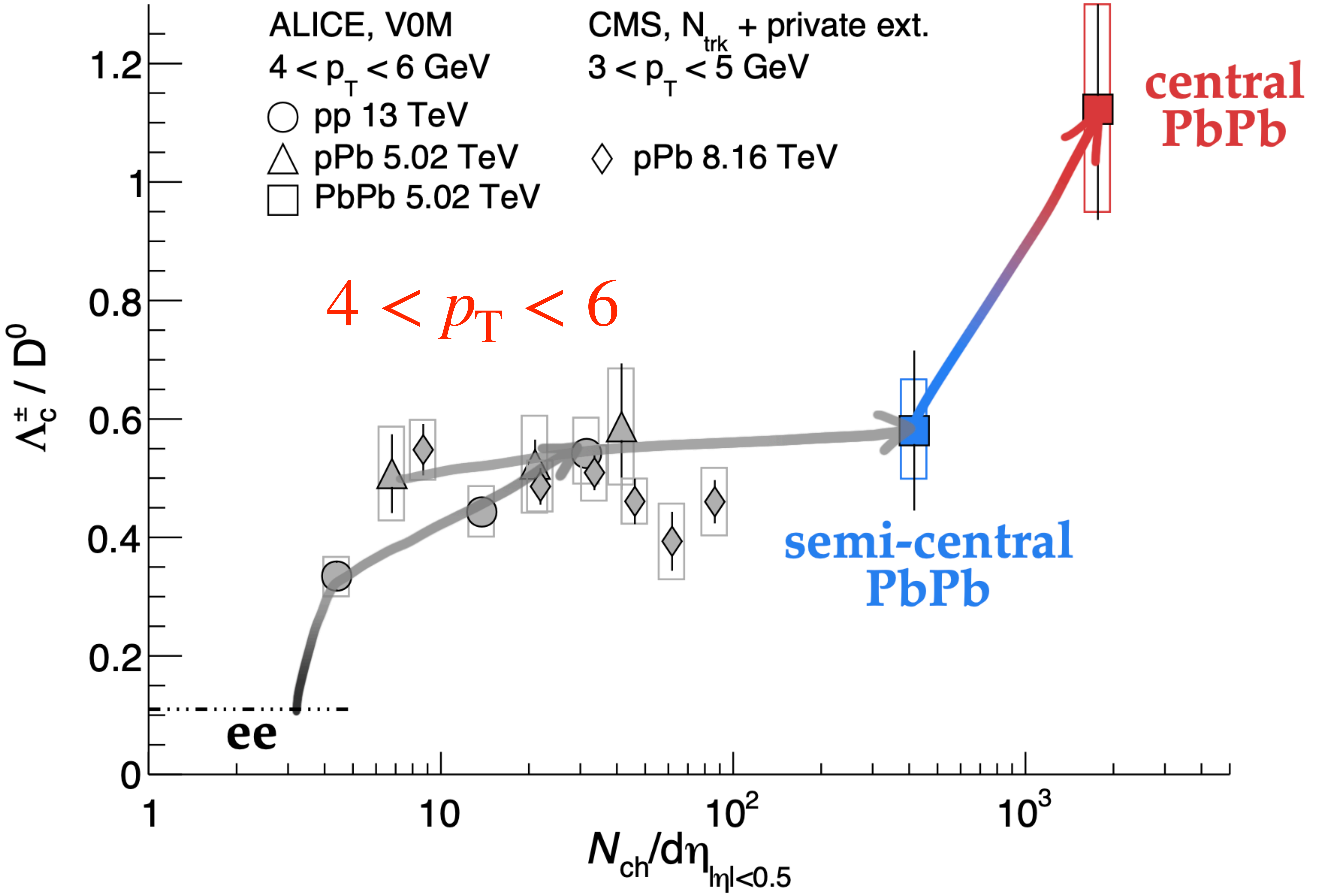
Ξ_c^0/D^0 in preparation, larger enhancement expected

- 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)

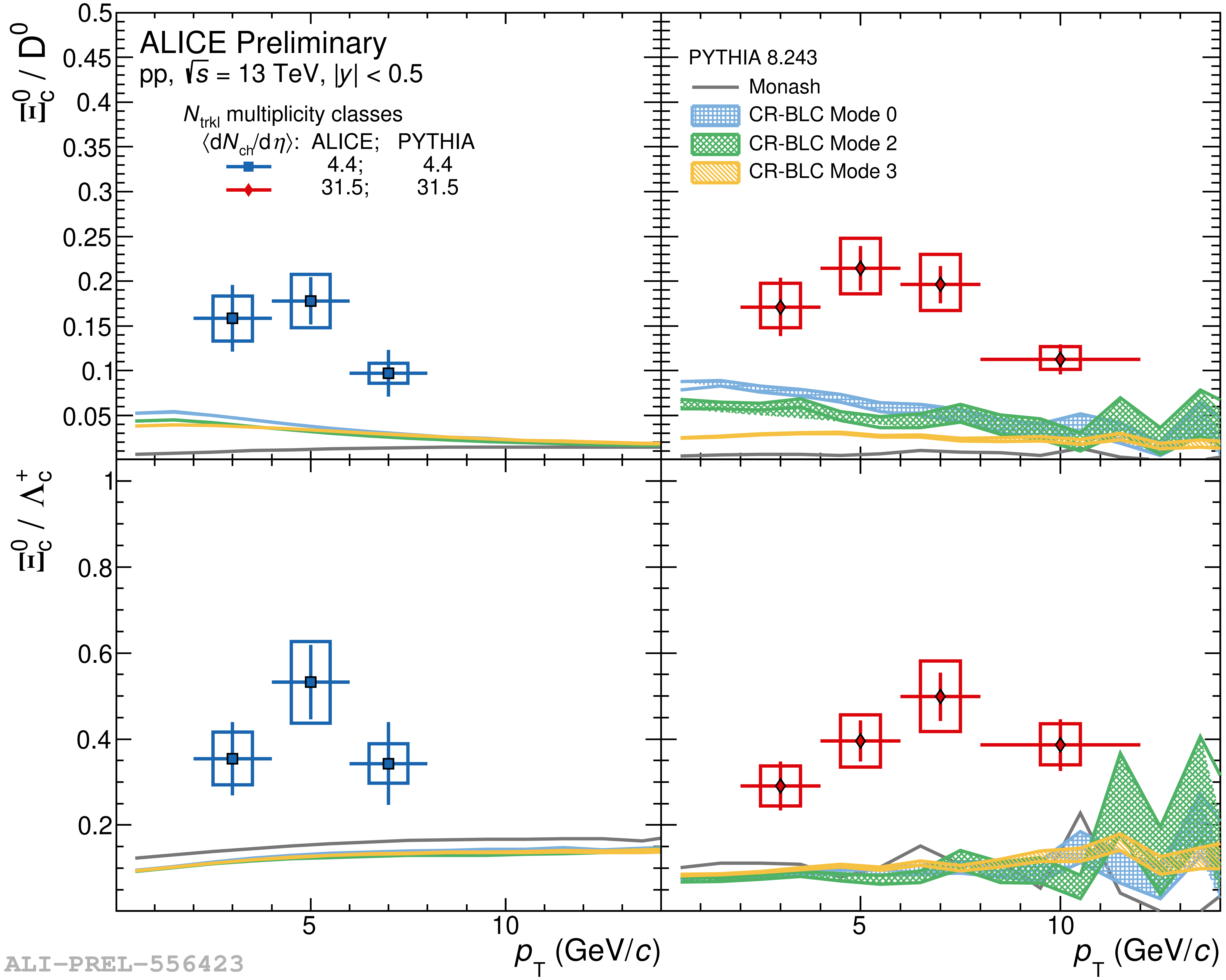


ALICE PLB 839 (2023) 137796



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

Hadronisation: system scan (by 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

Tao Fang's talk
on Friday at 15:50
Parallel 3

Hadronisation: rapidity dependence (more challenges)

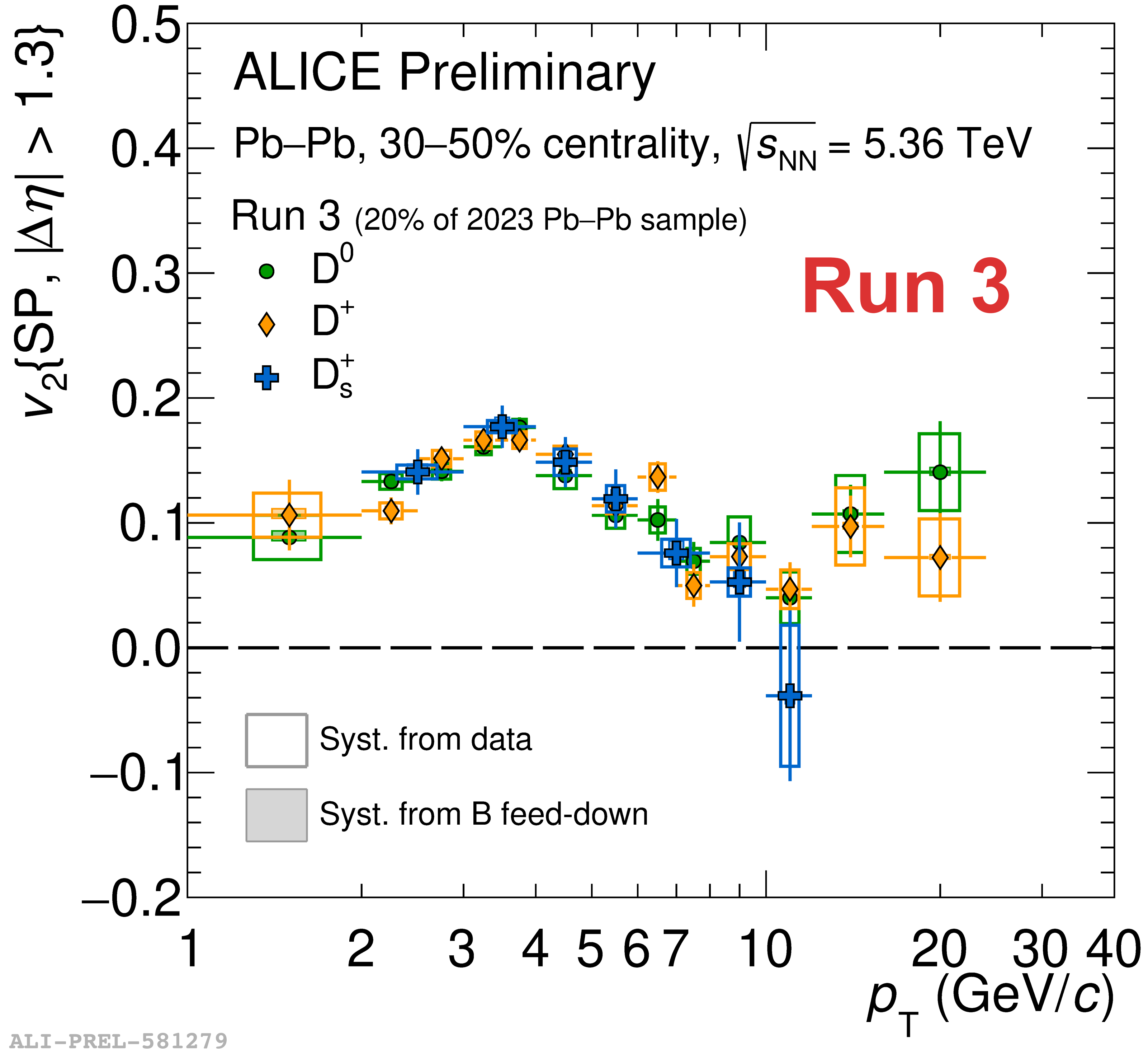
ALICE JHEP 12 (2019) 092
LHCb JHEP 01 (2024) 070

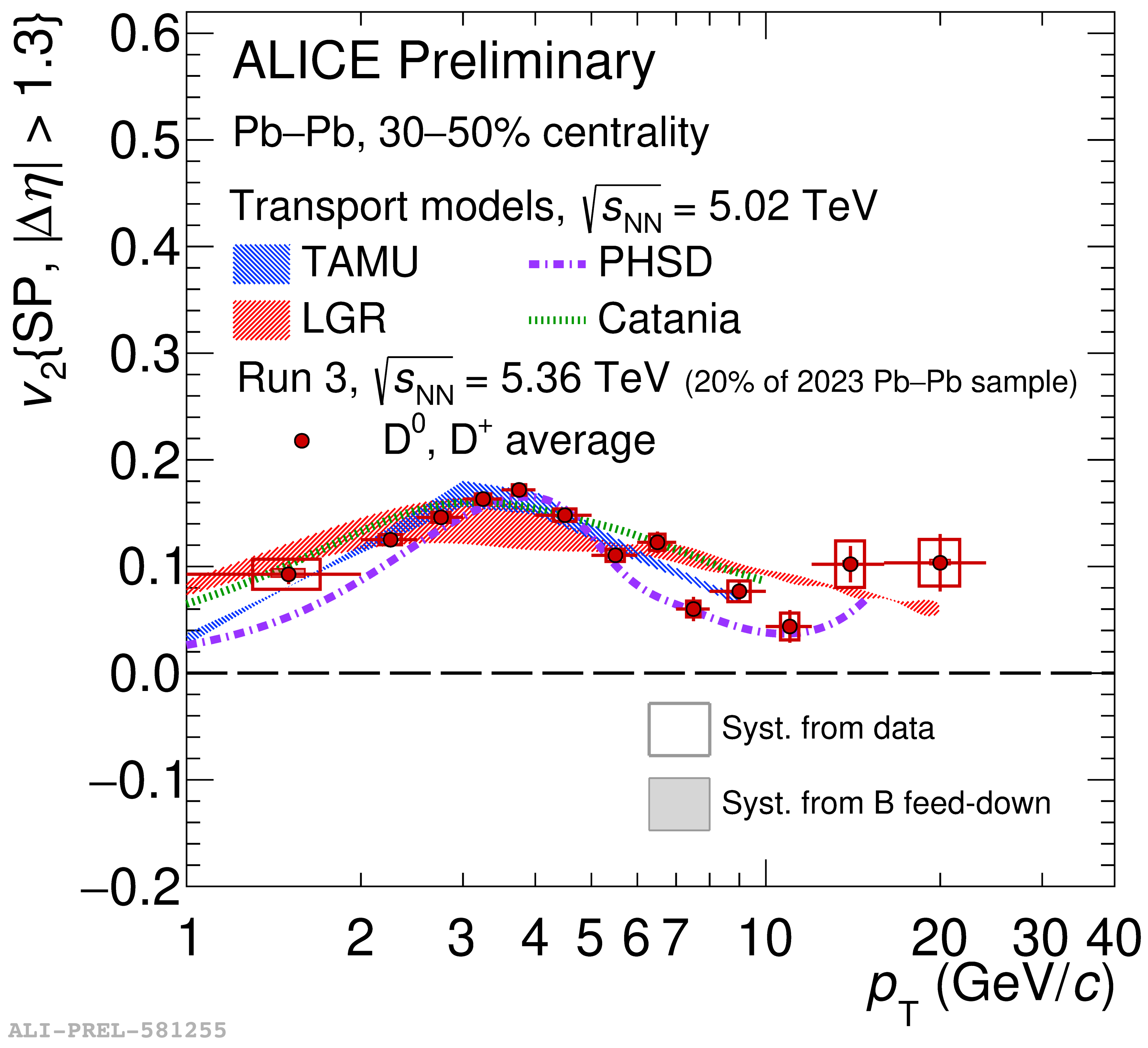
ALICE PRC 107 (2023) 064901
LHCb JHEP 02 (2019) 102

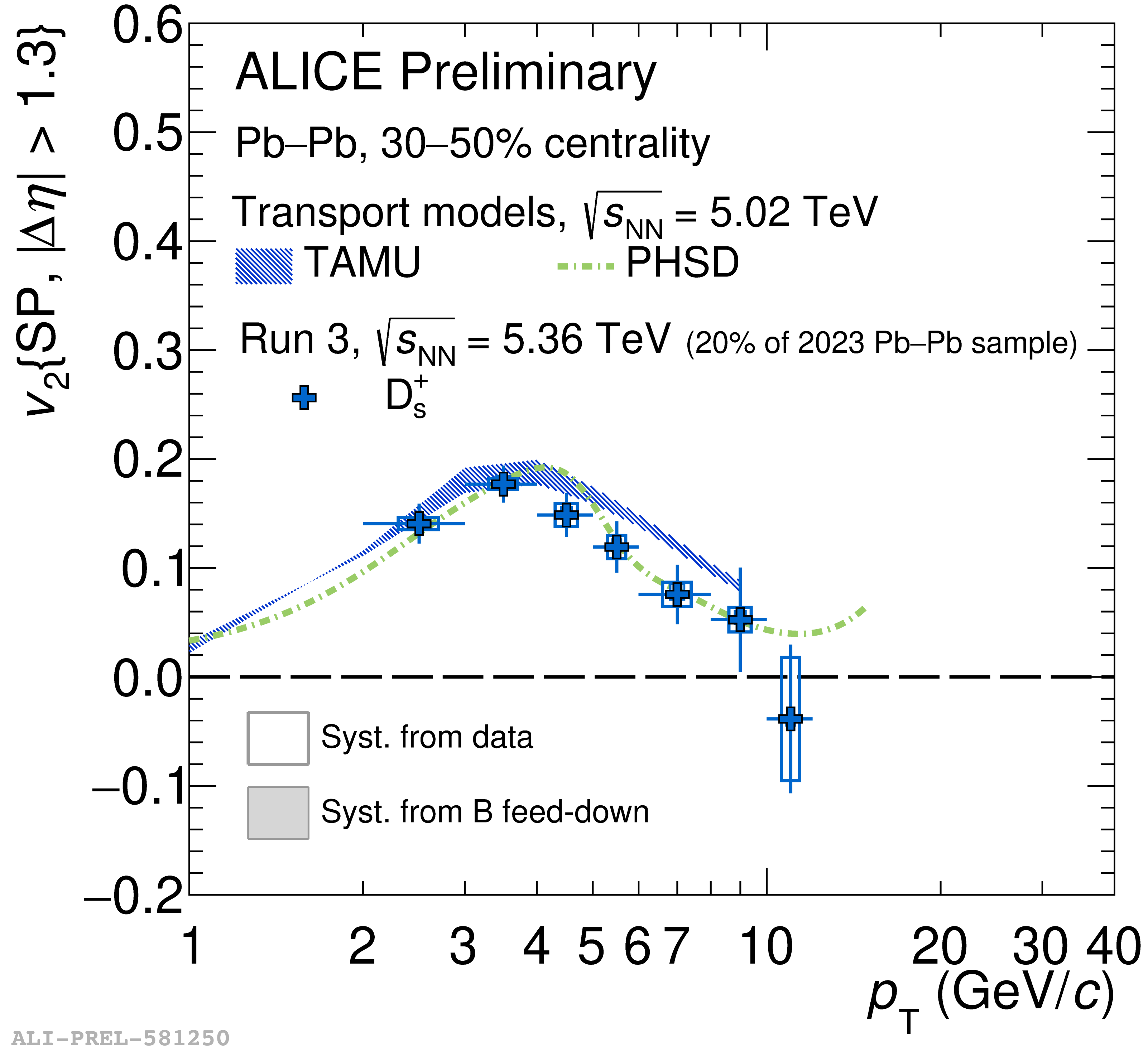
ALICE arXiv:2407.10593
LHCb PRD 99 (2019) 052011

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

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





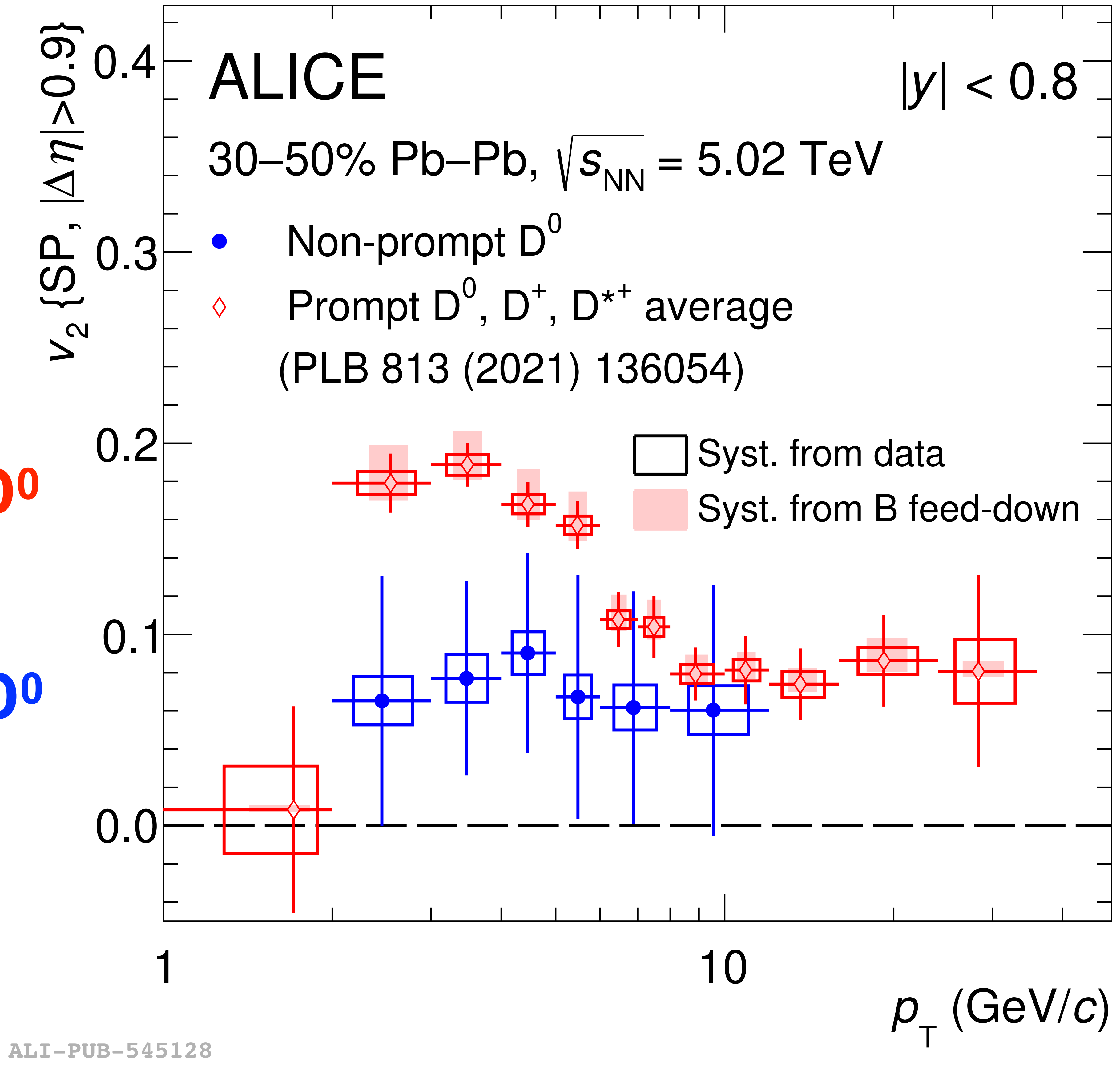


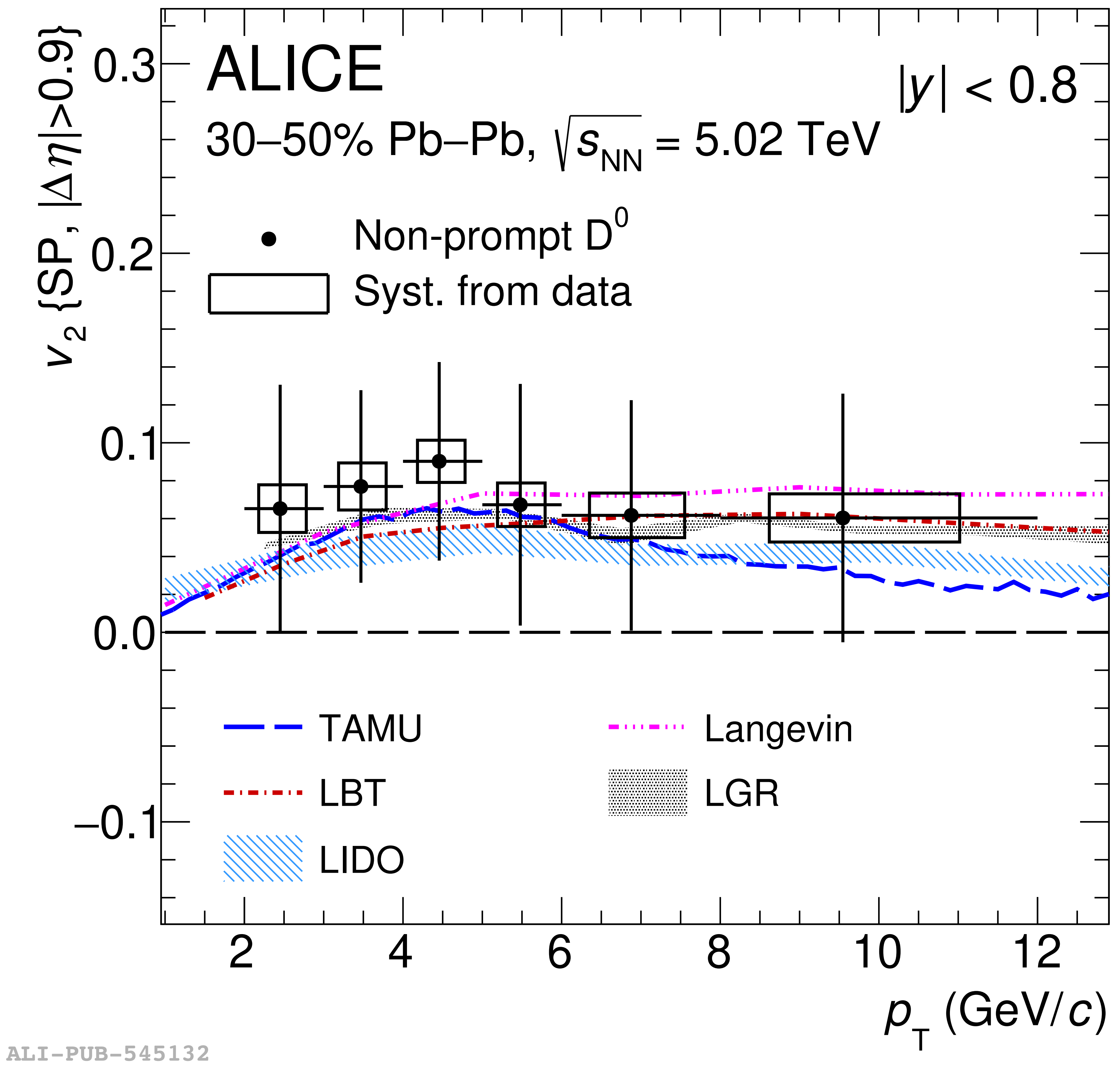
- About x4 larger statistics more than Run 2, x5 more statistics will come soon
- No significant difference between strange and non-strange D mesons
- Strange D-meson elliptic flow reproduced by transport models

