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ATHIC2023 The 9th Asian Triangle Heavy-Ion Conference

Heavy quarks and quarkonia

(Experiment)

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Heidelberg University

26. 04. 2023.


All matter in the universe was formed in one explosive event 13.7 billion years ago
What is the origin of matter?
How is matter formed?


u
Up quark
d
Down quark
c
Charm quark
s
Strange quark
t
Top quark
b
Bottom quark


$m_c \sim 1.5$ GeV/c^2
$m_b \sim 5$ GeV/c^2
c
u
d
s
t
b
Up quark
Down quark
Charm quark
Strange quark
Top quark
Bottom quark

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Top quark
Bottom quark
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c and **b** are **effective probes** of:

Presence of deconfinement and QGP temperature

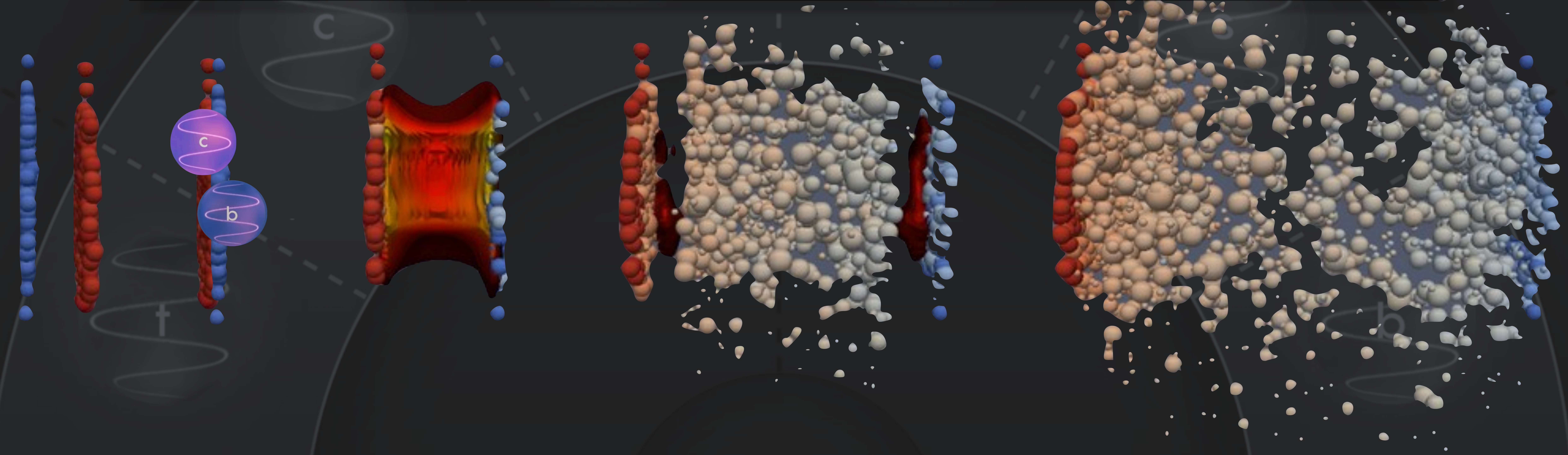
The mechanisms of quark-medium interaction

The strength of the collective expansion of the system

The initial state and the magnetic field

HIC and HF hadron production

$$f_{x_1} \times f_{x_2} \otimes \frac{\mathrm{d}\sigma^{\mathrm{c,b}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{c,b}}} \otimes P_{\mathrm{c,b}\rightarrow \mathrm{c'b'}} \otimes D_{\mathrm{c'b'}\rightarrow \mathrm{h}} = \frac{\mathrm{d}\sigma^{\mathrm{h}}}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{h}}}$$



HIC and HF hadron production

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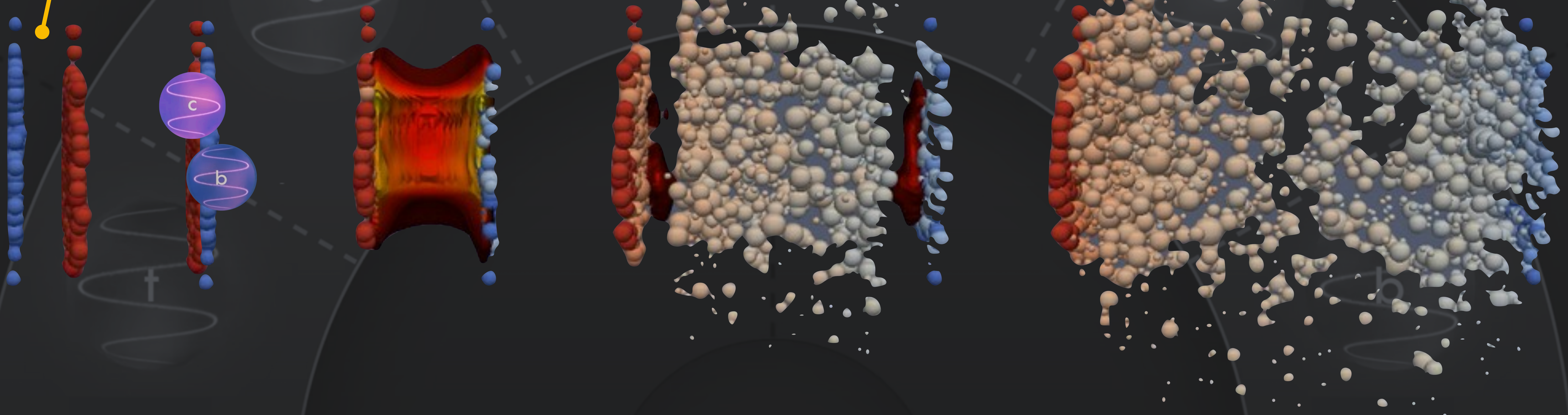

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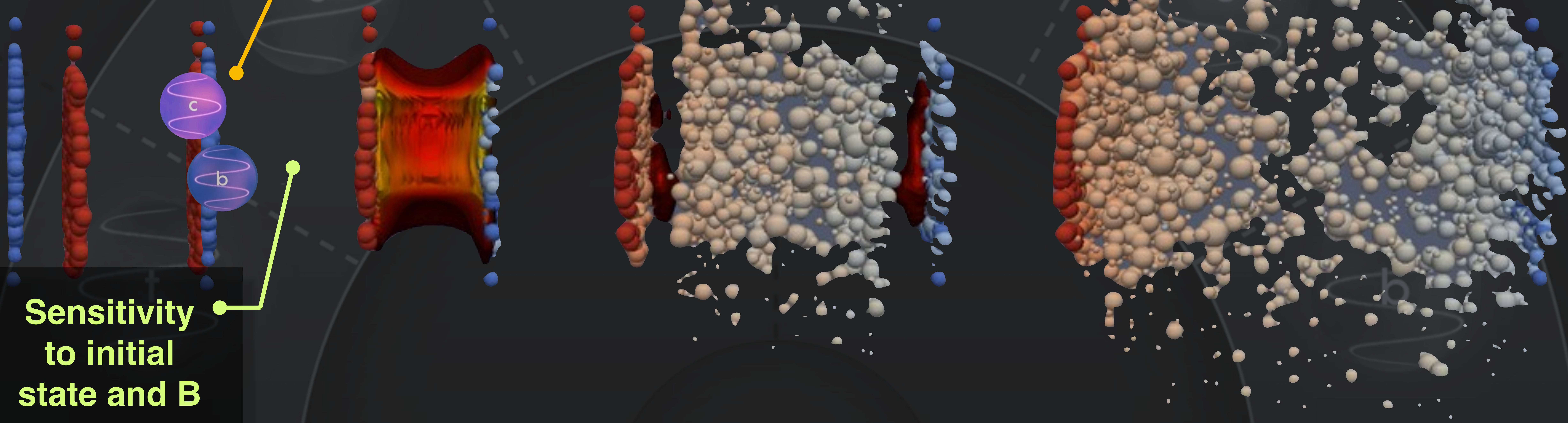

Sensitivity to initial state and B

HIC and HF hadron production

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$$f_{x_1} \times f_{x_2} \otimes \frac{d\sigma^{c,b}}{dp_T^{c,b}} \otimes P_{c,b \to c'b'} \otimes D_{c'b' \to h} = \frac{d\sigma^{h}}{dp_T^{h}}$$

Sensitivity to initial state and B

Interaction with QGP
Radiative energy loss
Thermalization?

HIC and HF hadron production

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Fragmentation
Coalescence

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Sensitivity to initial state and B

Interaction with QGP
Radiative energy loss
Thermalization?

Fragmentation
Coalescence

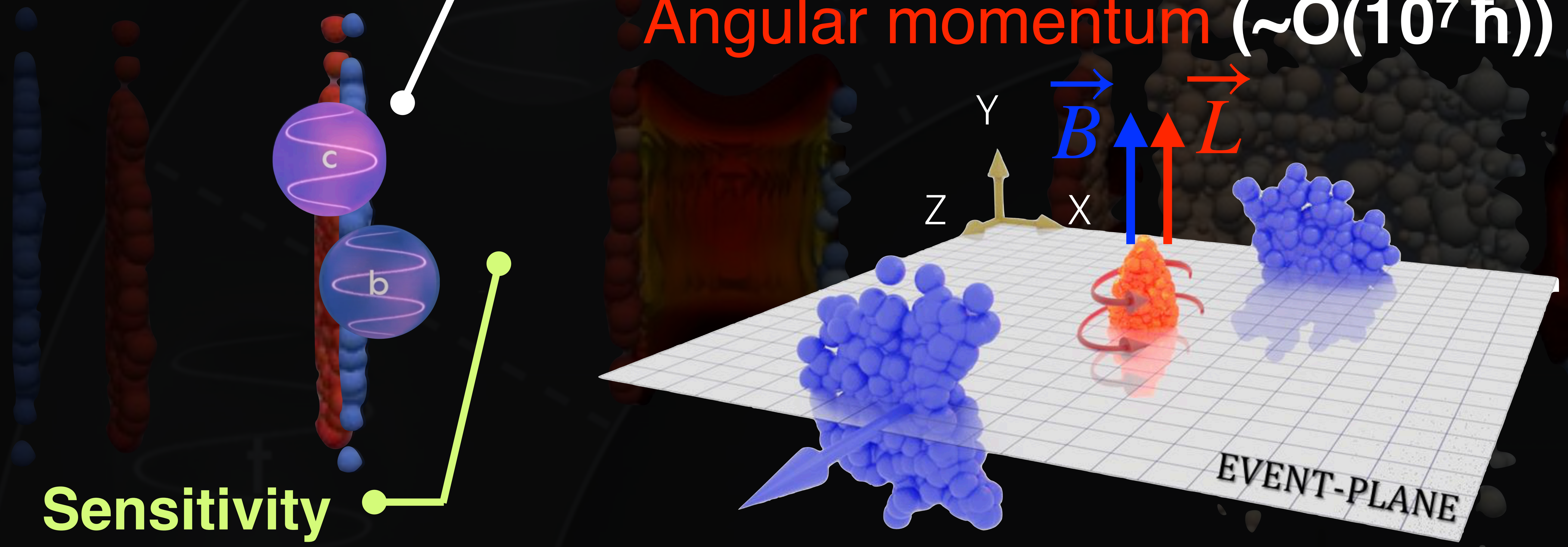
Interaction potential
Rescattering

Heavy flavor hadron production

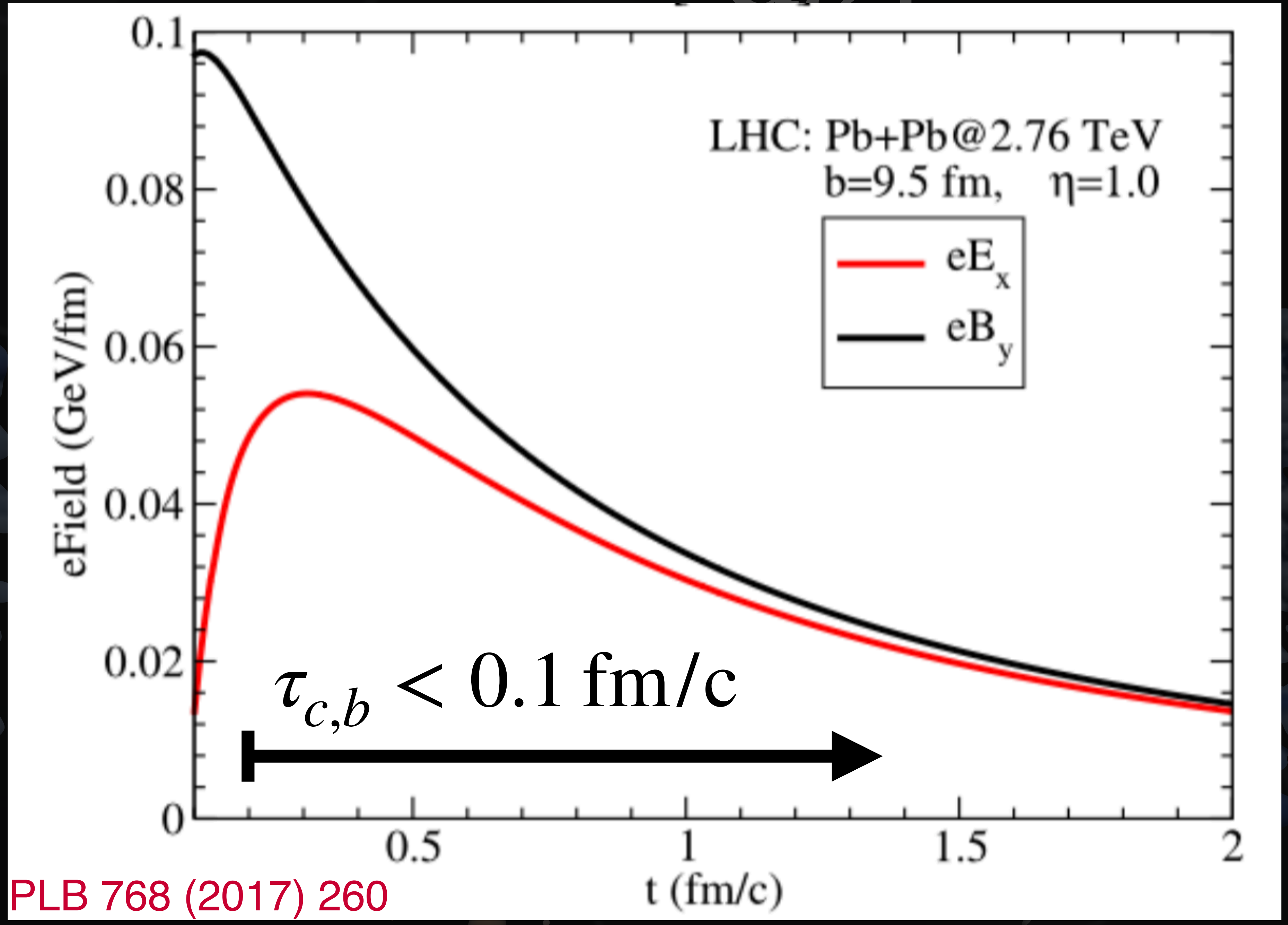
$$f_{x_1} \times f_{x_2} \otimes \frac{d\sigma^{c,b}}{dp_T^{c,b}} \otimes P_{c,b\to c'b'} \otimes D_{c'b'\to h} = \frac{d\sigma^{h}}{dp_T^{h}}$$

B: induced by positive charged spectators
E: induced by time differential B field

Magnetic field **(~10^{14} T)**
Angular momentum **(~O(10^{7} ħ))**



Sensitivity to initial state and B

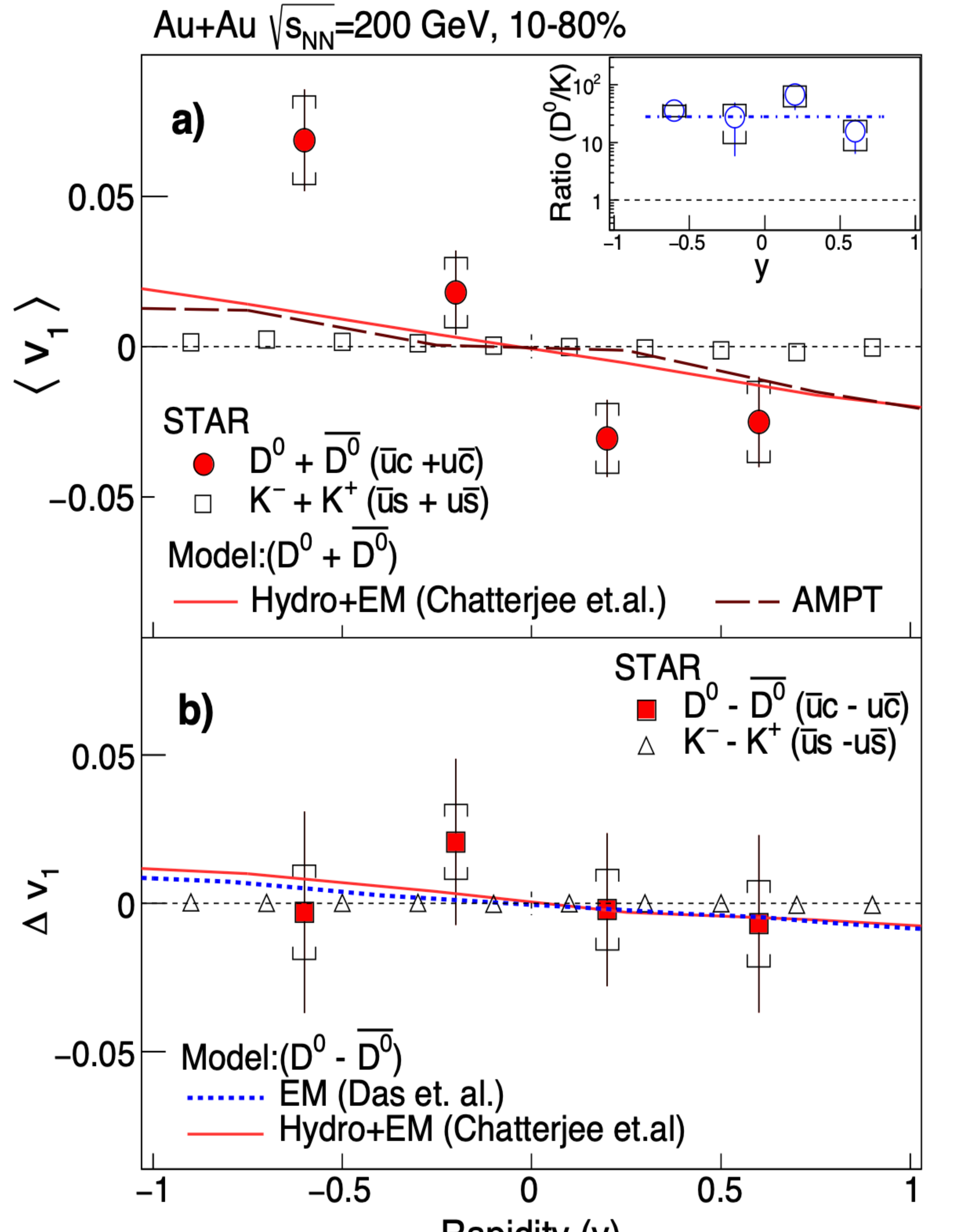


PLB 768 (2017) 260

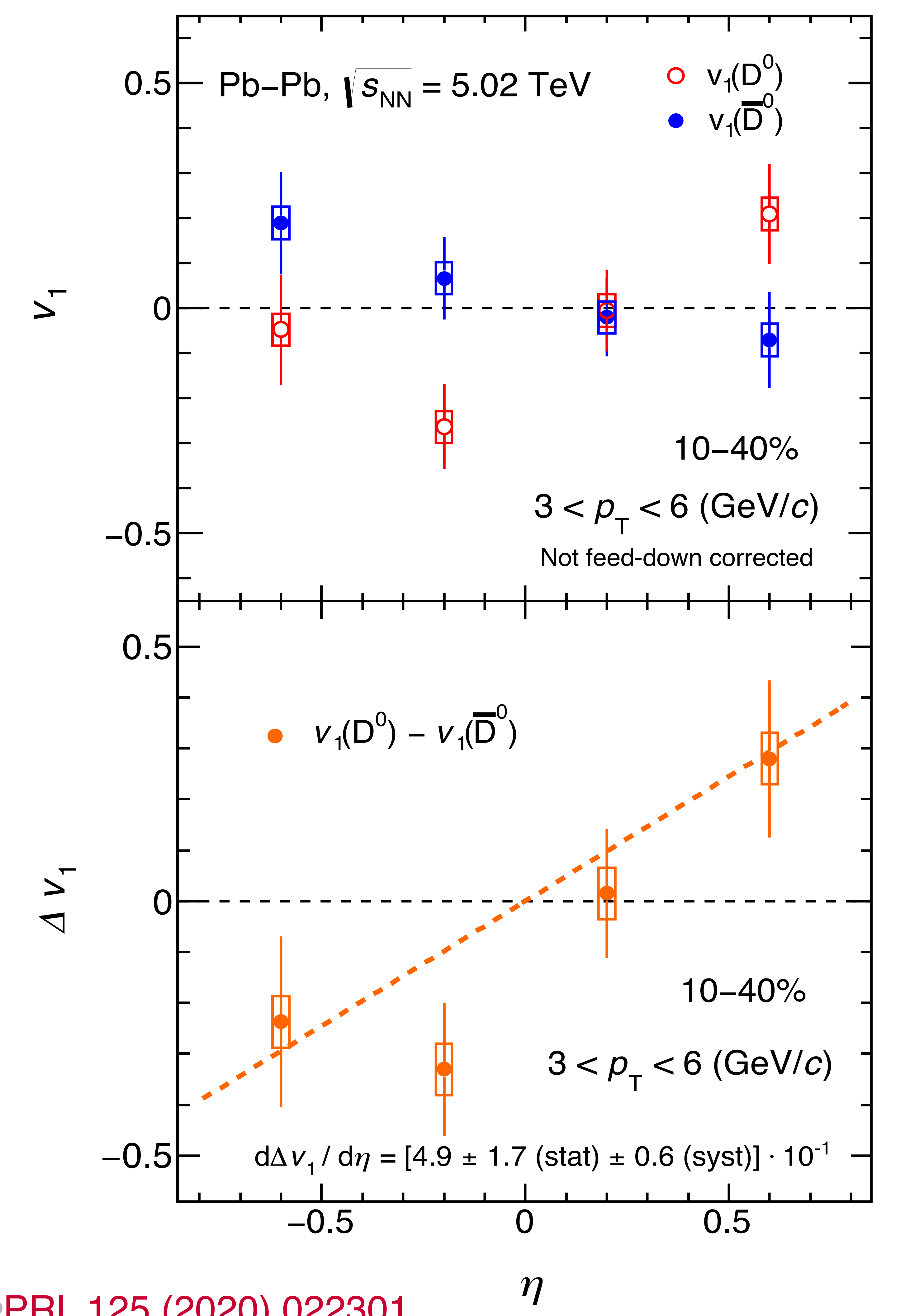
Charge dependent direct flow

- v_1
  - Interplay between the effects of the **rapidly decreasing magnetic field** and the **initial tilt of the source**
  - **HF > LF**

- Model & STAR measurements
  - Negative slope
- ALICE measurements
  - Positive slope



PRL 123 (2019) 162301



PRL 125 (2020) 022301

Charge dependent direct flow

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  - Interplay between the effects of the **rapidly decreasing magnetic field** and the **initial tilt of the source**
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  - Negative slope
- ALICE measurements
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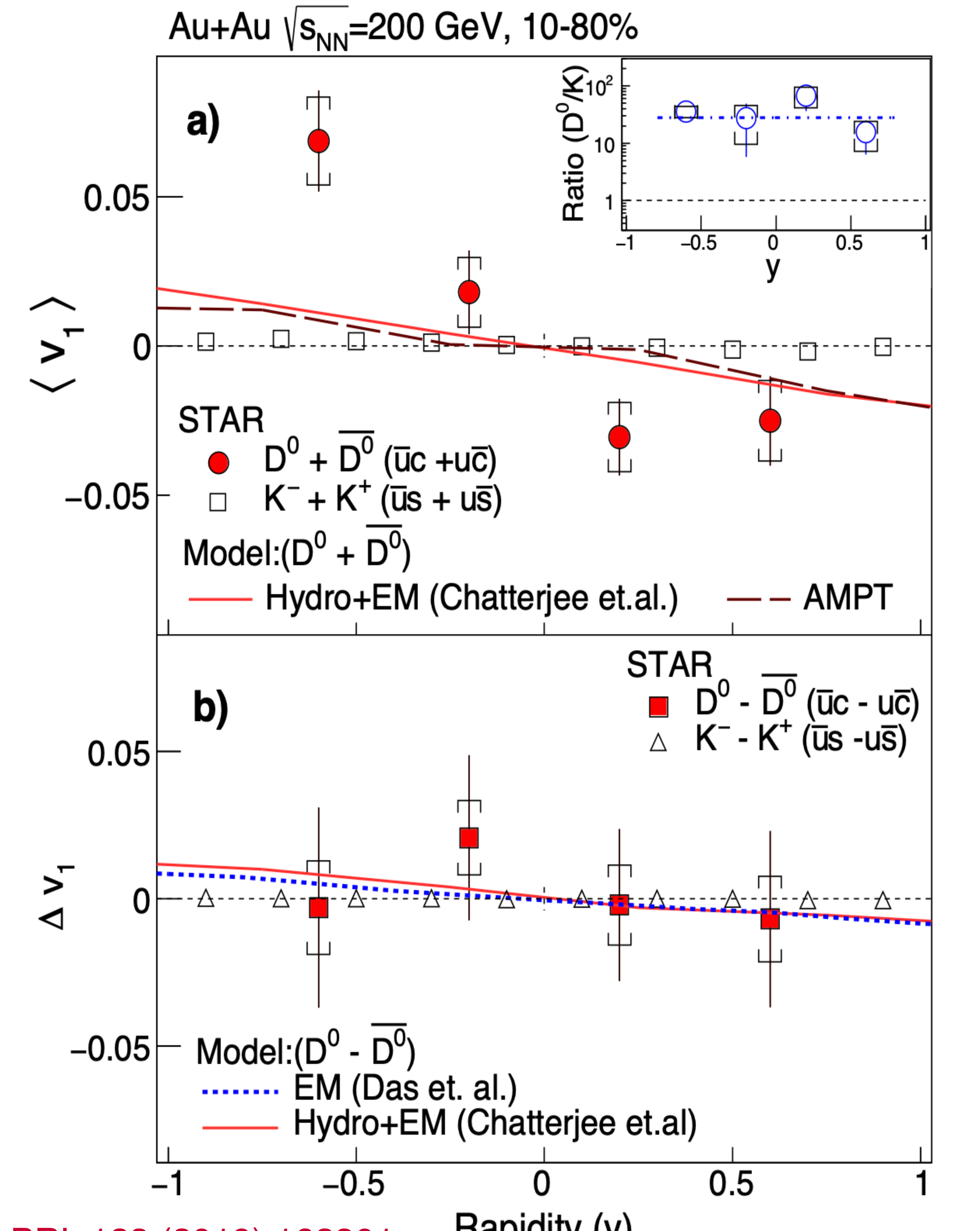
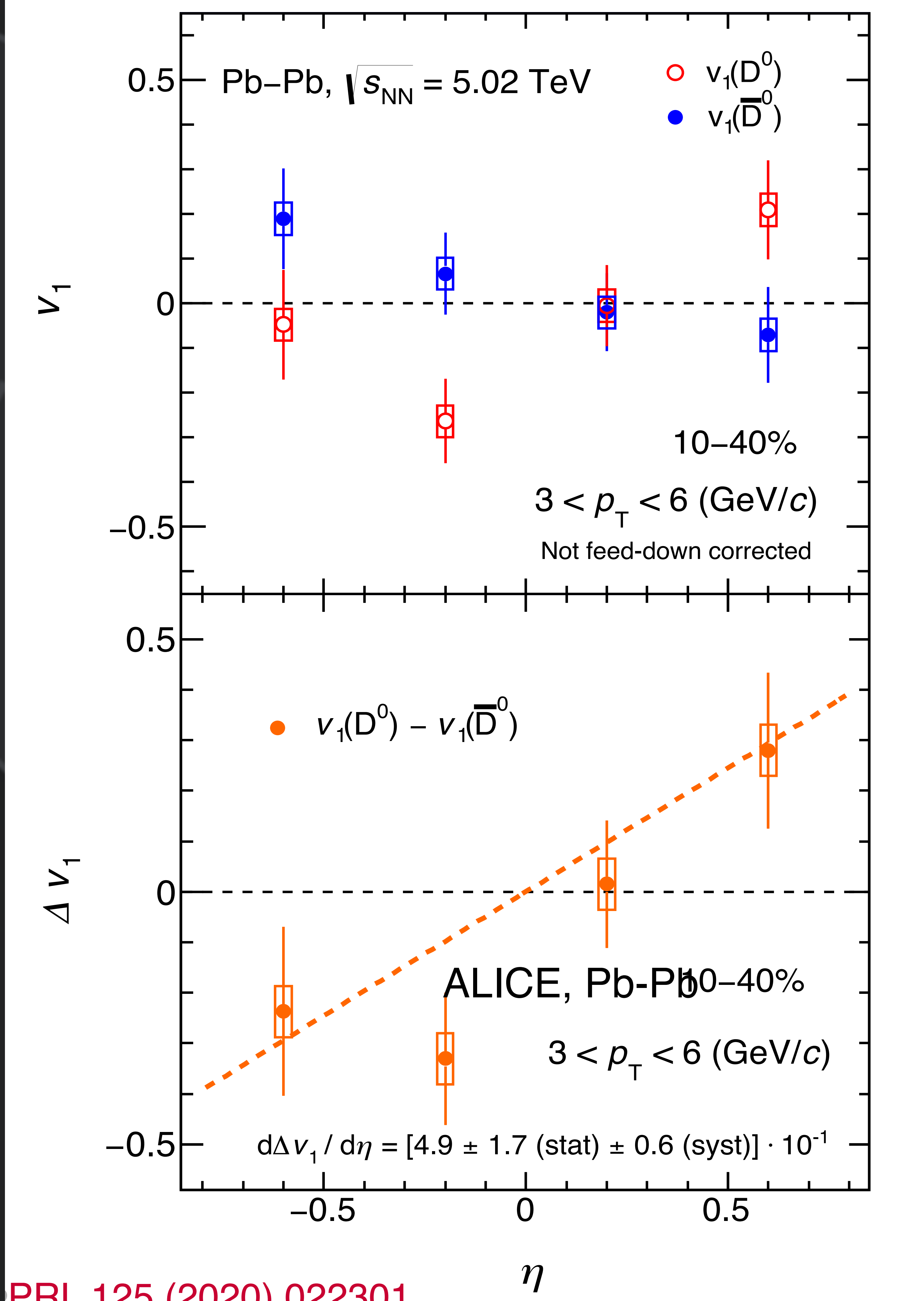
- **Larger B** than the induced E at LHC?



PRL 123 (2019) 162301

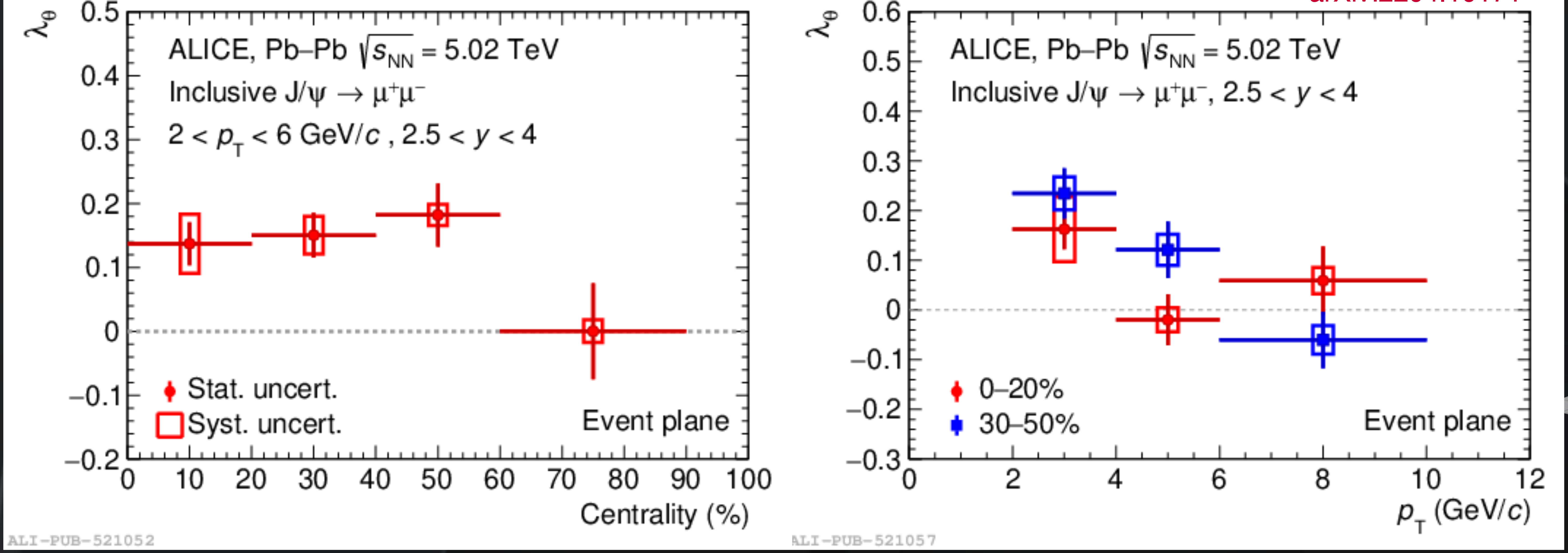


PRL 125 (2020) 022301

J/ψ polarization in Pb-Pb

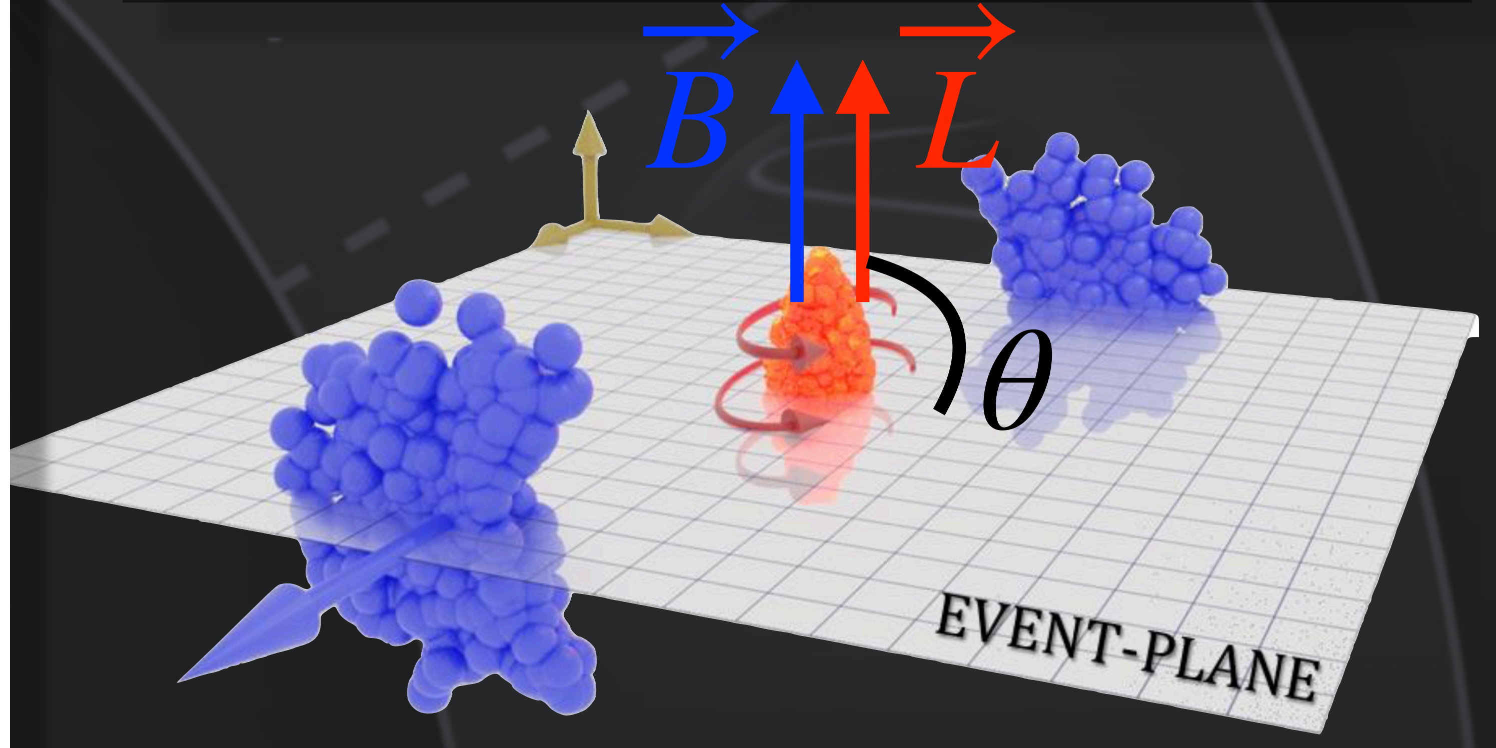
- **Significant non-zero polarization** from central collisions down to 40-60% centrality
- Polarization is **larger** at **low p_T** than at high p_T
  - Theory calculations need to understand the behavior and give an additional handle on the coupling of quarkonia with the nuclear matter

arXiv:2204.10171



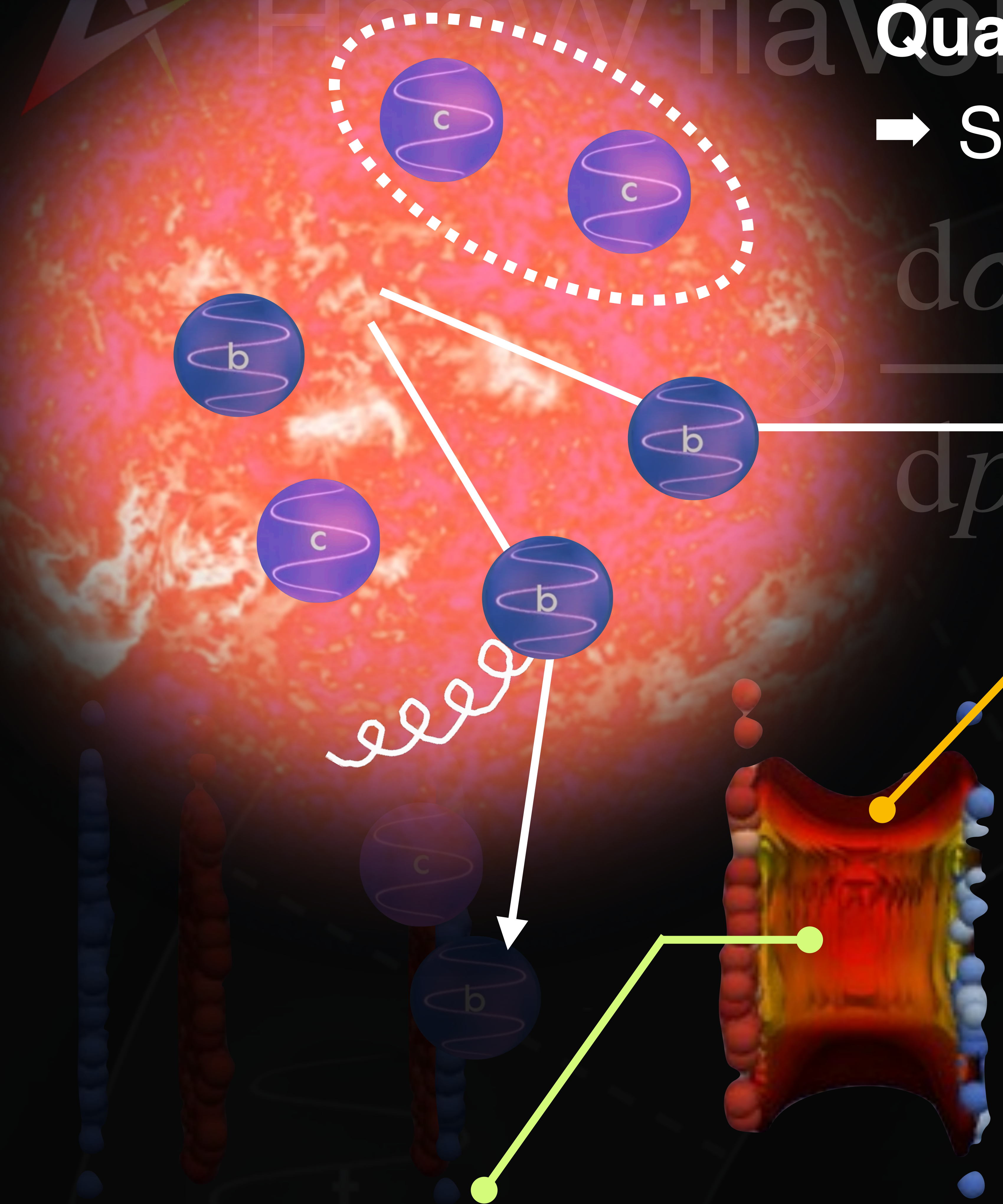
Polar angular distribution

$$\frac{dN}{d\cos\theta} \propto \left(1 + \frac{1}{3+\lambda_\theta}\lambda_\theta \cos^2\theta\right)$$

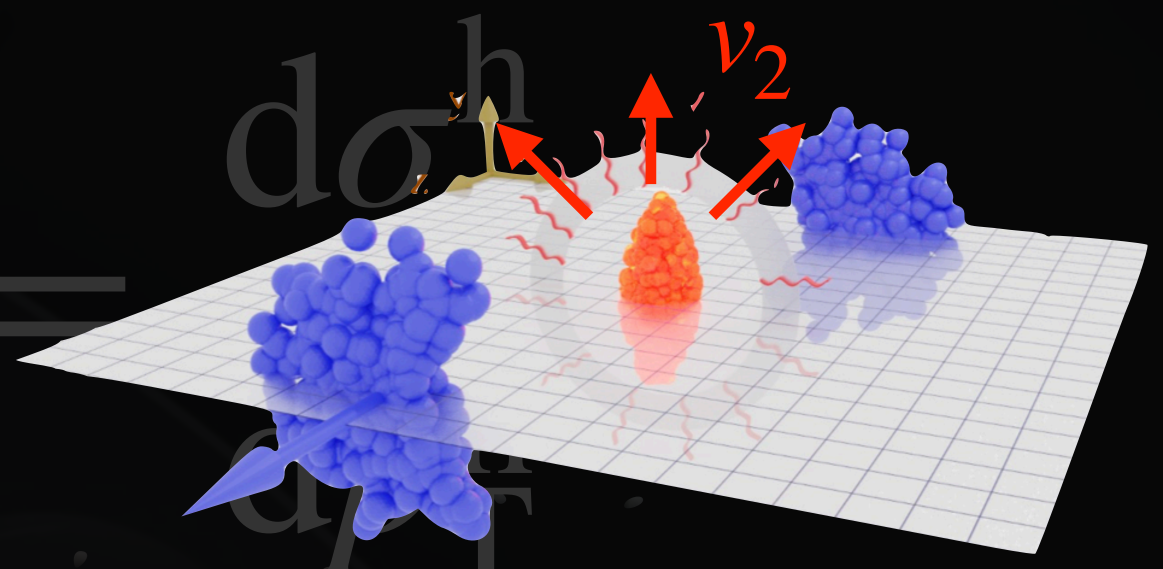


Quarkonium: dissociation & regeneration

➡ Study of **QGP temperature** and **deconfinement**

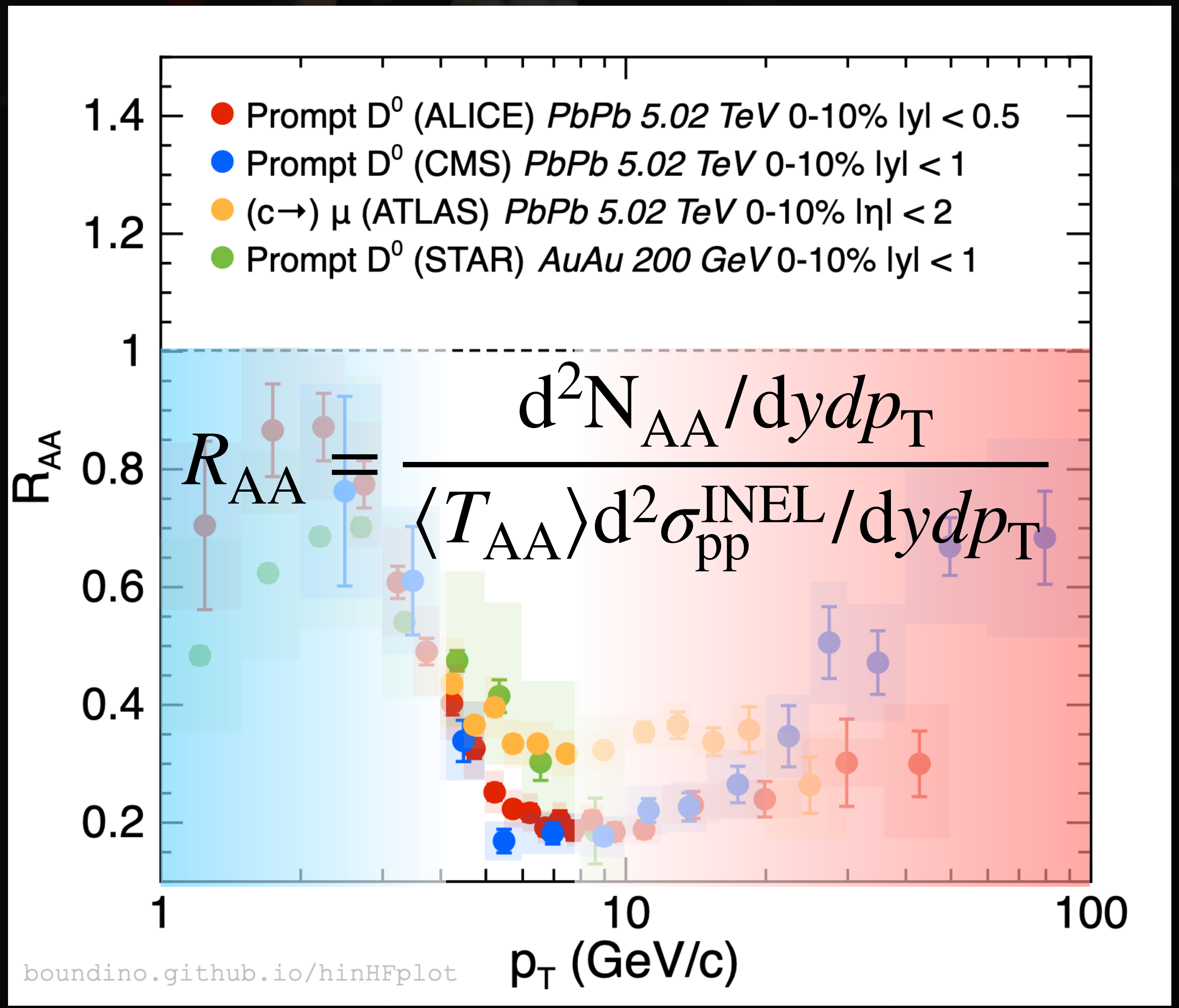


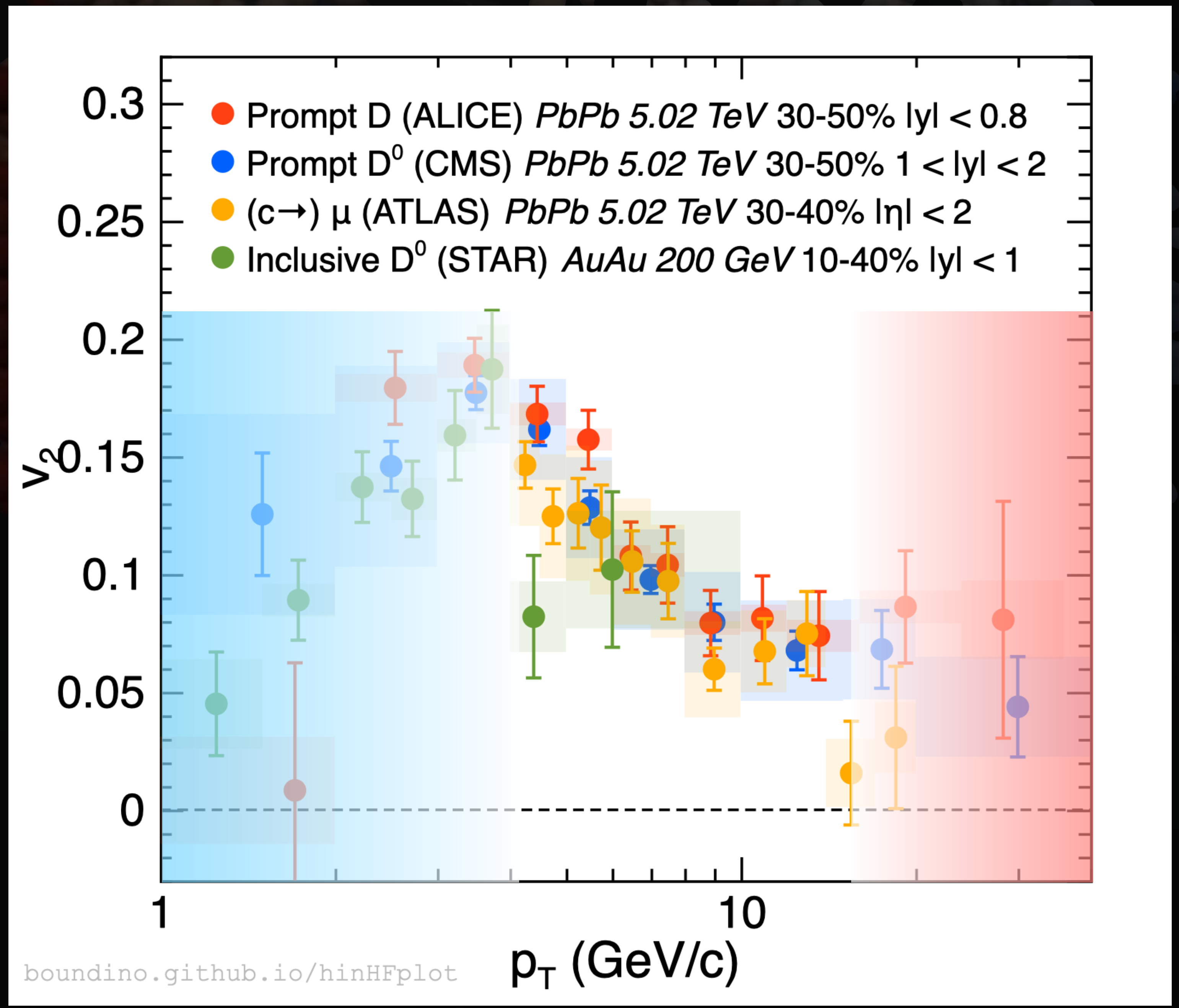
$P_{c,b \to c'b'}$



Low p_T: Elastic collision with medium constituents

High p_T: Radiative energy loss (gluon emission)

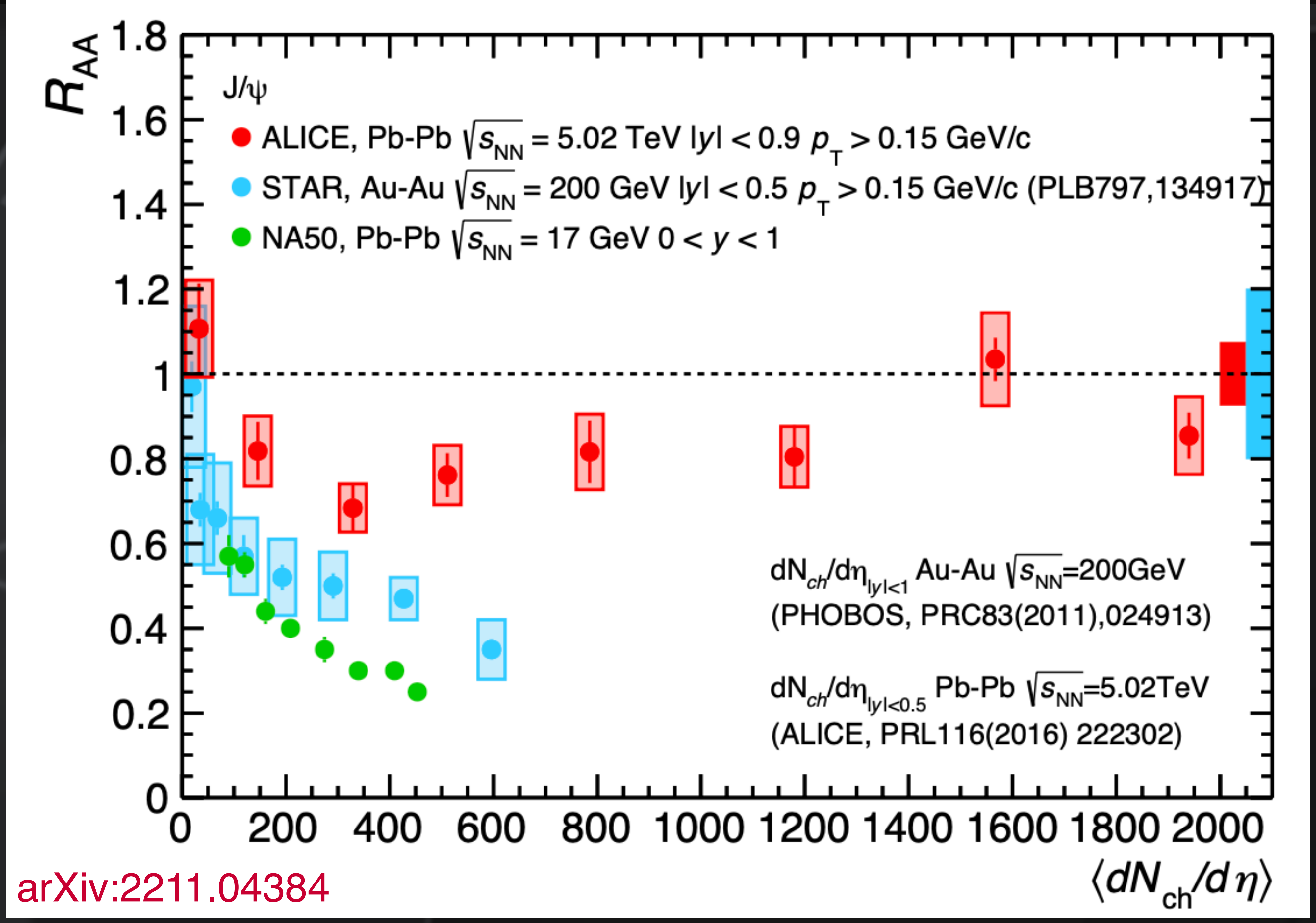




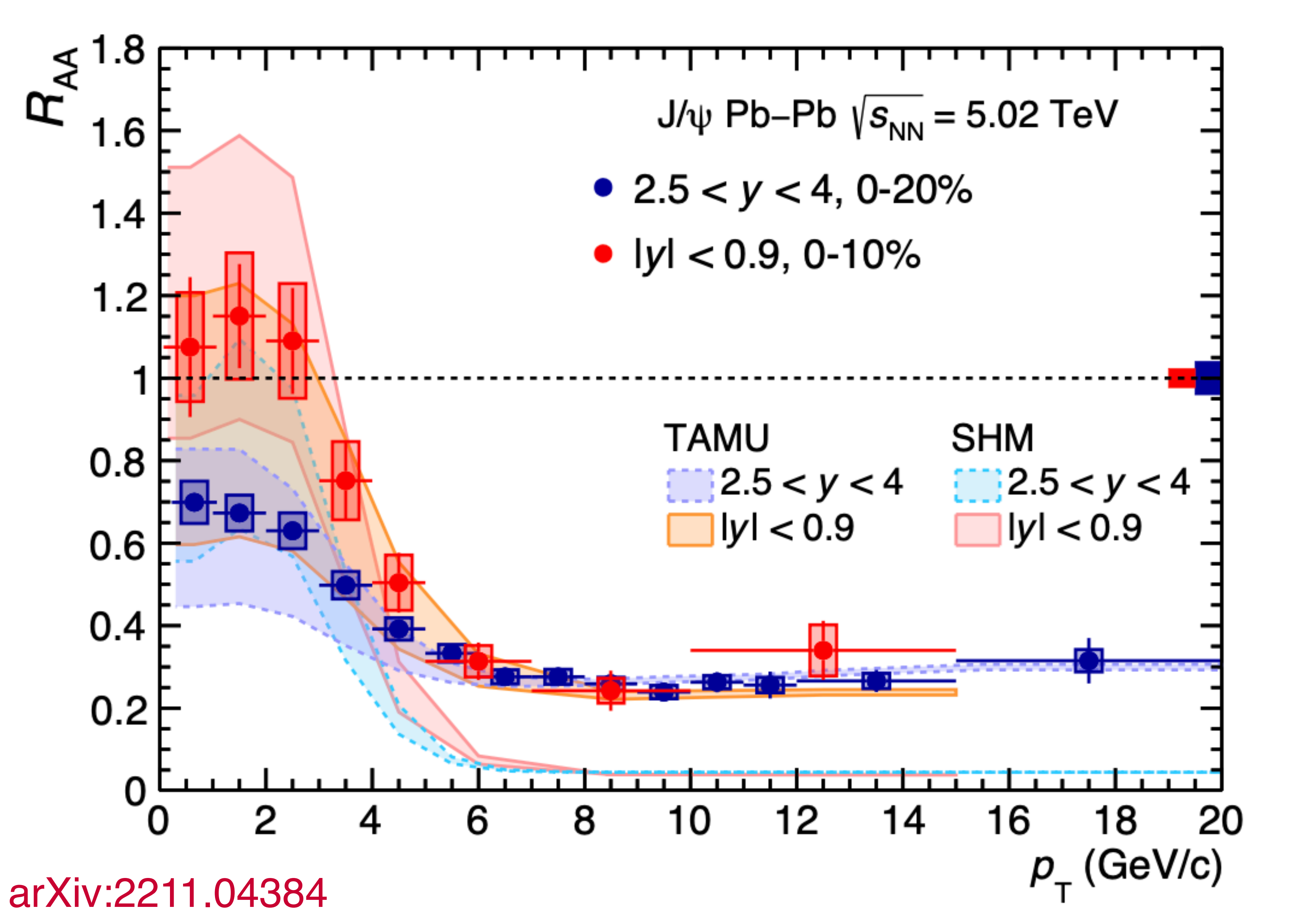
Interaction with QGP
Radiative energy loss
Thermalization?

