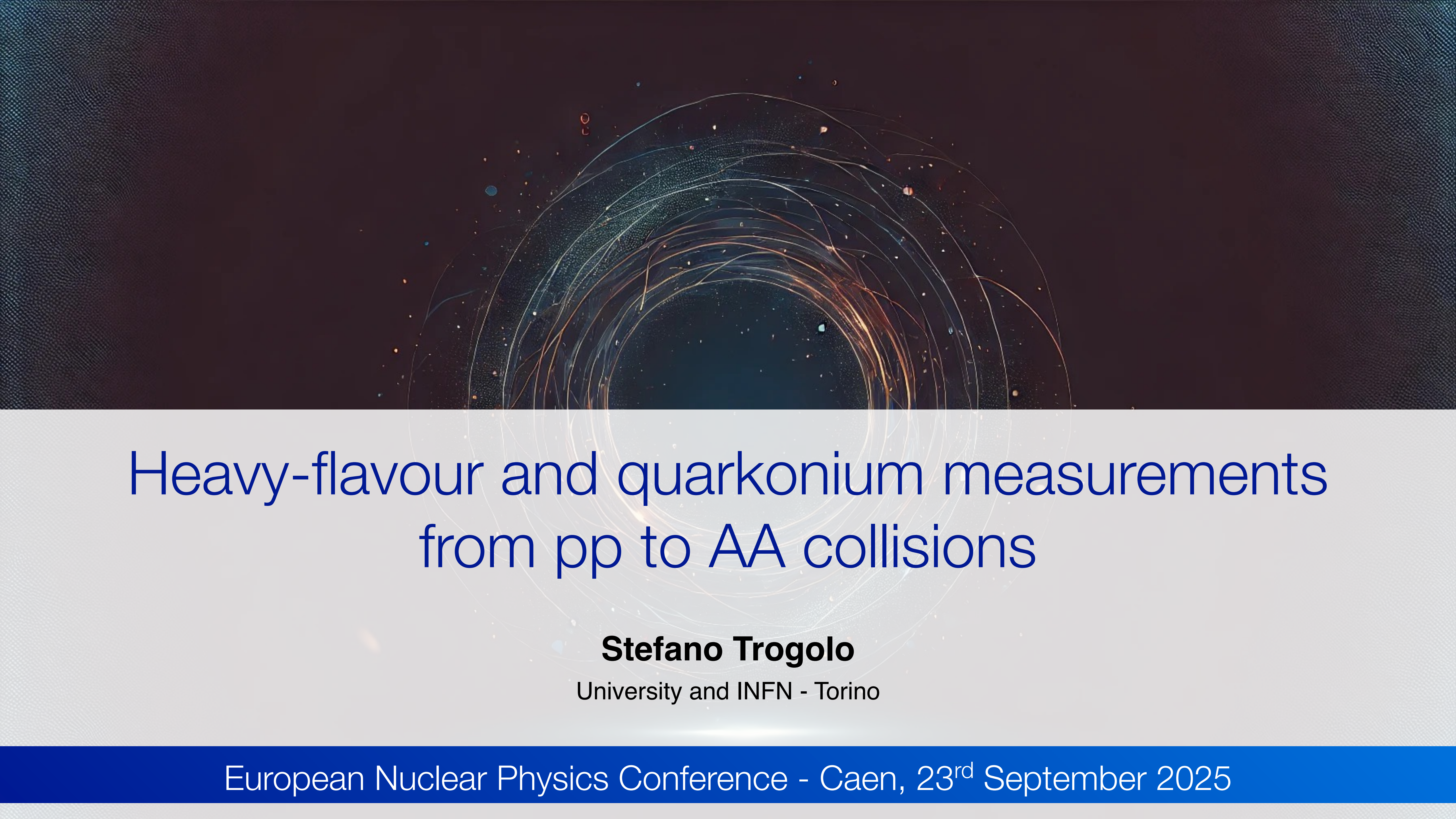


A visualization of particle tracks, likely from a heavy-ion collision, showing concentric, glowing arcs of light blue and orange against a dark background.

Heavy-flavour and quarkonium measurements from pp to AA collisions

Stefano Trogolo

University and INFN - Torino

European Nuclear Physics Conference - Caen, 23rd September 2025

A visualization of particle tracks, likely from a heavy-ion collision, showing concentric arcs of light blue and orange points against a dark background.

Heavy-flavor quarkonium measurements from pp to AA collisions

A personal perspective, not the full picture

Stefano Trogolo

University and INFN - Torino

Heavy-flavour hadron production

2

- ▶ Heavy quarks produced in initial hard-scattering processes (large Q^2)

→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

 PDG, Phys. Rev. D 110, 030001 (2024)

- ▶ Hadron production in hadronic collisions → factorization approach

Heavy-flavour hadron production

2

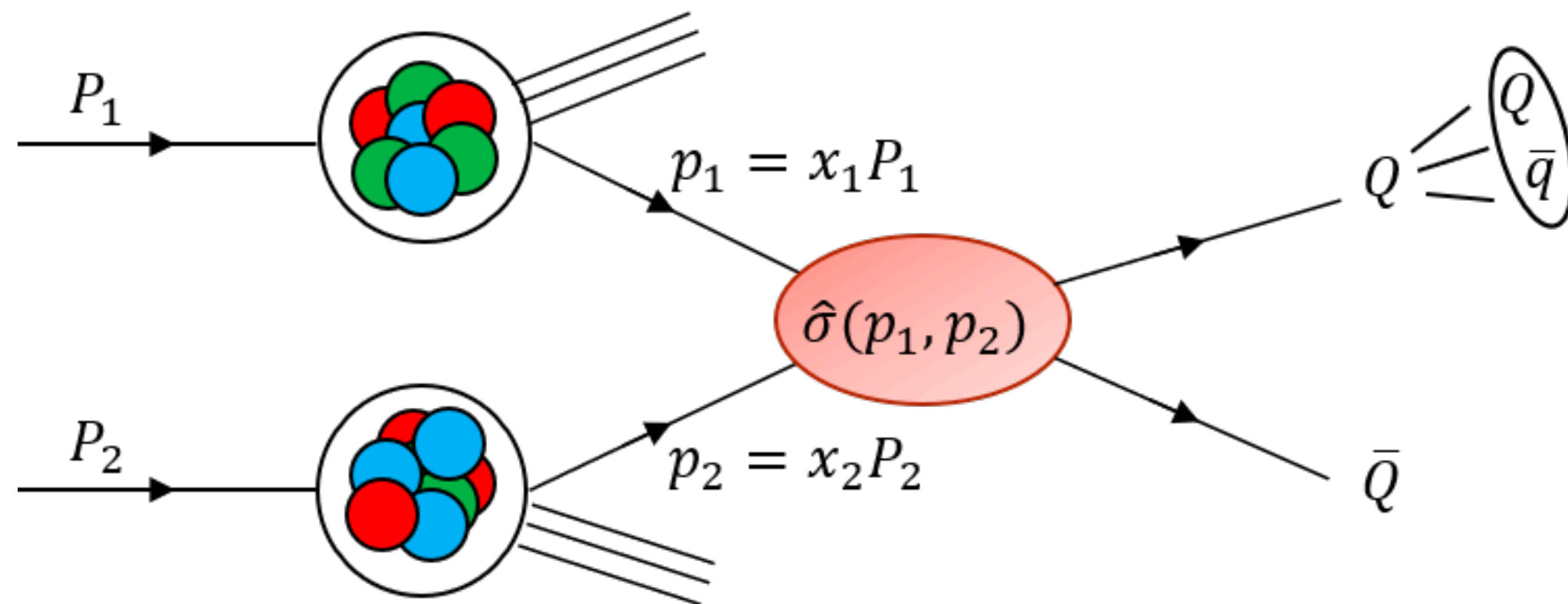
- Heavy quarks produced in initial hard-scattering processes (large Q^2)

→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

 PDG, Phys. Rev. D 110, 030001 (2024)

- Hadron production in hadronic collisions → factorization approach

$$\frac{d\sigma^{\text{H}_c}}{dp_T} =$$



Heavy-flavour hadron production

2

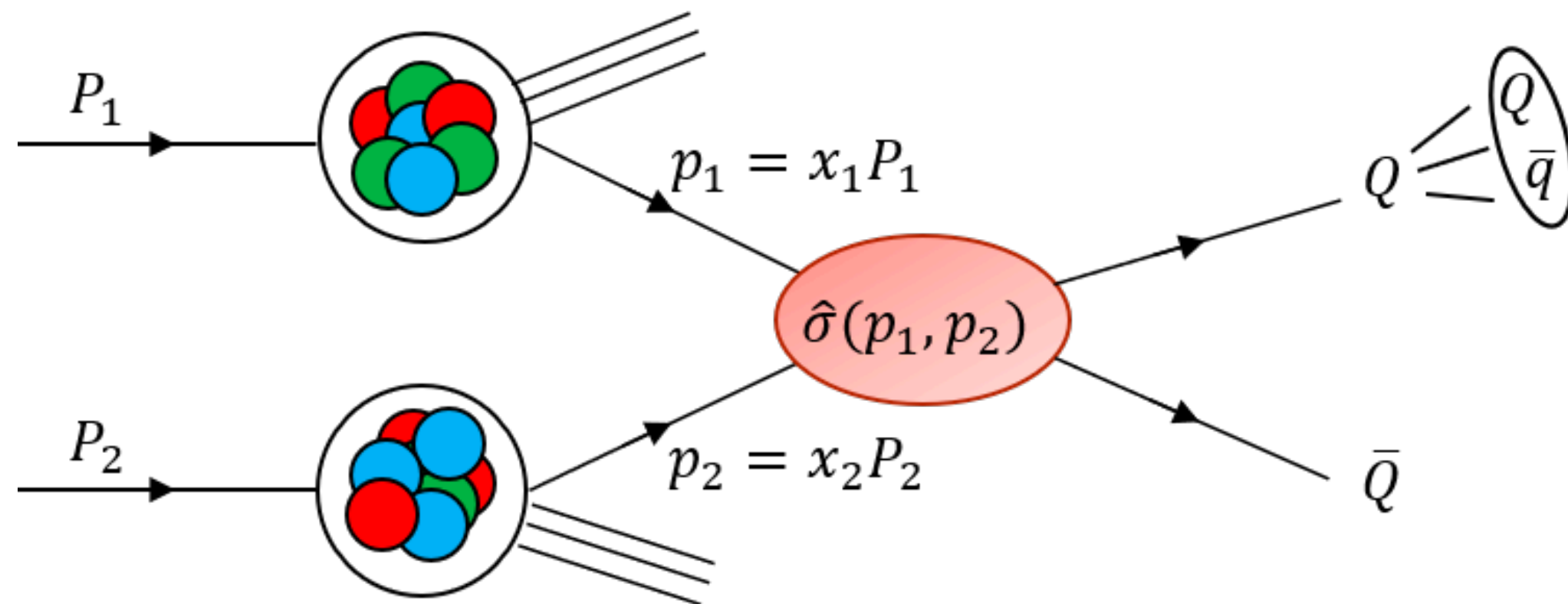
- Heavy quarks produced in initial hard-scattering processes (large Q^2)

→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

 PDG, Phys. Rev. D 110, 030001 (2024)

- Hadron production in hadronic collisions → factorization approach

$$\frac{d\sigma^{H_c}}{dp_T} = \text{PDF}(x_1, Q^2) \cdot \text{PDF}(x_2, Q^2) \otimes \frac{d\sigma^c}{dp_T^c}(x_1, x_2, Q^2) \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, Q^2)$$



Heavy-flavour hadron production

2

- Heavy quarks produced in initial hard-scattering processes (large Q^2)

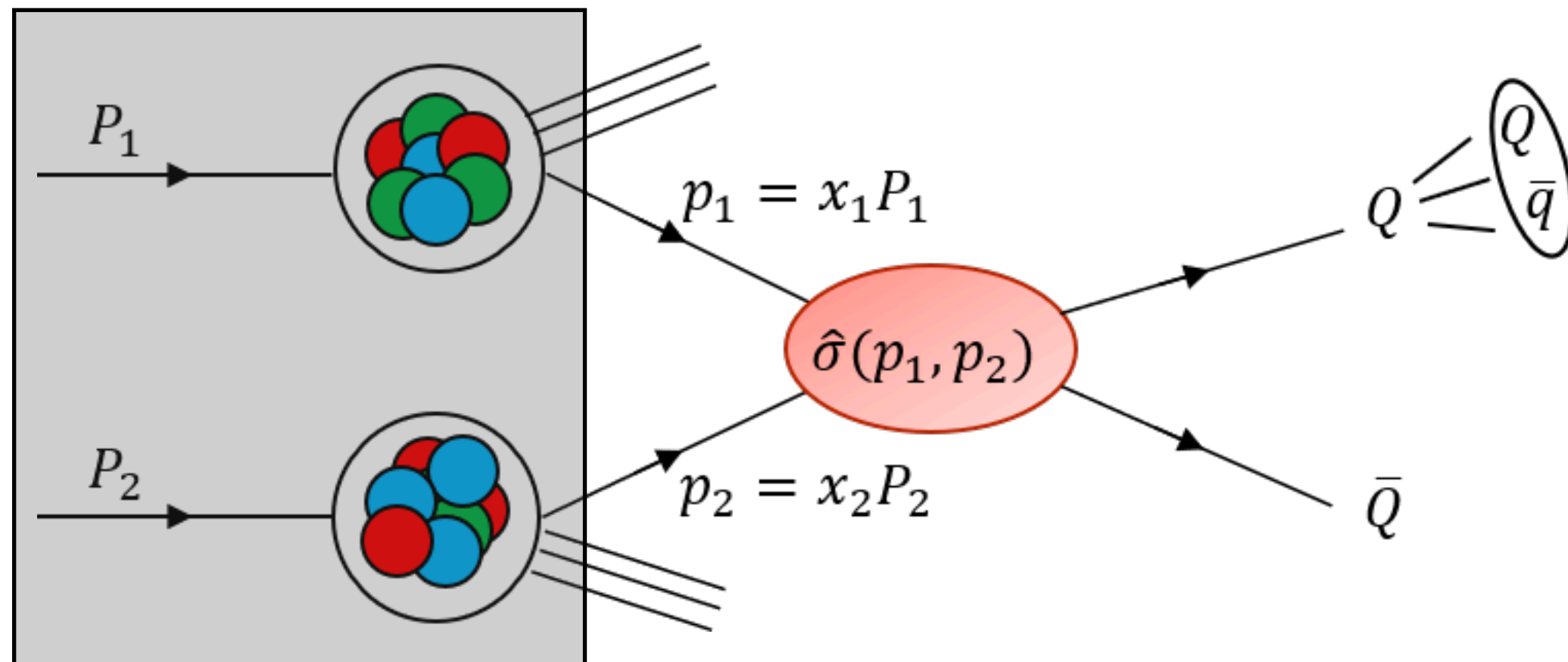
→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

 PDG, Phys. Rev. D 110, 030001 (2024)

- Hadron production in hadronic collisions → factorization approach

$$\frac{d\sigma^{H_c}}{dp_T} = \boxed{\text{PDF}(x_1, Q^2) \cdot \text{PDF}(x_2, Q^2)} \otimes \frac{d\sigma^c}{dp_T^c}(x_1, x_2, Q^2) \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, Q^2)$$

Parton distribution
functions (PDFs)



Heavy-flavour hadron production

2

- Heavy quarks produced in initial hard-scattering processes (large Q^2)

→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

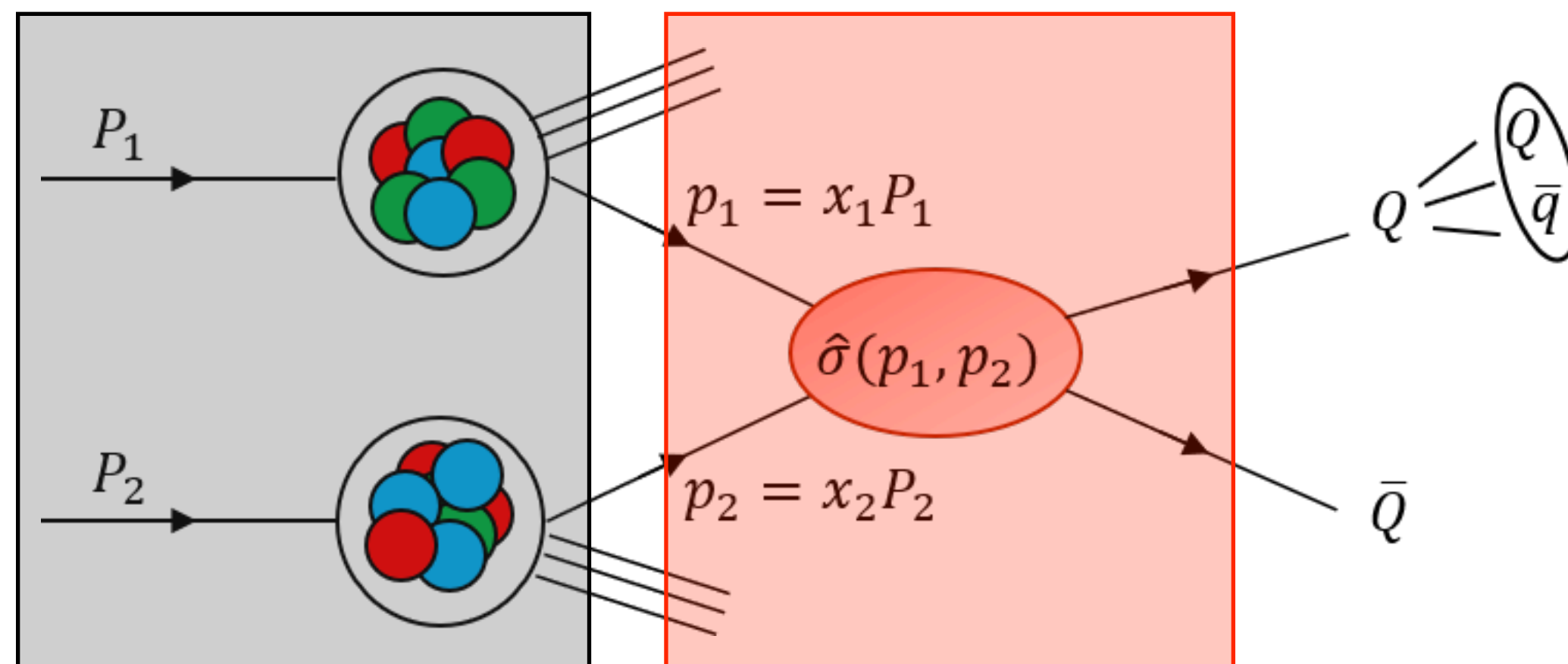
 PDG, Phys. Rev. D 110, 030001 (2024)

- Hadron production in hadronic collisions → factorization approach

$$\frac{d\sigma^{H_c}}{dp_T} = \boxed{\text{PDF}(x_1, Q^2) \cdot \text{PDF}(x_2, Q^2)} \otimes \boxed{\frac{d\sigma^c}{dp_T^c}(x_1, x_2, Q^2)} \otimes D_{c \rightarrow H_c}(z = p_{H_c}/p_c, Q^2)$$

Parton distribution
functions (PDFs)

Hard scattering
cross section
(pQCD)



Heavy-flavour hadron production

2

- Heavy quarks produced in initial hard-scattering processes (large Q^2)

→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

 PDG, Phys. Rev. D 110, 030001 (2024)

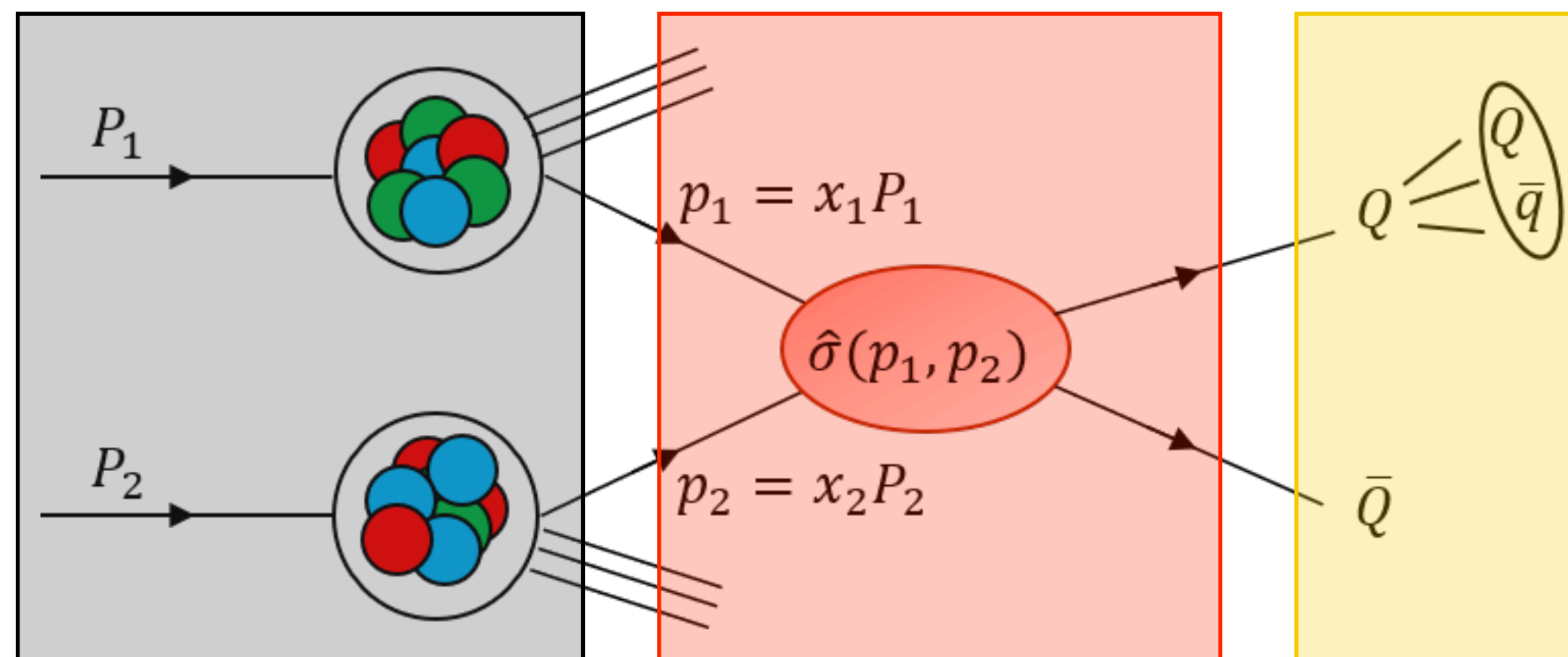
- Hadron production in hadronic collisions → factorization approach

$$\frac{d\sigma^{H_c}}{dp_T} = \boxed{\text{PDF}(x_1, Q^2) \cdot \text{PDF}(x_2, Q^2)} \otimes \boxed{\frac{d\sigma^c}{dp_T^c}(x_1, x_2, Q^2)} \otimes \boxed{D_{c \rightarrow H_c}(z = p_{H_c}/p_c, Q^2)}$$

Parton distribution
functions (PDFs)

Hard scattering
cross section
(pQCD)

Fragmentation
function
(hadronisation)



Heavy-flavour hadron production

2

- Heavy quarks produced in initial hard-scattering processes (large Q^2)

→ quark mass:  charm $\approx 1.273 \text{ GeV}/c^2$  beauty $\approx 4.183 \text{ GeV}/c^2$

 PDG, Phys. Rev. D 110, 030001 (2024)

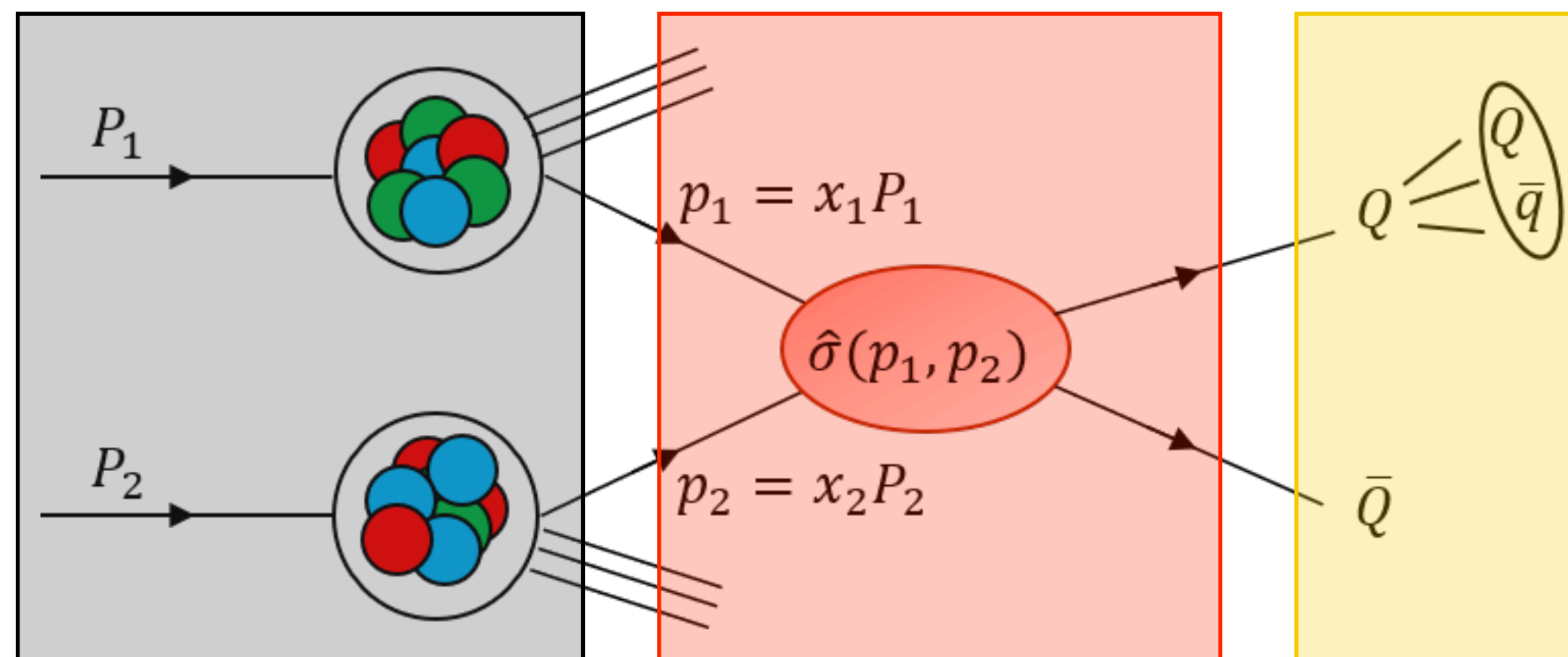
- Hadron production in hadronic collisions → factorization approach

$$\frac{d\sigma^{H_c}}{dp_T} = \boxed{\text{PDF}(x_1, Q^2) \cdot \text{PDF}(x_2, Q^2)} \otimes \boxed{\frac{d\sigma^c}{dp_T^c}(x_1, x_2, Q^2)} \otimes \boxed{D_{c \rightarrow H_c}(z = p_{H_c}/p_c, Q^2)}$$

Parton distribution
functions (PDFs)

Hard scattering
cross section
(pQCD)

Fragmentation
function
(hadronisation)



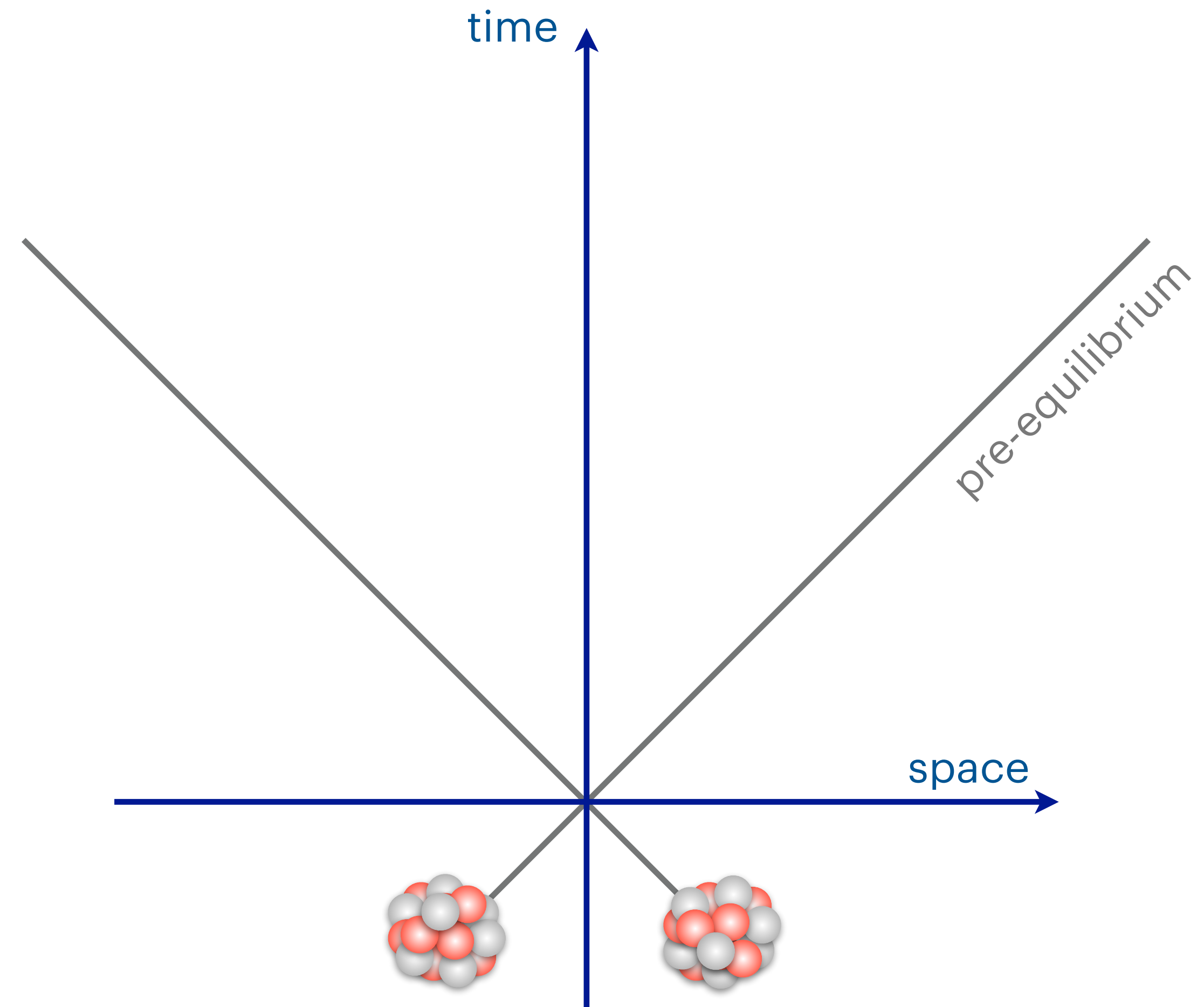
- Fragmentation functions $D_{c \rightarrow H_c}(z, Q^2)$

- phenomenological functions → non-perturbative parton-to-hadron transition
- z = fraction of the parton momentum taken by the hadron H_c
- parameterized on data and assumed to be universal

Heavy-flavour hadron production

3

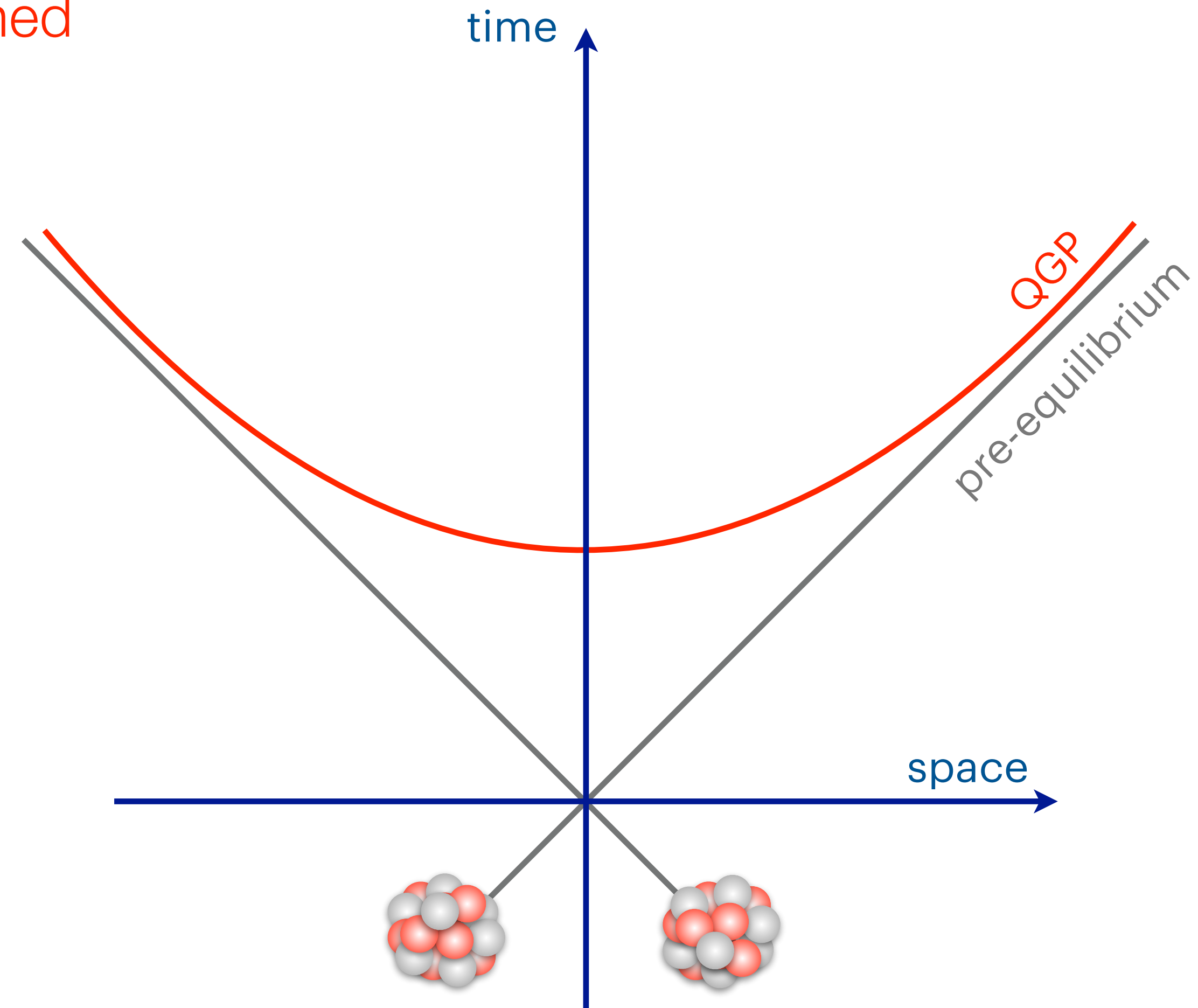
- Heavy quarks produced in initial hard-scattering processes (large Q^2)



Heavy-flavour hadron production

3

- ▶ Heavy quarks produced in initial hard-scattering processes (large Q^2)
- ▶ In ultra relativistic heavy-ion collisions → colour-deconfined medium, called quark-gluon plasma (QGP)
 - high energy density, e.g. $\epsilon > 15 \text{ GeV/fm}^3$ at LHC
 - hydrodynamic expansion after a pre-equilibrium phase



Heavy-flavour hadron production

3

► Heavy quarks produced in initial hard-scattering processes (large Q^2)

*f.o. = freeze-out

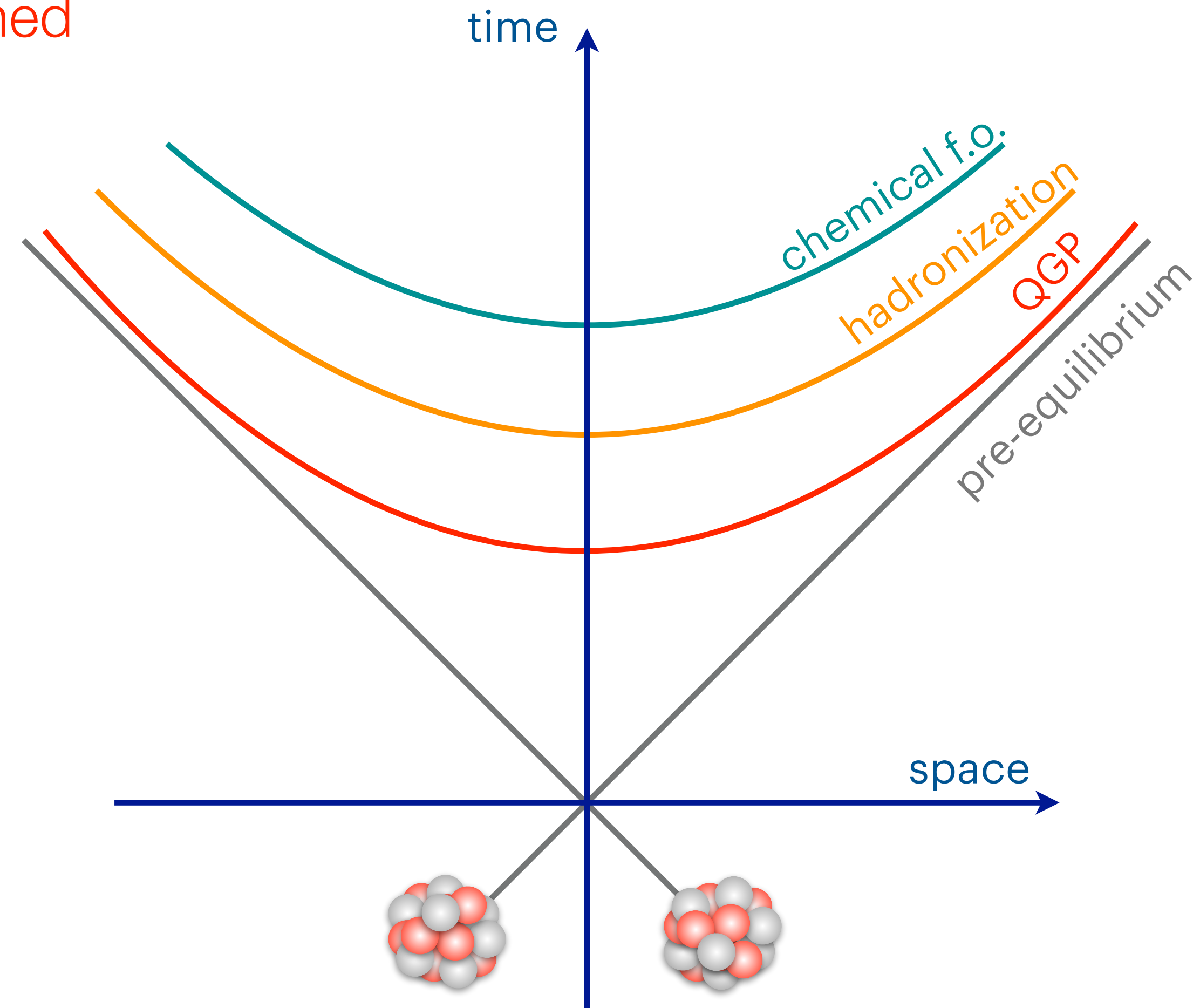
► In ultra relativistic heavy-ion collisions → colour-deconfined medium, called quark-gluon plasma (QGP)

→ high energy density, e.g. $\epsilon > 15 \text{ GeV/fm}^3$ at LHC

→ 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-flavour hadron production

