Heavy-flavour production and hadronisation with ALICE

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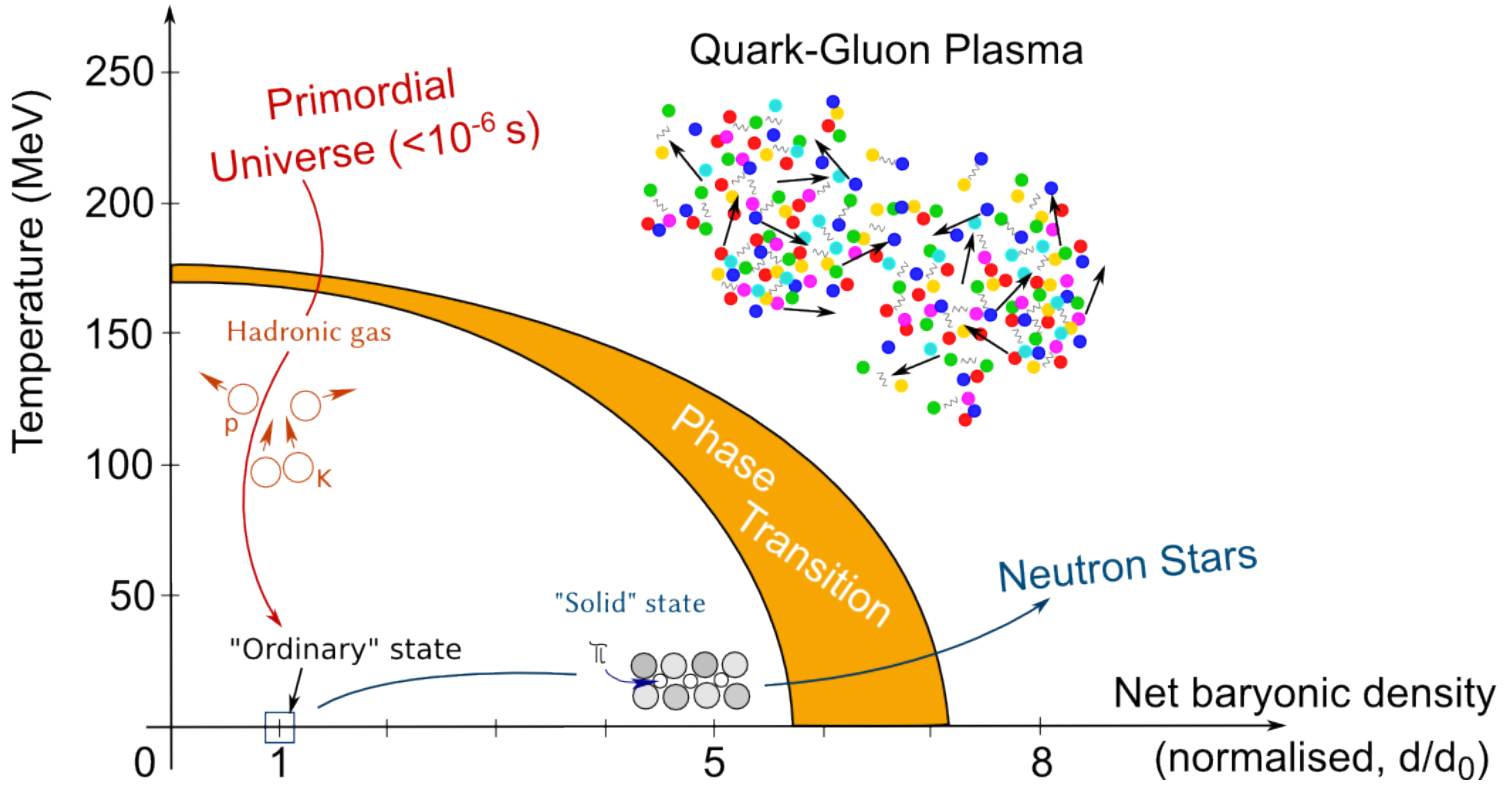
USTC-PNP-Nuclear Physics Mini Workshop

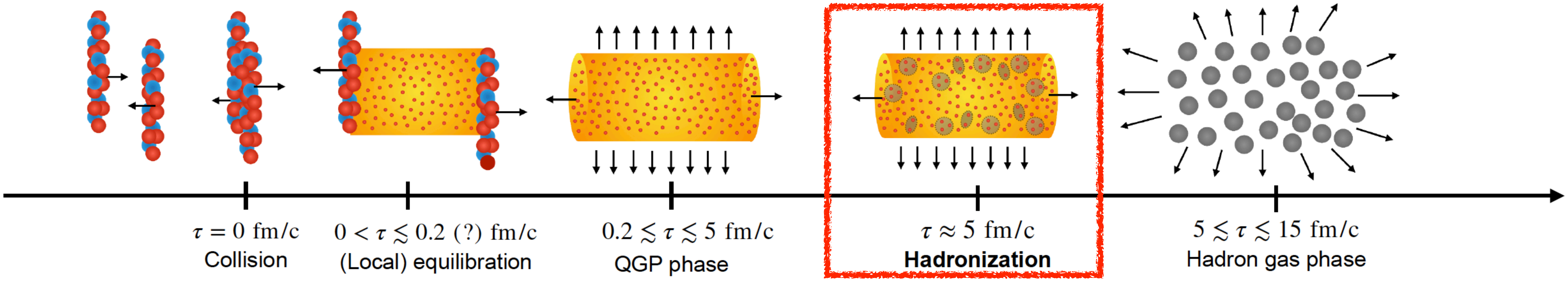
Quark-Gluon Plasma (QGP)

https://cds.cern.ch/record/2025215

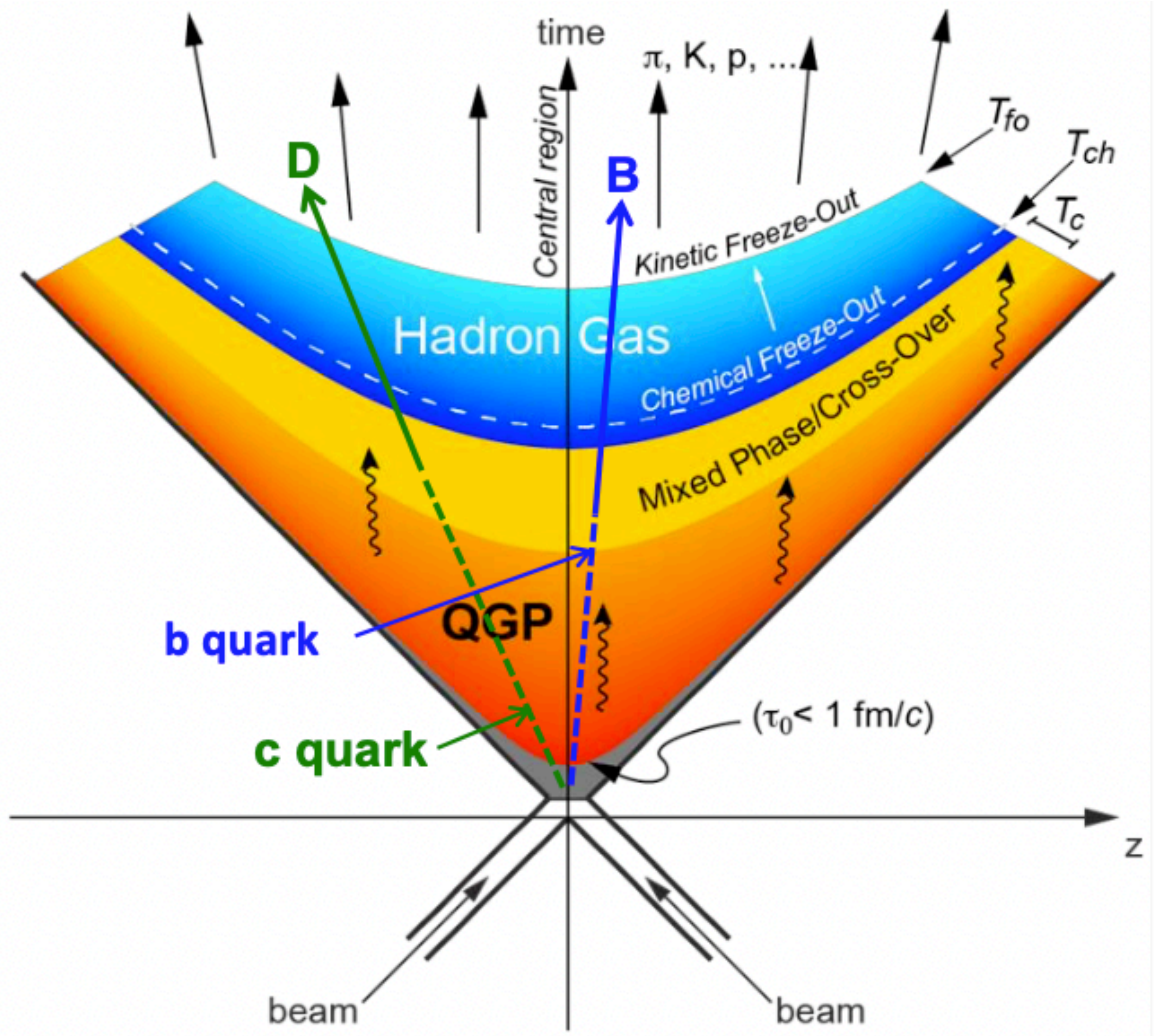


- Quark-gluon plasma: deconfined phase of quarks and gluons
- Phase transition at LHC is a smooth crossover
  - ➡ Similar to early universe (~few μs after the Big Bang)

Time evolution of ultra-relativistic heavy-ion collisions



Why Open Heavy Flavours



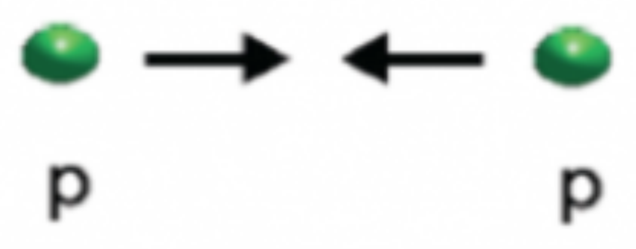
- Charm:

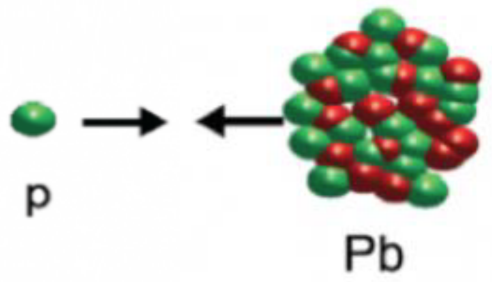
  $m_c \approx 1.3\ \mathrm{GeV}/c^2$

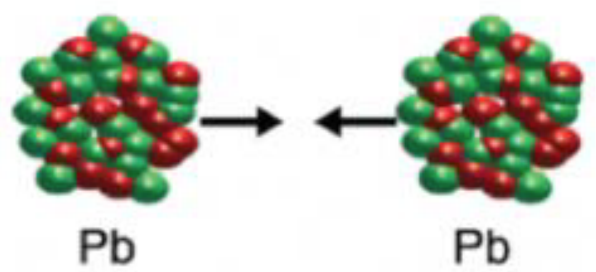
- Beauty:

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

- $m_Q \gg \Lambda_{QCD}$
  - 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







- Tests of pQCD calculations
- Reference for heavy-ion collisions

- Cold nuclear matter effects
  - Modification of parton distribution functions (PDF) in bound nucleons

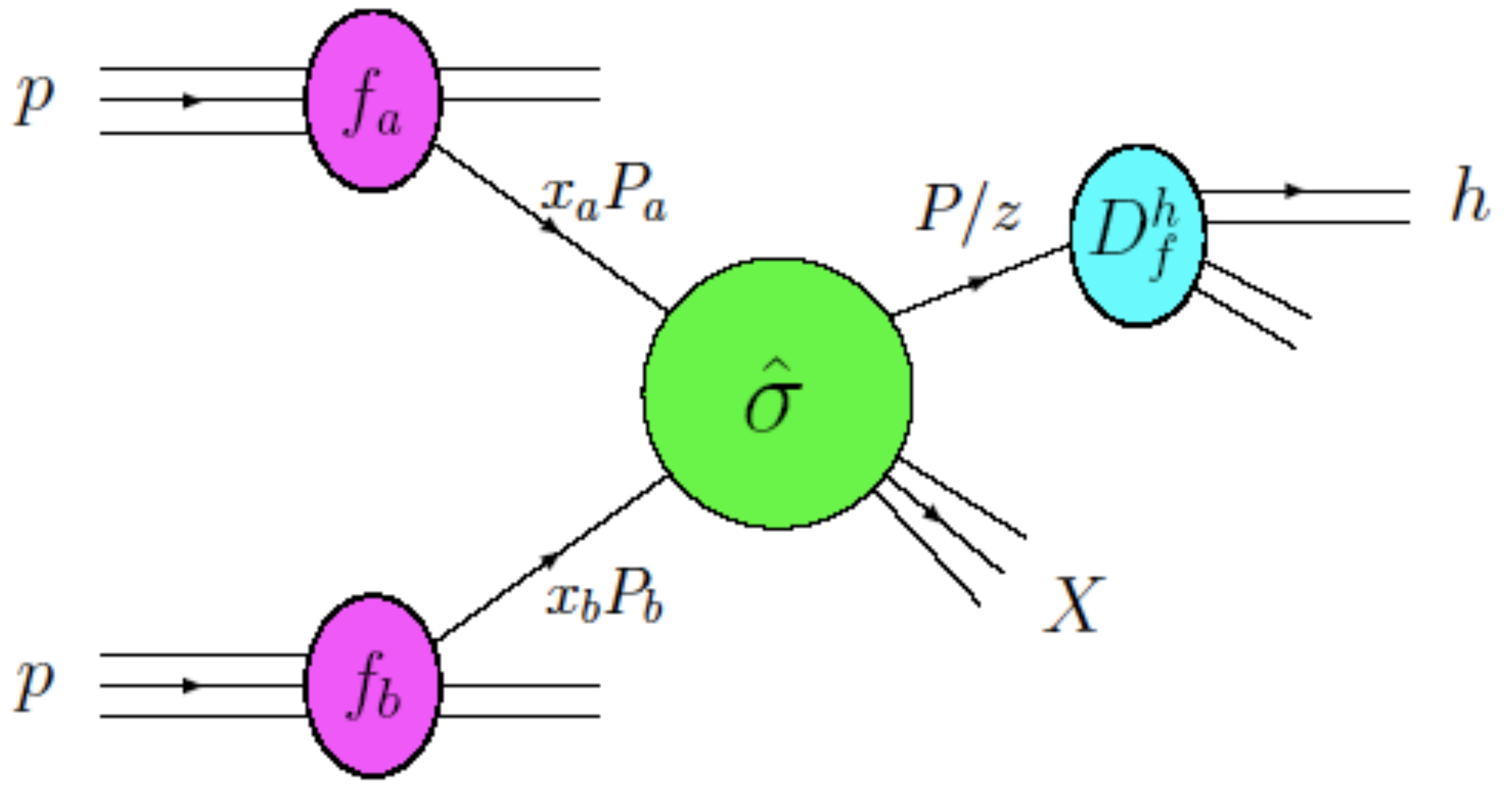
- Hot nuclear matter effects
  - Energy loss in the QGP
  - Collective motion of the system
  - Modification of hadronisation mechanisms

Heavy-flavour production

Hadroproduction described by factorisation approach, which works well for charm and beauty mesons :

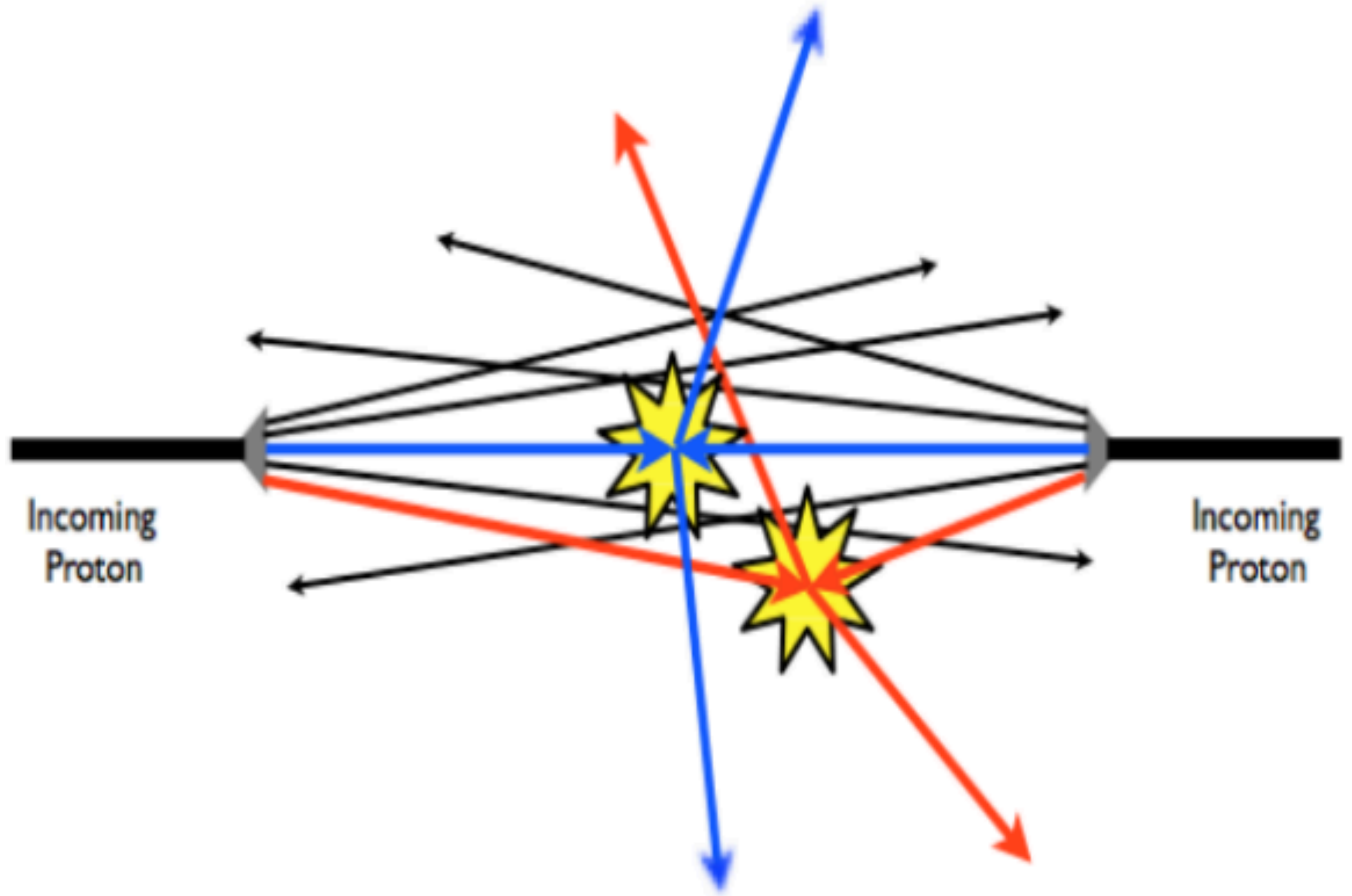
$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_T;\mu_F;\mu_R) = PDF(x_a,\mu_F)PDF(x_b,\mu_F) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_a,x_b,\mu_R,\mu_F) \otimes D_{c\rightarrow D}(z = p_D/p_c,\mu_F)$$

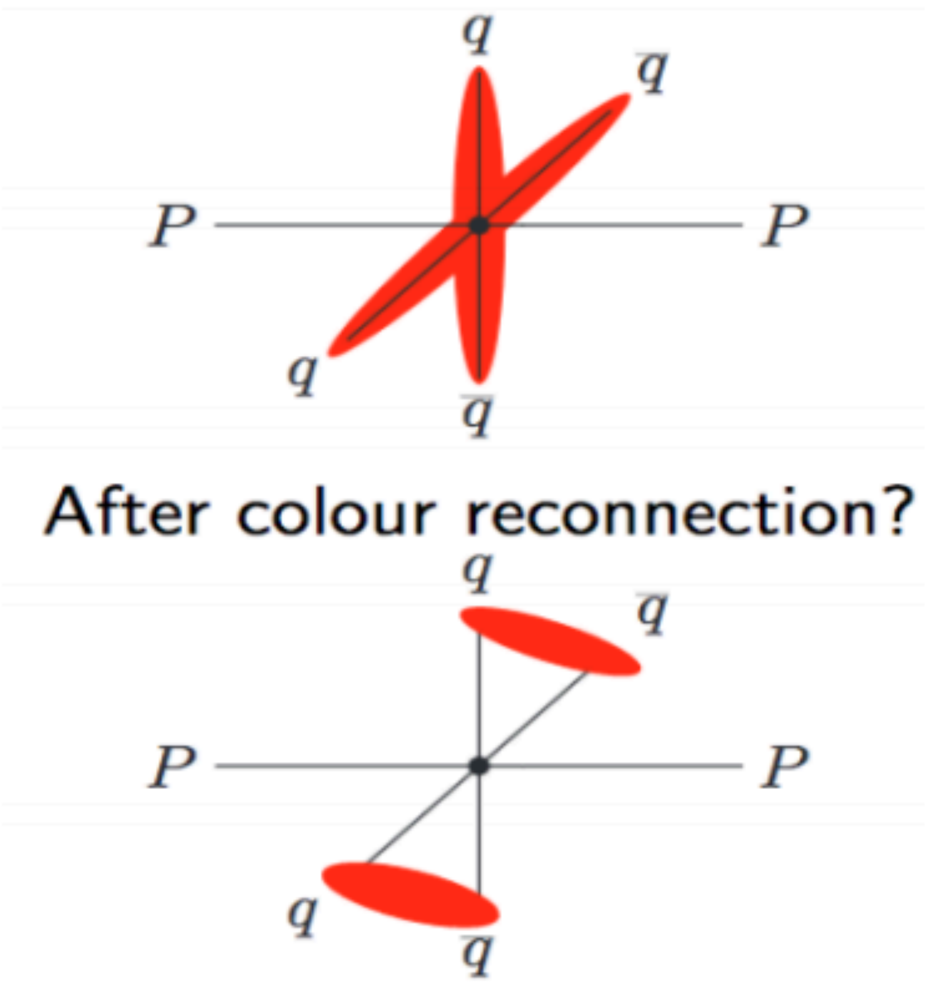
parton distribution function (PDF) (non-perturbative) | partonic cross section (perturbative) | hadronisation by fragmentation (non-perturbative)



- Current pQCD calculations based on factorisation approach use fragmentation functions tuned on e^+e^- and ep measurements, assuming them universal across different collision energies and systems

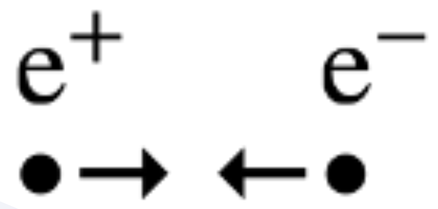
Multiple Parton Interaction (MPI)



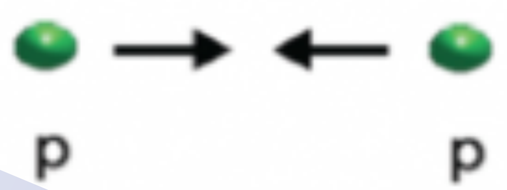


Heavy-flavour hadronization

- Open heavy-flavour (HF) hadron production cross section calculated using the factorization approach
  - Ratios of particle species sensitive to hadronization

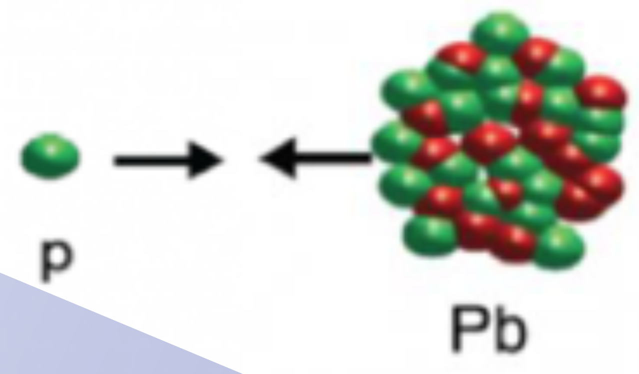


Vacuum



Not far from vacuum?

Or dense enough to alter hadronization?



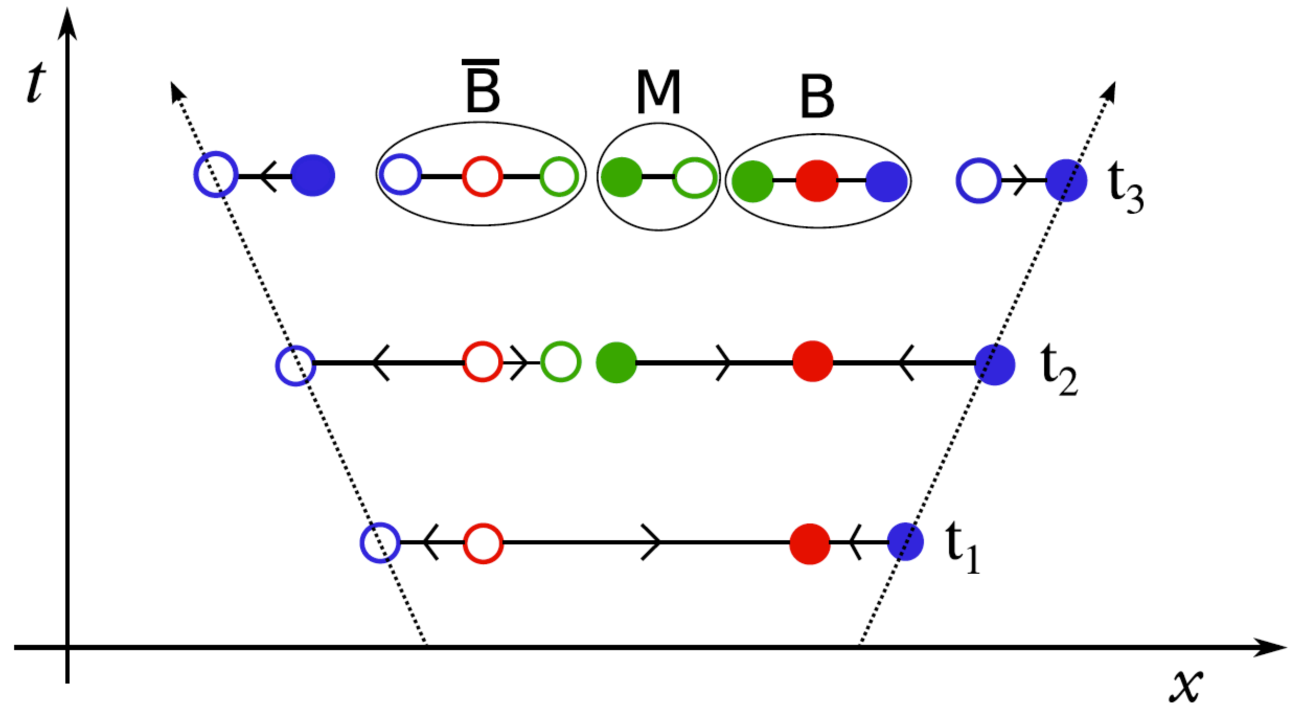
System size

Open questions

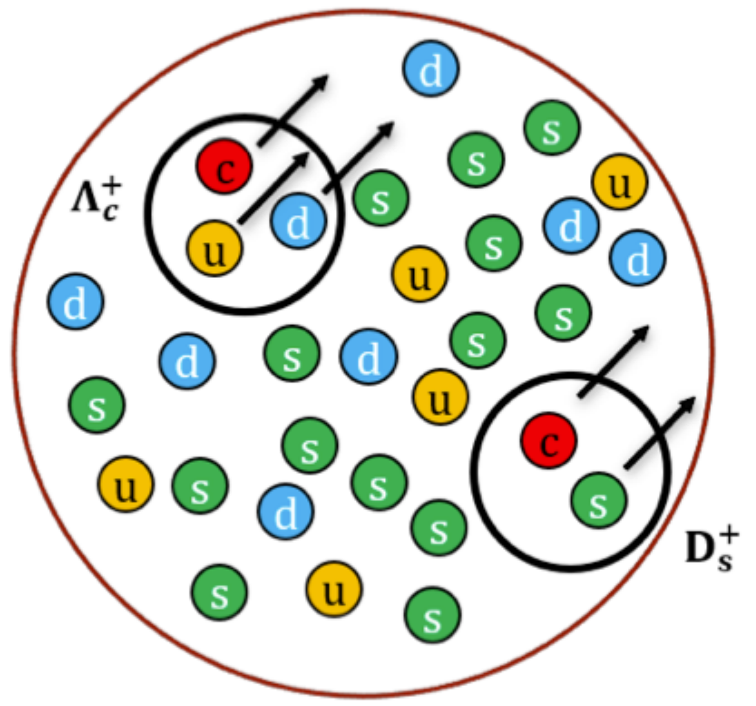
- Fragmentation fractions (FFs) universality violated already in pp collisions?
  - A system rich of quarks or gluons?
- Charm-strange baryons ($\Xi_c^{0,+}$ and Ω_c^0) production can not be described by models, which can describe Λ_c^+
  - Powerful constraints on models