R_{AA} of charmonium

- R_{AA}: ALICE(5.02 TeV) > STAR(200 GeV) > NA50(17 GeV)
  - Increase of **regeneration with collision energy** ($(dN_{c\bar{c}}/dy)^2$ increases by ~10^6 from SPS to LHC)
- At low p_T region
  - **Sizeable regeneration(recombination)** described by theoretical calculations
    - TAMU: Transport model, SHM: Statistical hadronization model
  - Medium modification decreases from **forward** to **central** rapidity



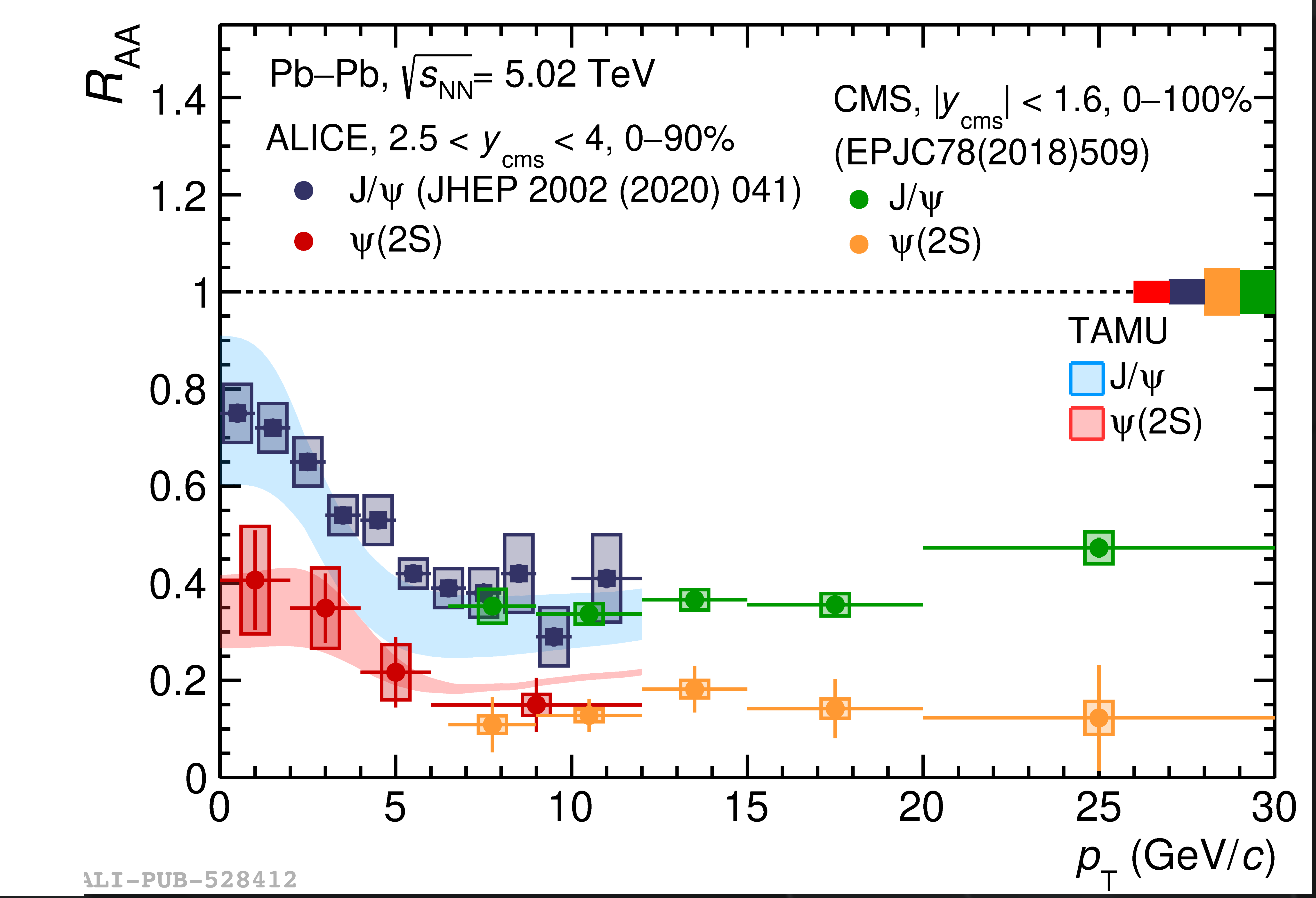
arXiv:2211.04384



arXiv:2211.04384

R_{AA} of charmonium

- Modification: $\psi(2S) > J/\psi$
- At low p_T
  - **Sizeable regeneration(recombination)**
- At high p_T
  - ALICE and CMS agree with each other
  - **No clear p_T dependence** on R_{AA}



R_{AA} of bottomonium

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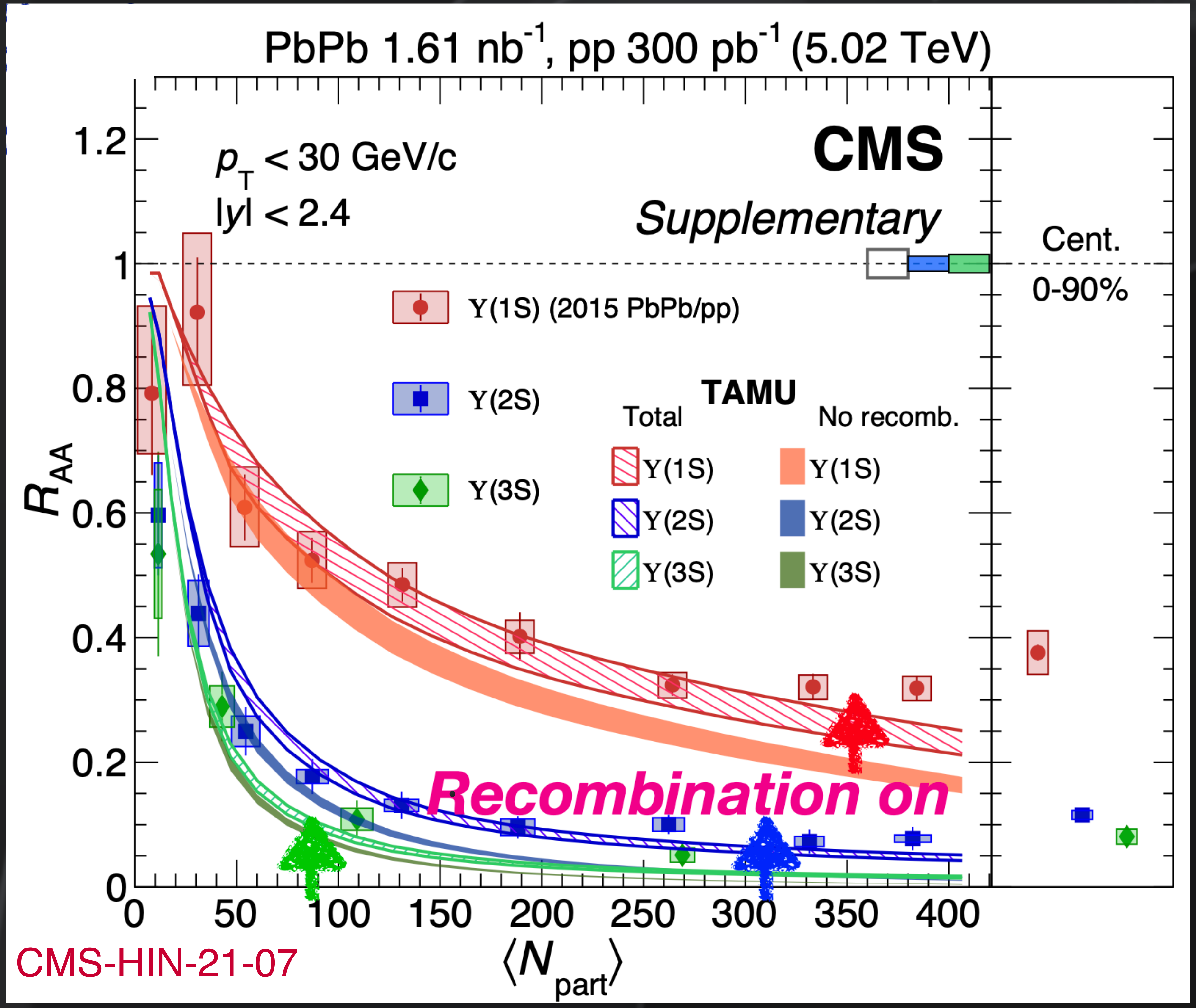
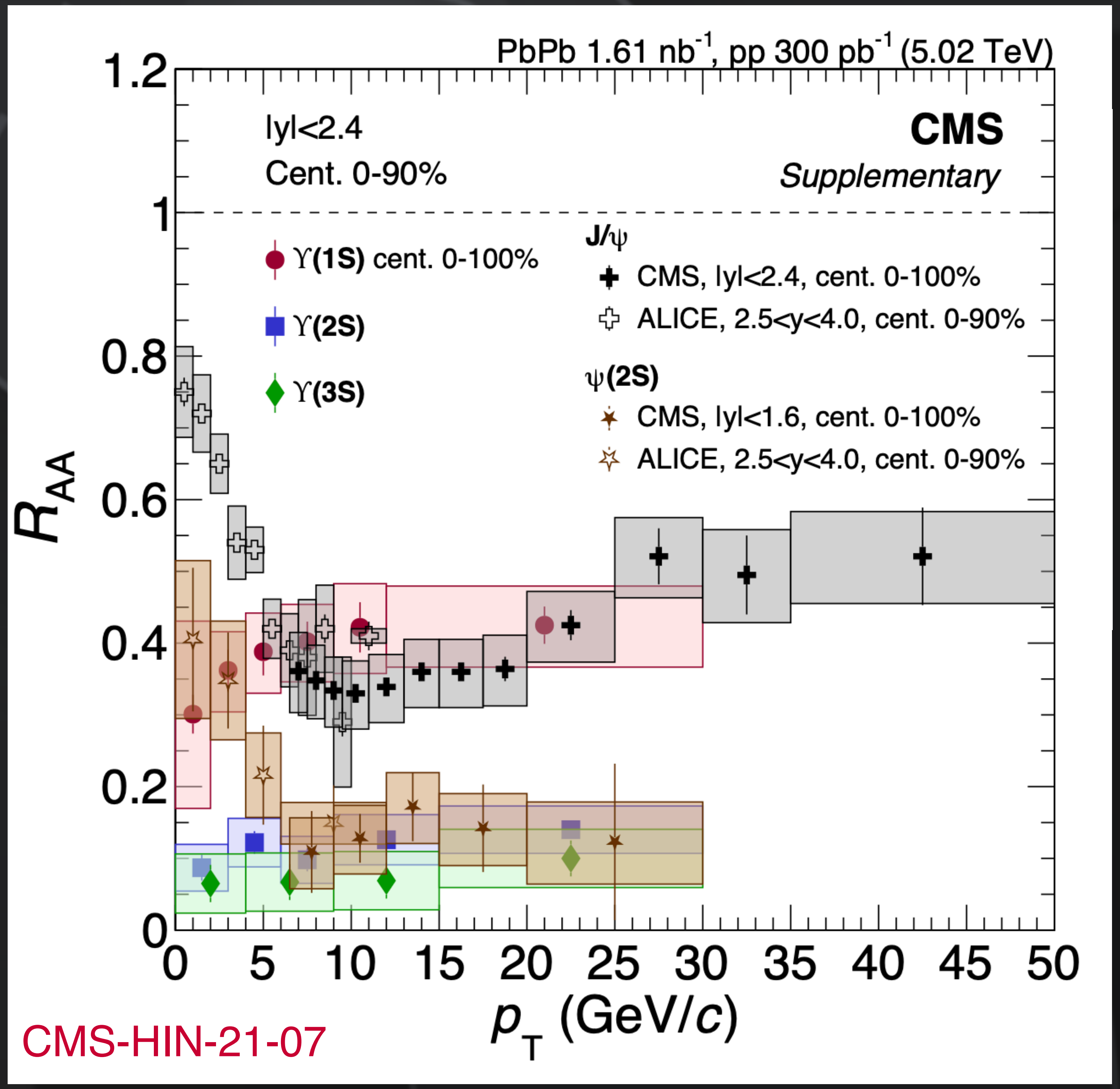
- **Gradual decrease** towards central collisions
- **Sequential suppression**: **Ordering with binding energy** (or radius of bound state)
- The **regeneration(recombination)** of **correlated (diagonal) quarks** is non-negligible
- $\Upsilon(nS)$: No significant p_T dependent





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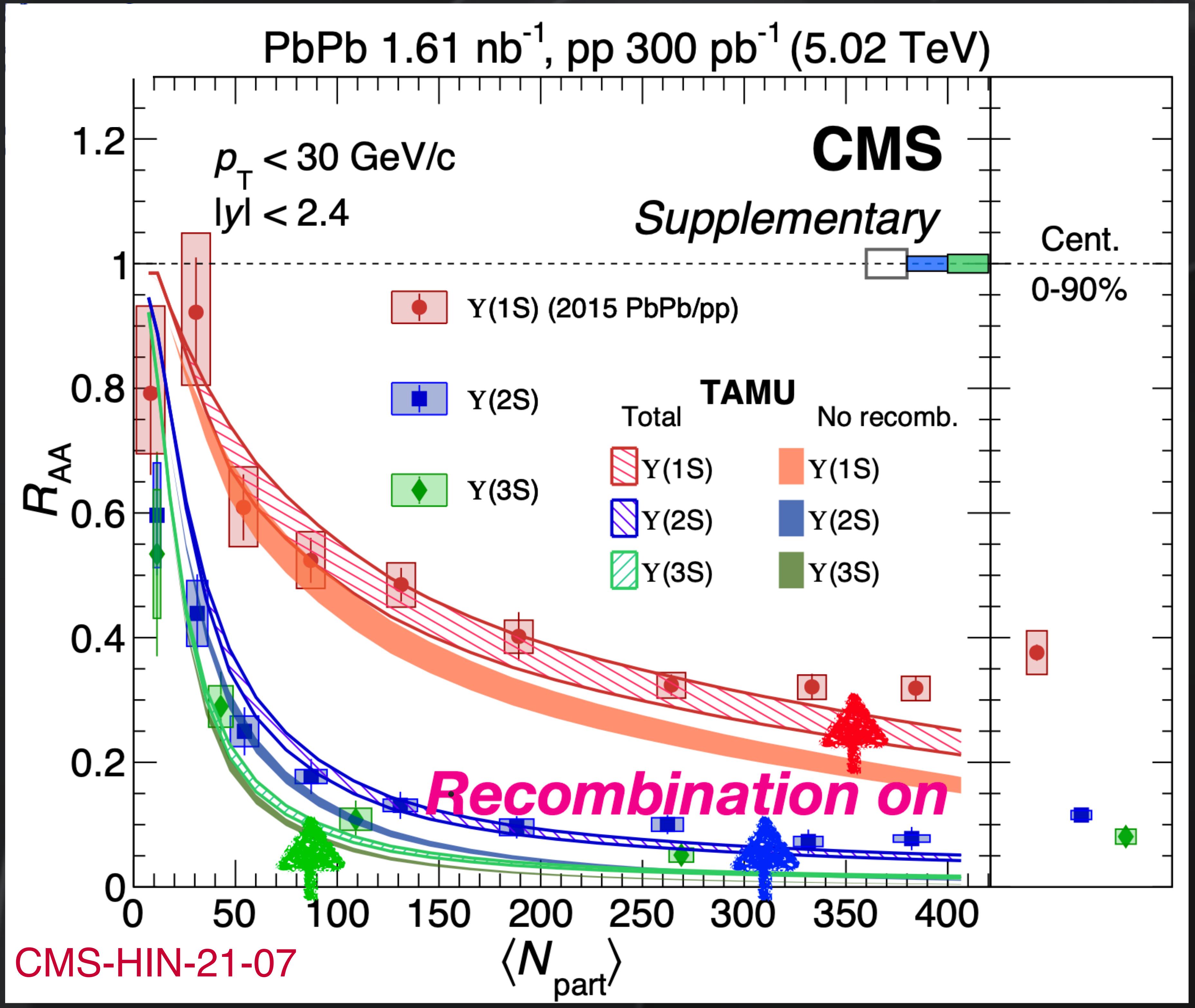
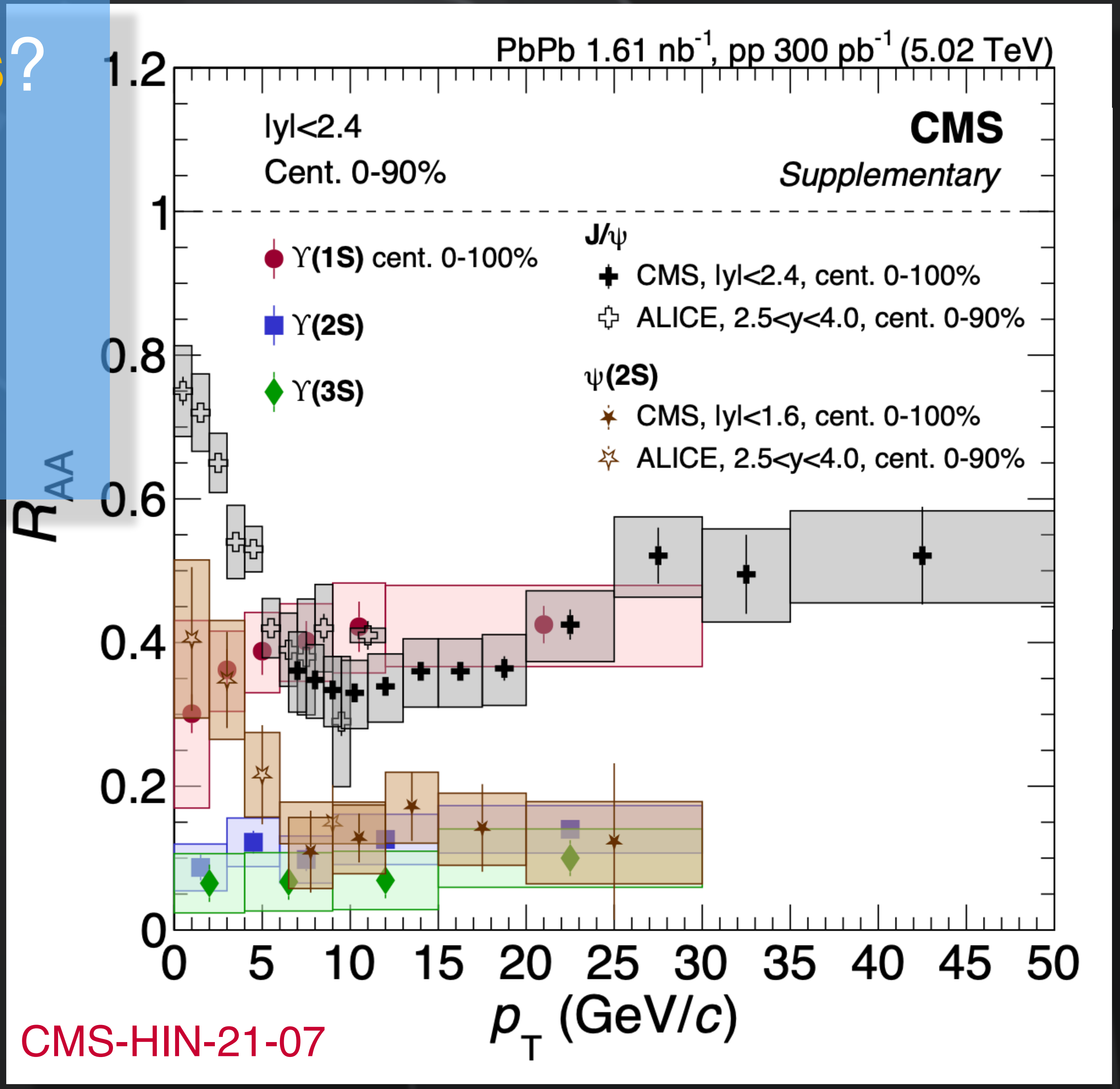


- Interplay of **multiple effects**?
  - Dissociation
  - Regeneration
  - Feed down fraction
  - Formation time



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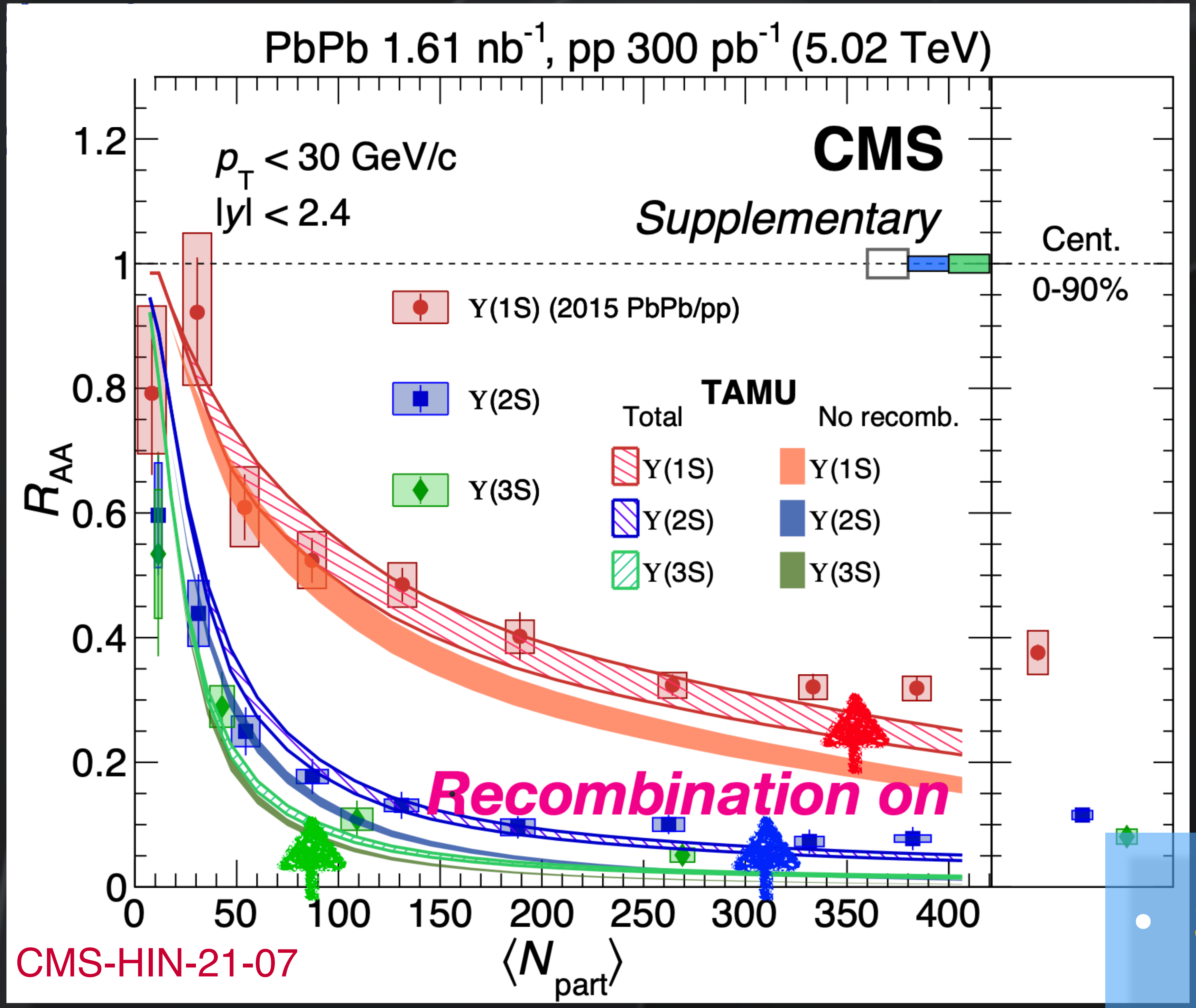

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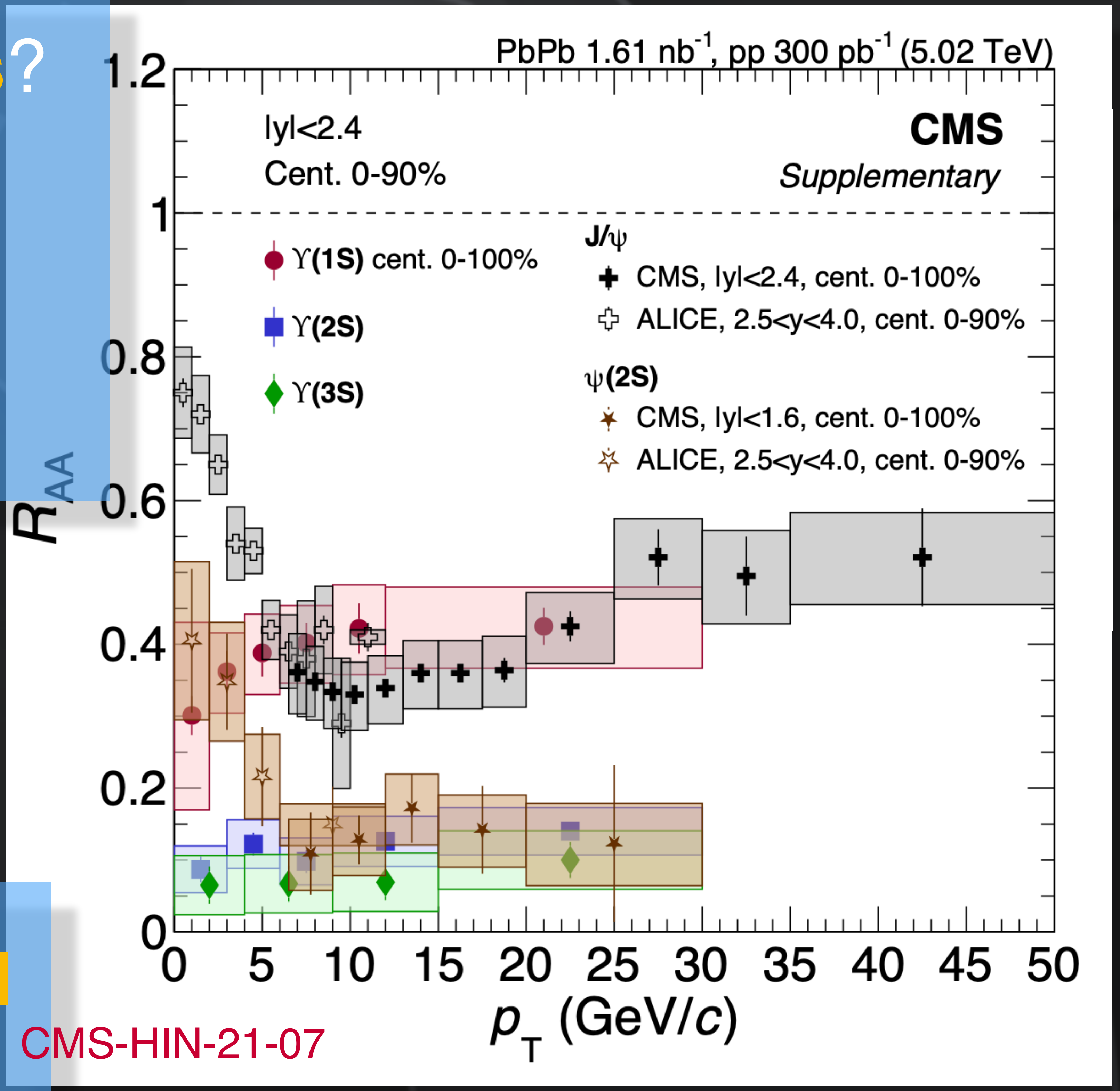
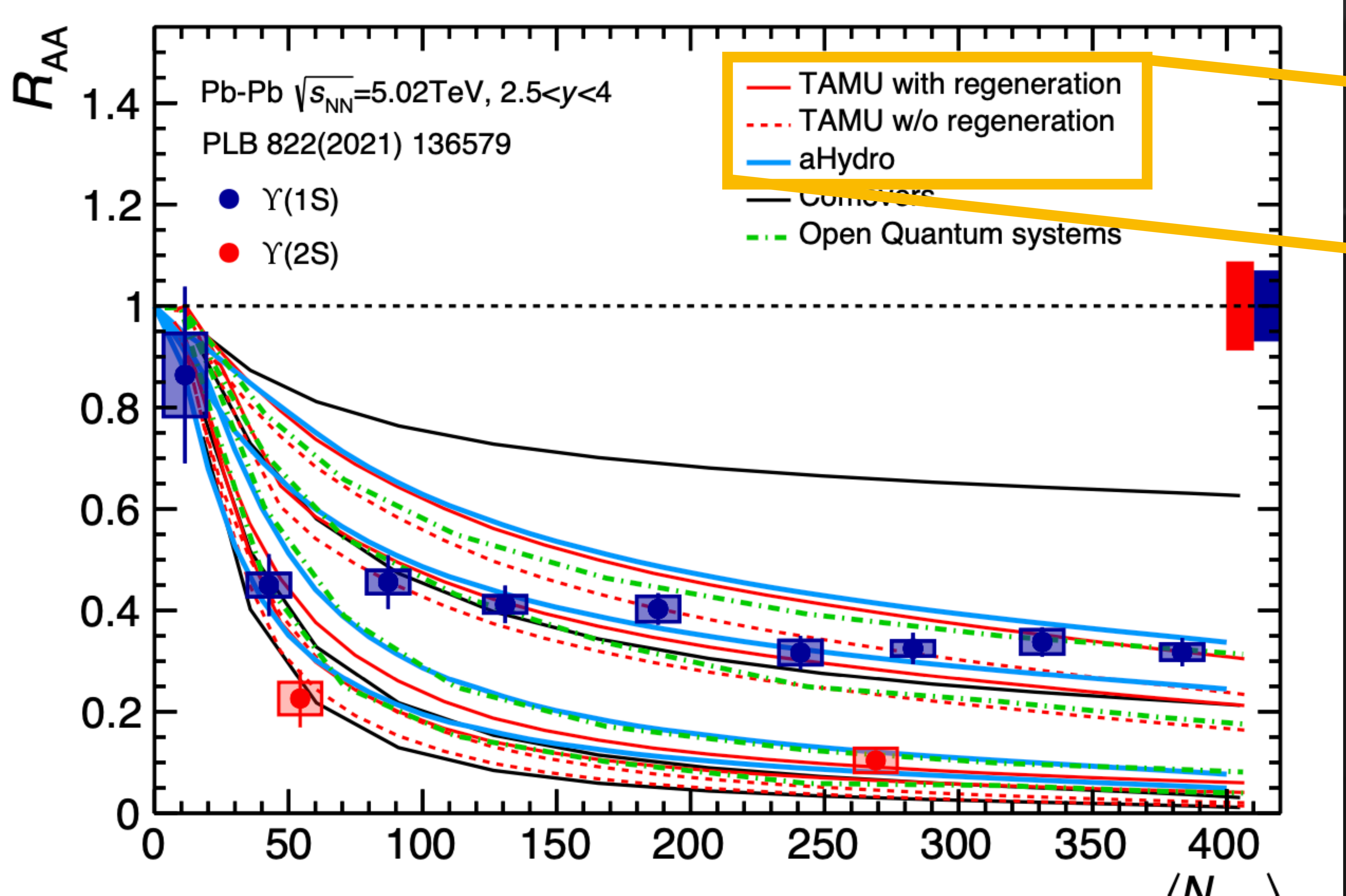


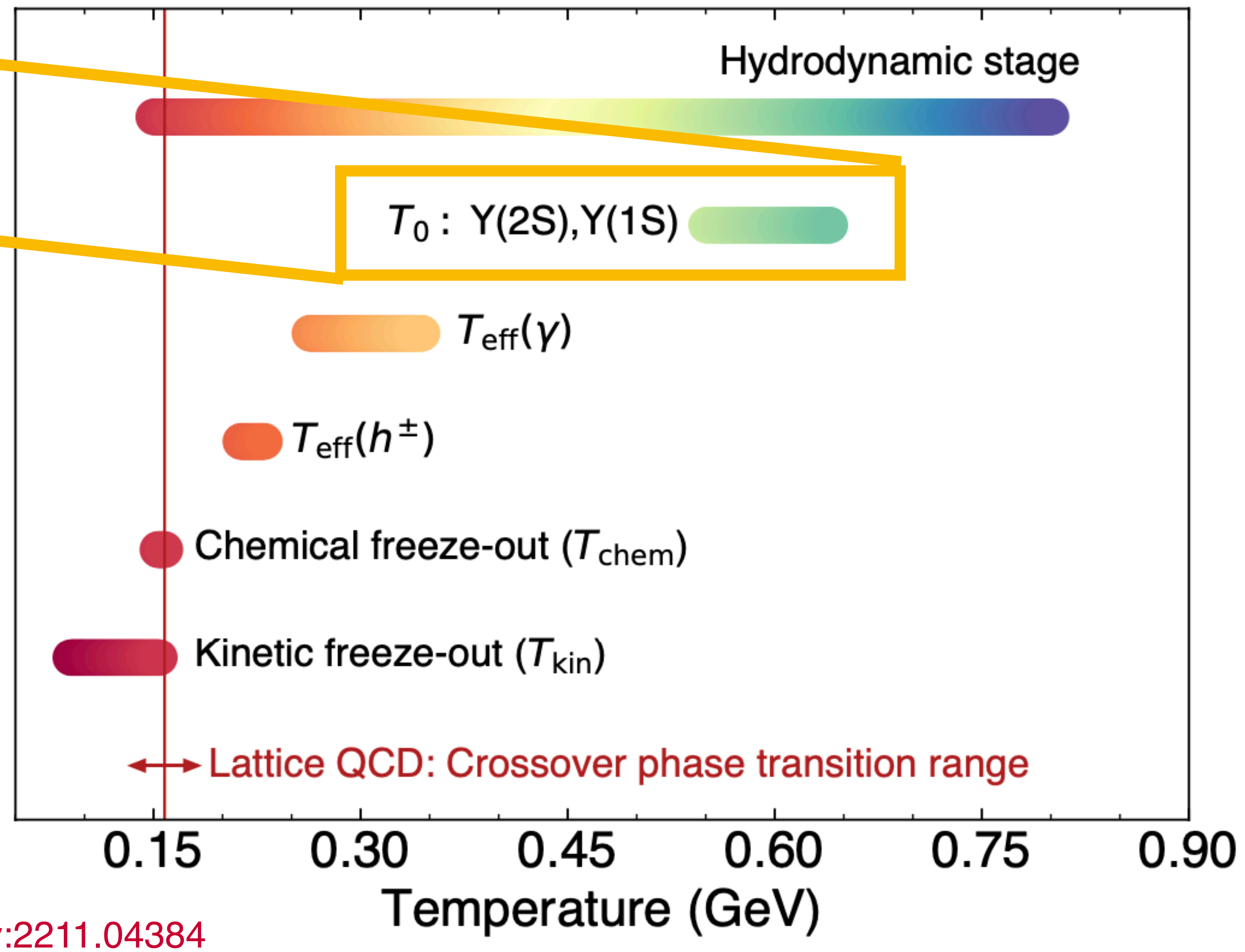
- **Strong suppression** and **small regeneration** on **bottomonium**

Towards QGP temperature

- **Two model calculations** implement color screening in hydro medium with initial **T_0 ~ 550-650 MeV**
  - Additional input to hydrodynamic descriptions of low-p_T light flavor observables to constrain the temperature range probed by heavy-ion collisions



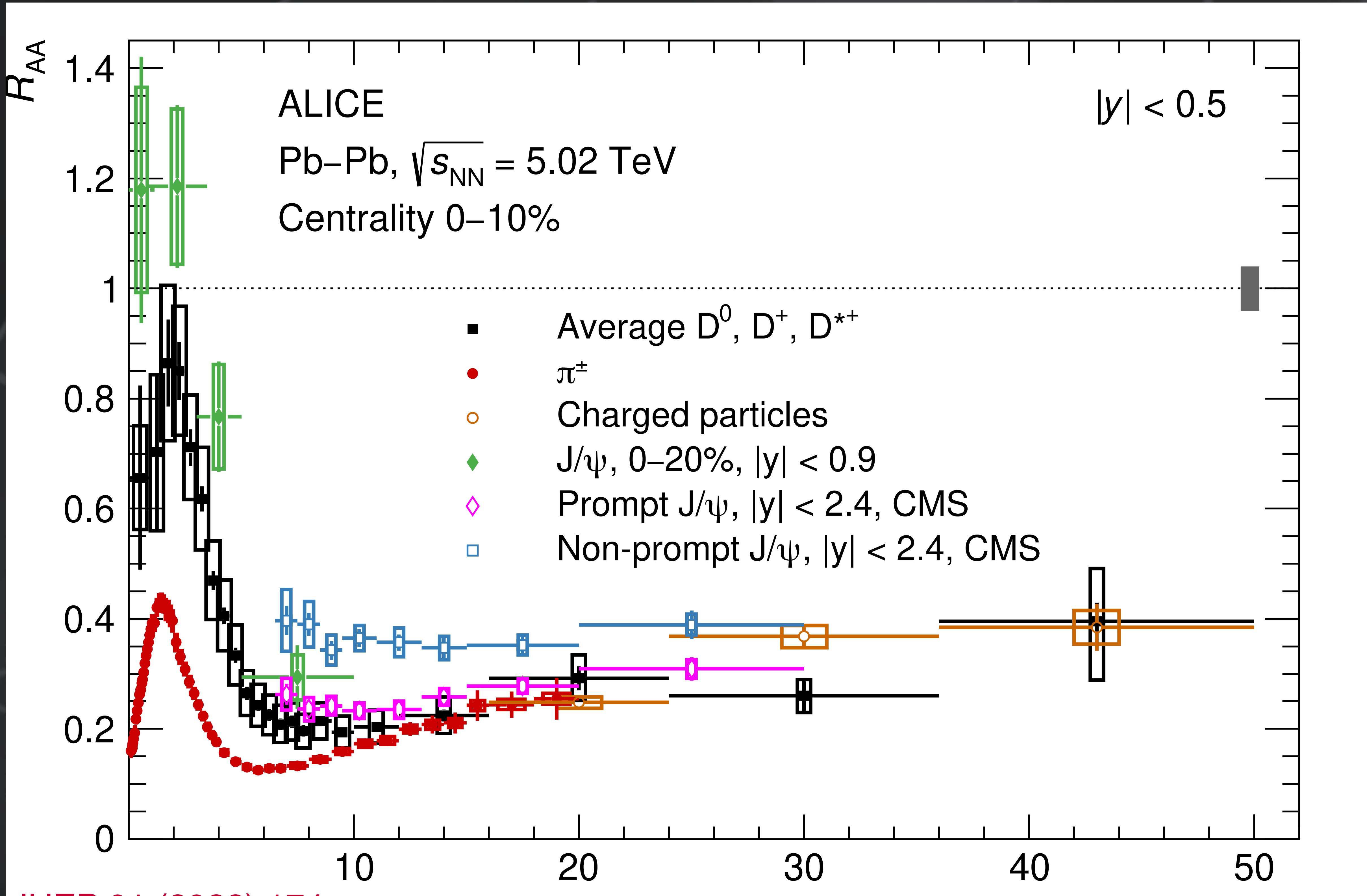
PLB 822(2021) 136579



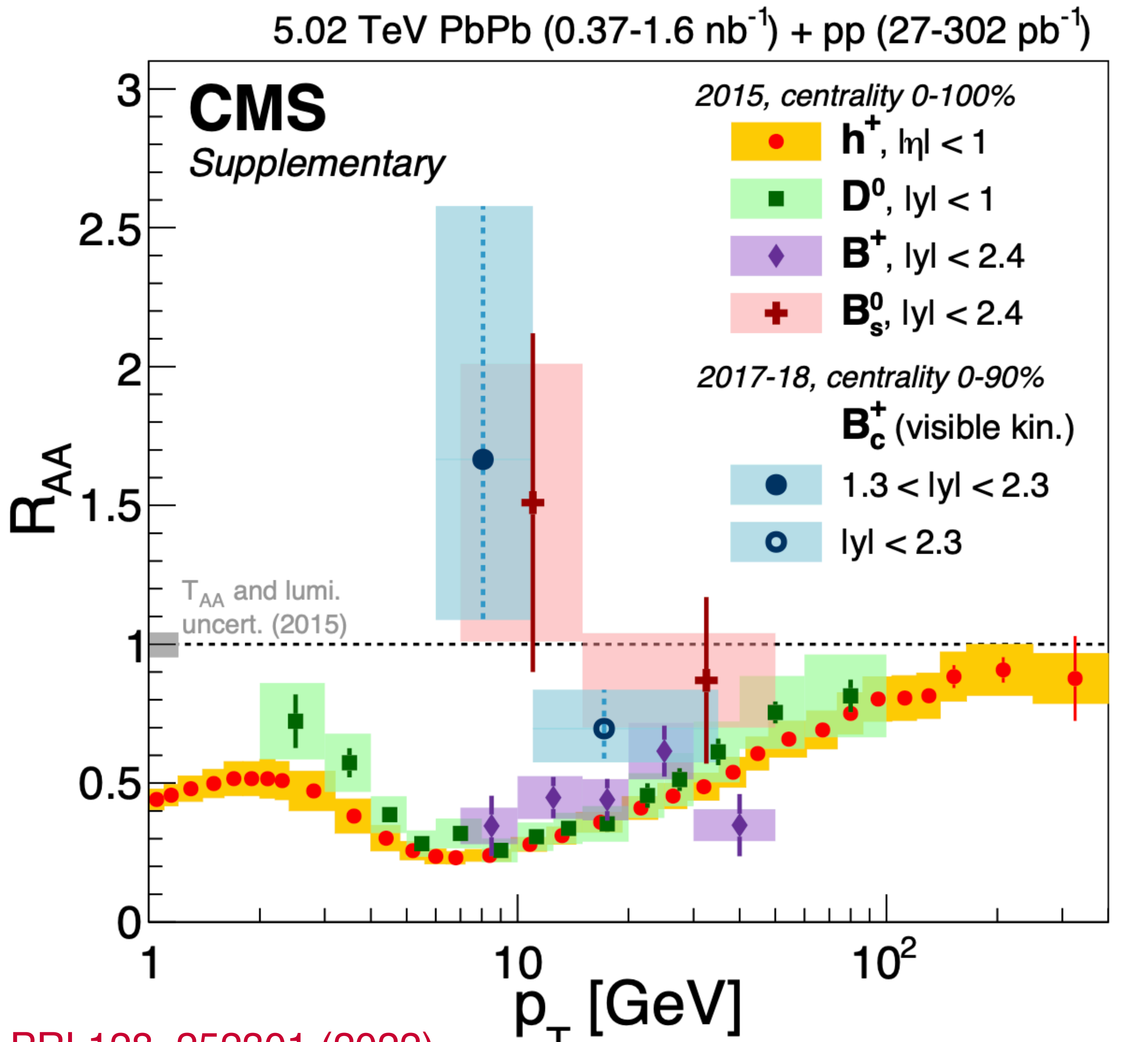
arXiv:2211.04384

R_{AA} of heavy-flavor hadrons

- R_{AA} hierarchy at intermediate p_T
  - $\pi^{\pm}$, $h^{\pm}$ < **prompt** D, **prompt** J/ψ < **non-prompt** J/ψ, B^{+} < B_c^{+}
  - Parton **mass energy loss** dependence



JHEP 01 (2022) 174
ALI-PUB-501944

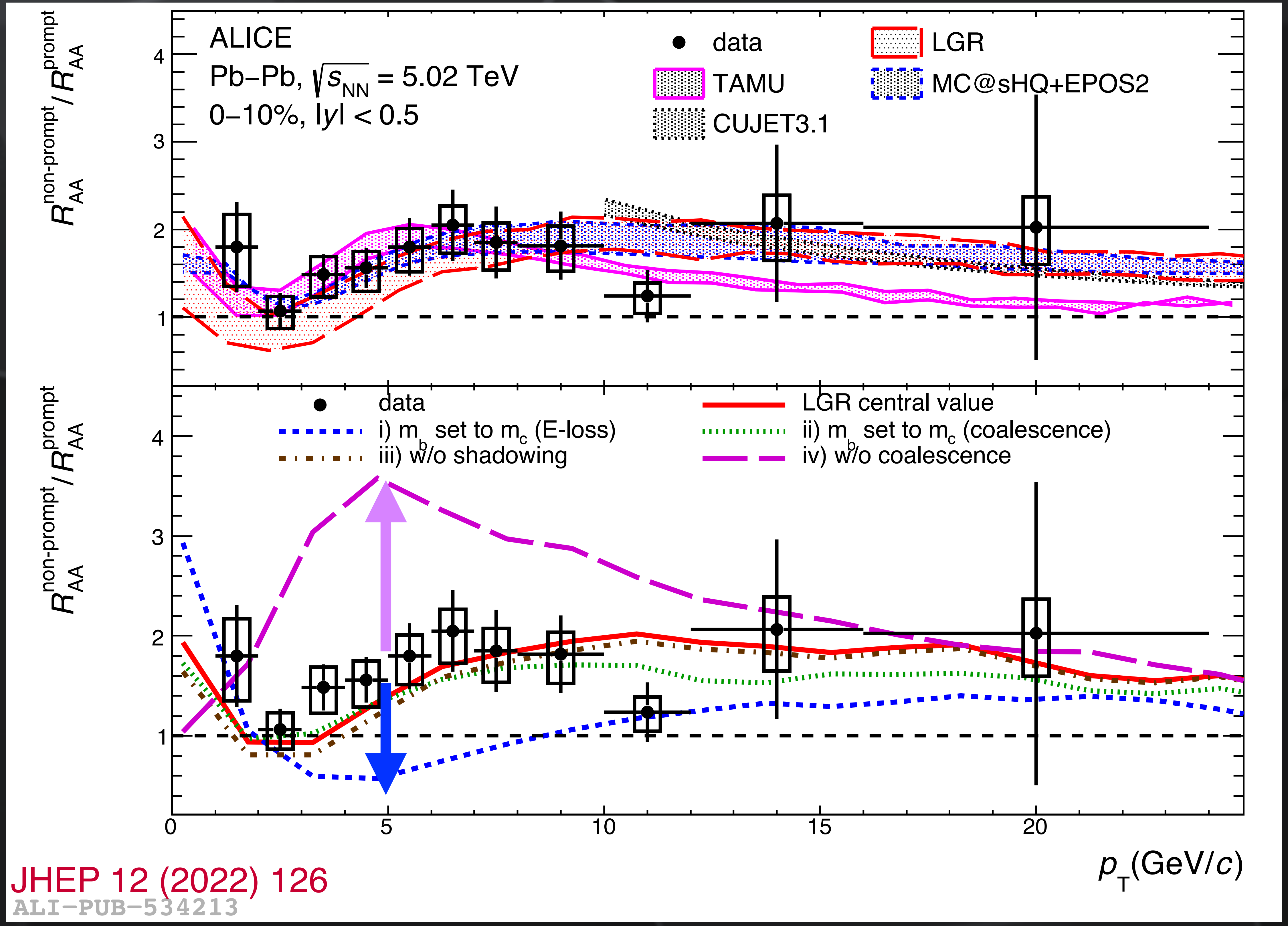


PRL128, 252301 (2022)

R_{AA} of heavy-flavor hadrons

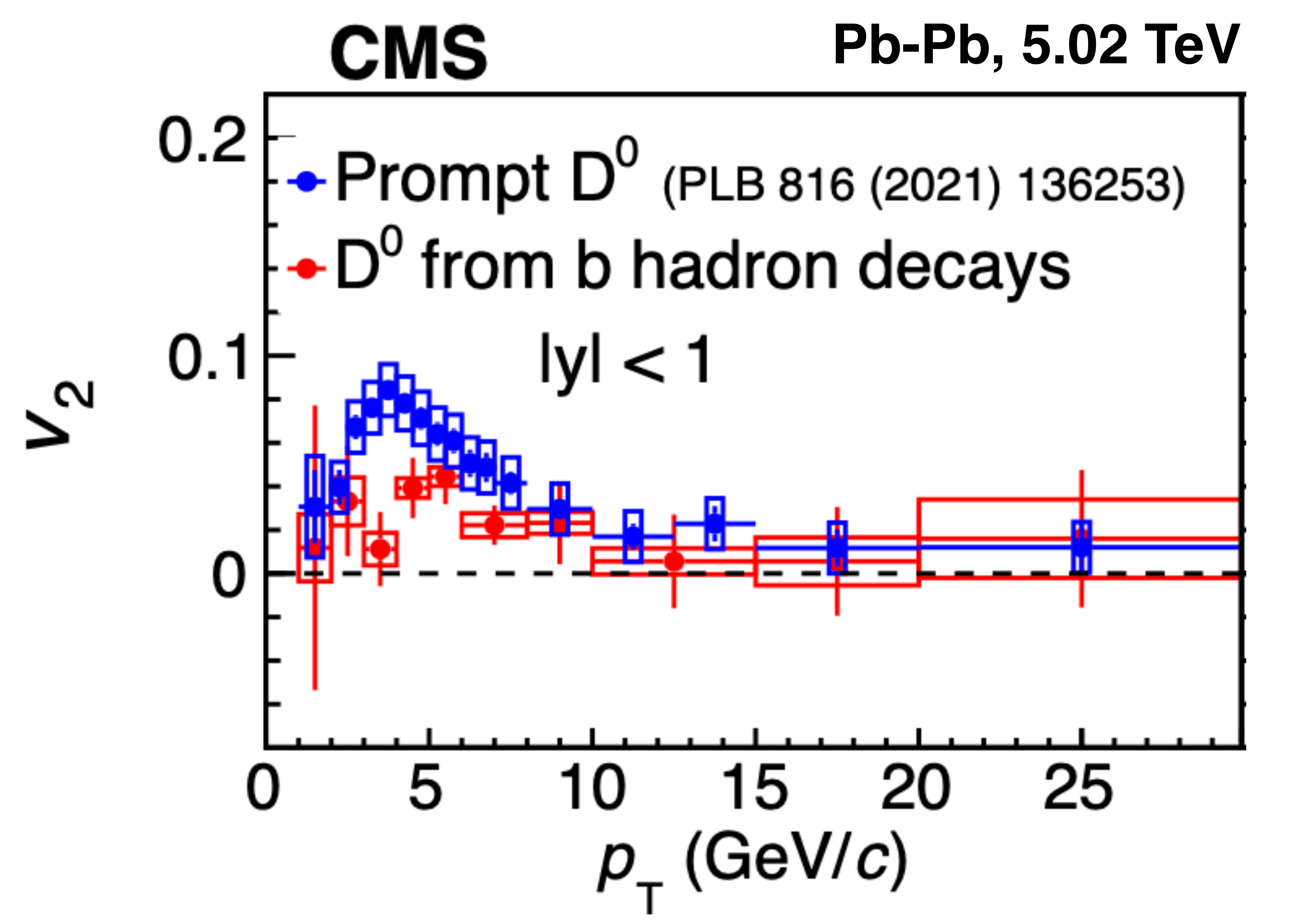
TAMU: PLB735 (2014) 445–450
CUJET: Chin. Phys. C 43 (2019) 044101
LGR: EPJC 80 (2020) 1113
MC@sHQ+EPOS2: PRC 89 (2014) 014905

- $R_{AA}^{non-prompt\,D}/R_{AA}^{prompt\,D} = 1.7 \pm 0.18$ ($p_T > 5$ GeV/c)
- **LGR model** shows a strong influence of **mass dependence** of parton energy loss and **coalescence**
  - **i) c mass in the calculation of the b energy loss**
  - ii) c mass in b coalescence
  - iii) w/o shadowing effects for c and b
  - **iv) w/o quark coalescence in c and b hadronization**