Collectivity: non-prompt D^0 elliptic flow

c → D^0

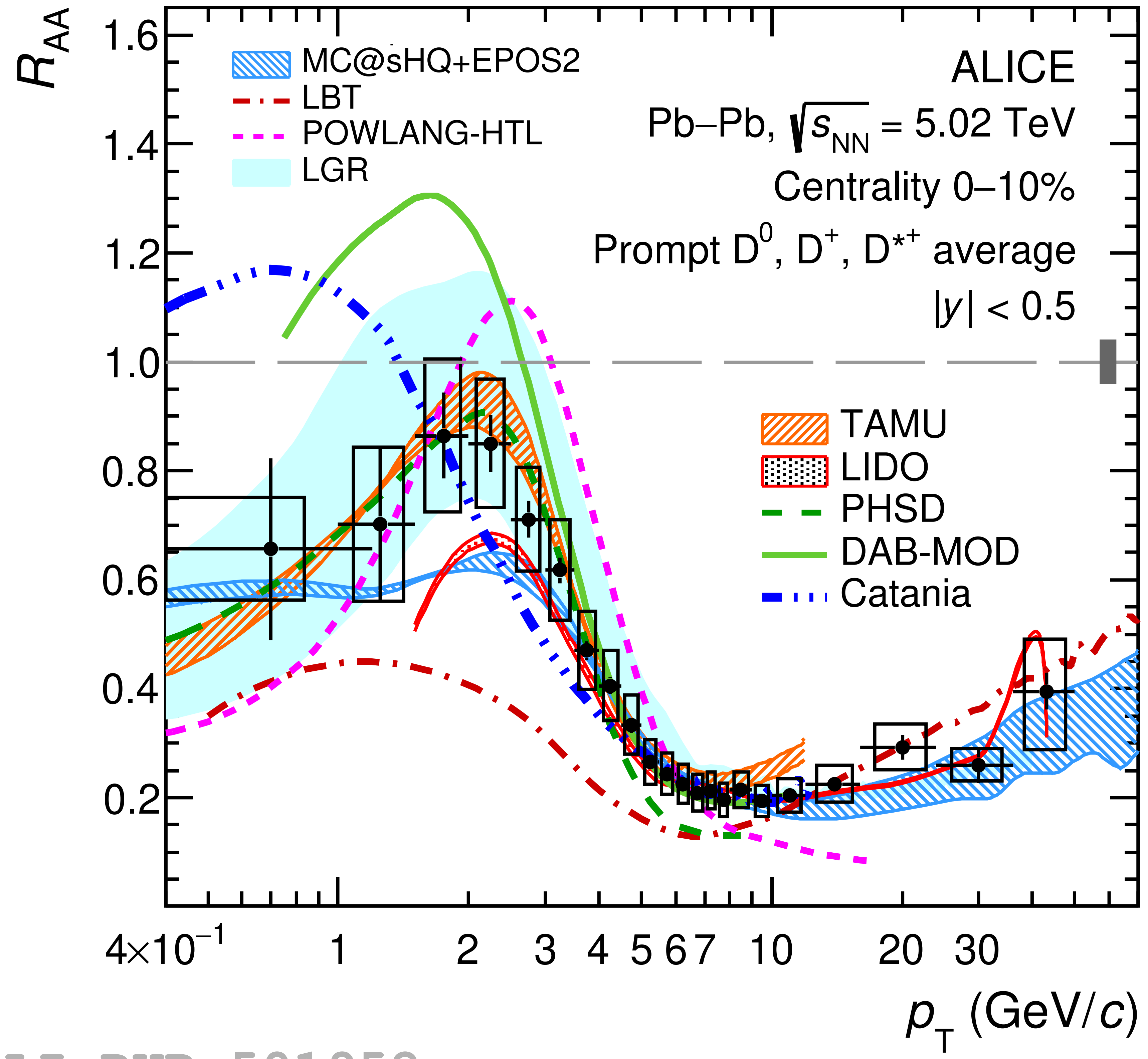
b → D^0





- 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}

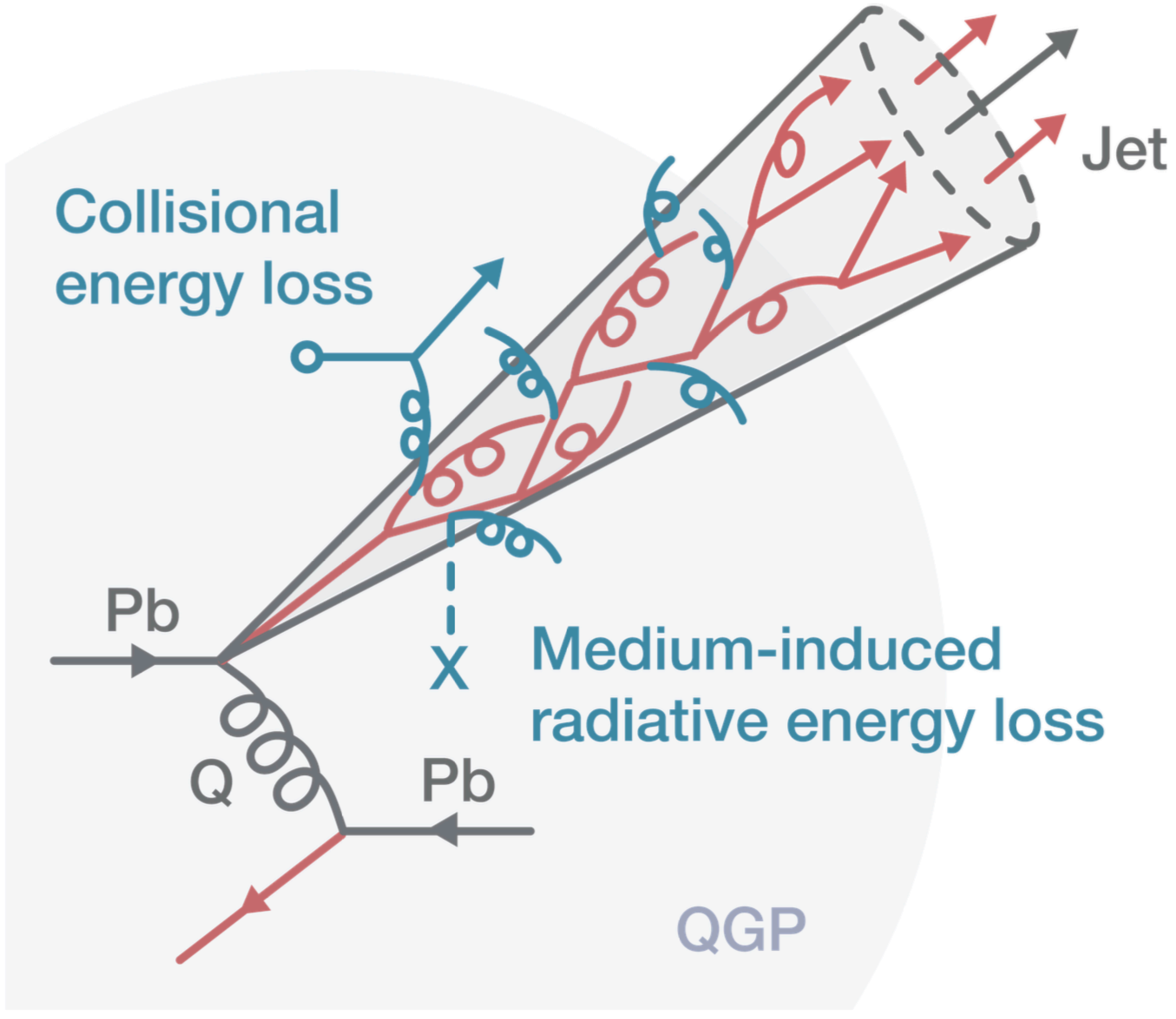


ALI−PUB−501952

collective flow, hadronisation, nuclear PDF

collisional E loss

radiative E loss



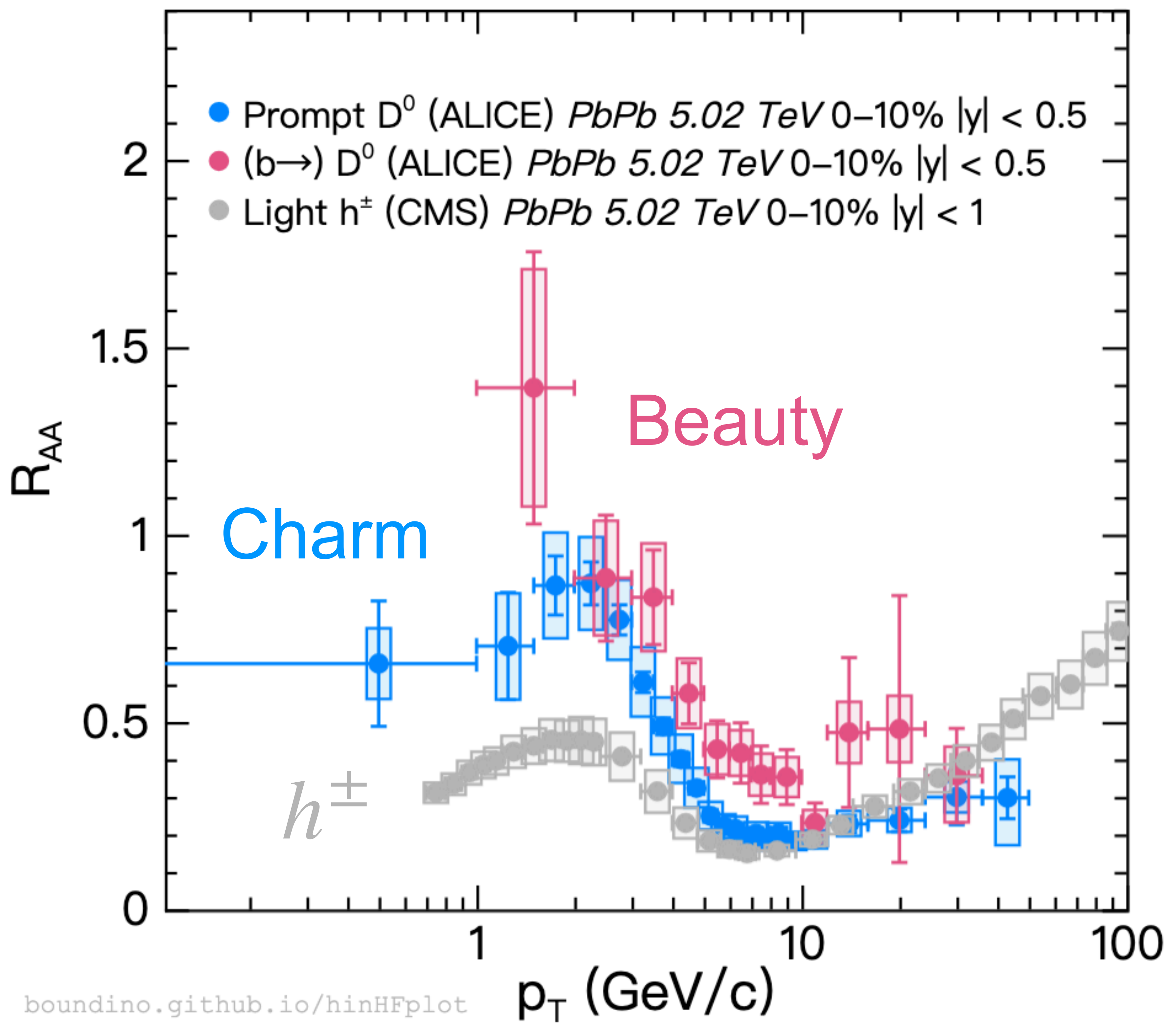
Energy loss of hard parton in QGP in pQCD picture

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

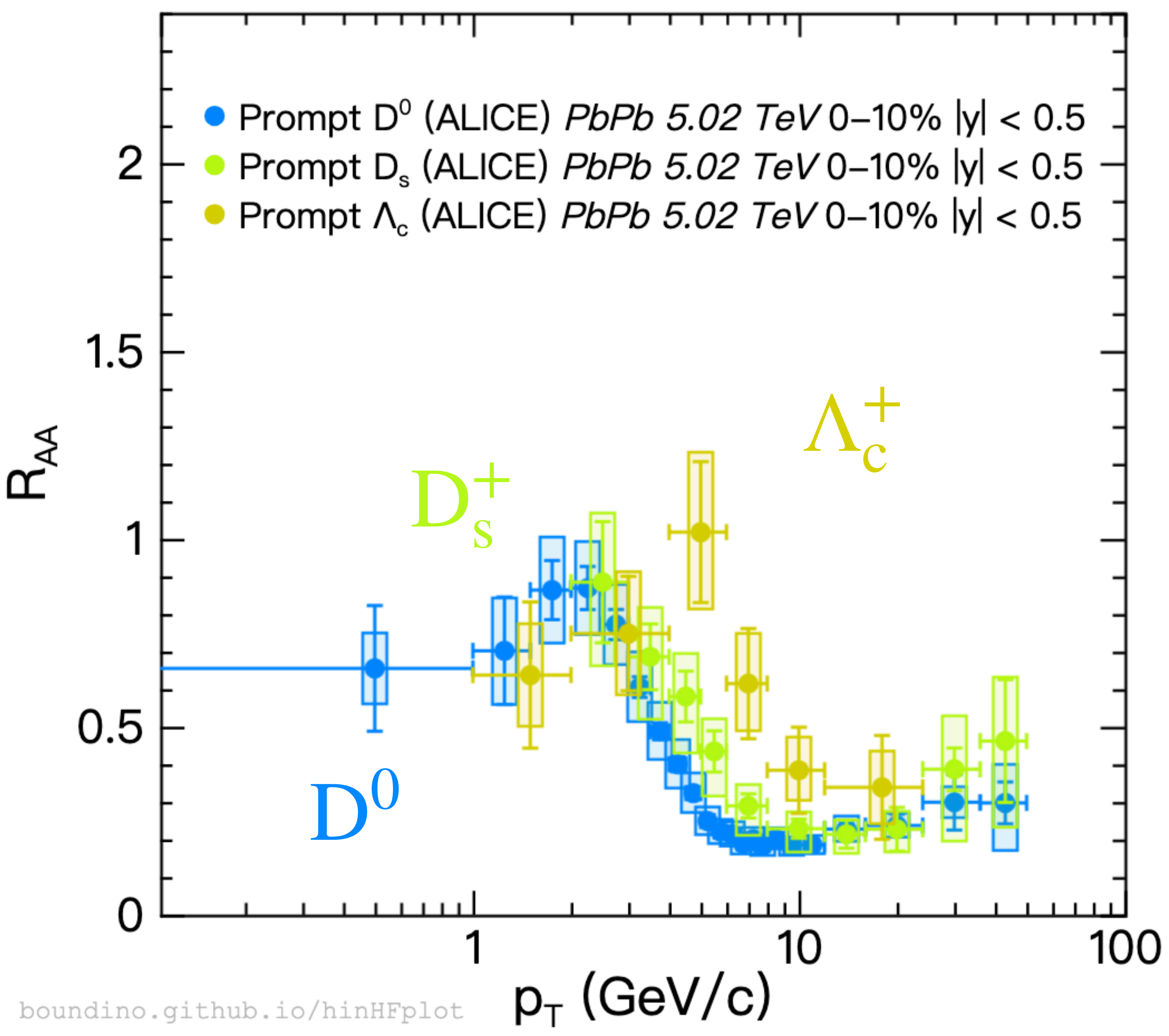
- Prompt D⁰ suppression in wide kinematics
  - Charm lose energy in QGP by collisions at low p_T and radiations at high p_T

- R_{AA} variable:
  - Advantage: BR unc. cancelled
  - Disadvantage: pp reference not well understood (QGP-like system in pp?)

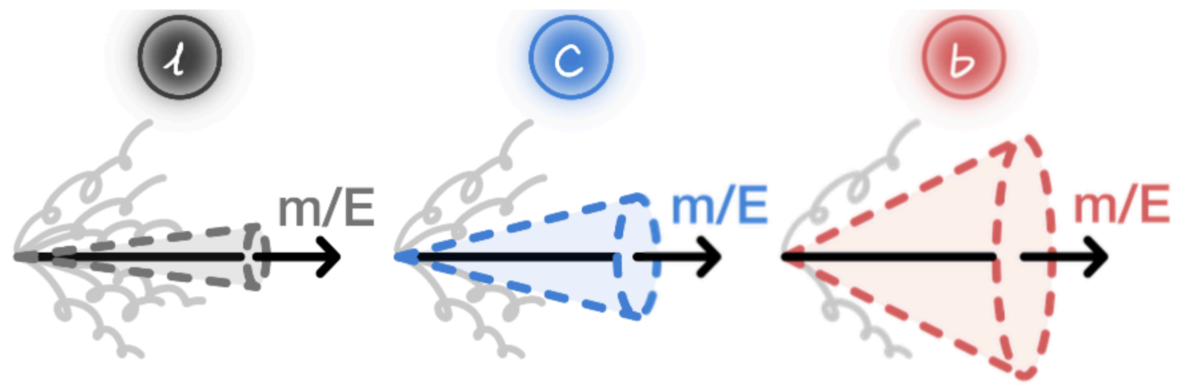
Energy loss: mass dependence



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



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



Larger energy loss → Smaller energy loss

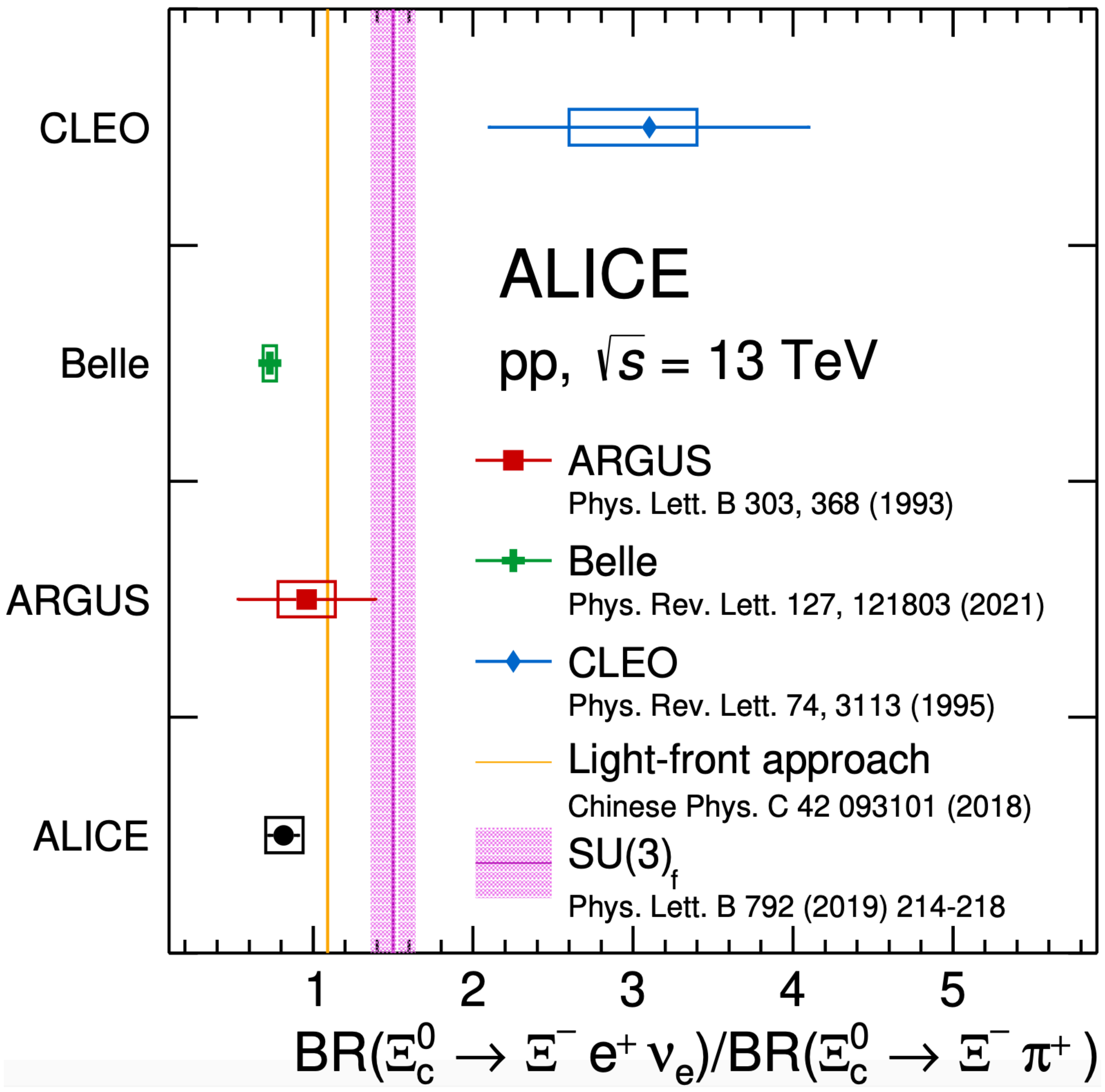
Dead cone effect

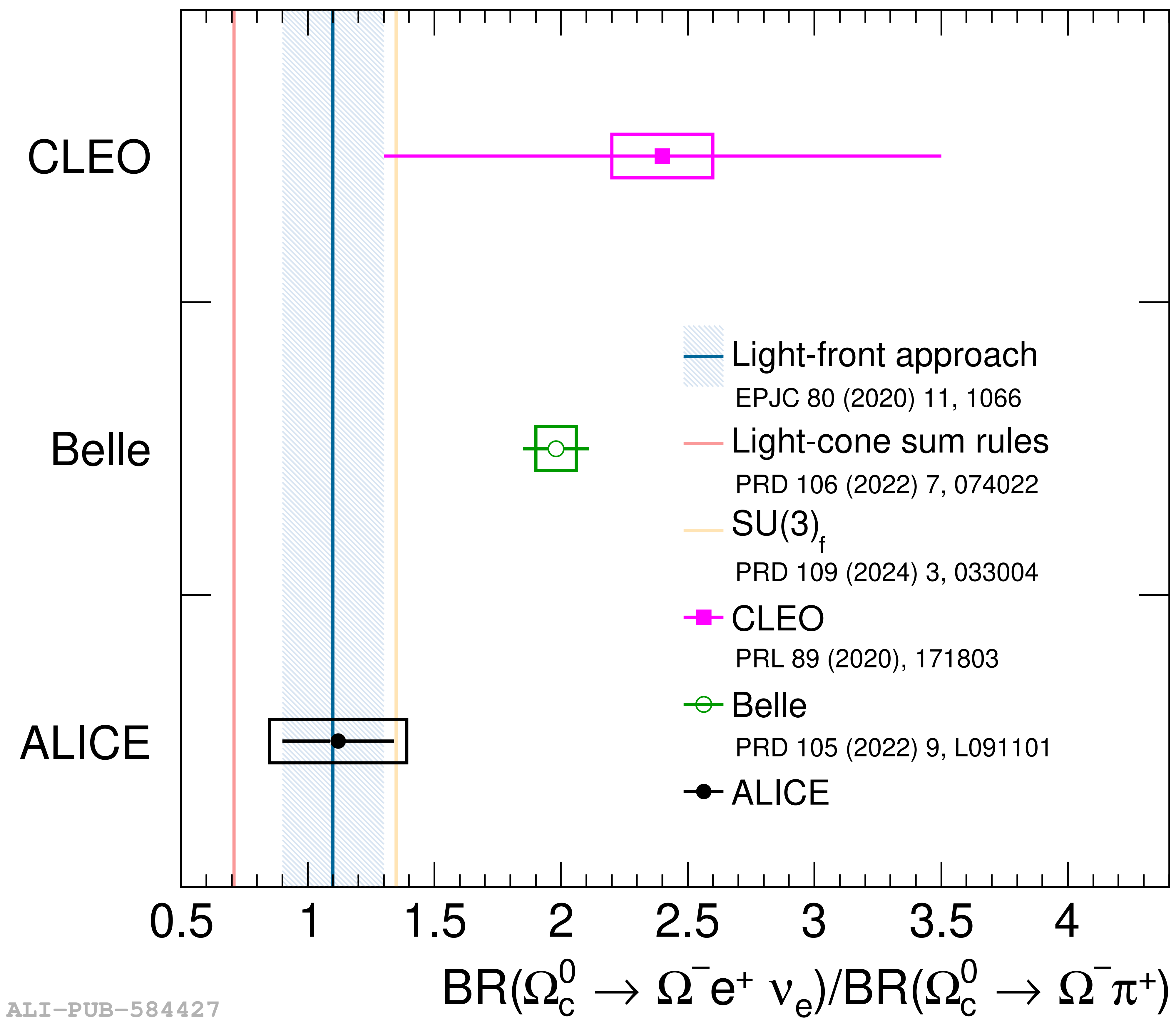
Radiation suppressed inside $\theta < m/E$