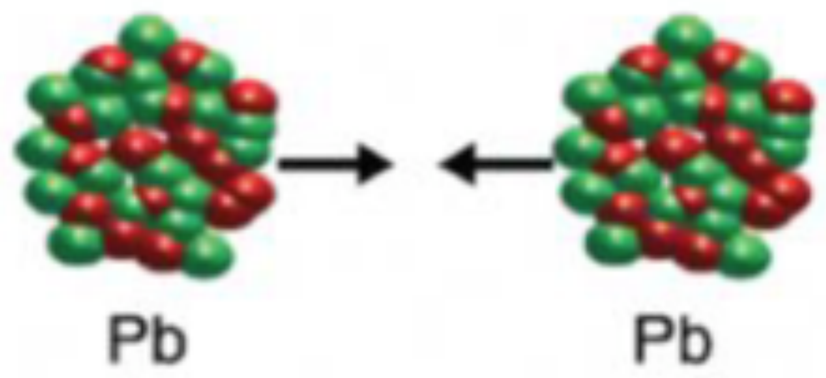
Fragmentation

- 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



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





Dense, extended-size system

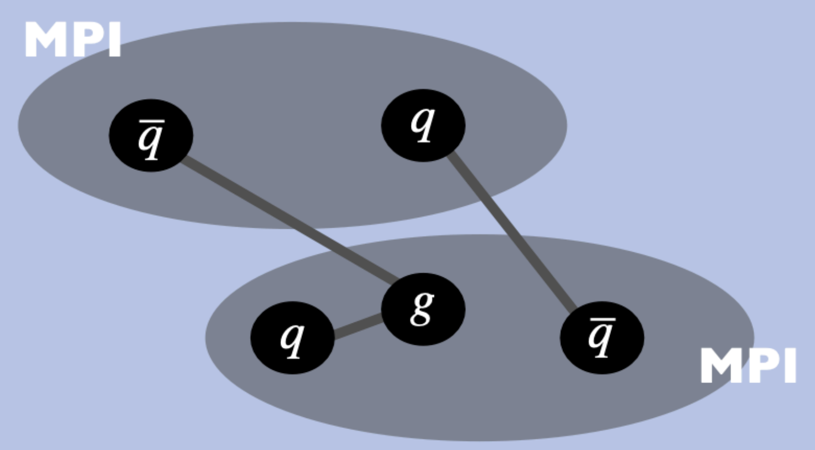
Coalescence

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

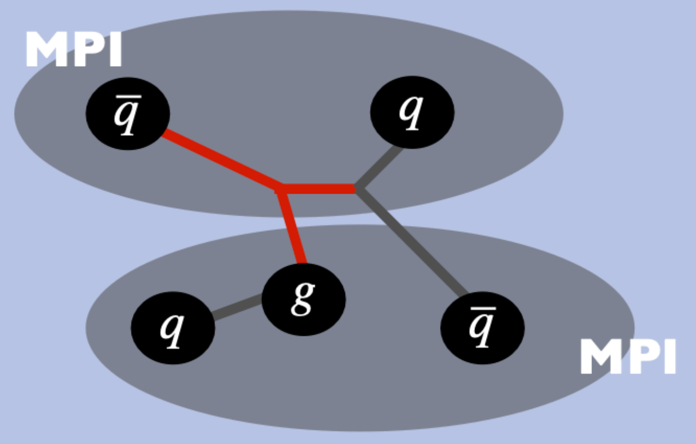
Modeling hadronization

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

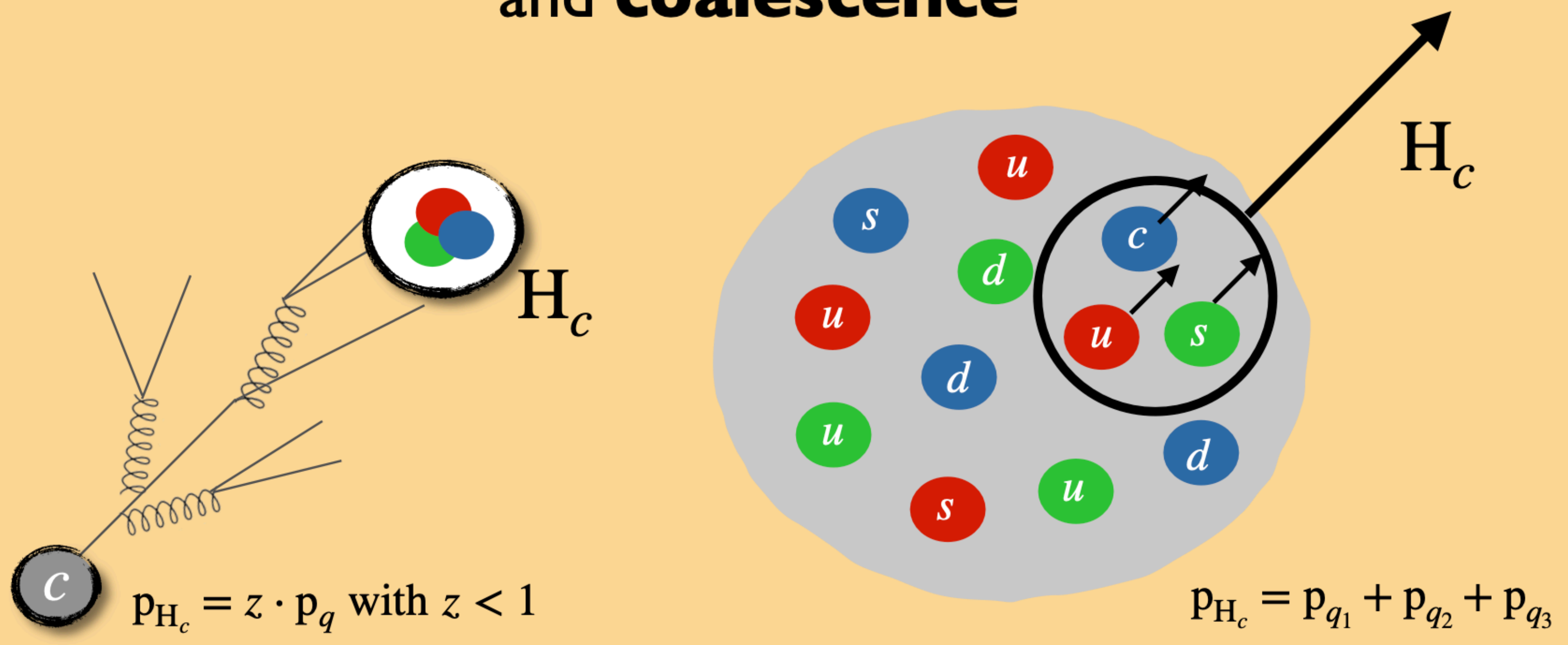


Mode 2
the **junction** topology leads to an increase of baryon production
JHEP 08 (2015) 003

CATANIA

Phys.Lett.B 821 (2021) 136622

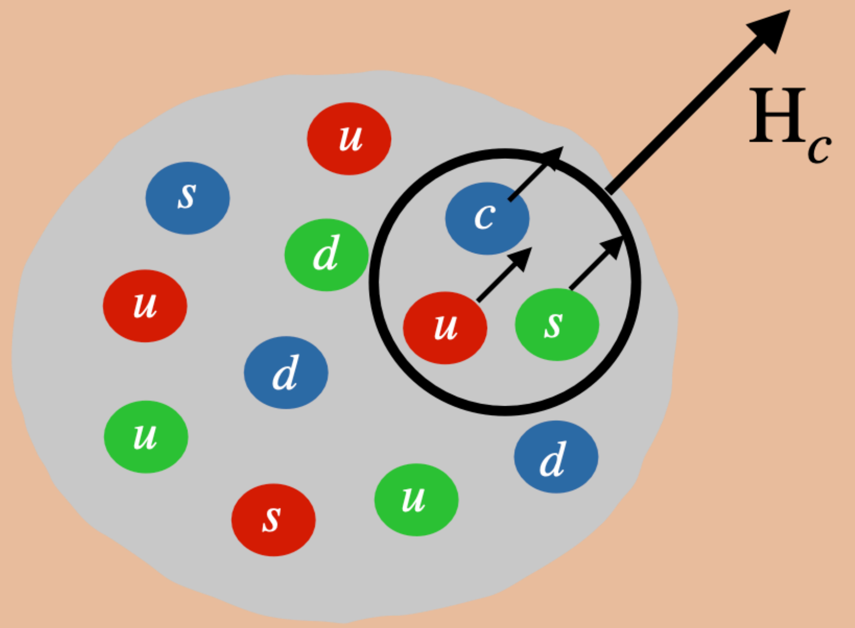
Hadronization via both **fragmentation** and **coalescence**



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

Charm fragmentation measured in e^+e^- and ep

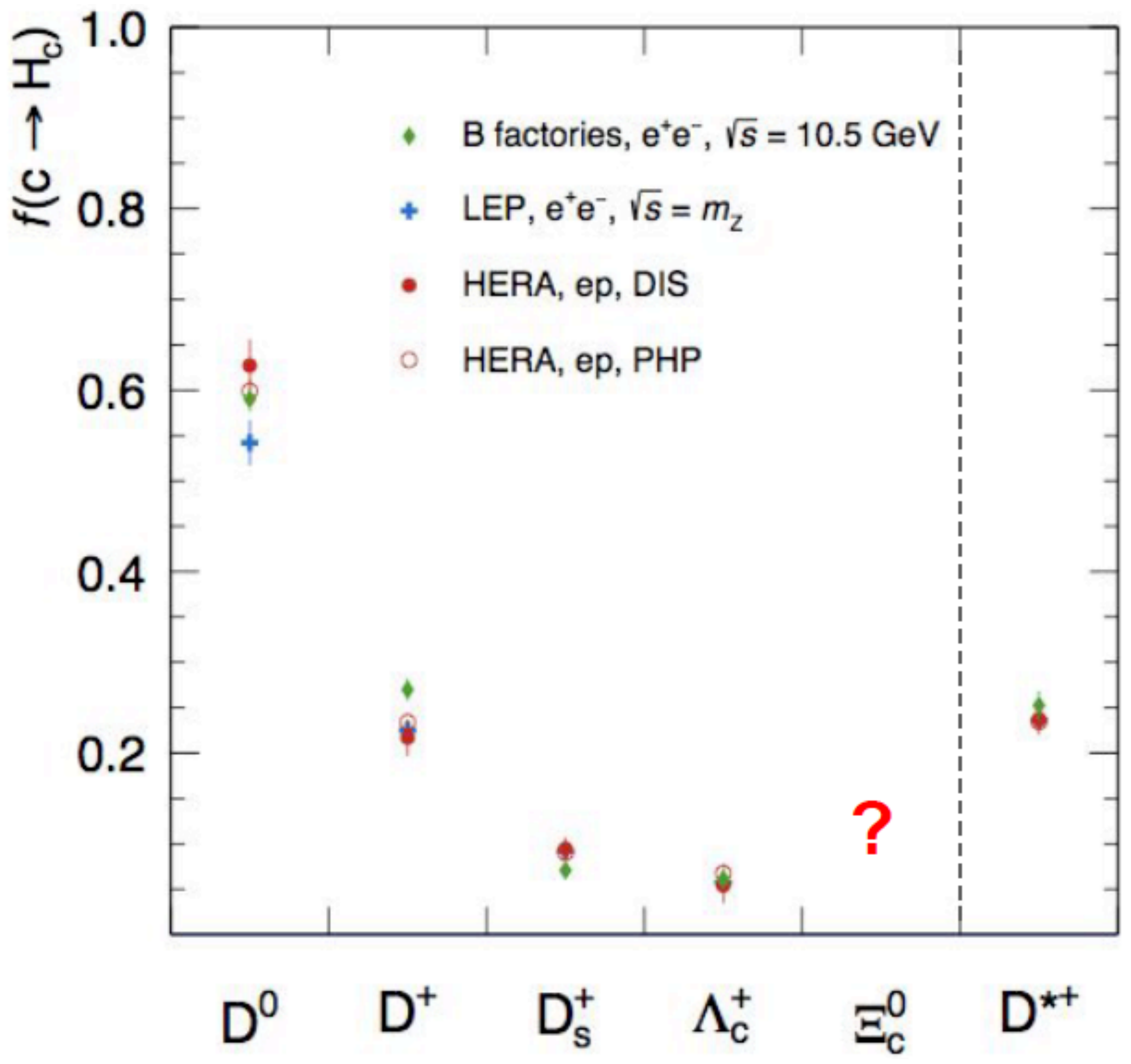
- Charm fragmentation fractions (FF)
  - $f(c \to H_c) = \sigma(H_c)/\sigma(c) = \sigma(H_c)/\sum_{w.d.} \sigma(H_c)$ (w.d.: weakly decaying)
  - Inputs used in a standard factorisation approach
- Production cross section of $\Xi_c^{0,+}$ are calculated under assumptions[1]:
  - $f(c \to \Xi_c^0)/f(c \to \Lambda_c^+) = f(s \to \Xi^-)/f(s \to \Lambda) \approx 0.004$

Average LEP FF

H_c	$f(c \to H_c)$ [%]
D^0	$54.2 \pm 2.4 \pm 0.7$
D^+	$22.5 \pm 1.0 \pm 0.5$
D_s^+	$9.2 \pm 0.8 \pm 0.5$
Λ_c^+	$5.7 \pm 0.6 \pm 0.3$
D^{*+}, rate	$23.4 \pm 0.7 \pm 0.3$
D^{*+}, double-tag	$24.4 \pm 1.3 \pm 0.2$
D^{*+}, combined	$23.6 \pm 0.6 \pm 0.3$

L. Gladilin, EPJC 75 (2015) 19

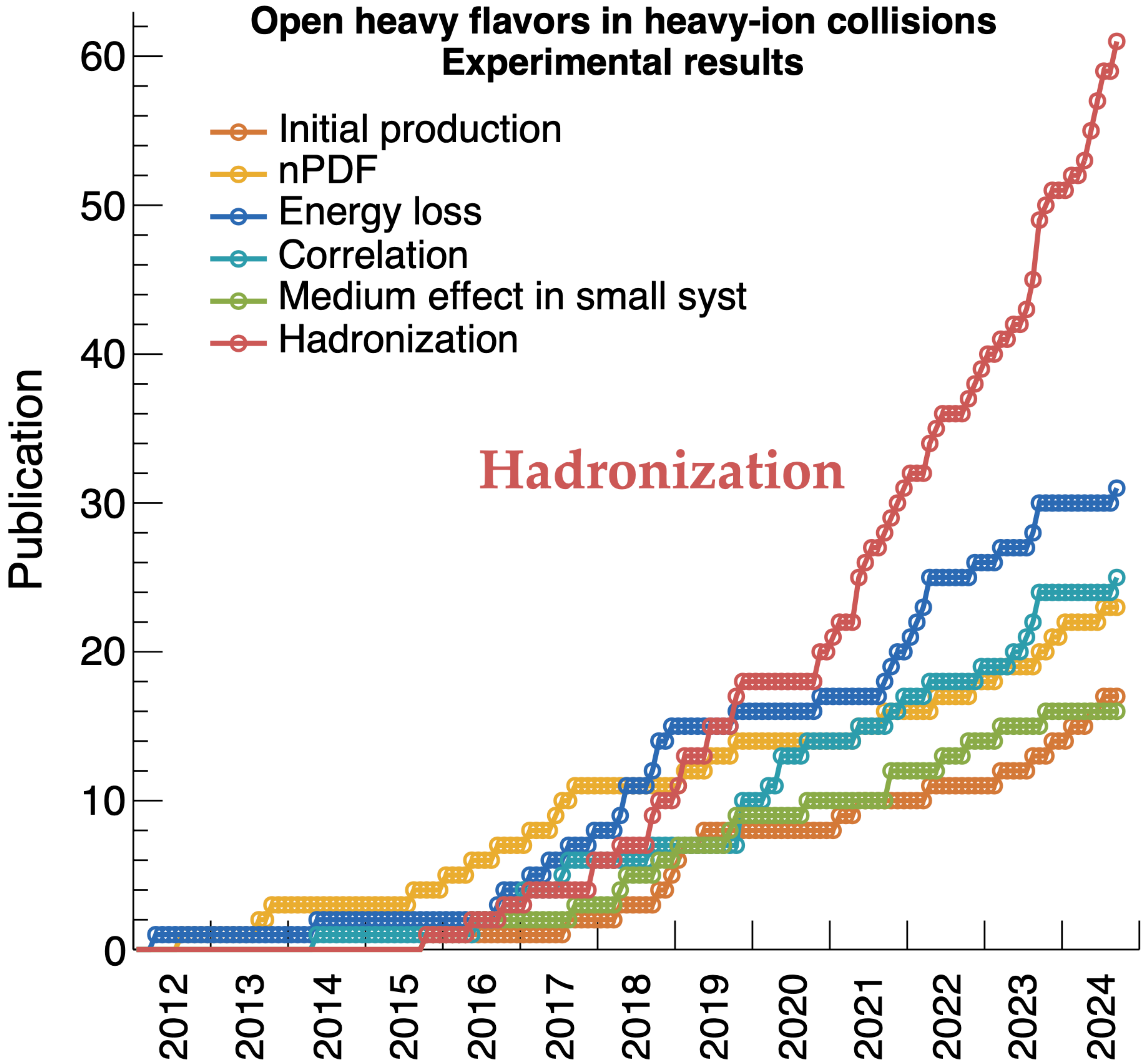
Sum of $f(c \to H_c)$ for D^0, D^+, D_s^+ and Λ_c^+: $91.6 \pm 3.3(\text{stat} \oplus \text{syst}) \pm 1.0(\text{BR})$ %



[1] M. Lisovyi, et al., EPJC 76 (2016) no.7, 397
[2] B factories: EPJC 76 no. 7, (2016) 397
[3] LEP: EPJC 75 no. 1, (2015) 19
[4] HERA: EPJC 76 no. 7, (2016) 397

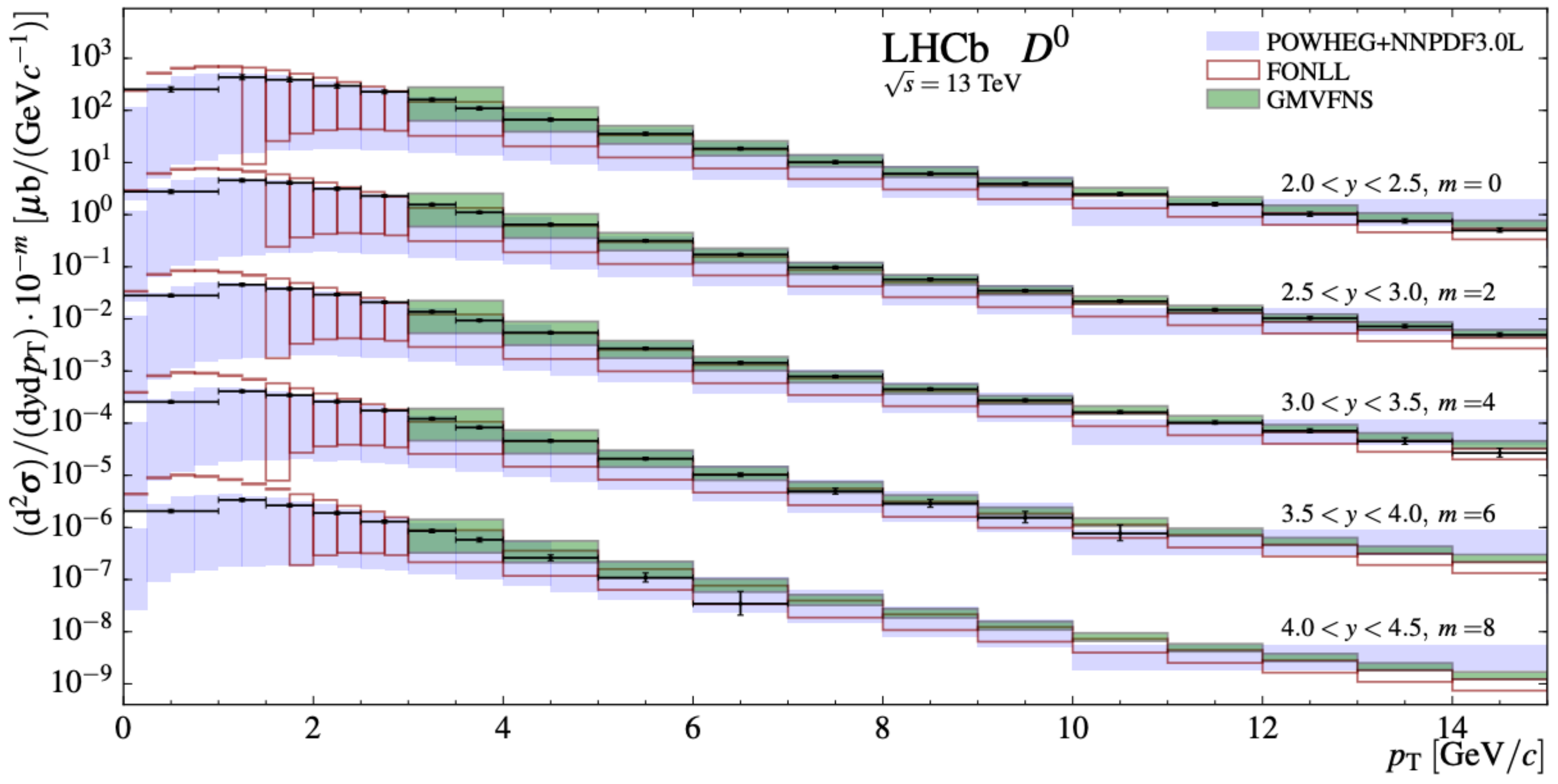
Open Heavy Flavours Fun Stats

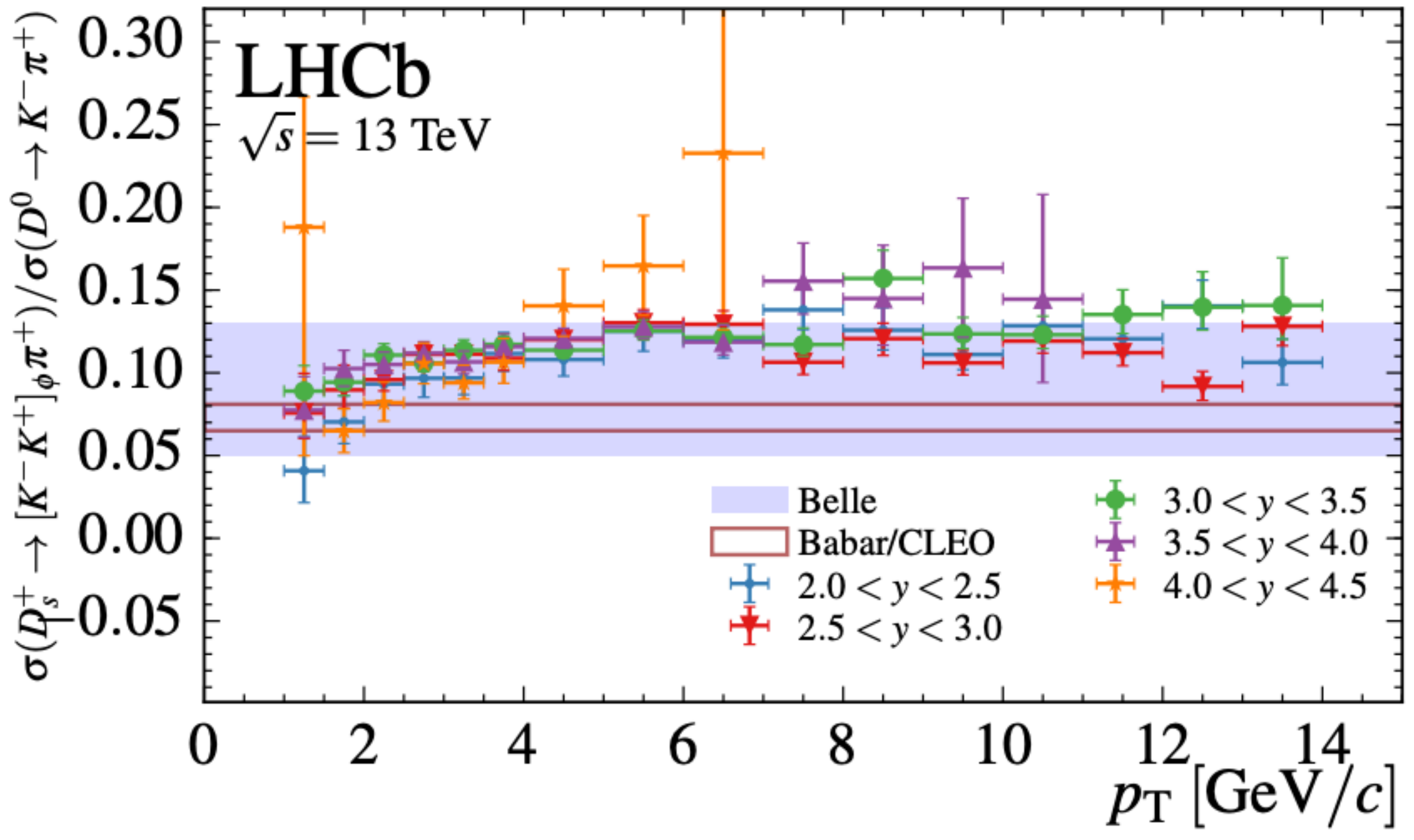
Big monster recently …



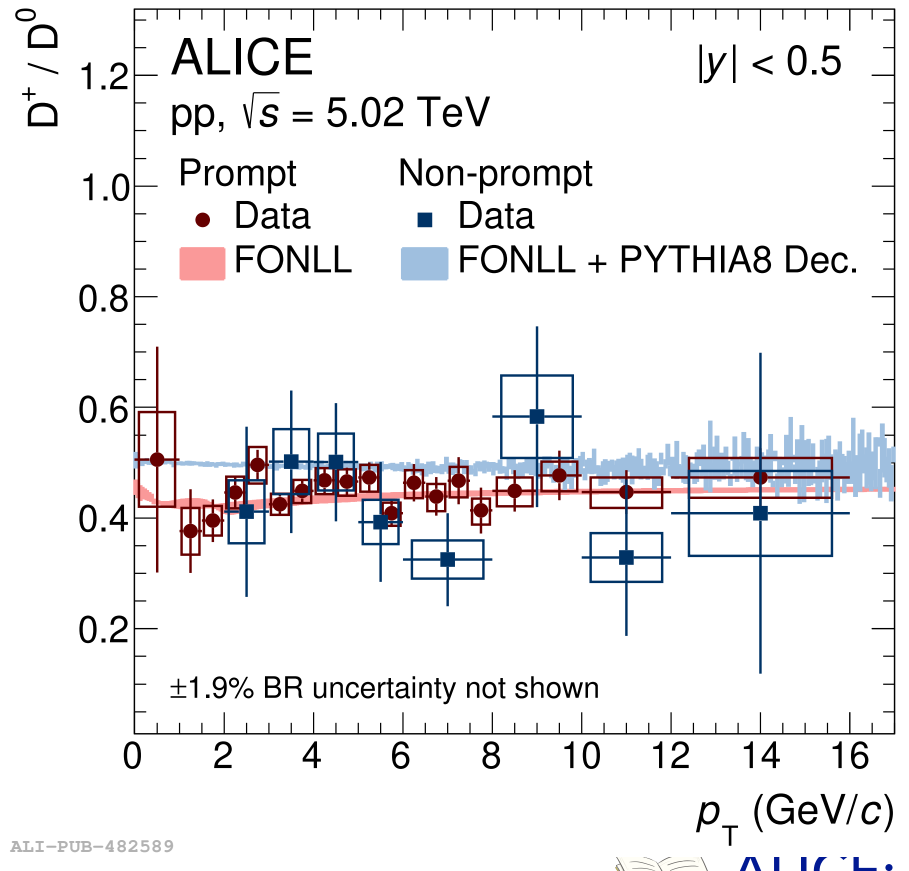
Factorisation: a very successful framework

LHCb: JHEP 03 (2016) 159, JHEP 09 (2016) 013 (erratum), JHEP 05 (2017) 074 (erratum)