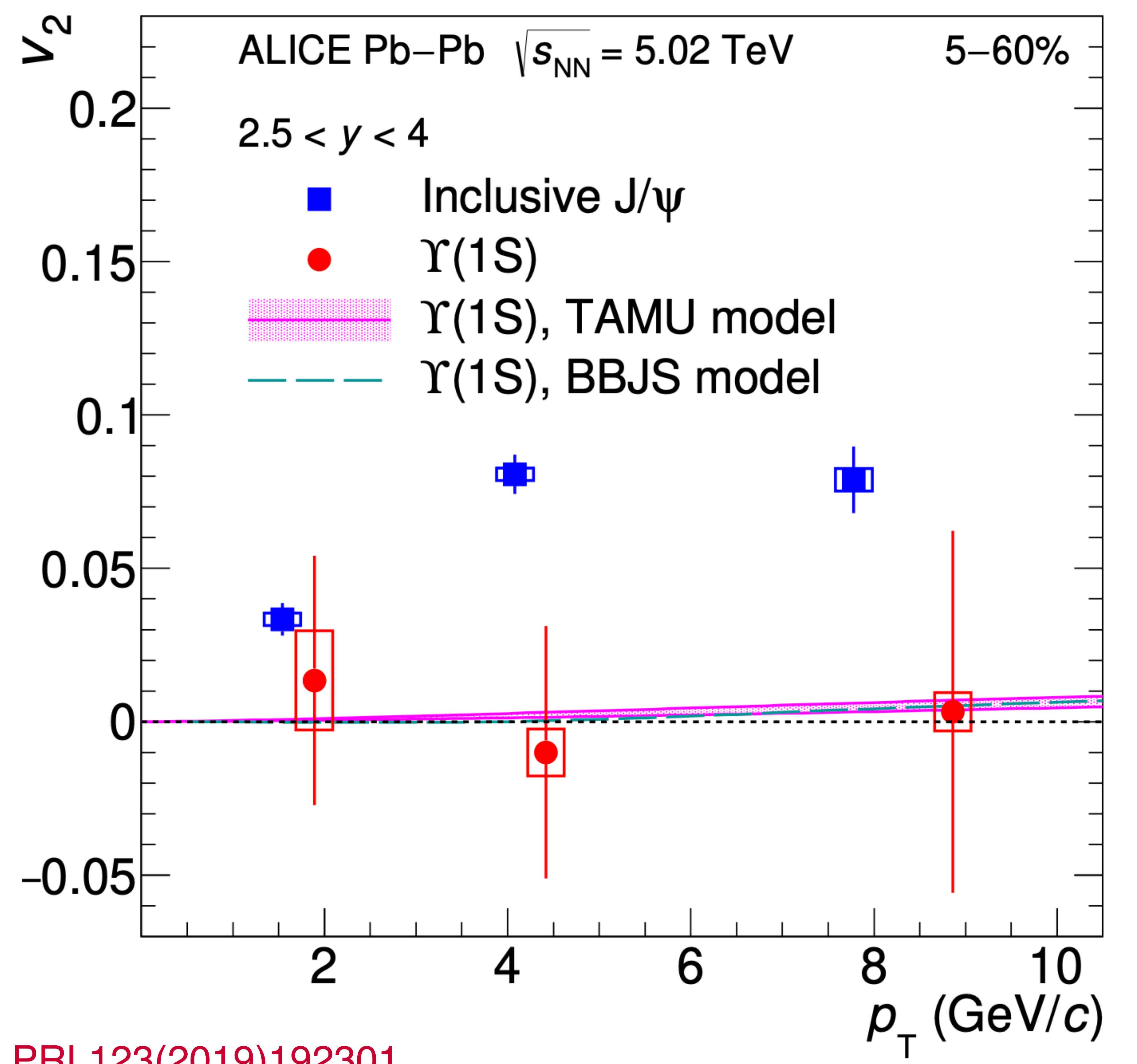


v_2 of open and hidden HF hadrons

- **Open HF hadrons**
  - Low p_T: **0 < beauty v_2 < charm v_2**
  - High p_T: **0 < beauty v_2 ~ charm v_2**
- **Hidden HF hadrons**
  - **$v_2(J/\psi) > 0$: Regeneration** from flowing **$c\bar{c}$ quarks**
  - **$v_2(\Upsilon(1S)) \sim 0$**: Large $\Upsilon(1S)$ **mass** & **small $b\bar{b}$ regeneration**



arXiv:2212.01636



PRL123(2019)192301

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- **Open HF hadrons**
  - Low p_T: **0 < beauty v_2 < charm v_2**
  - High p_T: **0 < beauty v_2 ~ charm v_2**
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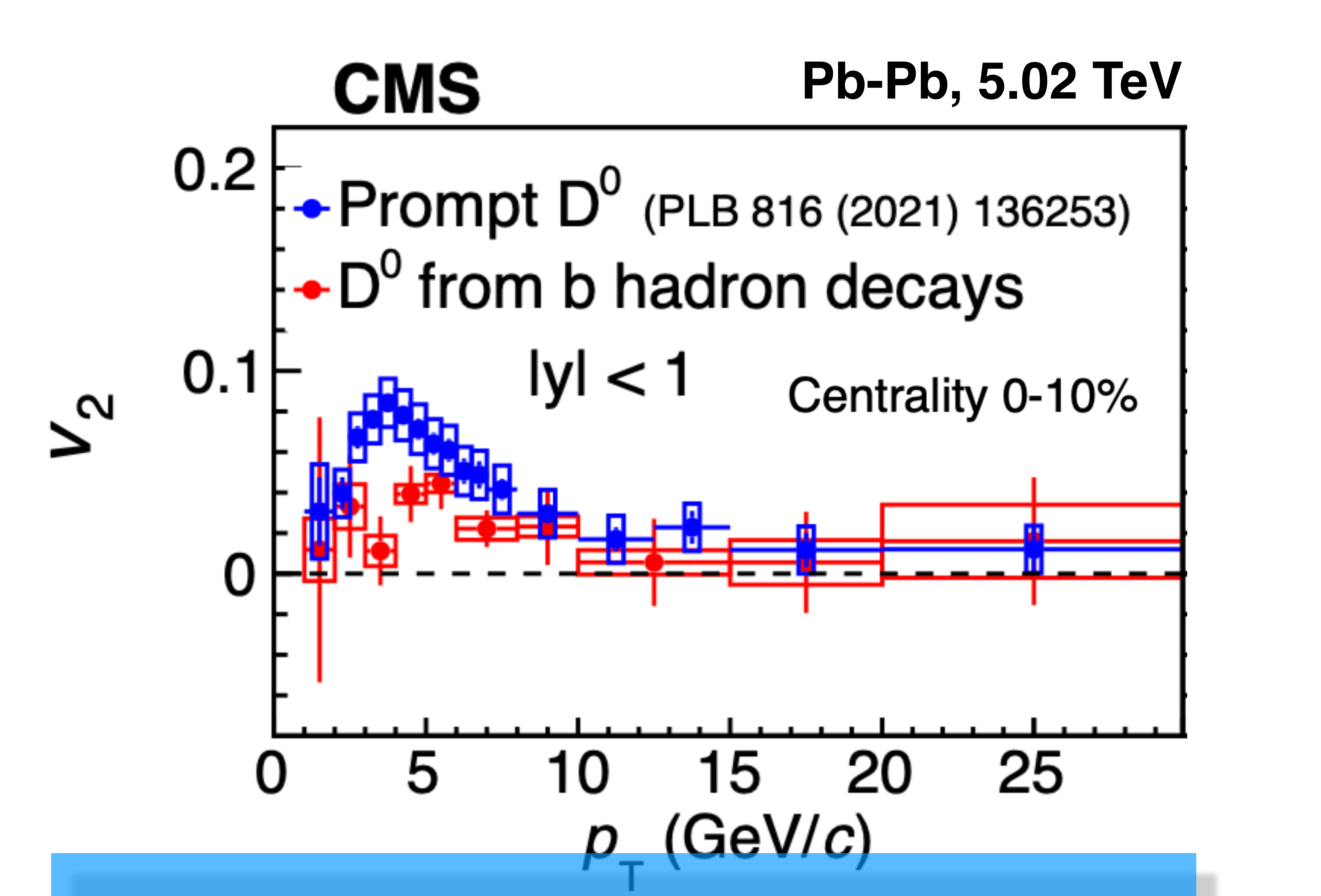
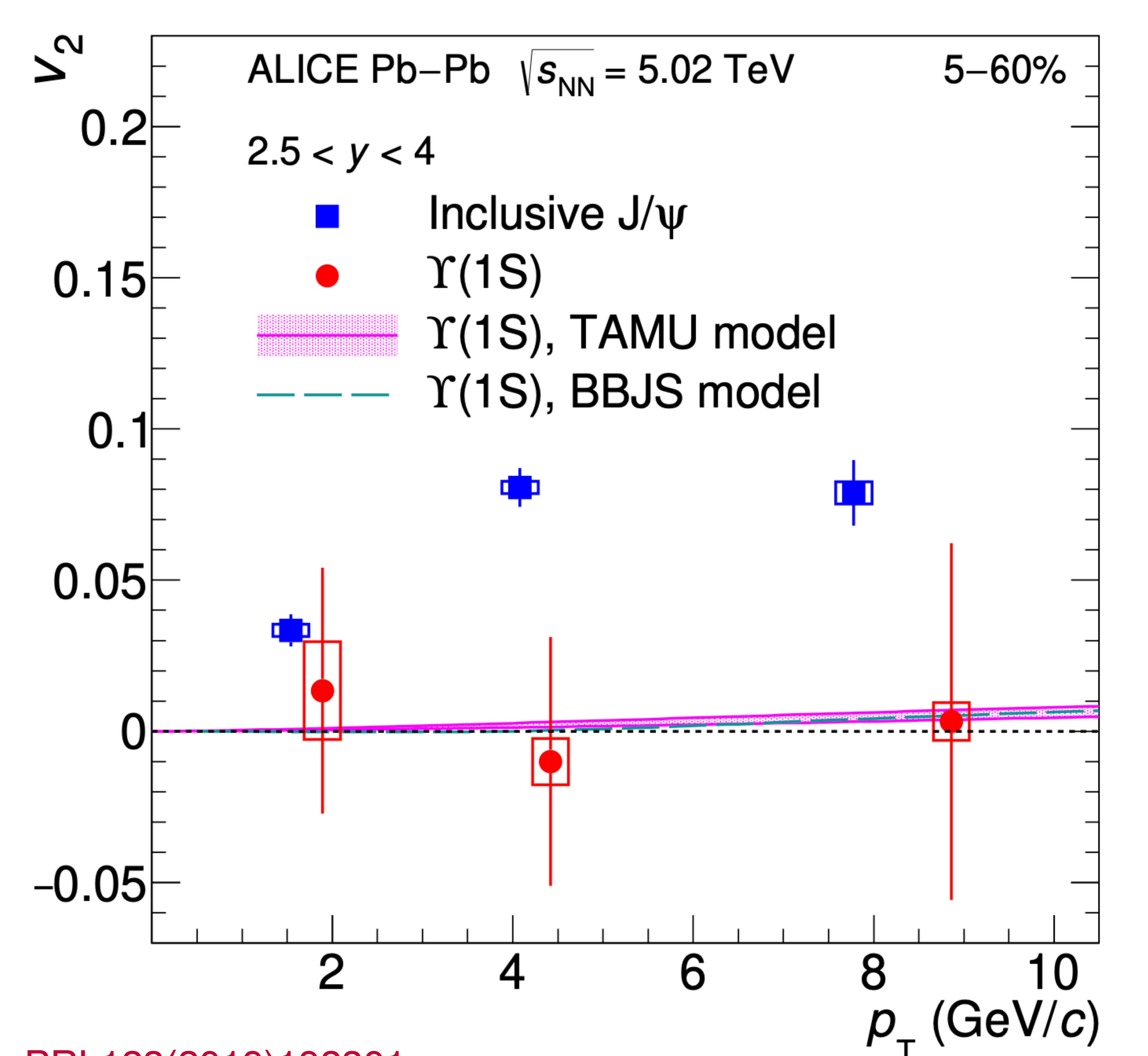


arXiv:2212.01636

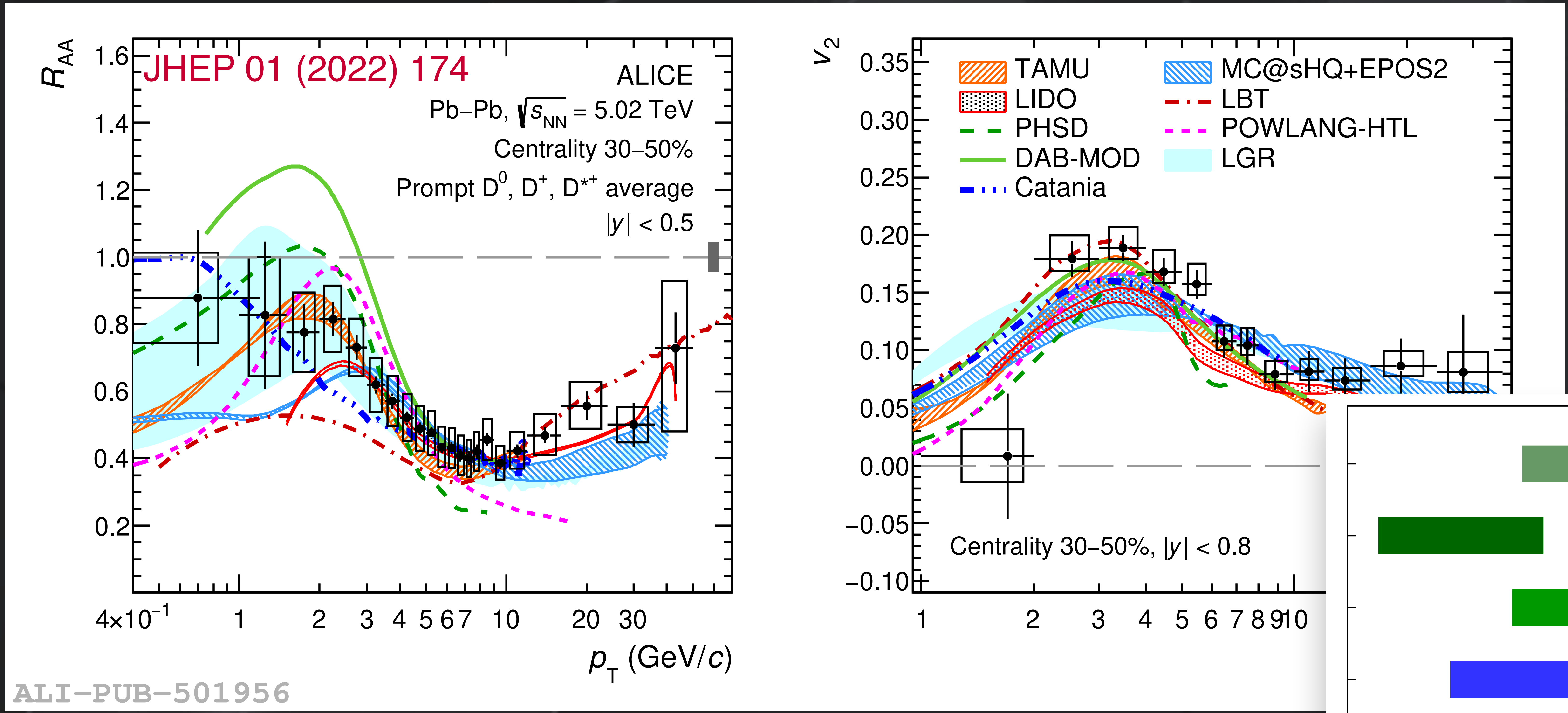
- **Smaller thermalization** for **beauty**?
- **Path-length dependence** of energy loss?



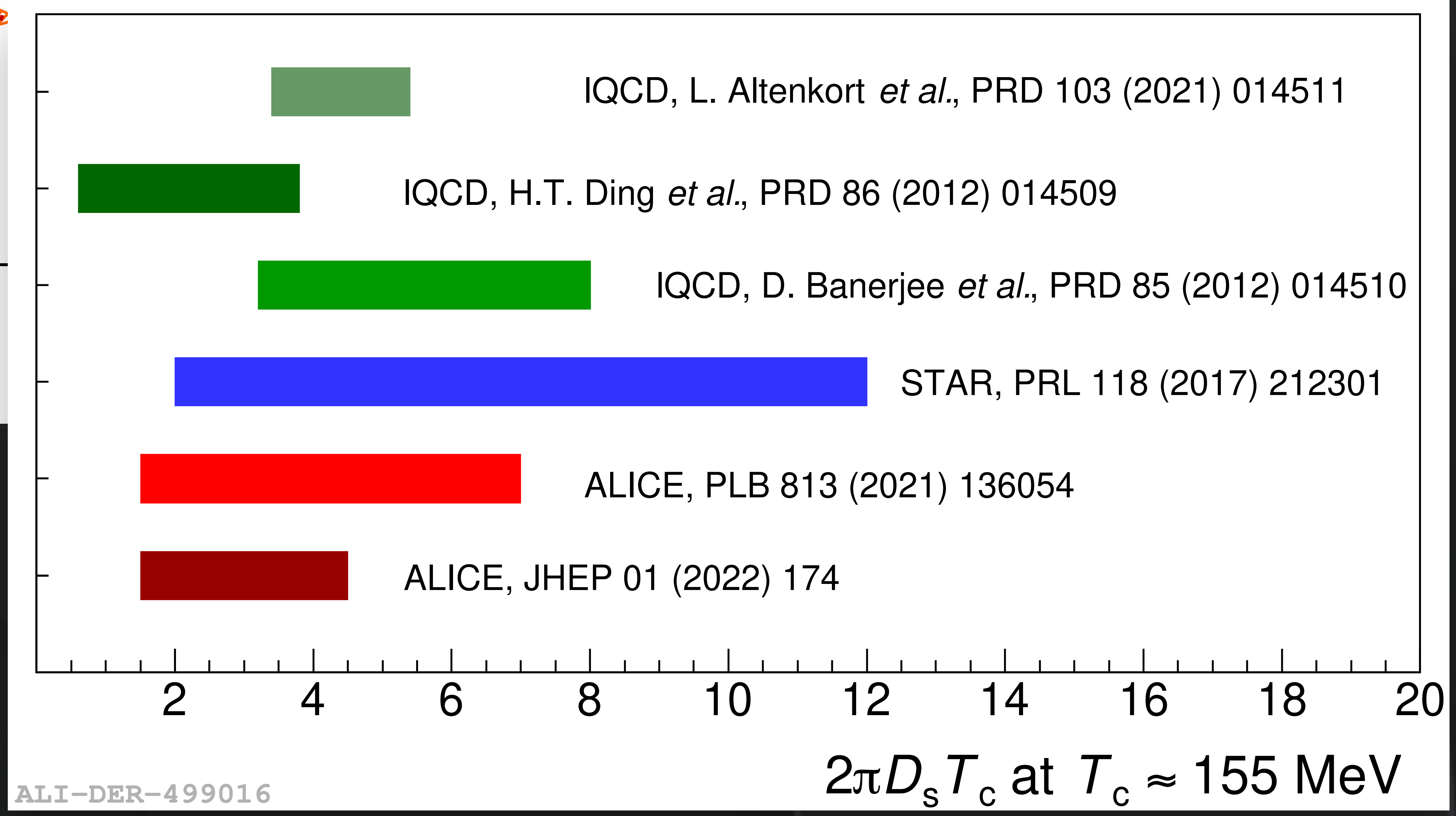
PRL123(2019)192301

Charm diffusion coefficient

- Diffusion coefficient(D_s) is obtained considering the measurements used in transport models



- Models include:
  - nPDF
  - Collisional + radiative process
  - Hydrodynamic expansion
  - Recombination

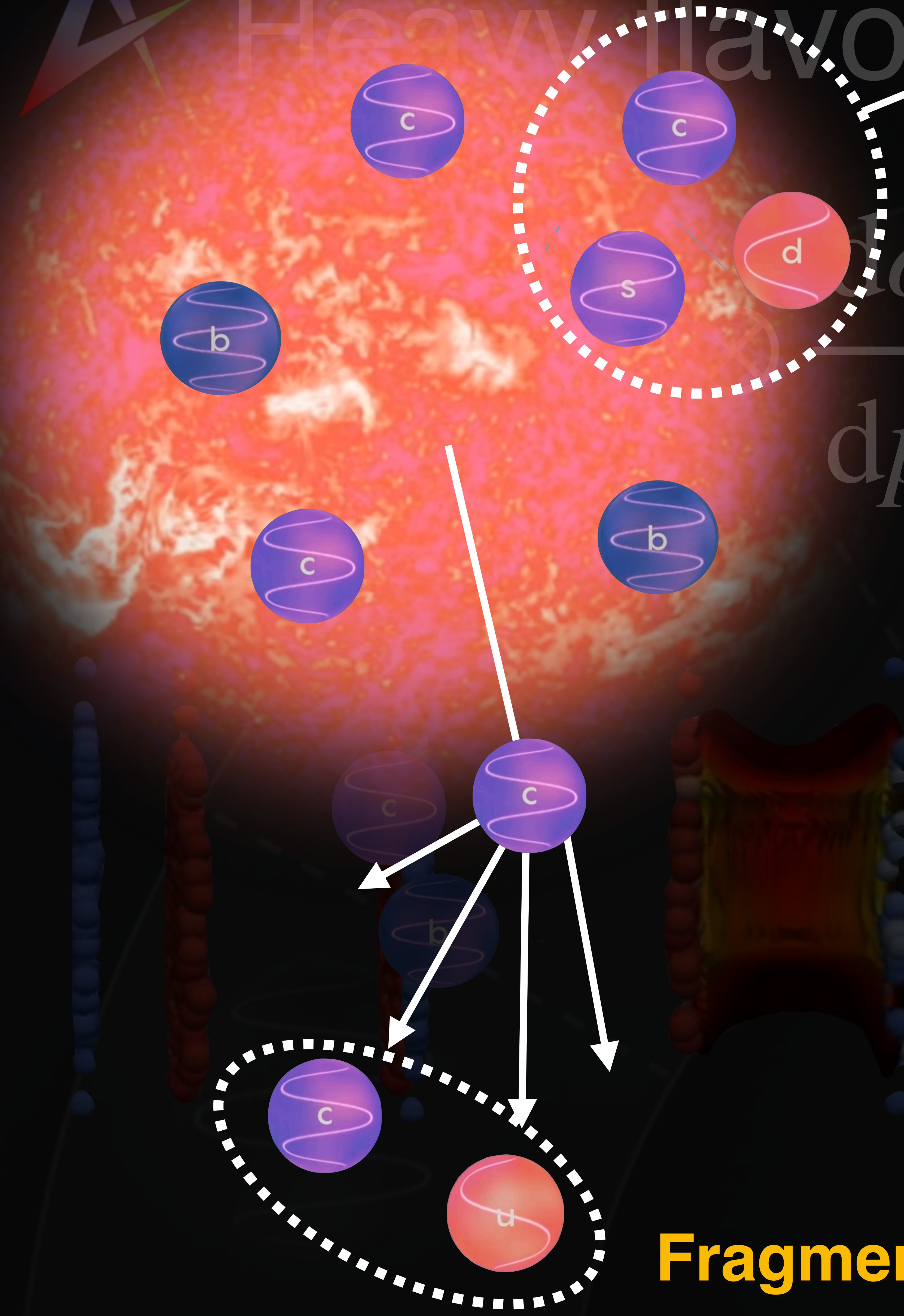


$3 < \tau_{charm} < 9$ fm/c

$$1.5 < 2\pi D_s T_c < 4.5$$

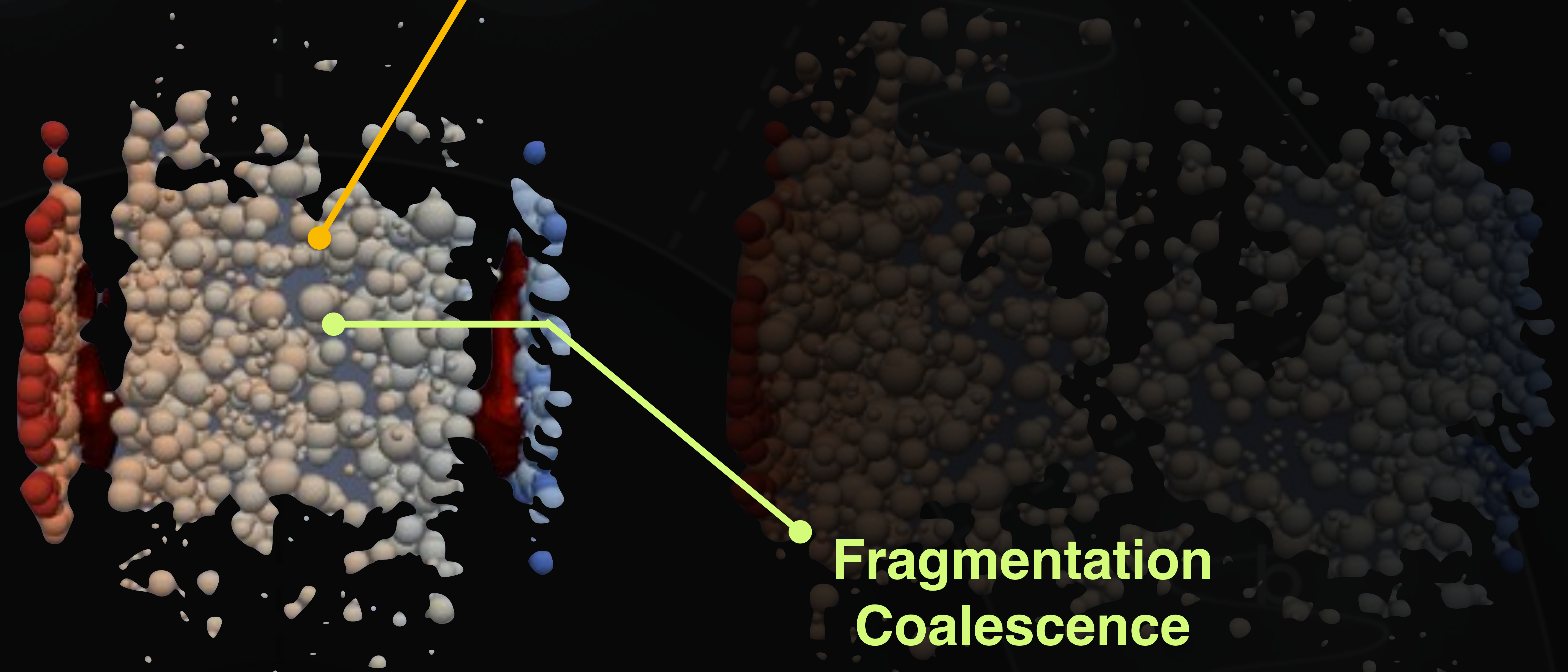
TAMU: PRL124 (2020) 042301
LIDO: PRC 100 n.6 (2019) 064911
PHSD: Phys. Rev. C 96 (2017) 014905
DAB-MOD: PRC 102 n.2 (2020) 024906
LBT: PRC 94 n.1 (2016) 014909
POWLANG+HLT: EPJC 75 n.3 (2015) 121
LGR: EPJC 80 (2020) 1113
MC@sHQ+EPOS2: PRC 89 (2014) 014905
Catania: PRC96 (2017) 044905

Heavy-flavor hadron production



Coalescence: Combitaion of quarks close in phase space

$$\frac{d\sigma^{c,b}}{dp_T^{c,b}} \otimes P_{c,b\to c'b'} \otimes D_{c'b'\to h} = \frac{d\sigma^{h}}{dp_T^{h}}$$



Fragmentation
Coalescence

Fragmentation: Break up of heavy-flavor quark as in $e^{+}+e^{-}$ collisions (also expected in pp collisions)

Meson-to-meson ratio in pp collisions

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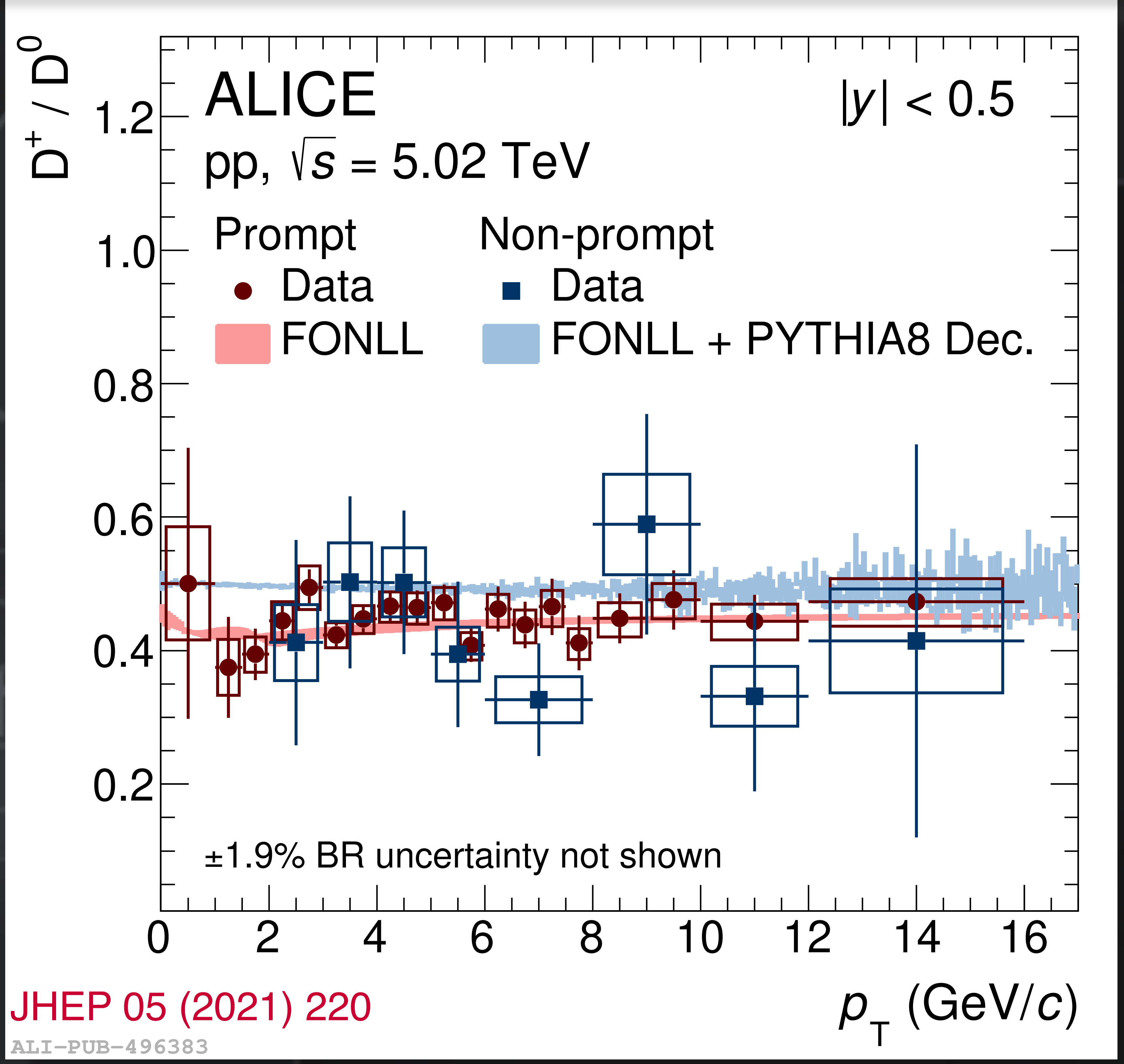
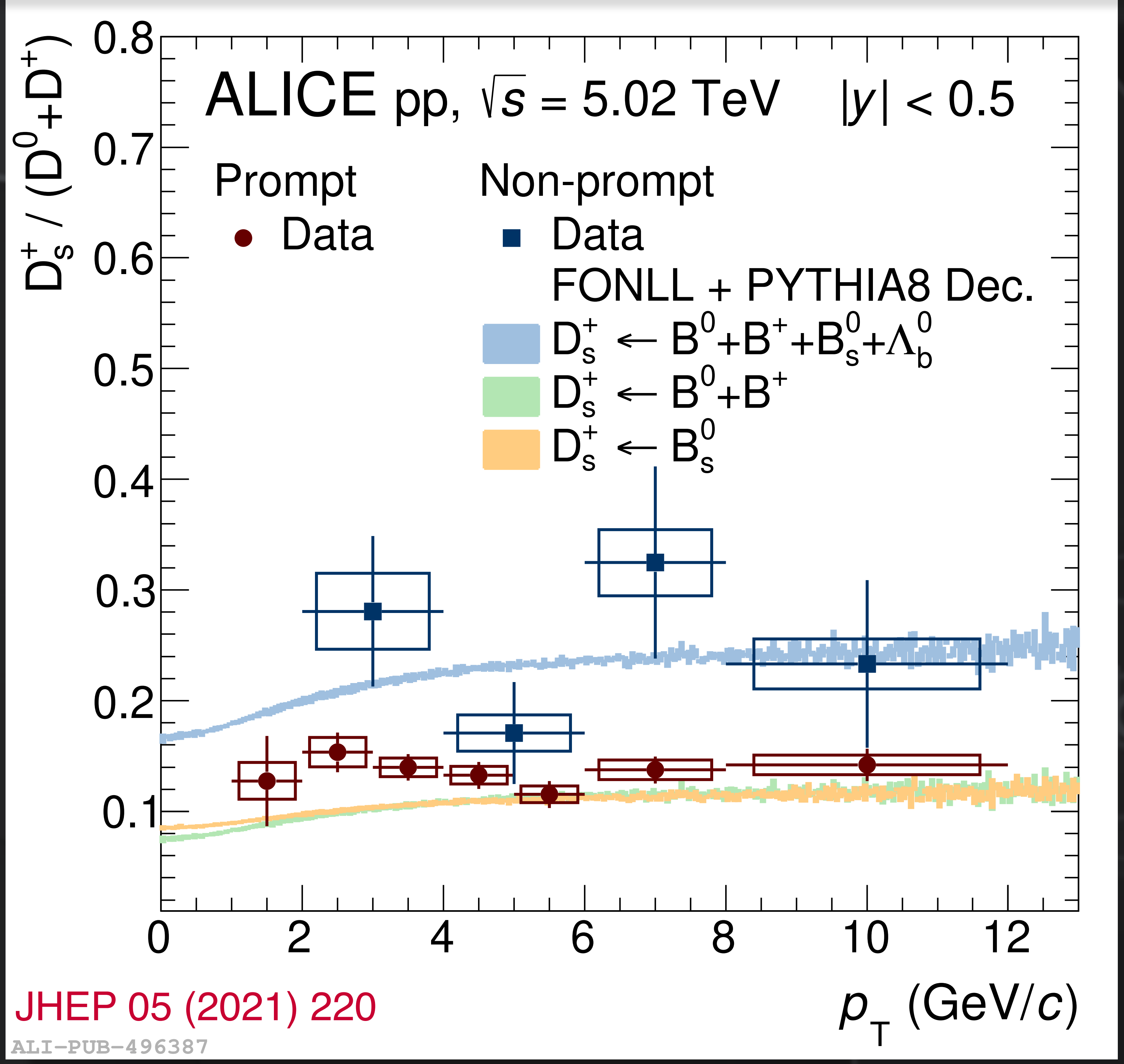
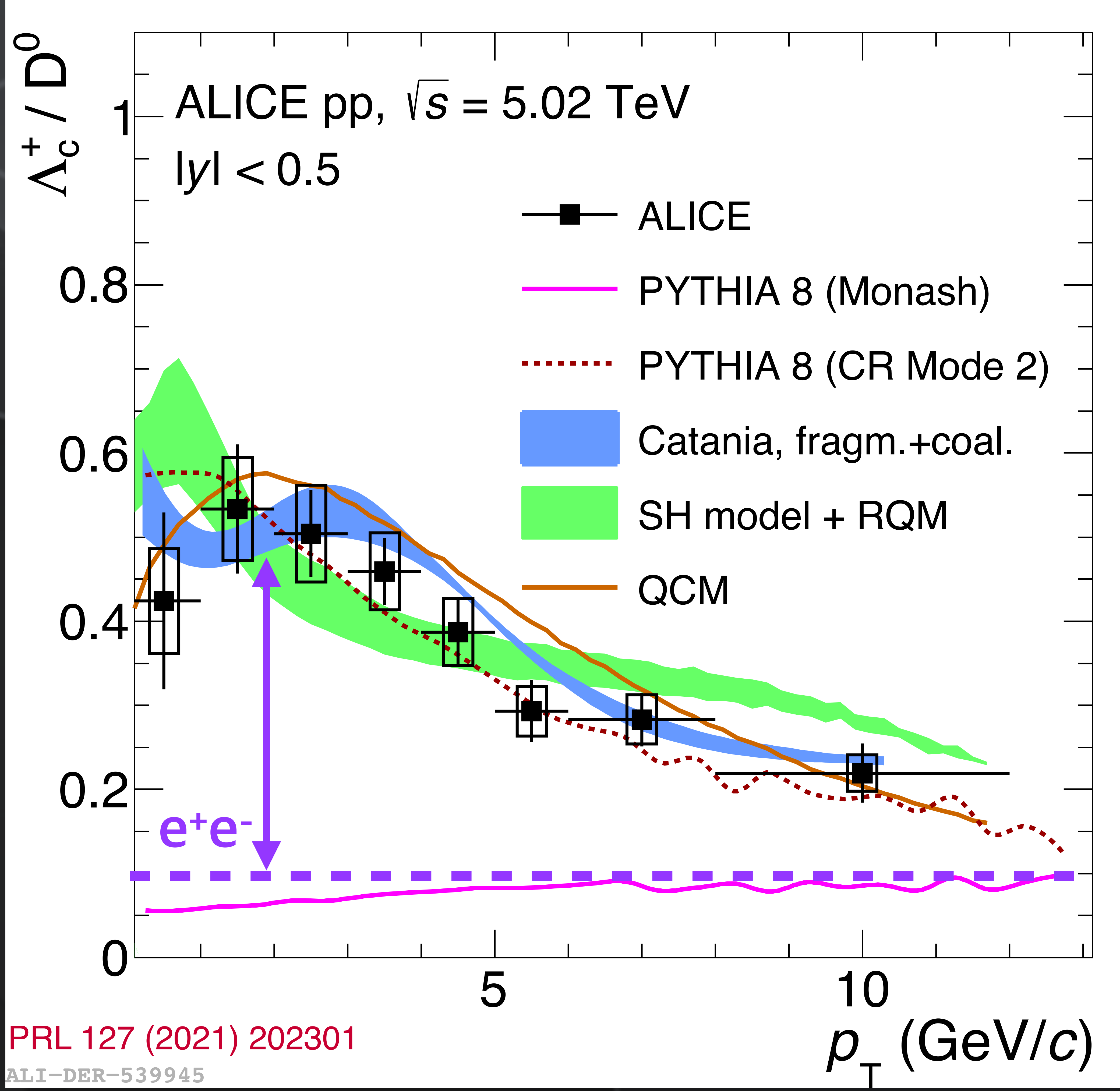
- Meson-to-meson ratios are independent of p_T and collision system
- Good agreement with theoretical calculations
  - NLO pQCD calculation with **fragmentation functions** from measurements at e^++e^- and ep colliders, assumed to be **universal** across collision systems





Λ_c^+/D^0 ratio in pp collisions

- **PYTHIA 8 with Color Reconnection (CR)**
  - **Monash**: Color reconnection between MPIs
  - **CR-BLC**: Add Junction connection
- **SHM + additional baryon states**
  - Hadronization by statistical weights + strong feed-down
    - **PDG**: 5Λ_c (I=0), 3Σ_c (I=1), 8Ξ_c (I=1/2), 2Ω_c (I=0)
    - **RQM**: Additional 18Λ_c, 42 Σ_c, 62 Ξ_c, 34Ω_c
- **Catania model**
  - c hadronize via **vacuum** fragmentation + **coalescence**
- **QCM (Quark (re-)Combination Model)**
  - Recombination of c and comving light quarks



Monash: EPJC 74 (2014) 3024
CR-BLC: JHEP 08 (2015) 003
Catania: PLB 821 (2021) 136622)

SHM: PLB 795 (2019) 117-121
RQM: PRD 84 (2011) 014025
QCM: EPJC 78 no.4, (2018) 344

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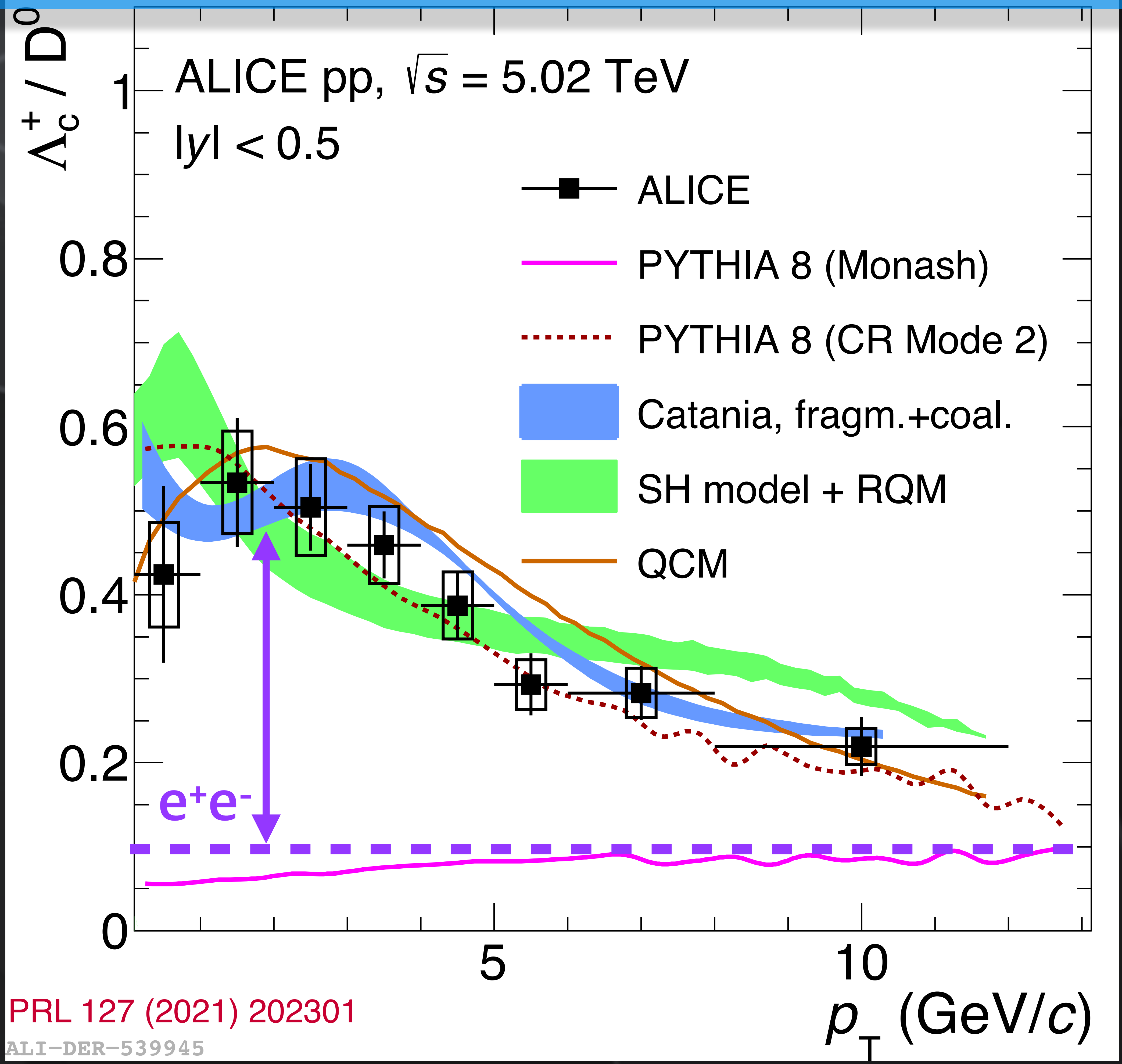
- **SHM + additional baryon states**
  - Hadronization by statistical weights + strong feed-down
    - **PDG**: 5Λ_c (I=0), 3Σ_c (I=1), 8Ξ_c (I=1/2), 2Ω_c (I=0)
    - **RQM**: Additional 18Λ_c, 42 Σ_c, 62 Ξ_c, 34Ω_c
- **Catania model**
  - c hadronize via **vacuum** fragmentation + **coalescence**
- **QCM (Quark (re-)Combination Model)**
  - Recombination of c and comving light quarks

- **Universality of charm fragmentation** is **broken** among **different collision system**



Monash: EPJC 74 (2014) 3024
CR-BLC: JHEP 08 (2015) 003
Catania: PLB 821 (2021) 136622)
SHM: PLB 795 (2019) 117-121
RQM: PRD 84 (2011) 014025
QCM: EPJC 78 no.4, (2018) 344

Λ_c^+/D^0 ratio in pp collisions

- **PYTHIA 8 with Color Reconnection (CR)**
  - **Monash**: Color reconnection between MPIs
  - **CR-BLC**: Add Junction connection
- **SHM + additional baryon states**
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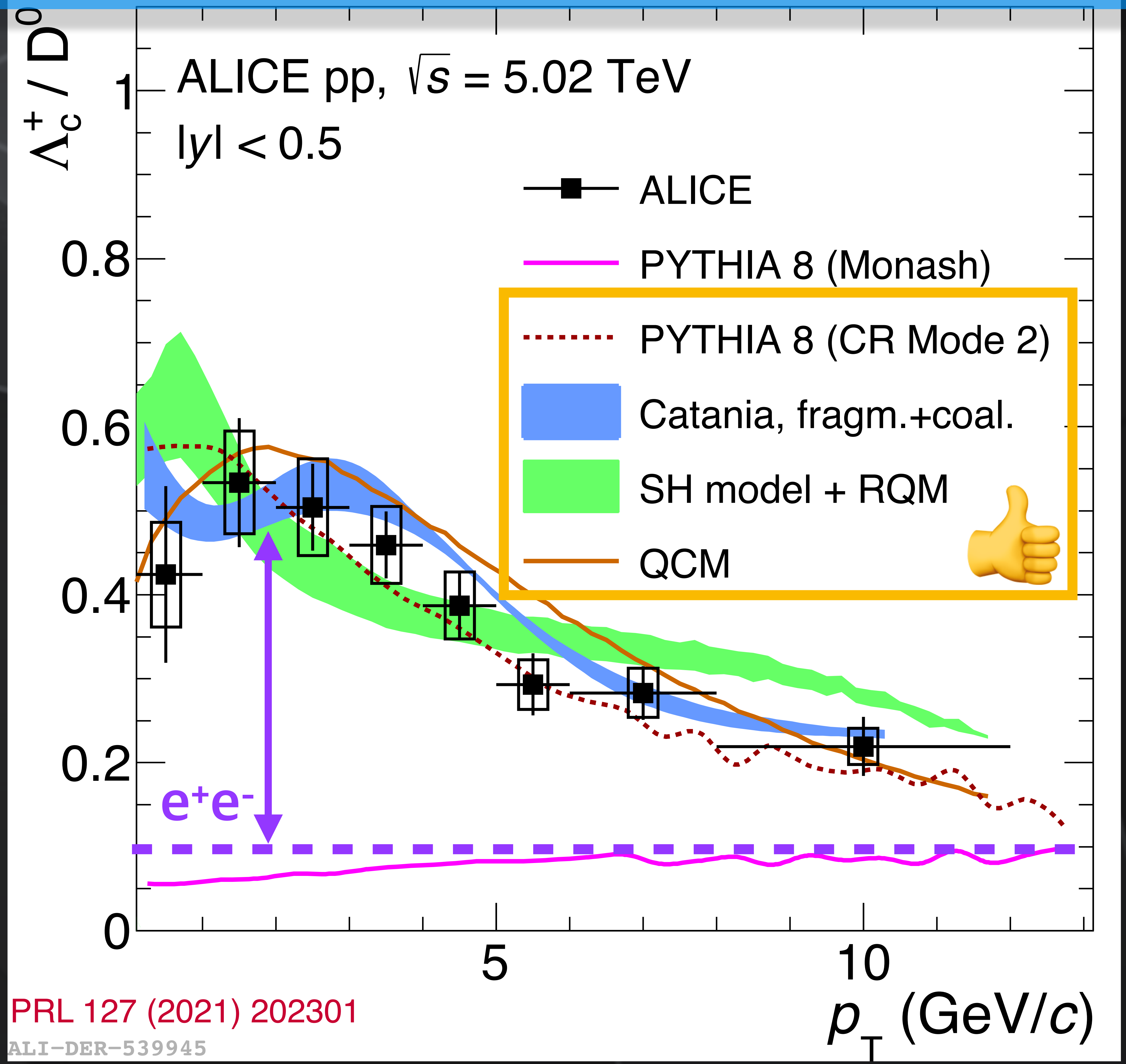

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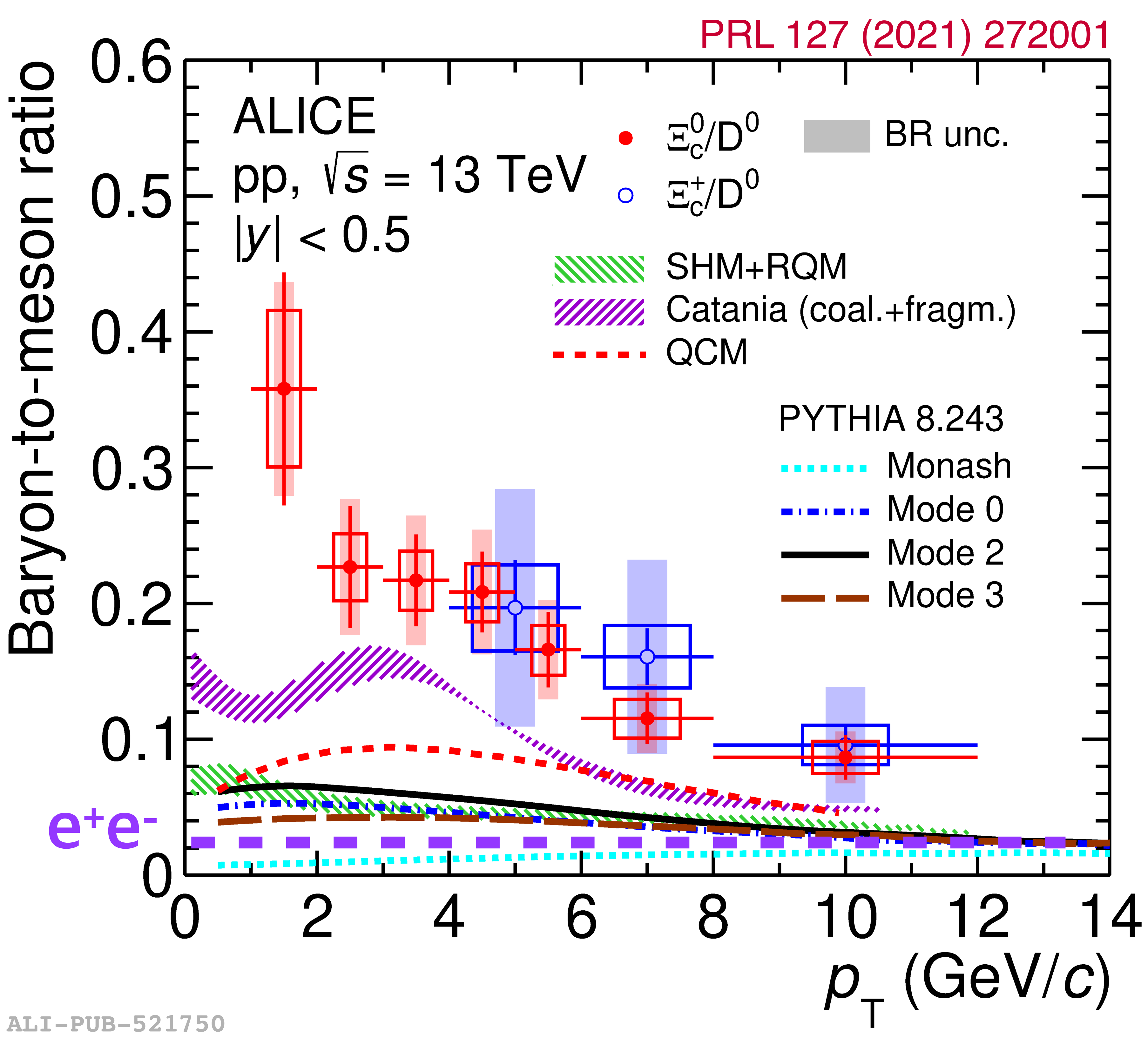
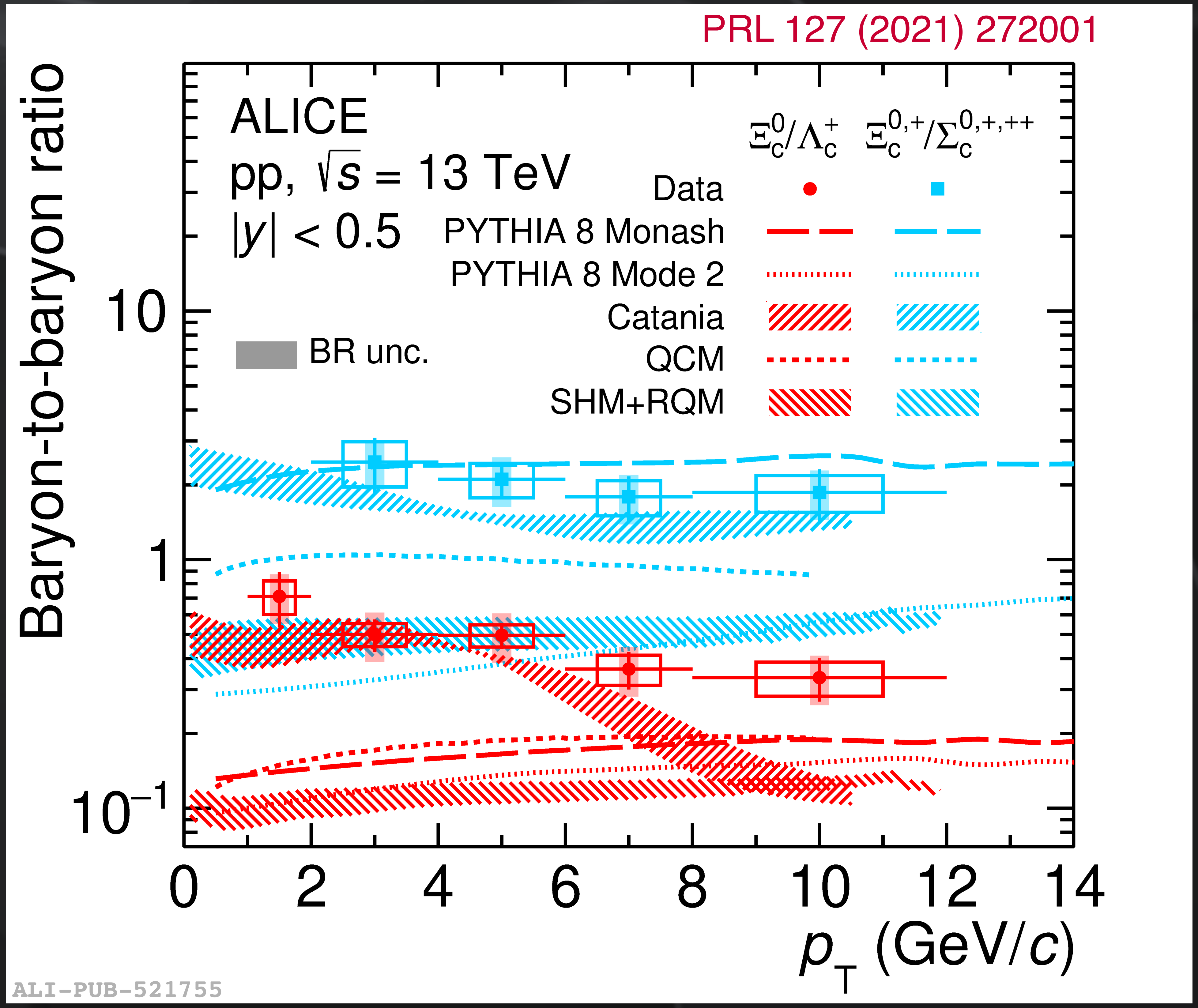
Charm strange baryons in pp collisions

- **Enhancement at low p_T** with respect to e^++e^-, ep measurements.
- Most model calculations underestimate the measurements.
- $\Xi_c^{0,+}/\Sigma_c^{0,++}$ in agreement with Monash tune.





