Experiment overview on open heavy-flavour production in large collisions systems

With personal bias

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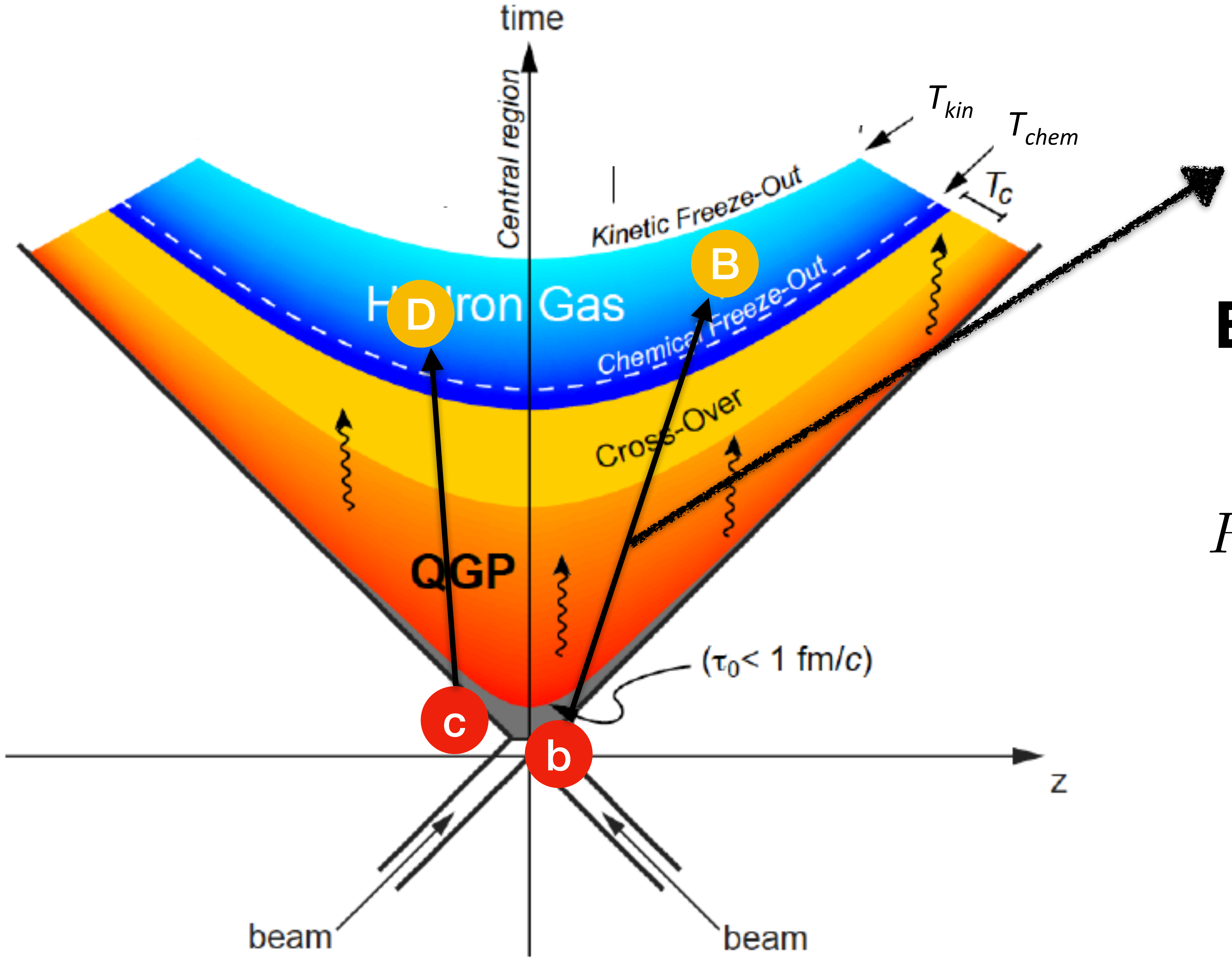
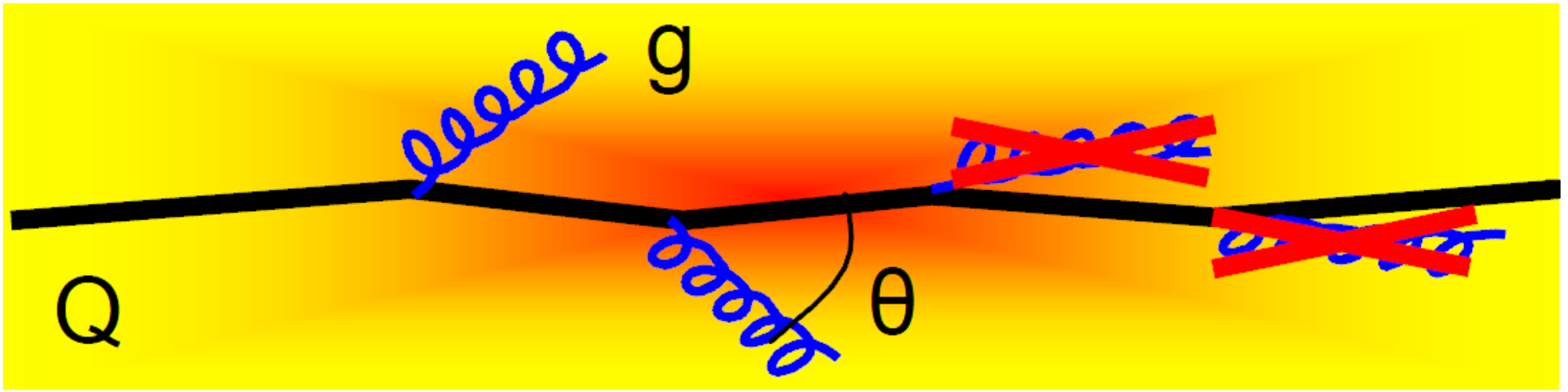
The 9th international symposium on HF-HNC
6–11 December 2024, Guangzhou, China

Part of materials are provided by https://boundino.github.io

Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of heavy-ion collisions before the QGP creation





Energy loss in QGP medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

QCD vacuum

- R_{AA} = 1 if no medium effect and/or initial state effects
- Radiative vs. collisional energy loss

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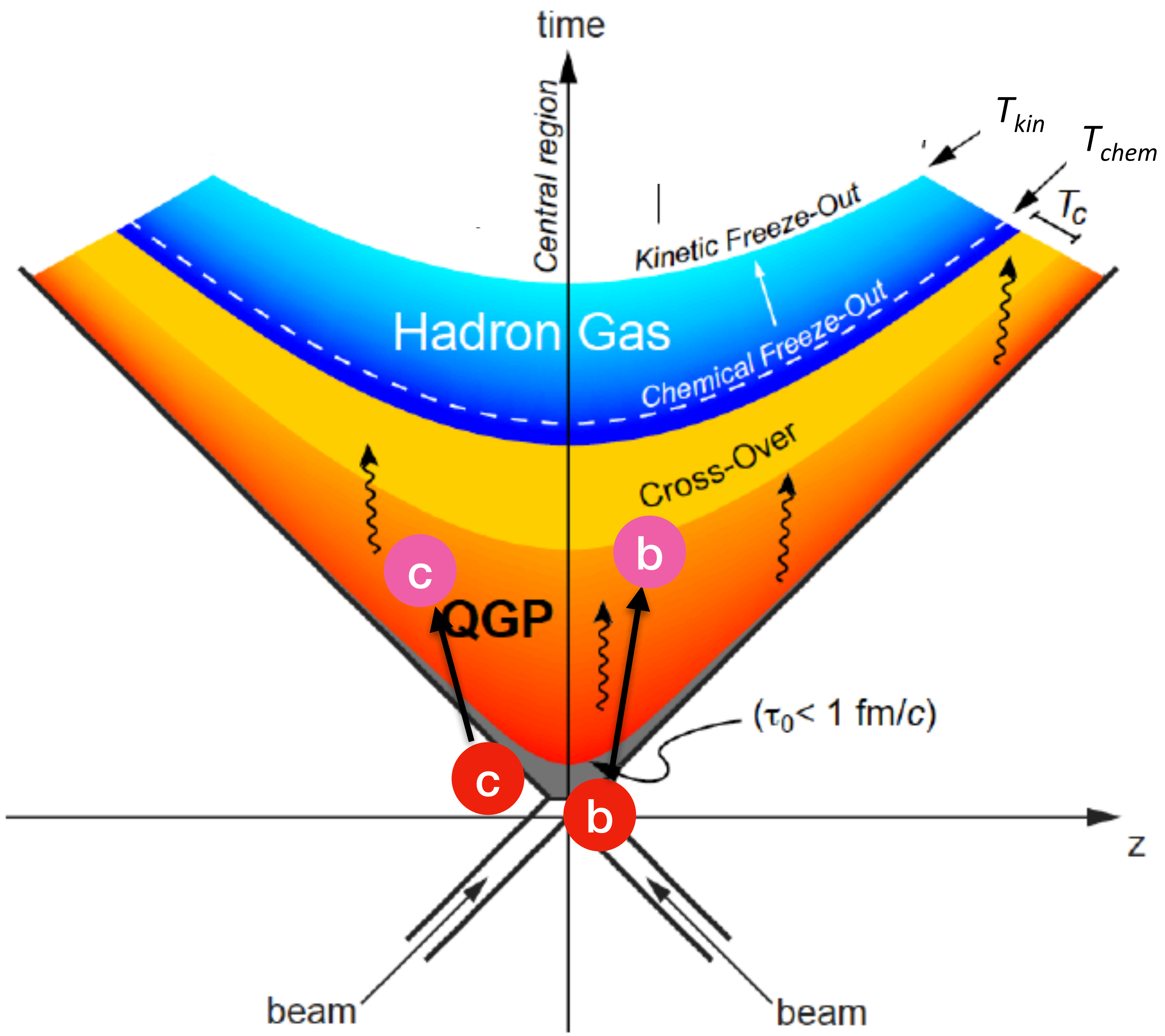
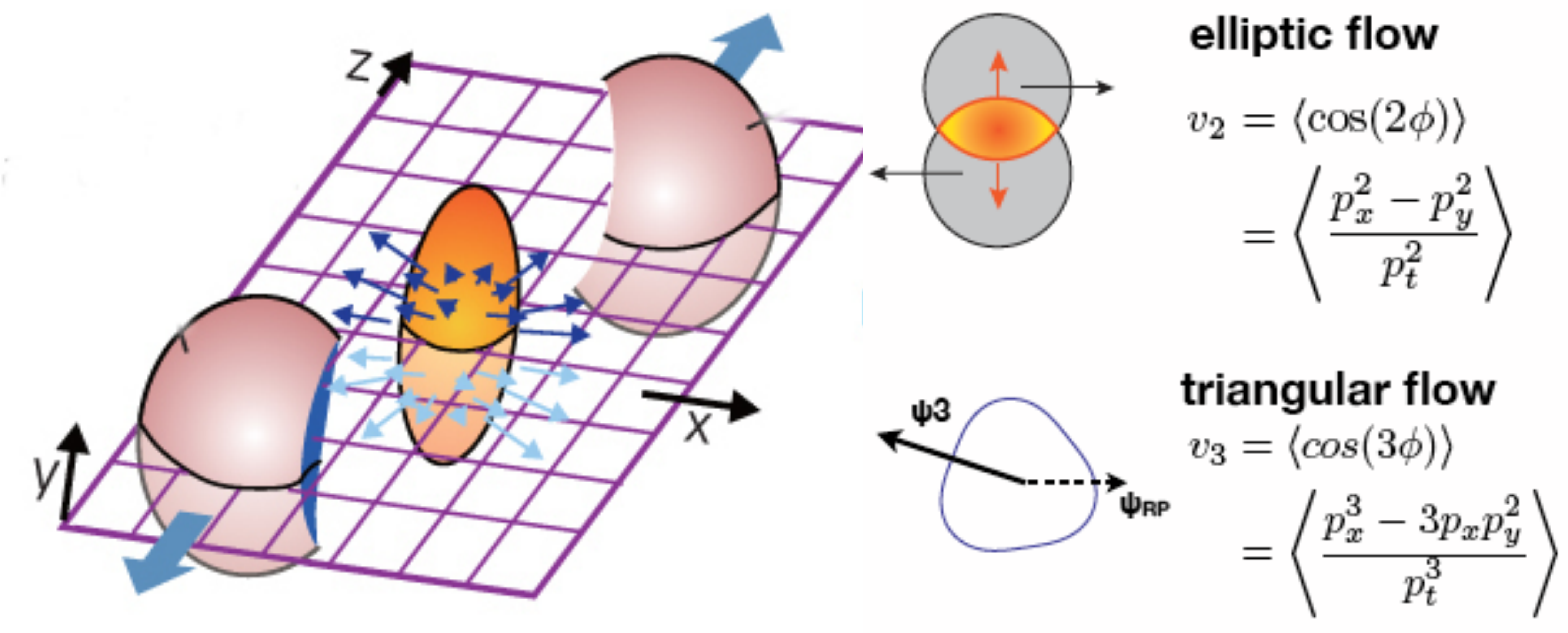


Collective expansion

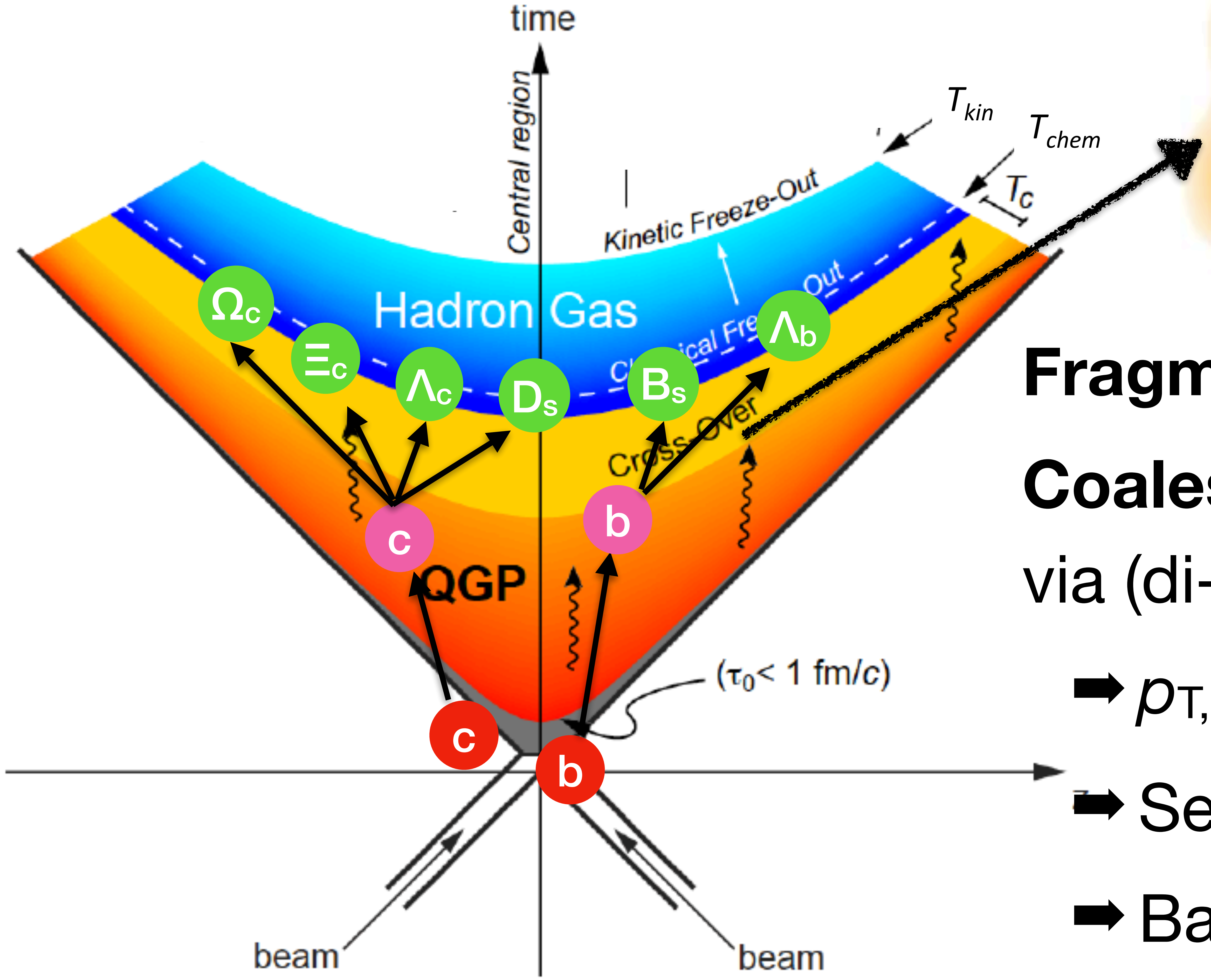
➡ Anisotropic flow

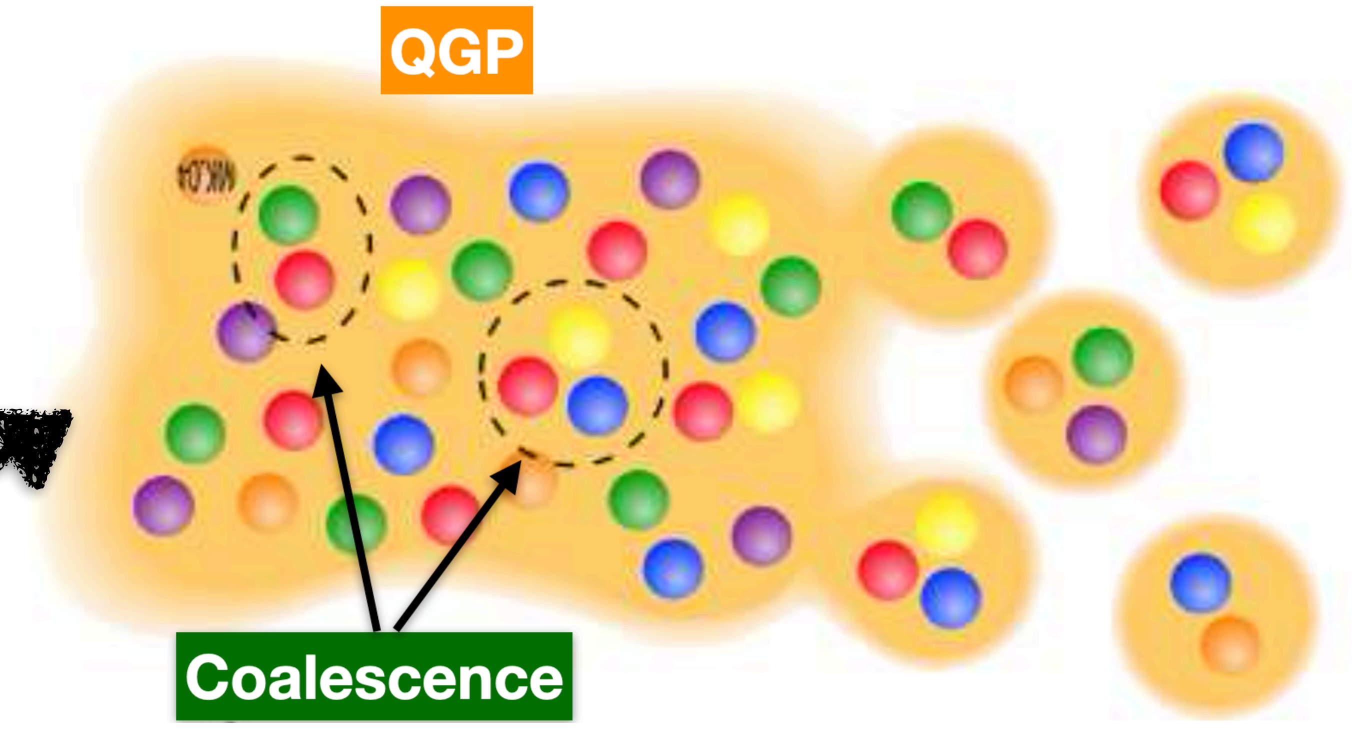


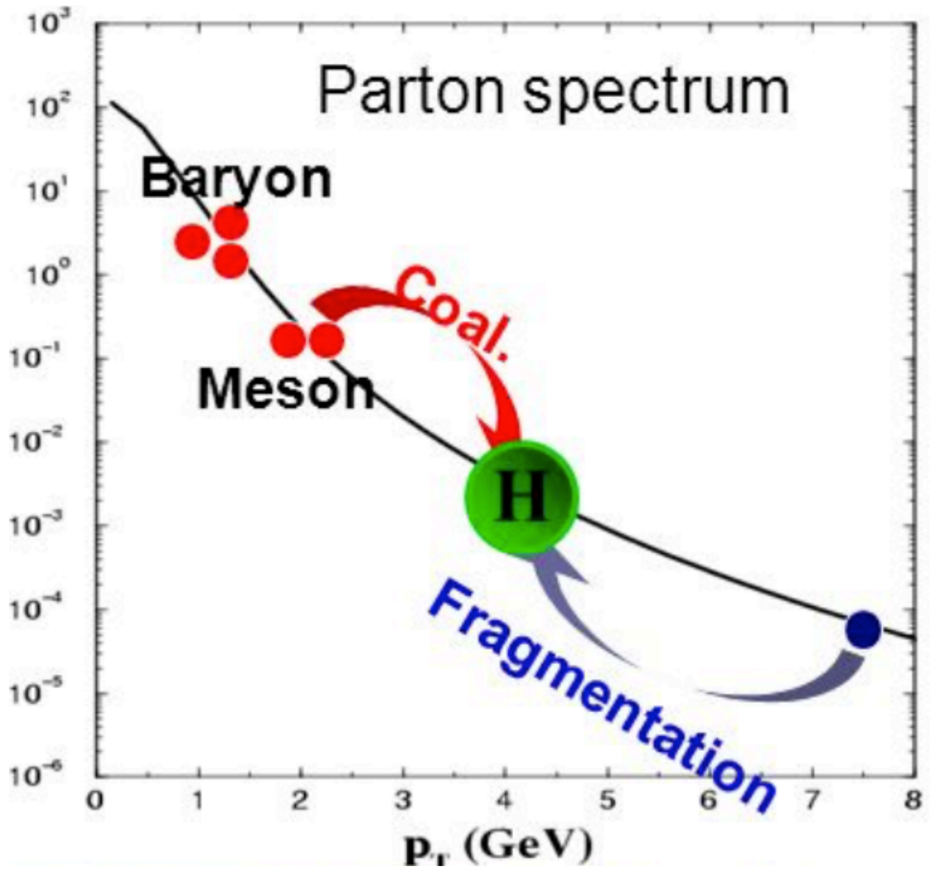
➡ Results in complex azimuthal structure of final-state particles

Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation





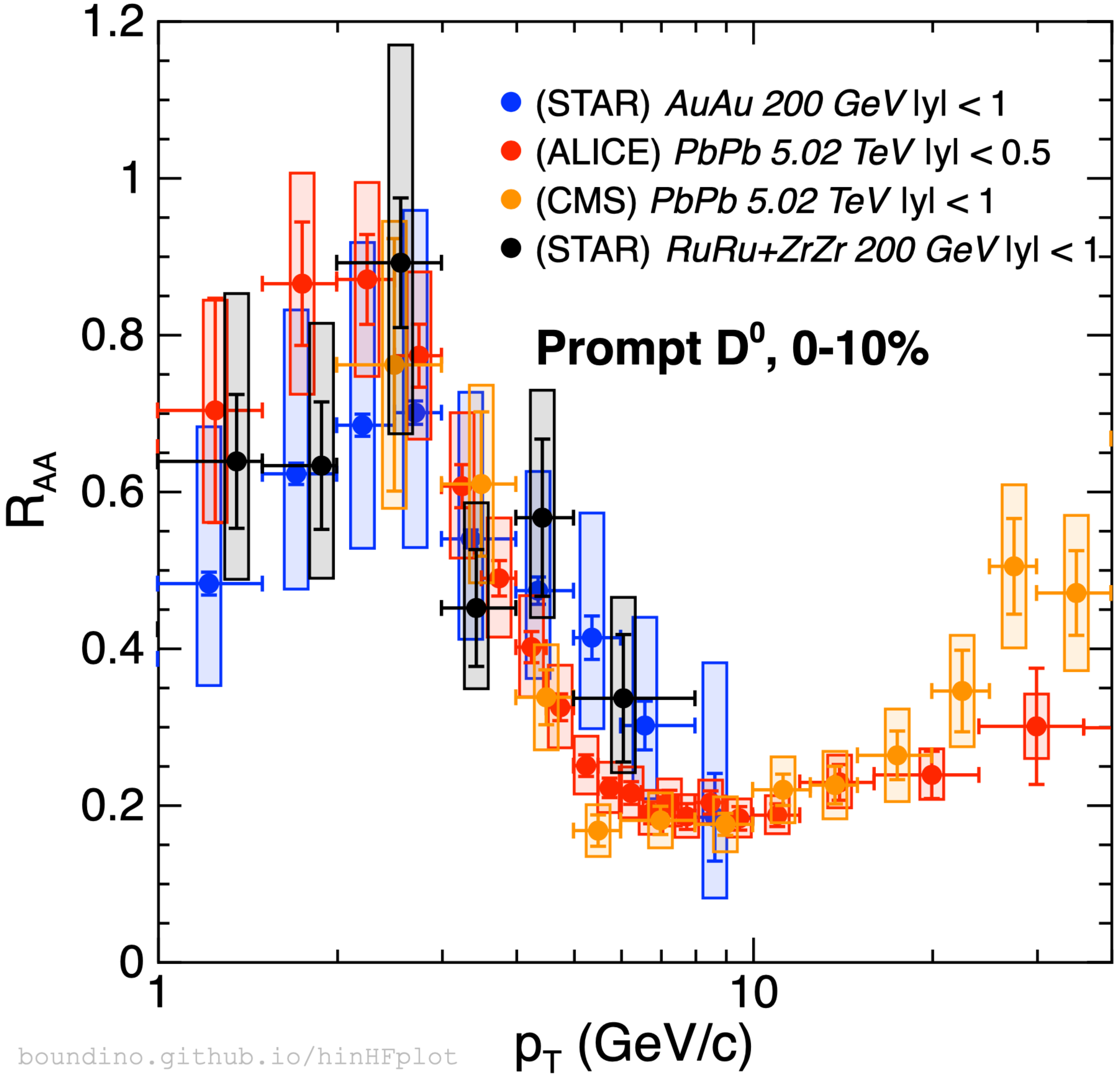


Fragmentation — hadrons from high p_T partons

Coalescence/recombination — hadron formation via (di-)quark combination in the QGP medium

- ➡ $p_{T,hadron} \simeq n\, p_{T,parton}$, n = 2 (meson), 3 (baryon)
- ➡ Sensitive to baryon and meson species
- ➡ Baryons from lower momenta partons (denser)

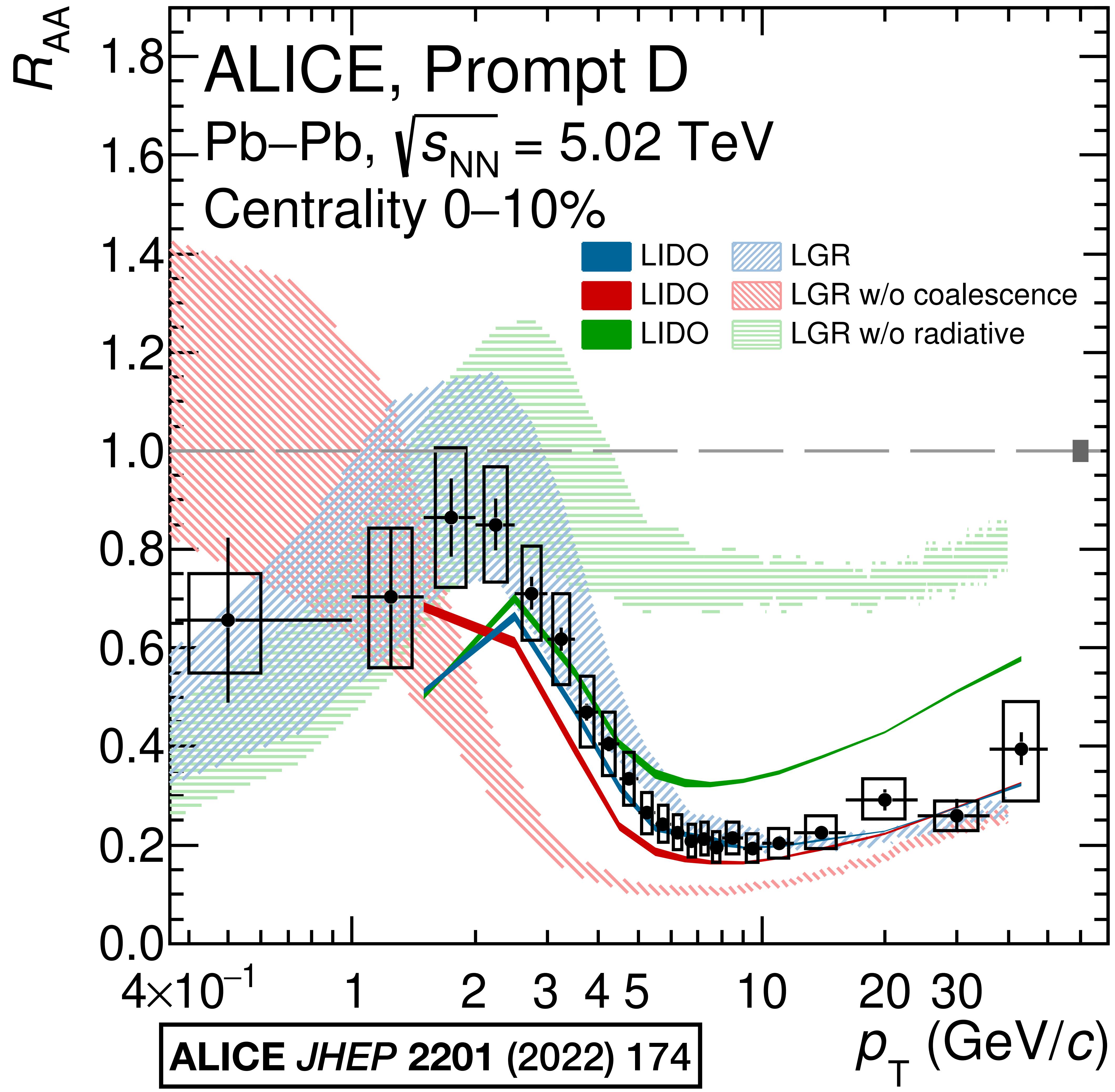
R_{AA} of prompt D mesons



ALICE *JHEP* **2201** (2022) 174
CMS *Phys. Lett.* **B782** (2018) 474
STAR *Phys. Rev.* **C99** (2019) 034908
STAR Preliminary

- Similarity between RHIC and the LHC and among collision systems
  - ➡ Counterbalance among different medium sizes and densities, p_T slopes, hadronizations…
- Suppression up to a factor of 3–5 at high p_T
  - ➡ Charm undergoes strong energy loss (?)

R_{AA} of prompt D mesons

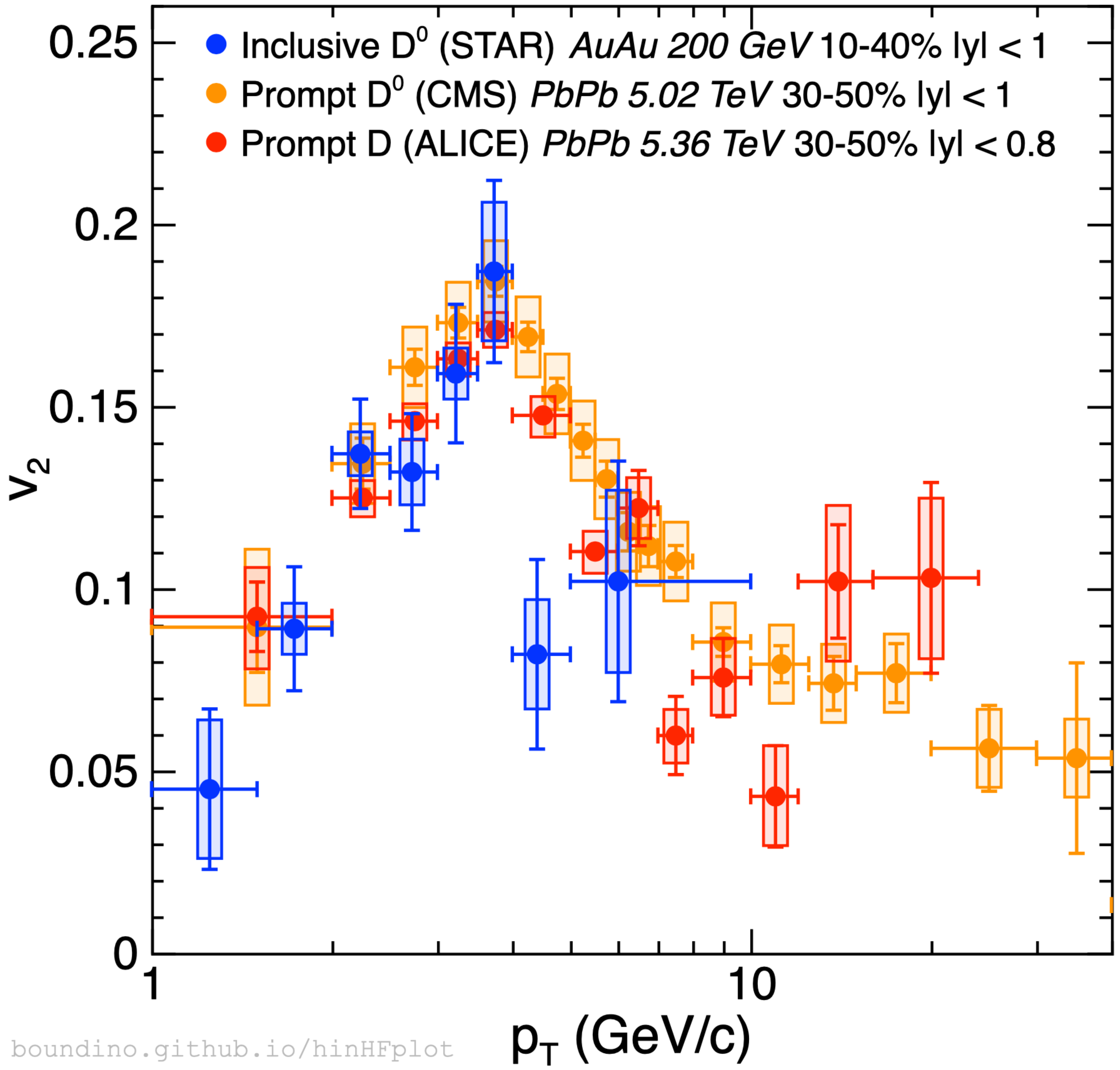


W/o coalescence: large deviation from data

W/o radiative energy loss: overestimate data at high p_T

➡ Both radiative and collisional energy loss and hadronization via coalescence are important to interpret data

v_2 of D mesons



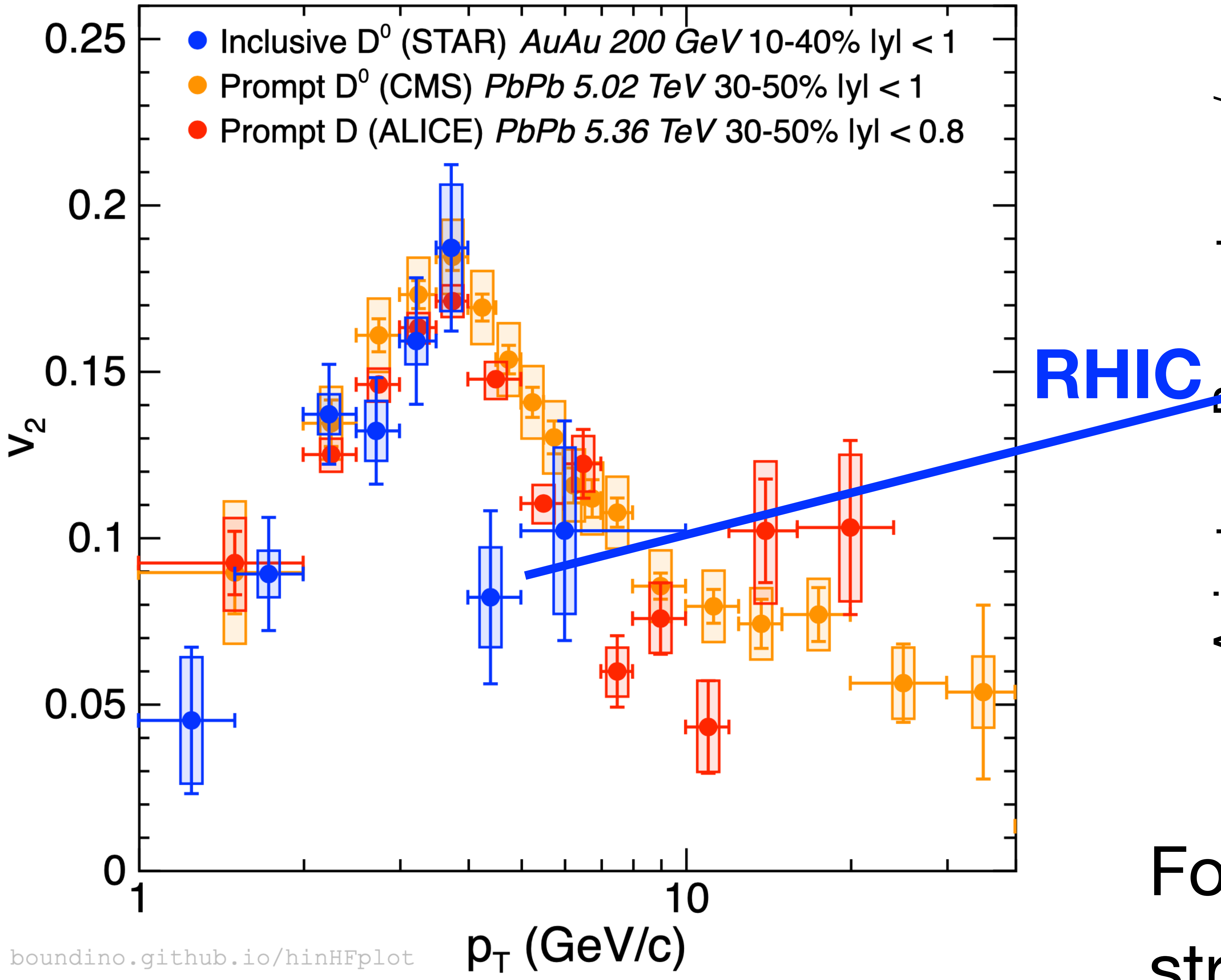
STAR *Phys. Rev. Lett.* **118** (2017) 212301
CMS *Phys. Rev. Lett.* **129** (2022) 022001
CMS *Phys. Lett.* **B816** (2021) 136253
ALICE Preliminary

