Heavy flavour hadronization from small to large collision systems

Stefano Trogolo

University of Houston

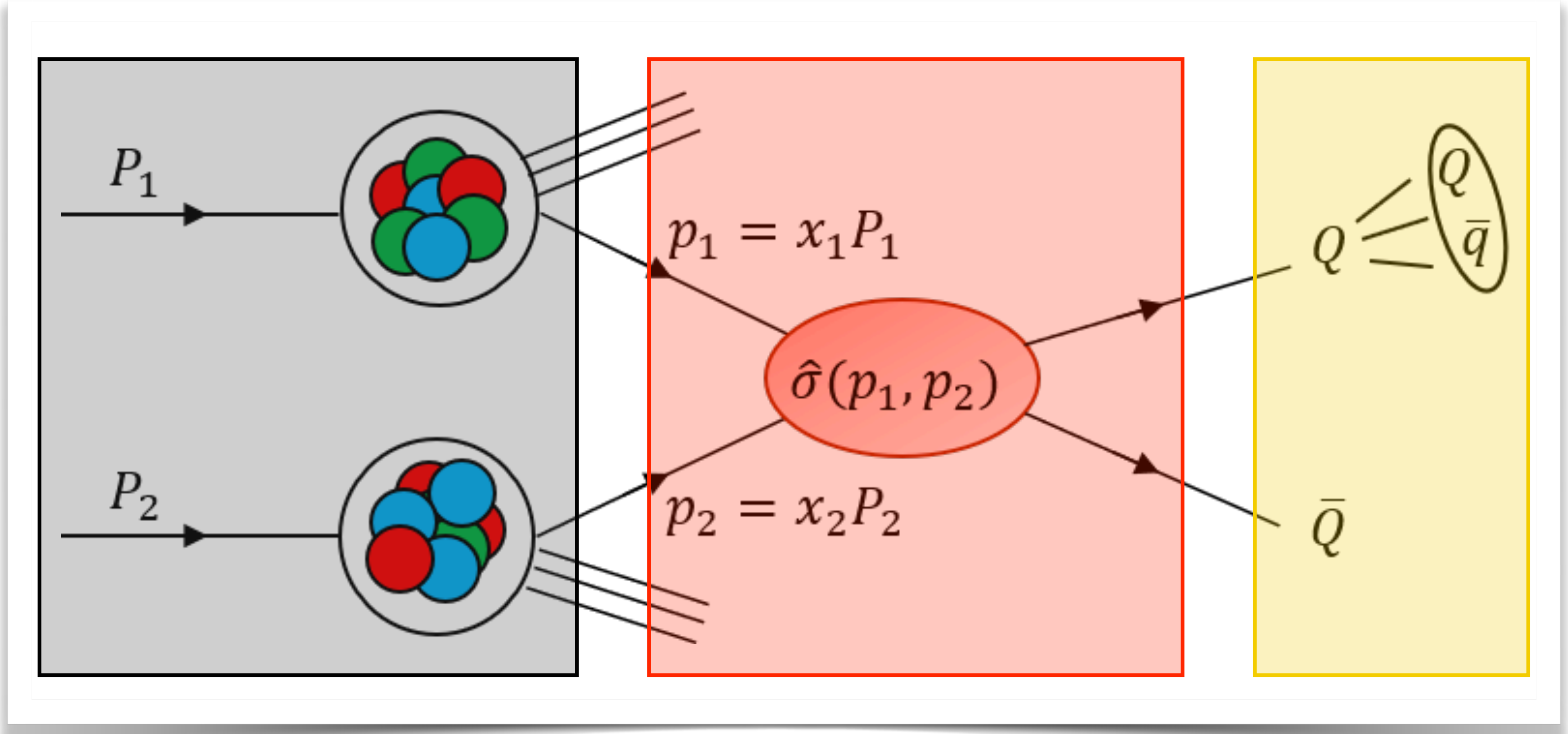
Heavy-flavour production in small systems

- Heavy quarks produced in initial hard-scattering processes

- Inclusive hadron production from hard-scattering processes (large Q^2)
  → factorization of: PDFs, partonic cross section, fragmentation function

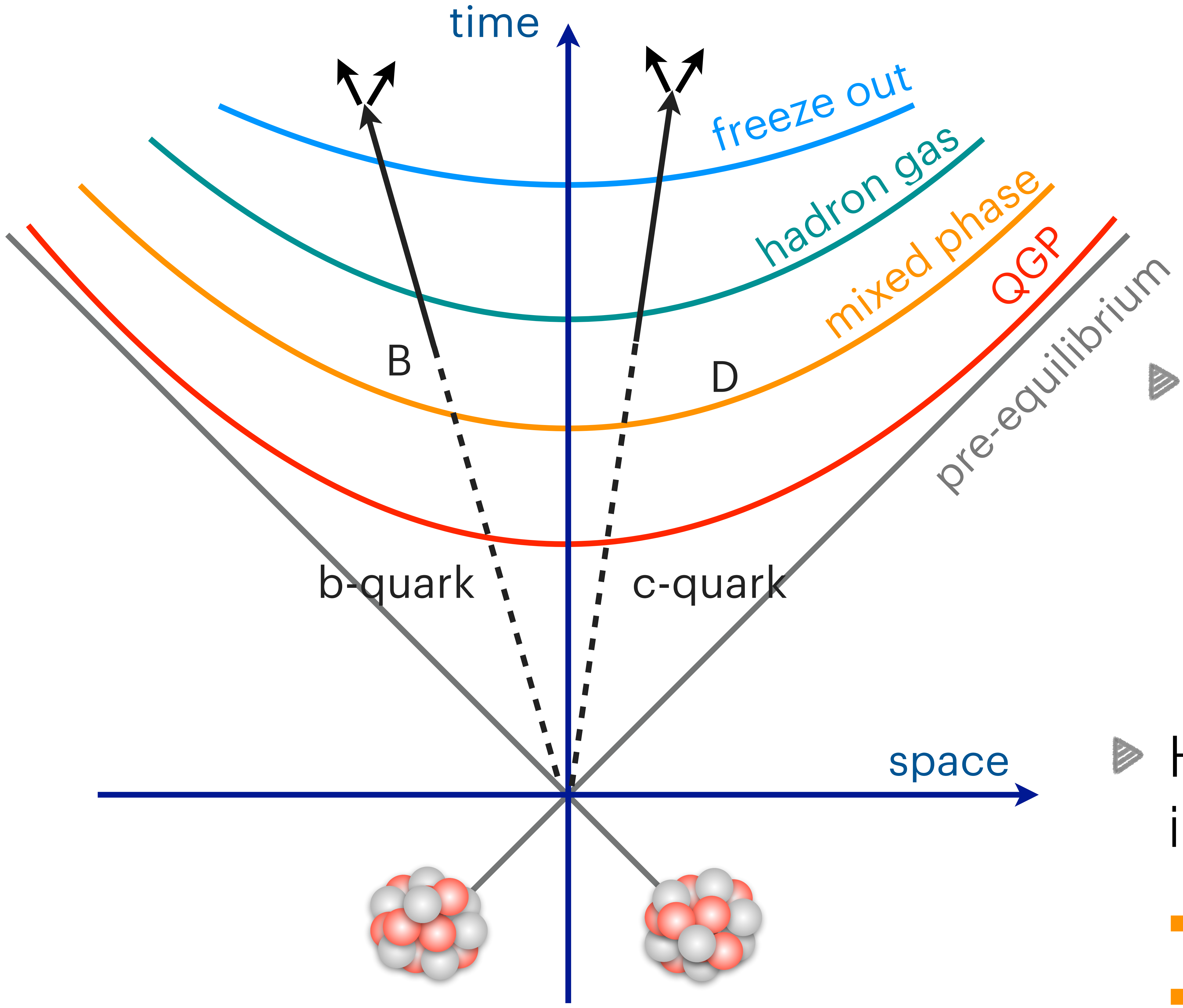
$$\frac{\mathrm{d}\sigma^{\mathrm{H_c}}}{\mathrm{d}p_{\mathrm{T}}} = \mathrm{PDF}(x_1, Q^2) \cdot \mathrm{PDF}(x_2, Q^2) \otimes \frac{\mathrm{d}\sigma^{\mathrm{c}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c}}}(x_1, x_2, Q^2) \otimes D_{\mathrm{c}\to\mathrm{H_c}}(z = p_{\mathrm{H_c}}/p_{\mathrm{c}}, Q^2)$$

Parton distribution functions (PDFs)	Hard scattering cross section (pQCD)	Fragmentation function (hadronisation)



- Fragmentation functions $D_{\mathrm{c}\to\mathrm{H_c}}(z, Q^2)$
  - phenomenological functions → non-perturbative parton-to-hadron transition
  - z = fraction of the parton momentum taken by the hadron $\mathrm{H_c}$
  - parameterized on data and assumed to be universal

Heavy-flavour production in large systems

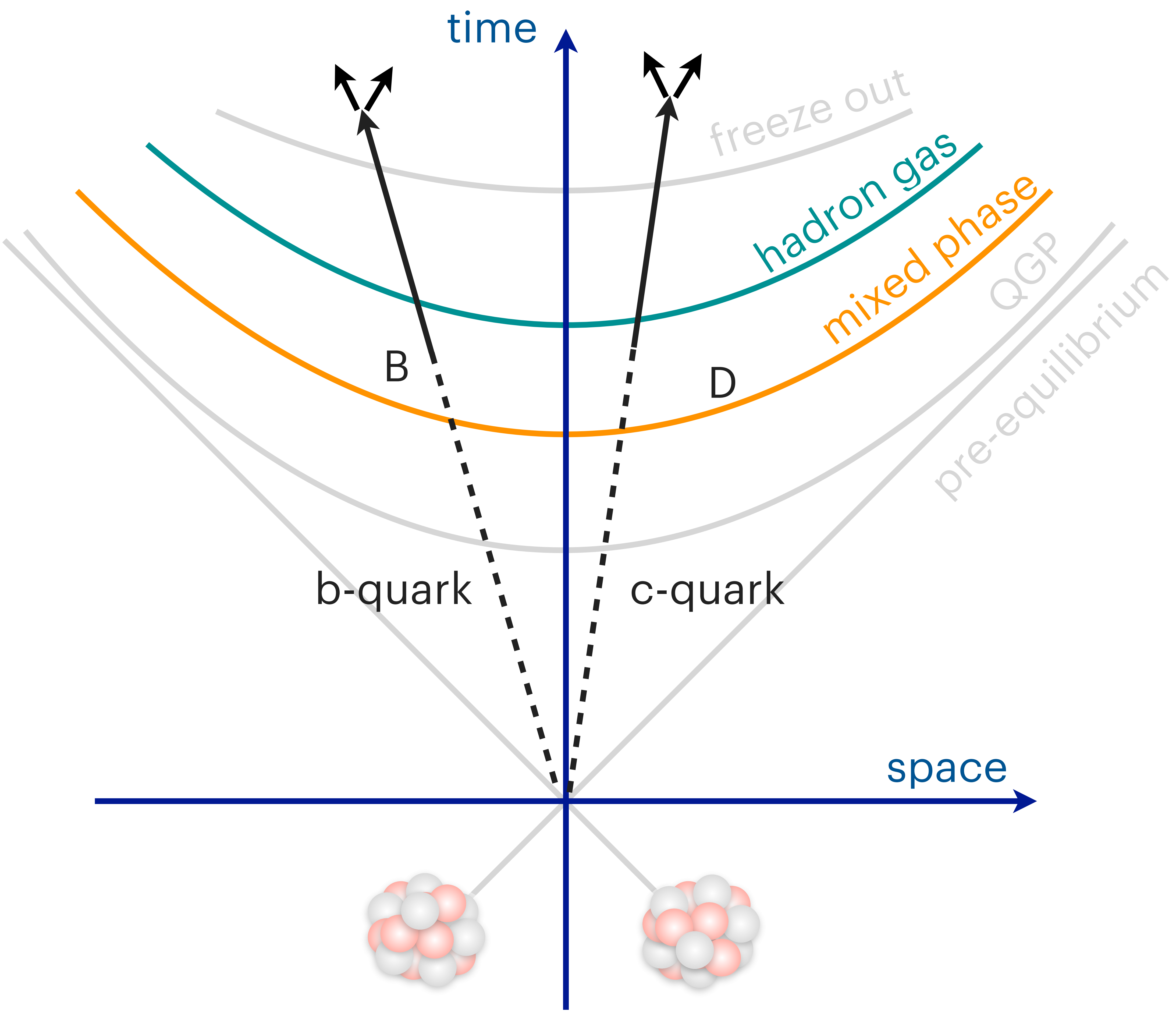


- In ultra relativistic heavy-ion collisions → colour-deconfined medium, called quark-gluon plasma (QGP)
  - ➡ high energy density $\varepsilon > 15\ \mathrm{GeV/fm^3}$
  - ➡ hydrodynamic expansion after a pre-equilibrium phase
- Hadronization from QGP medium at pseudo-critical temperature
  - ➡ transition from a deconfined medium to a colour-neutral hadronic matter
- Heavy flavours produced in hard-scattering processes in the early stages of the collision
  - ➡ $\tau_{\mathrm{HF}} \simeq \hbar/m \simeq 0.05\text{-}0.1\ \mathrm{fm}/c$
  - ➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) $\simeq 0.3\ \mathrm{fm}/c$

  ⟶ experience the full system evolution

F.M. Liu et al., PRC 89, 034906 (2014)

Heavy-flavour production in large systems



- Two mechanisms for HF hadronisation in heavy-ion collisions
  1. Fragmentation $D_{q \to h}(z_q, Q^2)$
  2. Coalescence
     ➡ partons close in space and with similar velocities

V. Greco et al., PRL 90, 202302 (2003)
R.C. Hwa et al., PRC 67, 064902 (2003)
R.J. Fries et al., PRL 90, 202303 (2003)
V. Greco et al., PLB 595 (2004) 202-208

- Statistical hadronisation model (SHM)
  ➡ hadrons from the interaction region in statistical equilibrium
  ➡ thermal origin of particle production → macroscopic description in terms of thermodynamic variables

A. Andronic et al., PLB 659 (2008) 149-155
A. Andronic et al., JHEP 07 (2021) 035

Heavy-flavour production in large systems

Two key observables

2003)

-208

A. Andronic et al., JHEP 07 (2021) 035

Two key observables

1. Nuclear modification factor

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

production yields in AA collisions

production yields in pp collisions

binary nucleon-nucleon collisions

2003)

-208

A. Andronic et al., JHEP 07 (2021) 035

Heavy-flavour production in large systems

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- production yields in AA collisions
- production yields in pp collisions
- binary nucleon-nucleon collisions

2003)

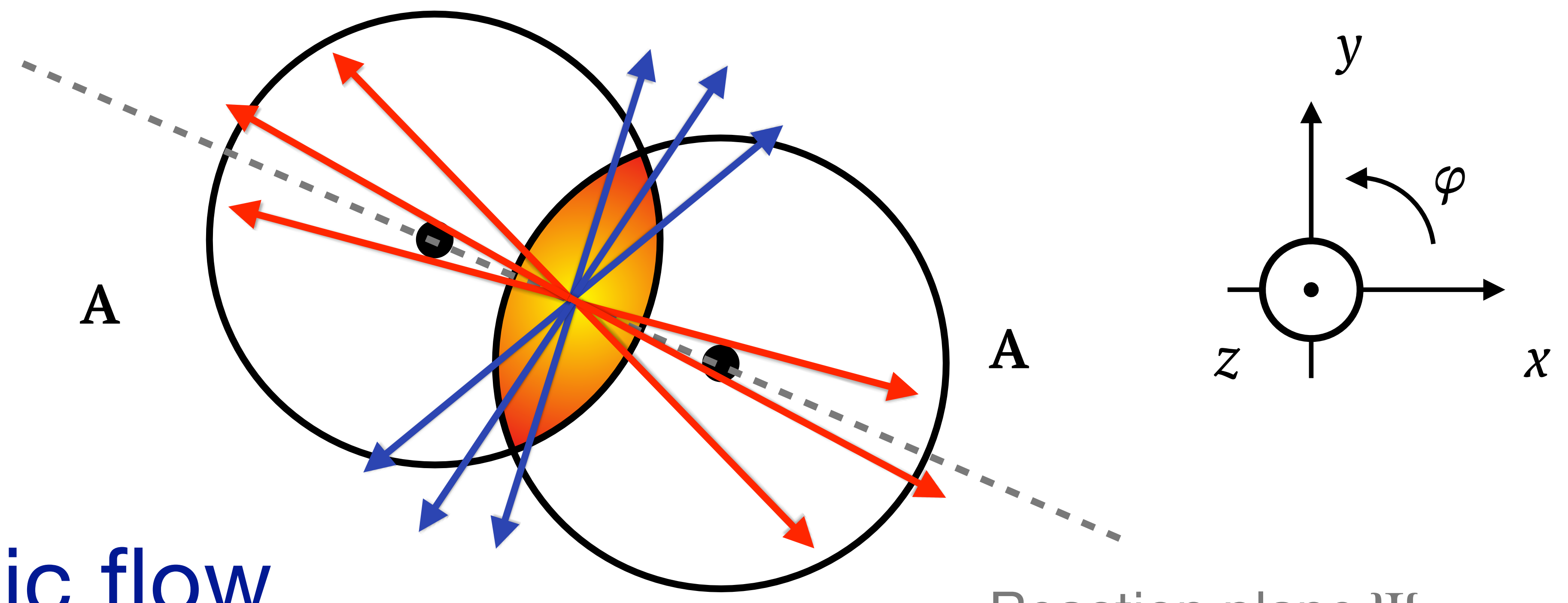
-208

2. Azimuthal anisotropies

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p_{\mathrm{T}}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\left\{1 + \sum_{i=1}^{\infty} v_{\mathrm{n}} \cos[\mathrm{n}(\varphi - \Psi_{\mathrm{n}})]\right\}$$

$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

second harmonic coefficient elliptic flow



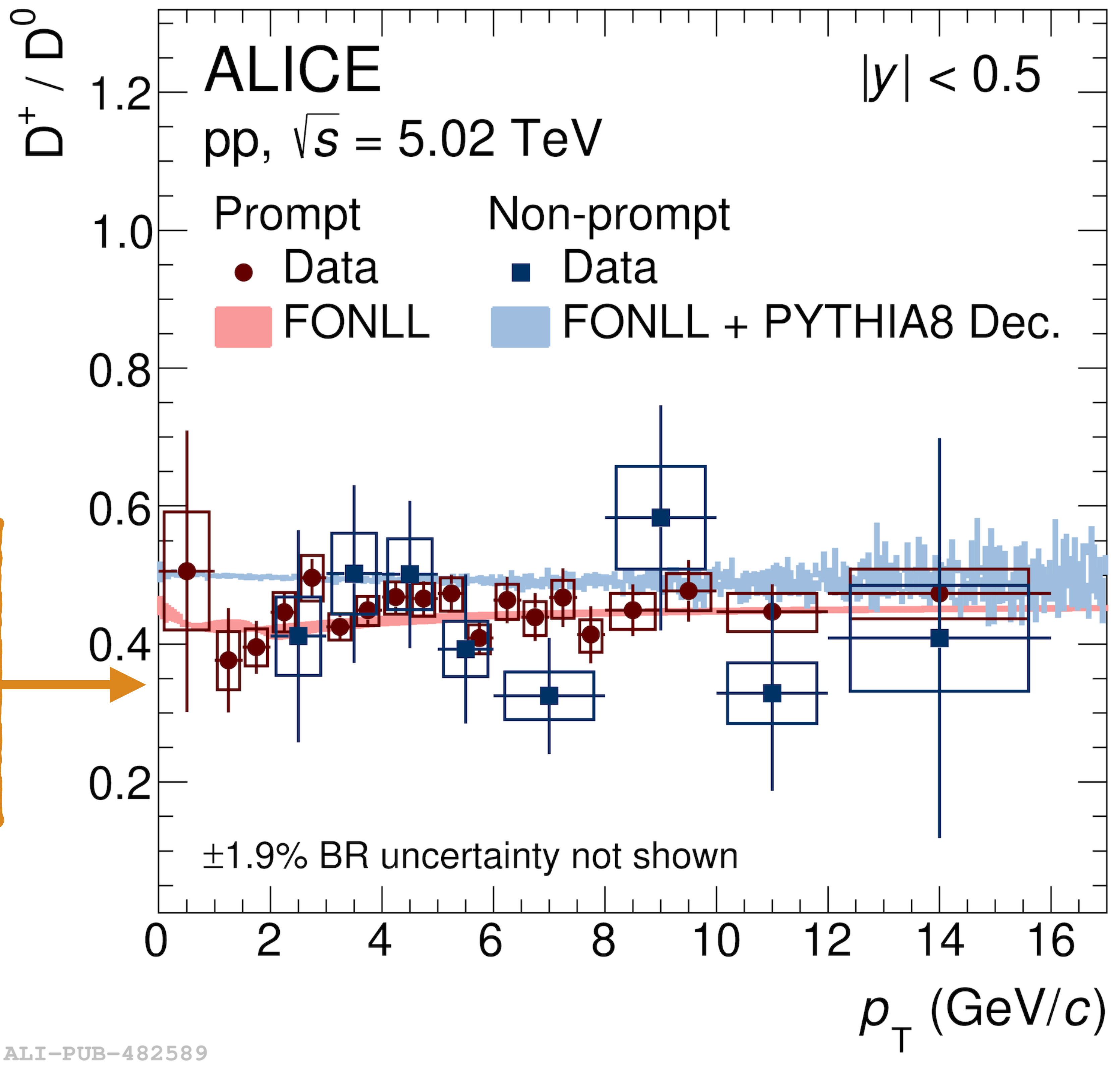
A. Andronic et al., JHEP 07 (2021) 035

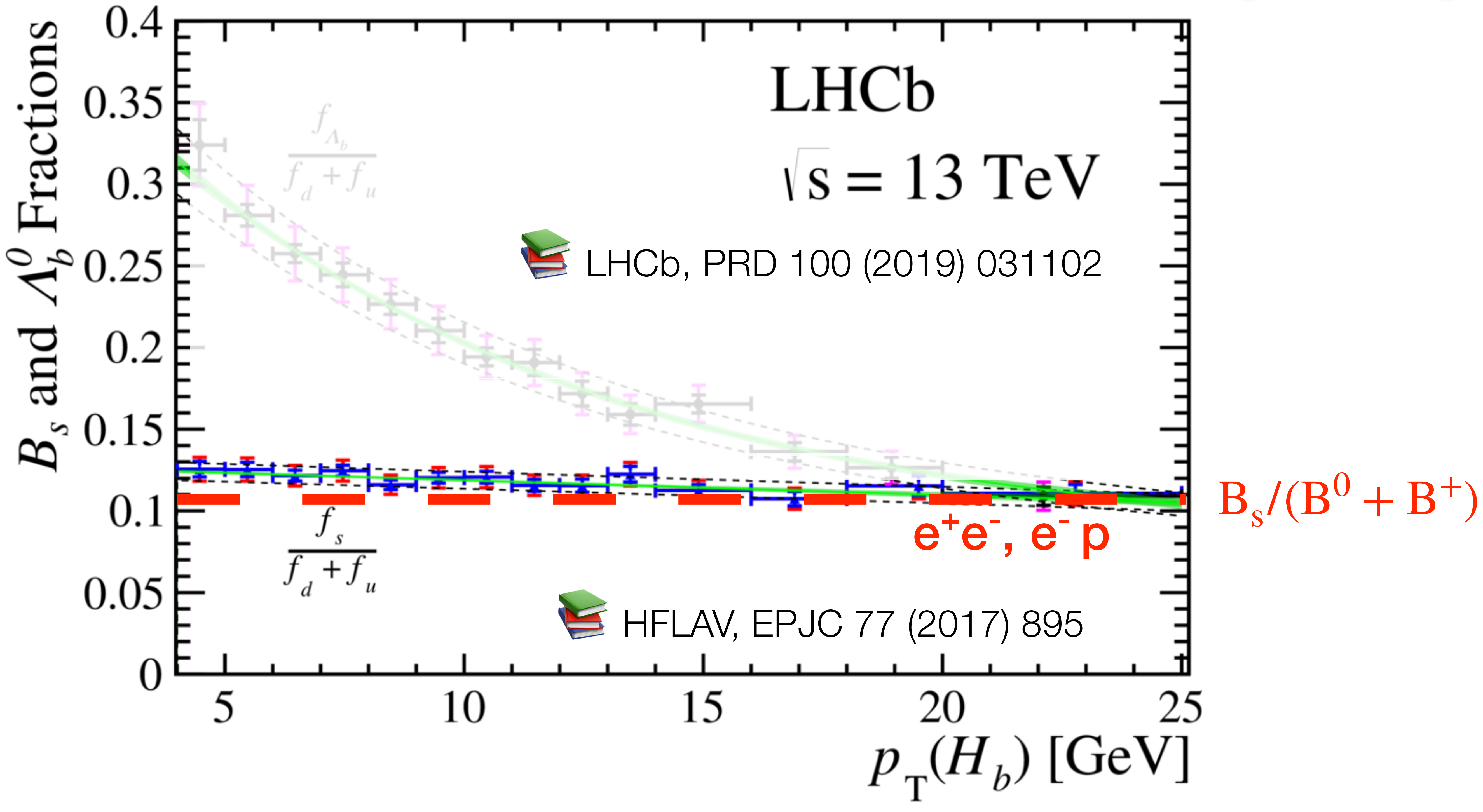
Mesons

Charm and beauty meson production in pp collisions

ALICE, JHEP 05 (2021) 220

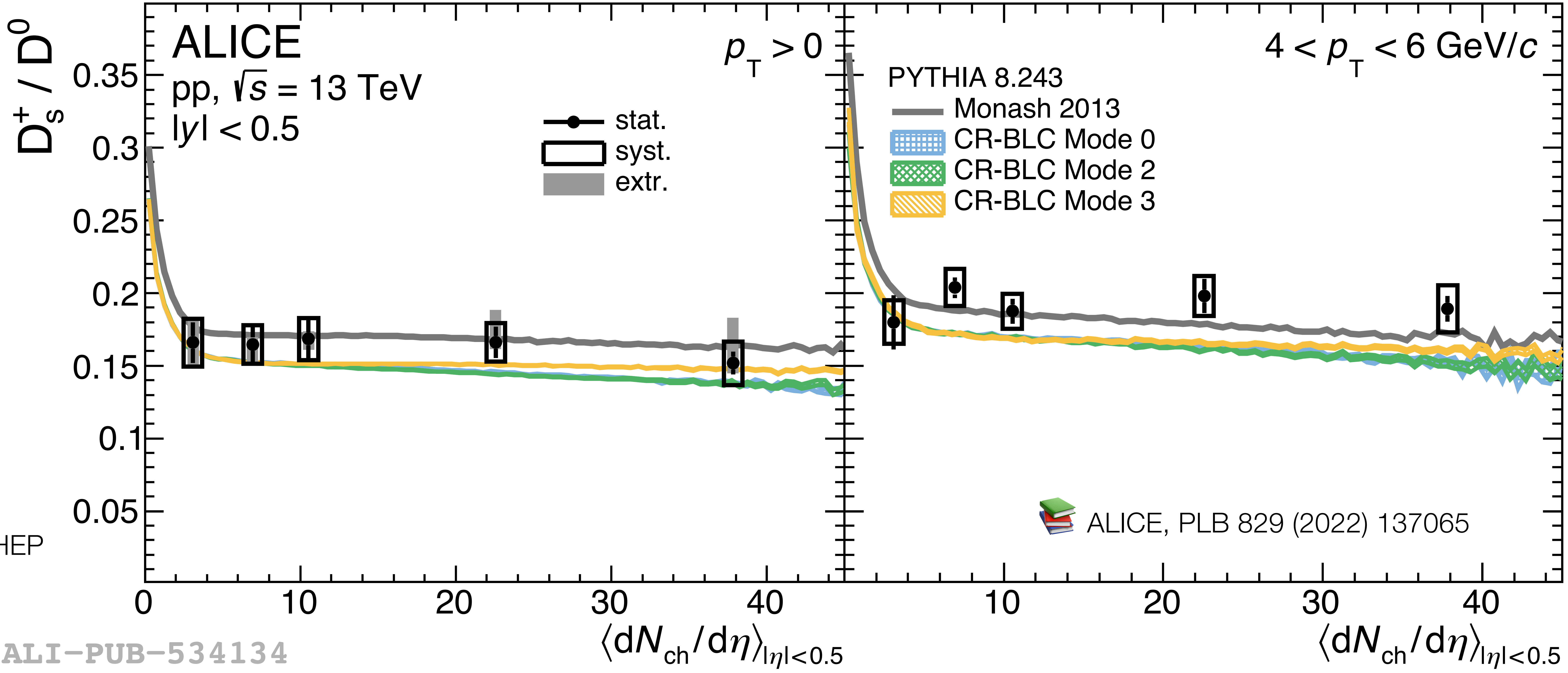
Ratios independent of p_T





- Agreement with model calculations (FONLL) based on factorisation approach and relying on fragmentation functions universality (e^+e^-, e^-p)
  - ➡ D meson ratios compatible with e^+e^- measurements
- $B^0_s/(B^0 + B^+)$ compatible with e^+e^- measurements

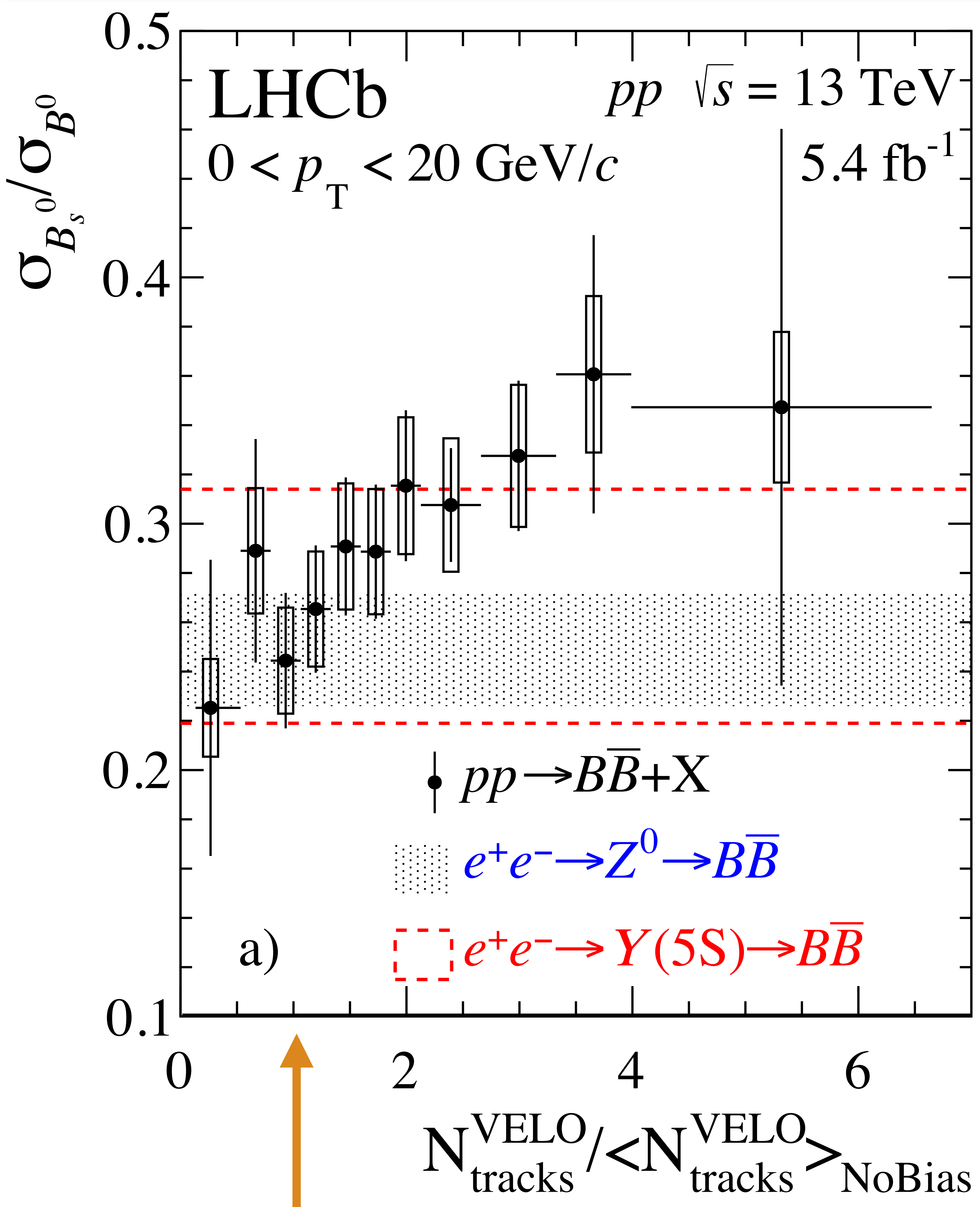
Charm hadronization vs. multiplicity in pp collisions

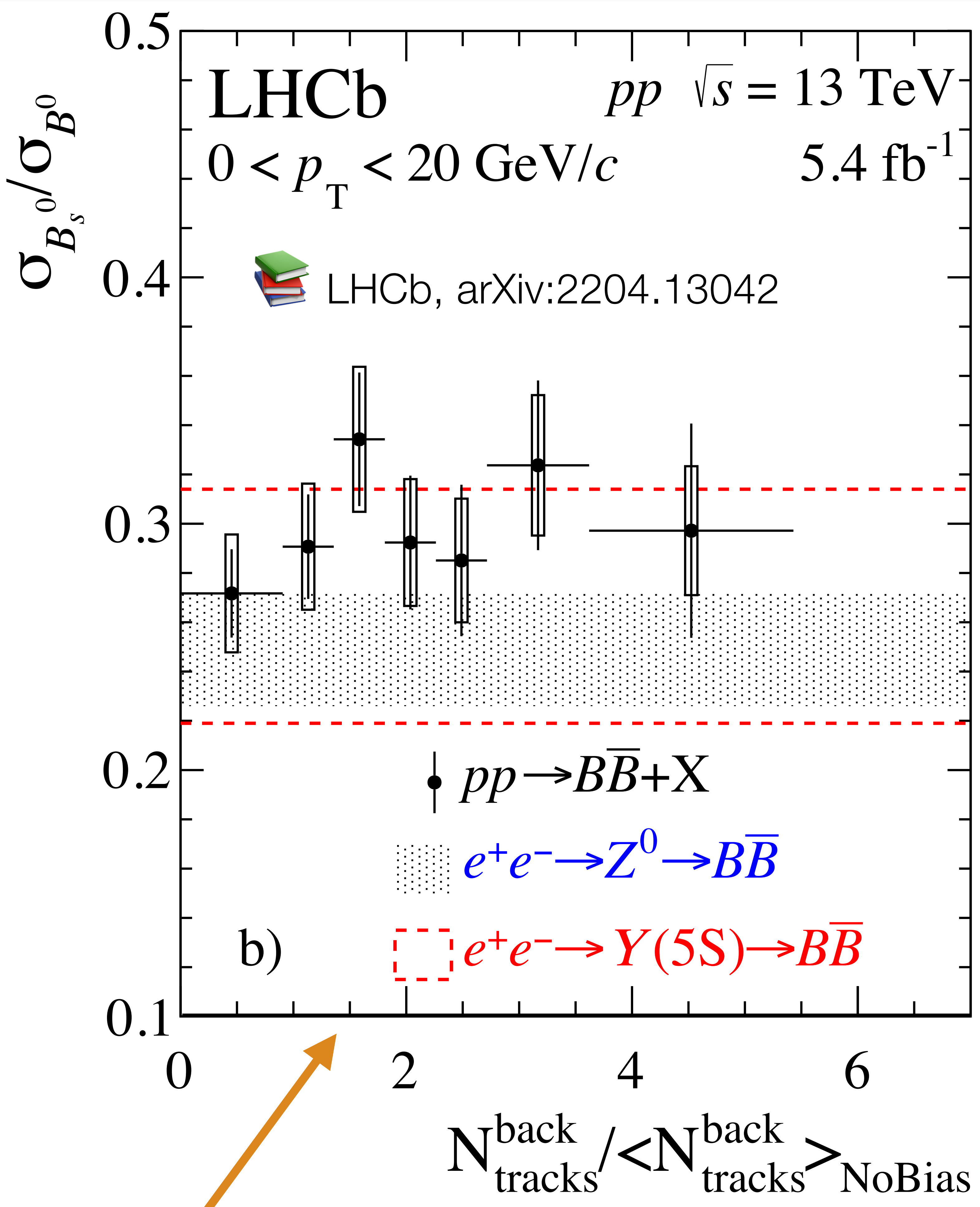


PYTHIA 8: JHEP 1508 (2015) 003

- Charm quark production dominated by hard parton-parton scatterings
- D_s/D^0 does not show dependence with increasing multiplicity
  - ➡ better agreement with Monash 2013 tuning, though CR-BLC compatible within uncertainties

CR-BLC → based on Monash + additional topologies for Color Reconnection mechanisms





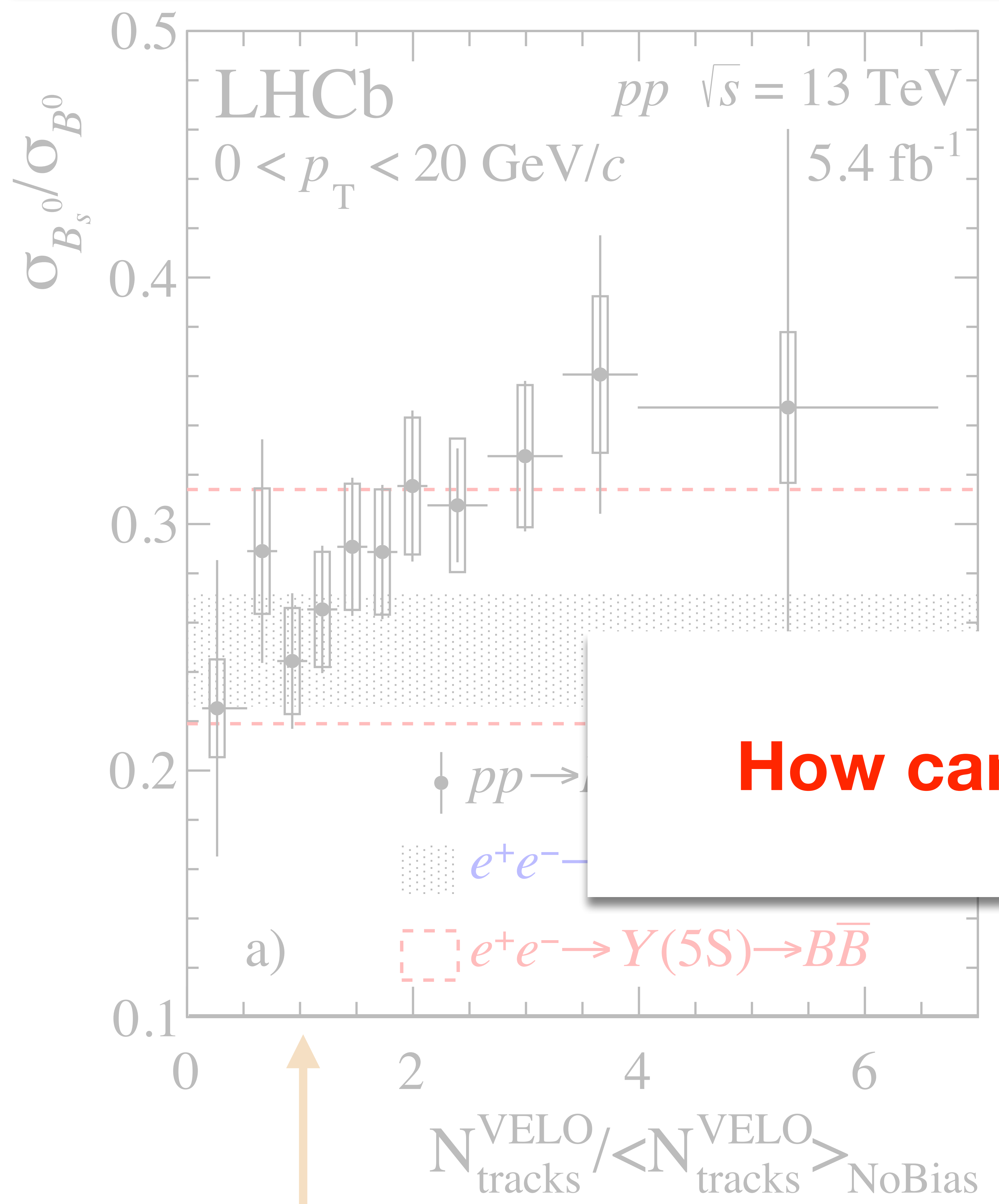
- Beauty quark production dominated by hard parton-parton scatterings
- Increase of strangeness production with increasing multiplicity
- Hadronization via recombination may enhance B_s/B^0 with increasing multiplicity

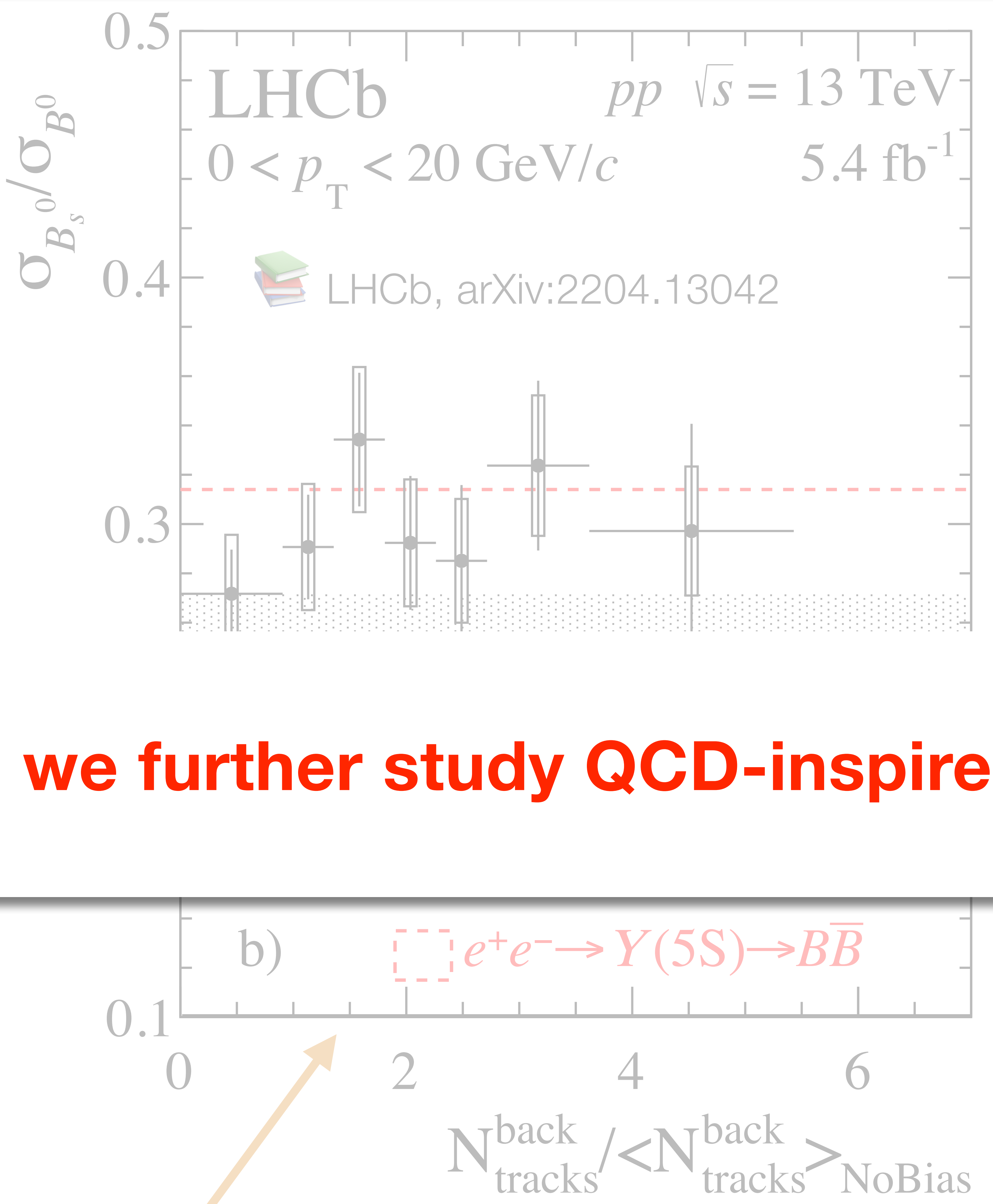
➡ B_s/B^0 at low p_T increases with local particle density

Increasing B_s/B^0 vs. multiplicity in the VELO

B_s/B^0 vs. multiplicity → no significant dependence at backward rapidity

Beauty hadronization vs. multiplicity in pp collisions





- Beauty quark production dominated by hard parton-parton scatterings
- Increase of strangeness production with increasing multiplicity
- ...n via recombination ... B_s/B^0 with increasing multiplicity