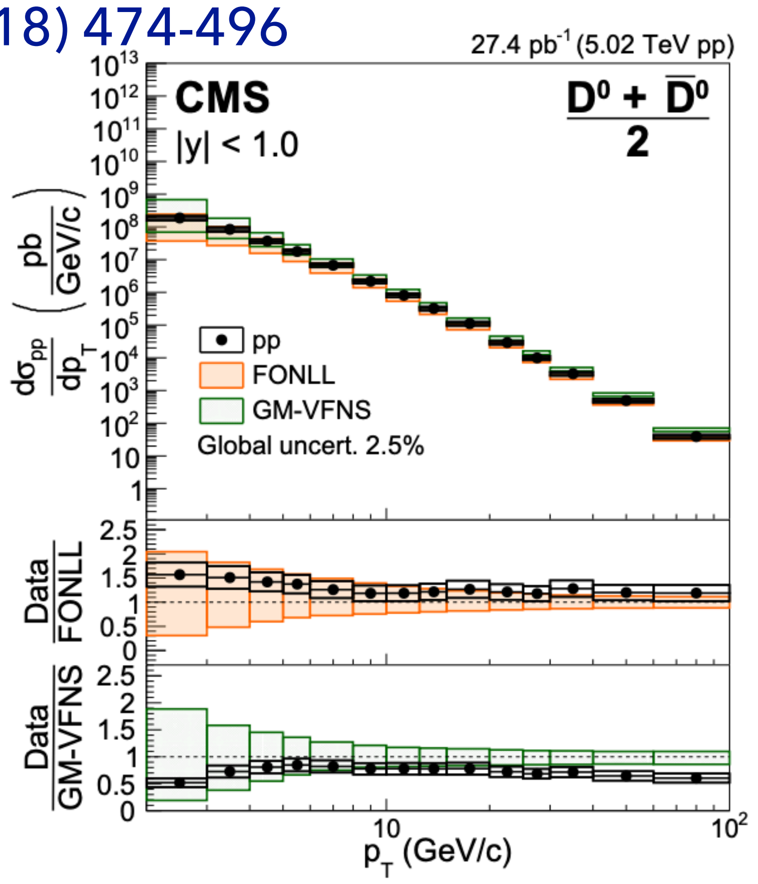


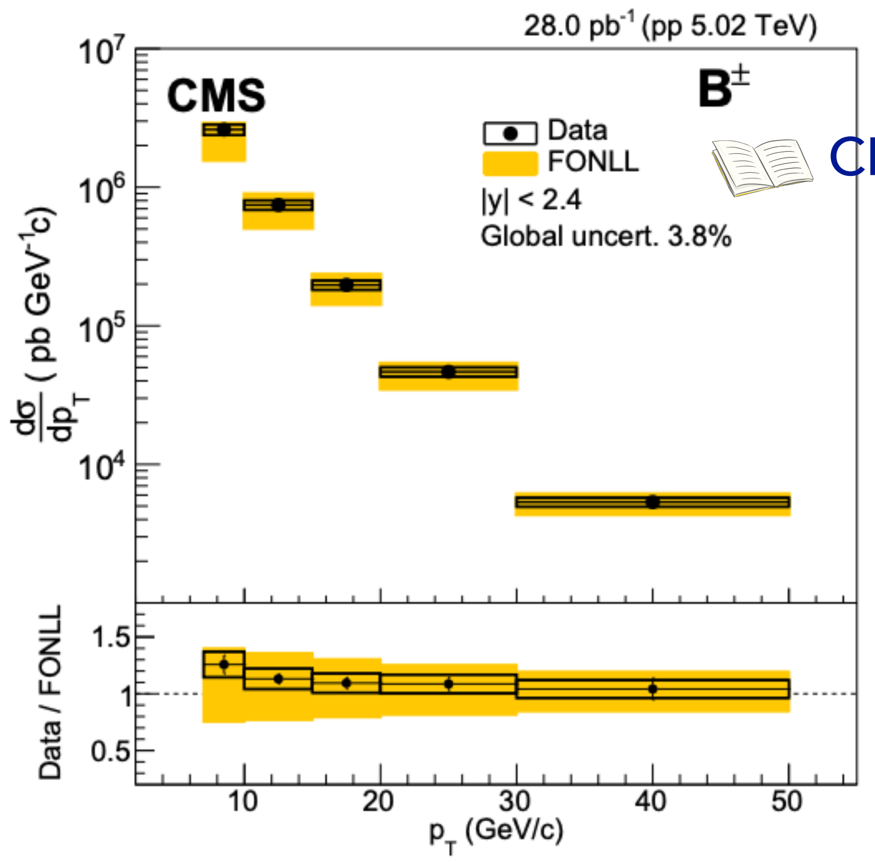


ALICE: JHEP 05 (2021) 220



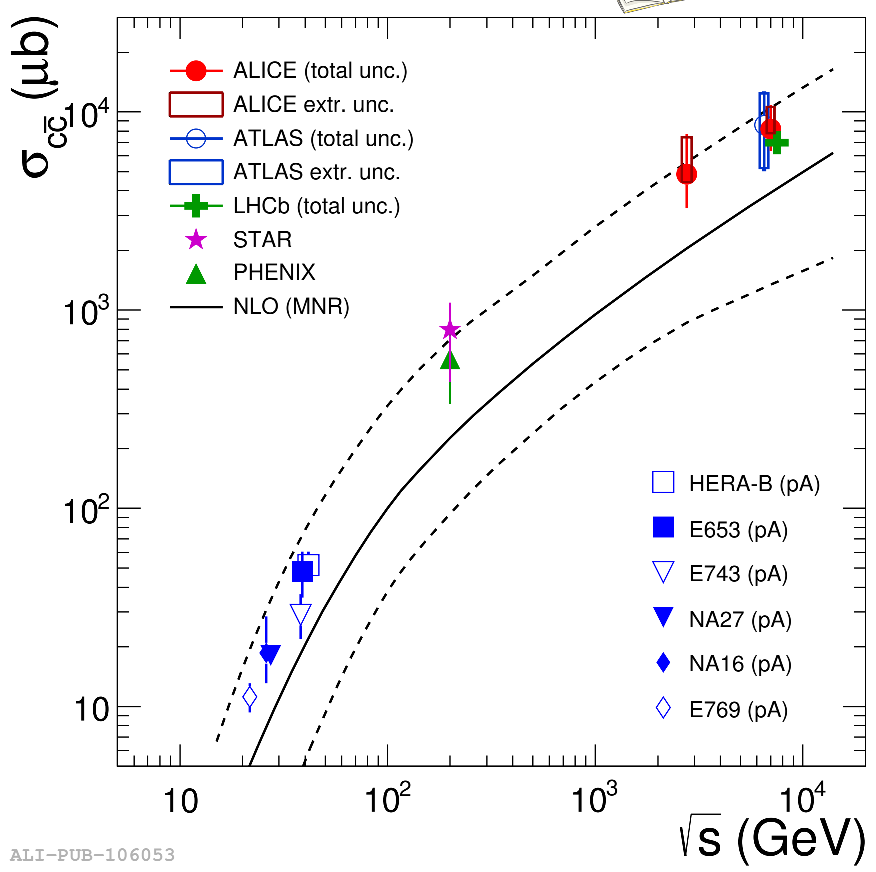
CMS: PLB 782 (2018) 474-496





CMS: PRL 119 (2017) 15, 152301

ALICE: PRC 94 (2016) 5, 054908



Only D mesons

- Plethora of data on open-charm and open-beauty **meson** production
  - vs. p_T and y (wide range)
  - in different collision energies
  - relative abundance of charm meson species

} ⟶ Described by pQCD calculations relying on factorisation

Charm-hadron reconstruction

Hadronic decays

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

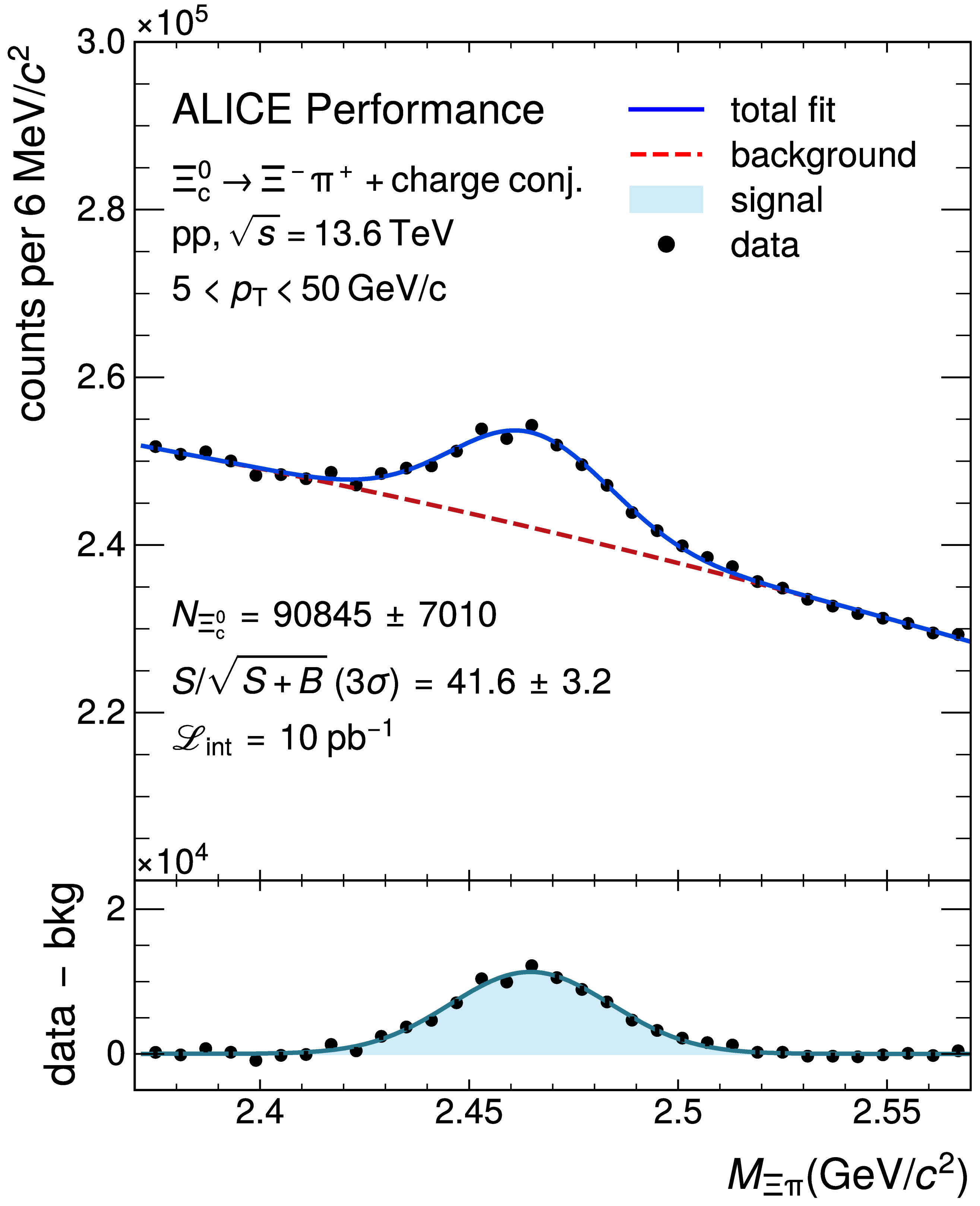
Semileptonic decays

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

Charge conjugates are included

Prompt

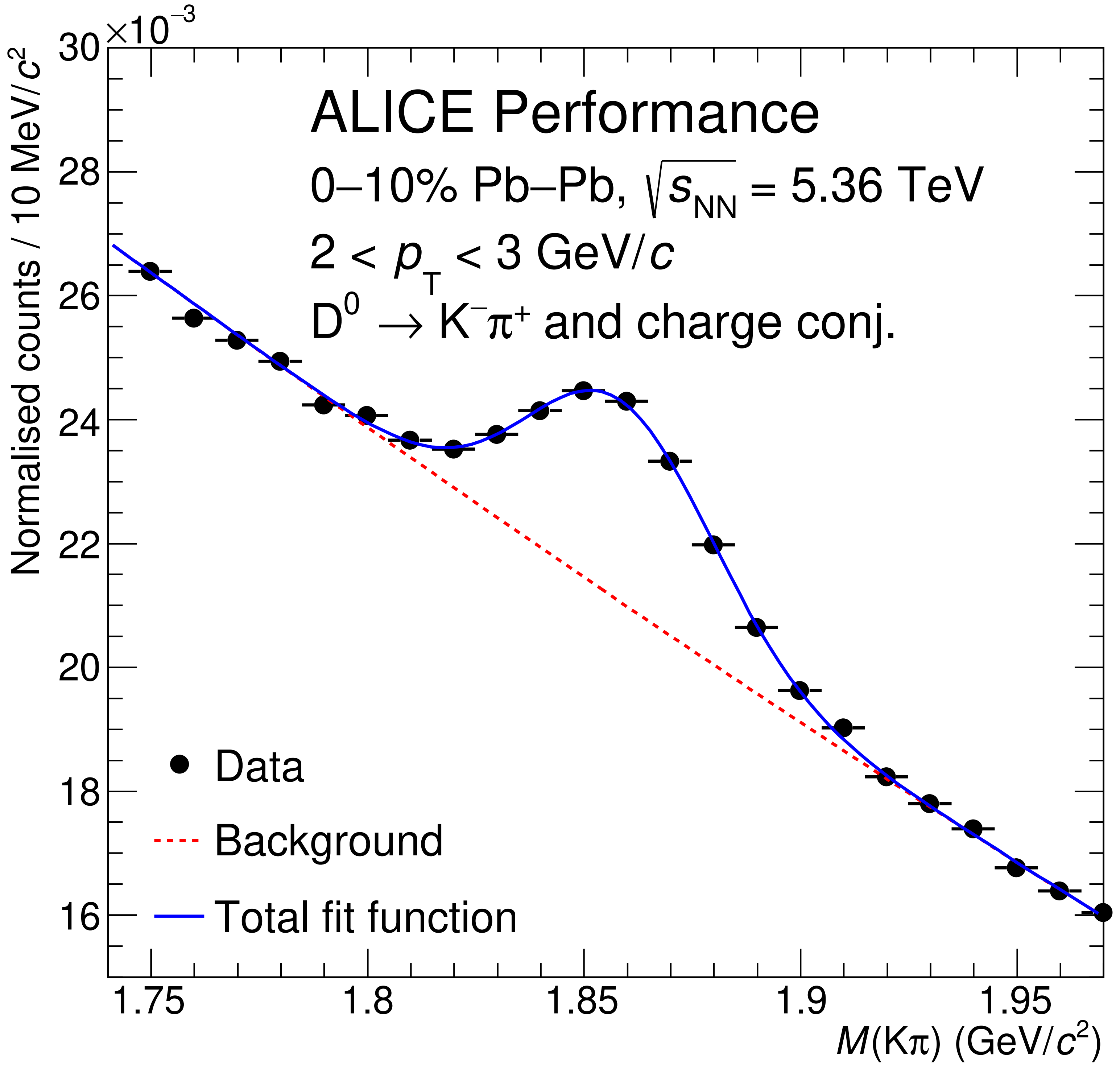
- $c \rightarrow$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$



ALI-PERF-578571

Non-Prompt

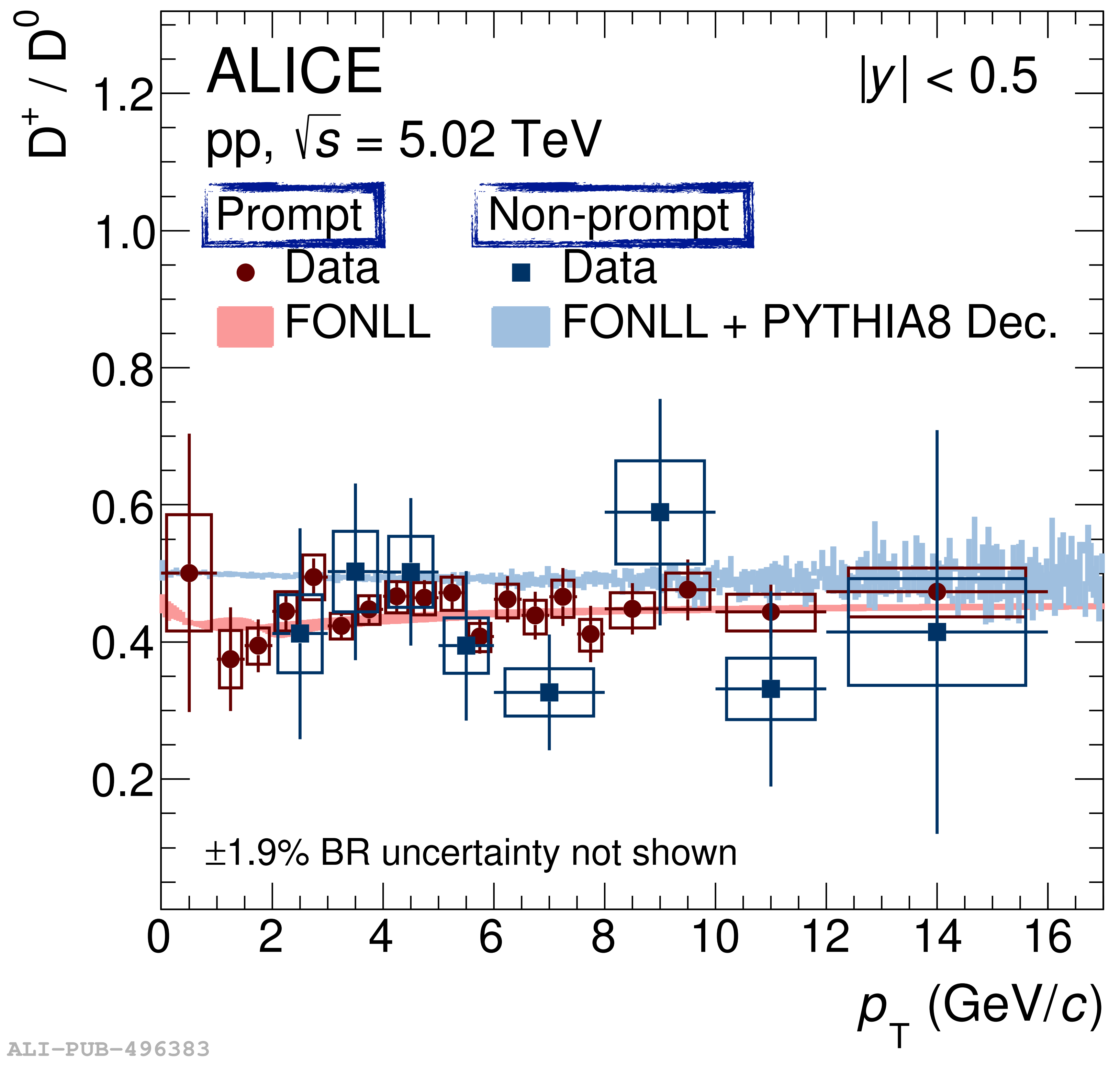
- $b \rightarrow c \rightarrow$ charm hadrons $(D^0, \Lambda_c^+, \ldots)$



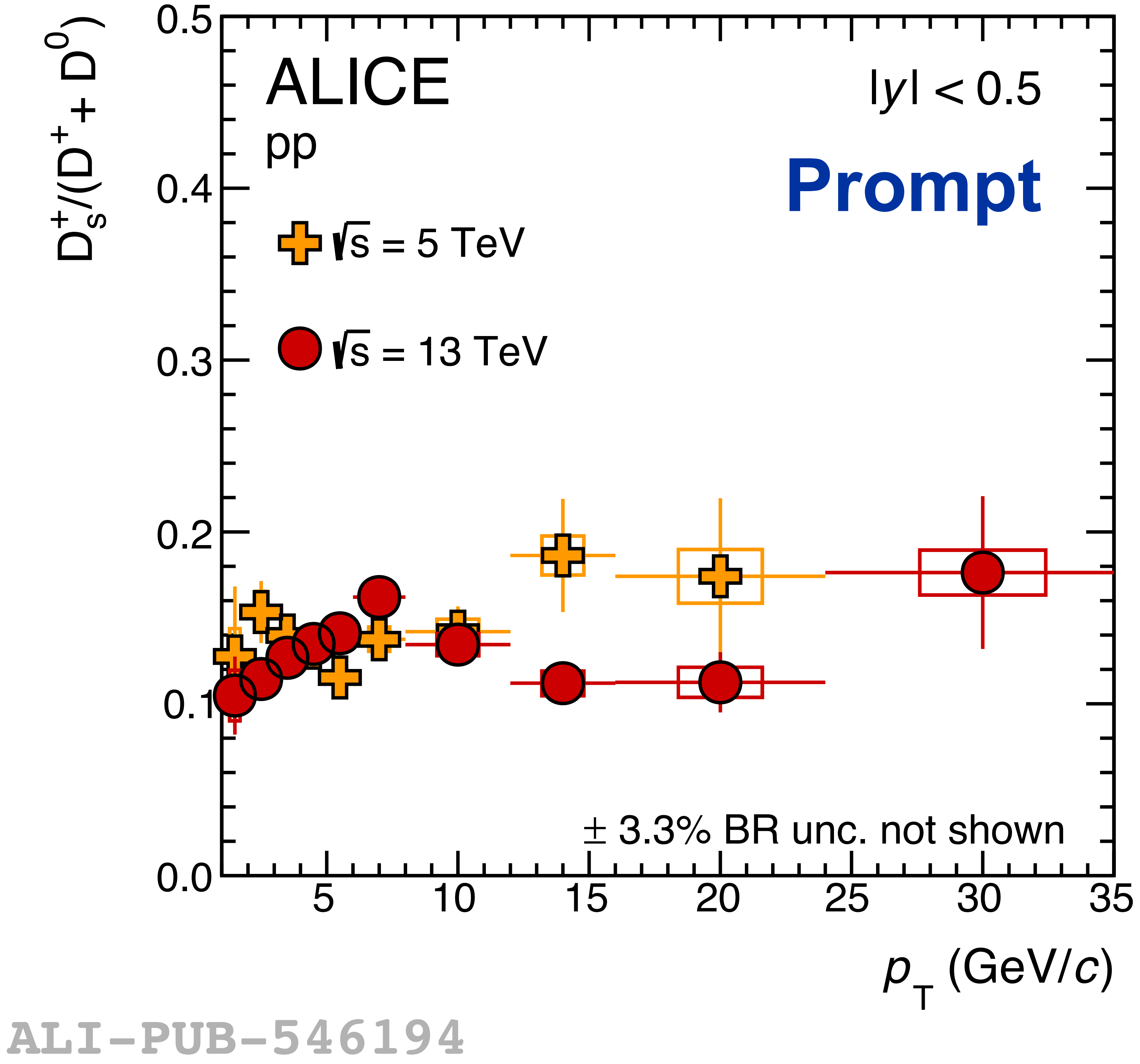
ALI-PERF-568645

D-meson production in pp collisions (Run 2)

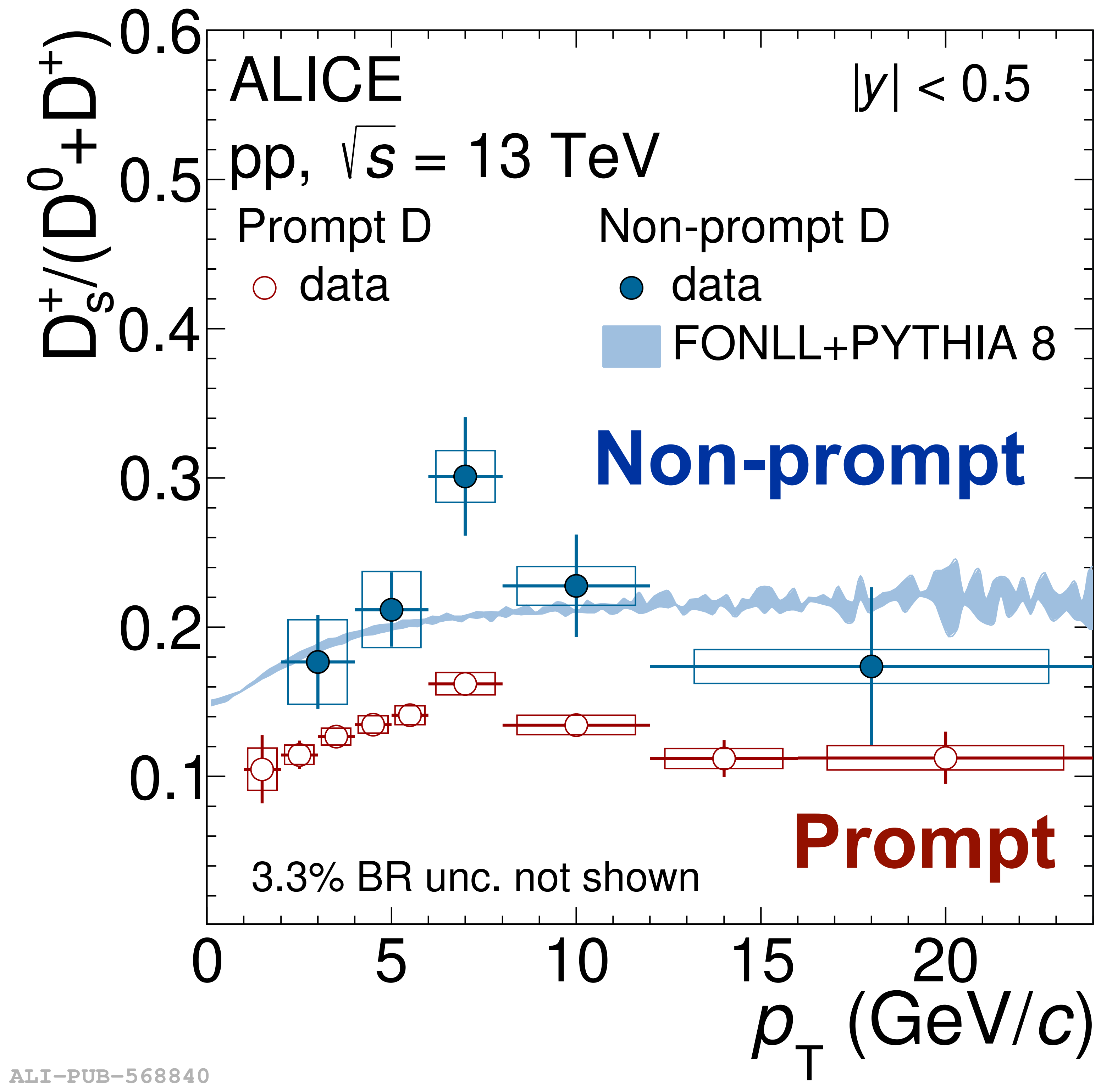
JHEP 05 (2021) 220



JHEP 12 (2023) 086



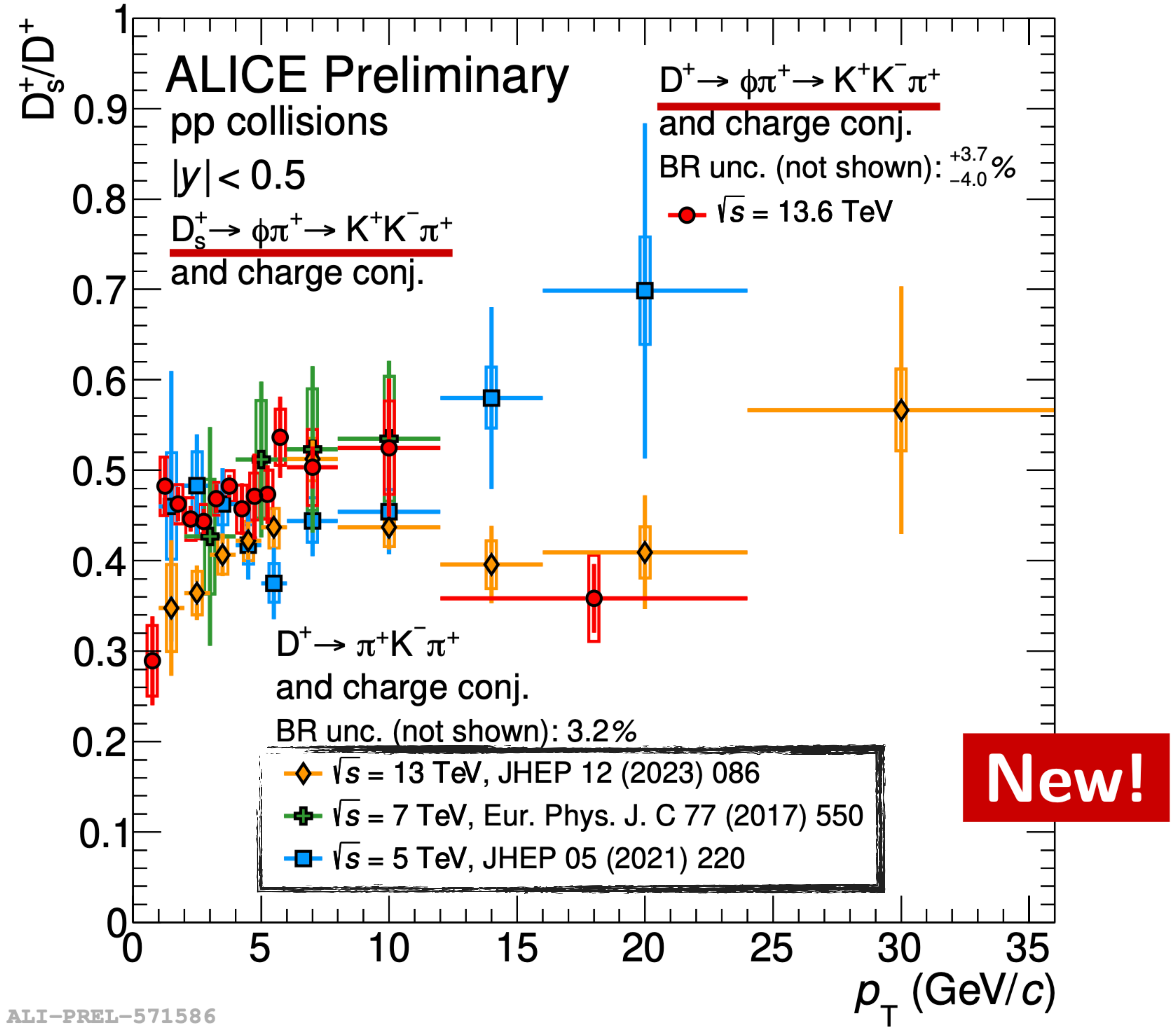
arXiv:2402.16417

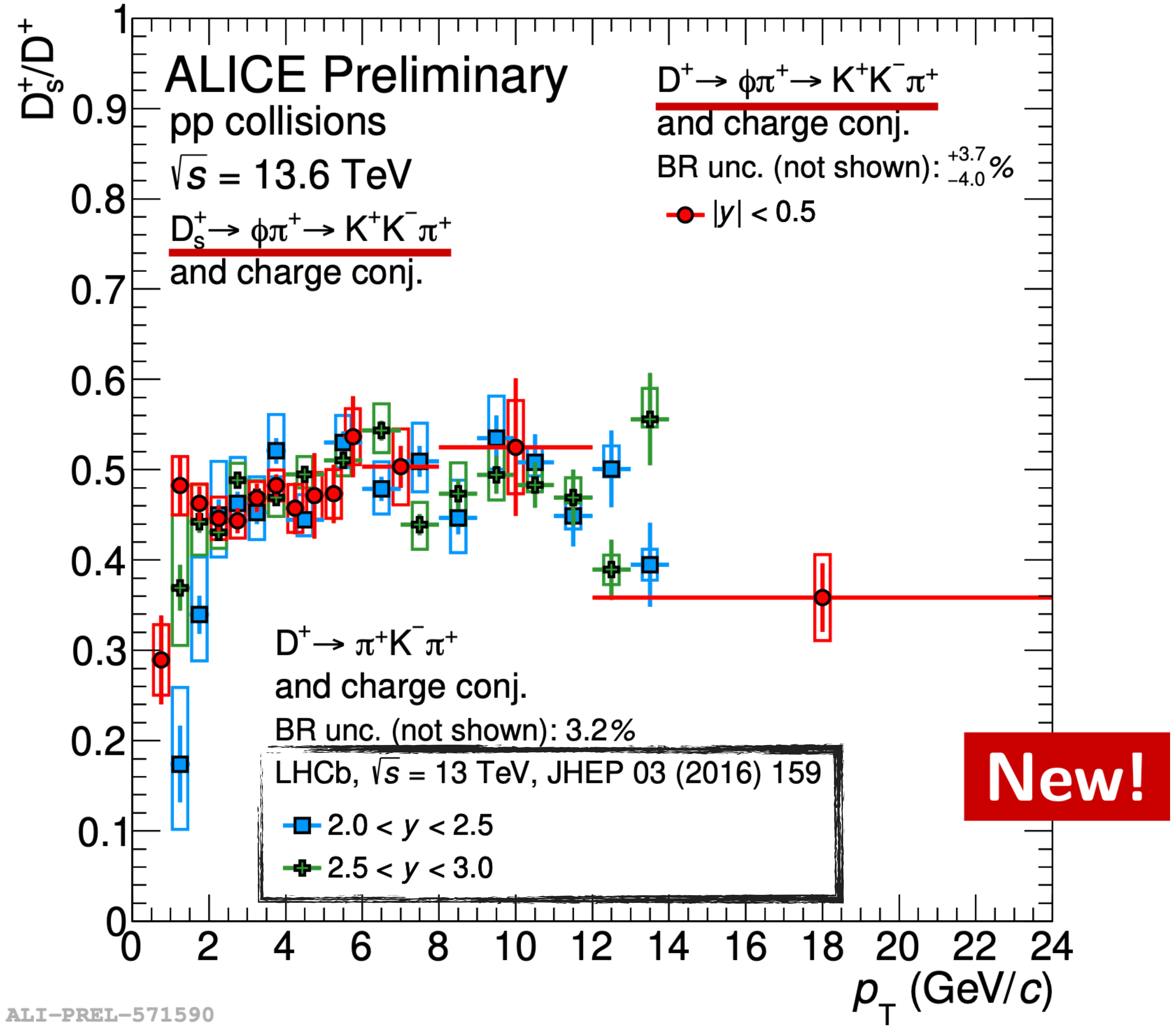


FONLL: *JHEP 05 (1998) 007* $f(c \rightarrow H_c)$: *Eur.Phys.J.C 75 (2015) 19*

- No strong p_T and collision energy dependence in prompt and non-prompt charm meson-to-meson yield ratios
- Well described by model calculations, based on factorization assuming FFs from e^+e^- collisions