(Again) similarity between RHIC and the LHC

Additional dependence on

- Initial geometry, fluctuations…
- Medium viscosity
- Hadronic interactions
- …

v_2 of D mesons



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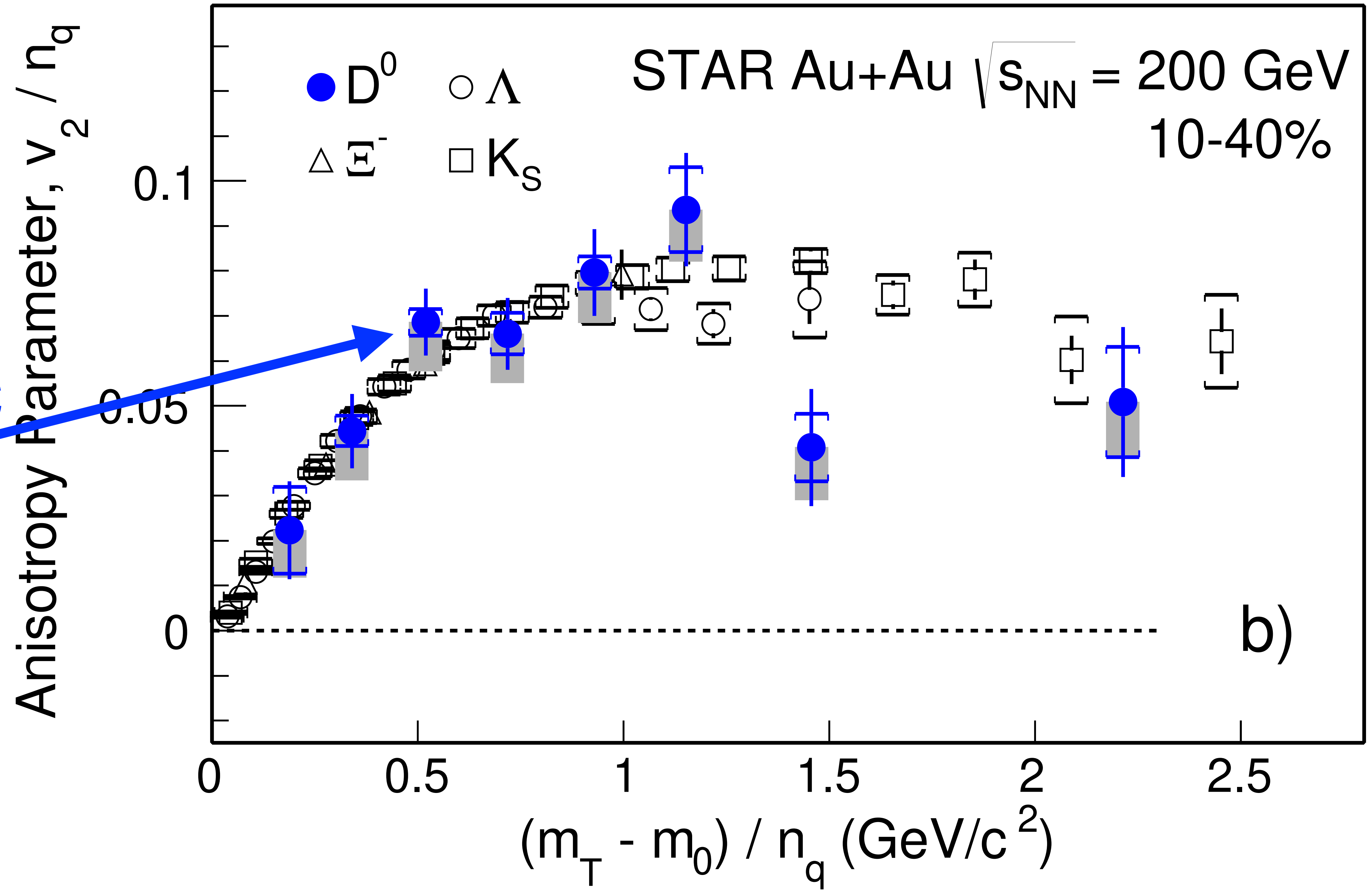
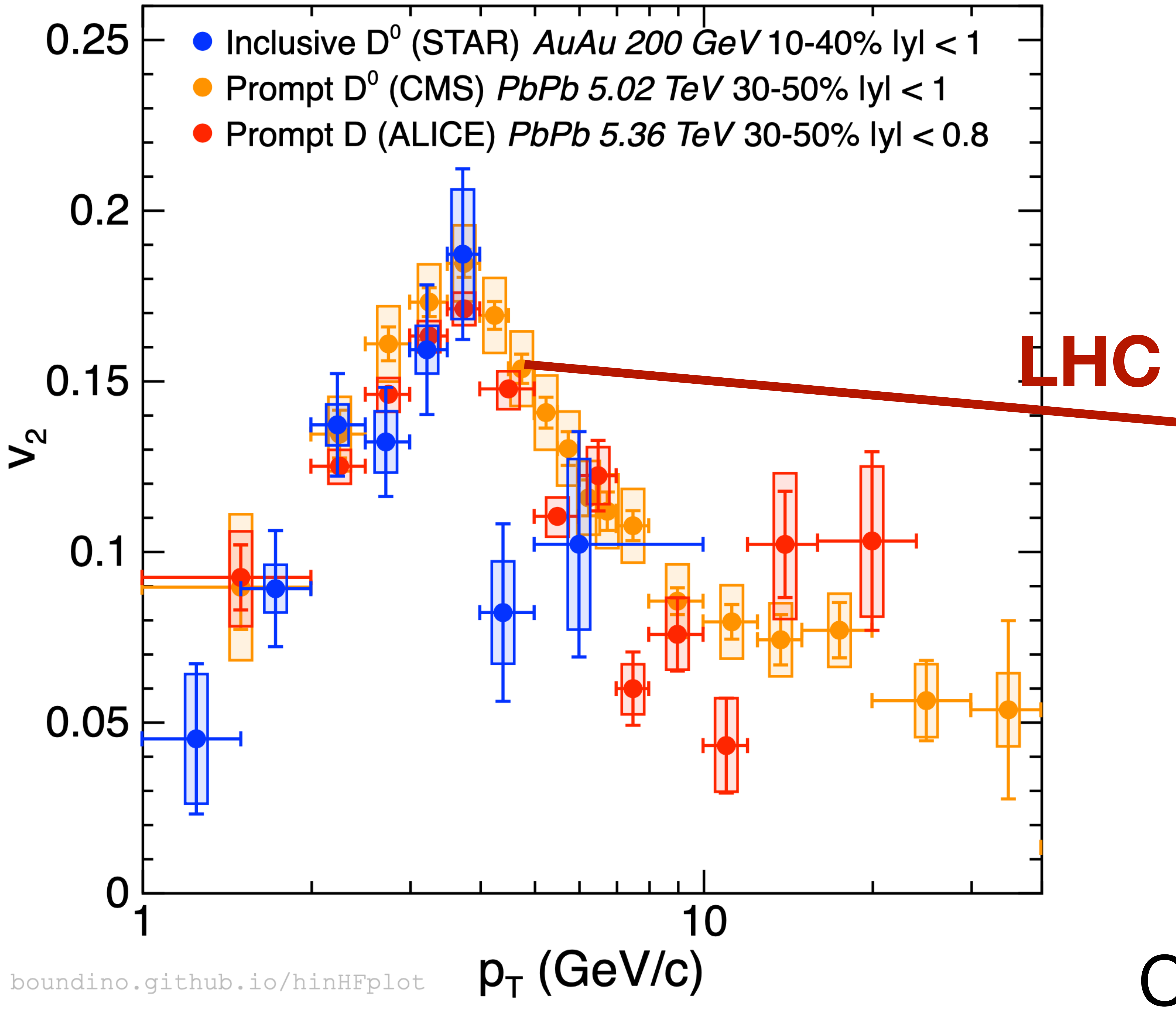


Follows the NCQ–KET scaling established by strange hadrons in KET/n_q < 1

➡ Charm significantly gains flow through interactions with the medium

v_2 of D mesons



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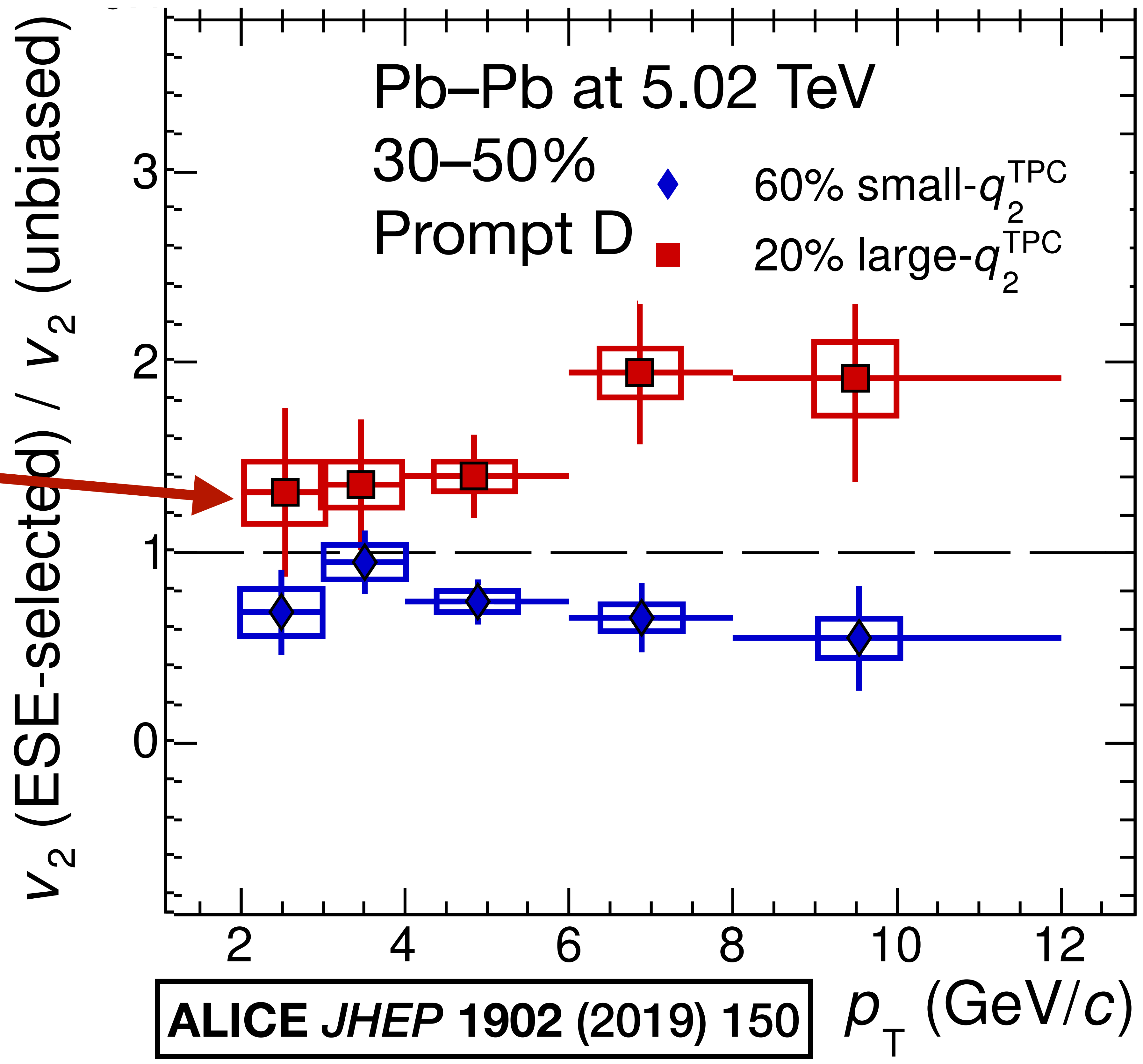
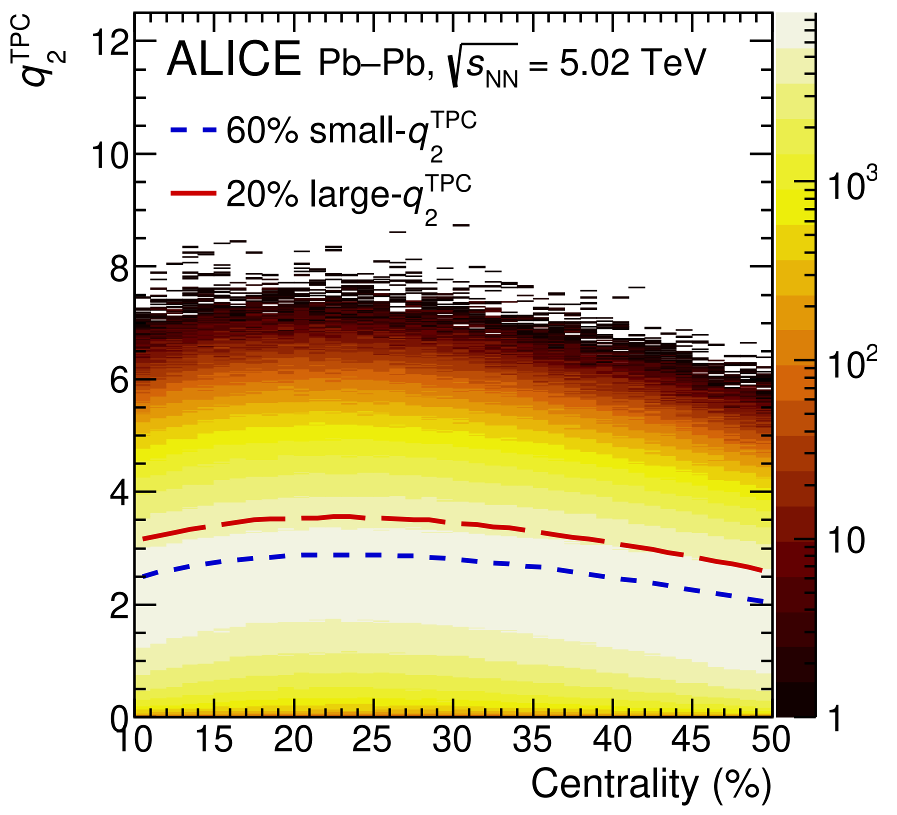
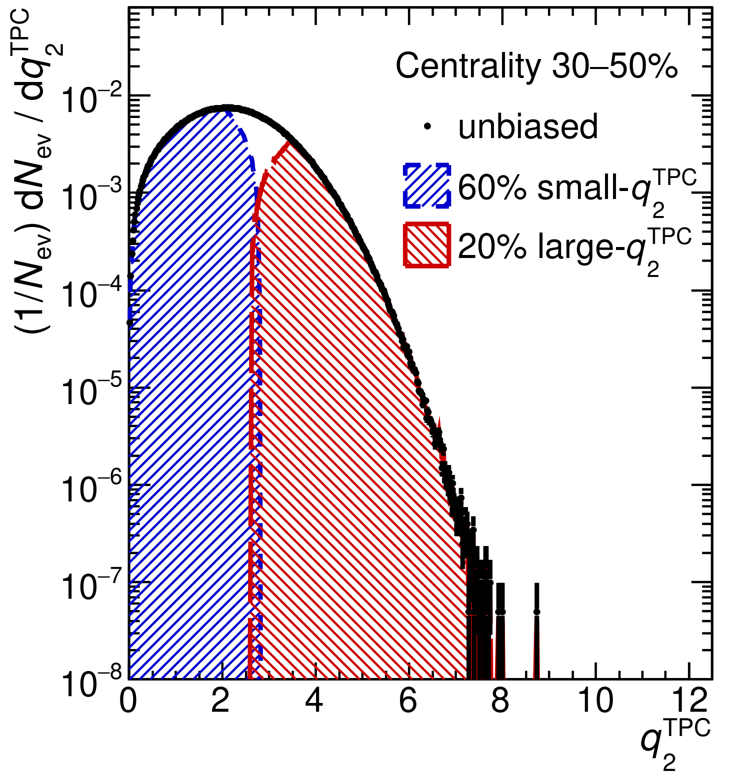


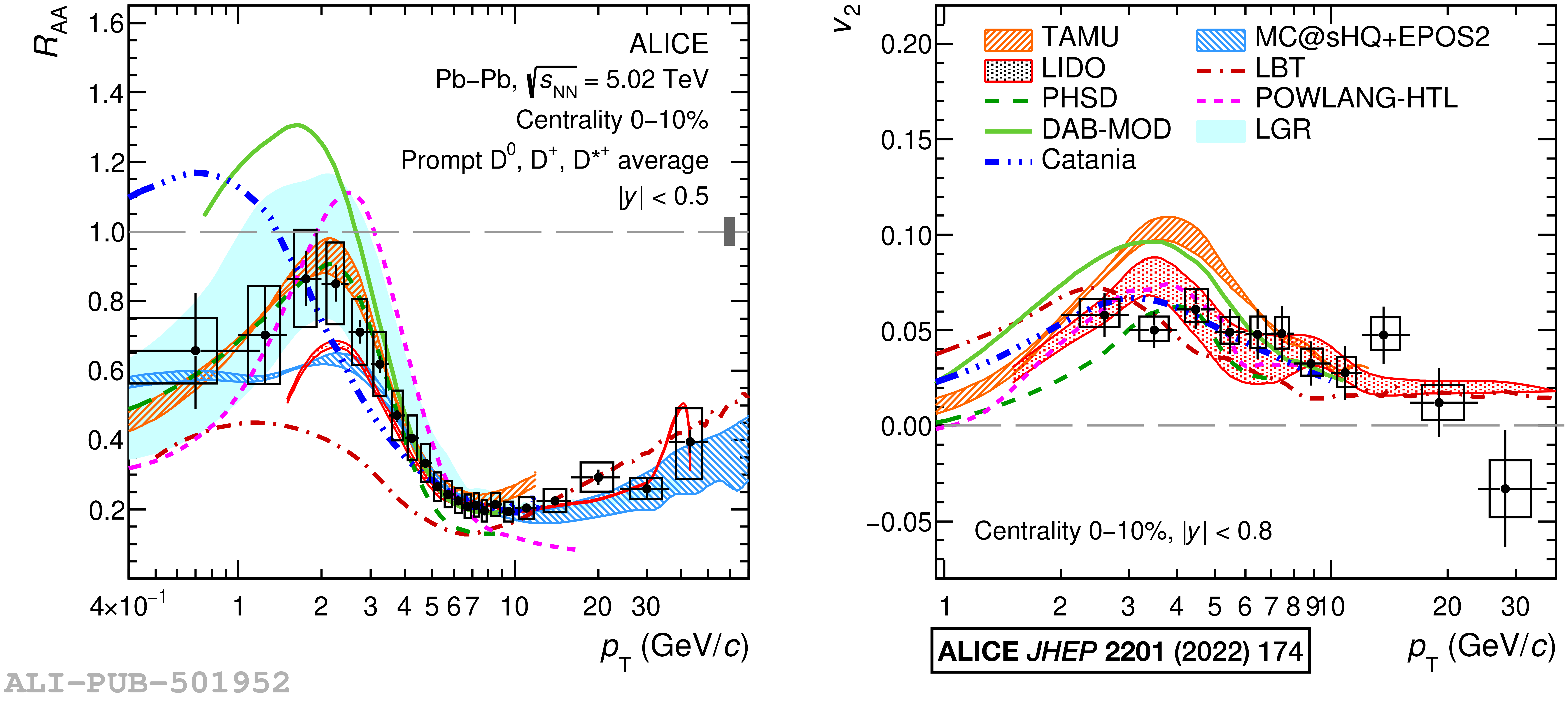




Clear correlations with eccentricity

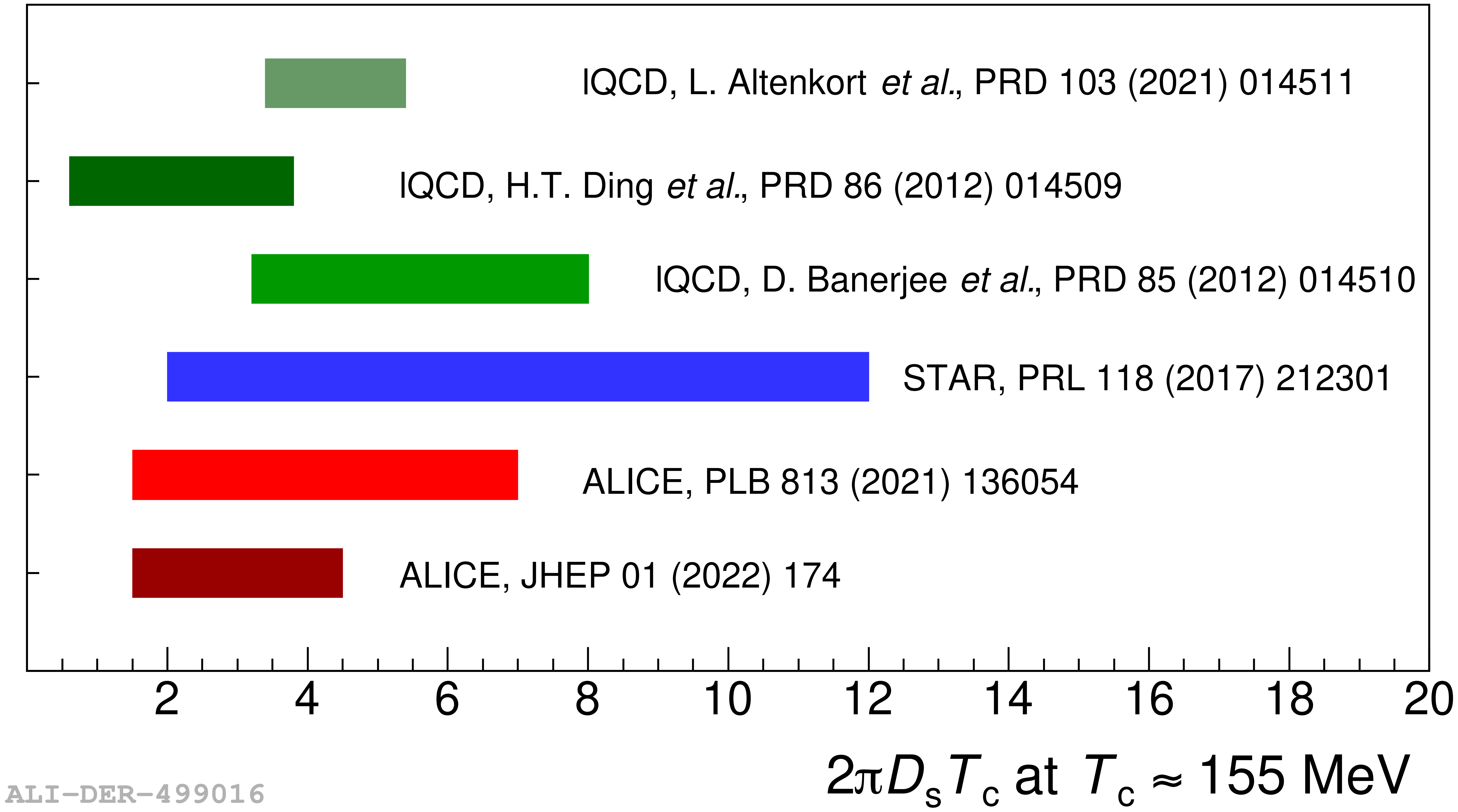
➡ Suggest charm participating the collective expansion of the light hadron bulk