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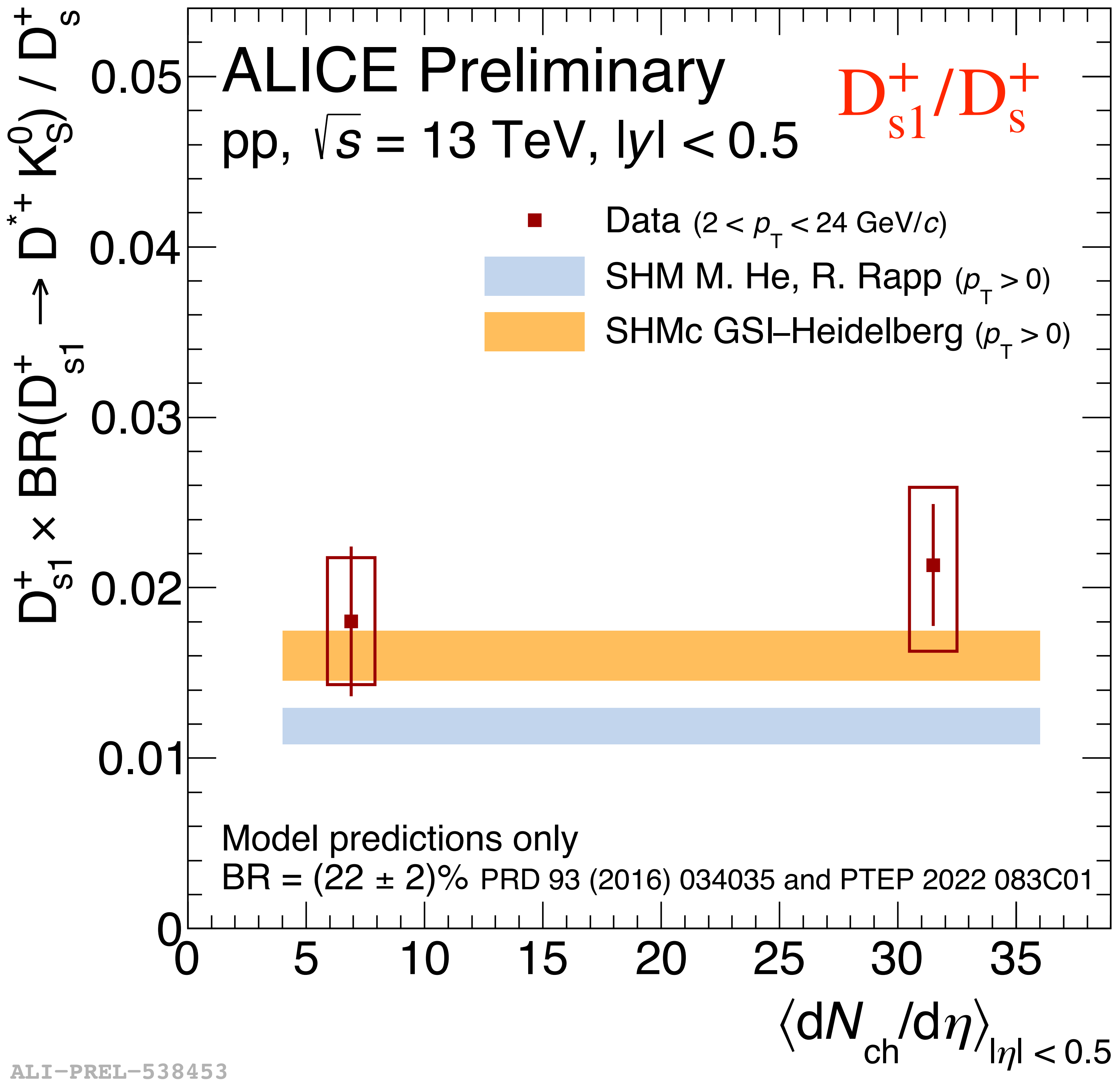
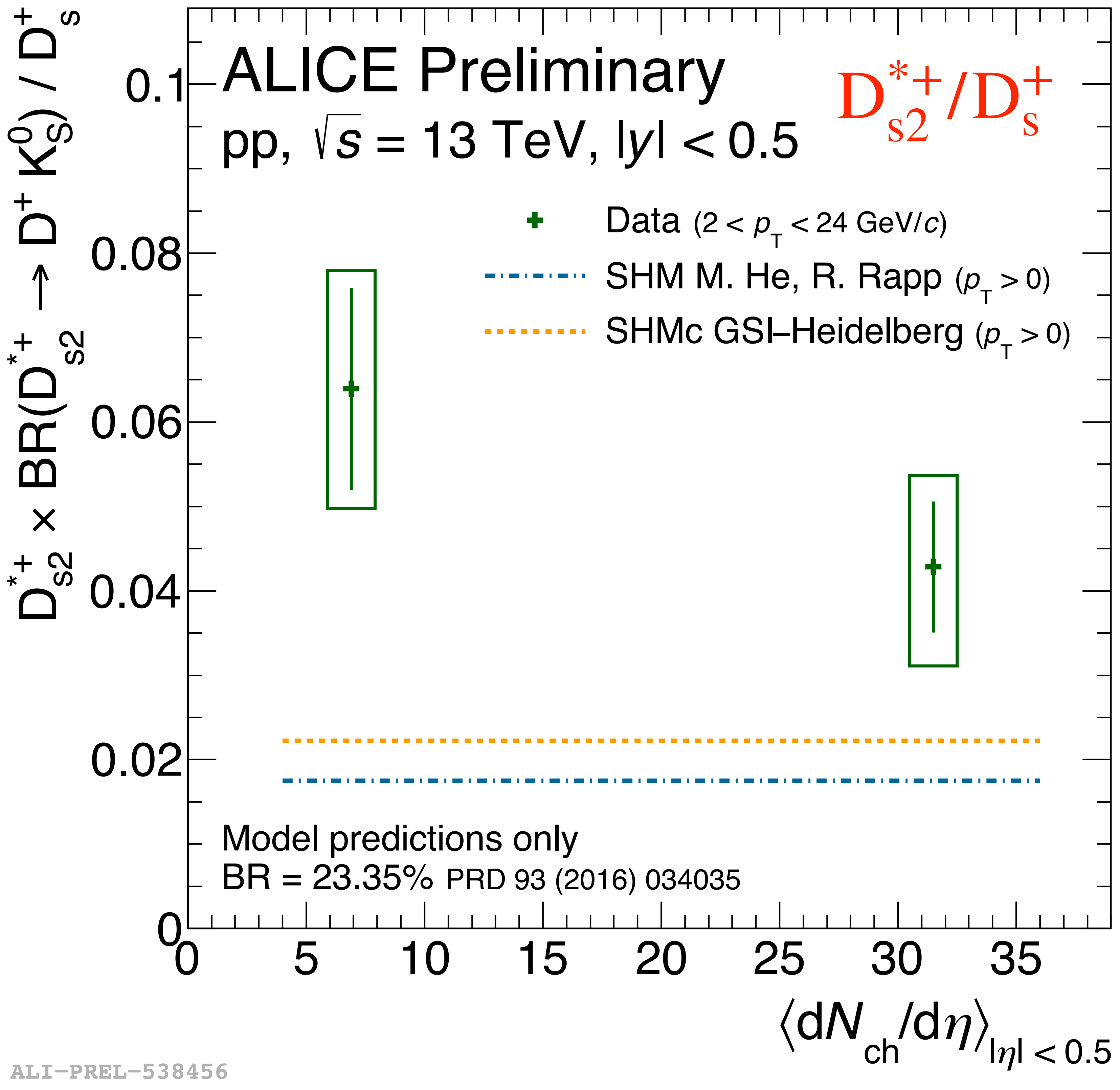
How can we further study QCD-inspired models?

Increasing B_s/B^0 vs. multiplicity in the VELO

B_s/B^0 vs. multiplicity → no significant dependence at backward rapidity





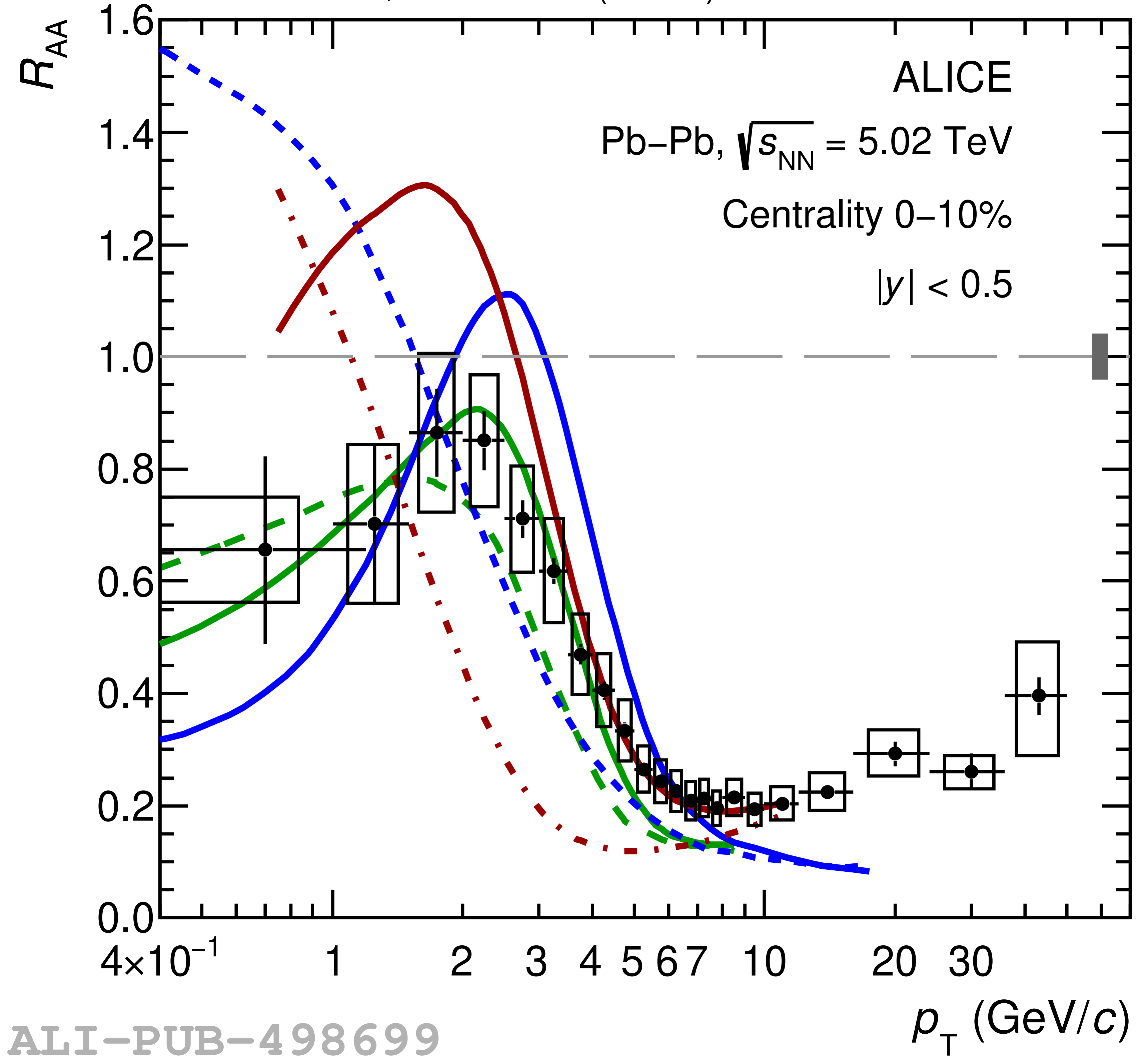
- Ratio to ground states factorise strangeness and charm dependencies for prediction
- No multiplicity dependence expected from SHM and SHMc

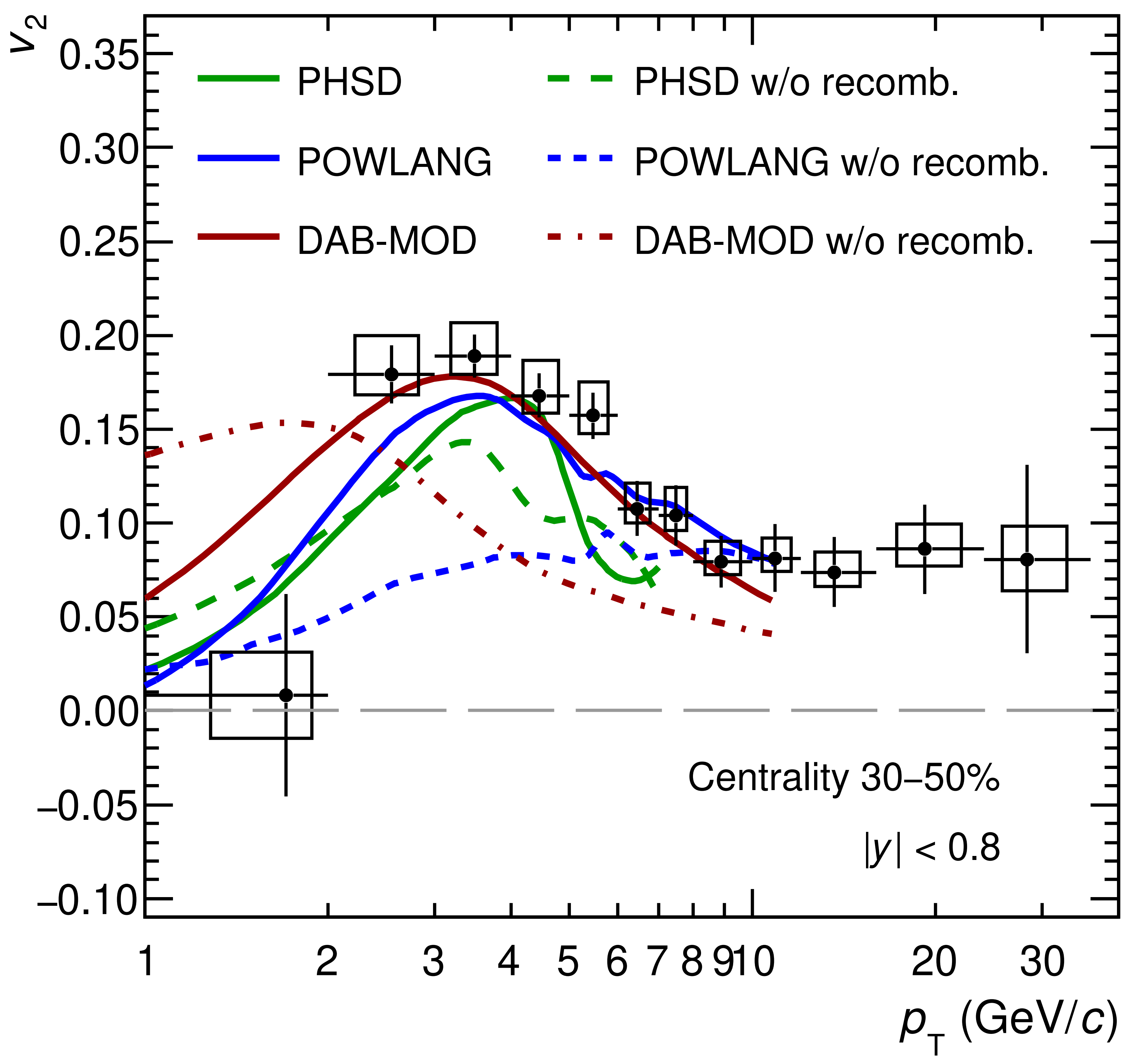
$\tau(D_{s1}^+) \sim 219$ fm/c;
$\tau(D_{s2}^{*+}) \sim 11.61$ fm/c

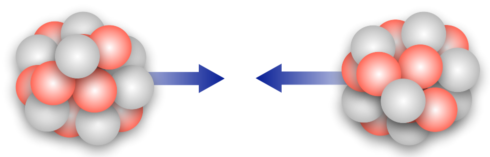
- D_{s1}^+/D_s^+ and D_{s2}^{*+}/D_s^+ p_T-integrated yield ratios → compatible vs. mult. within uncertainties
  - ➡ D_{s1}^+/D_s^+ no multiplicity dependence observed in data and agreement with models within uncertainties
  - ➡ D_{s2}^{*+}/D_s^+ potential trend which might arise from hadronic rescattering due to D_{s2}^{*+} lifetime

SHM: He et al., PLB 795 (2019) 171
SHMc: Andronic et al., JHEP 07 (2021) 035

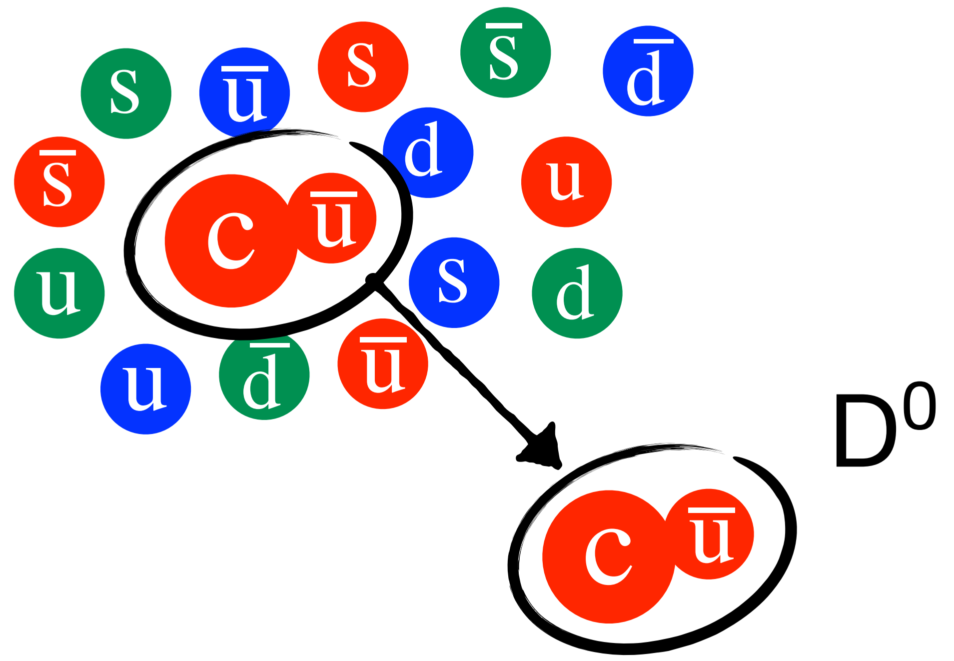
ALICE, JHEP 01 (2022) 174







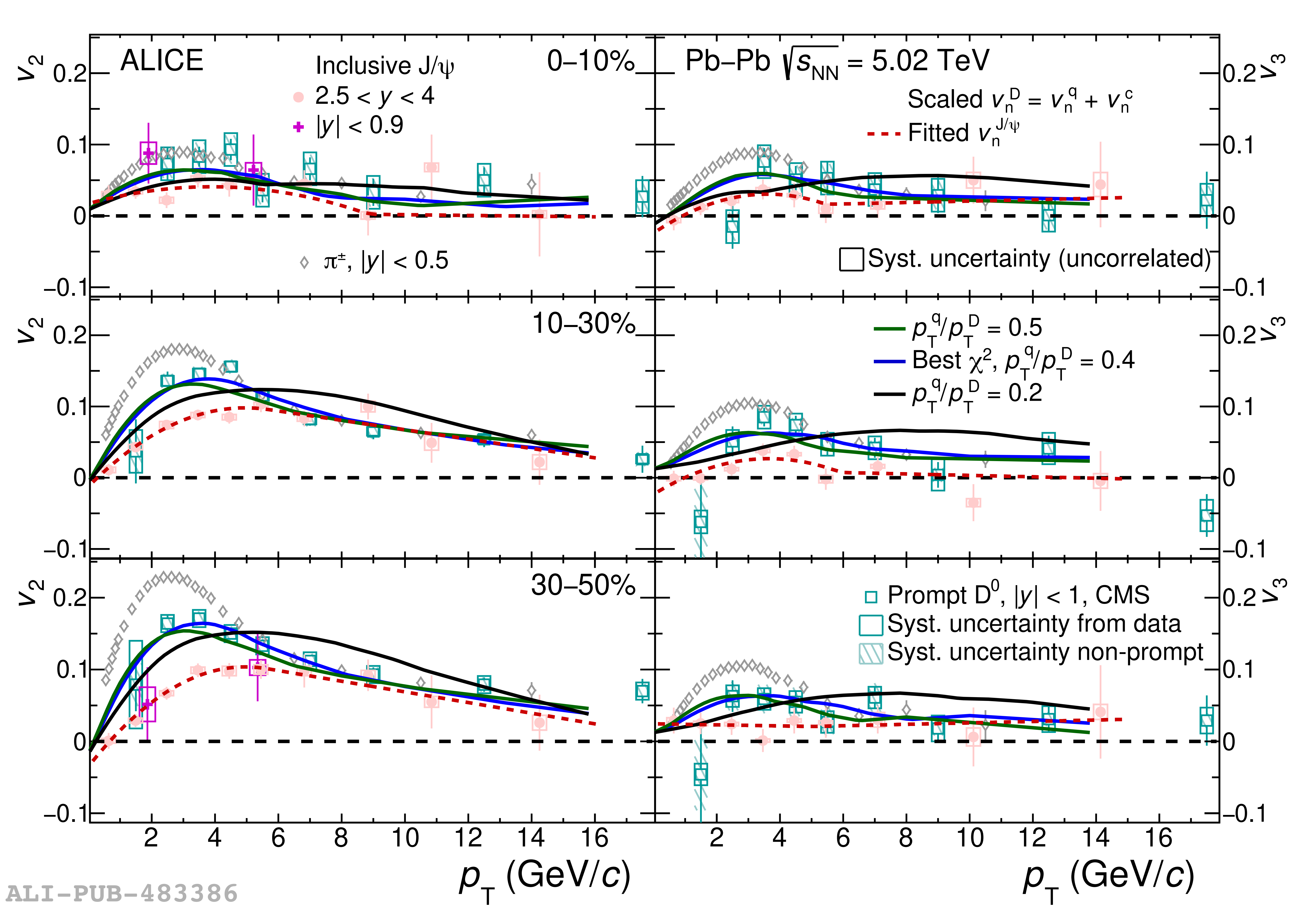
- Recombination of heavy quarks with light quarks from QGP affects HF hadrons momentum distribution
  ➡ HF hadrons pick-up the radial and elliptic flow of light quark



- Relation between p_{charm} and p_D is different for fragmentation and recombination
  ➡ recombination → $p_D > p_{charm}$ and D meson inherits also the flow of light quark

Recombination is a crucial component to describe the data at low/mid p_T

Recombination in heavy-ion collisions



- Test of the n-quark scaling and coalescence mechanism
  - ➡ quark flow obtained by interpolating $v_n(J/\psi)$ and $v_n(\pi)$
  - ➡ assumption $v_n^{\pi}(p_T^{\pi}) = 2 \cdot v_n^{q}(p_T^{\pi}/2)$

$$v_n^{D}(p_T^{D}) = v_n^{q}(p_T^{q}) + v_n^{c}(p_T^{c})$$

  - ➡ good description of D^0 flow when light quark carries a large fraction (i.e. $p_T^q/p_T^D = 0.4$) of D-meson p_T

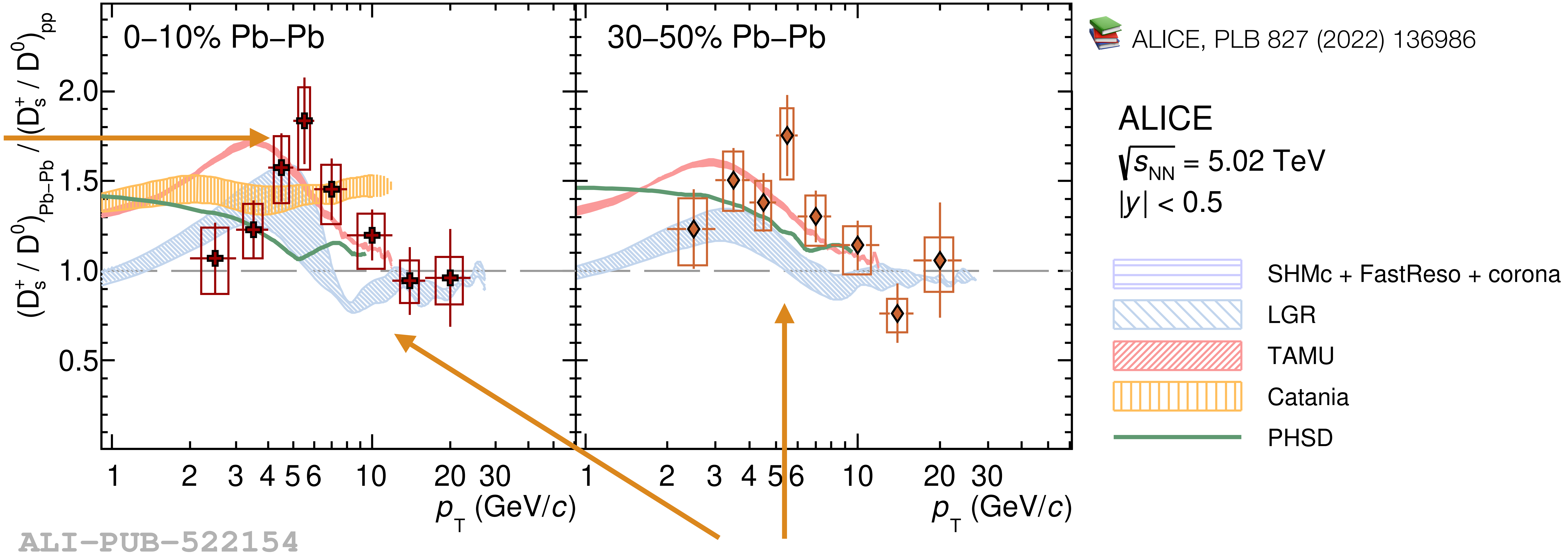
ALICE J/ψ: JHEP 10 (2020) 141

Recombination is a crucial component to describe the data at low/mid p_T

Open charm hadrochemistry: D_s^+/D^0

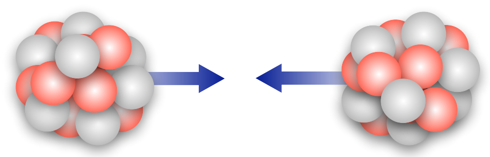
- Recombination of heavy quarks with light quarks from the QGP affects HF hadrochemistry
  - ➡ enhanced D_s^+ yield relative to non-strange mesons (strange quarks more abundant in QGP)
  - ➡ as expected in a scenario with hadronization via fragmentation and recombination

D_s/D^0 ratios in central and semicentral Pb-Pb hint of enhancement at mid p_T relative to pp



ALICE, PLB 827 (2022) 136986

Described by SHMc and by different models including hadronization via recombination



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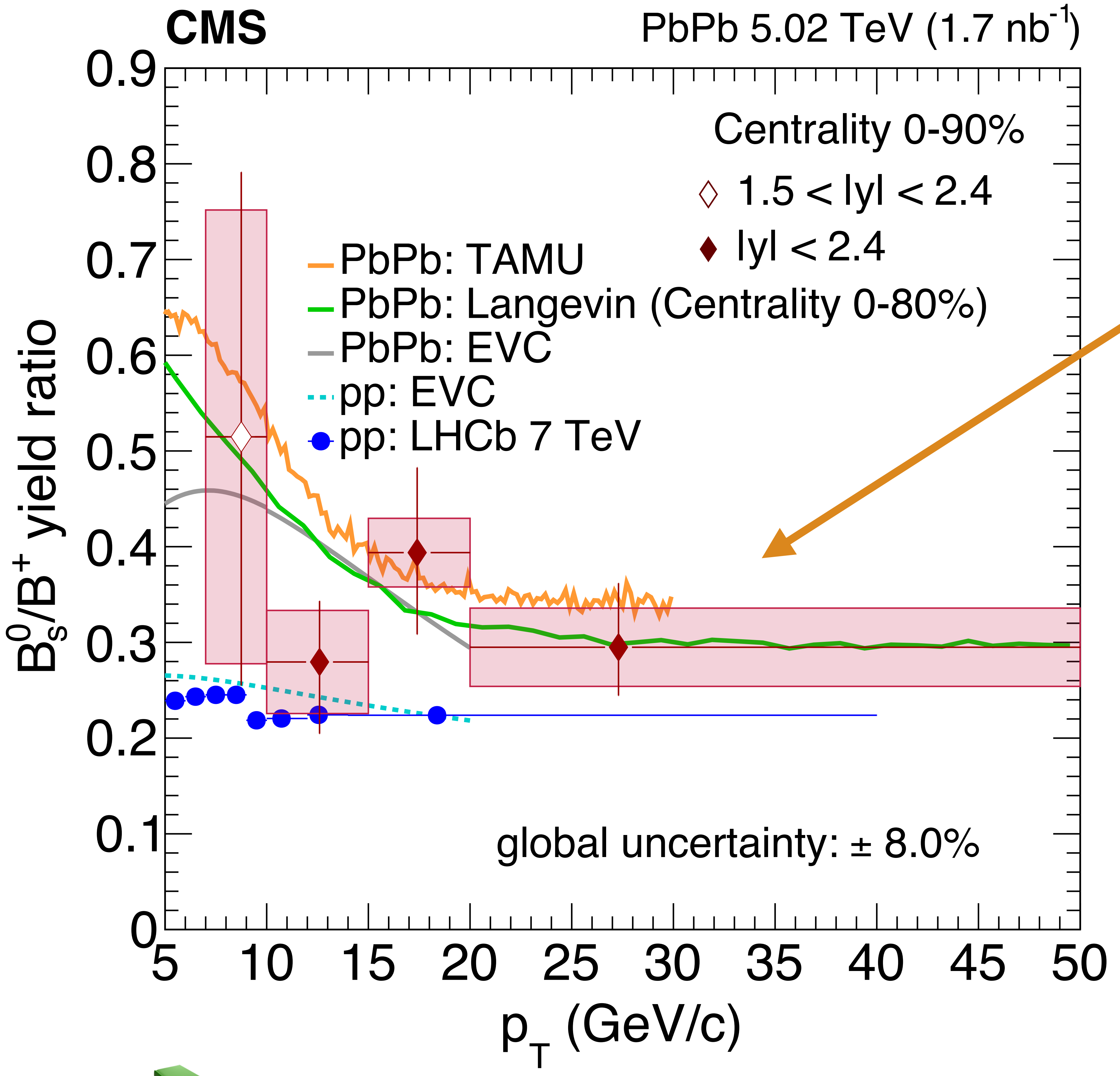
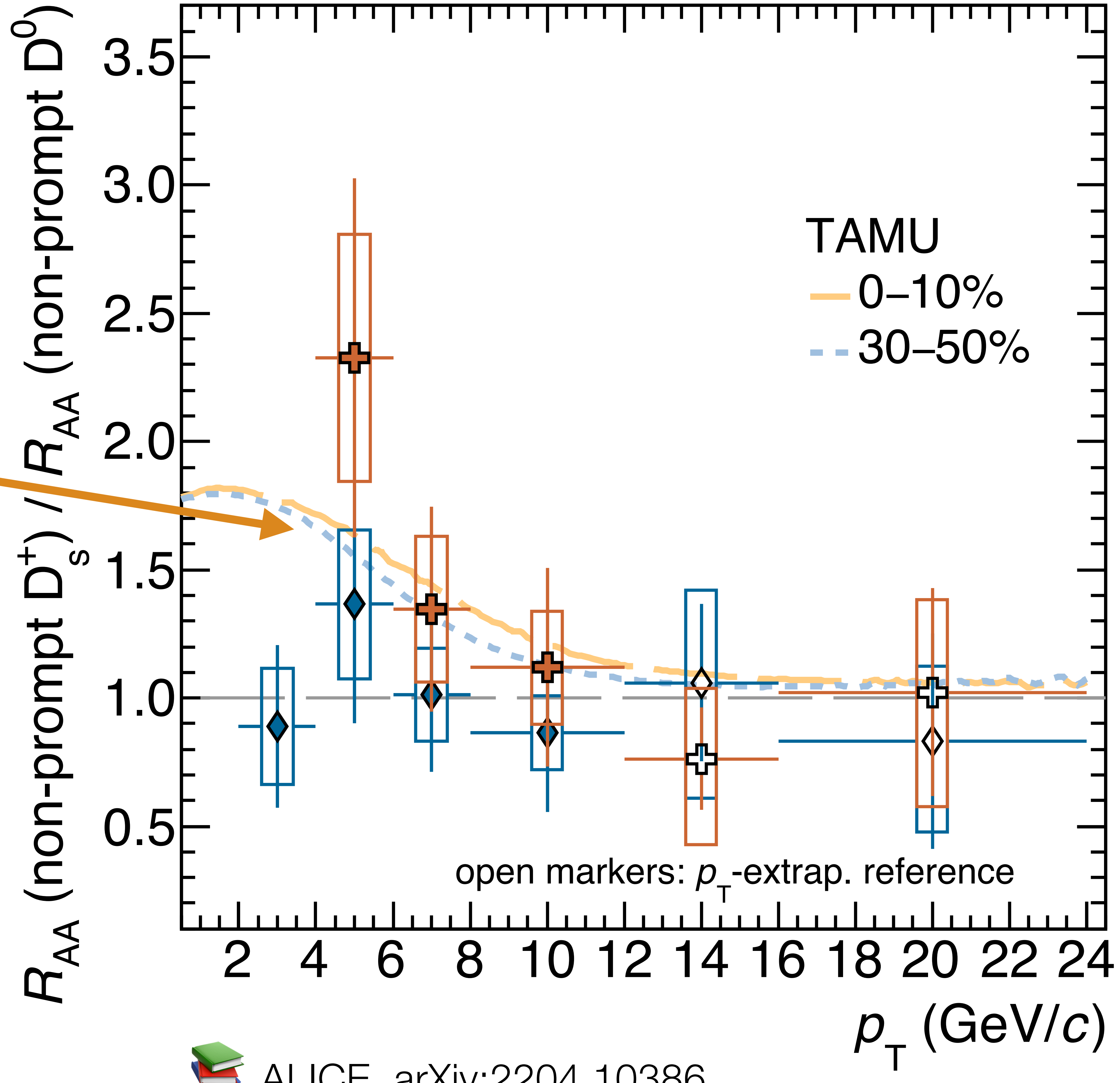


B_s/B^+ in Pb-Pb tend to lie systematically above the pp results

Hint of R_{AA} of non-prompt D_s larger than non-prompt D^0

➡ Non-prompt D_s origin:

- 50% from B_s
- 50% from B^0, B^+

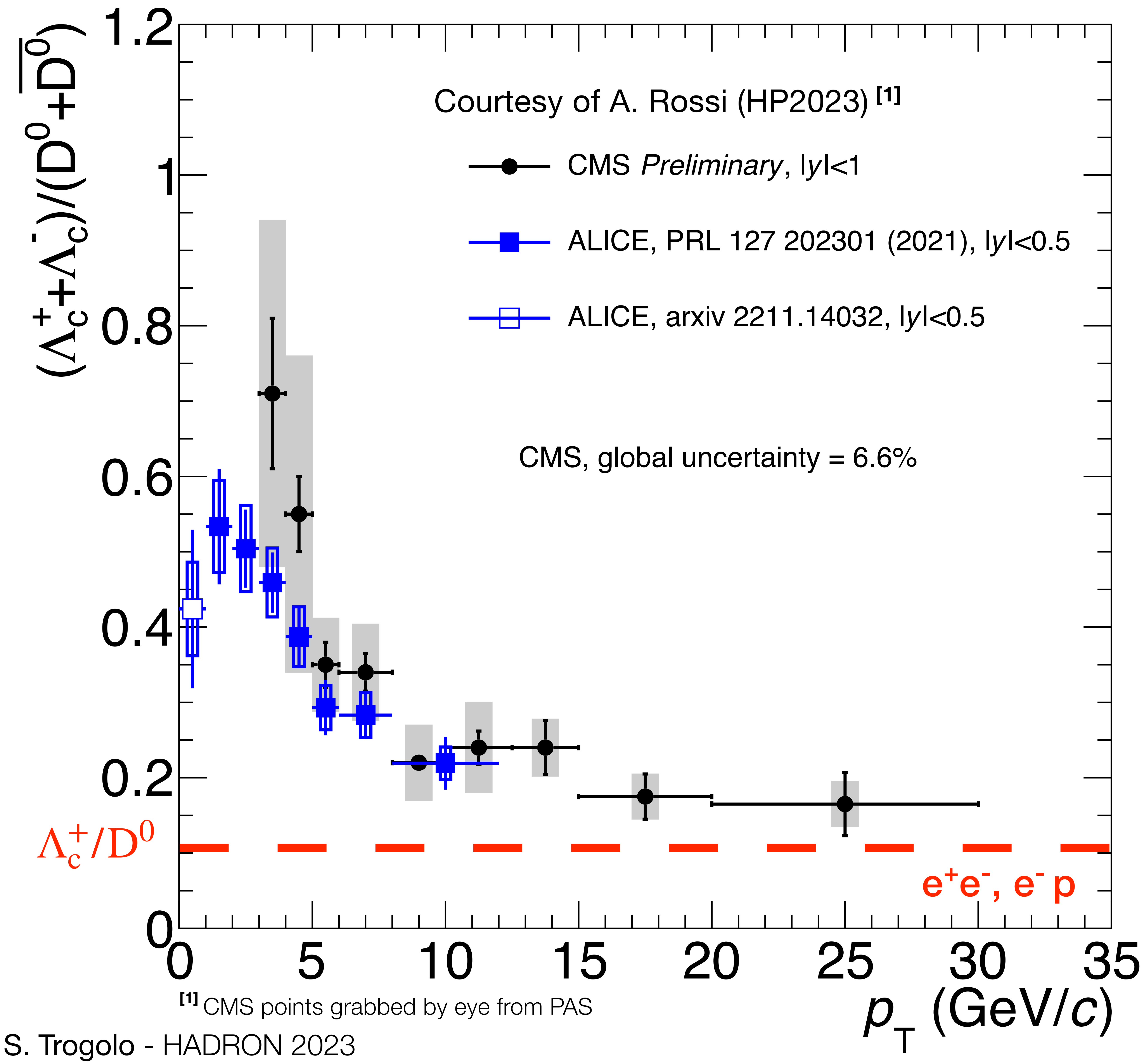


CMS, PLB 829 (2022) 137062

ALICE, arXiv:2204.10386

Baryons

Baryon-to-meson ratio in pp collisions - charm

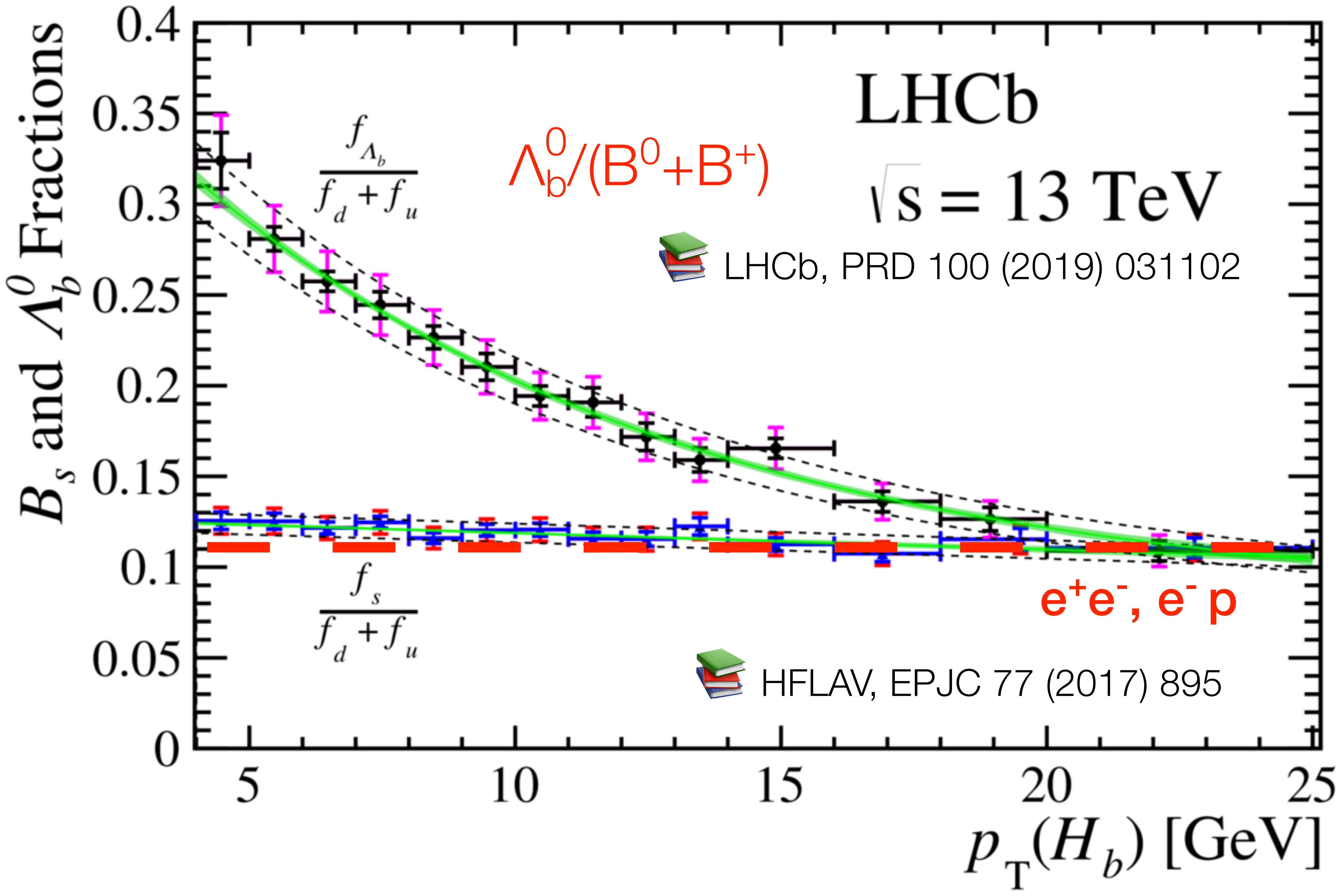


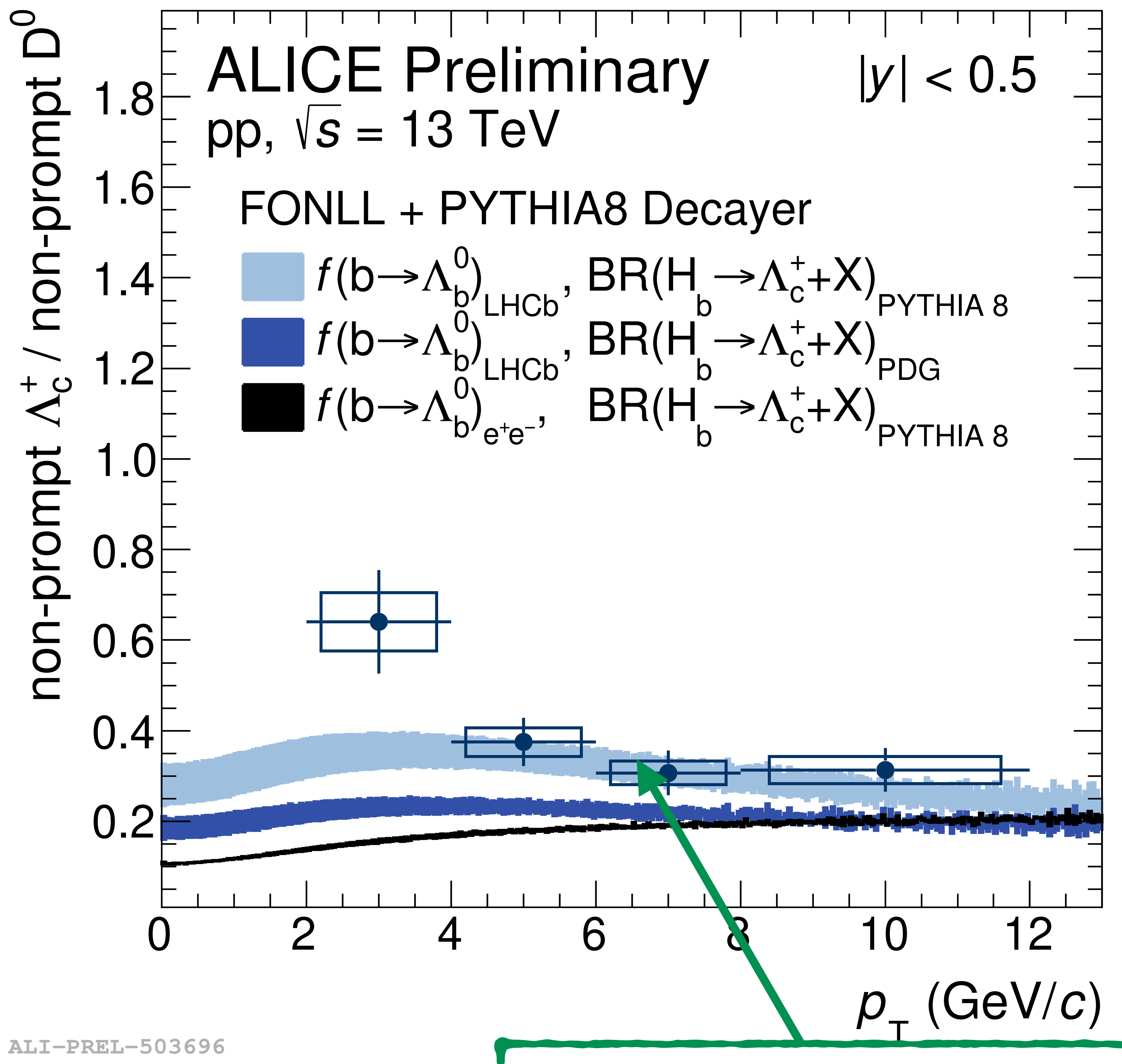
[1] CMS points grabbed by eye from PAS

- Enhancement at low p_T with respect to measurements at e^+e^-/e^-p:
  - ➡ Λ_c^+/D^0 ratio higher (x 4-5) at low p_T
  - → approaching e^+e^-/e^-p at high p_T