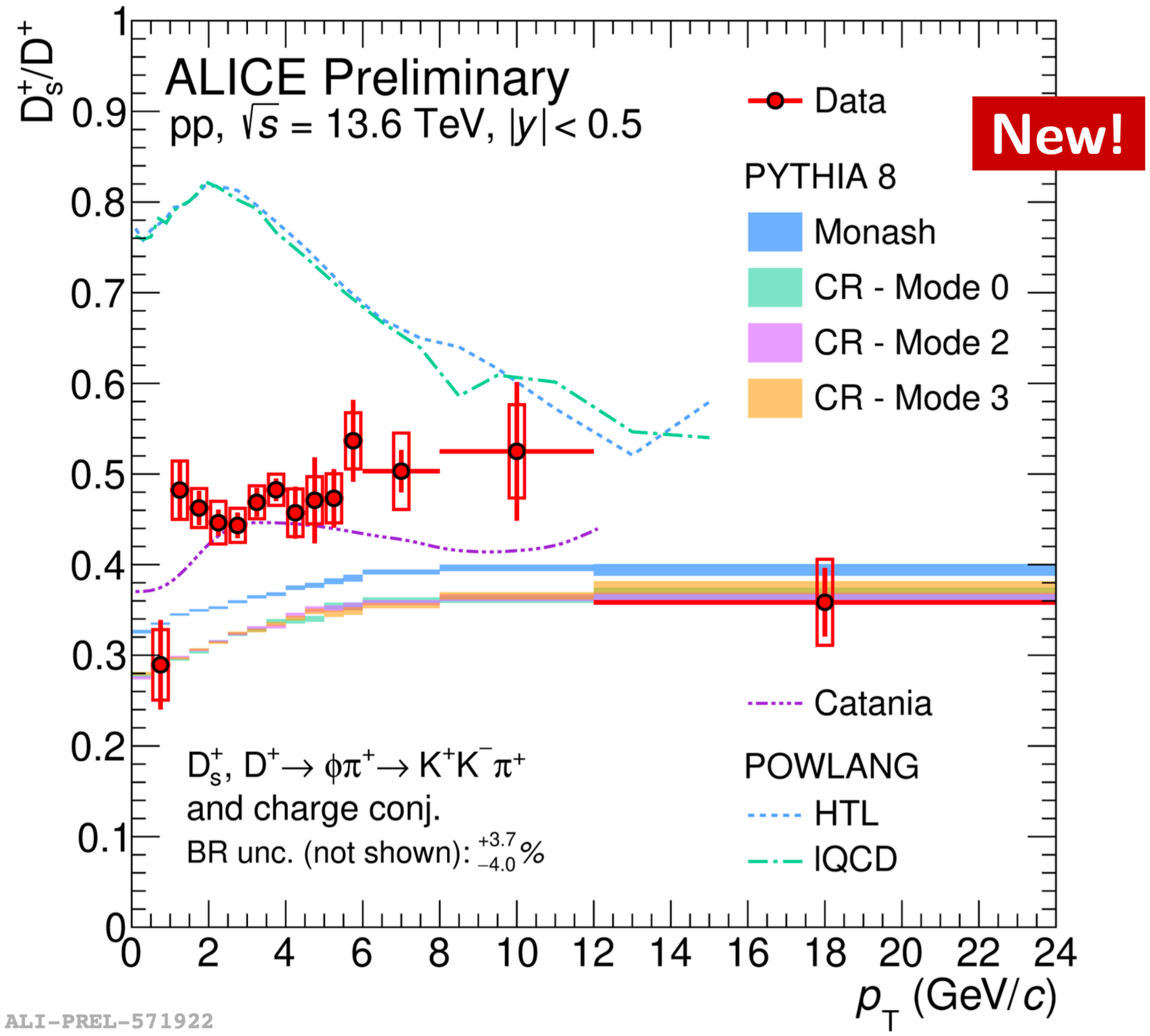
D-meson production in pp collisions (Run 3)





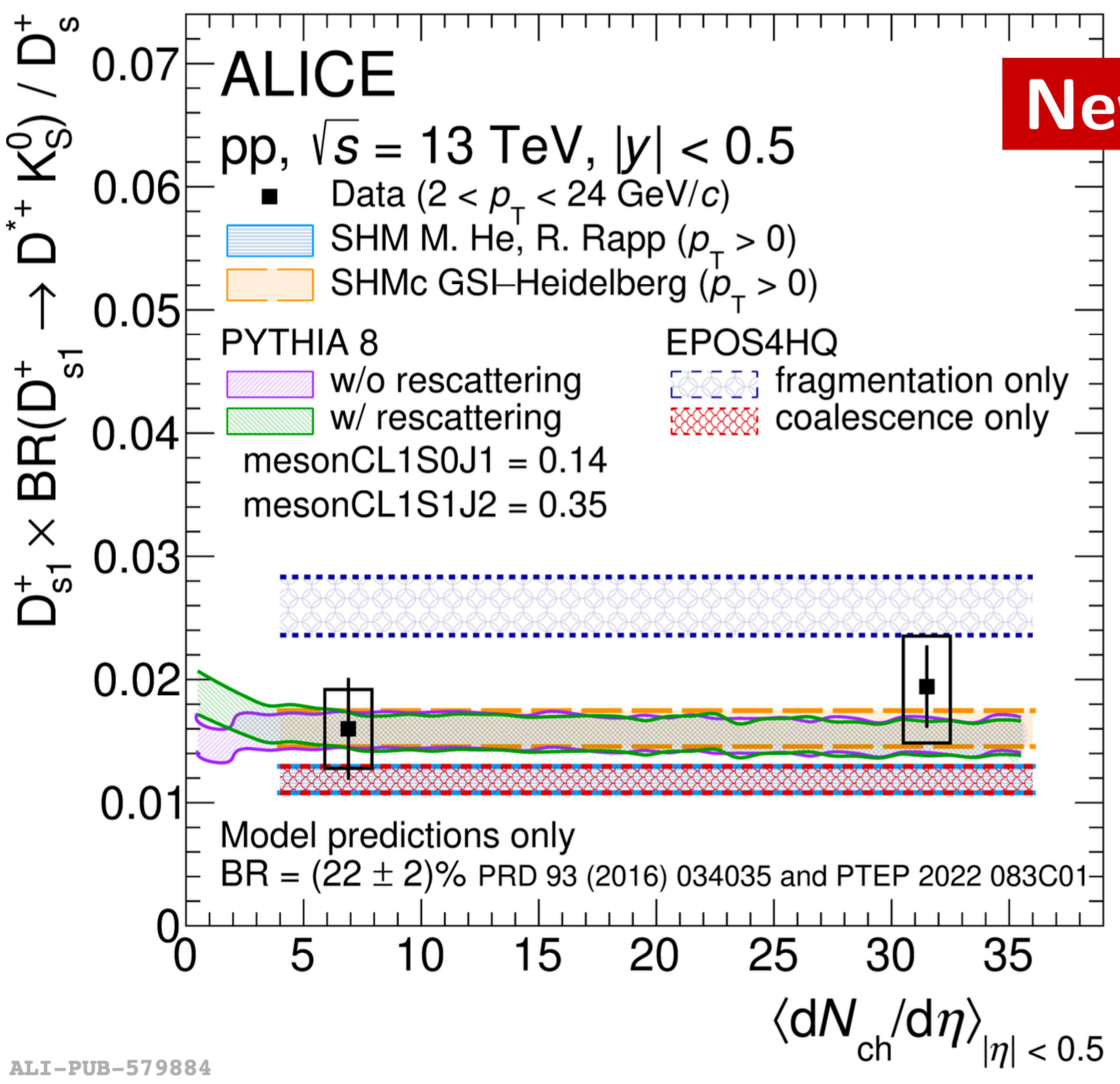
- Improved granularity and p_T reach w.r.t. Run 2 results
- No significant energy and rapidity dependence observed

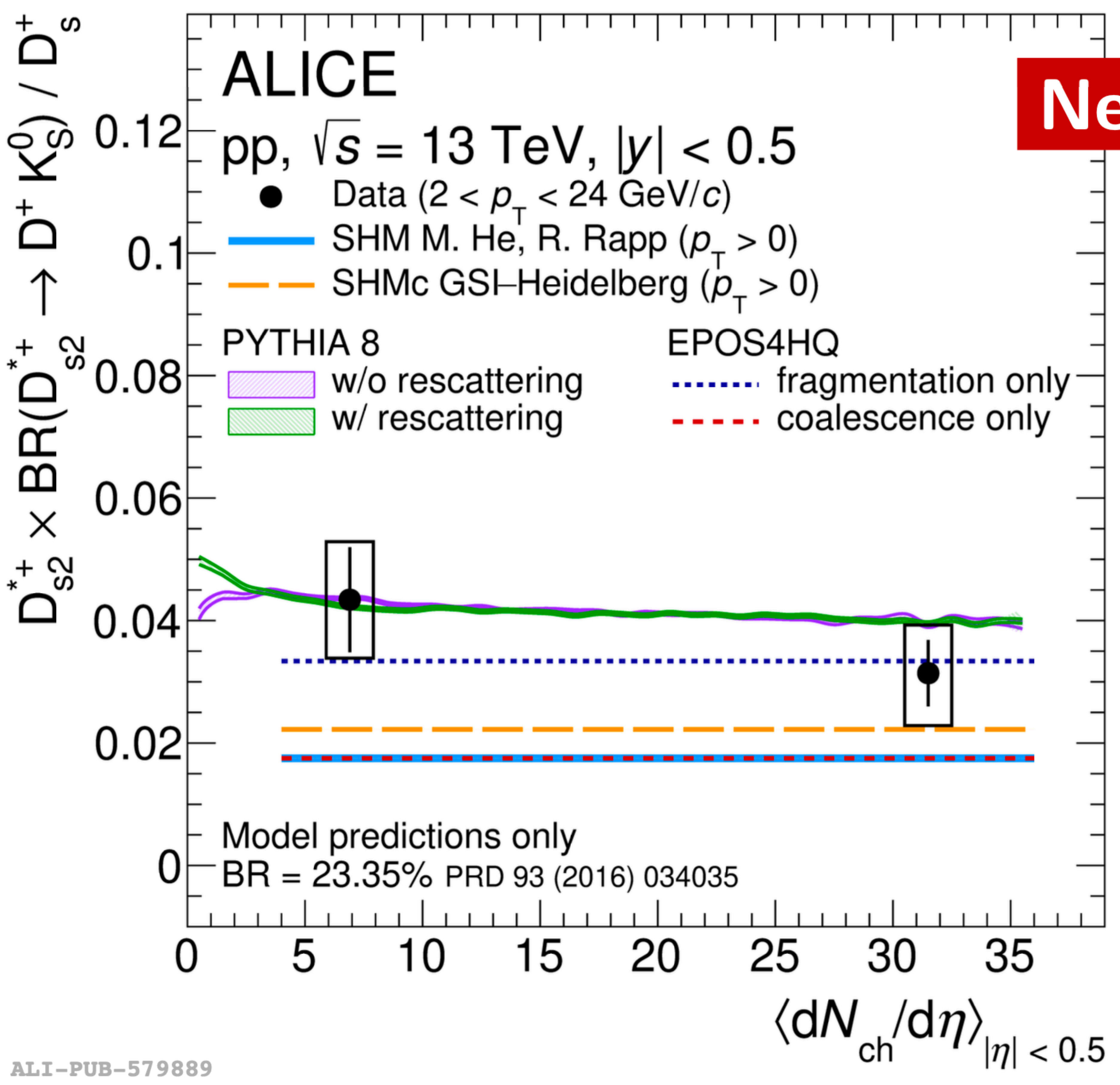
Prompt D_s^+/D^+ in pp collisions (Run 3)



- PYTHIA 8
  - Monash: colour reconnection among multiparton interactions only with leading-colour topology
  - CR Modes: string formation beyond leading-colour approximation, resulting in baryon enhancement
- Catania and POWLANG
  - hadronization via coalescence and fragmentation processes in a thiermalised QGP-like system
- Catania qualitatively describes D_s^+/D^+
  - PYTHIA 8 and POWLANG underestimate or overestimate the measurement

Strange D-meson resonances in pp collisions (Run 2)

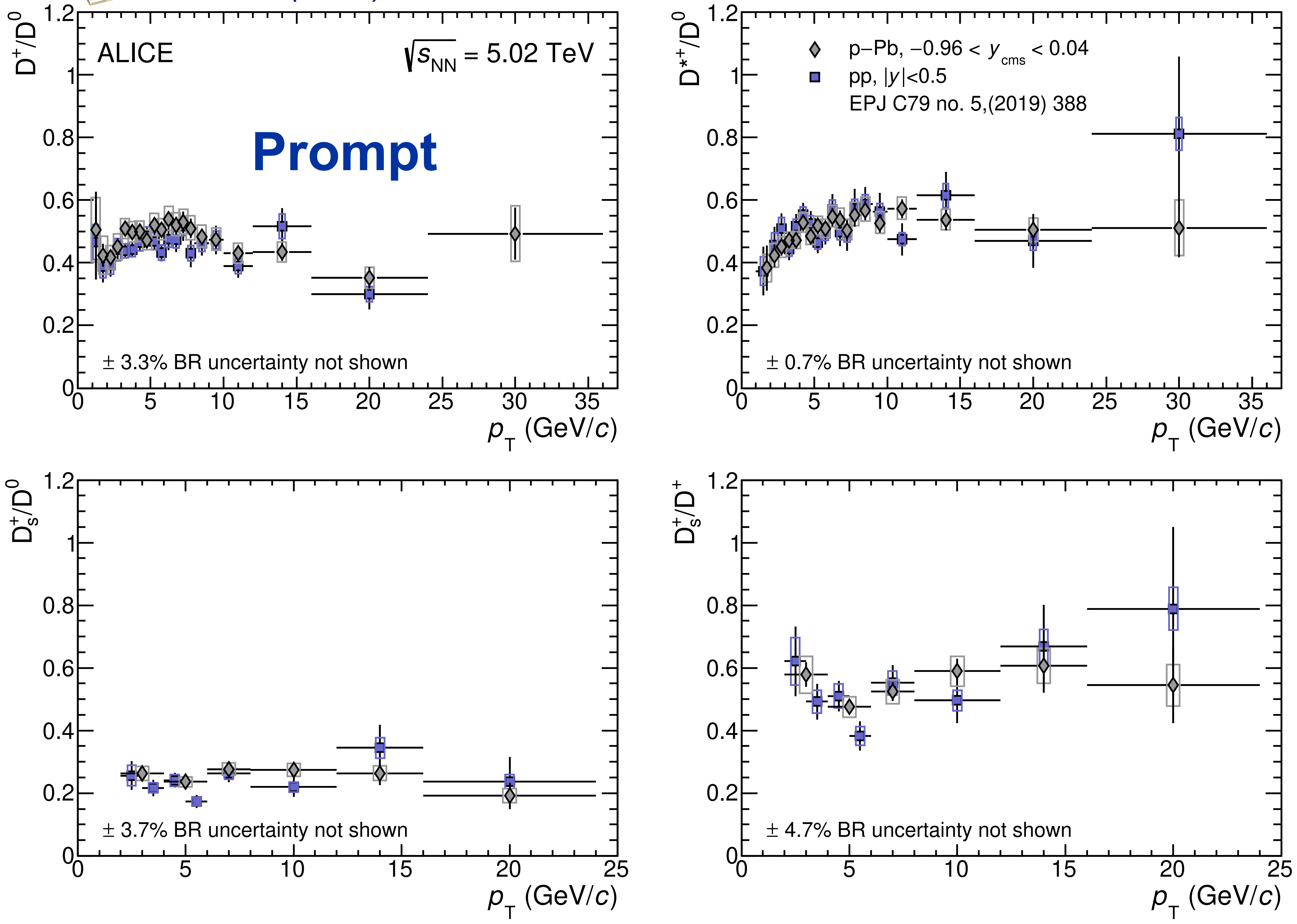




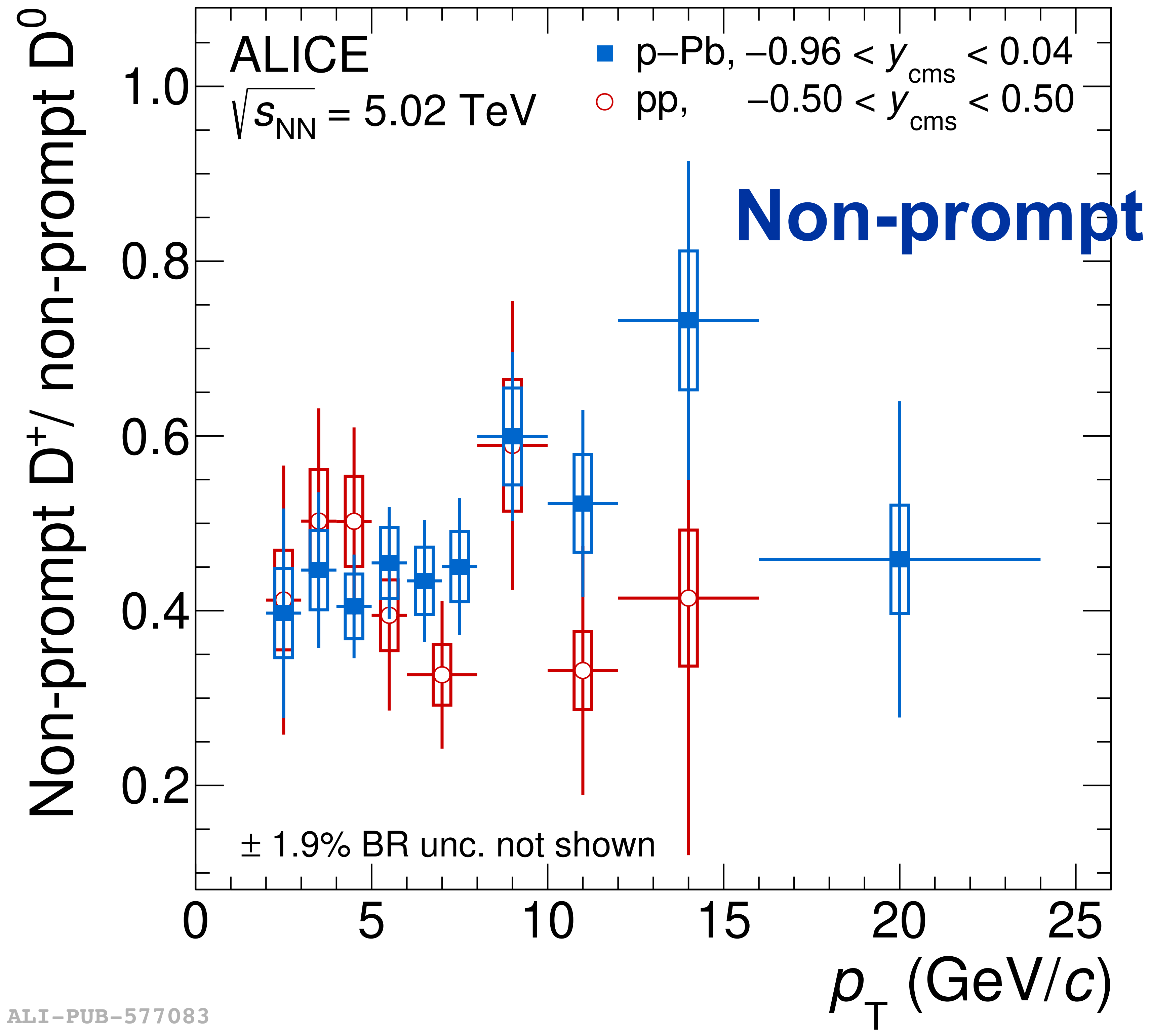
- D^+_{s1}/D^+_s and D^{*+}_{s2}/D^+_s ratios flat vs. charged-particle multiplicity, as ground-state D-meson ratios
- Multiplicity trend described by SHM, SHMc, EPOS4HQ models and by PYTHIA 8 calculations