3

► Heavy quarks produced in initial hard-scattering processes (large Q^2)

*f.o. = freeze-out

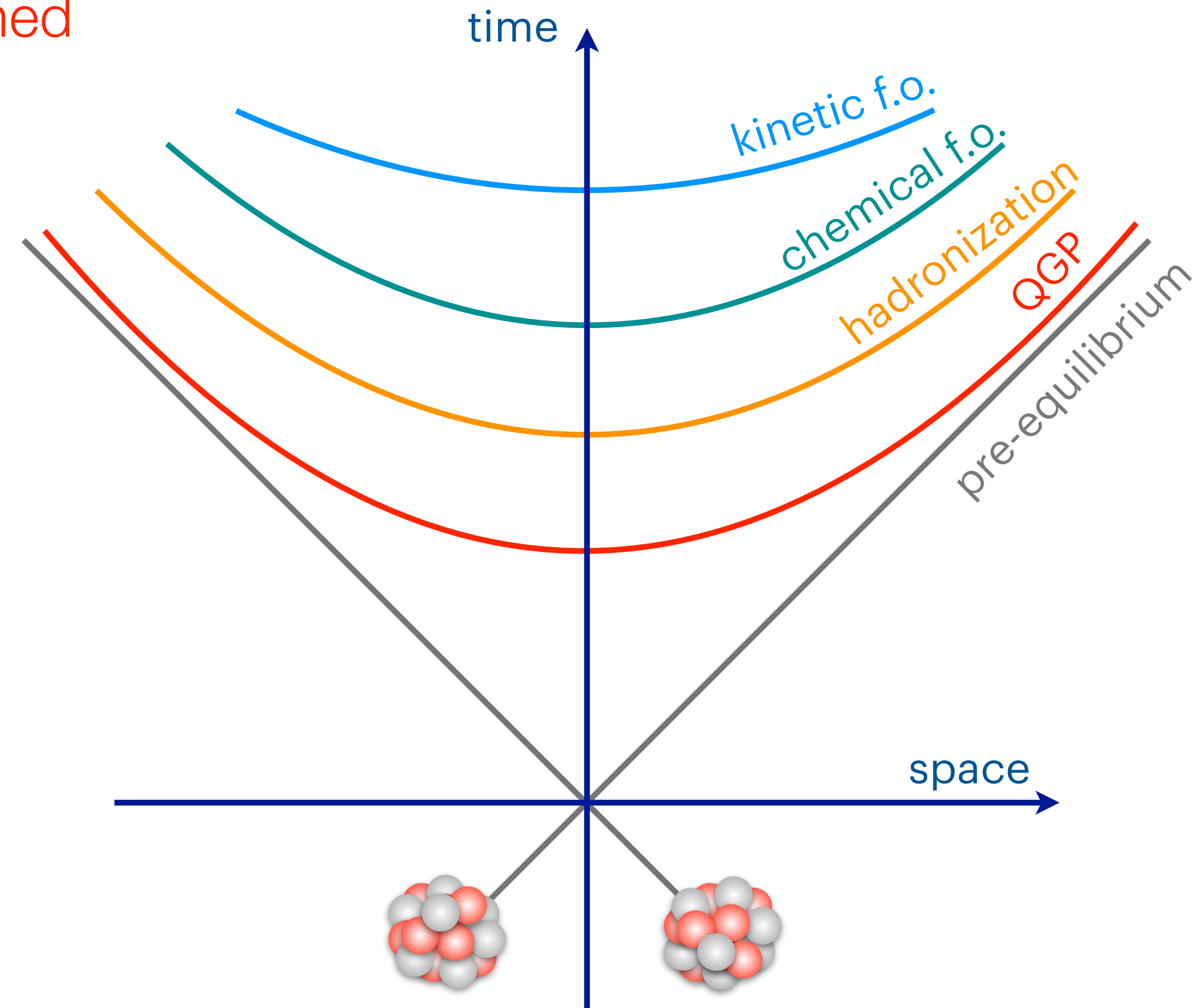
► In ultra relativistic heavy-ion collisions → colour-deconfined medium, called quark-gluon plasma (QGP)

→ high energy density, e.g. $\epsilon > 15 \text{ GeV/fm}^3$ at LHC

→ 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-flavour hadron production

3

► Heavy quarks produced in initial hard-scattering processes (large Q^2)

*f.o. = freeze-out

► In ultra relativistic heavy-ion collisions → colour-deconfined medium, called quark-gluon plasma (QGP)

→ high energy density, e.g. $\varepsilon > 15 \text{ GeV/fm}^3$ at LHC

→ 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

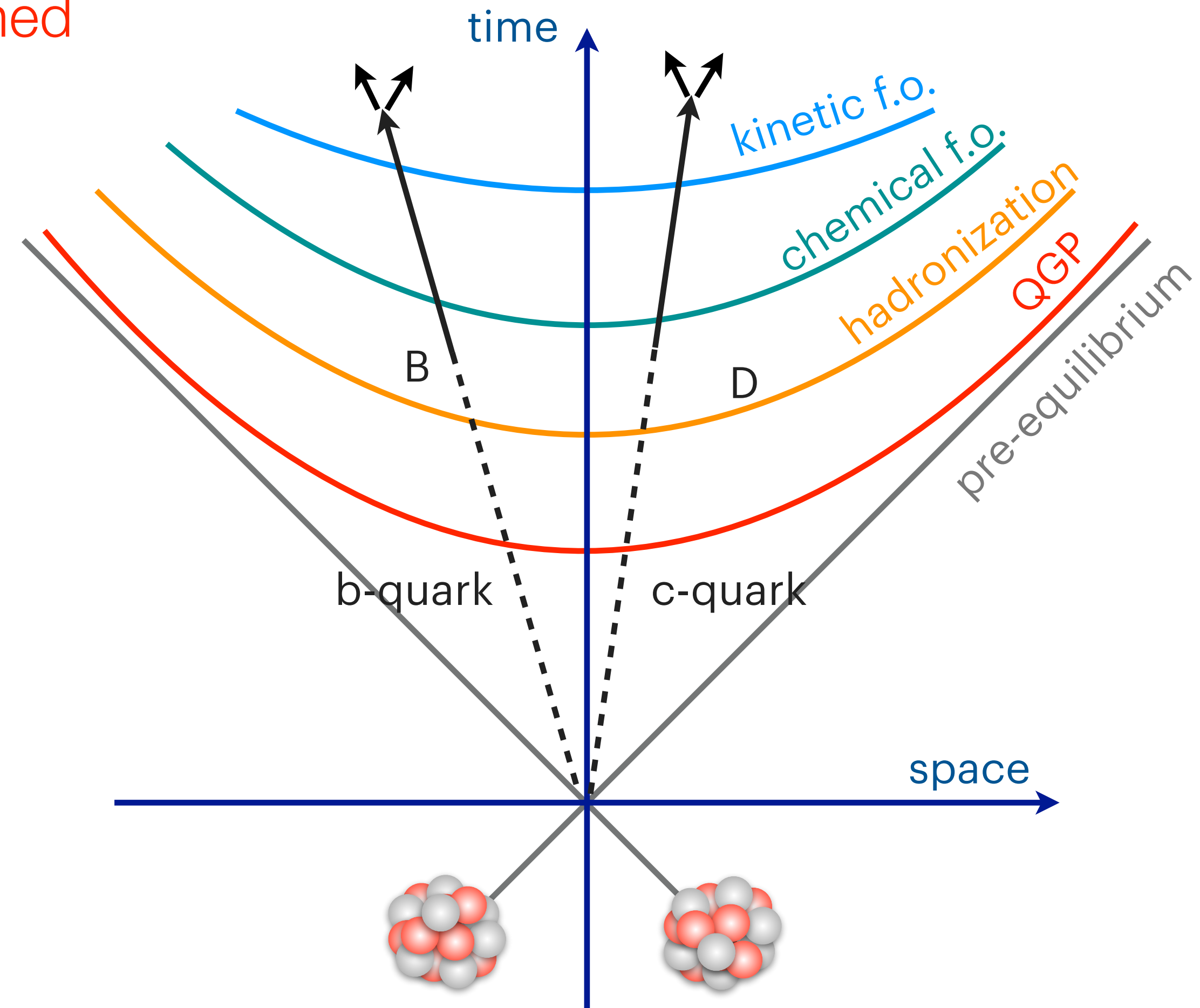
► Heavy quarks experience the full system evolution

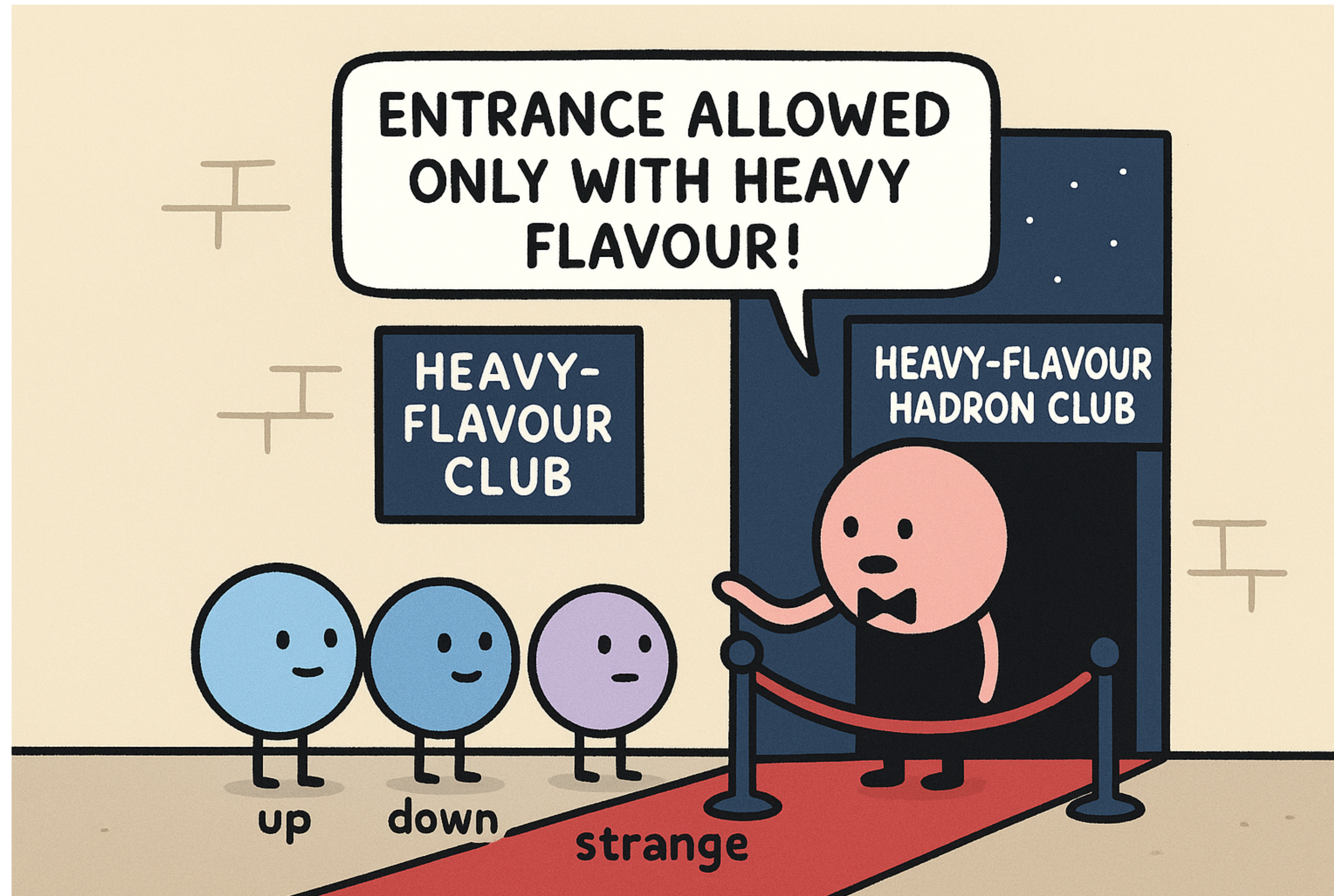
→ $\tau_{\text{HF}} \approx h/m \approx 0.05\text{-}0.1 \text{ fm}/c$

→ $\tau_{\text{QGP form}} (\text{LHC}) \approx 0.3 \text{ fm}/c$



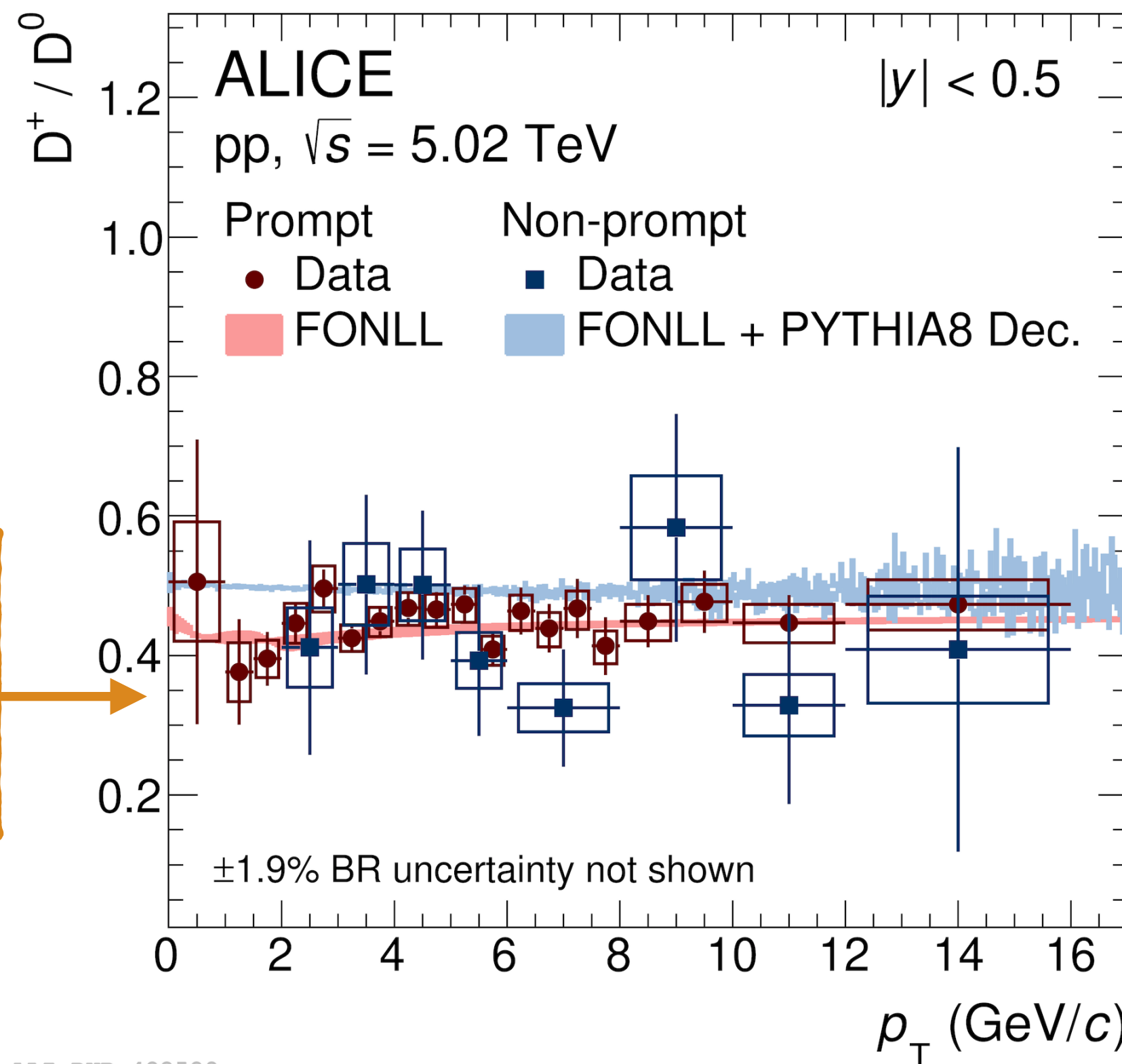
F.M. Liu et al., PRC 89, 034906 (2014)



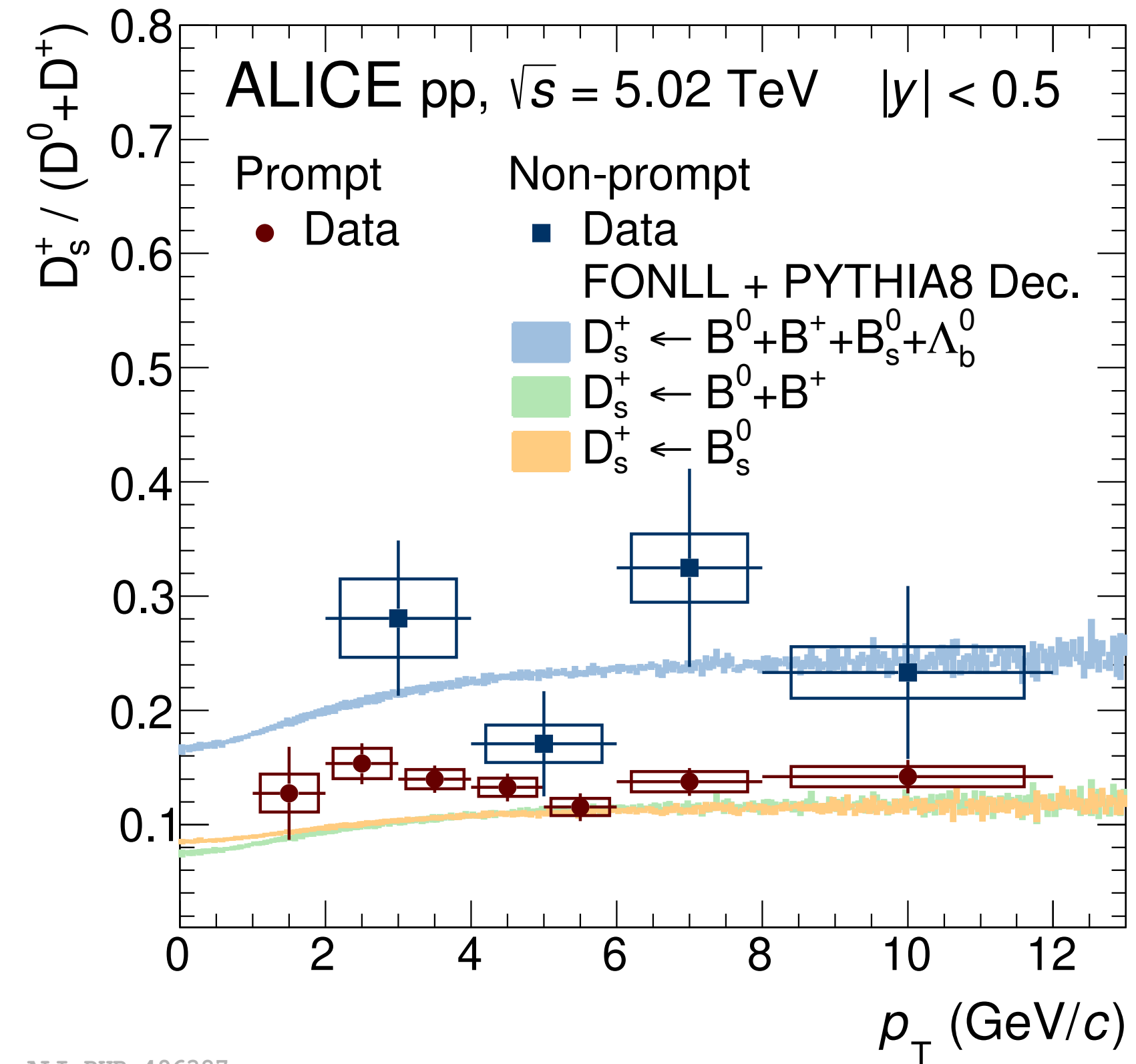


ALICE, JHEP
05 (2021) 220

Ratios
independent
of p_T



ALI-PUB-482589

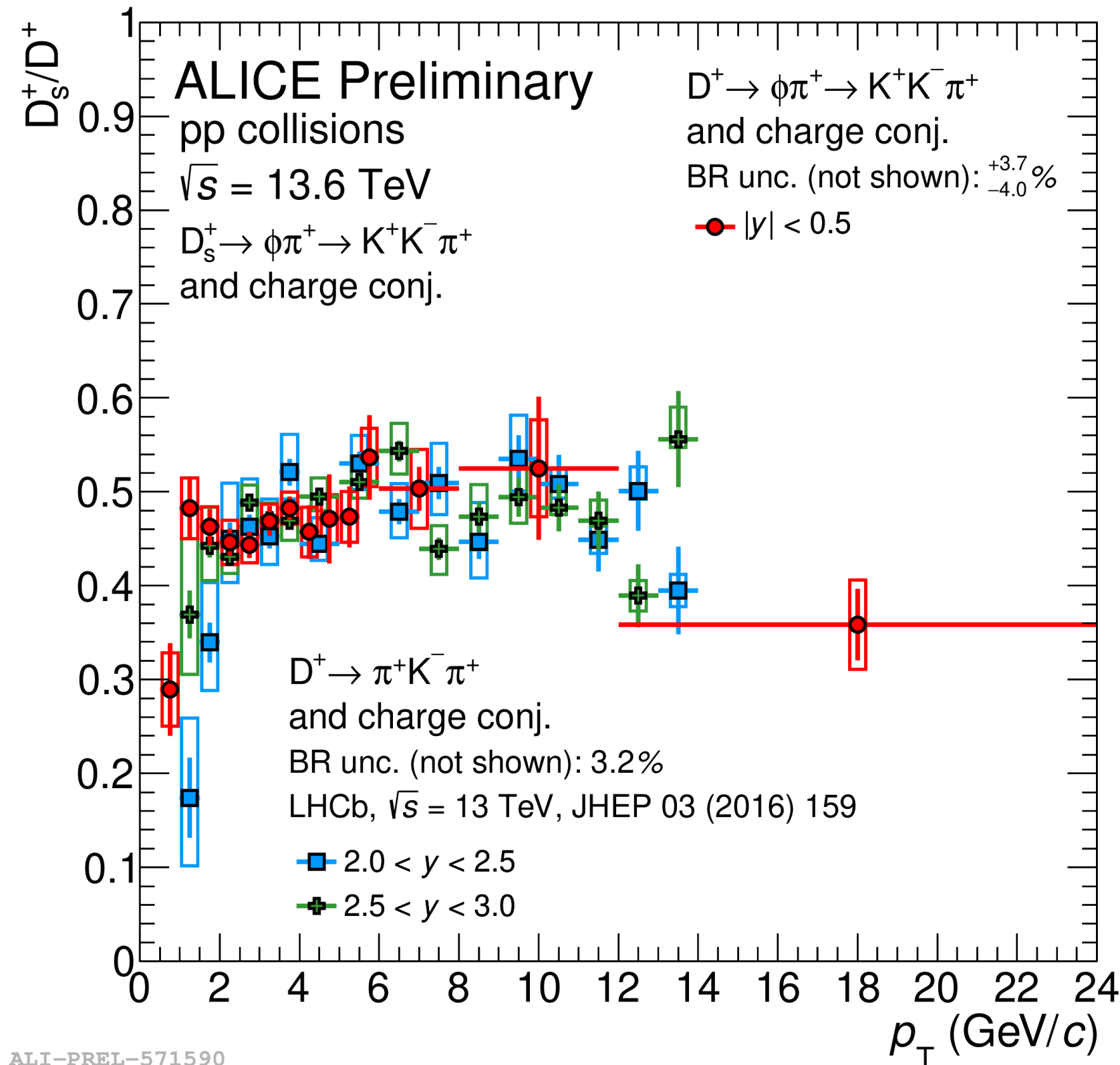


ALI-PUB-496387

- 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
- $D_s^+/(D^0 + D^+)$ higher for non-prompt mesons → substantial B^0 and B^+ decay contribution to D_s^+

Charm meson production

6



► D_s/D^+ as a function of p_T

➔ fresh new measurements from LHC Run 3

➔ results compatible at mid (ALICE) and forward (LHCb) rapidity → **no rapidity dependence**

📖 PYTHIA8 Monash: EPJC 74 (2014) 3024

📖 PYTHIA8 CR-BLC: JHEP 1508 (2015) 003

📖 Catania: PLB 821 (2021) 136622

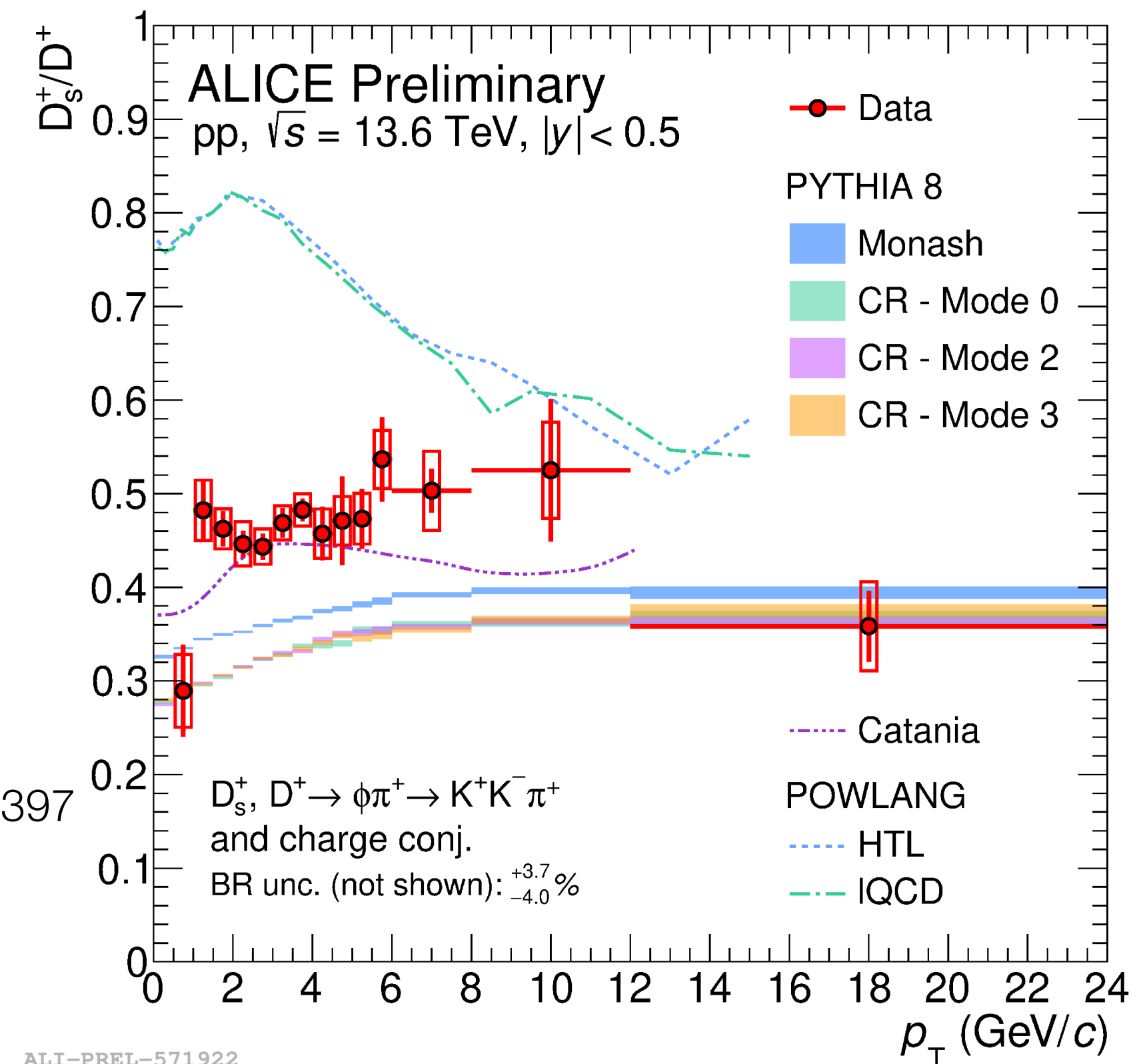
📖 POWLANG: arXiv:2306.02152

► D_s/D^+ comparison to model predictions

➔ Results in pp **compatible** with measurements performed in e^+e^- collisions

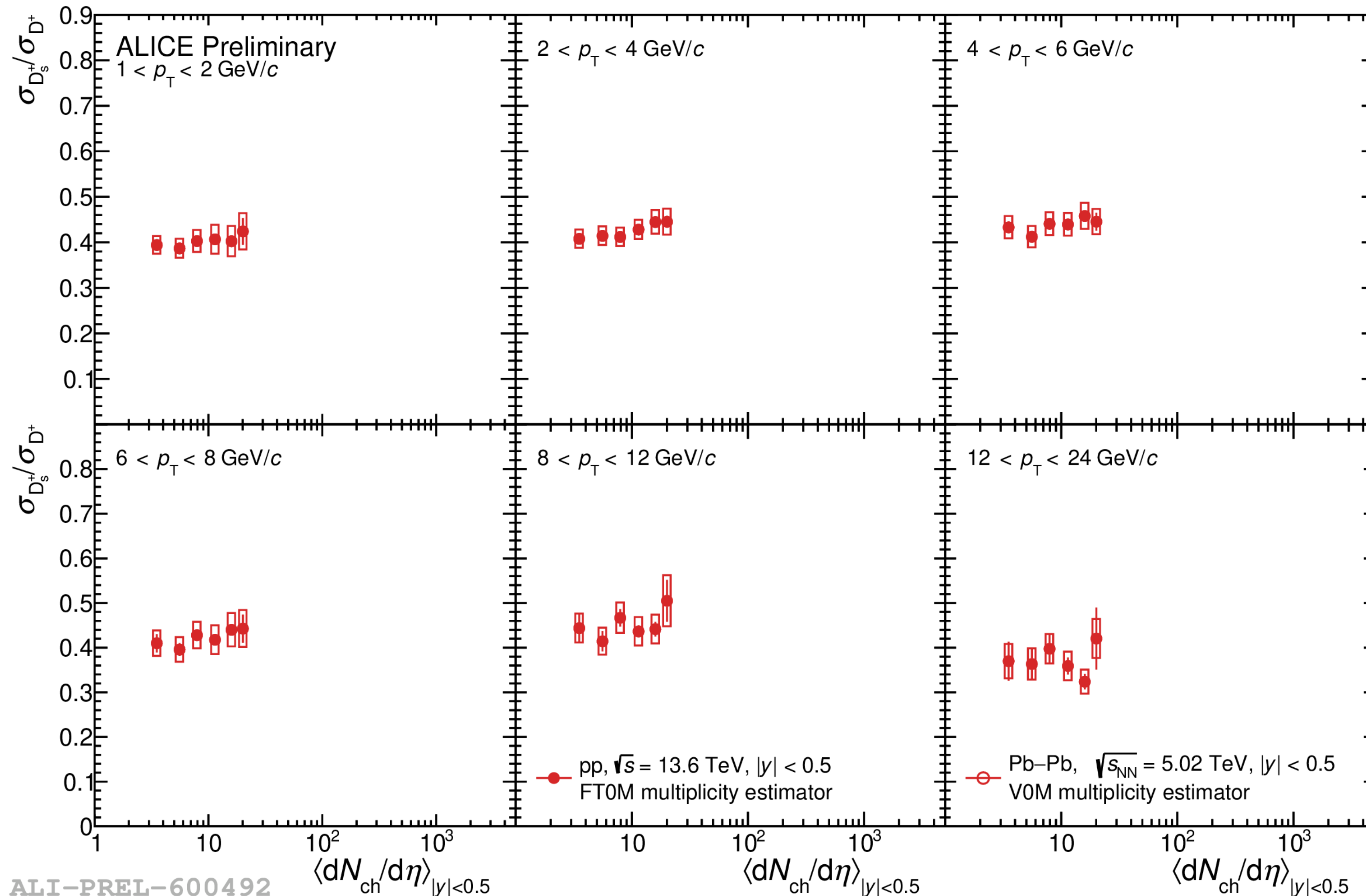
LEP average: (0.408 ± 0.040) 📖 Eur. Phys. J. C 76 (2016) 397

➔ PYTHIA 8 underestimates both with **Monash** (e^+e^-) and **Color Reconnection Modes**



Charm meson production vs. multiplicity

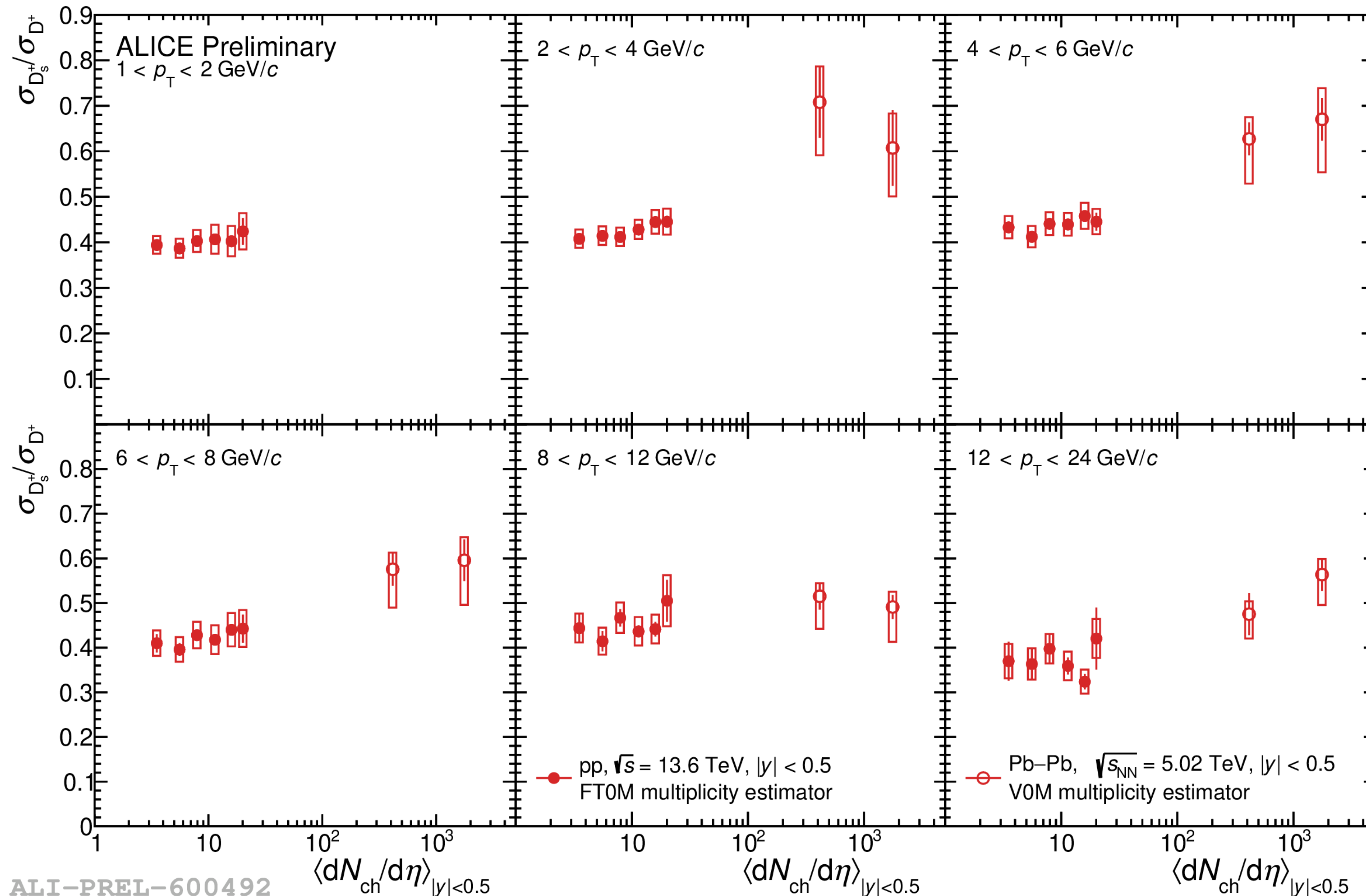
7



- ▶ No p_T and multiplicity dependence observed in pp collisions
- ▶ Results in pp compatible to e^+e^- results
- ➔ hadronisation not modified in the charm meson sector

Charm meson production vs. multiplicity

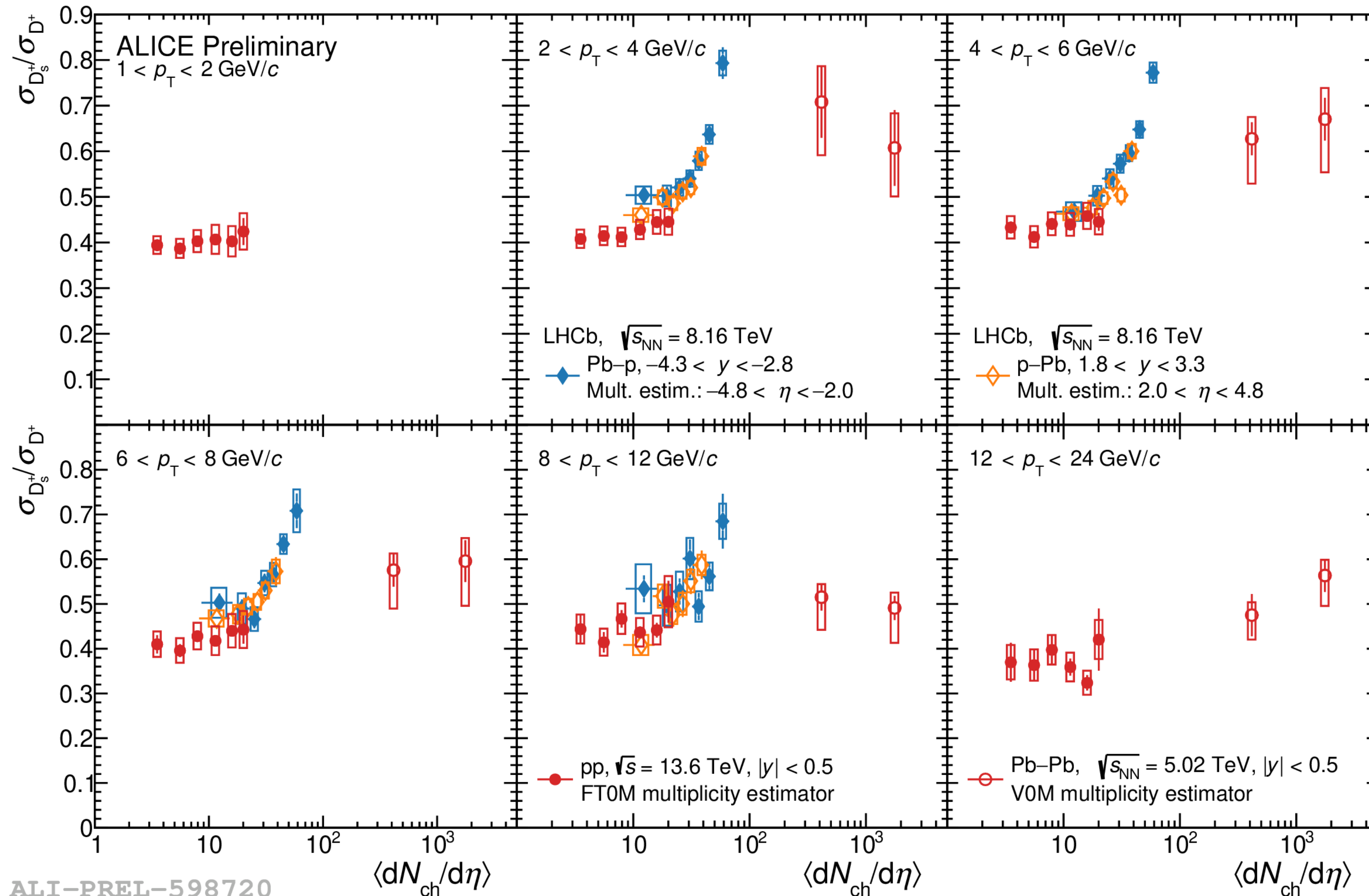
7



- ▶ No p_T and multiplicity dependence observed in pp collisions
- ▶ Results in pp compatible to e^+e^- results
 - ➔ hadronisation not modified in the charm meson sector
- ▶ Higher D_s^+/D^+ ratio at low/intermediate p_T in Pb-Pb collisions compared to pp
 - ➔ recombination of charm quarks with strange quarks?