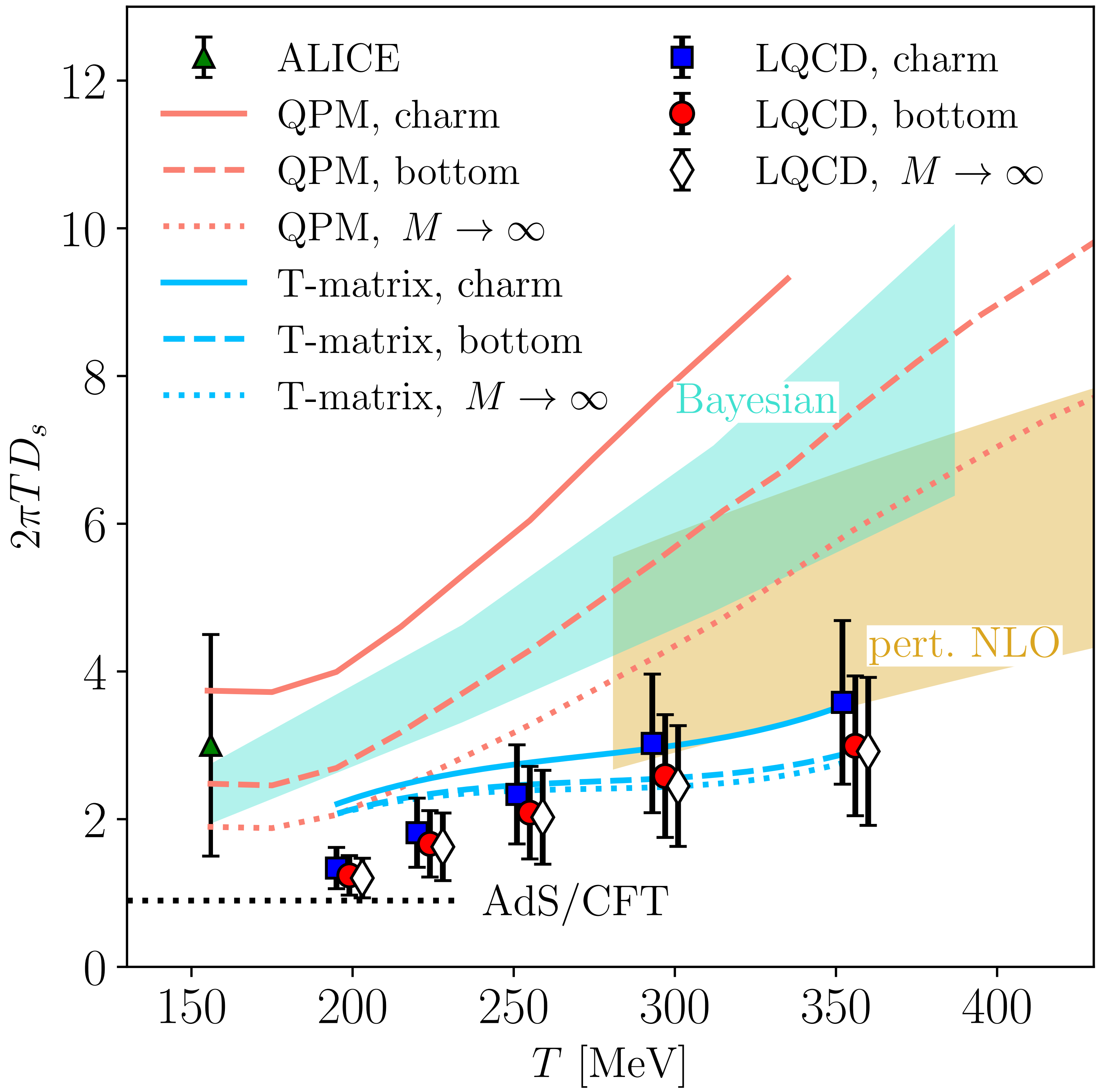
Charm quark transport



Most charm quark transport models able to fit both R_{AA} and v_2 data

Charm quark transport



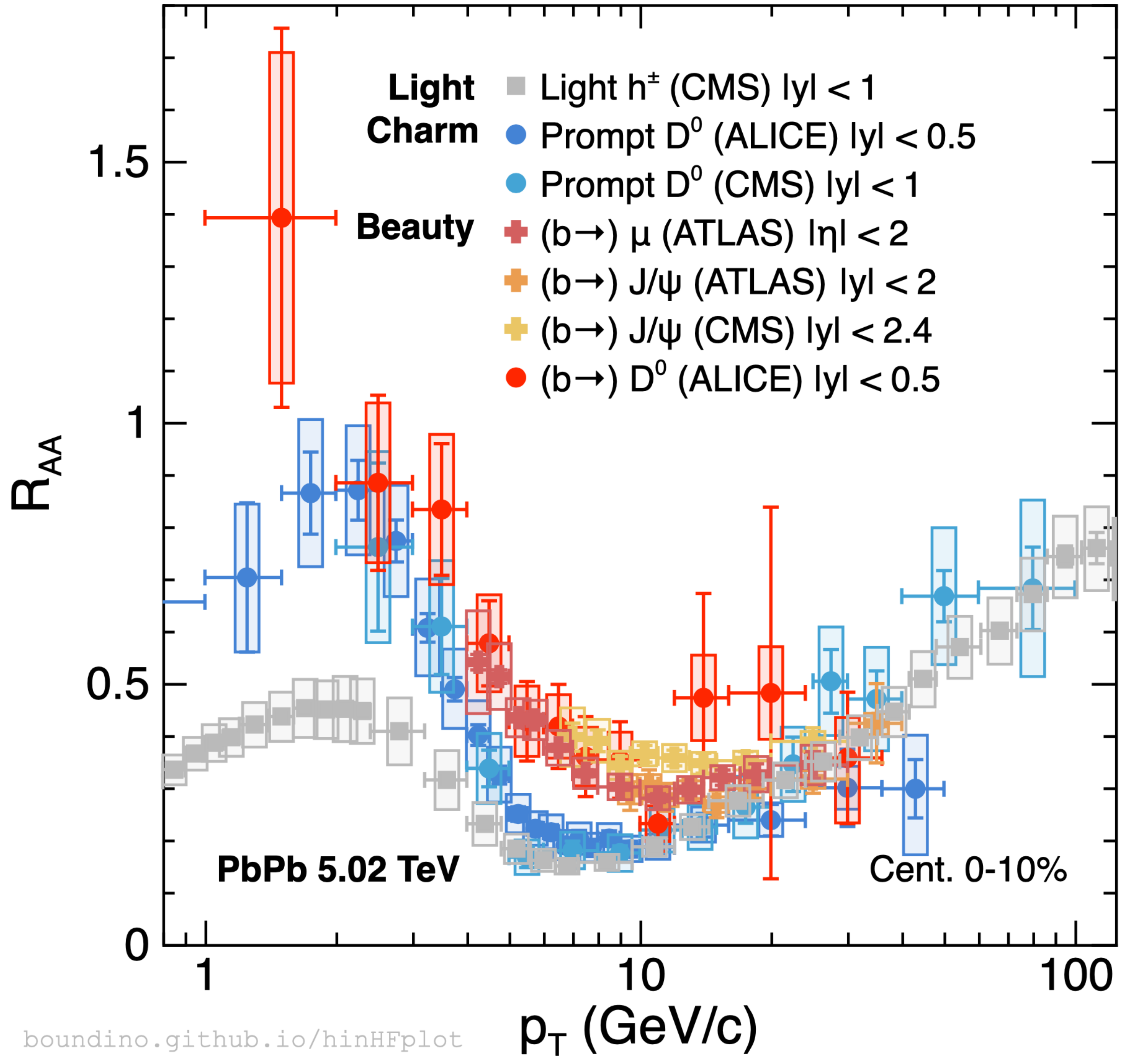


Hot QCD ***Phys. Rev. Lett.*** **132 (2024) 051902**

$1.5 < 2\pi D_s(T) < 4.5$, $\tau_{charm} = (m_{charm} / T)\, D_s(T) = 3\text{–}9$ fm/c $< \tau_{medium} \approx 10$ fm/c

➡ Indicate charm may thermalize in the medium

Quark mass dependent R_{AA}



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CMS *Eur. Phys. J.* **C78** (2018) 509
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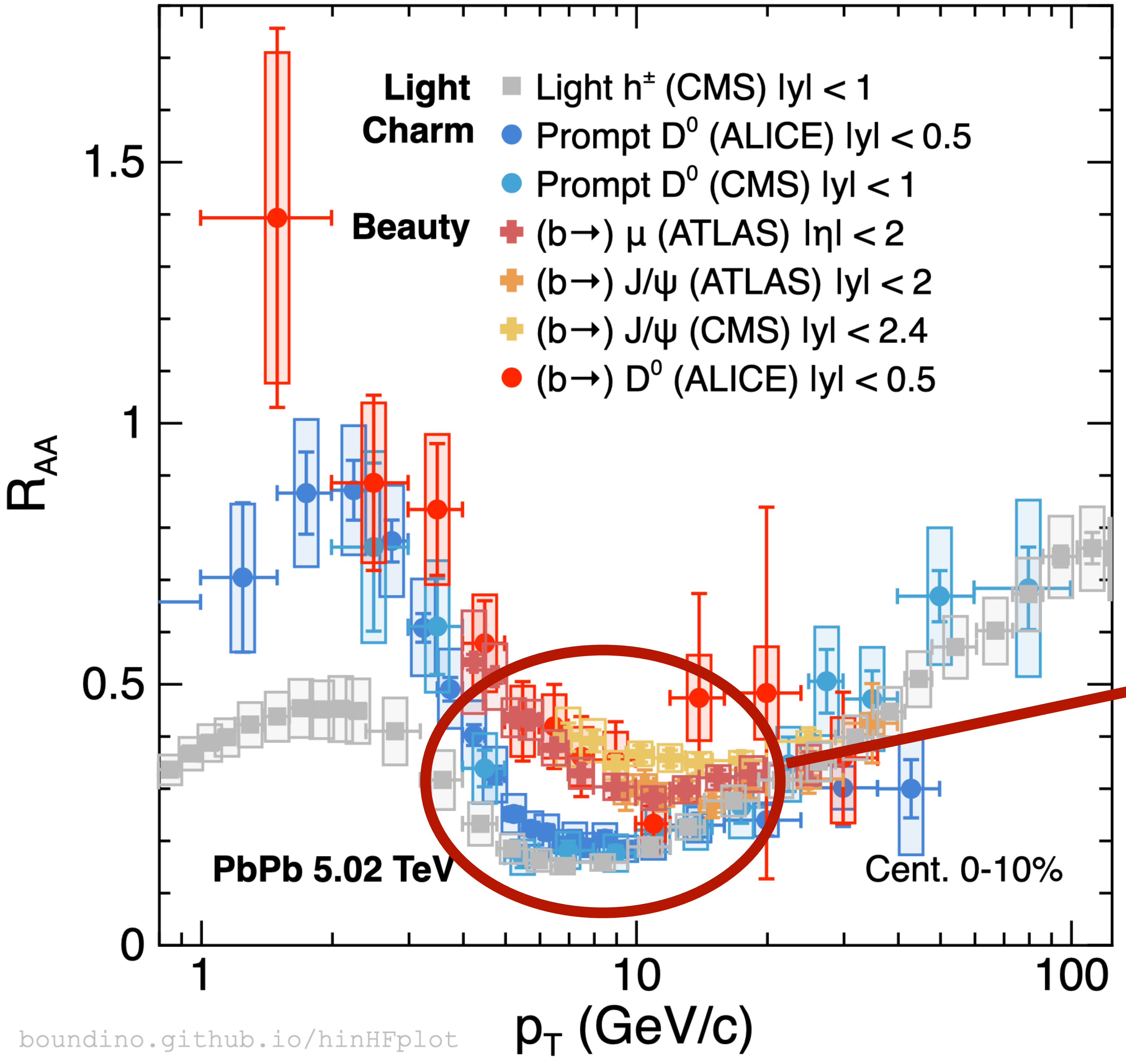
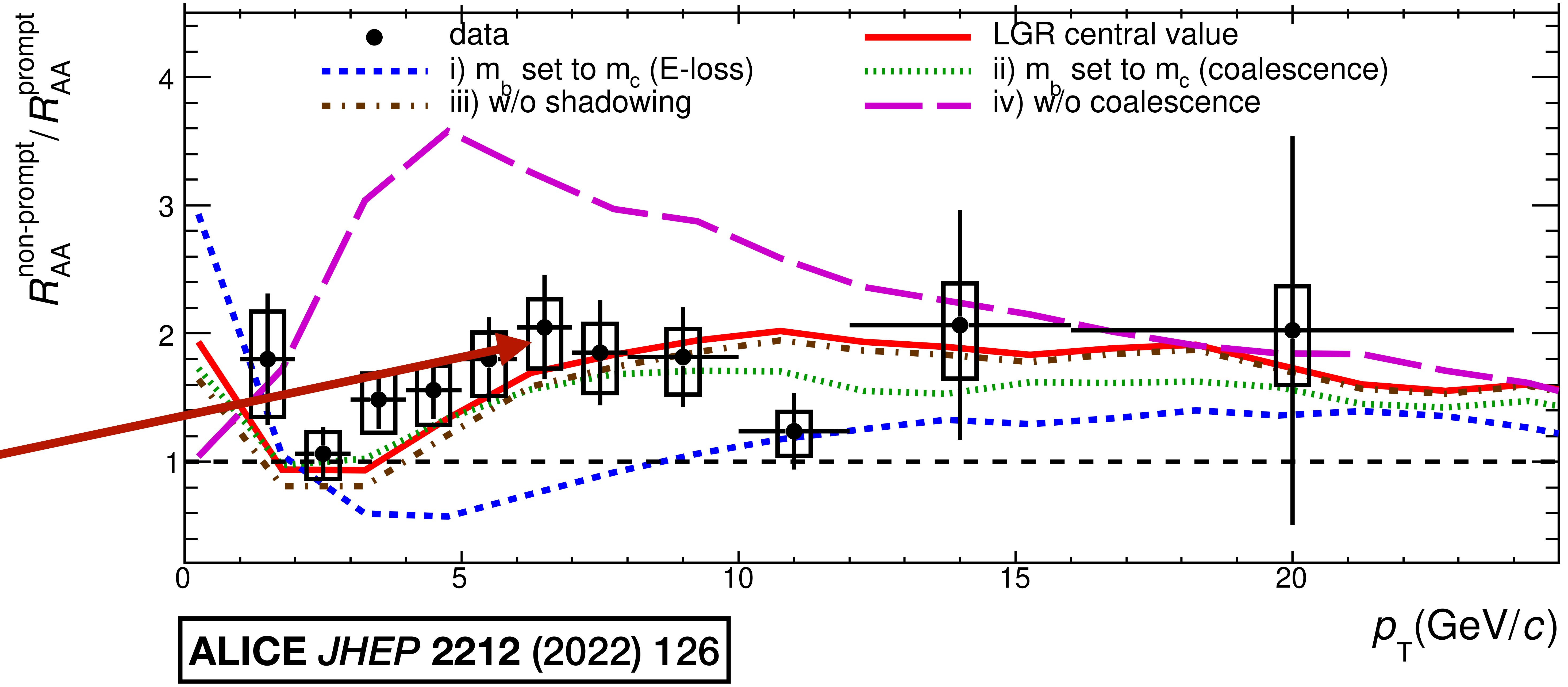
Quark mass dependent R_{AA}





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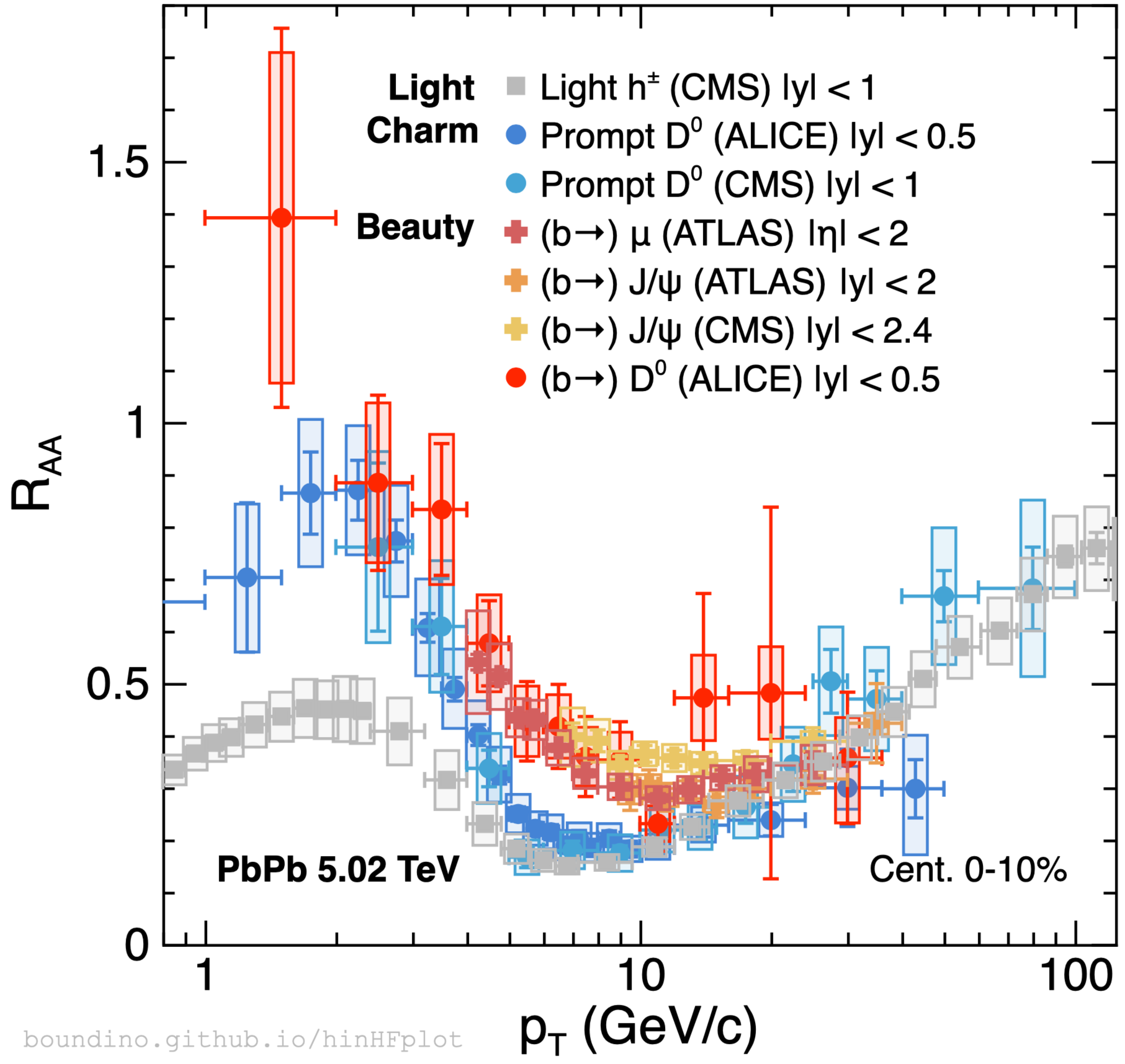
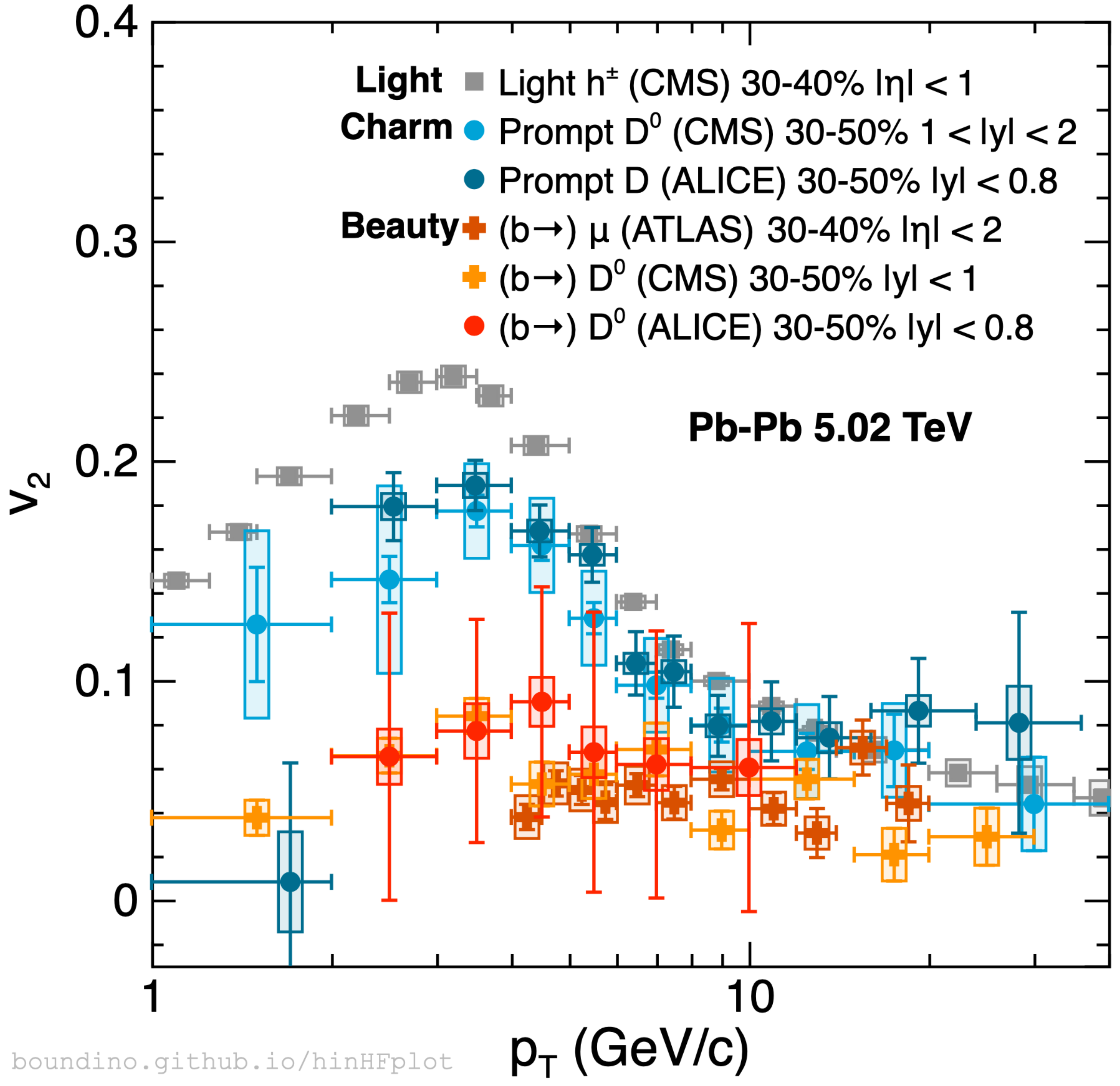
- Mass effects are important to describe data
- Coalescence plays relevant role at intermediate p_T