H_c	$f(c \to H_c)$ [%]	$f(b \to H_c)$ [%]
D^0	$54.2 \pm 2.4 \pm 0.7$	$58.7 \pm 2.1 \pm 0.8$
D^+	$22.5 \pm 1.0 \pm 0.5$	$22.3 \pm 1.1 \pm 0.5$
D_s^+	$9.2 \pm 0.8 \pm 0.5$	$13.8 \pm 0.9 \pm 0.6$
Λ_c^+	$5.7 \pm 0.6 \pm 0.3$	$7.3 \pm 0.8 \pm 0.4$
D^{*+}, rate	$23.4 \pm 0.7 \pm 0.3$	$23.3 \pm 1.0 \pm 0.3$
D^{*+}, double-tag	$24.4 \pm 1.3 \pm 0.2$	$17.5 \pm 2.0 \pm 0.1$
D^{*+}, combined	$23.6 \pm 0.6 \pm 0.3$	$22.1 \pm 0.9 \pm 0.3$

Λc/D (LEP) L. Gladilin, EPJC 75 (2015) 19
ALICE, PRC 104 (2021) 054905
ALICE, PRL 127 (2021) 202301
ALICE, arXiv:2211.14032
CMS, PAS-HIN-21-004



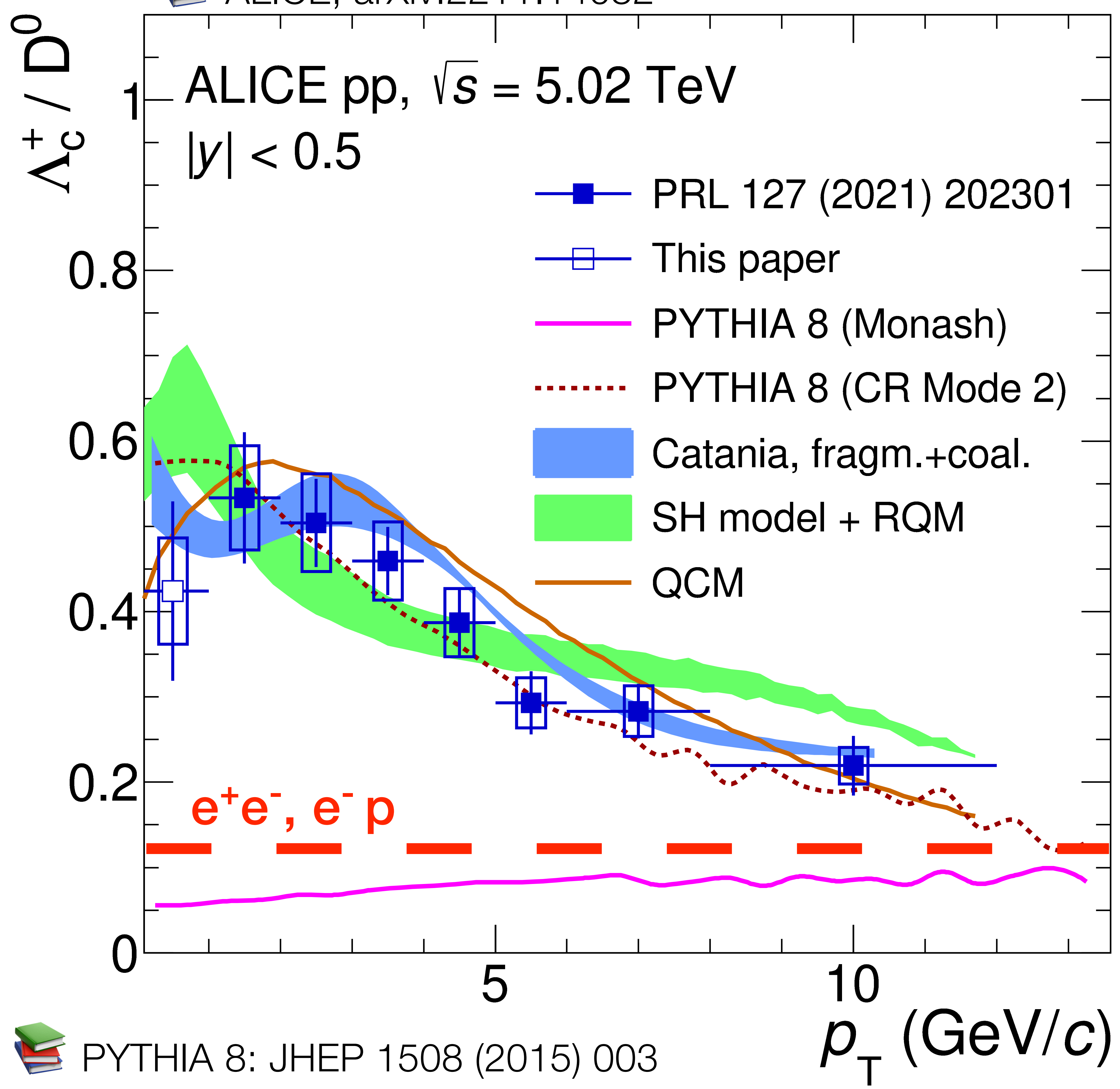


Access to the frag. of beauty quark via non-prompt ratio

- Enhanced beauty-baryon production w.r.t. e^+e^- collisions
  - ➡ similar trend observed in the beauty sector
  - ➡ non-prompt Λ_c^+/D^0 ratio well described with LHCb fragmentation fractions and PYTHIA 8 decay table

Prompt Λ_c^+/D^0 in pp collisions vs. models

ALICE, arXiv:2211.14032



PYTHIA 8: JHEP 1508 (2015) 003

Catania: PLB 821 (2021) 136622

SHM+RQM: PLB 795 (2019) 117-121

QCM: EPJC 78 (2018) 344

- Ratio well described by:
  - ➡ PYTHIA 8 with updated CR modelling
    → "junction" topology enhances charm baryon production
  - ➡ Catania model
    → thermalised system of u,d,s and gluons; hadronization via coalescence in addition to fragmentation
  - ➡ Quark (re-)Combination Mechanism
    → recombination model based on statistical weights and equal quark-velocity
  - ➡ Statistical Hadronization Model and Relativistic Quark Model
    → strong feed-down from augmented set of excited charm baryons
    - PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
    - RQM: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

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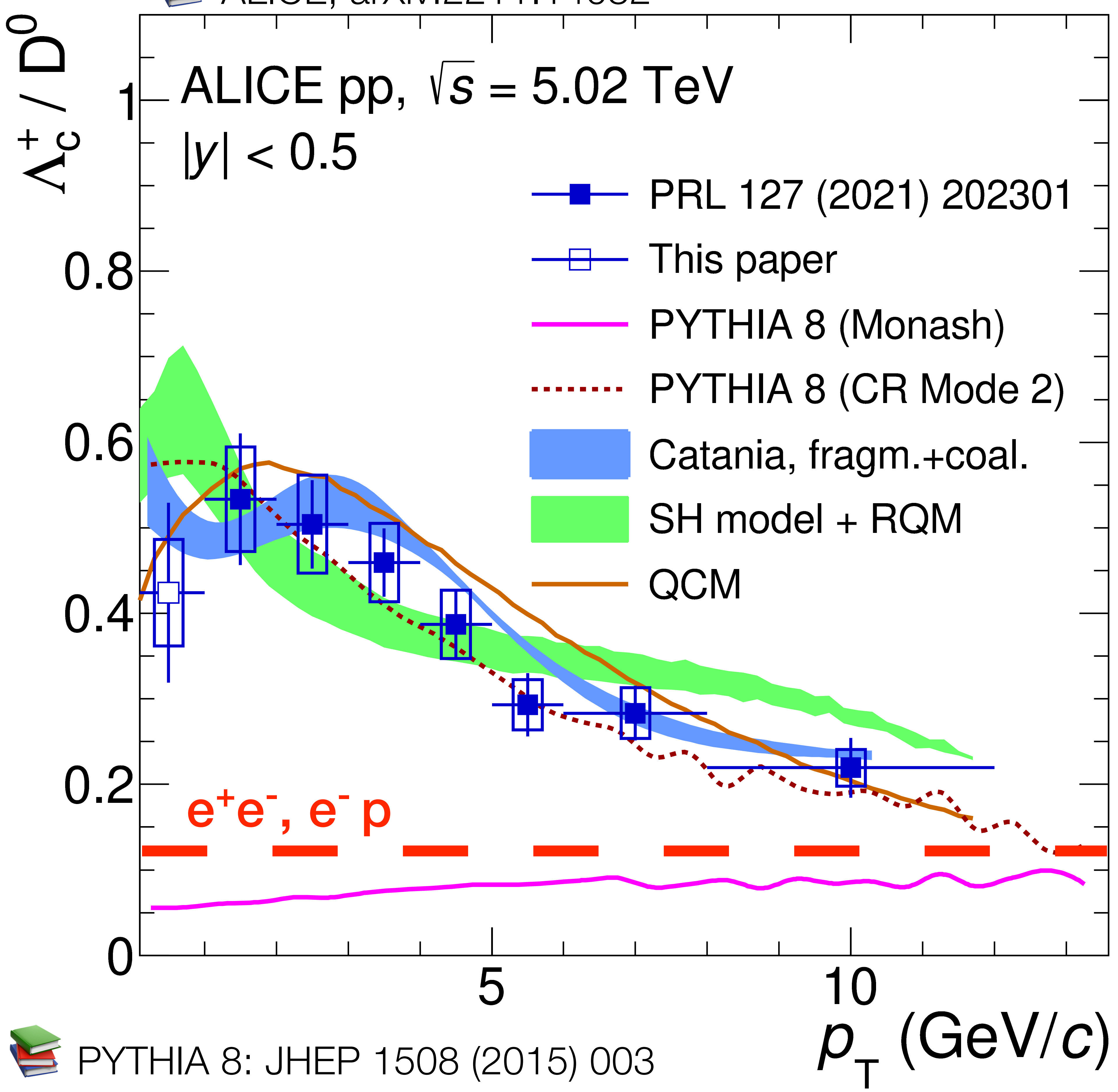
ALICE, arXiv:2211.14032



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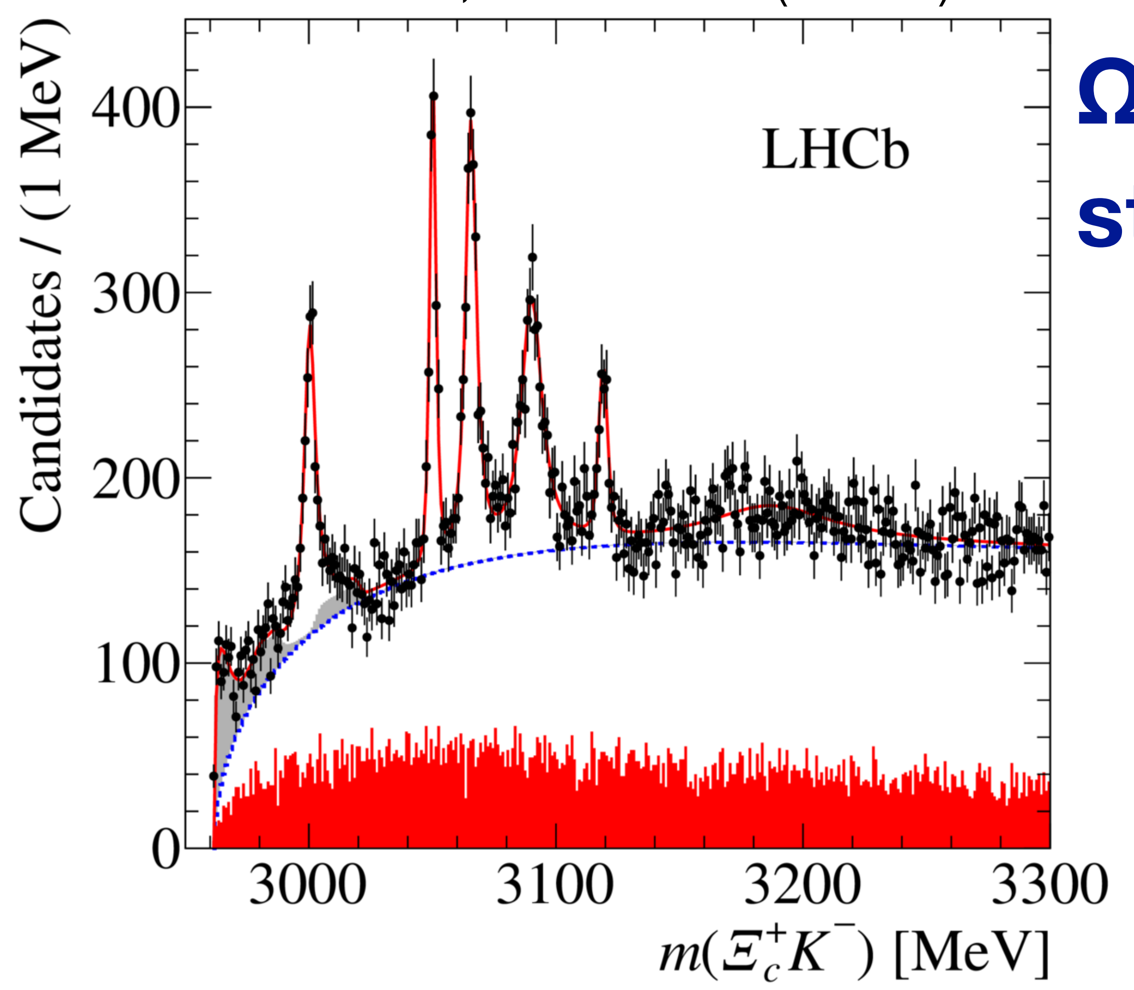
Do these states exist?

Prompt Λ_c^+/D^0 in pp collisions vs. models

- Higher-mass states: new states popping up

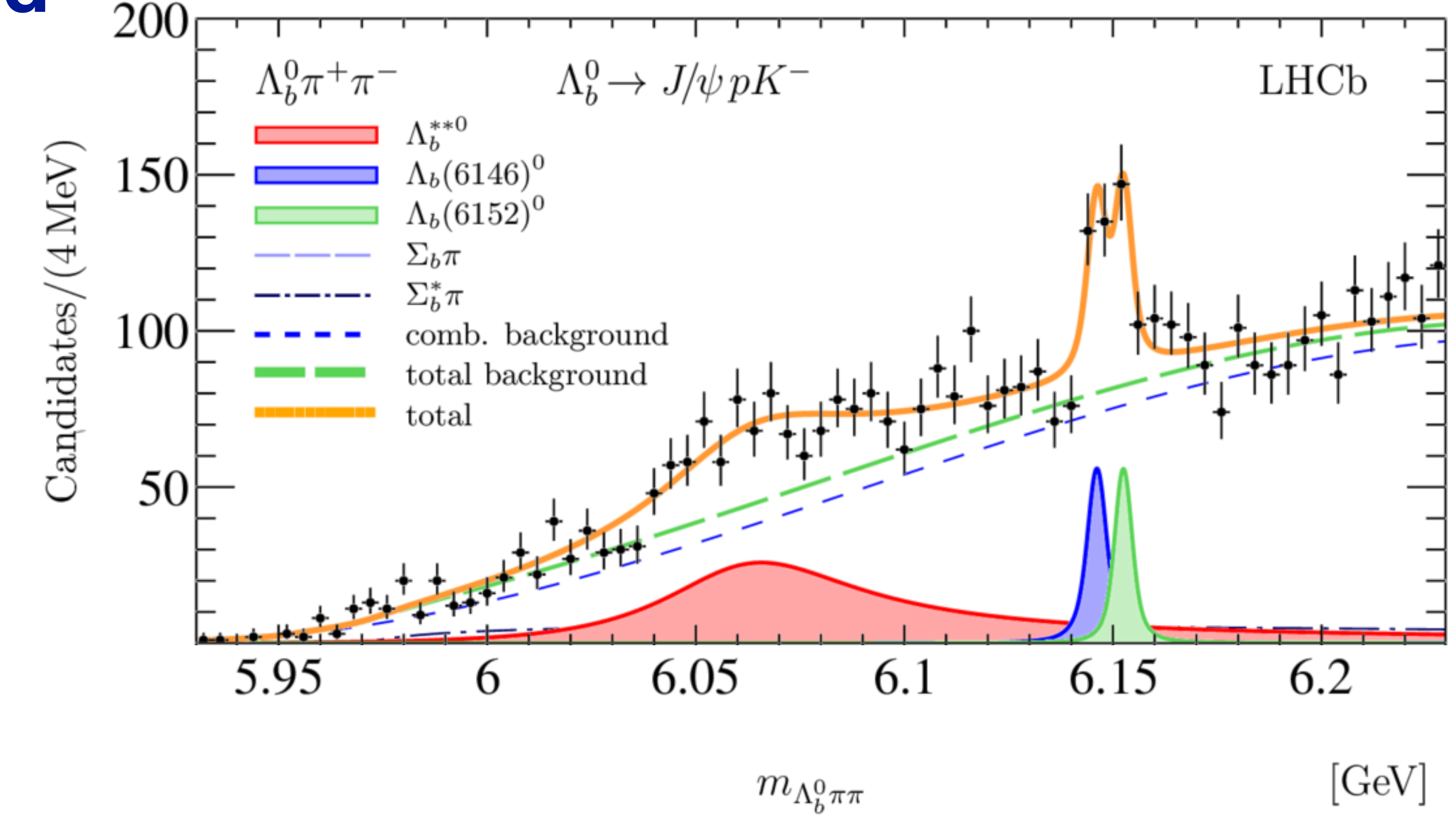
LHCb, PRL 118 (2017) 182001

Ω_c excited states

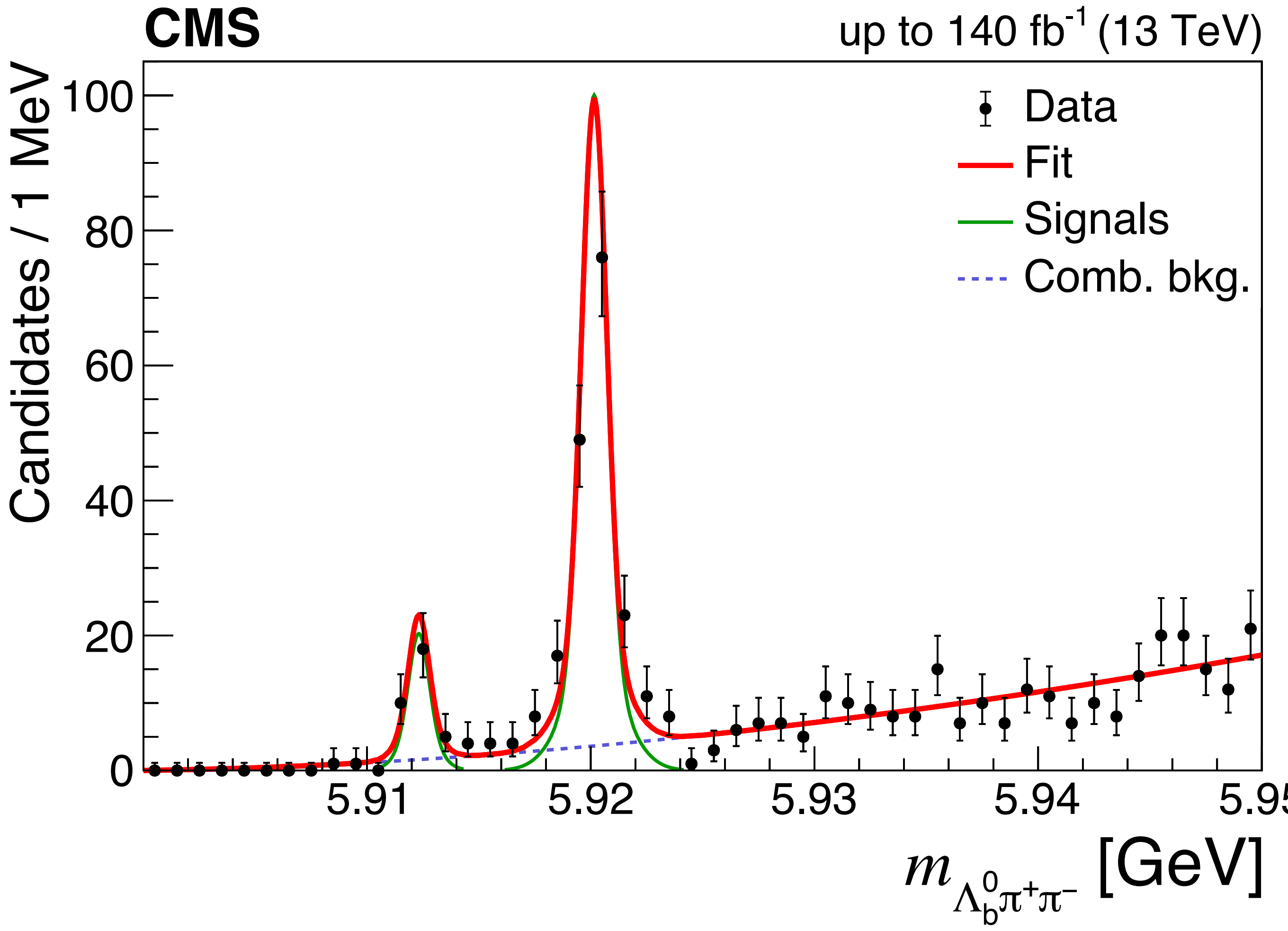


LHCb, JHEP 06 (2020) 136

Λ_b excited states

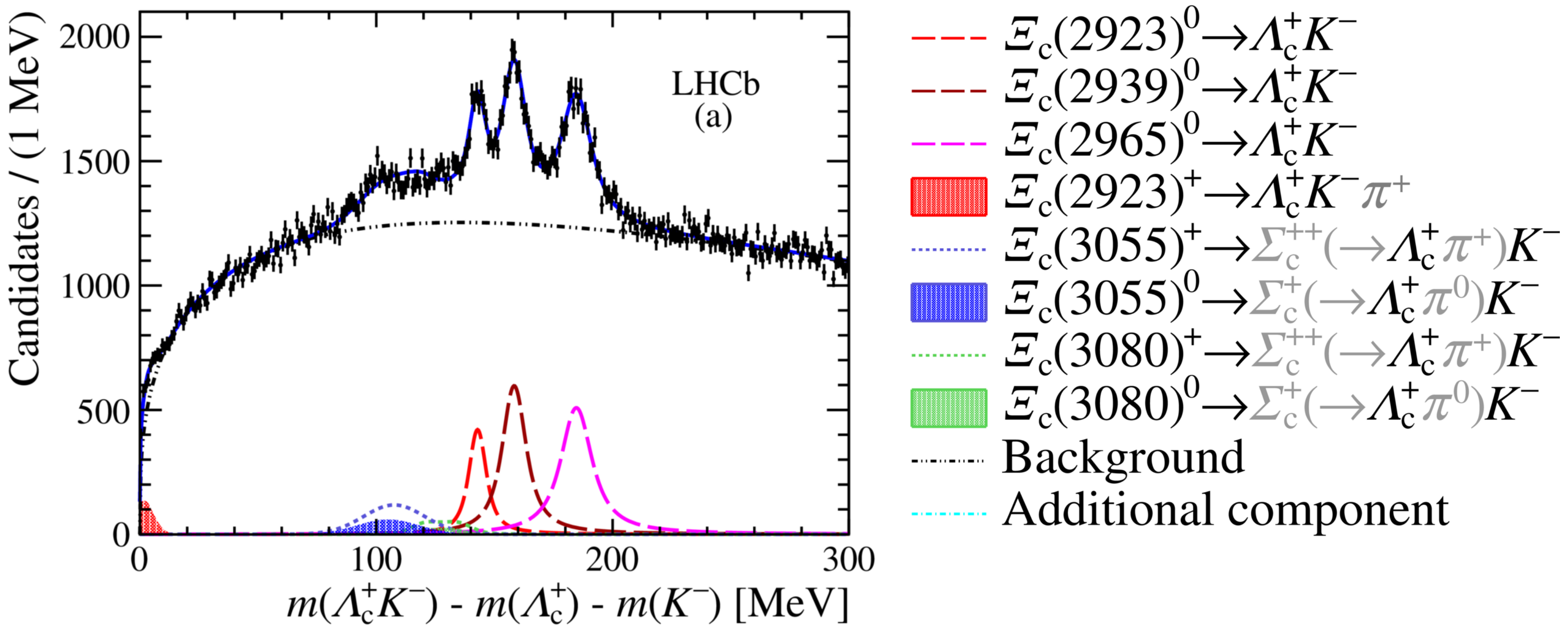


CMS, PLB 803 (2020) 135345



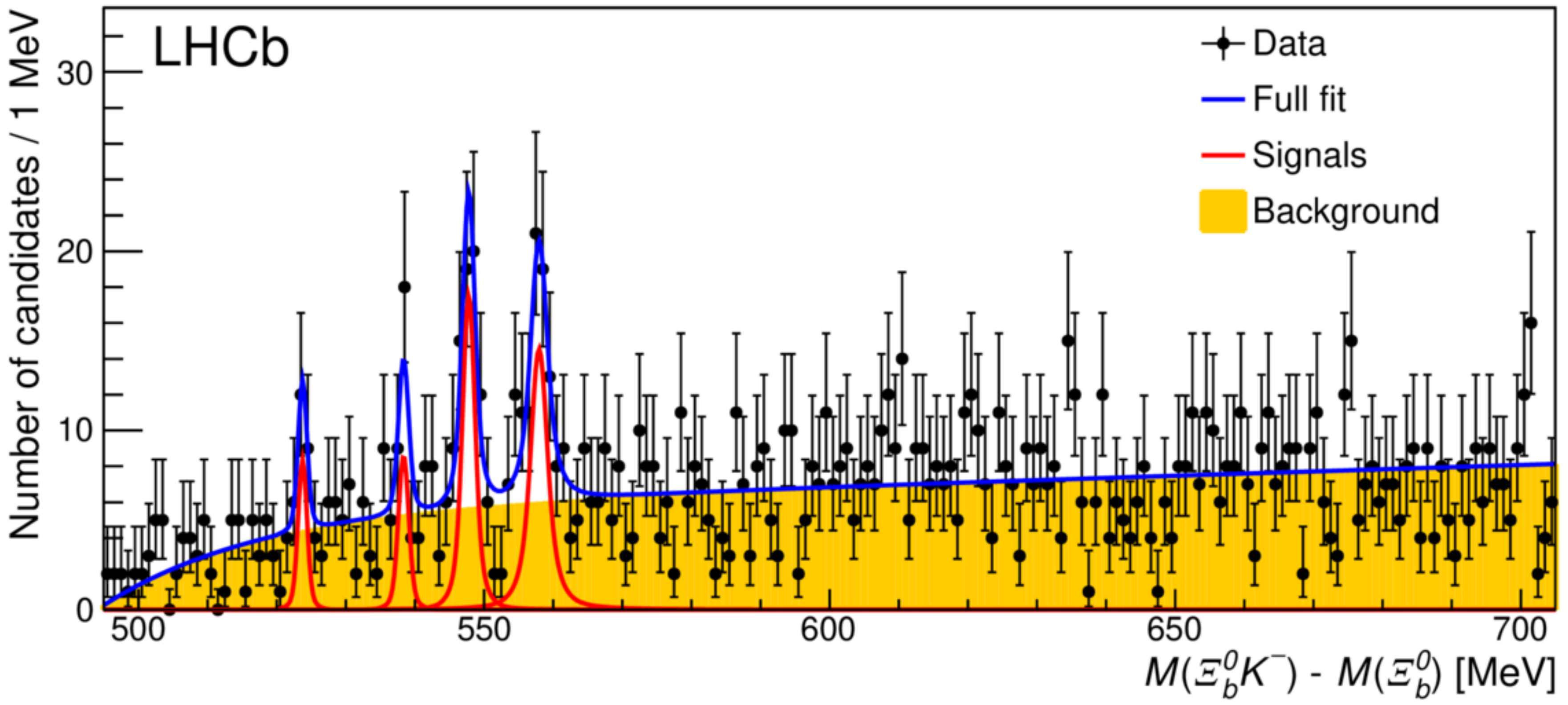
LHCb, PRL 124 (2020) 222001

Ξ_c excited states



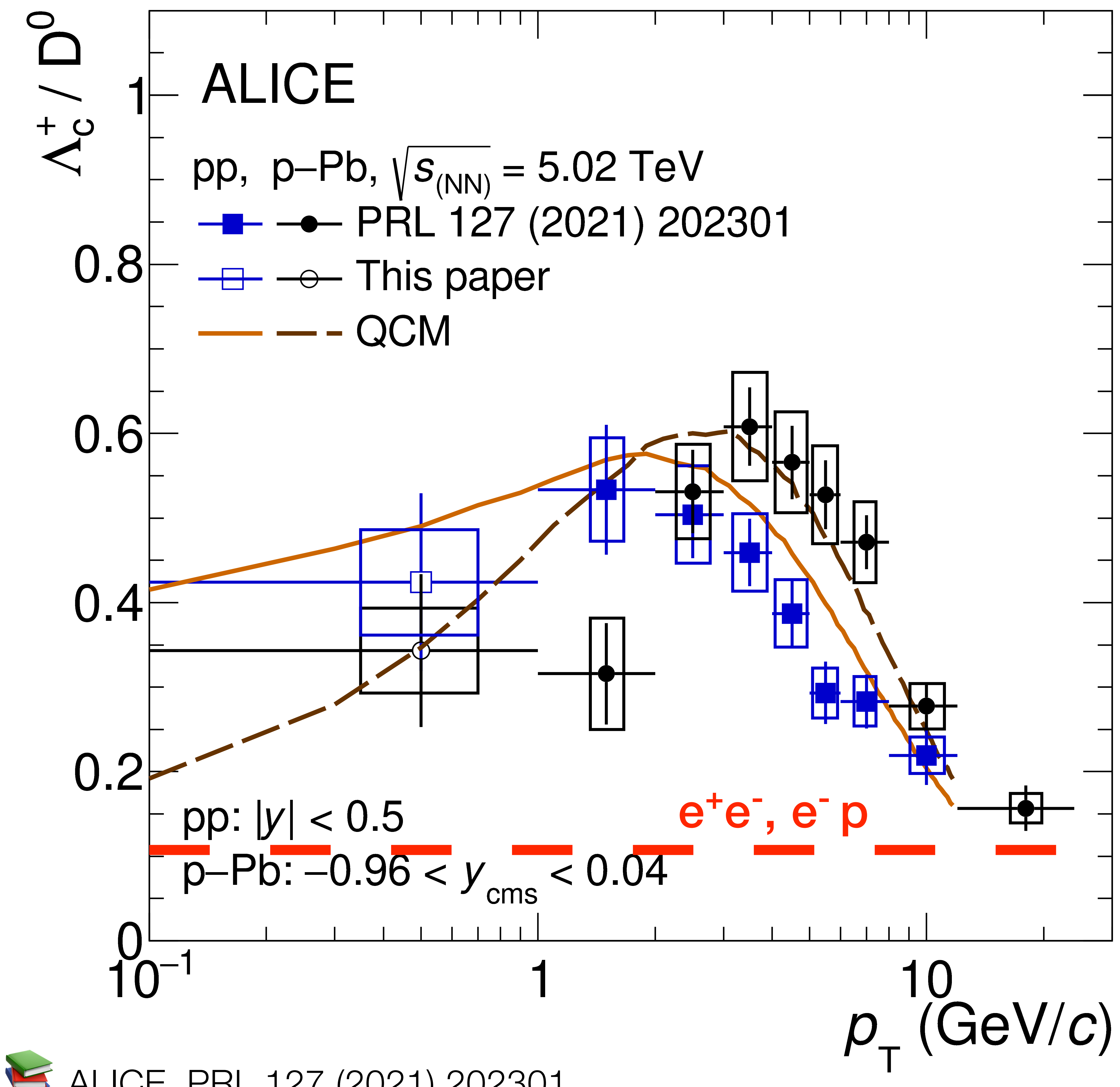
Ω_b excited states

LHCb, PRL 124 (2020) 082002



Prompt Λ_c^+/D^0 in p-Pb collisions vs. models

ALICE, arXiv:2211.14032



ALICE, PRL 127 (2021) 202301

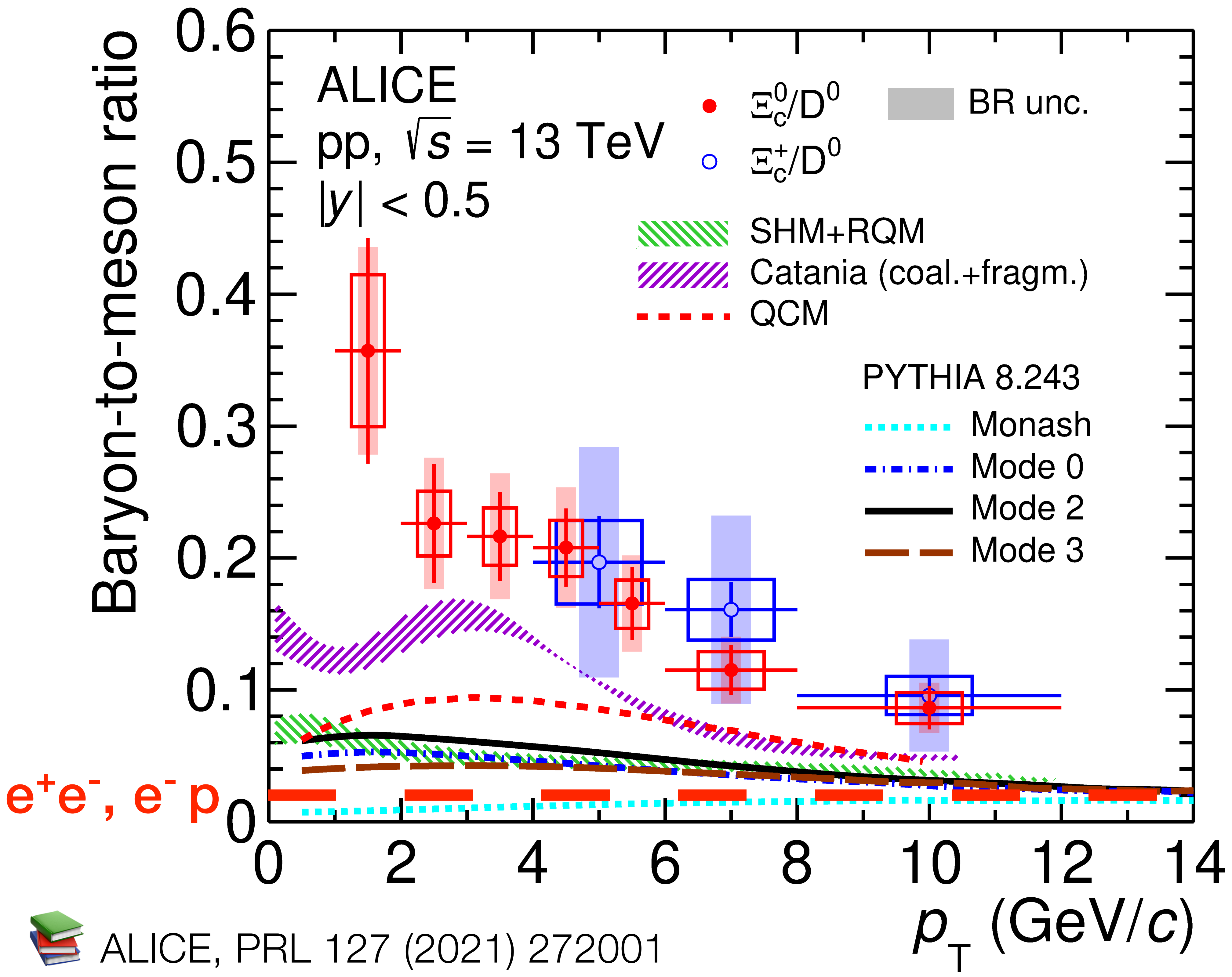
QCM: EPJC 78 (2018) 344

- Enhancement with respect to e^+e^- measurements:
  - ➡ peak towards higher p_T → contribution of collective effects?
  - ➡ both ratios described by QCM model

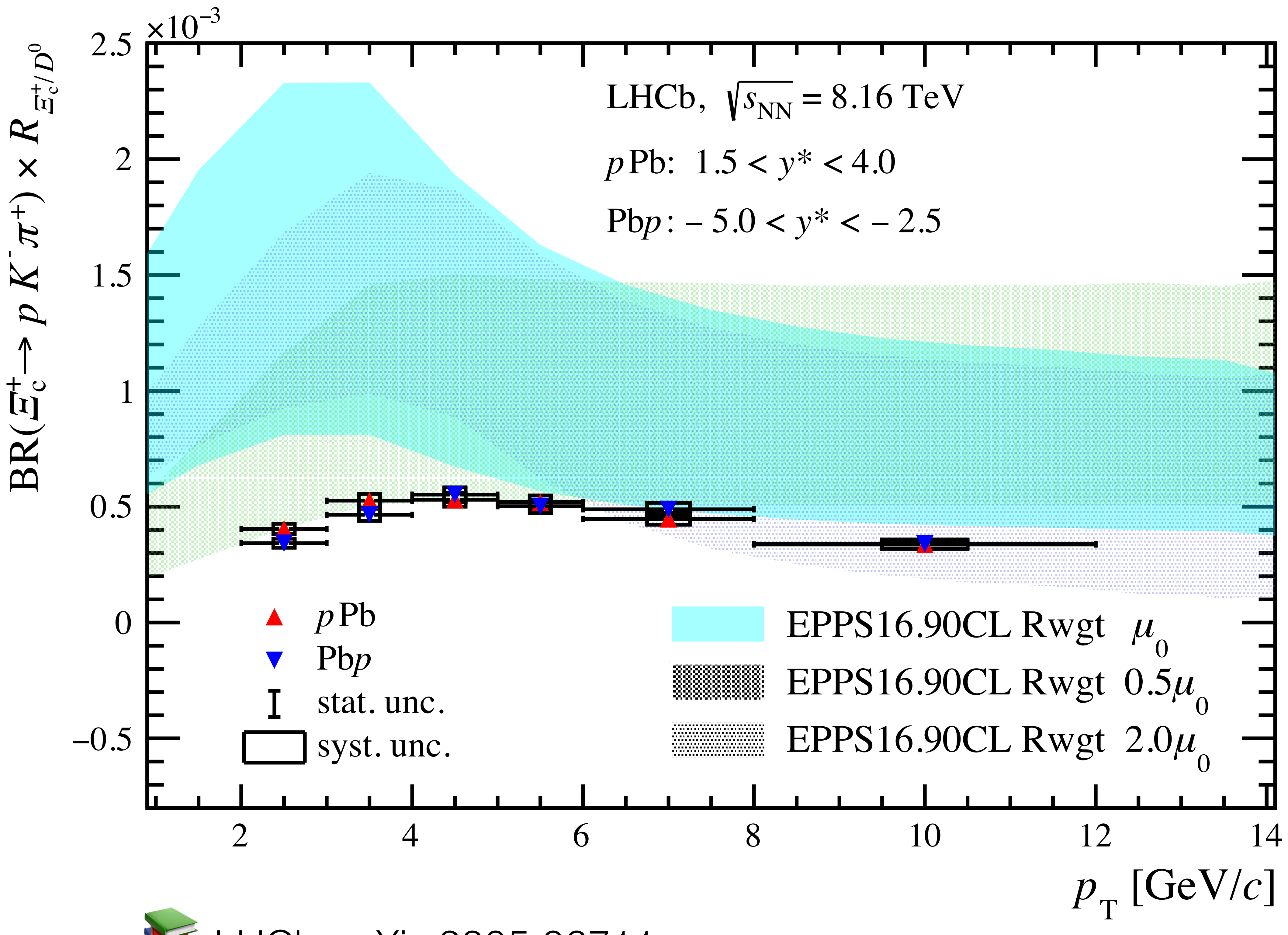
	$\langle p_T \rangle$ (GeV/c)	
	pp	p–Pb
D^0	2.06 ± 0.03 (stat.) ± 0.03 (syst.)	2.07 ± 0.02 (stat.) ± 0.04 (syst.)
Λ_c^+	1.86 ± 0.06 (stat.) ± 0.03 (syst.)	2.29 ± 0.06 (stat.) ± 0.06 (syst.)

- Comparing pp and p-Pb results:
  - ➡ larger $\langle p_T(\Lambda_c^+) \rangle$ in p-Pb than in pp, but p_T-integrated ratios compatible
  - ➡ modification of p_T distribution different for baryons and mesons from pp to p-Pb collisions?

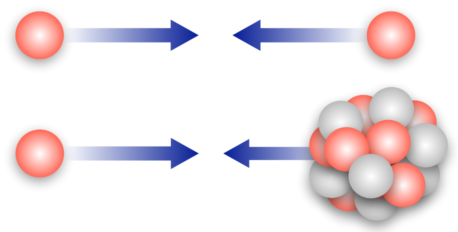
Heavier charm baryons: $\Xi_c^{0,+}$



ALICE, PRL 127 (2021) 272001



LHCb, arXiv:2305.06711



PYTHIA 8: JHEP 1508 (2015) 003

Catania: PLB 821 (2021) 136622

SHM+RQM: PLB 795 (2019) 117-121

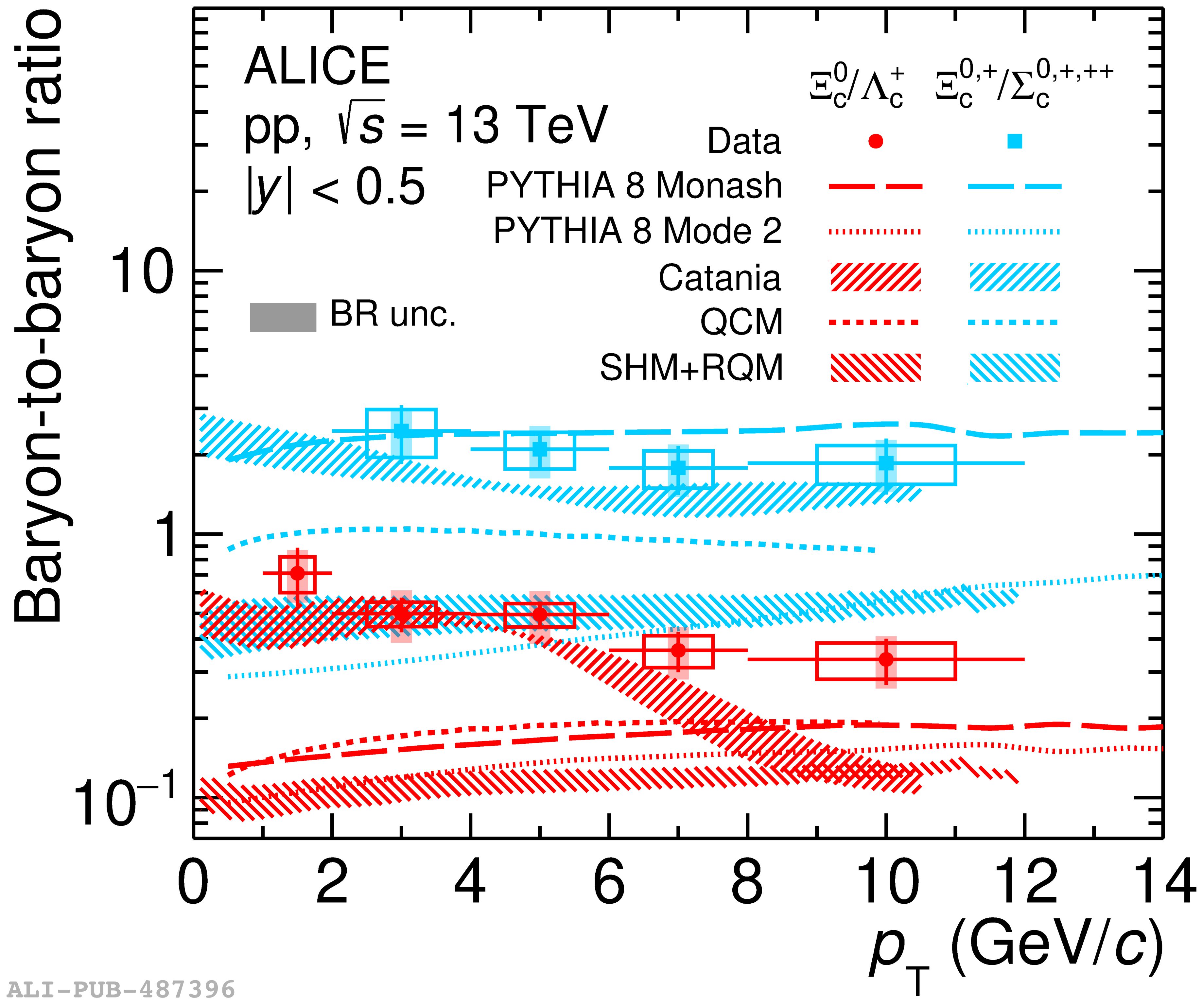
QCM: EPJC 78 (2018) 344

EPPS16: EPJC 77 (2017) 163

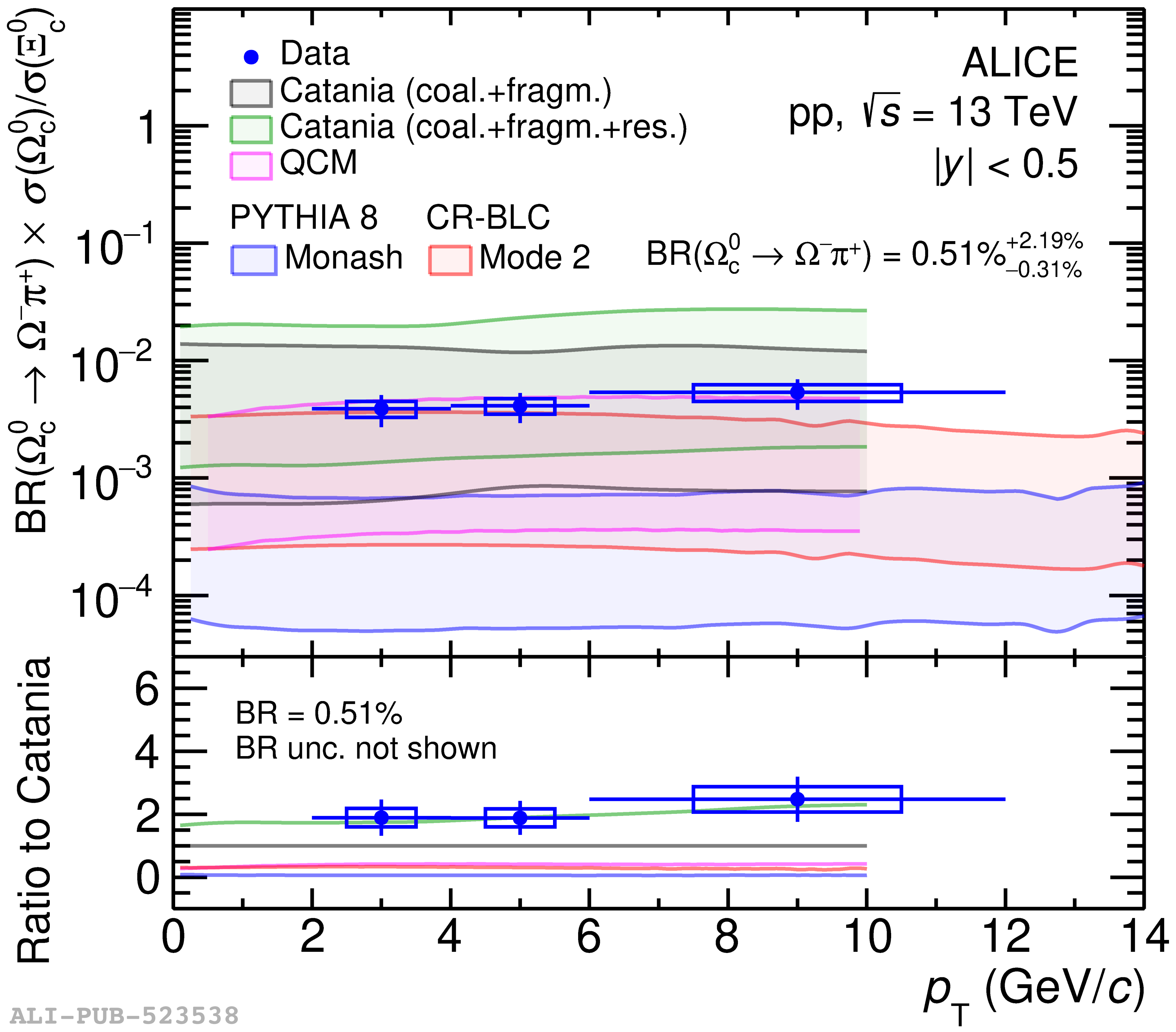
- $\Xi_c^{0,+}/D^0$ in pp collisions → higher than PYTHIA Monash (e^+e^- tuning)
  - ➡ only recombination models are able to get closer to the measurement
- Ξ_c^+/D^0 in p-Pb collisions mild p_T dependence at forward/backward y
  - ➡ likely lower than mid y but larger than e^+e^- → is there a rapidity dependence?

- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio close to PYTHIA 8 Monash, which underestimates their production
  - ➡ similar suppression in e^+e^- for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$?
- Ω_c^0/Ξ_c^0 only described by Catania model (recombination)

ALICE, JHEP 10 (2021) 159



ALICE, arXiv:2205.13993



BR from theoretical pred. used to scale predictions

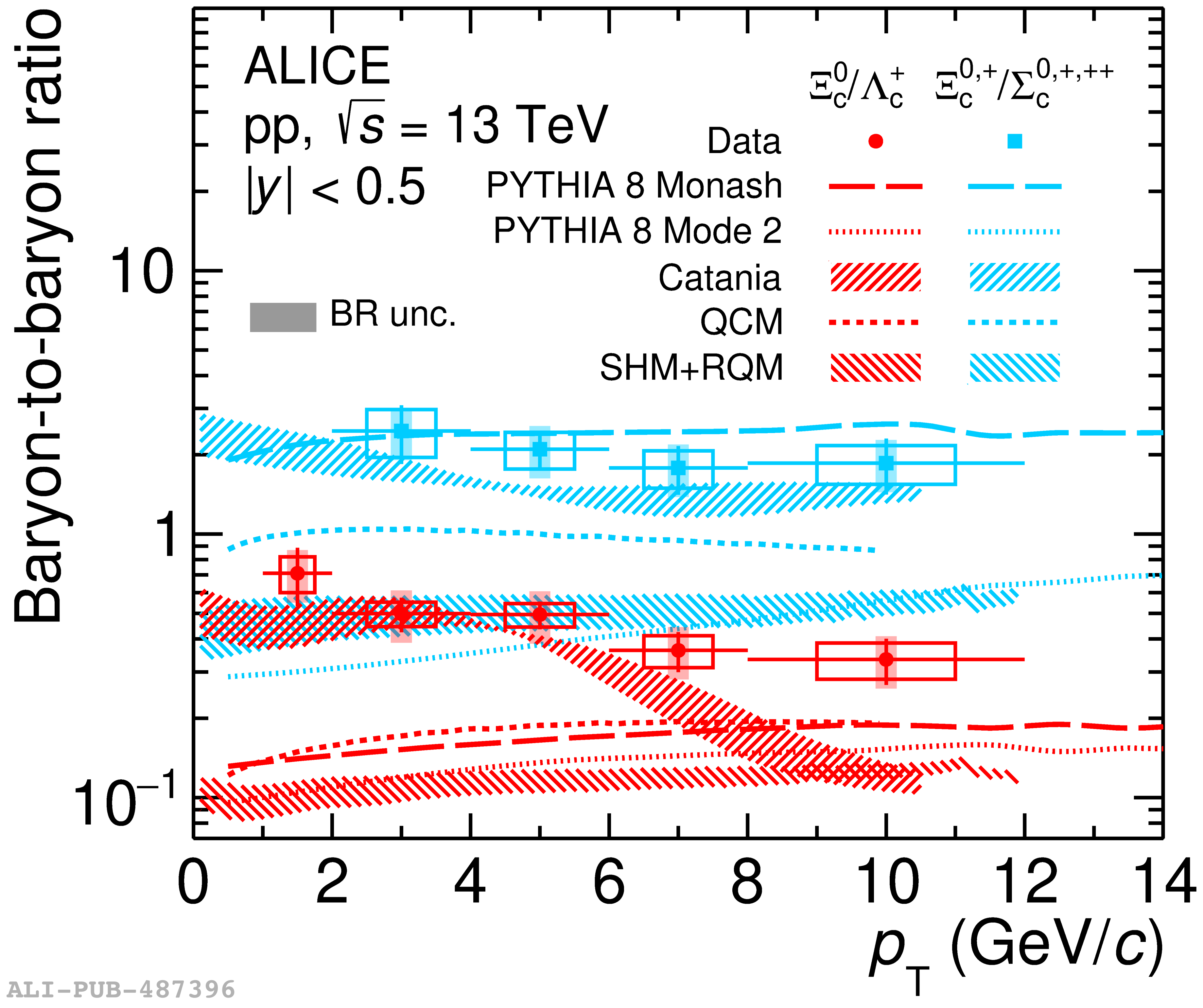
Additional challenge from strange-quark production?

- ➡ baryon-to-meson higher than e^+e^-
- ➡ baryon-to-baryon:
  - → strange/non-strange inline with e^+e^-
  - → double-strange/strange higher e^+e^-

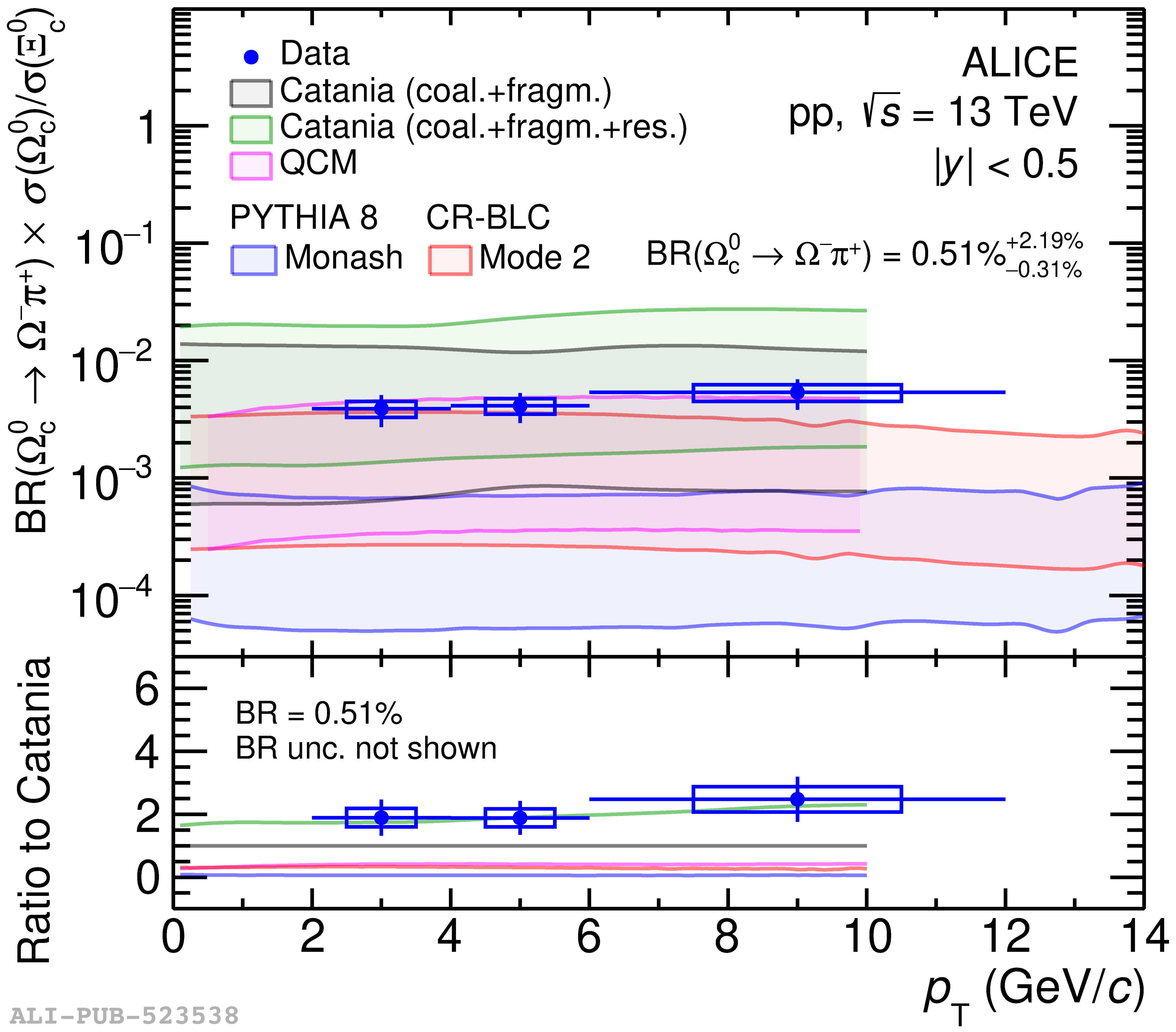
Heavier charm baryons: $\Xi_c^{0,+}$, Ω_c^0

- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ ratio close to PYTHIA 8 Monash, which underestimates their production
  - ➡ similar suppression in e^+e^- for $\Xi_c^{0,+}$ and $\Sigma_c^{0,+,++}$?
- Ω_c^0/Ξ_c^0 only described by Catania model (recombination)

ALICE, JHEP 10 (2021) 159



ALICE, arXiv:2205.13993



BR from theoretical pred. used to scale predictions

Additional challenge from strange-quark production?

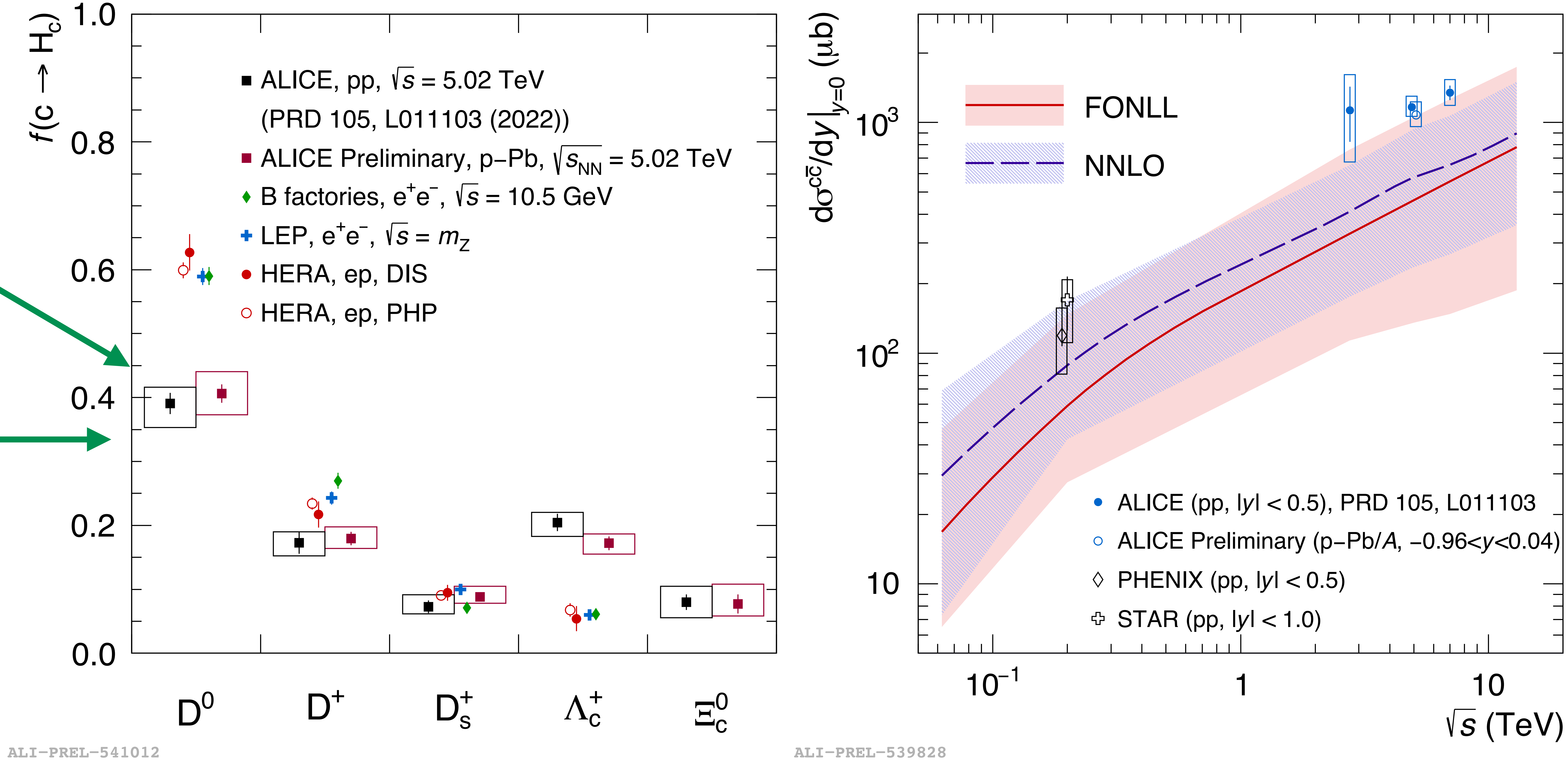
Full description of charm-baryon production in pp collisions still a puzzle

→ double-strange/strange higher e^+e^-

charm production in pp and p-Pb collisions

Comparing to e^+e^-:
- D mesons ↓ factor 1.4-1.6
- Λ_c^+ baryon ↑ factor ~3

charm fragmentation fractions → pp ~ p-Pb



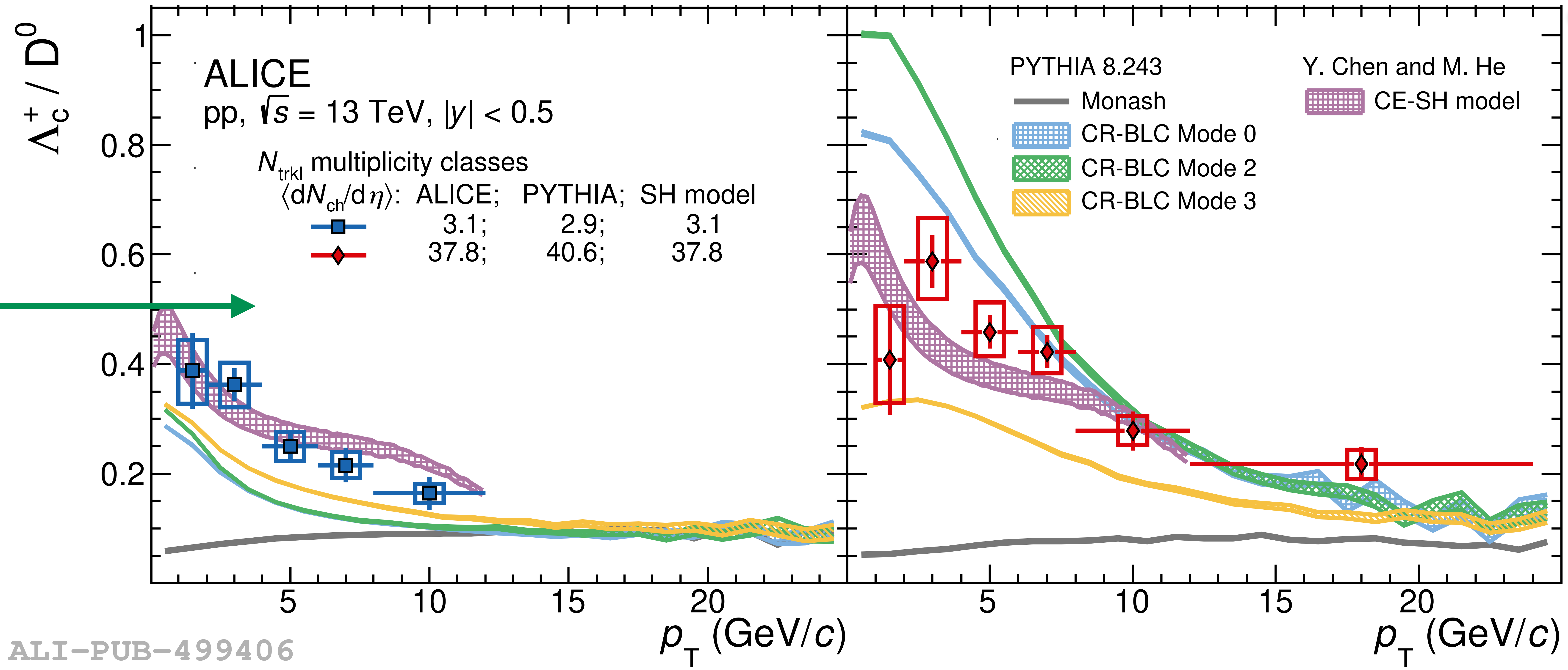
- FONLL, JHEP 1210 (2012) 137
- NNLO, JHEP 03 (2021) 029
- PHENIX, PRC 84 (2011) 044905
- STAR, PRD 86 (2012) 072013

- $c\bar{c}$ production cross section at $|y|<0.5$ measured as sum of ground state hadron cross sections
  - ➡ compatible within systematic uncertainties
  - ➡ previous results in pp at 2.76 and 7 TeV updated with the fragmentation fraction at 5.02 TeV

Prompt Λ_c^+/D^0 vs. event multiplicity in pp collisions

ALICE, PLB 829 (2022) 137065

Difference low-high multiplicity with 5.3σ significance



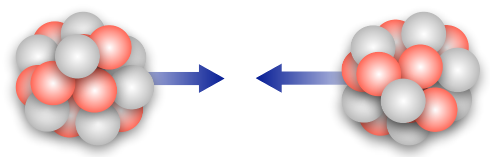
PYTHIA 8: JHEP 1508 (2015) 003

CE-SH: PLB 815 (2021) 136144

- Λ_c^+/D^0 larger at highest multiplicity than at lowest multiplicity
  - ➡ p_T and multiplicity dependence qualitatively described by:
    - → PYTHIA with colour reconnection beyond leading-colour approximation (CR-BLC)
    - → Statistical Hadronization Model (CE-SH)
- Λ_c^+/D^0 does not exhibit a multiplicity dependence in p-Pb (backup)

Prompt Λ_c^+/D^0 in Pb-Pb collisions

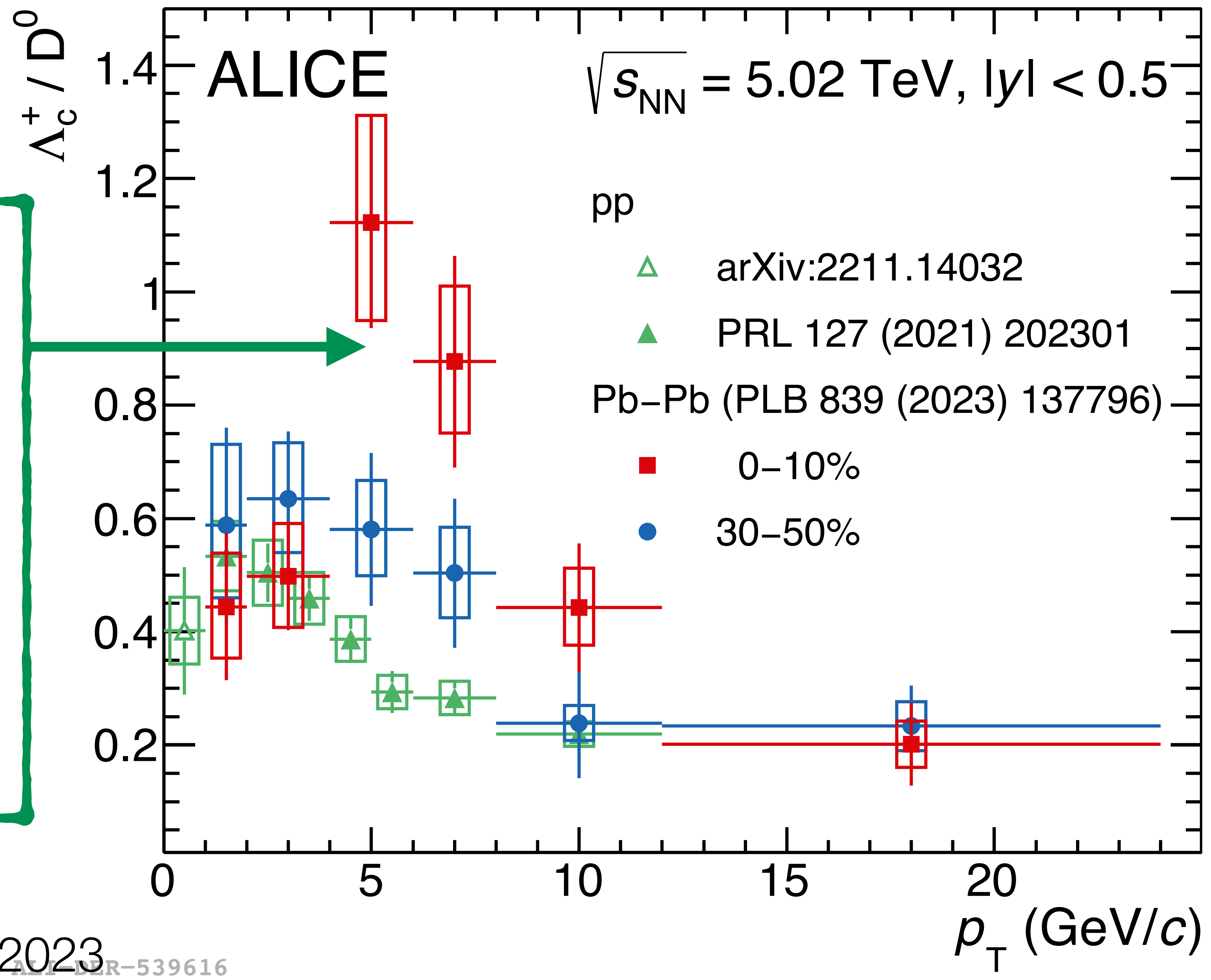
- Recombination of heavy quarks with light quarks from the QGP affects HF hadrochemistry
  - ➡ enhanced production of baryons relative to mesons
  - ➡ observed enhancement Λ_c^+/D^0 → interplay of collective motion and recombination?



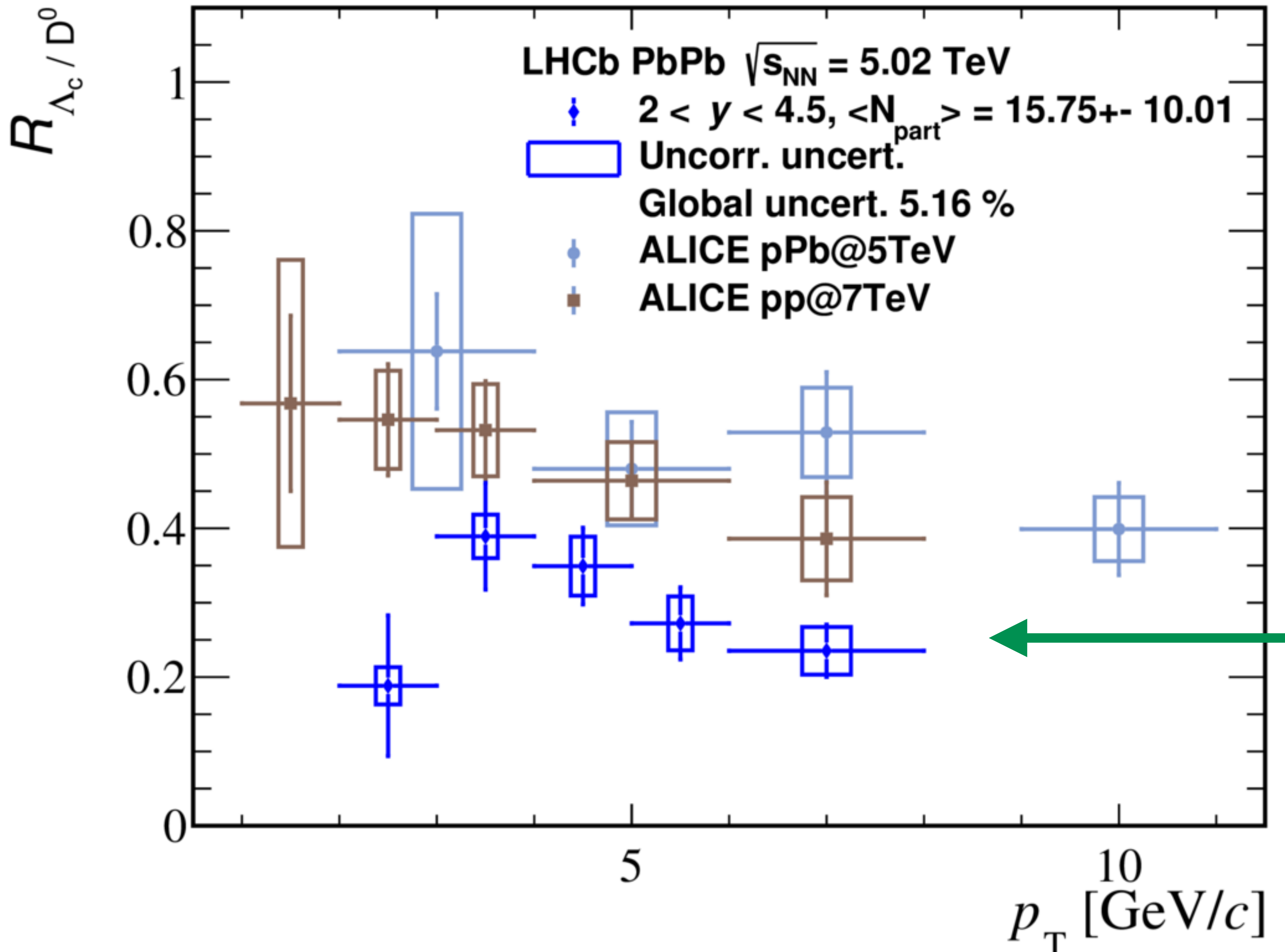
- Λ_c^+/D^0 ratios in central and semicentral Pb–Pb collisions described by different models including hadronization via recombination (backup)
  - ➡ CMS preliminary results compatible (backup)

ALICE, PLB 839 (2023) 137796

Hint of enhancement at mid p_T in central and semicentral collisions

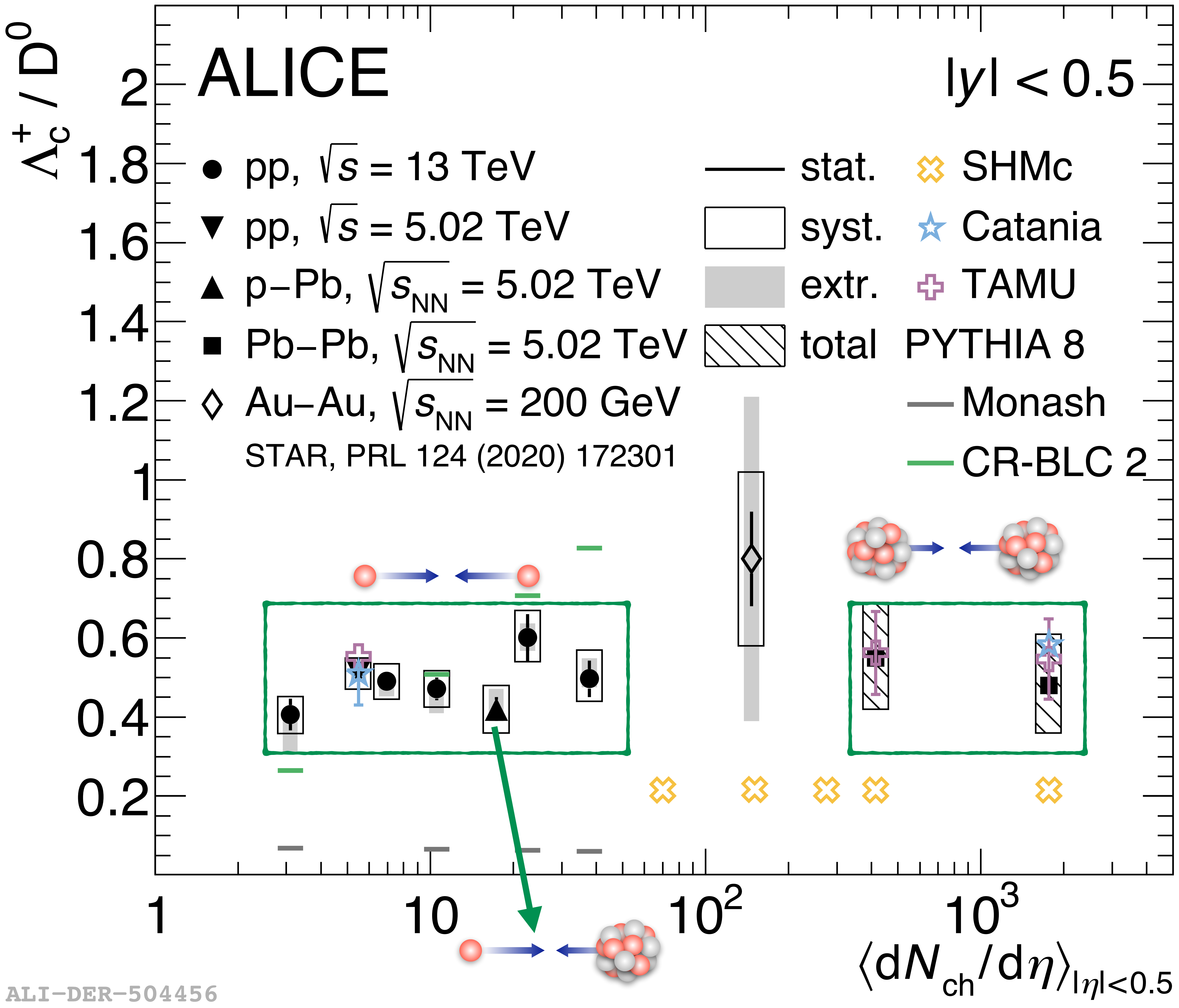


LHCb, arXiv:2210.06939



Ratios in peripheral Pb-Pb at forward y close to pp at mid y

Λ_c^+/D^0 vs. multiplicity in hadronic collisions



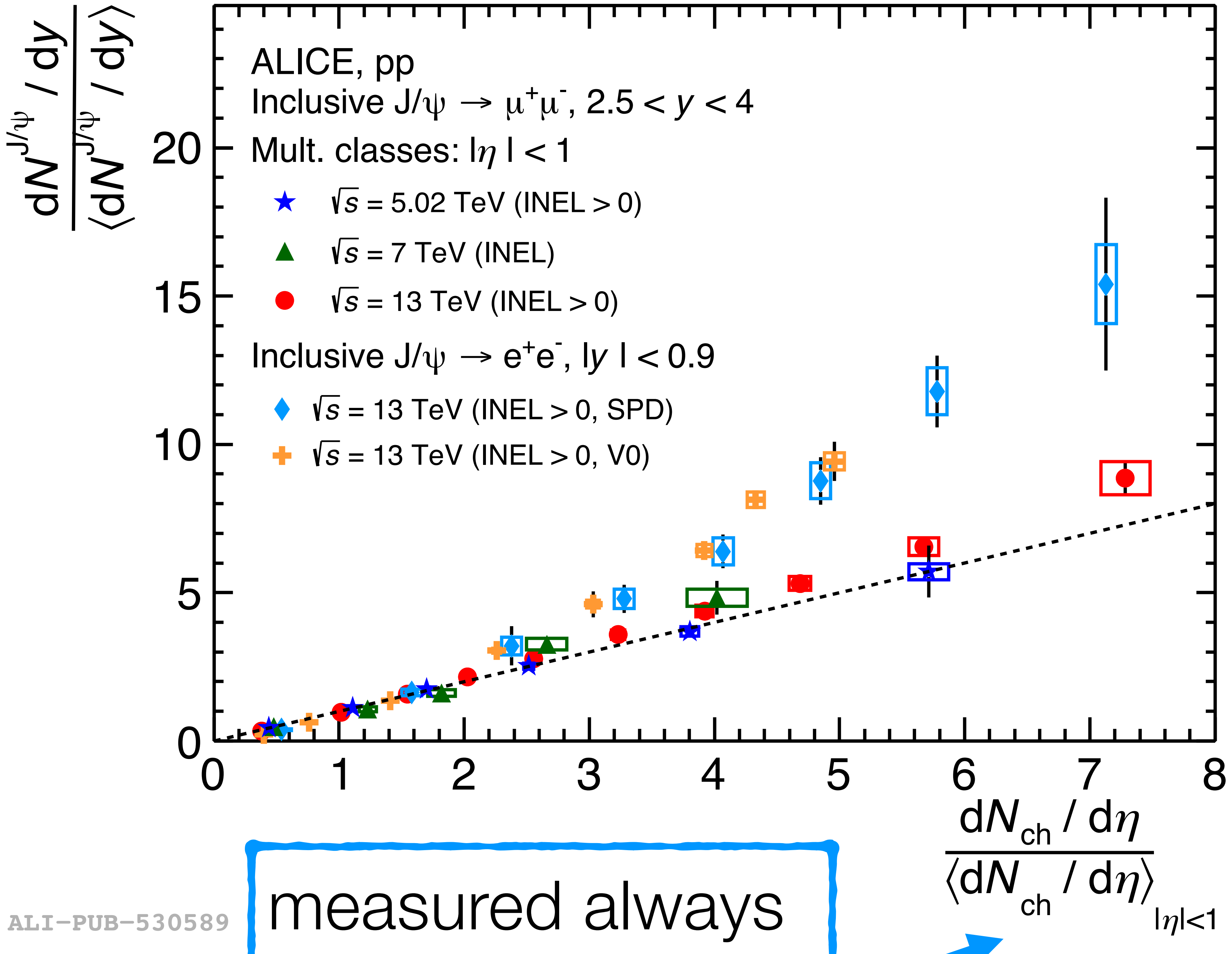
- p_T-integrated Λ_c^+/D^0 ratio not dependent on multiplicity, collision system and energy within uncertainties
  - ➡ Monash predictions ruled out by the measurements in pp collisions
- increasing trend (1< p_T <24 GeV/c) from a different redistribution of p_T for mesons and baryons?
  - ➡ Flow effects in Pb-Pb collisions

ALICE, PLB 829 (2022) 137065
ALICE, PRL 127 (2021) 202301
ALICE, PRC 104 (2021) 054905
ALICE, PLB 839 (2023) 137796
STAR, PRL 124 (2020) 172301

Quarkonium

Quarkonium production vs. multiplicity

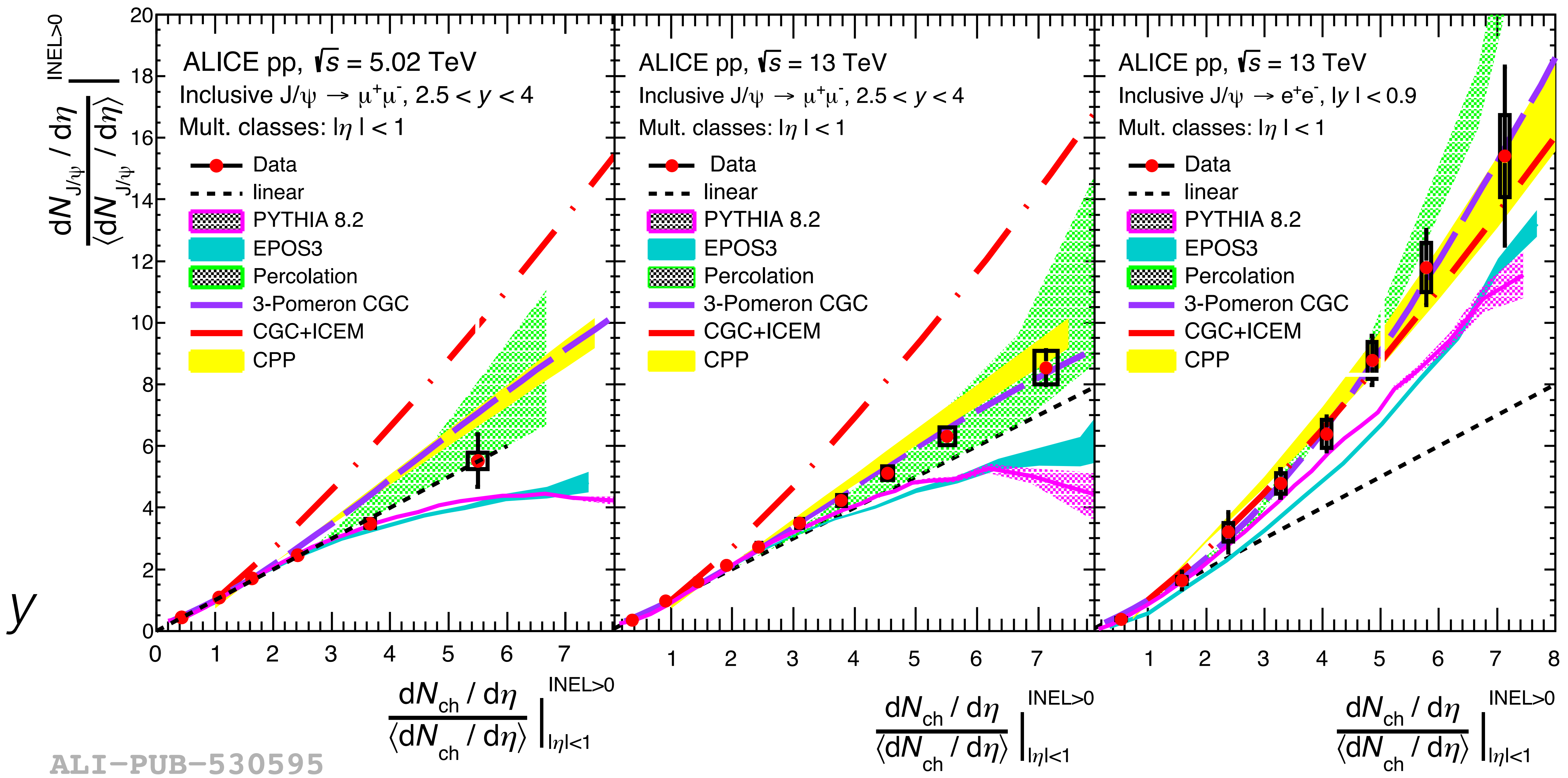
ALICE, JHEP 06 (2022) 015



ALI-PUB-530589

measured always at mid *y*

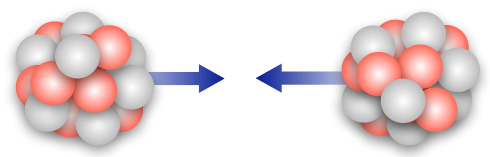
- Inclusive J/ψ production measurement in pp collisions
- $J/\psi \rightarrow e^+e^-$ at midrapidity
  - ➡ stronger than linear increase of the self-normalised yield with multiplicity
- $J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity
  - ➡ compatible with linear dependence and independent of $\sqrt{s}$



ALI-PUB-530595

- Results described by different models due to different mechanisms:
  - ➡ CPP and 3-Pomeron models at mid and forward *y*
  - ➡ CGC+ICEM only at mid *y*