Charm meson production vs. multiplicity

7



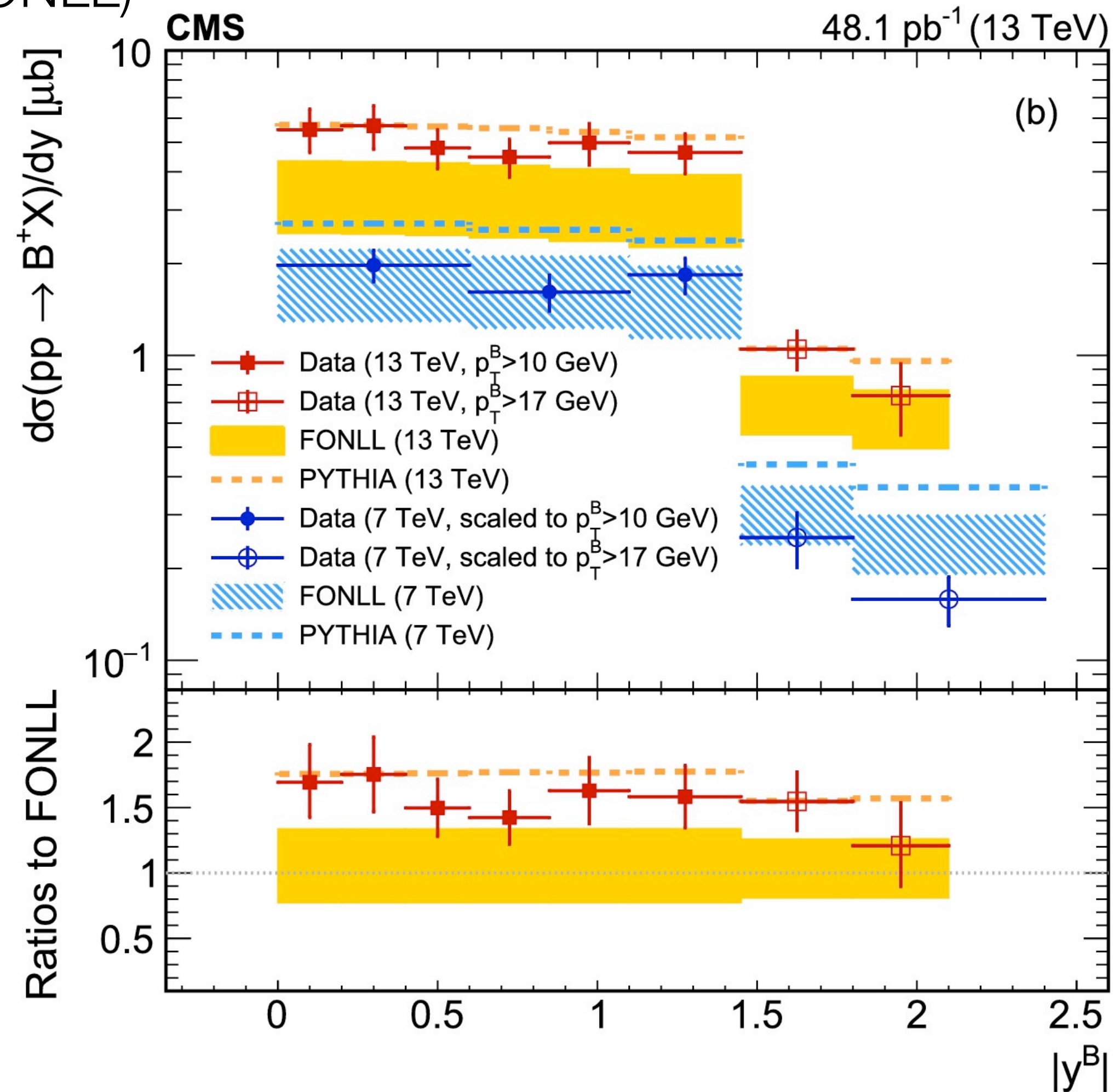
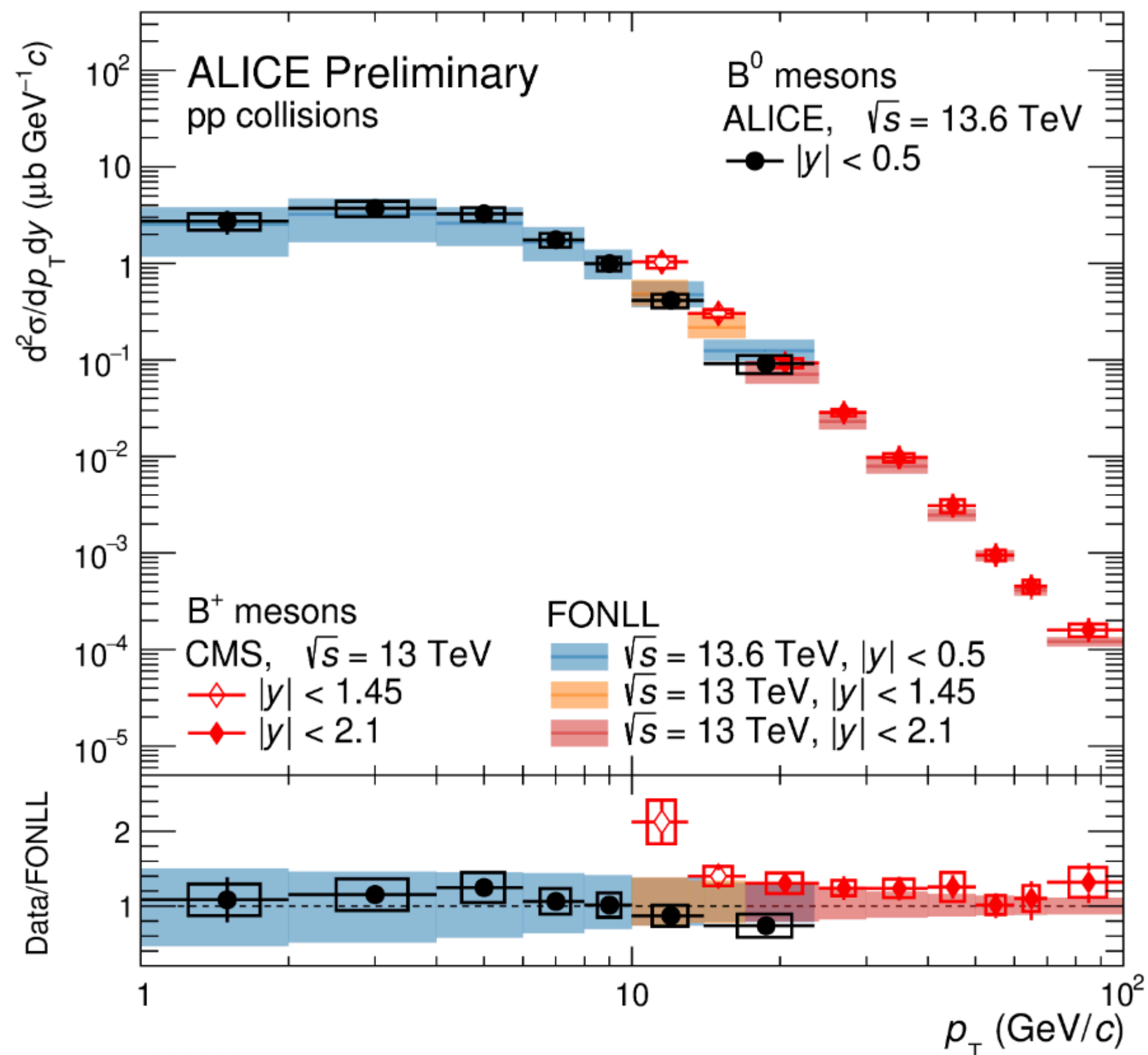
- ▶ No p_T and multiplicity dependence observed in pp collisions
- ▶ Results in pp compatible to e^+e^- results
 - ➔ hadronisation not modified in the charm meson sector
- ▶ Higher D_s^+/D^+ ratio at low/intermediate p_T in Pb-Pb collisions compared to pp
 - ➔ recombination of charm quarks with strange quarks?
- ▶ Hint of rapidity dependence
 - ➔ need of a common multiplicity estimator

Beauty meson production

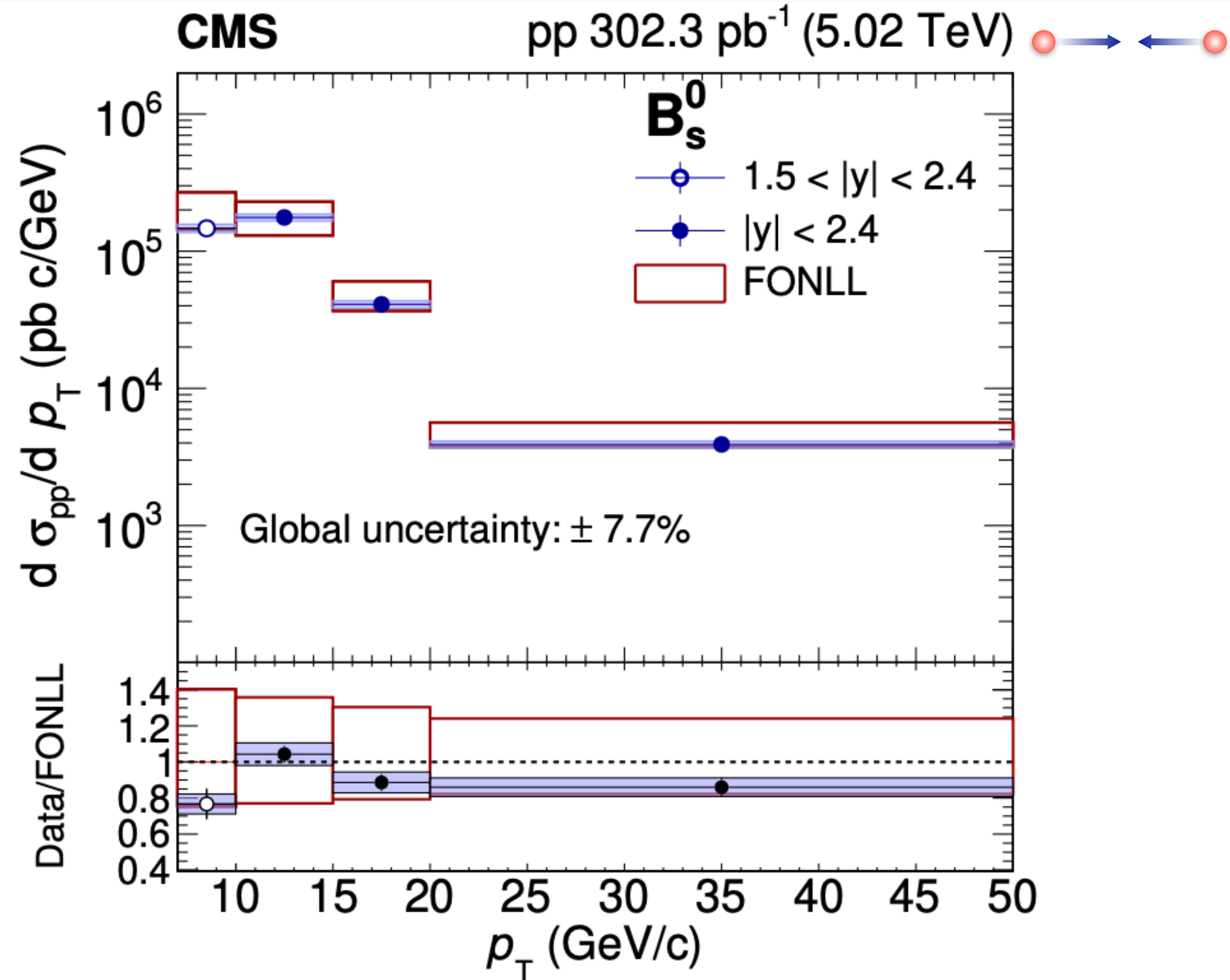
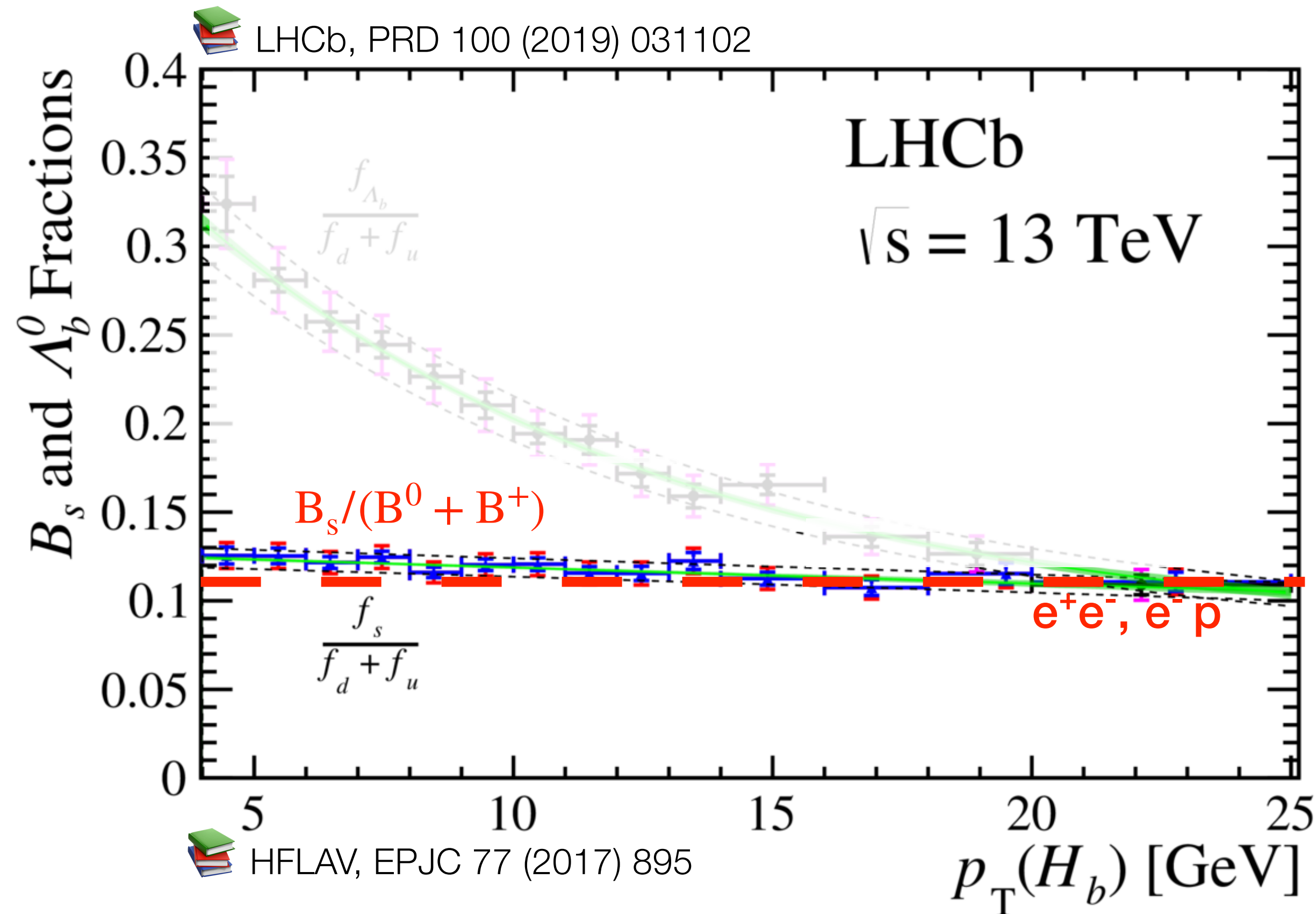
8

- Measurements of **fully reconstructed** B^0 and B^+ in a **wide p_T range**, including **very low p_T** at **midrapidity**, with Run 3 data

➔ agreement with **pQCD-based calculation** (FONLL)



CMS, PLB 771
(2017) 431
 FONLL, JHEP 10
(2012) 137
 PYTHIA, Comput.
Phys. Commun. 191
(2015) 159



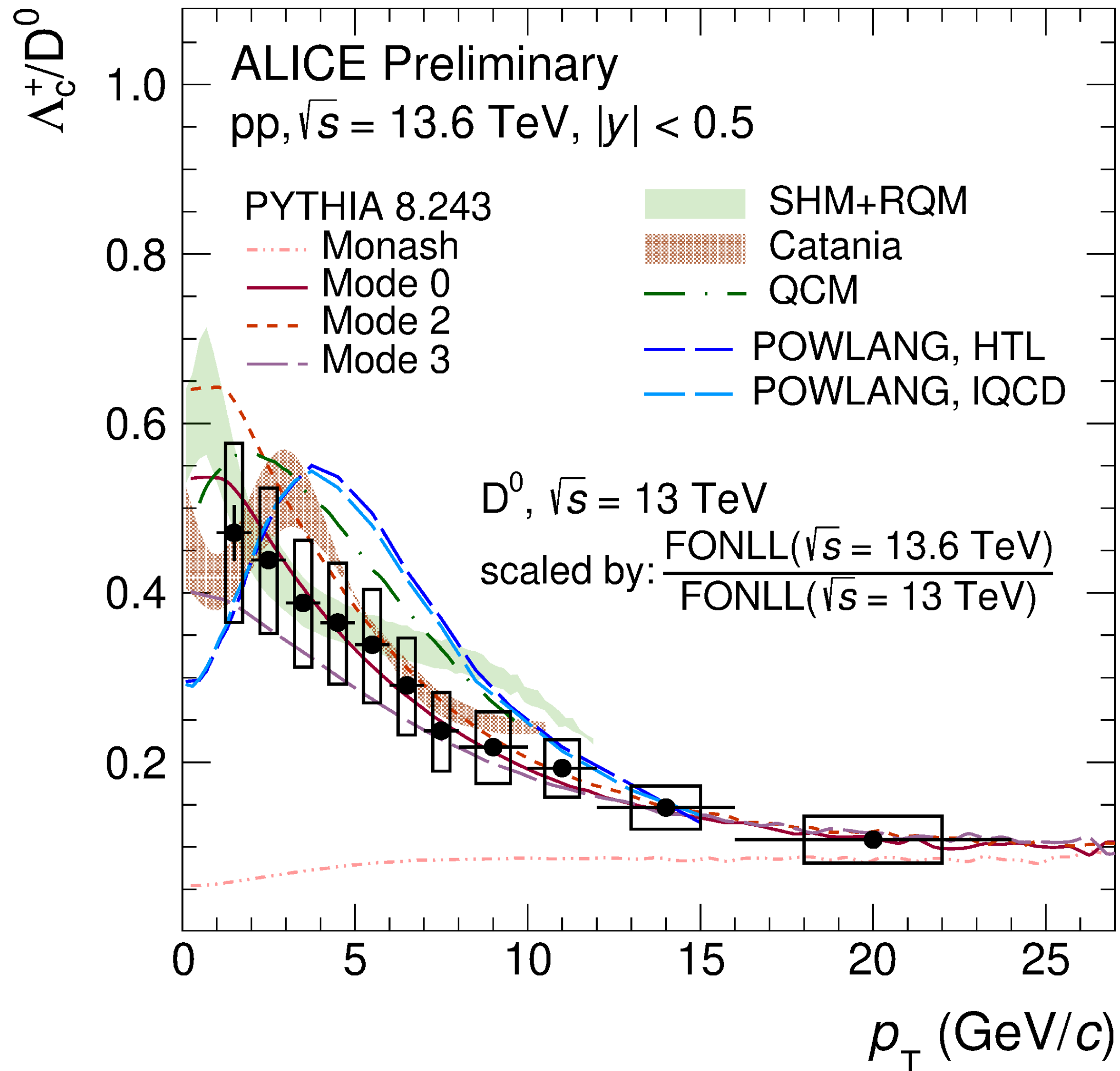
- B mesons measurements at **forward rapidity**
 - $B_s/(B^0 + B^+)$ **compatible** with e^+e^- measurements
- New B_s better agreement with FONLL predictions

FONLL, JHEP 10 (2012) 137

PYTHIA, Comput. Phys. Commun. 191 (2015) 159

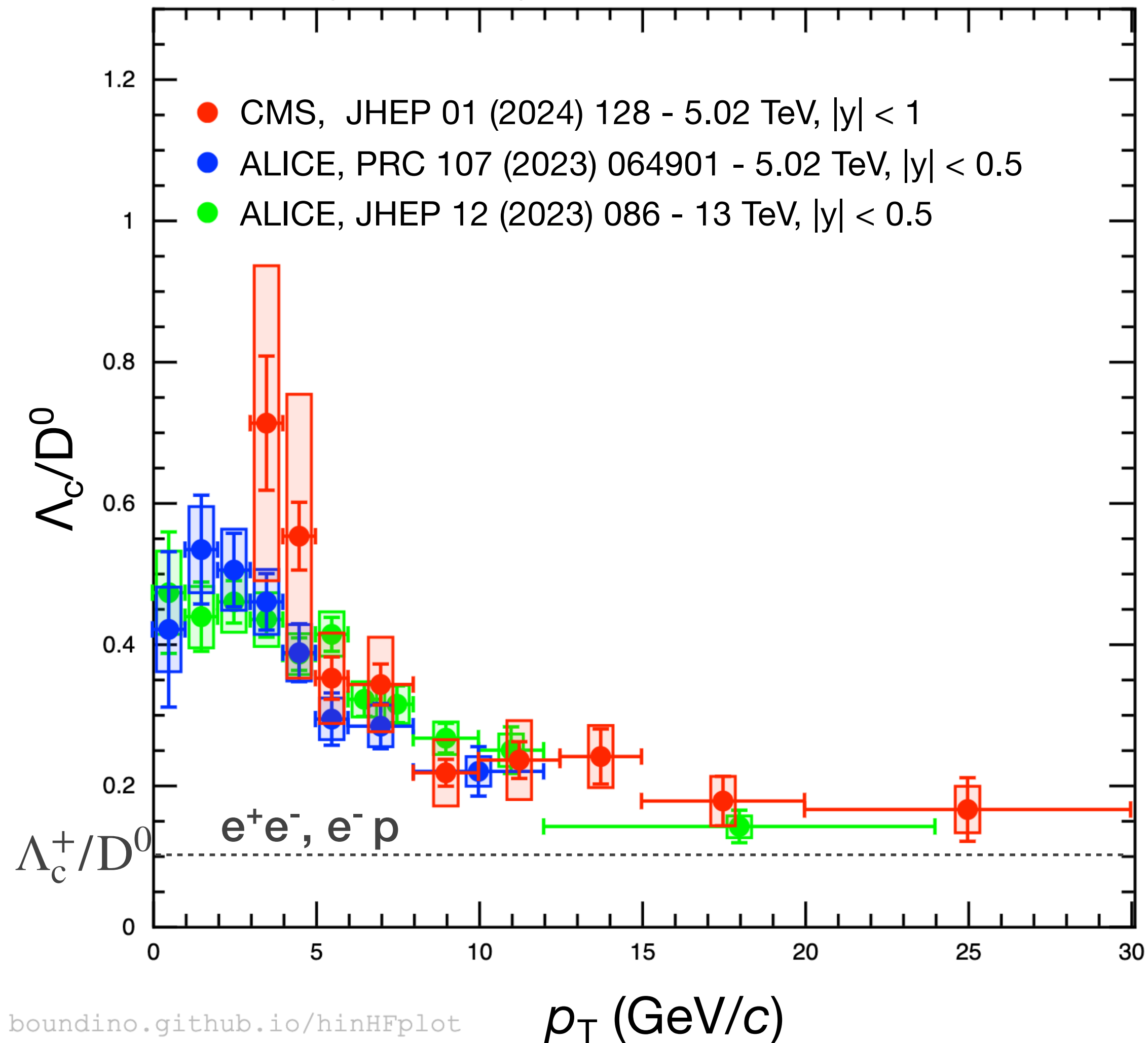
CMS, JHEP 02 (2025) 195

► LHC Run 3 new differential measurement show Λ_c/D^0 enhancement, described by:



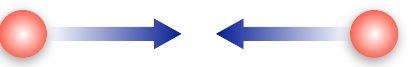
- **PYTHIA 8** with updated **Color Reconnection** modelling
 - “junction” topology enhances charm baryon prod.
- **Catania model**, **POWLANG**
 - thermalised system of u,d,s and gluons; hadronization via coalescence in addition to fragmentation
- **Quark (re-)Combination Mechanism**
 - recombination 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

J. Wang, [boundino.github.io/hinHFplot/](https://github.com/boundino/hinHFplot/)

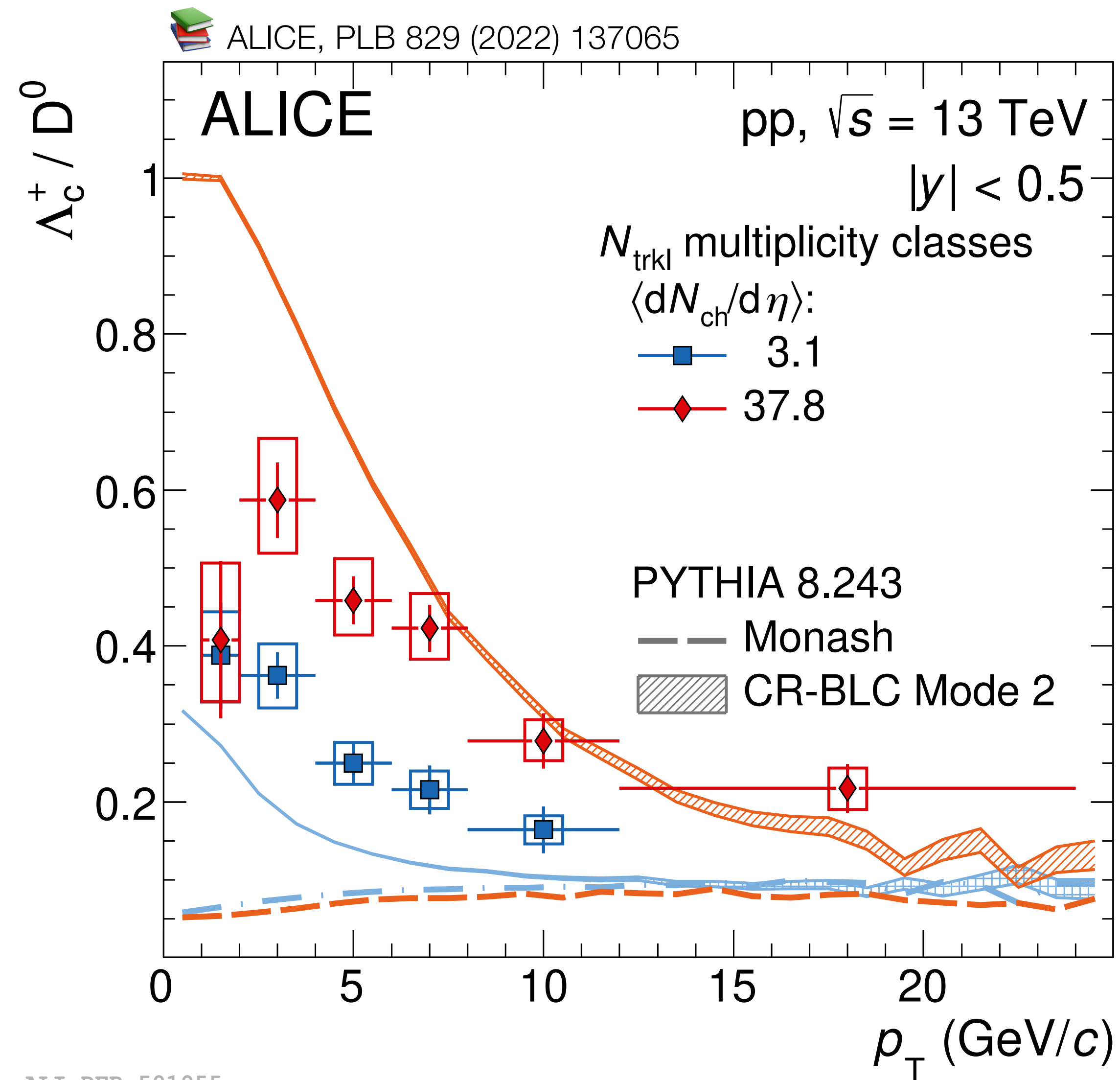


In pp collisions at LHC Run 2

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



Λ_c/D (LEP) L. Gladilin, EPJC 75 (2015) 19



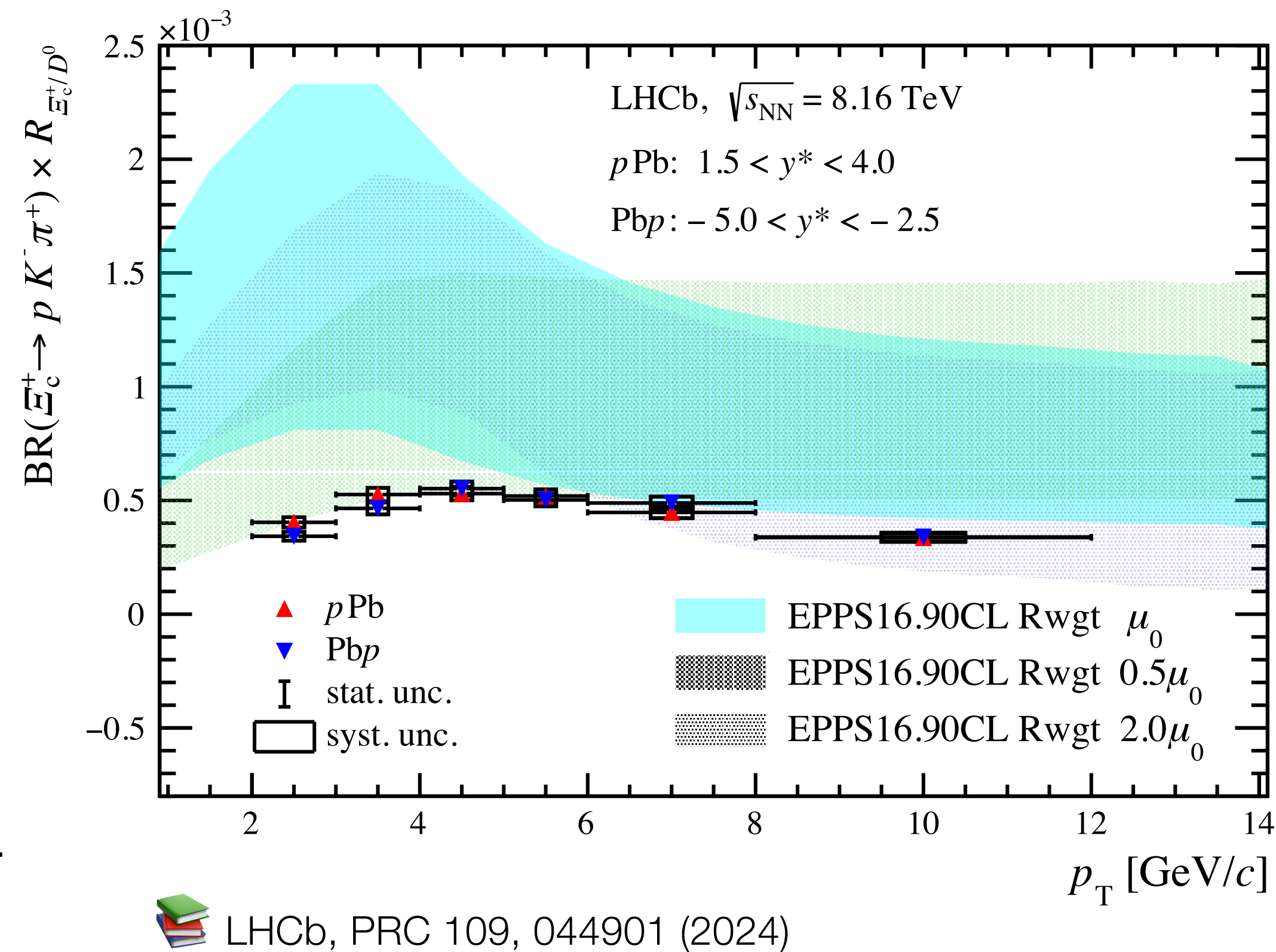
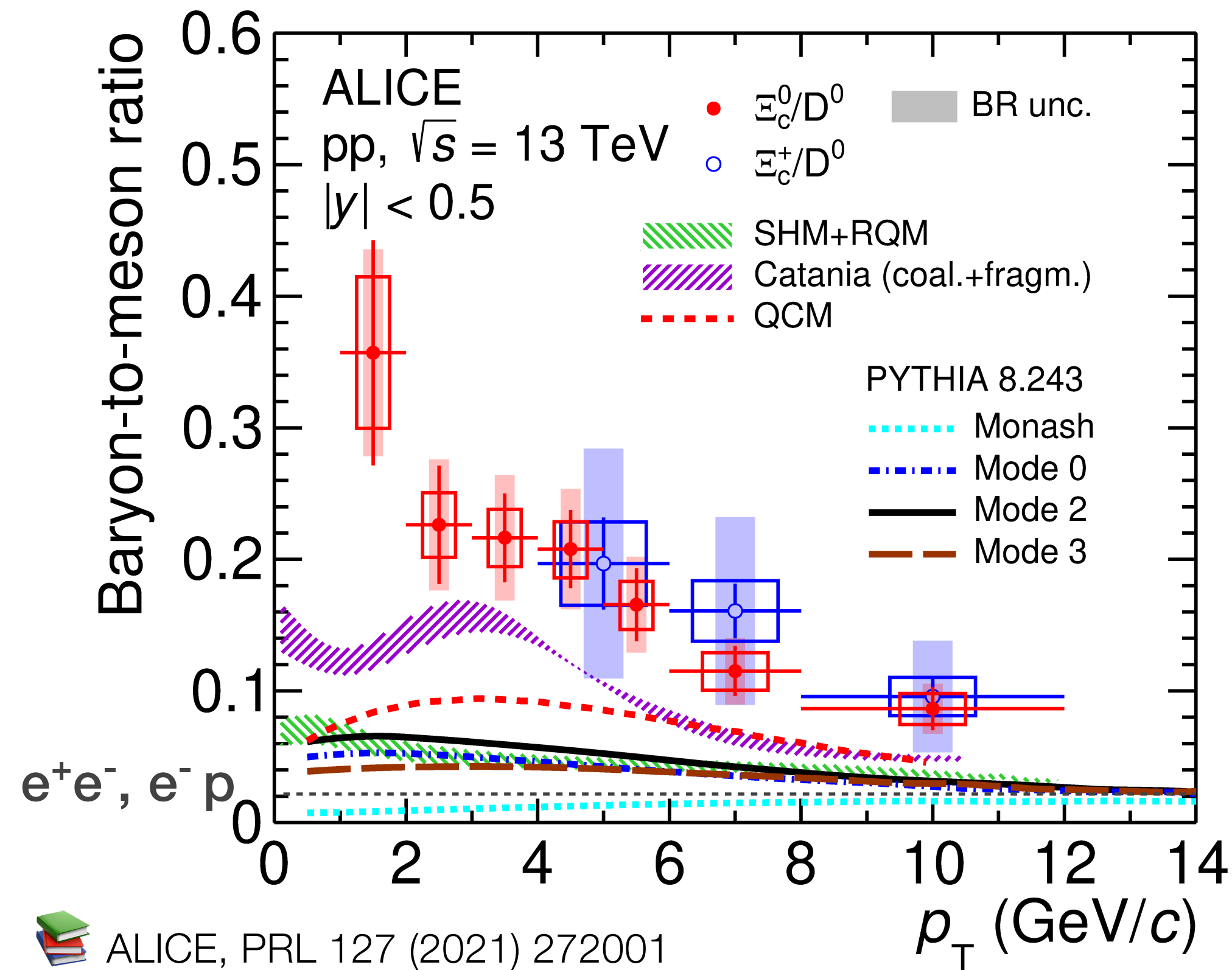
In pp collisions at LHC Run 2

- Prompt Λ_c/D^0 enhancement at low p_T with respect to measurements at e^+e^-/e^-p :
 - ratio higher (x 4-5) → approaching e^+e^-/e^-p at high p_T
- Multiplicity-differential results show similar enhancement at low p_T with respect to predictions based on e^+e^-/e^-p measurements
 - Monash tuning → underestimate the low p_T and approaching results at high p_T
 - CR-BLC → reproduce the trend in all multiplicity classes
- p_T -integrated results add questions to the puzzle
 - low-multiplicity measurements
 - common multiplicity estimators

[backup](#)