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





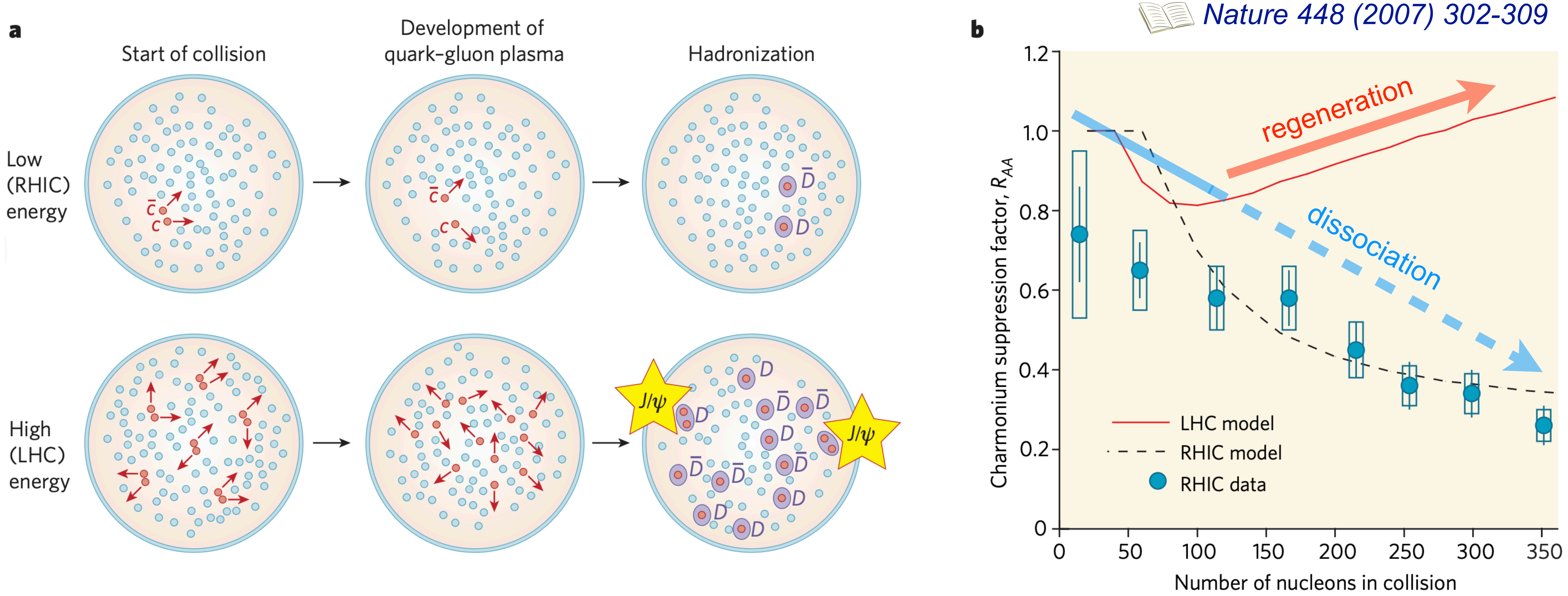
- Consistent with Belle result in 0.54σ
- Models overestimate ALICE and Belle results

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

Quarkonia

Quarkonia as probes of QGP

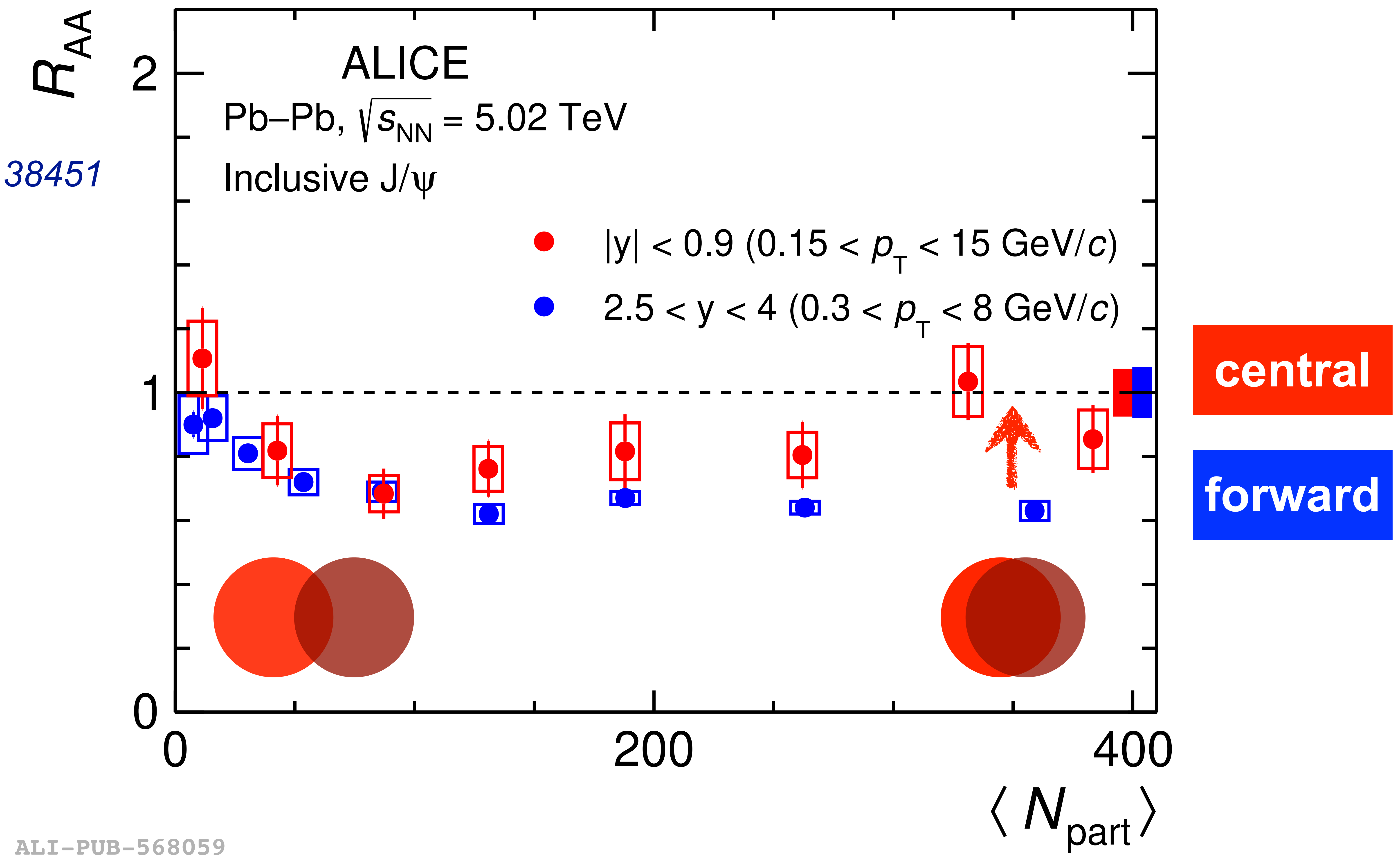
Nature 448 (2007) 302-309



- Suppression of the direct charmonium due to colour screening and dynamic dissociation
- (Re)generation enhanced charmonium production close to transition at LHC energies
- ψ(2S)-to-J/ψ ratio in Pb–Pb collisions has strong discriminating power between regeneration scenarios

Inclusive J/ψ production vs. centrality

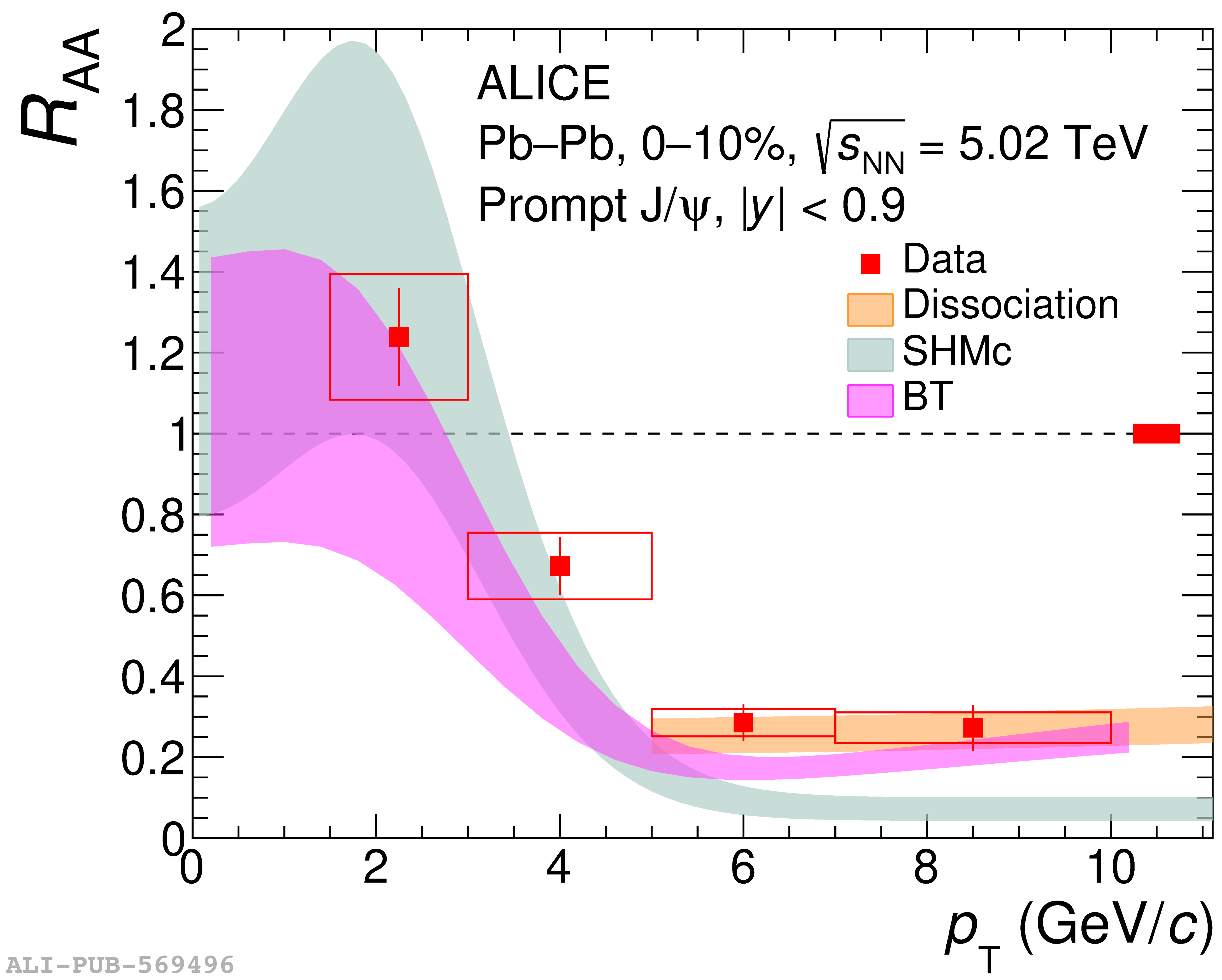
PLB 849 (2024) 138451

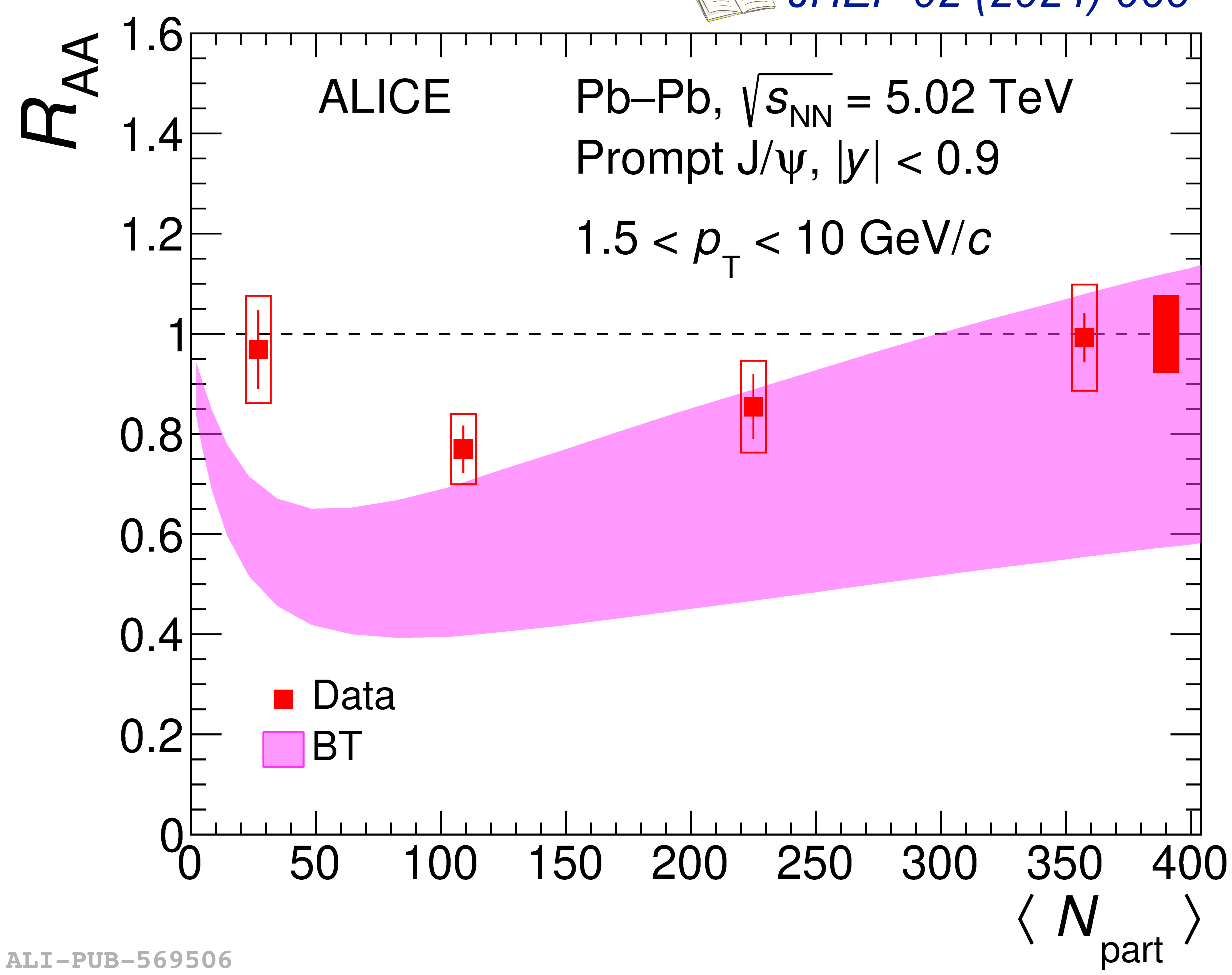


- Evidence for J/ψ (re)generation in central collisions, with larger contribution at midrapidity compared to forward rapidity

Prompt J/ψ production in Pb–Pb collisions

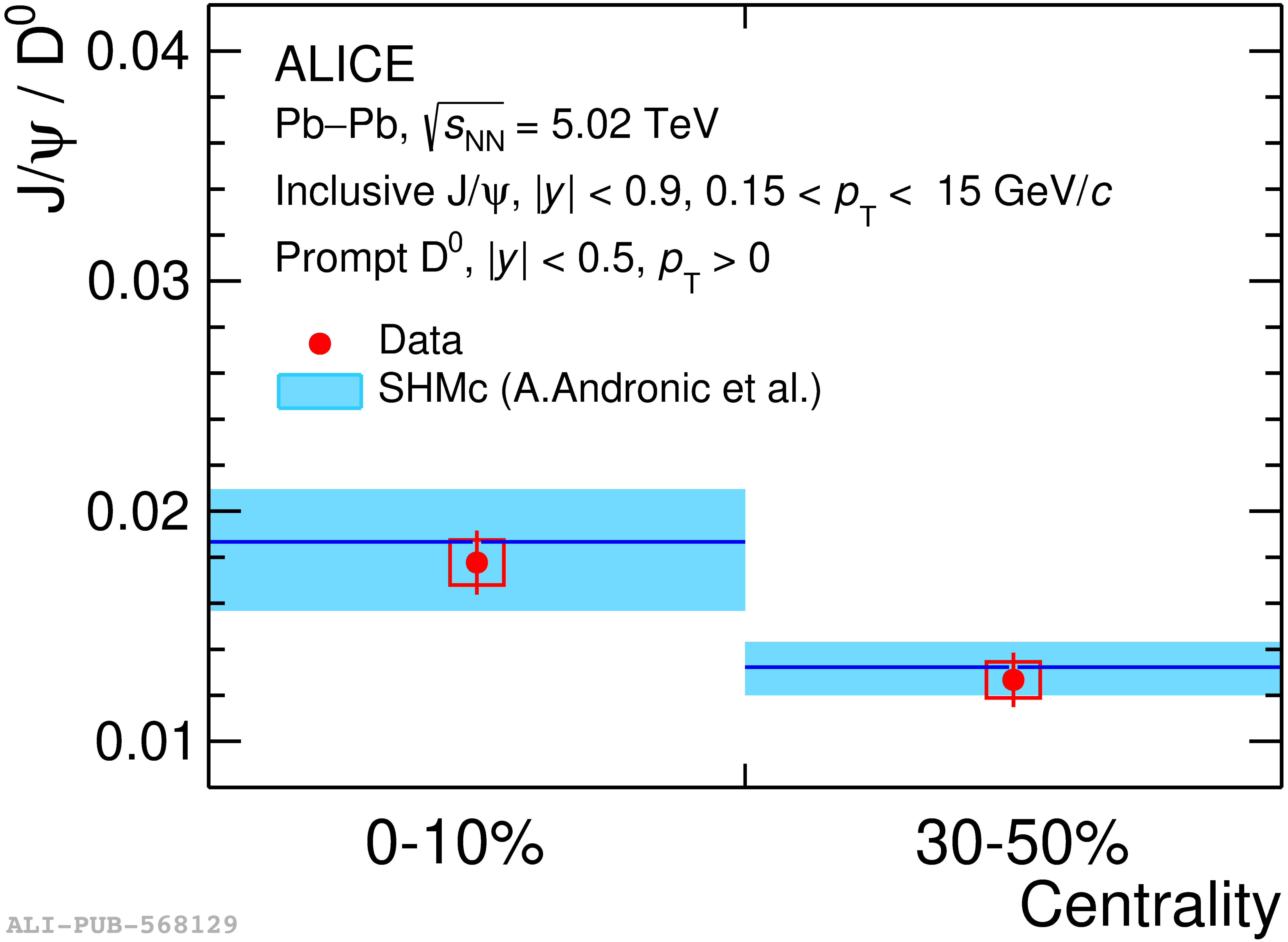
JHEP 02 (2024) 066





- SHMc and transport microscopic calculations that include a contribution from regeneration are compatible with the measured prompt J/ψ R_{AA} at low p_T
- BT model exhibits a similar trend to the data from peripheral to central collisions

Hadronisation: J/ψ-to-D^0 ratio in Pb–Pb collisions

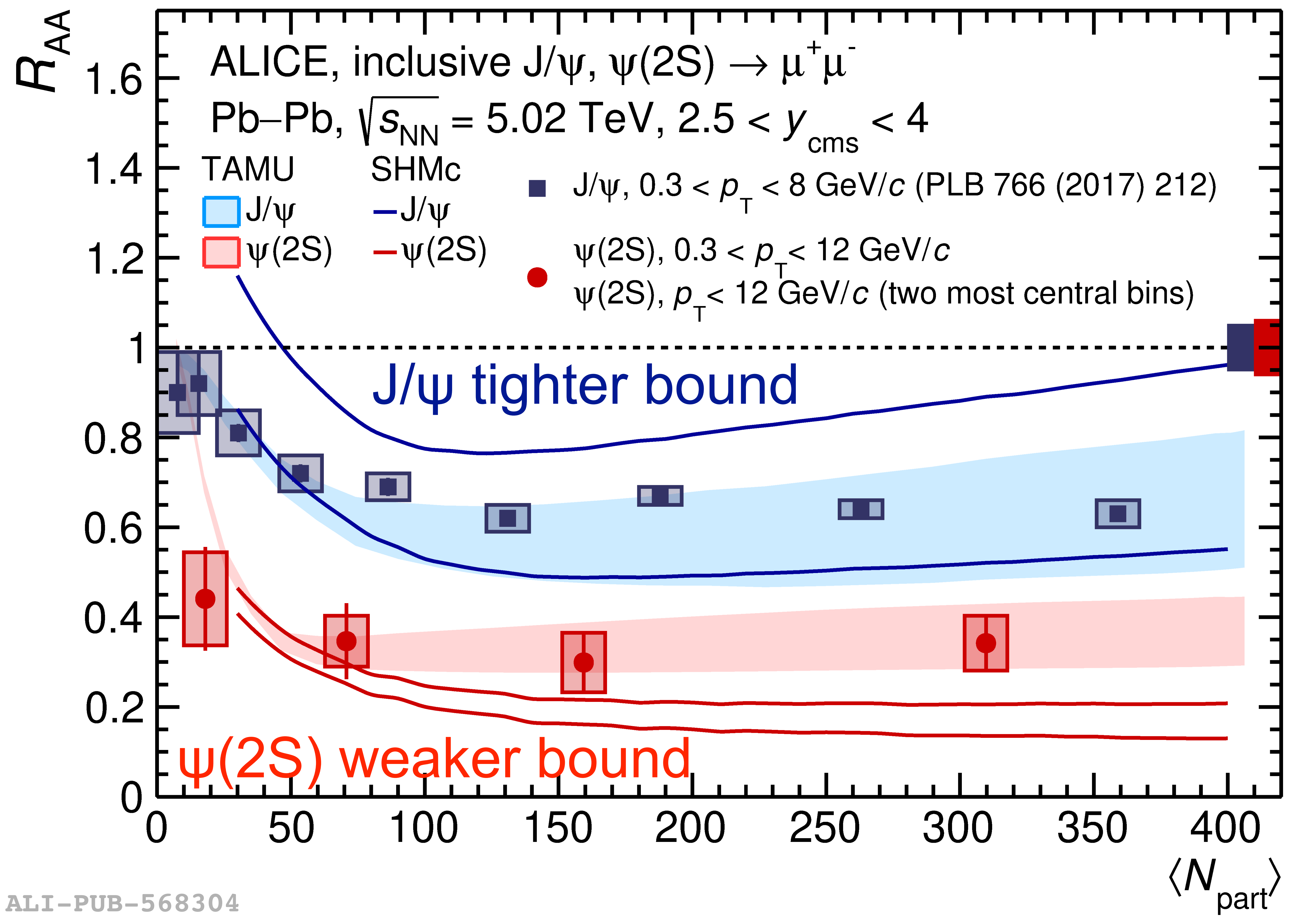


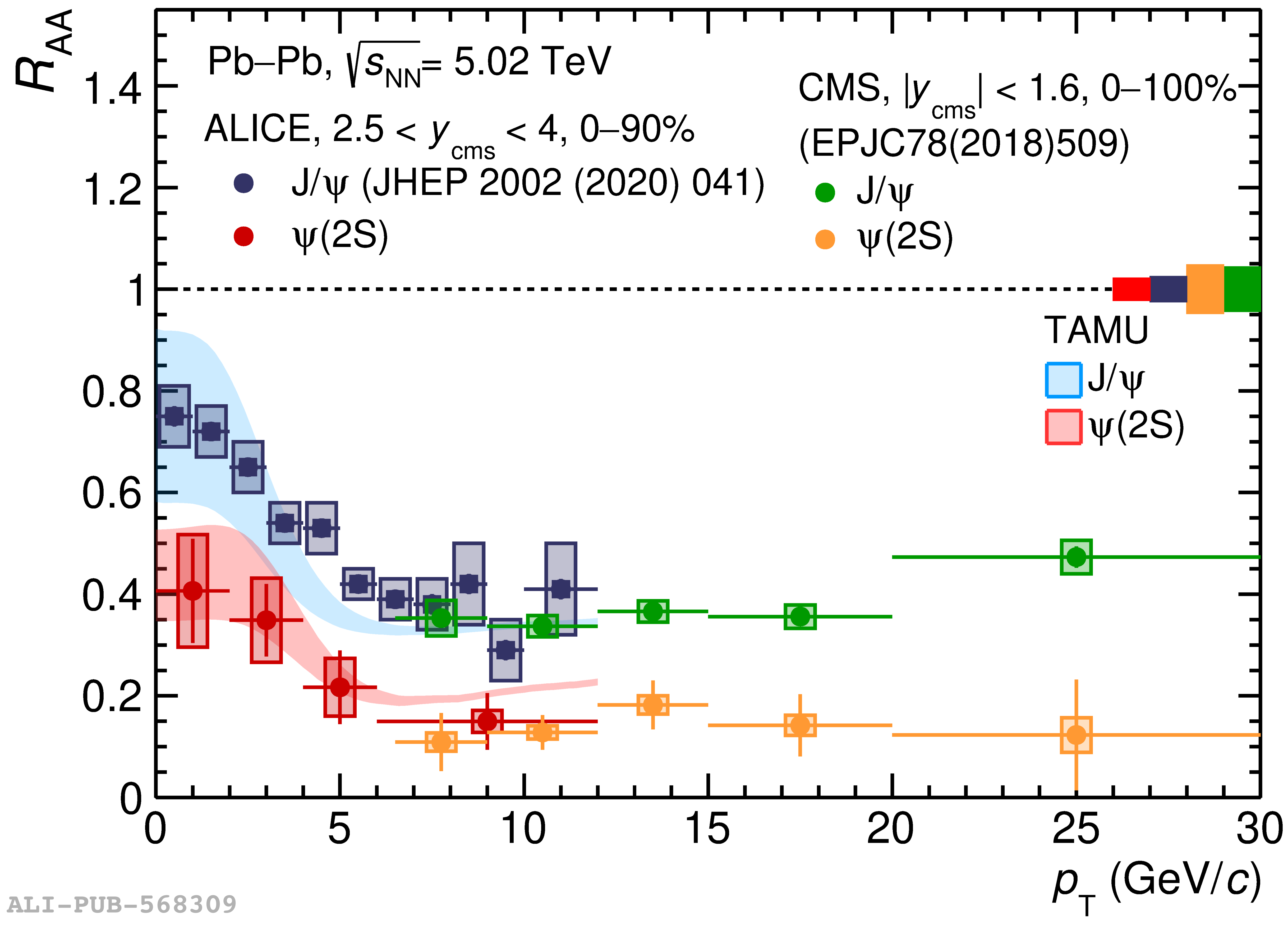
PLB 849 (2024) 138451

- Sensitive to hadronisation for open and hidden charm hadrons
- The centrality-dependent trend of the J/ψ to D^0 can be explained by the increase of charm fugacity towards most central collisions according to SHMc prediction