D-meson production in p–Pb collisions

JHEP 12 (2019) 092



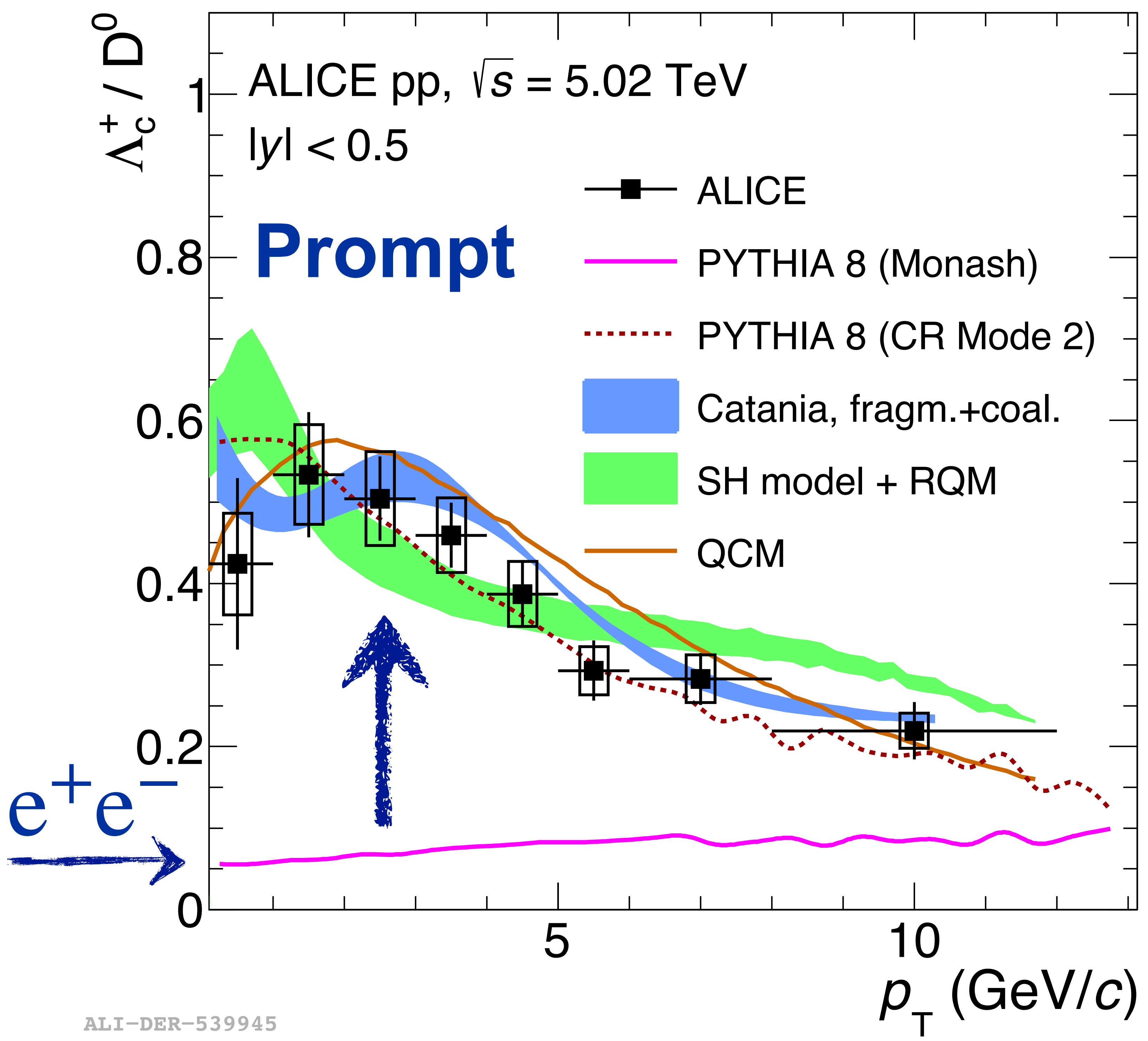
arXiv:2407.10593



- (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

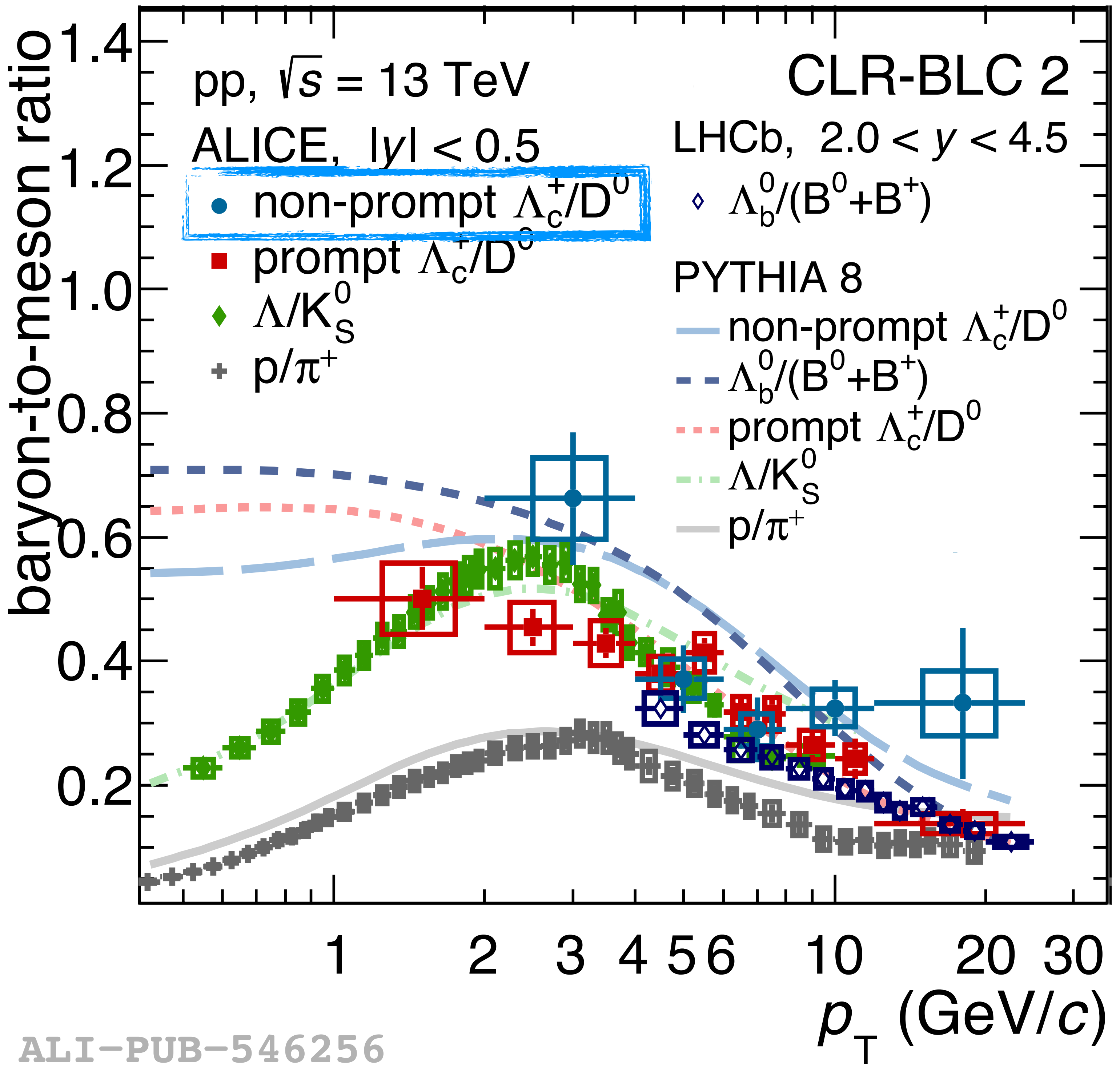
Λ_c^+(udc) in pp collisions

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



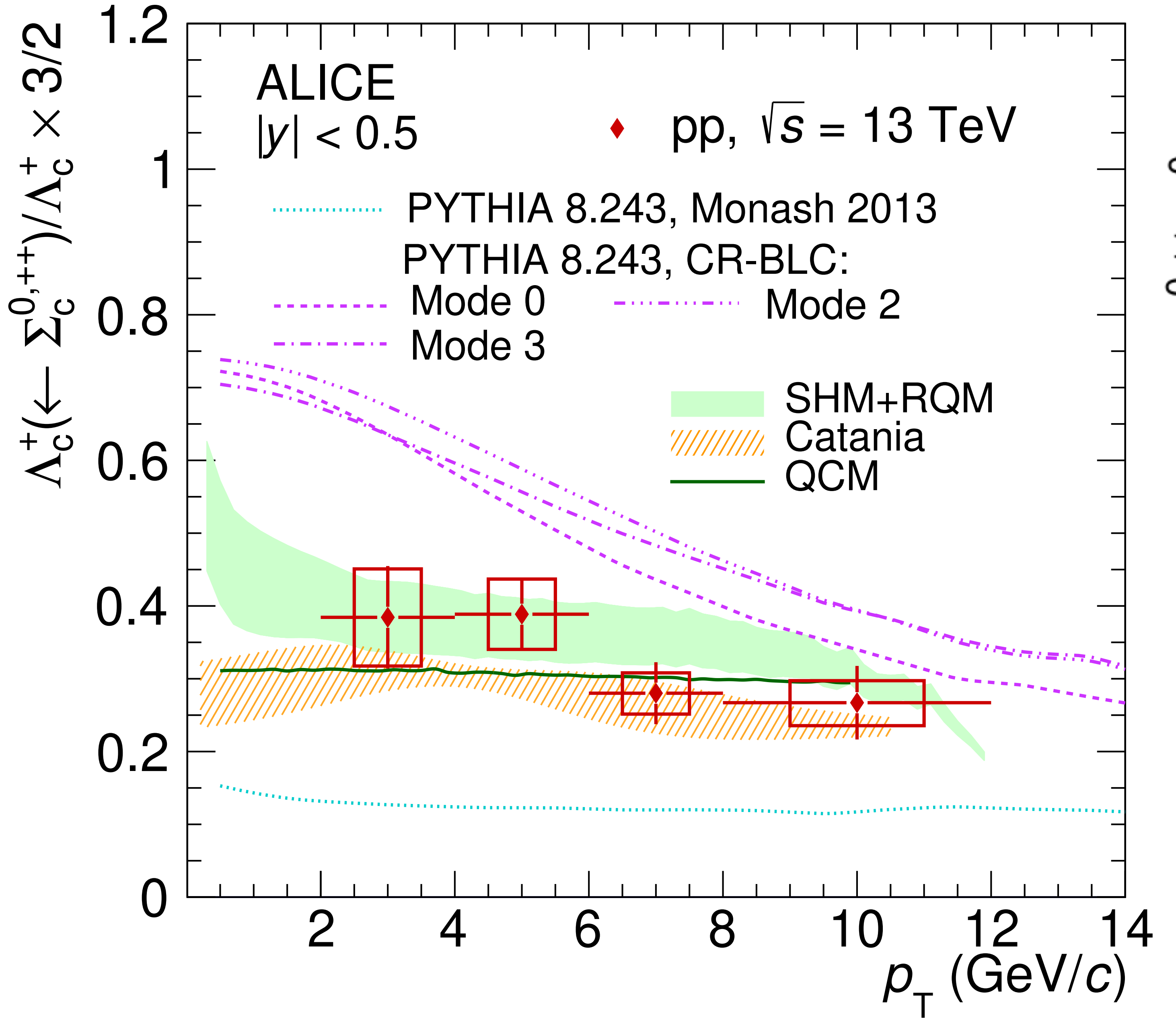
Prompt Λ_c^+/D^0 in pp collisions

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

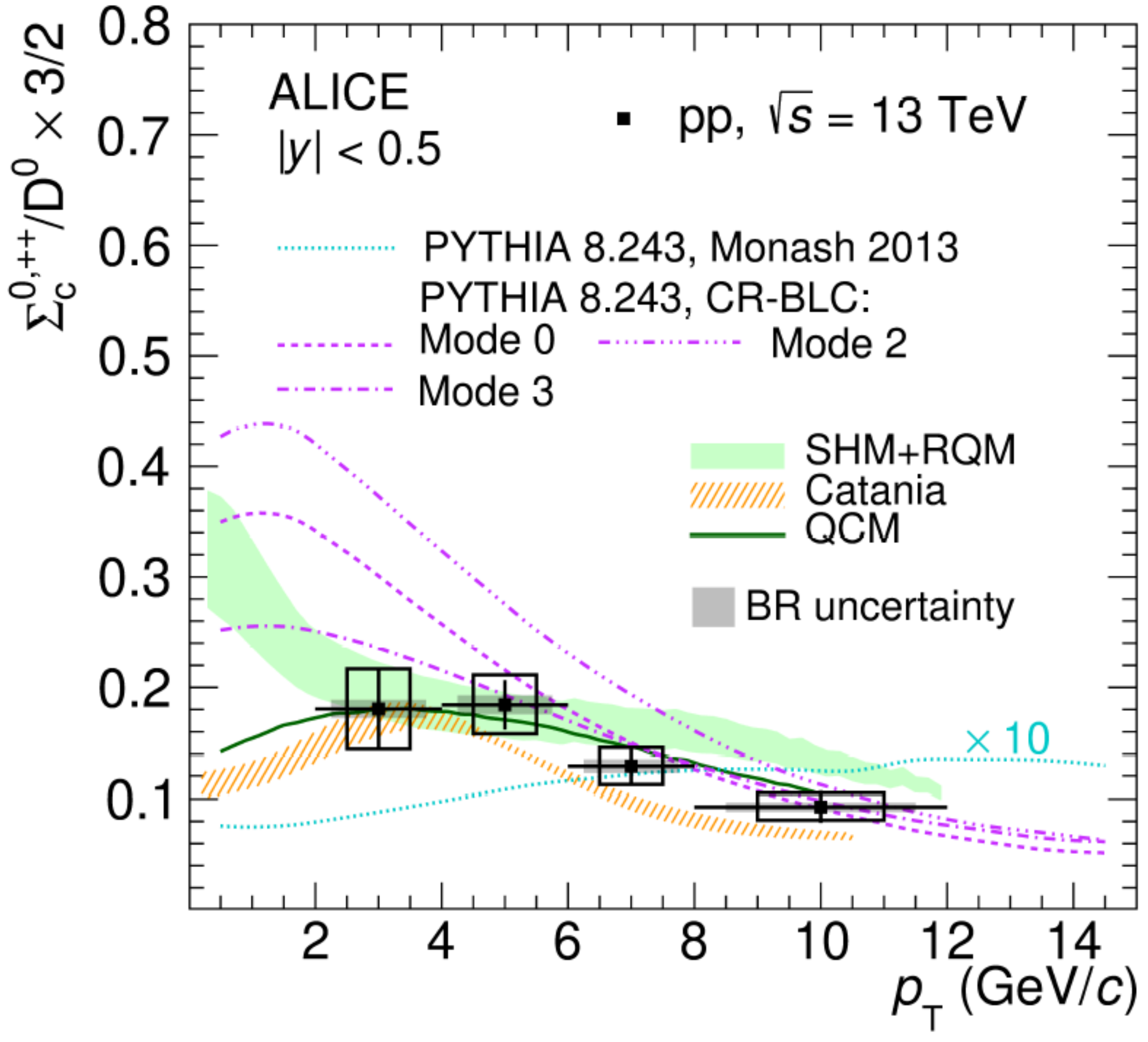
Non-prompt Λ_c^+/D^0 in pp collisions

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

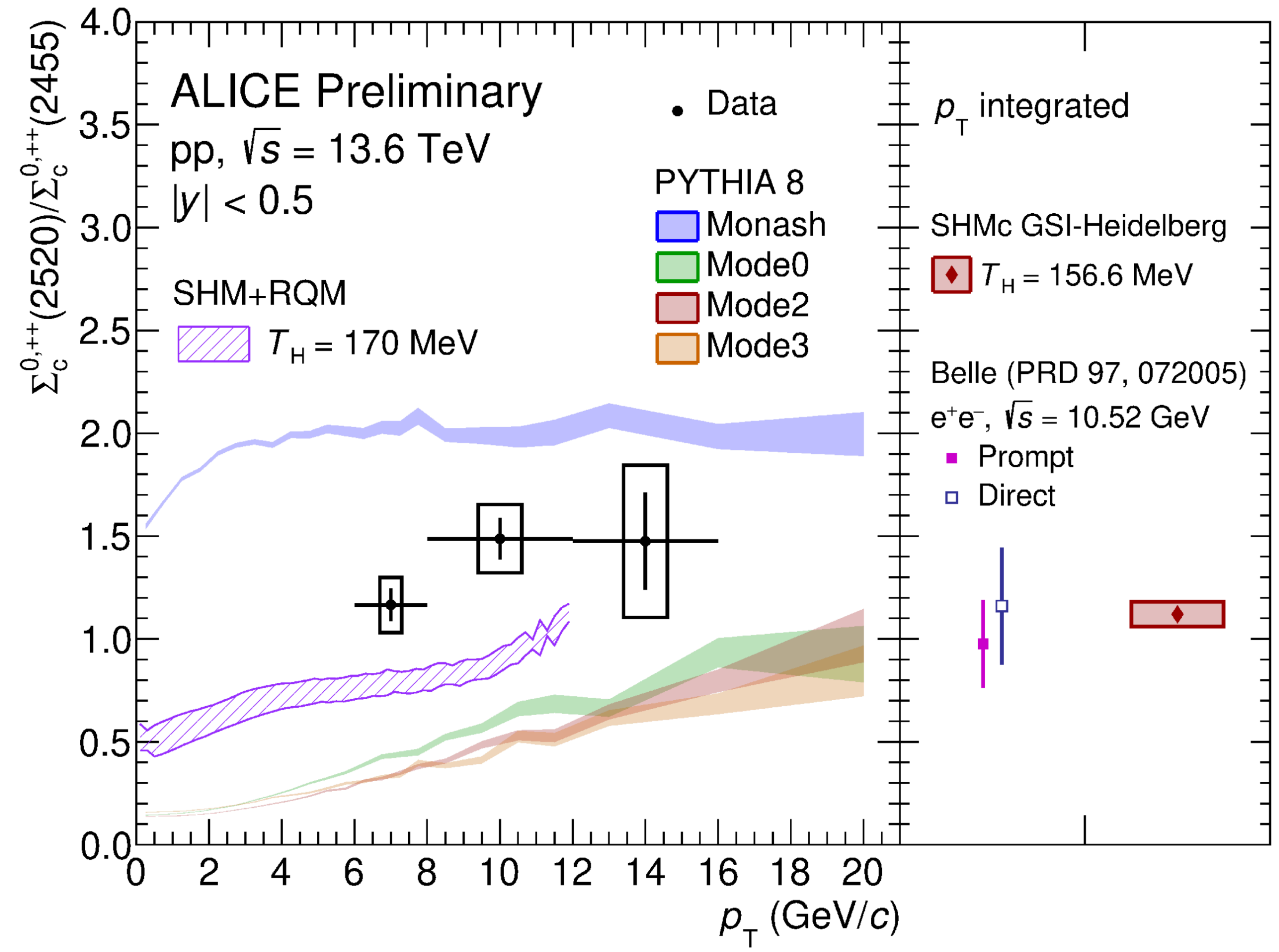
$\Sigma_c^{0,+,++}$ in pp collisions



ALI-DER-493906



ALI-DER-493901



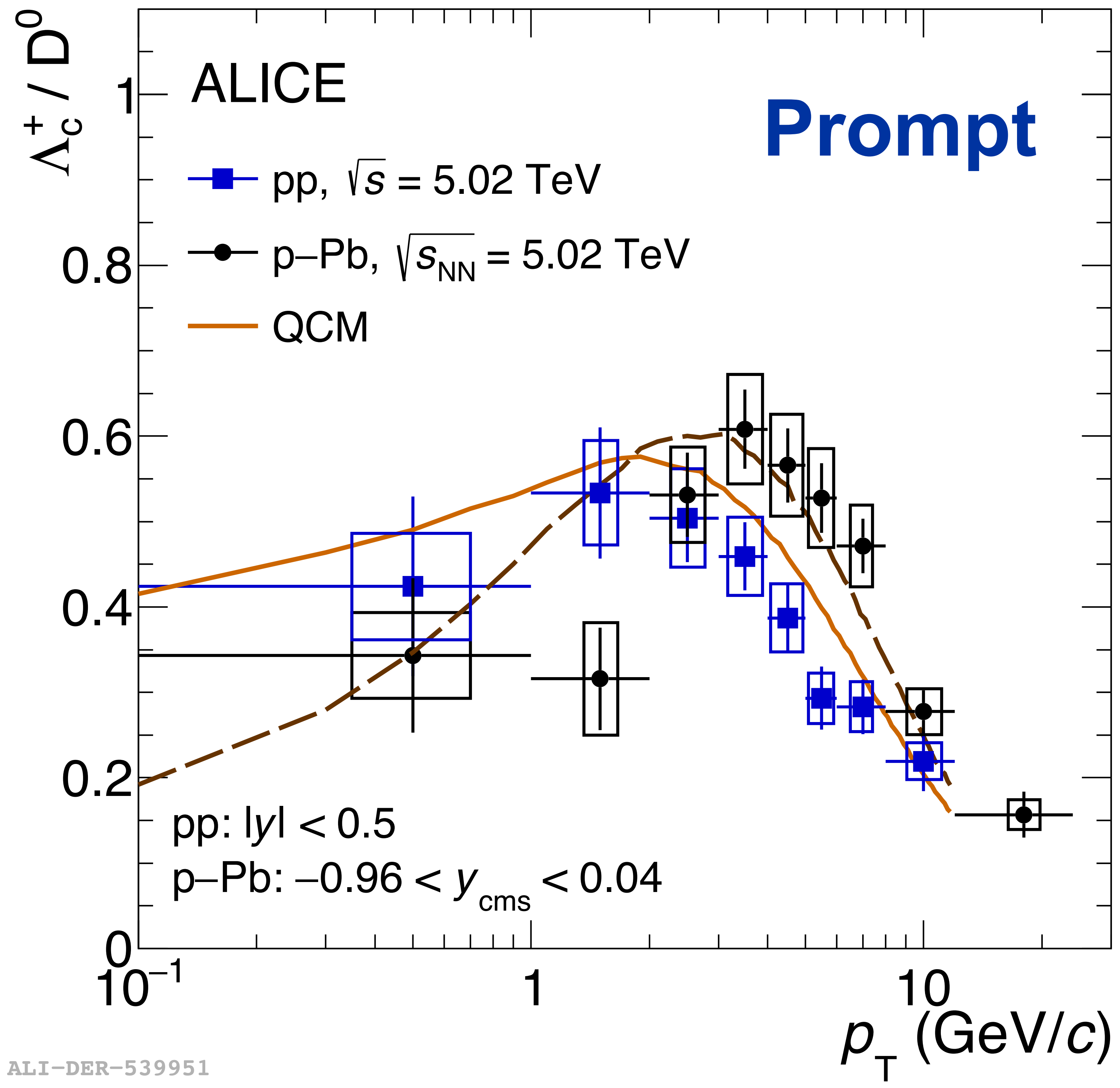
ALI-PREL-574270

- ~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

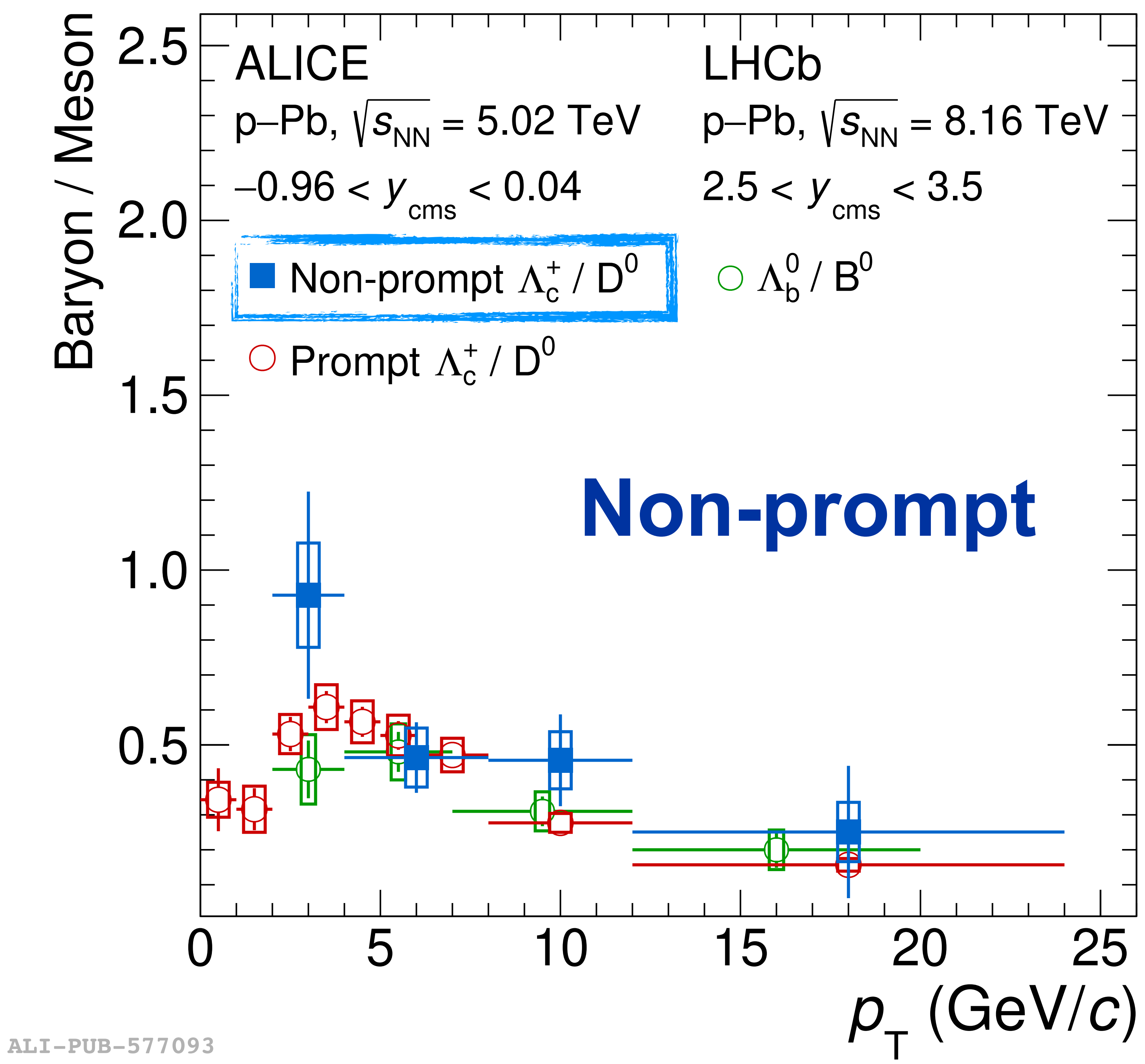
- Ratios between the two $\Sigma_c^{0,++}$ states consistent with pT integrated result from e+e- collisions within uncertainties
- Overestimated by PYTHIA 8 Monash, underestimated by CR and SHM+RQM

Λ_c^+(udc) in p–Pb collisions

Phys.Rev.C 107 (2023) 064901



arXiv:2407.10593



Prompt Λ_c^+/D^0 in p–Pb collisions

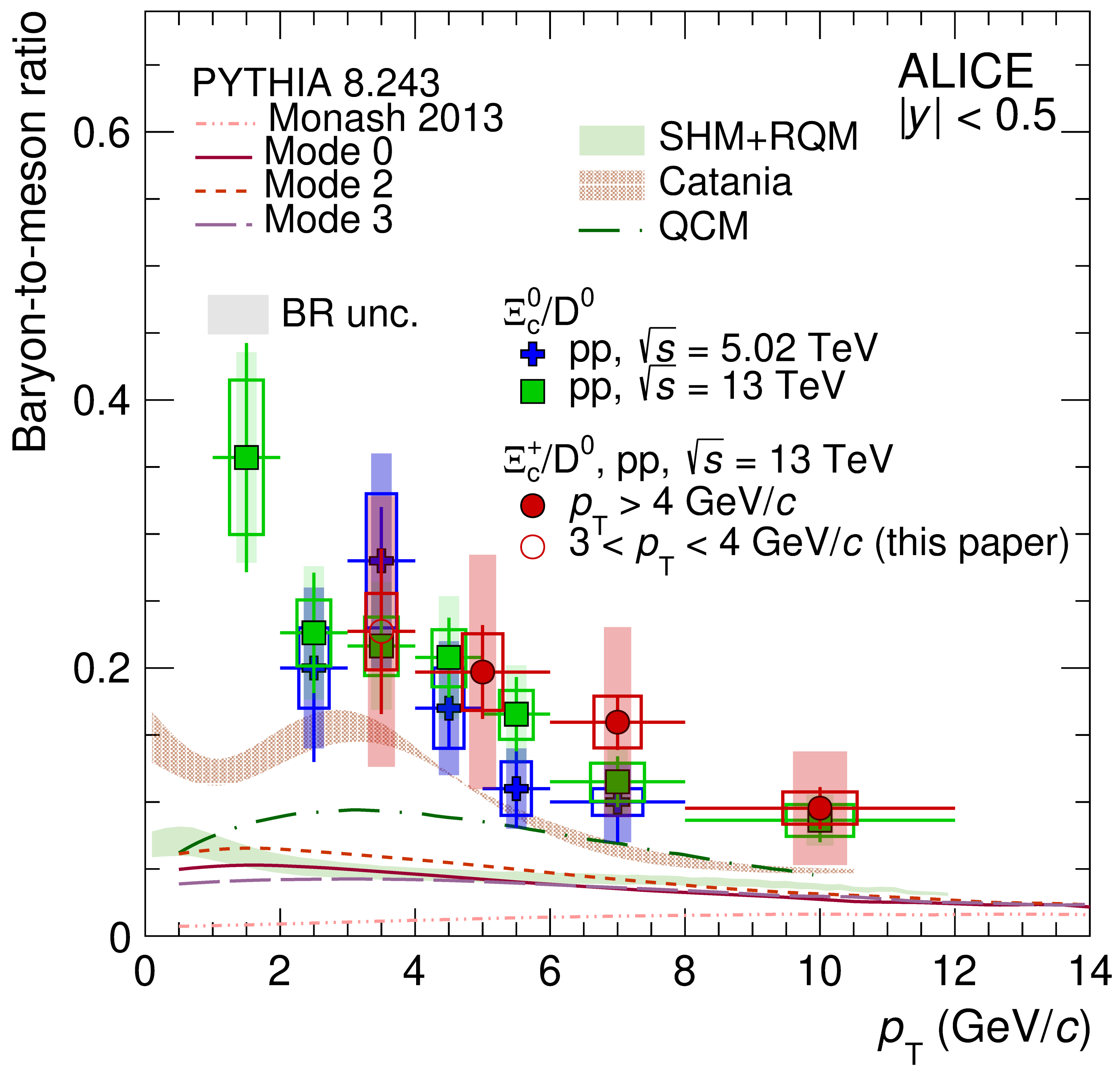
- First measurement down to $p_T = 0$
- Shift of peak towards higher p_T could be due to quark recombination or collective effects (e.g. radial flow)
- Well described by quark (re)combination model (QCM)

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

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

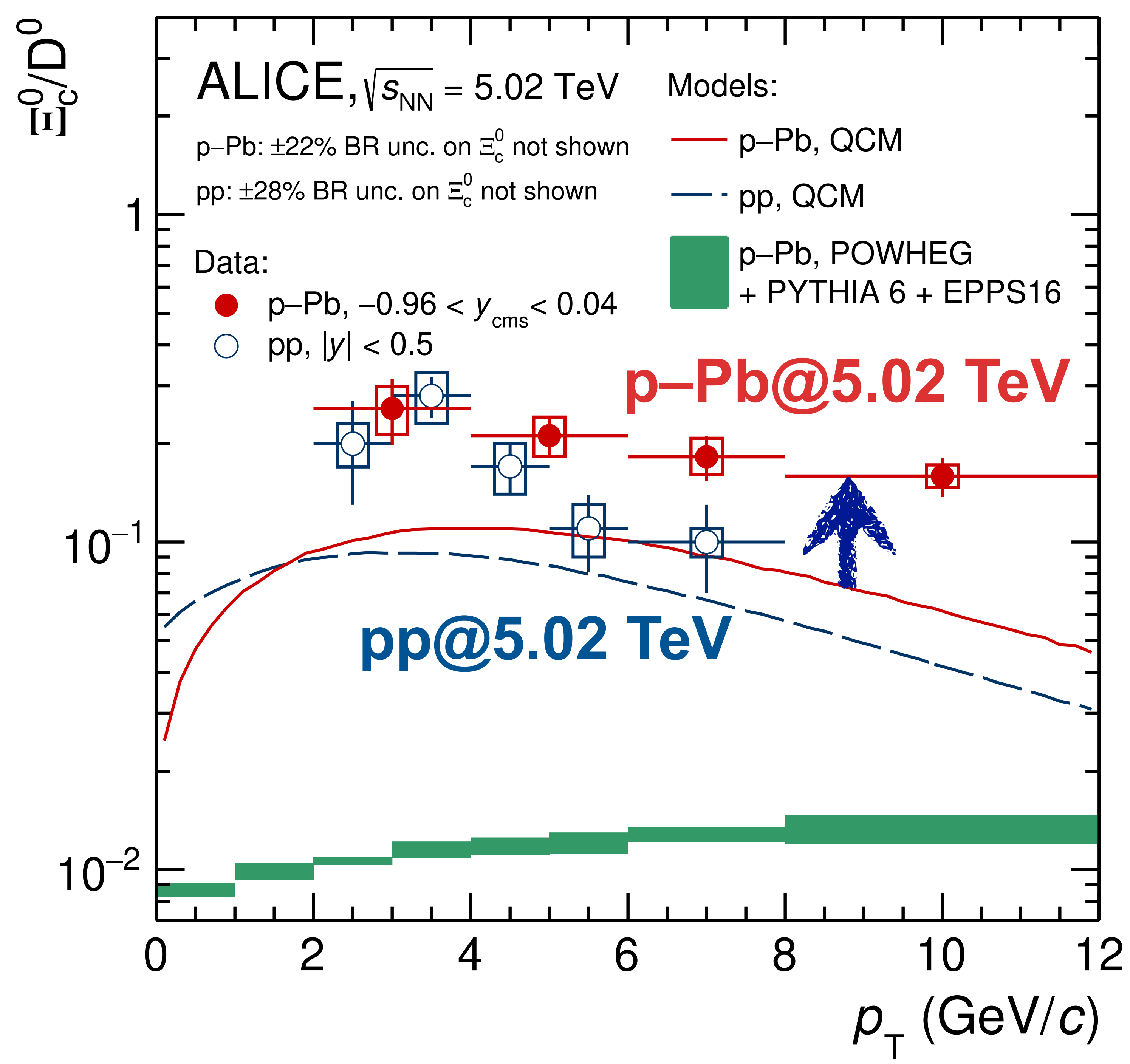
Ξ_c^0(dsc) and Ξ_c^+(usc) in pp and p–Pb collisions