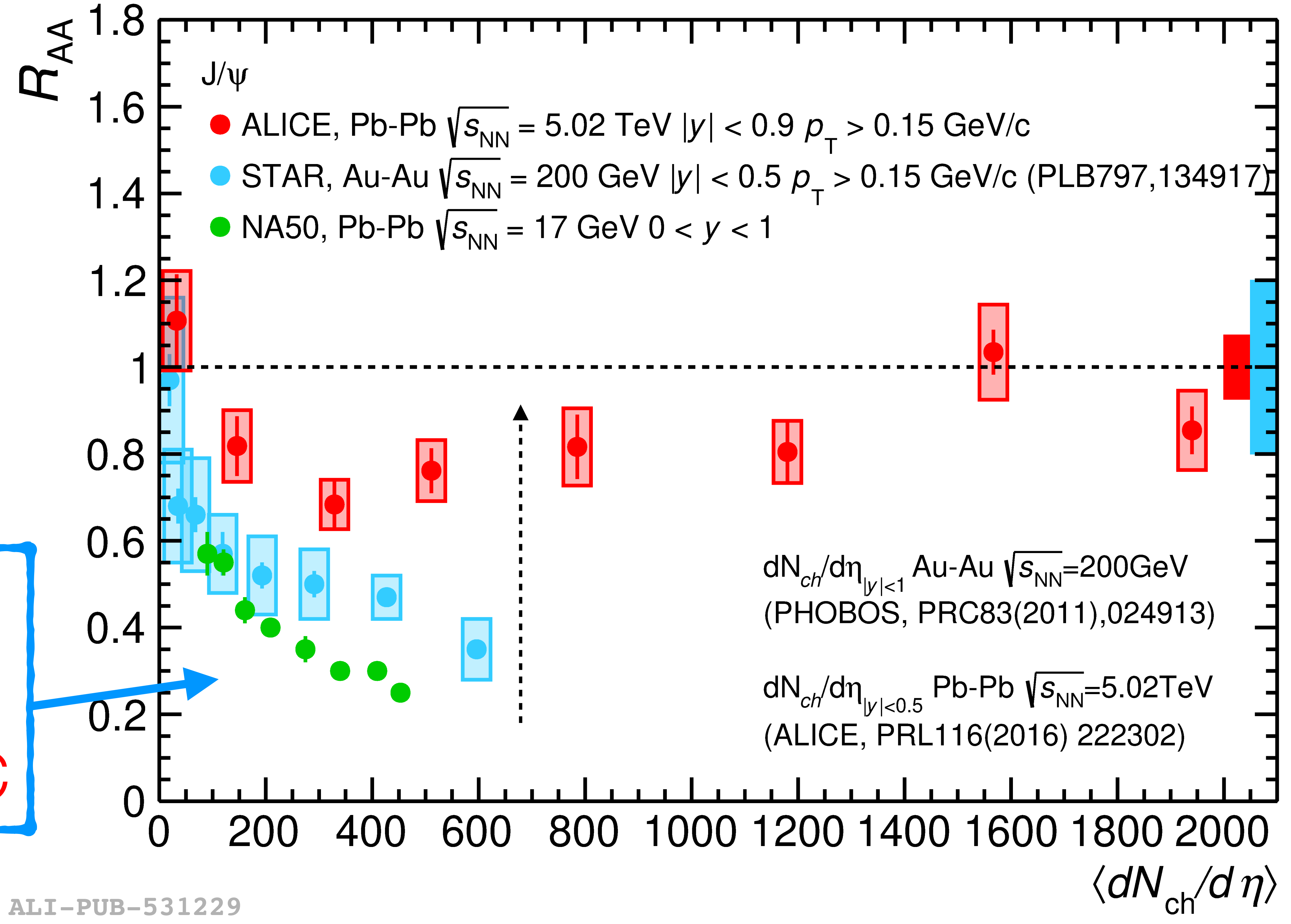
Role of regeneration in quarkonia: J/ψ



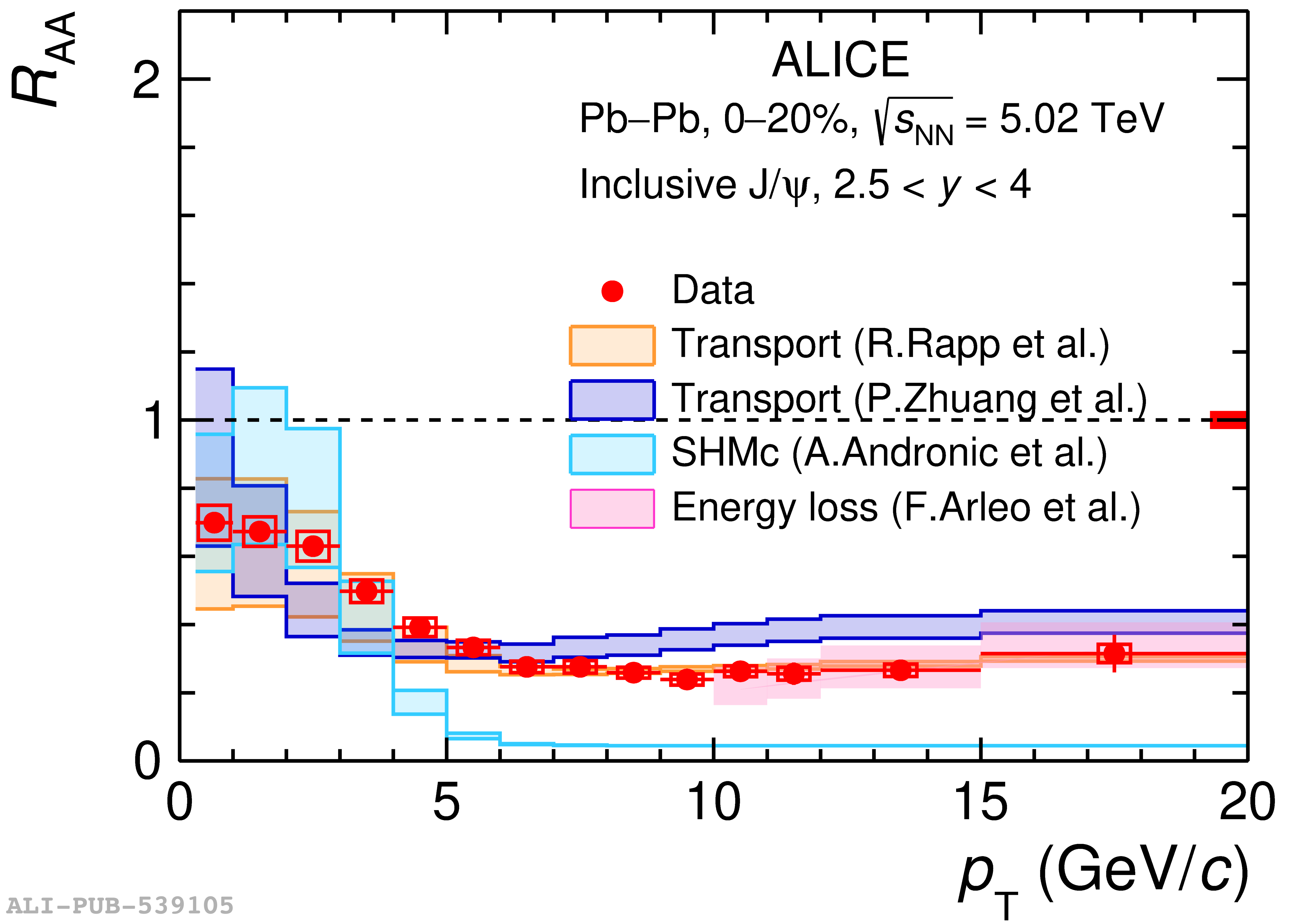
- Quarkonium dissociation in QGP → Debye screening of $q\bar{q}$ potential
- Production can occur also via quark (re)combination → evidence from LHC results
  - ➡ Data described by:
    - → SHMc: melting of initially produced $c\bar{c}$ pairs + combination at phase boundary
    - → Transport models: in-medium charmonium dissociation + recombination (relevant at low p_T)

ALICE, arXiv:2211.04384
NA50, EPJC 39 (2005) 335
STAR, PLB 797 (2019) 134917

Increasing R_{AA} from SPS to RHIC until LHC



ALICE, arXiv:2303.13361

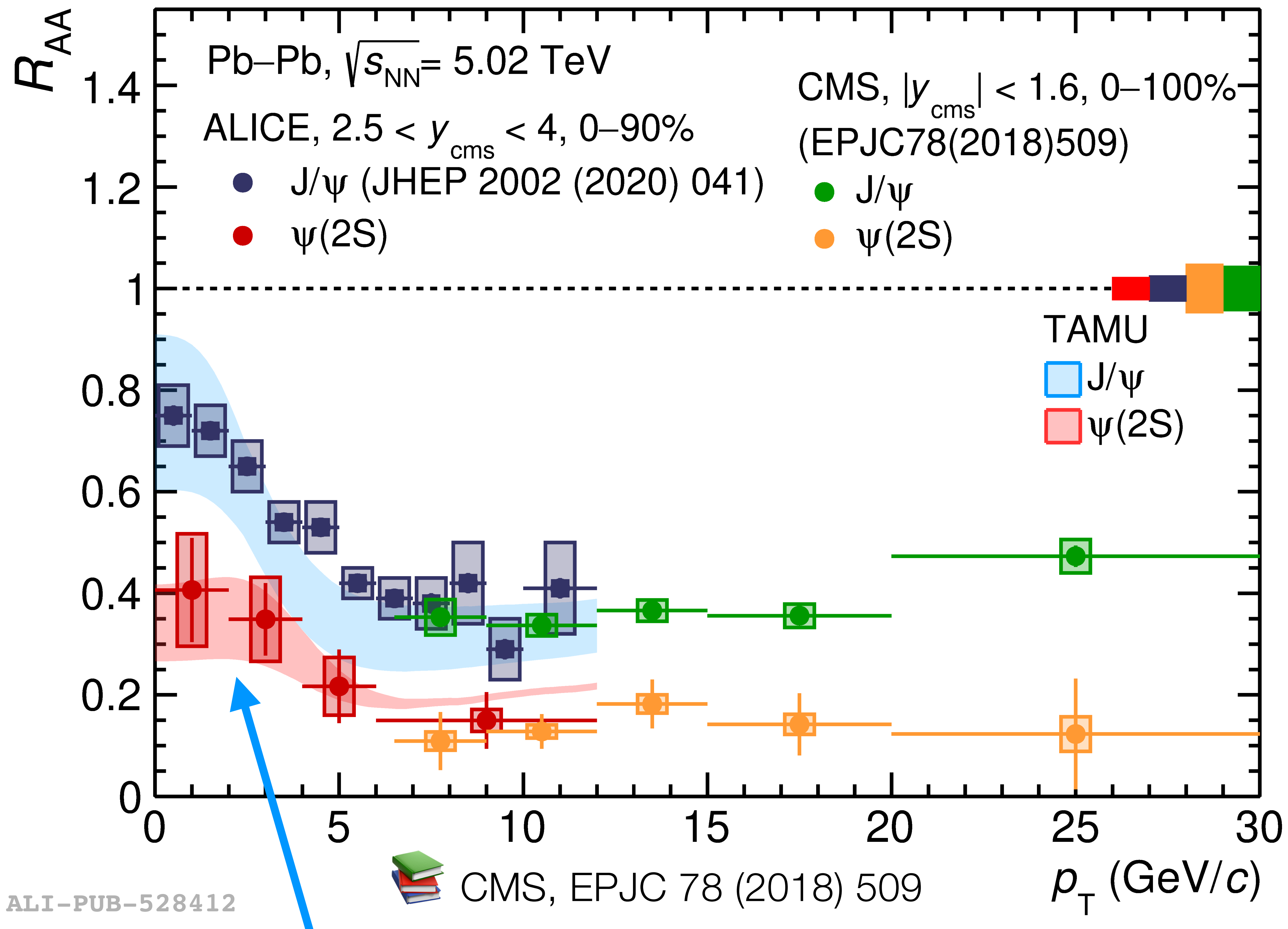


Role of regeneration in quarkonia: $\psi(2s)$

- Quarkonium dissociation in QGP → Debye screening of $q\bar{q}$ potential
- Production can occur also via quark (re)combination → evidence from LHC results

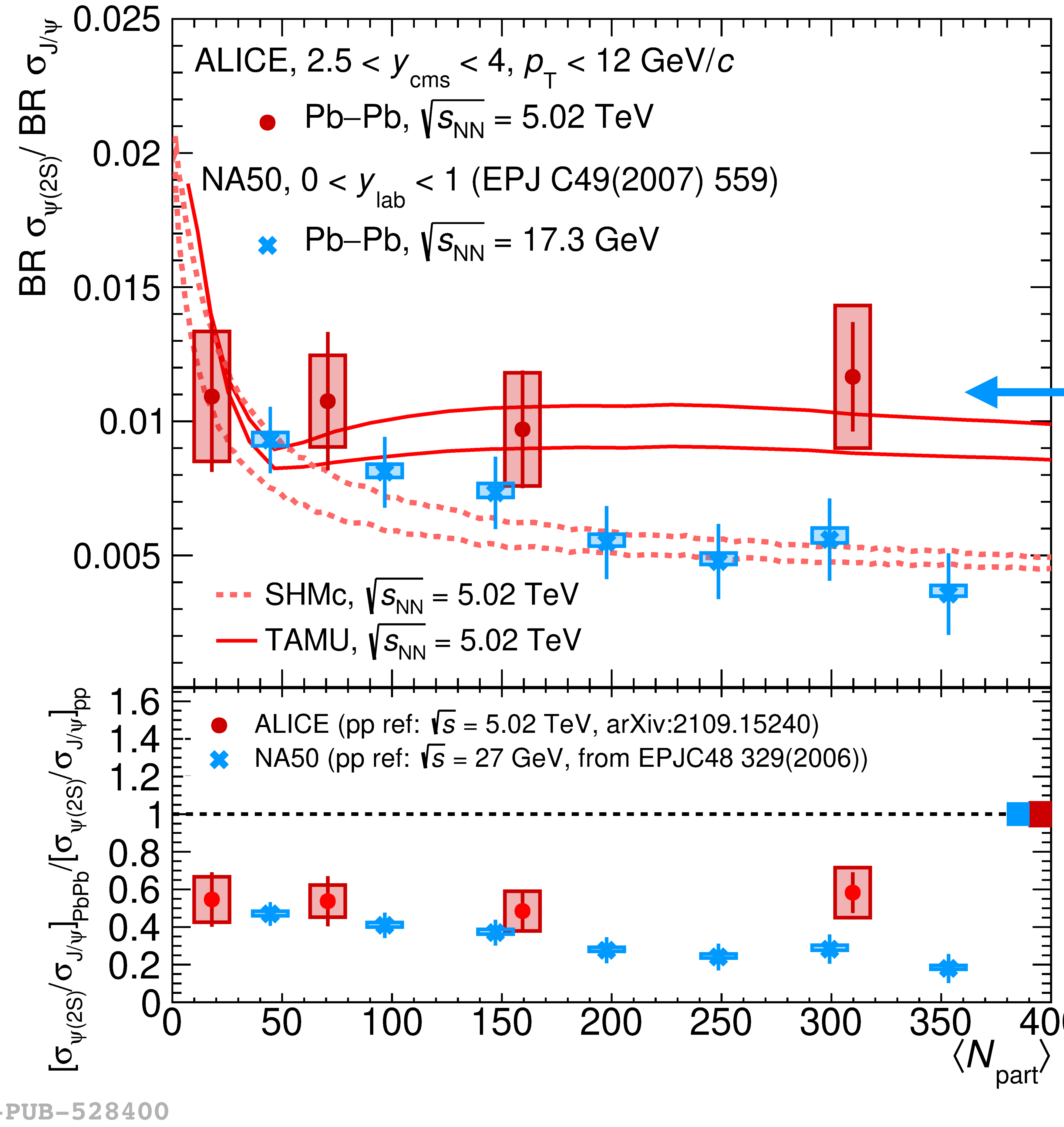
➡ relevant for $\psi(2s)$ at low p_T

ALICE, arXiv:2210.08893



CMS, EPJC 78 (2018) 509

low p_T increase due to recombination



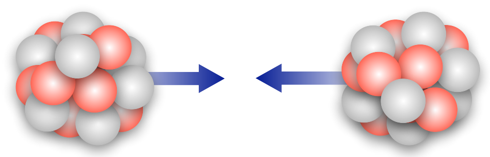
No centrality dependence at LHC

Smaller values reached by NA50 in central collisions

TAMU, NPA 943 (2015) 147

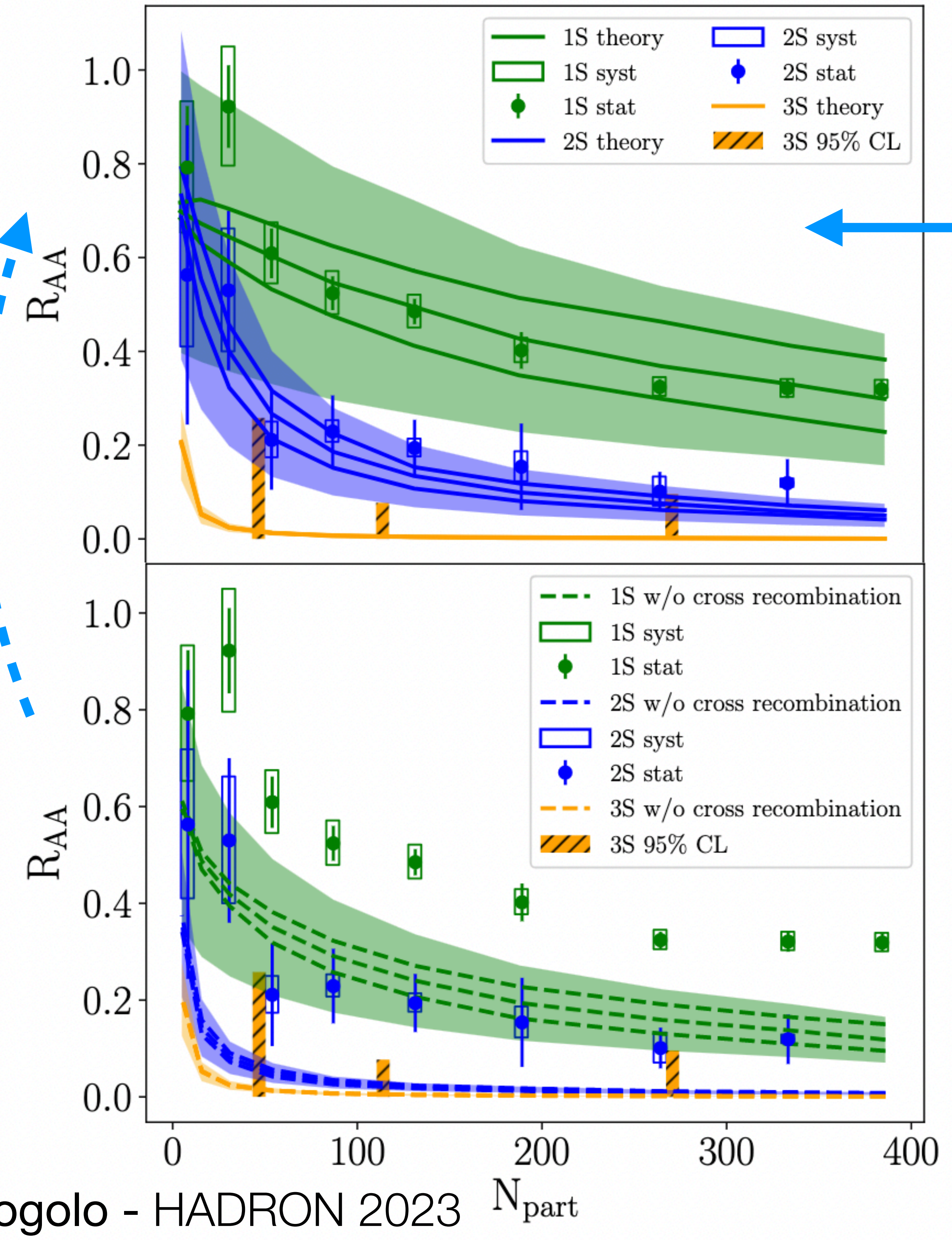
SHMc, PLB 797 (2019) 134836

Role of regeneration in quarkonia: $\Upsilon(nS)$



- Quarkonium dissociation in QGP → Debye screening of $q\bar{q}$ potential
- Production can occur also via quark (re)combination → evidence from LHC results
  - ➡ relevant also for bottomonia?
  - ➡ ATLAS results compatible with CMS (backup)

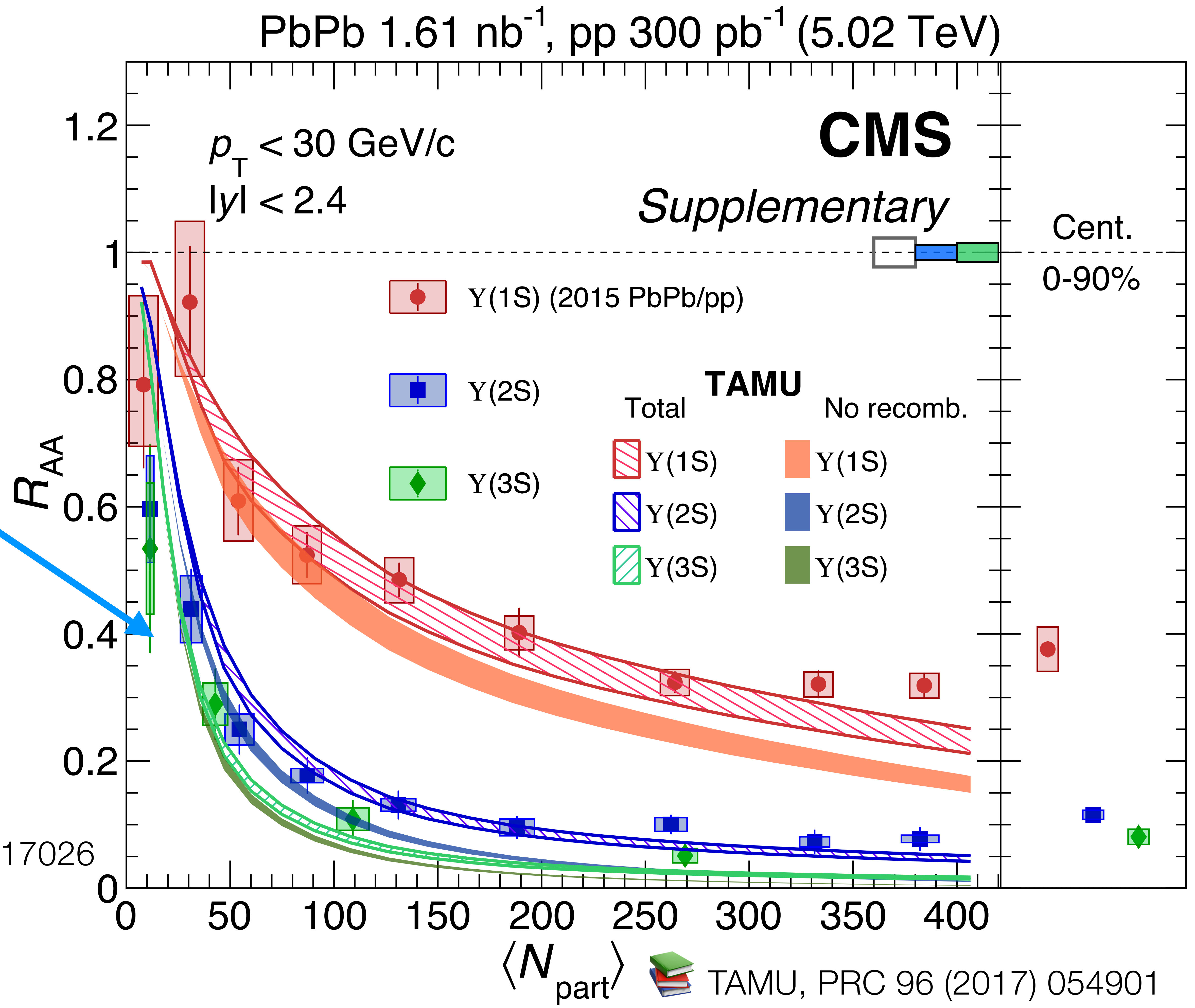
Recombination ON



Recent theory calculations showed importance of recombination for $\Upsilon(nS)$

X. Yao et al., JHEP 01 (2021) 046

CMS, arXiv:2303.17026

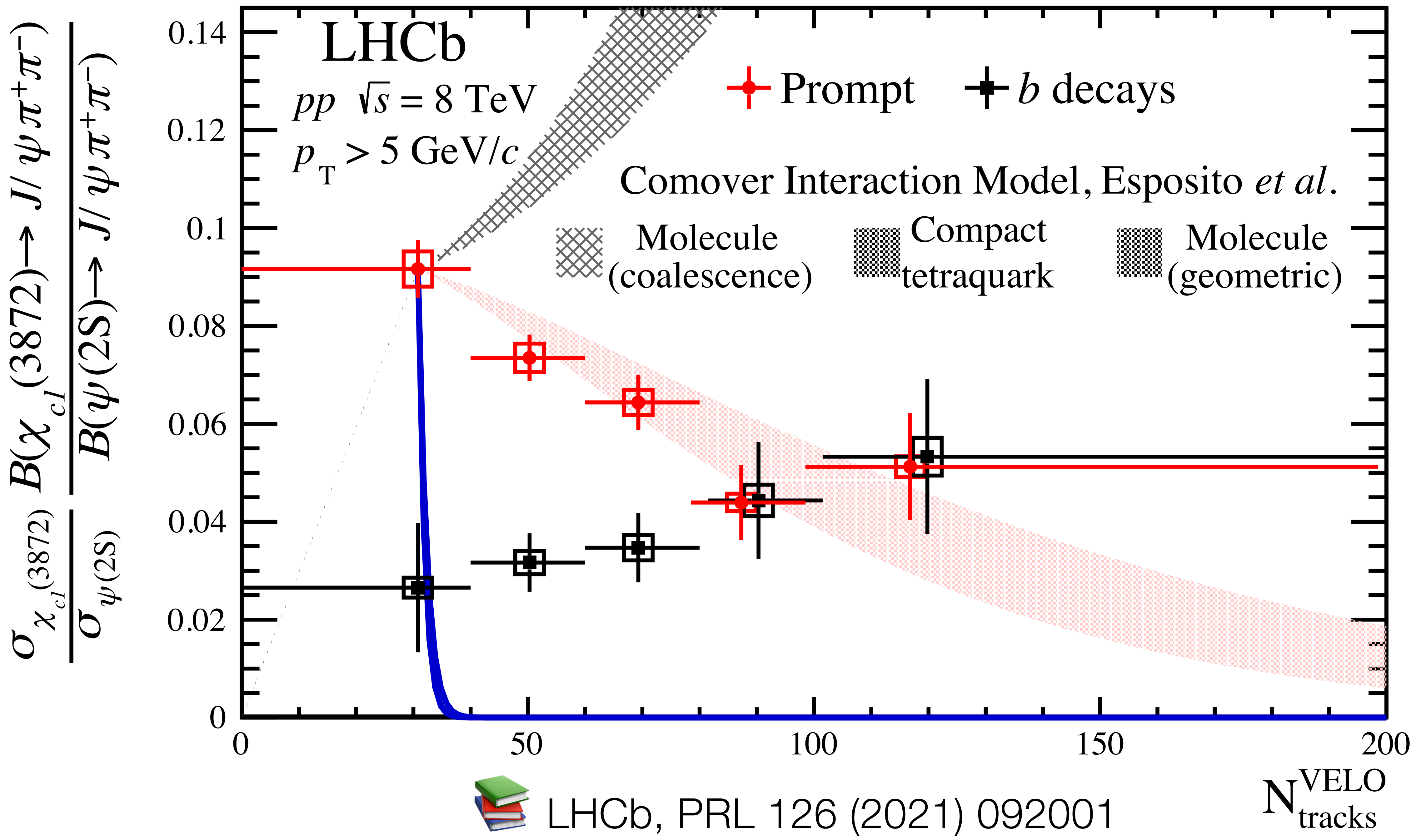


TAMU, PRC 96 (2017) 054901

Exotic states: $\chi_c(3872)/\psi(2S)$

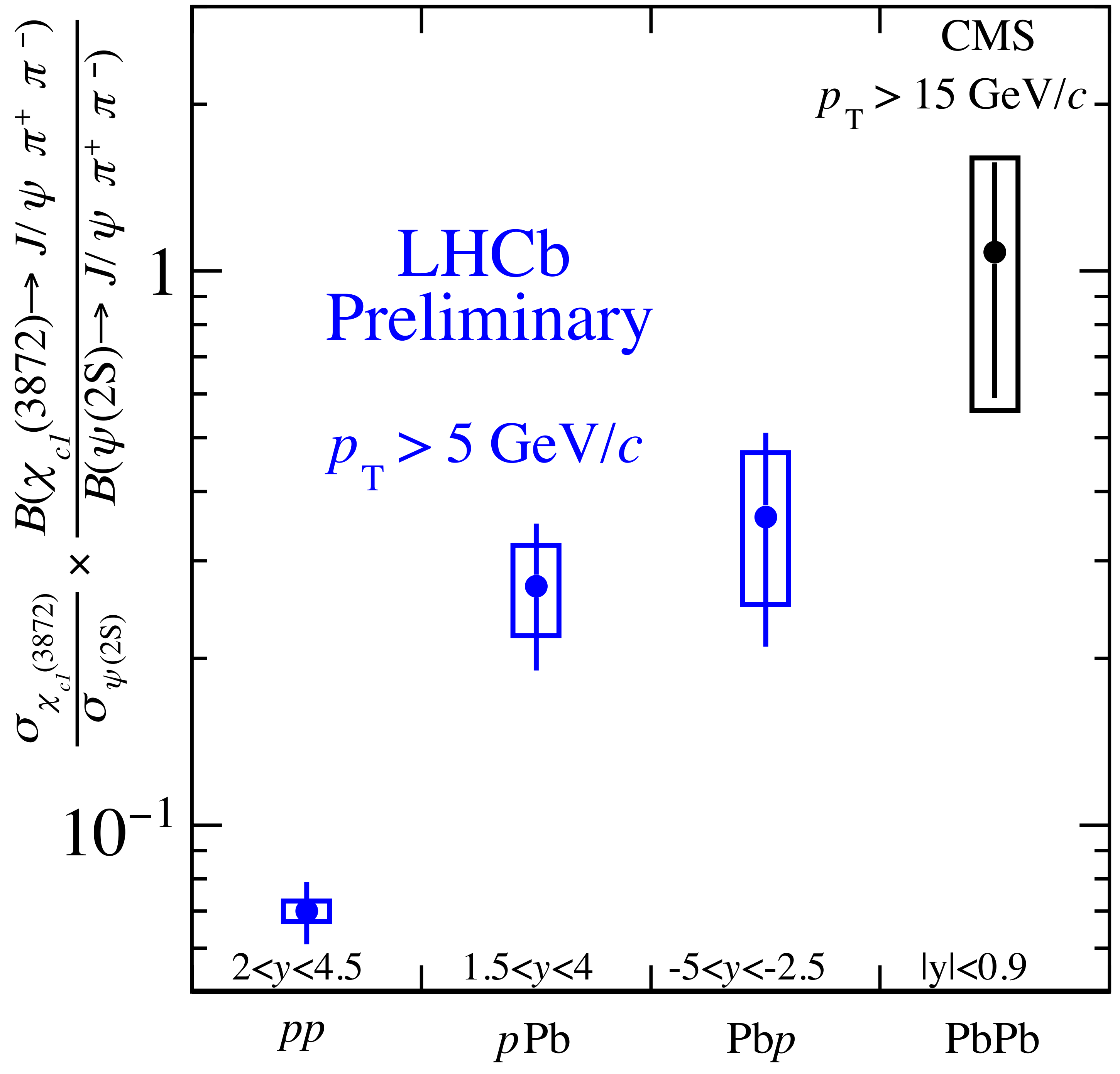
- Understanding exotic-state production → insight into hadronization process
- $\chi_c(3872)/\psi(2S)$ ratio as a function of charged particles tracks in pp collisions
  - ➡ described by Comover Model assuming a tetraquark structure
- Increase of the ratio can be due to
  - ➡ larger suppression of $\psi(2S)$ relative to exotic hadrons → better to change reference?
  - ➡ enhancement of $\chi_c(3872)$ in high density medium → coalescence mechanism?

Esposito A. et al., EPJC 81 (2021) 7



LHCb, PRL 126 (2021) 092001

LHCb, CONF-2022-001

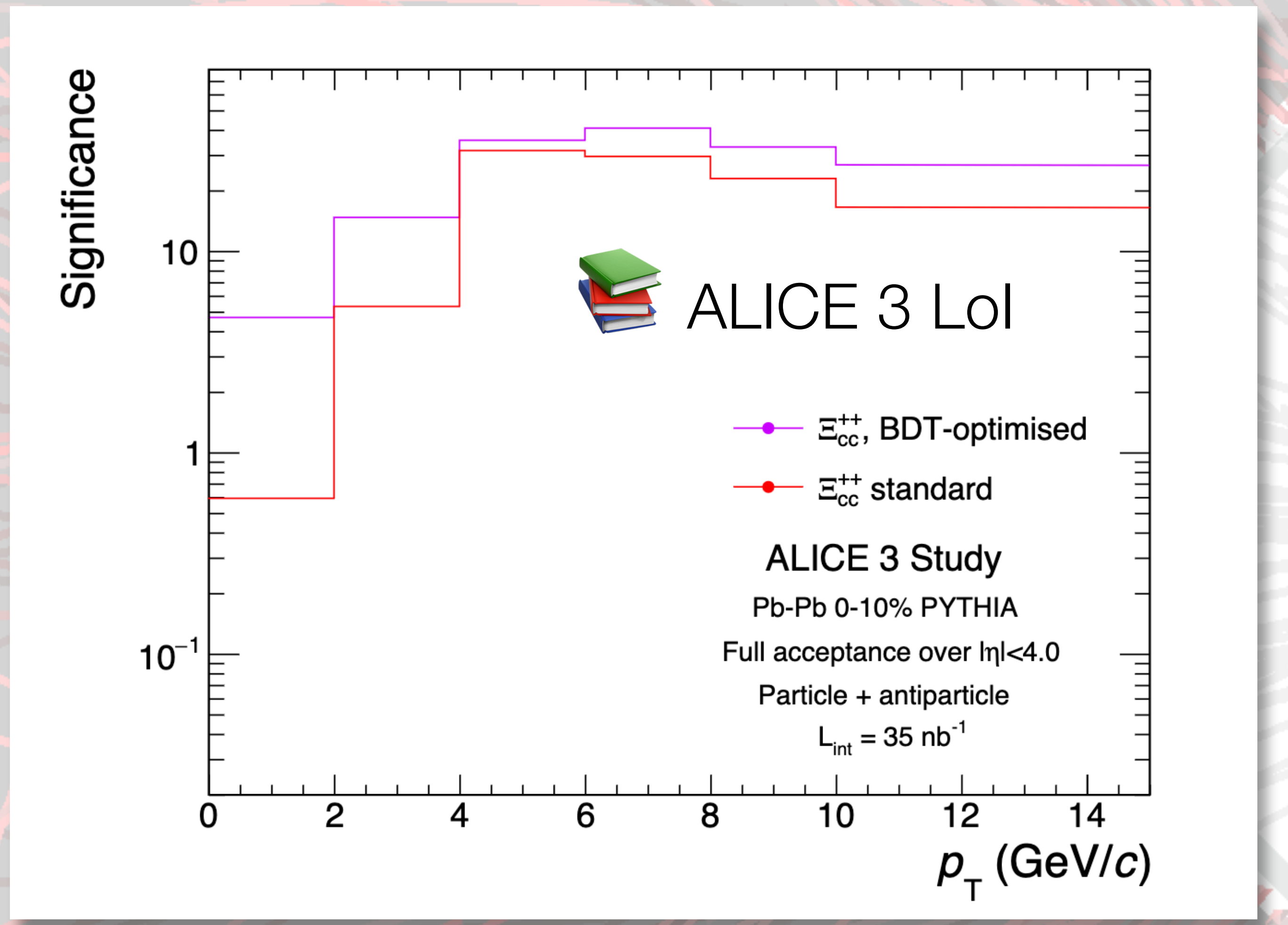


Outlook and future

LHC program

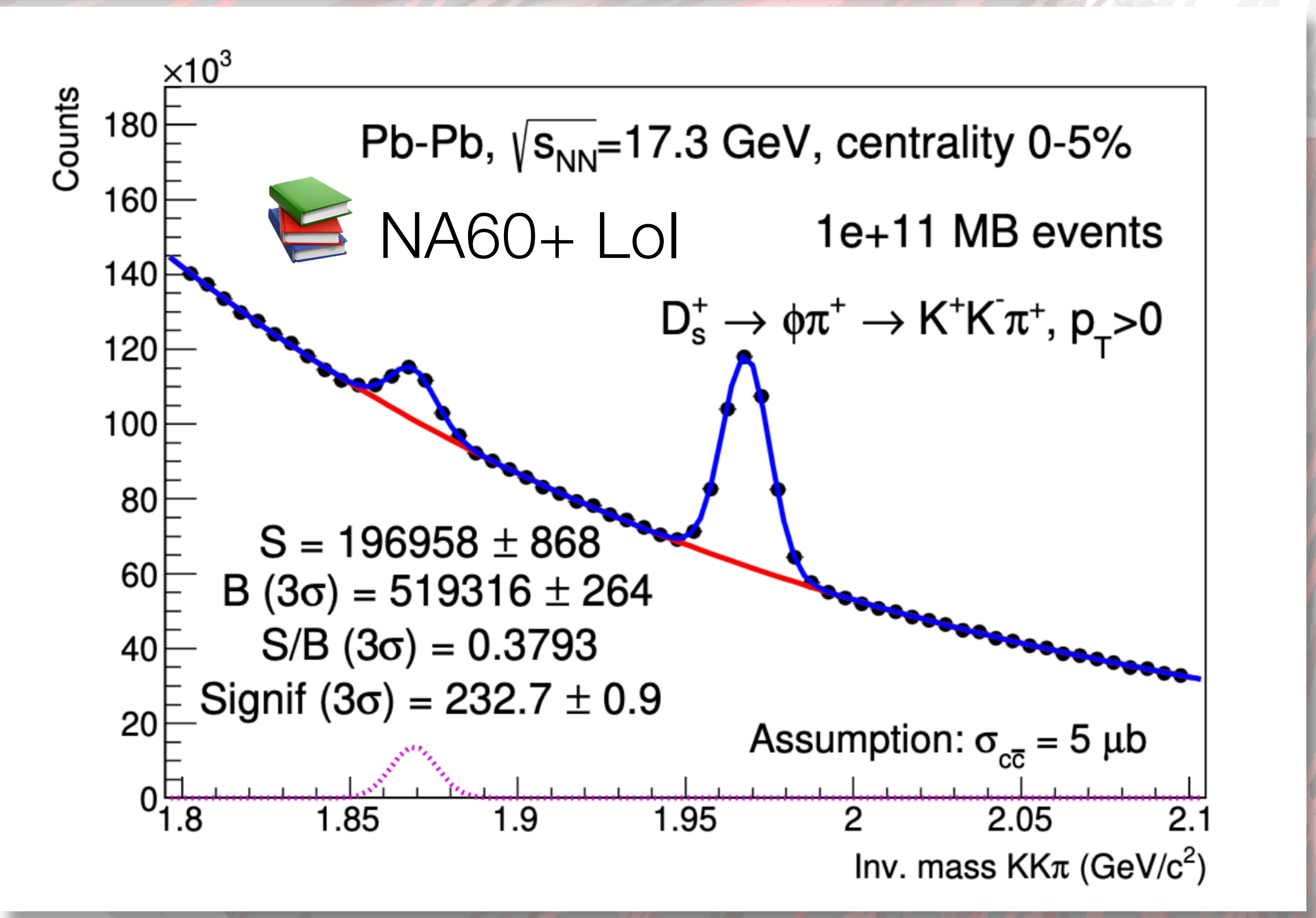
Run 1 2010-2012 → LS1 → Run 2 2015-2018 → LS2 → Run 3 2022-2024 → LS3 → Run 4 2028-2030 → LS4 → Run 5 2032-2034 → LS5 → Run 6 2036-2039

- Important upgrades in Long Shutdown 2:
  - ➡ ALICE 2 and LHCb major upgrade; ATLAS and CMS Phase I
- What next?
  - ➡ High Luminosity LHC installation
  - ➡ ATLAS and CMS Phase II,
  - ➡ ALICE (FoCal, ITS3), LHCb Phase I-II, ALICE 3

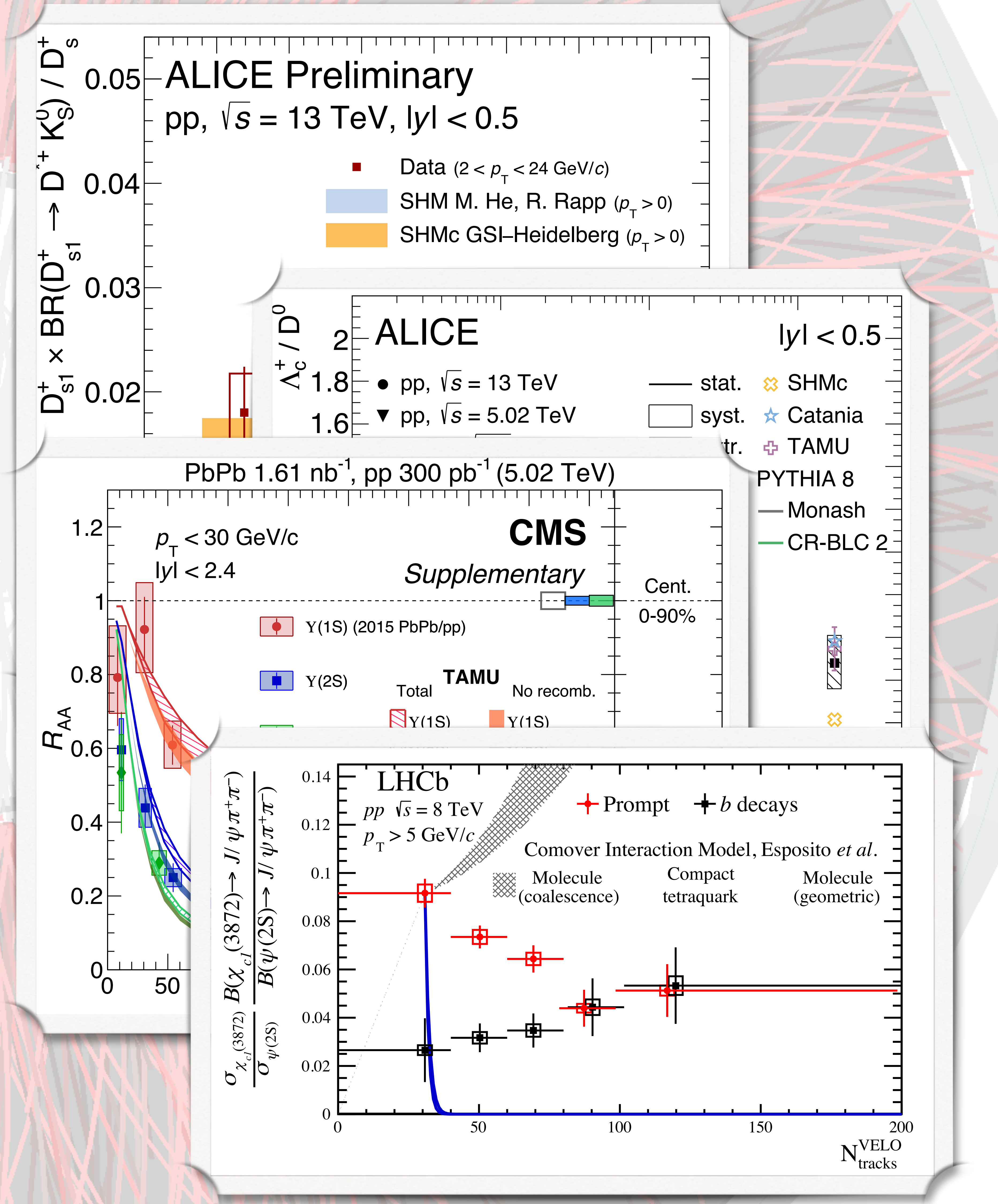


Not only LHC...

- Many other projects exploring QCD phase diagram:
  - ➡ NA61/SHINE, NA60+ at SPS
  - ➡ CBM at FAIR
  - ➡ Electron Ion Collider at BNL



Conclusions



- Huge effort in the last years to investigate the hadronization mechanisms of HF across colliding systems
  - ➡ Fragmentation functions universality violated already in pp collisions
  - ➡ pp collisions is a system dense enough to alter the hadronization
- In heavy-ion collisions:
  - ➡ Crucial role of coalescence mechanism for open HF production
  - ➡ (Re-)combination is more relevant at LHC energies for charmonia and bottomonia states
- An exciting period ahead:
  - ➡ wider investigation of HF production, especially beauty hadrons
  - ➡ hadronization in high multiplicity pp and p-A collisions with higher precise
  - ➡ large improvement on exotic states production

Conclusions

Thanks a lot for fruitful discussion to:
A. Dainese, A. Rossi, C. Terrevoli, F. Prino, L. Micheletti, M. Faggin

Conclusions

Thank you for your attention!