The heavy-flavour baryon saga - episode II

11



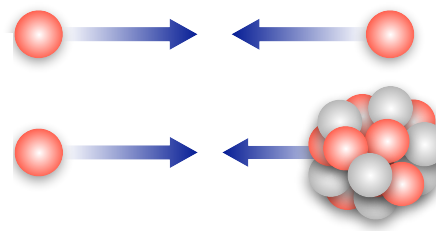
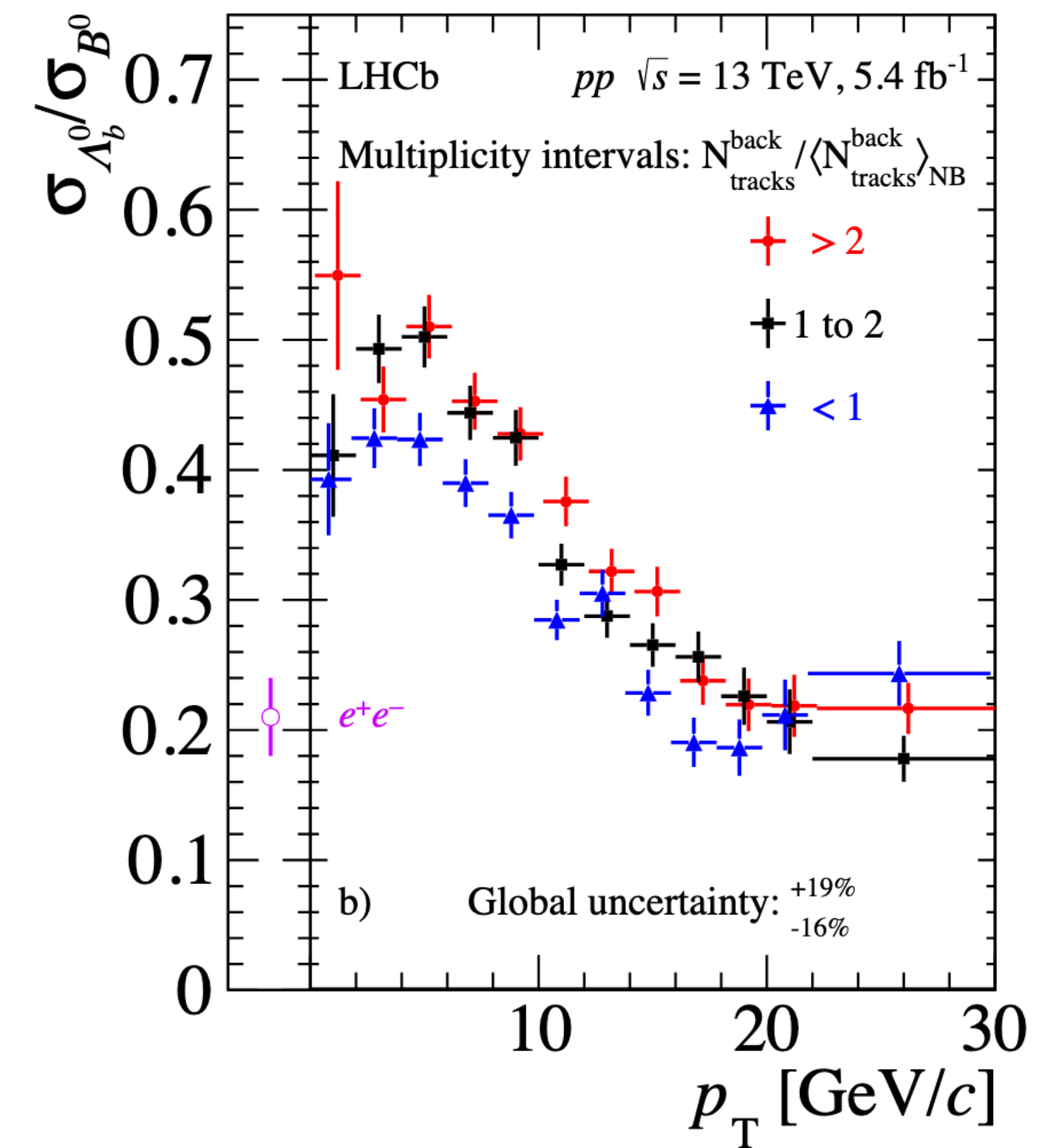
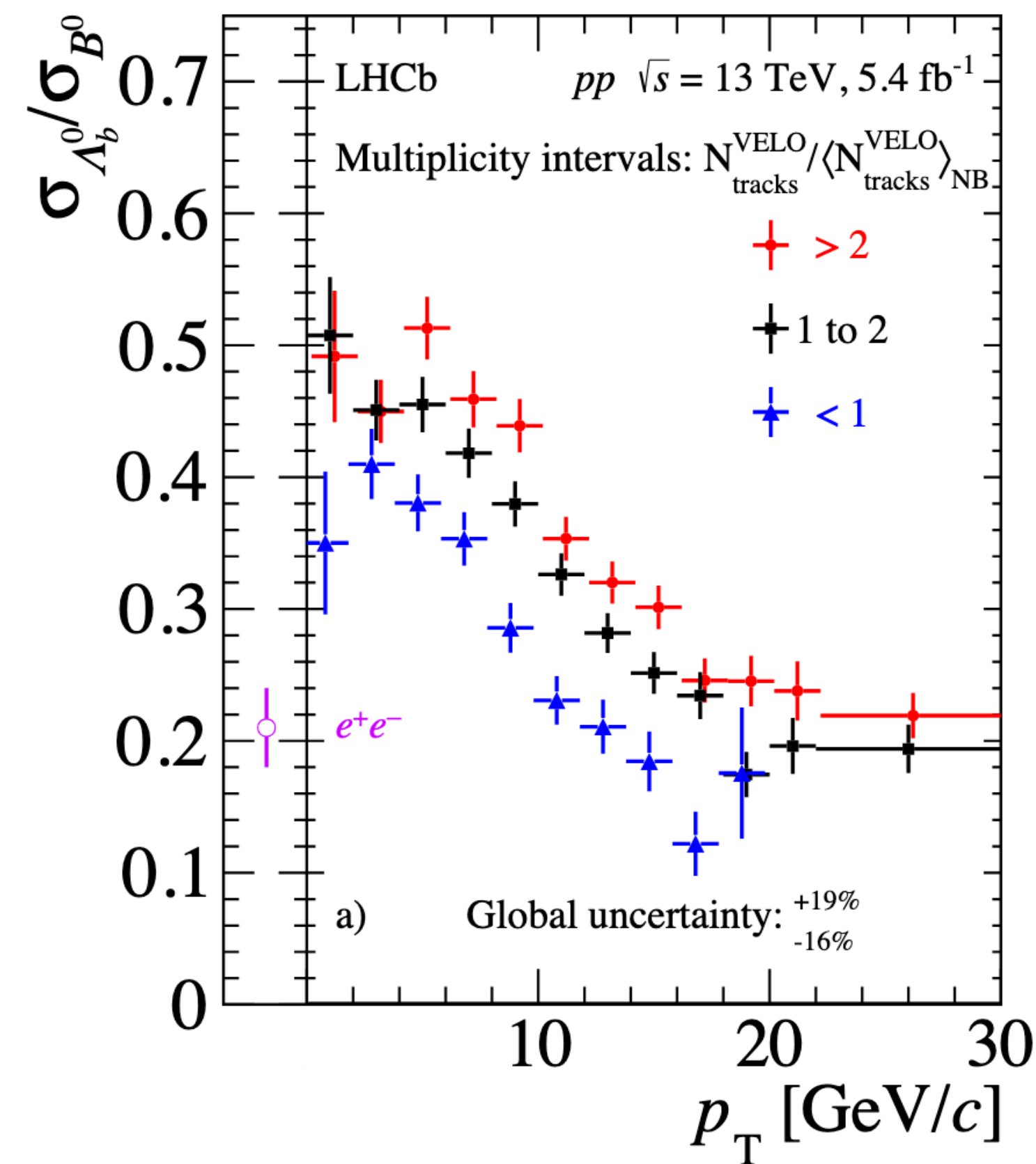
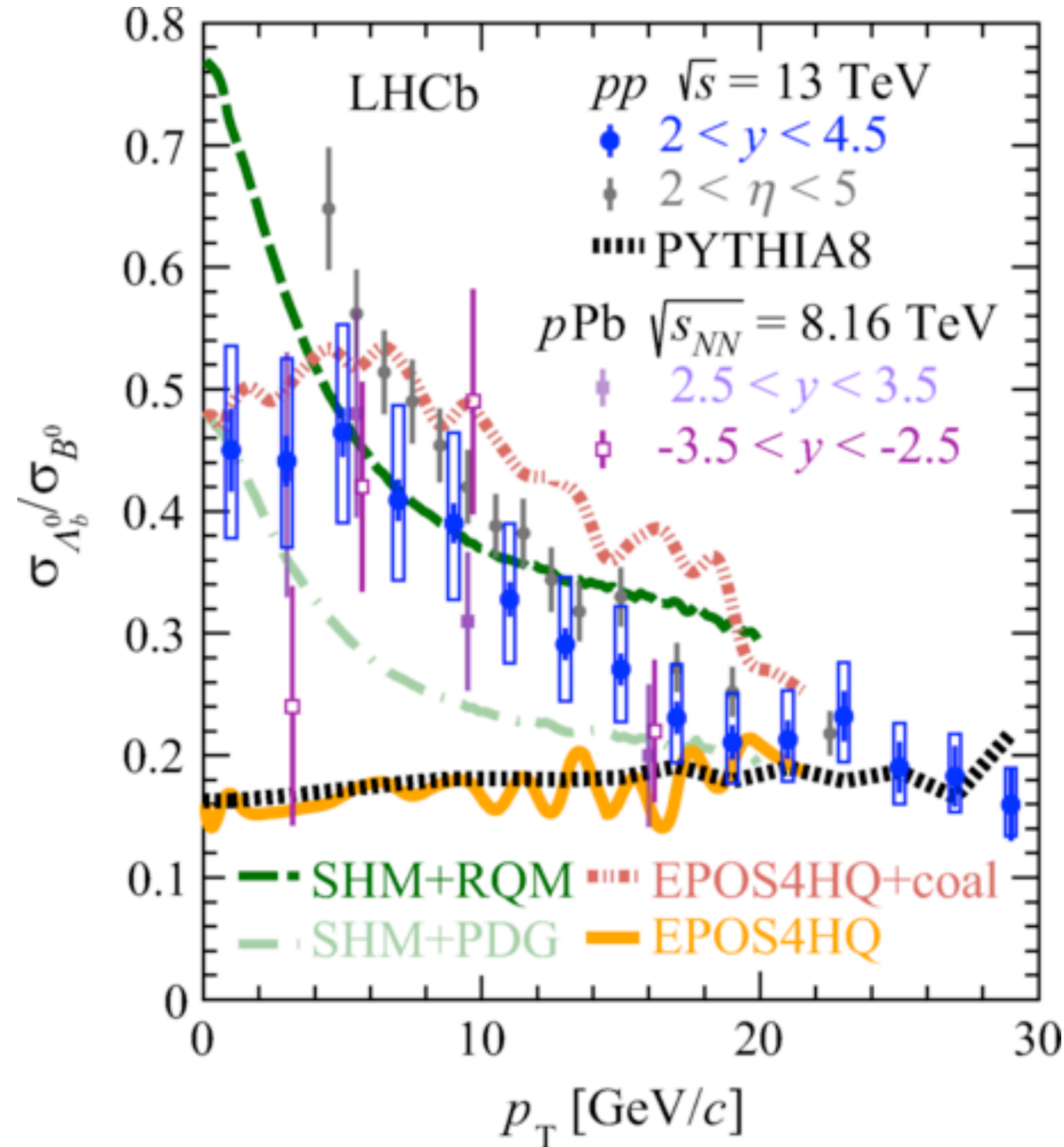
- PYTHIA 8: JHEP 1508 (2015) 003
- Catania: PLB 821 (2021) 136622
- SHM+RQM: PLB 795 (2019) 117-121
- QCM: EPJC 78 (2018) 344
- EPPS16: EPJC 77 (2017) 163

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

The heavy-flavour baryon saga - episode III

12

LHCb, PRL 132 (2024) 081901



► Λ_b^0 / B^0 in pp and p-Pb collisions → higher than PYTHIA Monash (e^+e^- tuning)

➡ only **statistical hadronisation** and **recombination models** are able to **get closer** to the measurement

► Λ_b^0 / B^0 multiplicity-dependent results approach e^+e^- only at high p_T

Two key observables in heavy-ion collisions

Two key observables in heavy-ion collisions

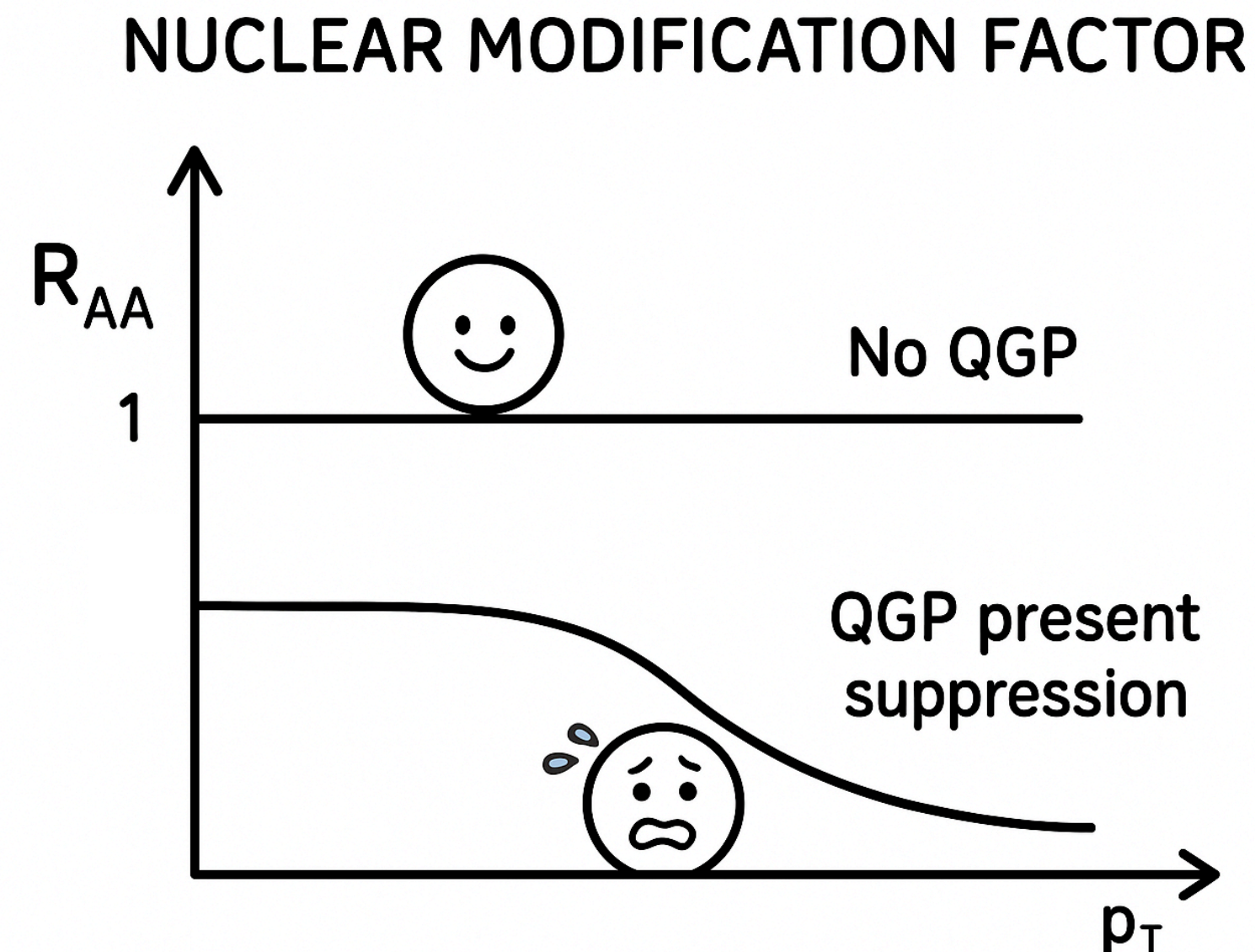
1. Nuclear modification factor

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

production yields in AA collisions

production yields in pp collisions

binary nucleon-nucleon collisions



Two key observables in heavy-ion collisions

1. Nuclear modification factor

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

production yields in
AA collisions

production yields in
pp collisions

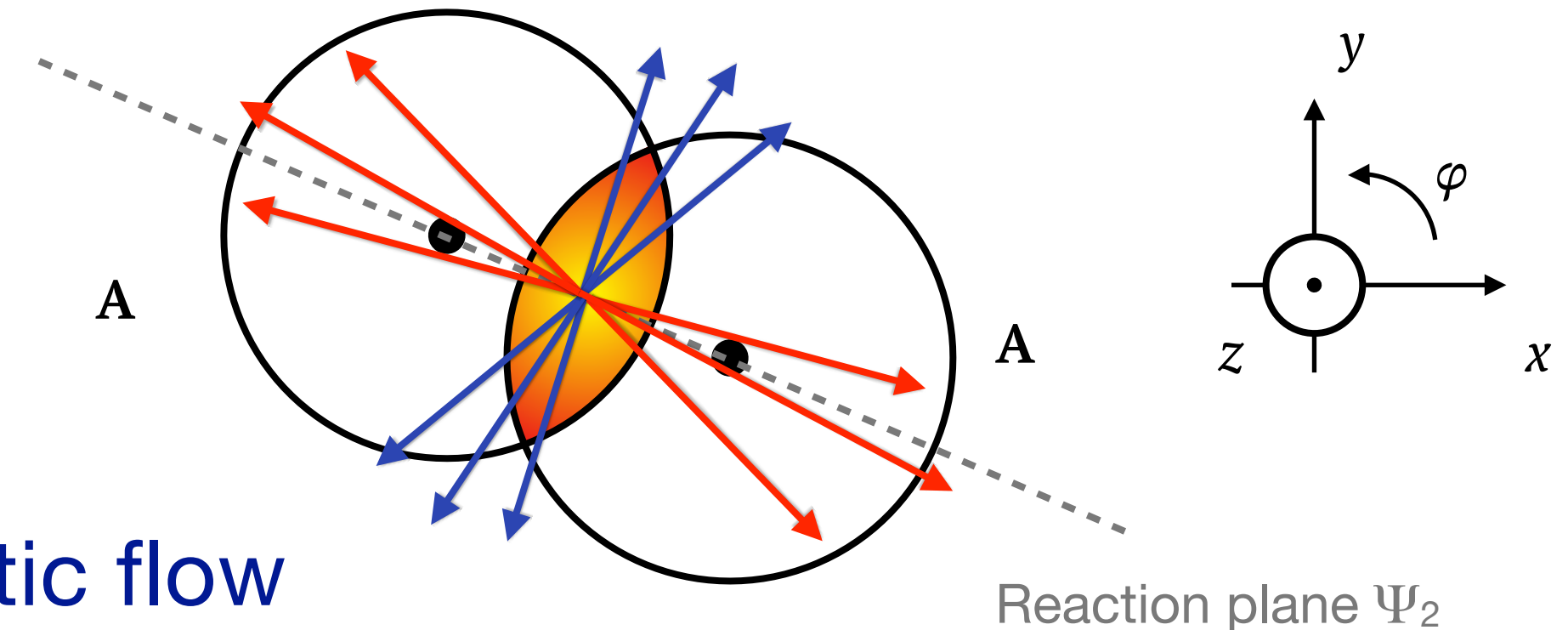
binary nucleon-
nucleon collisions

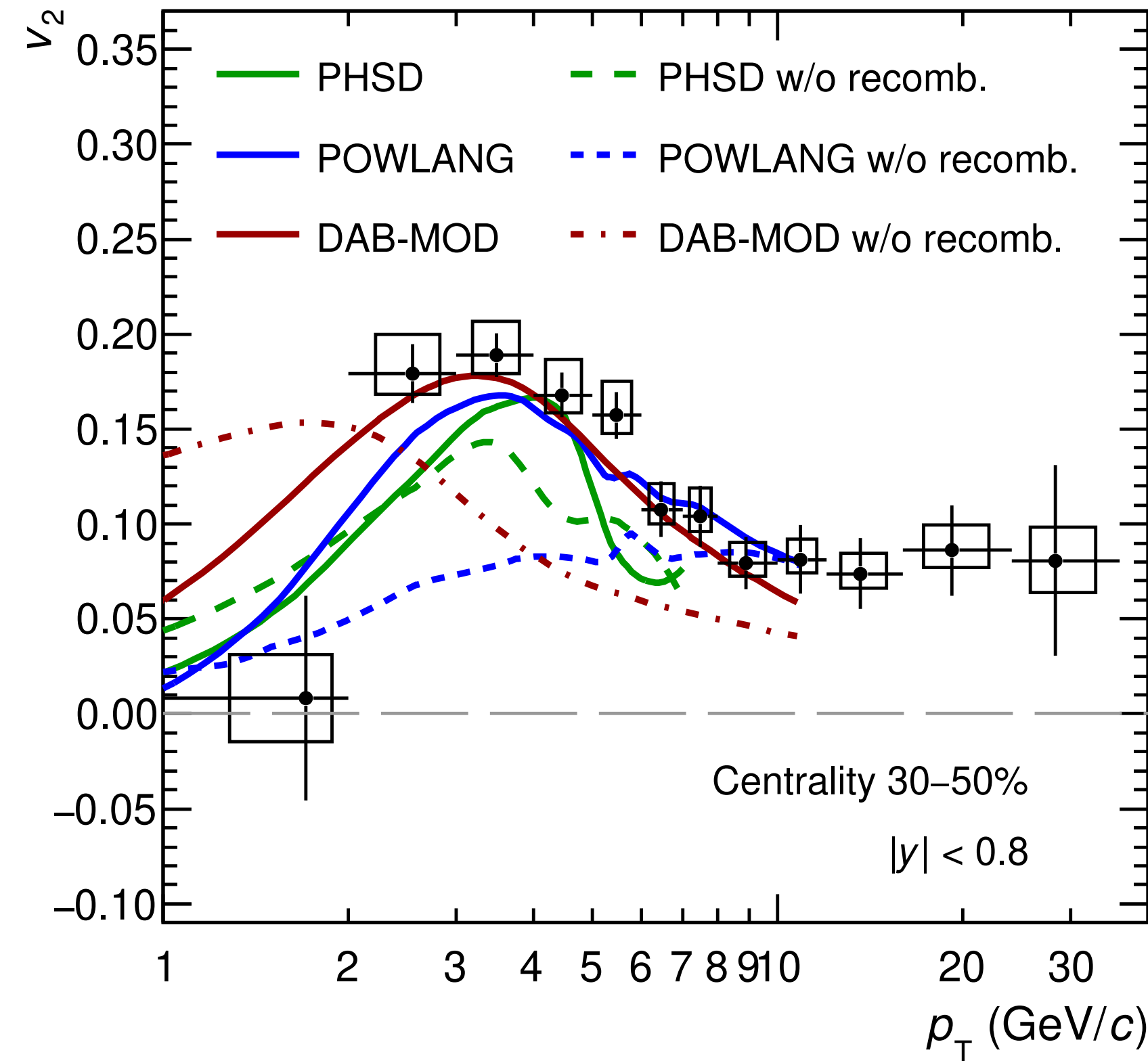
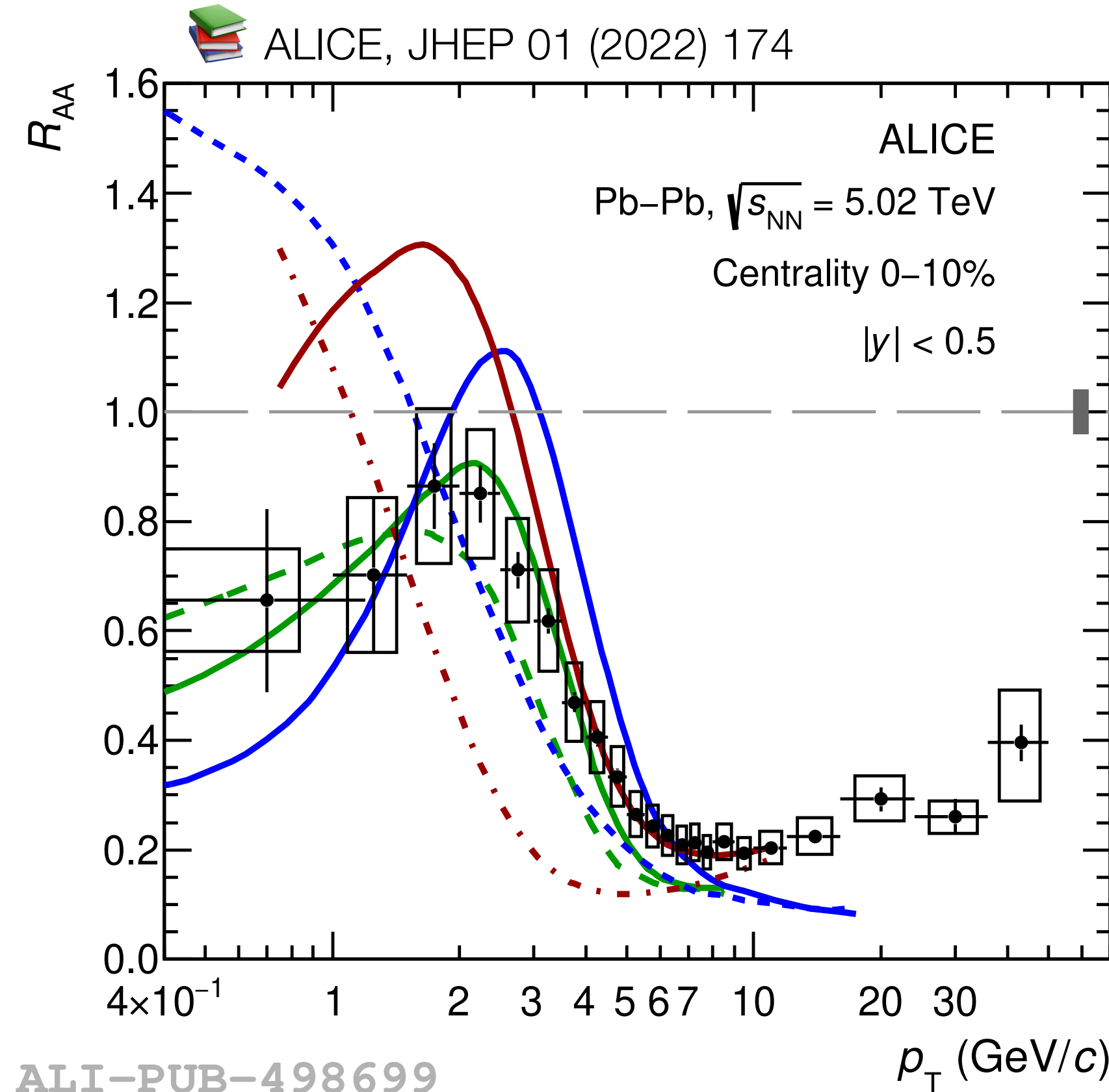
2. Azimuthal anisotropies

$$E \frac{d^3N}{dp_T} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left\{ 1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right\}$$

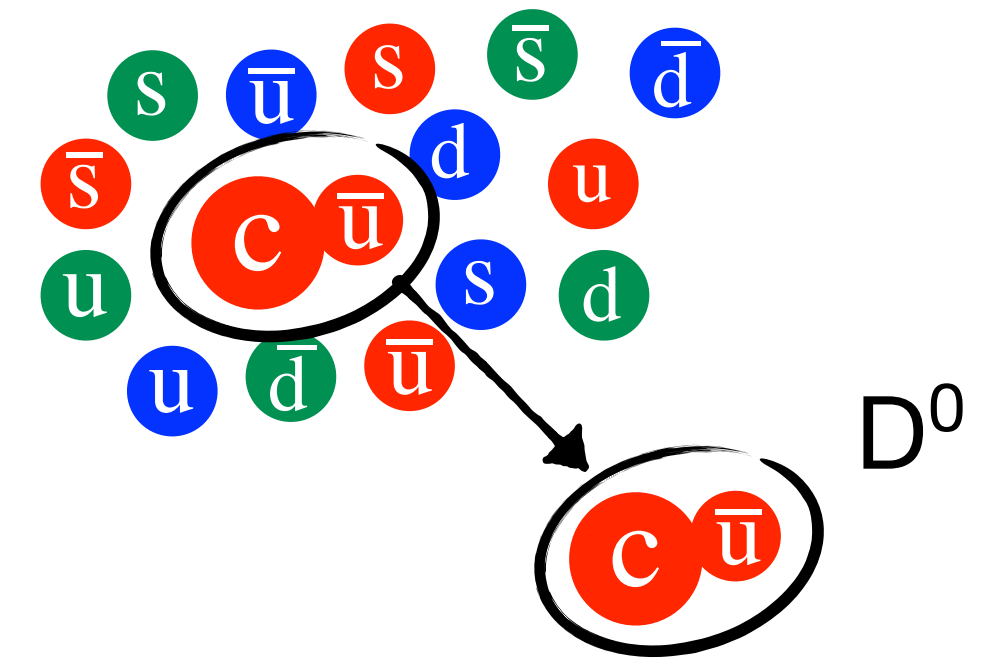
$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$

second harmonic coefficient **elliptic flow**



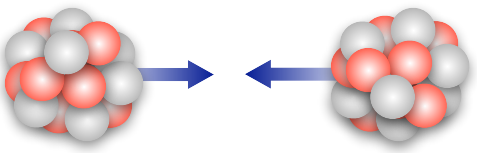
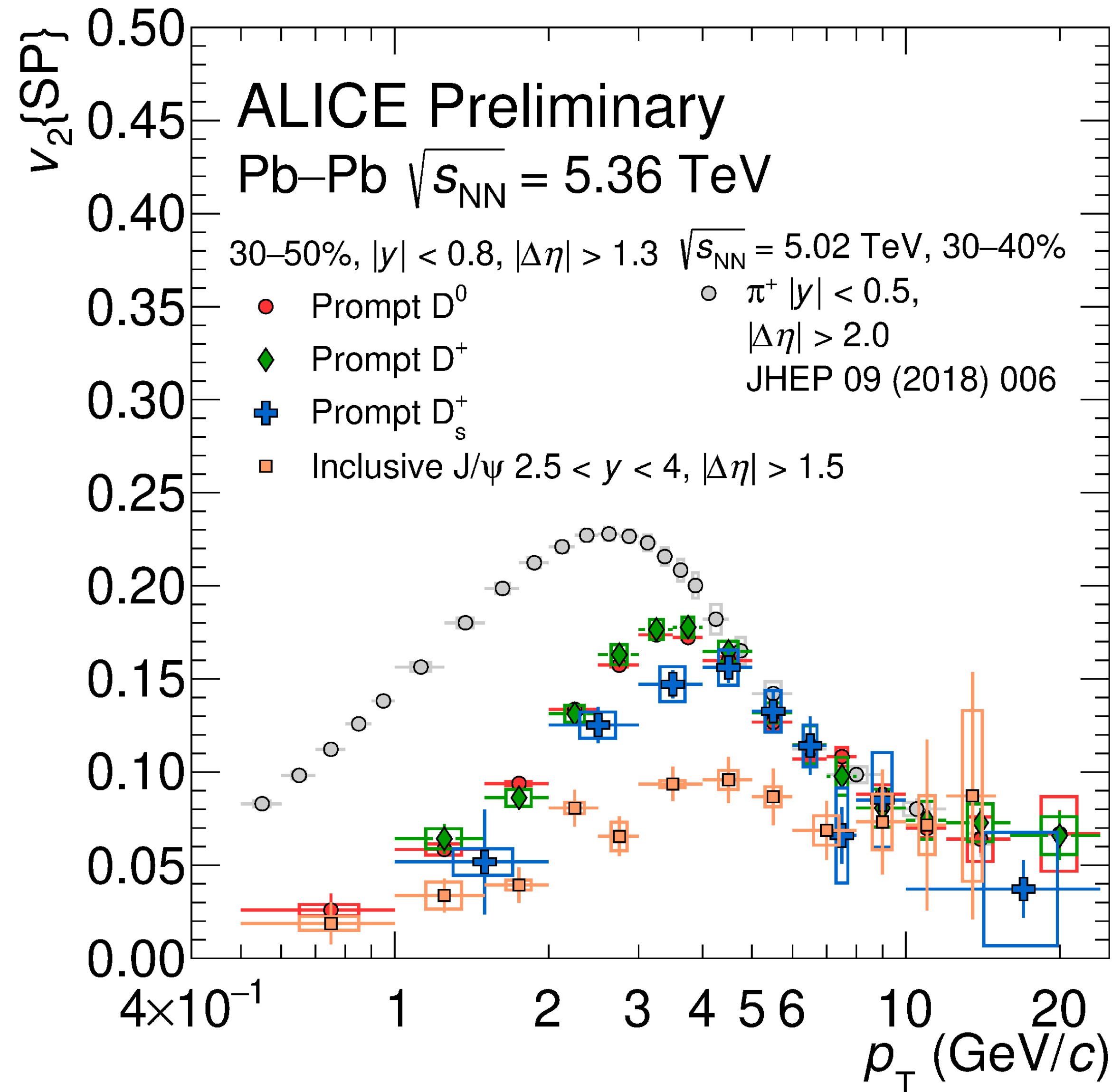


- **Recombination** of heavy quarks with light quarks from QGP affects **HF hadrons momentum distribution**
- ➔ HF hadrons pick-up the radial and elliptic flow of light quark



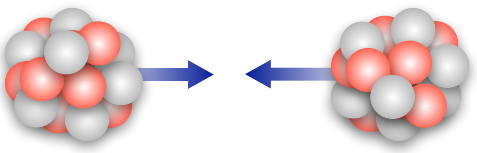
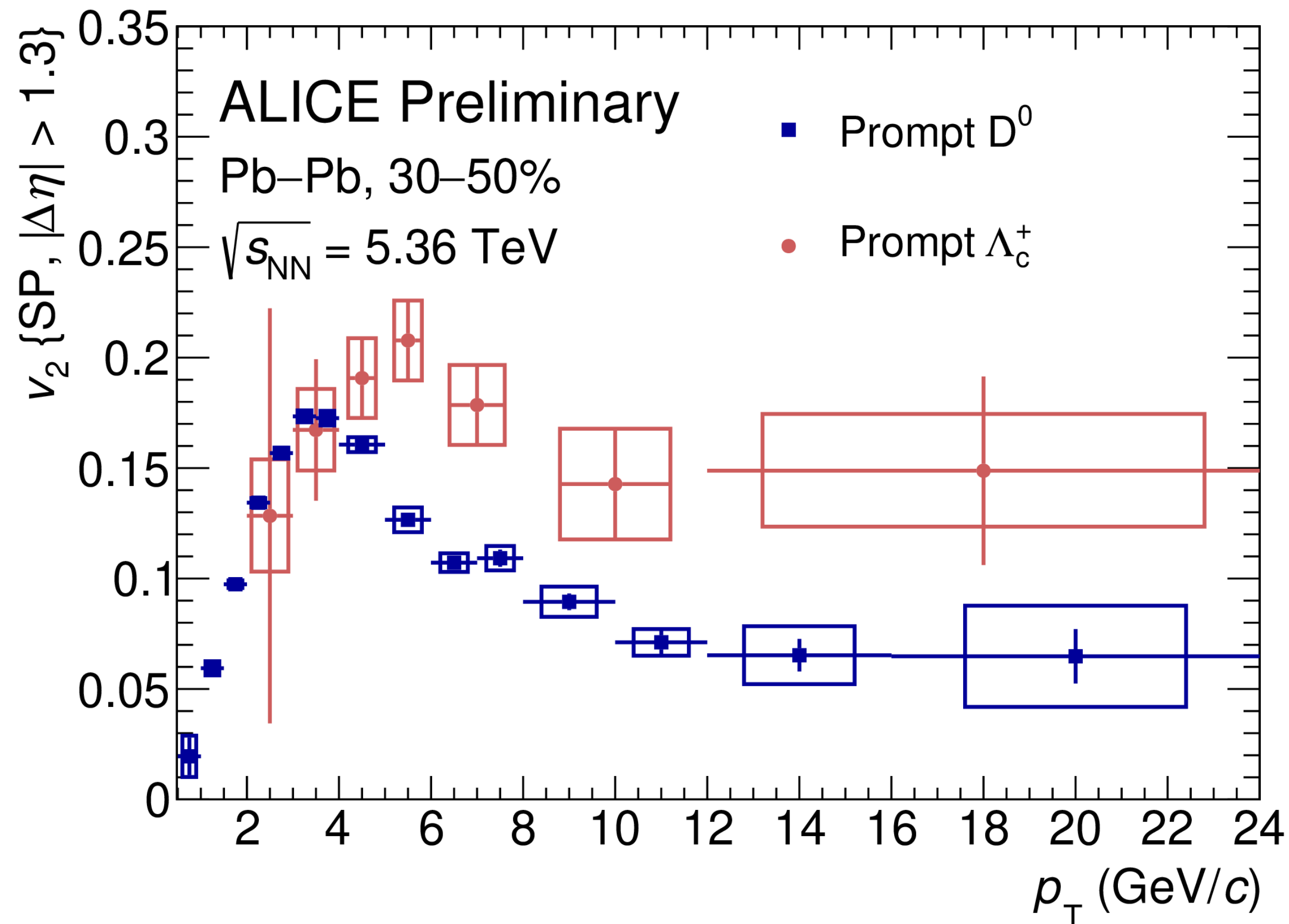
- Relation between p_{charm} and p_D is different for fragmentation and recombination
- ➔ **recombination** $\rightarrow p_D > p_{charm}$ and D meson inherits also the flow of light quark

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



► Recent LHC Run 3 measurements

- First **prompt D^0 v_2** below $p_T < 1$ GeV/c
- **D_s^+ v_2** close to non-strange D v_2 though tendency to be smaller for $p_T < 4$ GeV/c
- **Inclusive J/ψ v_2** lower than **prompt D v_2** at intermediate p_T



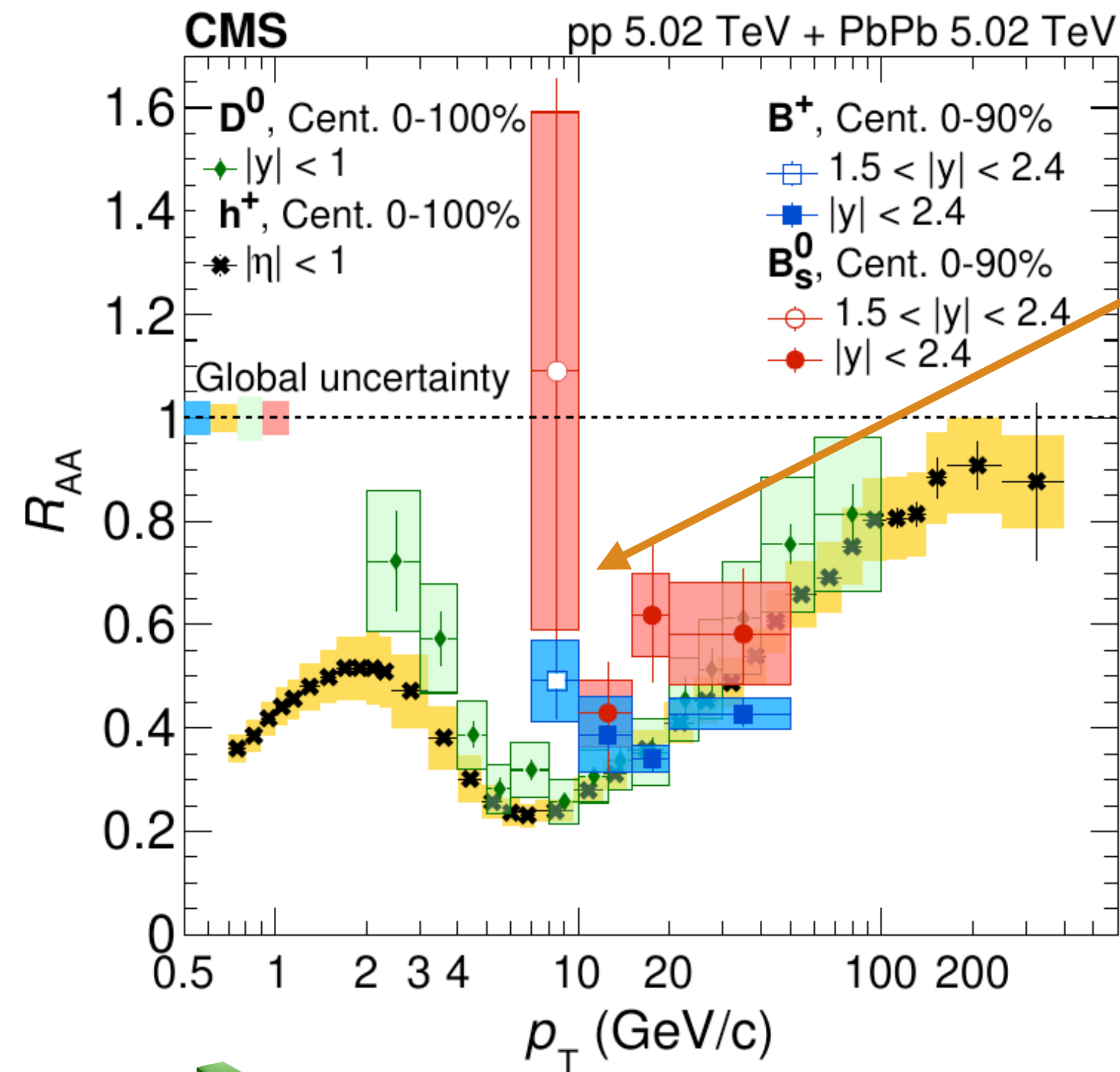
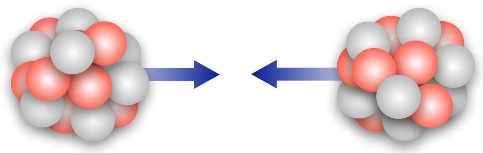
► Recent LHC Run 3 measurements

- ➔ First prompt D^0 v_2 below $p_T < 1$ GeV/c
- ➔ D_s^+ v_2 close to non-strange D v_2 though tendency to be smaller for $p_T < 4$ GeV/c
- ➔ Inclusive J/ψ v_2 lower than prompt D v_2 at intermediate p_T

► First prompt charm-baryon v_2 measurement in heavy-ion collisions

- ➔ $p_T > 4$ GeV/c: $v_2(\Lambda_c) > v_2(D)$ with 3.6σ significance $\Rightarrow$ first evidence of charm baryon/meson splitting
- ➔ crucial role of coalescence?