JHEP 12 (2023) 086

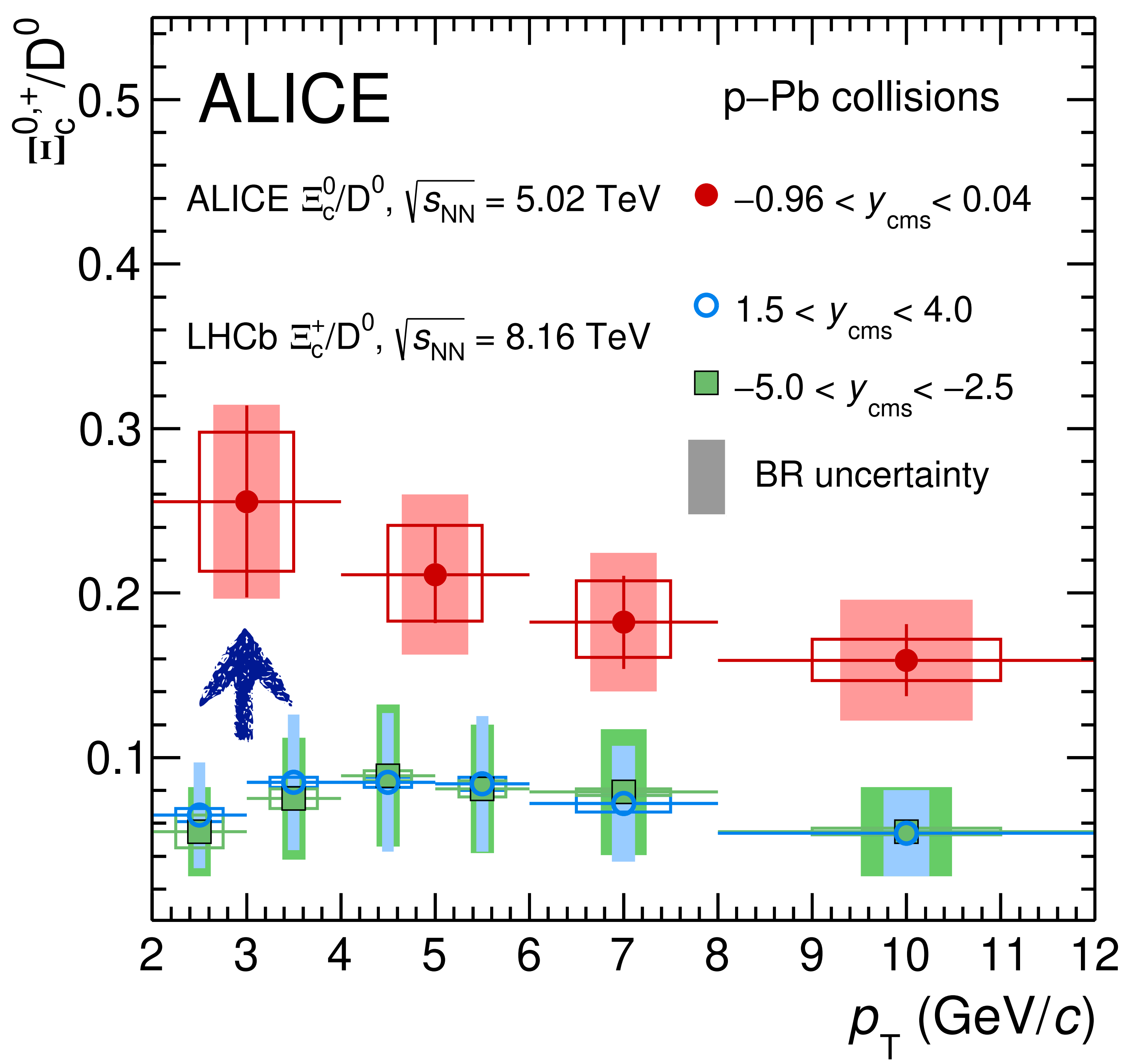


ALI-PUB-546202

arXiv:2405.14538



ALI-PUB-571011

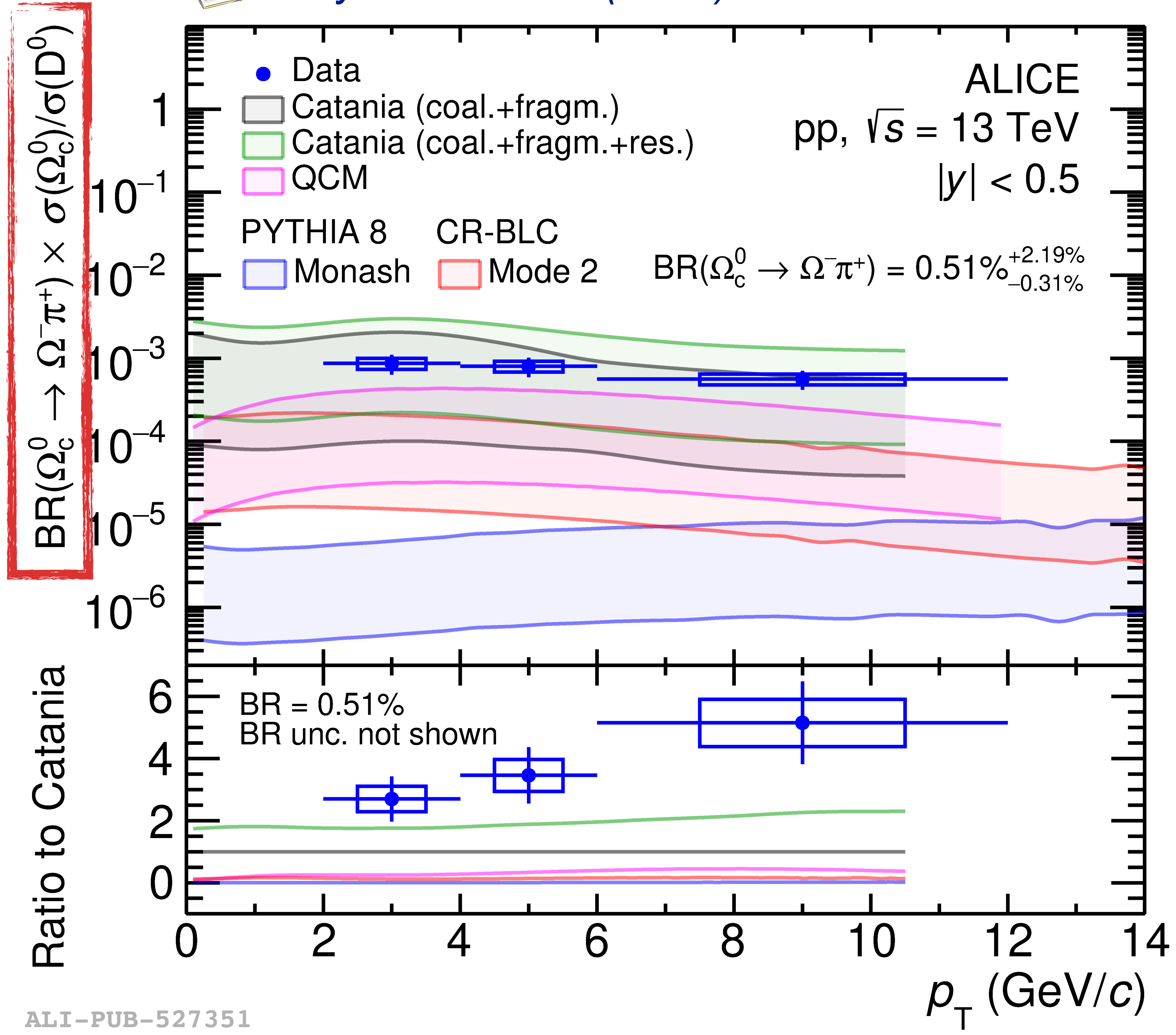


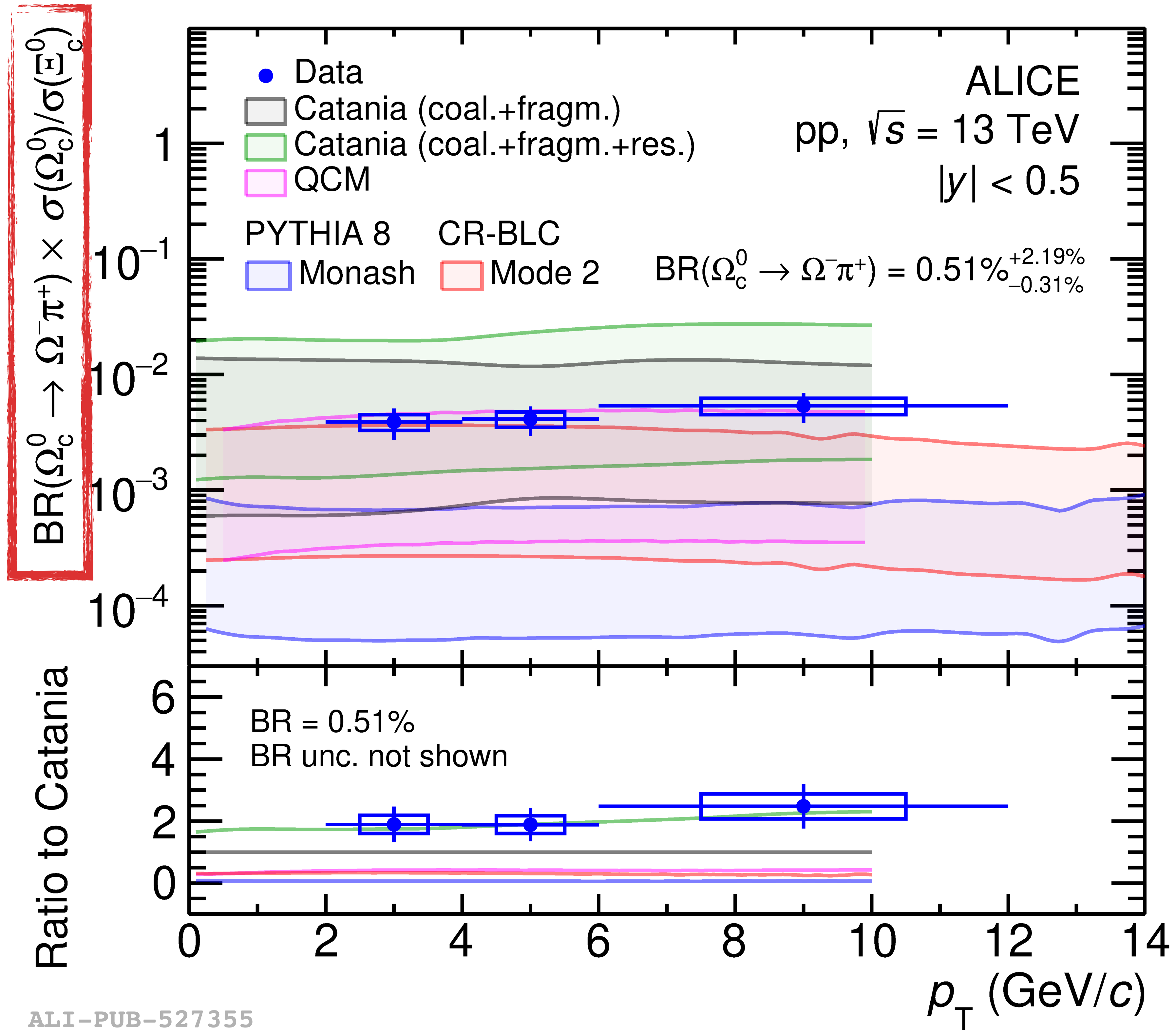
ALI-PUB-571019

- 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?

$\Omega_c^0(ssc)$ in pp collisions

Phys.Lett.B 846 (2023) 137625

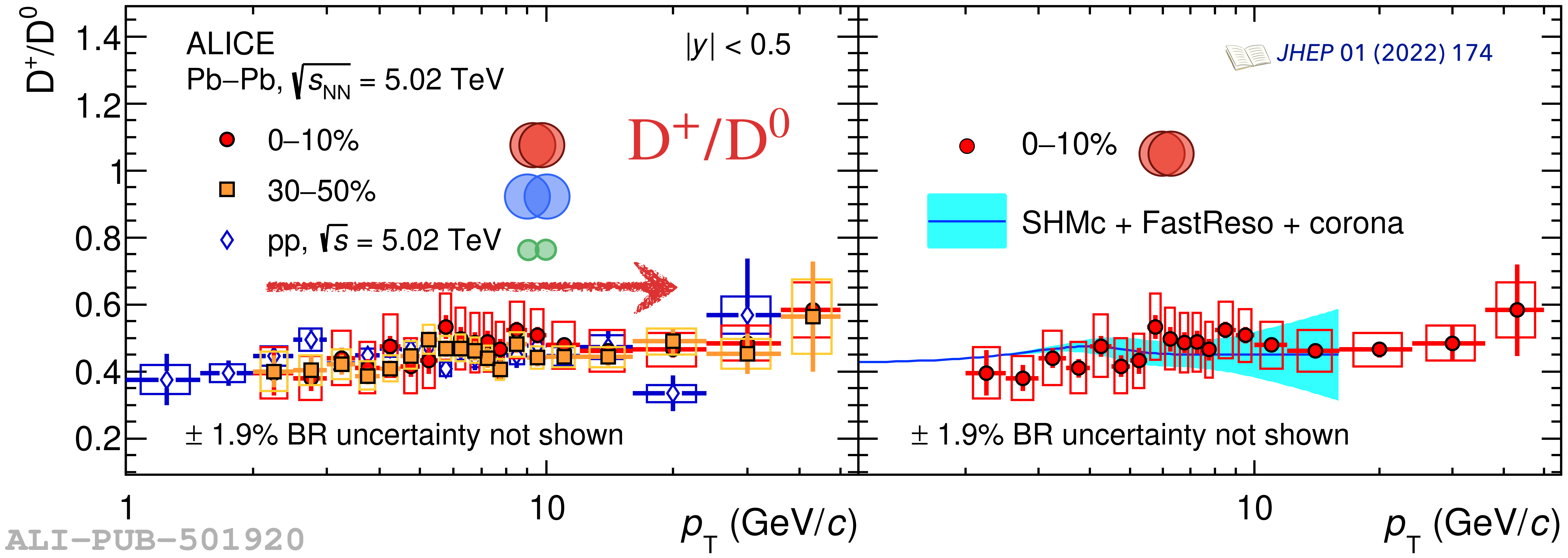




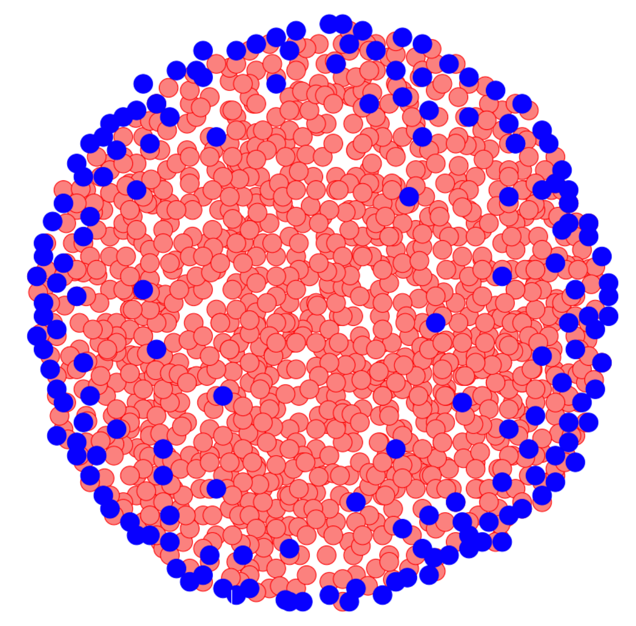
- No measurement of $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)$, loose bound from theoretical calculations
- Only Catania (coalescence + resonance decay) close to the data

Extremely important to measure BR to discriminate models

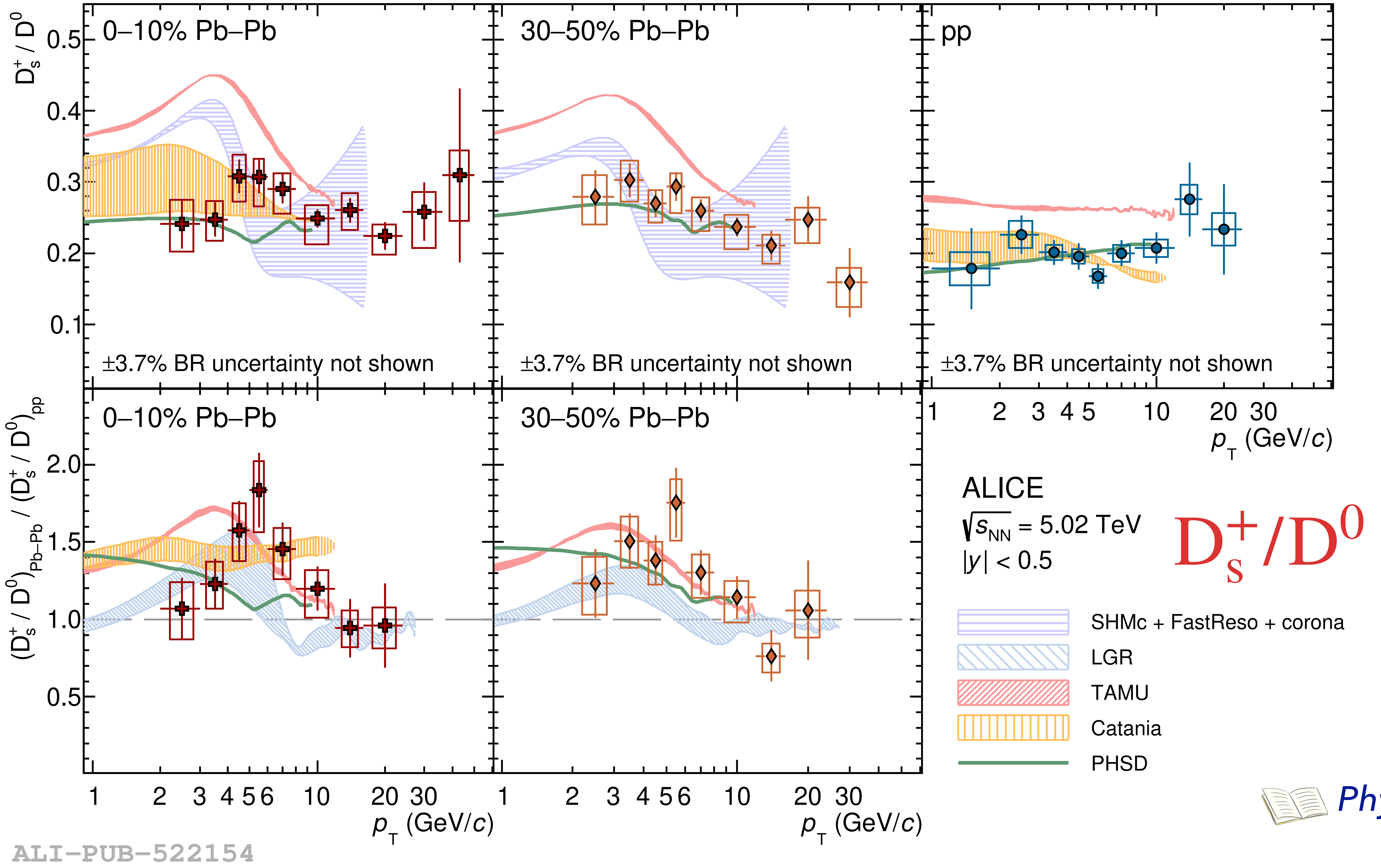
D^+/D^0 in Pb–Pb collisions



- D^+/D^0: flat distribution, NOT modified in QGP, described by SHMc
  - p_T spectra of charm hadrons are modelled with a core-corona approach
  - Resonance decays computed with FastReso package
  - Low p_T: dominated by the core contribution described with a Blast-Wave function
  - High p_T: corona contribution more relevant and is parameterized from pp measurements



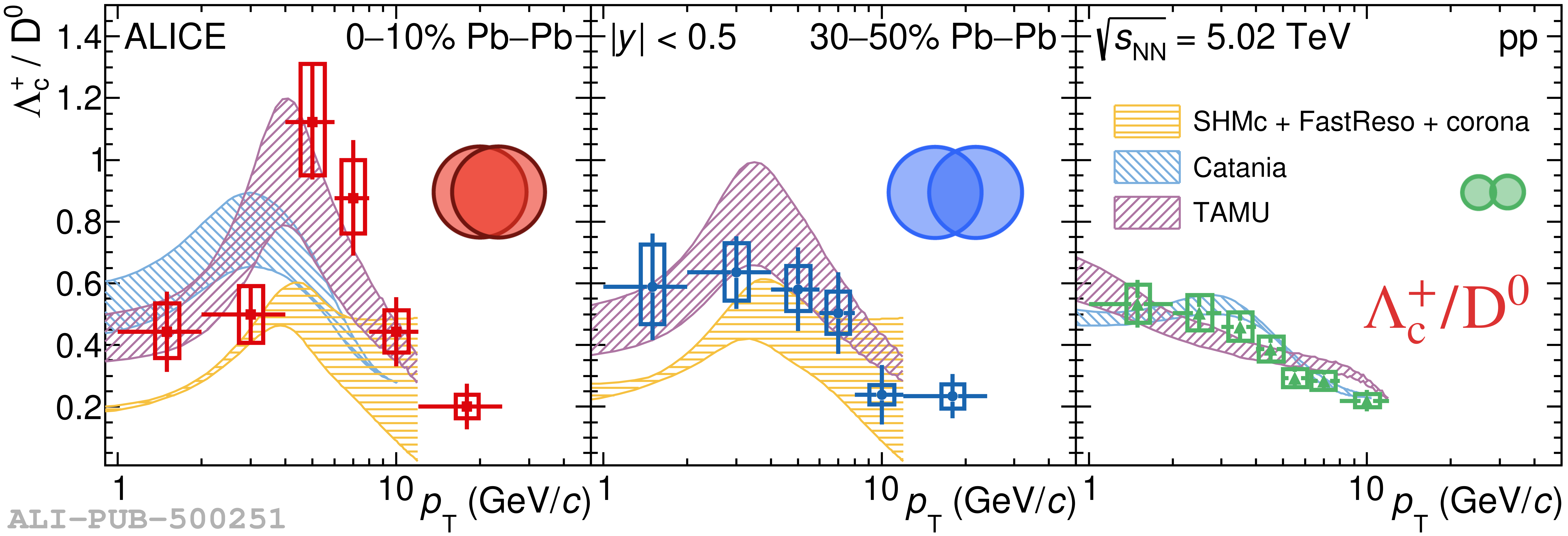
D_s^+/D^0 in Pb–Pb collisions



Phys.Lett.B 827 (2022) 136986

- D_s^+/D^0: hint of enhancement in $2 < p_T < 8$ GeV/c in 0-10% (30-50%) Pb-Pb by 2.3σ (2.4σ)
- Described by models including strangeness enhancement and fragmentation + recombination
  - TAMU (coalescence implemented with a Resonance Recombination Model) significantly overestimates data
  - Catania and LGR (coalescence implemented with Wigner formalism) describe data
  - PHSD (coalescence implemented with MC) describe data

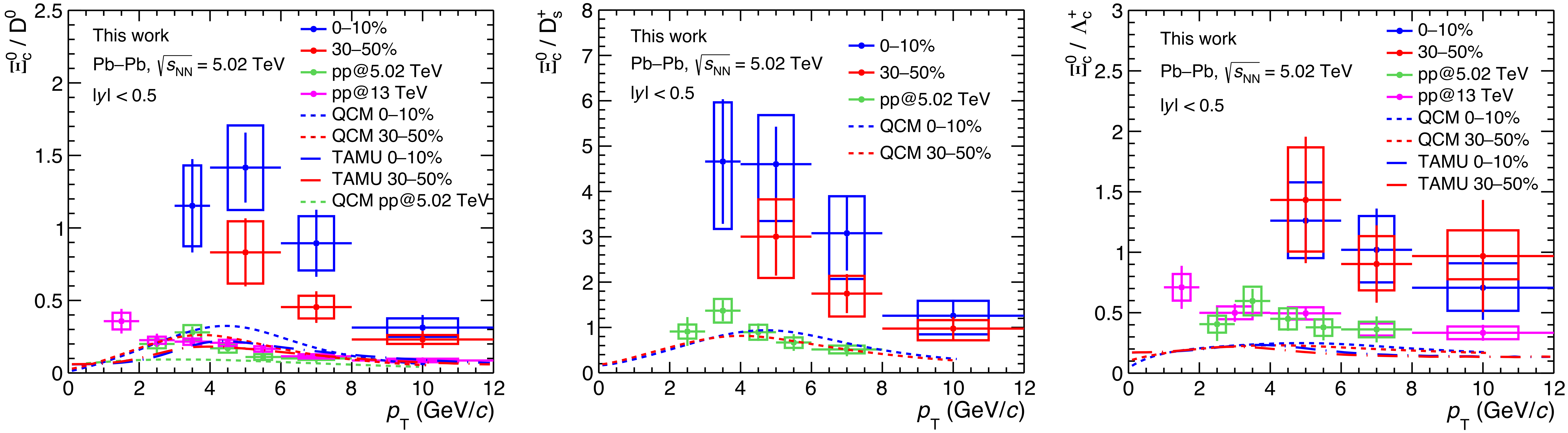
Λ_c^+/D^0 in Pb–Pb collisions



Phys.Lett.B 839 (2023) 137796

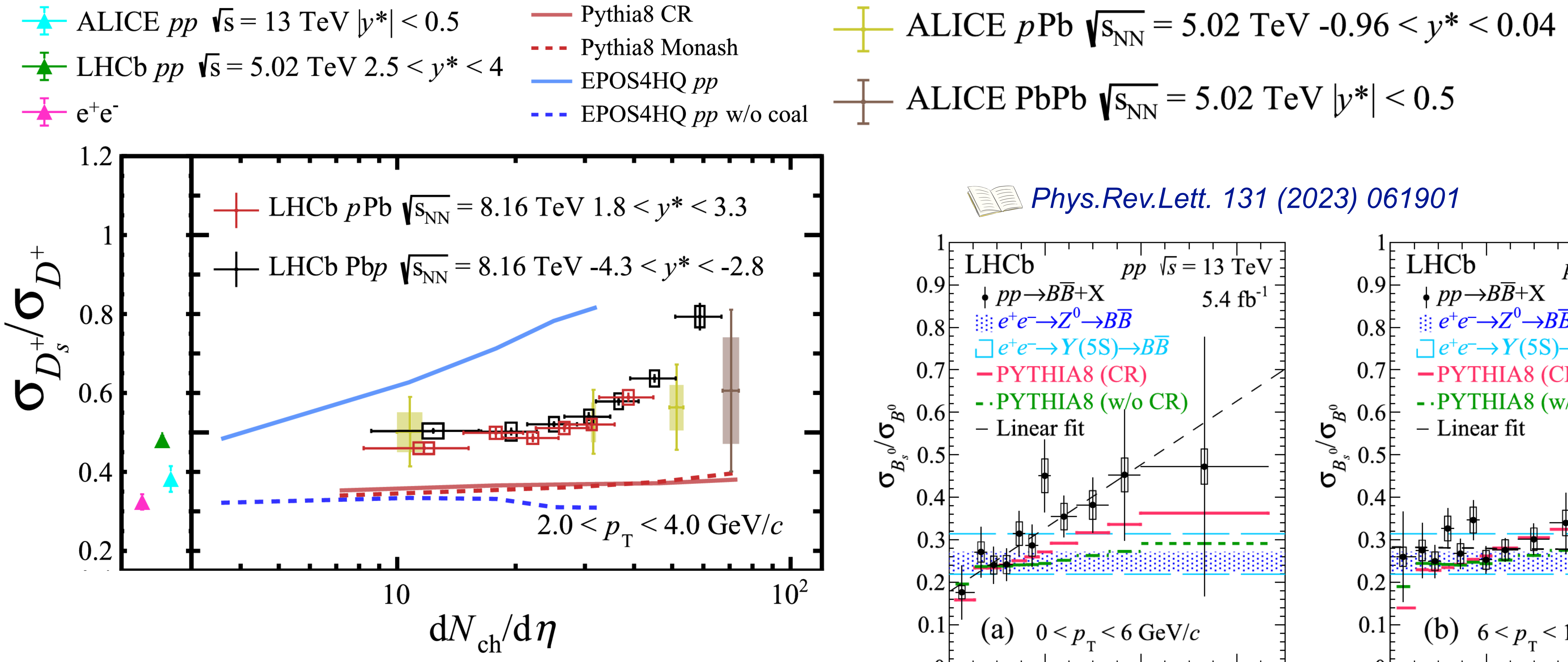
- Λ_c^+/D^0: enhanced in $4 < p_T < 8$ GeV/c for central Pb-Pb w.r.t. pp by 3.7σ
  - Also seen for light-flavor baryon-to-meson ratios
  - Described by TAMU
  - The shapes of the Catania and SHMc predictions agree qualitatively

Ξ_c^0 in Pb–Pb collisions



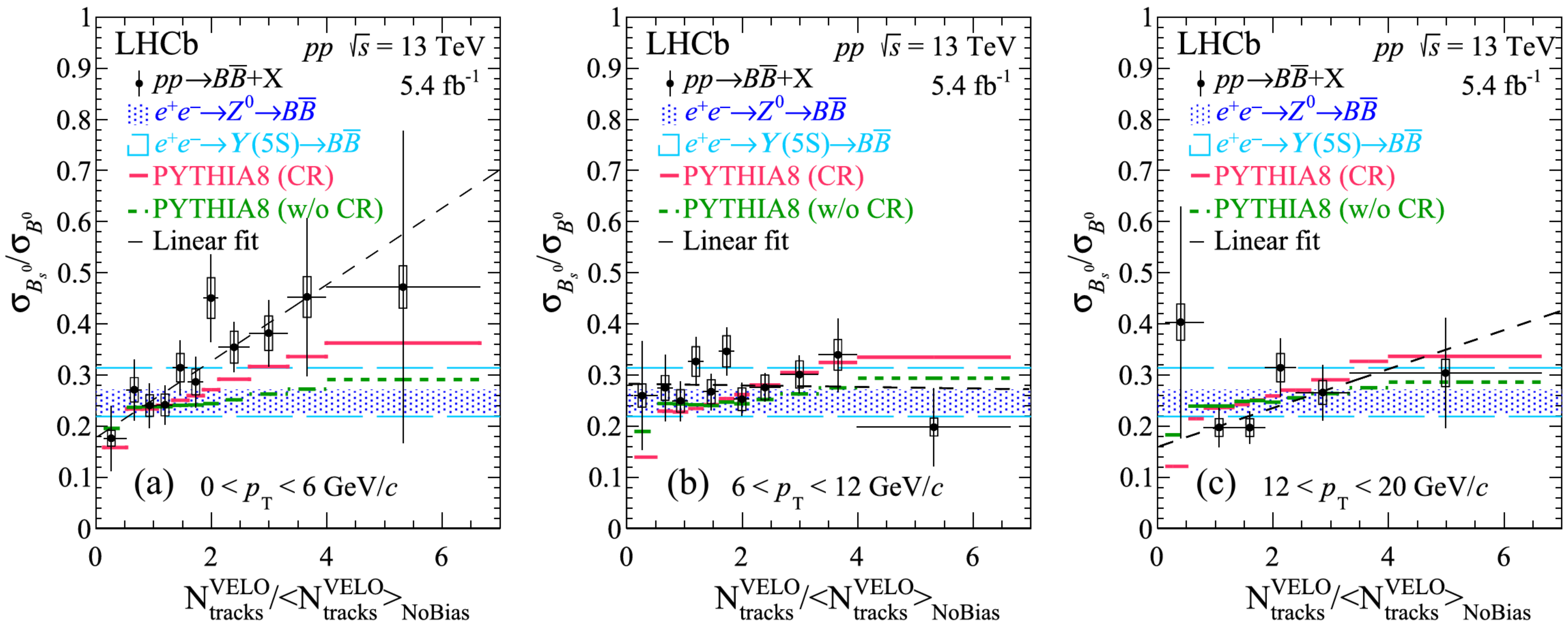
- Very large enhancement in Pb-Pb w.r.t. pp collisions
  - Strangeness enhancement (coalescence) + Flow + Resonance decay