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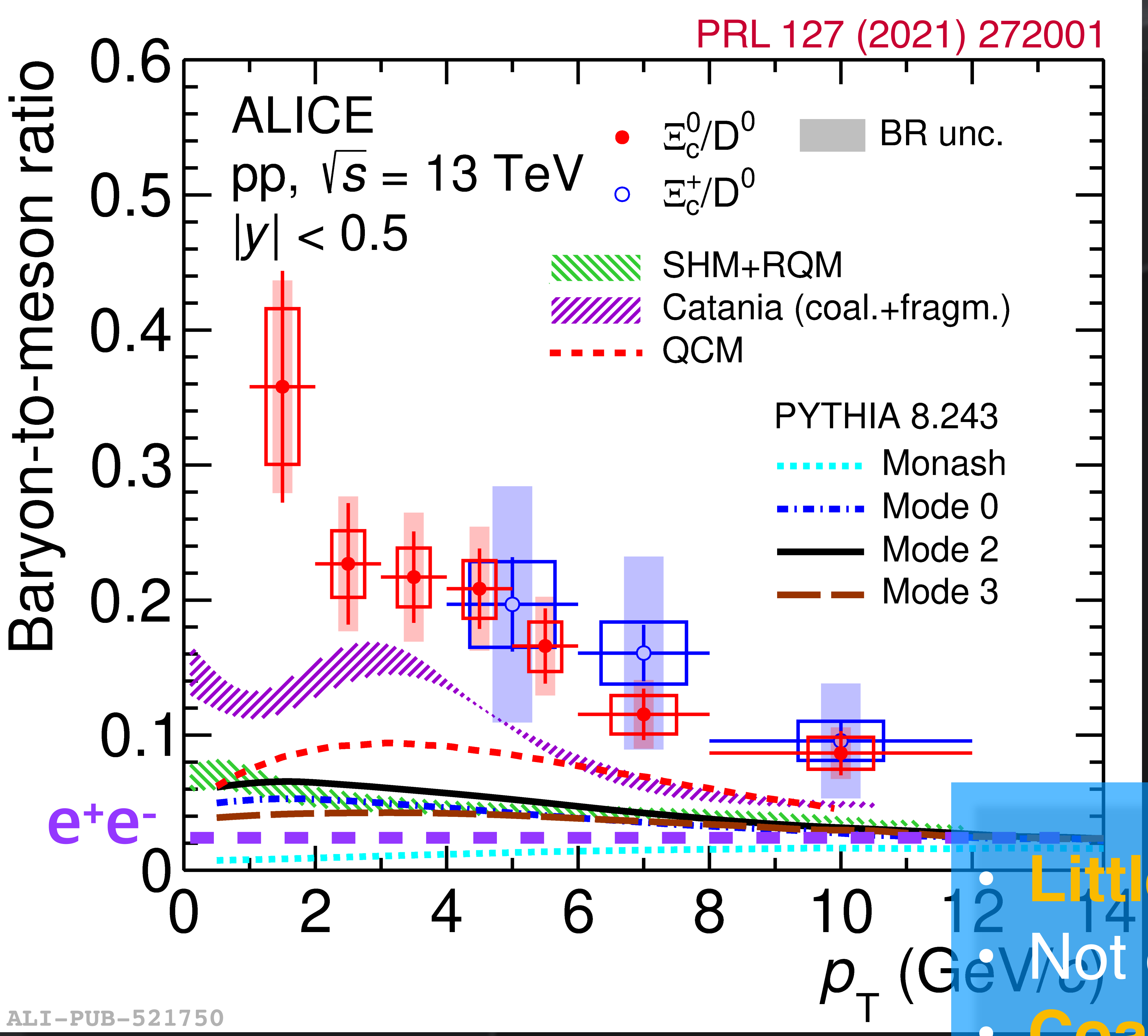
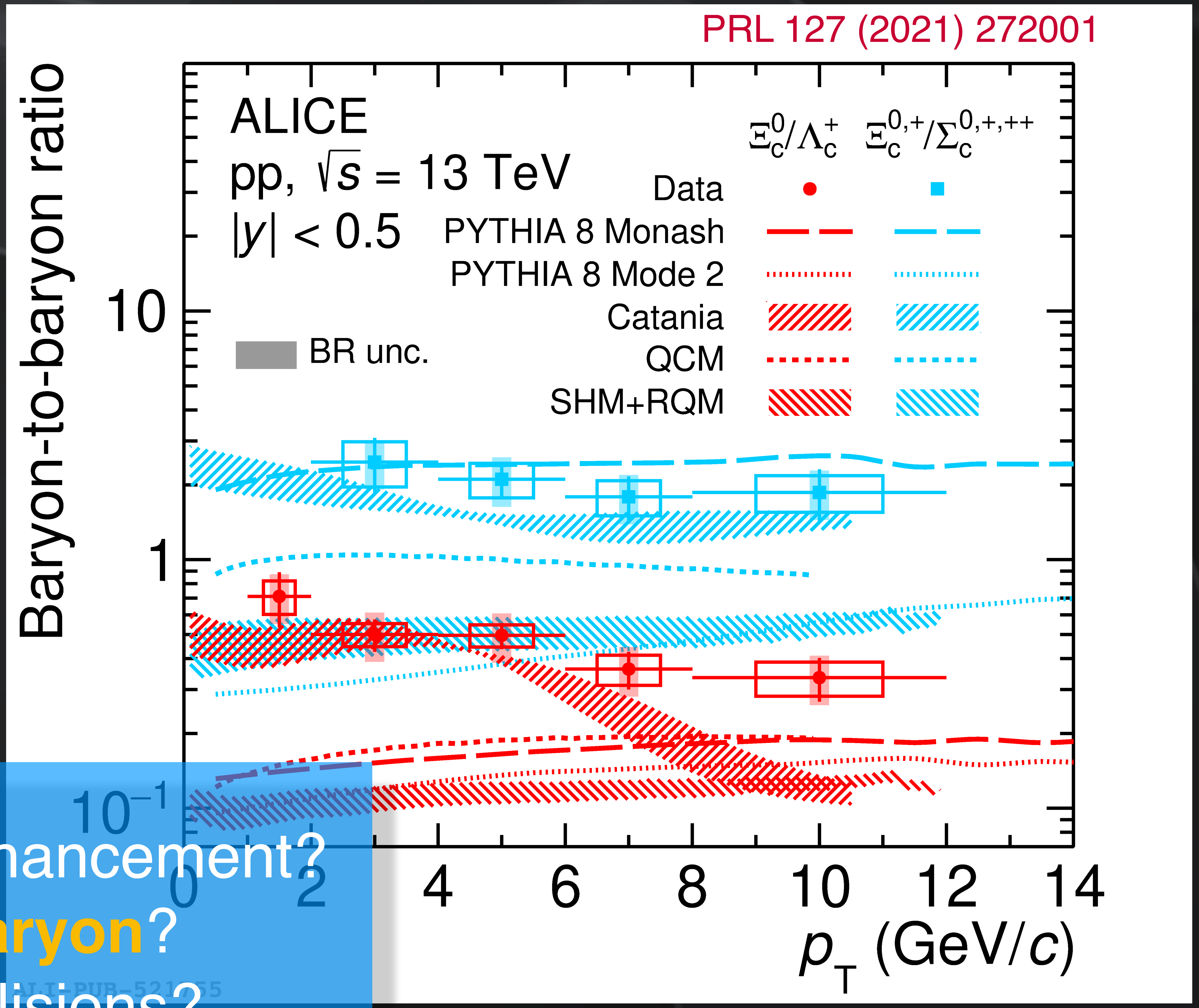


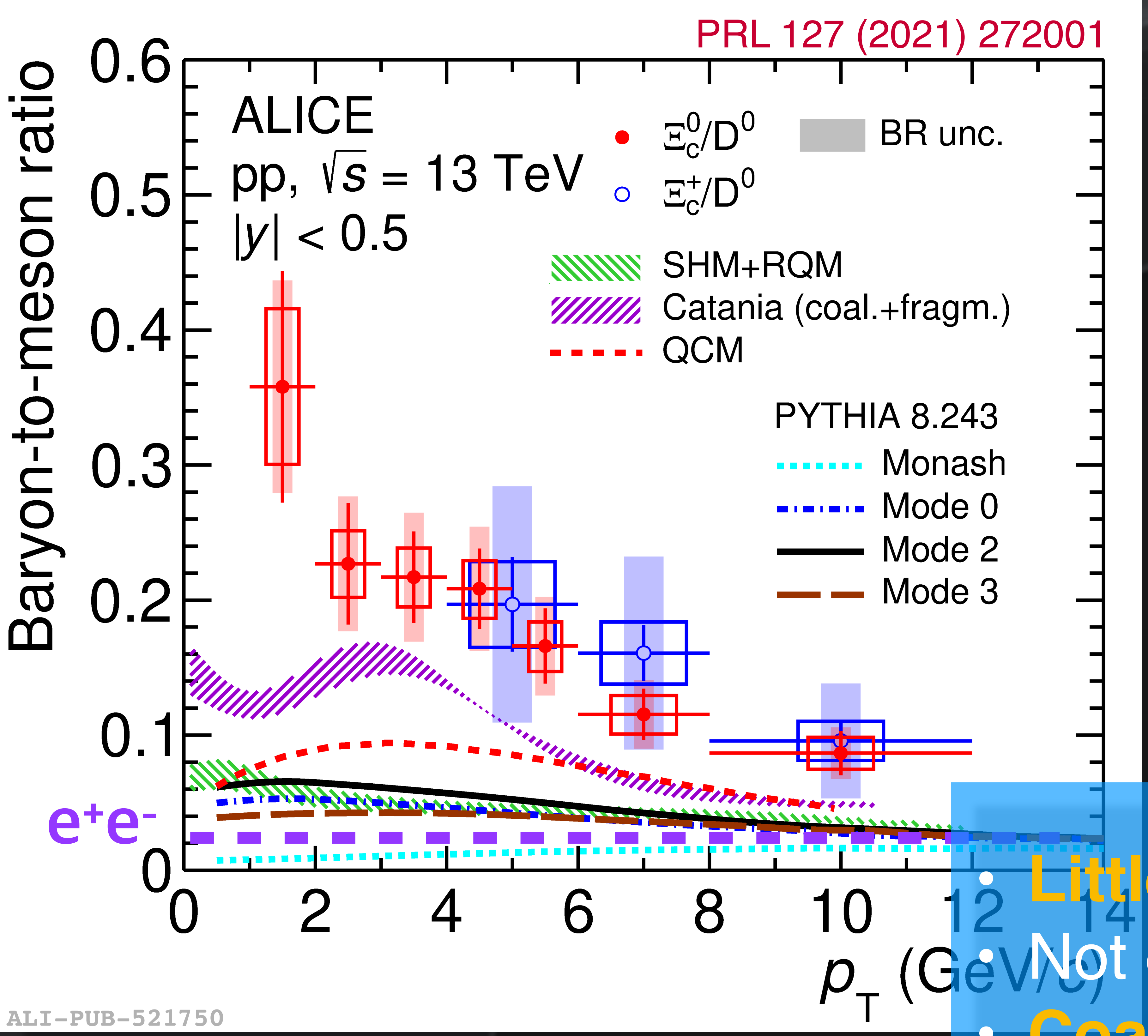


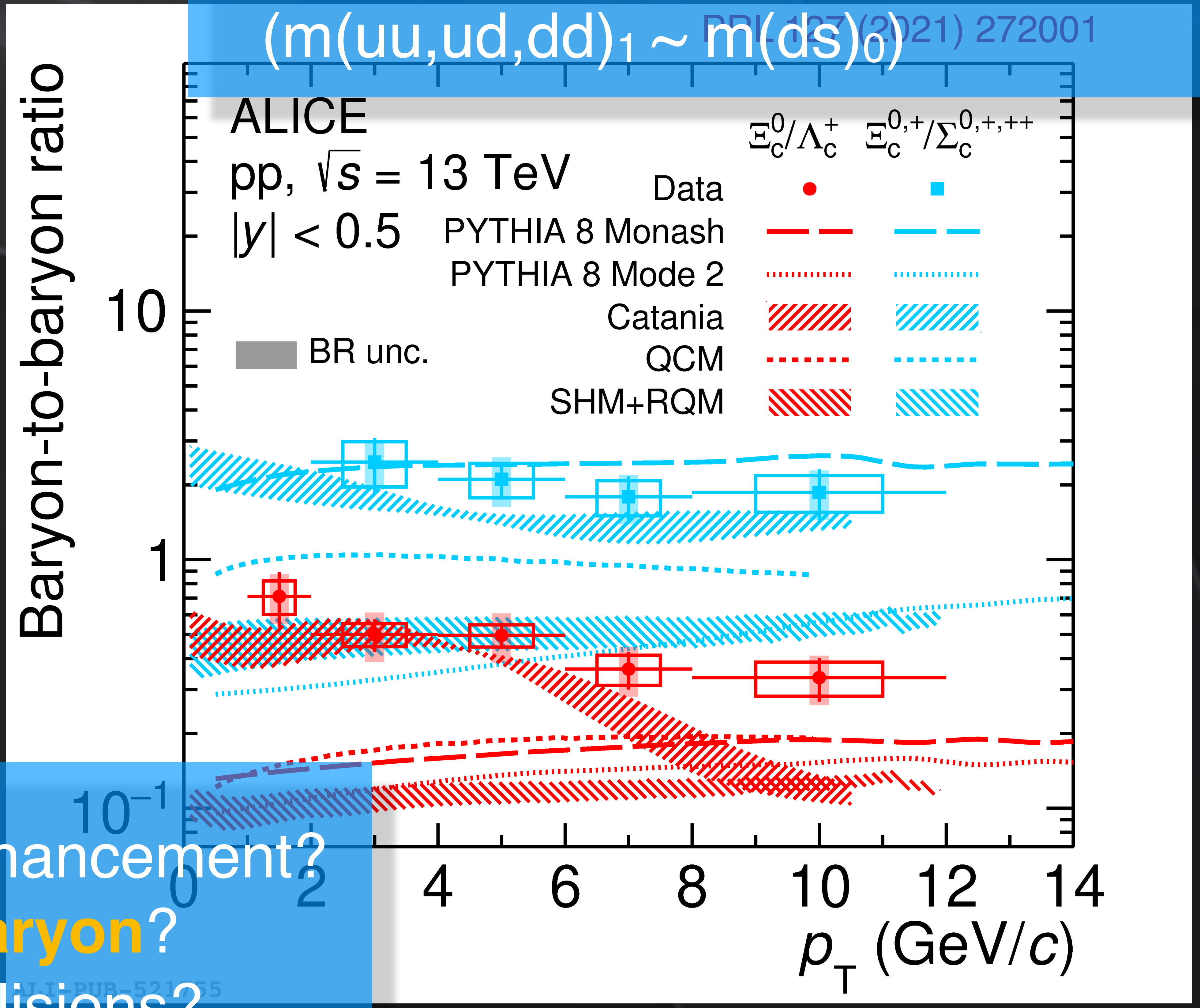
- **Little strangeness** enhancement?
- Not enough **excited baryon**?
- **Coalescence** in pp collisions?

Charm strange baryons in pp collisions

- **Enhancement at low p_T** with respect to $e^+ + e^-$, ep measurements.
- Most model calculations underestimate the measurements.
- $\Xi_c^{0,+}/\Sigma_c^{0,++}$ in agreement with Monash tune.

- **Similar suppression of $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$ in $e^+ + e^-$ collisions?**
- Matter of **similar (diquark) mass?** $(m(uu,ud,dd)_1 \sim m(ds)_0)$





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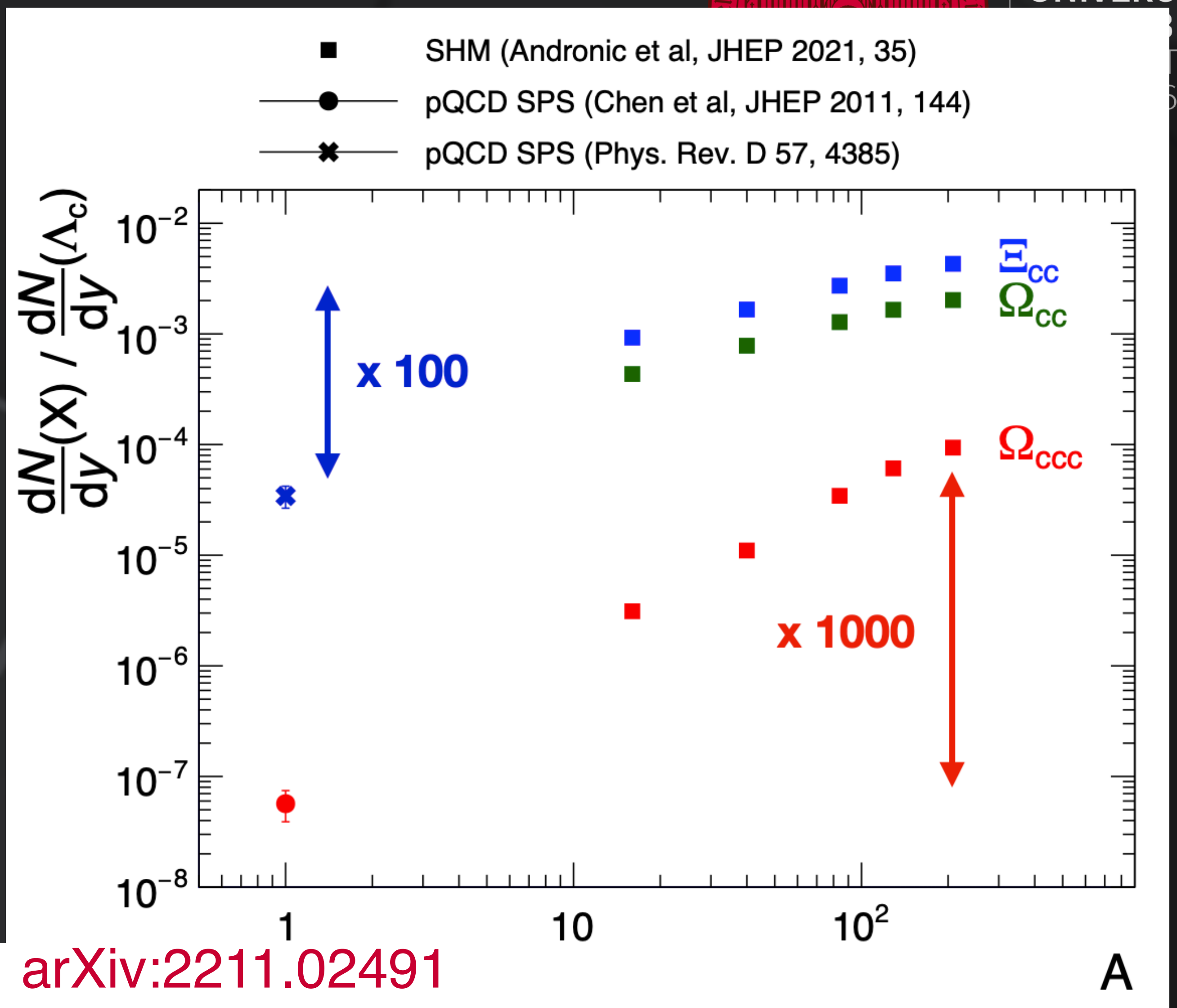
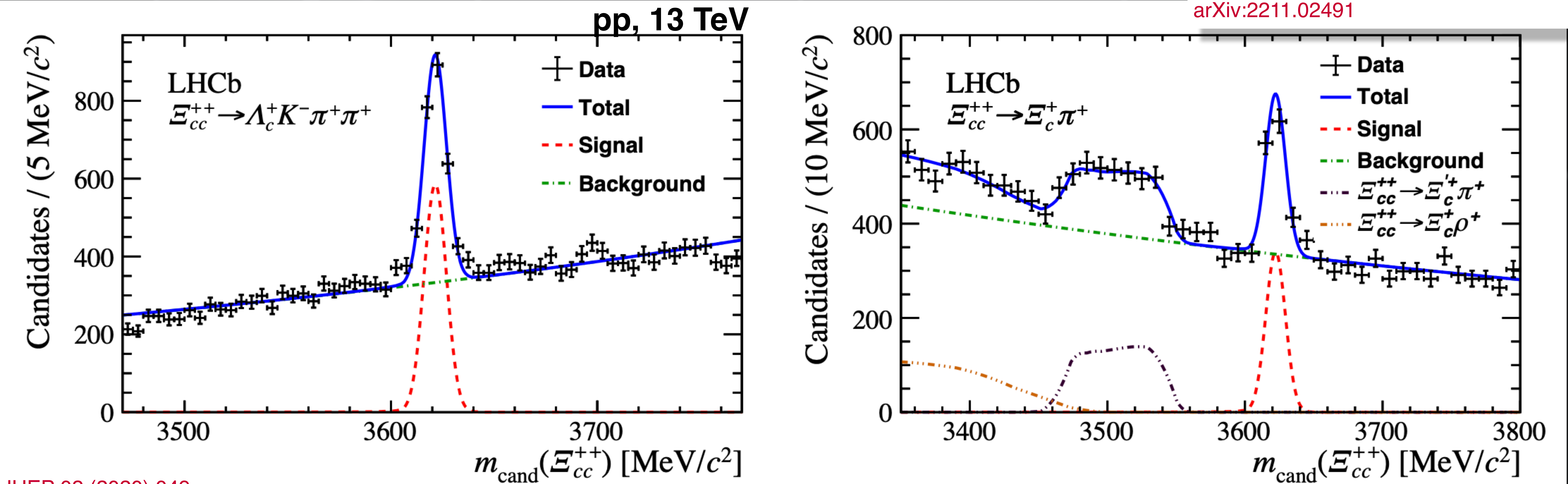
Test probe for coalescence

- **Multi-charm baryons** are produced **purely by coalescence**
  - Expected to show a large enhancement in AA collisions.
  - ➡ Investigate microscopic **thermalization** in the QCD medium.



arXiv:2211.02491



JHEP 02 (2020) 049

Test probe for coalescence

- **Multi-charm baryons** are produced **purely by coalescence**
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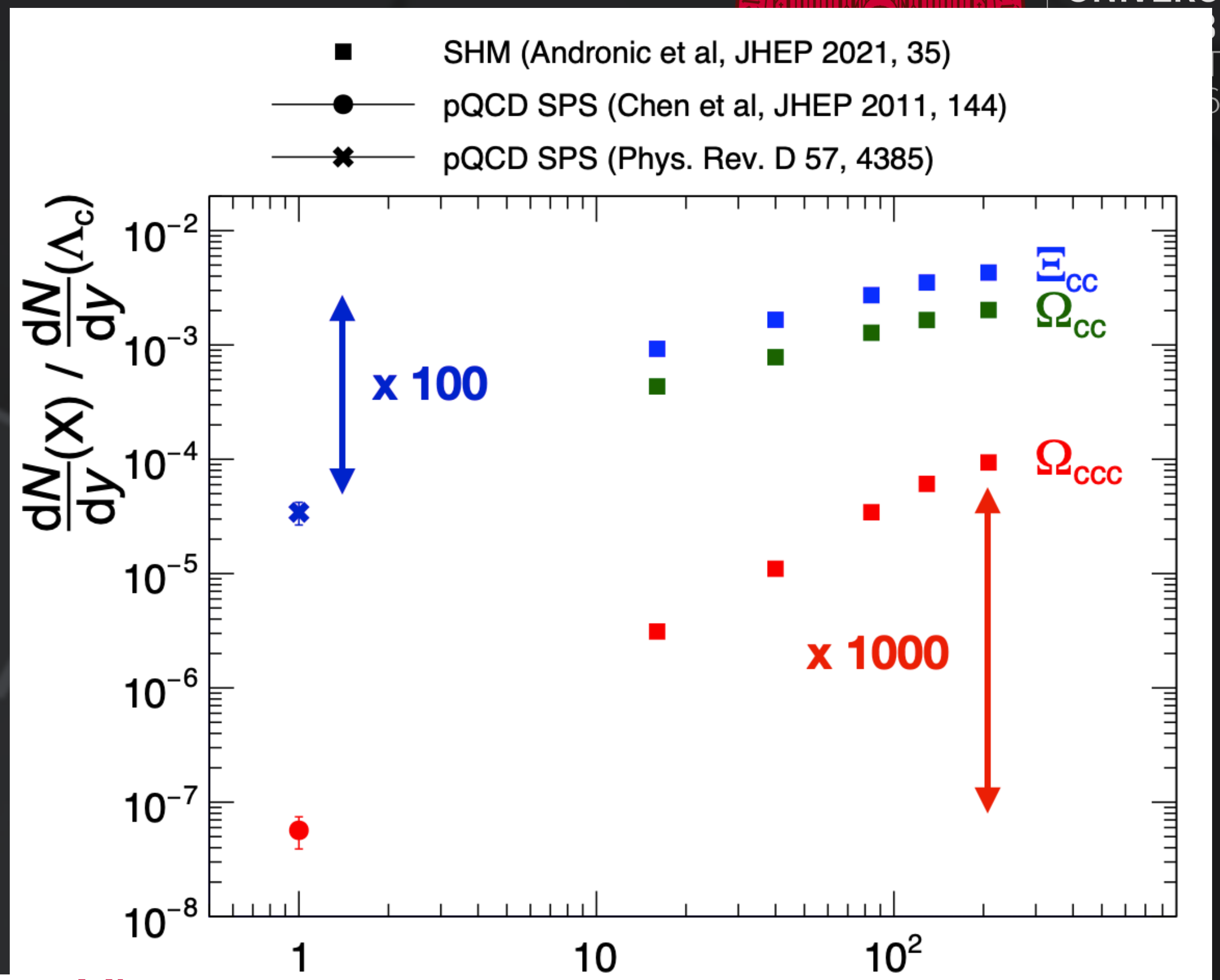
  - ➡ Investigate microscopic **thermalization** in the QCD medium.

- Need more **differential(p_T and centrality) measurements** to investigate the coalescence process in the hadronization



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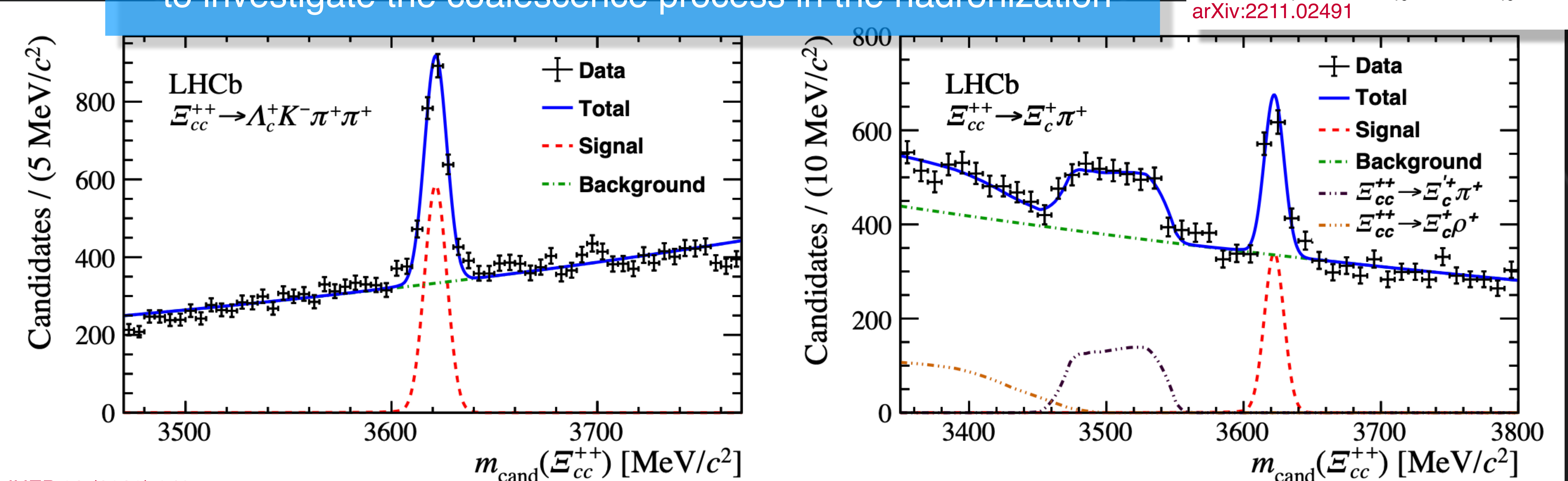
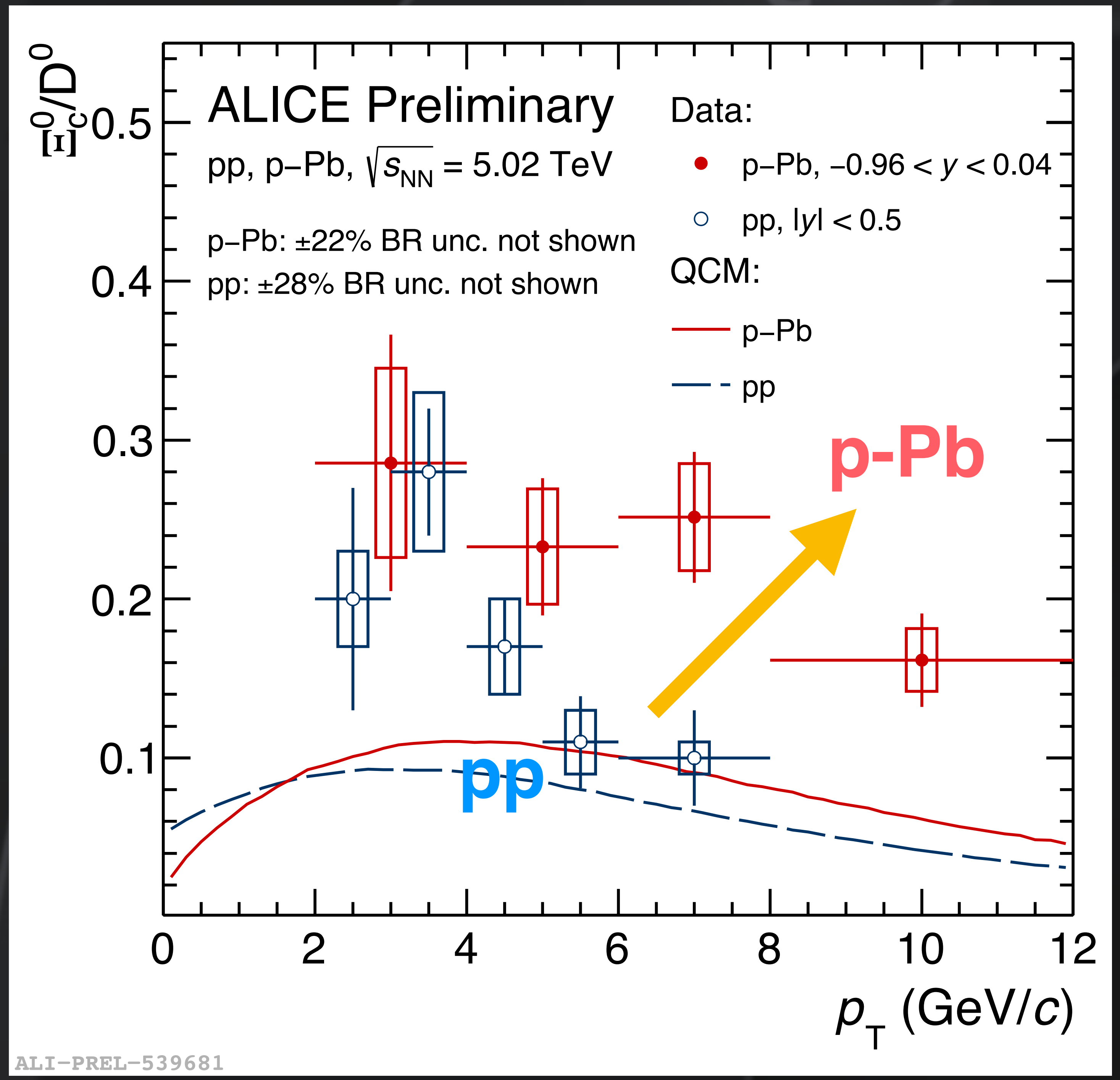


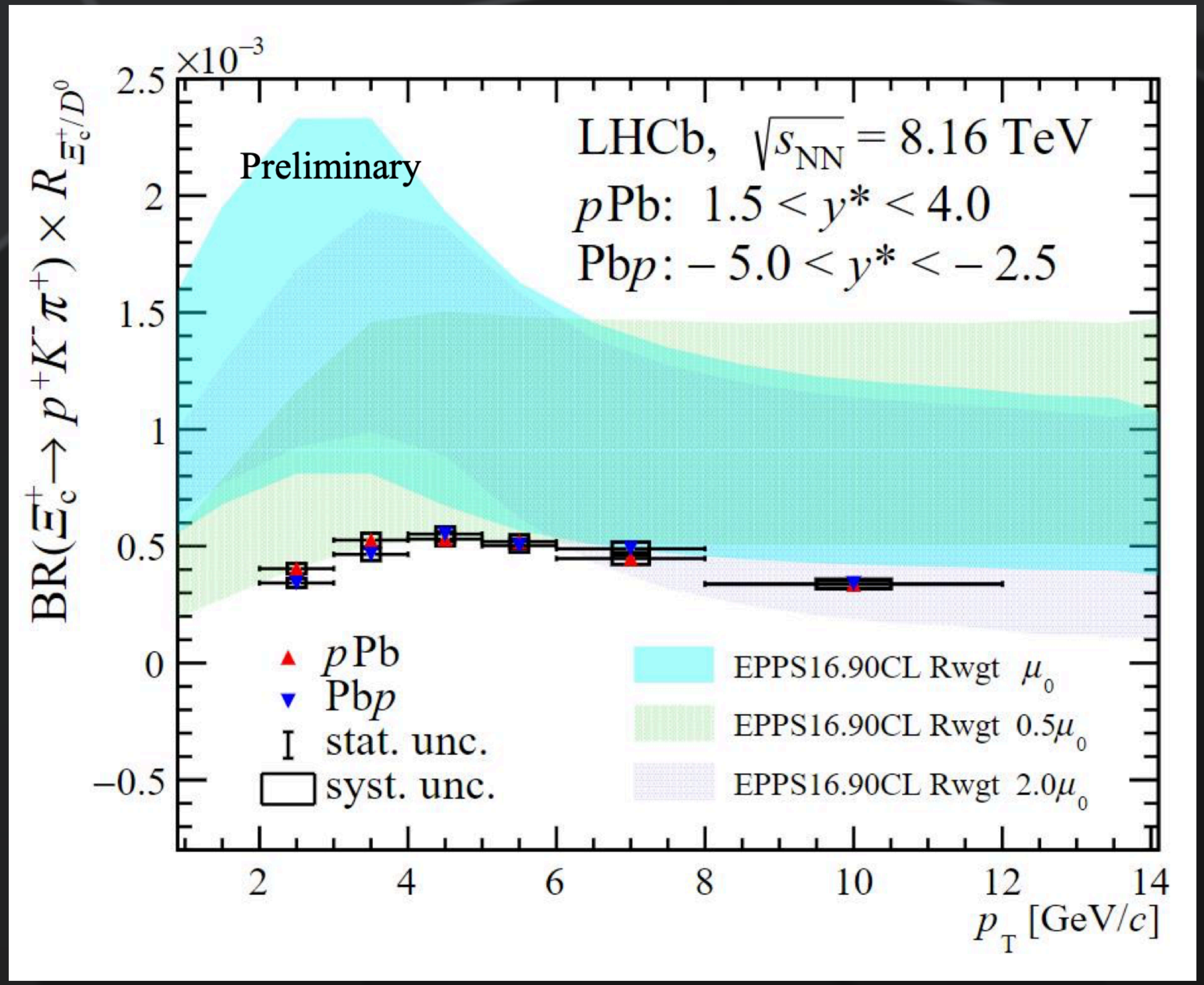
JHEP 02 (2020) 049

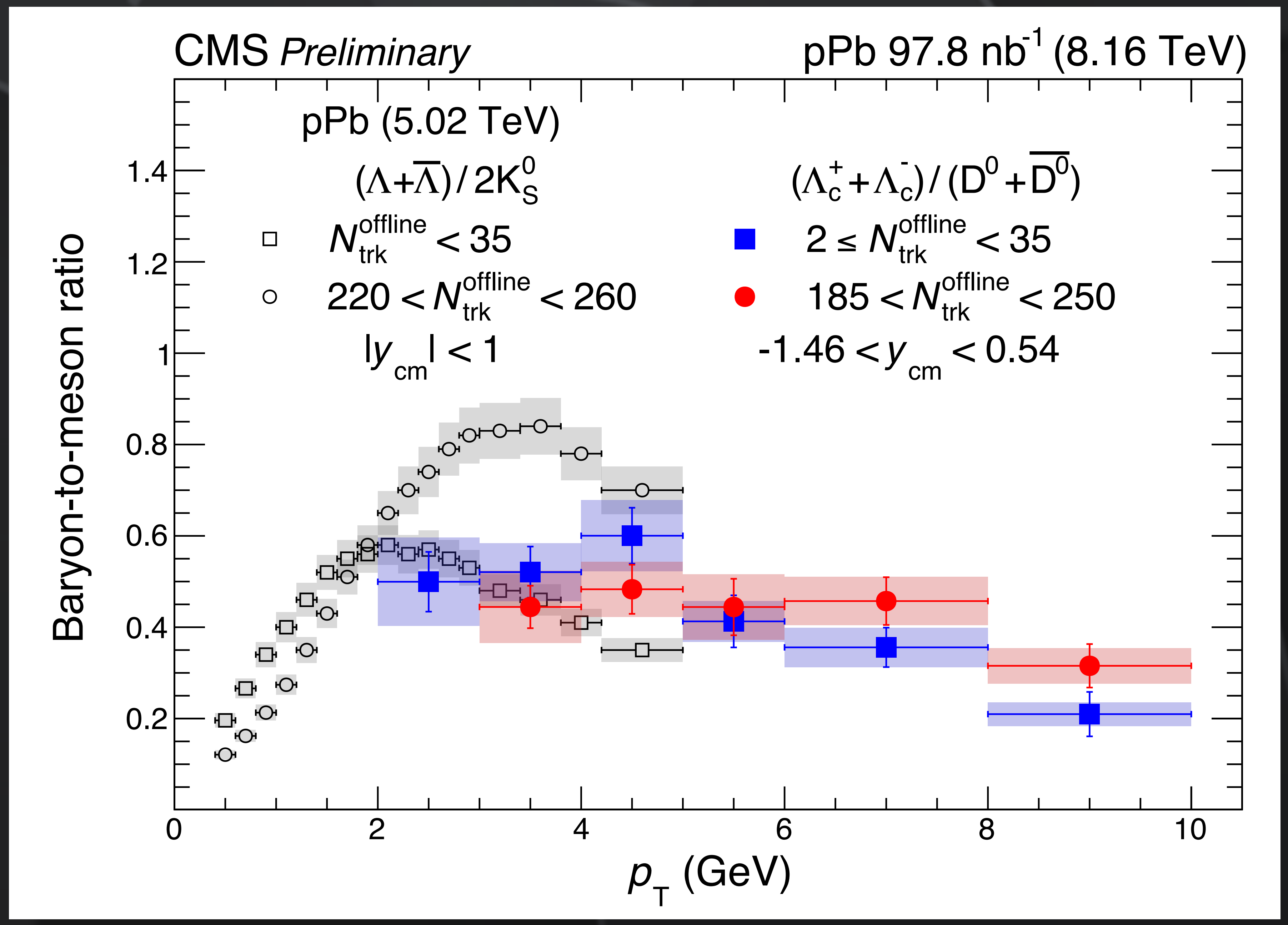
p_T distribution modification

- **Push towards higher p_T** of charm baryon-to-meson ratio from pp to p-Pb.
  - **Radial flow**? **Coalescence** effect?
- BR ~ 0.45% - 1.1% → Ξ_c^+/D^0 (LHCb) ~ **0.045 - 0.11**
  - likely **LHCb below ALICE**, but also LHCb **larger than e⁺+e⁻ (~0.02)**
- **No multiplicity dependence** in **p-Pb (and Pb-Pb)** over p_T in contrast to light-flavor hadrons.



QCM: EPJC 77 (2017)163





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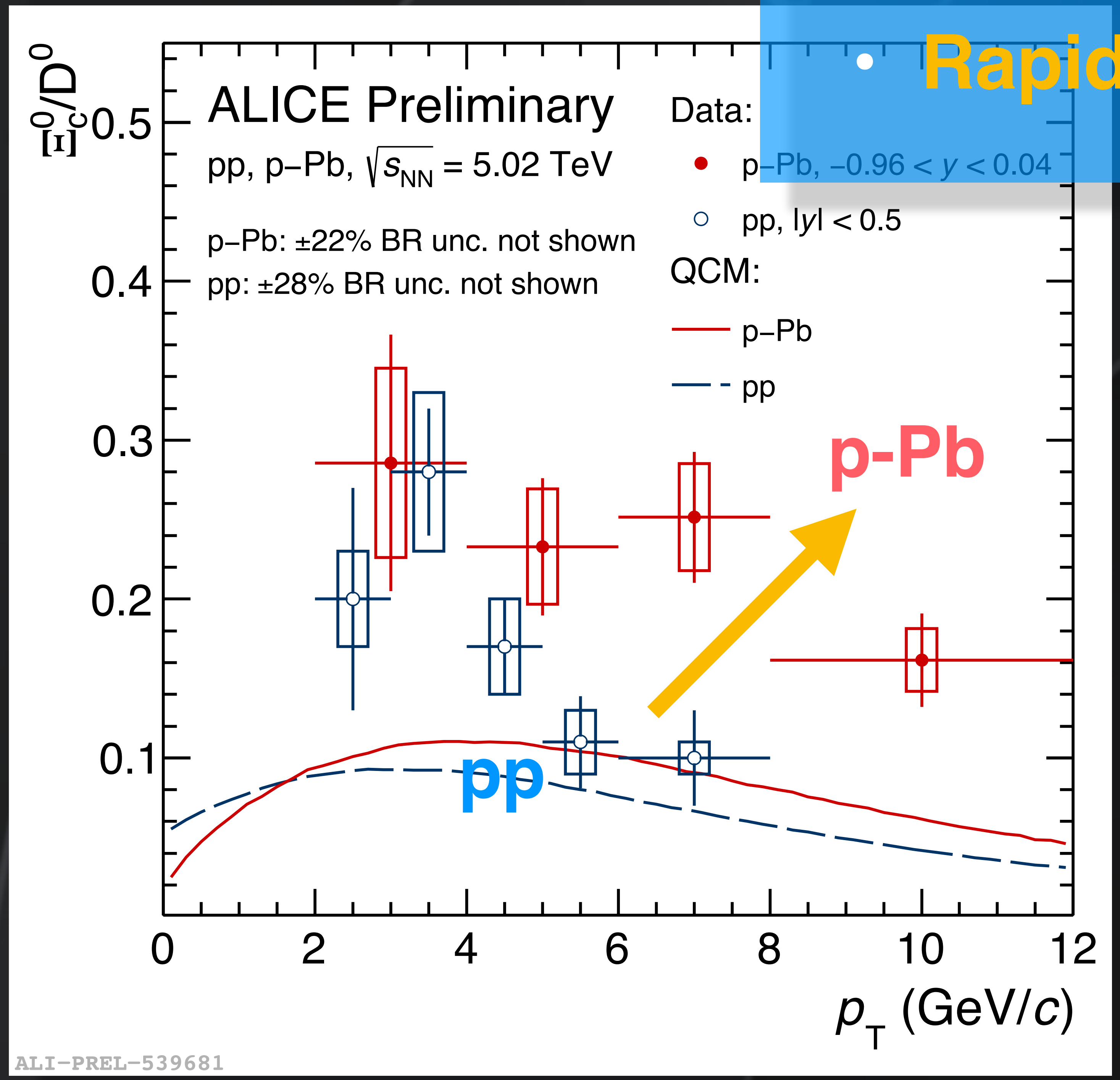
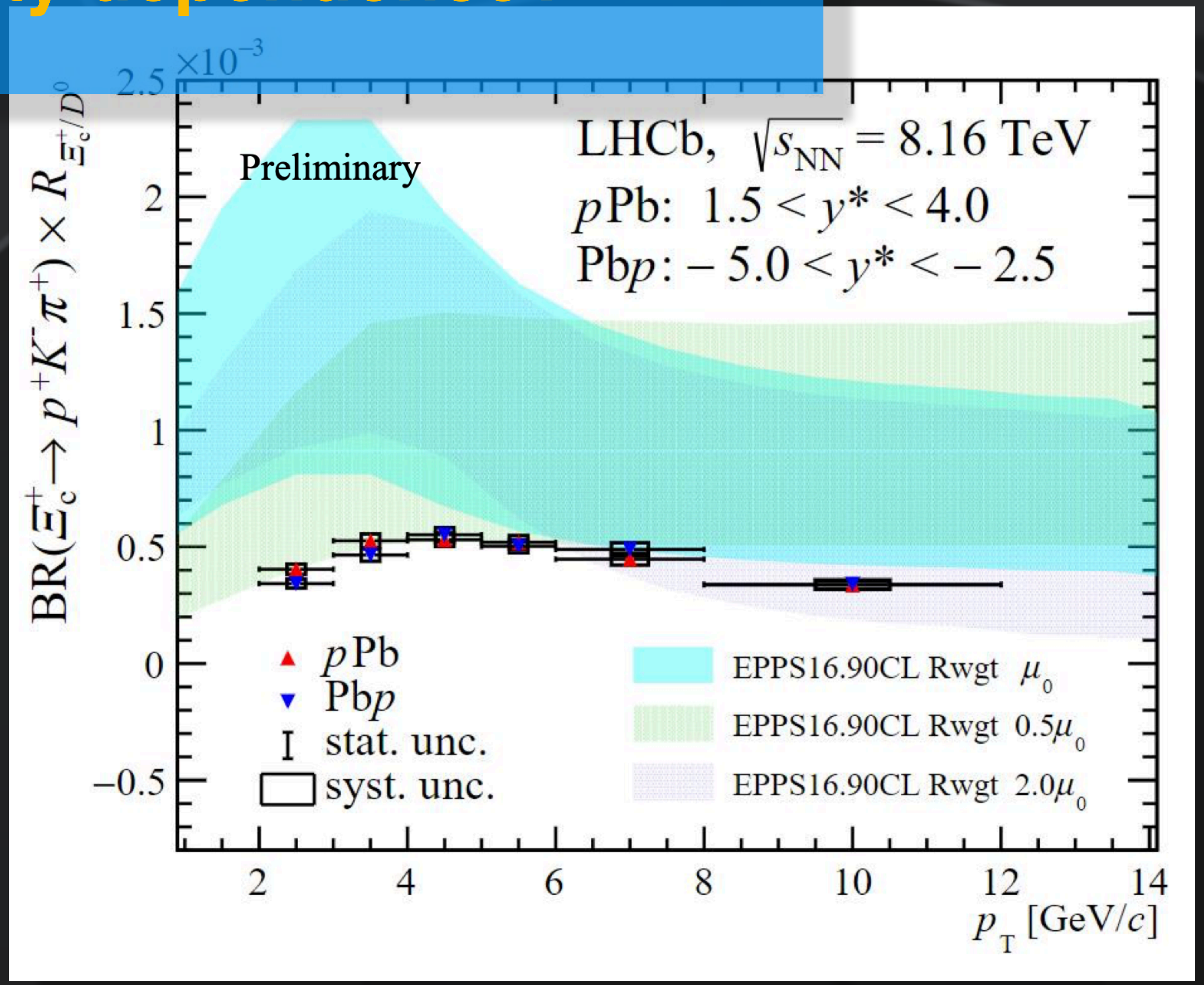
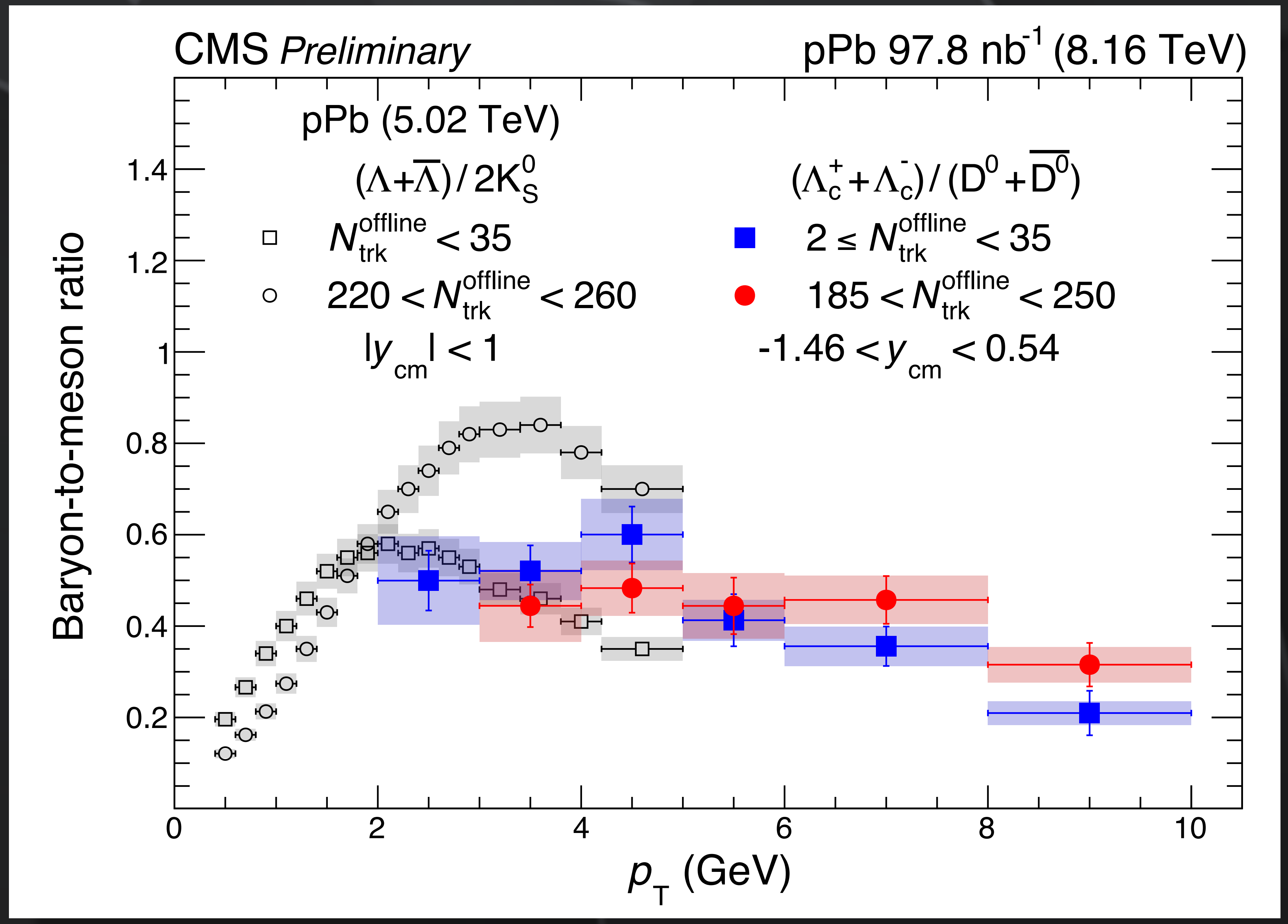
- **Rapidity dependence?**







QCM: EPJC 77 (2017)163

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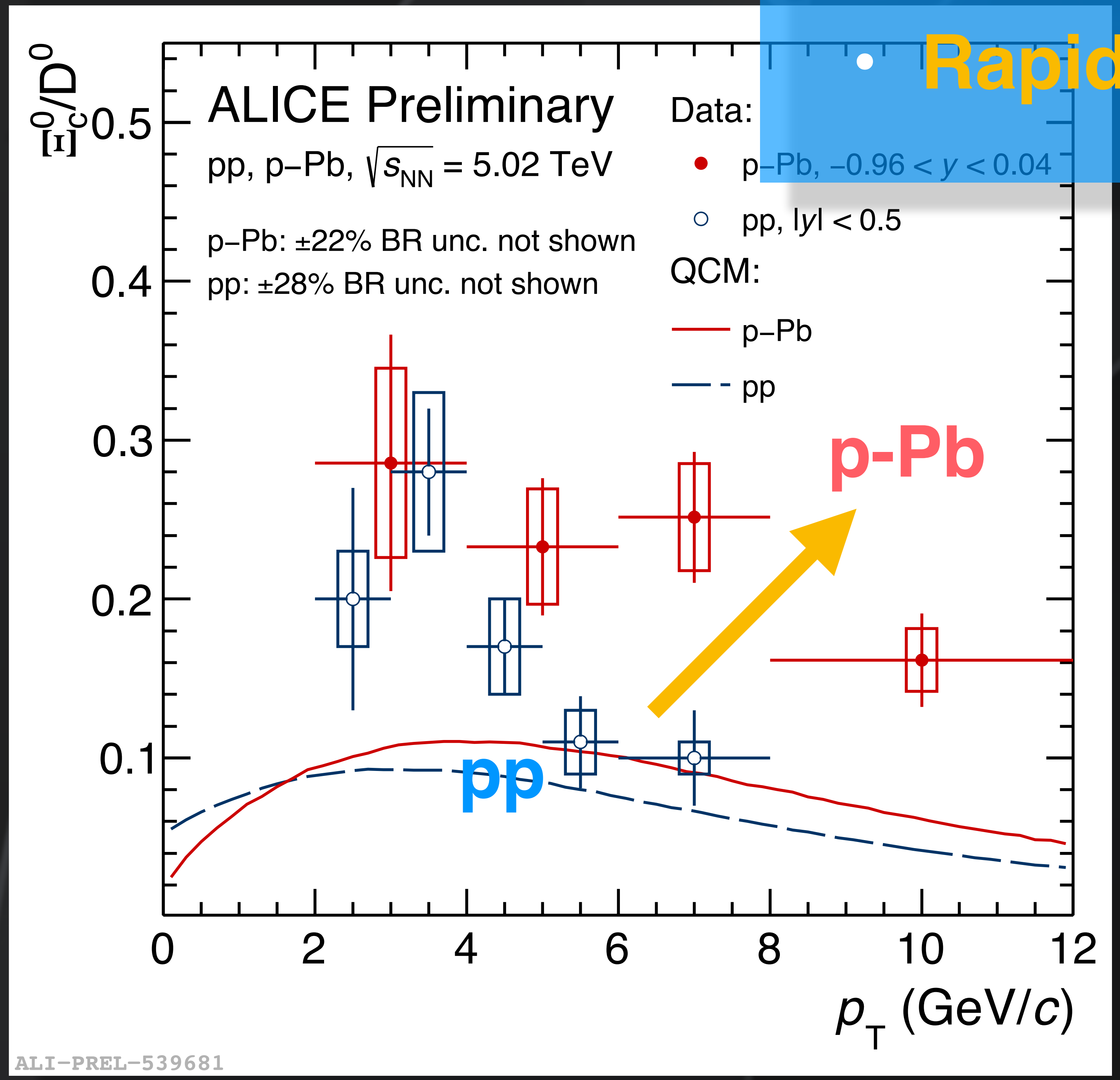
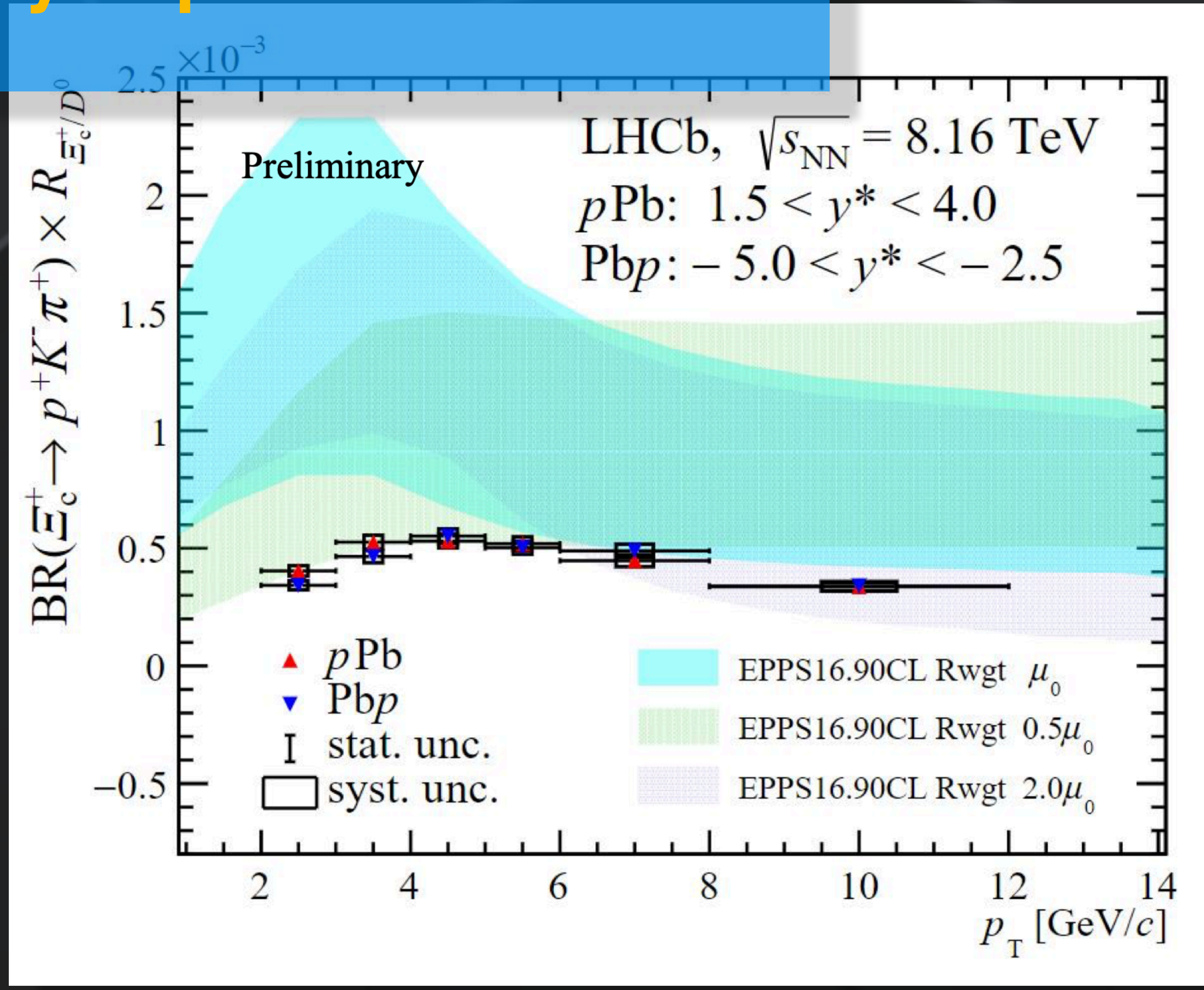
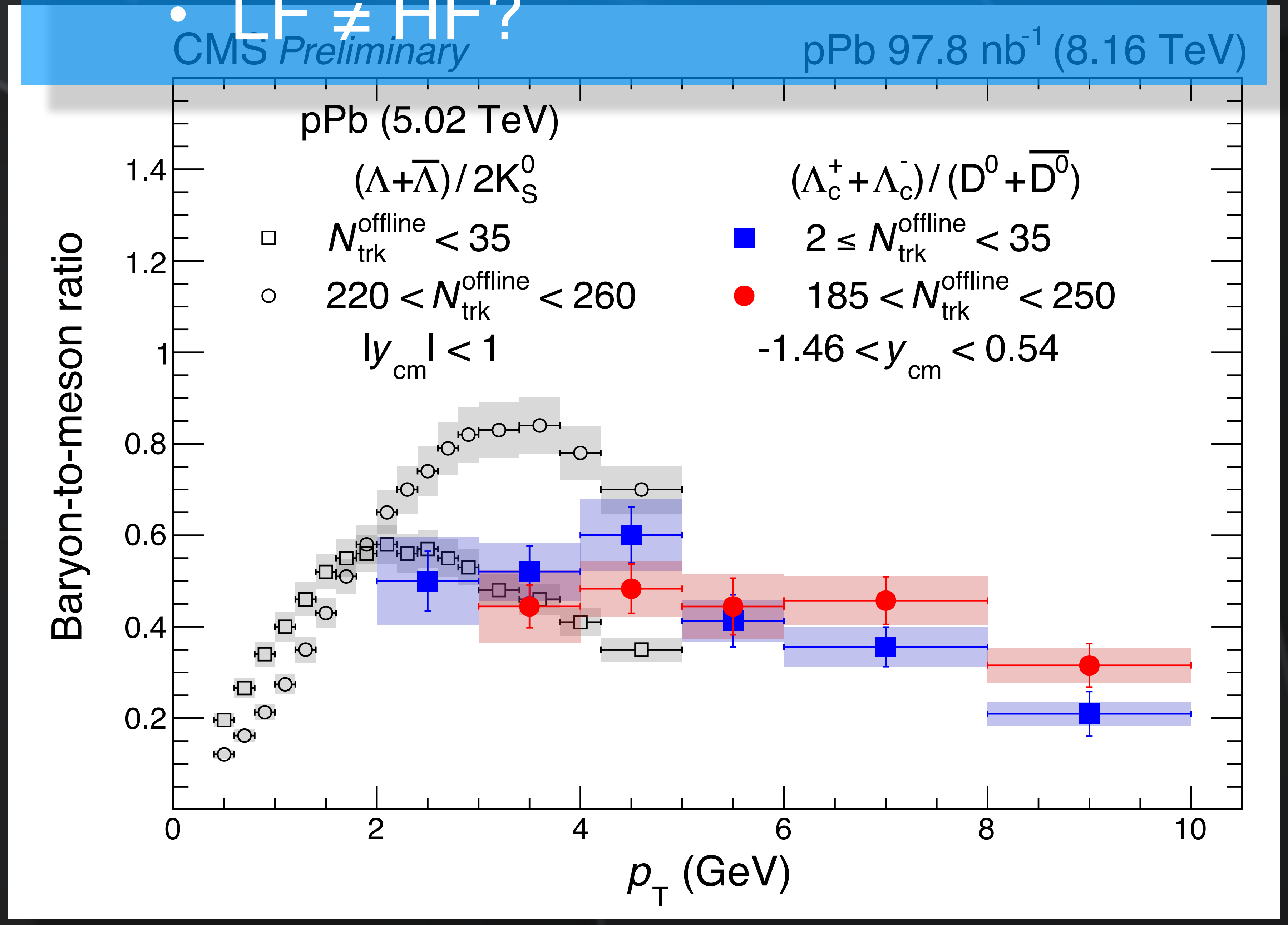


- Rapidity dependence?



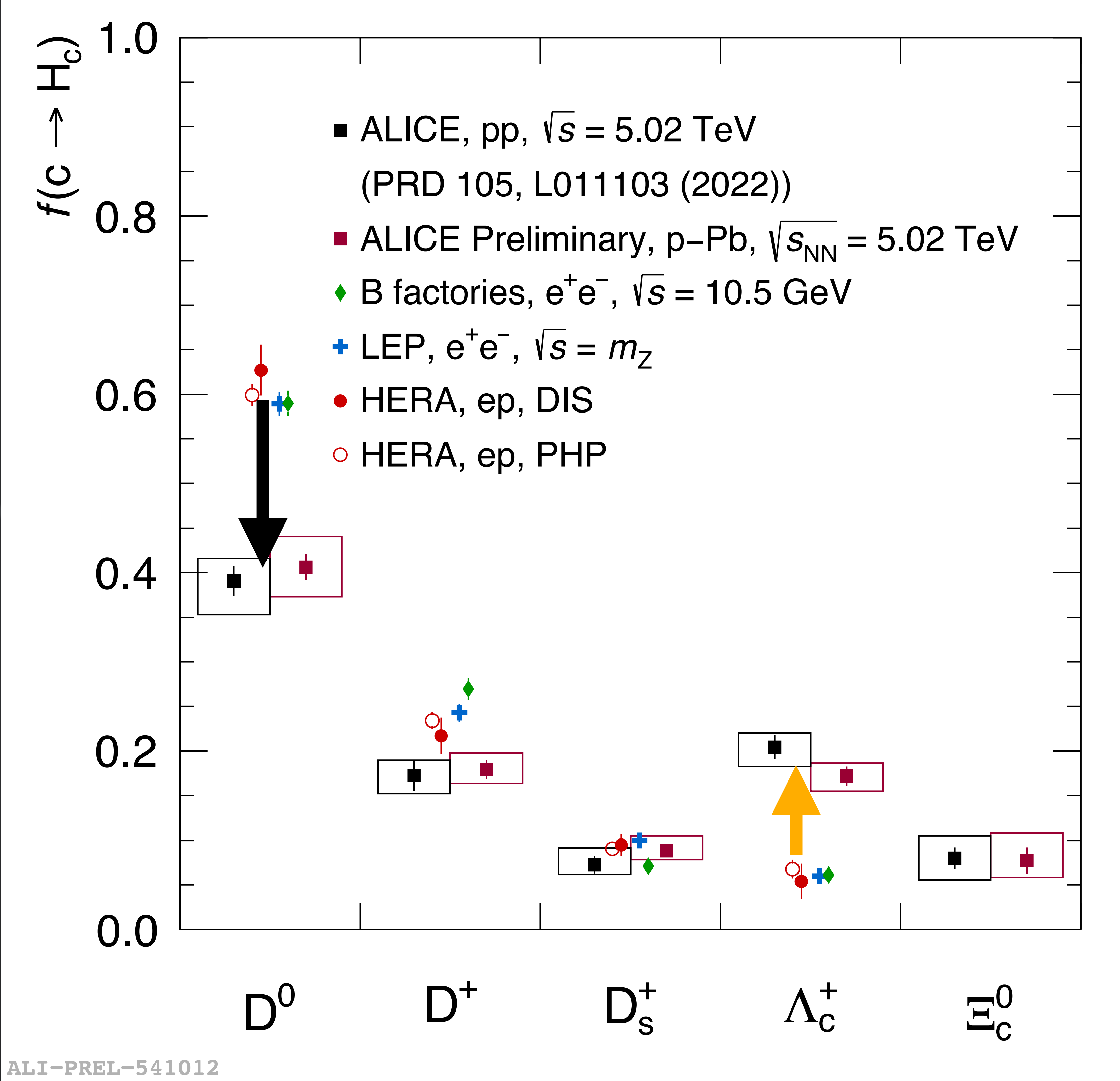
- **Hadronization mechanism**
  - LF ≠ HF?