- Recombination of **heavy quarks** with **light quarks** from the QGP affects **HF hadrochemistry**
 ➔ **enhanced B_s** yield relative to non-strange mesons (strange quarks more abundant in QGP)

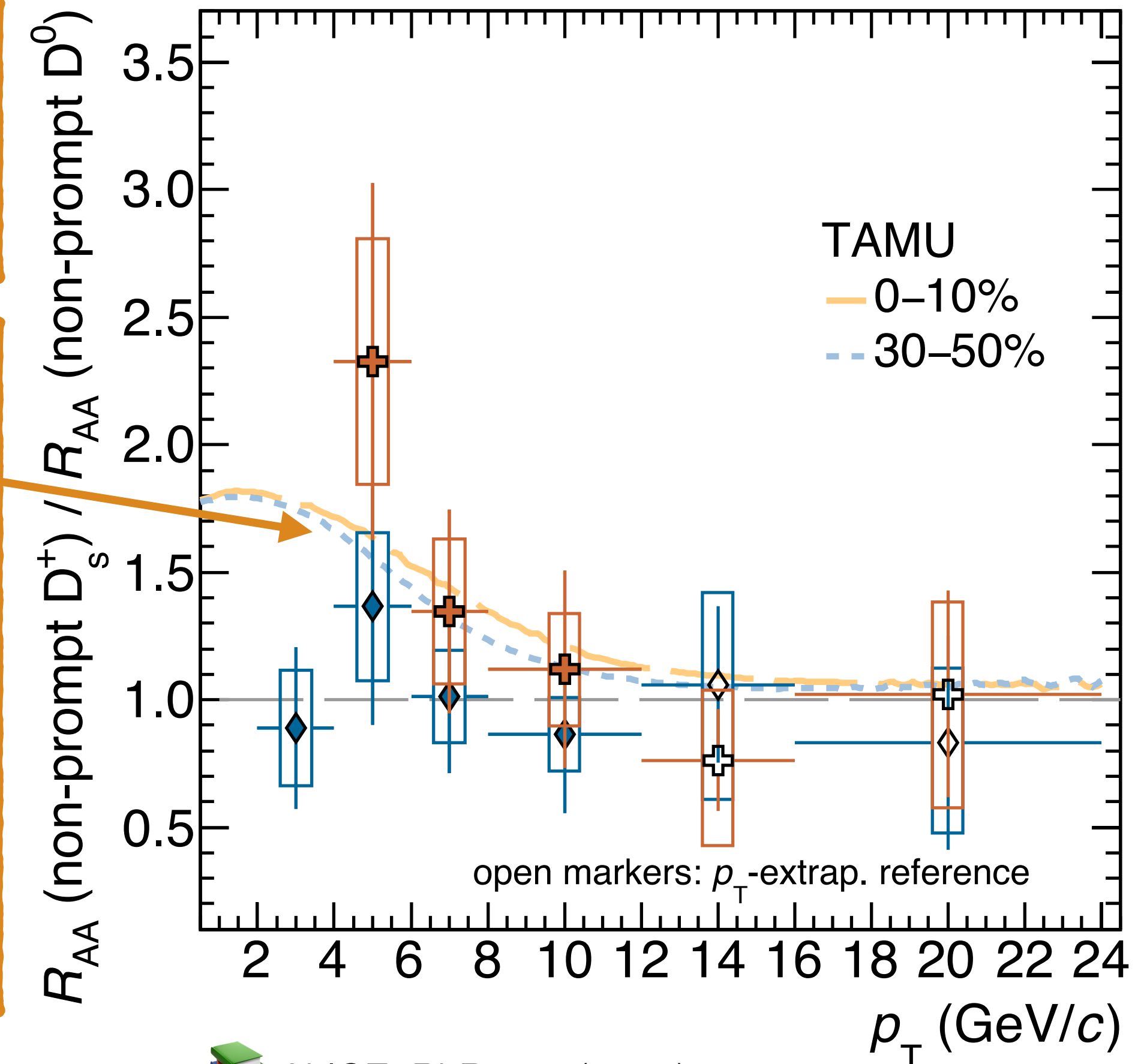


R_{AA} at **low p_T** : B_s and B^+ tend to lie above lighter particles

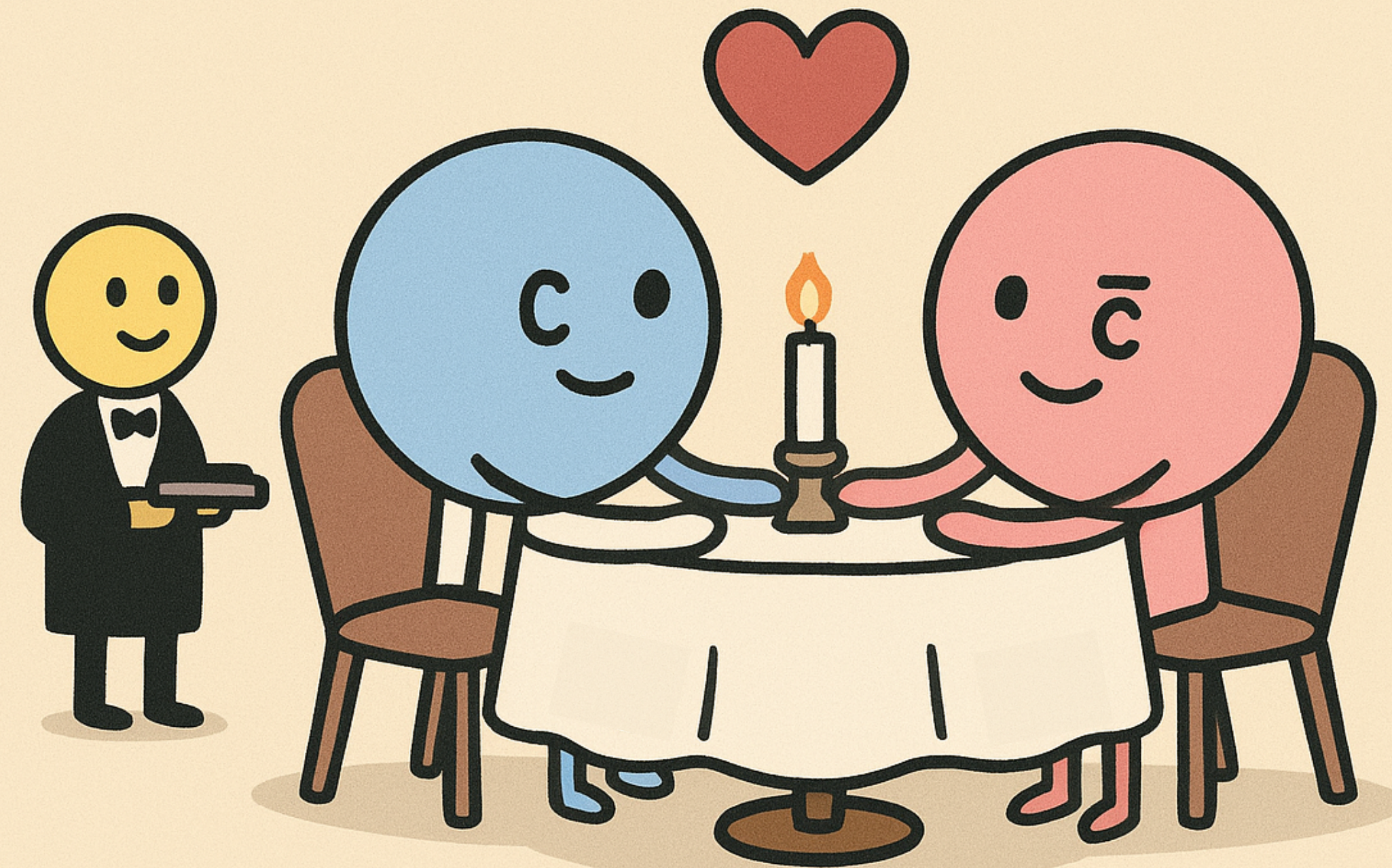
Hint of R_{AA} of **non-prompt D_s** larger than non-prompt D^0

➔ **Non-prompt D_s** origin:

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

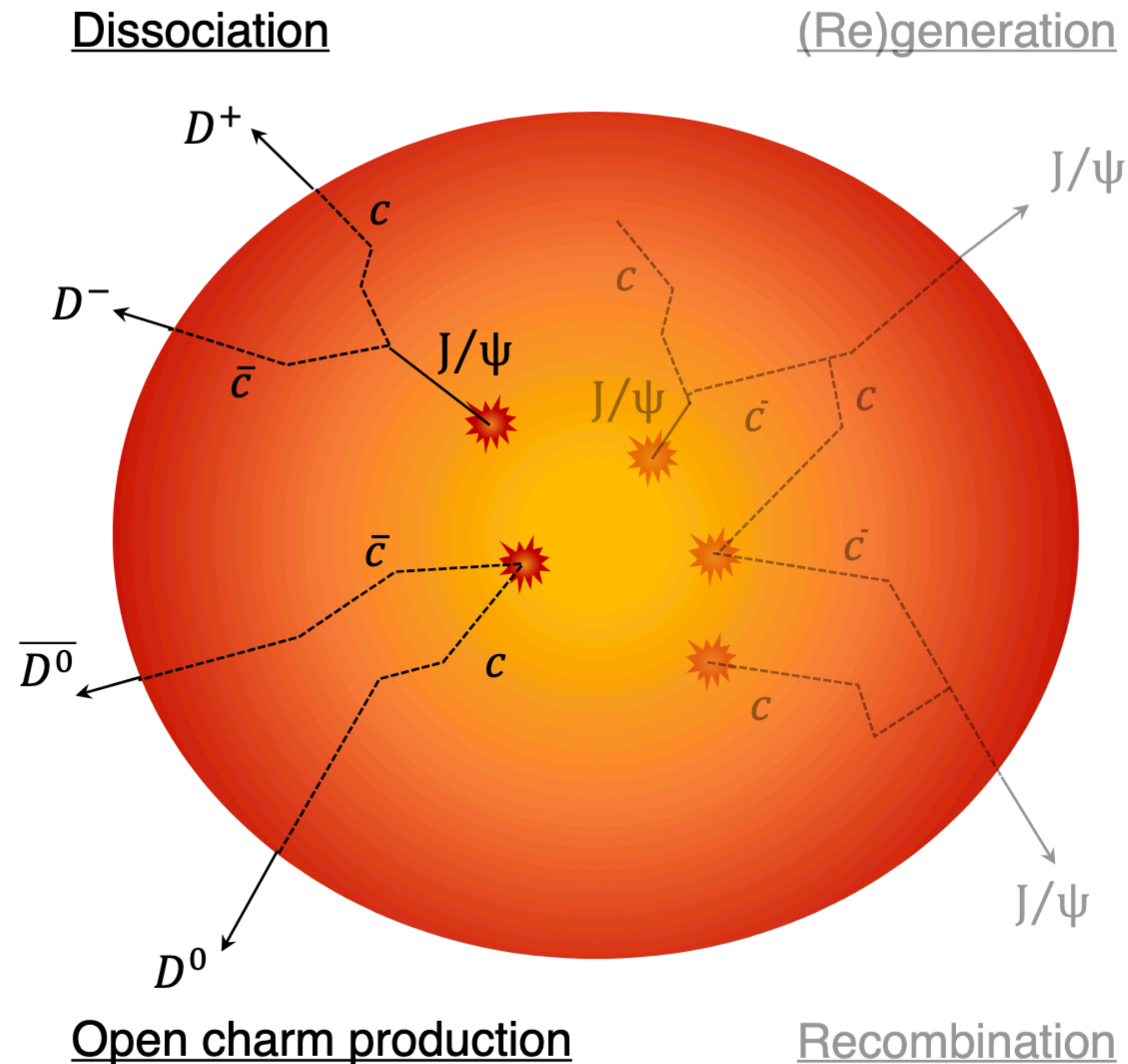


A BOUND STATE RELATIONSHIP quarkonium



- ▶ **Quarkonia** ($c\bar{c}$ and $b\bar{b}$): a meson whose constituents are a **heavy quark** and its own **antiquark**
 - ➔ cross section can be computed within the **factorization approach** (NRQCD)  Bodwin et al., PRD 51, 1125 (1995)

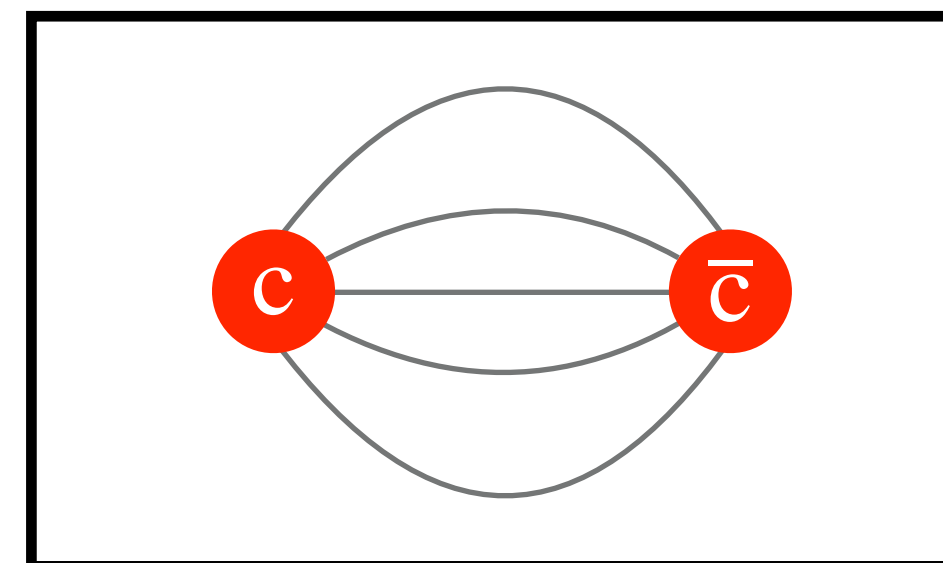
- **Quarkonia** ($c\bar{c}$ and $b\bar{b}$): a meson whose constituents are a **heavy quark** and its own **antiquark**
- ➔ cross section can be computed within the **factorization approach** (NRQCD)  Bodwin et al., PRD 51, 1125 (1995)



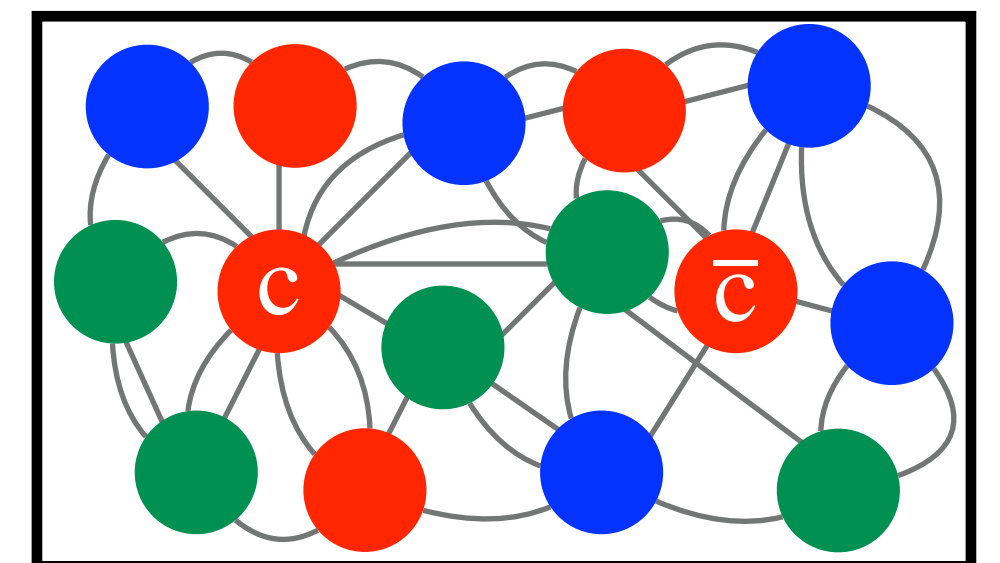
What happens to quarkonia in QGP?

- **Quarkonium suppression**
- ➔ In a strongly interacting medium quarkonium states can be **dissociated** by a **color screening mechanism**

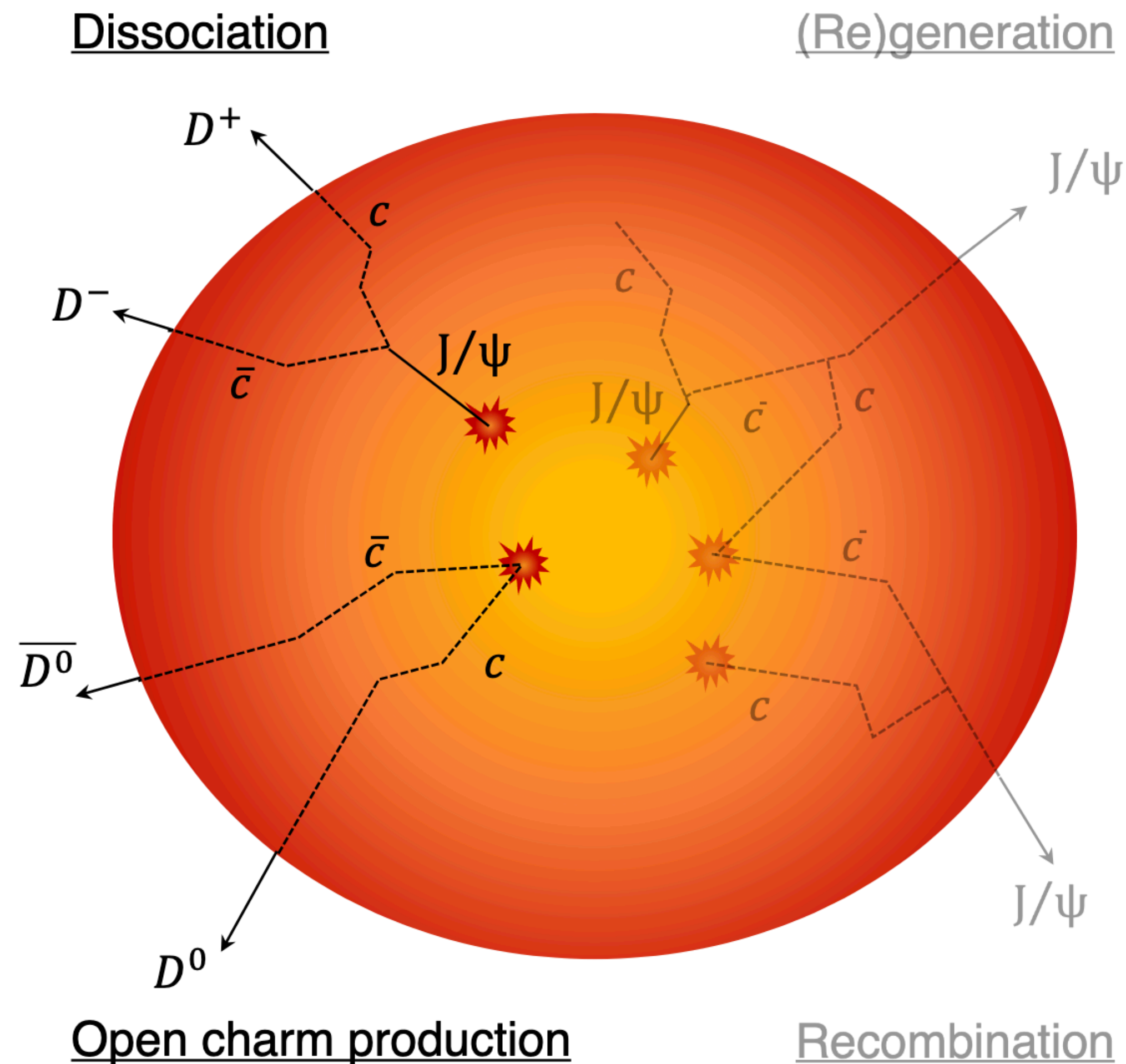
In vacuum



In QGP



- **Quarkonia** ($c\bar{c}$ and $b\bar{b}$): a meson whose constituents are a **heavy quark** and its own **antiquark**
- ➔ cross section can be computed within the **factorization approach** (NRQCD)  Bodwin et al., PRD 51, 1125 (1995)



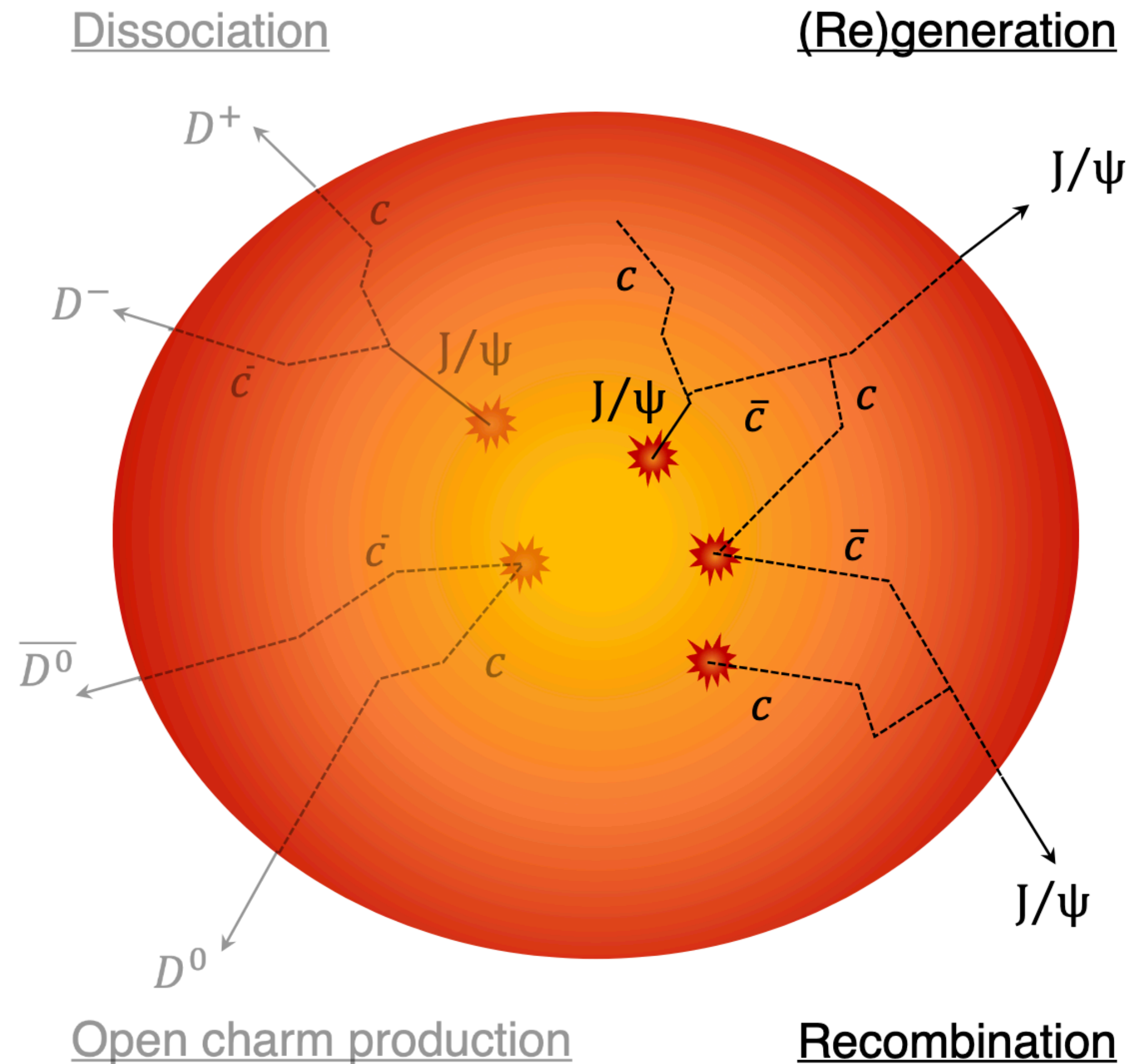
What happens to quarkonia in QGP?

- **Quarkonium suppression**
- ➔ In a strongly interacting medium quarkonium states can be **dissociated** by a **color screening mechanism**
- ➔ **Sequential melting** of the quarkonium states according to the binding energy

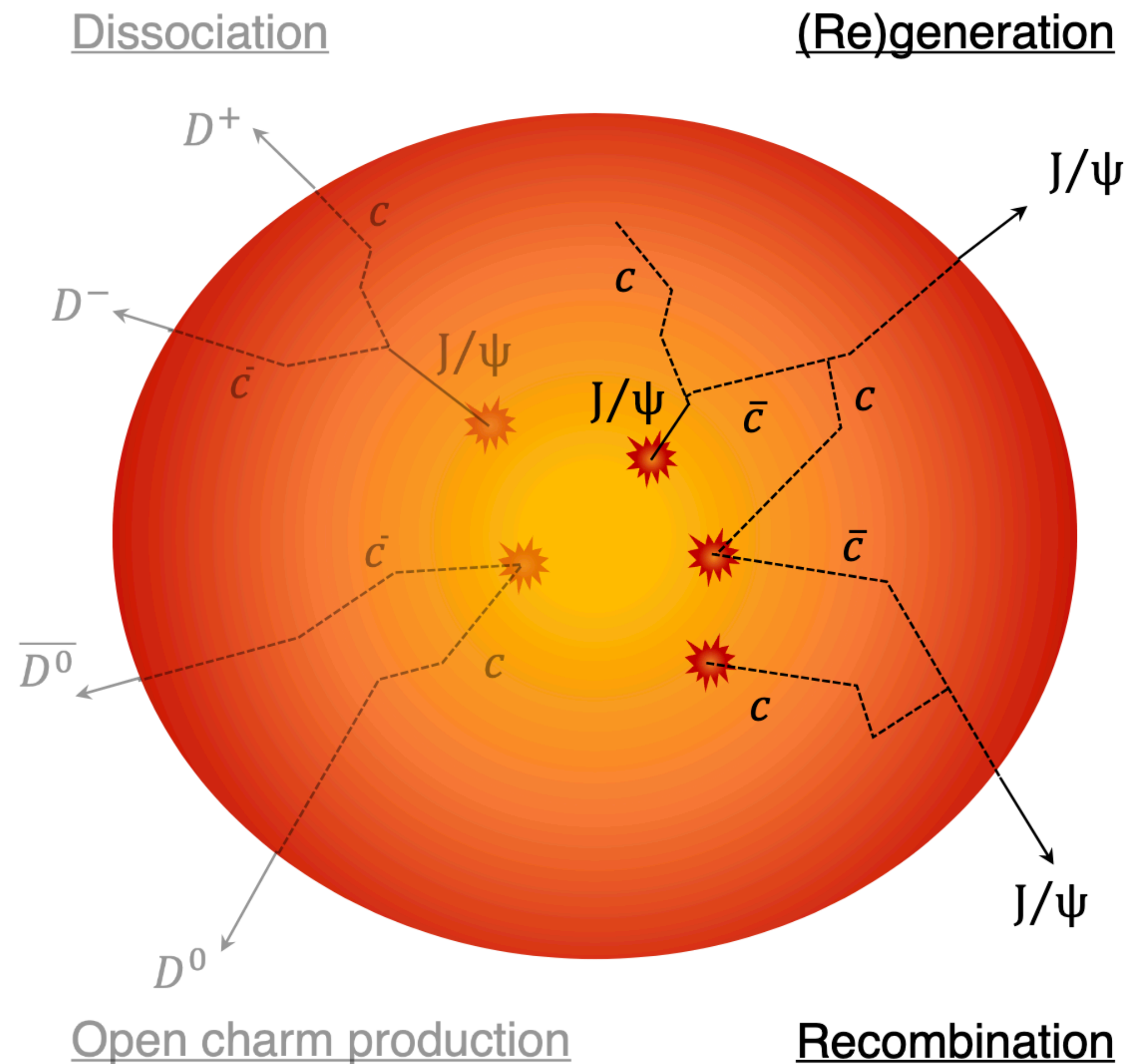
	charmonia			bottomonia		
	J/ψ	χ _c	ψ(2S)	Y(1S)	Y(2S)	Y(3S)
Mass (GeV)	3.10	3.53	3.68	9.46	10.02	10.36
E _B (GeV)	0.64	0.20	0.05	1.10	0.54	0.20

- ▶ **Quarkonia** ($c\bar{c}$ and $b\bar{b}$): a meson whose constituents are a **heavy quark** and its own **antiquark**
 - ➔ cross section can be computed within the **factorization approach** (NRQCD)  Bodwin et al., PRD 51, 1125 (1995)

What happens to quarkonia in QGP?



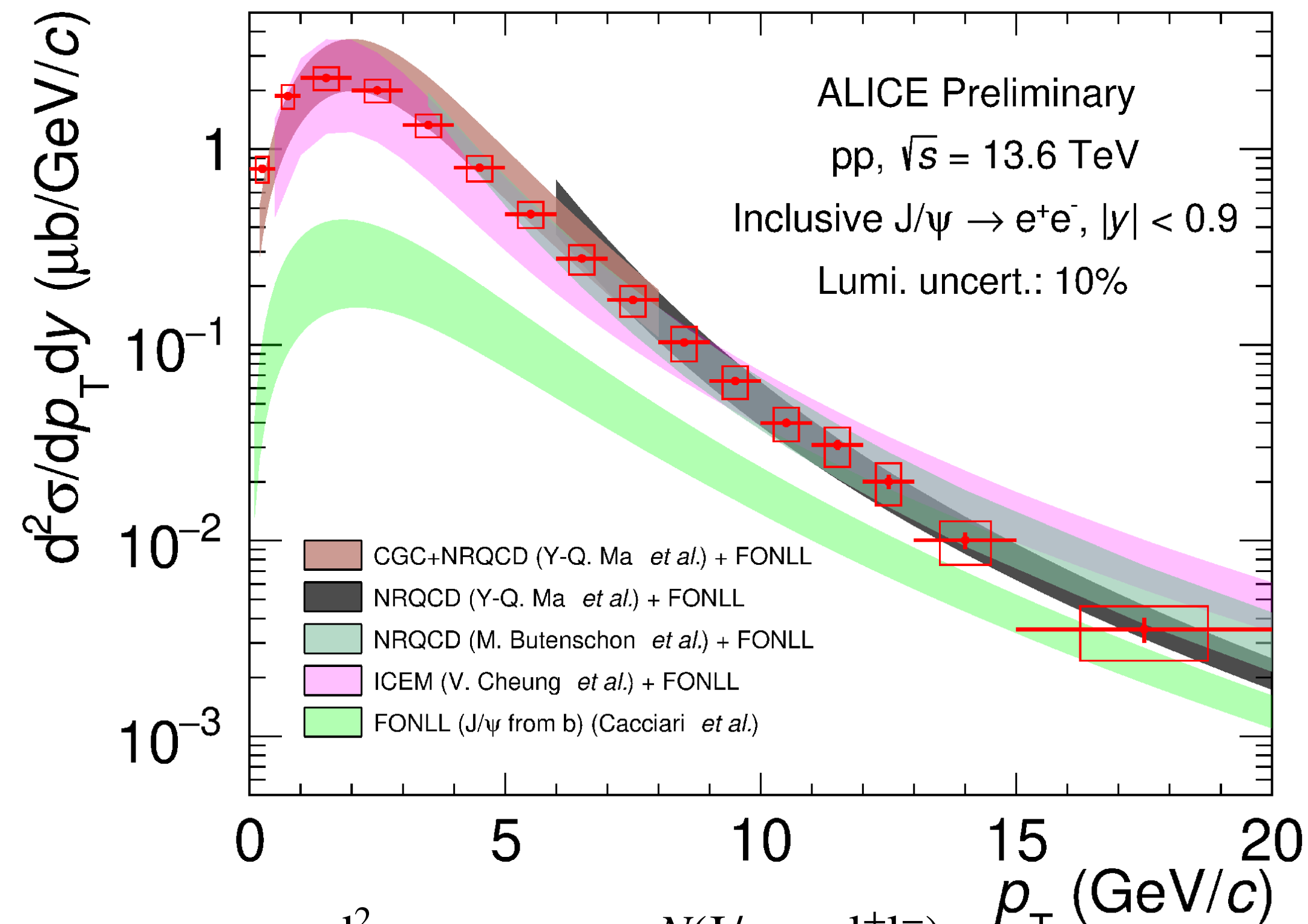
- ▶ **Quarkonia** ($c\bar{c}$ and $b\bar{b}$): a meson whose constituents are a **heavy quark** and its own **antiquark**
- ➔ cross section can be computed within the **factorization approach** (NRQCD)  Bodwin et al., PRD 51, 1125 (1995)



What happens to quarkonia in QGP?

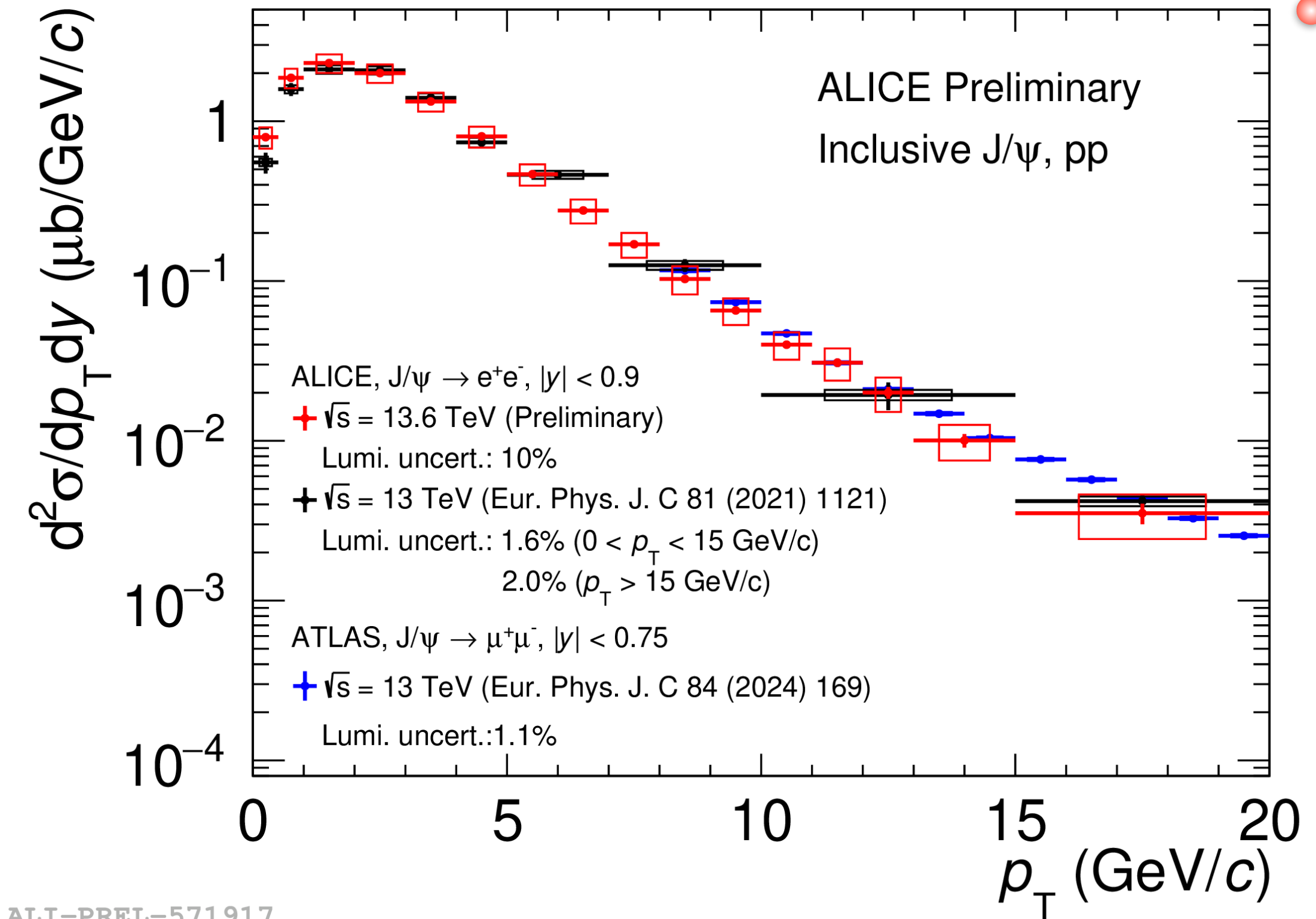
- ▶ **Quarkonium (re)generation/recombination**
- ➔ The abundance of heavy quarks produced in heavy-ion collisions at LHC energies determines the statistical **(re)combination** of uncorrelated $q\bar{q}$
- ➔ The larger low- p_T J/ψ production at LHC w.r.t. RHIC is interpreted as a consequence of **(re)generation**

	RHIC $\sqrt{s_{NN}} = 200 \text{ GeV}$	LHC $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
$N_{c\bar{c}}/\text{event}$	10	115
$N_{b\bar{b}}/\text{event}$	0.05	3



ALI-PREL-571318

$$\frac{d^2\sigma}{dp_T dy} = \frac{N(J/\psi \rightarrow l^+l^-)}{(A \cdot \epsilon) \cdot BR_{J/\psi \rightarrow l^+l^-} \cdot dp_T dy \cdot L_{\text{int}}}$$