M-to-M event multiplicity dependence (LHCb)



Phys. Rev. D 110 (2024) L031105

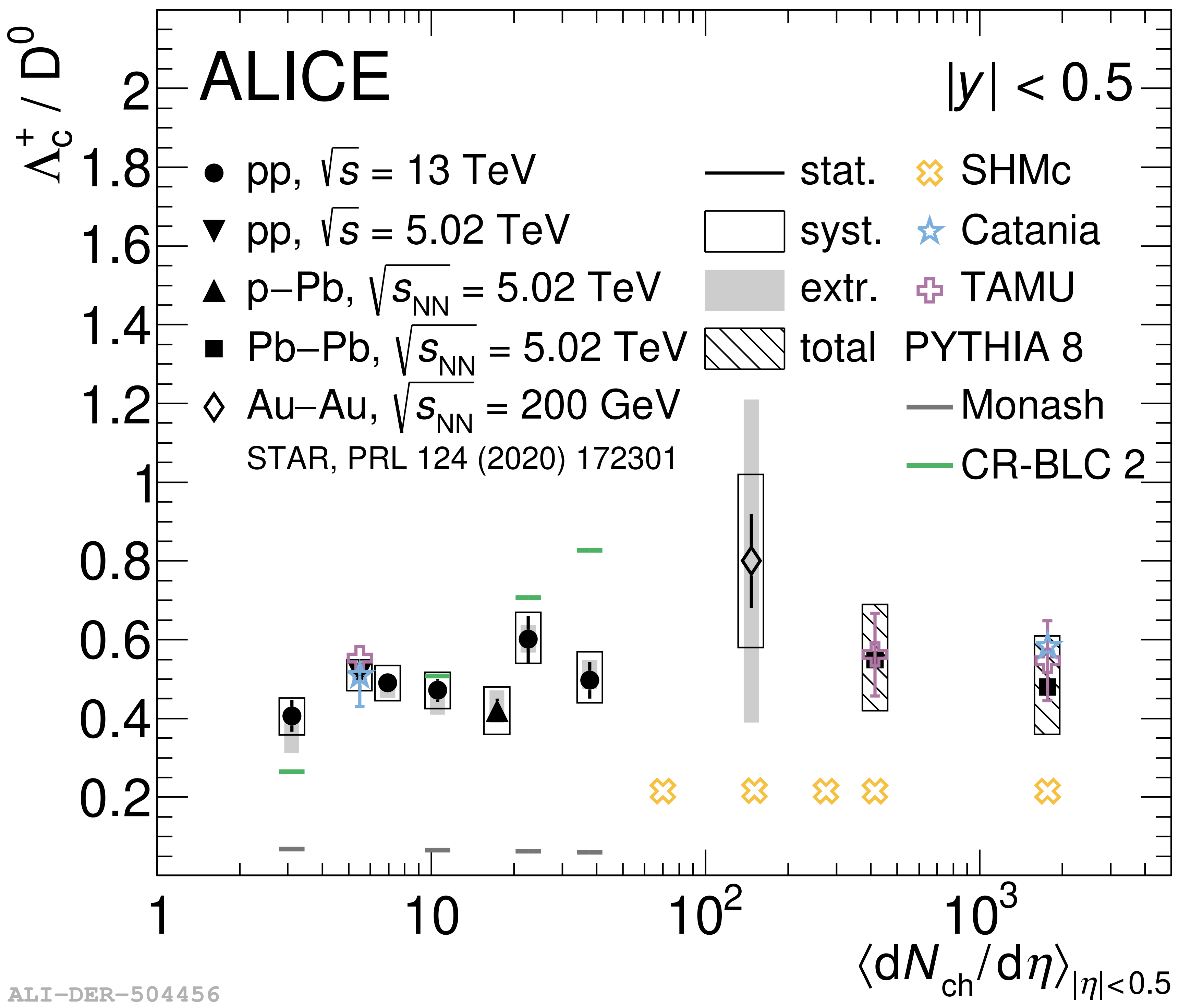
Phys.Rev.Lett. 131 (2023) 061901

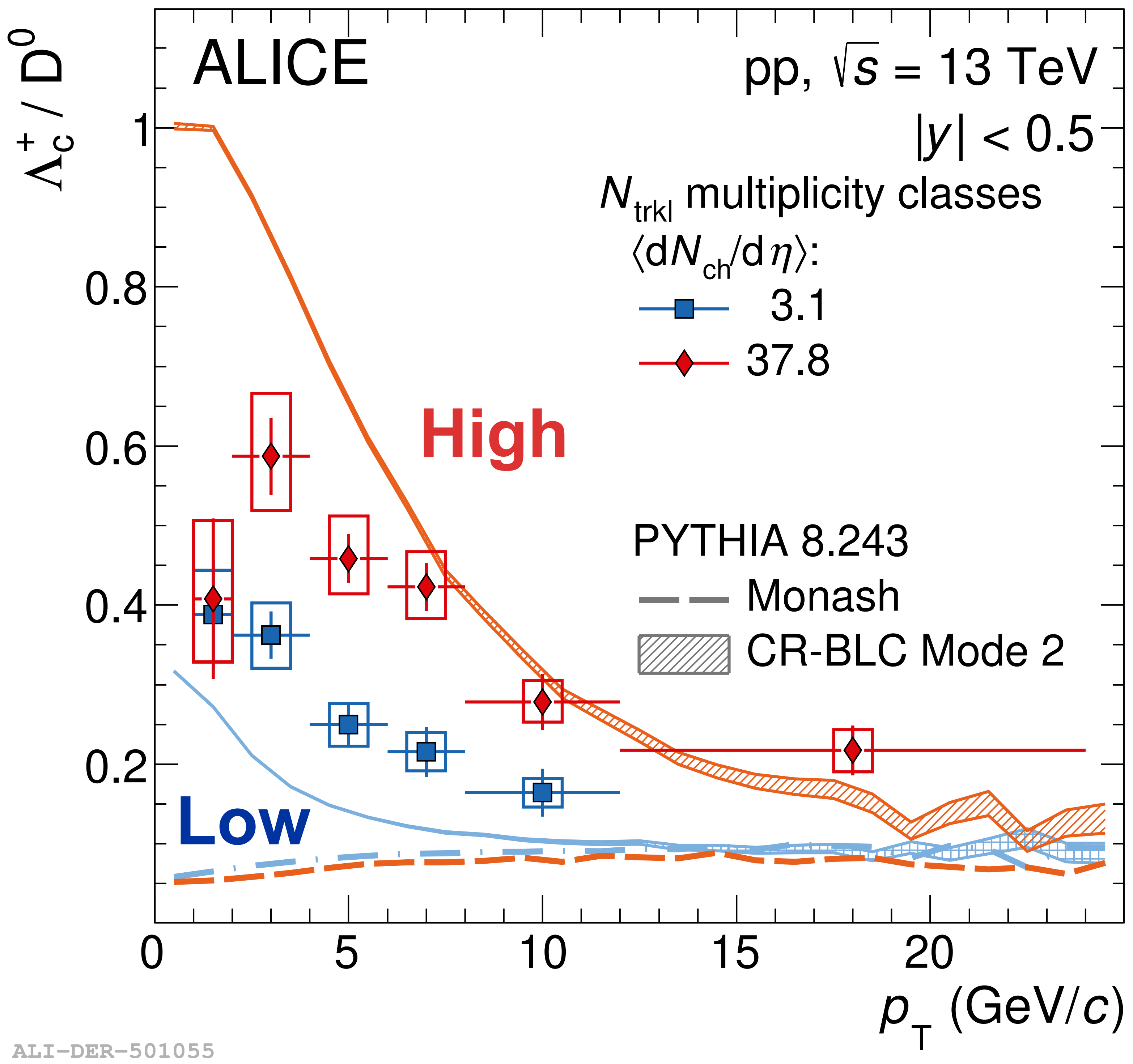


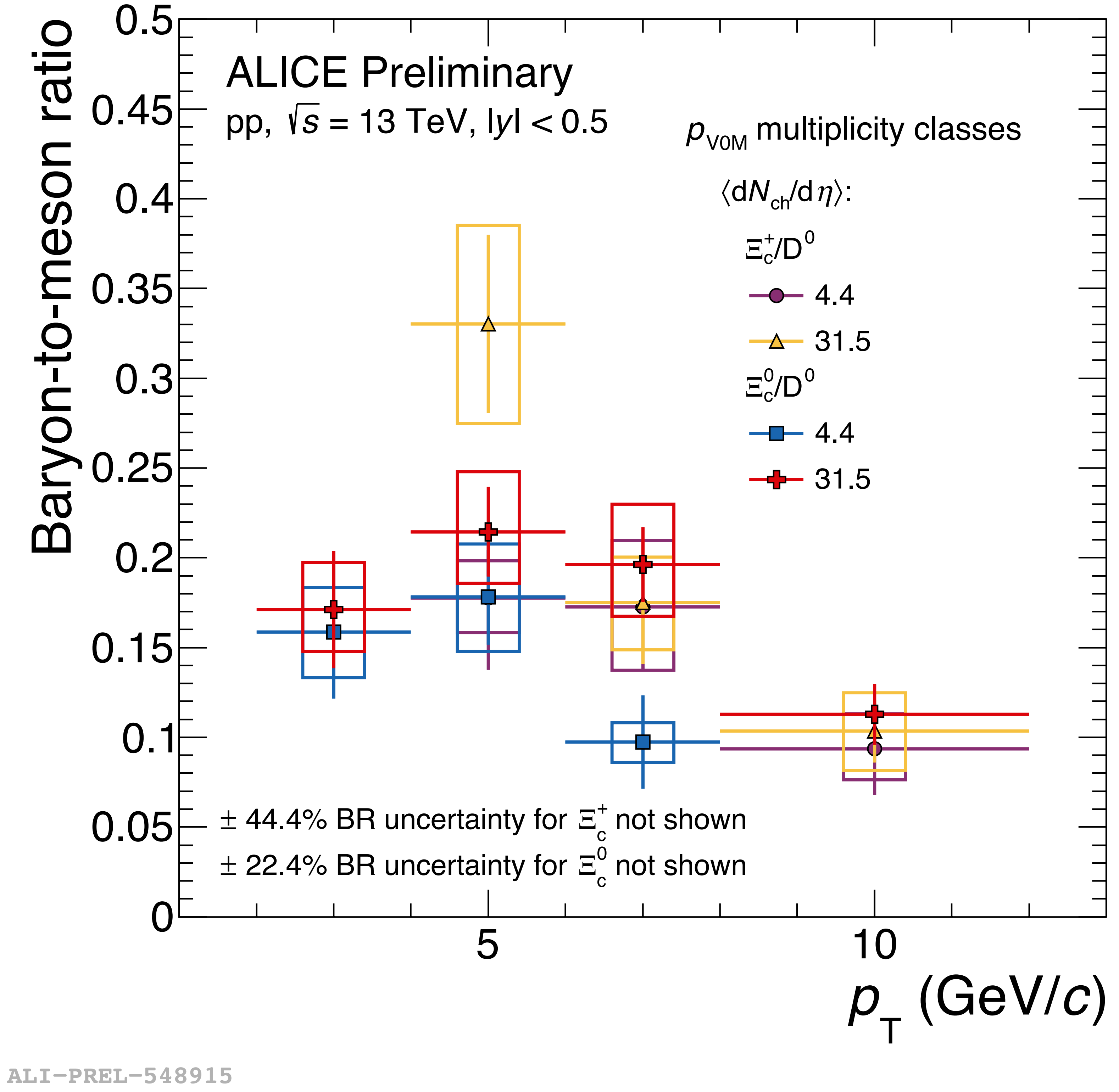
- Observed clear indications of strangeness enhancement in both charm and beauty sectors
- Final state effects such as coalescence are important at low p_{T} and high multiplicity

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

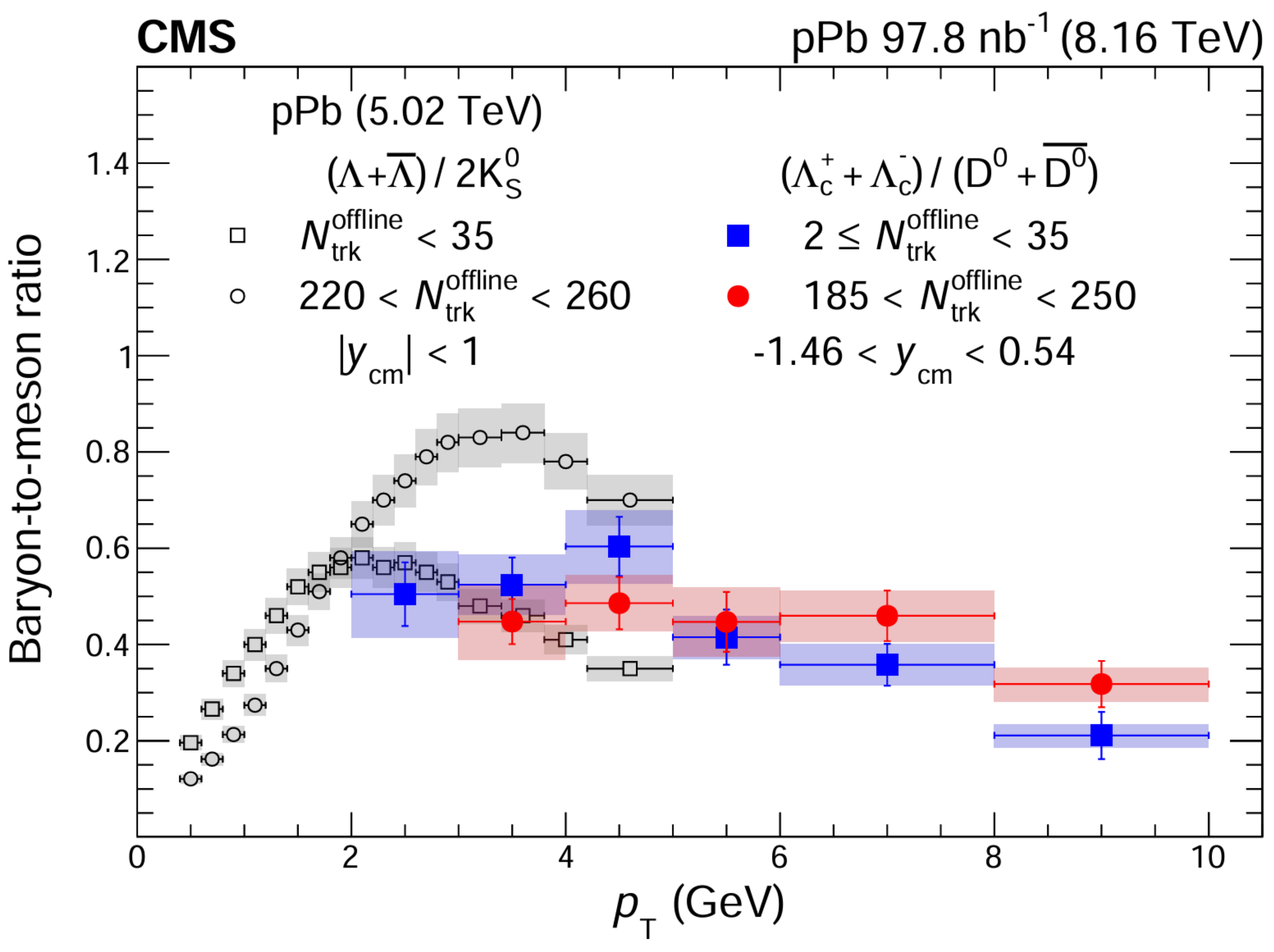
- Multiplicity-dependent enhancement with 5.3σ from lowest to highest multiplicity

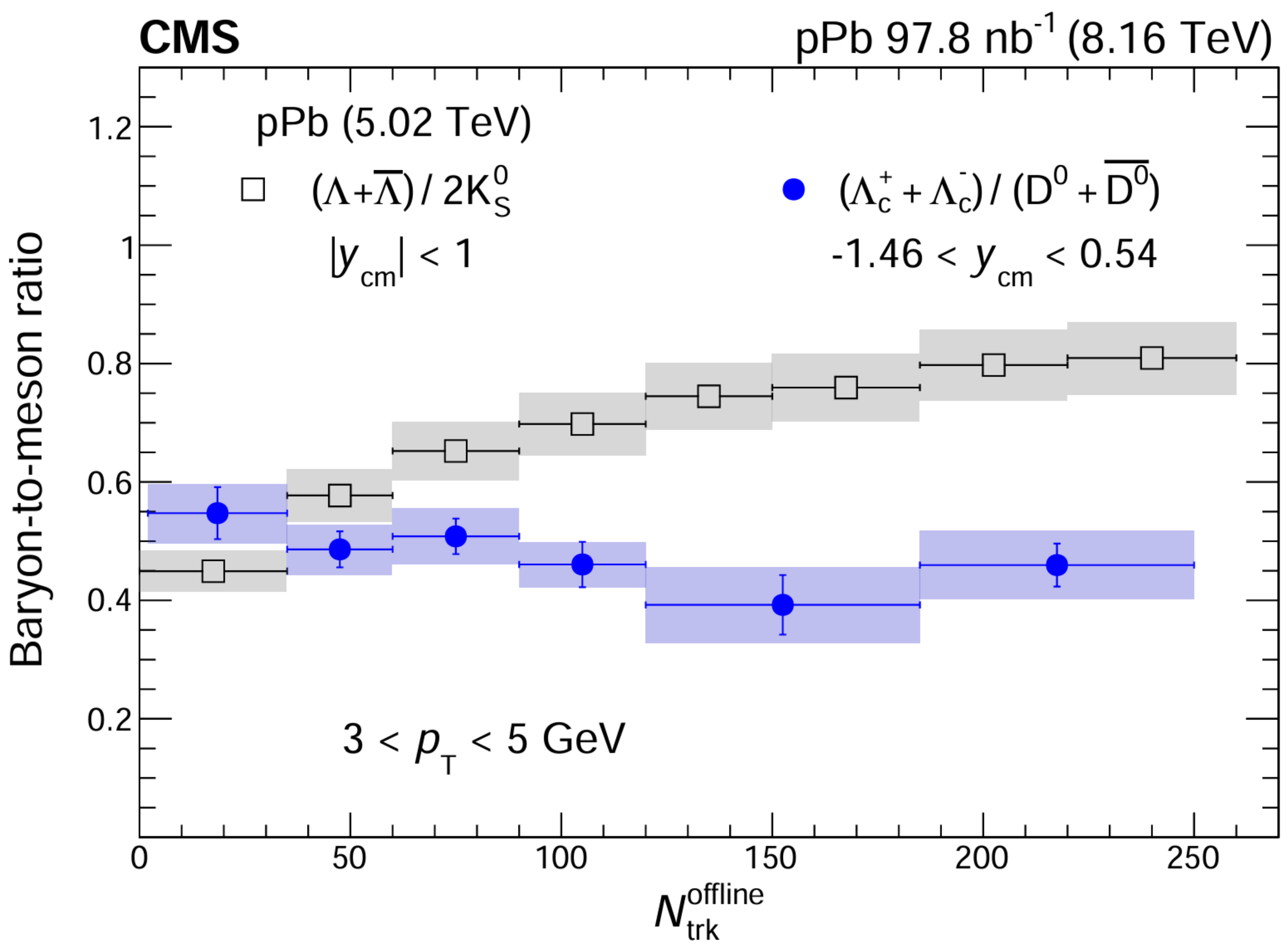
$\Xi_c^{0,+}/D^0$ vs. p_T in different multiplicity

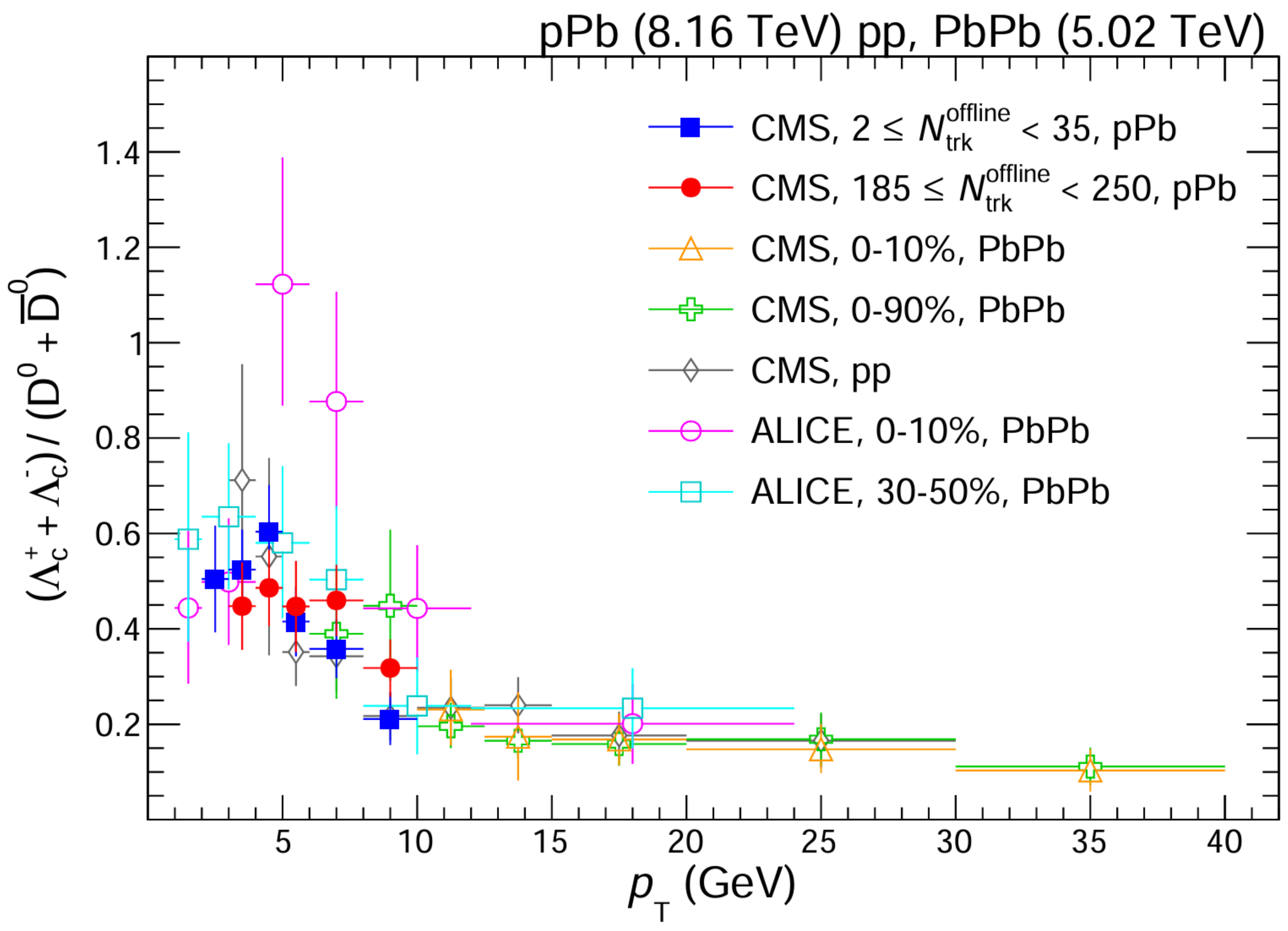
- No significant multiplicity dependence as a function of p_T within uncertainties

B-to-M event multiplicity dependence (CMS)

arXiv:2407.13615

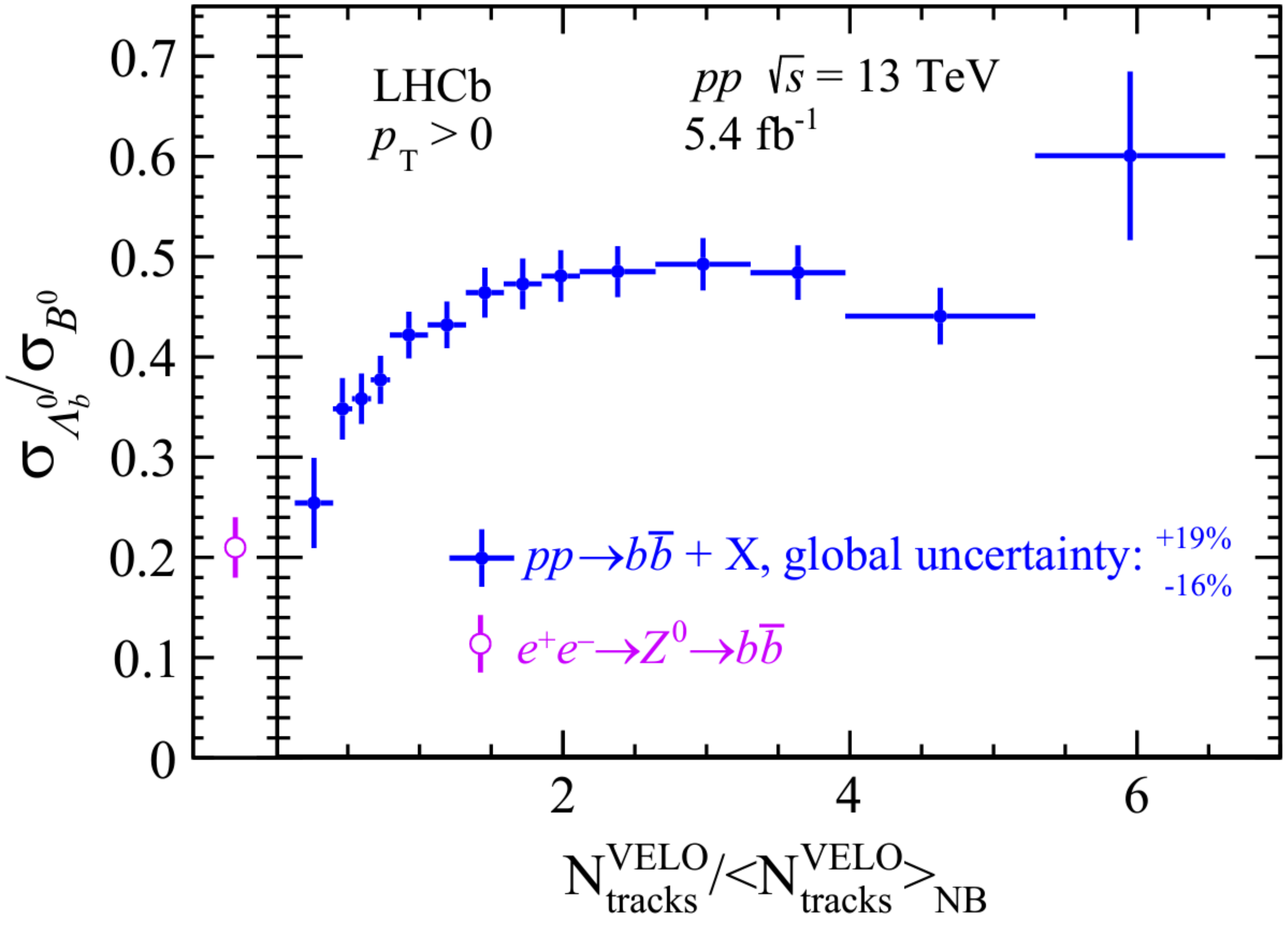


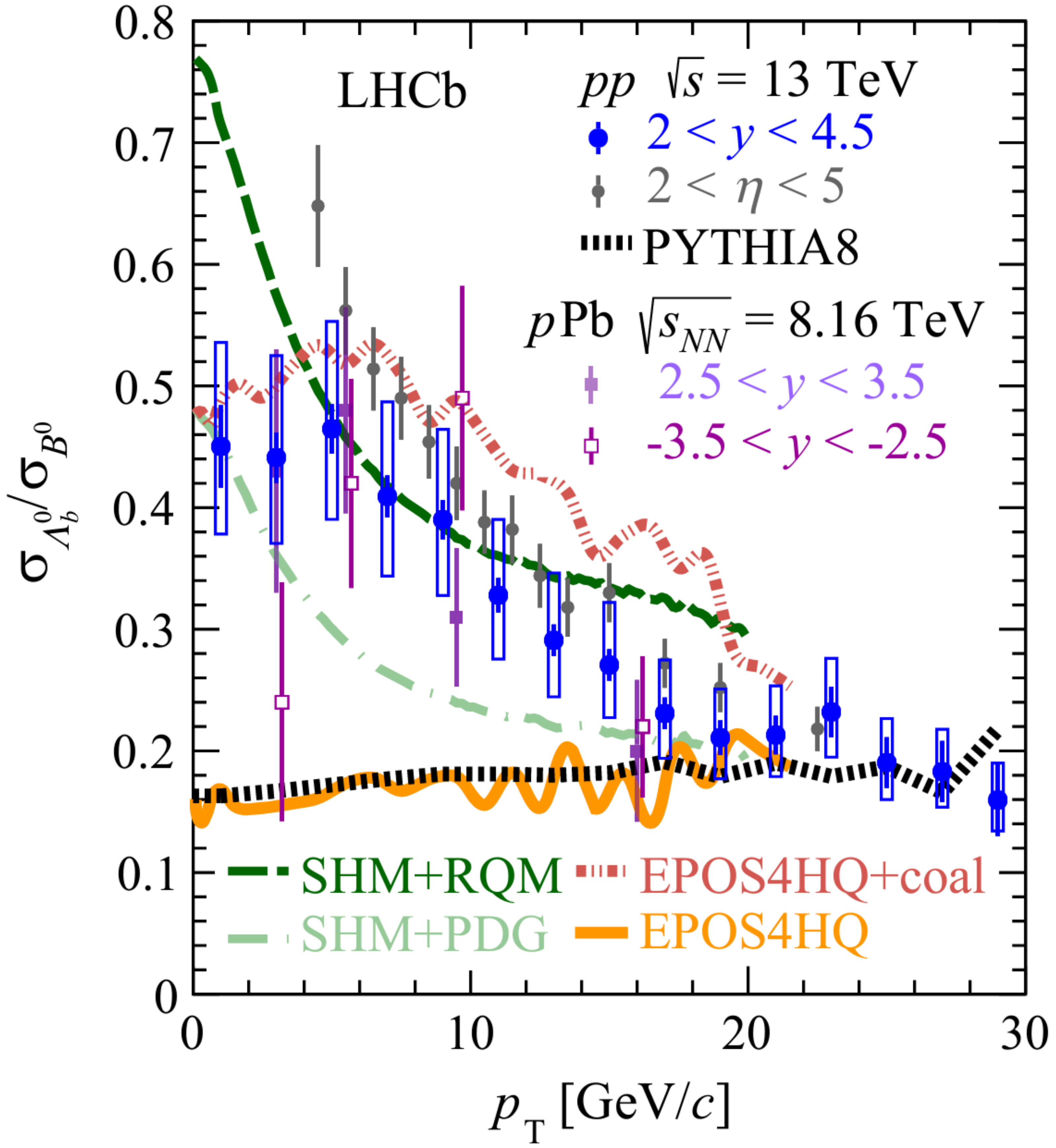




B-to-M event multiplicity dependence (LHCb)