ψ(2S) production: sequential melting

PRL 132 (2024) 042301

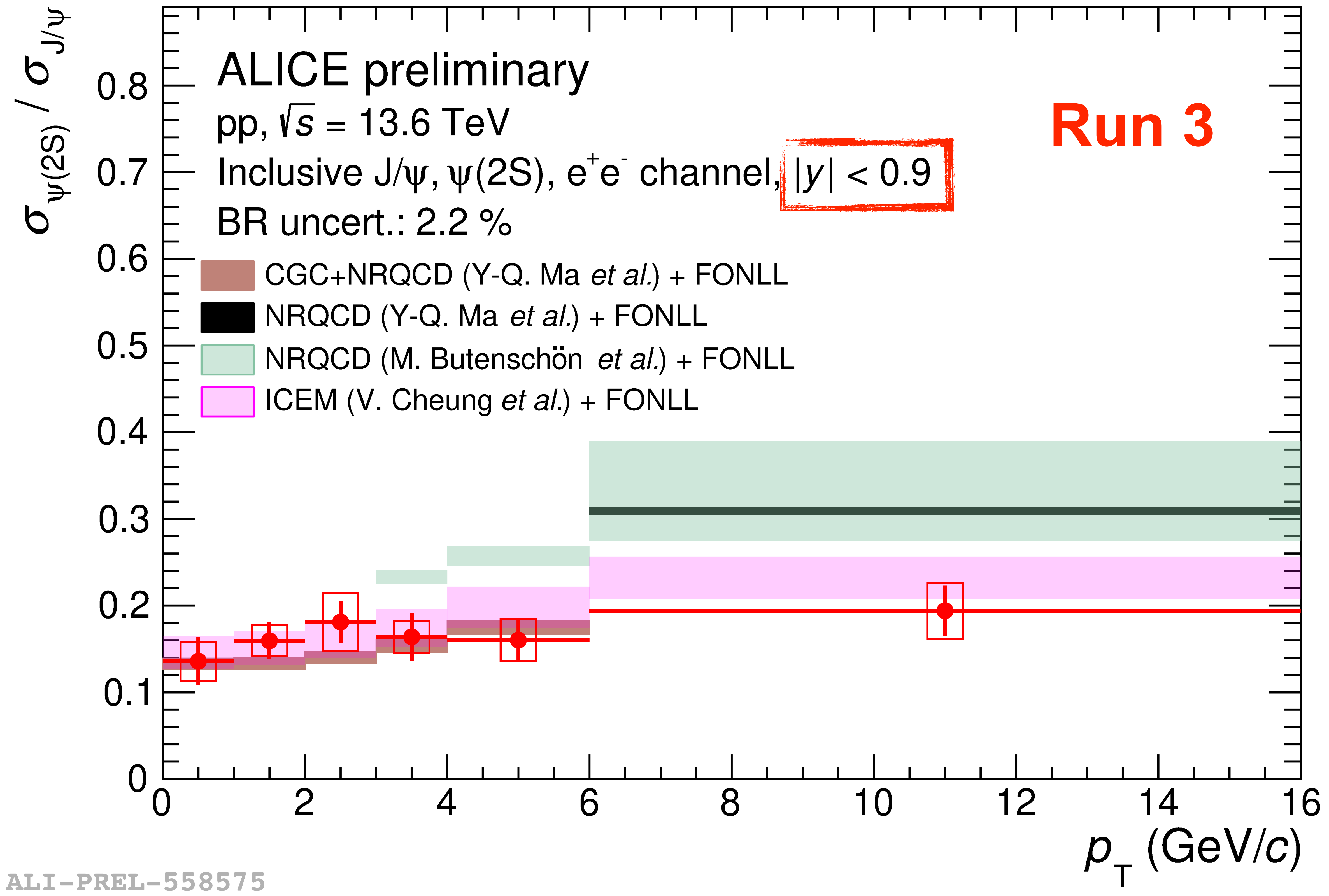


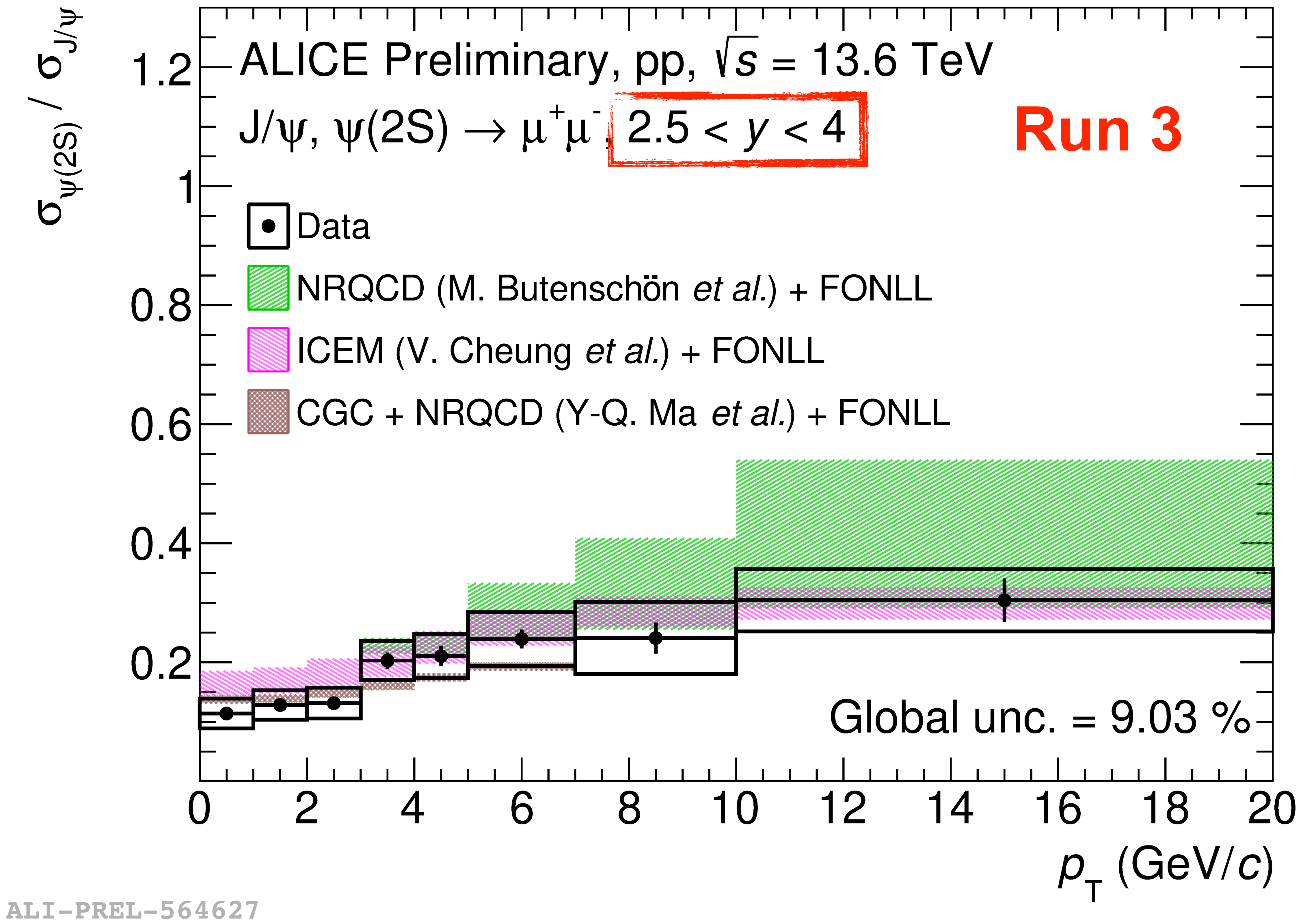


- A large suppression of ψ(2S) w.r.t. J/ψ is observed
- ψ(2S) R_{AA} increases at low p_T, which is a hint of ψ(2S) regeneration
- TAMU describes data better than SHMc in central collisions

Yiping Wang's talk on Saturday at 15:50 Parallel 3

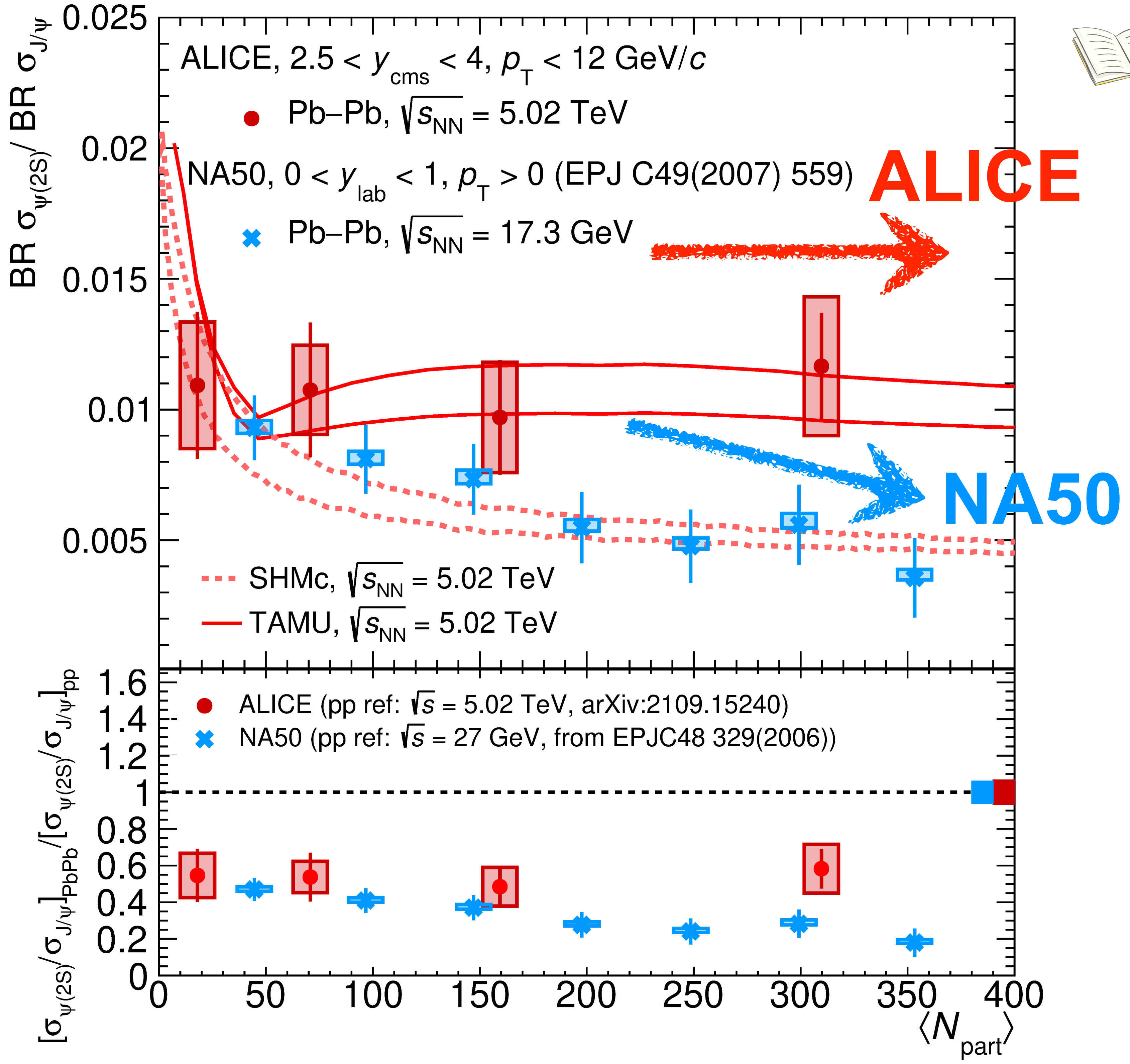
ψ(2S)-to-J/ψ ratio in pp collisions





- The CGC+NRQCD and ICEM can describe the data at low p_T
  - NRQCD: non-relativistic QCD approach, long-distance matrix elements (LDME) fitted to experimental data
  - CGC+NRQCD: color glass condensate effective theory coupled to leading order NRQCD calculations
  - ICEM: using the kt-factorisation approach to improve color evaporation model (CEM)

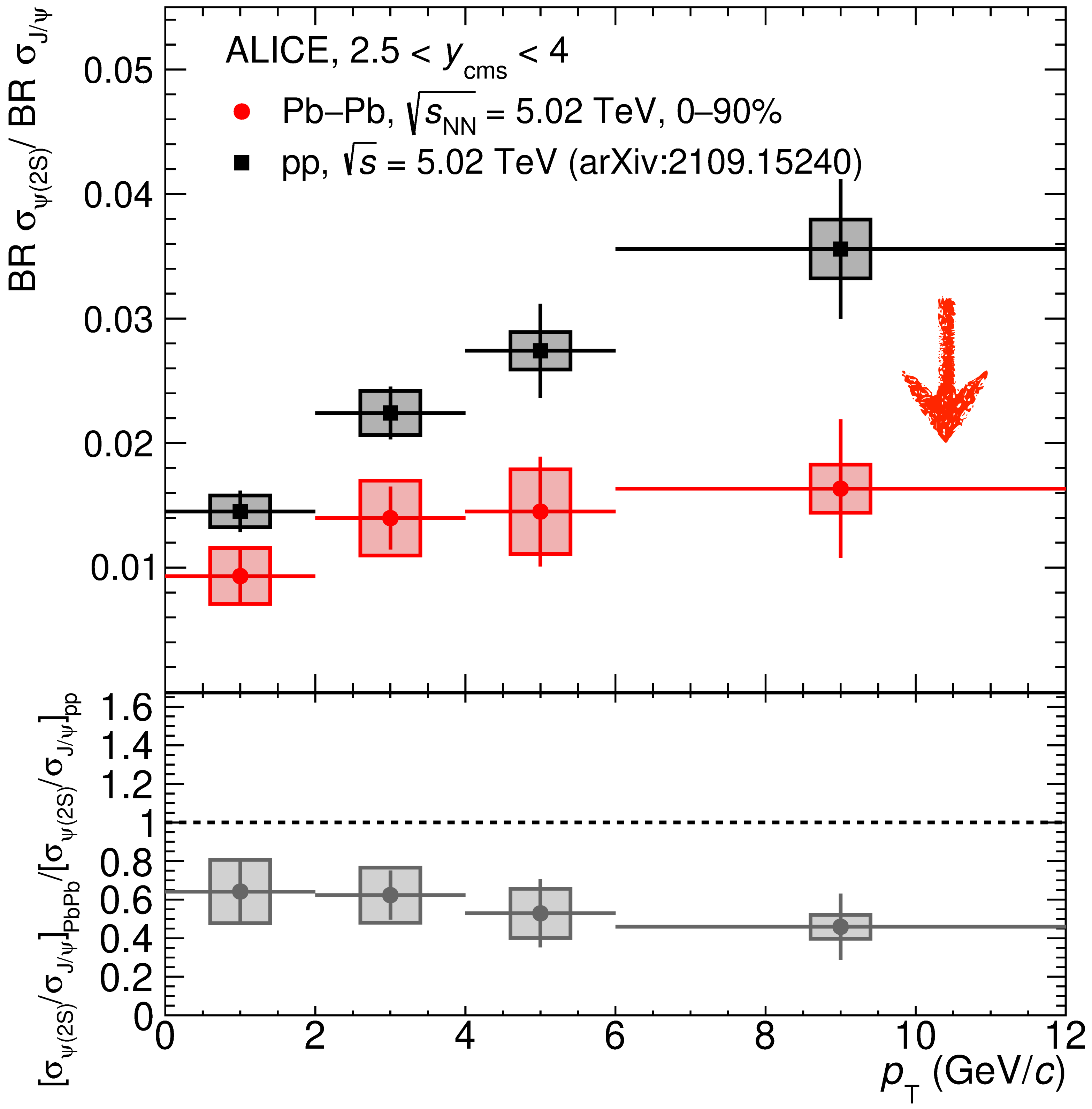
ψ(2S)-to-J/ψ ratio in Pb–Pb collisions



ALI-PUB-568299

📖 *PRL 132 (2024) 042301*

Yiping Wang's talk on Friday at 18:10 Parallel 3

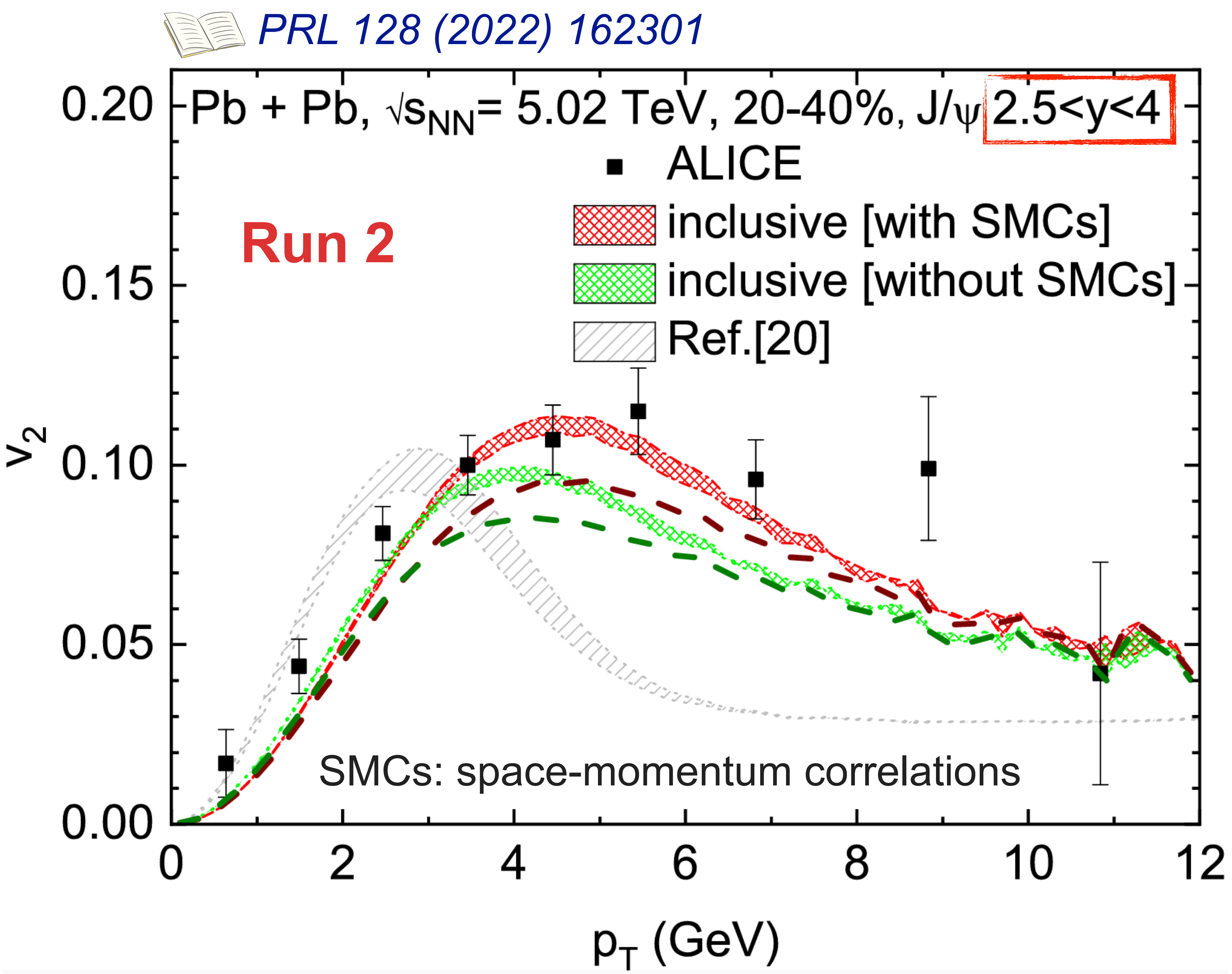


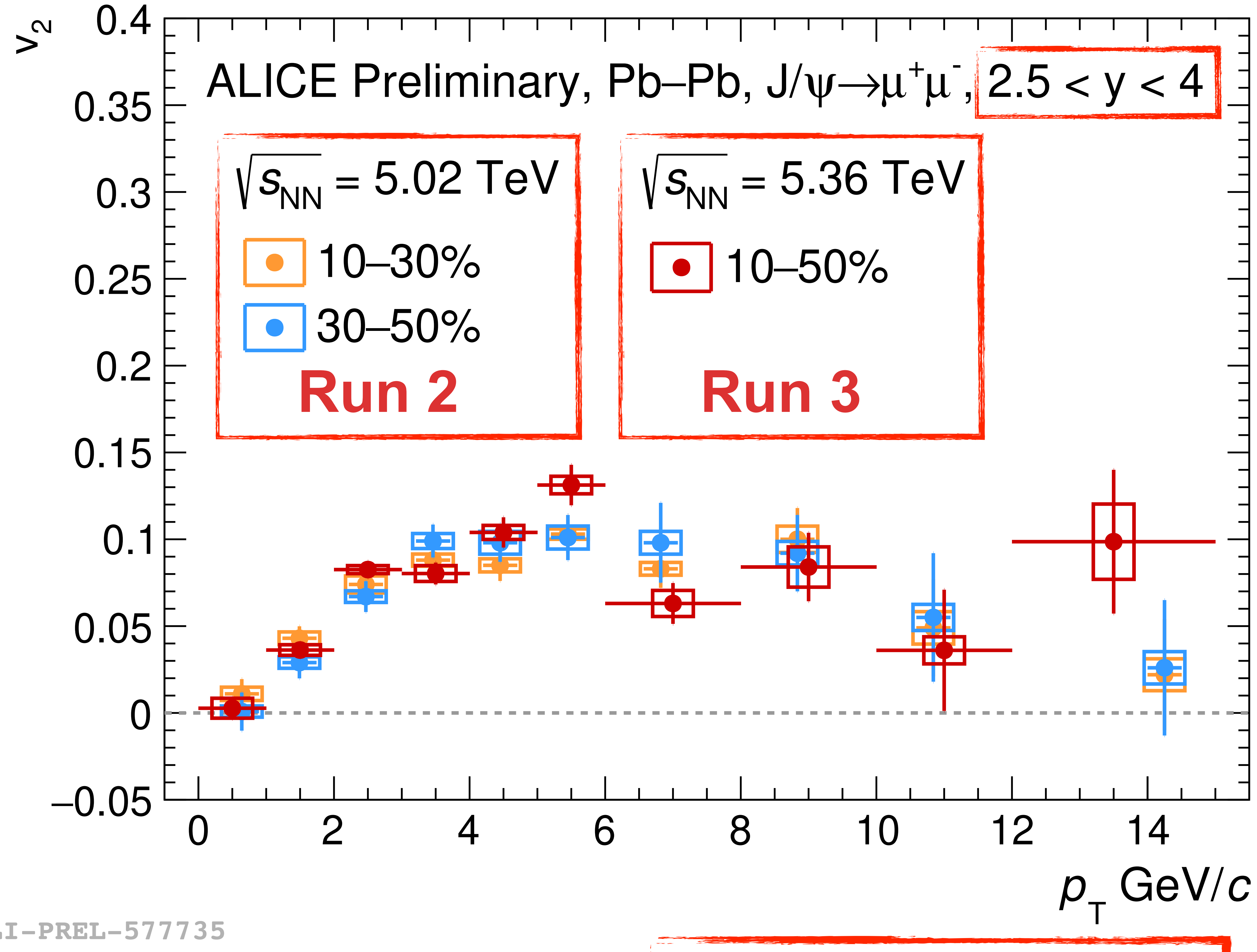
ALI-PUB-568354

- Flat centrality dependence at the LHC
- Stronger centrality dependence at lower energy
- TAMU describes data slightly better than SHMc in central collisions