Beauty particle transport





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ALICE Eur. Phys. J. C83 (2023) 1123

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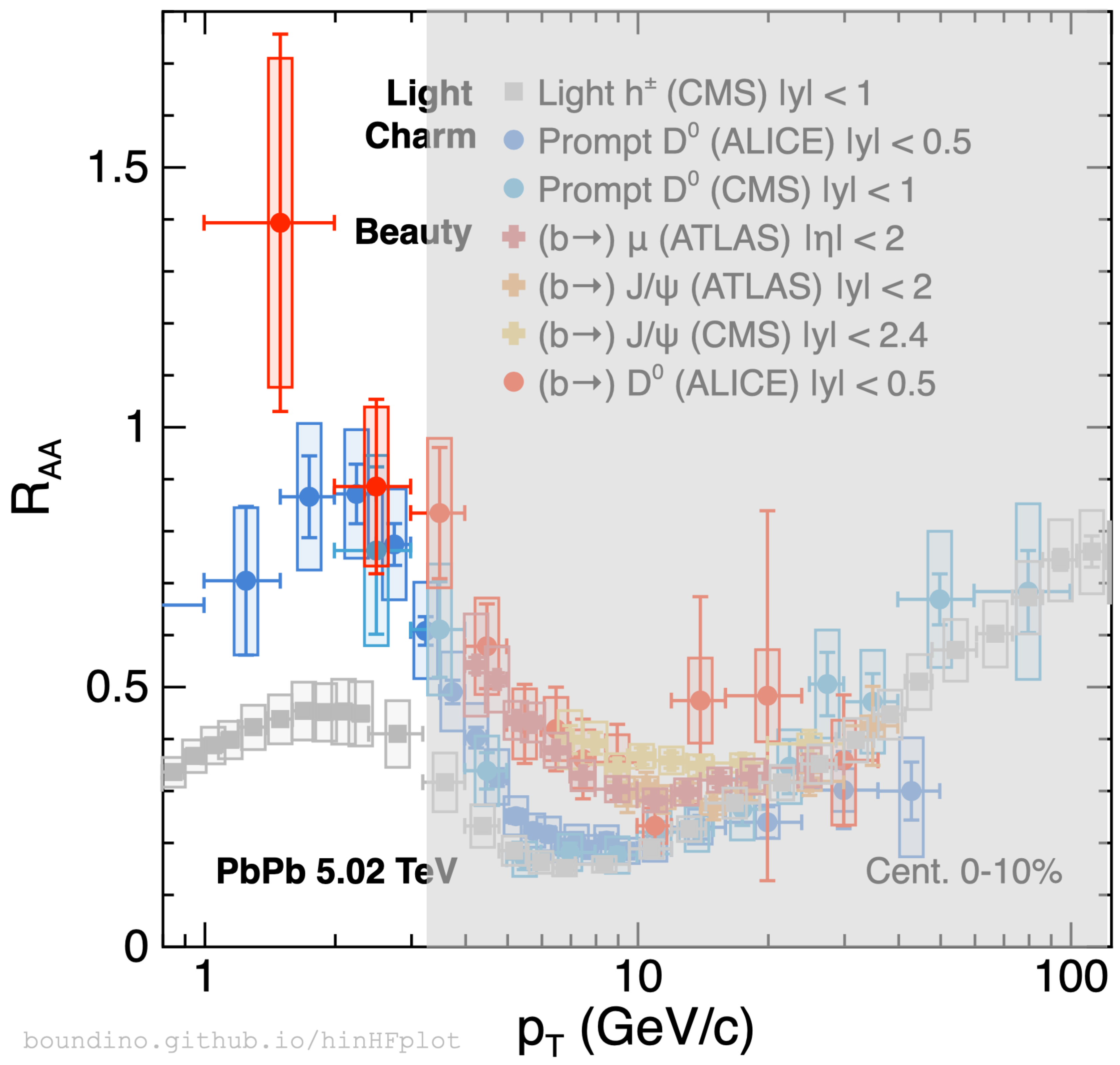

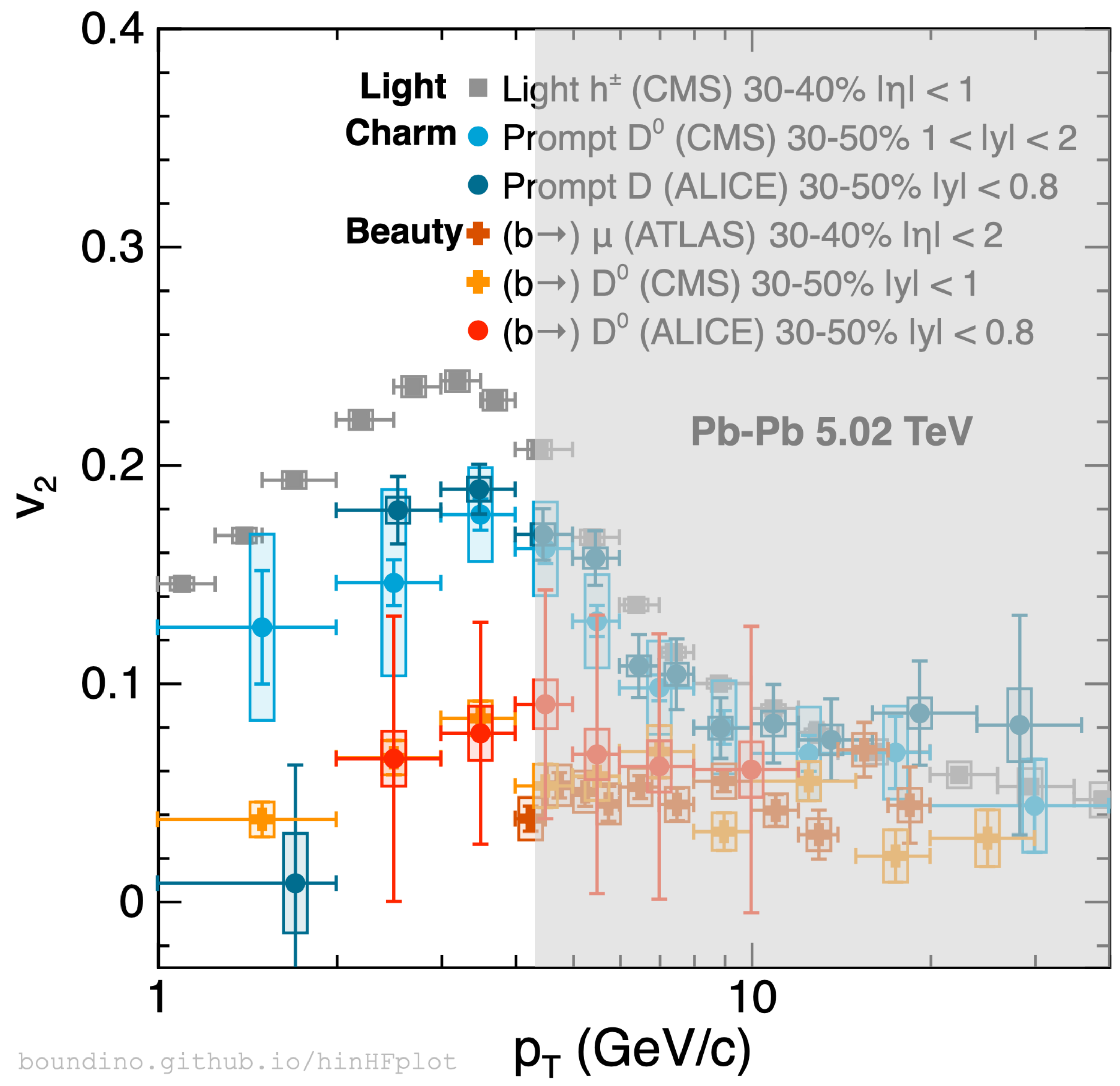

p_T < 3–4 GeV/c

➡ $R_{AA}(B) \approx R_{AA}(D) > R_{AA}(h^{\pm})$

➡ $v_2(B) < v_2(D) < v_2(h^{\pm})$

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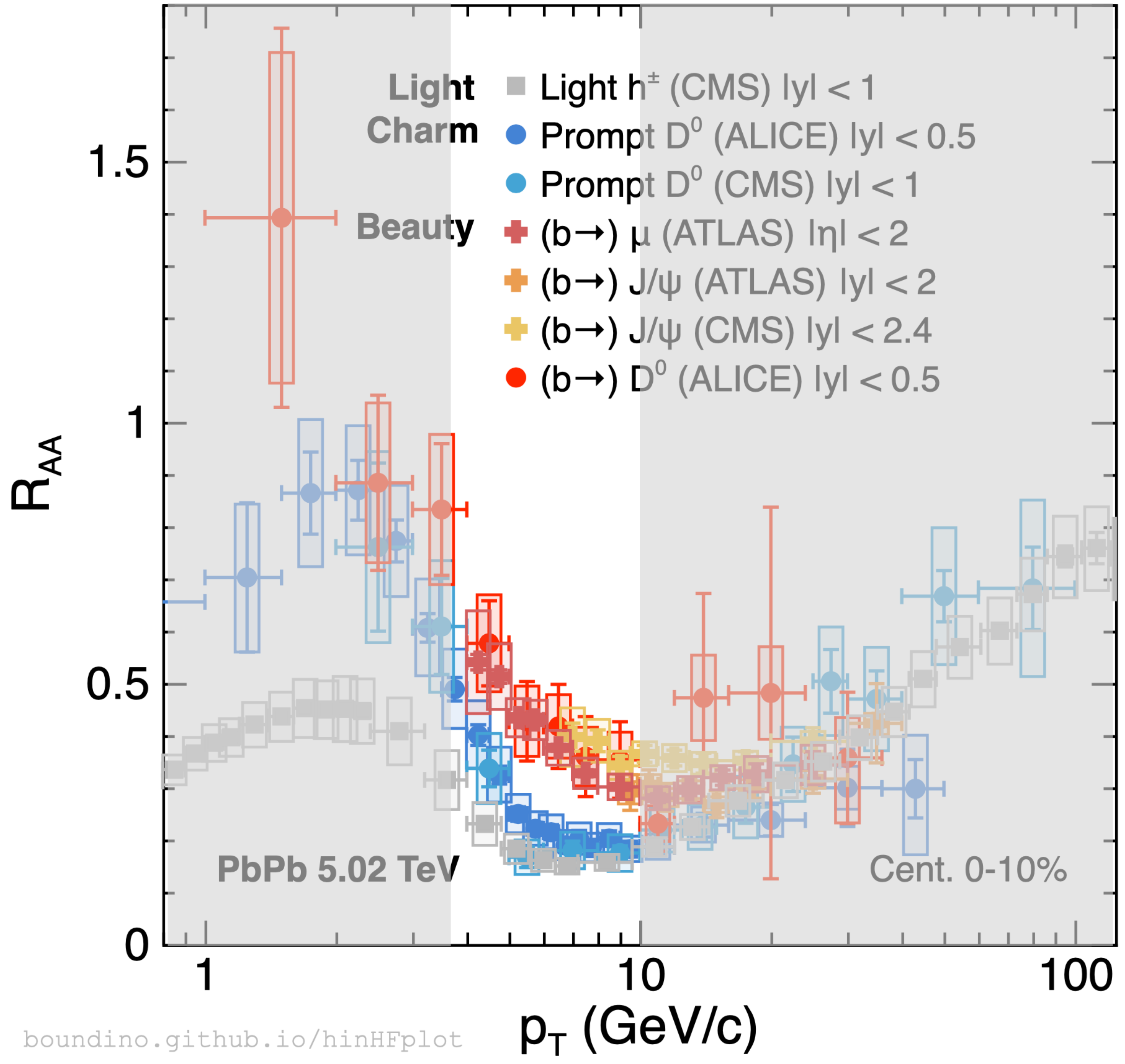

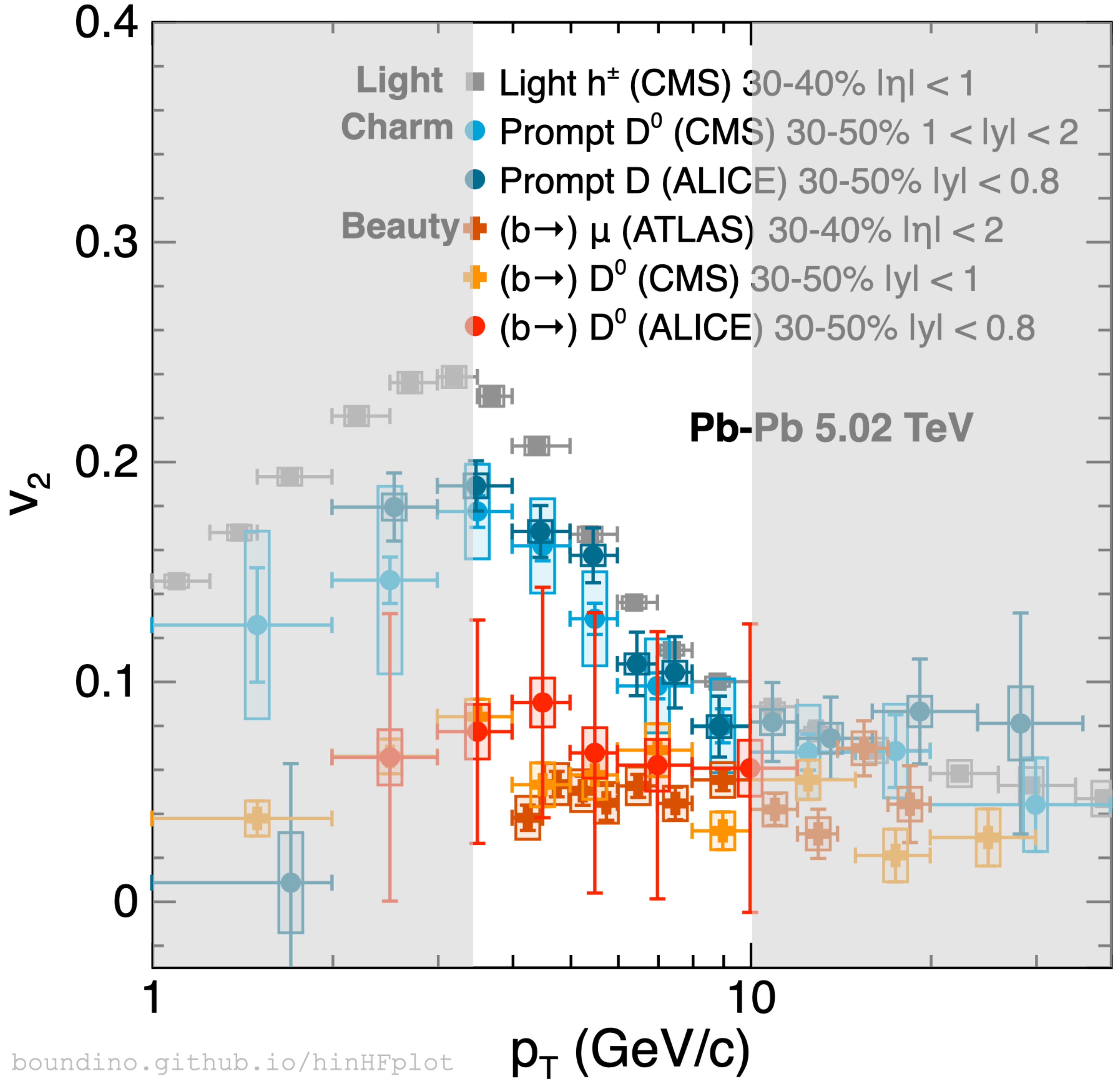

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3–4 < p_T < 10 GeV/c

➡ $R_{AA}(B) > R_{AA}(D) > R_{AA}(h^{\pm})$

➡ $v_2(B) < v_2(D) \approx v_2(h^{\pm})$

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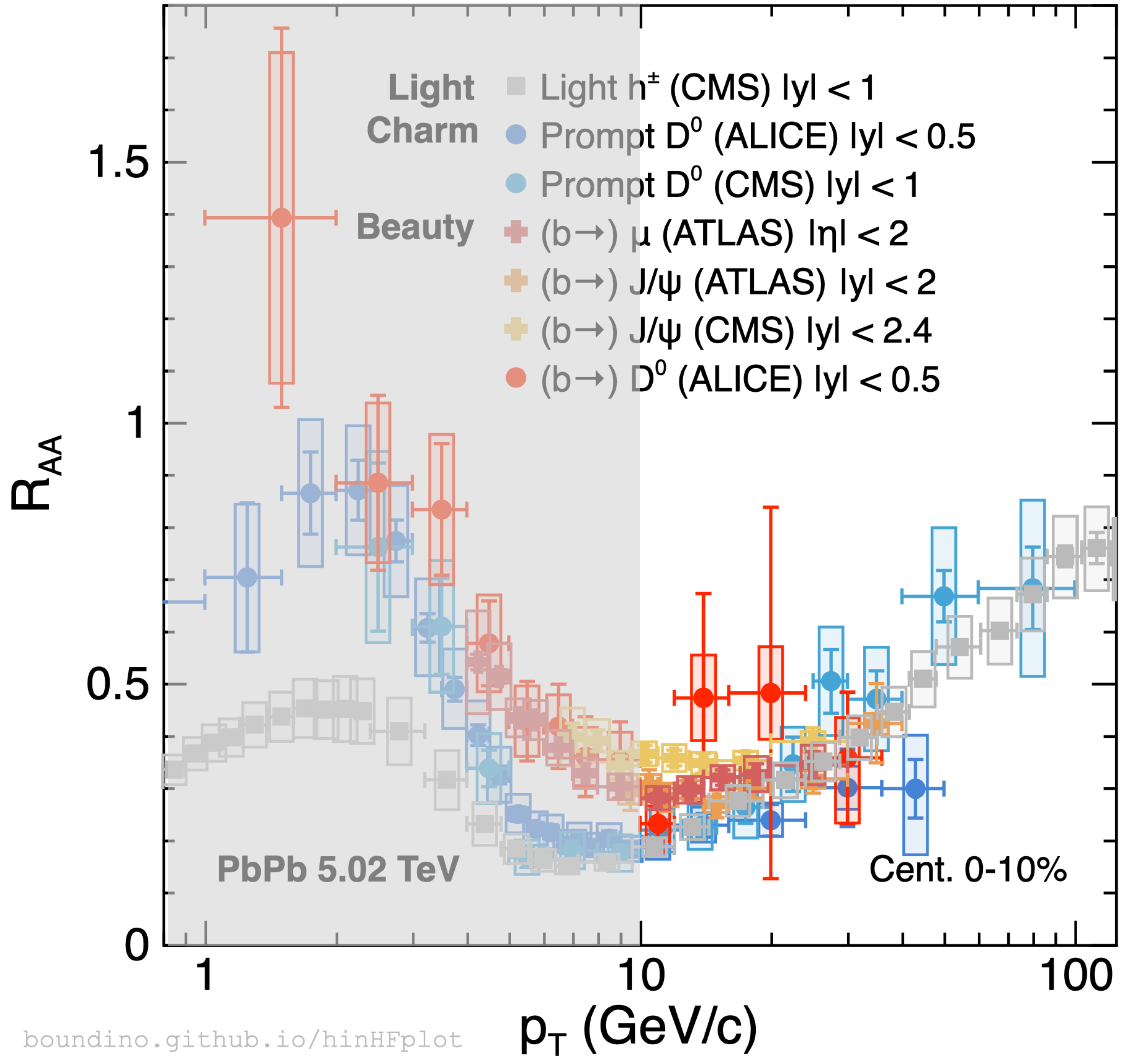