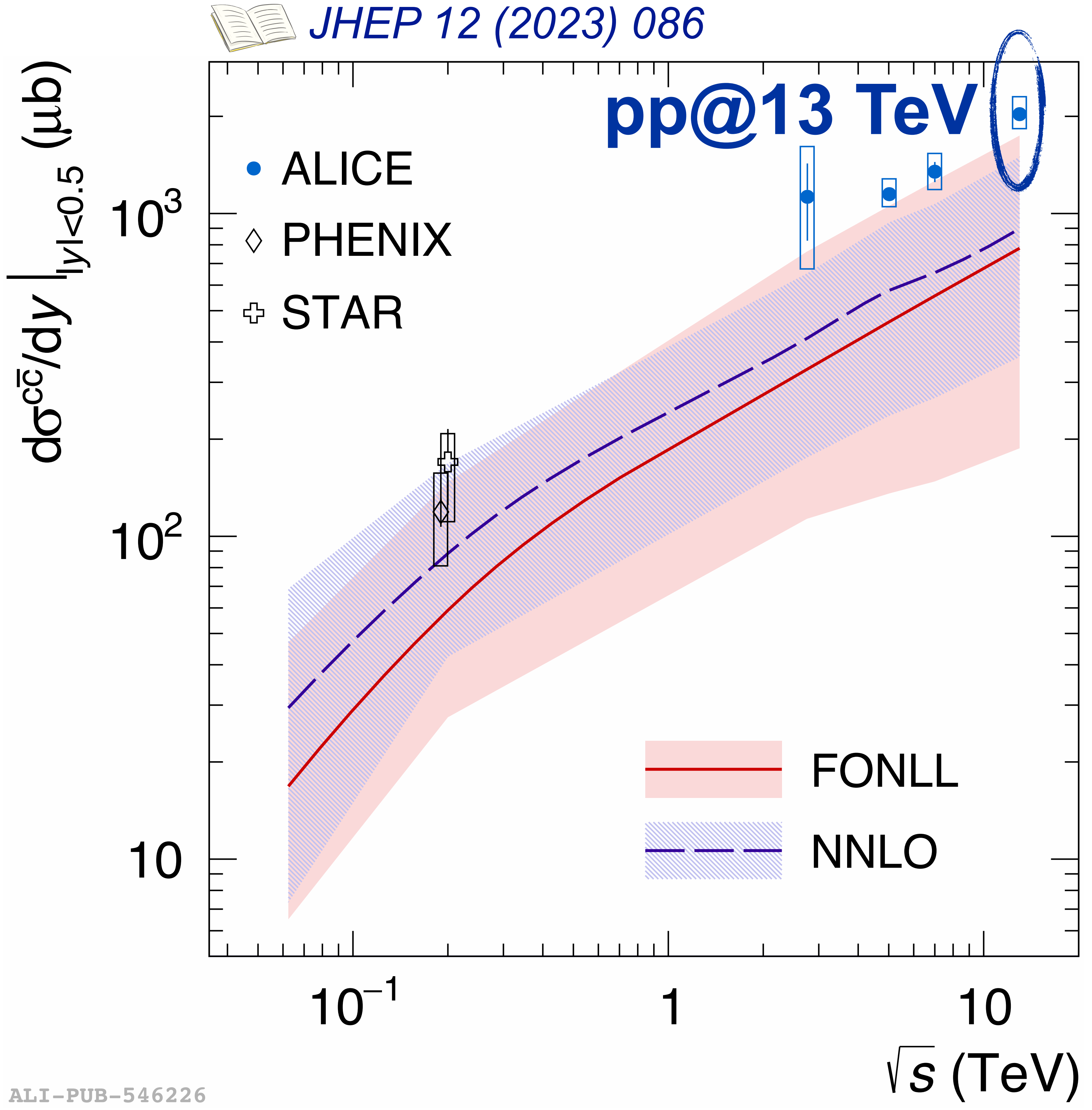
Phys.Rev.Lett. 132 (2024) 081901



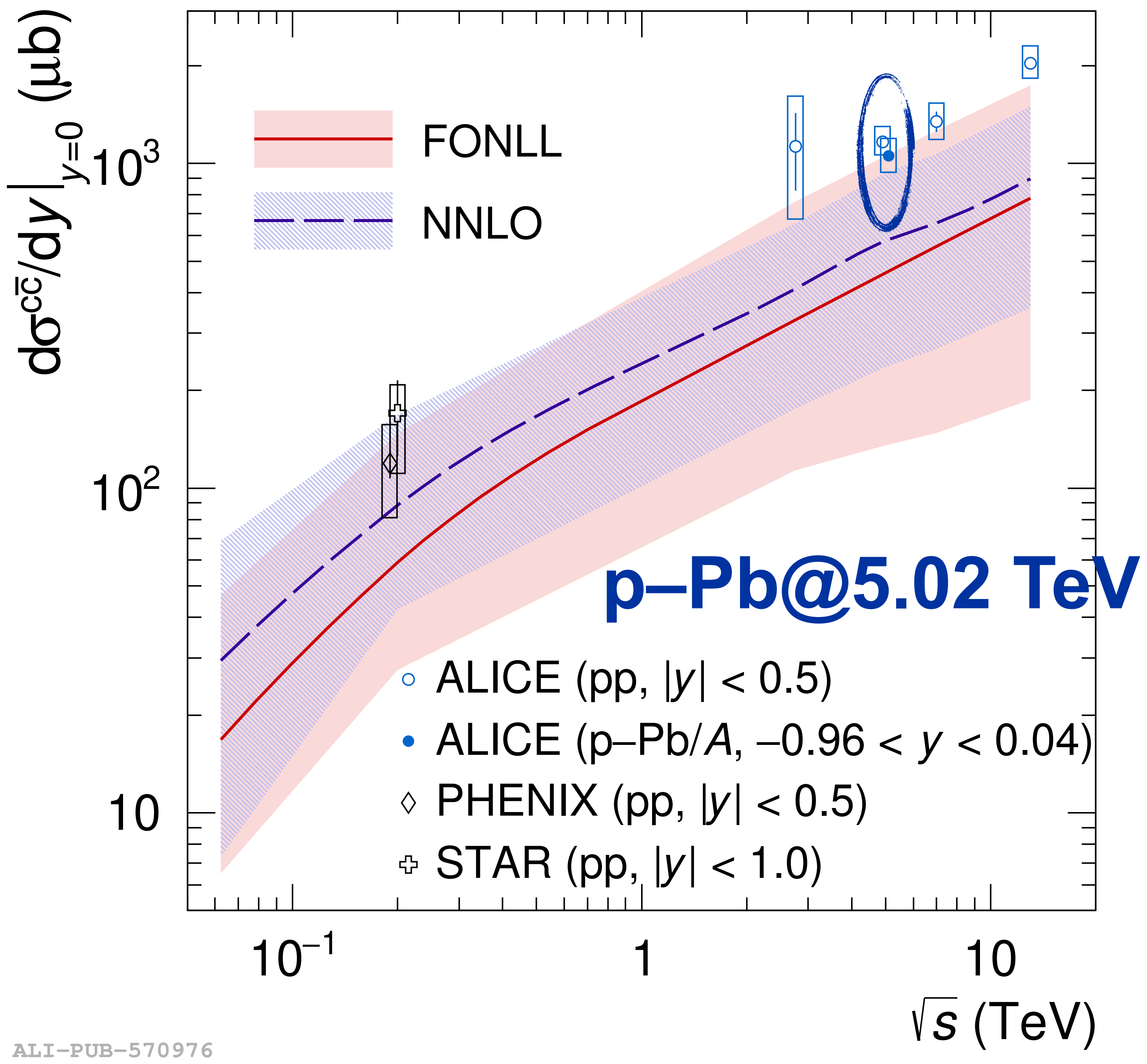


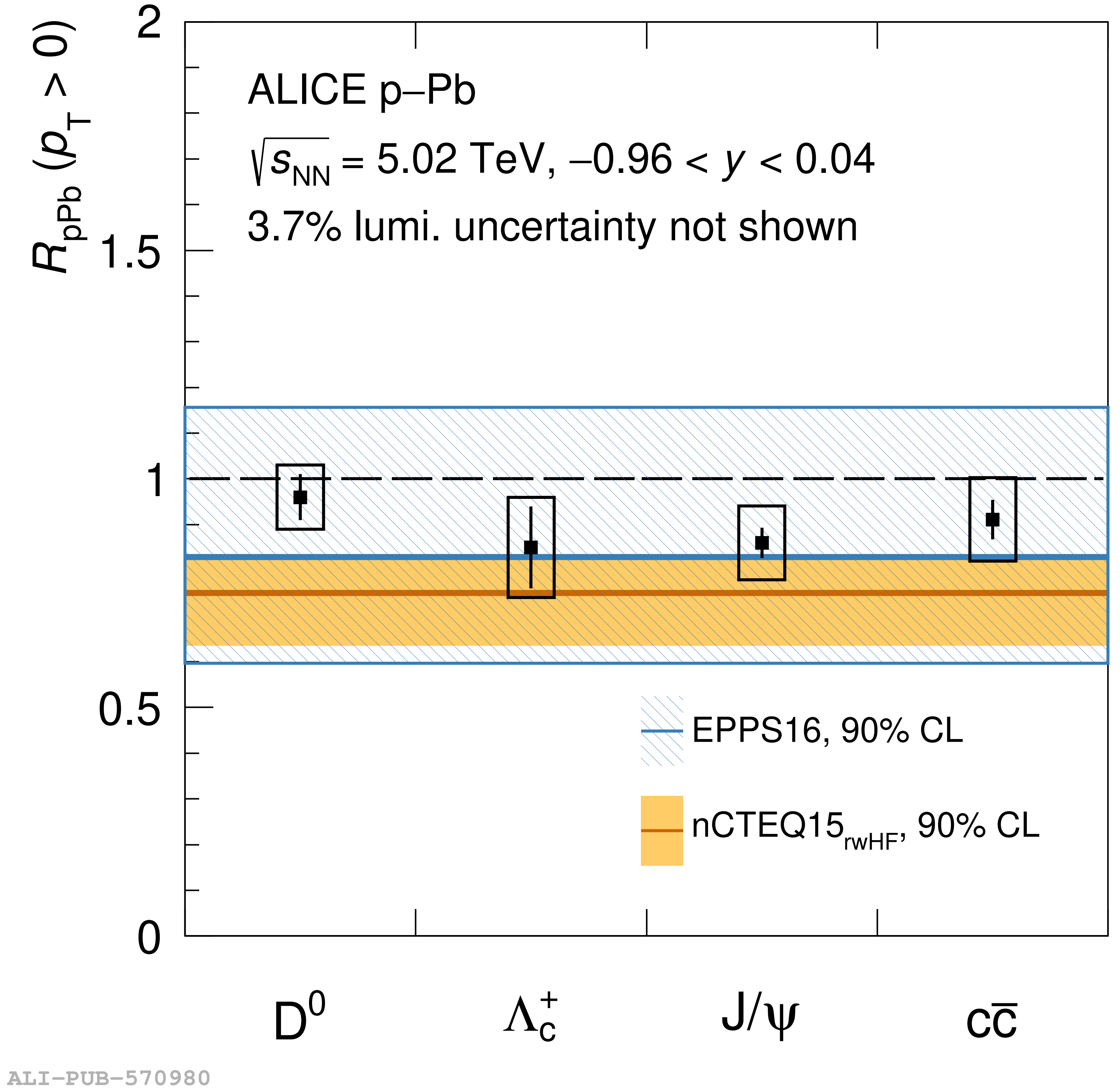
Charm production in pp and p–Pb collisions

JHEP 12 (2023) 086



arXiv:2405.14571

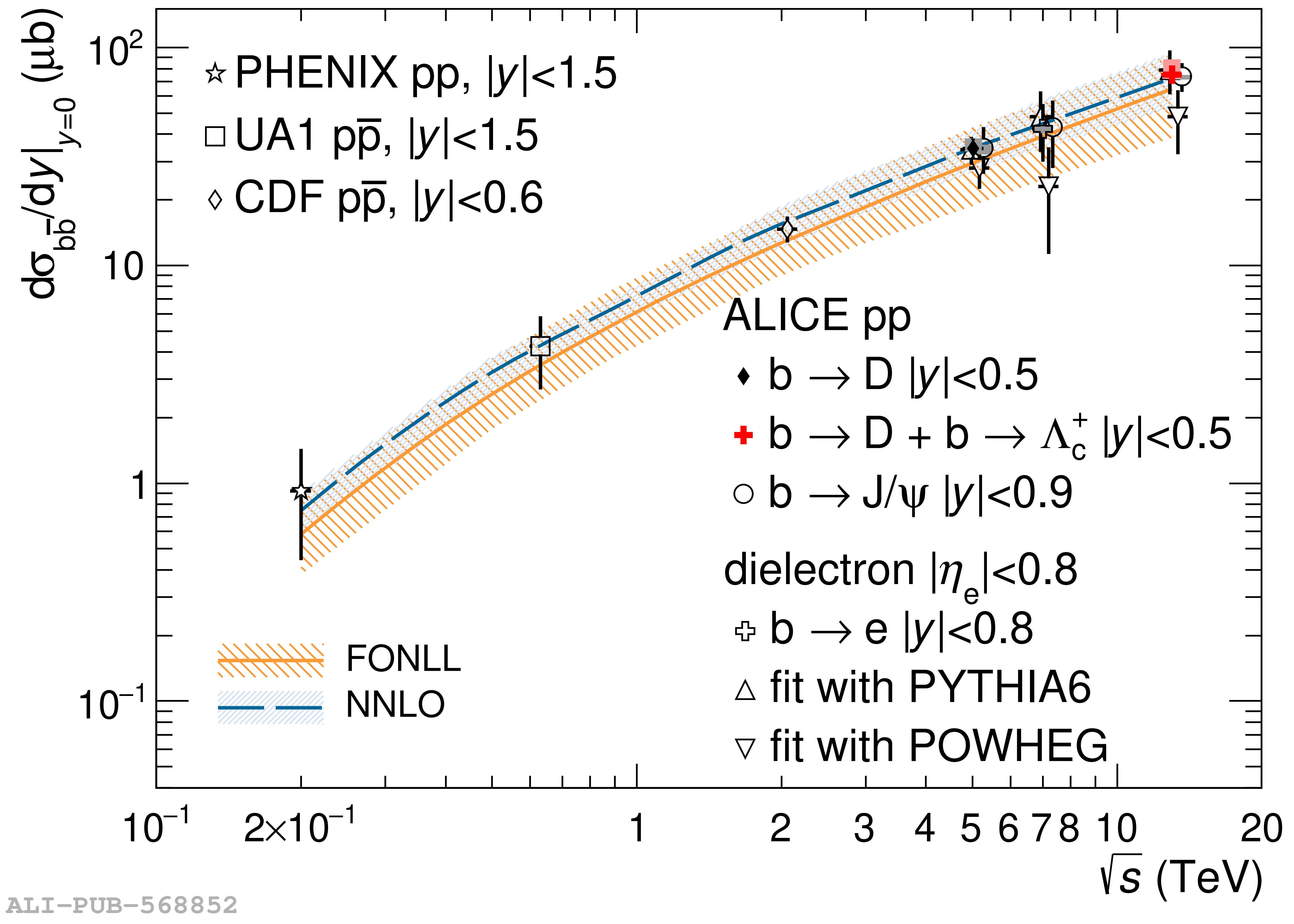


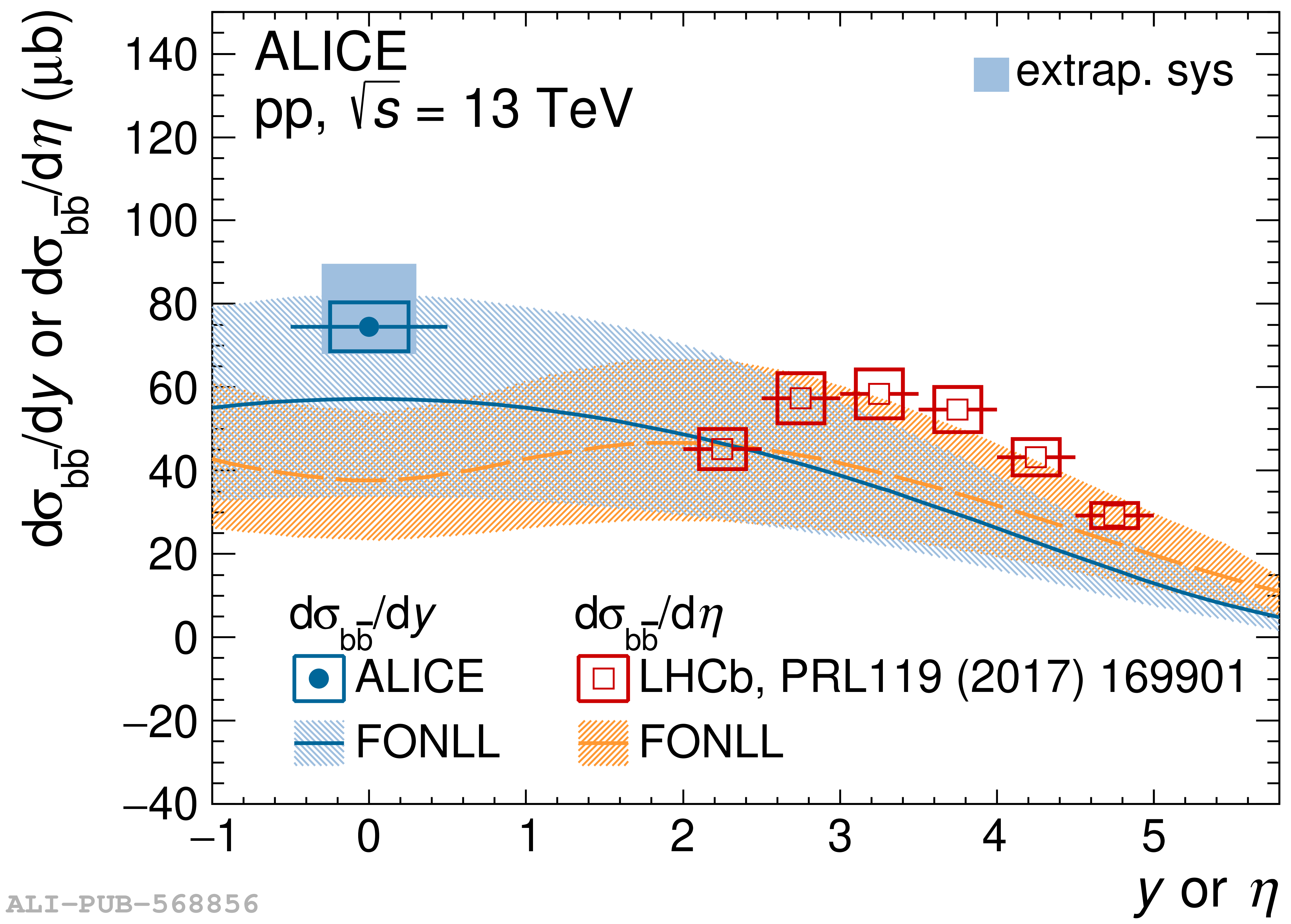


- $\sigma(c\bar{c})$ at midrapidity at the upper bound of state-of-the-art pQCD calculations
- No significant difference in the overall production of charm between pp and p–Pb collisions

Beauty production in pp collisions

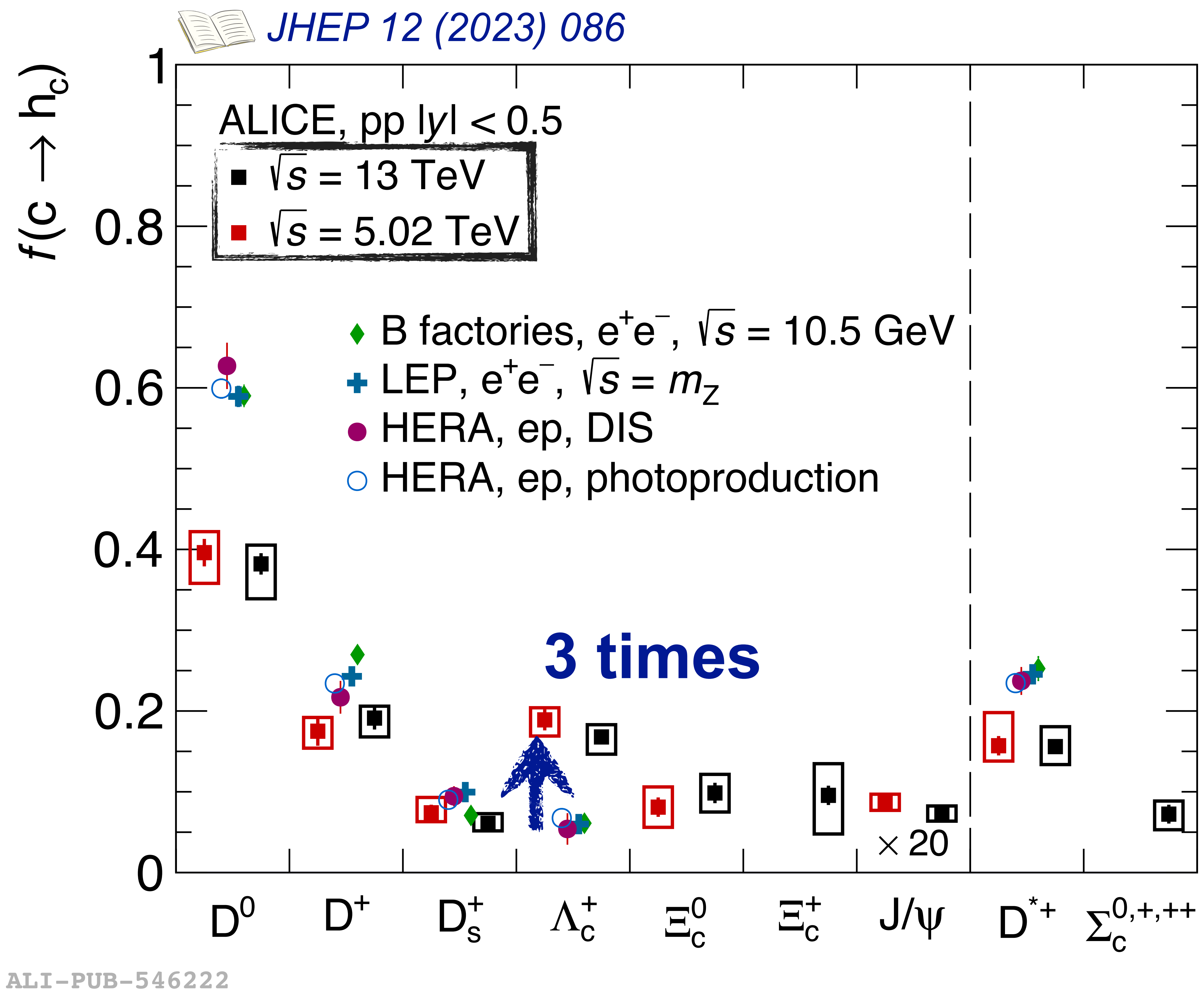
arXiv:2402.16417

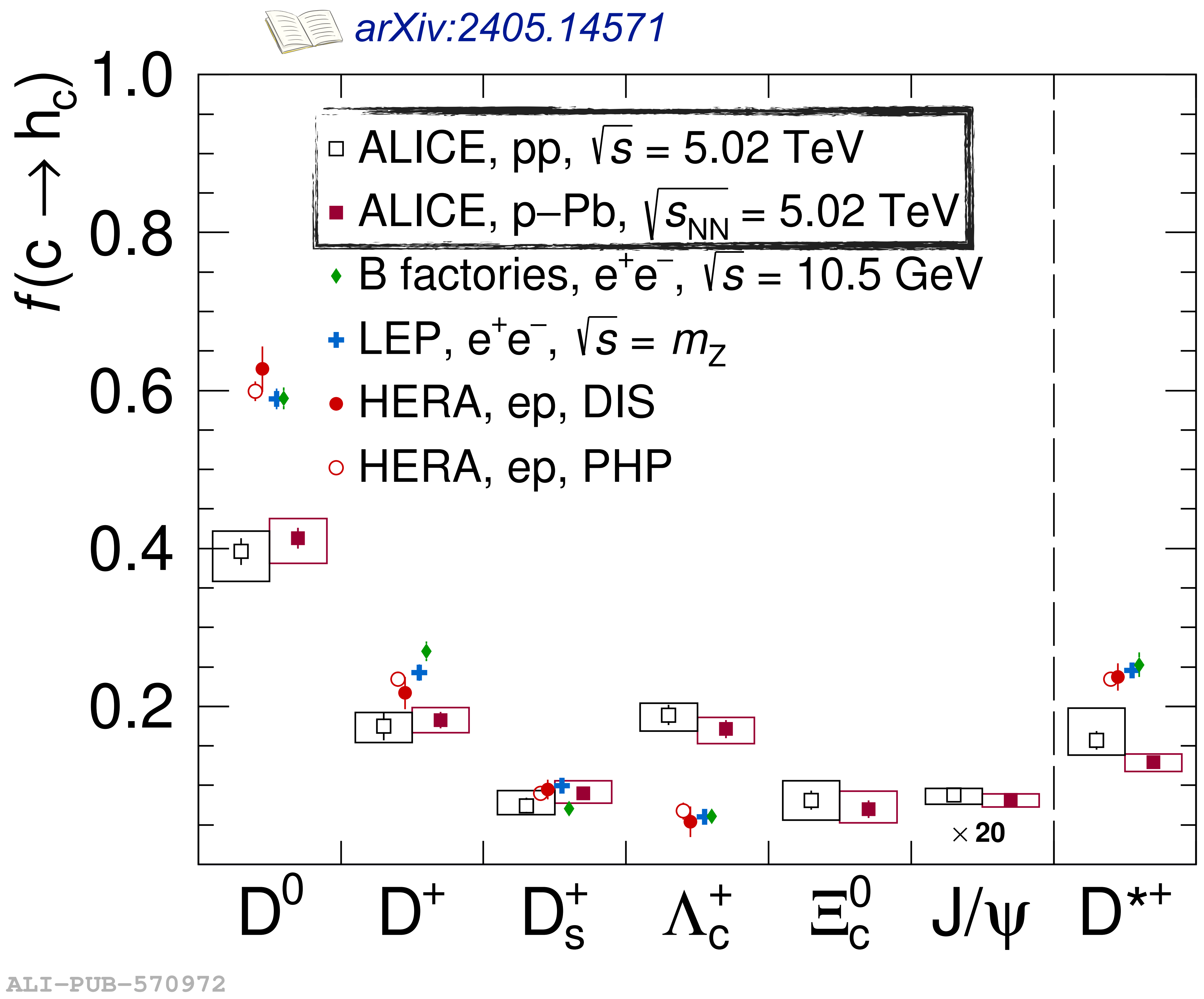




- p_T-integrated measurement at midrapidity based on the production cross sections of D^0, D^+, D_s^+, Λ_c^+
- The cross section vs. centre-of-mass energy is well described by pQCD, especially NNLO
- Results are compatible with pQCD but tend to lie close to the upper boundary of the uncertainty bands

Charm fragmentation fractions in pp and p–Pb collisions





- Independent of centre-of-mass energy: pp@5.02 TeV and pp@13 TeV
- 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

Fragmentation fractions universality is challenged

Summary

- Assumption of universal parton-to-hadron fragmentation fractions not valid at LHC energies
- HF hadronization mechanisms in small collision systems at LHC need further investigations
  - Resonance decay? Coalescence? Radial flow?

Backup

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}