- Increase for both pp and Pb–Pb
- Pb–Pb tends to show a slower rise
- Double ratio decrease, indicating possible increase of relative suppression of ψ(2S)

Collectivity: J/ψ elliptic flow in Run 3





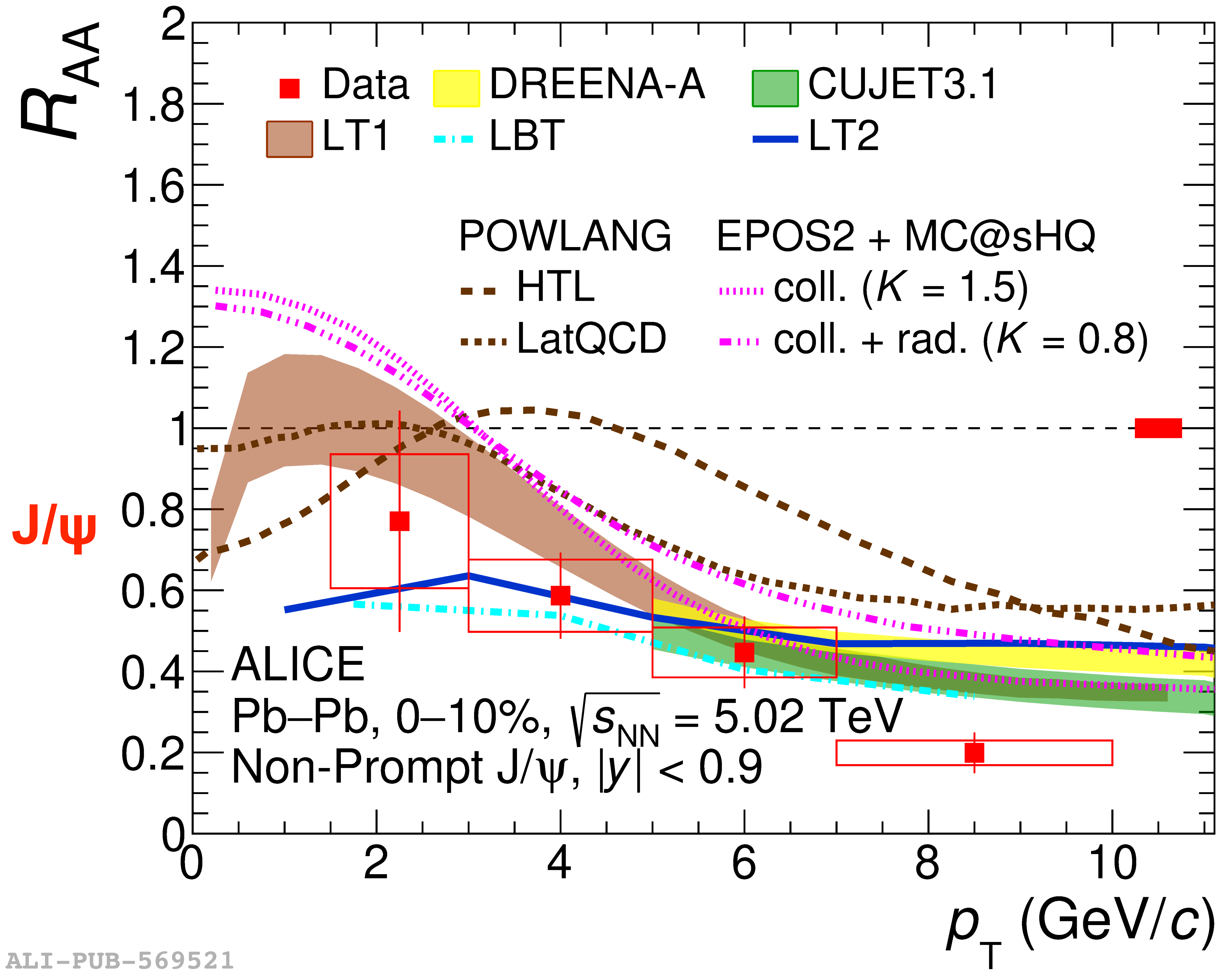
- Run 3 is consistent with Run 2, with statistical precision improved at low p_T
- A significant J/ψ v_2 is observed, consistent with charm quark thermalisation

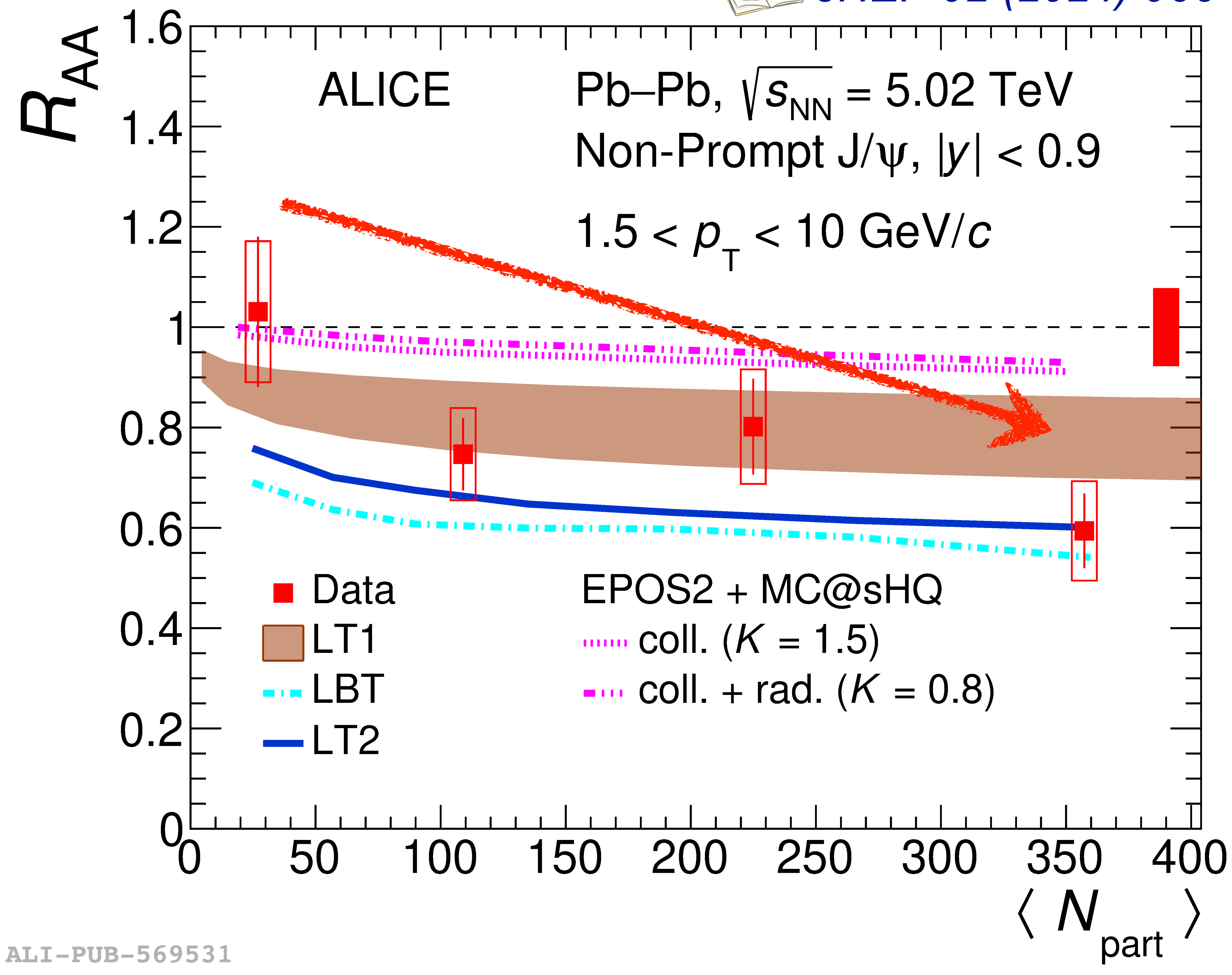
Liuyao Zhang's talk on Saturday at 14:35 Parallel 3

Non-prompt J/ψ production in Pb–Pb collisions

JHEP 02 (2024) 066

b → J/ψ





- Described within uncertainties by models implementing collisional and radiative energy loss
  - POWLANG including only collisional contributions overestimate R_{AA} at intermediate and high p_T
- R_{AA} integrated over p_T: hint at a decreasing trend towards more central collisions

Summary

Open heavy-flavour

- 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

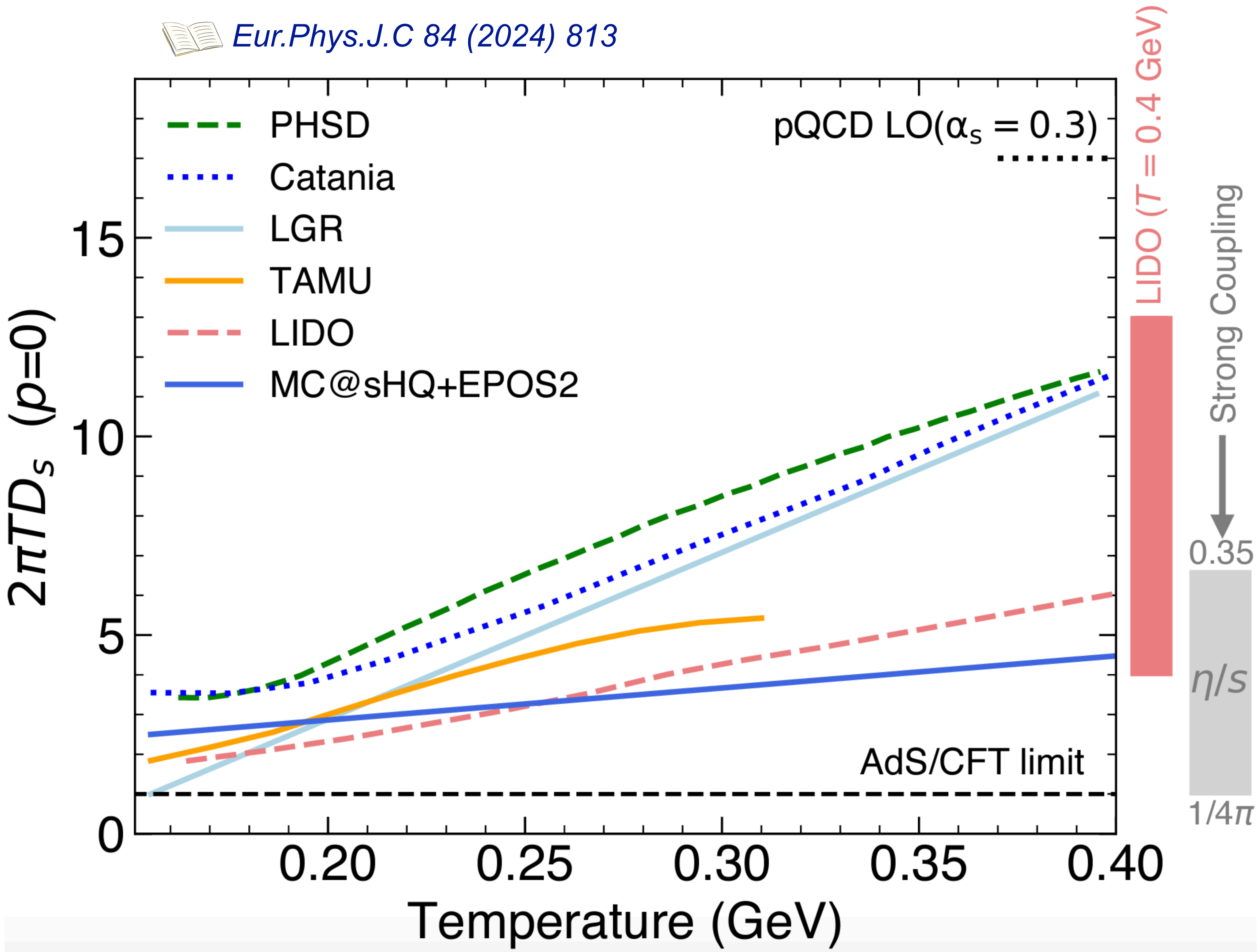
Quarkonia

- Dominant contribution from (re)generation in central collisions and low p_{T} for inclusive and prompt J/ψ
- Larger suppression of ψ(2S) w.r.t. J/ψ is observed
- Significant J/ψ v_2 is observed, consistent with charm quark thermalisation

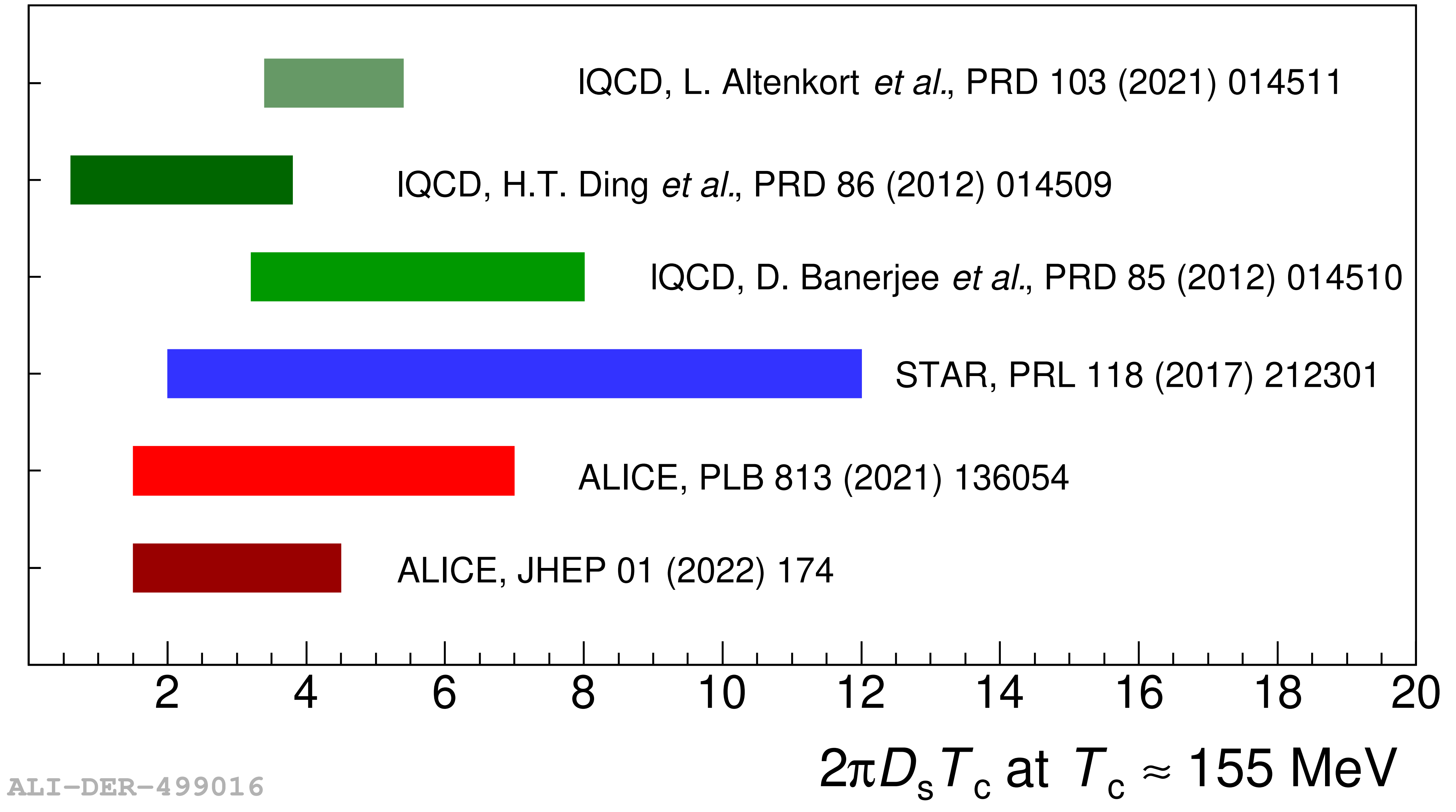
Backup

Charm spatial diffusion coefficient D_s

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



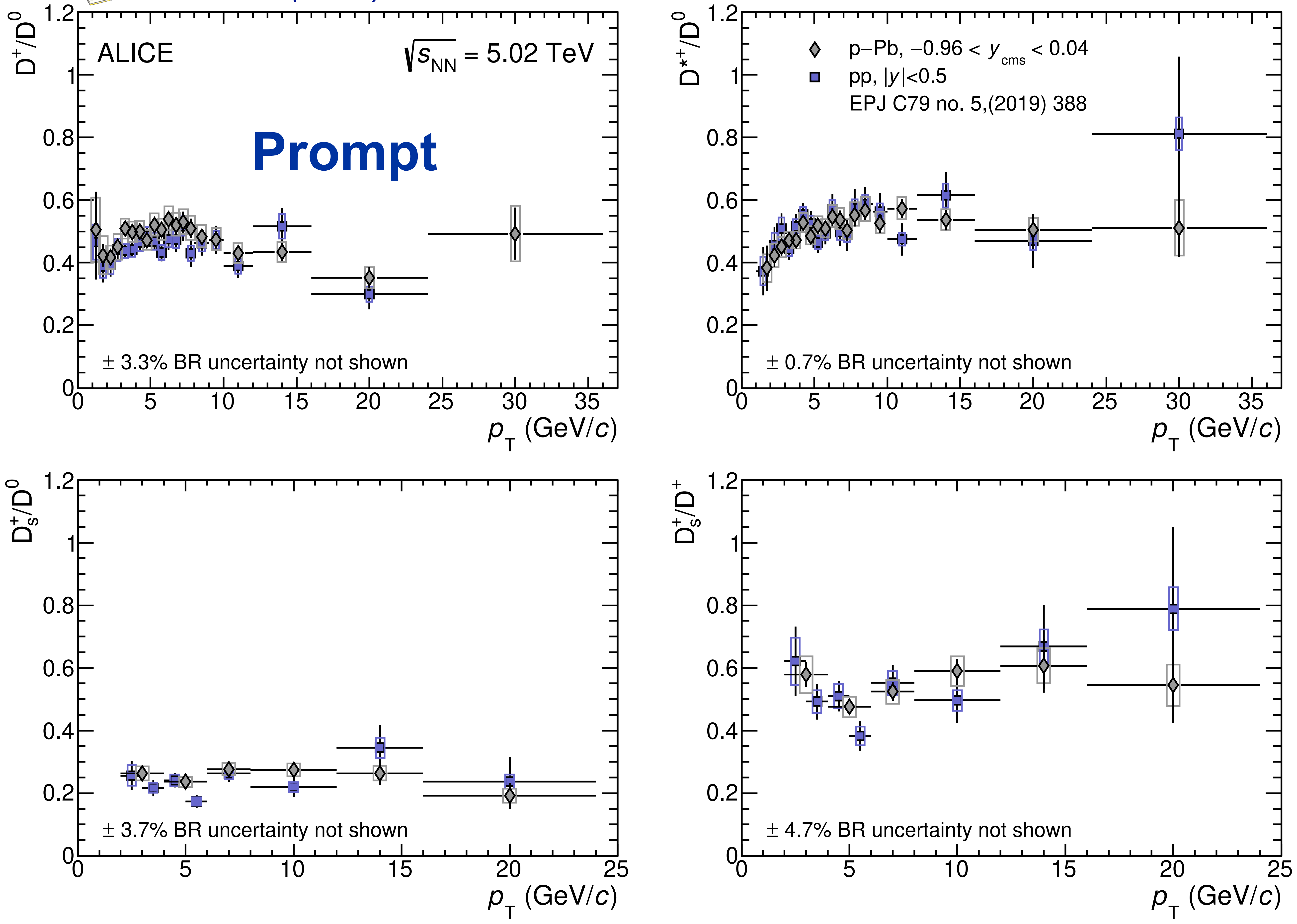
JHEP 01 (2022) 174



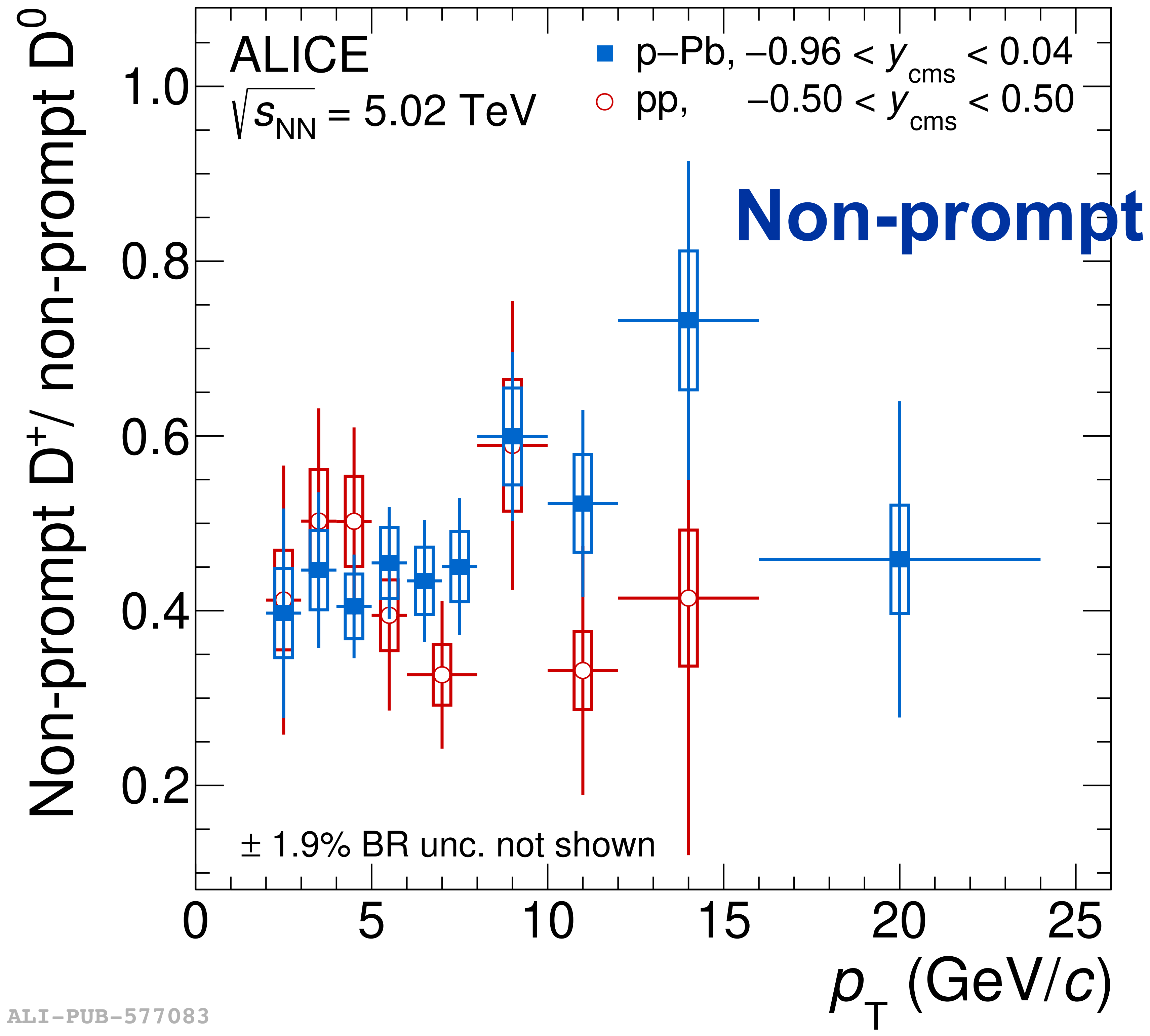
- Constraint by R_{AA} and flow of D mesons
  - $1.5 < 2\pi D_s T_c < 4.5$ at $T_{pc} = 155$ MeV
  - $D_s \propto$ relaxation time
  - $\tau_{relax} = (3-9)\ \mathrm{fm}/c \lesssim \tau_{QGP}$
- Charm readily participates in the collective motion of the QGP after production