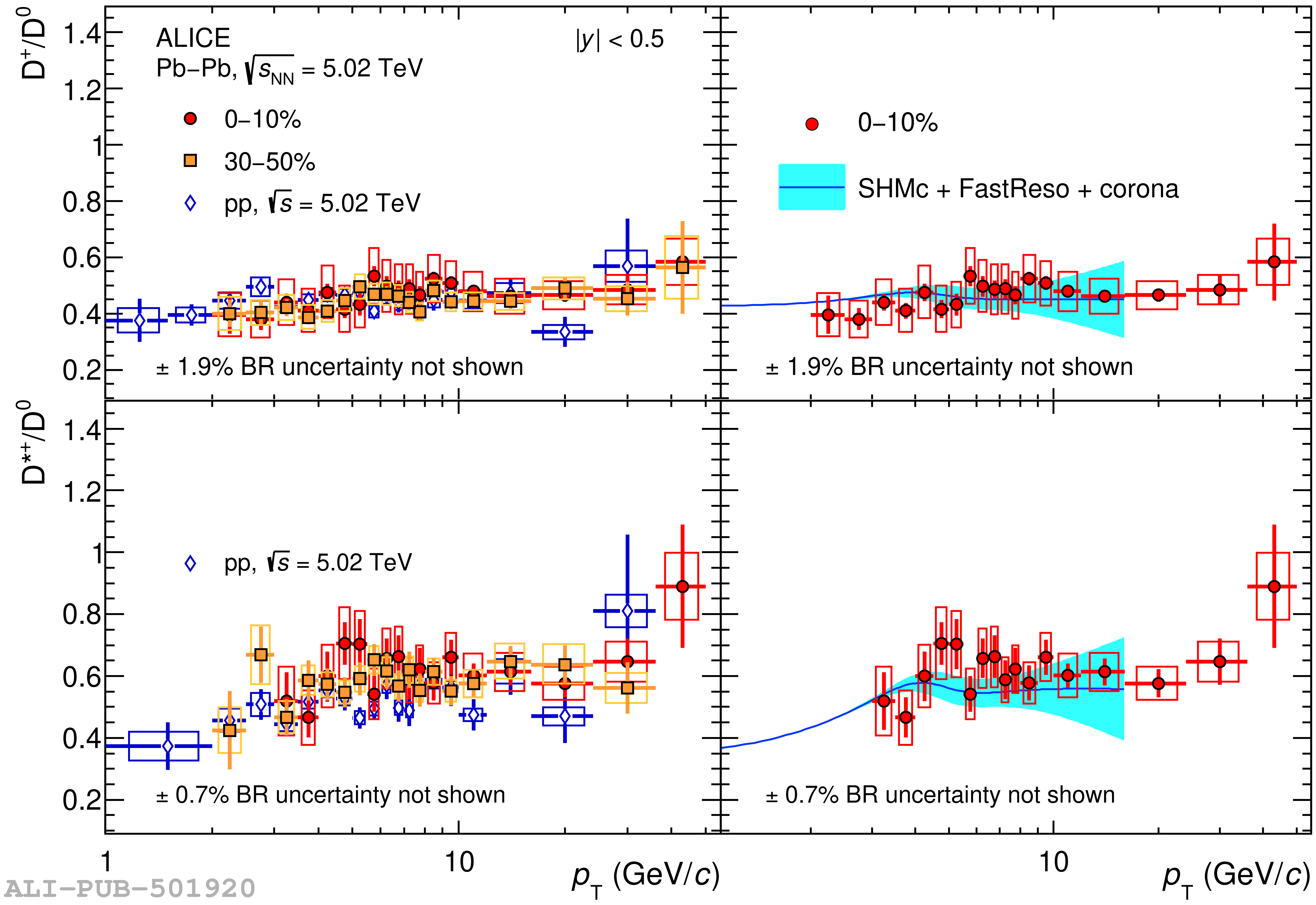
Thanks a lot for fruitful discussion to:

A. Dainese, A. Rossi, C. Terrevoli, F. Prino, L. Micheletti, M. Faggin

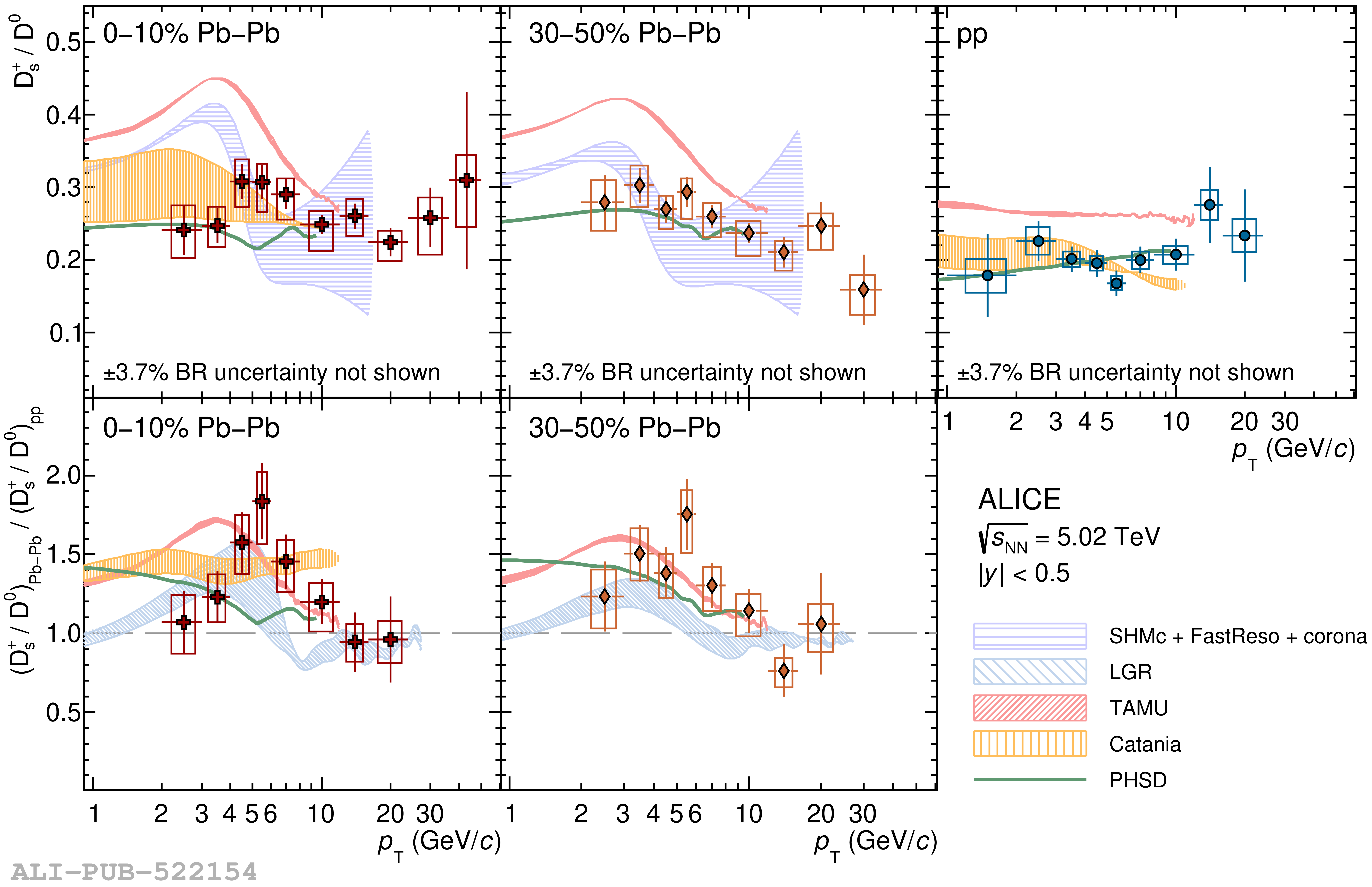
Additional material

Meson-to-meson ratios

ALICE, JHEP 01 (2022) 174

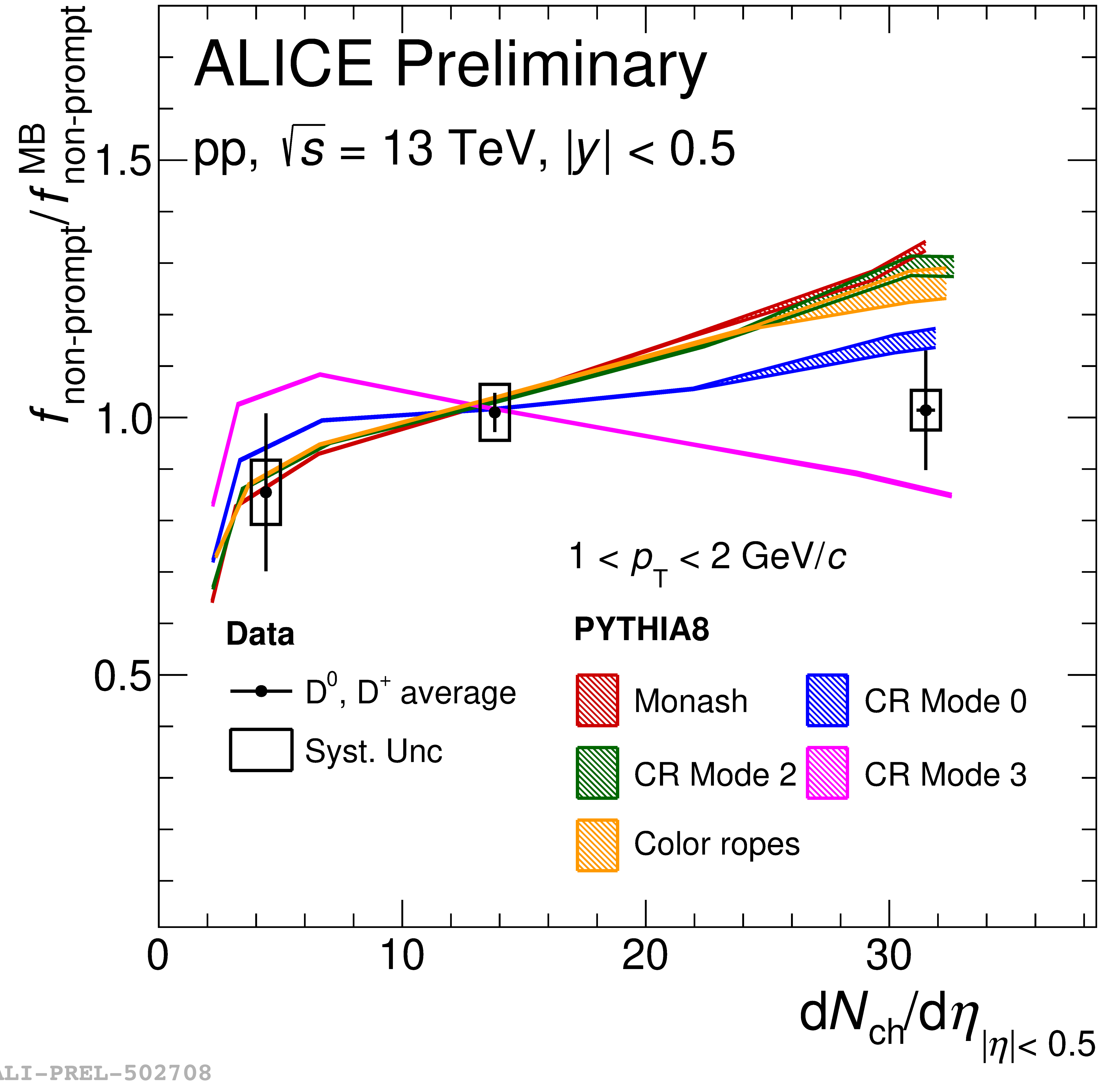


Meson-to-meson ratios



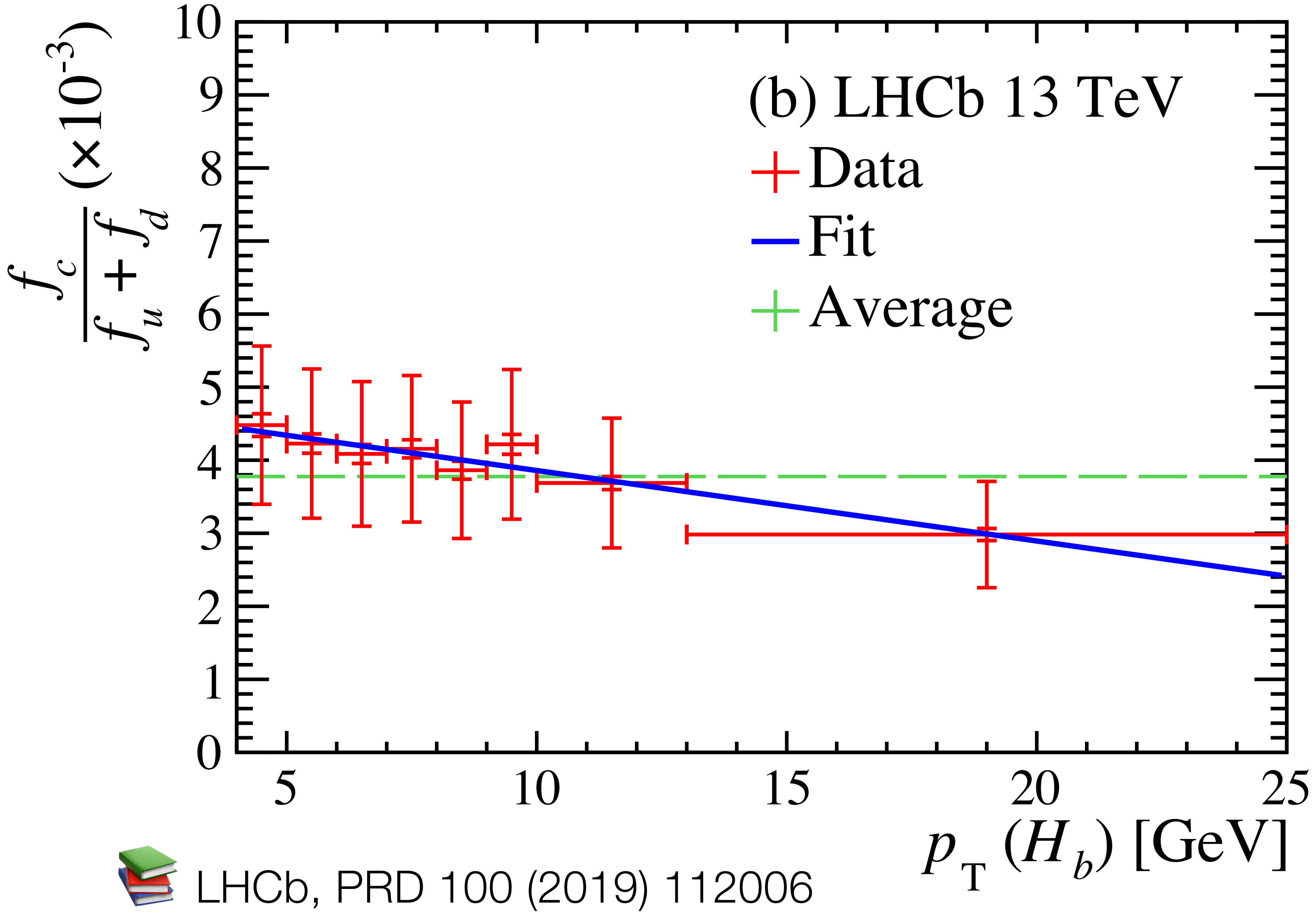
ALICE, PLB 827 (2022) 136986

non-prompt D vs. multiplicity

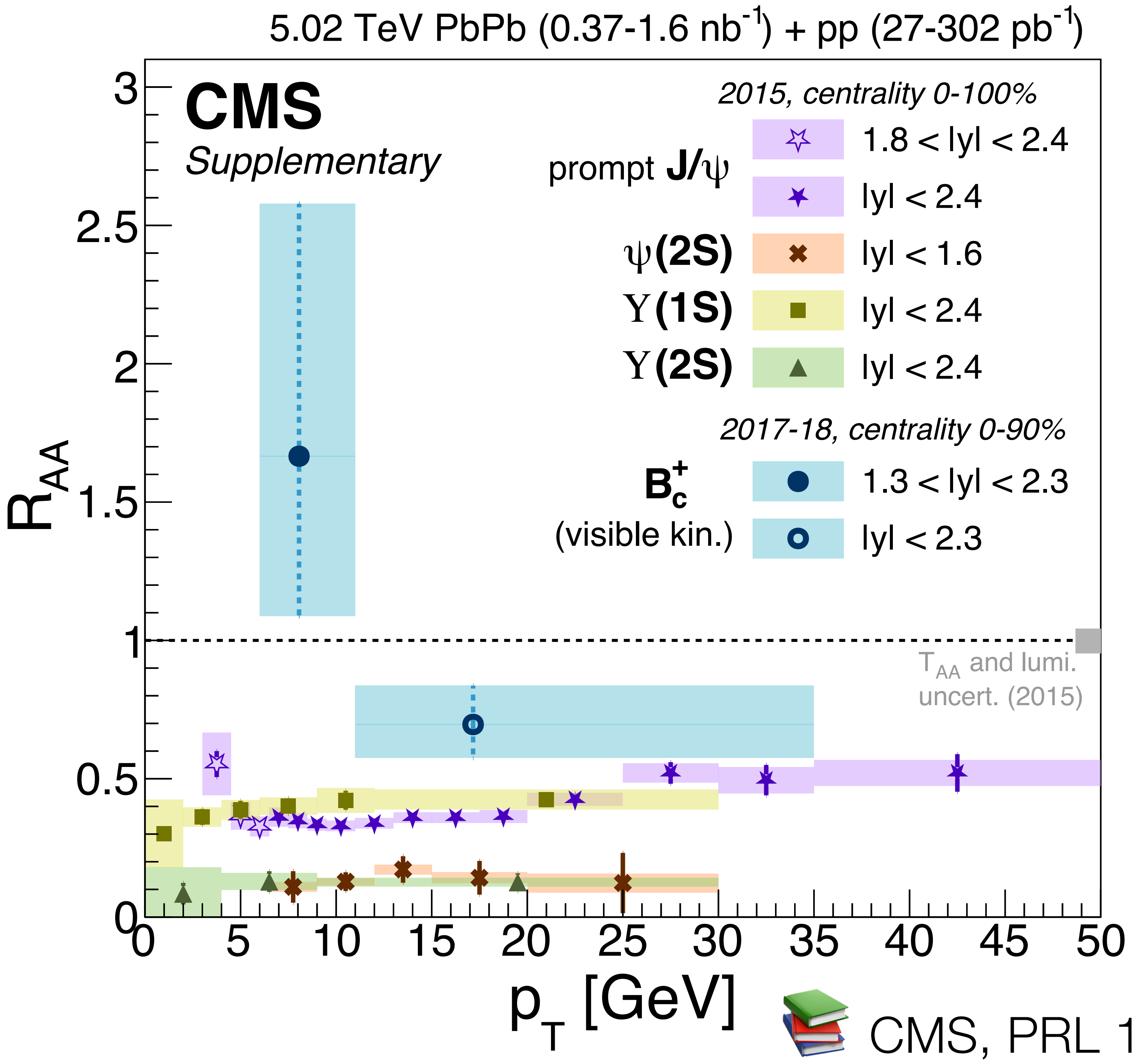


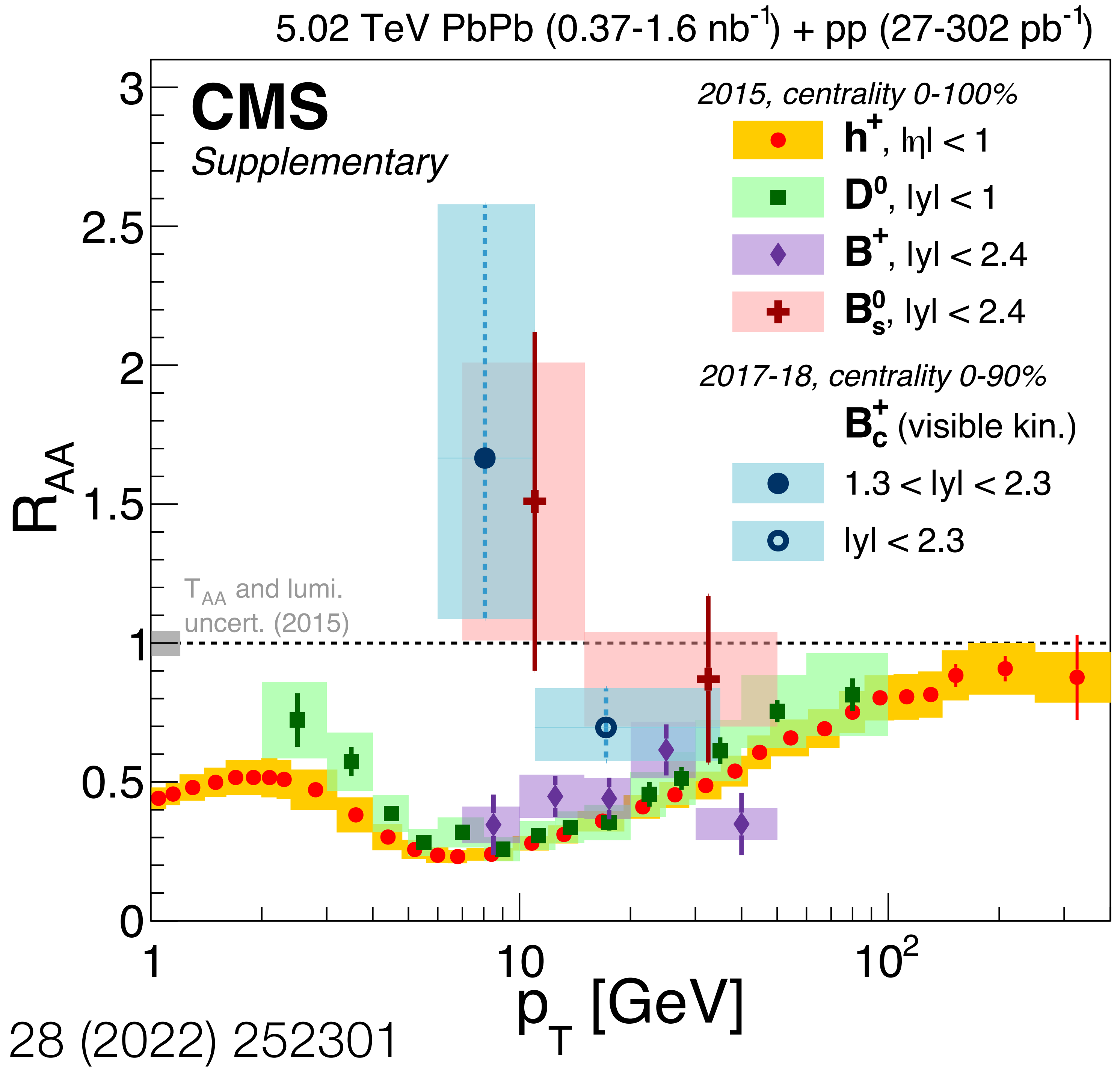
- non-prompt D^0, D^+ as a function of charged particle multiplicity
  - ➡ non-prompt fraction measured in different $dN_{ch}/d\eta$ intervals
  - ➡ ratio to the non-prompt fraction measured for minimum bias

Beauty hadronization vs. multiplicity in pp collisions



LHCb, PRD 100 (2019) 112006





CMS, PRL 128 (2022) 252301

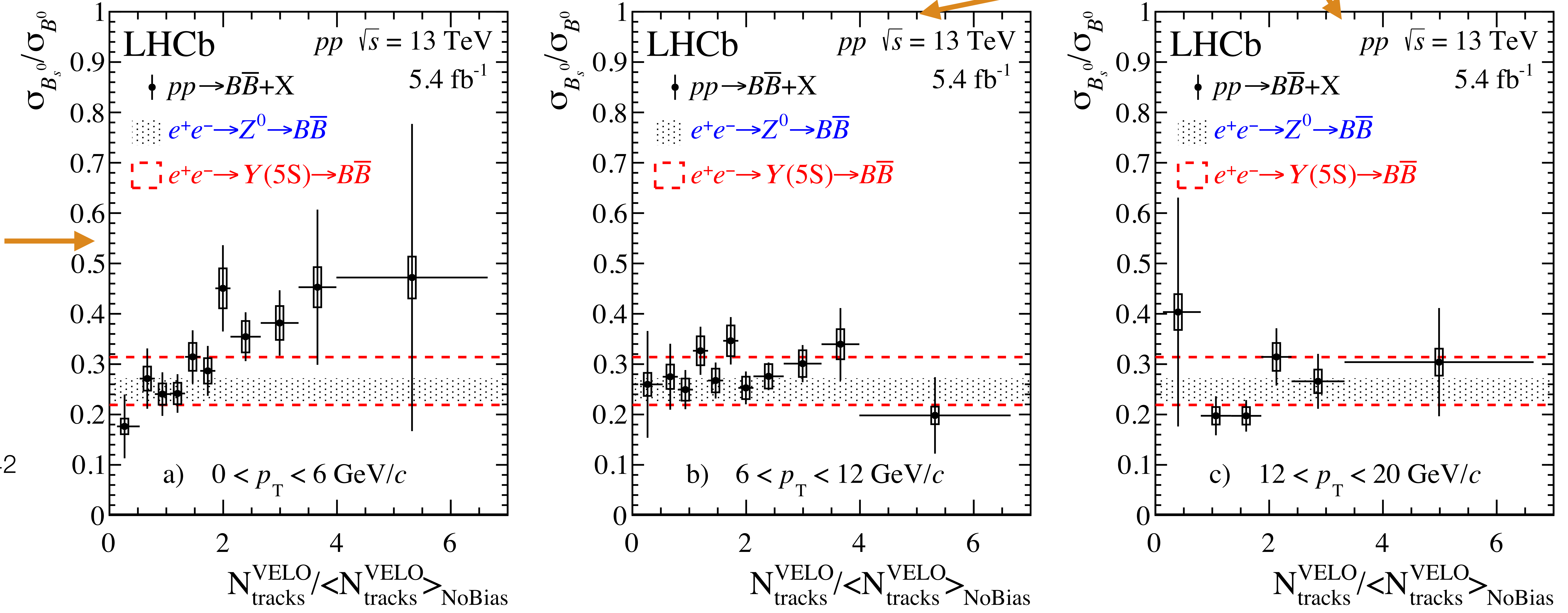
- B_c^+ production in pp not yet theoretically well understood
- Enhanced in Pb-Pb at low p_T? Less suppressed than other quarkonia?
- Production dominated by recombination in both pp and Pb-Pb?

Beauty hadronization vs. multiplicity in pp collisions

- Hadronization via recombination may enhance B_s/B^0 with increasing multiplicity
  - ➡ B_s/B^0 at low p_T increases with local particle density
  - ➡ qualitatively as expected in the recombination approach

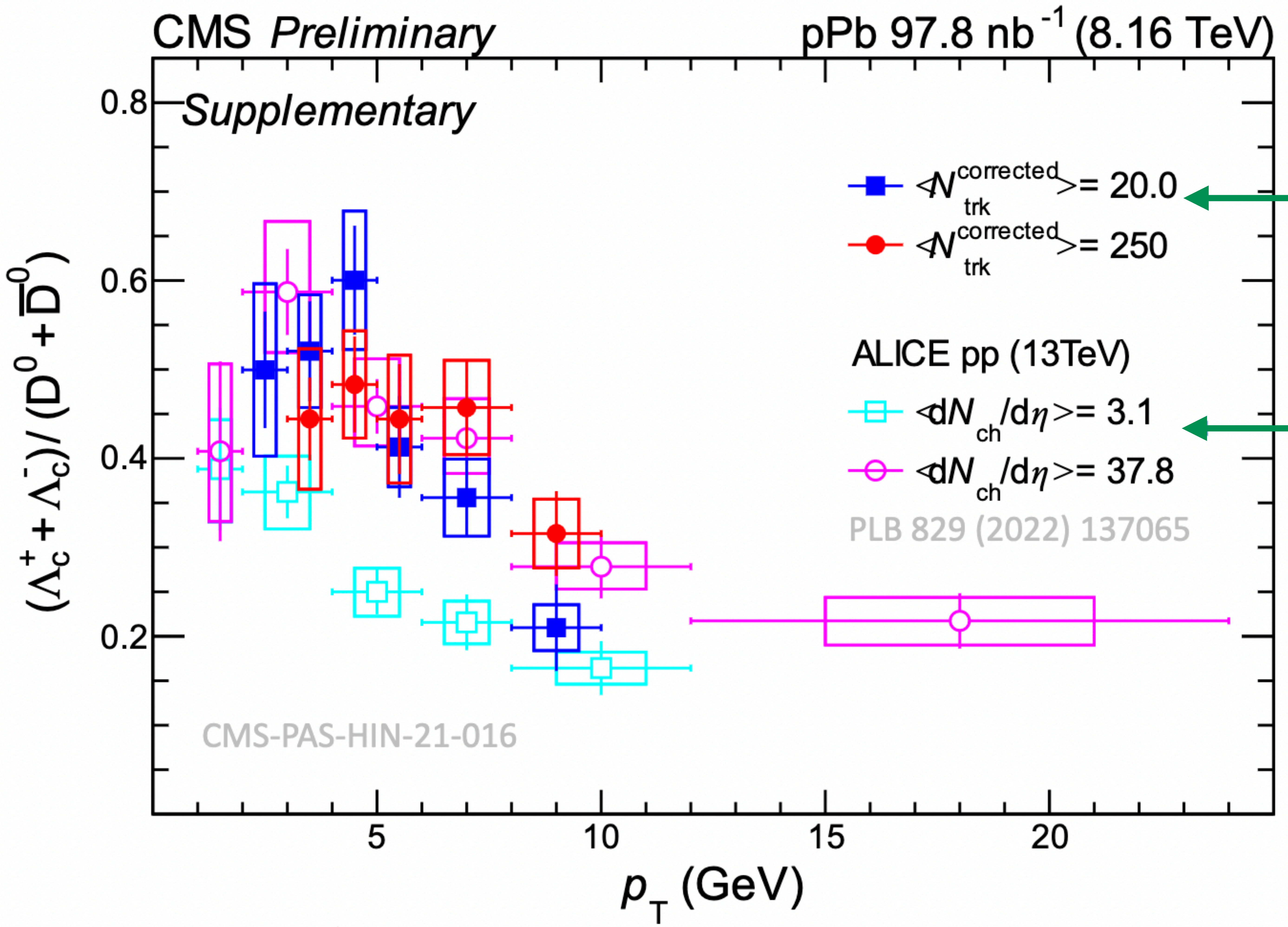
No significant dependence of B_s/B^0 vs. multiplicity at higher p_T

Increasing B_s/B^0 vs. multiplicity in the VELO at low p_T



LHCb, arXiv:2204.13042

Prompt Λ_c^+/D^0 vs. event multiplicity in p-Pb collisions



CMS, PAS-HIN-21-016

$p_T > 0.4$ GeV/c

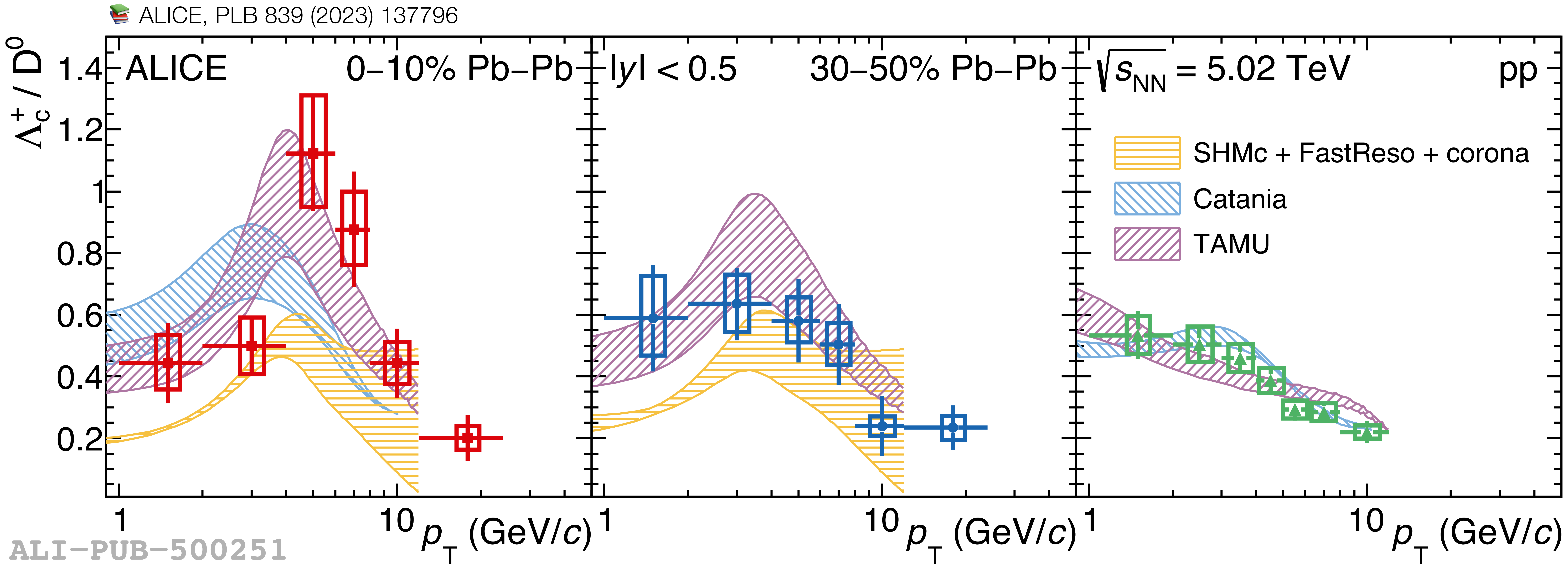
$|\eta| < 2.4$

Down to $p_T \sim 0$ GeV/c

- Prompt Λ_c^+/D^0 in p-Pb comparable to high multiplicity pp events → no significant evolution with multiplicity

(return to main)

Prompt Λ_c^+/D^0 in Pb-Pb collisions

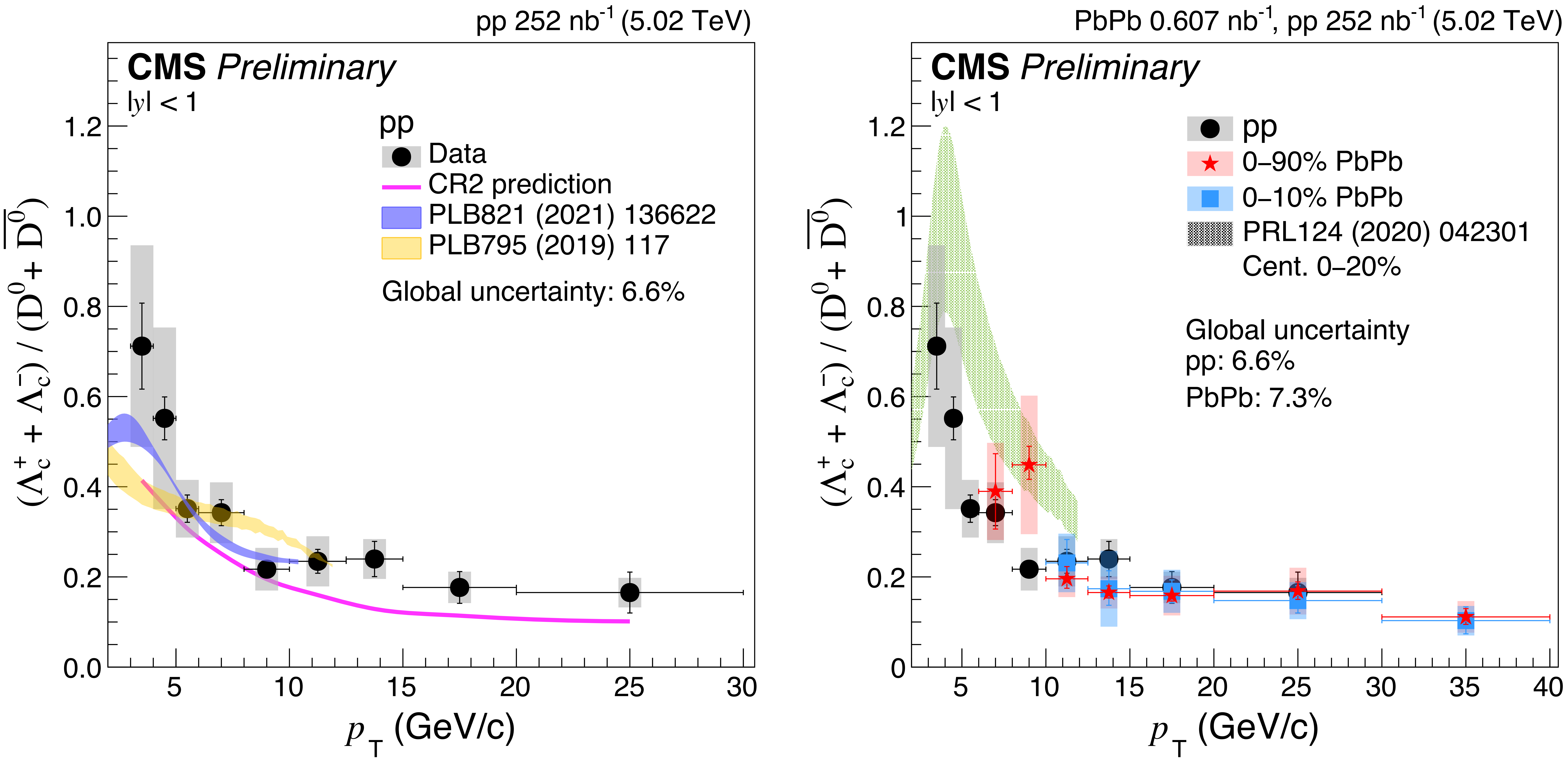


- Prompt Λ_c^+/D^0 in p-Pb comparable to high multiplicity pp events → no significant evolution with multiplicity

(return to main)

Prompt Λ_c^+/D^0 in Pb-Pb collisions

CMS, PAS-HIN-21-004



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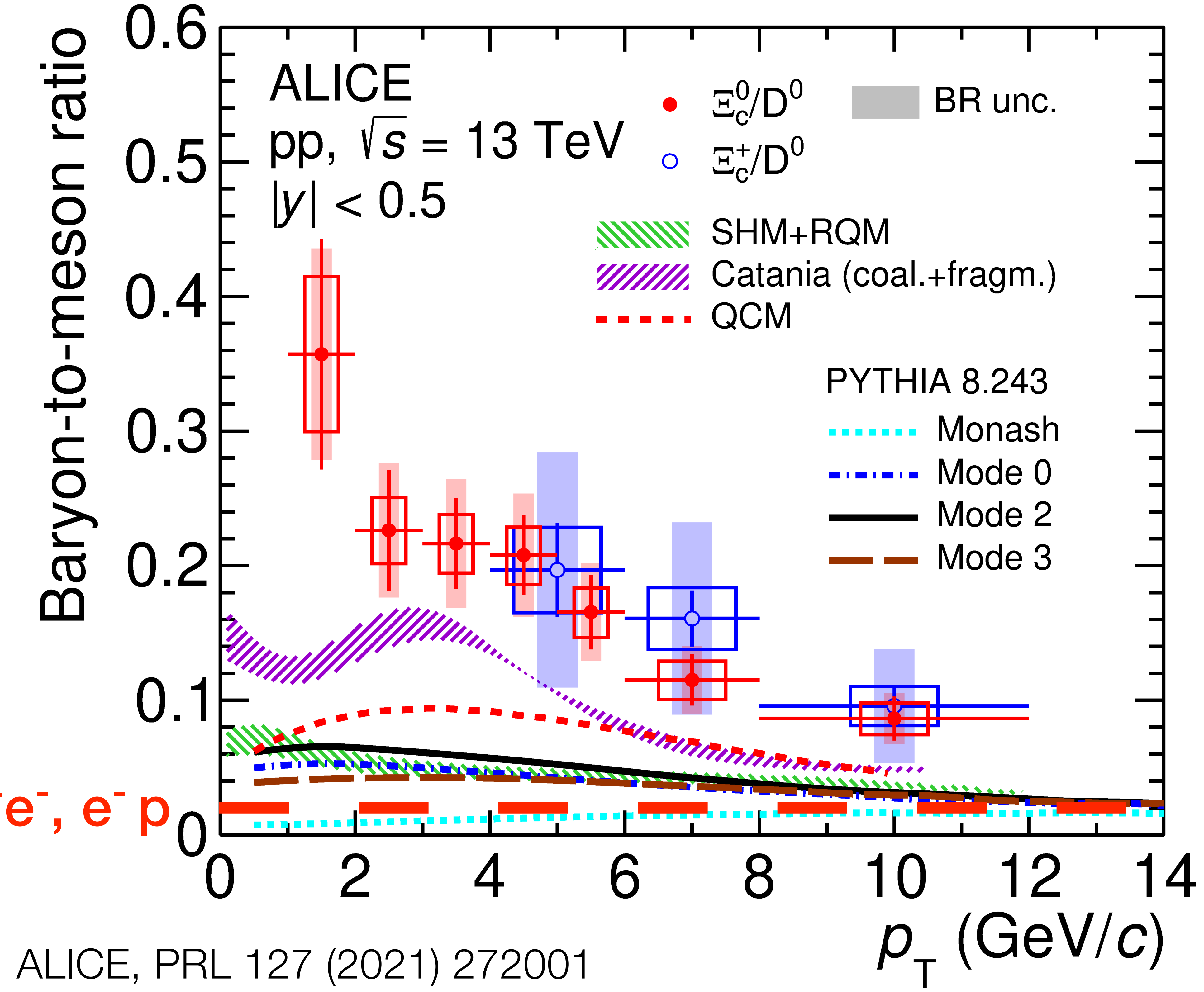
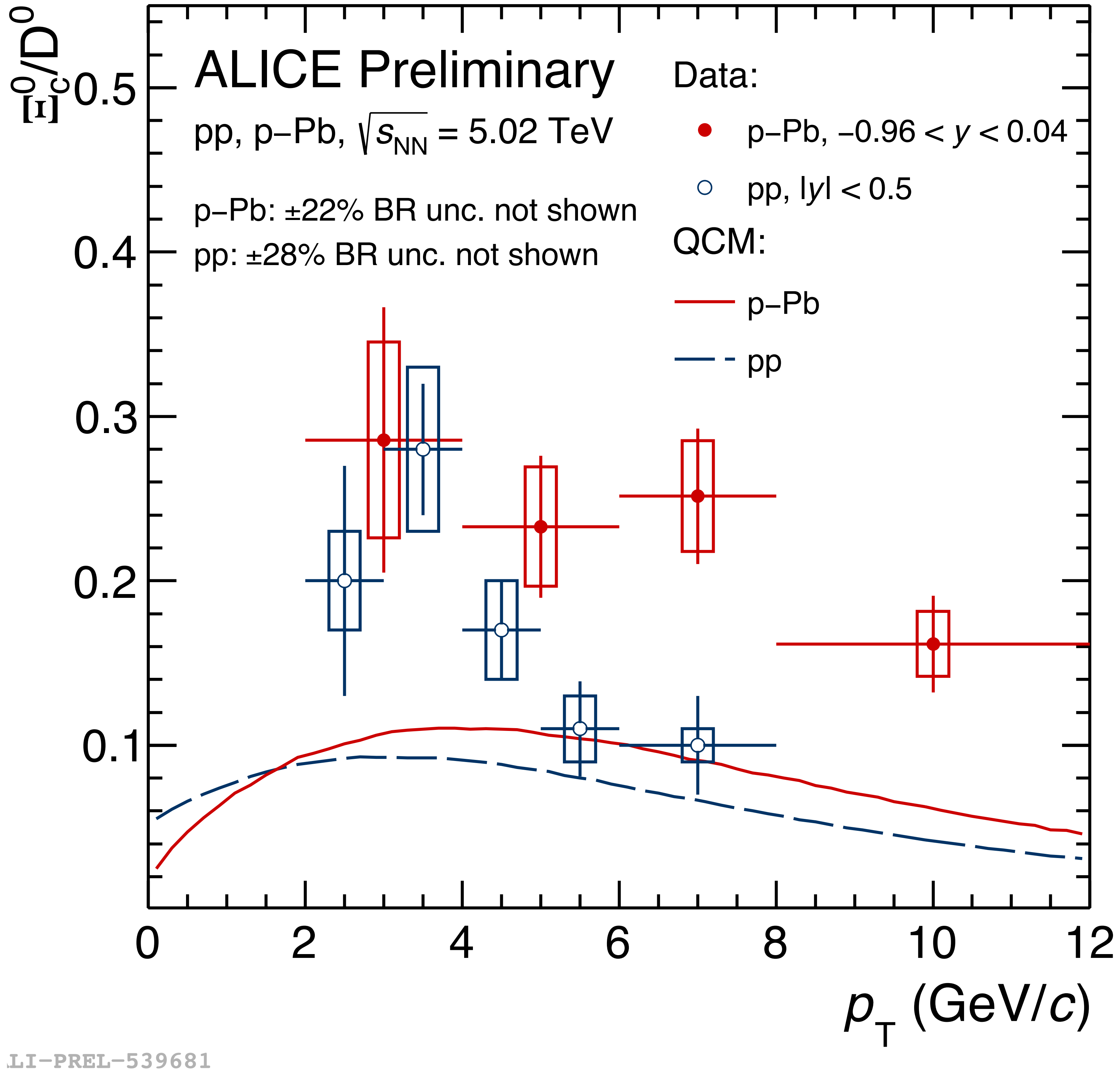
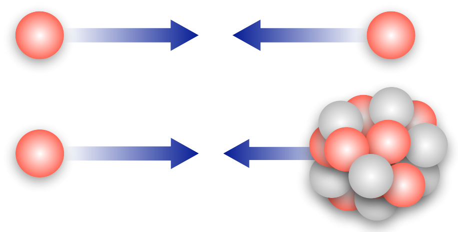


ALICE, PRL 127 (2021) 272001





PYTHIA 8: JHEP 1508 (2015) 003

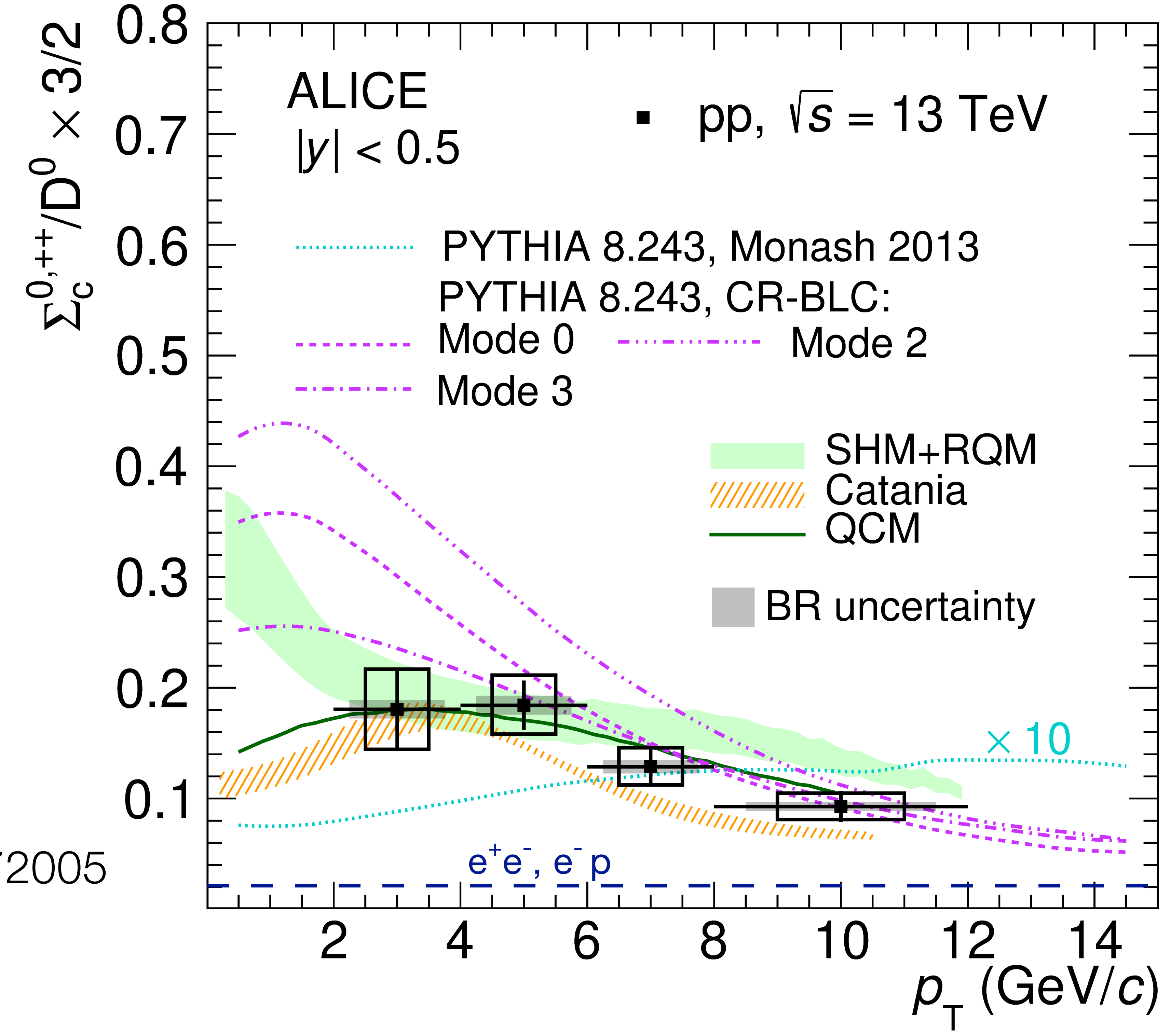
Catania: PLB 821 (2021) 136622

SHM+RQM: PLB 795 (2019) 117-121

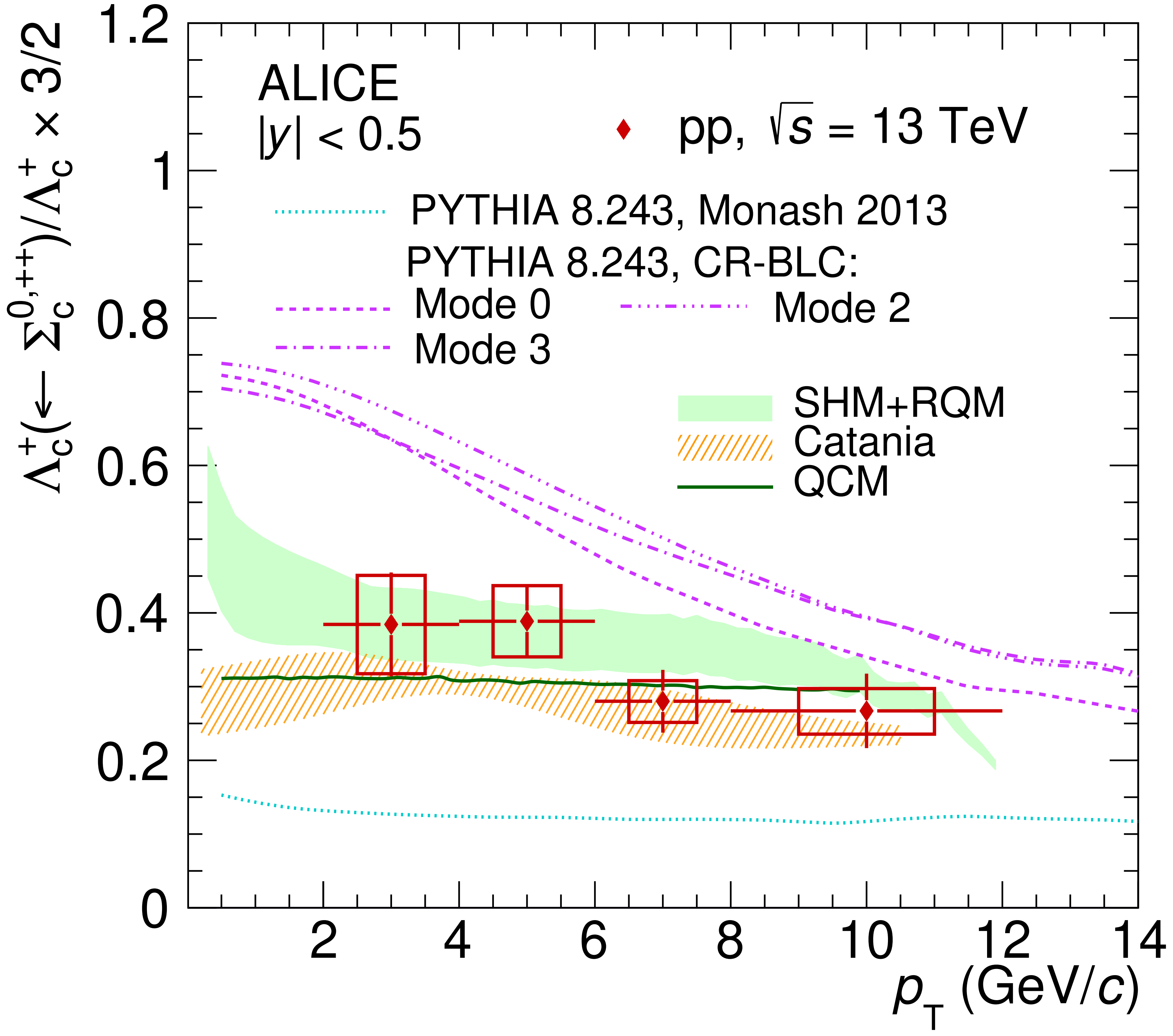
QCM: EPJC 78 (2018) 344

- $\Xi_c^{0,+}/D^0$ in pp collisions at two different energies → higher than PYTHIA Monash (e^+e^- tuning)
  - ➡ only recombination models are able to get closer to the measurement
- Hint of higher Ξ_c^0/D^0 in p-Pb collisions compared to pp collisions
  - ➡ similar p_T re-distribution from pp to p-Pb as observed for Λ_c^+/D^0 ratio?