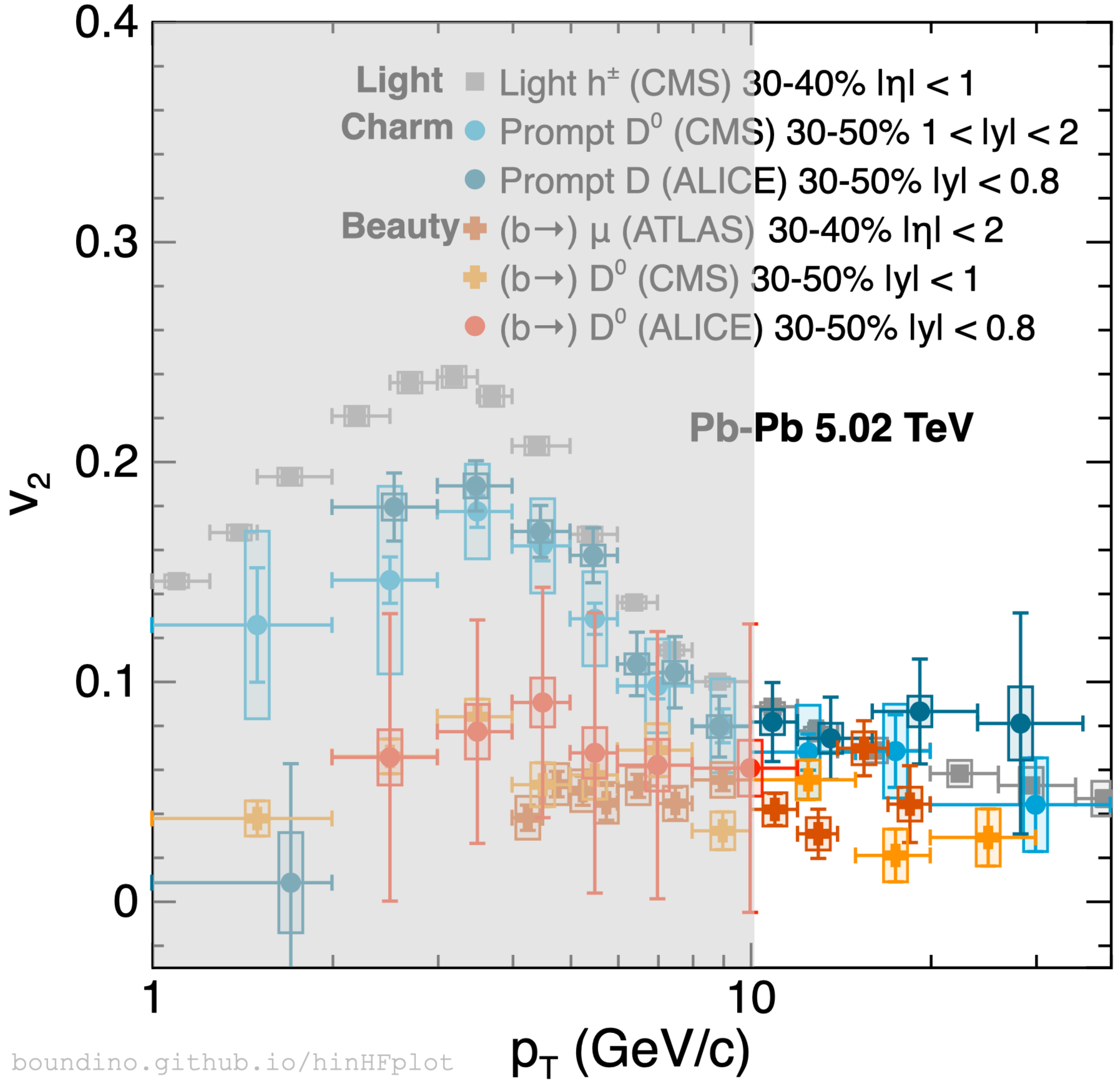

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3–4 < p_T < 10 GeV/*c*

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➡ $v_2(B) < v_2(D) \approx v_2(h^\pm)$

p_T > 10 GeV/*c*

➡ $R_{AA}(B) \gtrsim R_{AA}(D) \approx R_{AA}(h^\pm)$

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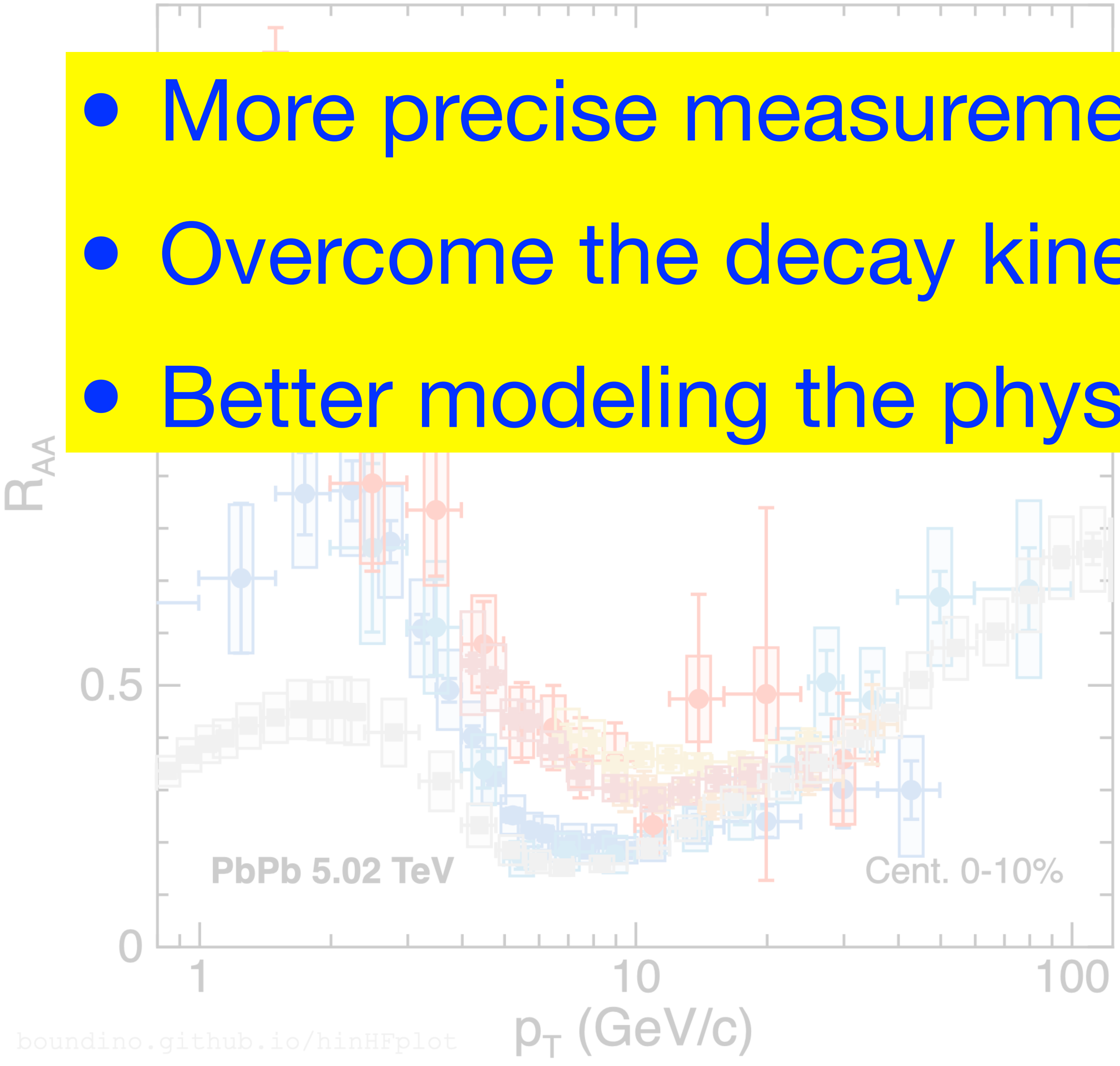
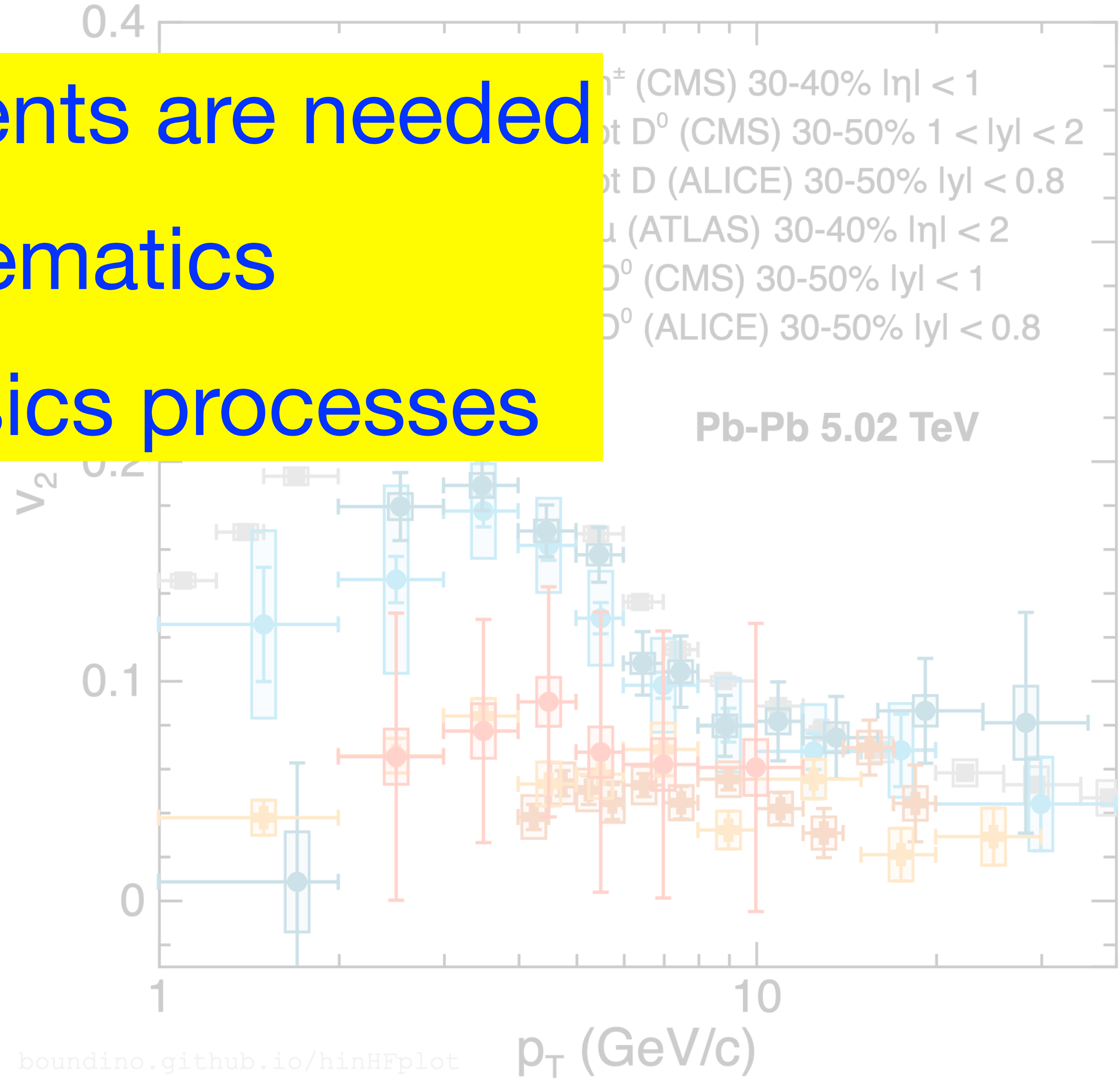
Beauty particle transport

- More precise measurements are needed
- Overcome the decay kinematics
- Better modeling the physics processes





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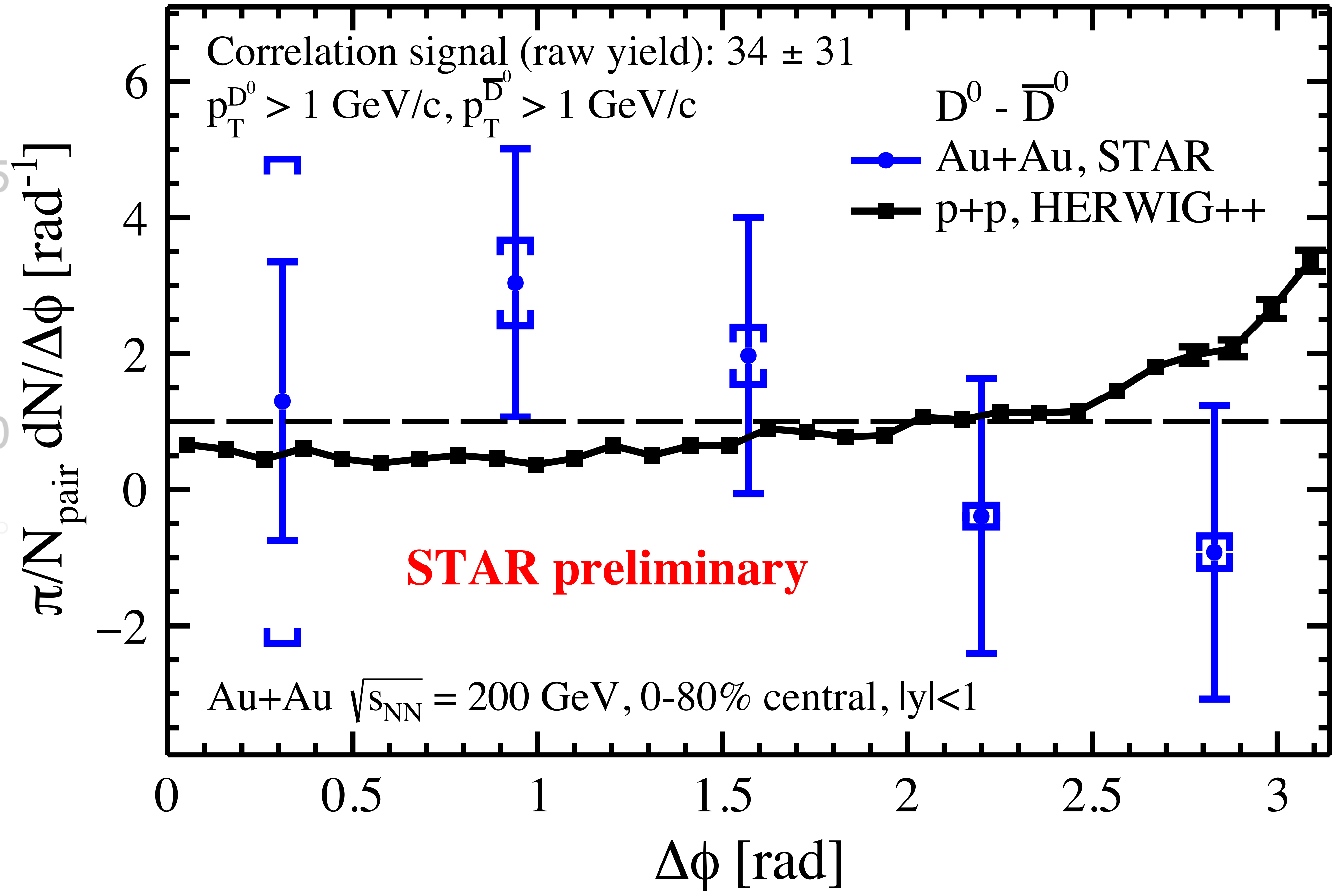
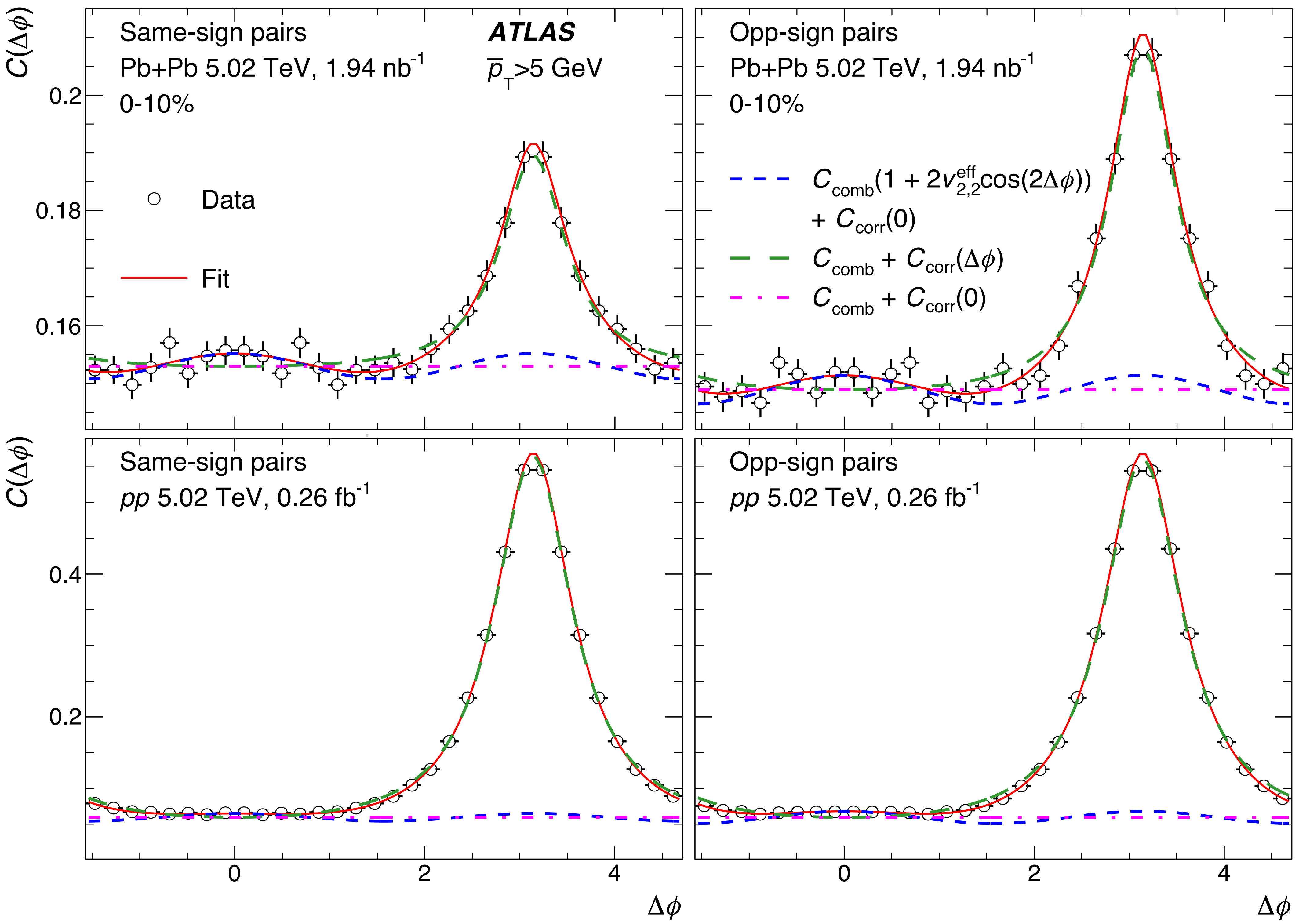