D-meson production in p–Pb collisions

JHEP 12 (2019) 092



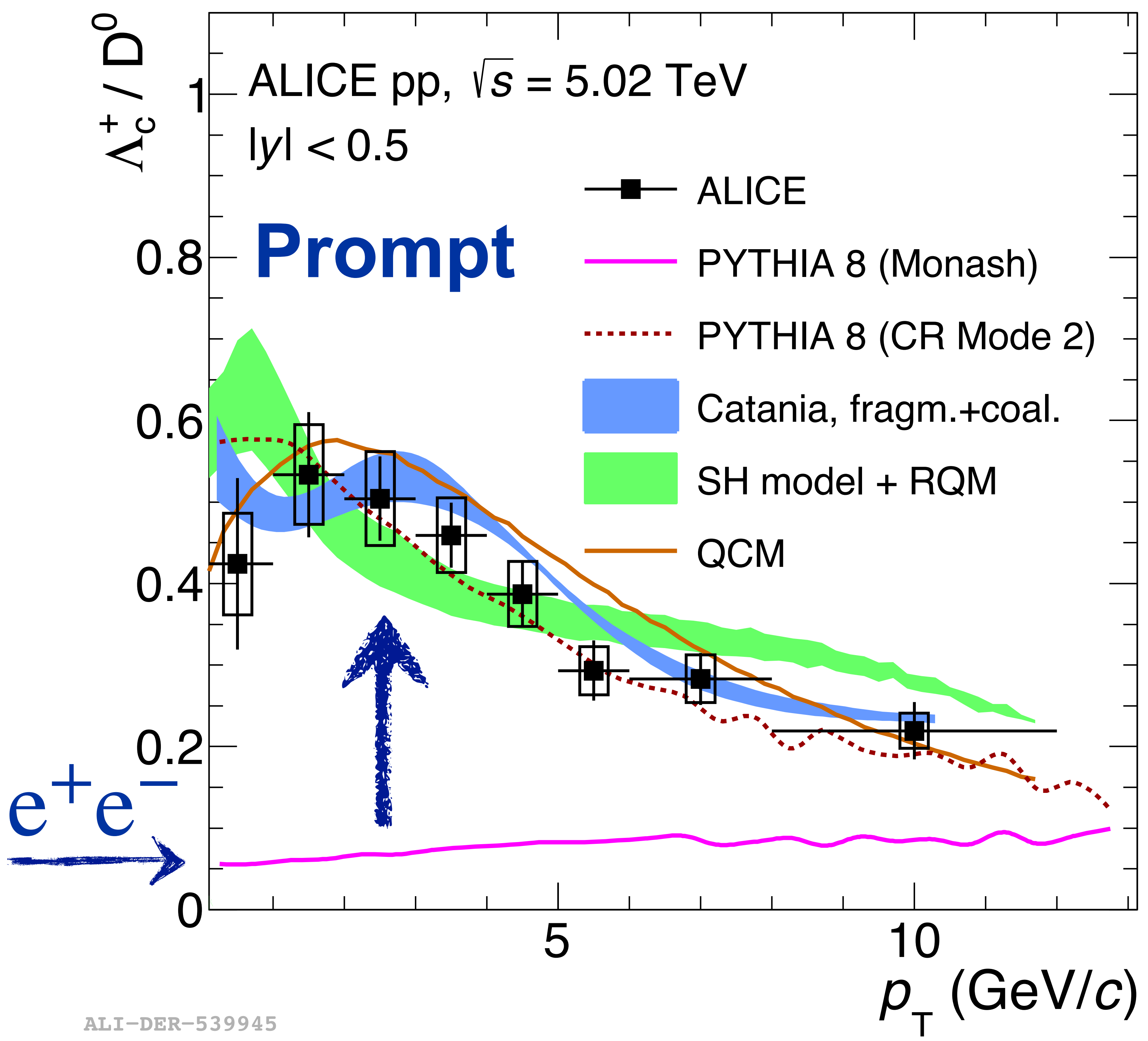
arXiv:2407.10593



- (Prompt D^+ or 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

Λ_c^+(udc) in pp collisions

Phys.Rev.C 107 (2023) 064901



PYTHIA 8 Monash: *Eur.Phys.J.C 74 (2014) 3024*

PYTHIA 8 CR Mode: *JHEP 08 (2015) 003*

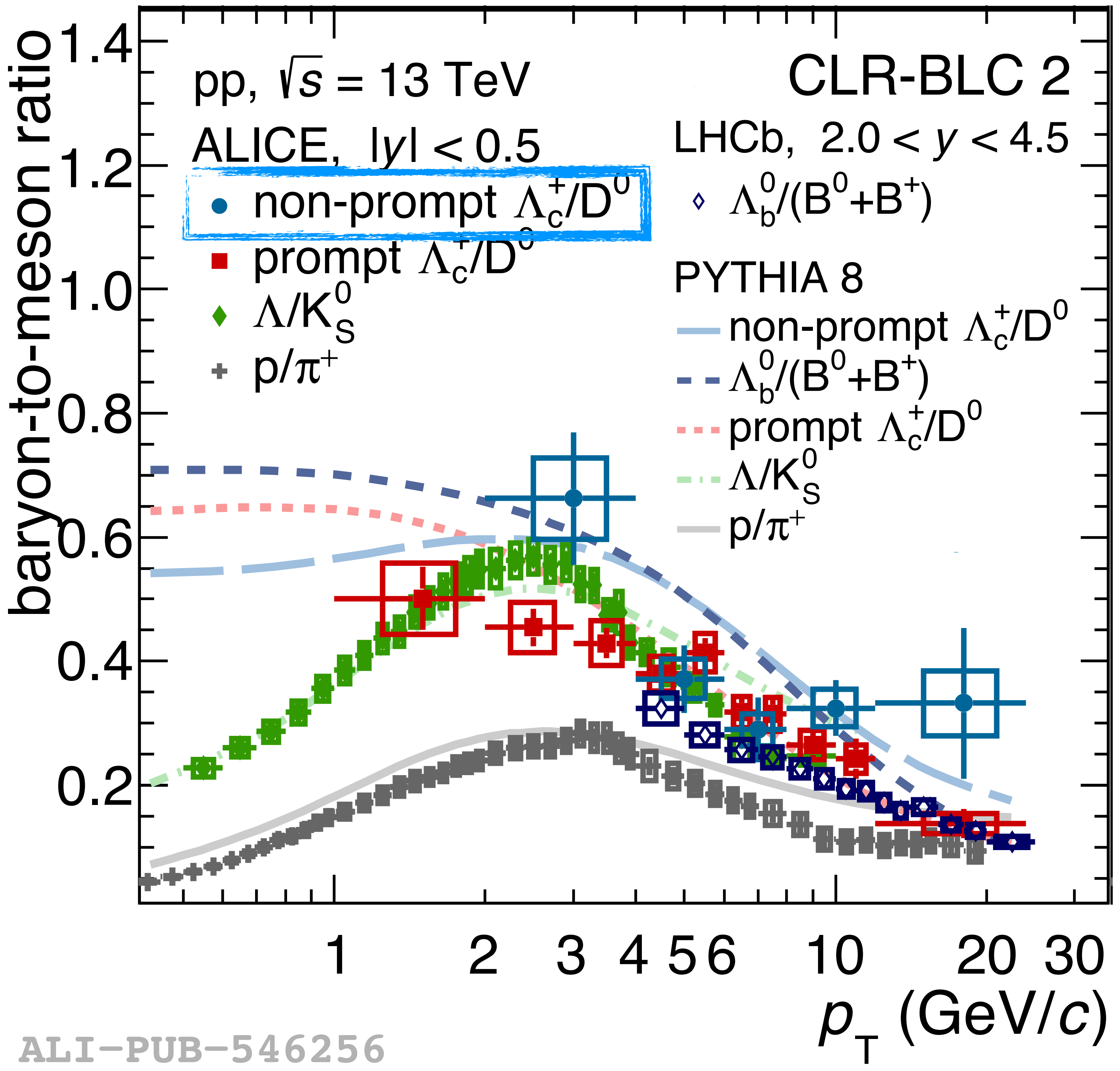
Catania: *Phys.Lett.B 821 (2021) 136622*

SHM: *Phys.Lett.B 795 (2019) 117-121*

RQM: *Phys.Rev.D 84 (2011) 014025*

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

Phys.Rev.D 108 (2023) 112003



Prompt Λ_c^+/D^0 in pp collisions

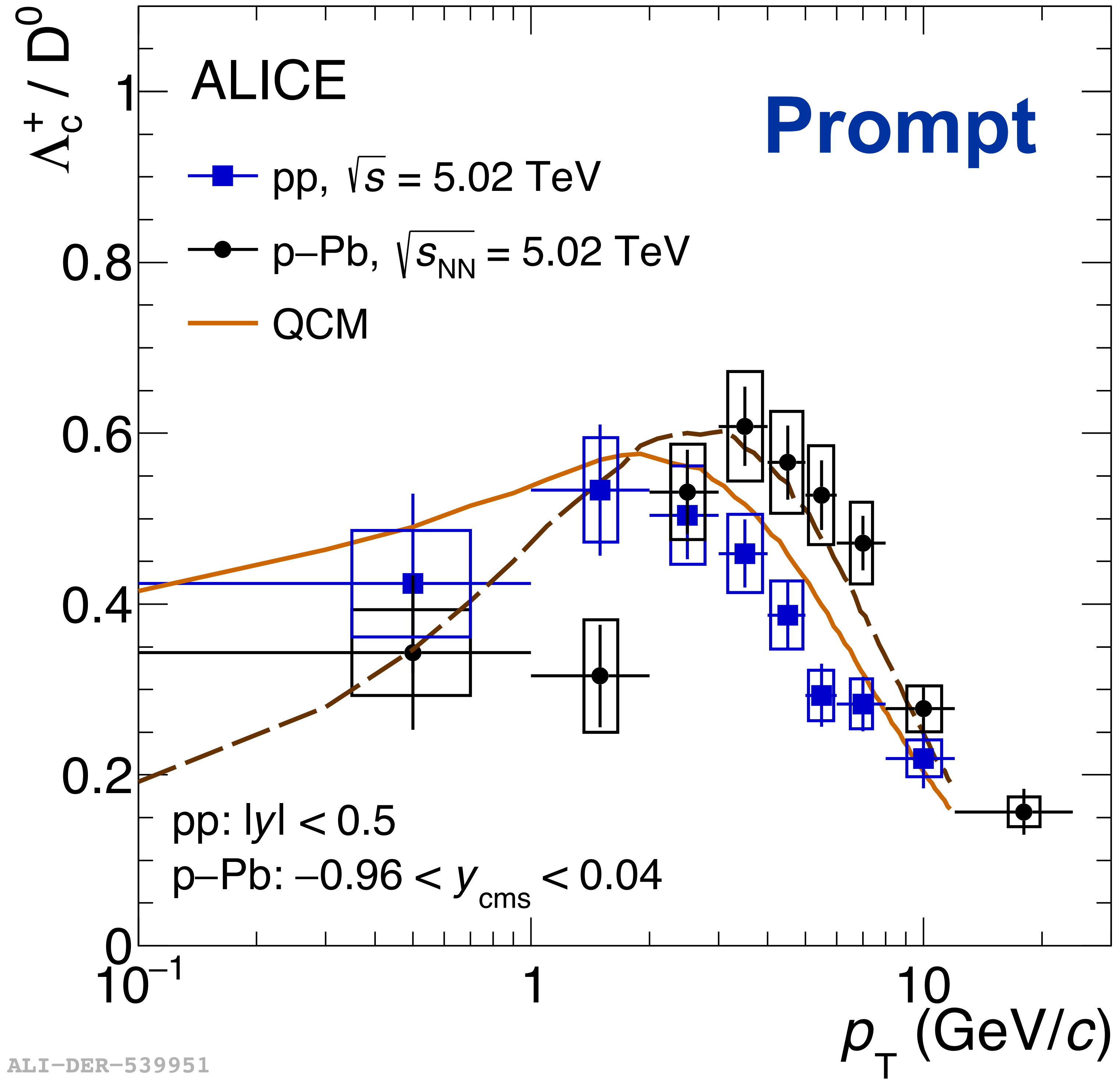
- First measurement down to $p_T = 0$
- Well described by model calculations, except PYTHIA 8 Monash based on FFs from e^+e^- collisions

Non-prompt Λ_c^+/D^0 in pp collisions

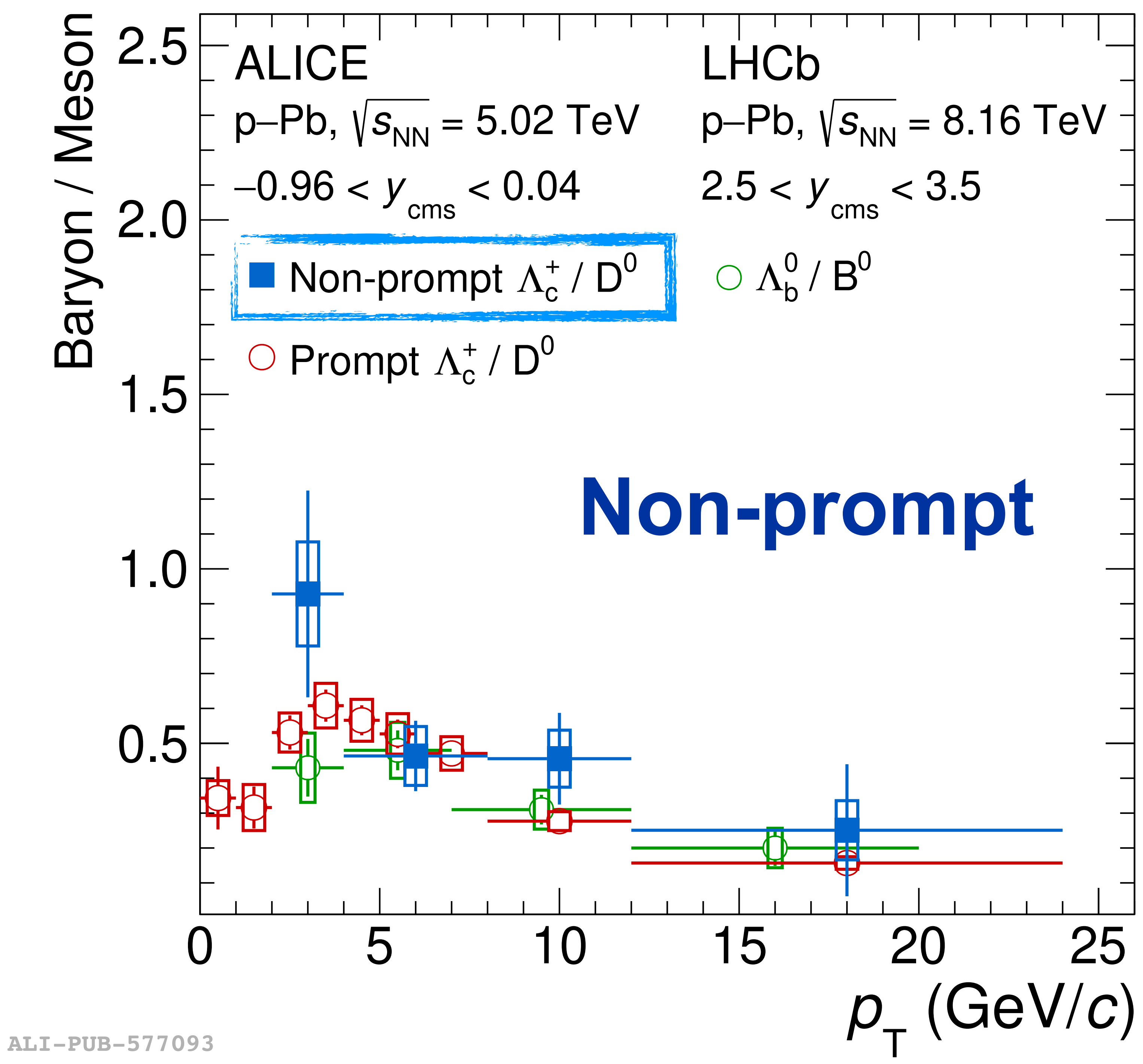
- First measurement of non-prompt Λ_c^+/D^0
- Beauty, charm, and strange hadrons show a similar p_T trend

$\Lambda_c^+(udc)$ in p–Pb collisions

Phys.Rev.C 107 (2023) 064901



arXiv:2407.10593



Prompt Λ_c^+/D^0 in p–Pb collisions

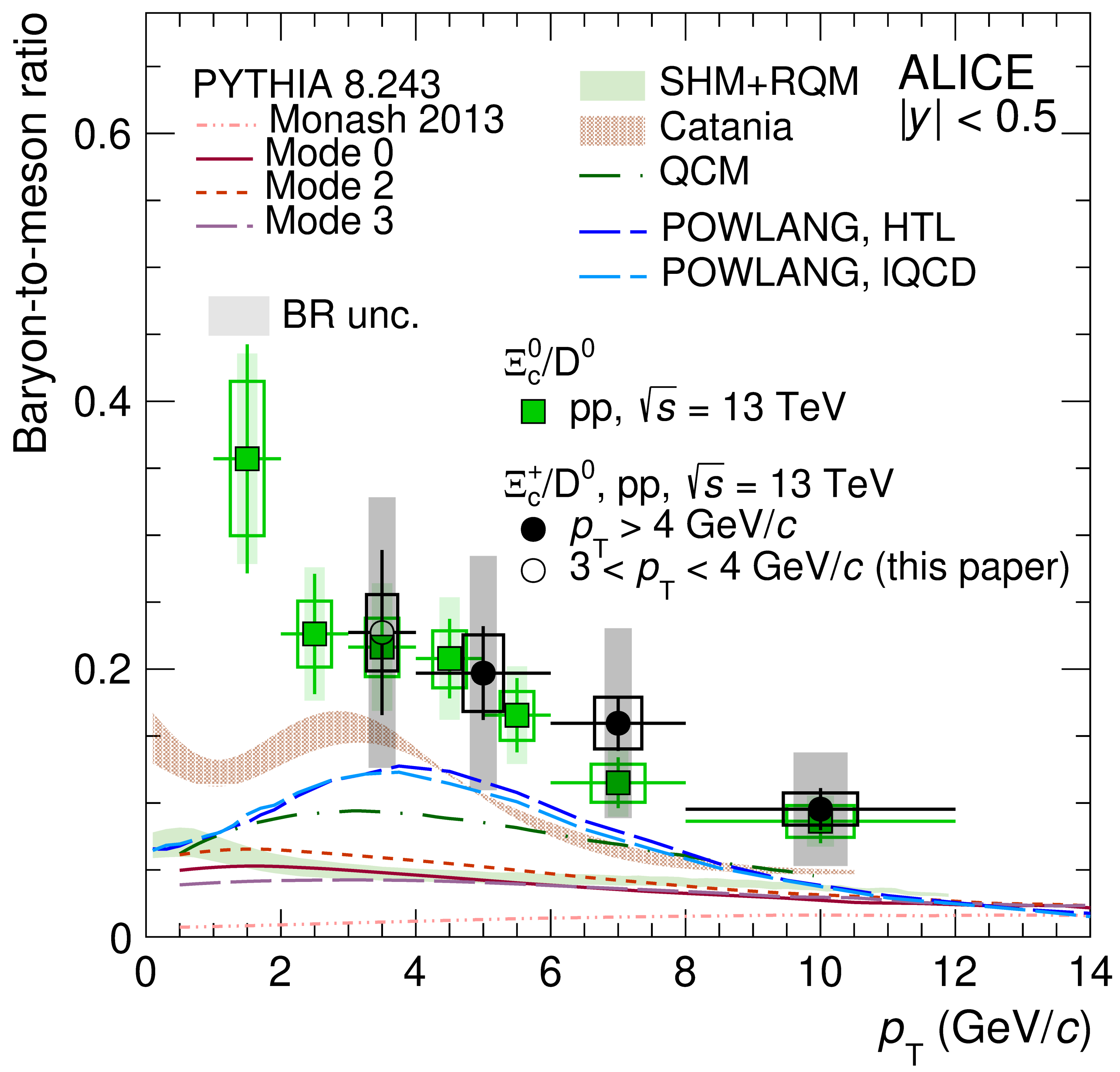
- First measurement down to $p_T = 0$
- Shift of peak towards higher p_T could be due to quark recombination or collective effects (e.g. radial flow)
- Well described by quark (re)combination model (QCM)

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

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

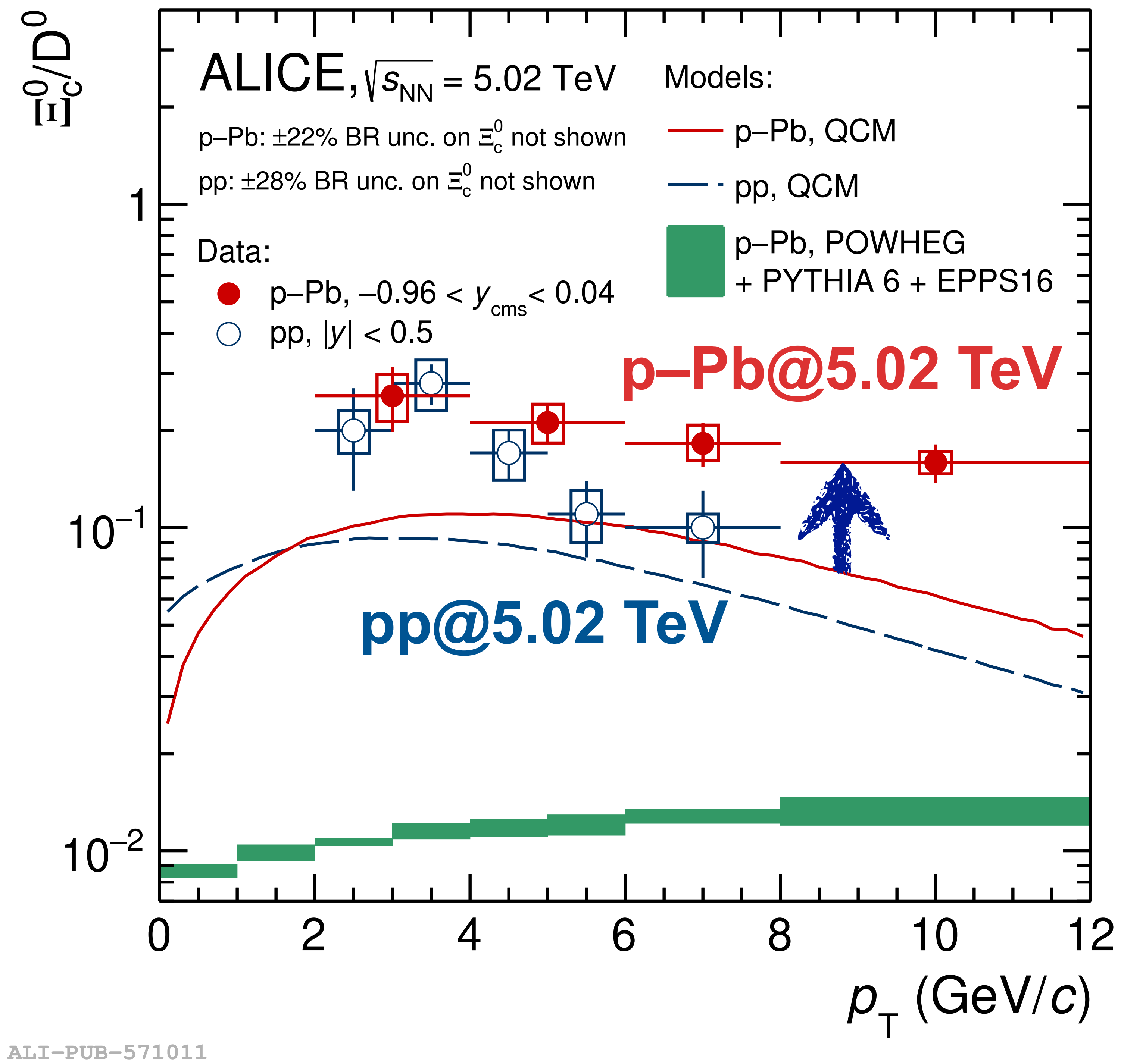
Ξ_c^0(dsc) and Ξ_c^+(usc) in pp and p–Pb collisions