Heavier charm baryons: $\Sigma_c^{0,+,++}$



Belle, PRD 97, 072005

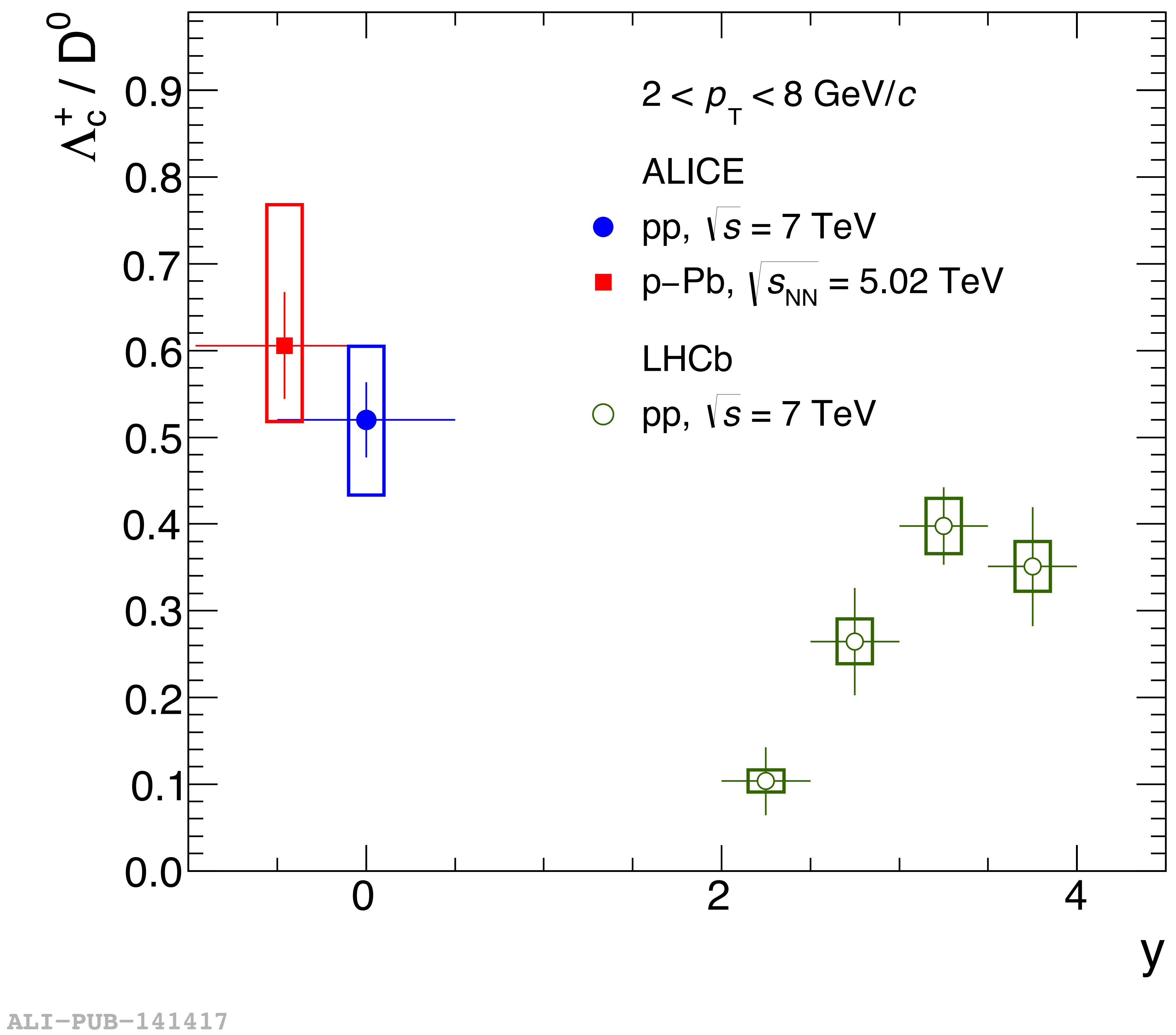


ALICE, PRL 128 (2022) 012001

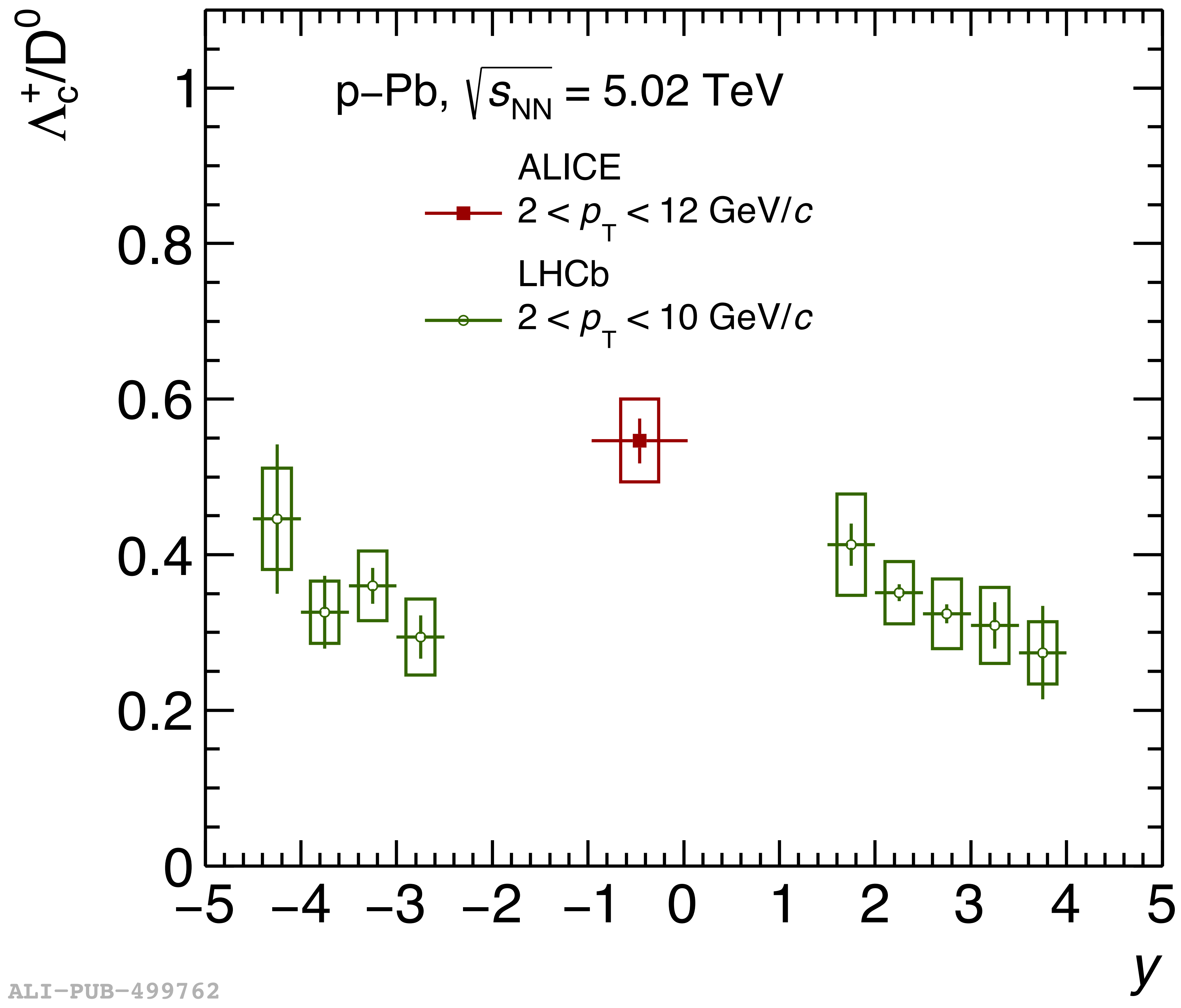
- $\Sigma_c^{0,++}/D^0$
  - ➡ larger than e^+e^- results → larger relative enhancement than Λ_c^+/D^0
  - ➡ well described by SHM+RQM, Catania and QCM
- $\Sigma_c^{0,++}/D^0$ partially accounts for Λ_c^+/D^0
  - ➡ measurements of feed-down Λ_c^+ from $\Sigma_c^{0,++}$ → overestimated by CR modes

Rapidity dependence - charm

pp

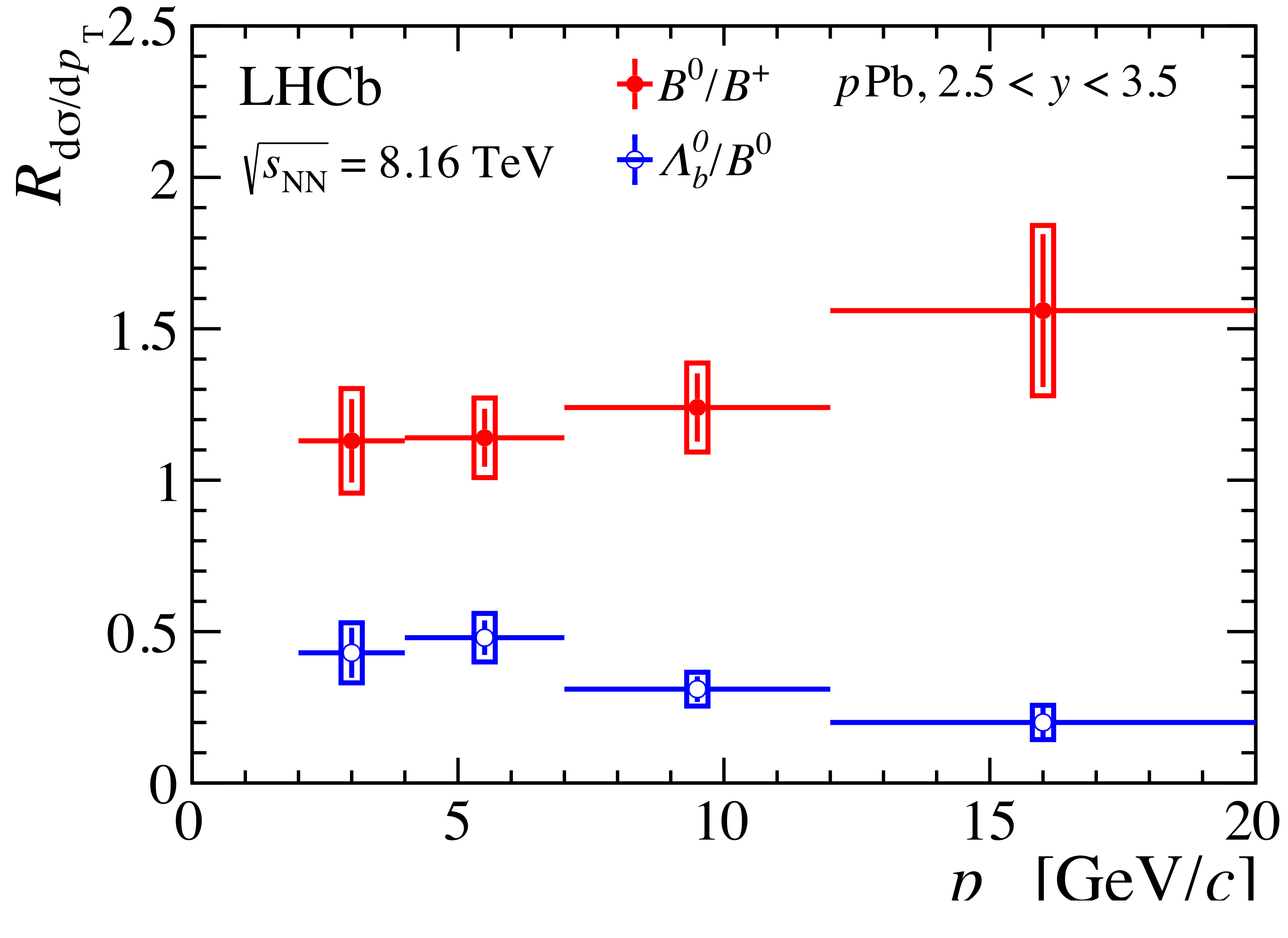


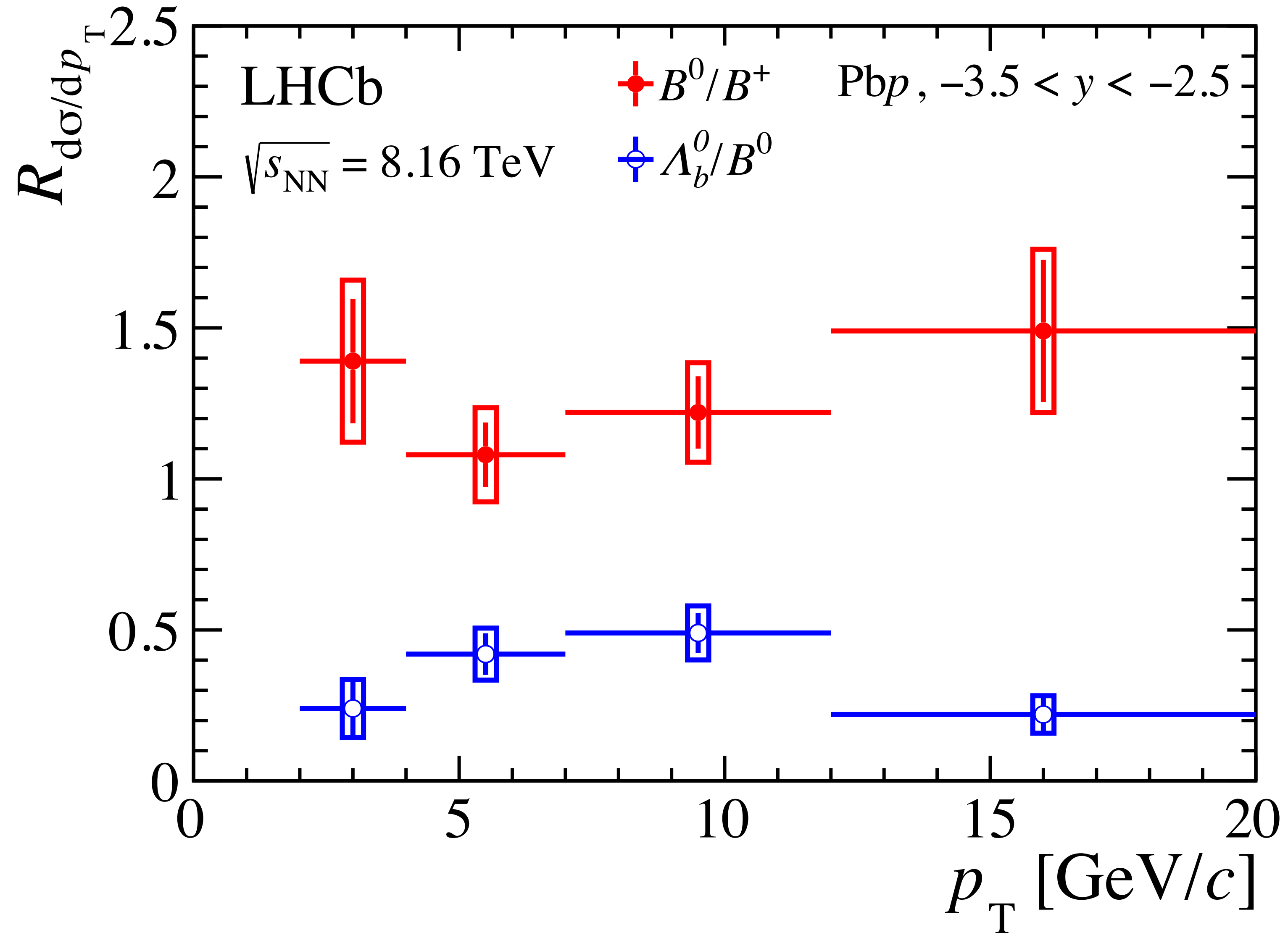
p-Pb

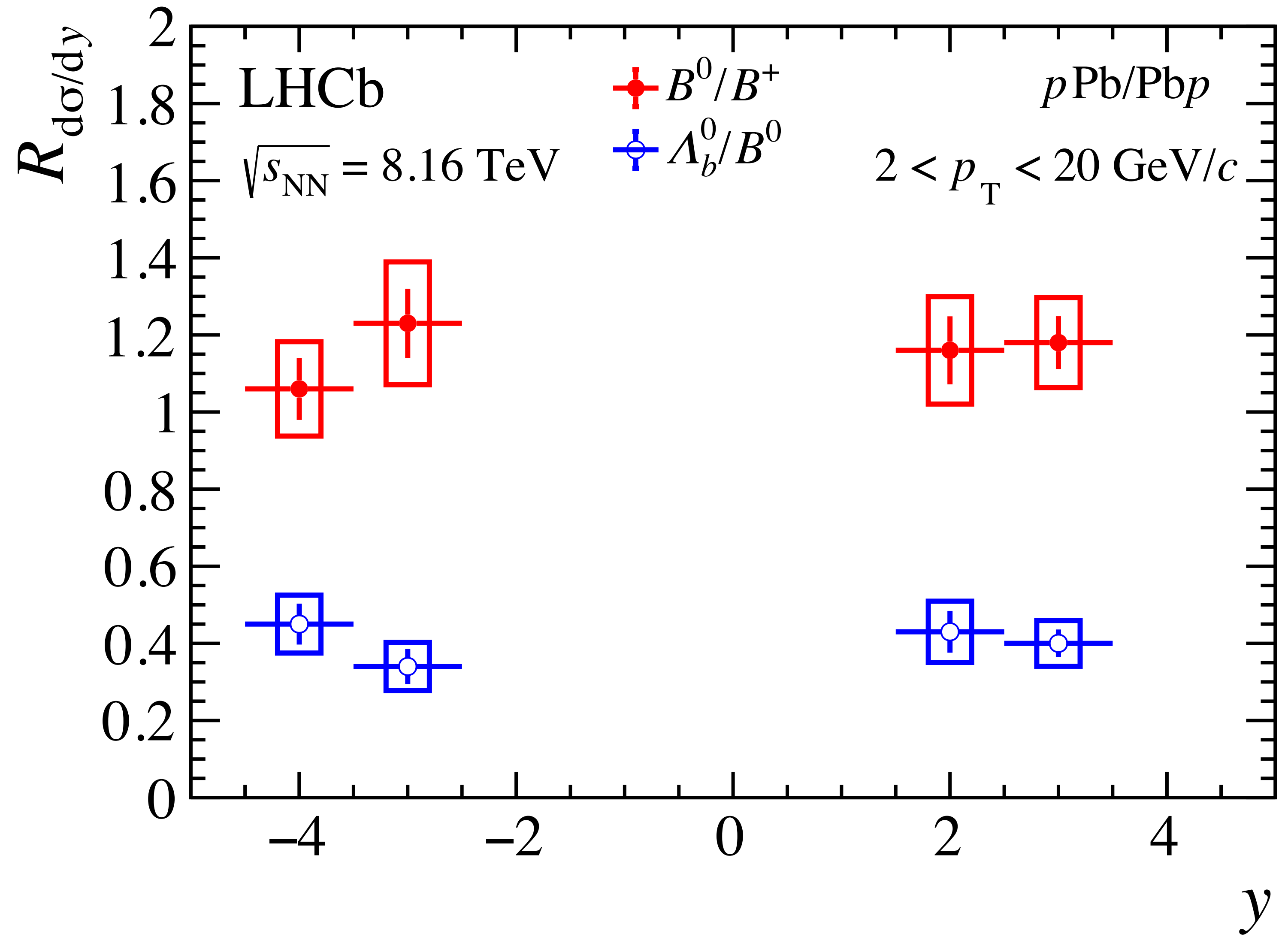


ALICE, PRC 104 (2021) 054905

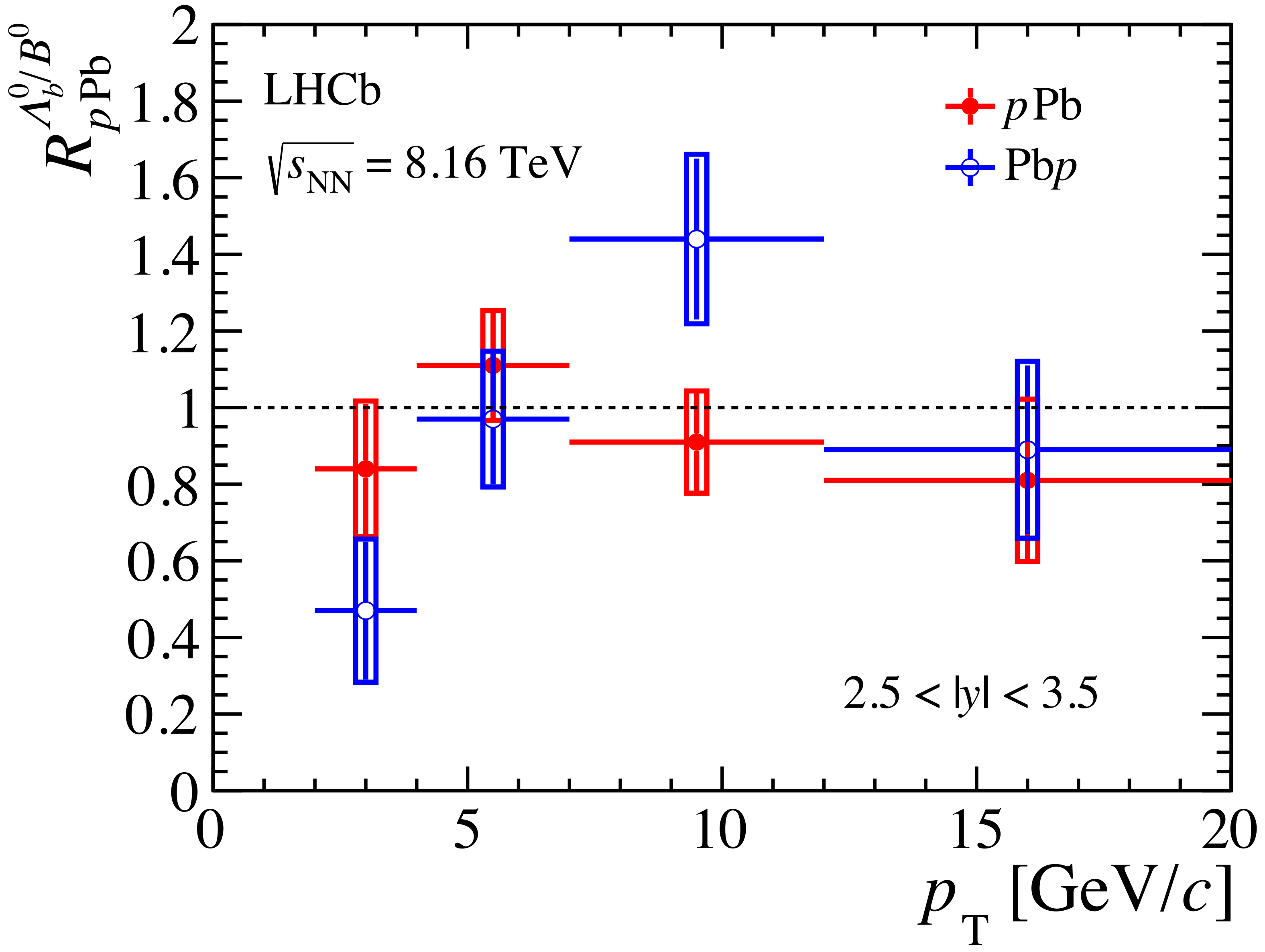
- Possible trend, to be revisited with run 3 data (also in pp)?





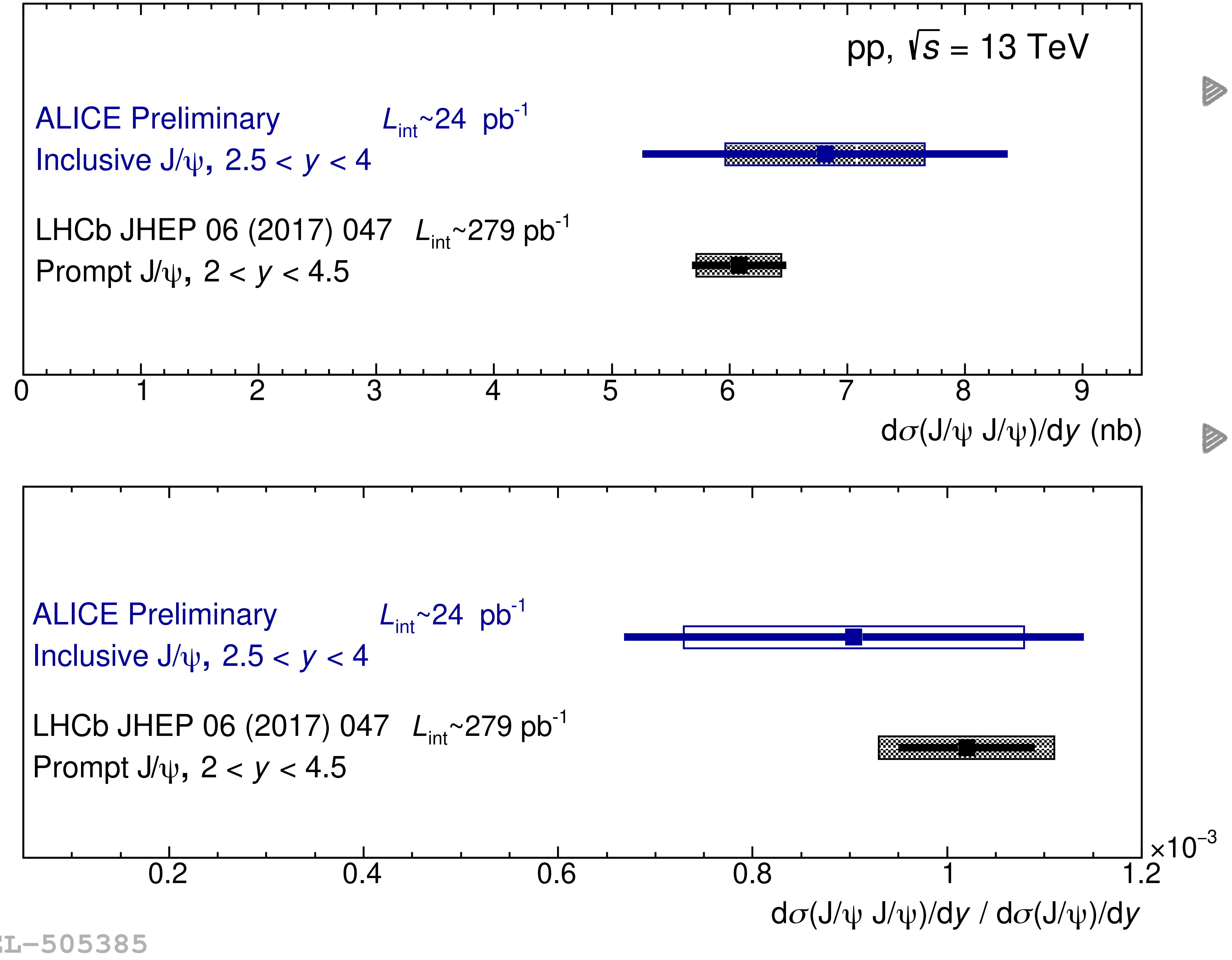


LHCb, PRD 99 (2019) 052011



- Λ_b/B^0 ratio in p–Pb compatible with pp one
  - ➡ more precision needed to clarify possible hints of modification

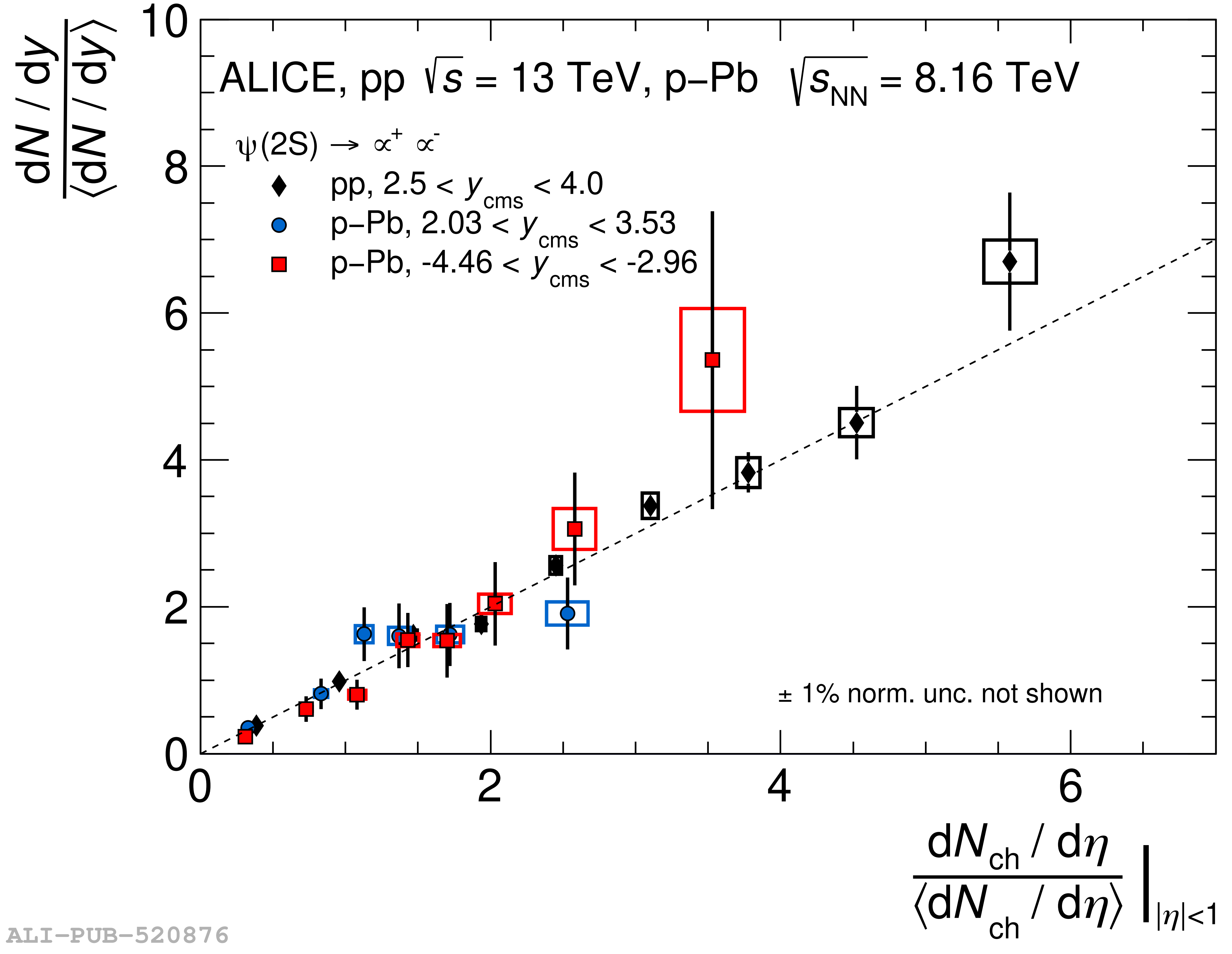
J/ψ pair production

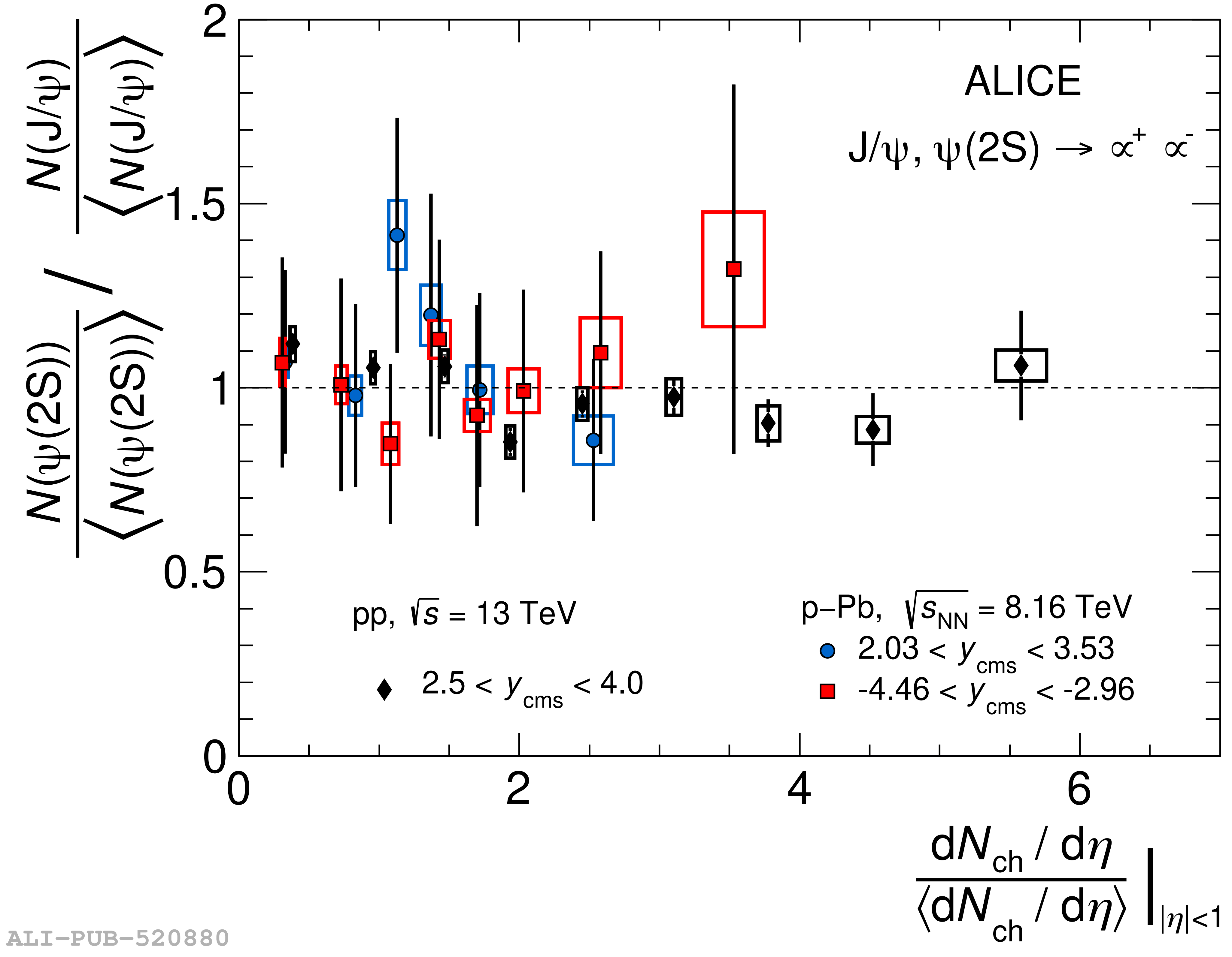


- J/ψ pair production measurement at 13 TeV
  - ➡ disentagle mechanisms for J/ψ production
  - ➡ insights on double parton scattering
- di-J/ψ production cross section
  - ➡ both results are in agreement with LHCb
  - ➡ CAVEAT:
    - ALICE measures inclusive J/ψ while LHCb prompt J/ψ
    - slightly different rapidity ranges

$\psi(2s)$ production in pp and p-Pb

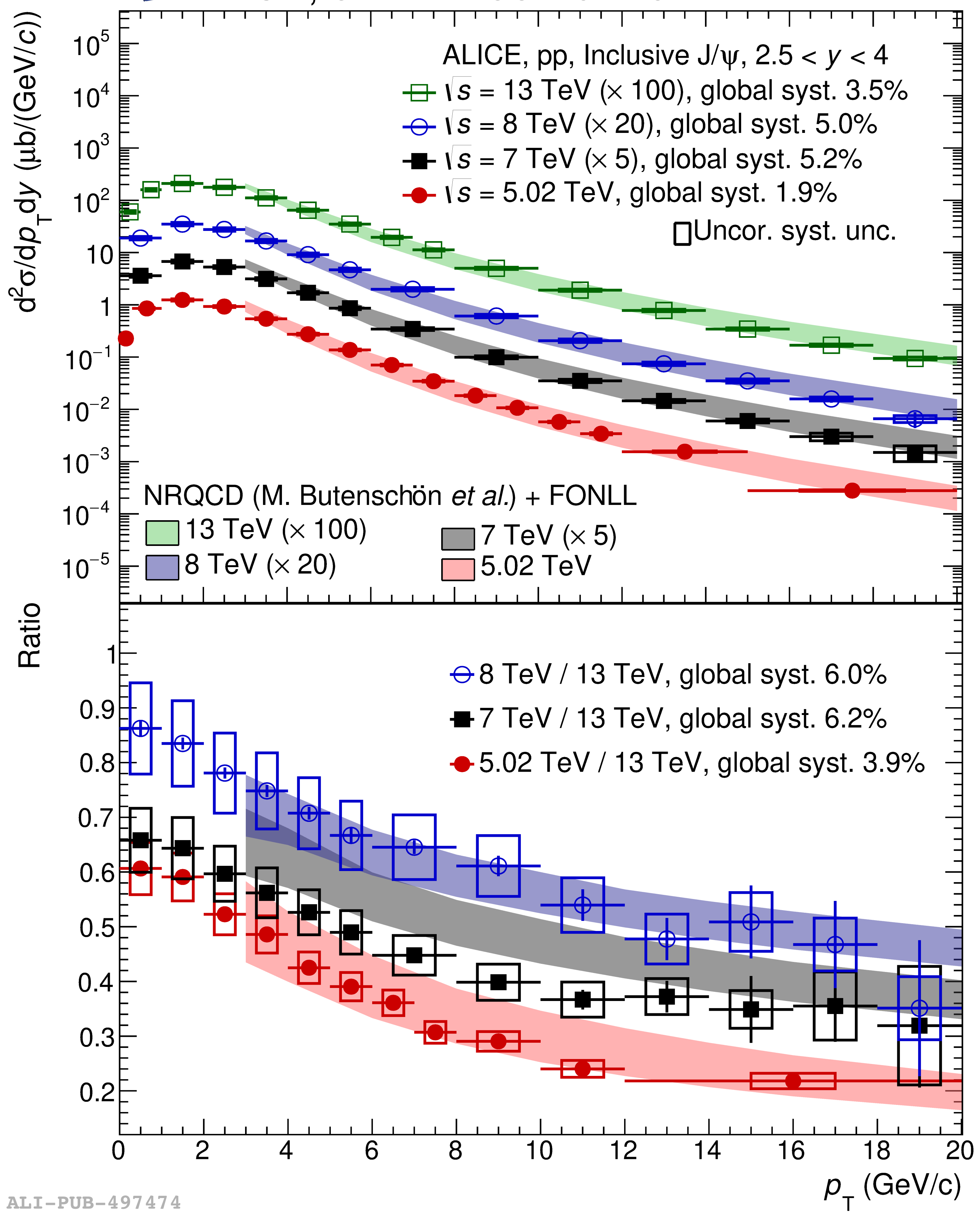
ALICE, arXiv:2204.10523



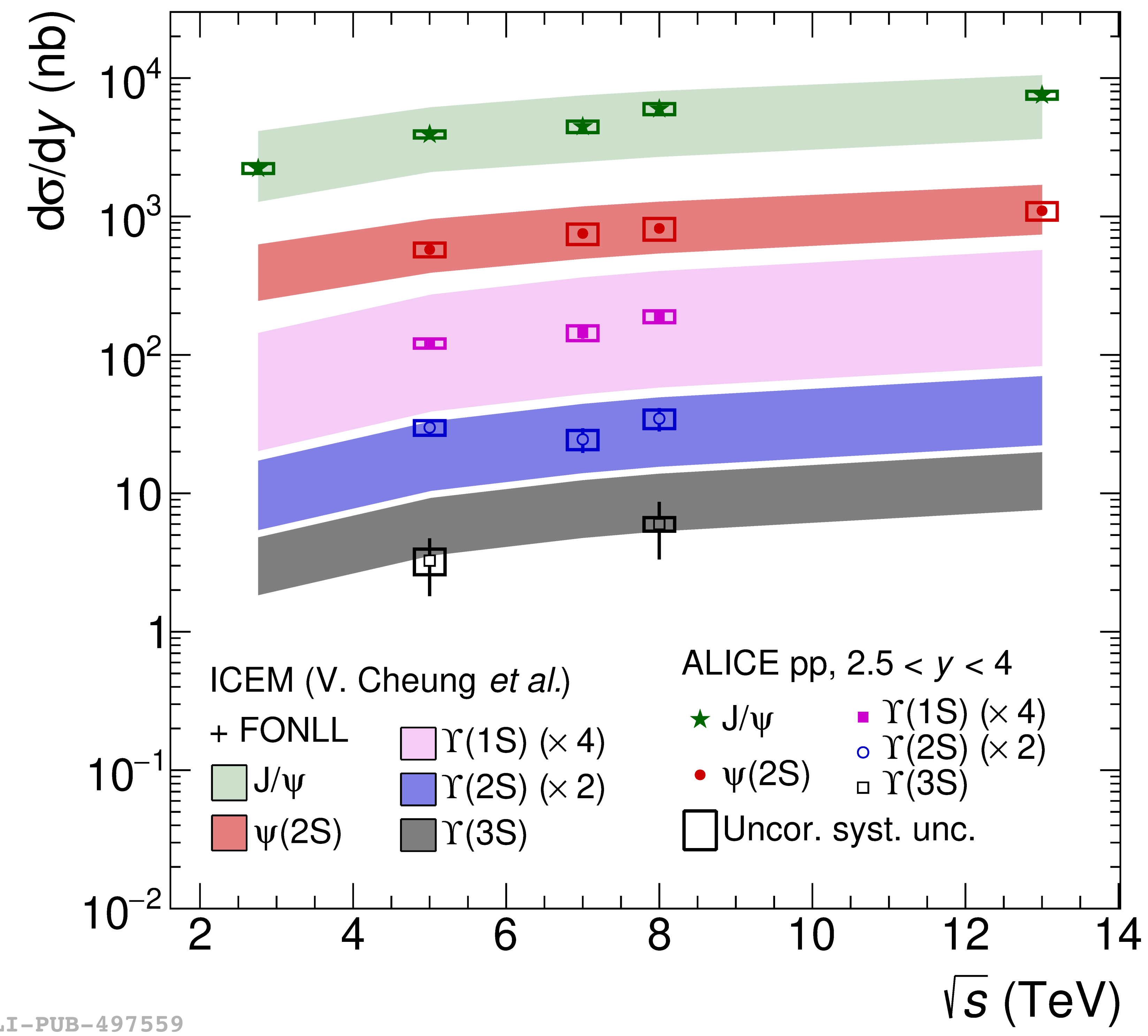


- Normalized $\psi(2s)$ yield goes linearly with charged particle multiplicity at midrapidity and $\psi(2s)$-to-J/ψ ratio is compatible with unity
  - ➡ same behaviour regardless of charmonium state and system size