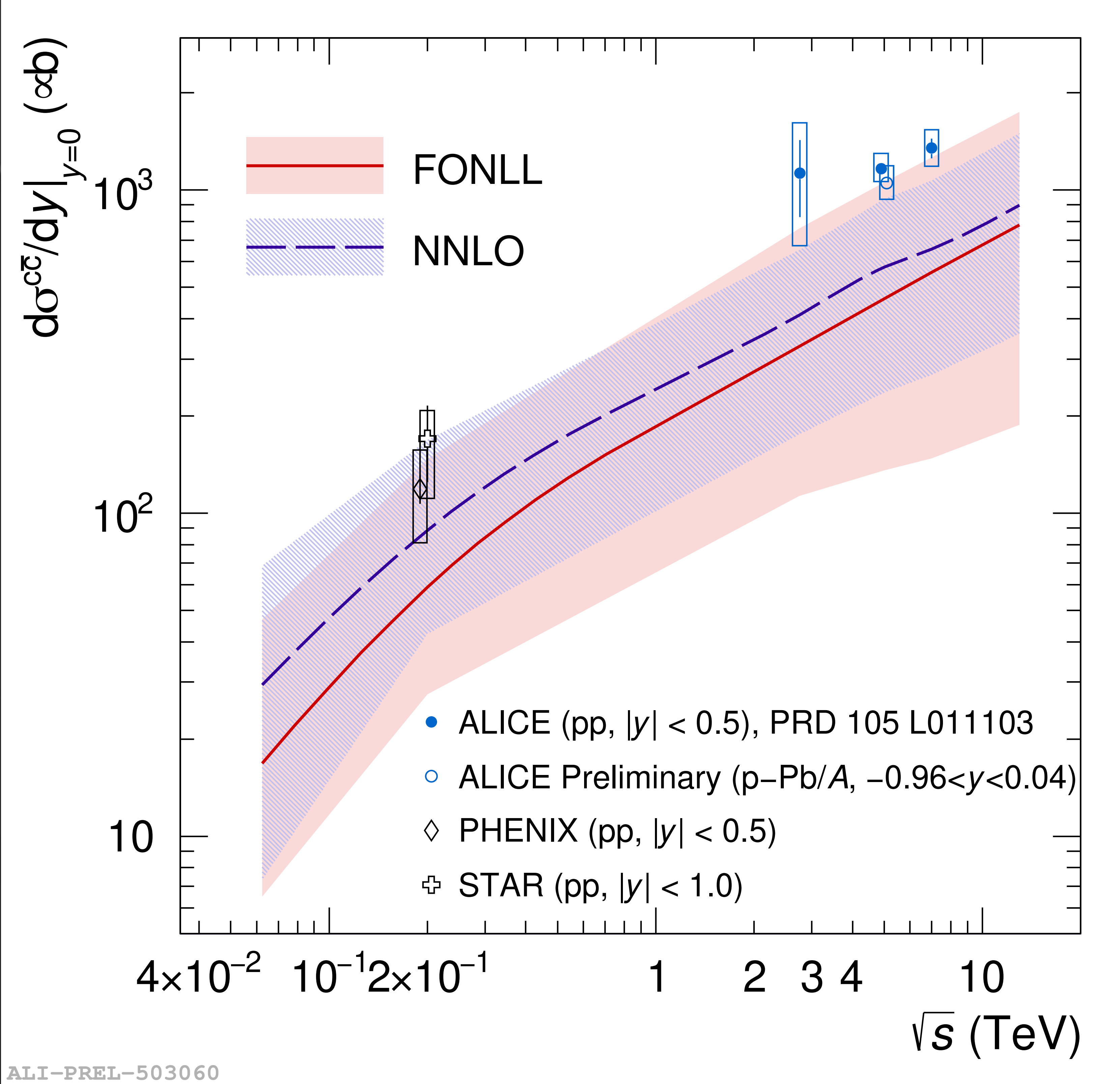
QCM: EPJC 77 (2017)163

Charm fragmenataion fraction

- pp and p-Pb results are compatible.
- **Significant baryon enhancement** with respect to e^+e^- and ep collisions.
  - The **universality** of charm fragmentation fractions is **broken**.
- Total charm cross section is ~30% higher than the previously published results.



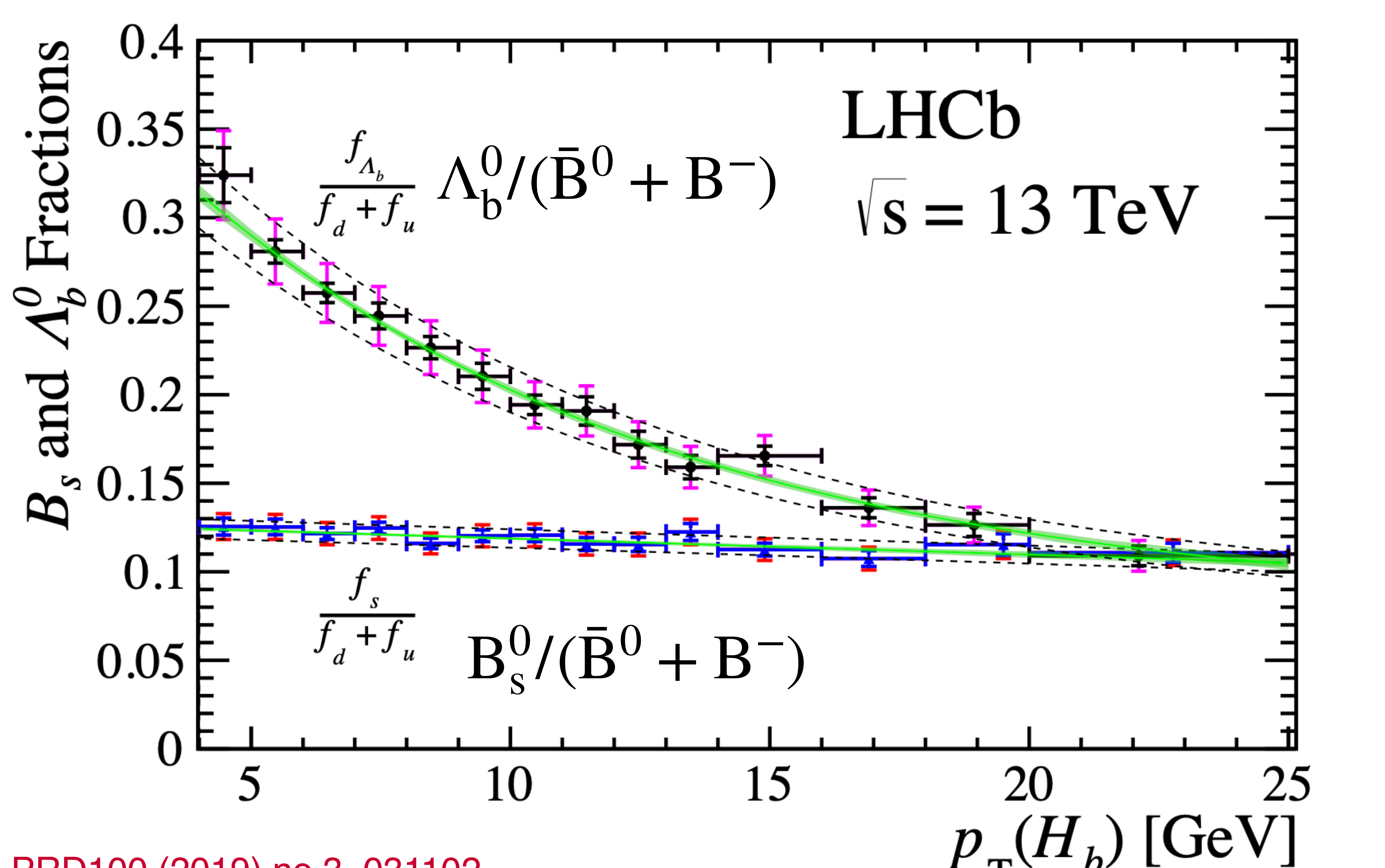
EPJC 76 no.7, (2016) 397
EPJC 77 no.1, (2015) 19
EPJC 76 no.7, (2016) 397



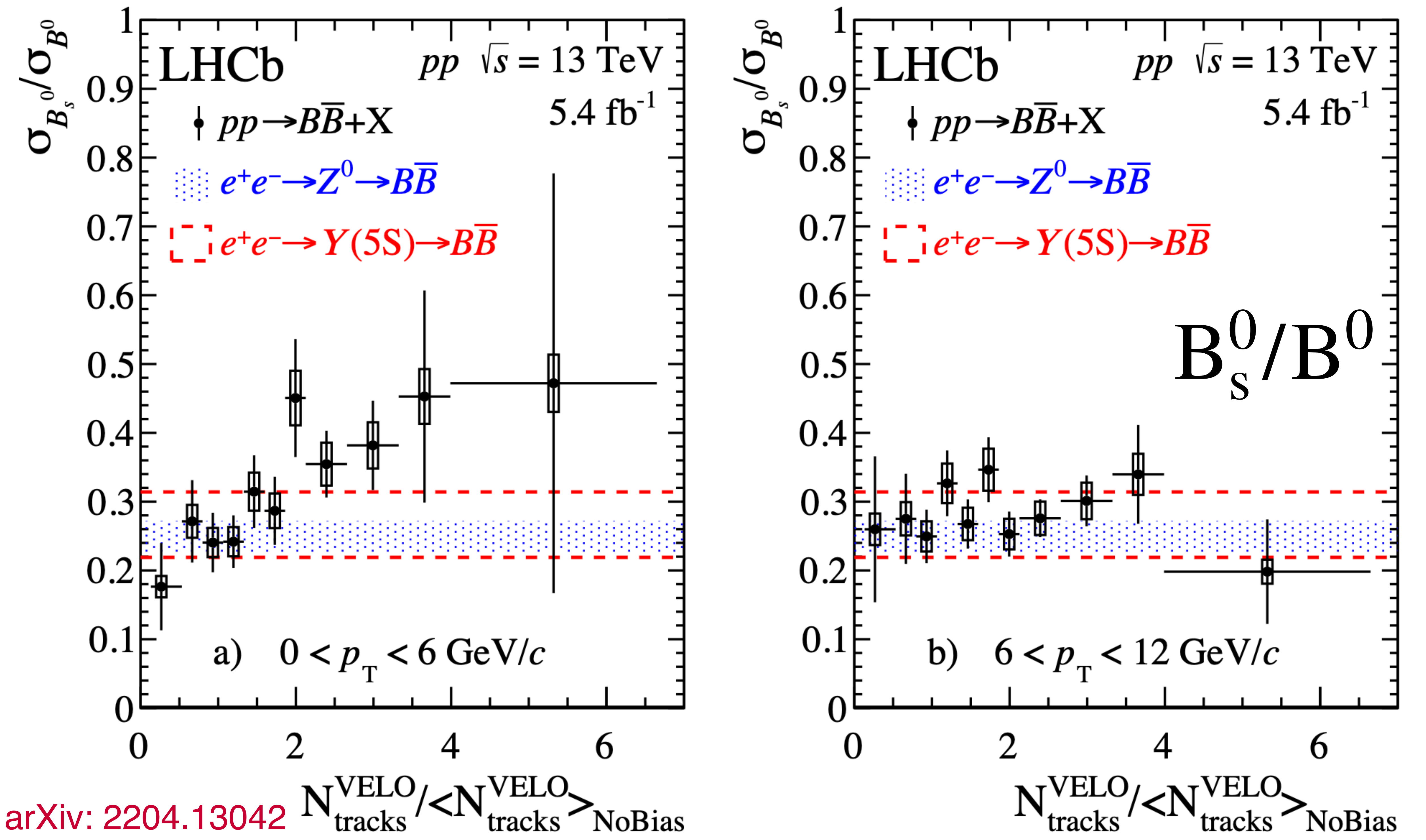
PRD 86 (2012) 072013
PRC 84 (2001) 044905
JHEP 10 (2012) 137
PRL 118 (2017) 12, 122001

Beauty hadron ratio in pp collisions

- **No p_T dependence** of the **meson-to-meson ratios**
- **p_T dependence** of the **baryon-to-meson ratio,** showing the **enhancement at low p_T**
- Multiplicity dependence of B_s^0/B^0 at low p_T, no dependence at intermediate-to-high p_T
  - low p_T: sizable coalesence, intermediate-to-high p_T: dominant vacuum fragmentation



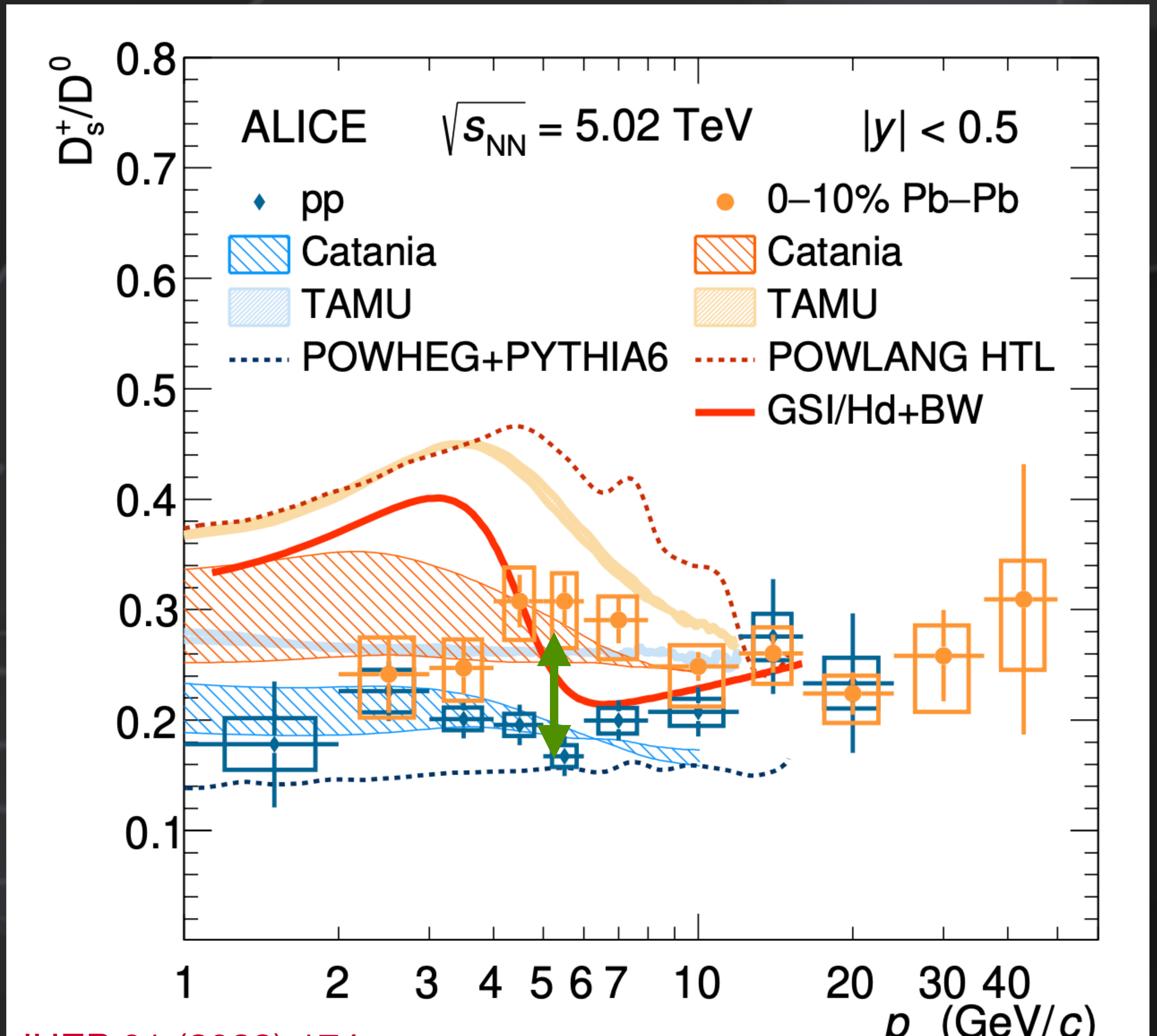
PRD100 (2019) no.3, 031102



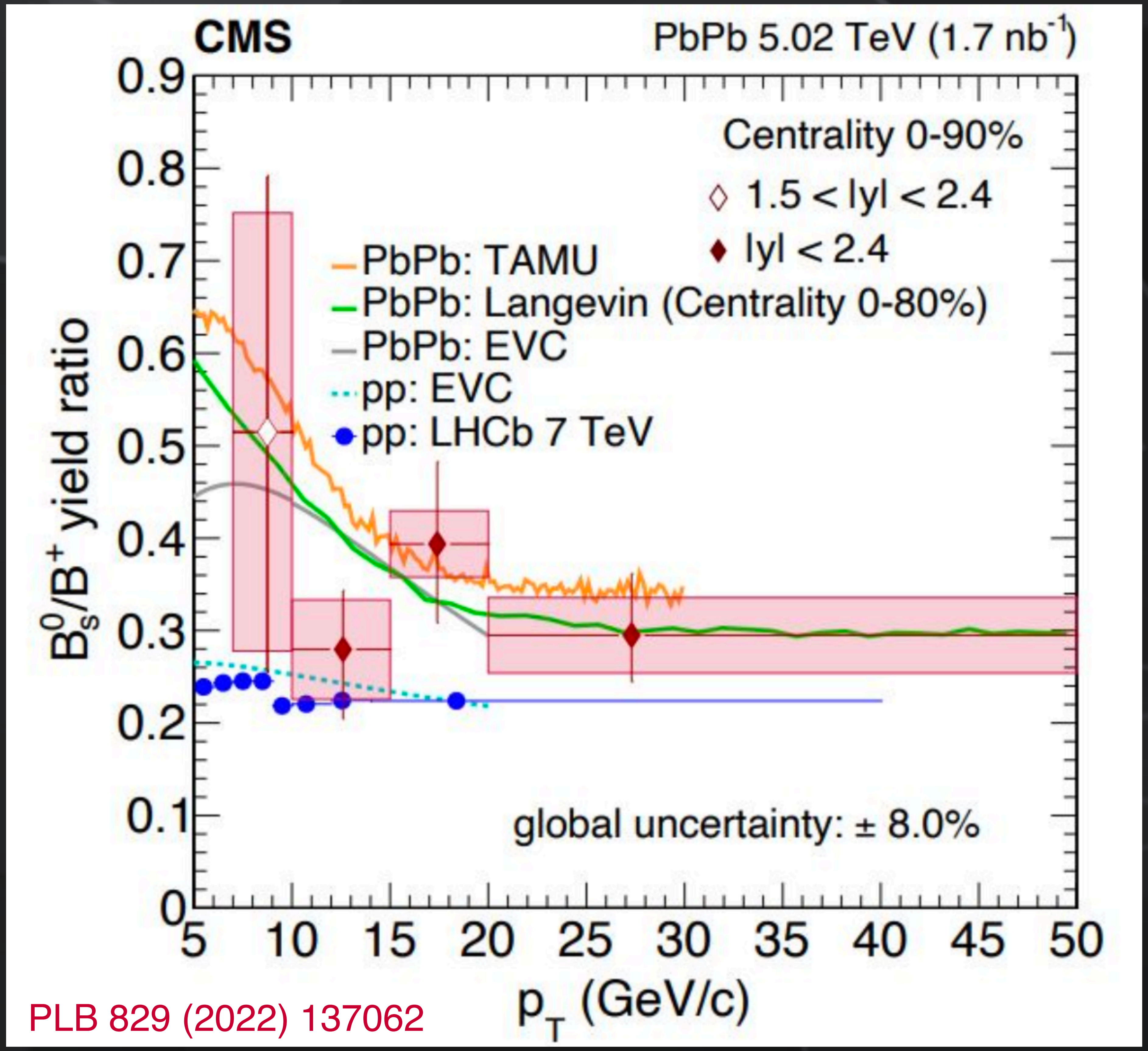
arXiv: 2204.13042

Heavy flavor hadrochemistry

- **Abundant** production of **strange quarks** in the QGP
  - **Coalescence** of heavy quarks with strange quarks from the QGP affects the HF hadrochemistry
    - **Enhanced charm(beauty?) strange hadron** yield relative non-strange hadrons



JHEP 01 (2022) 174



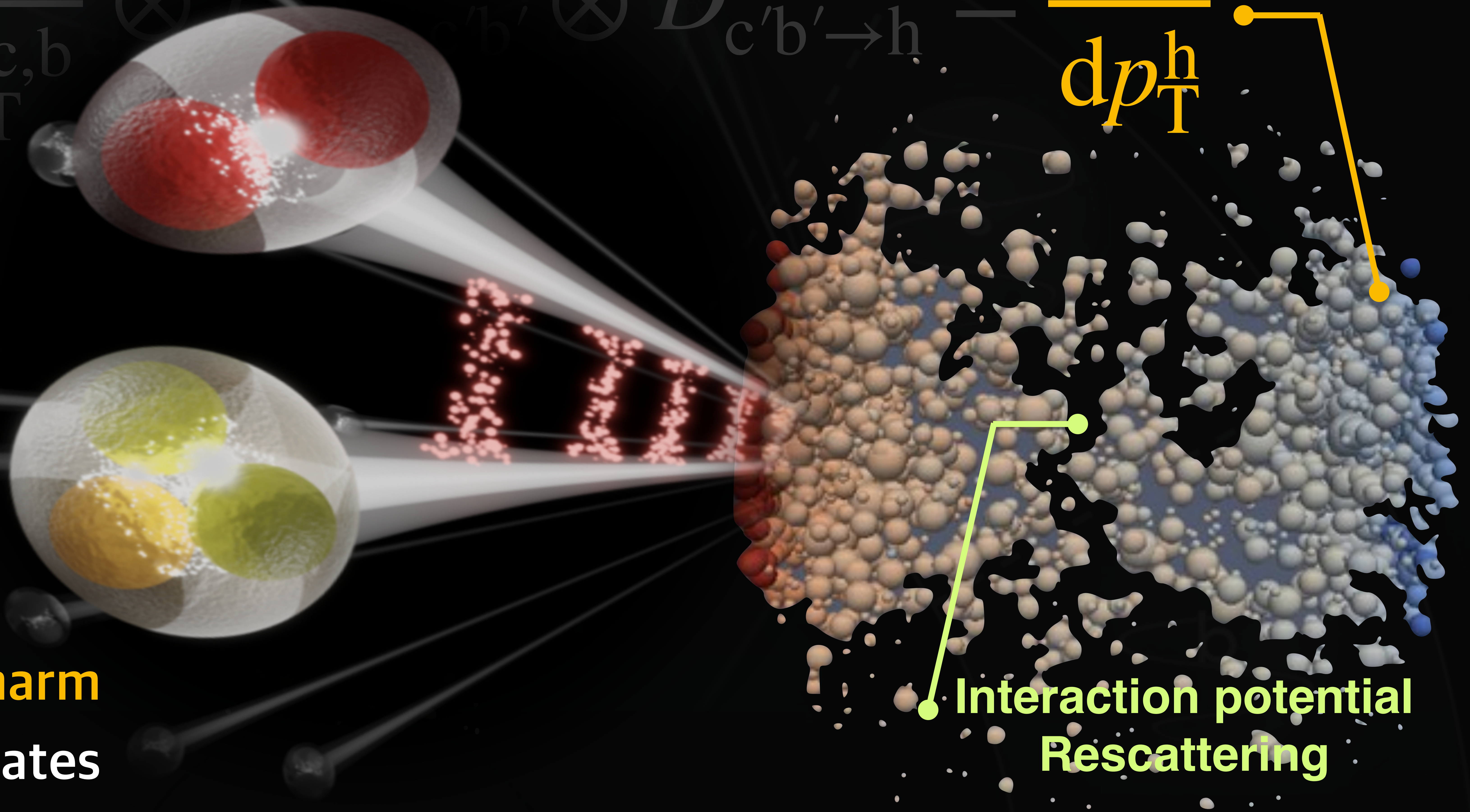
PLB 829 (2022) 137062

Charm hadron resonance

Charm resonances are sensitive to the hadrons interaction

What is the **rescattering** process in the heavy flavor sector?

$$\frac{d\sigma^{h}}{dp_{T}^{h}}$$



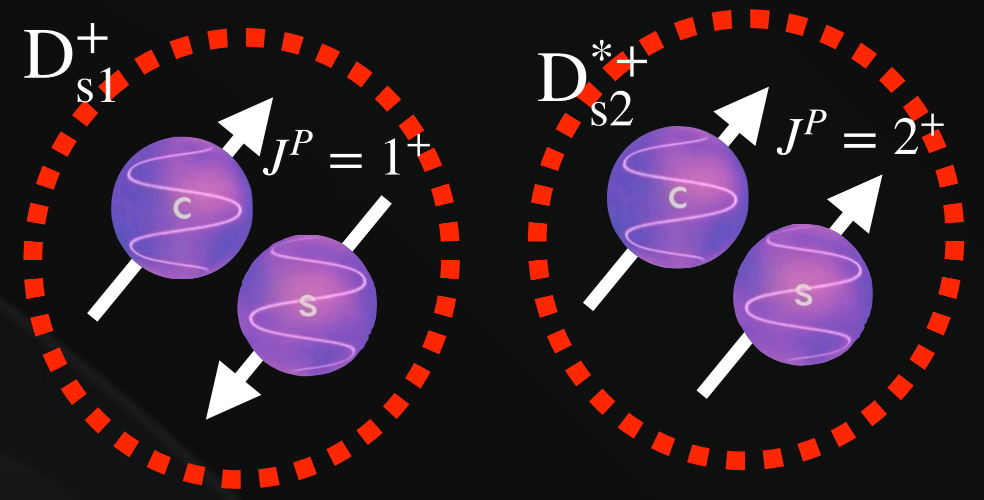
Two-body interactions with charm

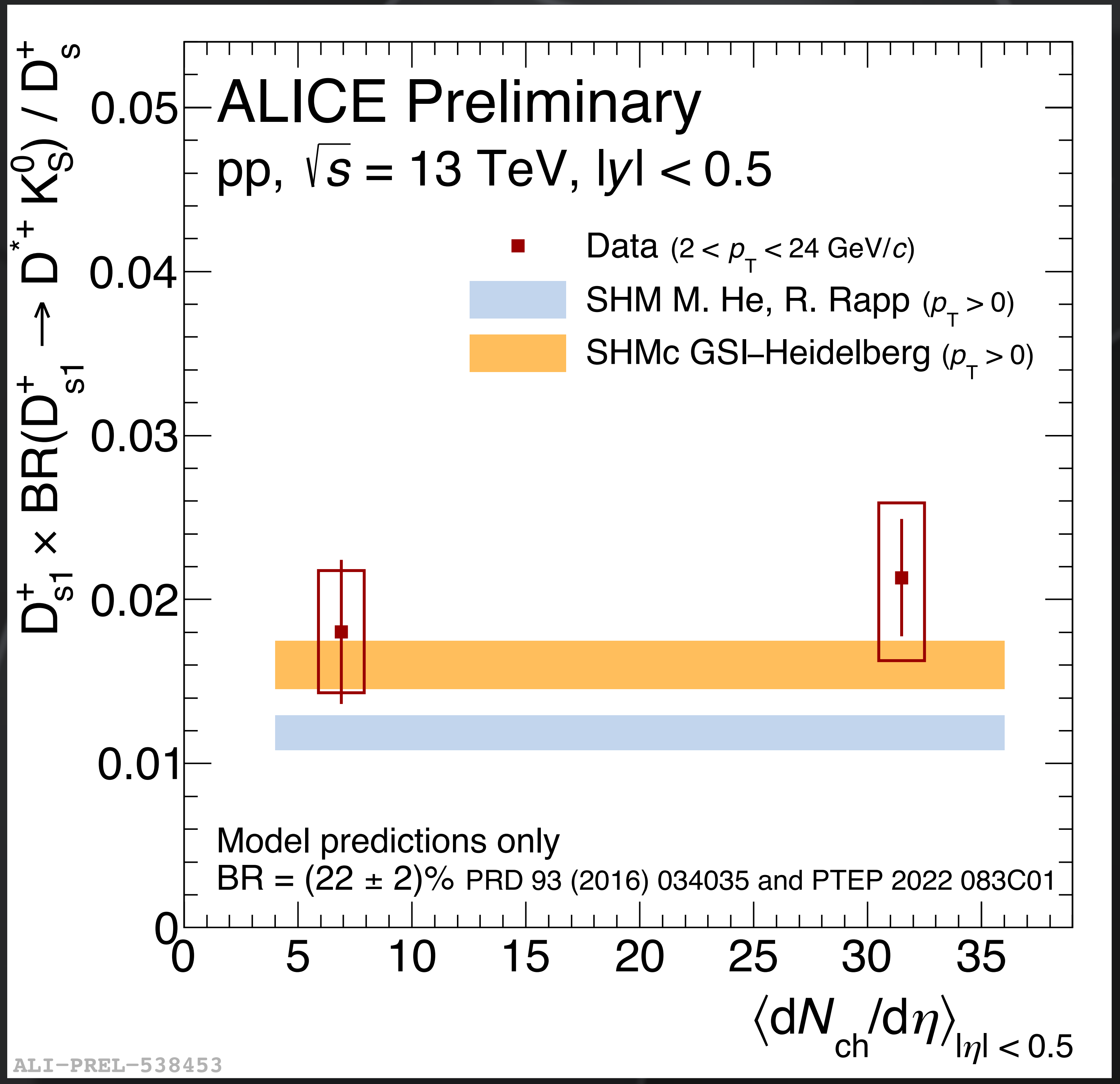
Investigation of **exotic bound states**

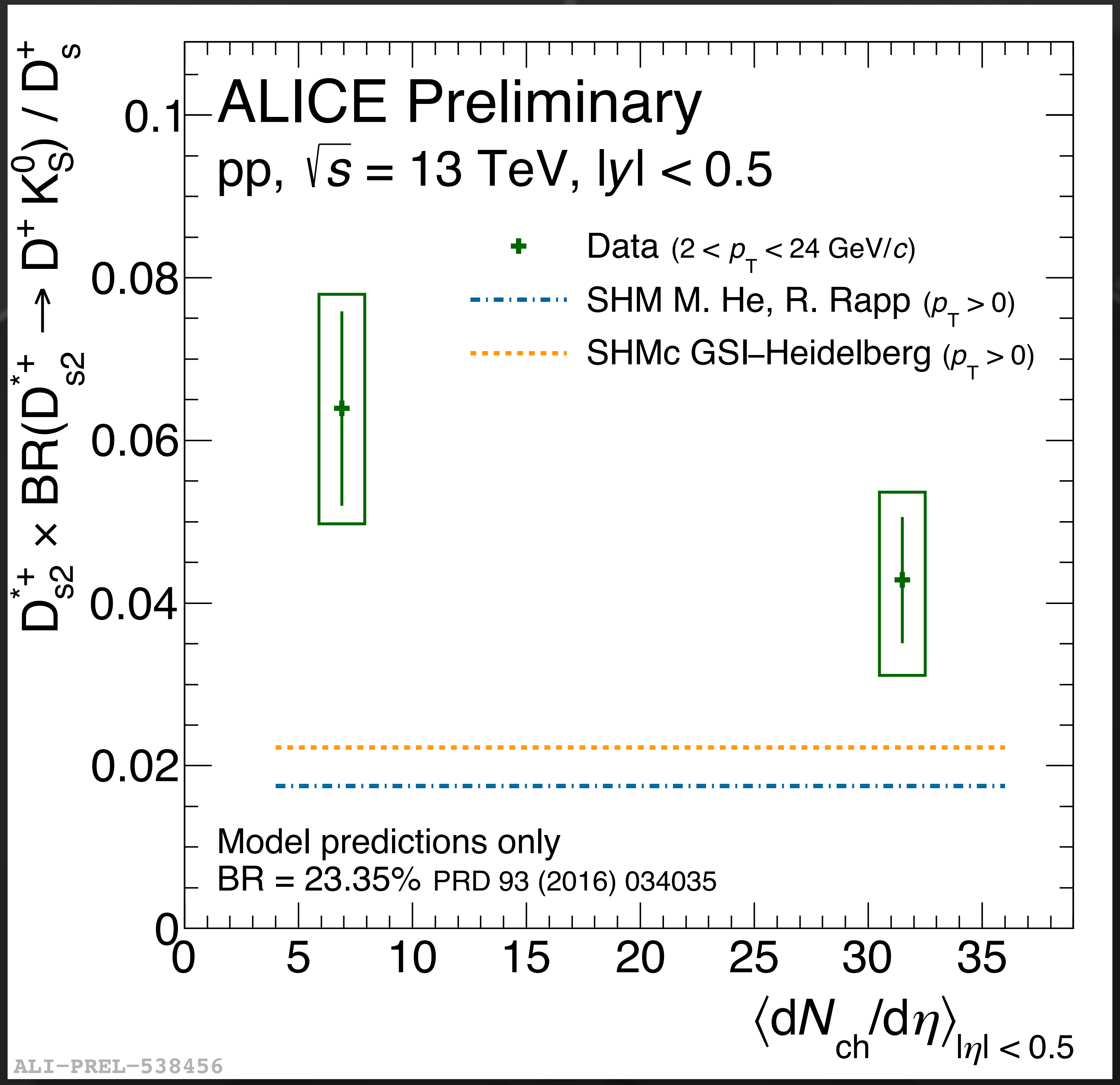
Hadron-gas phase ~ 10-15 fm/c

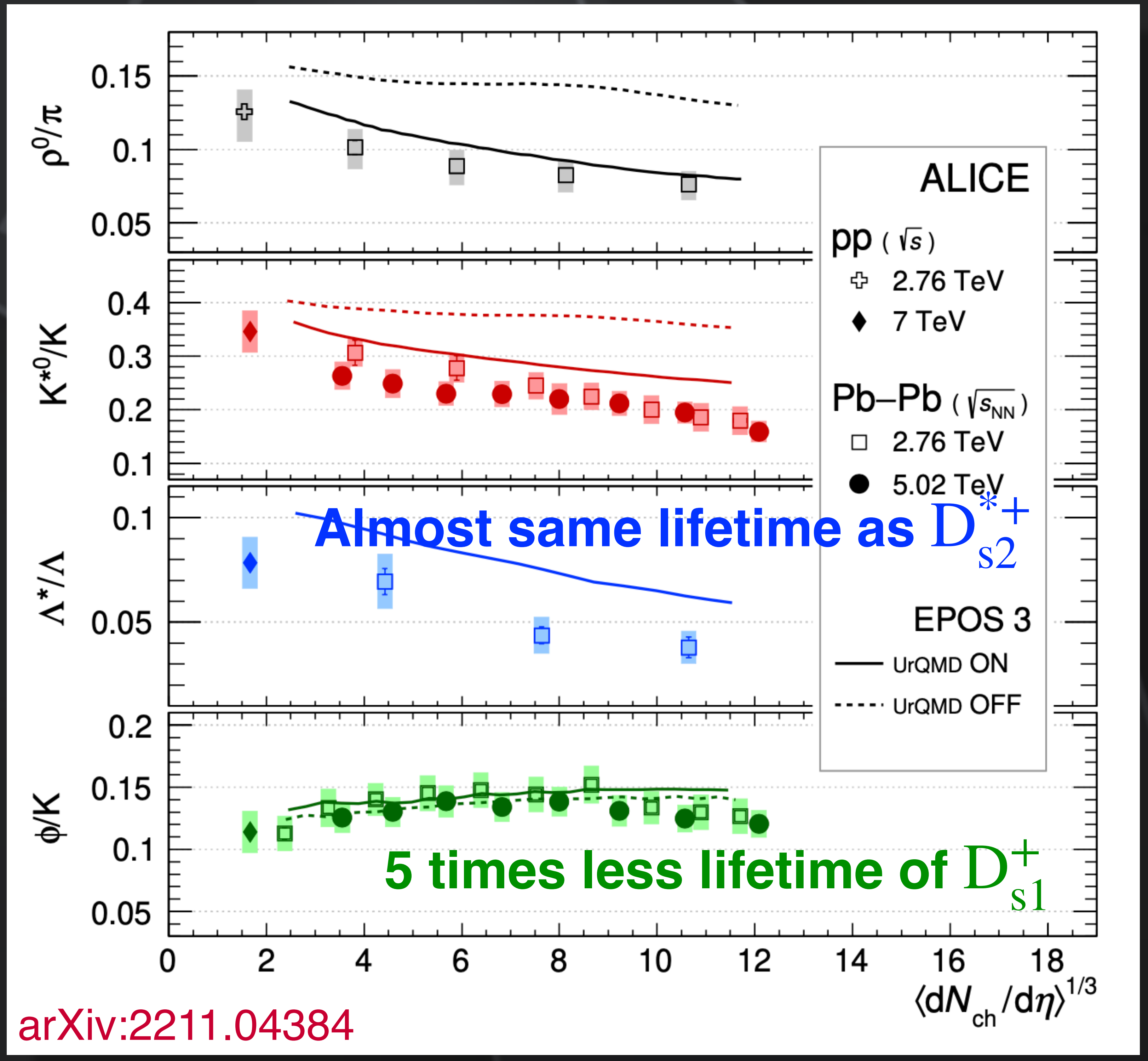
Heavy flavor hadronic resonance

- $D^{+}_{s1} \times BR(D^{+}_{s1} \rightarrow D^{*+}K^{0}_{S})/D^{+}_{s}$: **No multiplicity dependence** in data and SHM and SHMc
- $D^{*+}_{s2} \times BR(D^{*+}_{s2} \rightarrow D^{+}K^{0}_{S})/D^{+}_{s}$
  - Hint of enhancement at low multiplicity might arise from **hadronic rescattering**
    - Lifetime: $\tau(D^{+}_{s1}) \sim 219\ \mathrm{fm}/c$, $\tau(D^{*+}_{s2}) \sim 11.61\ \mathrm{fm}/c$









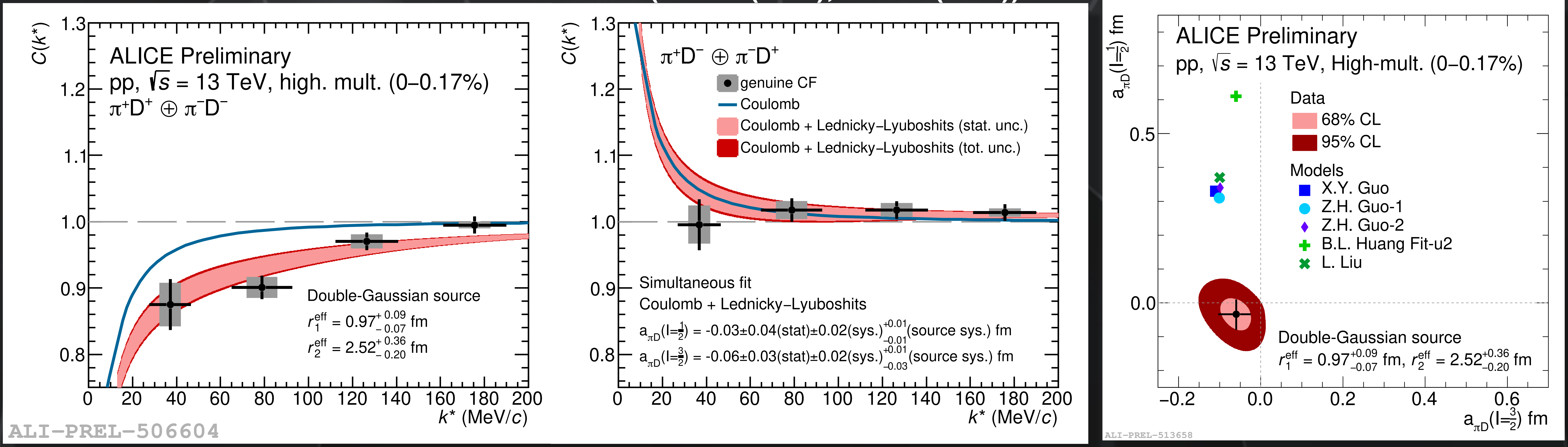
HF hadrons in hadronic phase

- Scattering length for **I = 3/2** in agreement with models
- Scattering length for **I = 1/2** significantly smaller than models
  - Indicate a **small interaction of between charm mesons** and light hardrons in the hadronic phase

$$C(k^*) = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Same charge pair (I = 3/2 only)

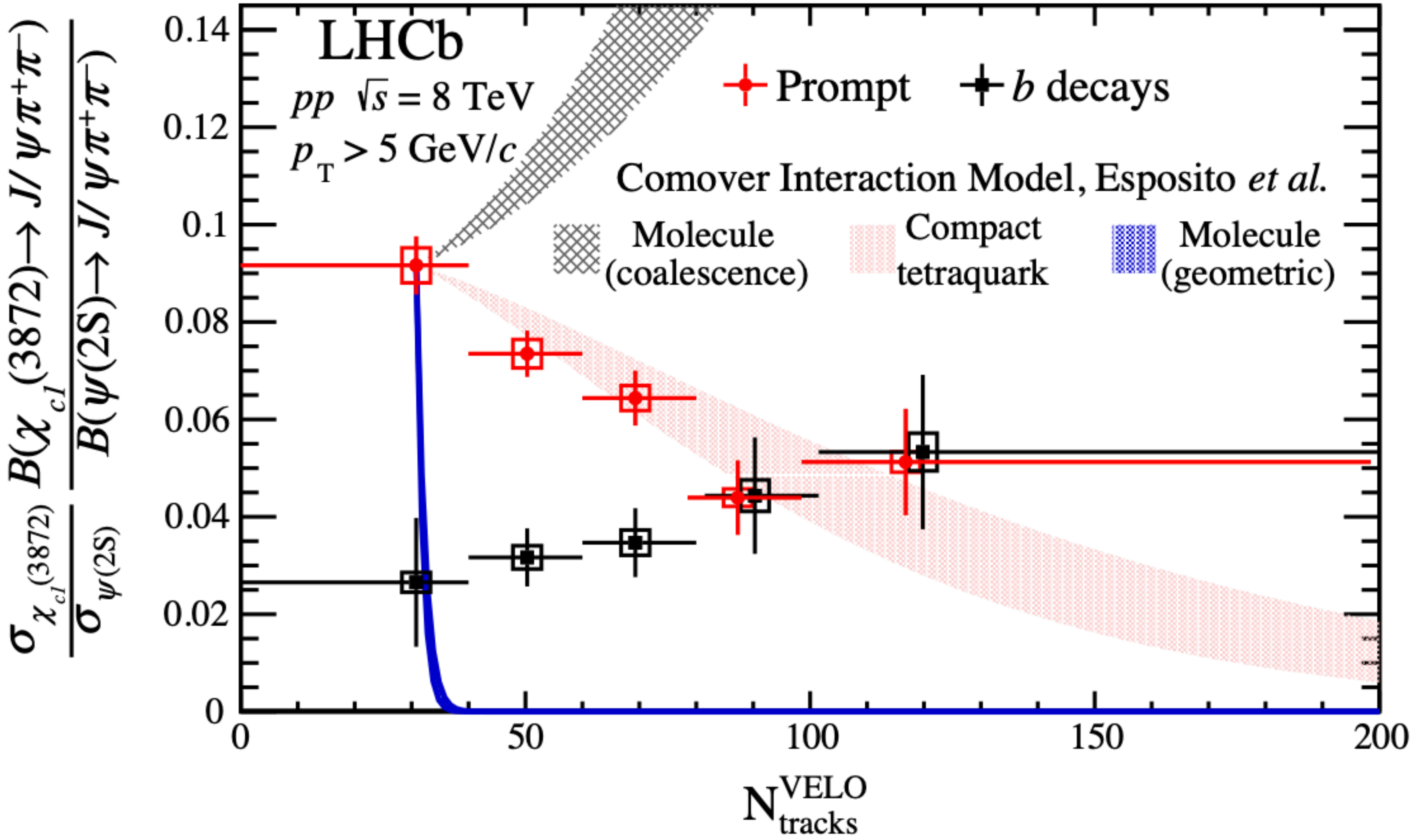
Oposite charge pair (I = 3/2 (33%), I = 1/2 (66%))



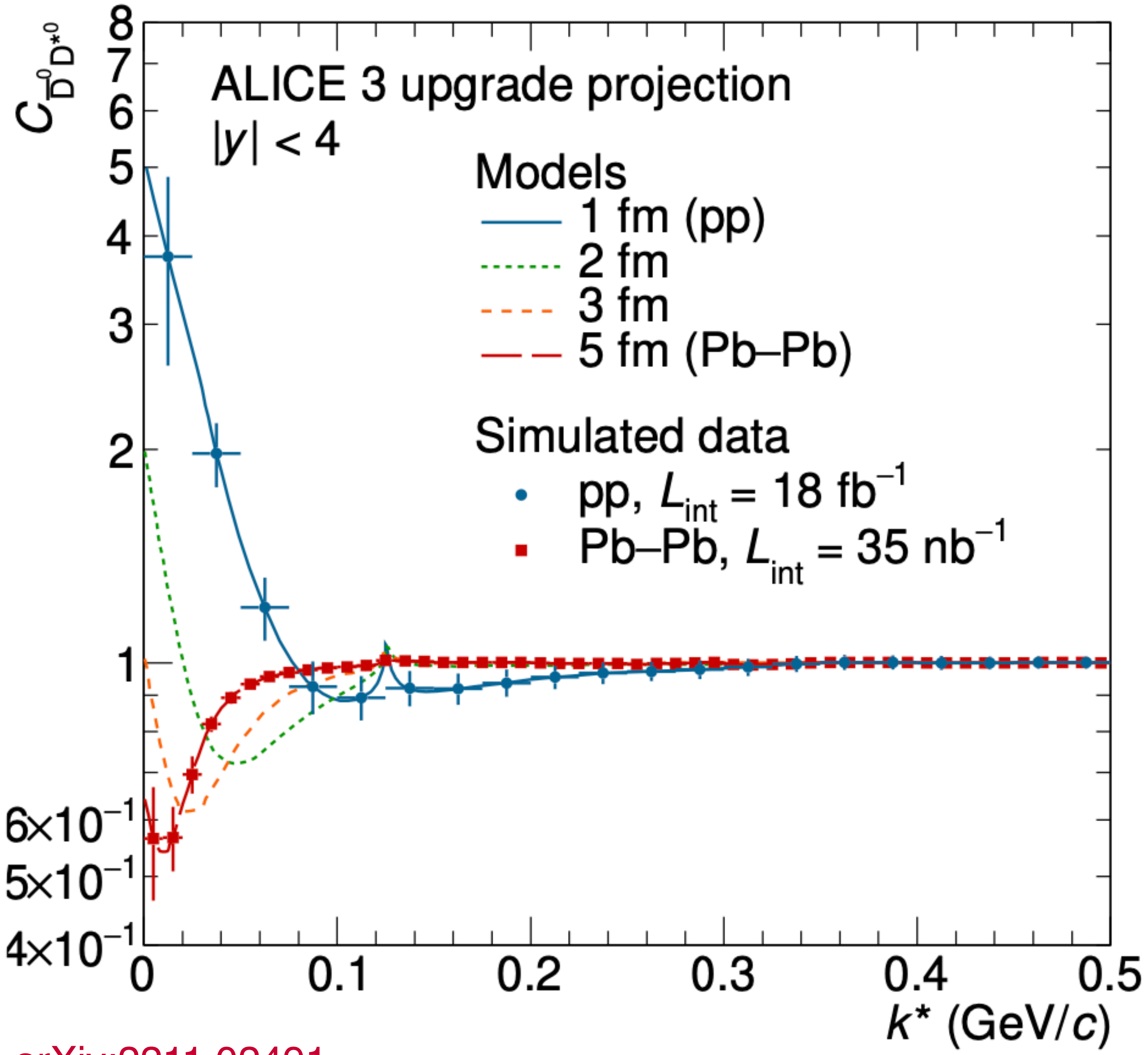
$$k^* = 1/2\,|p^*_{x_1} - p^*_{x2}|$$

Exotic charm states

- $\chi_{c1}(3872)$ structure: a compact tetraquark? hadronic molecule?
- $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$: nature of $\chi_{c1}(3872)$
  - Interaction between $\mathrm{D}^0\bar{\mathrm{D}}^{*0}$ will offer an additional constraint for the structure of exotic charm states



PRL 126, 092001



arXiv:2211.02491

Sensitivity to initial state and B

Interaction with QGP
Radiative energy loss
Thermalization

Fragmentation
Coalescence

Interaction potential
Rescattering

Sensitivity to initial state and B

Interaction with QGP
Radiative energy loss
Thermalization

Fragmentation
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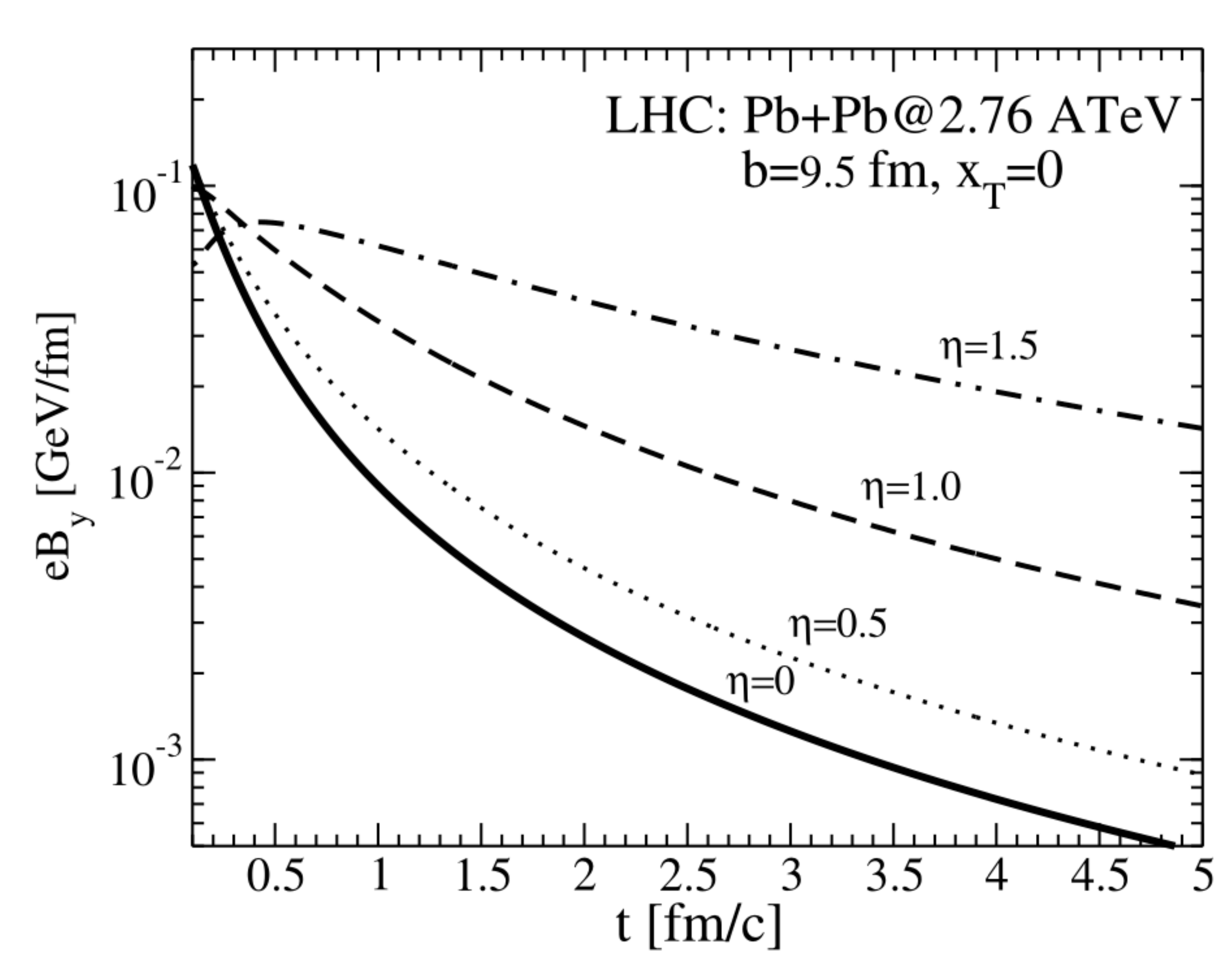
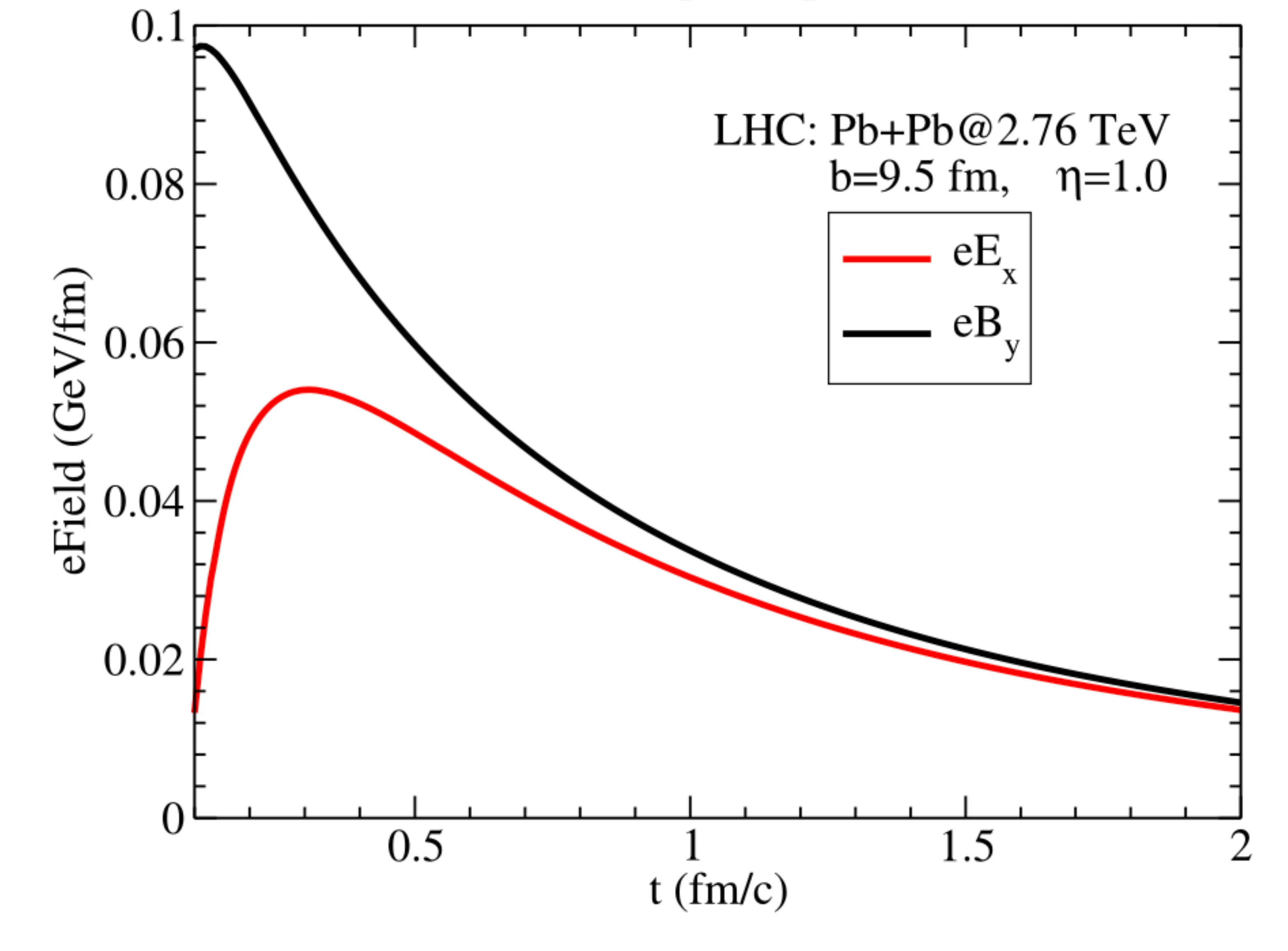
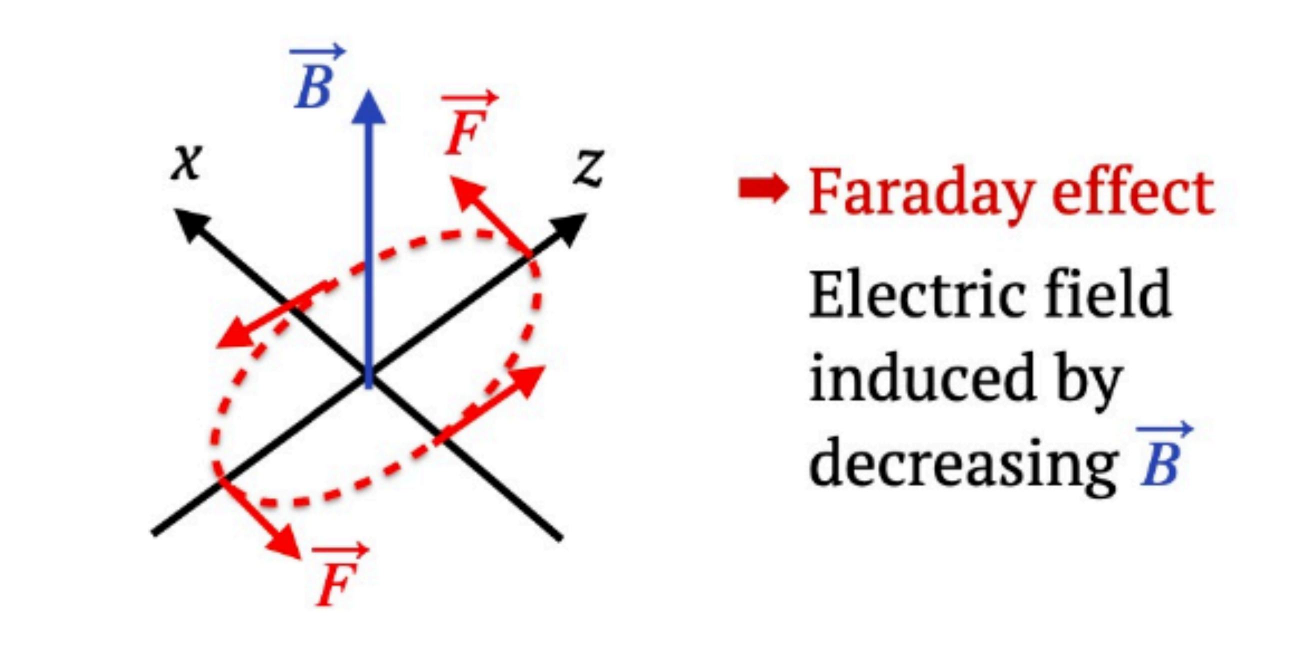
Interaction potential
Rescattering