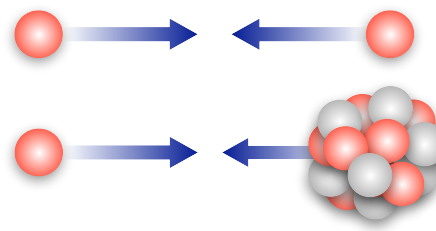
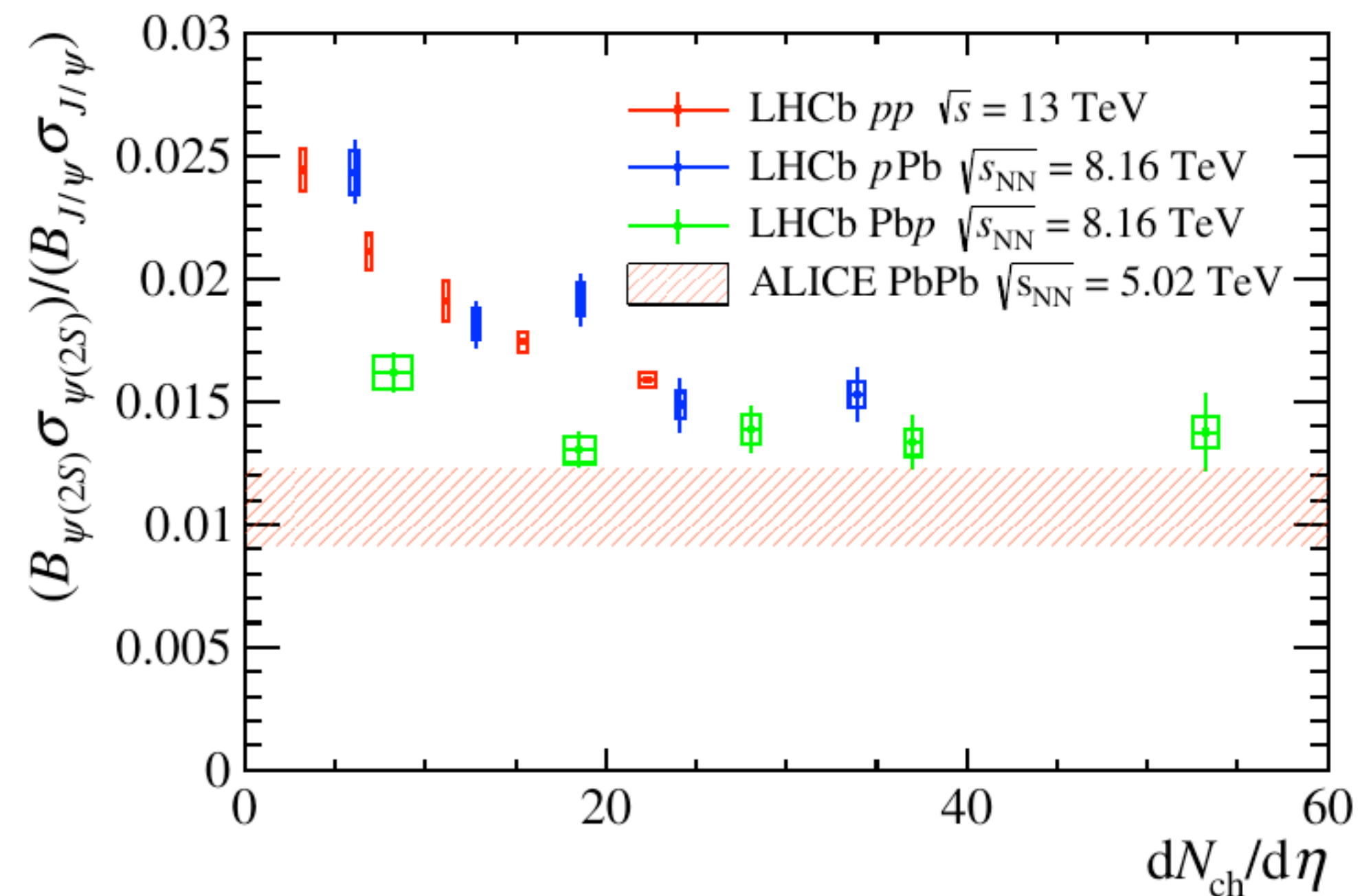
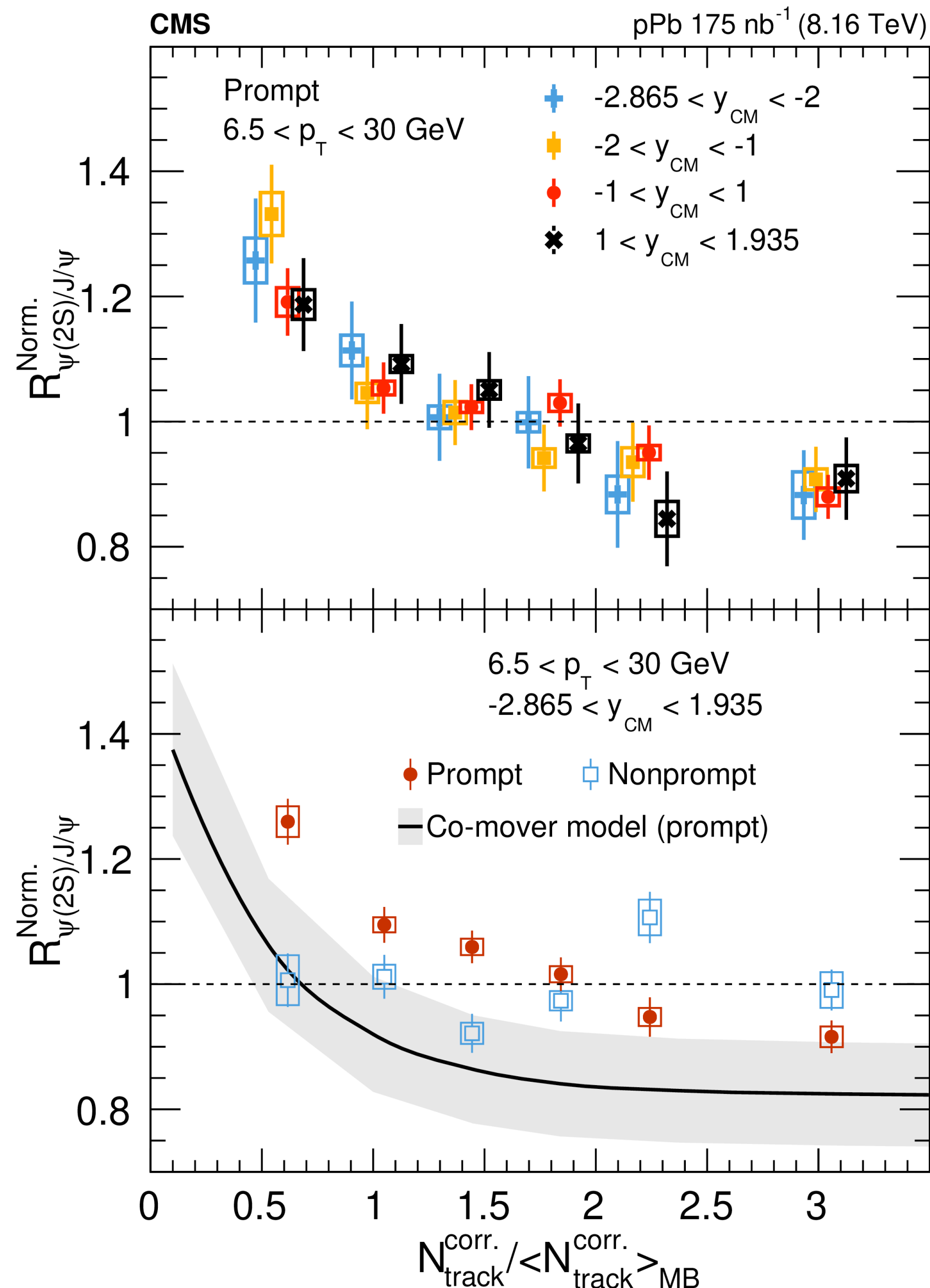


ALI-PREL-571917

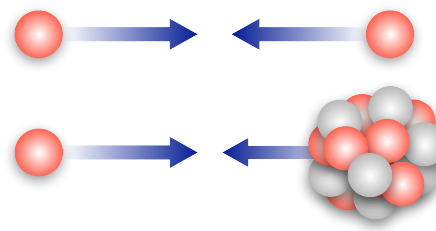
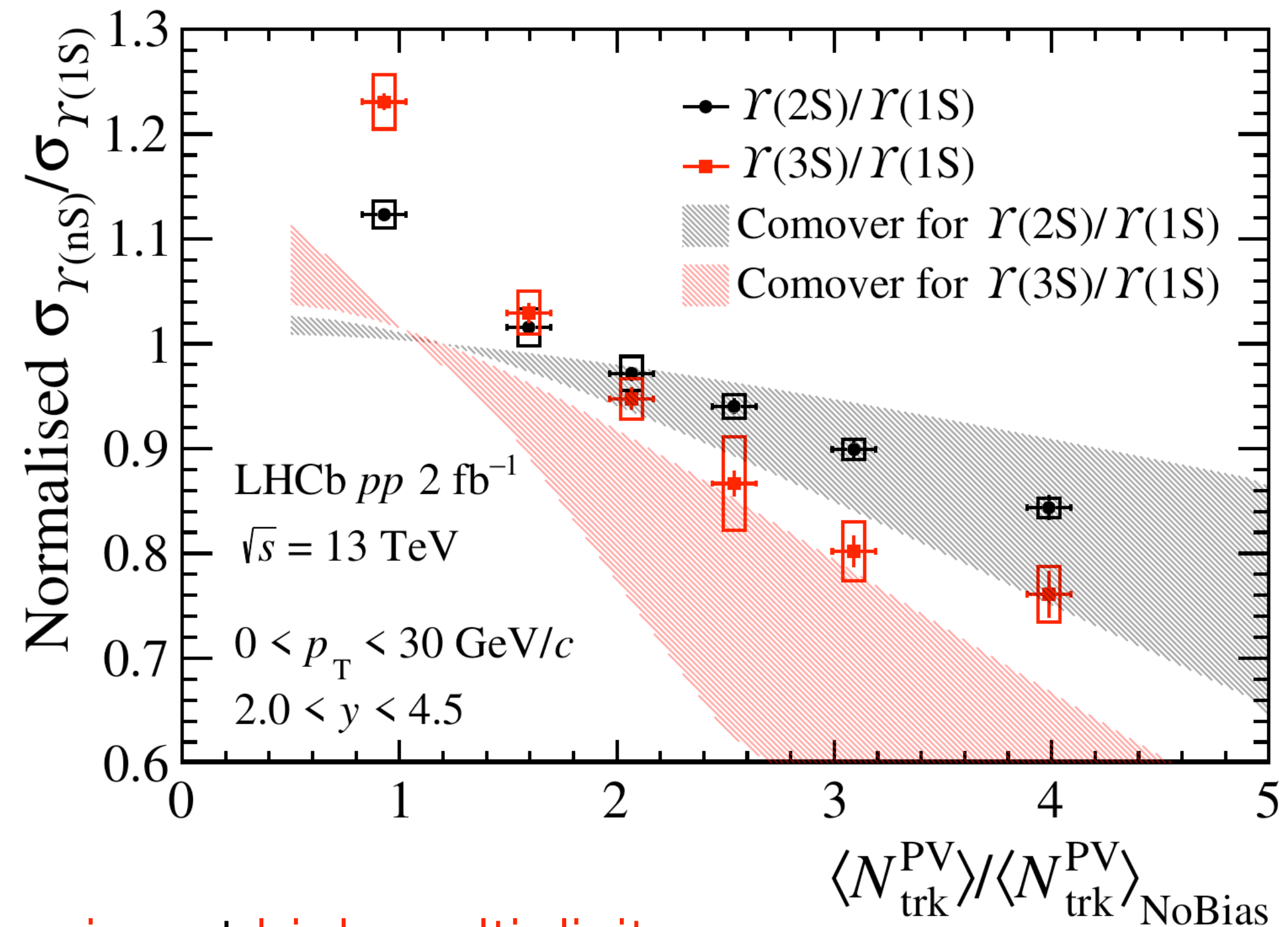
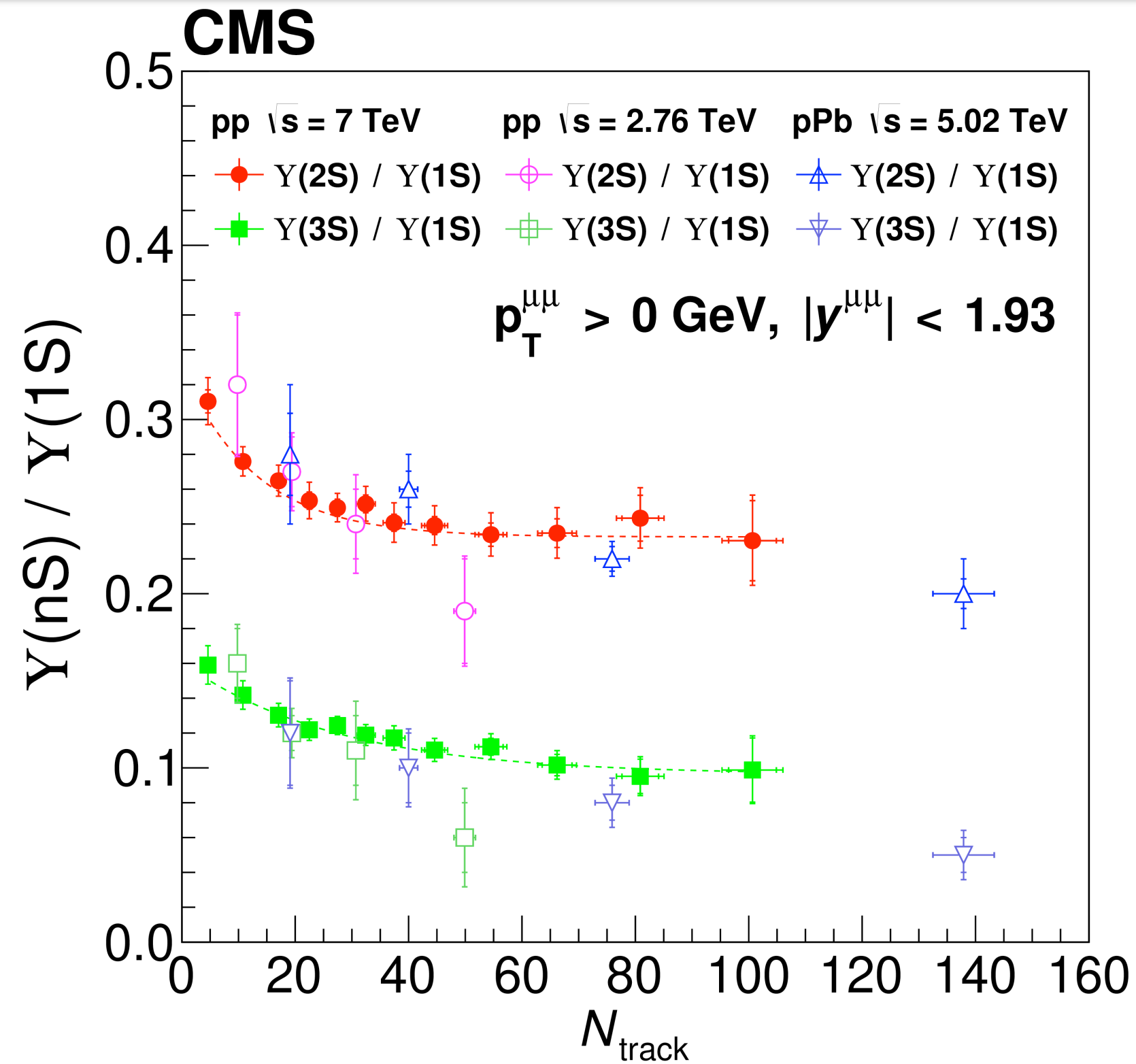
► J/ψ measurements from LHC Run 3

➡ good agreement with ICEM and NRQCD models → mainly prompt J/ψ (non-prompt at higher p_T)

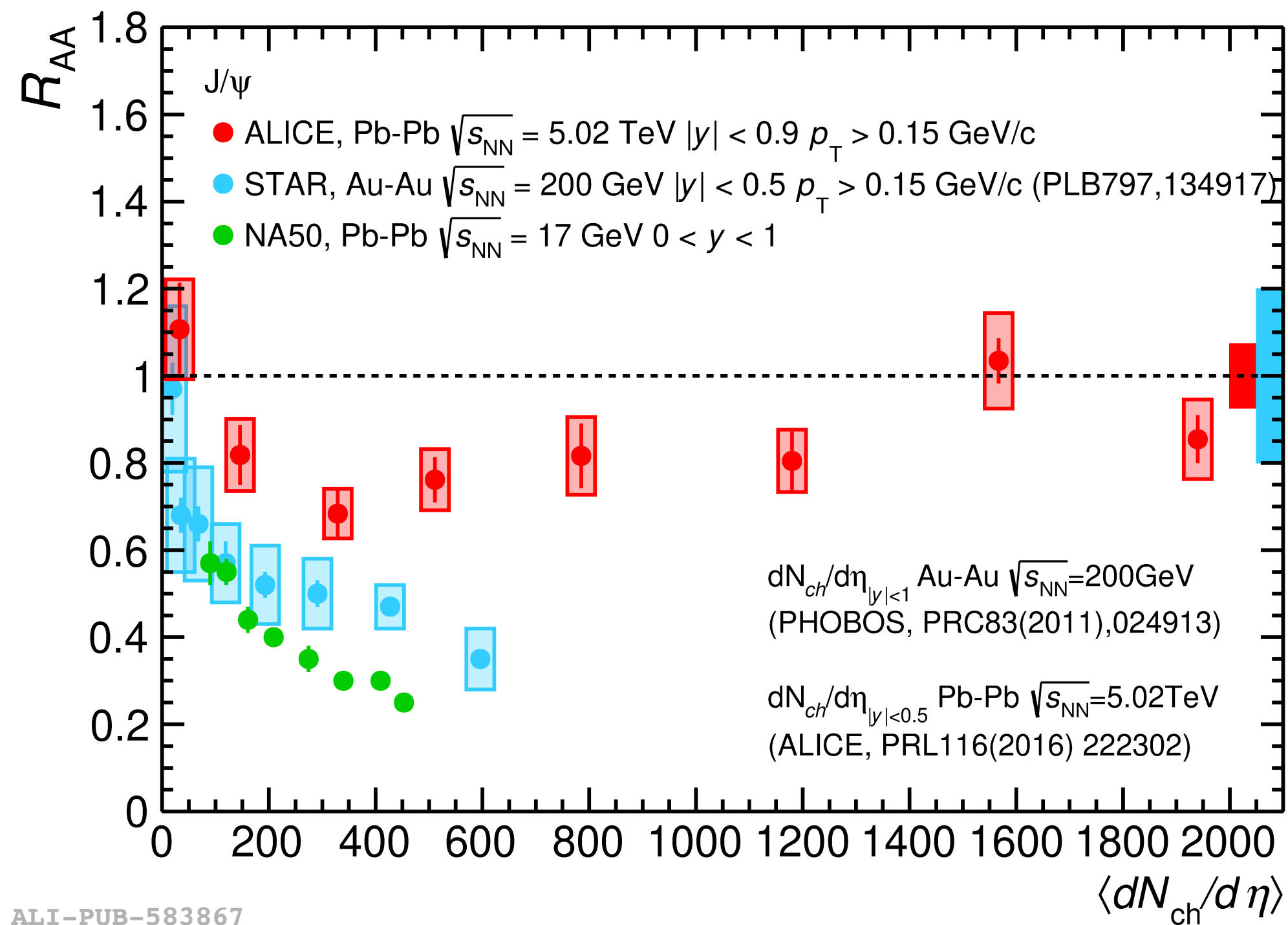
► **Good agreement** among different experiments and energies e^+e^- only at high p_T



- $\psi(2S)$ suppression effects observed at high multiplicity
- effect qualitatively described by destruction via ‘rescattering’: comover model
- For a quantitative physics interpretation
 - ➔ experiments: absolute multiplicity corrected on particle level
 - ➔ model: full event modelling

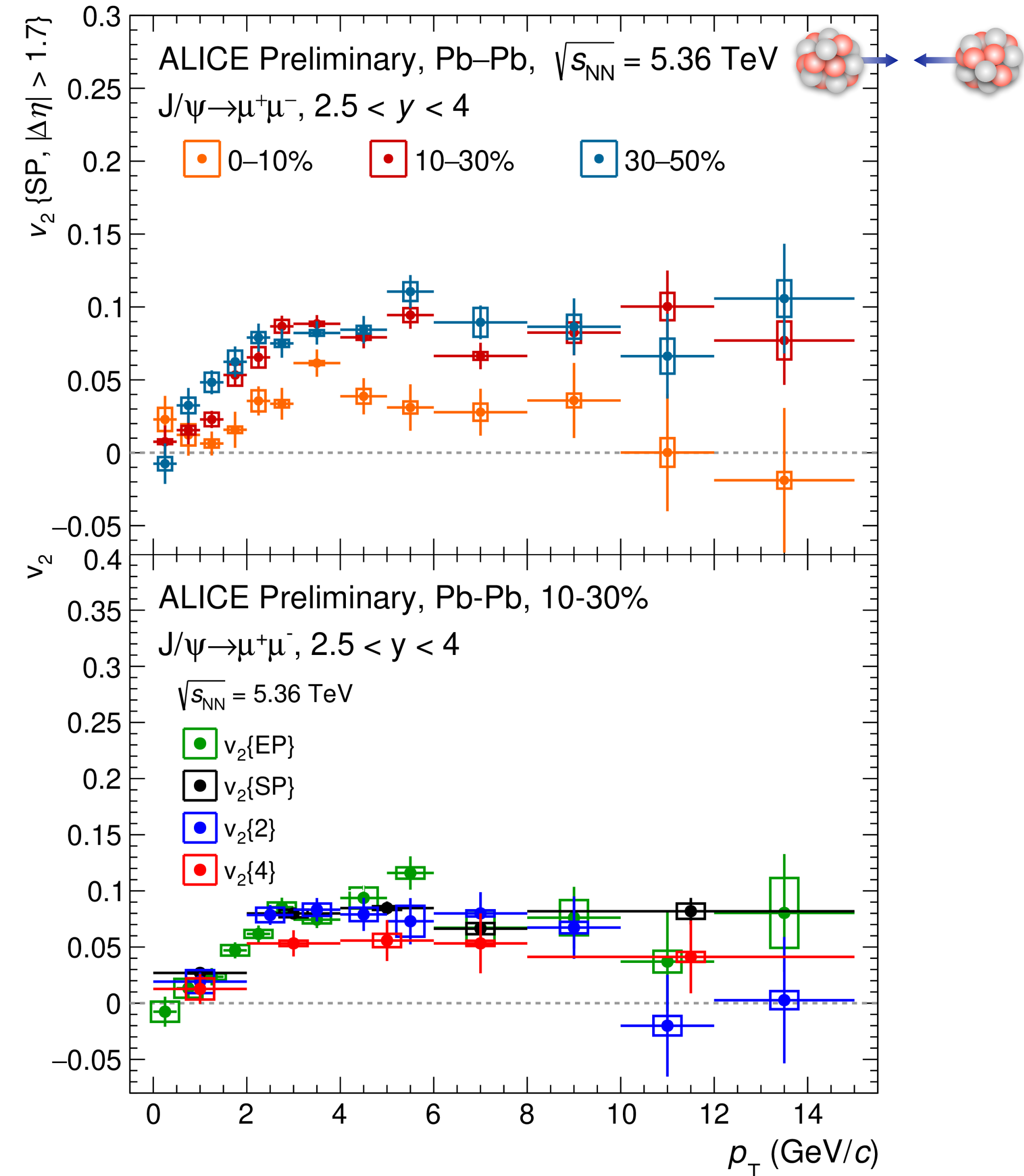


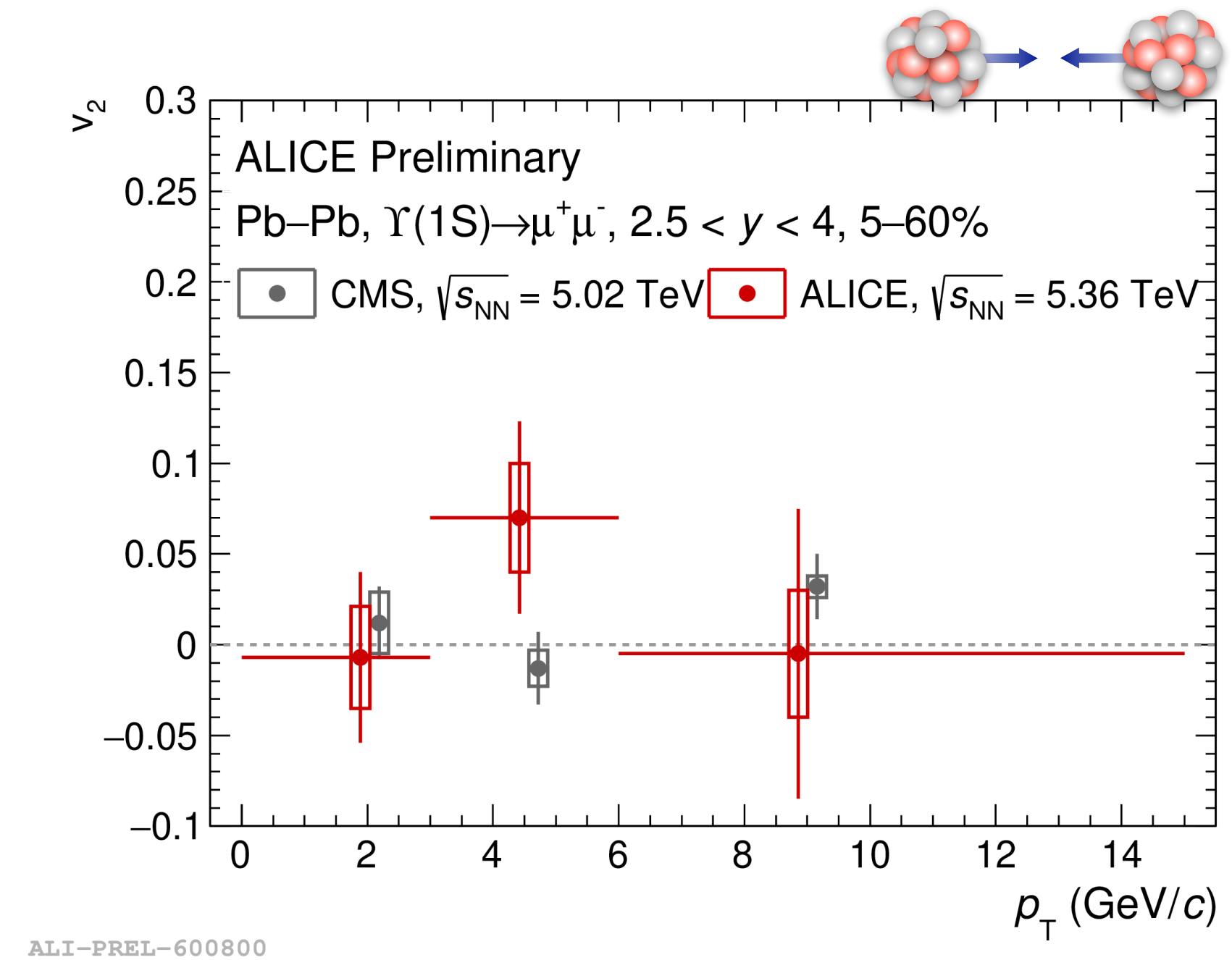
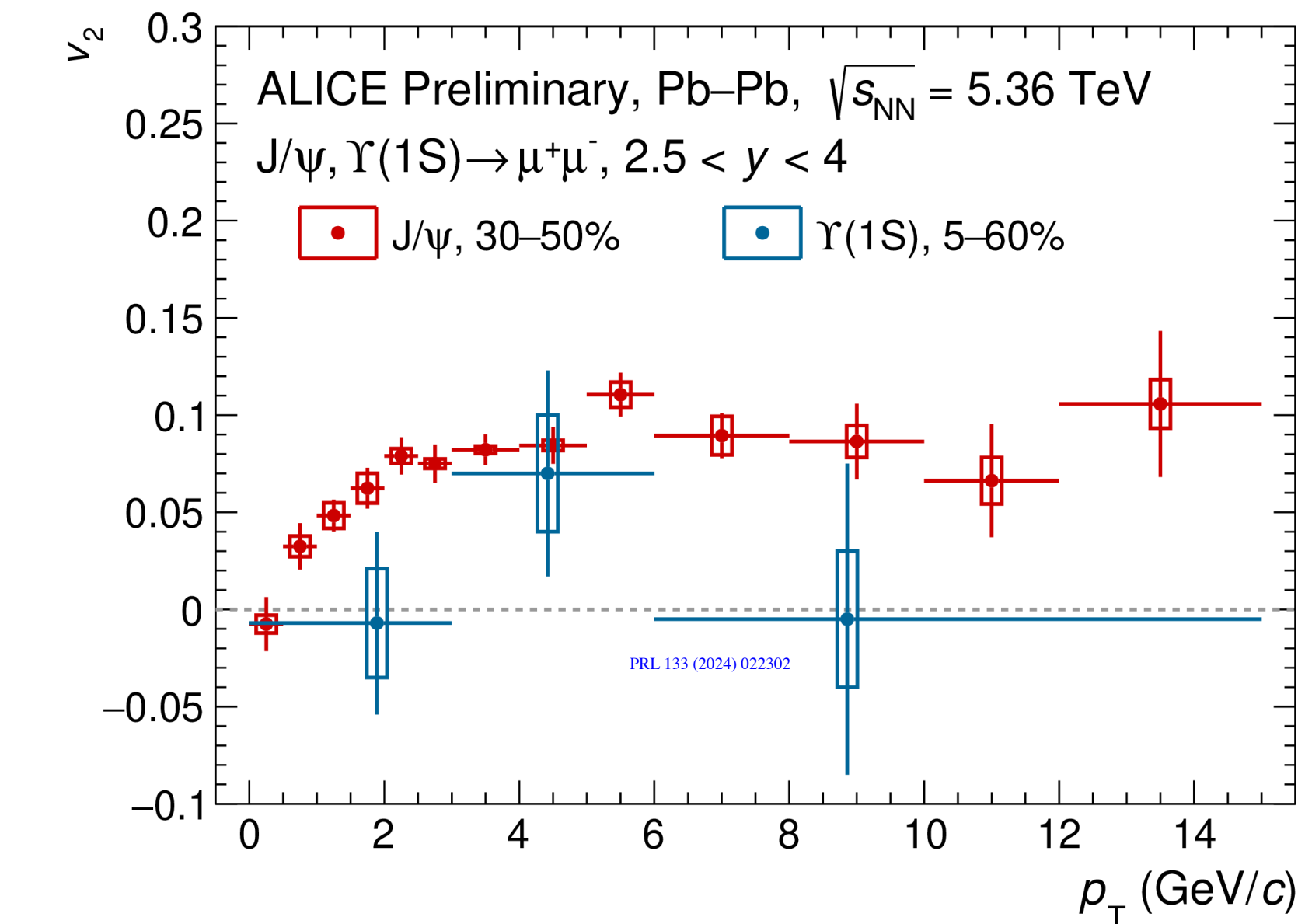
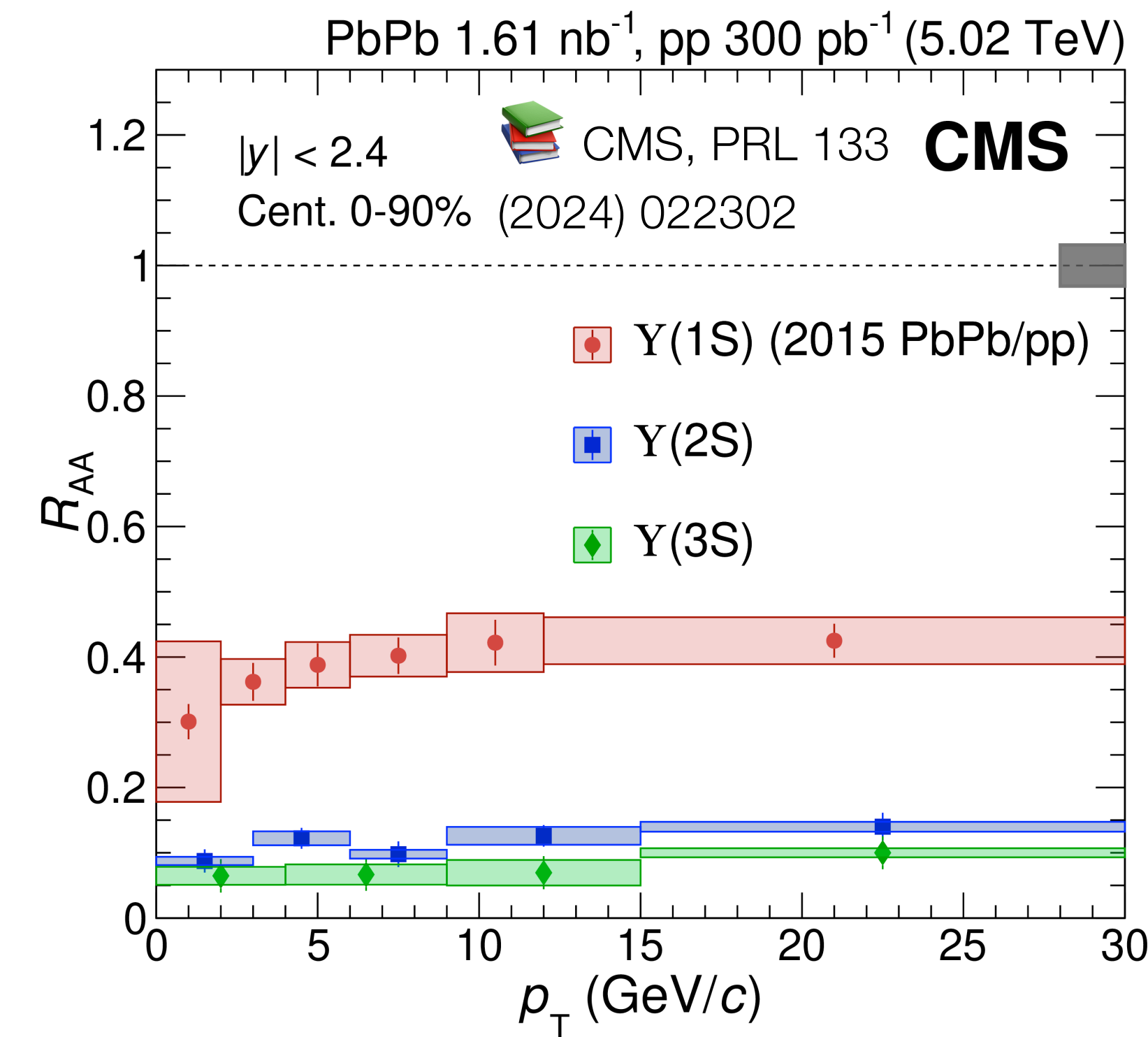
- ▶ relative $r(2S)$ and $r(3S)$ to $r(1S)$ suppression at high multiplicity
- ▶ qualitatively described by comover model
- ▶ For a quantitative physics interpretation
 - ➔ experiments: absolute multiplicity corrected on particle level
 - ➔ model: full event modelling



ALICE, EPJC
84 (2024) 813

- Strong J/ψ flow signal at LHC in line with regeneration expectations
- ➔ regeneration at play observed in Run 2 R_{AA} at the LHC
- New flow observables for charmonium
- ➔ push model implementation details → discrimination between transport and SHMc



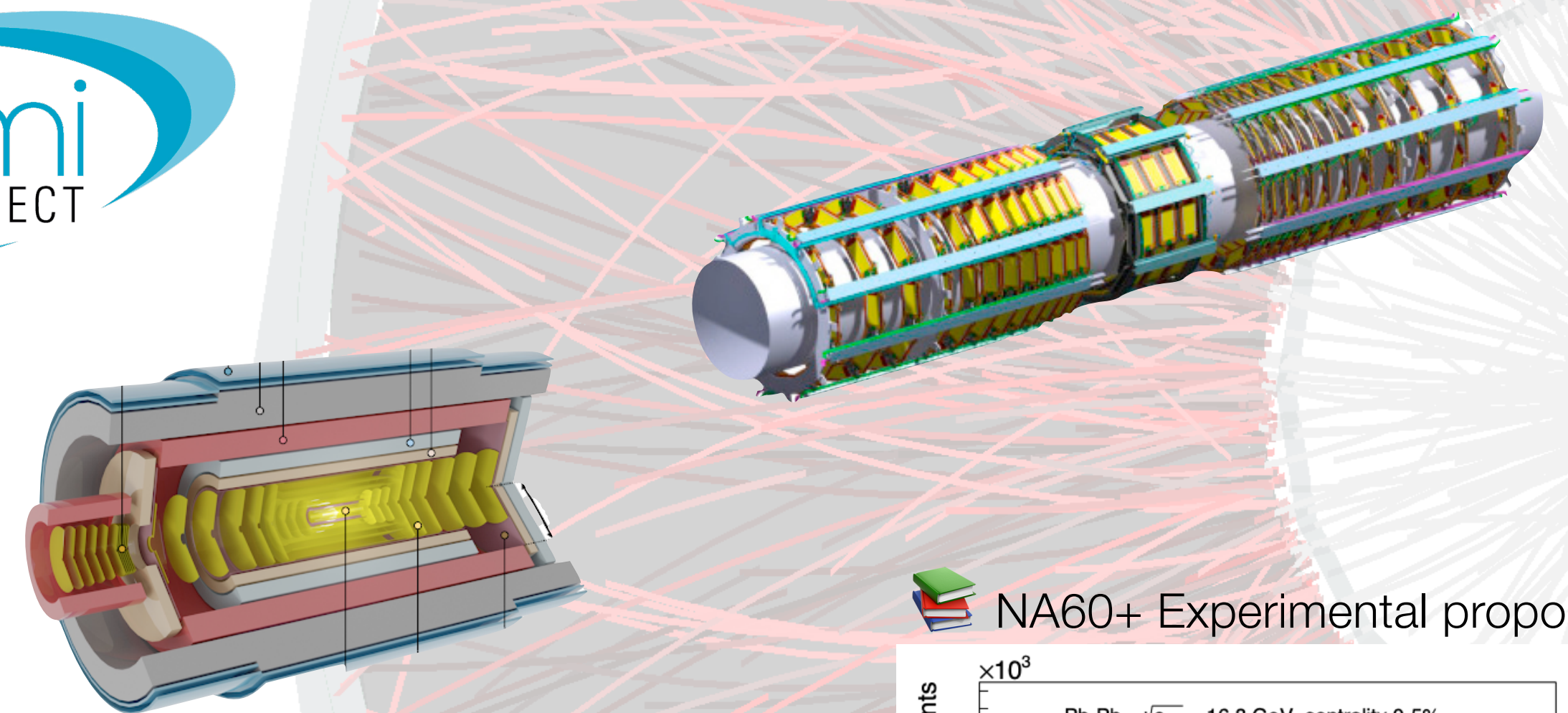


- **Suppression hierarchy between 3 vector states established**
 - ➔ coherent statement based on ATLAS ([PRC 107 \(2023\) 054912](#)), ALICE (PLB 790 (2019) 89) and CMS results
- Run 3 flow measurements confirm Run 2 outcome
 - ➔ $\Upsilon(1S)$ v_2 lower than J/ψ v_2 → b-quark less thermalised? different role of recombination to bottomonium?