ALICE, arXiv:2109.15240

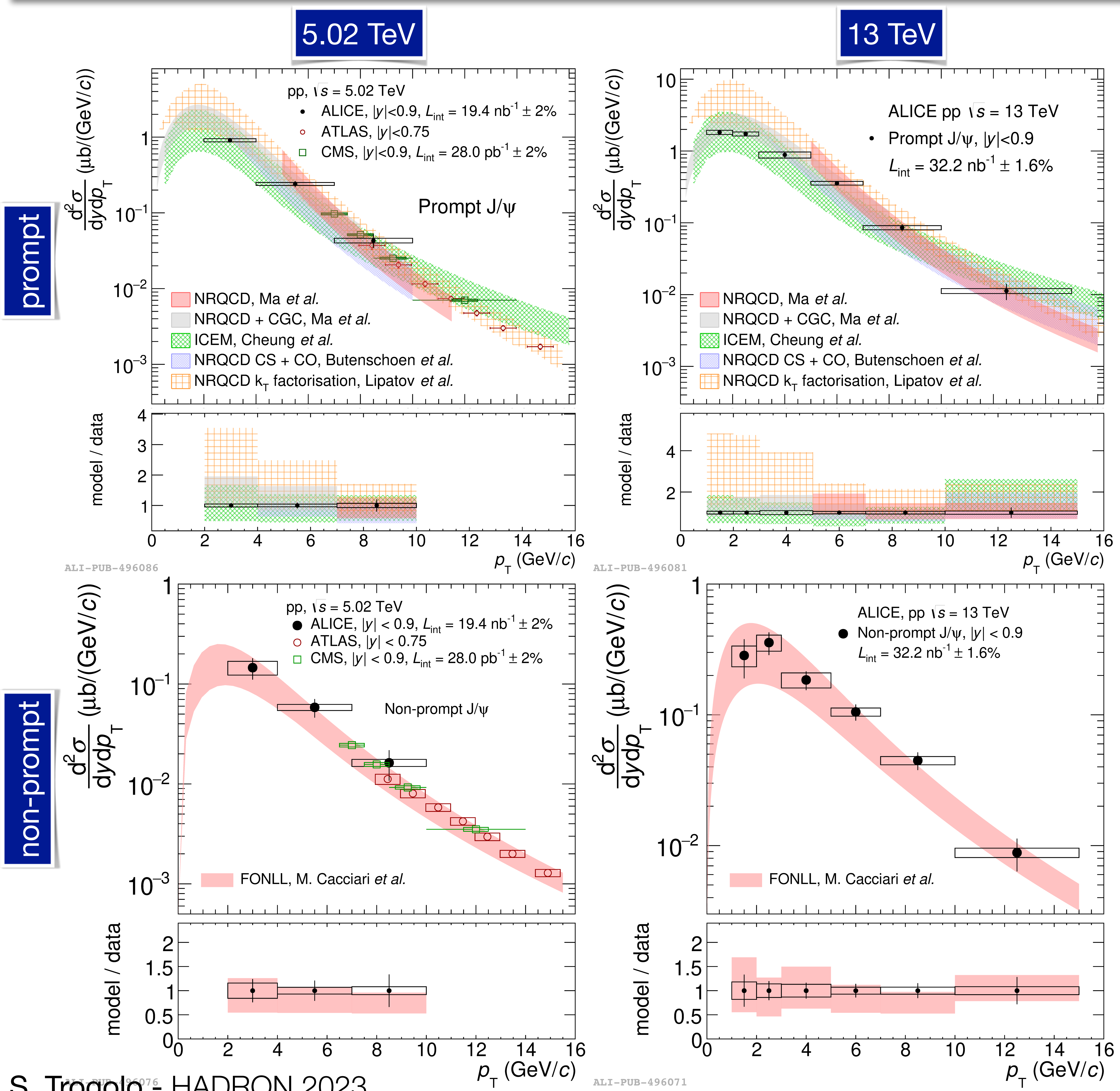


- Inclusive J/ψ production in pp collisions at $\sqrt{s}$ = 5.02, 7, 8 and 13 TeV
  - ➡ measurements down to p_T = 0 GeV/c
- Cross section increases with increasing collision energy
  - ➡ agreement between data and NRQCD+FONLL model
- Ratio as a function of p_T
  - ➡ agreement for 8-to-13 TeV and 5-to-13 TeV ratios
  - ➡ 7-to-13 TeV ratio slightly overestimated by model



- Quarkonium production cross section with energy well reproduced by ICEM+FONLL calculations for different species

Prompt/non-prompt J/ψ at midrapidity

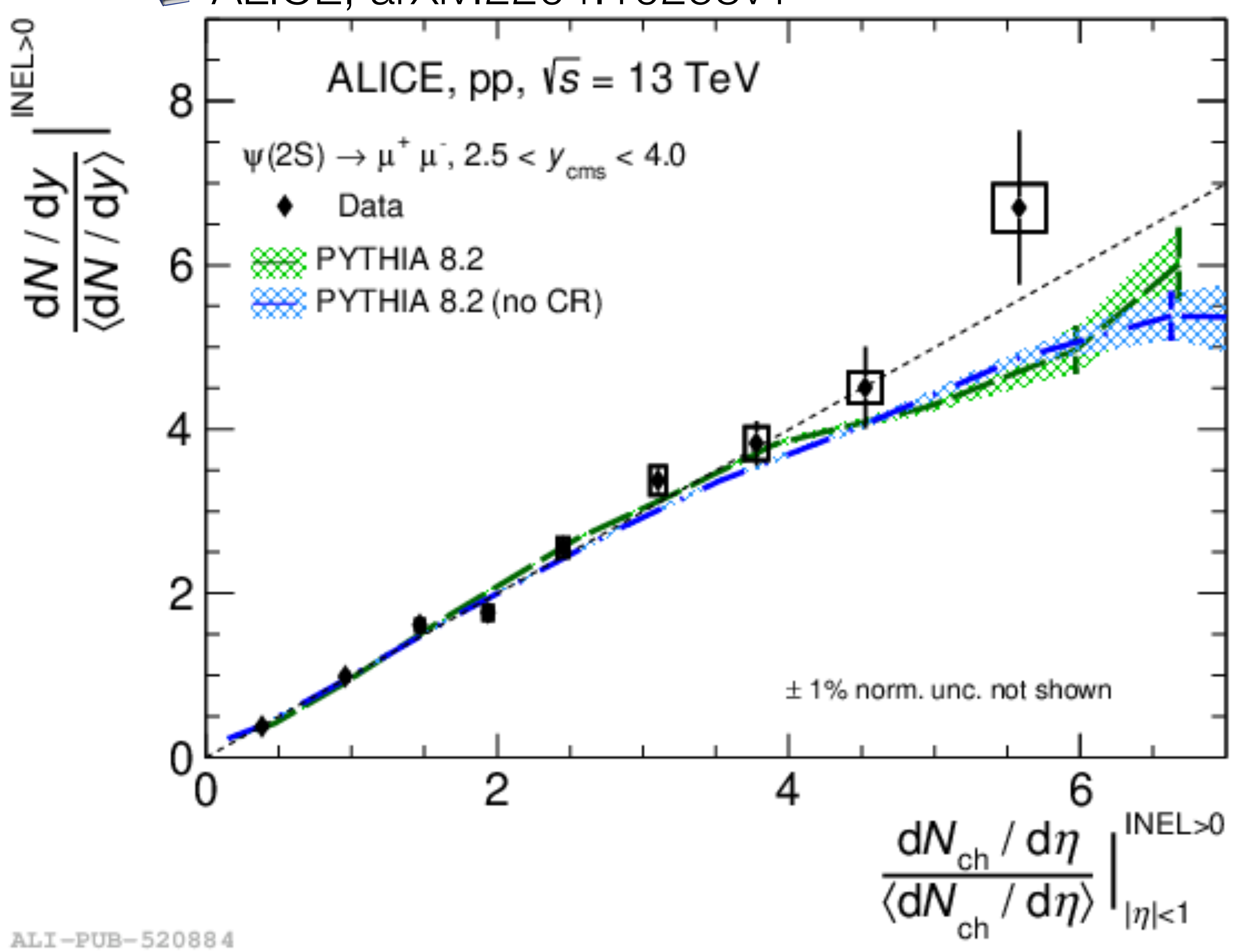


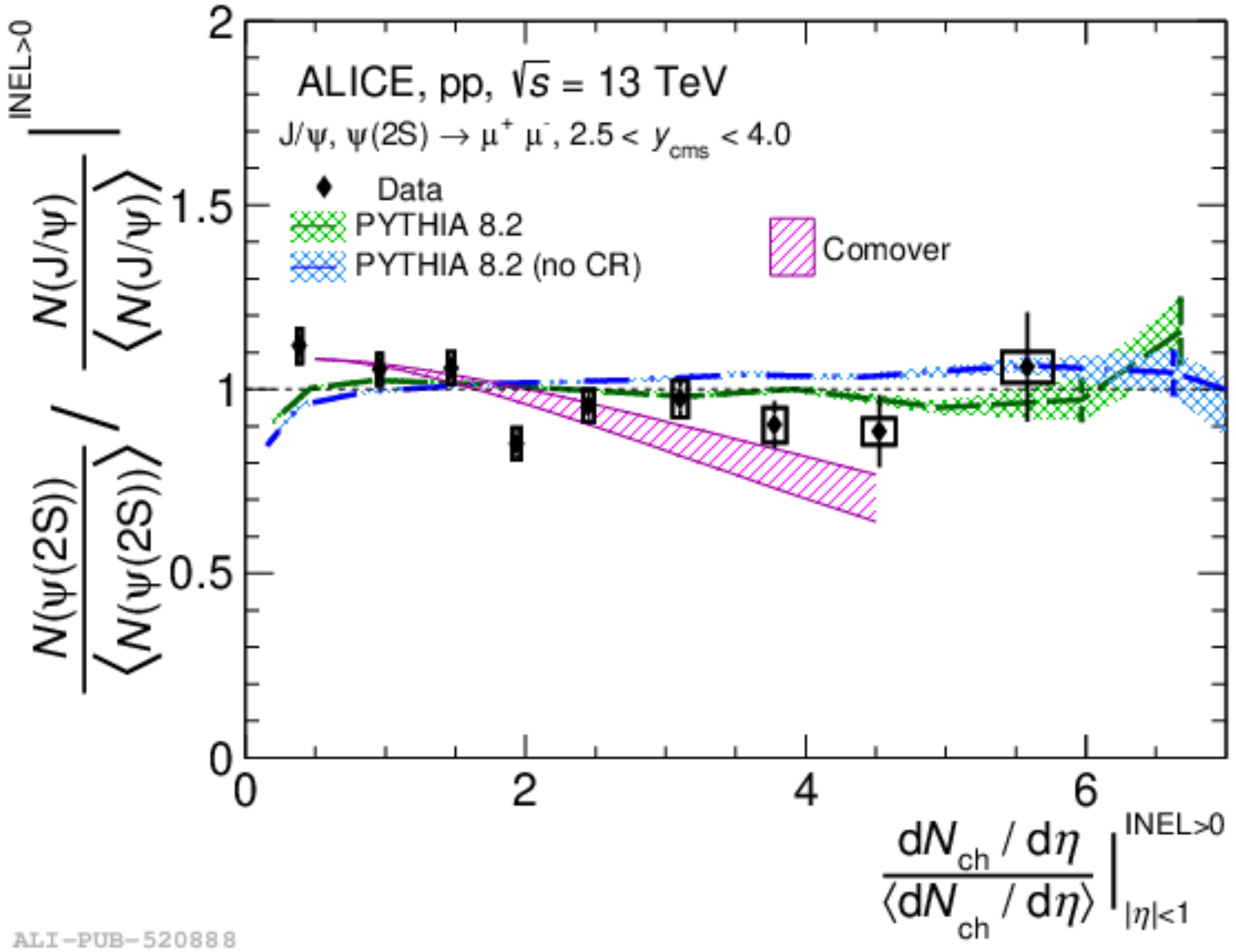
- J/ψ production measurement in pp collisions at midrapidity ($|y| < 0.9$)
  - ➡ down to p_T = 1 GeV/c for $\sqrt{s}$ = 13 TeV
  - ➡ down to p_T = 2 GeV/c for $\sqrt{s}$ = 5.02 TeV
- Prompt J/ψ cross section
  - ➡ ICEM and NRQCD in agreement with data
  - ➡ NRQCD Lipatov slightly overestimates the data at low p_T
- Non-prompt J/ψ cross section
  - ➡ FONLL in agreement with data
- Results compared with CMS and ATLAS → consistency in the common p_T range

ALICE, JHEP 03 (2022) 190

Quarkonium production vs. multiplicity

📚 ALICE, arXiv:2204.10253v1

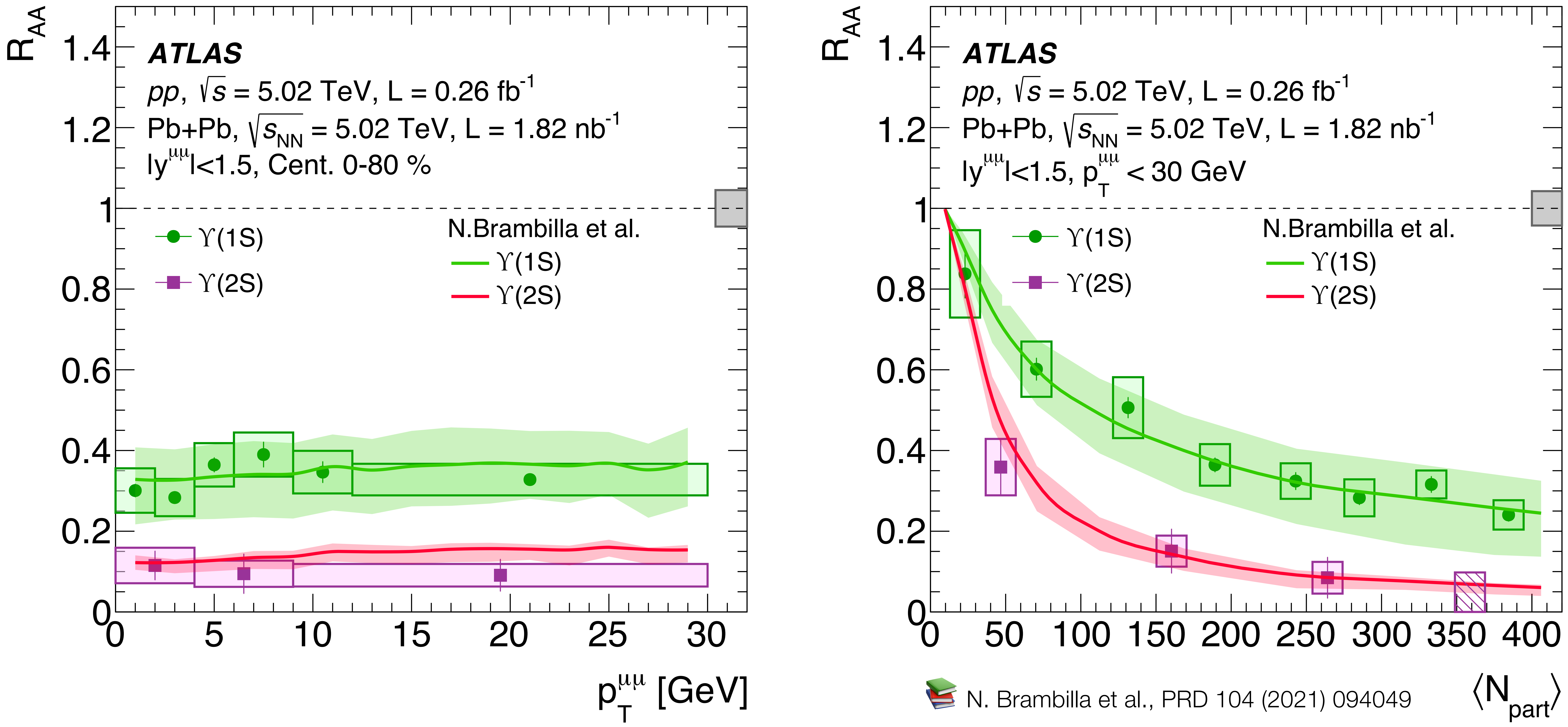




- $\psi(2s)$ production at forward rapidity as a function of multiplicity at midrapidity in pp collisions
  - ➡ linear dependence of productions yields and $\psi(2s)$-to-J/ψ ratio compatible with unity
  - ➡ production at forward rapidity independent of charmonium state and collision energy
- Comparison with models:
  - ➡ production yields in agreement with PYTHIA8 at low multiplicity, tension at high multiplicity
  - ➡ tension between $\psi(2s)$-to-J/ψ ratio and PYTHIA8 at low multiplicity

Role of regeneration in quarkonia: $\Upsilon(nS)$

ATLAS, PRC 107 (2023) 054912



N. Brambilla et al., PRD 104 (2021) 094049

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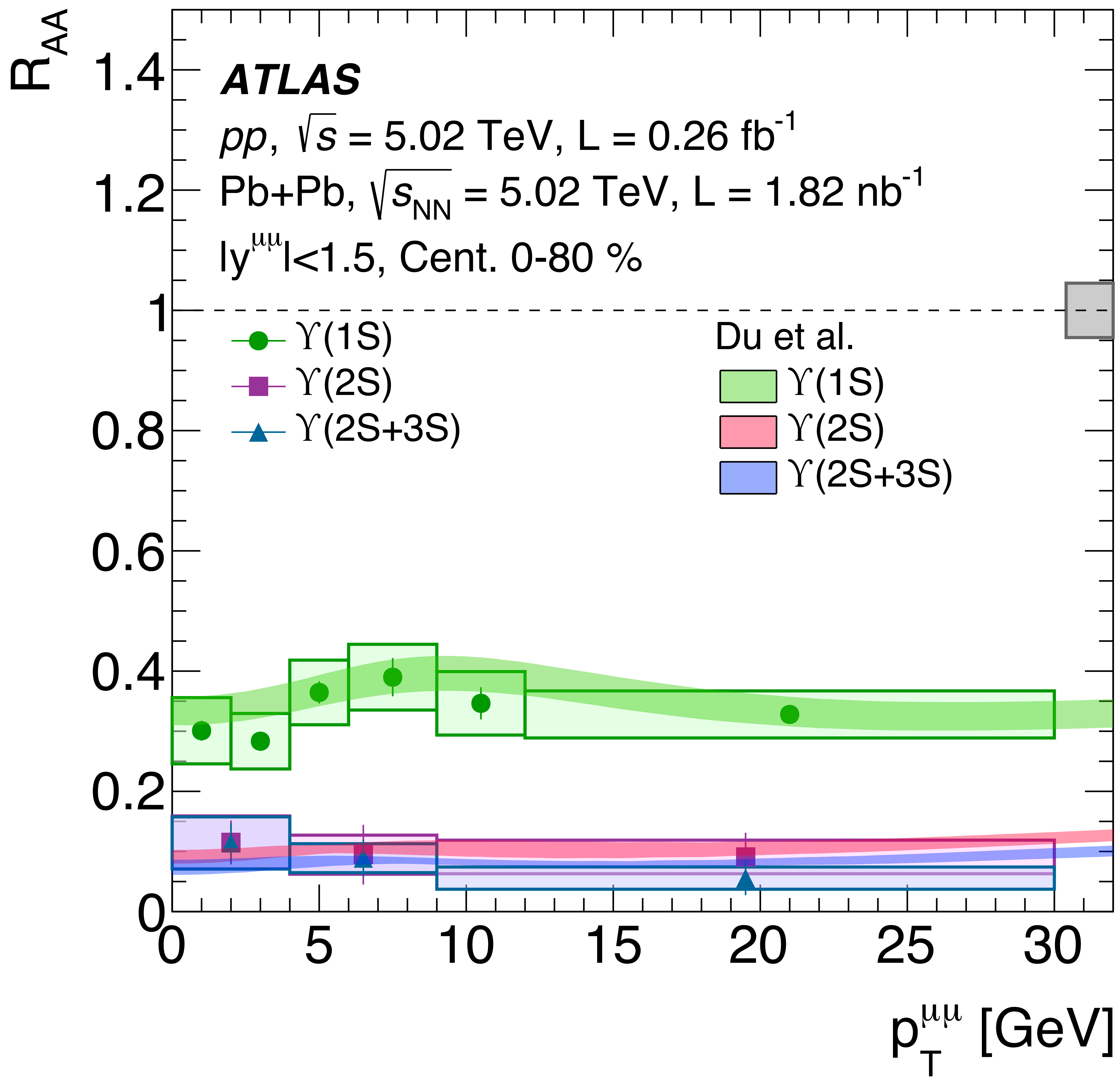
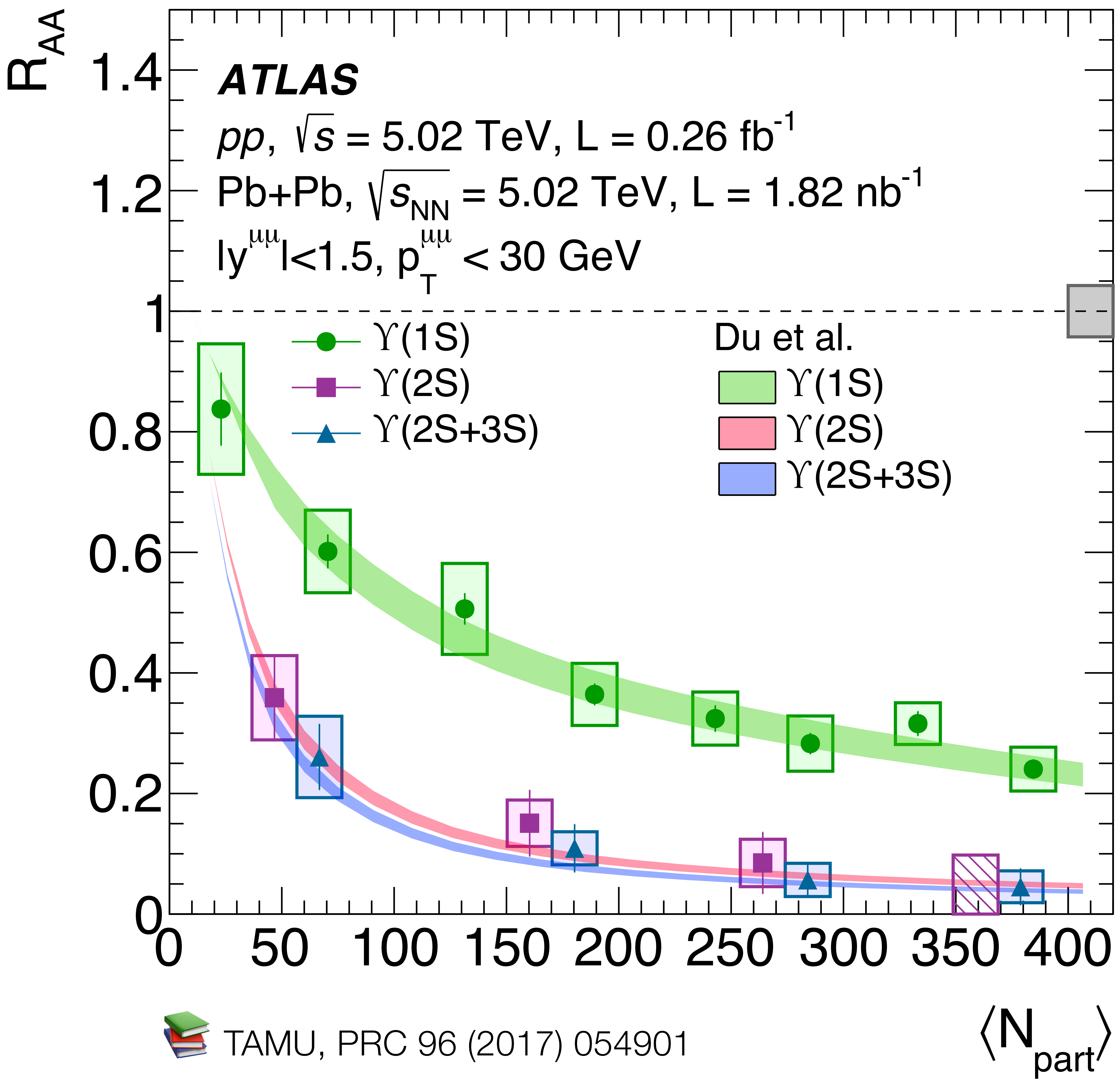
Role of regeneration in quarkonia: $\Upsilon(nS)$

ATLAS, PRC 107 (2023) 054912





TAMU, PRC 96 (2017) 054901

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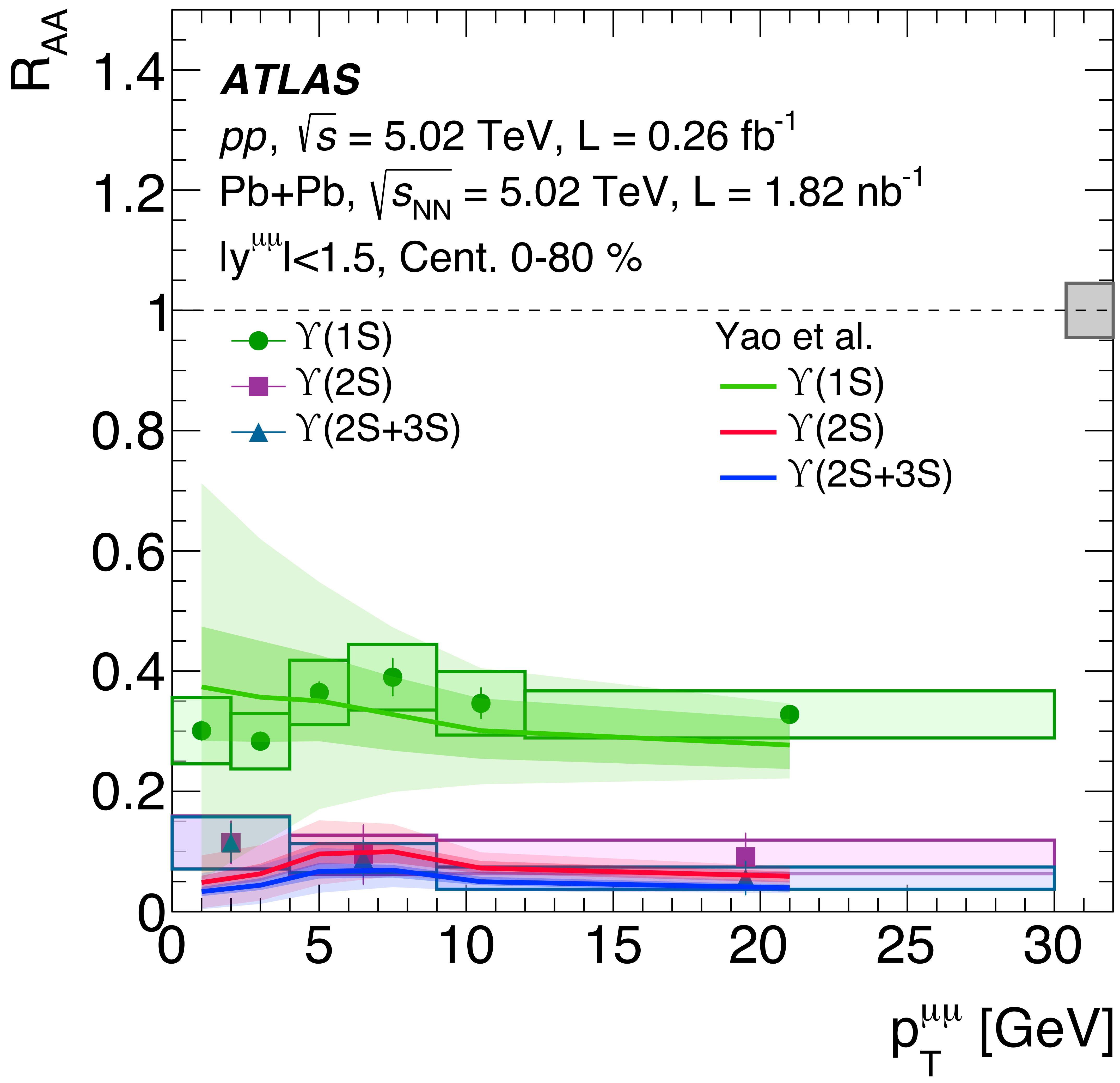
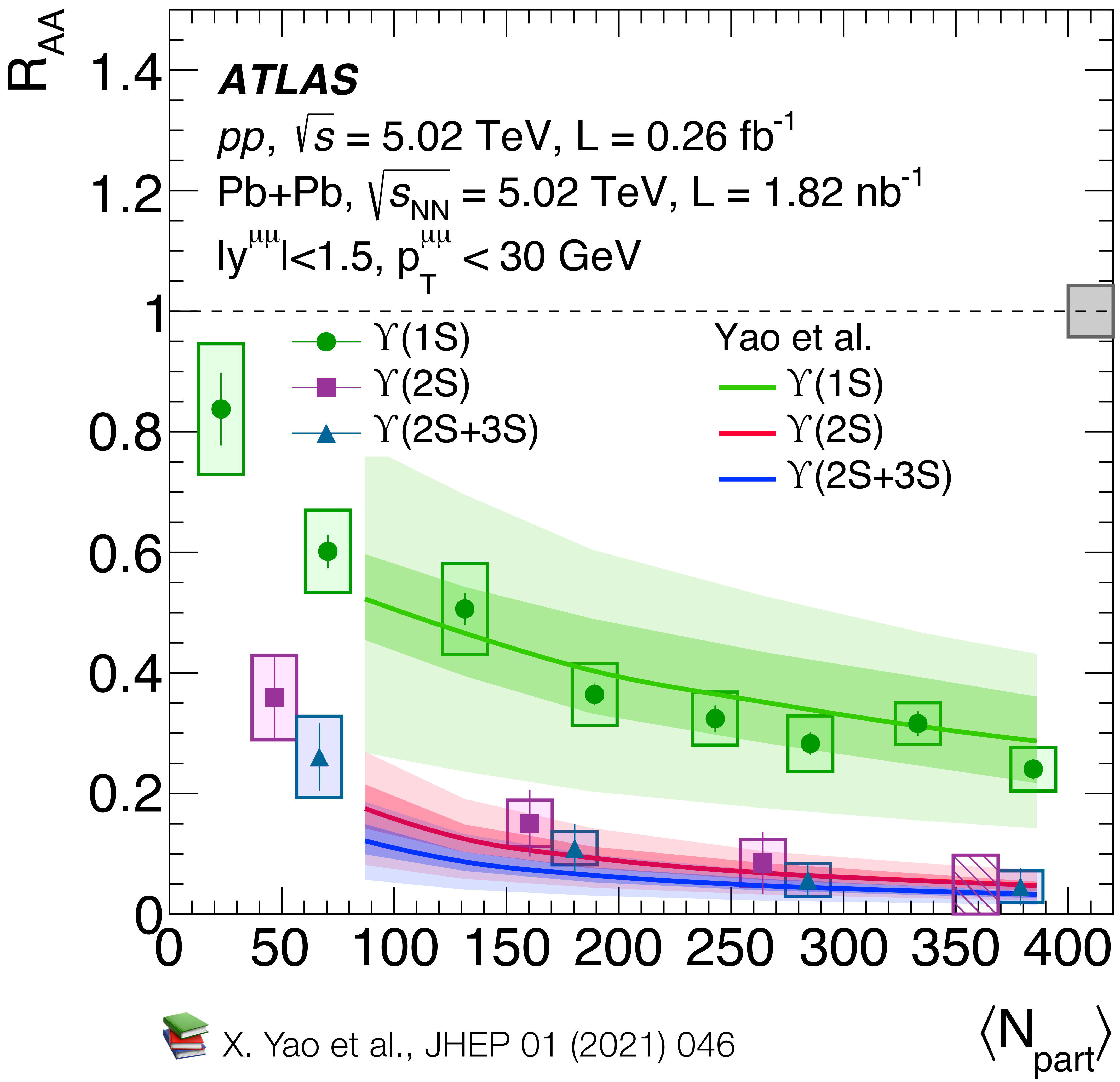
Role of regeneration in quarkonia: $\Upsilon(nS)$

ATLAS, PRC 107 (2023) 054912





X. Yao et al., JHEP 01 (2021) 046

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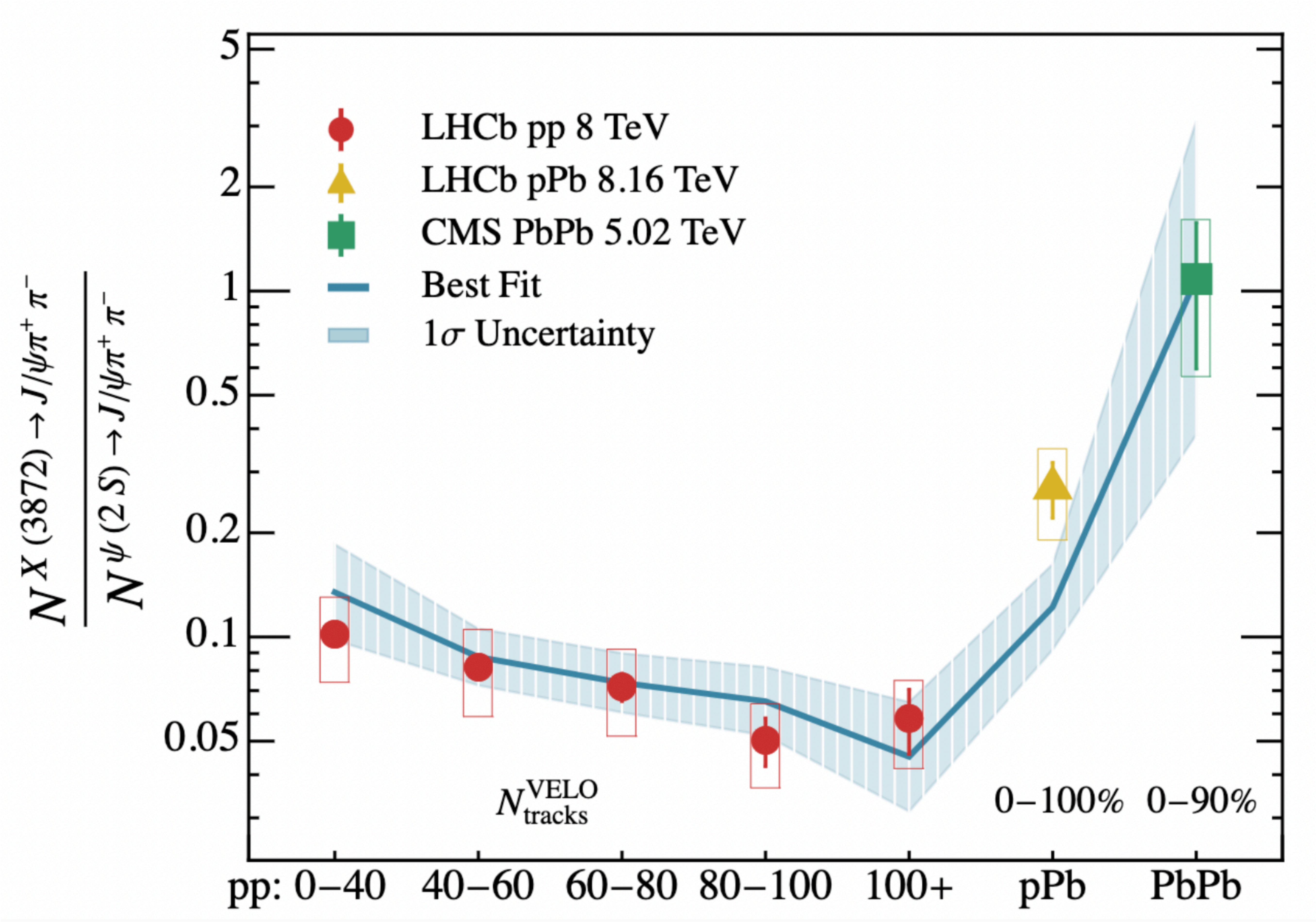
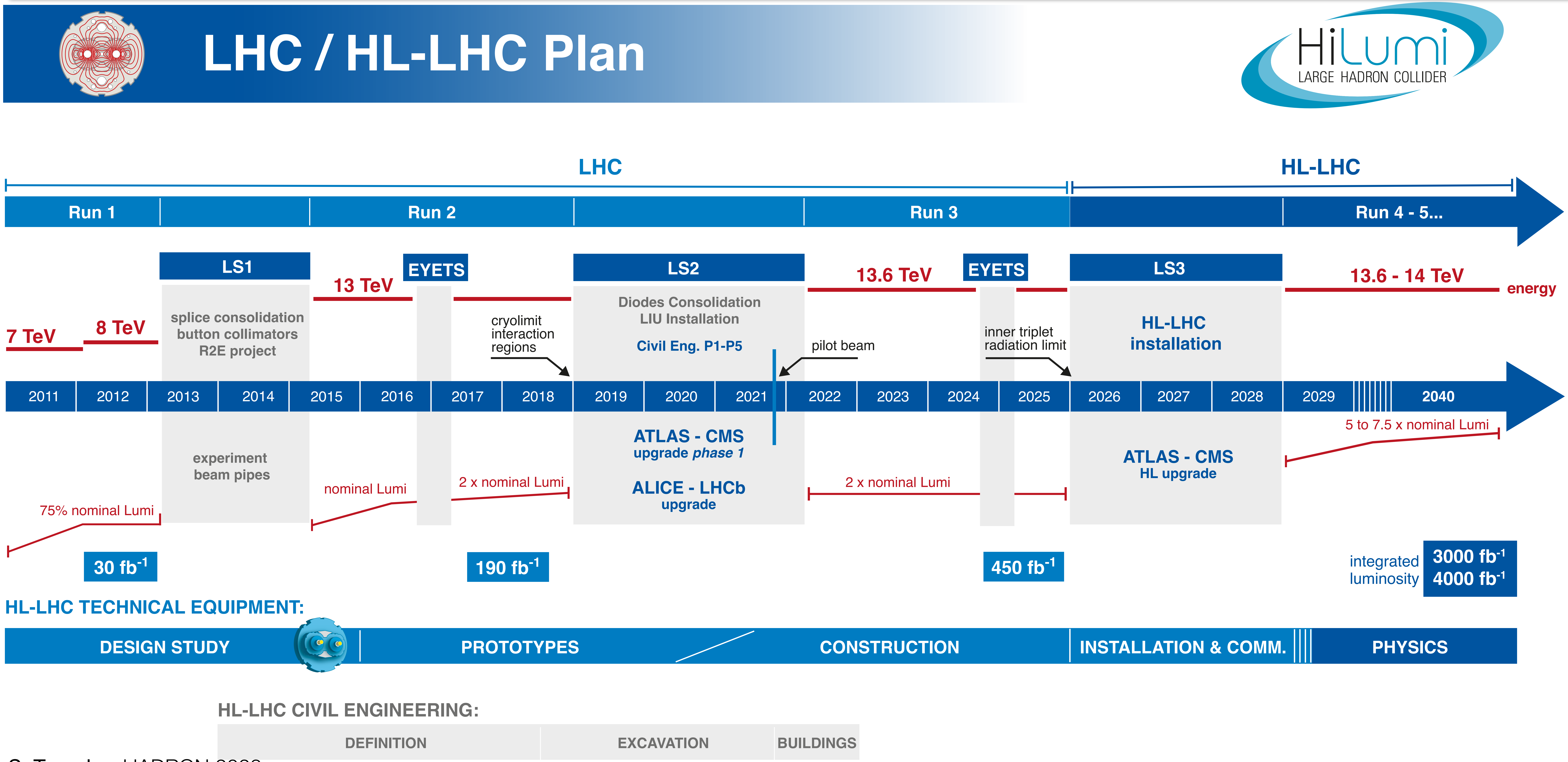
Exotic states: $\chi_c(3872)/\psi(2S)$



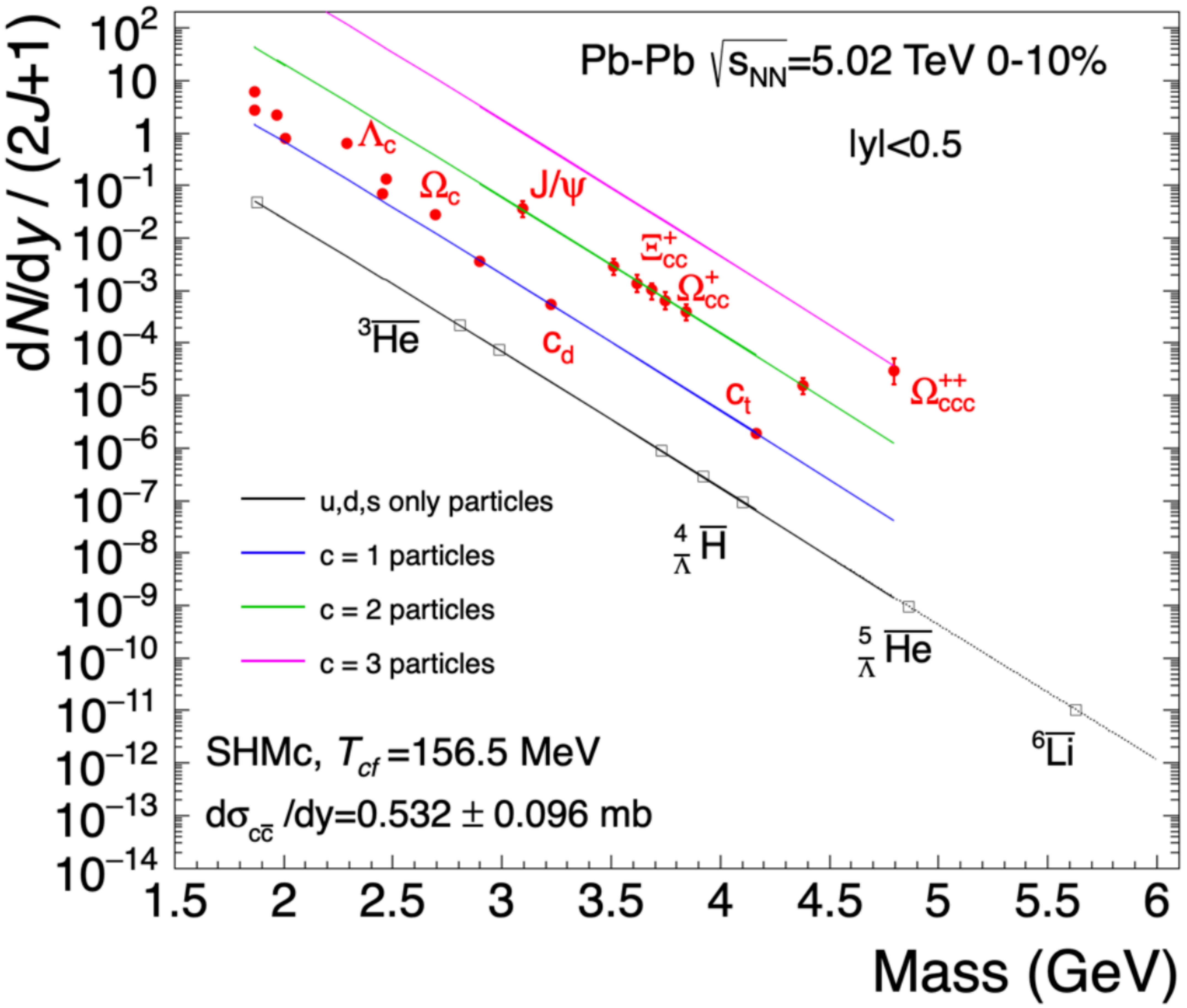
HL-LHC plan



LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
EYETS
LS3
7 TeV
8 TeV
13 TeV
13.6 TeV
13.6 - 14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
Civil Eng. P1-P5
pilot beam
inner triplet
radiation limit
HL-LHC
installation
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
5 to 7.5 x nominal Lumi
30 fb-1
190 fb-1
450 fb-1
integrated
luminosity
3000 fb-1
4000 fb-1
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION
BUILDINGS

Multi-charm hadrons

ALICE 3 LoI, arXiv:2211.02491



A. Andronic et al., JHEP 07 (2021) 035