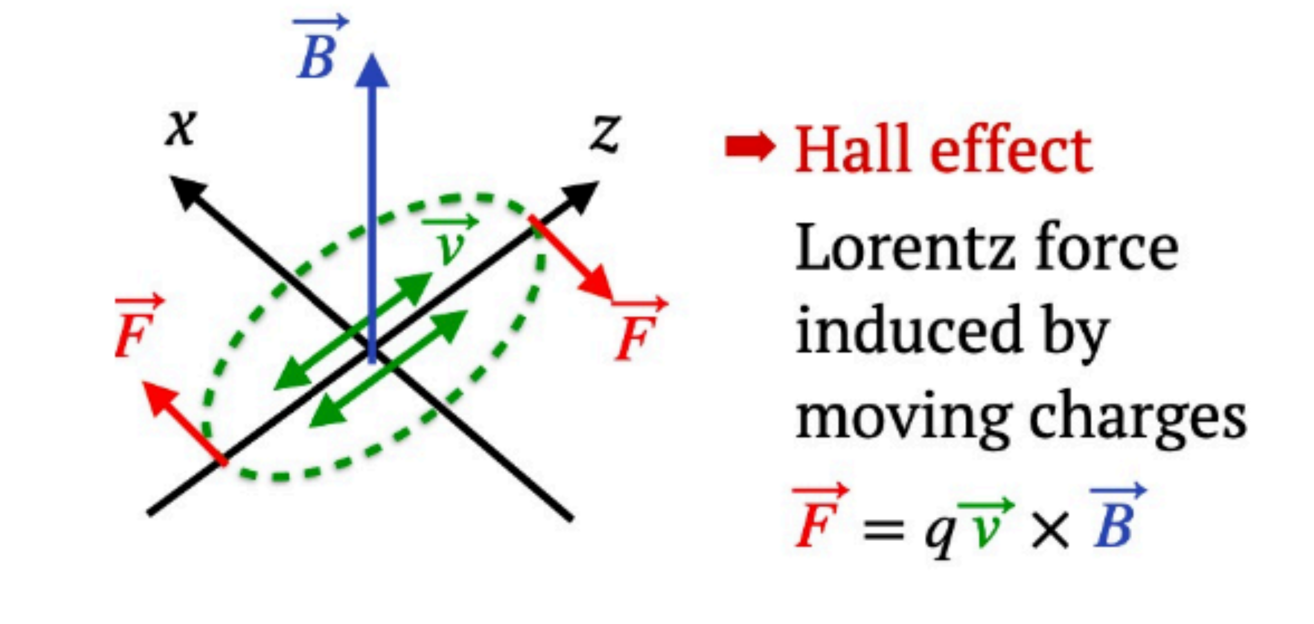
Back up

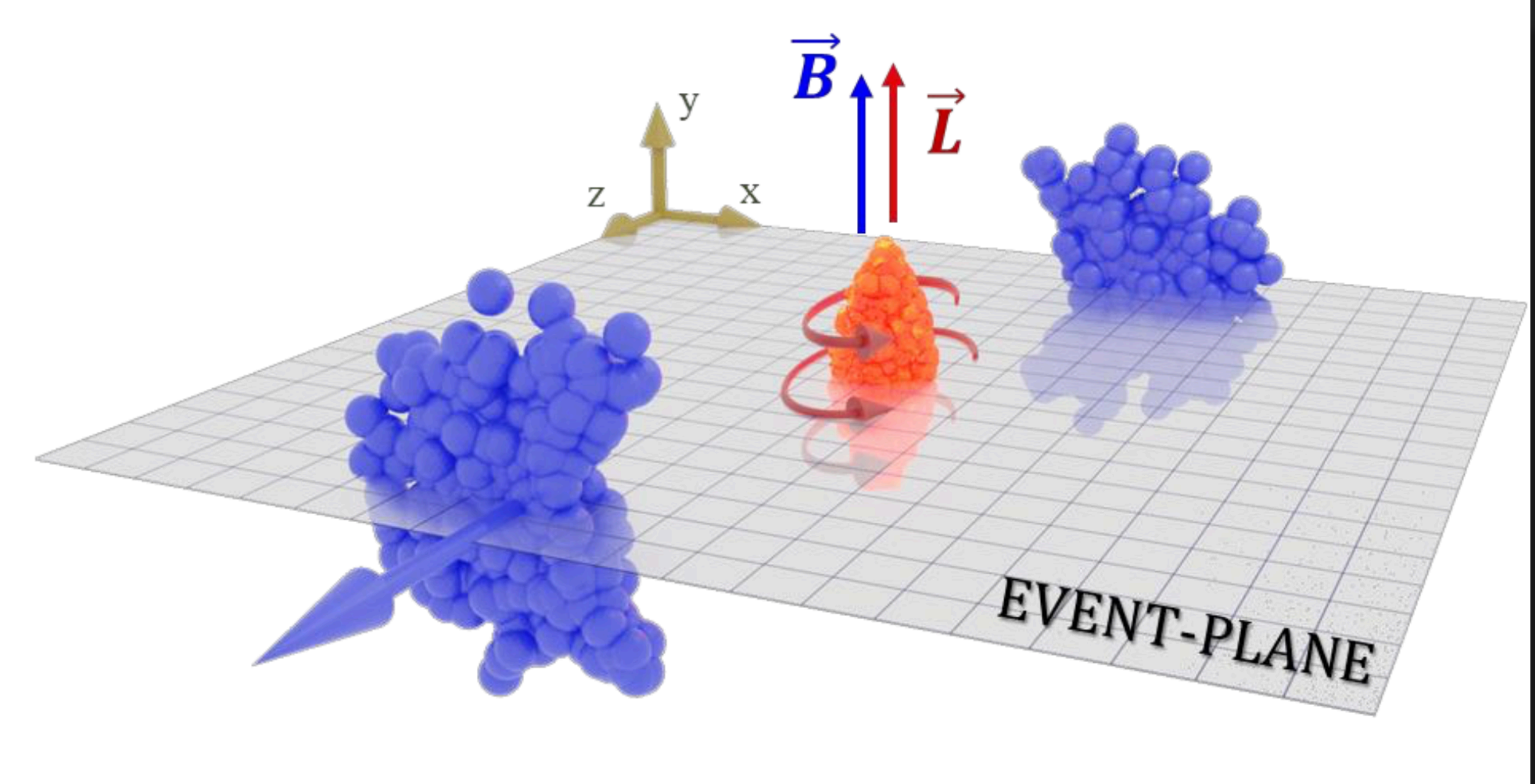
Large magnetic field in HIC

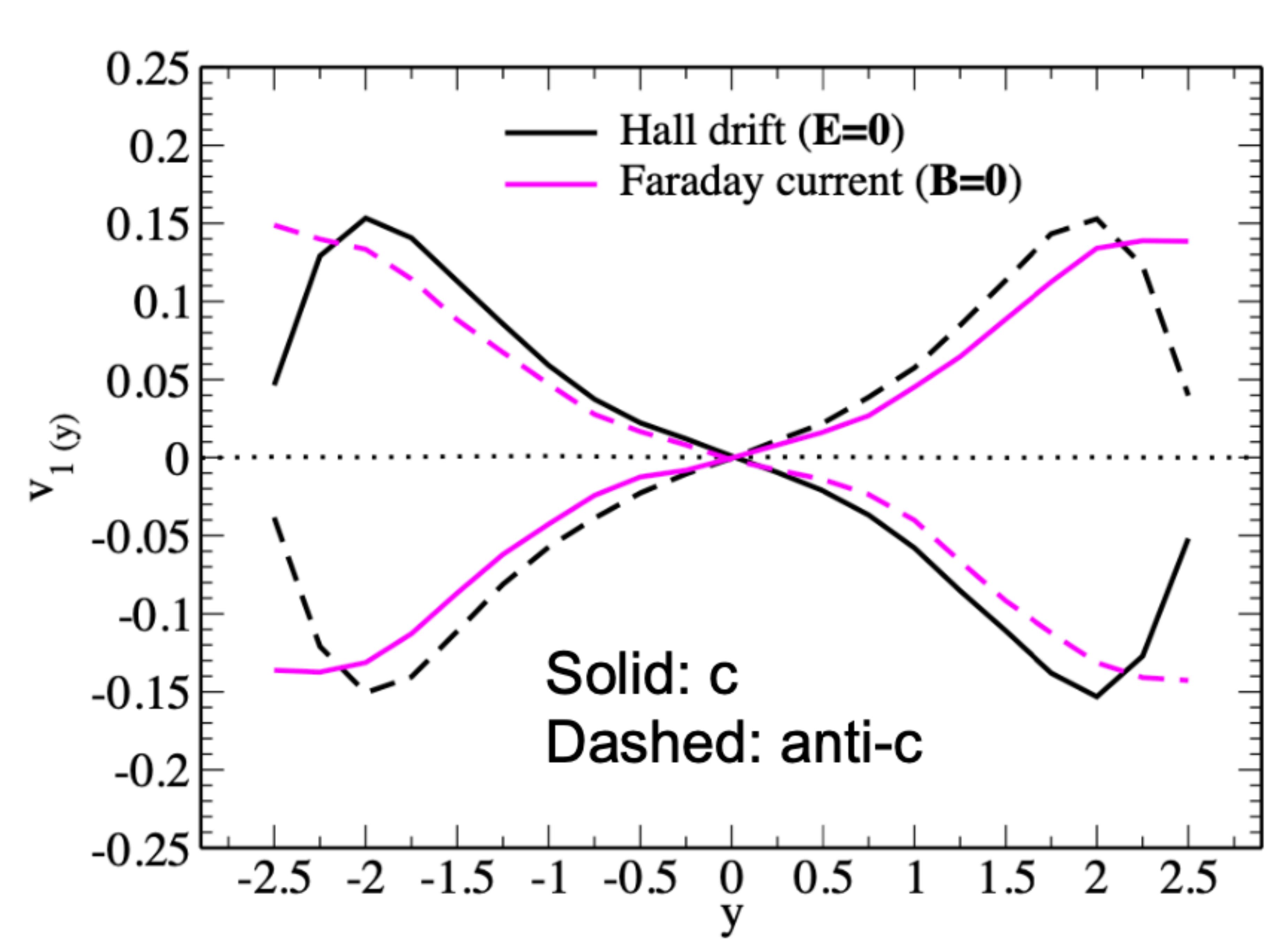






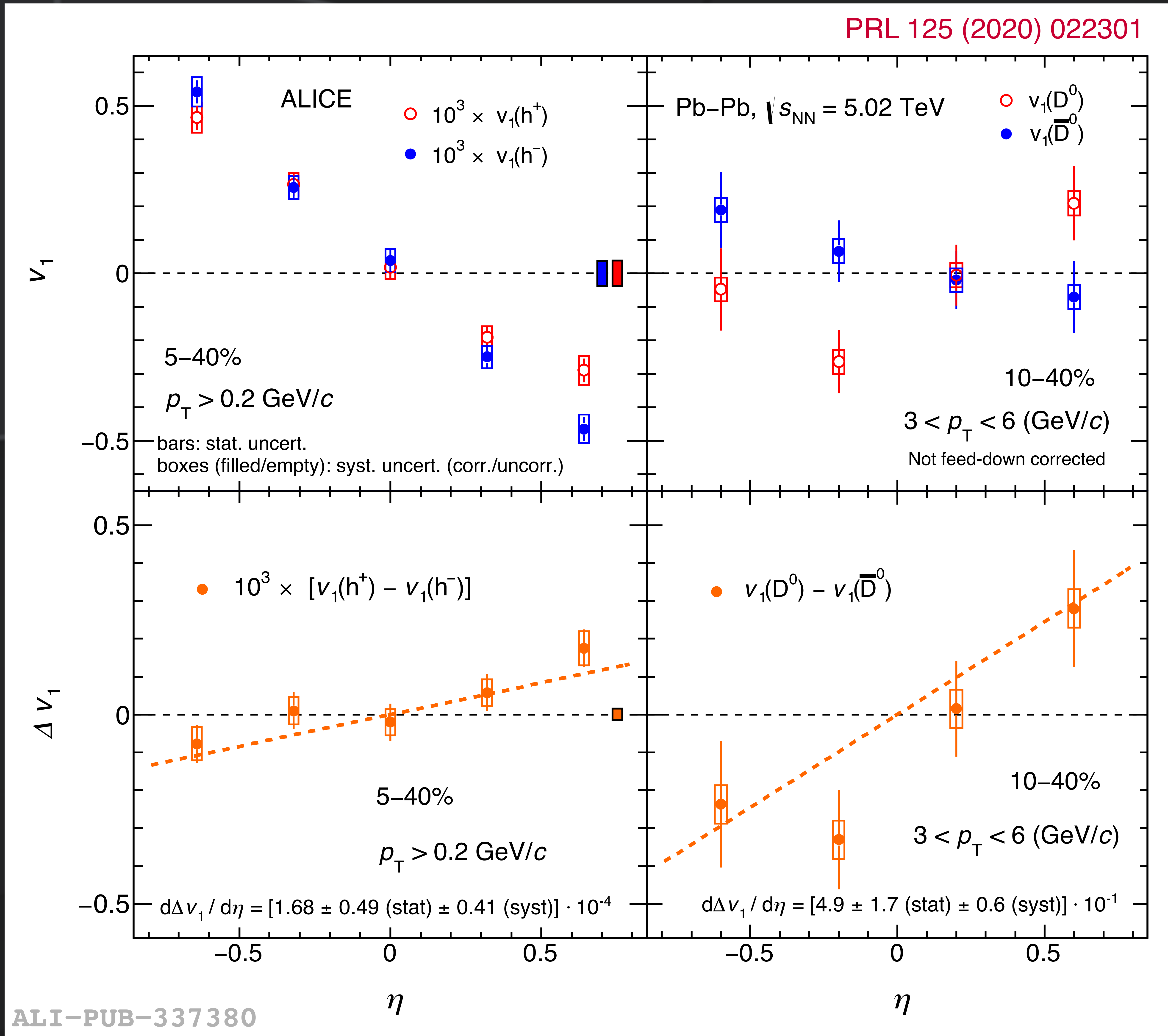






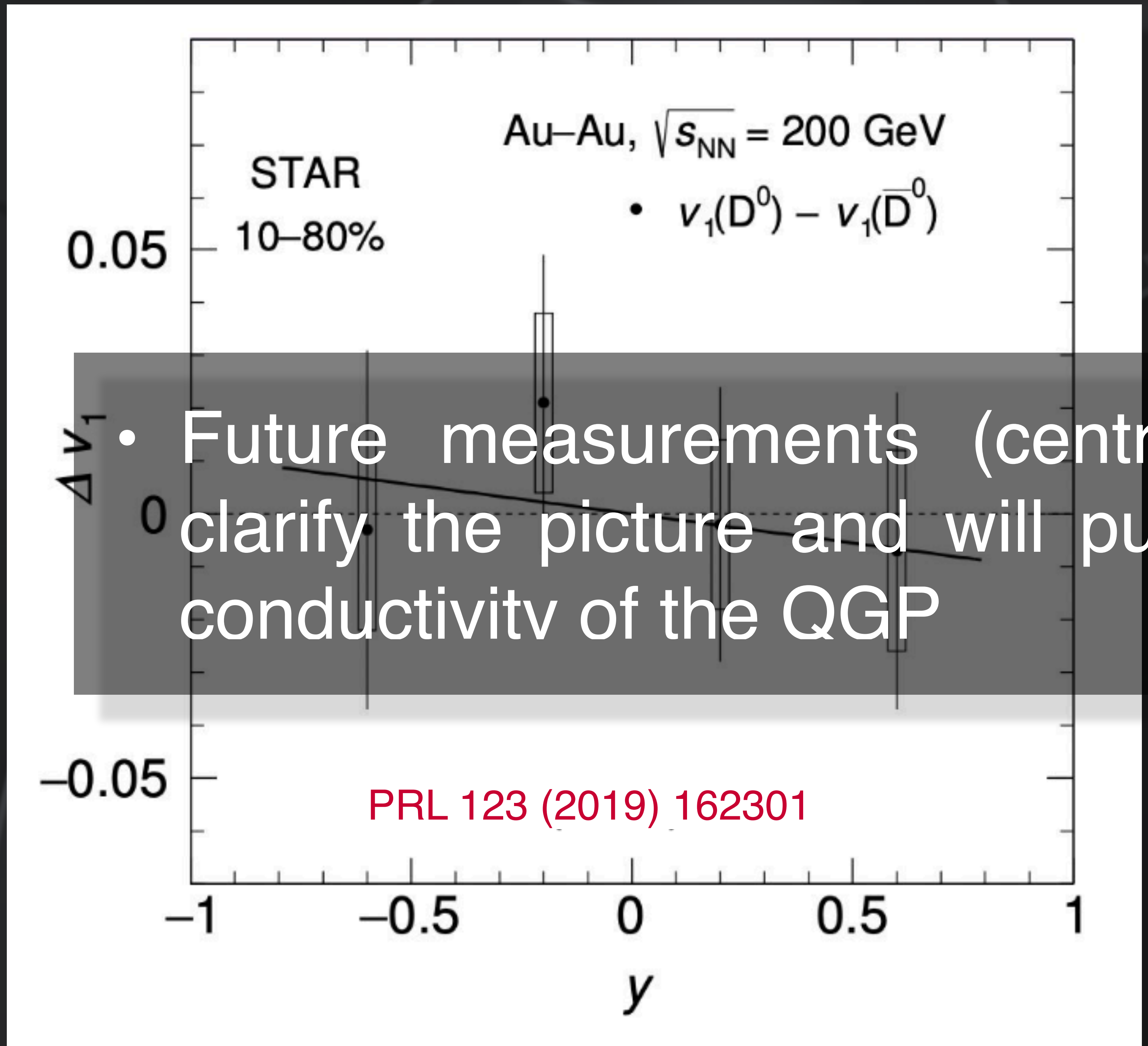
Charge dependent direct flow

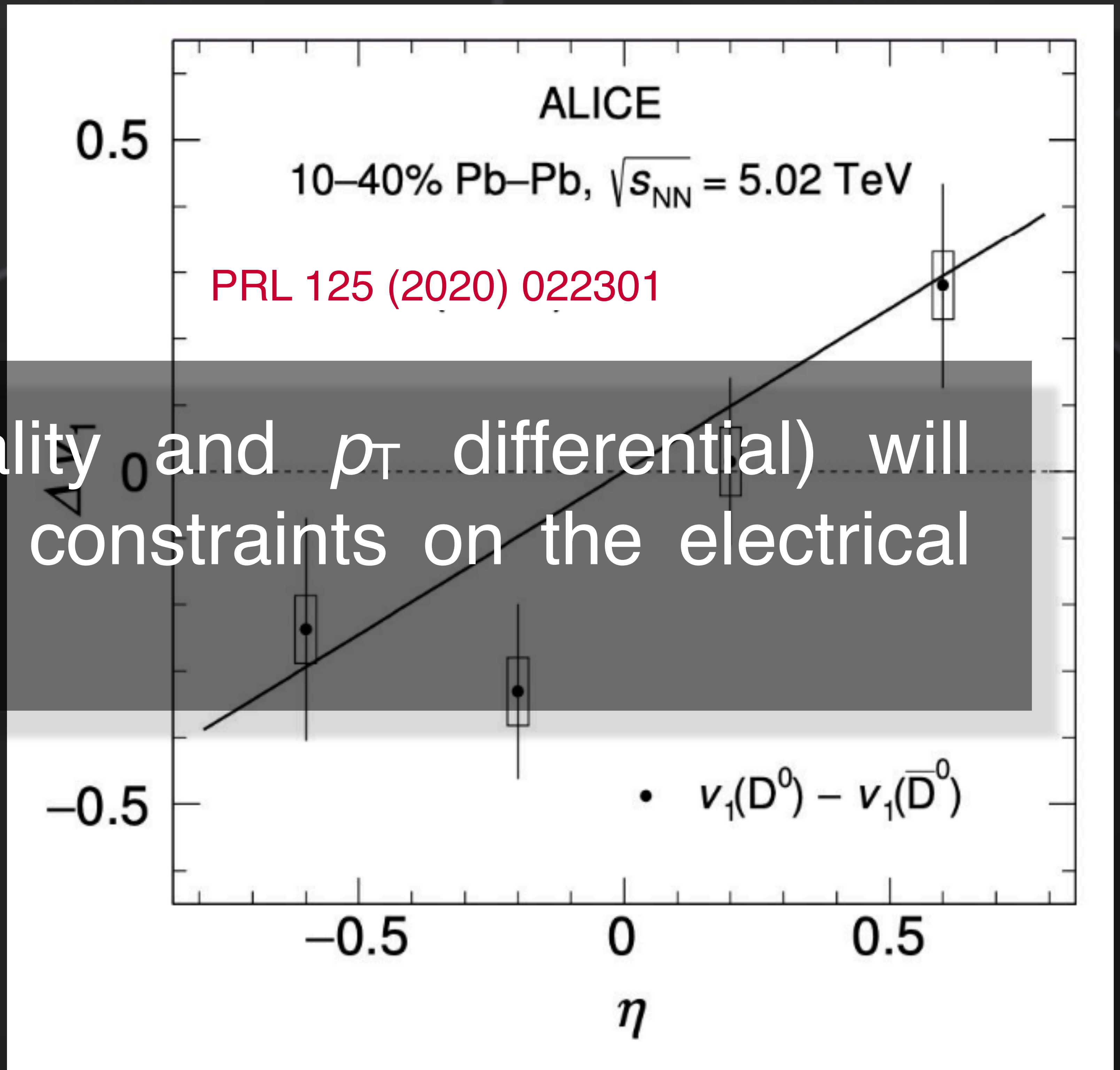
- **v_1 of charm hadrons** (D^0 mesons) is **larger** than that of lighter particles
- **Opposite sign of v_1** for particles is shown with charm and anti-charm
- **3 orders of magnitude larger** slopes w.r.t. charged hadrons

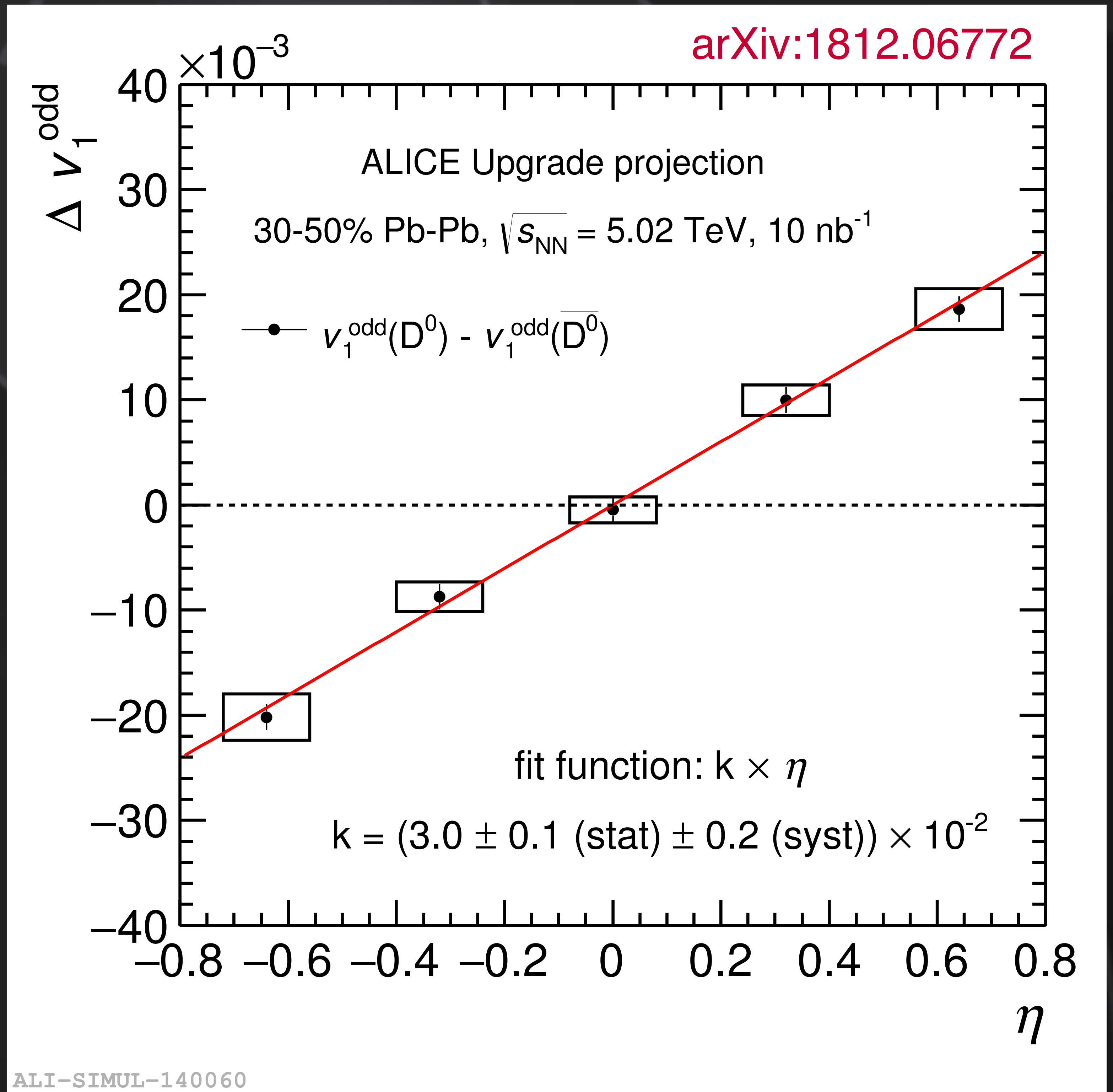


Charge dependent direct flow

- Interplay between the effects of the **rapidly decreasing magnetic field** and the **initial tilt of the source** affects the directed flow observable
- The results measured at **RHIC and LHC energies** show the **opposite slope**
- **LHC** shows a **larger slope** w.r.t. RHIC





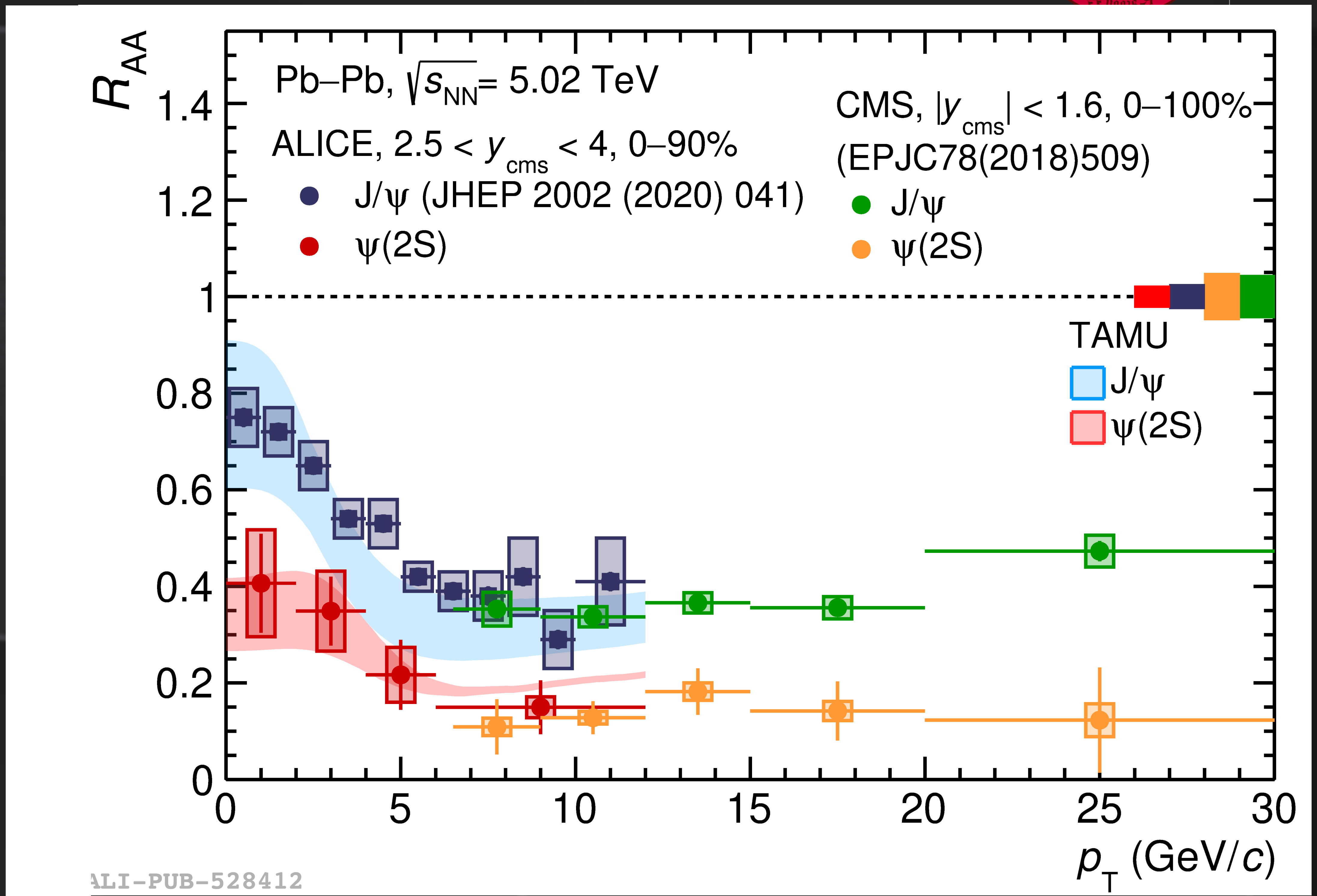


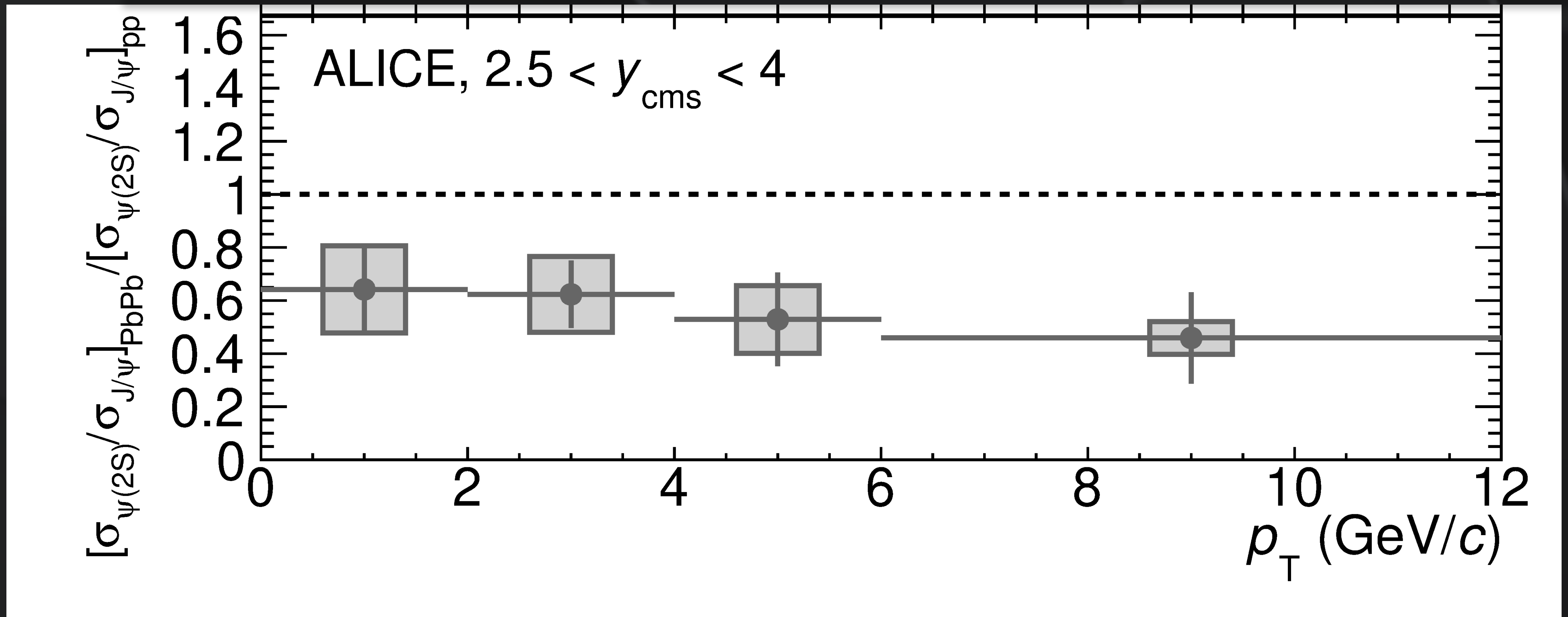
- Future measurements (centrality and p_T differential) will clarify the picture and will put constraints on the electrical conductivity of the QGP

R_{AA} of charmonium

- At low p_T
  - **Sizeable regeneration(recombination)**
- At high p_T
  - ALICE and CMS agree with each other
  - **No clear p_T dependence** on R_{AA}

- Double ratio
  - **Significant relative suppression of** $\psi(2S)$





p_T distribution modification

- R_{pPb} is described by **QCM** within uncertainties.
- **Push towards higher p_T** of Λ_c^+/D^0 and Ξ_c^0/D^0 from pp to p-Pb.
  - **Radial flow**? **Coalesence** effect?
- BR ~ 0.45% - 1.1% → Ξ_c^0/D^0 (LHCb) ~ **0.045 - 0.11**

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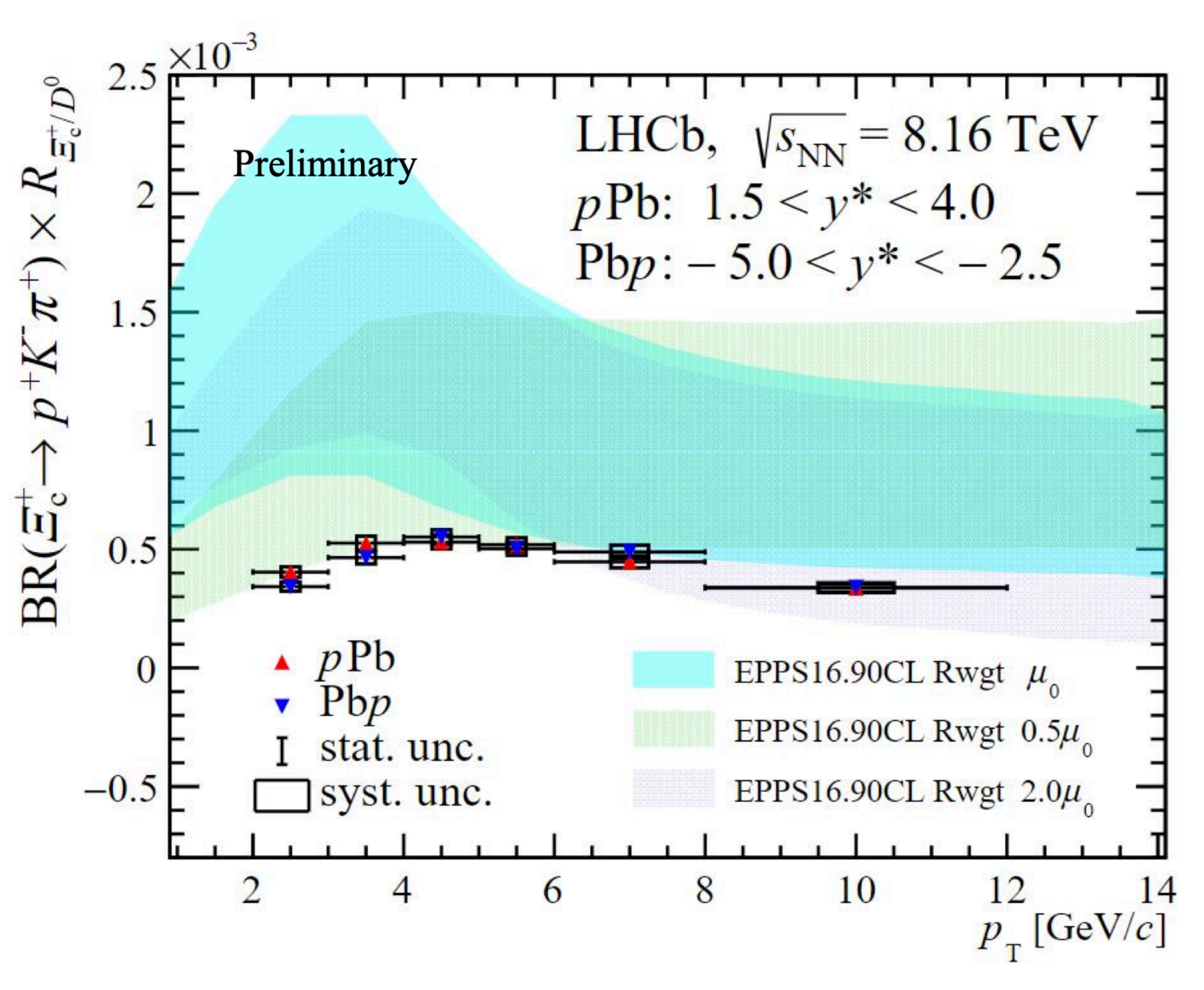
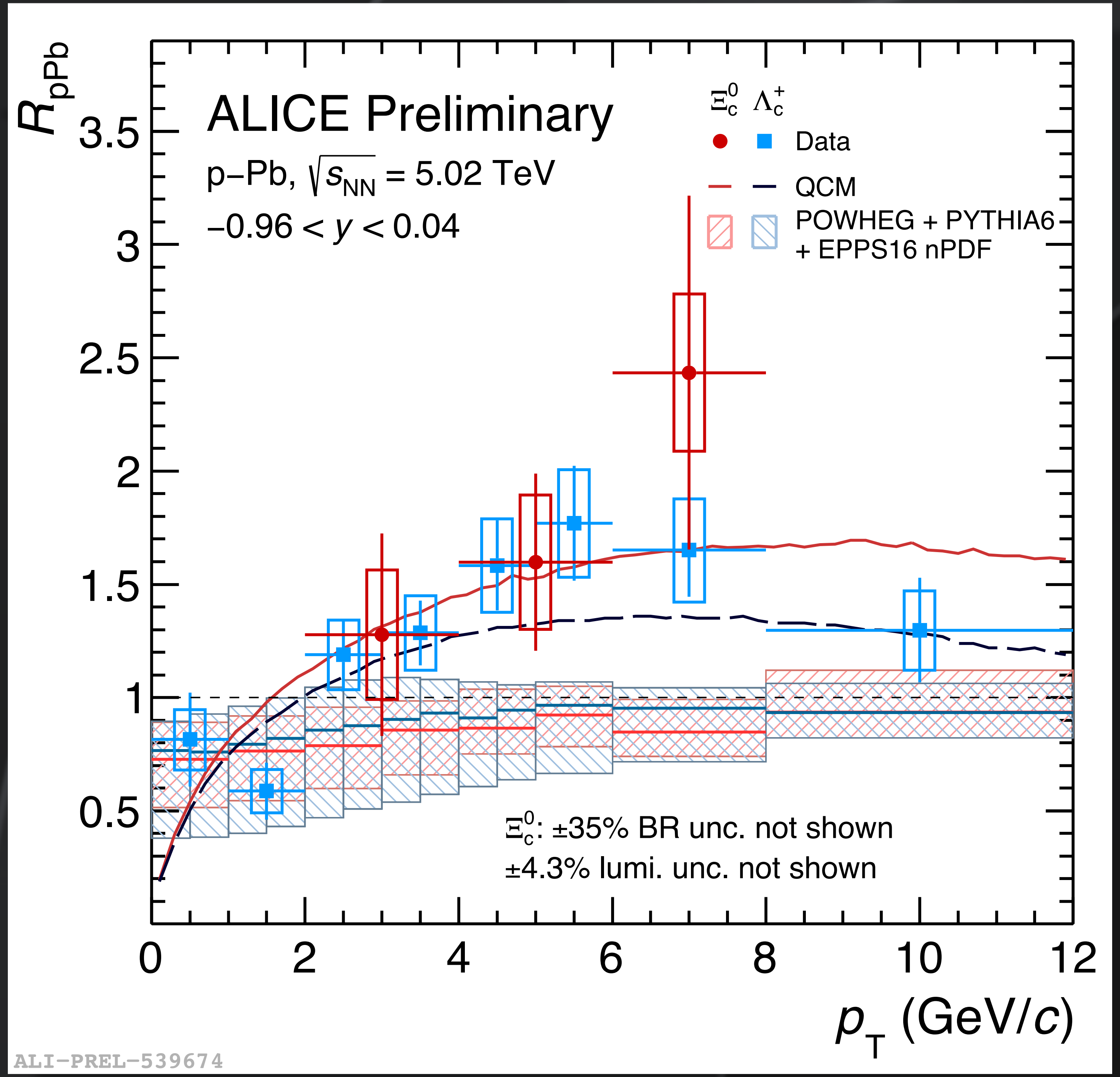
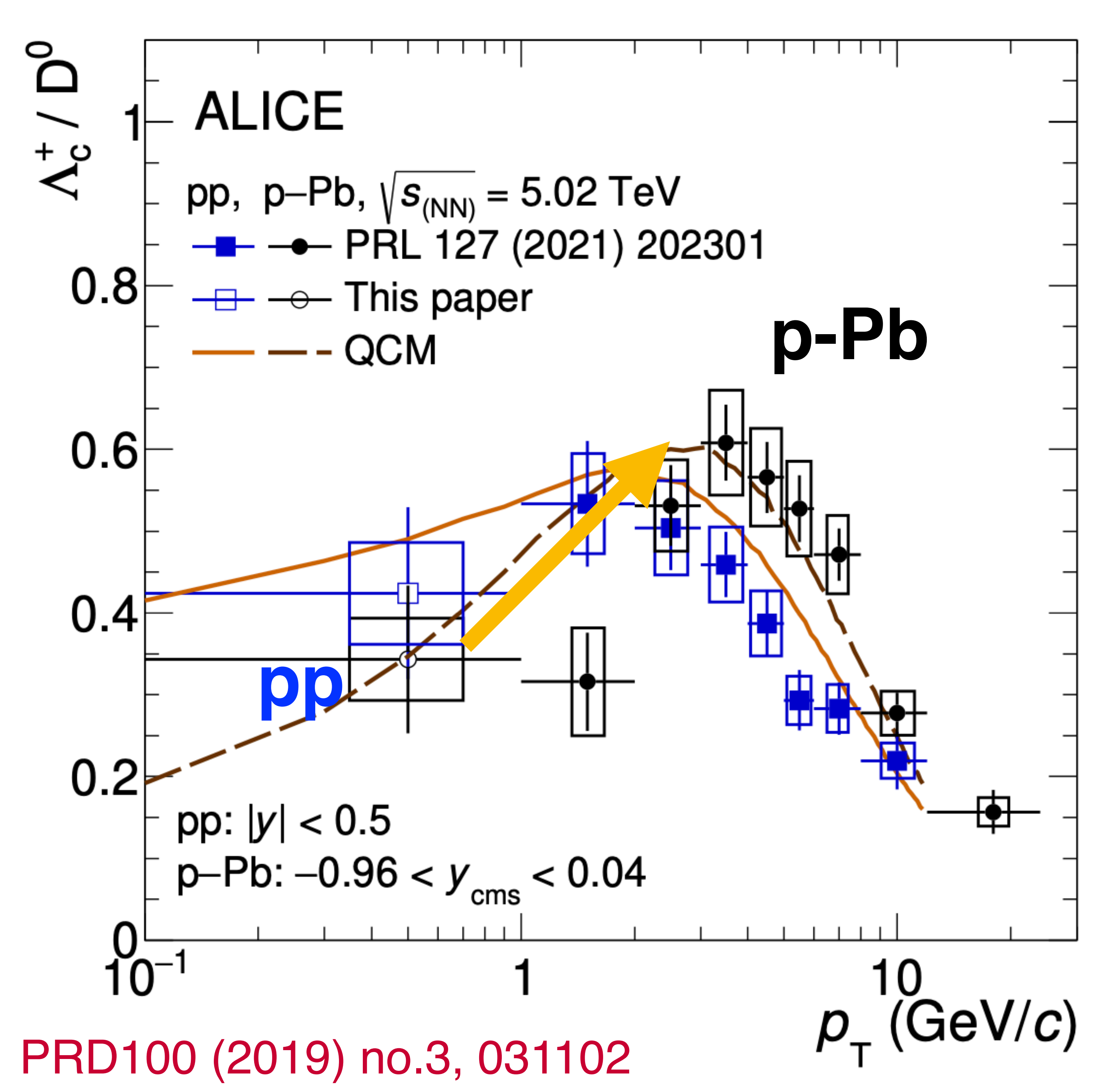
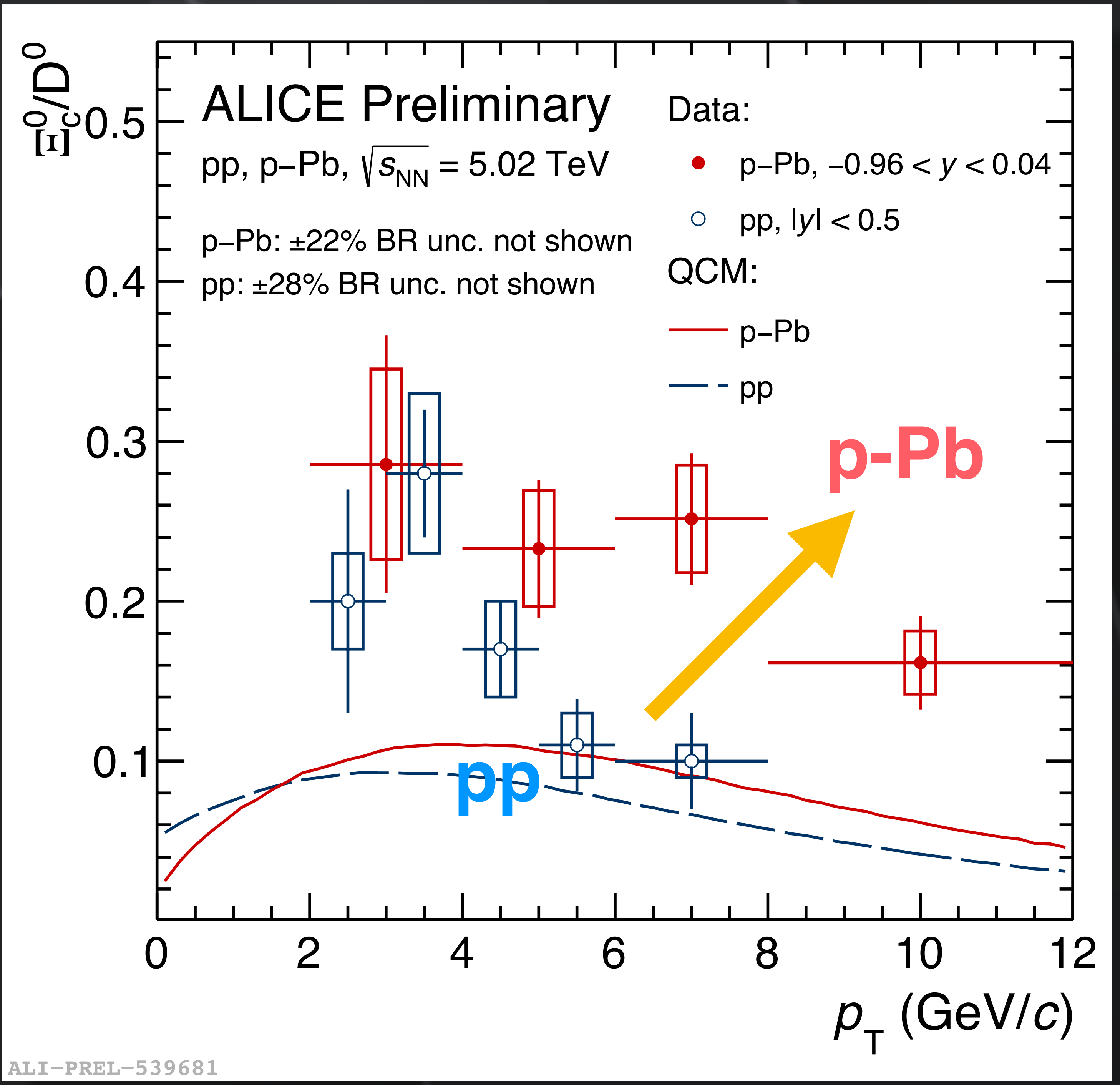
QCM: EPJC 77 (2017)163





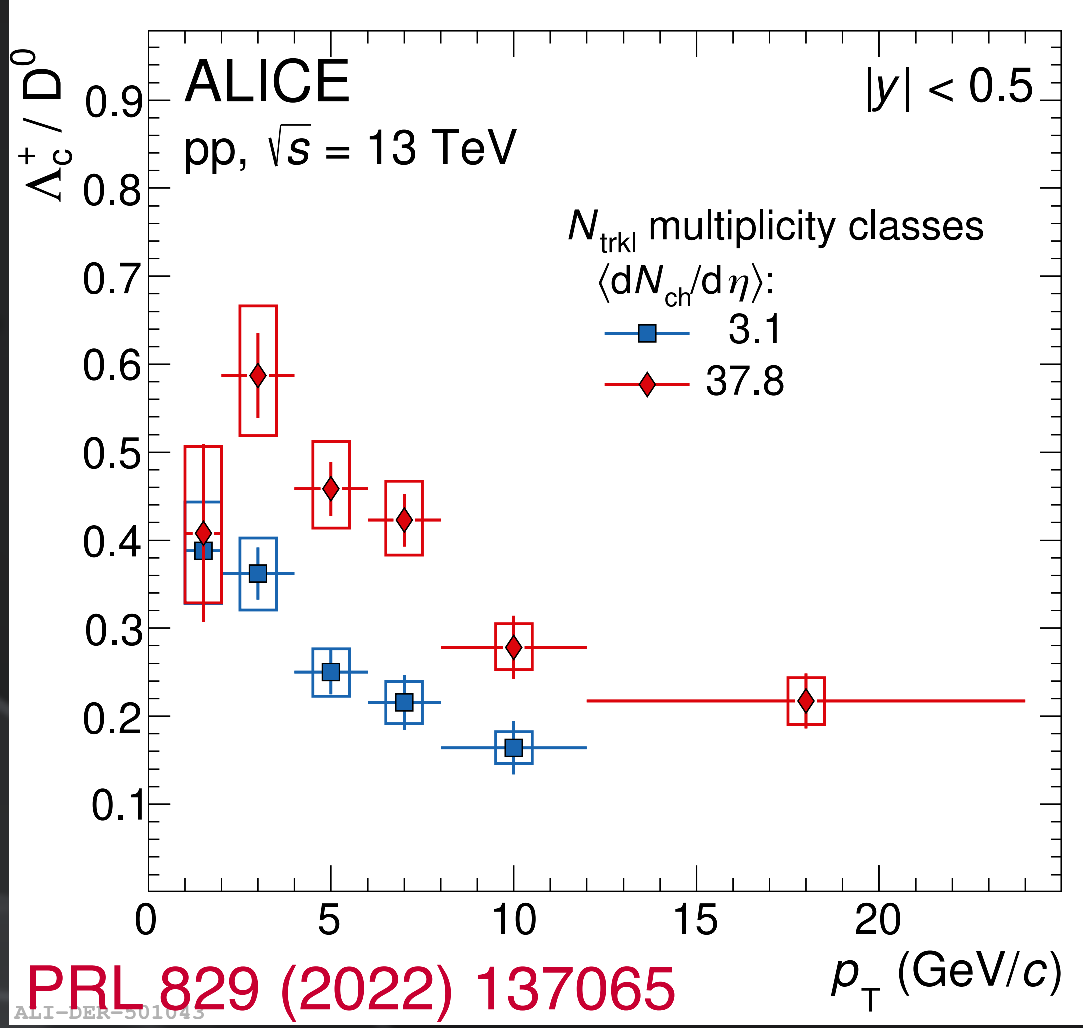




QCM: EPJC 78 no.4, (2018) 344

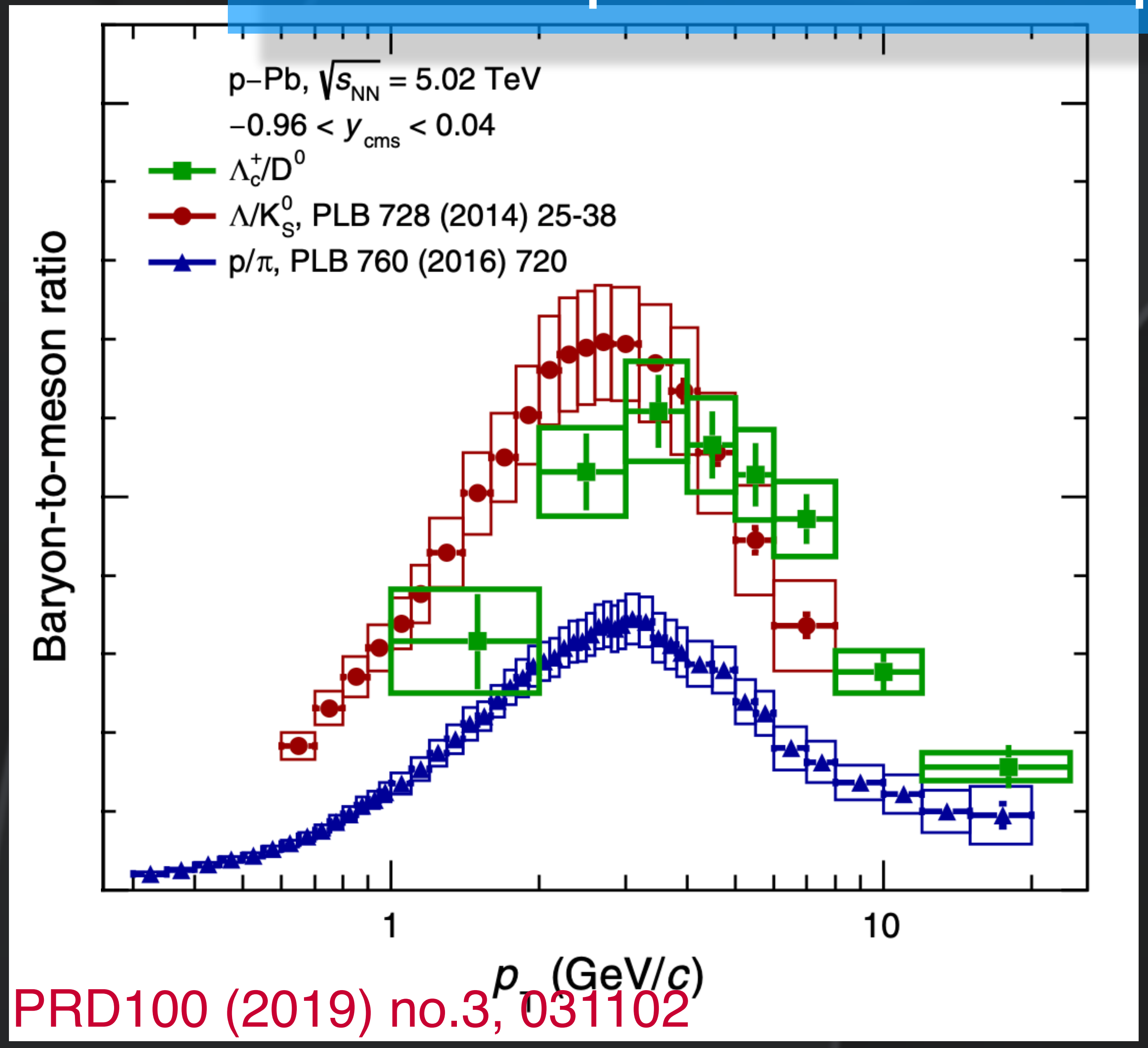
Multiplicity dependence

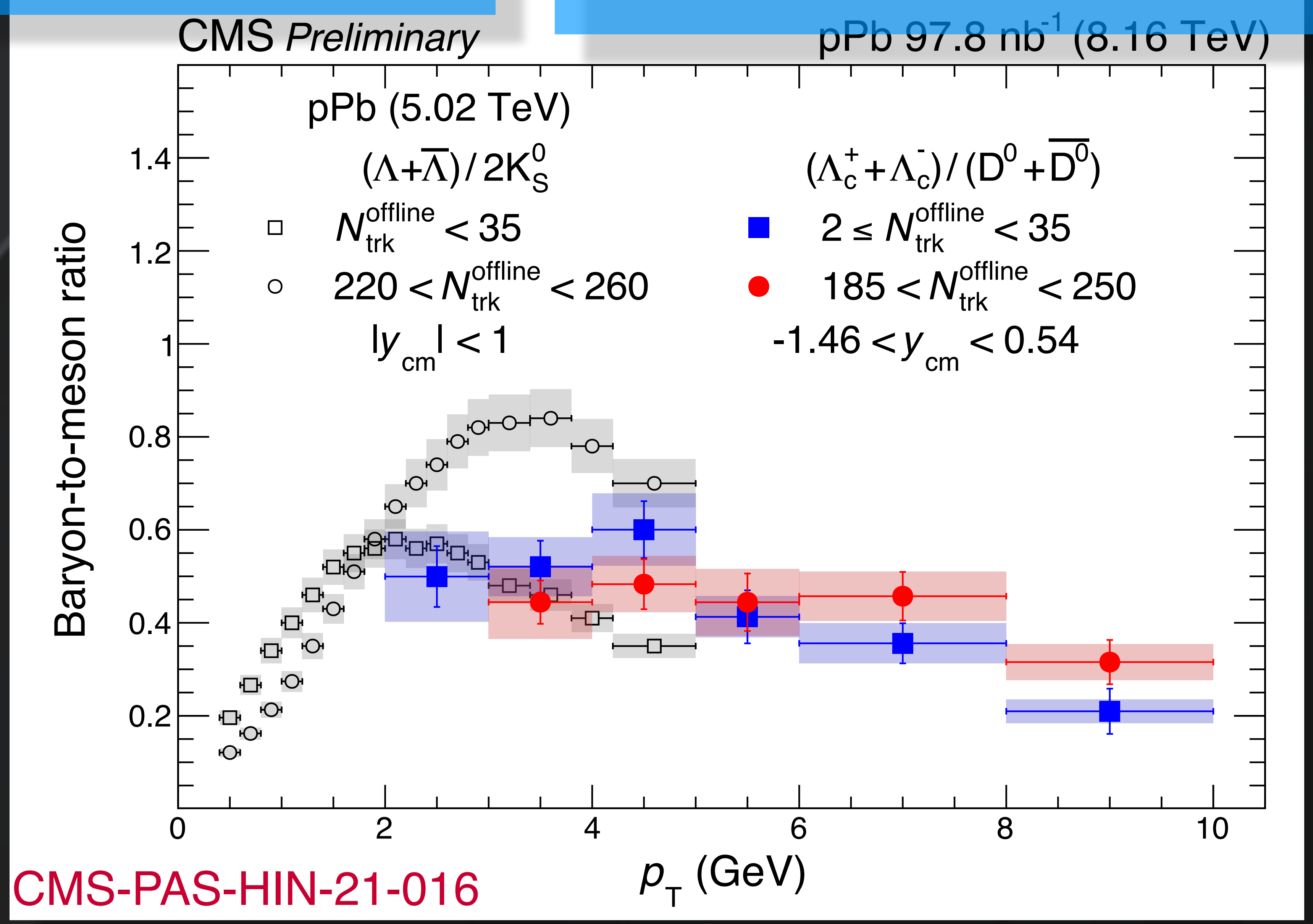
- **Clear multiplicity dependence** of the baryon-to-meson ratio in **pp** collisions.
- **Similar p_T dependence** in the **charm** and **light** sector in **MB p-Pb**.
- **No multiplicity dependence** in **p-Pb** over p_T in contrast to strange hadrons.
- No multiplicity dependence of the p_T-integrated ratio.
  - Significantly higher values than e^+e^-.