JHEP 12 (2023) 086

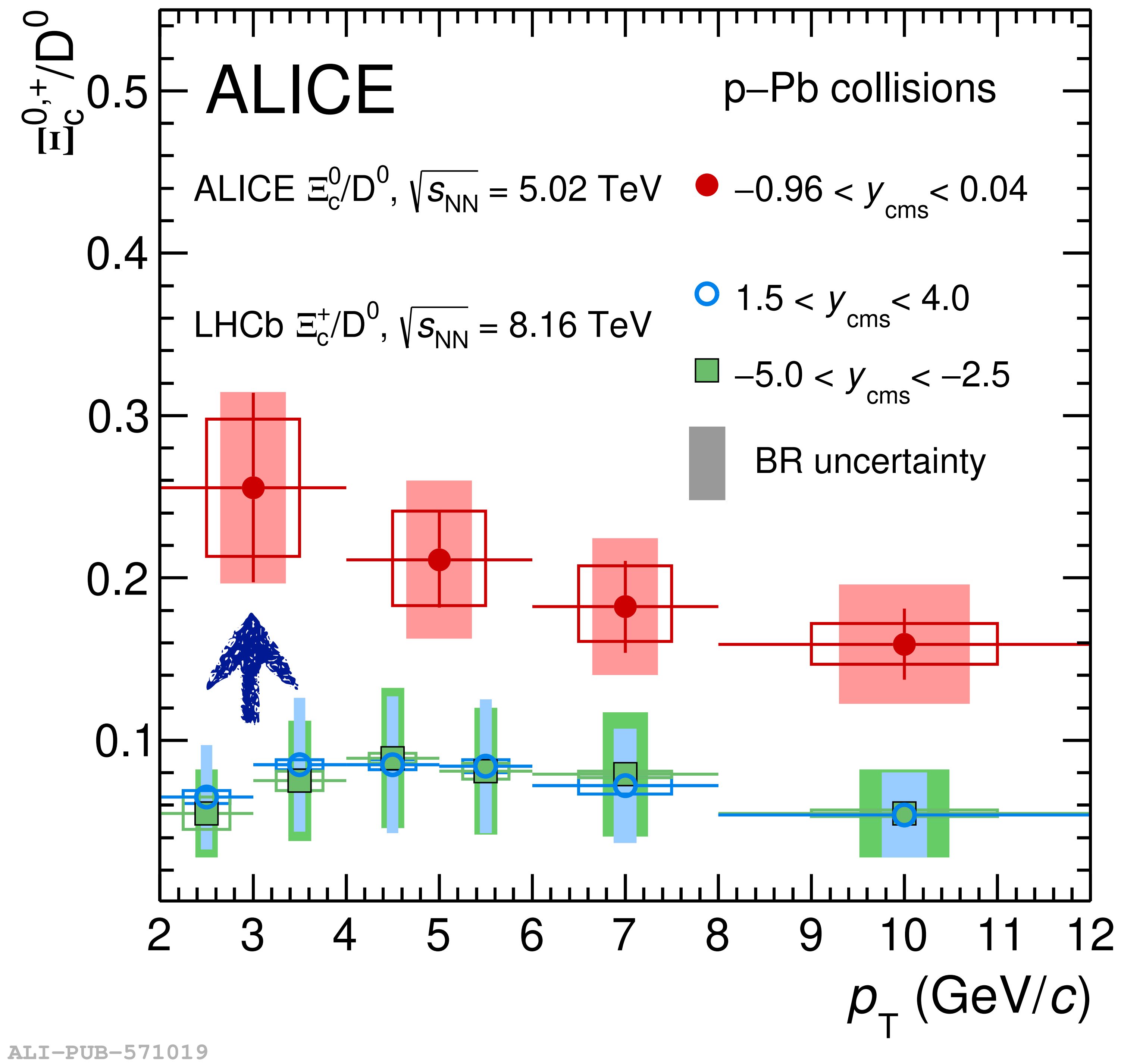


ALI-PUB-567881

arXiv:2405.14538



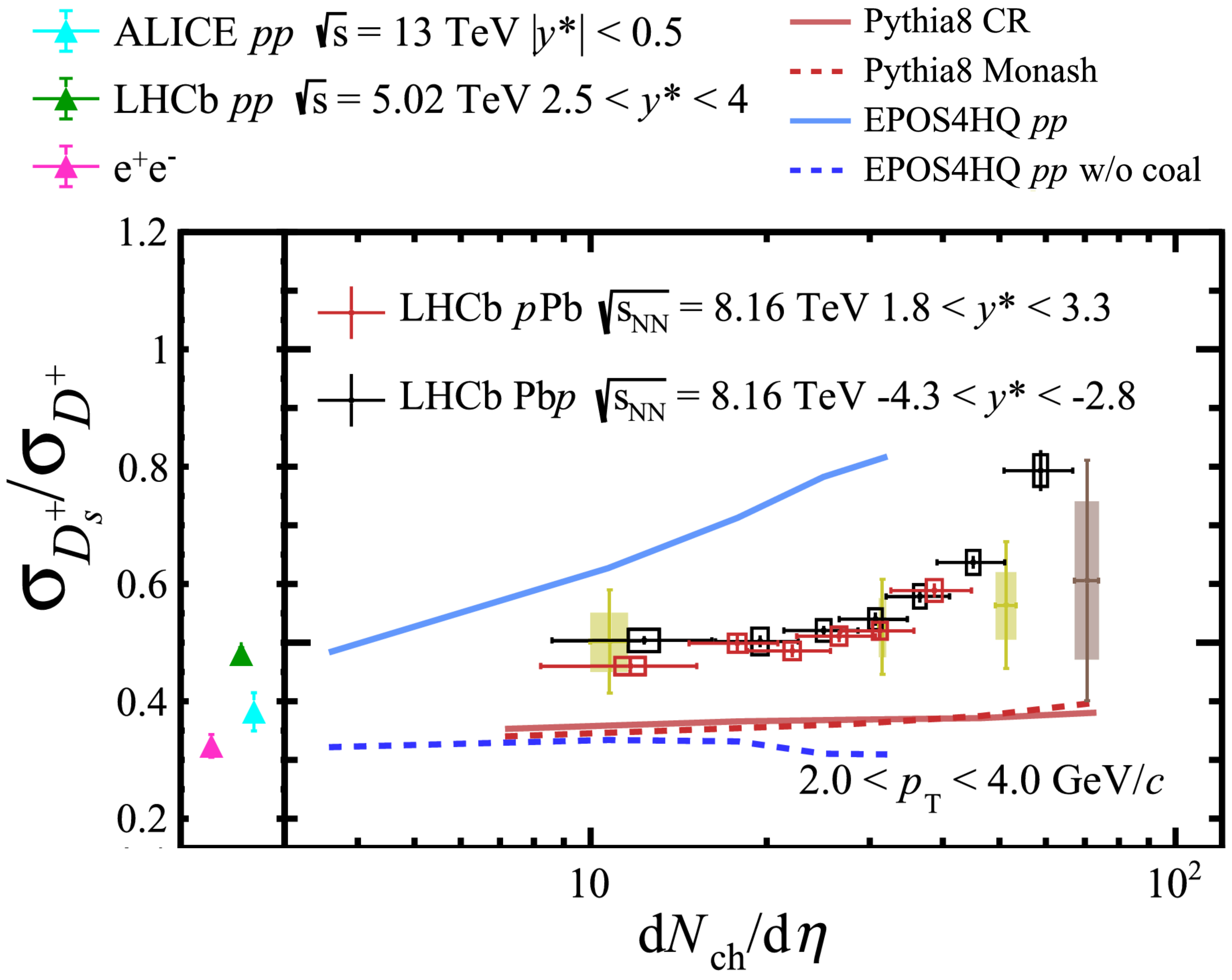
ALI-PUB-571011

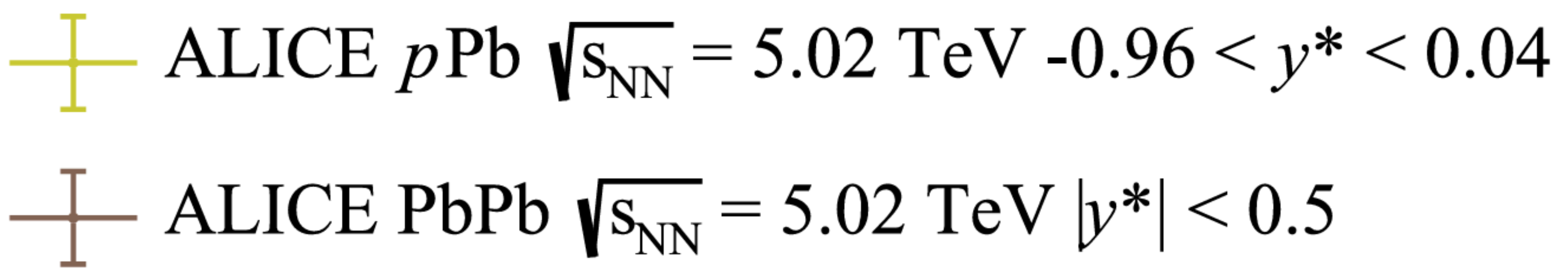


ALI-PUB-571019

- 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
- LHCb results systematically less than ALICE measurements -> rapidity dependence?

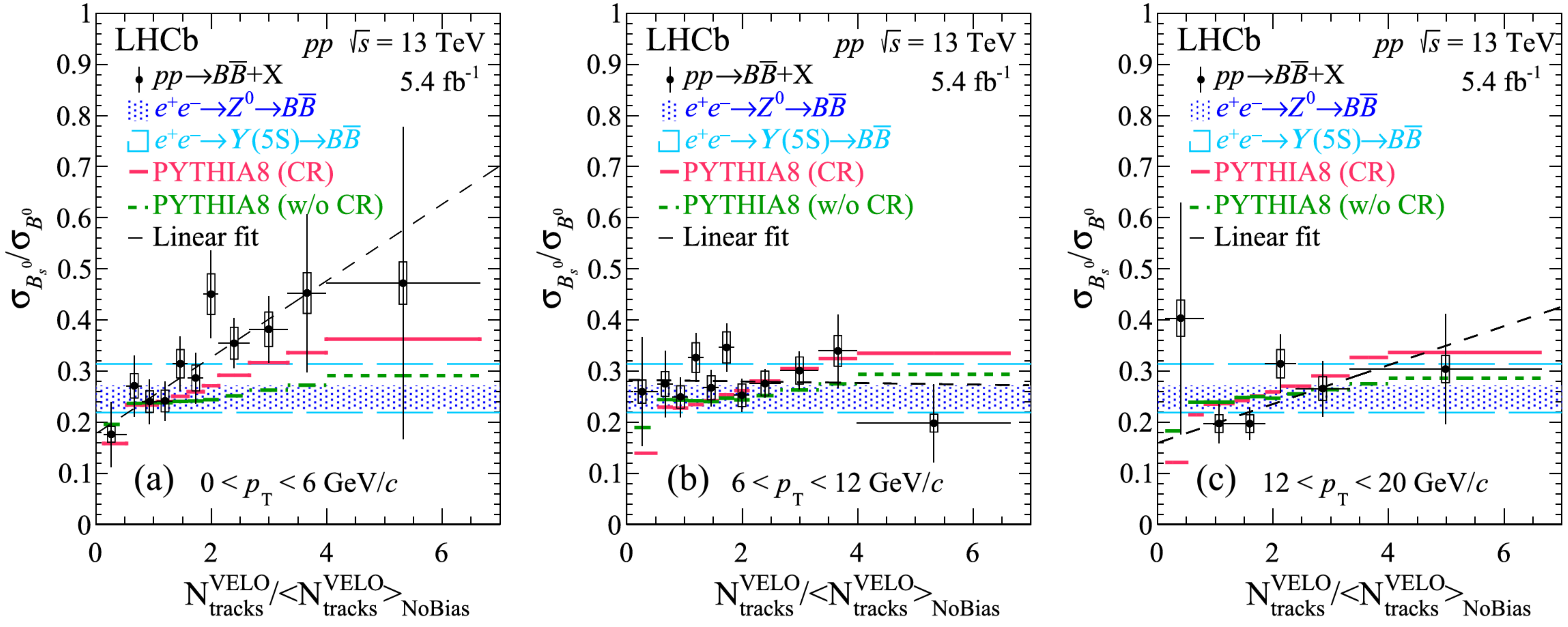
M-to-M event multiplicity dependence (LHCb)





Phys. Rev. D 110 (2024) L031105

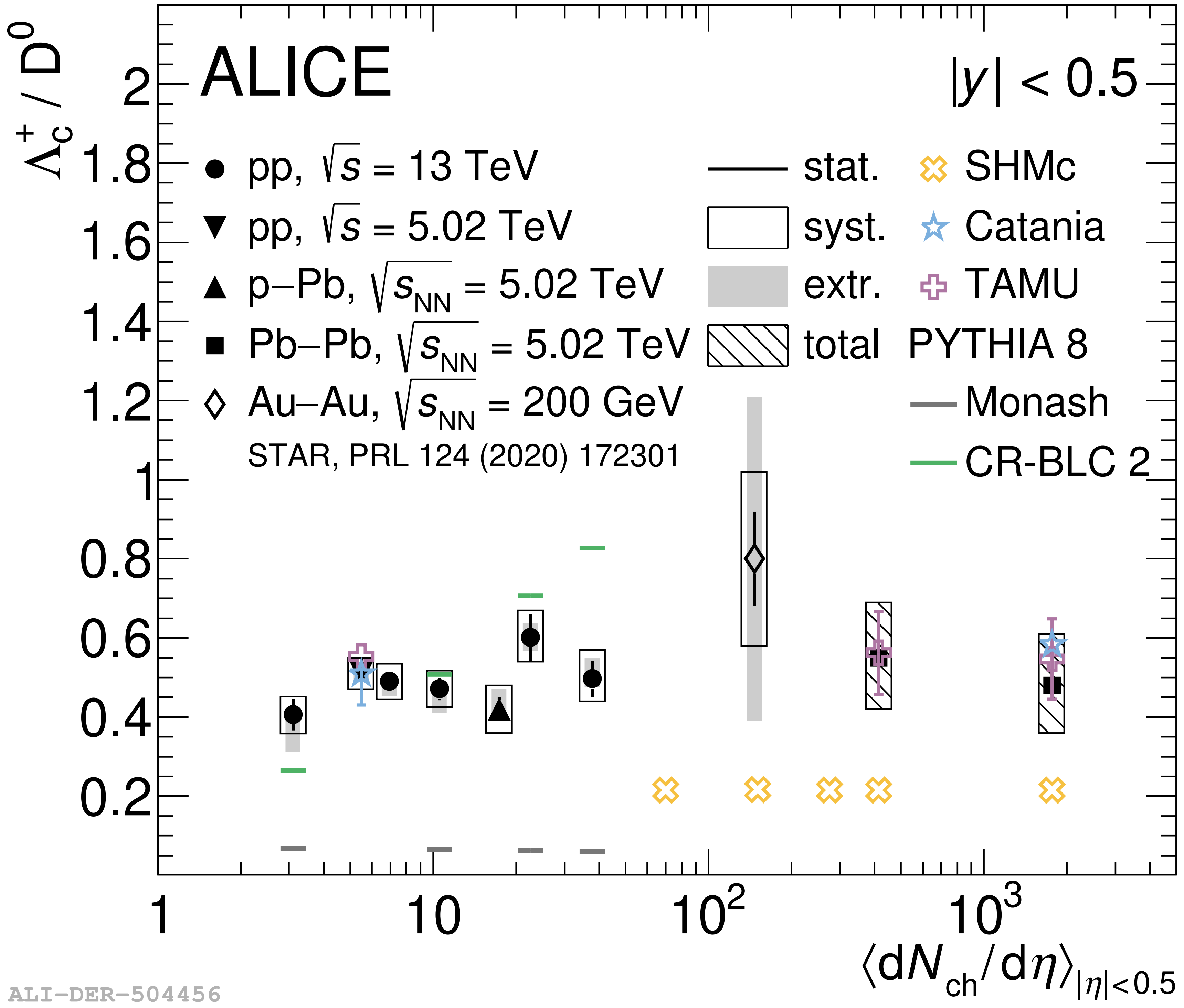
Phys.Rev.Lett. 131 (2023) 061901

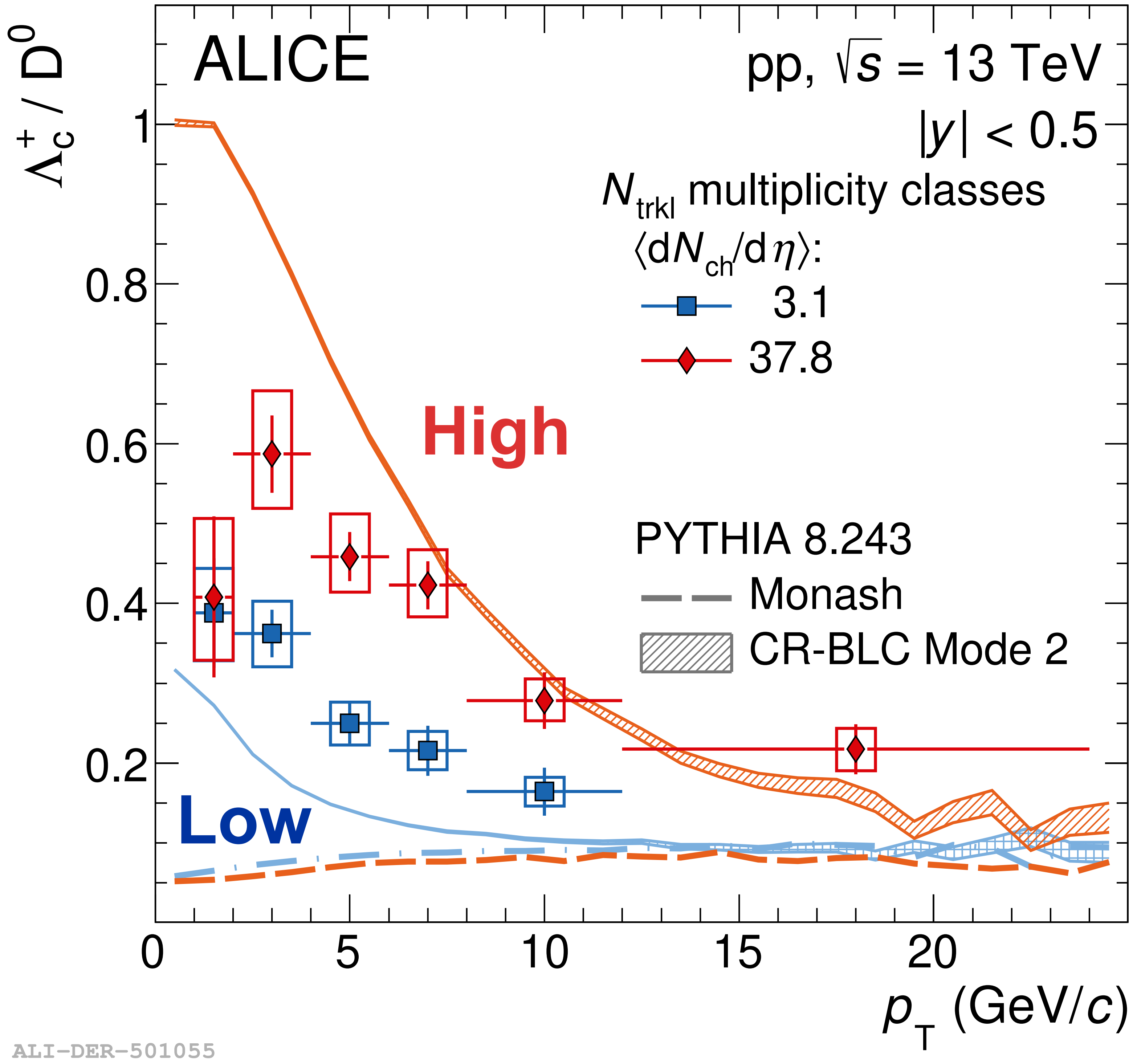


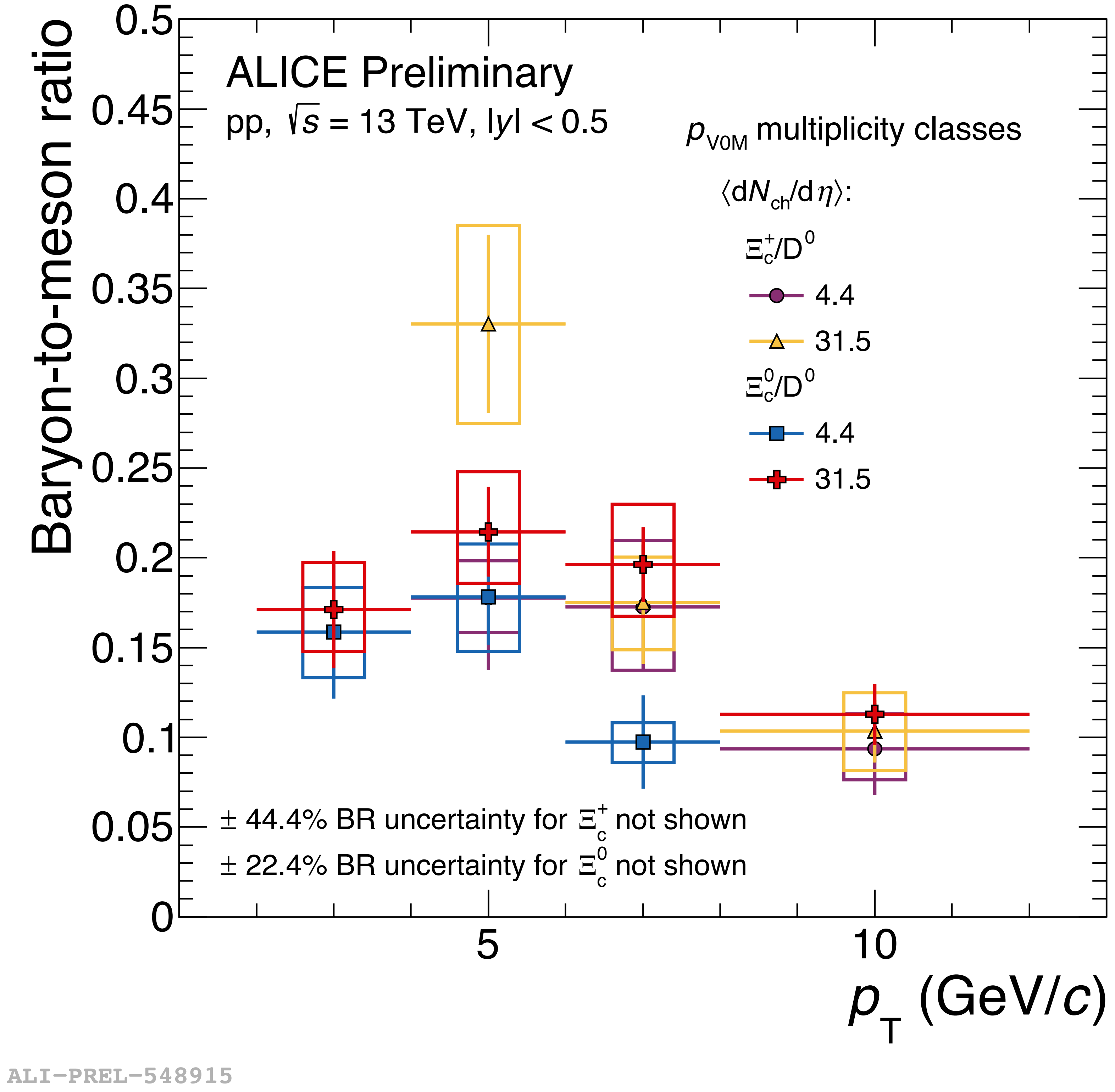
- Observed clear indications of strangeness enhancement in both charm and beauty sectors
- Final state effects such as coalescence are important at low p_T and high multiplicity

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

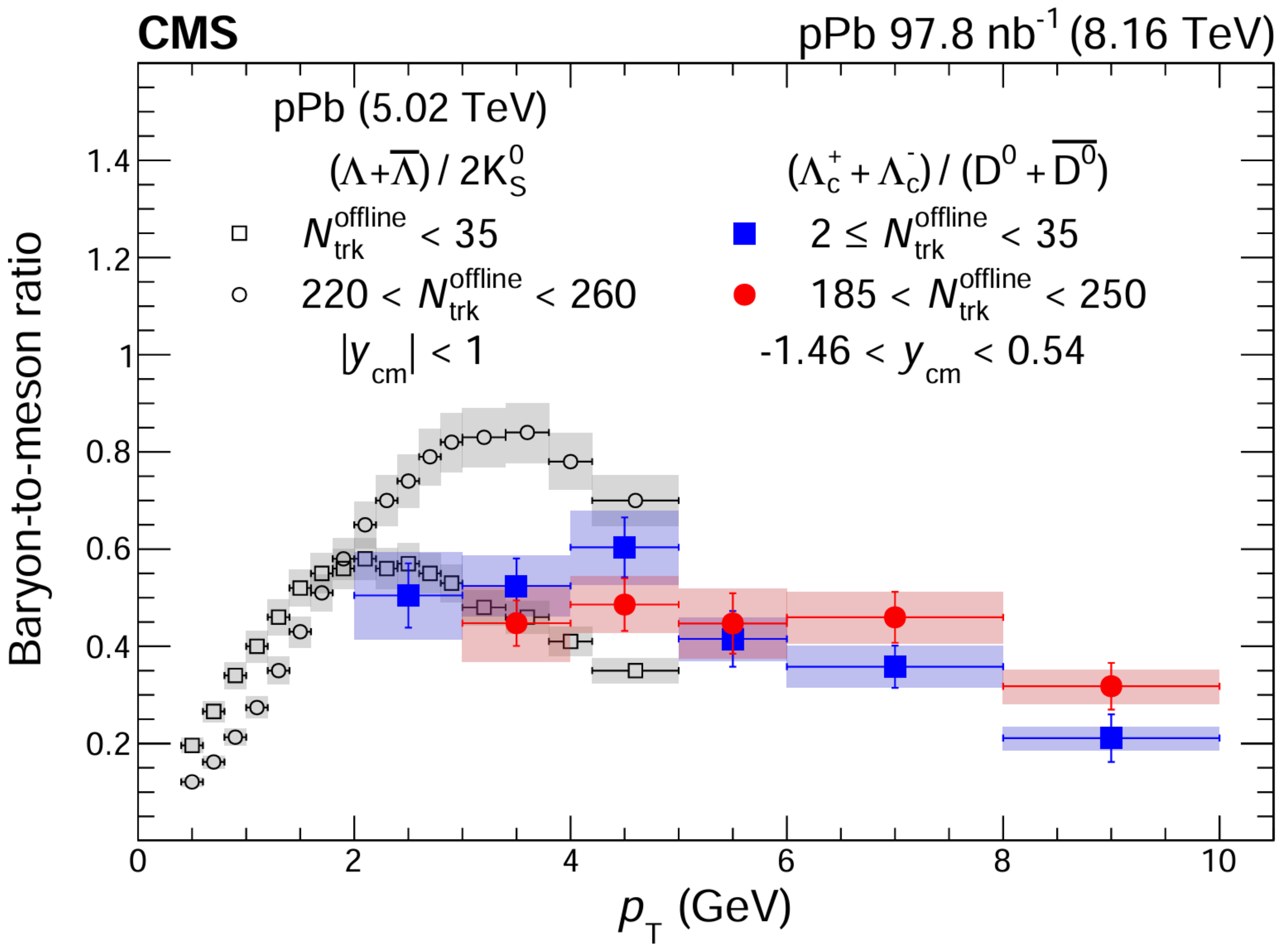
- Multiplicity-dependent enhancement with 5.3σ from lowest to highest multiplicity