At the LHC

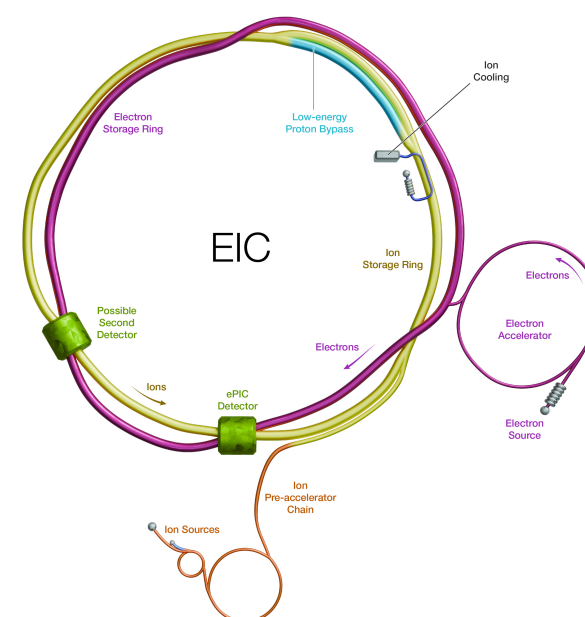


- In the next (short/long) future
 - ➔ High Luminosity LHC installation
 - ➔ ATLAS and CMS Phase II,
 - ➔ ALICE (FoCal, ITS3), LHCb Phase I-II, ALICE 3

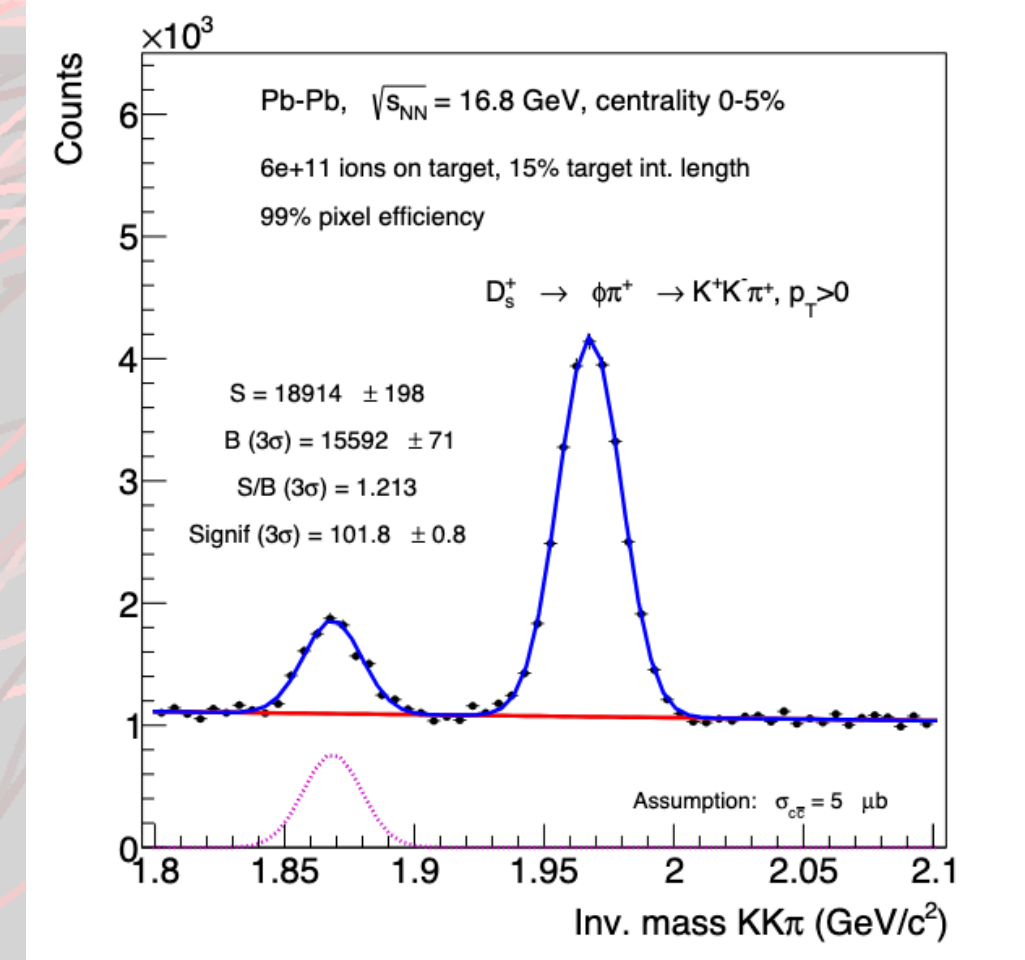


Other facilities and accelerators complex

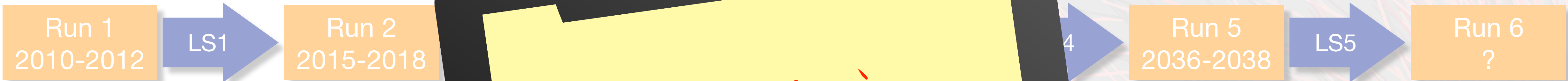
- Many other projects exploring QCD phase diagram:
 - ➔ NA61/SHINE, NA60+ at SPS
 - ➔ CBM at FAIR
 - ➔ Electron Ion Collider at BNL



NA60+ Experimental proposal



At the LHC

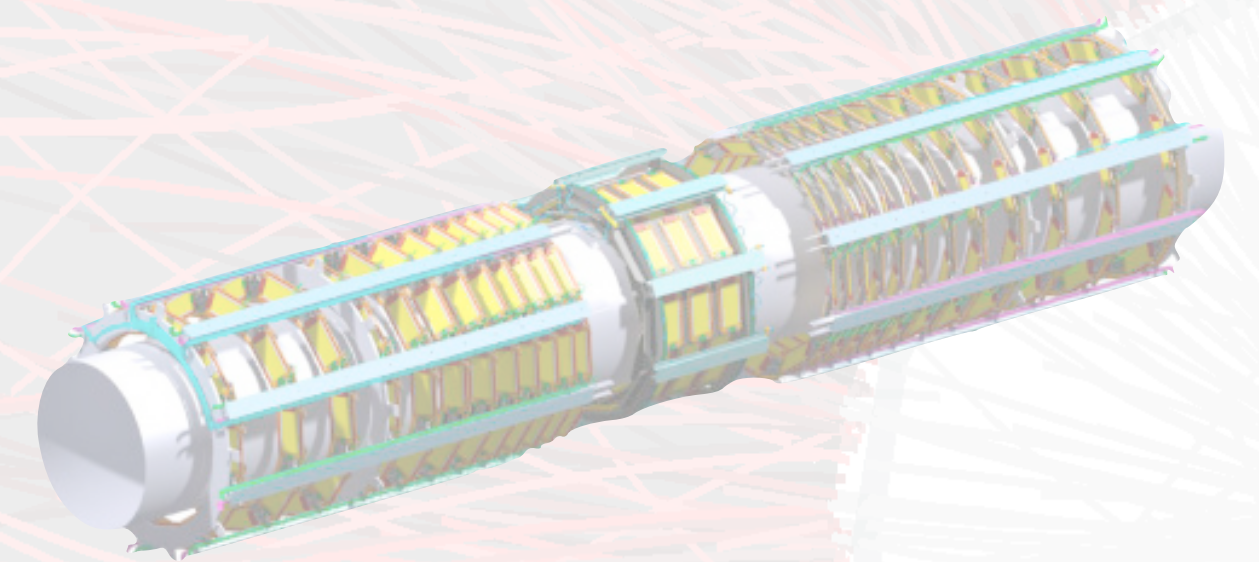


- In the next (short/long) future
 - ➔ High Luminosity LHC installa
 - ➔ ATLAS and CMS Phase II,
 - ➔ ALICE (FoCal, ITS3), LHCb Ph

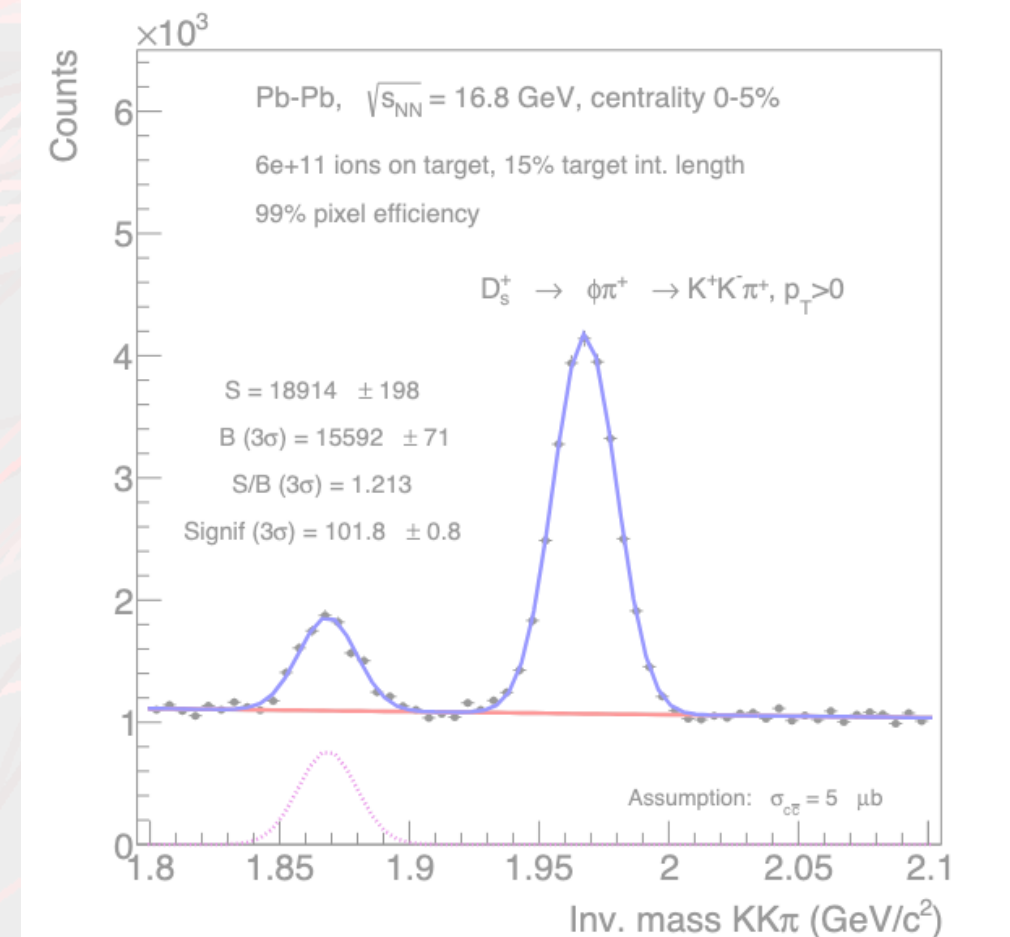
Other facilities and accelerators c

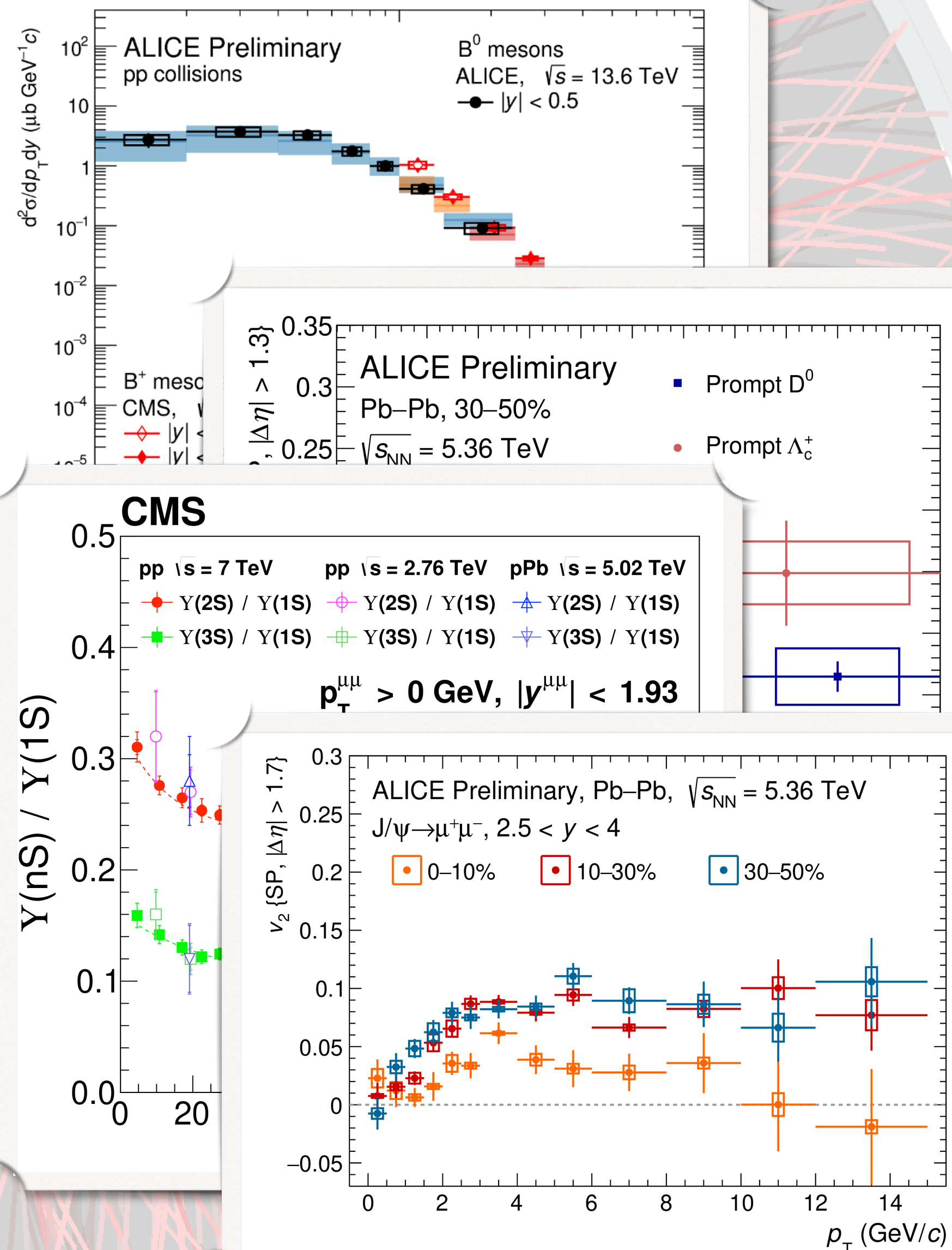
- Many other projects exploring Q
 - ➔ NA61/SHINE, NA60+ at SPS
 - ➔ CBM at FAIR
 - ➔ Electron Ion Collider at BNL

- Heavy-quark menu*
- ✓ complete picture of heavy-quark hadronization
 - ✓ quantification of recombination's role
 - ✓ total heavy-quark cross sections
 - ✓ precise measurement of thermalisation
 - ✓ flow in small systems search
 - ✓ new inputs from exotica searches
 - ✓ multicharm investigation

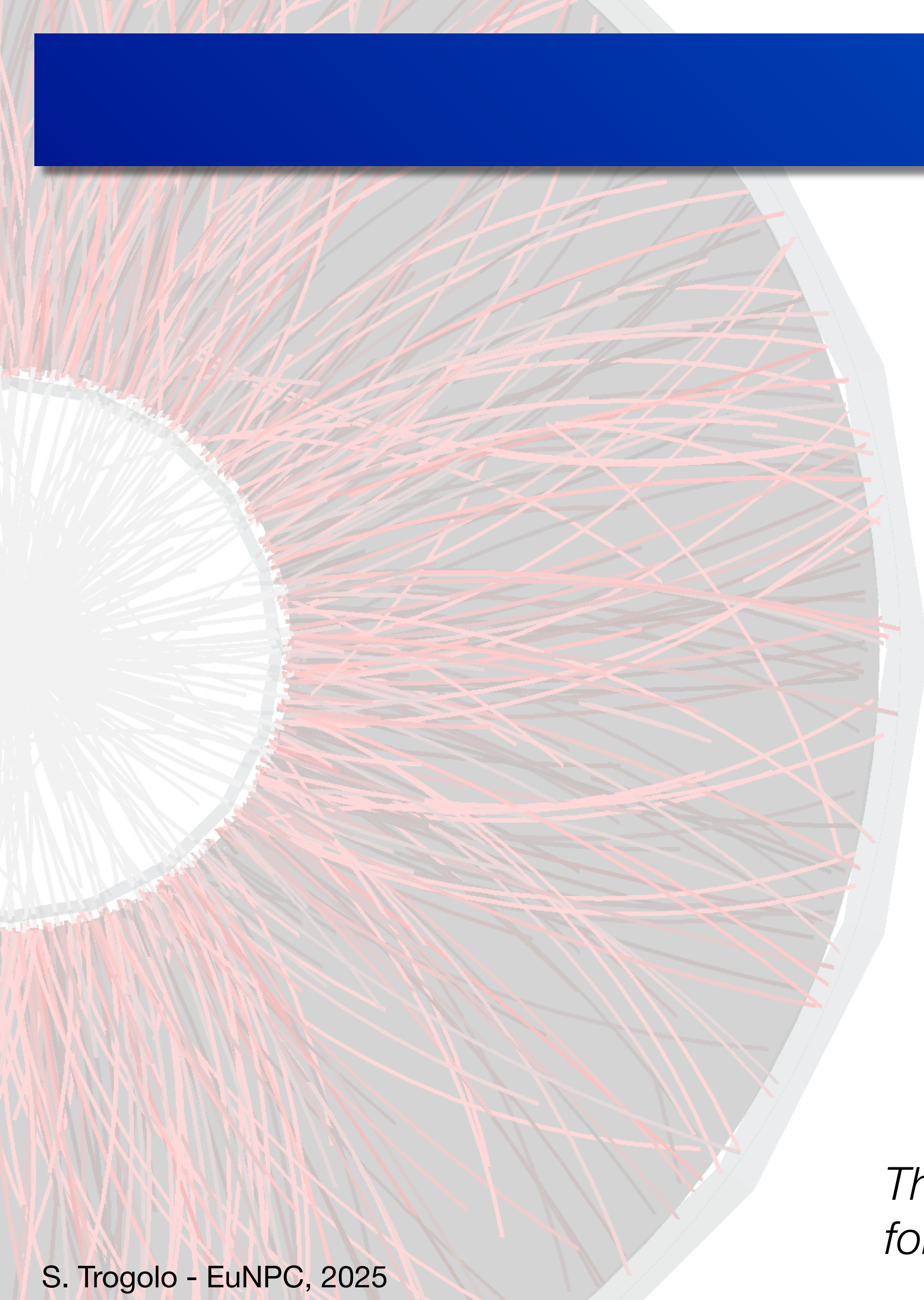


NA60+ Experimental proposal





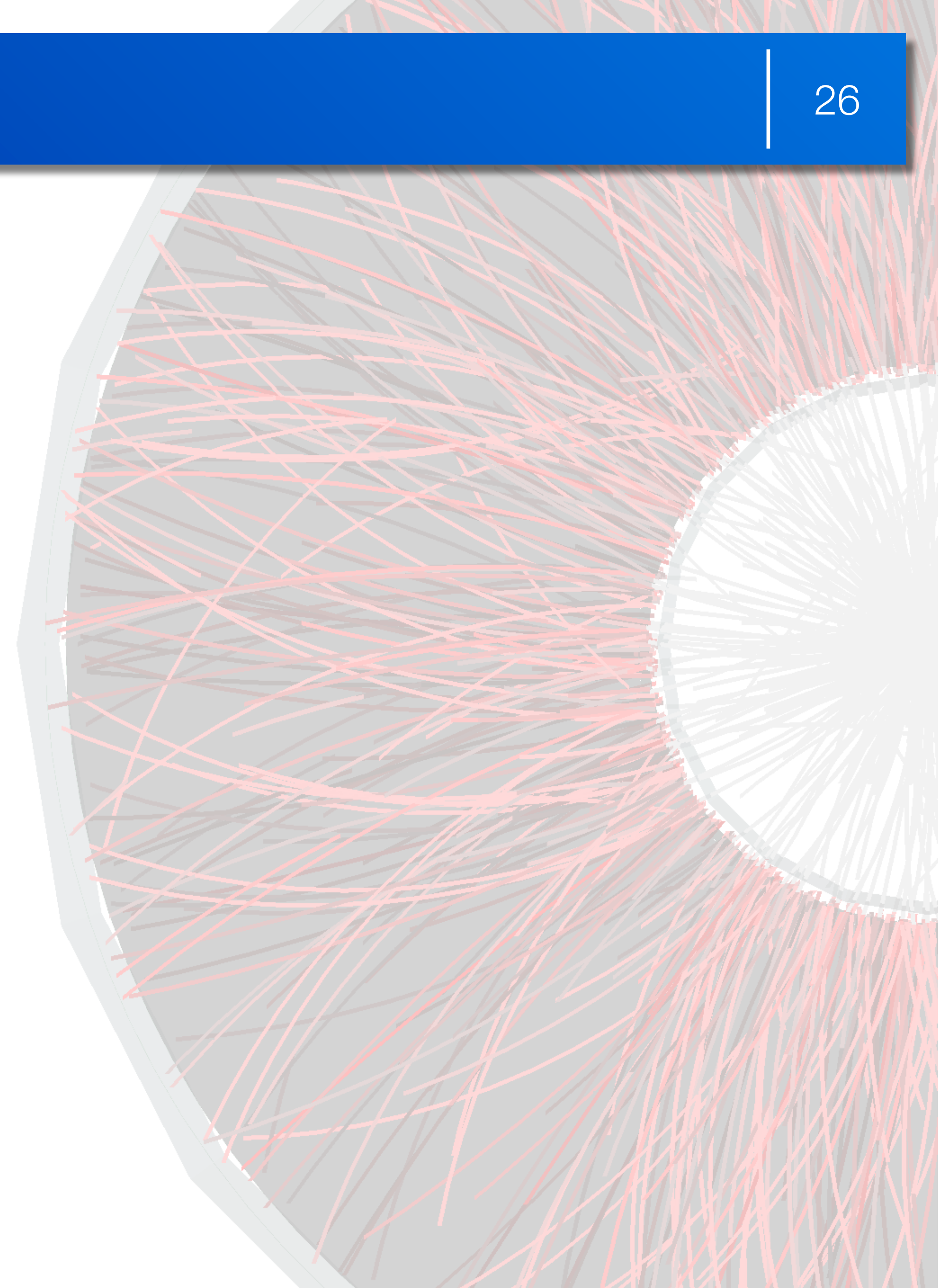
- Huge effort in the last decades to investigate the hadronization mechanisms of heavy quarks across colliding systems
 - ➔ Fragmentation functions universality violated already in pp collisions
 - ➔ pp collisions is a system dense enough to alter the hadronization
- In heavy-ion collisions:
 - ➔ Crucial 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

An abstract graphic on the left side of the slide, featuring a dense, chaotic pattern of thin, intersecting red and grey lines. The lines are concentrated in a circular area on the left, with some lines extending outwards towards the right. The overall effect is a textured, almost organic-looking pattern.

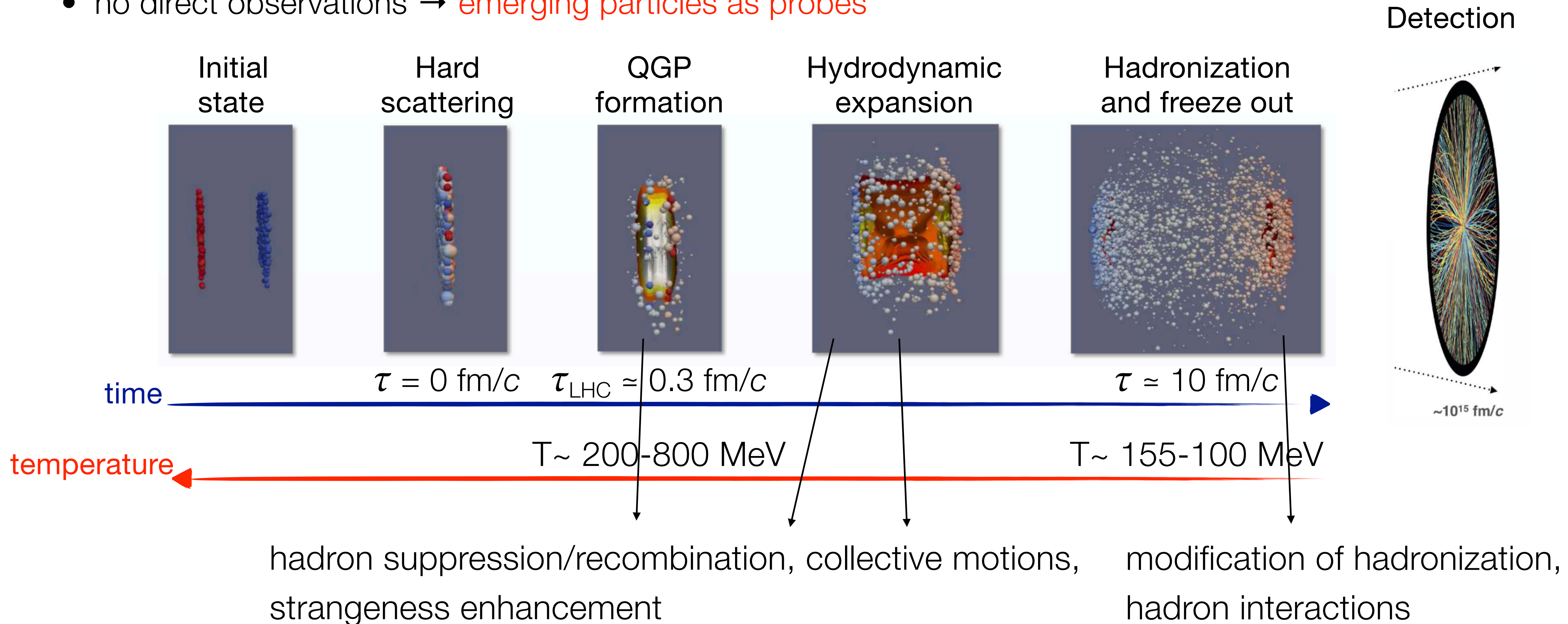
**Thank you for
your attention!**

*Thanks to L. Micheletti, X. Peng, F. Prino, A. Rossi and C. Terrevoli
for the fruitful discussion in preparing the content*

Additional material

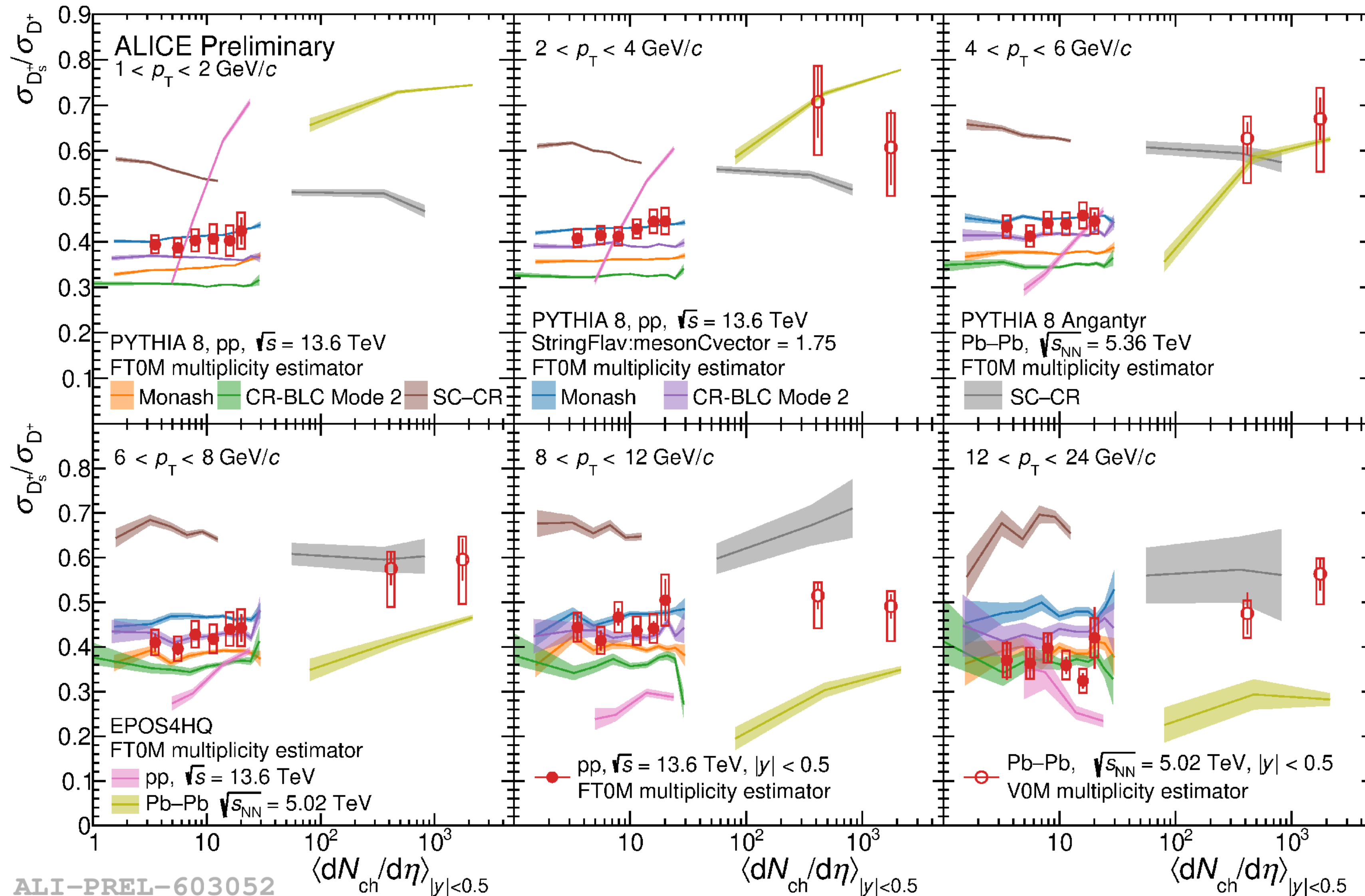


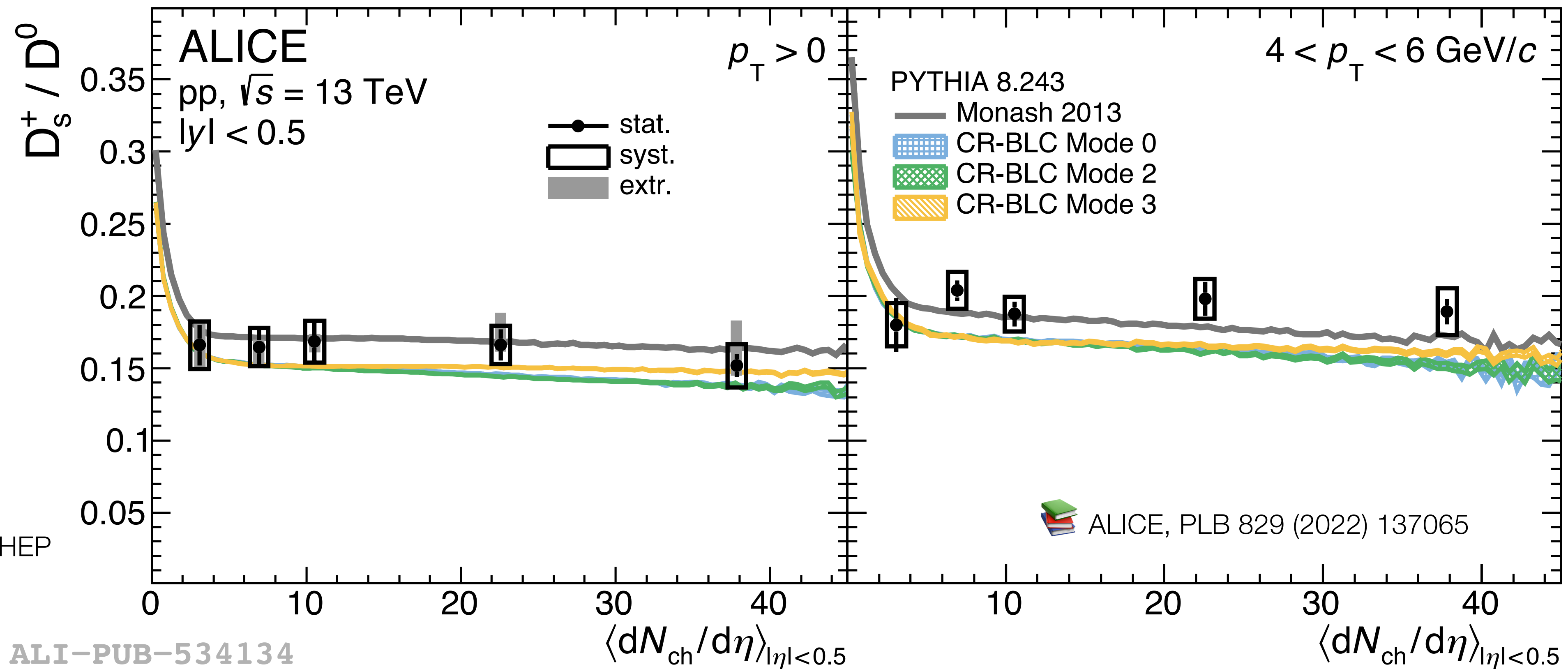
- theory approach to prod. in heavy-ion
- brief life of the QGP
 - no direct observations → **emerging particles as probes**



Charm meson production vs. multiplicity

28



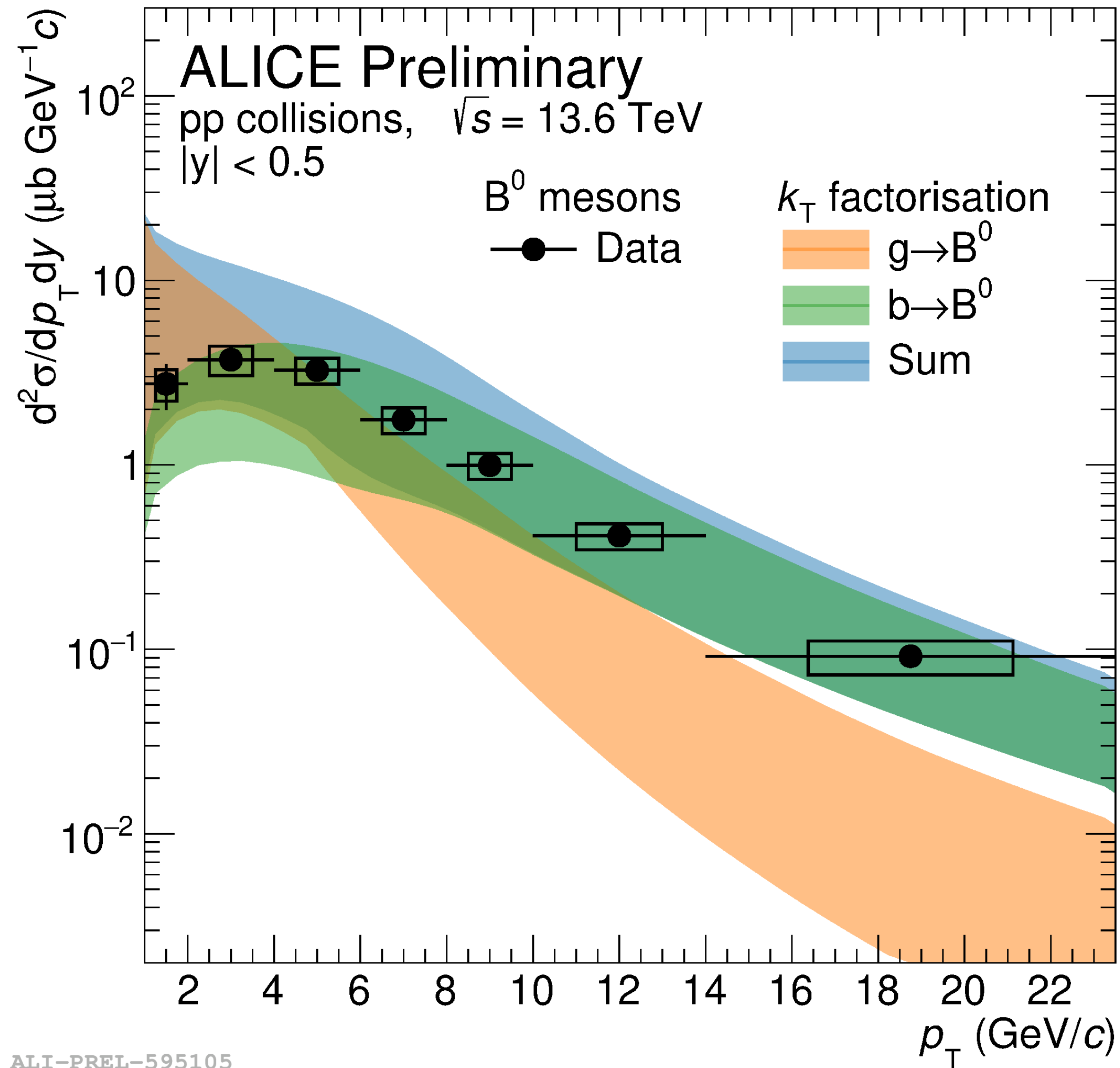


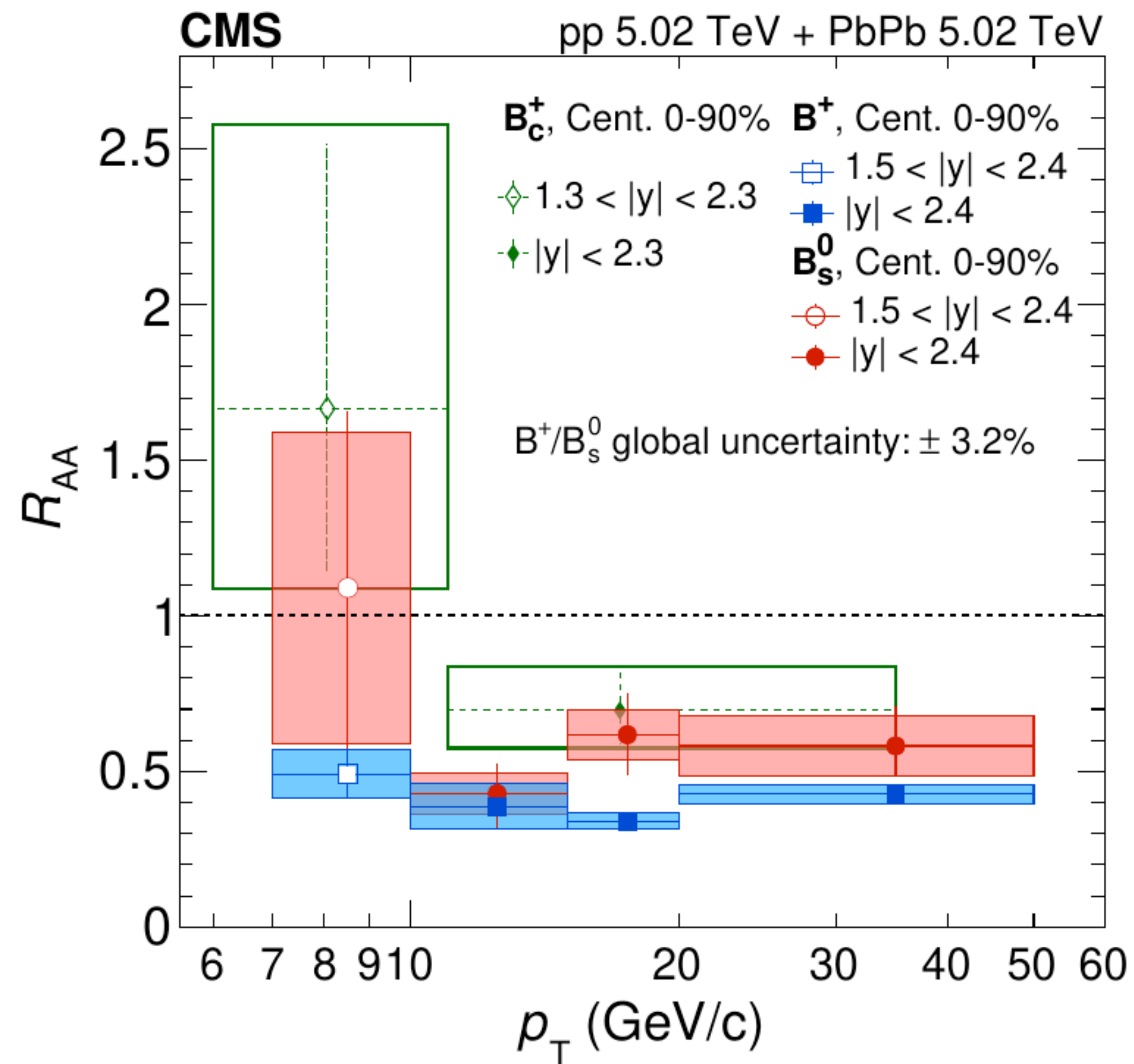
PYTHIA 8: JHEP
1508 (2015) 003

ALI-PUB-534134

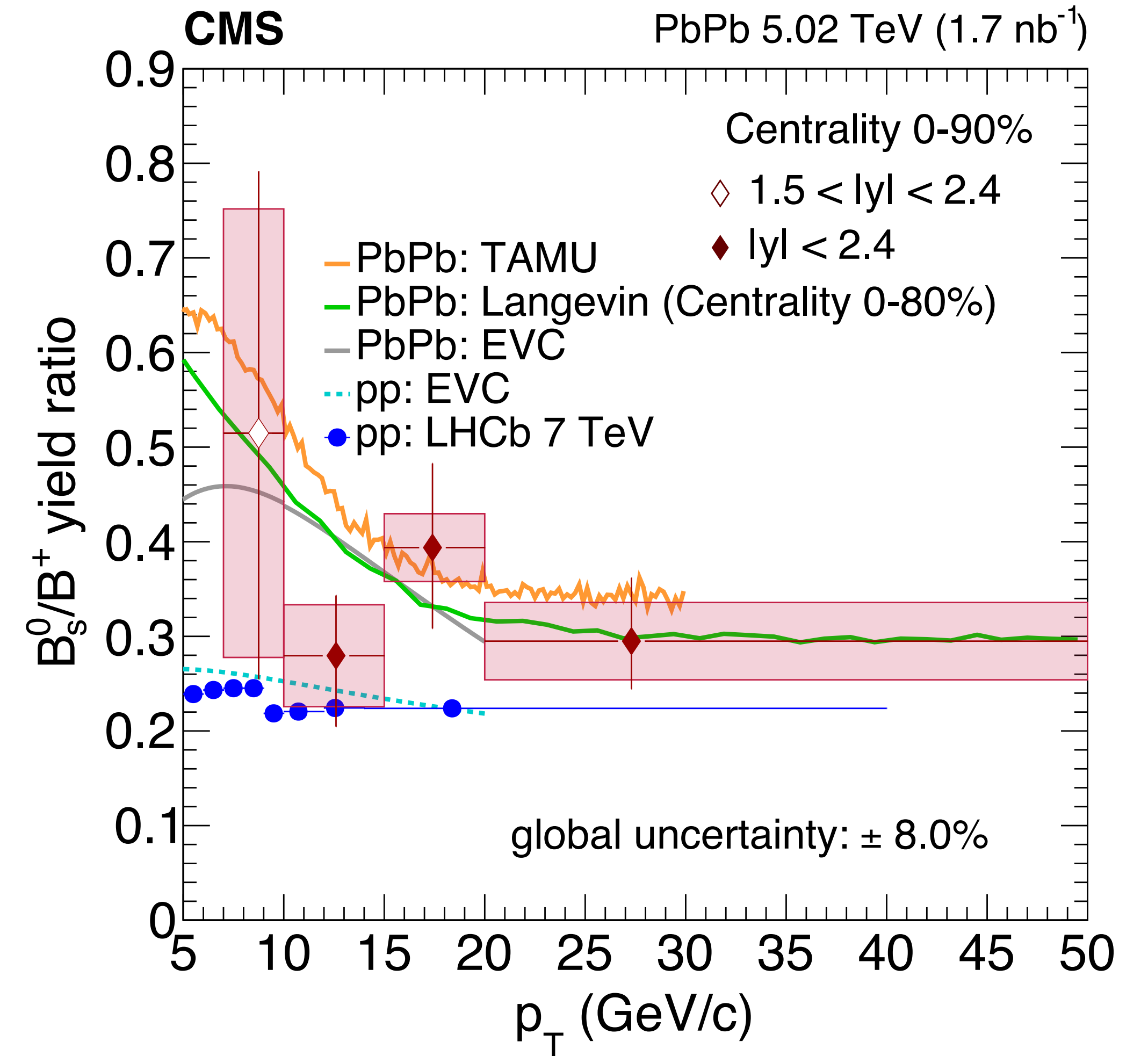
- Charm quark production dominated by hard parton-parton scatterings
- D_s/D^0 does not show dependence with increasing multiplicity
 - ➔ better agreement with Monash 2013 tuning, though CR-BLC compatible within uncertainties