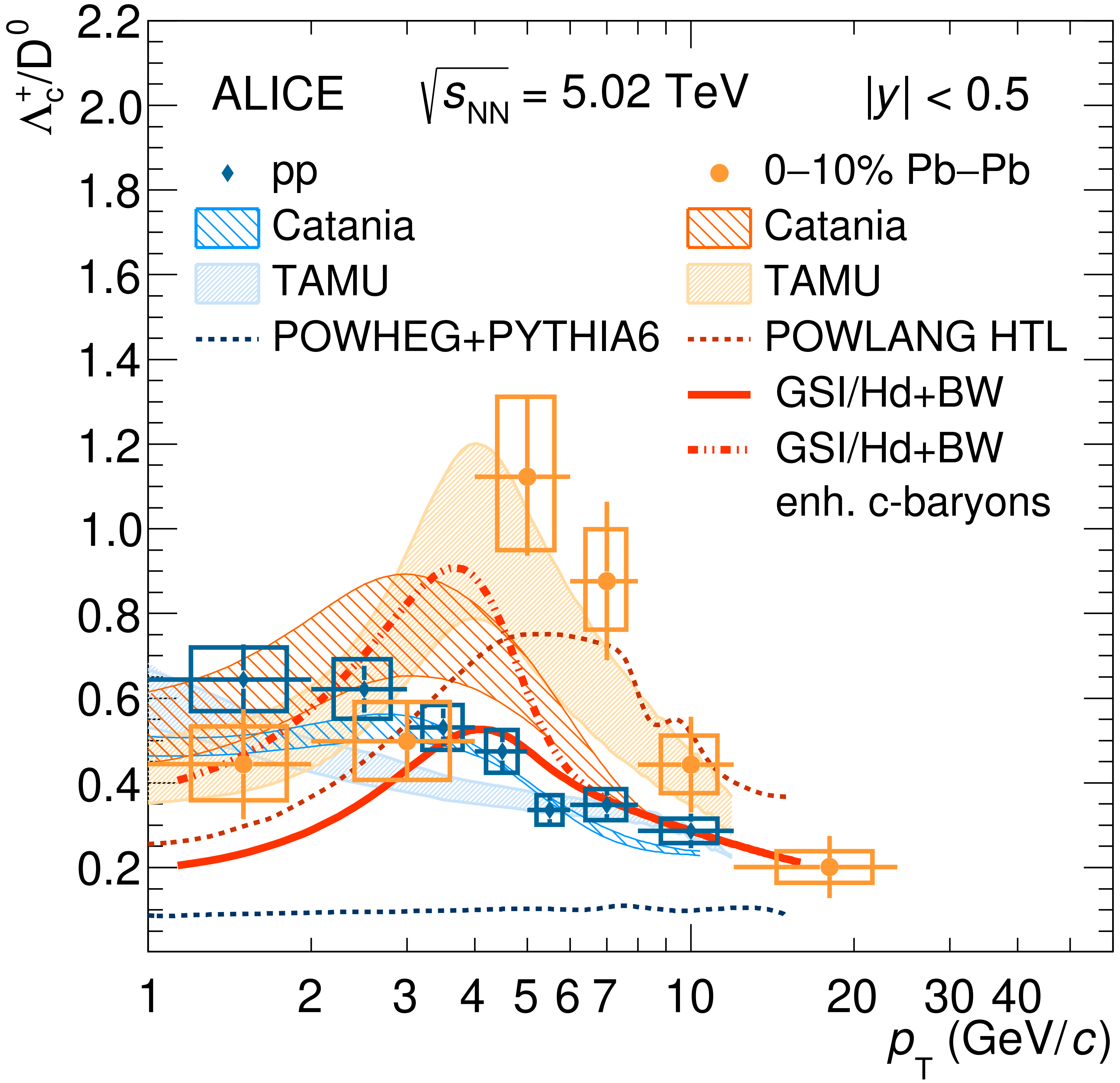


ATLAS *Phys. Rev. Lett.* 132 (2024) 202301

HF correlations may shed light on interaction dynamics

X. Zhu, *et al.*, *Phys. Lett.* **B647** (2007) 366

Constrain on hadronizaton?



ALICE *Phys. Lett.* **B846** (2023) 137561
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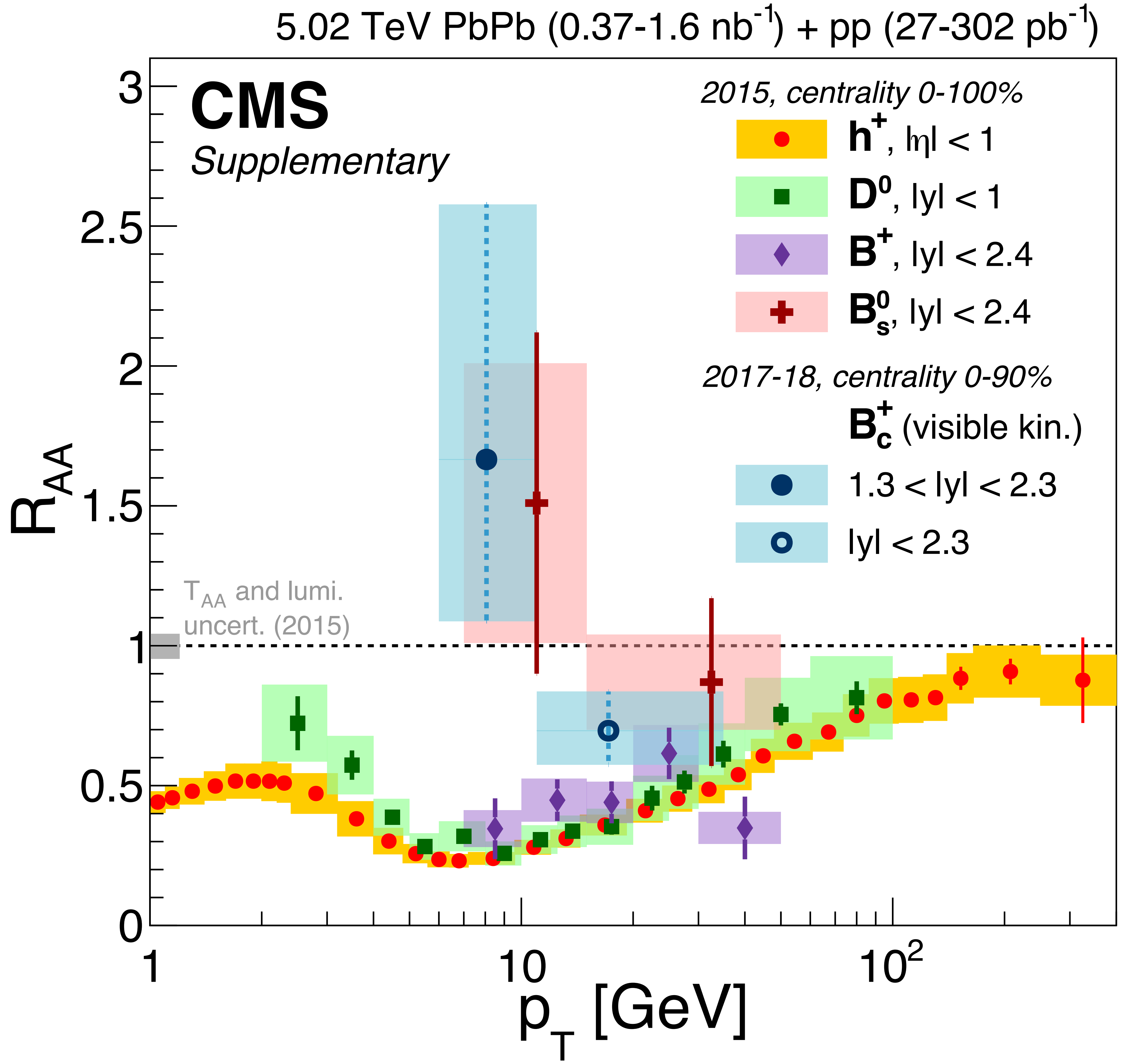
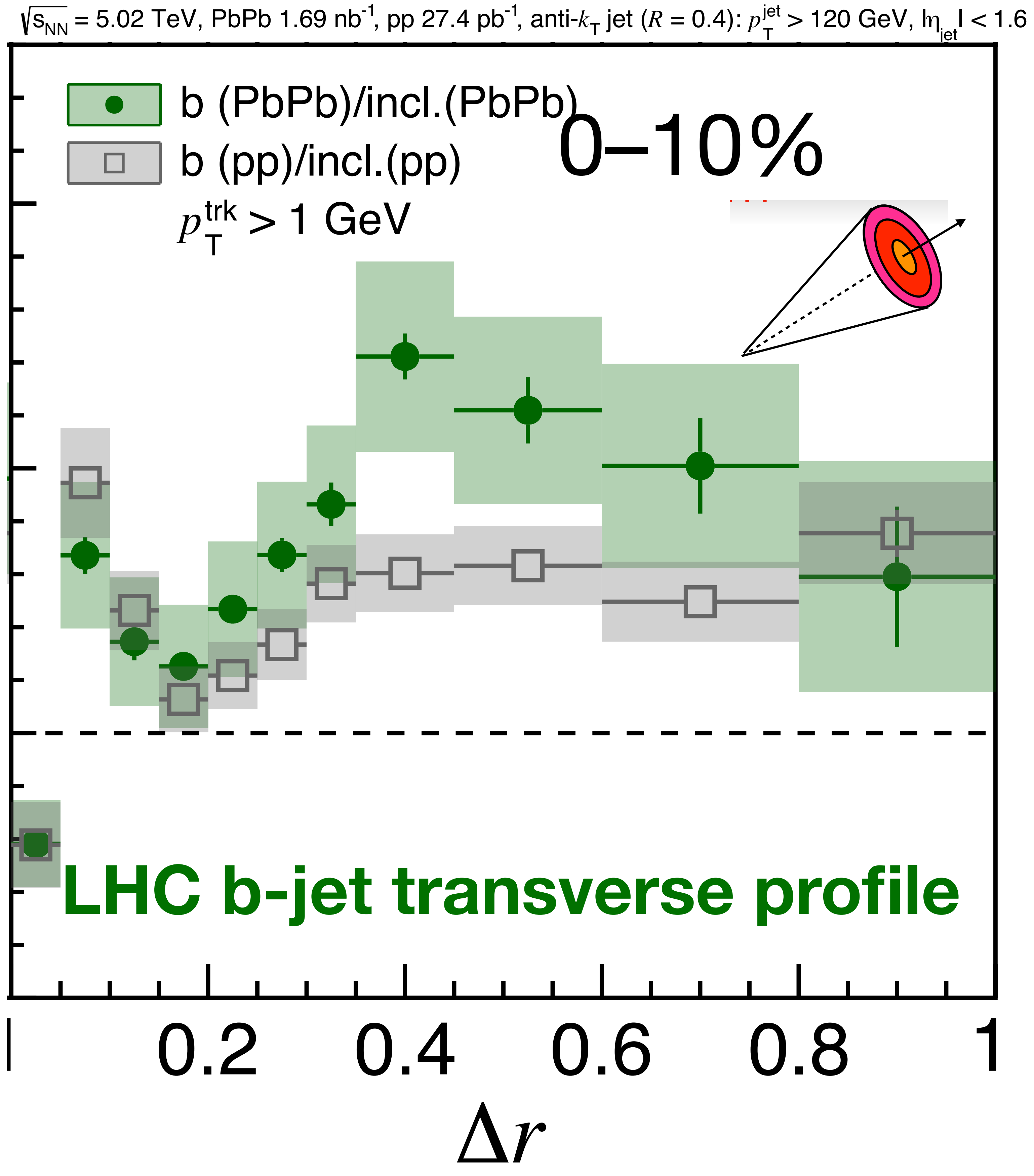
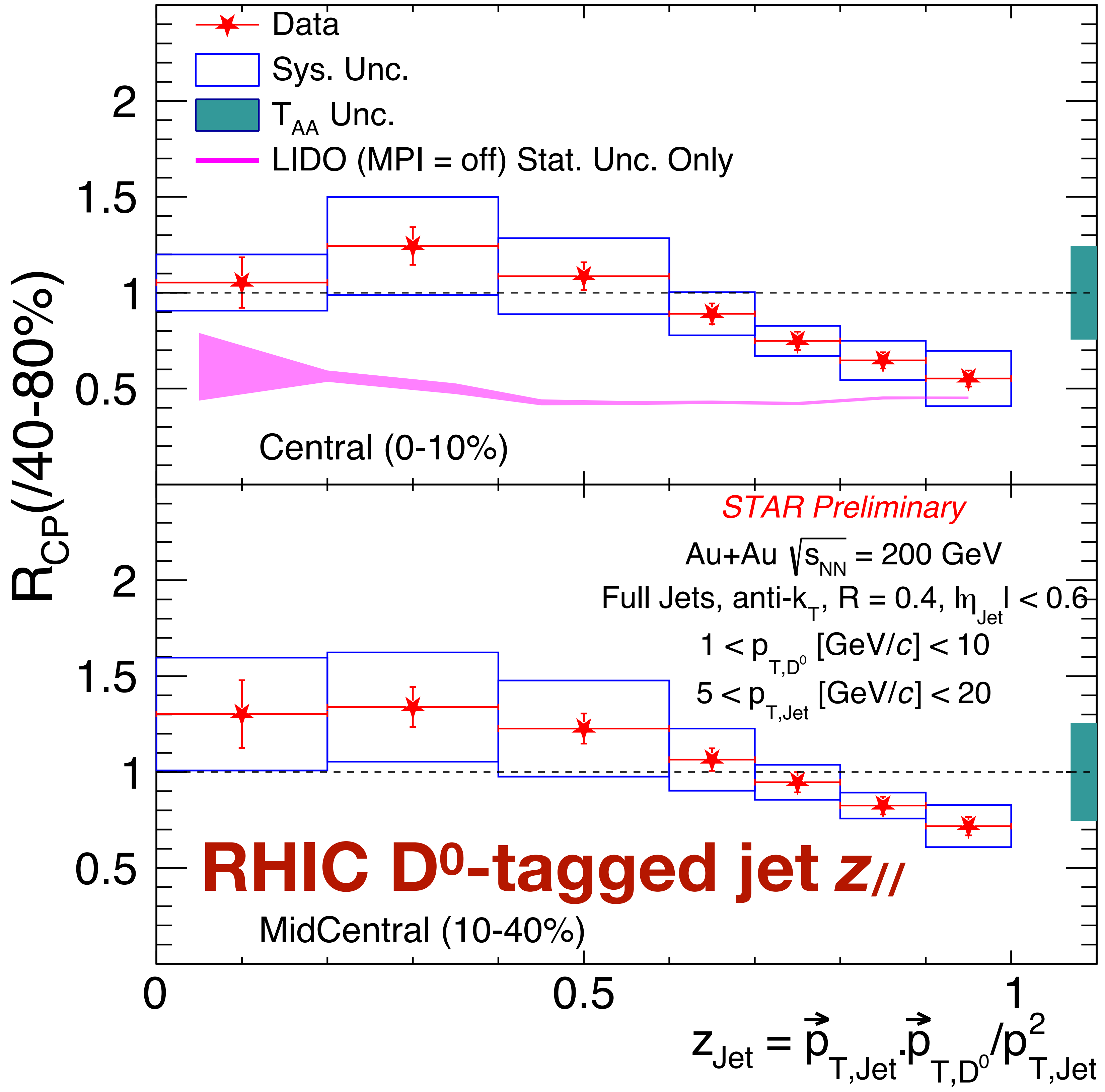


CMS CMS-PAS-HIN-21-014
CMS *JHEP* **2401** (2024) 128
CMS *Phys. Rev. Lett.* **128** (2022) 252301

Interplay between hadronization and energy loss — higher precision is needed

HF jet structure



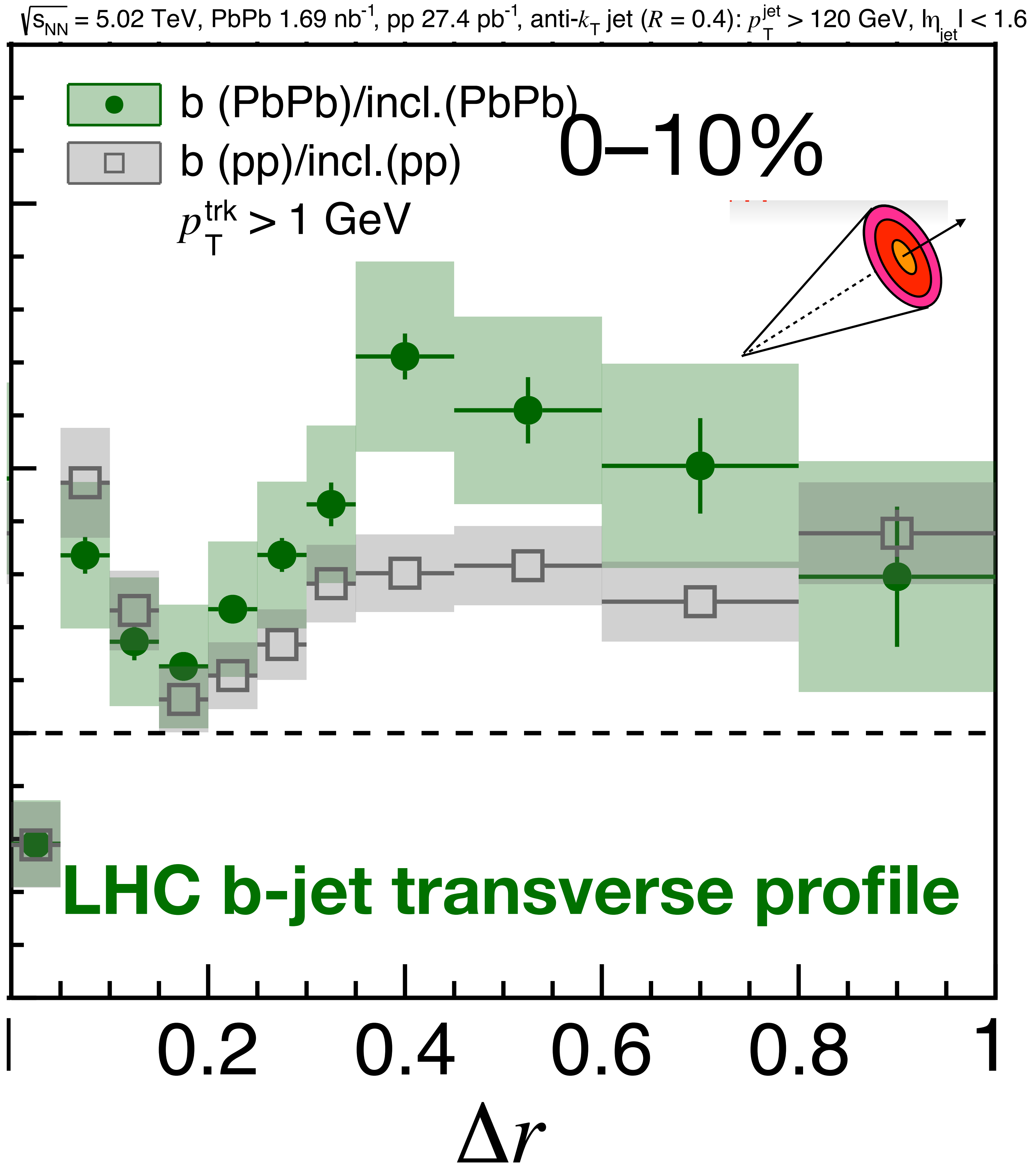


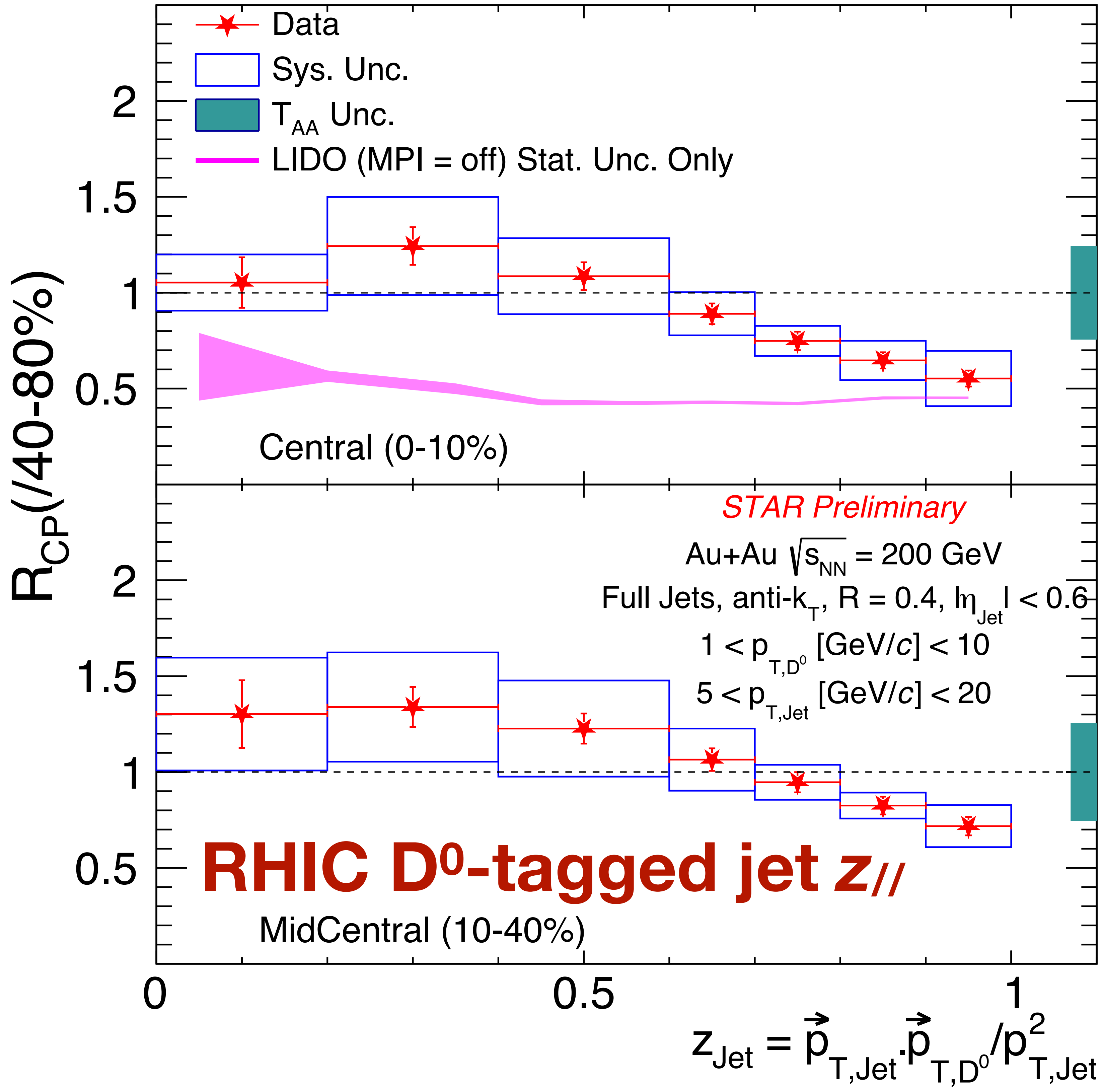
ATLAS *Eur. Phys. J.* **C83** (2023) 438
CMS *Phys. Lett.* **B844** (2023) 137849