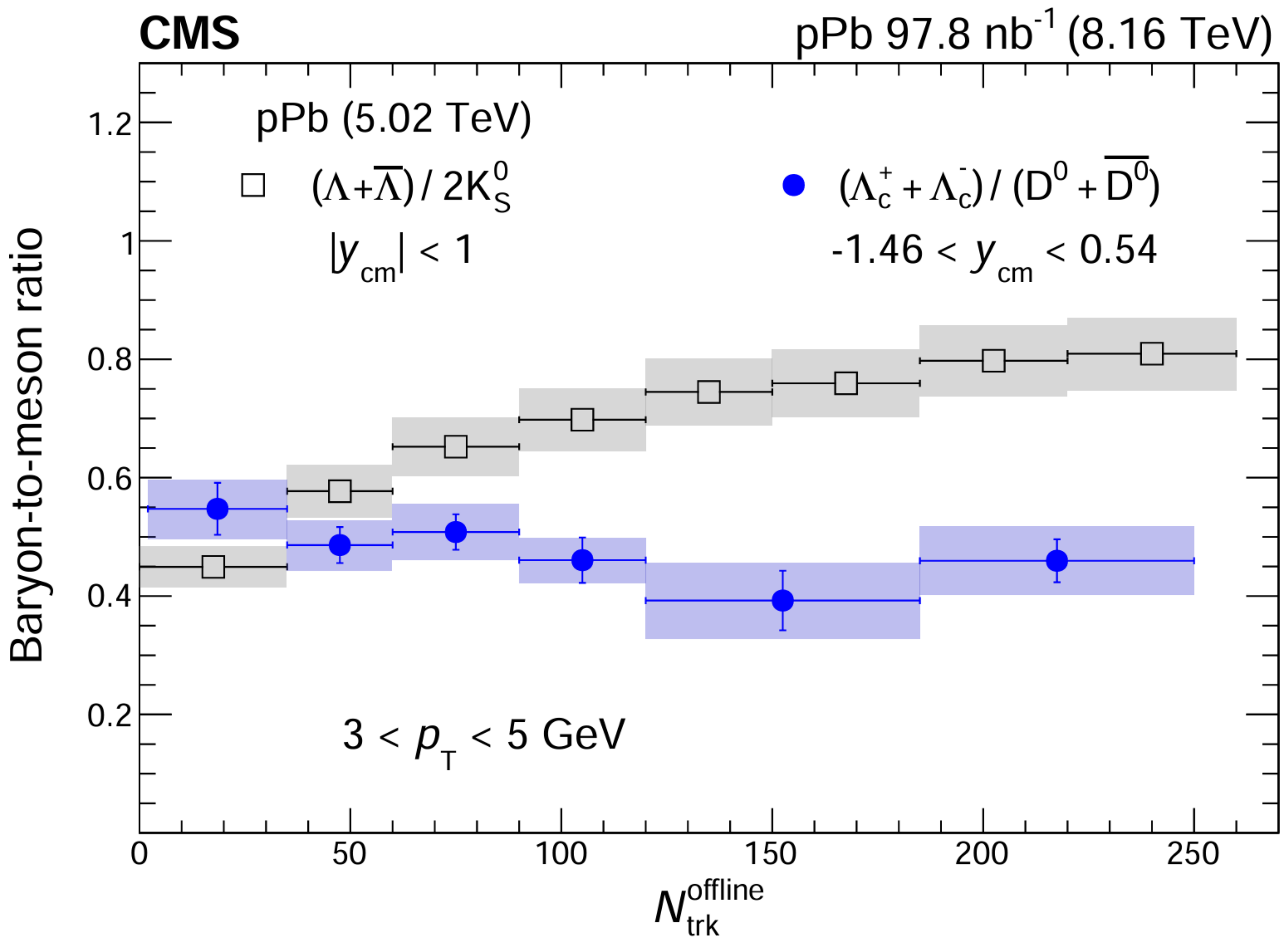
$\Xi_c^{0,+}/D^0$ vs. p_T in different multiplicity

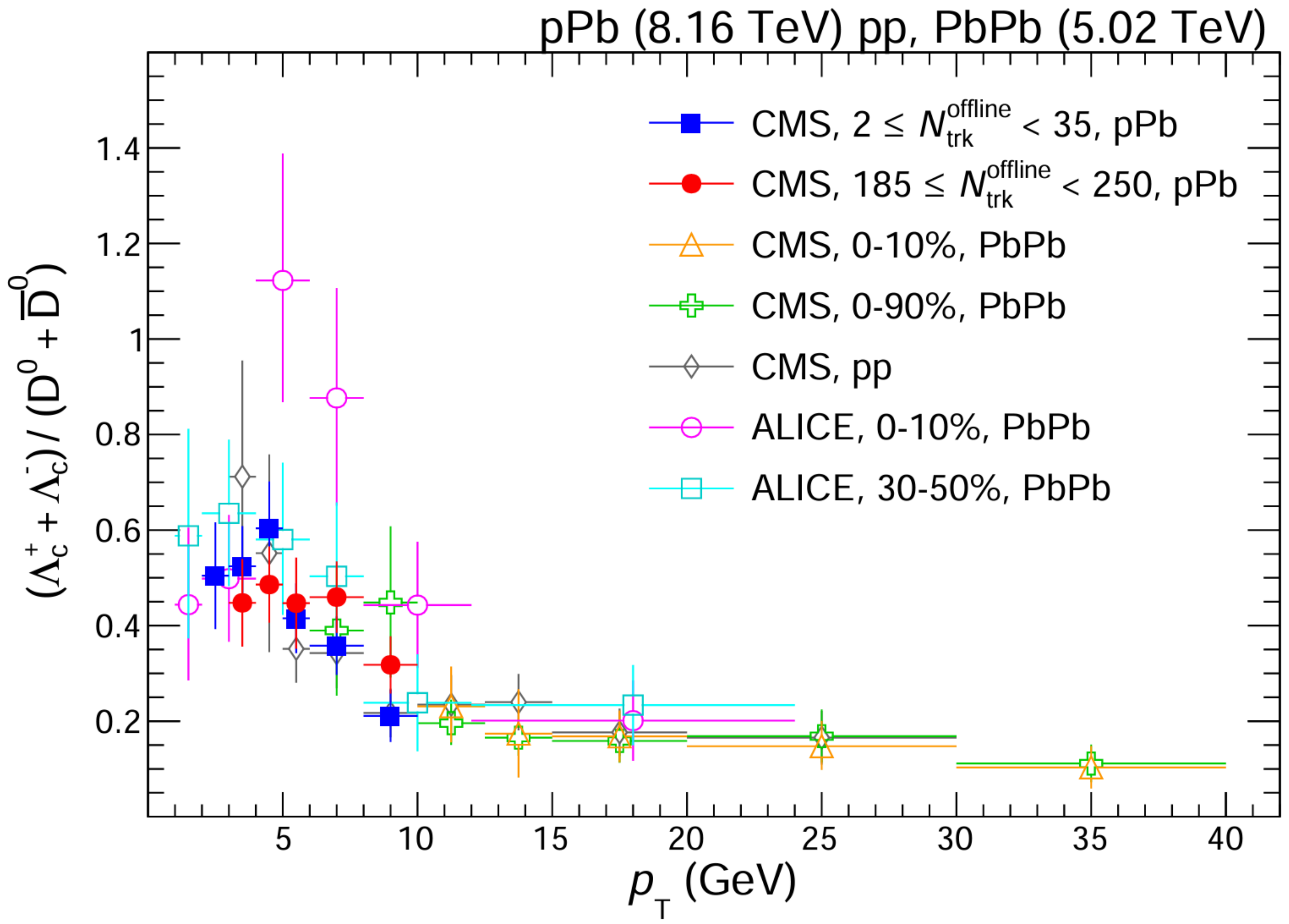
- No significant multiplicity dependence as a function of p_T within uncertainties

B-to-M event multiplicity dependence (CMS)

arXiv:2407.13615

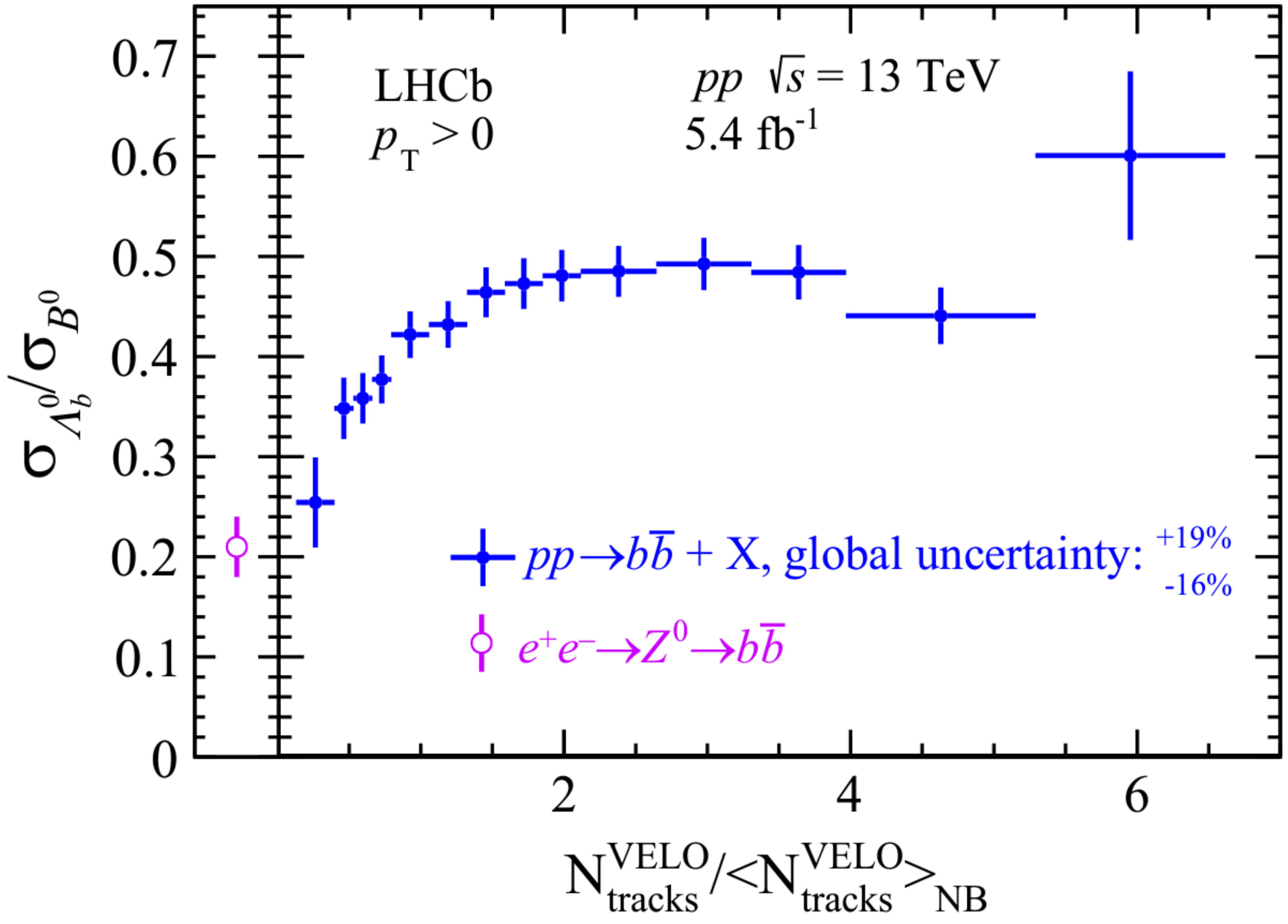


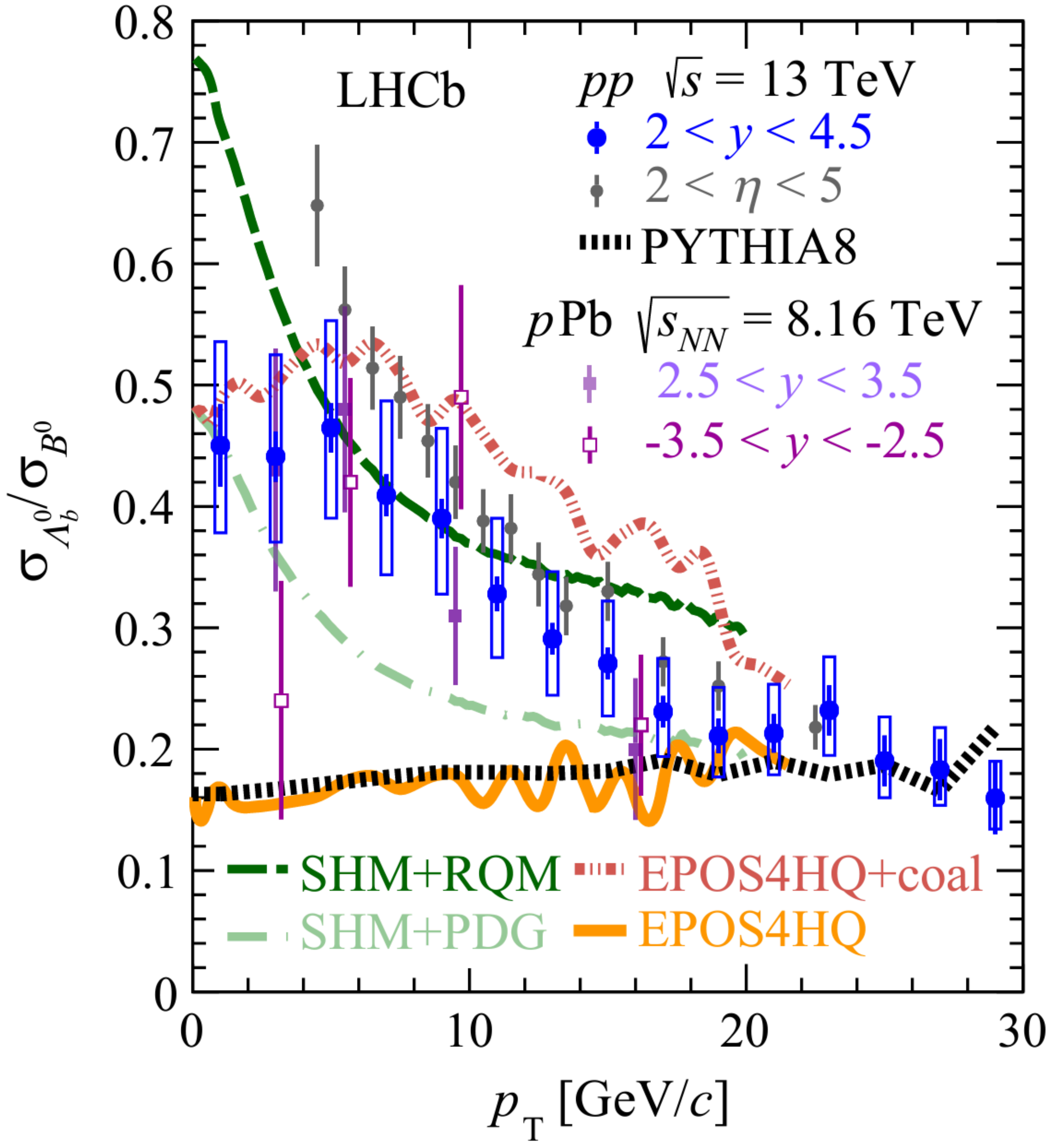




B-to-M event multiplicity dependence (LHCb)

Phys.Rev.Lett. 132 (2024) 081901





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

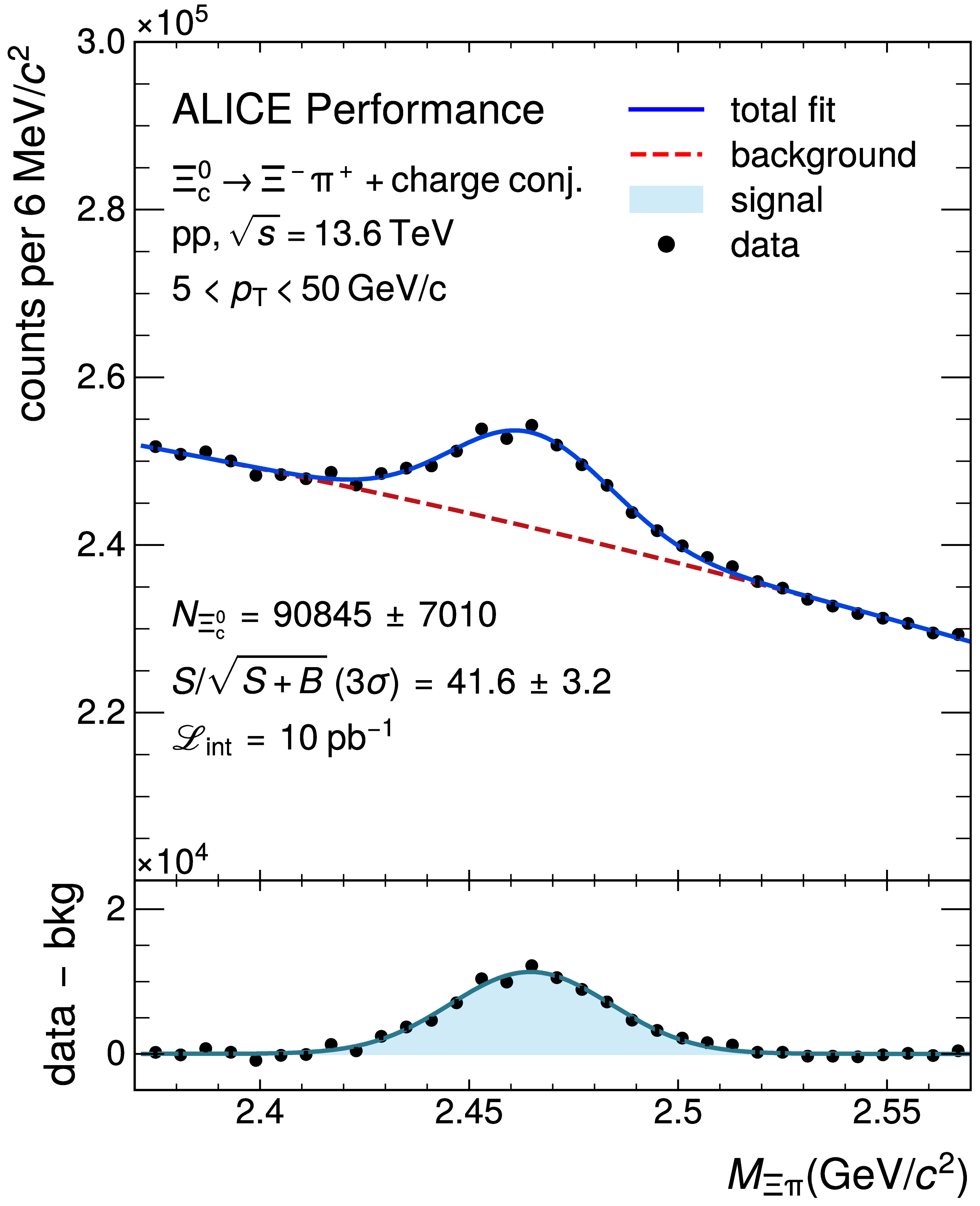
Semileptonic decays

- $\Lambda_c^+(udc) \to \Lambda e^+\nu_e$, 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

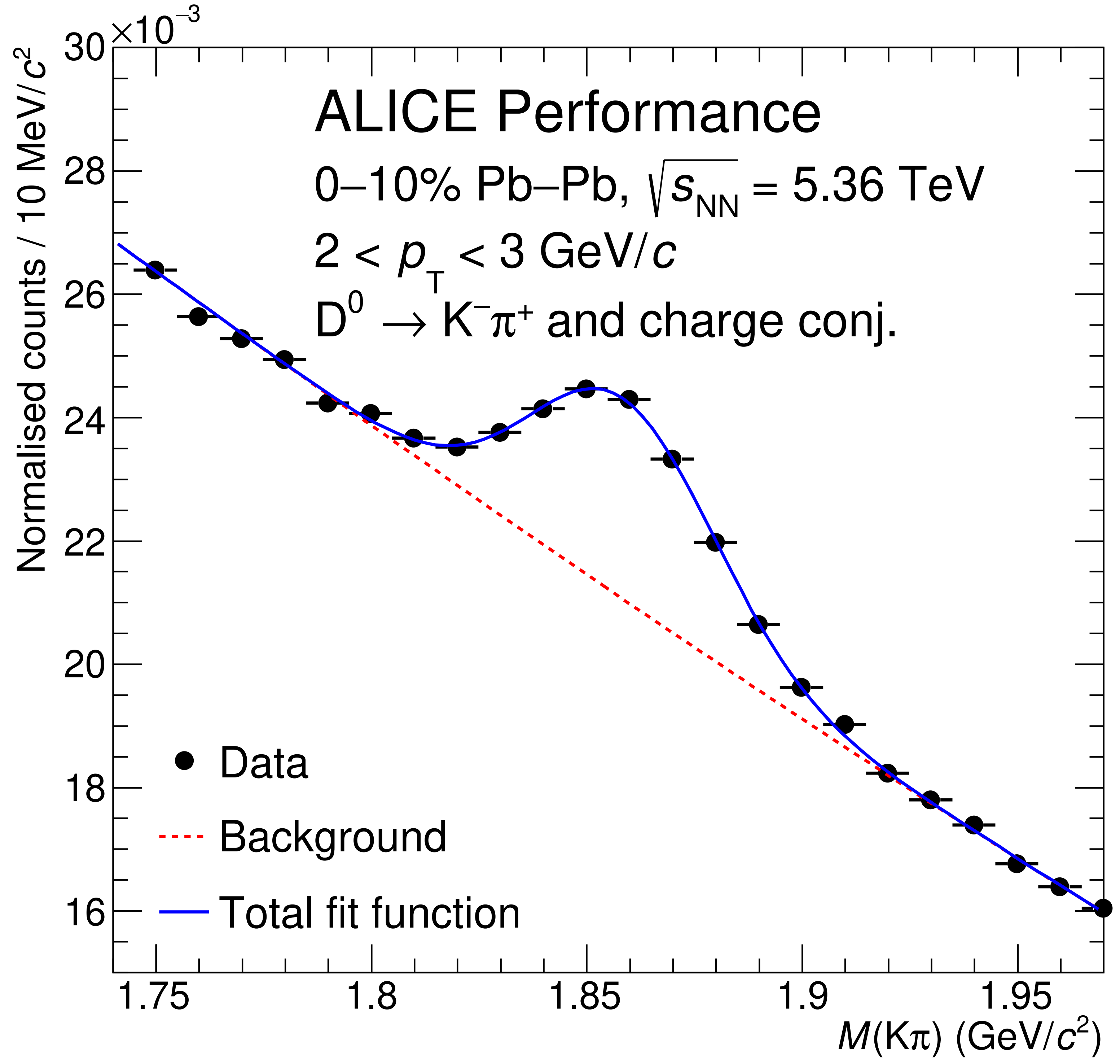
- $c \to$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$



ALI-PERF-578571

Non-Prompt

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



ALI-PERF-568645

ALICE detector for Run 1 and Run 2

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

System	Year(s)	$\sqrt{s_{NN}}$	L_{int}
pp	2017	5.02 TeV	~20 nb^{-1}
	2016 – 2018	13 TeV	~32 nb^{-1}
p–Pb	2016	5.02 TeV	~287 μb^{-1}
Pb–Pb (0-10%)	2018	5.02 TeV	~131 μb^{-1}
Pb–Pb (30-50%)	2018	5.02 TeV	~56 μb^{-1}