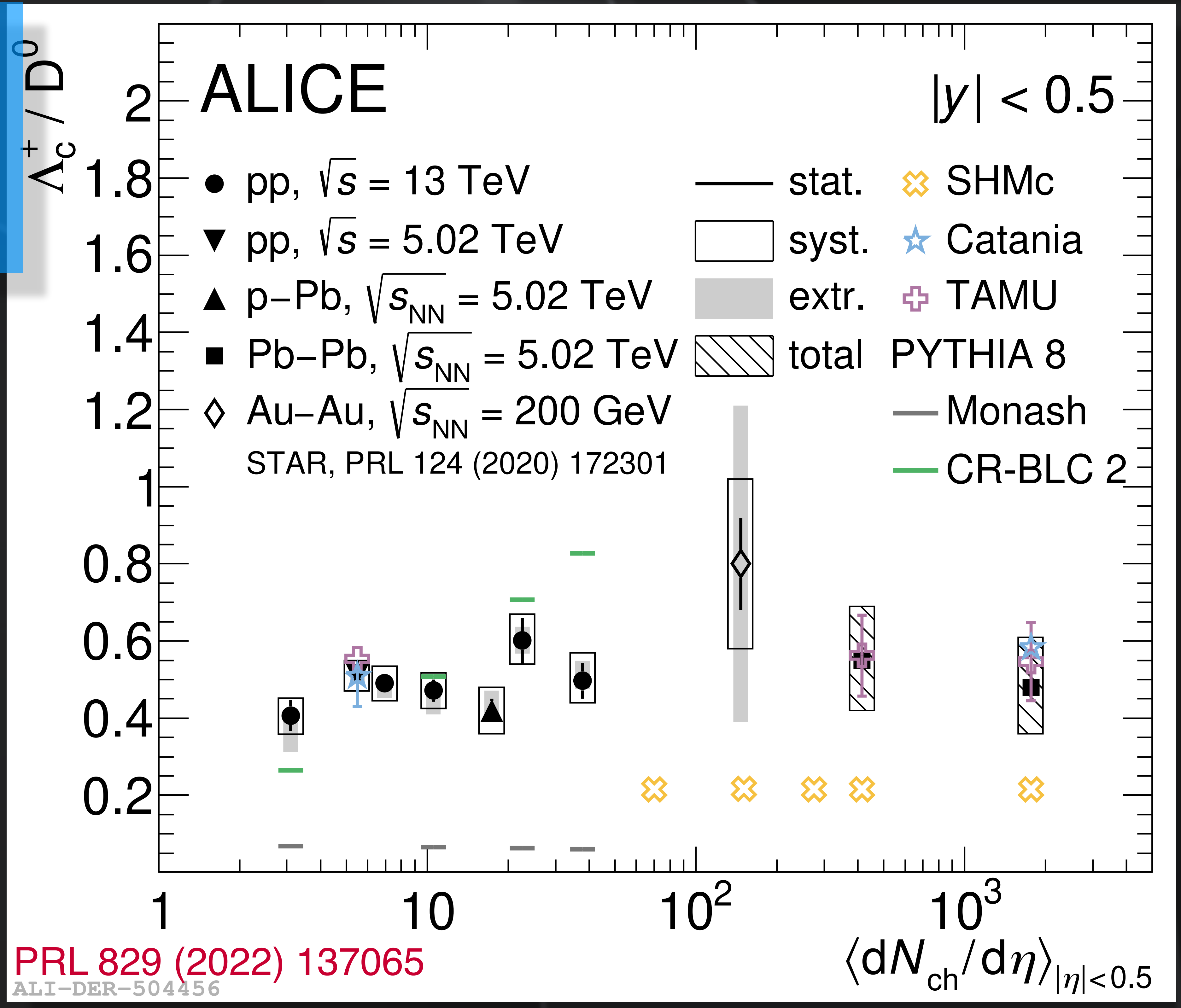


- **Hadronization mechanism**
  - LF ~ HF? or LF ≠ HF?
  - Depends on multiplicity?

- Go down to the **lowest** multiplicity?

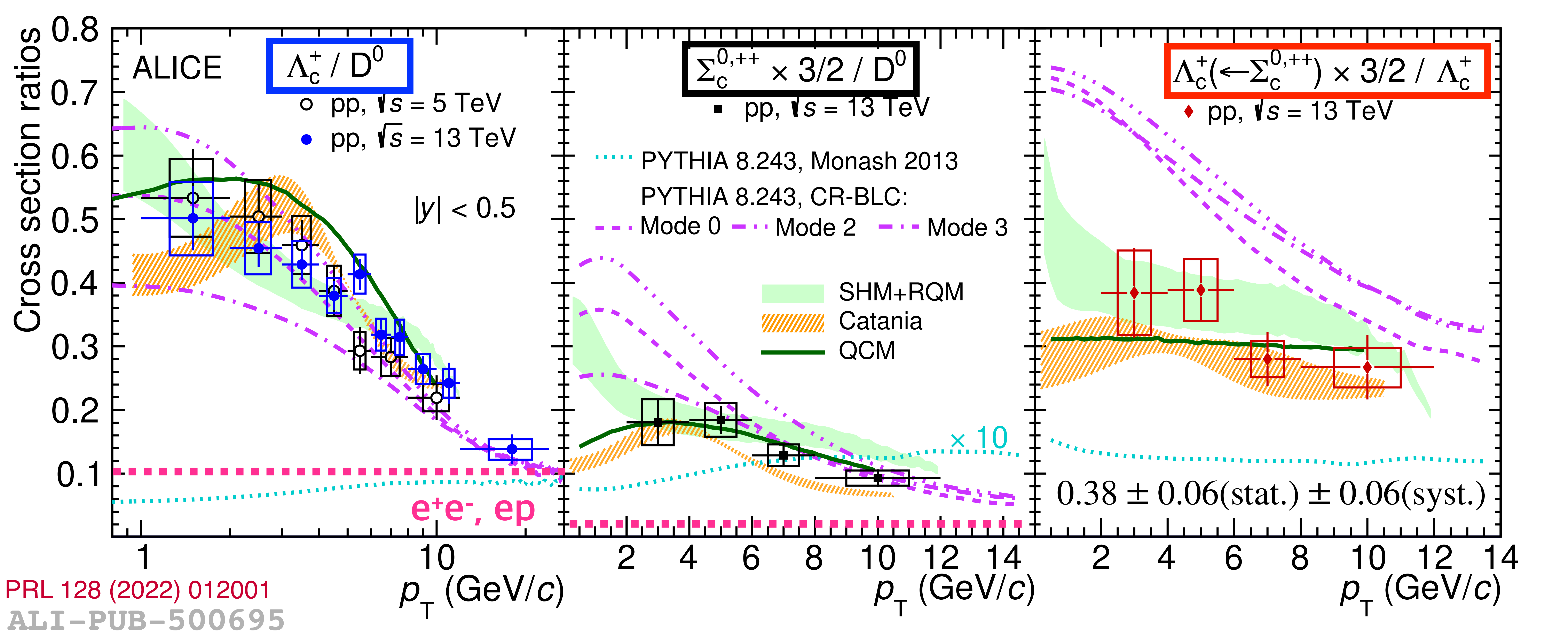






Λ_c^+/D^0 ratio in pp collisions

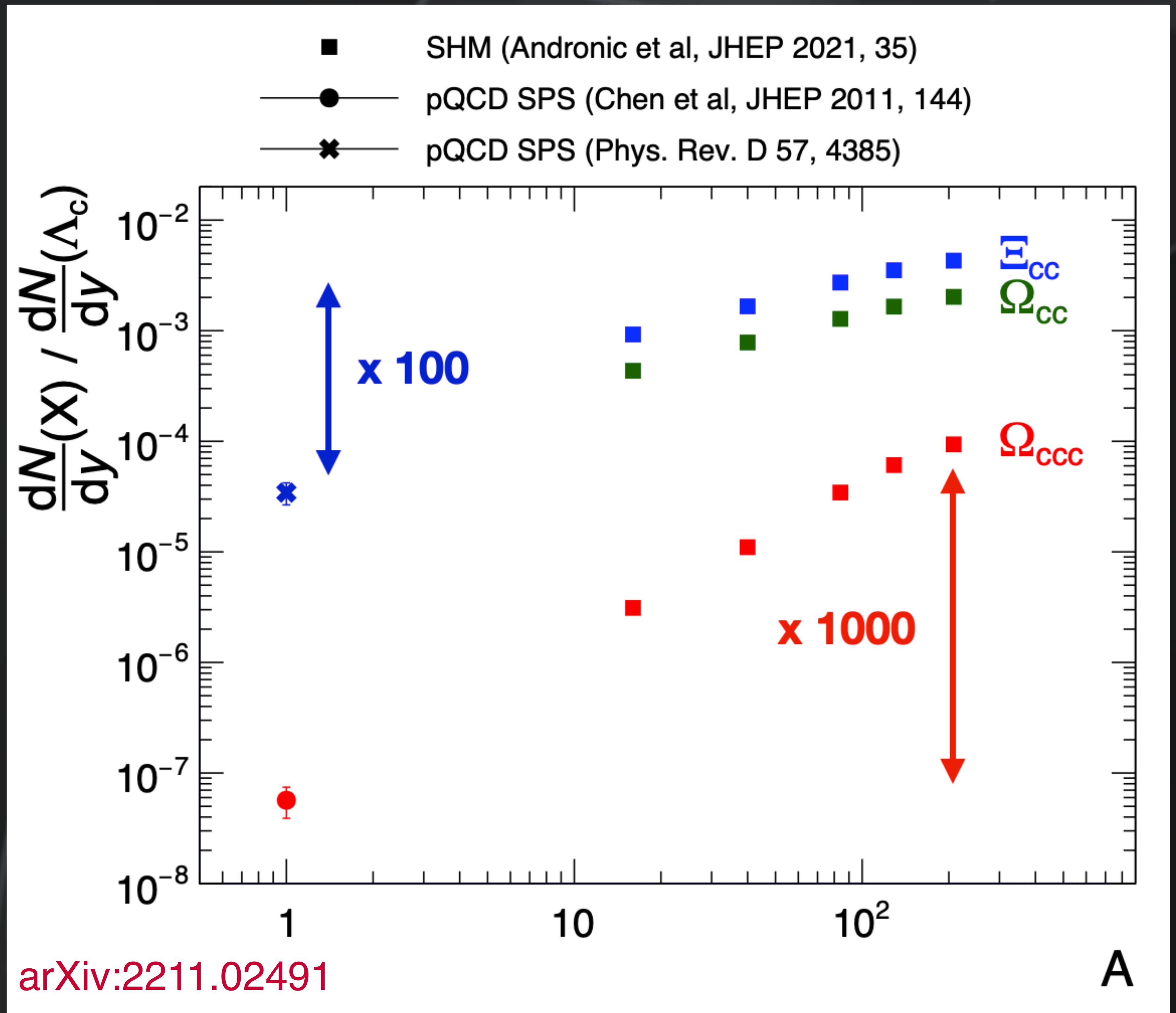
- Enhancement at low p_T w.r.t to e⁺e⁻, ep collisions
  ➡ **Universality of charm fragmentation** among different collision systems **broken**?
- Well described by SHM+RQM, Catania, and QCM
- The feed-down from $\Sigma_c^{0,++}$ partially explains the Λ_c^+/D^0 enhancement in pp collisions

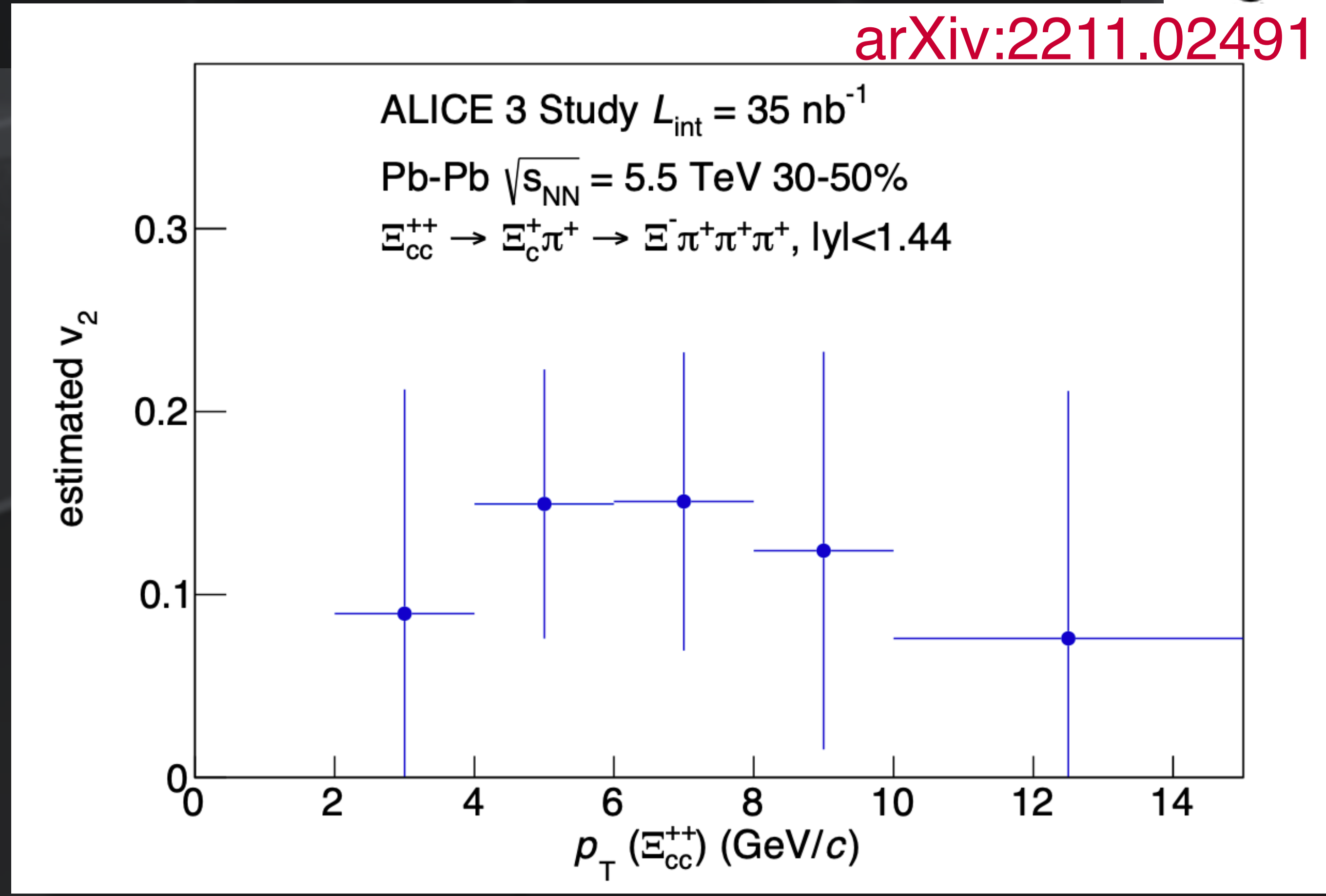


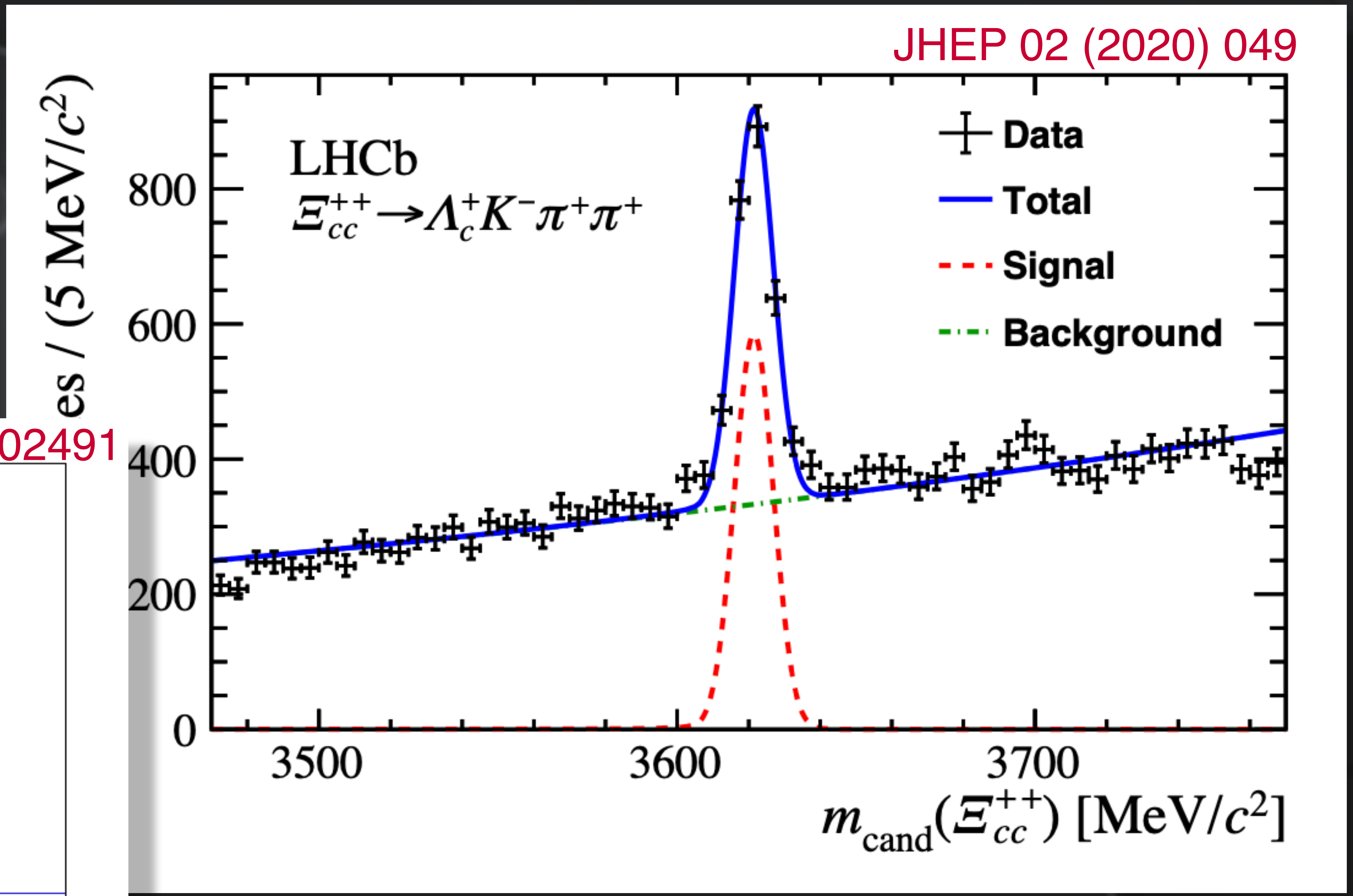
Monash: EPJC 74 (2014) 3024
CR-BLC: JHEP 08 (2015) 003
Catania: PLB 821 (2021) 136622)
SHM: PLB 795 (2019) 117-121
RQM: PRD 84 (2011) 014025

Test probe for coalescence

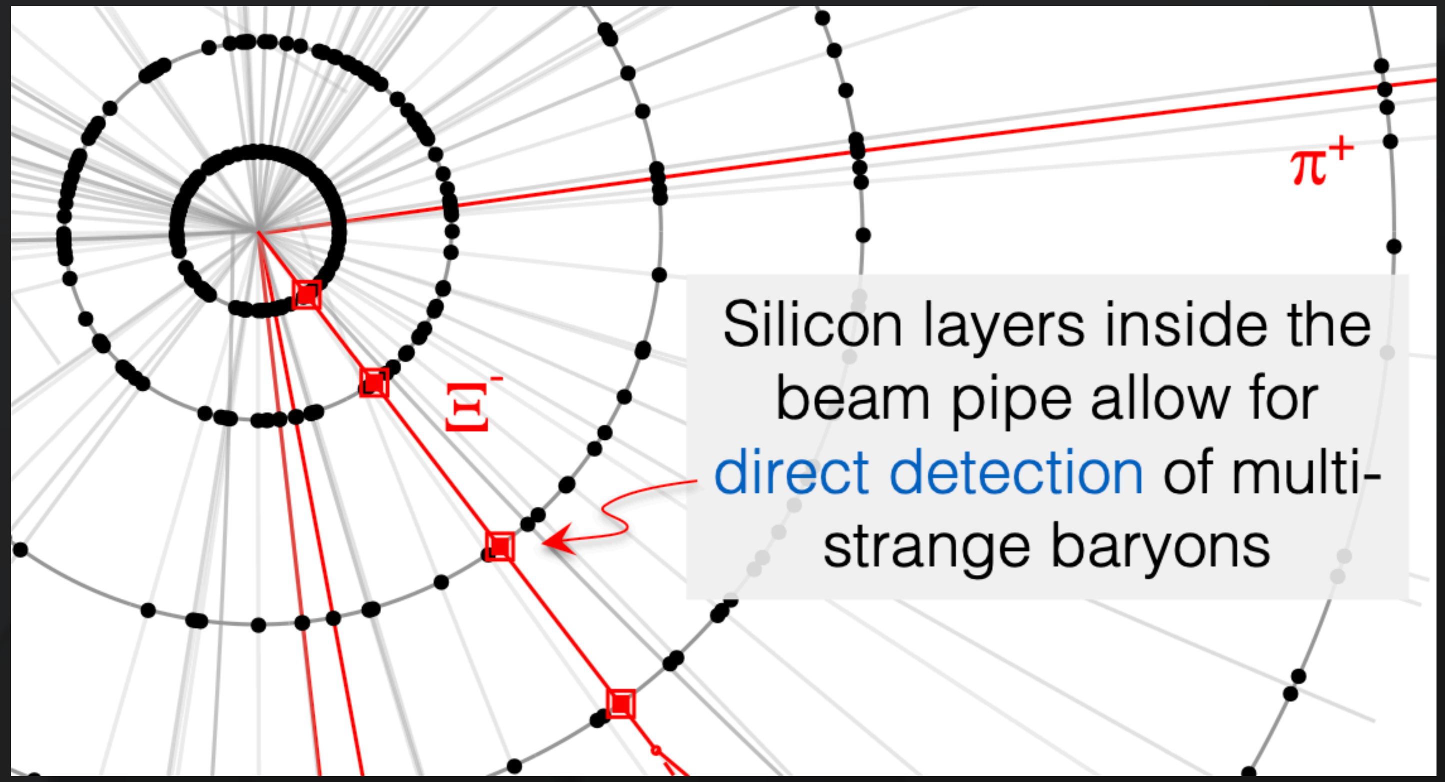
- **Multi-charm baryons** are produced **purely by coalescence**
  - Expected to show a large enhancement in AA collisions.
    ➡ Investigate microscopic **thermalization** in the QCD medium.

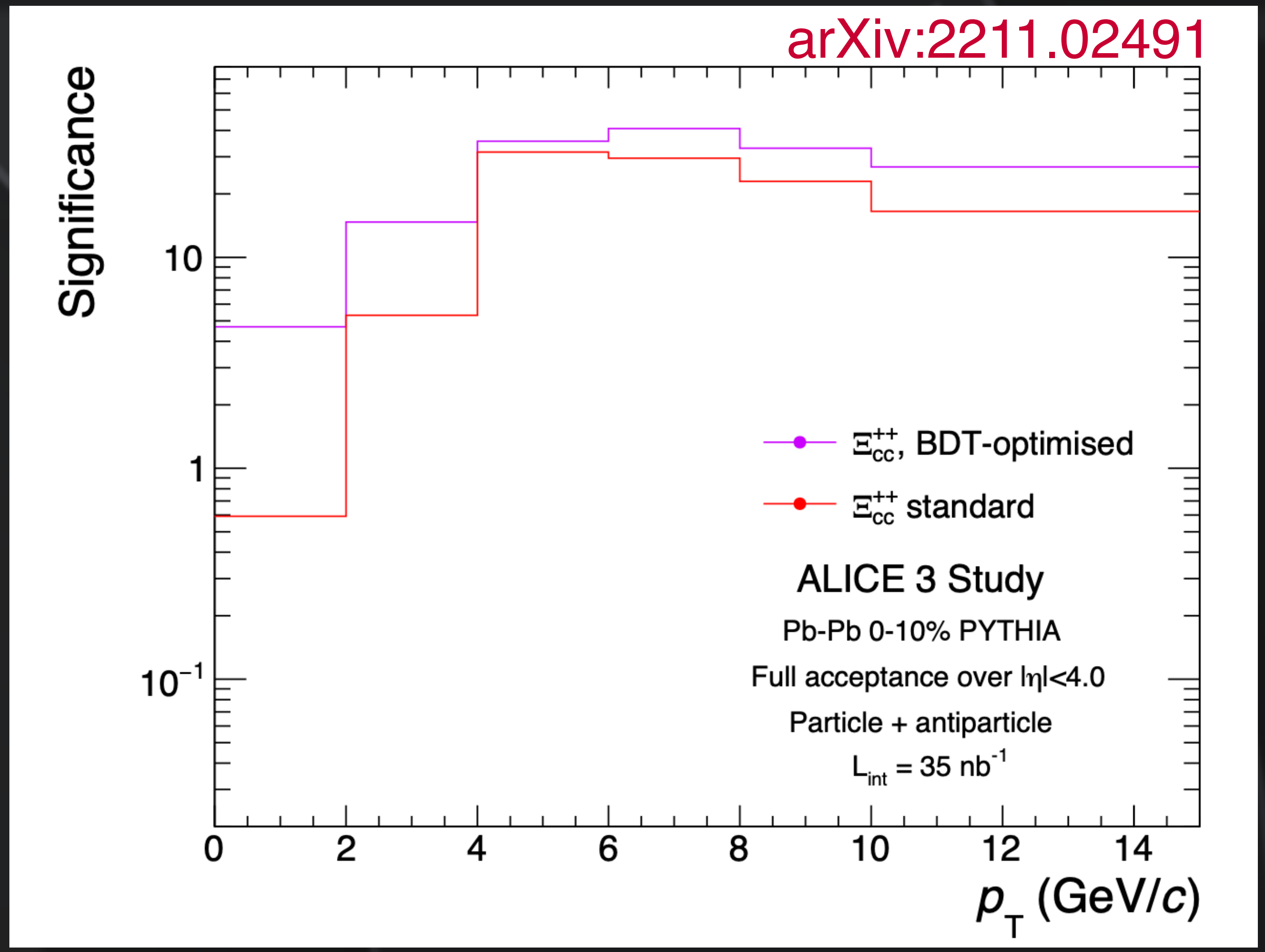






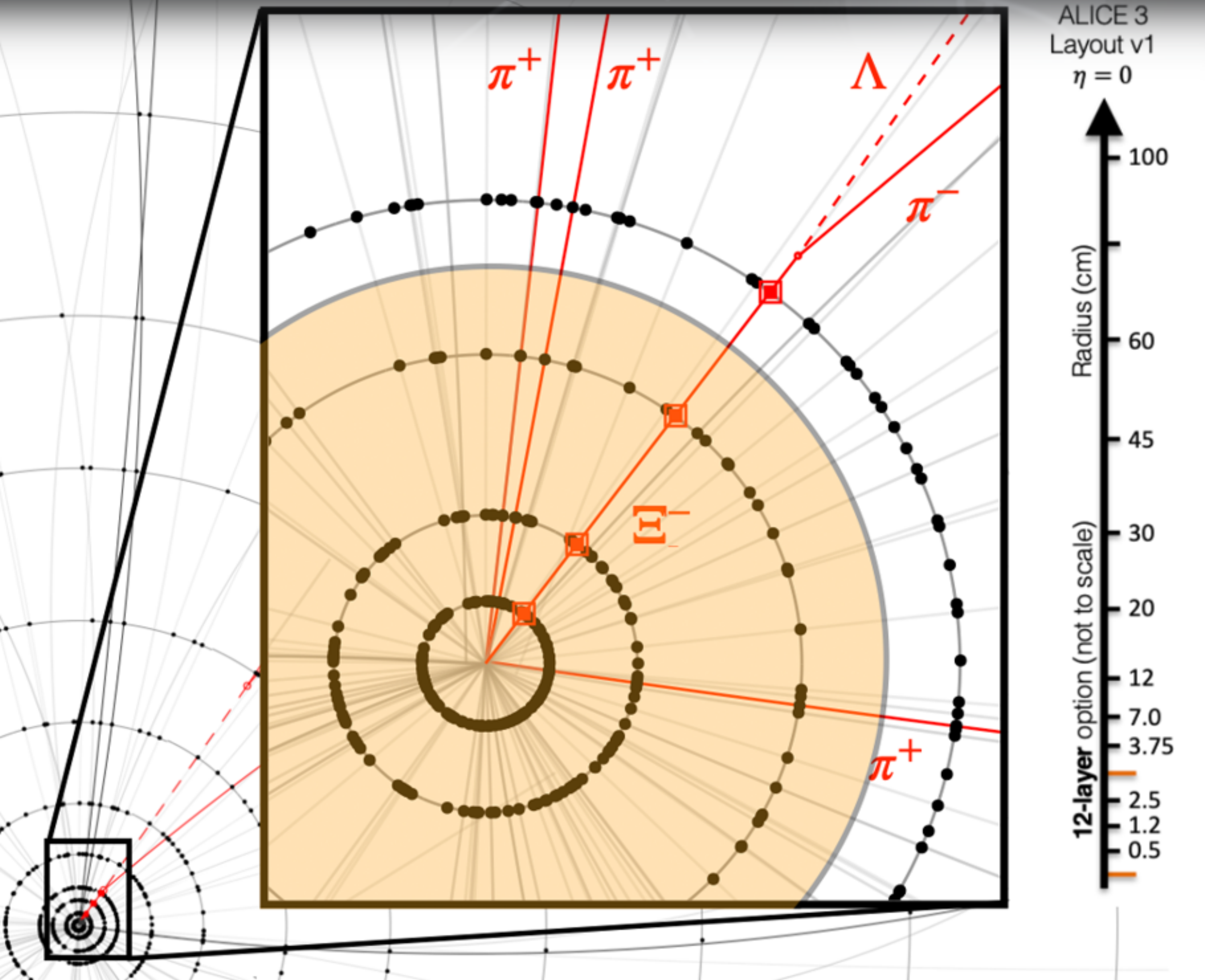
Strangeness tracking in ALICE 3

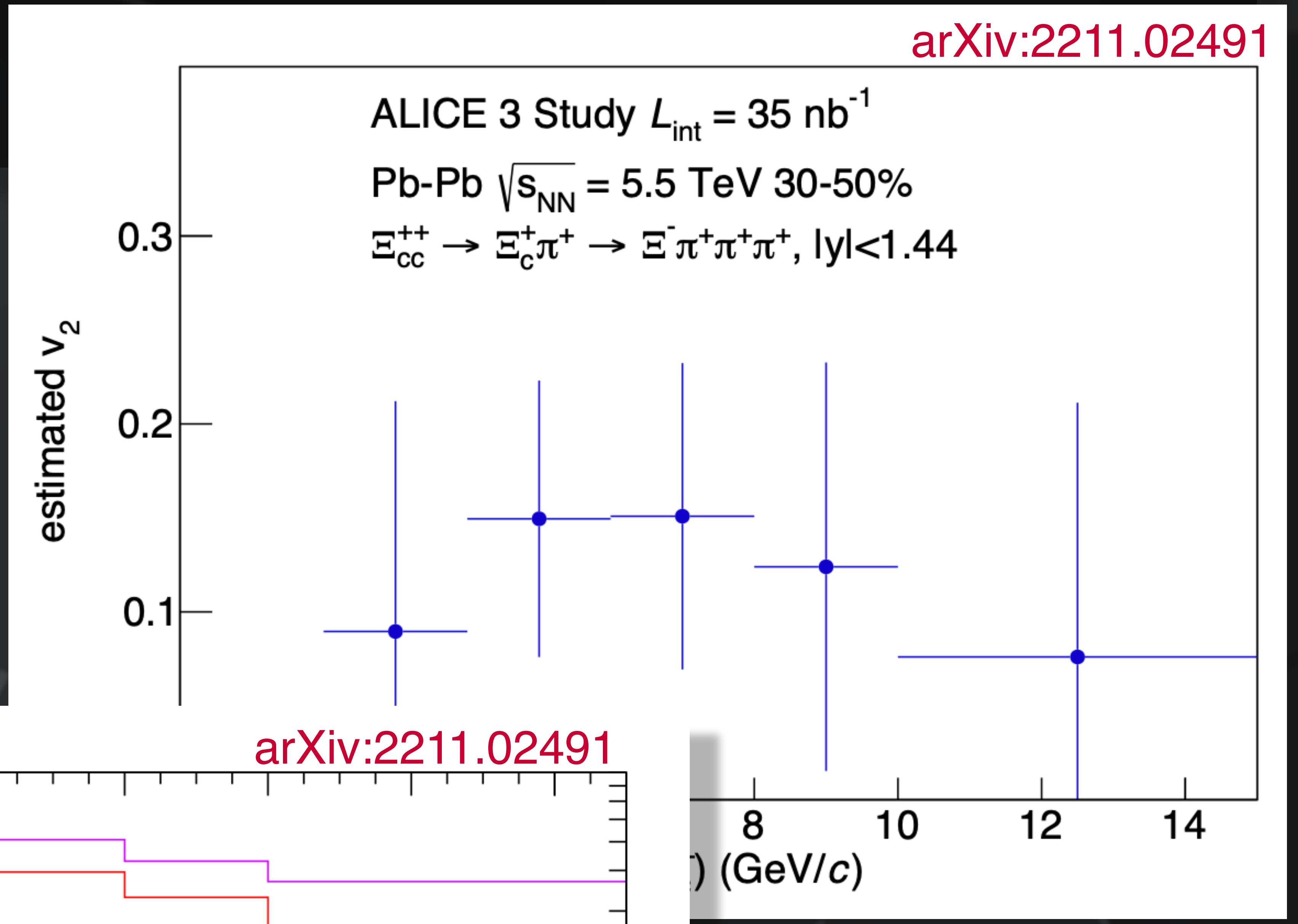


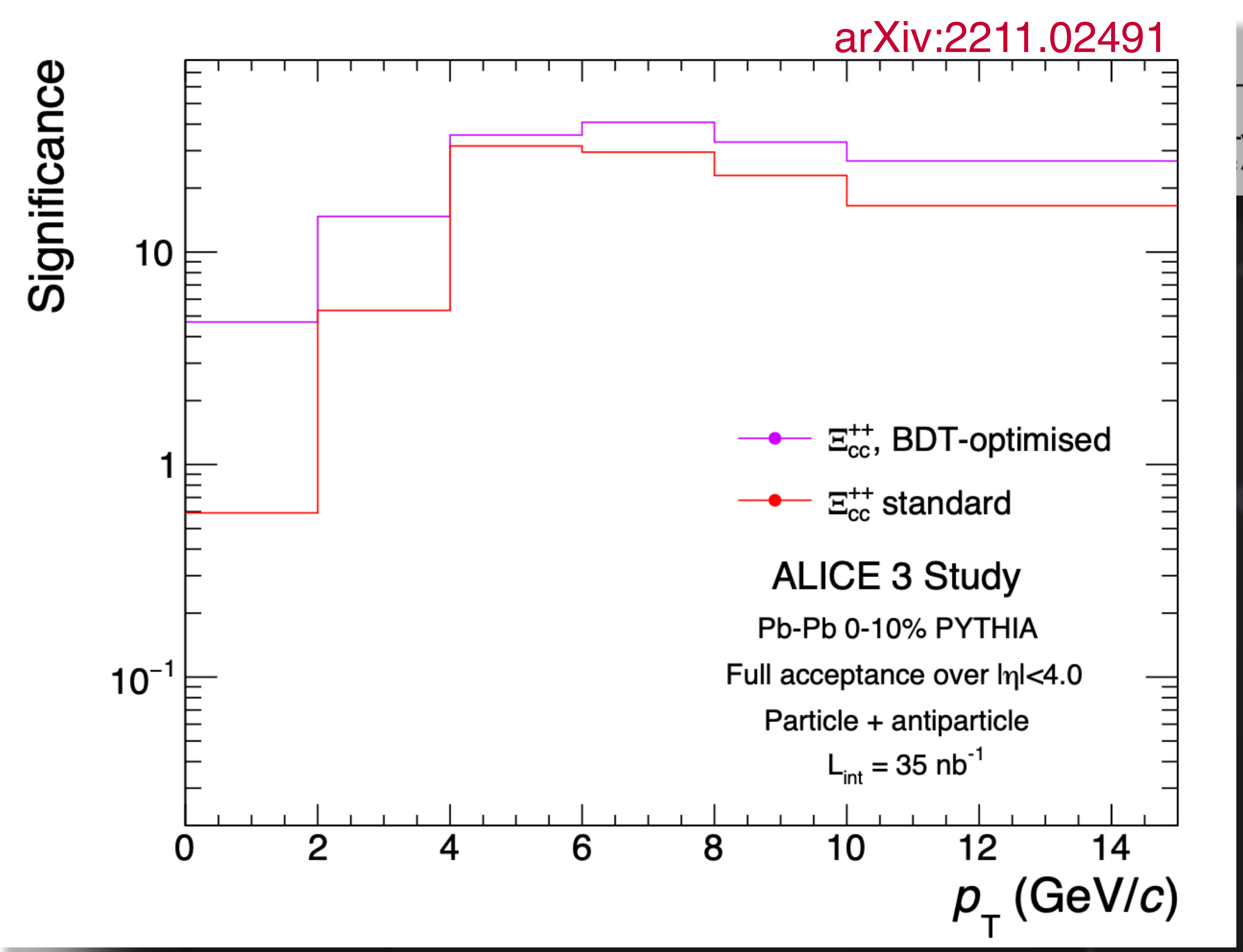


Test probe for coalescence

- Silicon layer inside the beam pipe allow for **direct strangeness tracking** in ALICE 3
- $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+}\pi^{+} \rightarrow (\Xi^{-}\pi^{+}\pi^{+})\pi^{+}$ reconstruction is possible precisely

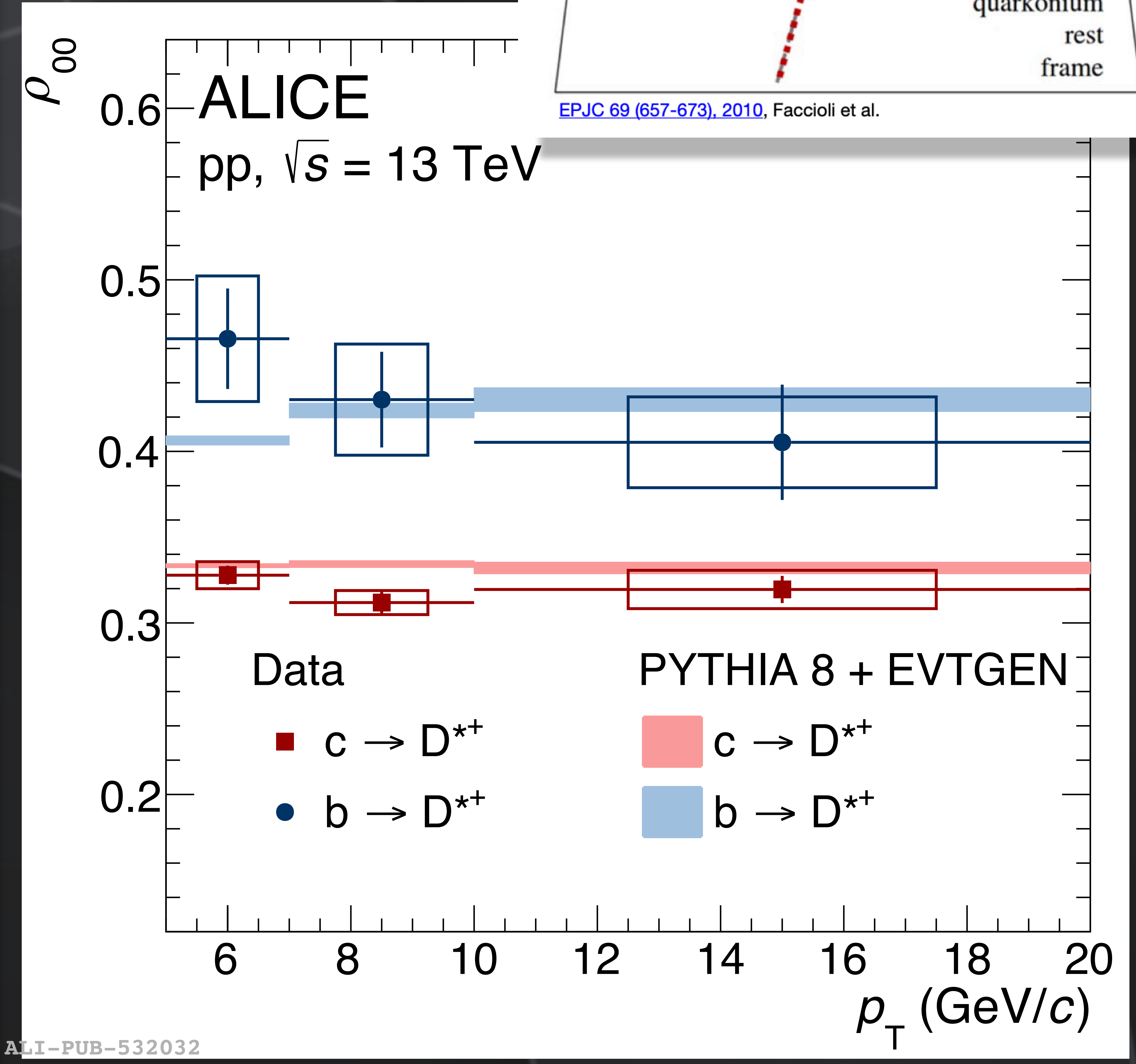


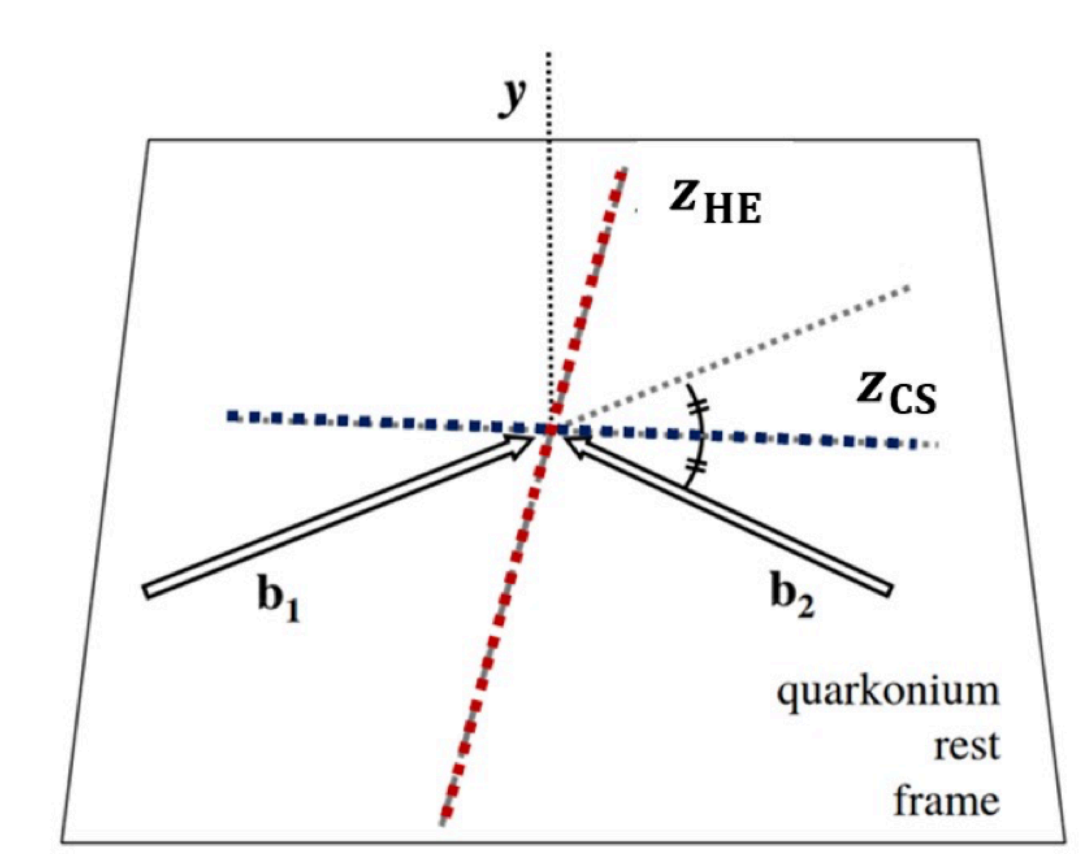




D*+ spin alignment at the LHC

- First First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC
  - ρ_{00}(prompt D^{*+}) = 0.324 ± 0.004 (stat.) ± 0.008 (syst.)
    - Prompt D^{*+} compatible with no polarization
  - ρ_{00}(non-prompt D^{*+}) = 0.455 ± 0.022 (stat.) ± 0.035 (syst.)
    - Non-prompt D^{*+} ρ_{00} > 1/3 due to the helicity conservation
    - B(S=0) ⟶ D*+(S=1) + X
- PYTHIA8 + EvtGen describes both the components
- Helicity conservation implemented in EvtGen
- Important baseline for A-A collisions
  - Disentangles medium-induced from genuine polarisation effects





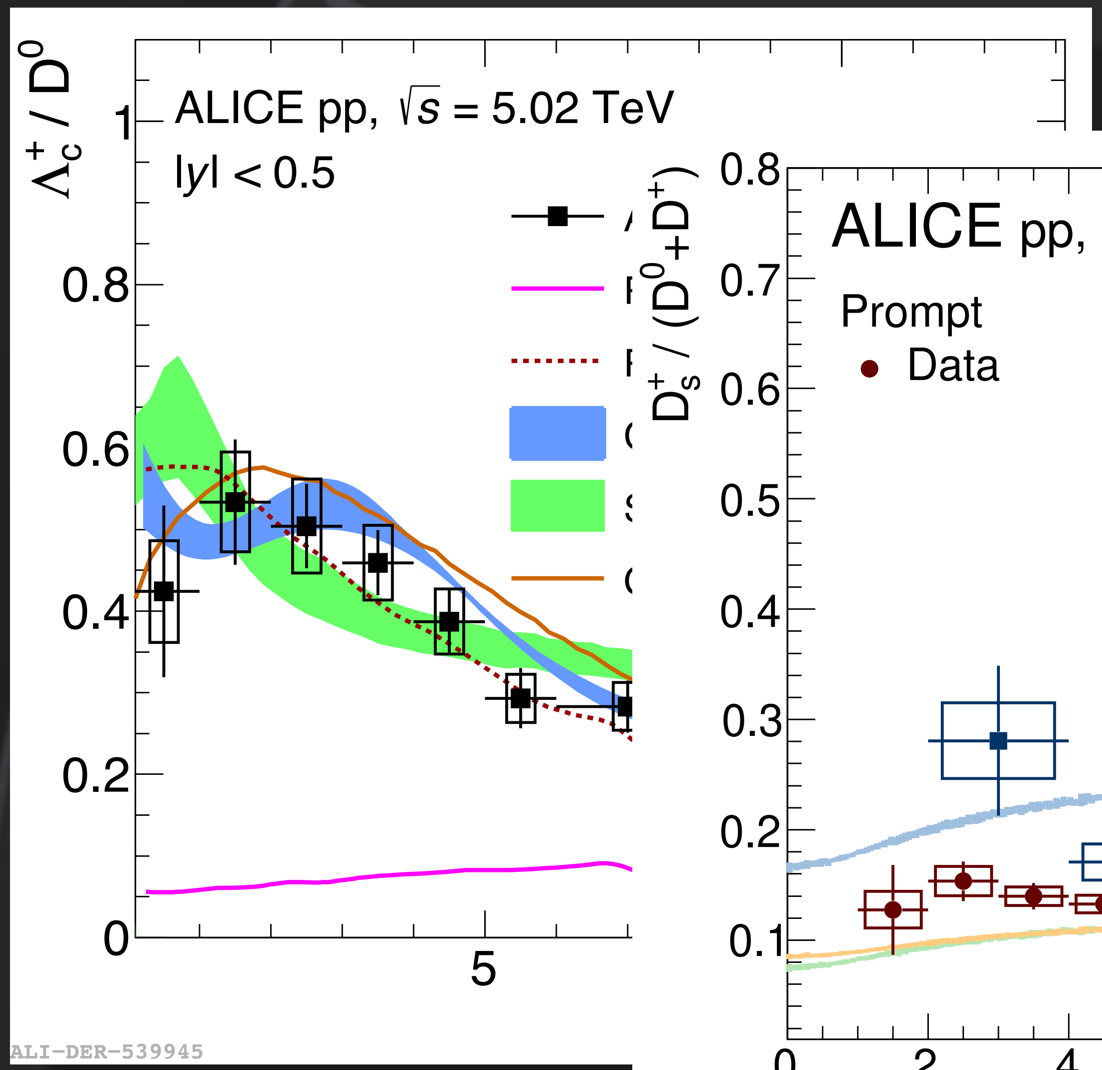
EPJC 69 (657-673), 2010, Faccioli et al.

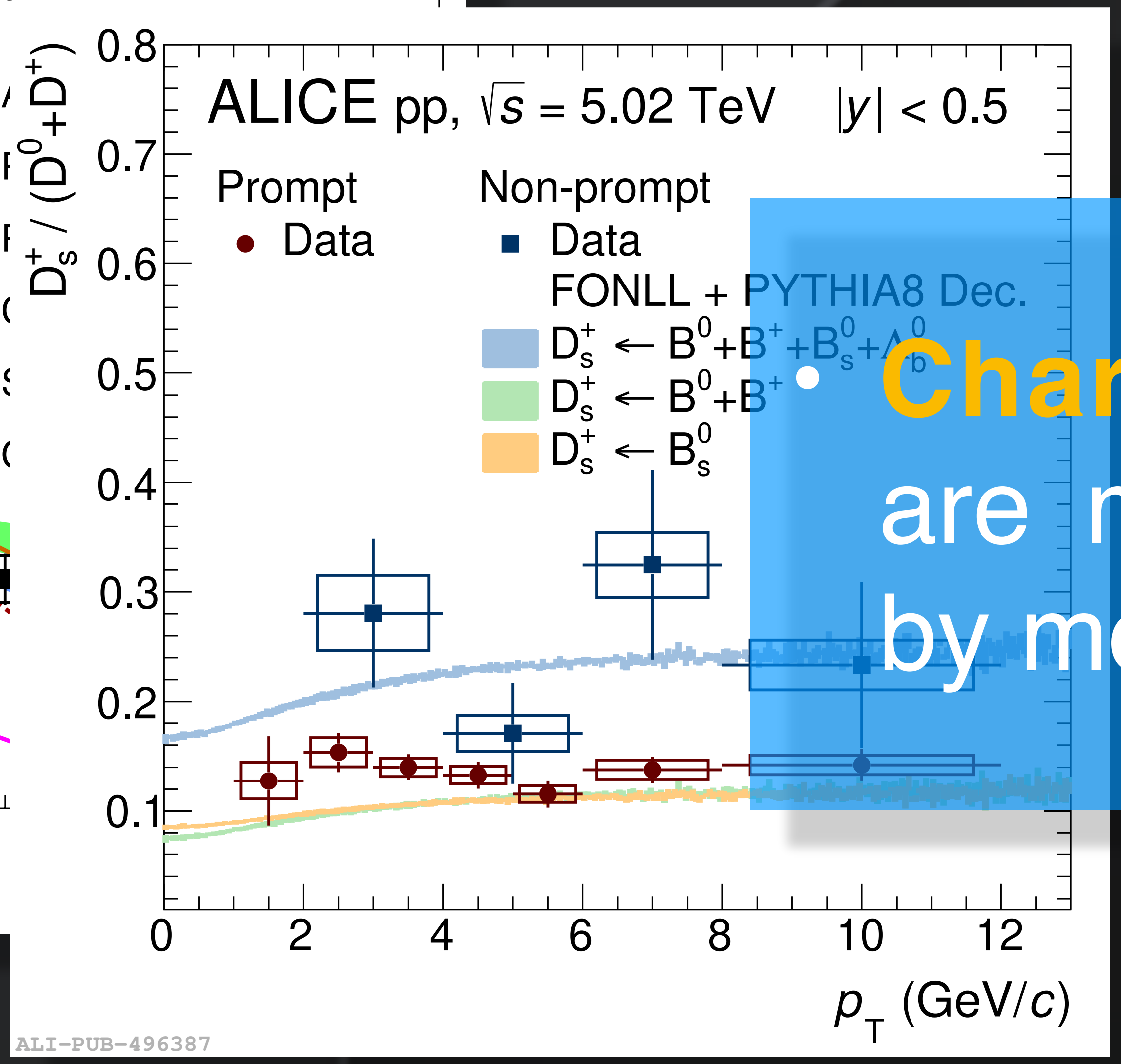
Charm strange baryons in pp collisions

- Only **Catania** gets closer to the measurements when considering the **additional resonance states.**
  - ✓ No measurement of $\mathrm{BR}(\Omega_c^0 \rightarrow \Omega^-\pi^+)$ → BR from theory calculation: $0.51\ \%^{+2.19\%}_{-0.31\%}$ EPJC 80, 1066 (2002)

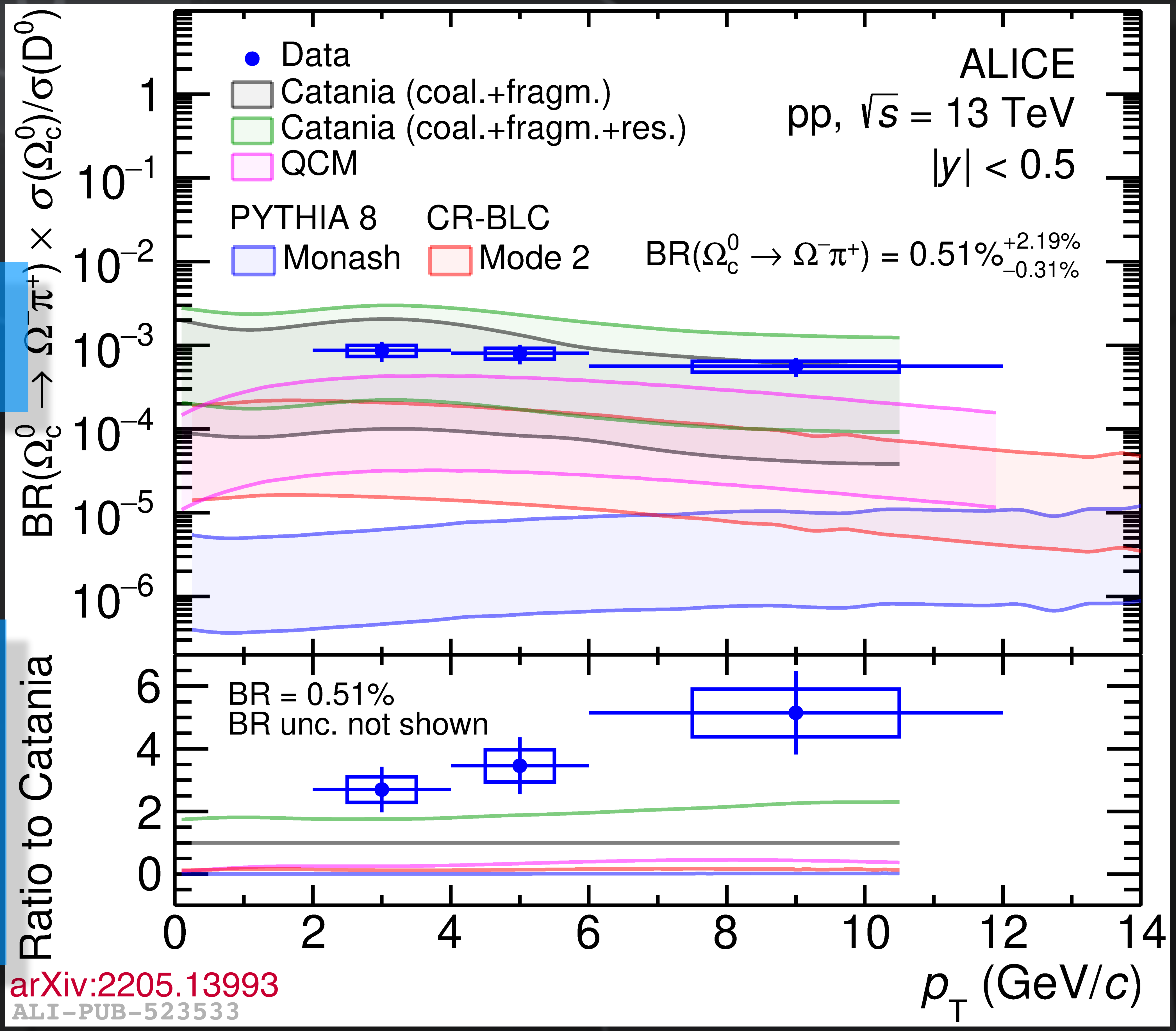
Ratio	ALICE (pp@13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^-@10.52 GeV) visible
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96 \pm 0.42 \pm 0.13) \times 10^{-3}$	$(9.70 \pm 1.27 \pm 0.66) \times 10^{-5}$
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) \times \sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99 \pm 0.96 \pm 0.96) \times 10^{-3}$	$(5.82 \pm 0.78 \pm 1.34) \times 10^{-4}$

- **Sizable contribution** of Ω_c^0 at **LHC energies**?