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

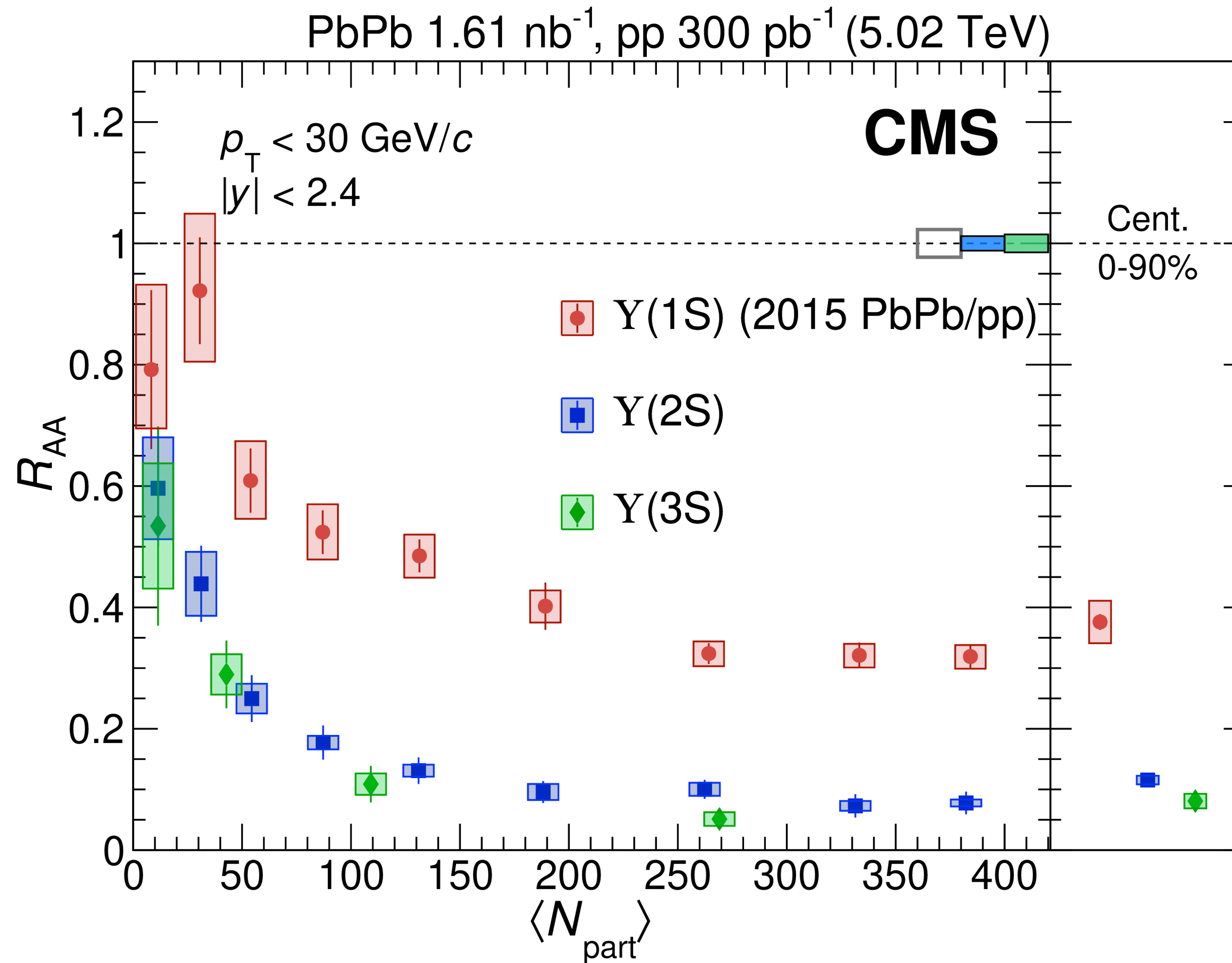


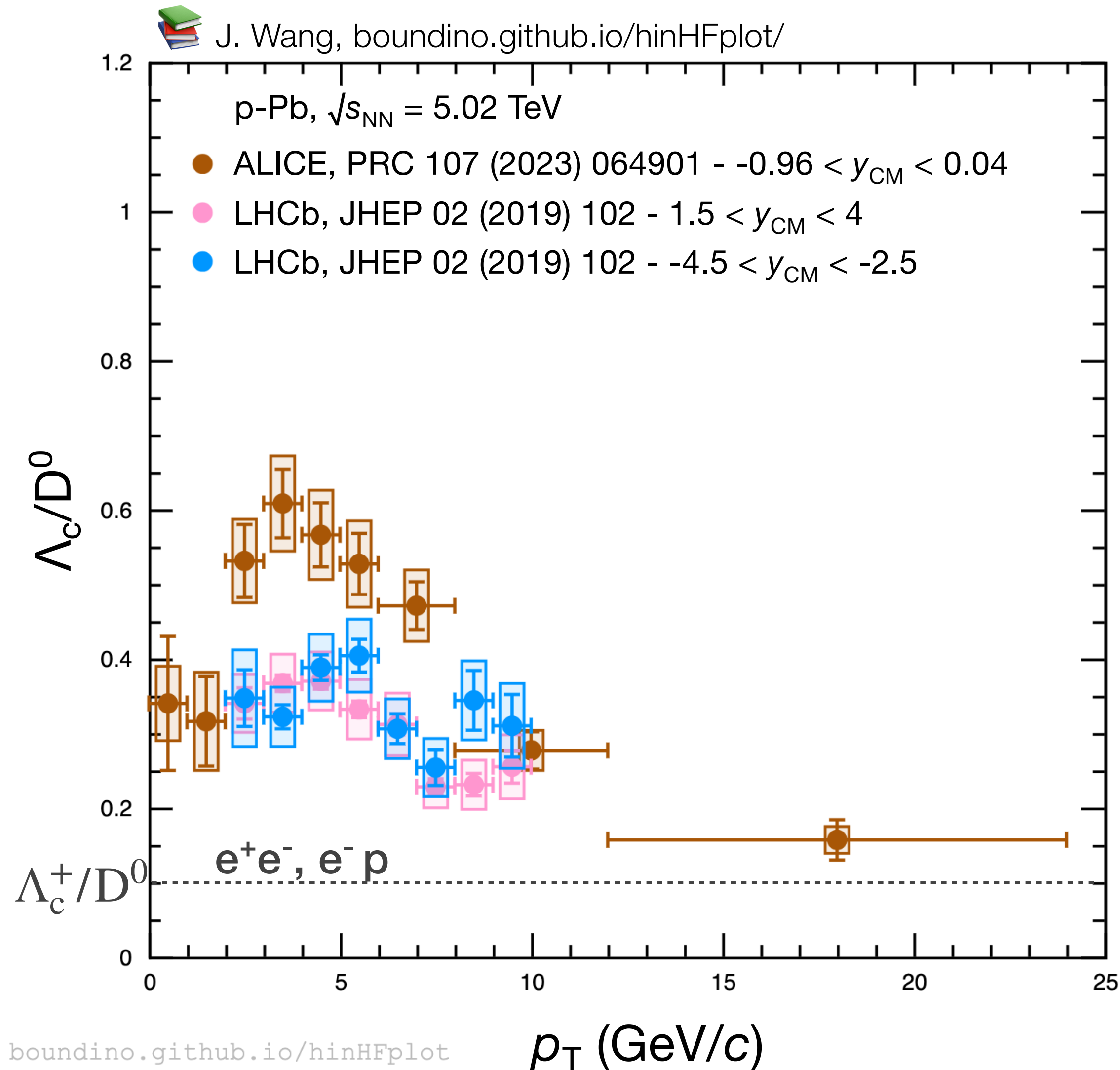


 CMS, JHEP 2502 (2025) 195



 CMS, PLB 829 (2022) 137062





Λ_c/D (LEP) L. Gladilin, EPJC 75 (2015) 19

In pp collisions at LHC Run 2

► Prompt Λ_c/D^0 enhancement at low p_T with respect to measurements at $e^+e^-/e-p$:

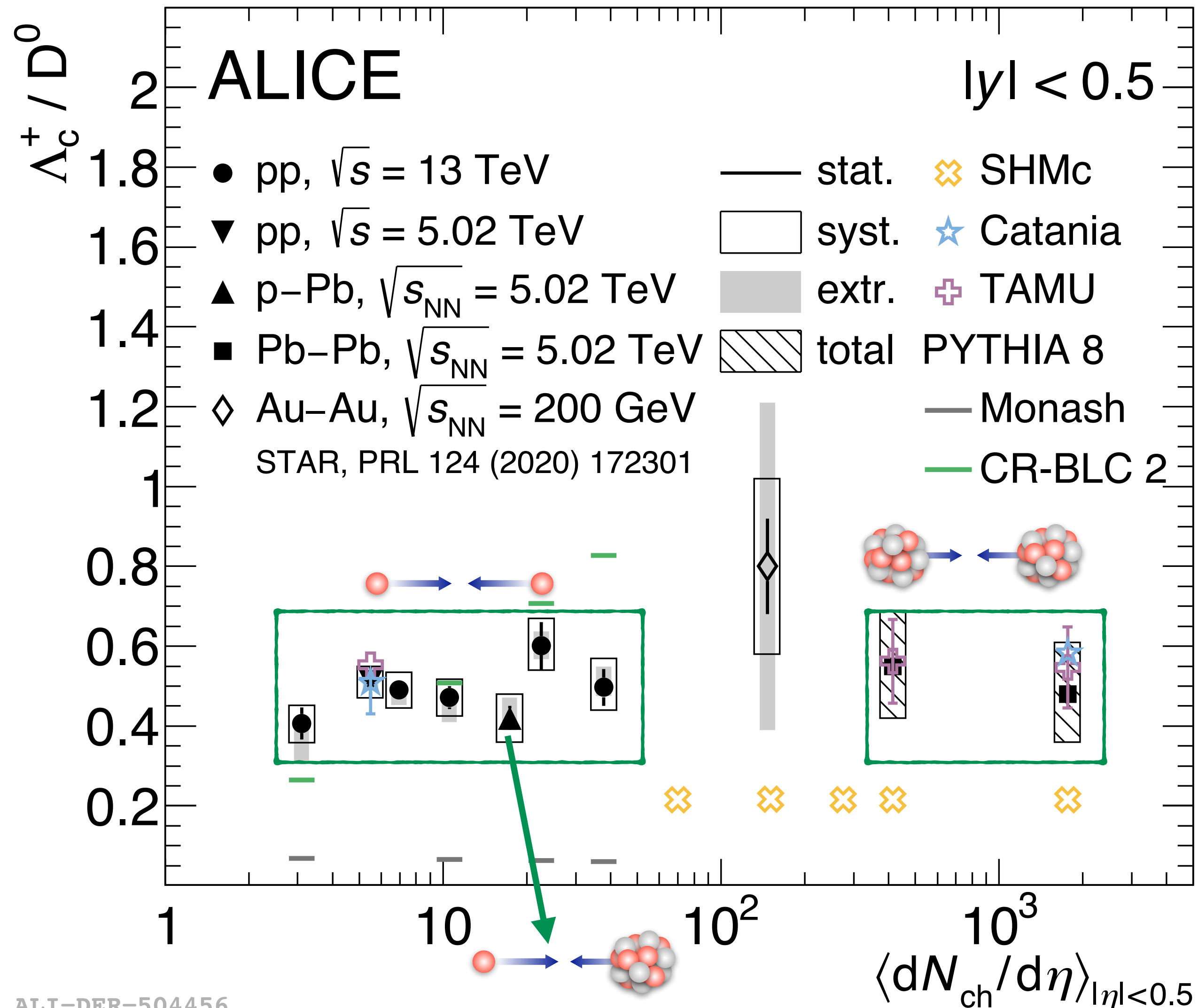
→ ratio higher (x 4-5) → approaching $e^+e^-/e-p$ at high p_T

► Multiplicity-differential results show similar enhancement at low p_T with respect to predictions based on $e^+e^-/e-p$ measurements

In p-Pb collisions at LHC Run 2

► Prompt Λ_c/D^0 enhancement at low p_T as observed in smaller collision systems

→ more pronounced at midrapidity → hint of rapidity dependence?



- 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

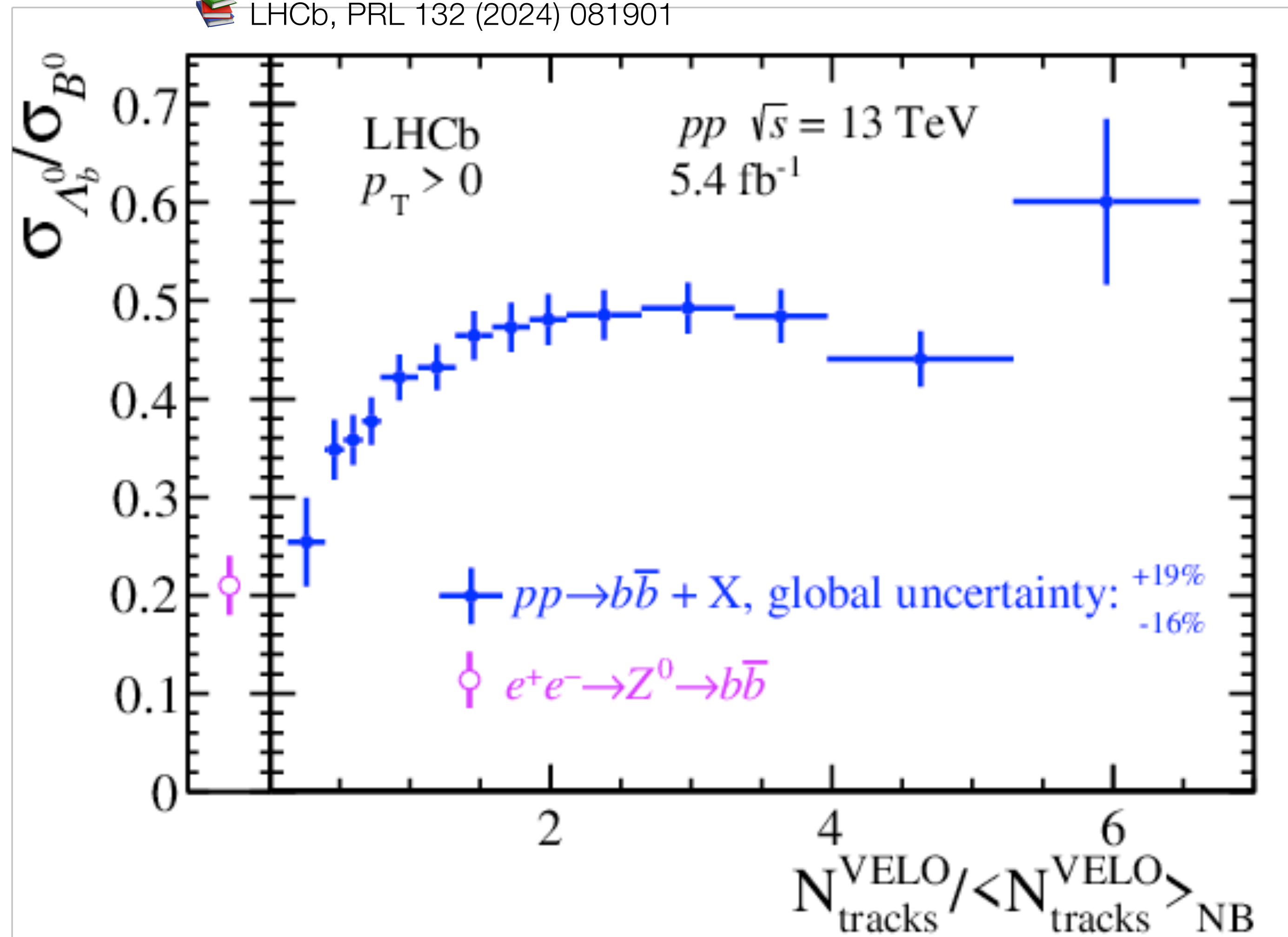
ALICE, PRC 104 (2021) 054905

ALICE, PLB 839 (2023) 137796

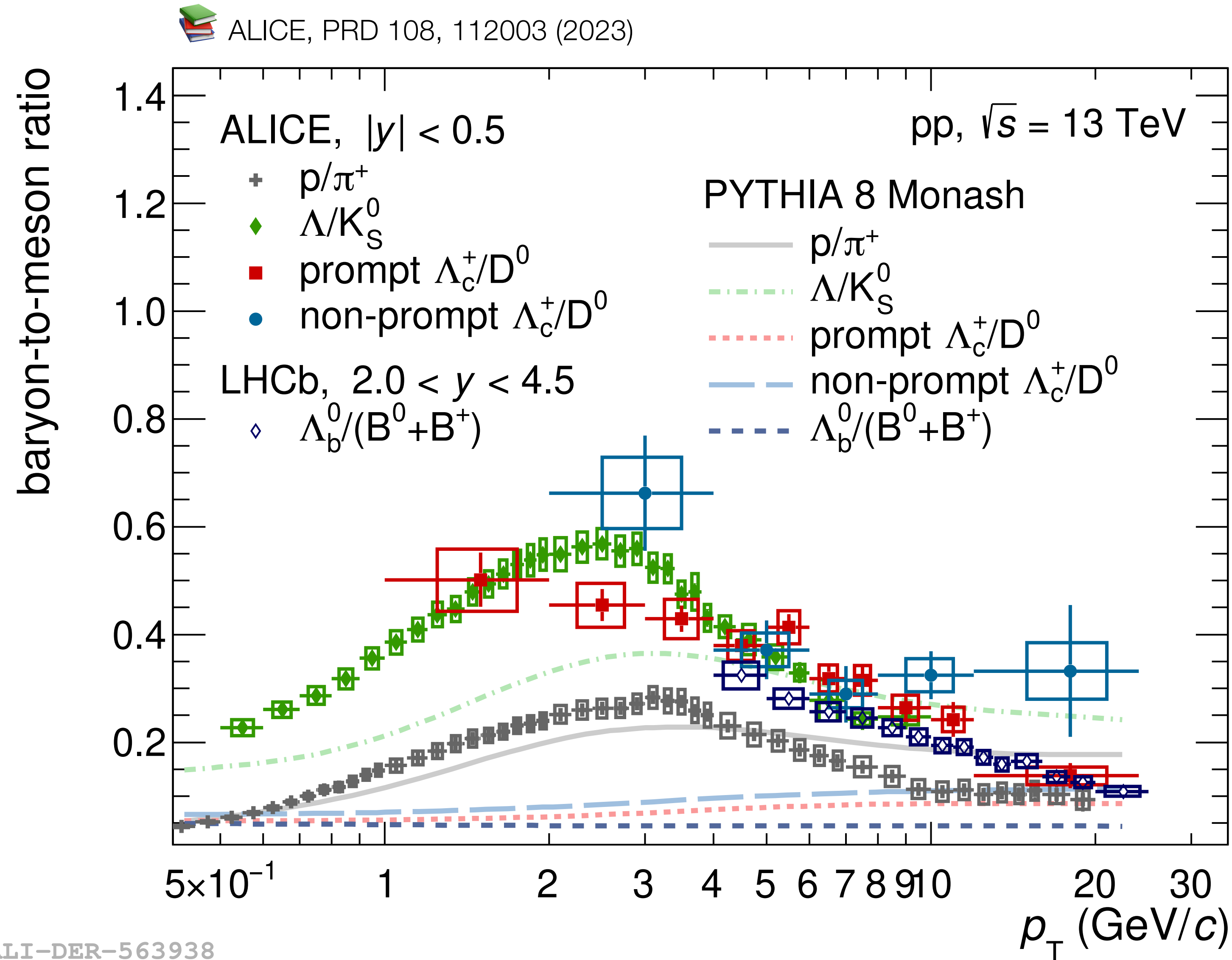
STAR, PRL 124 (2020) 172301



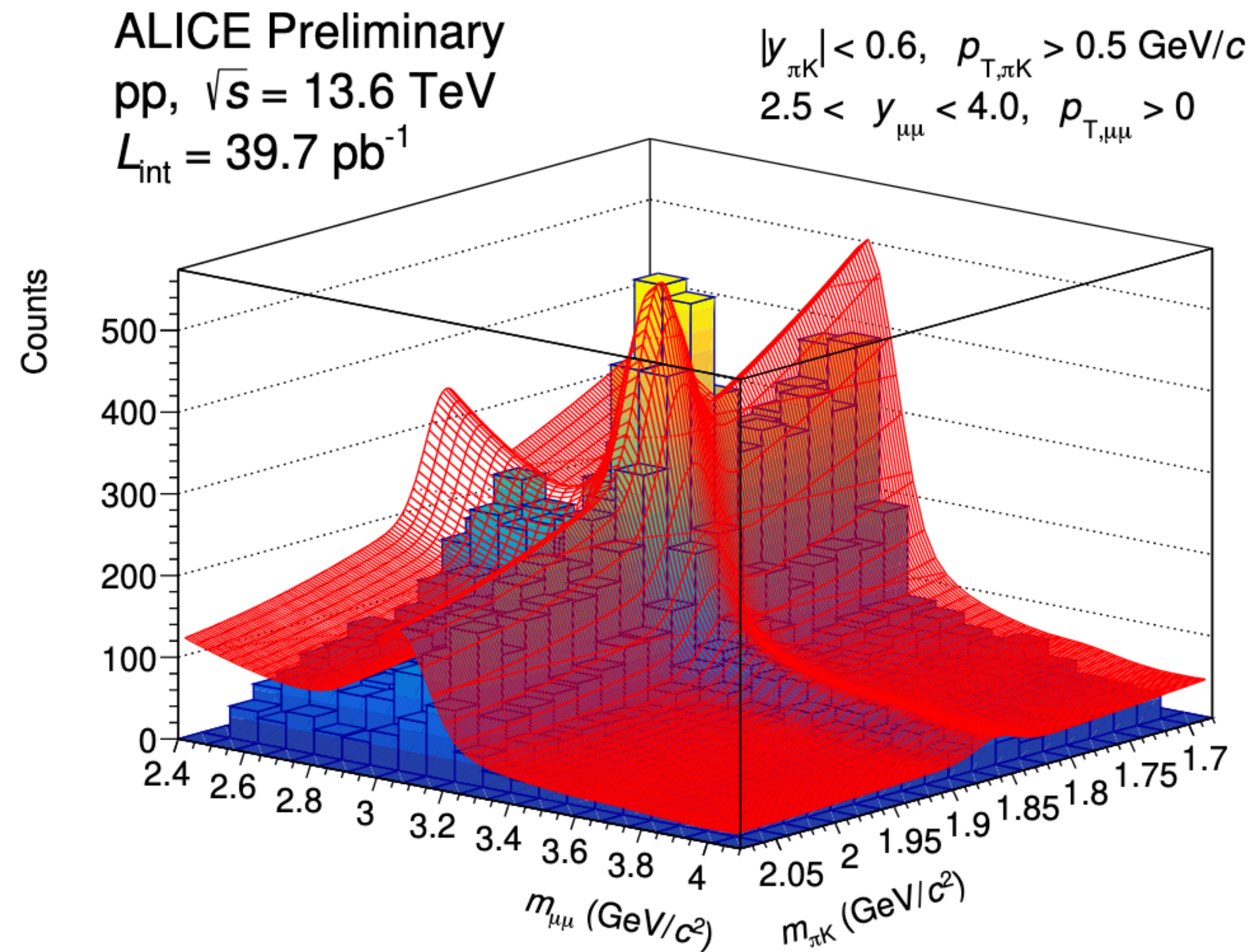
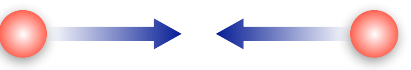
LHCb, PRL 132 (2024) 081901



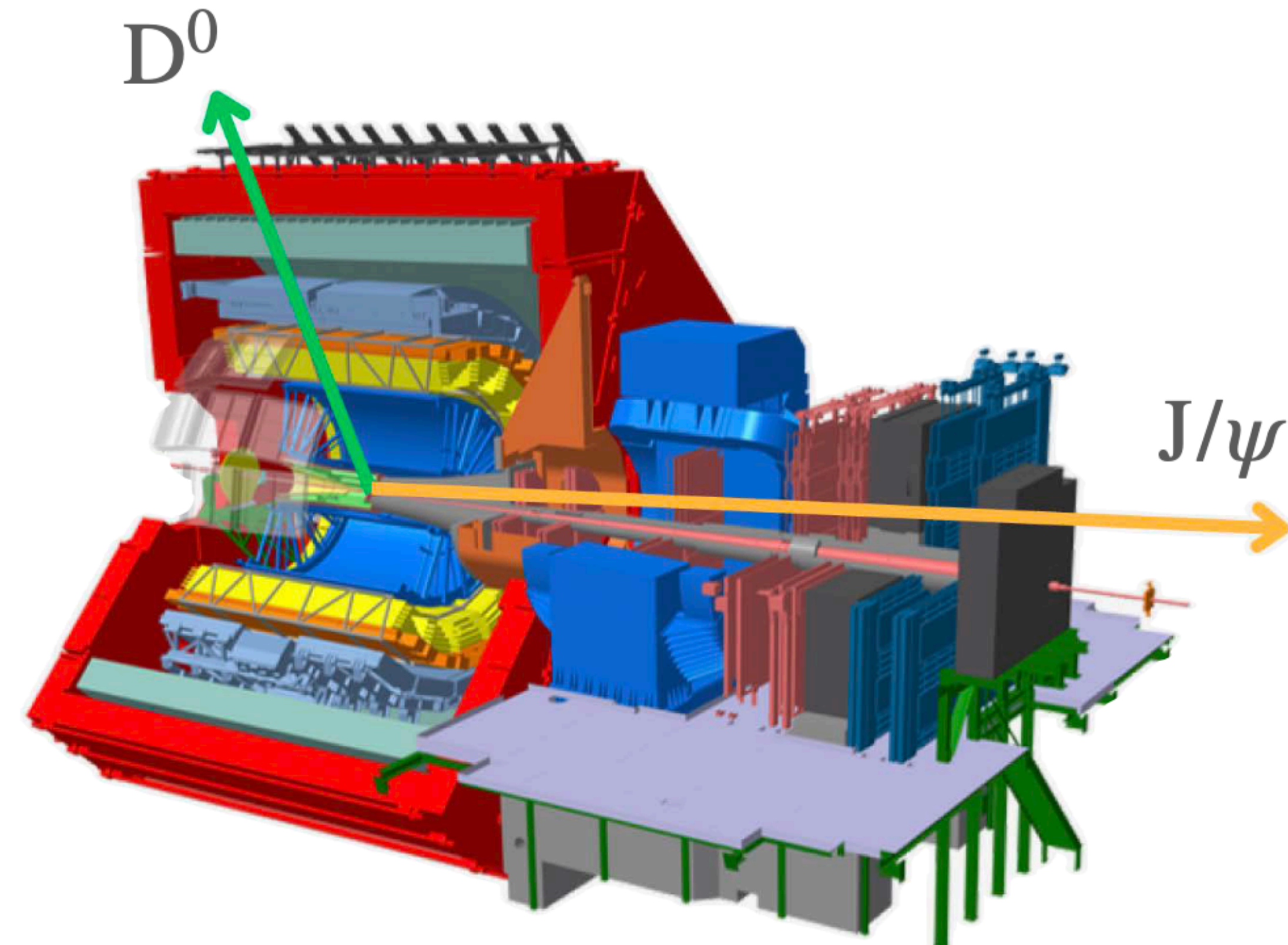
- p_T -integrated Λ_b/B^0 ratio multiplicity-dependent
 - ➔ approaching e^+e^- at very low multiplicity
- p_T -integrated results add questions to the puzzle
 - ➔ low-multiplicity measurements
 - ➔ common multiplicity estimators

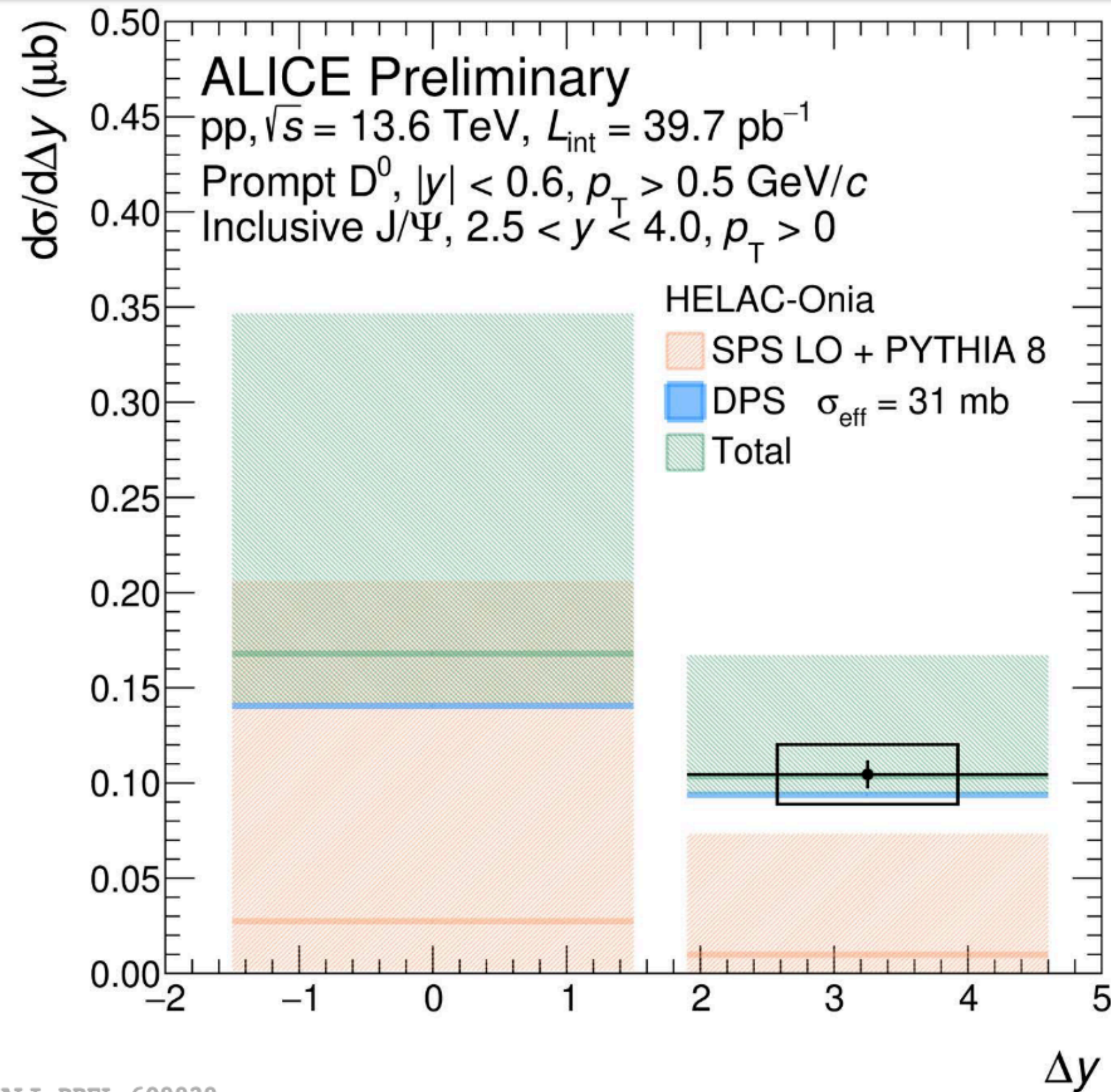


ALI-DER-563938

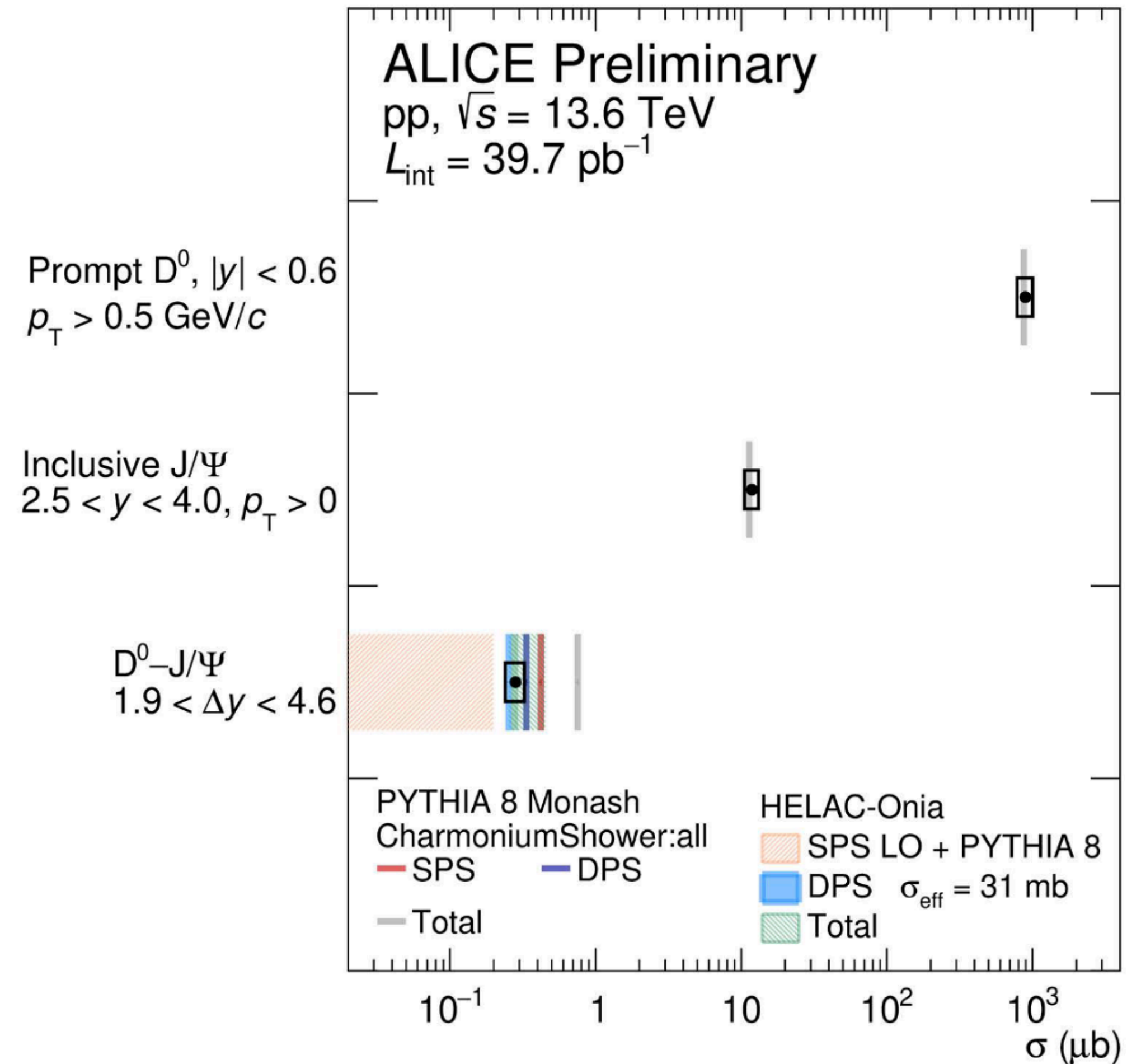


ALI-PREL-609894





ALI-PREL-609929



ALI-PREL-609949

- PYTHIA 8 overestimates the J/ψ - D^0 cross section
- HELAC-Onia reproduces the J/ψ - D^0 cross section considering a σ_{eff} of 31 mb