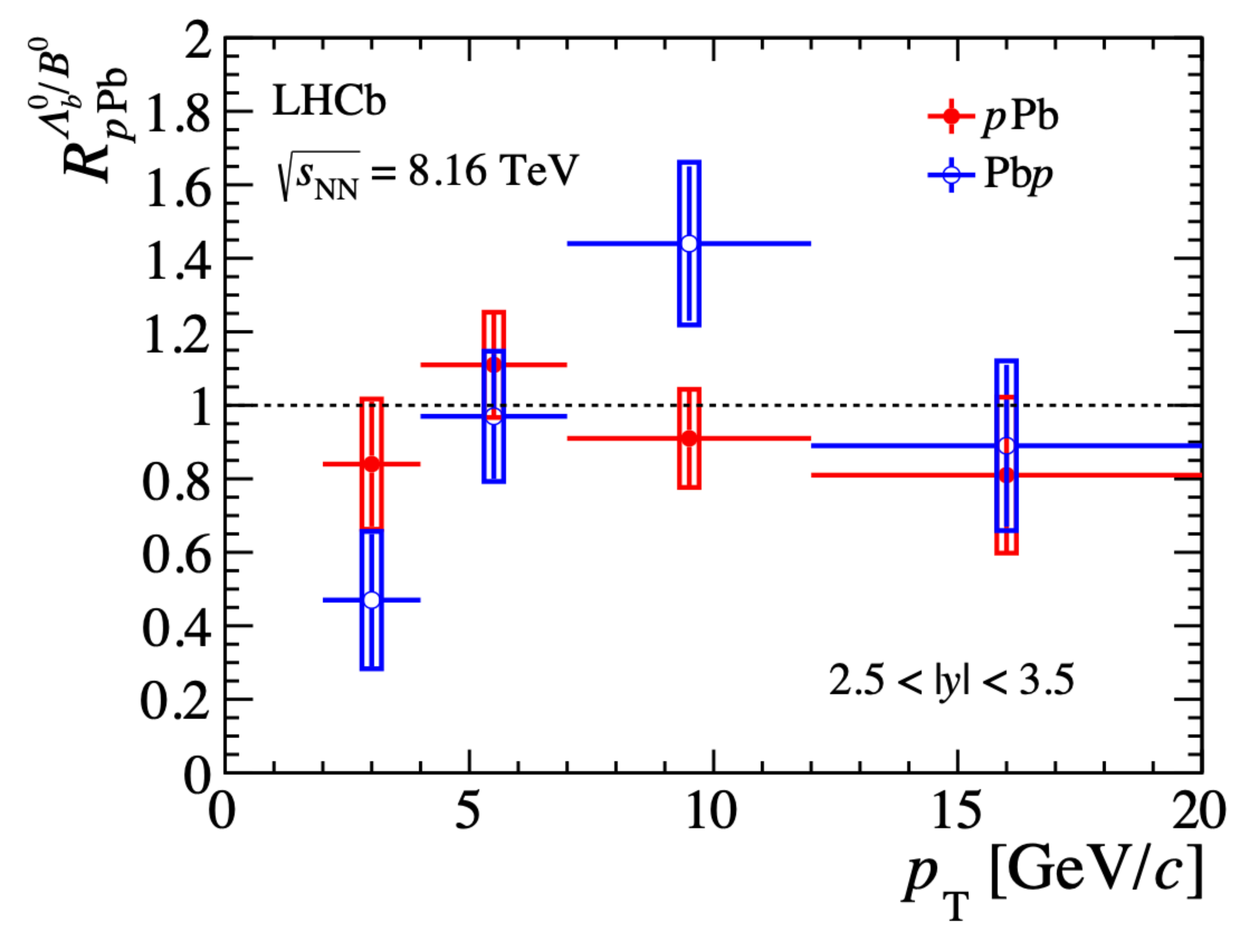


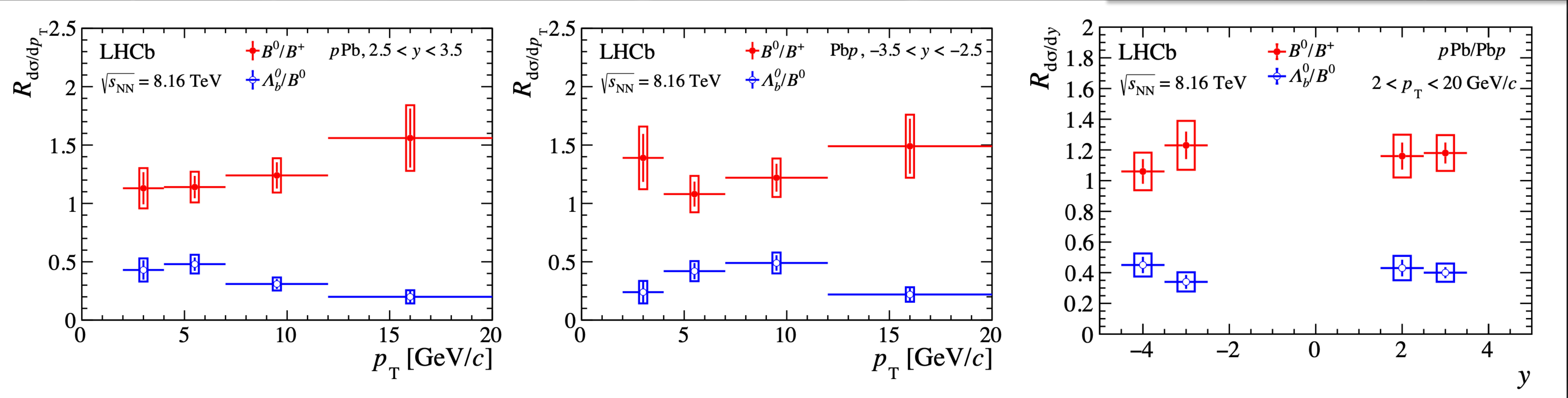
- **Charm strange baryons** are mostly **underestimated** by models



p_T distribution modification

- Λ_b^+/B^0 ratio in p-Pb is compatible with the one in pp.
  - More precision is required to clarify possible hints of modification.
- **No rapidity dependence** from backward to forward rapidity.

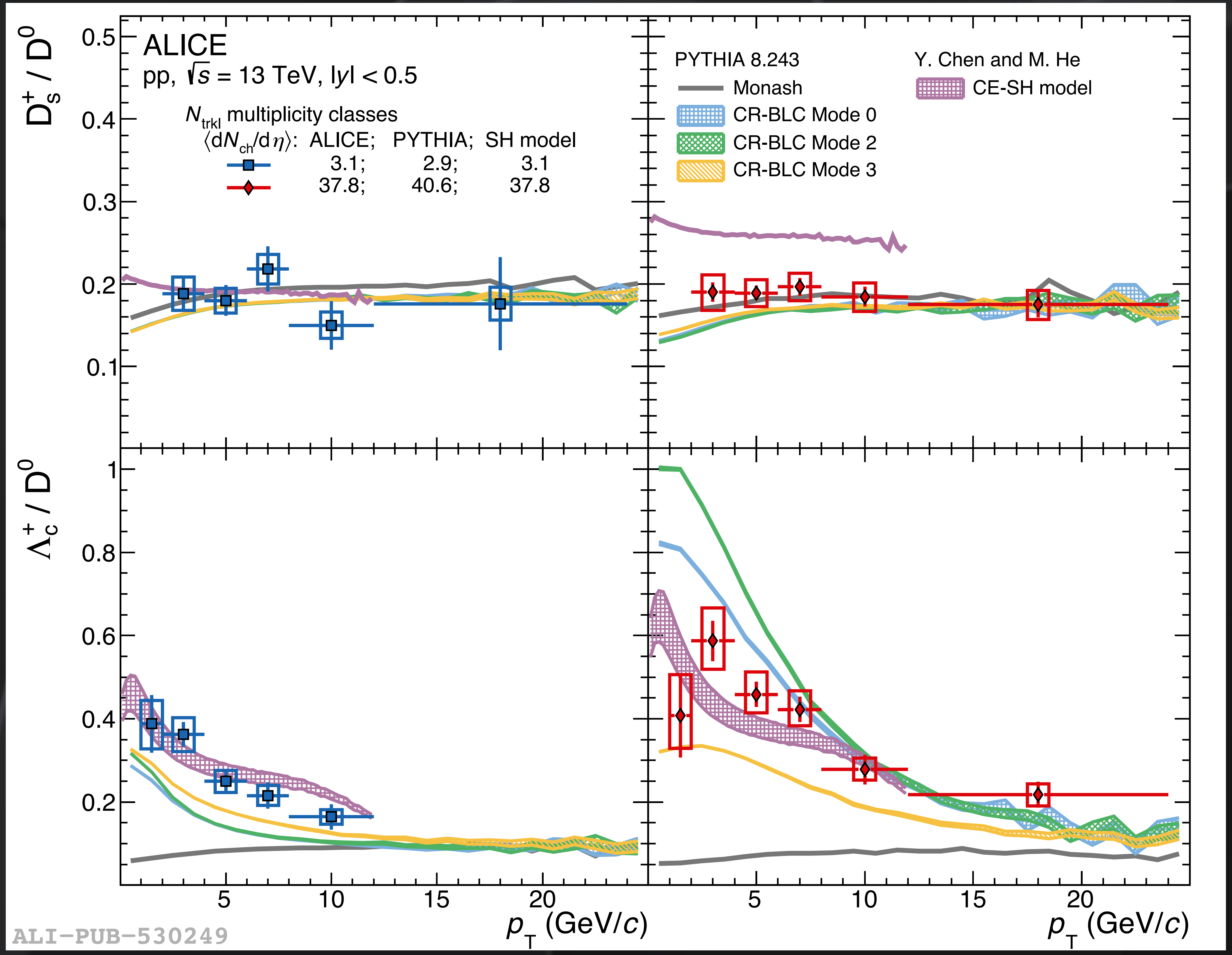


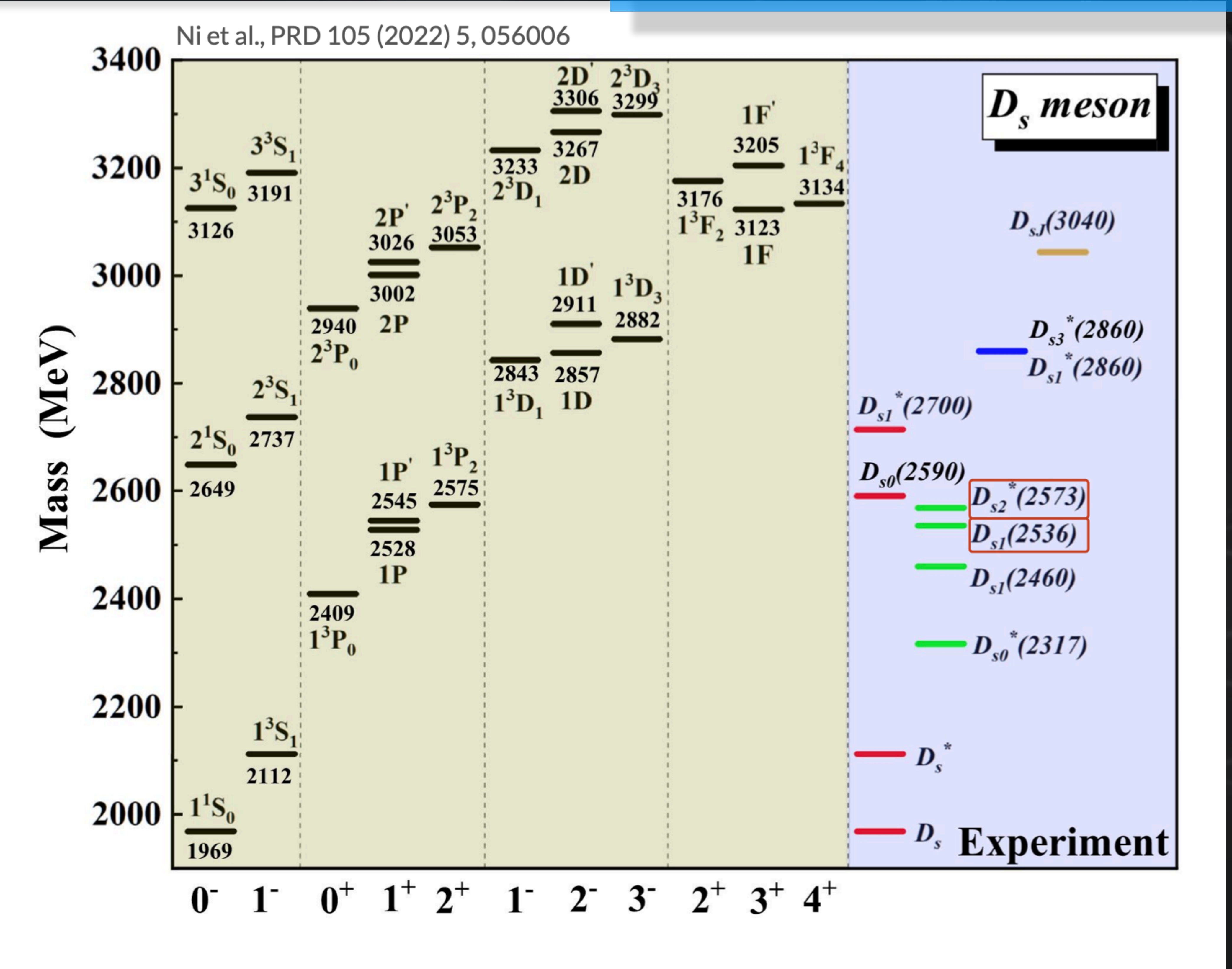


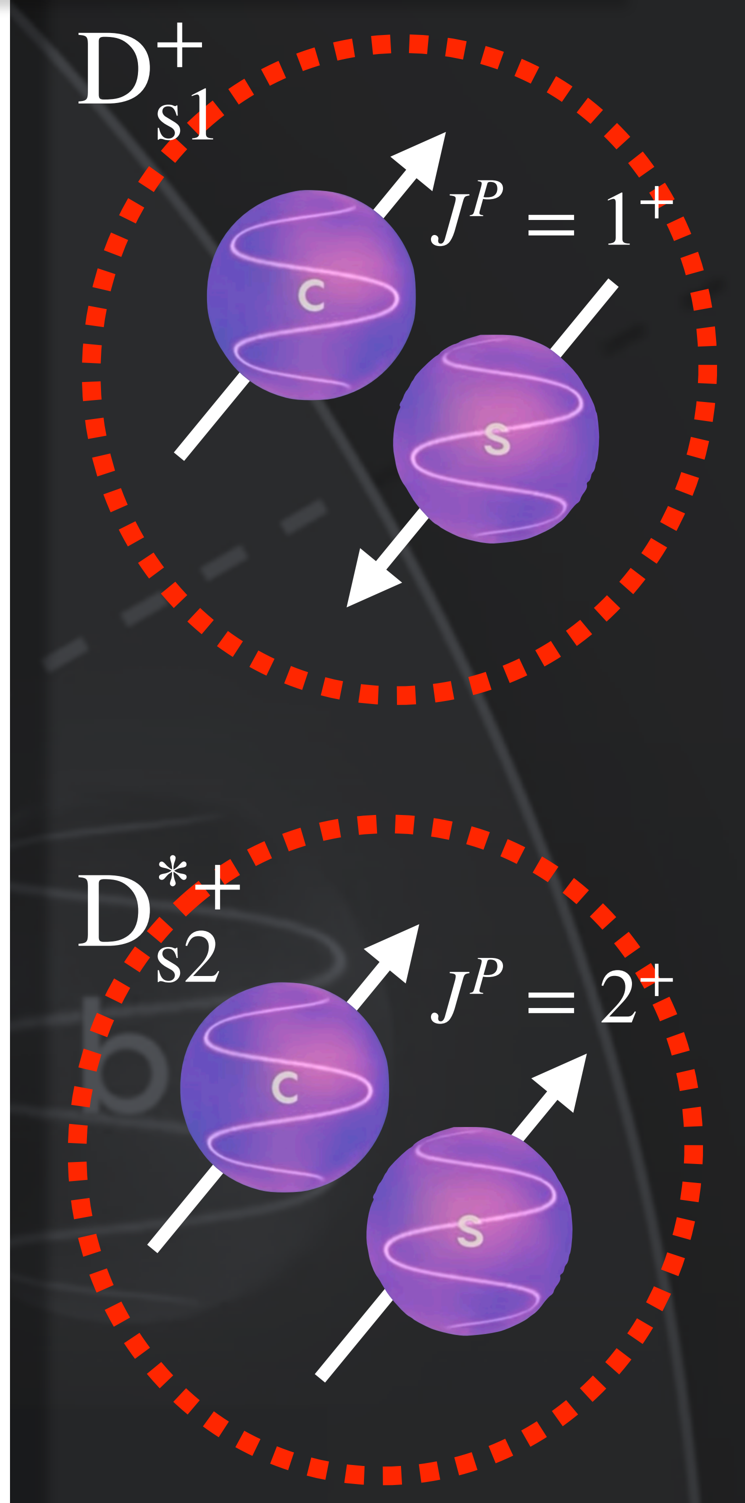
Heavy flavor hadronic resonance

- **No significant multiplicity dependence** in **charm meson** sector.
- **Strong multiplicity dependence** observed in **charm baryon sector** in pp collisions.
  - Well described by color reconnection and **SHM** models
    - **SHM**: consider strong feed-down from the **excited states**

- **Missing something for mesons?**

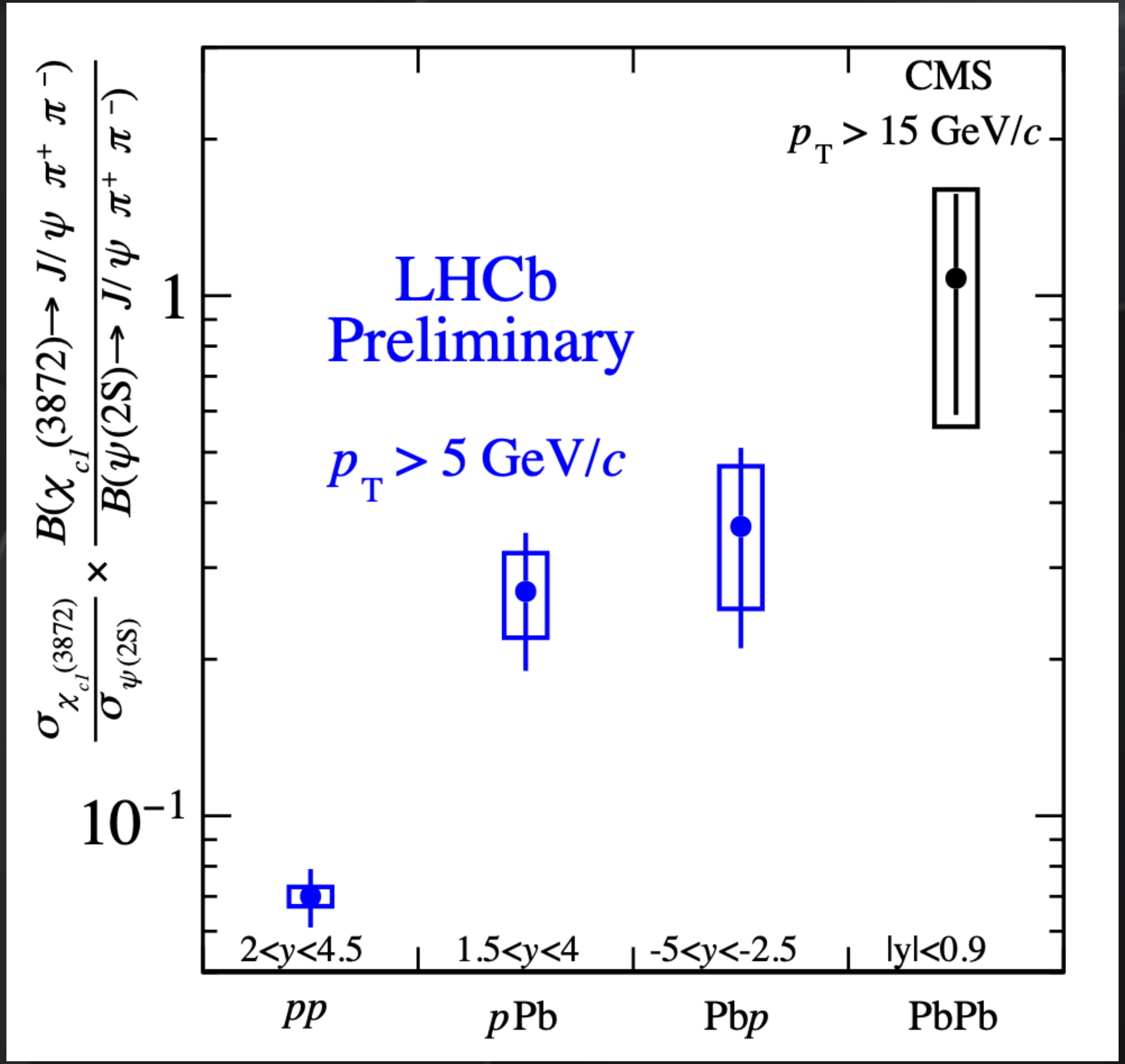


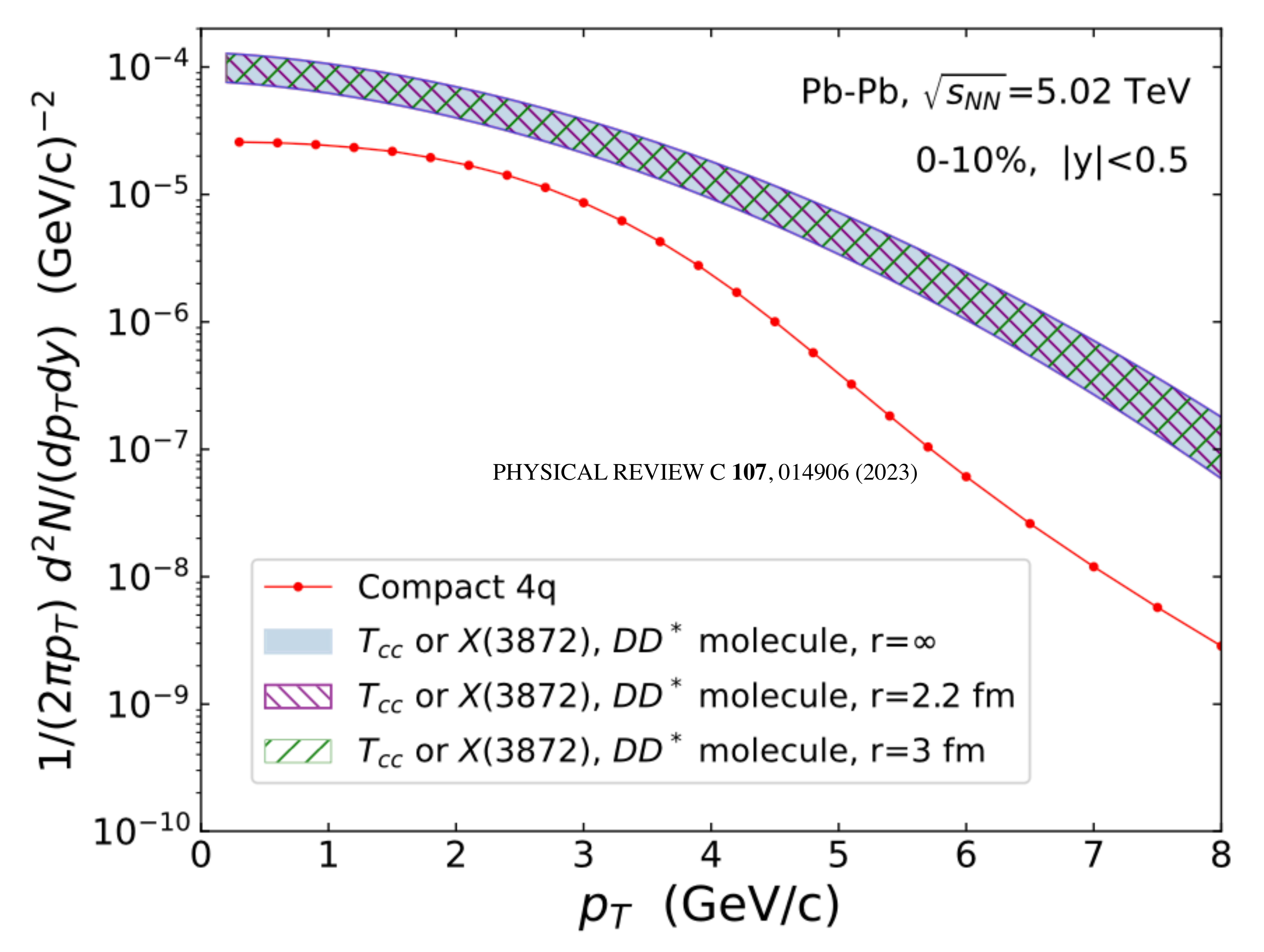




Charm exotic states

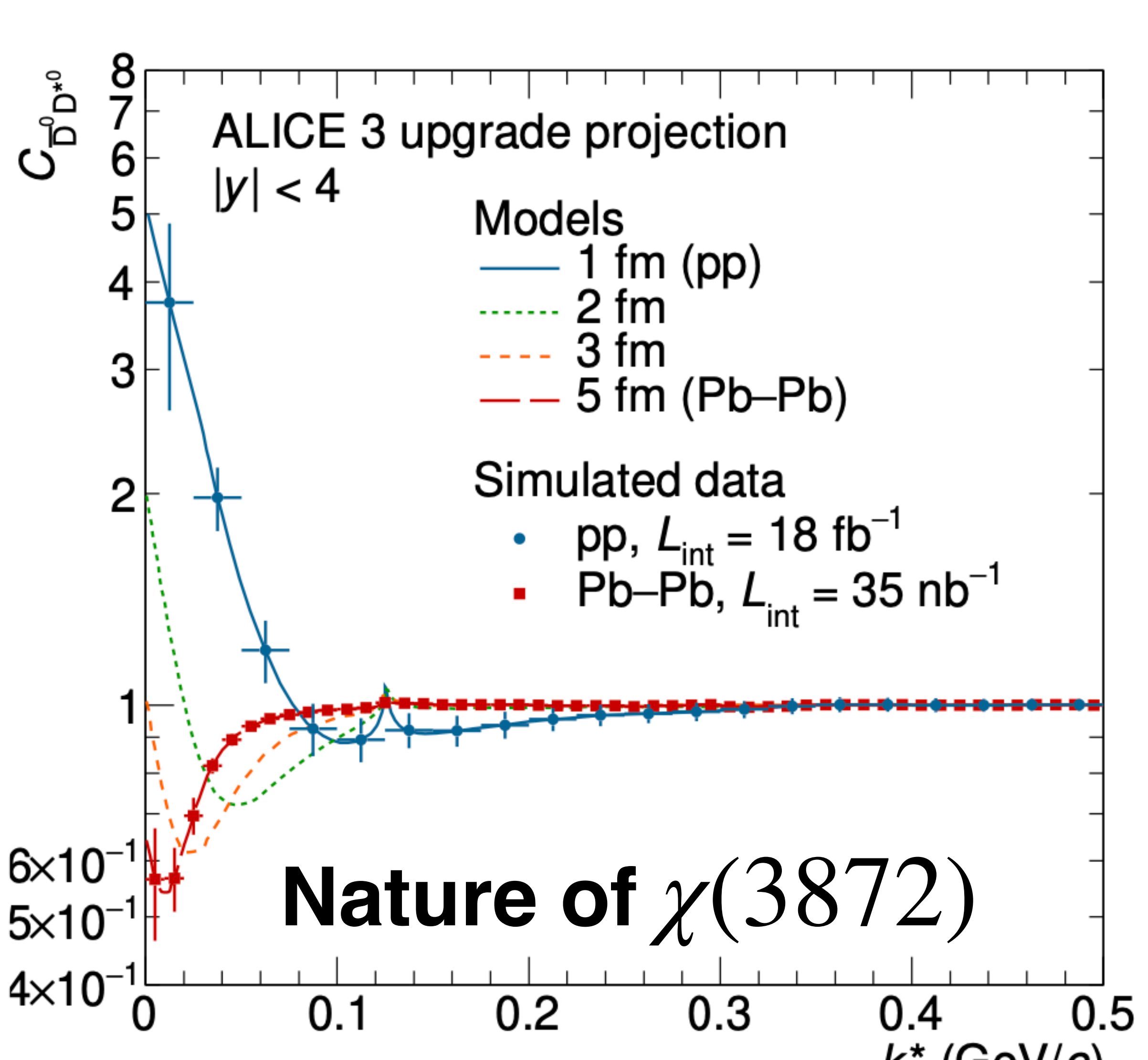
- $\chi_{c1}(3872)$ breaking up in a higher multiplicity environment
- Possibility to constrain the interaction potential of charm exotic states and hyper nuclei
  - **Distinct source size dependence** of the correlation function in the presence of bound states.



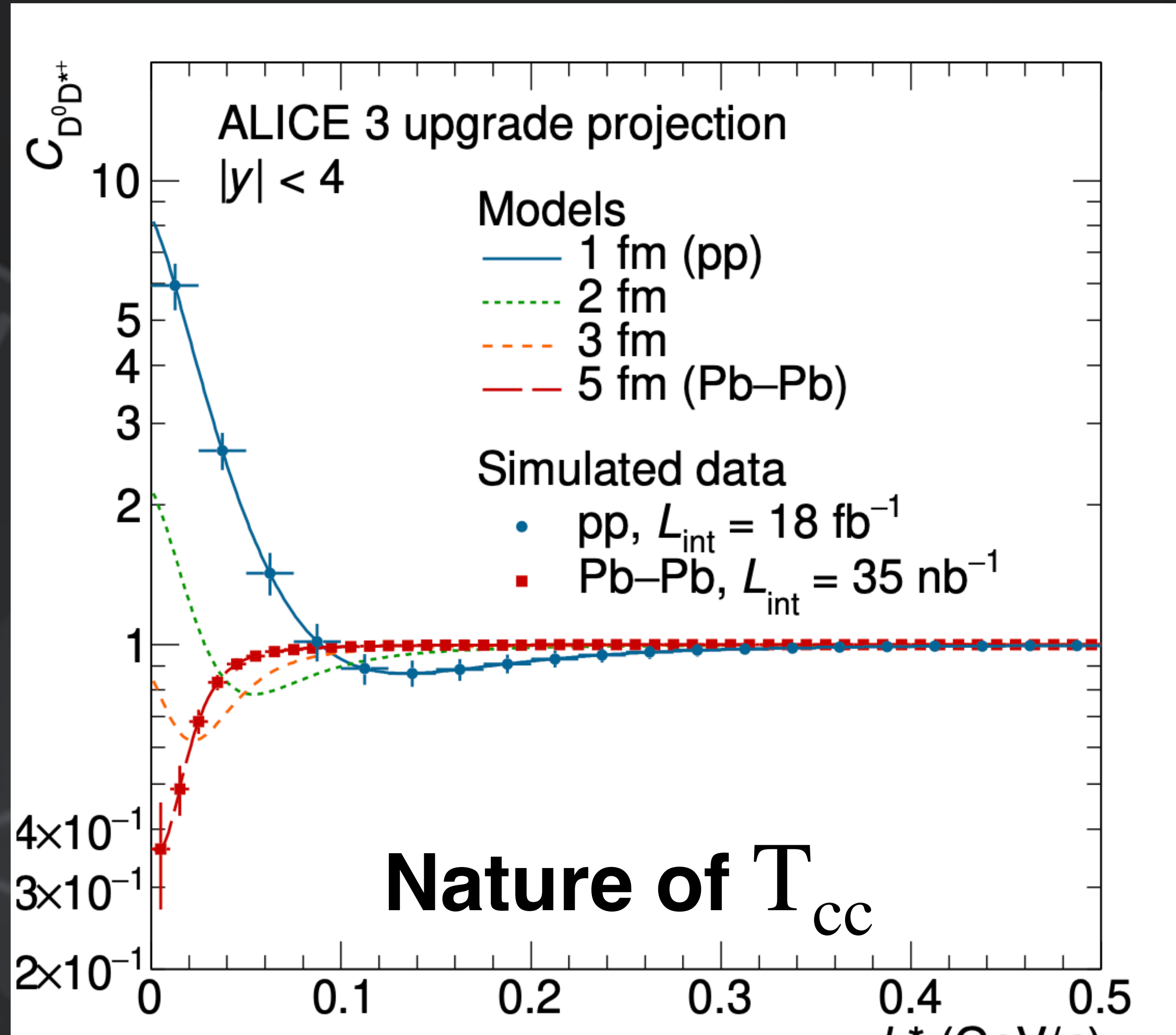


Charm exotic states and hyper-nuclei

- Possibility to constrain the interaction potential of charm exotic states and hyper nuclei
  - **Distinct source size dependence** of the correlation function in the presence of bound states.
- Possibility of full decay reconstruction $c_d \rightarrow dK^{-}\pi^{+}$



arXiv:2211.02491



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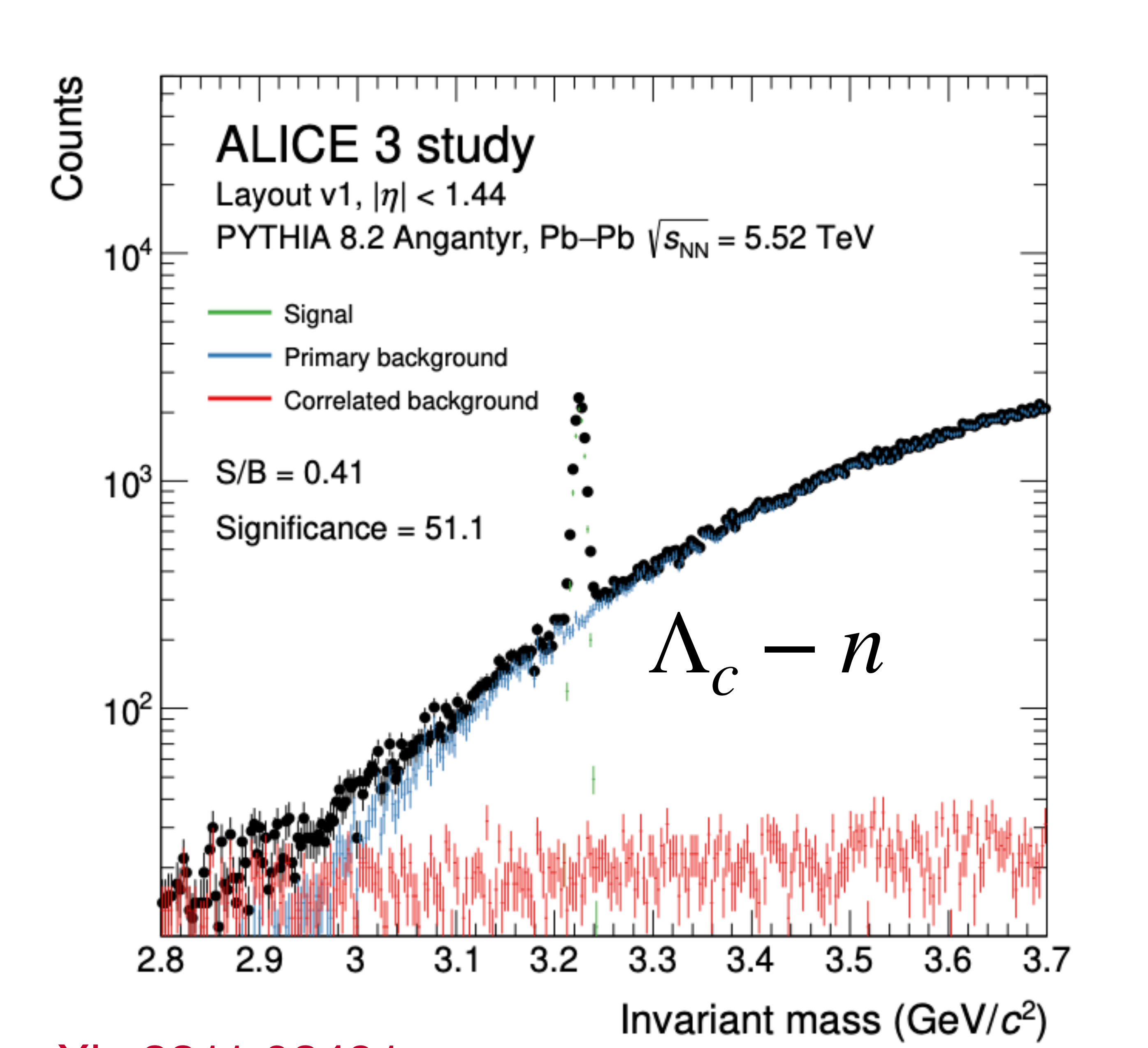

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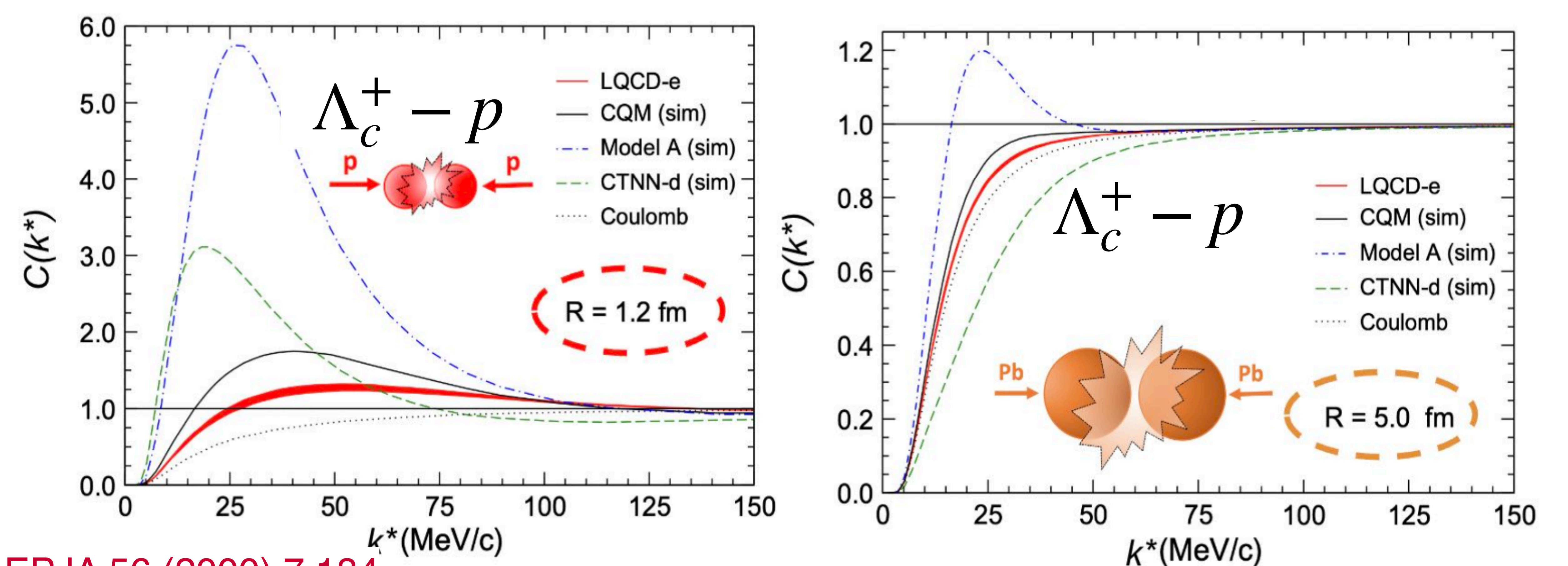
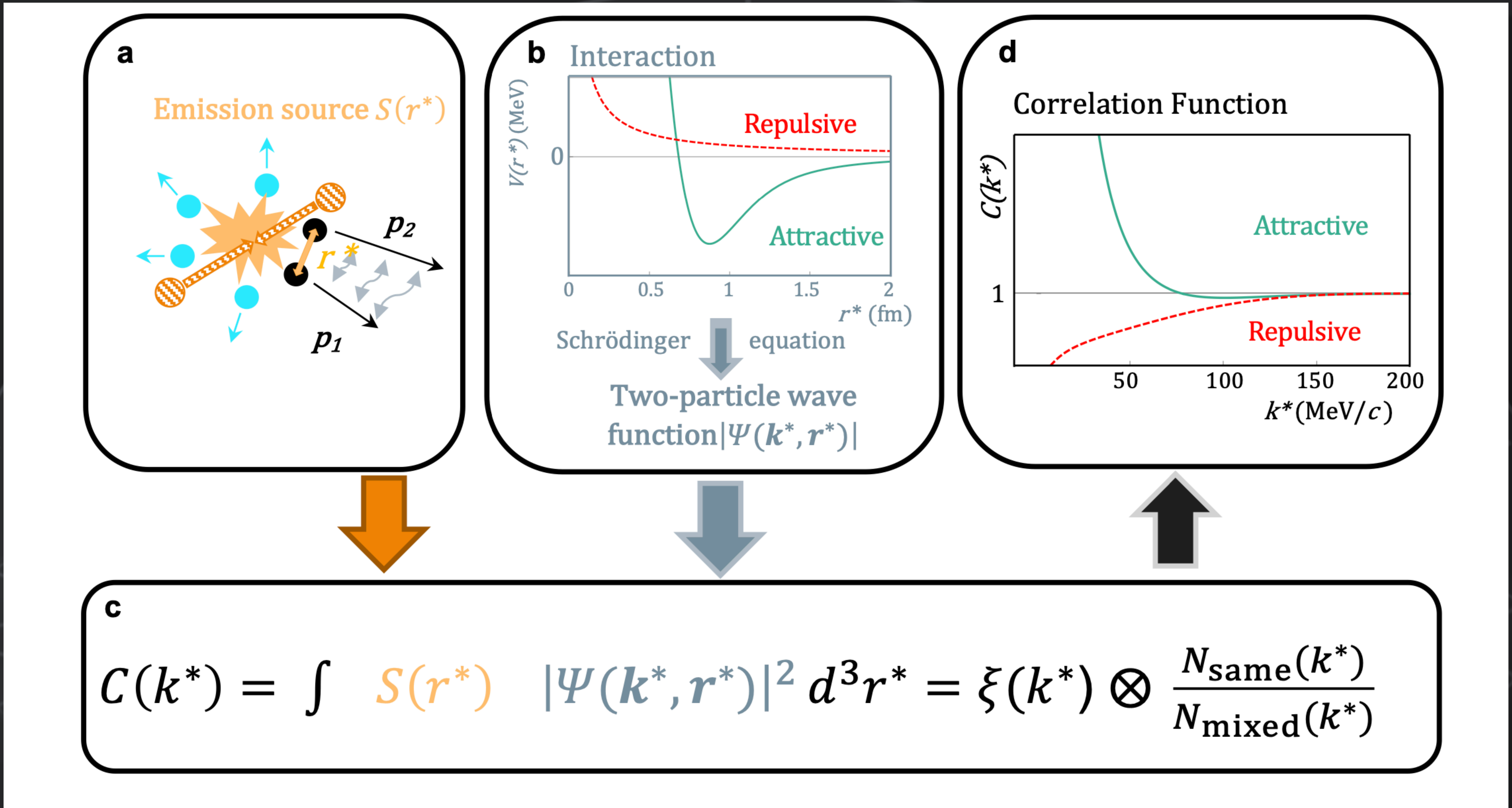


EPJA 56 (2000) 7 184

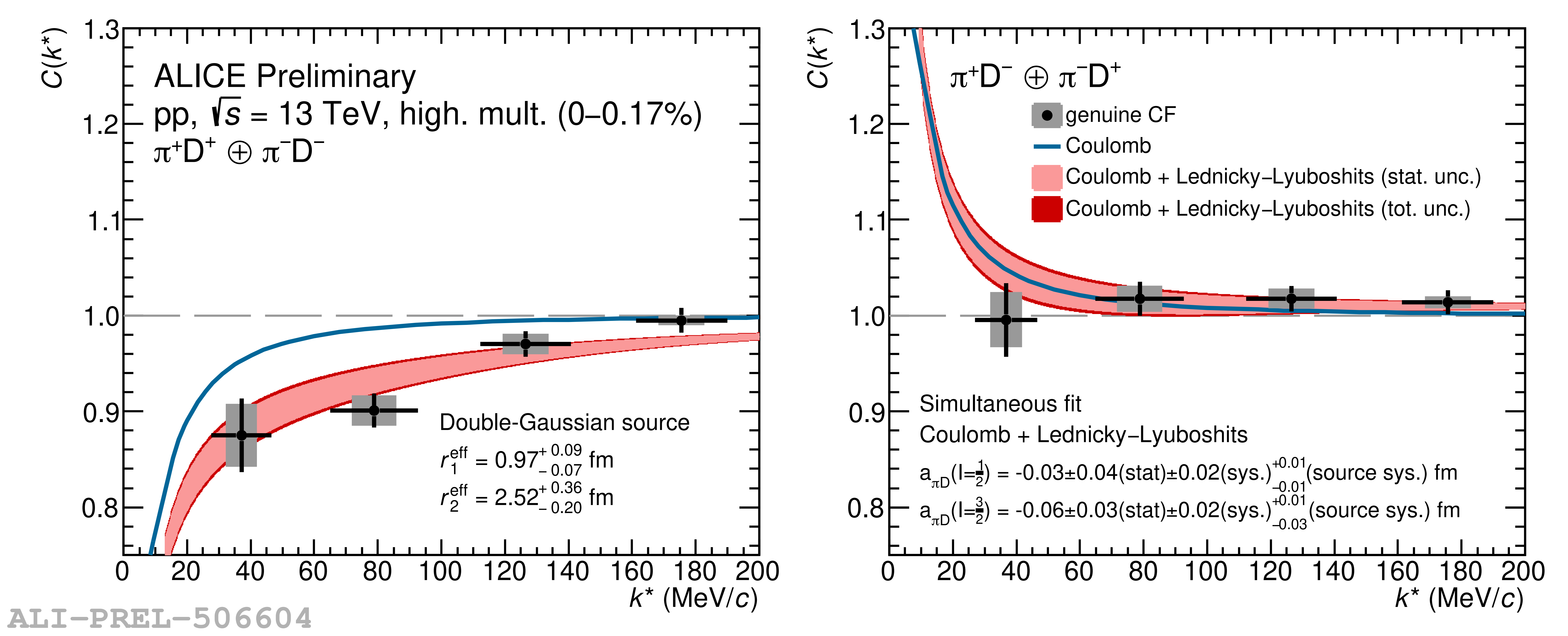
Correlation function

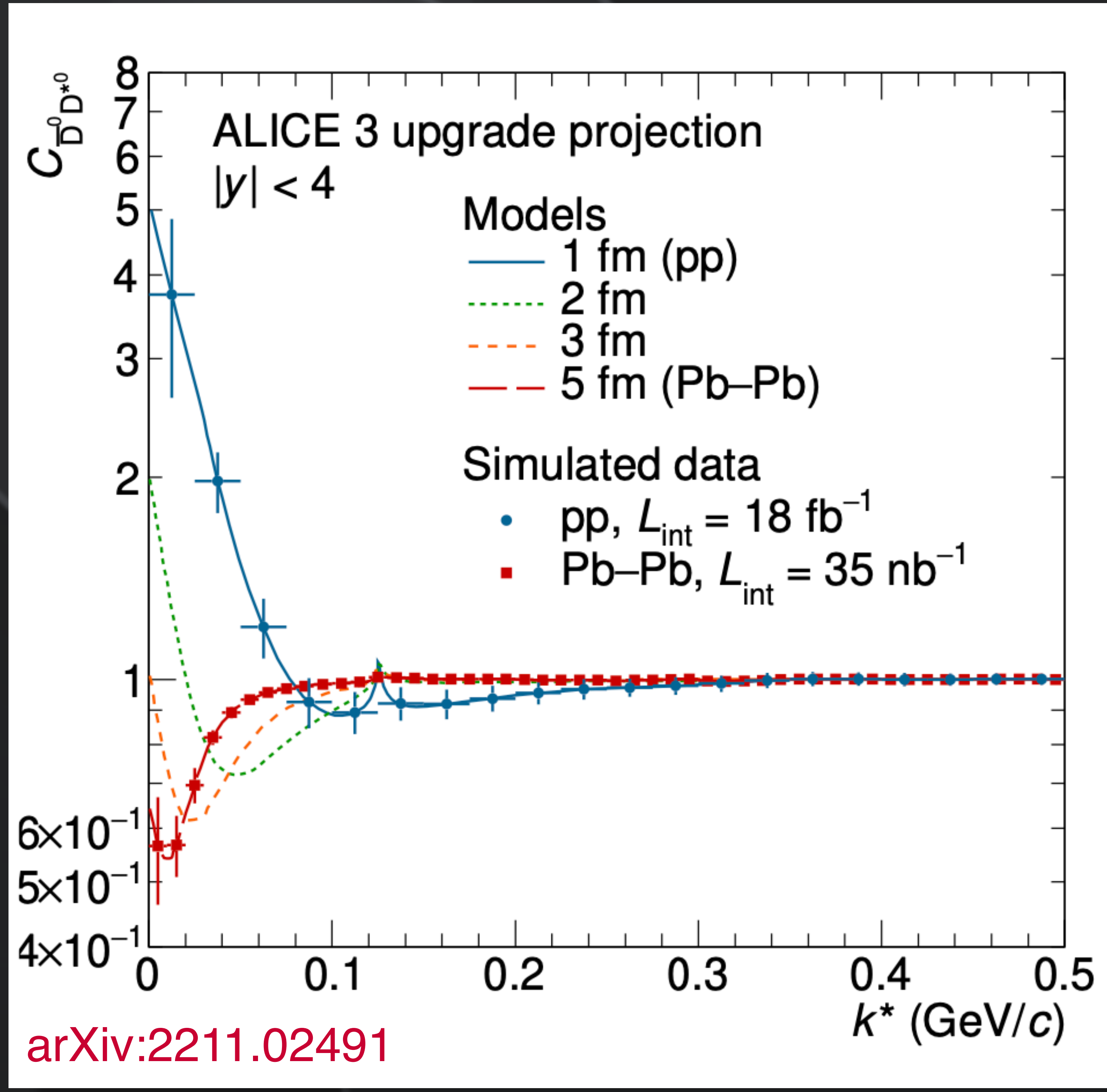


HF hadrons in hadronic phase

- Final state hadron-hadron interactions can be studied via the femtoscopic correlation function
- Indicate a **small interaction between charm mesons** and light hadrons in the hadronic phase
- Possibility to constrain the interaction potential of charm exotic states

Same charge pair **Oposite charge pair**



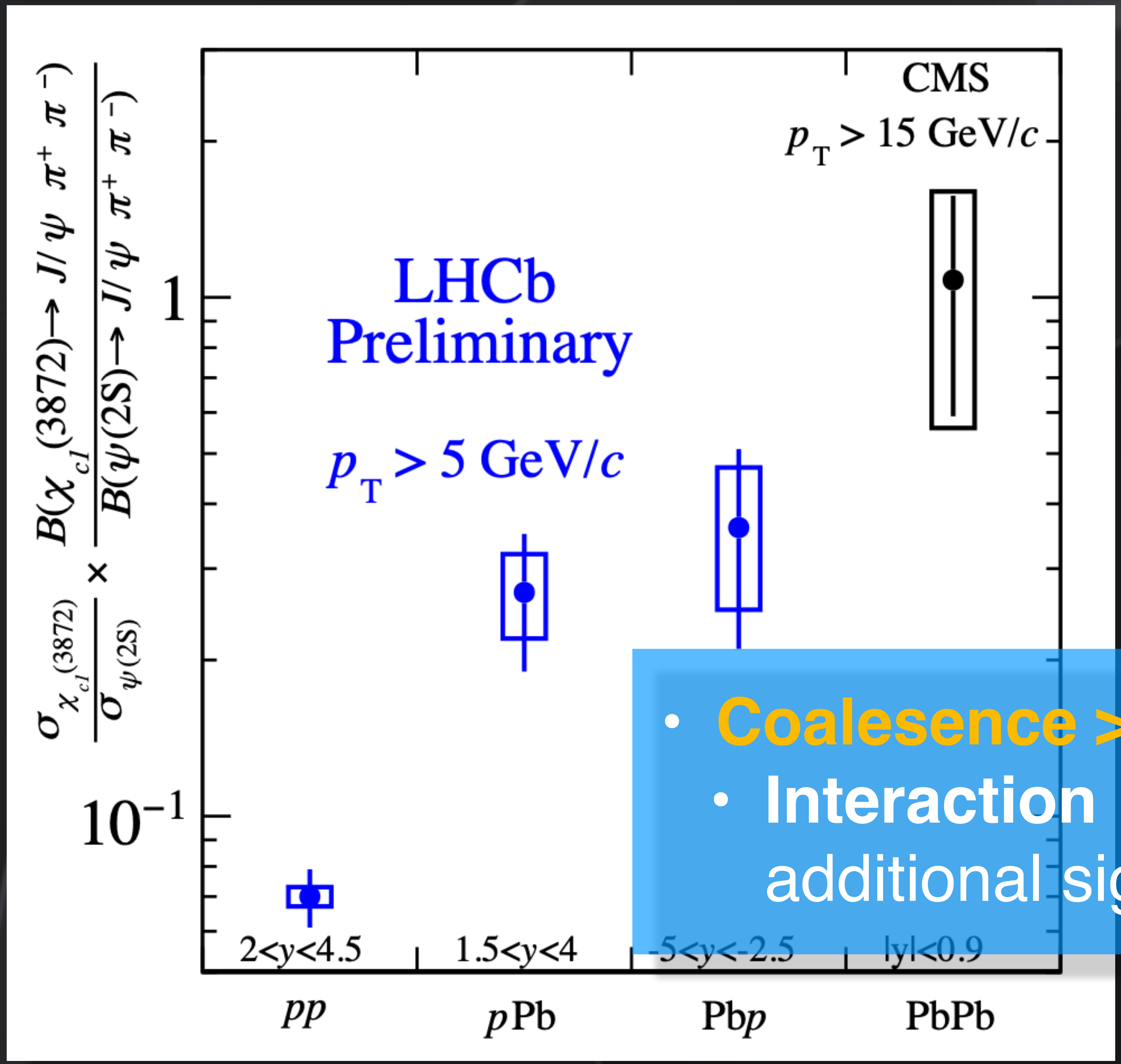


$$C(k^*) = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$$k^* = 1/2\,|p^*_{x_1} - p^*_{x2}|$$

Charm exotic states

- $\chi_{c1}(3872)$ structure as a compact tetraquark
- Possibility to constrain the interaction potential of charm exotic states
  - **Distinct source size dependence** of the correlation function in the presence of bound states



- **Coalesence > comover break up?**
  - **Interaction between DD*** will give additional sight on $\chi_{c1}(3872)$