LHC: Jet core stays intact, transverse profile broadening of b-jets

RHIC: Quenched core for D^0-tagged jets

HF jet structure



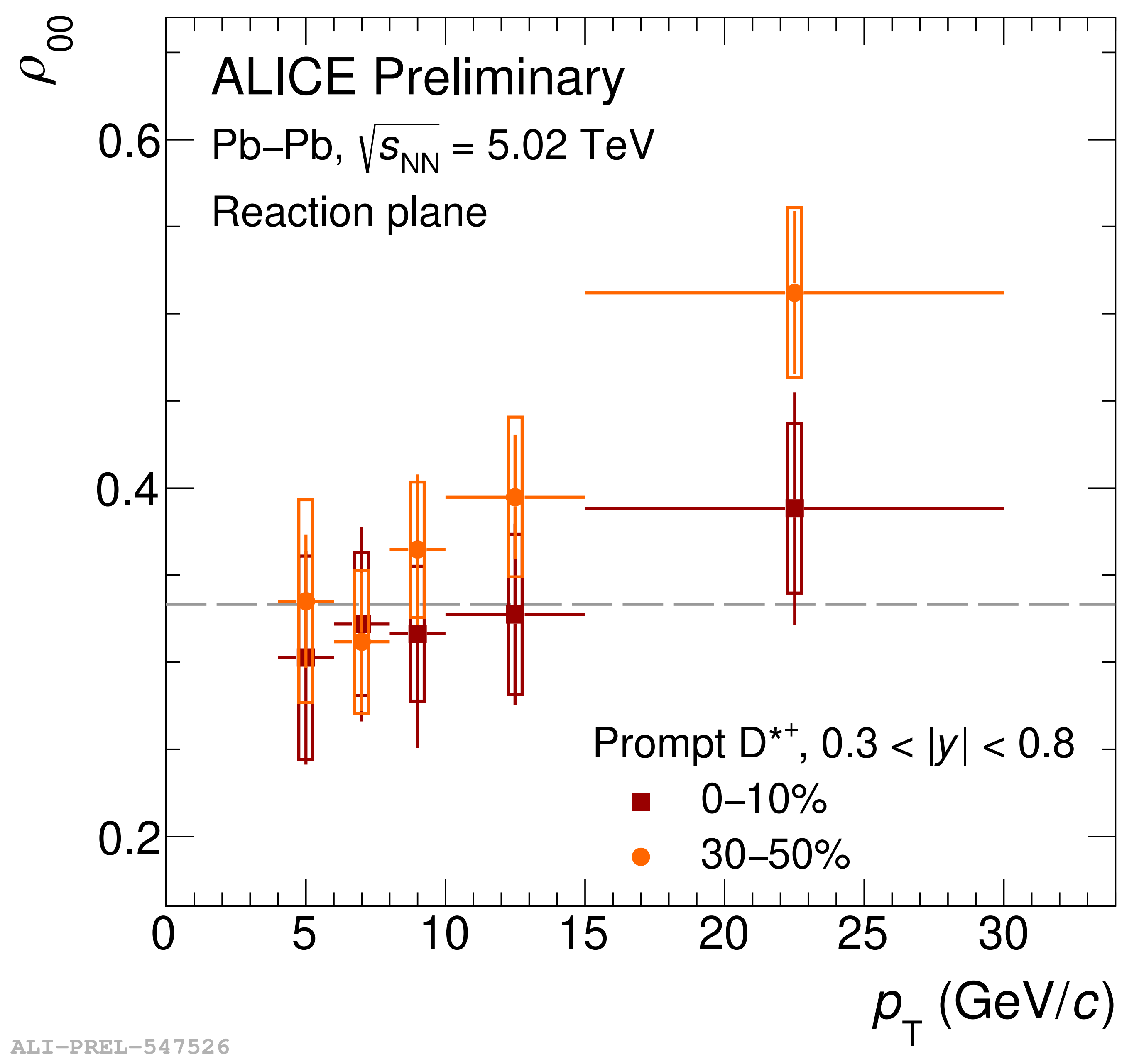


LHC: ... sverse

Open question: Is it possible to observe dead-cone effect directly in heavy-ion collisions?

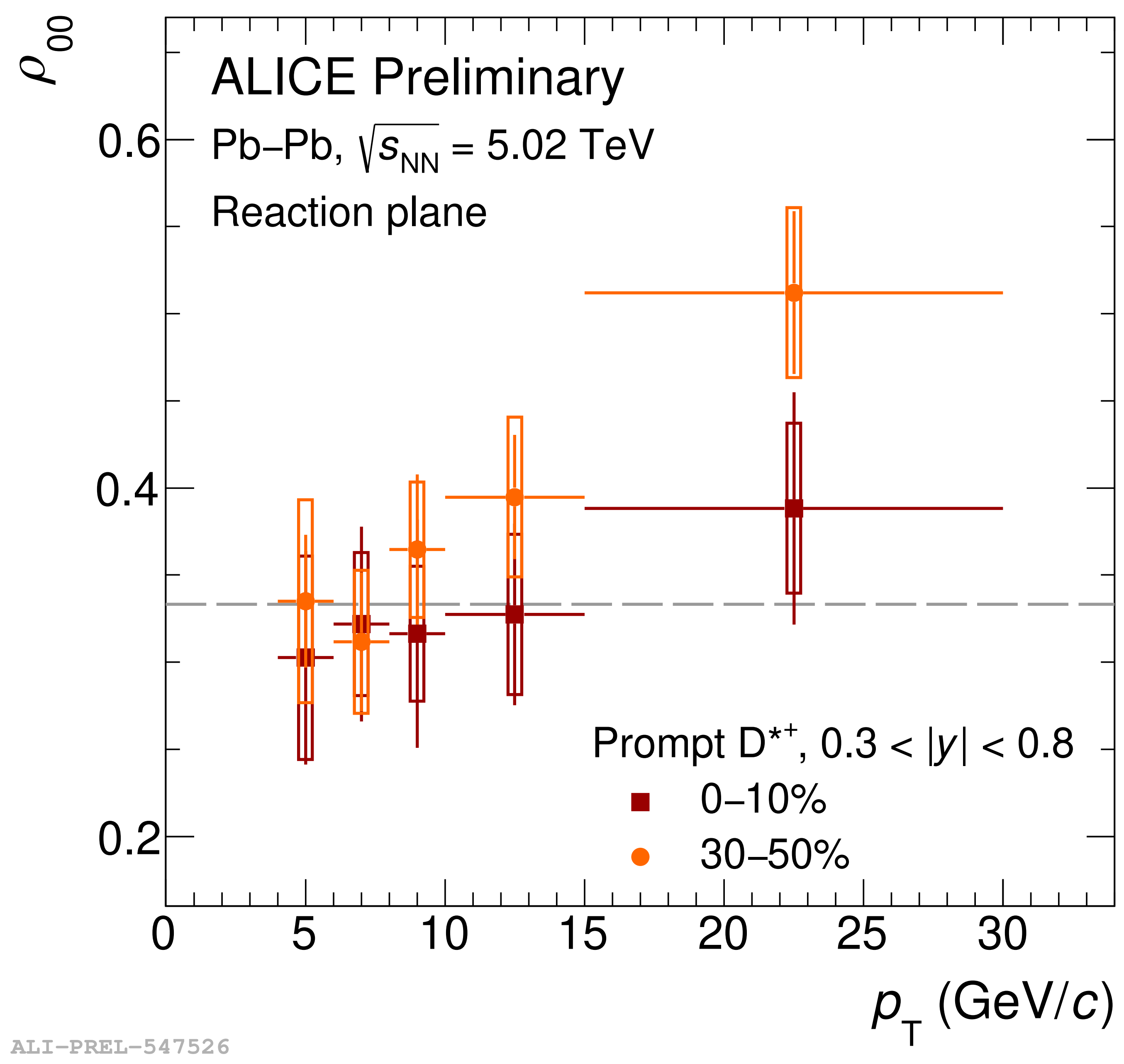
RHIC: Quenched core for D^0-tagged jets

More open questions…



How to understand the HF spin alignment in HIC?

More open questions…



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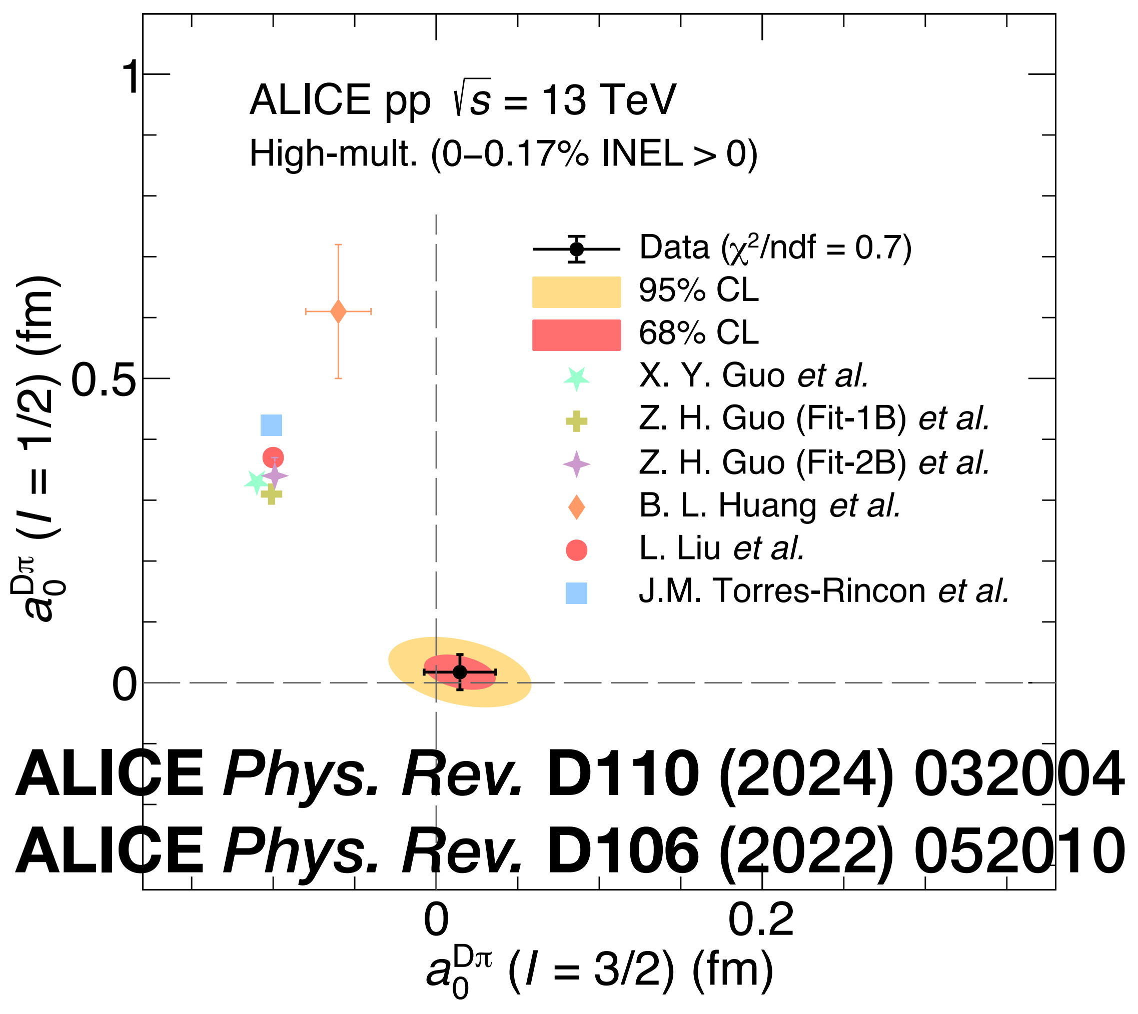
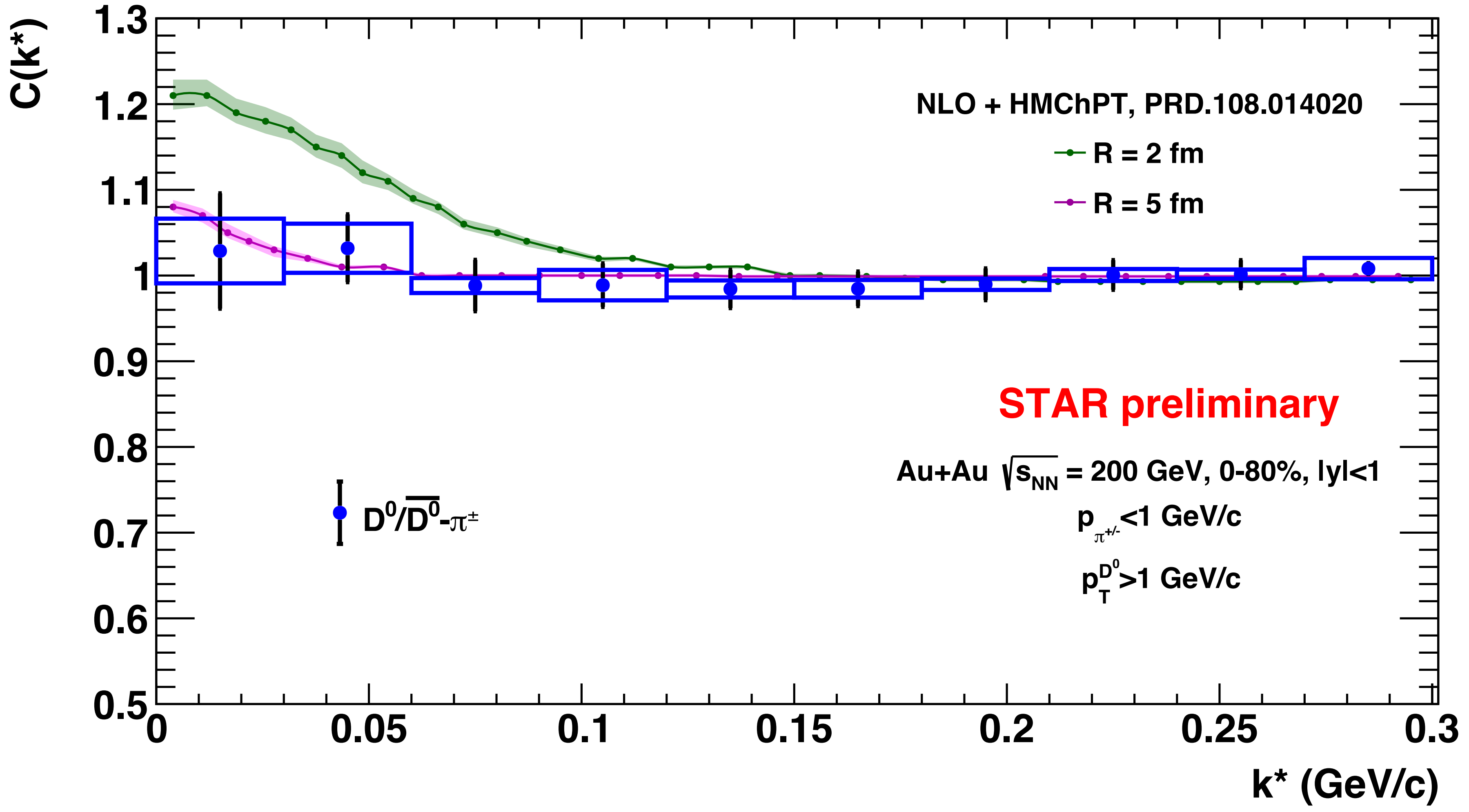
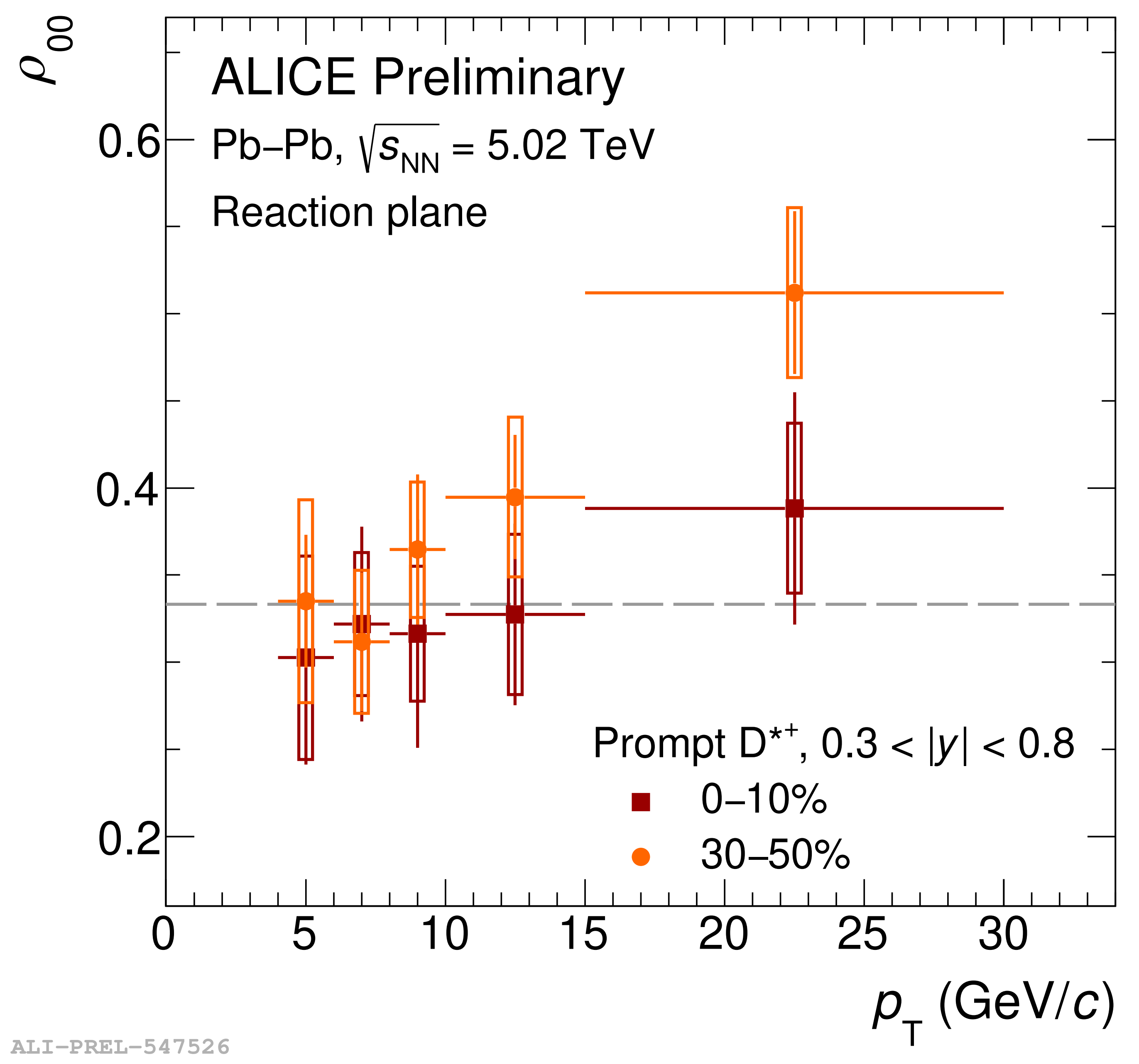


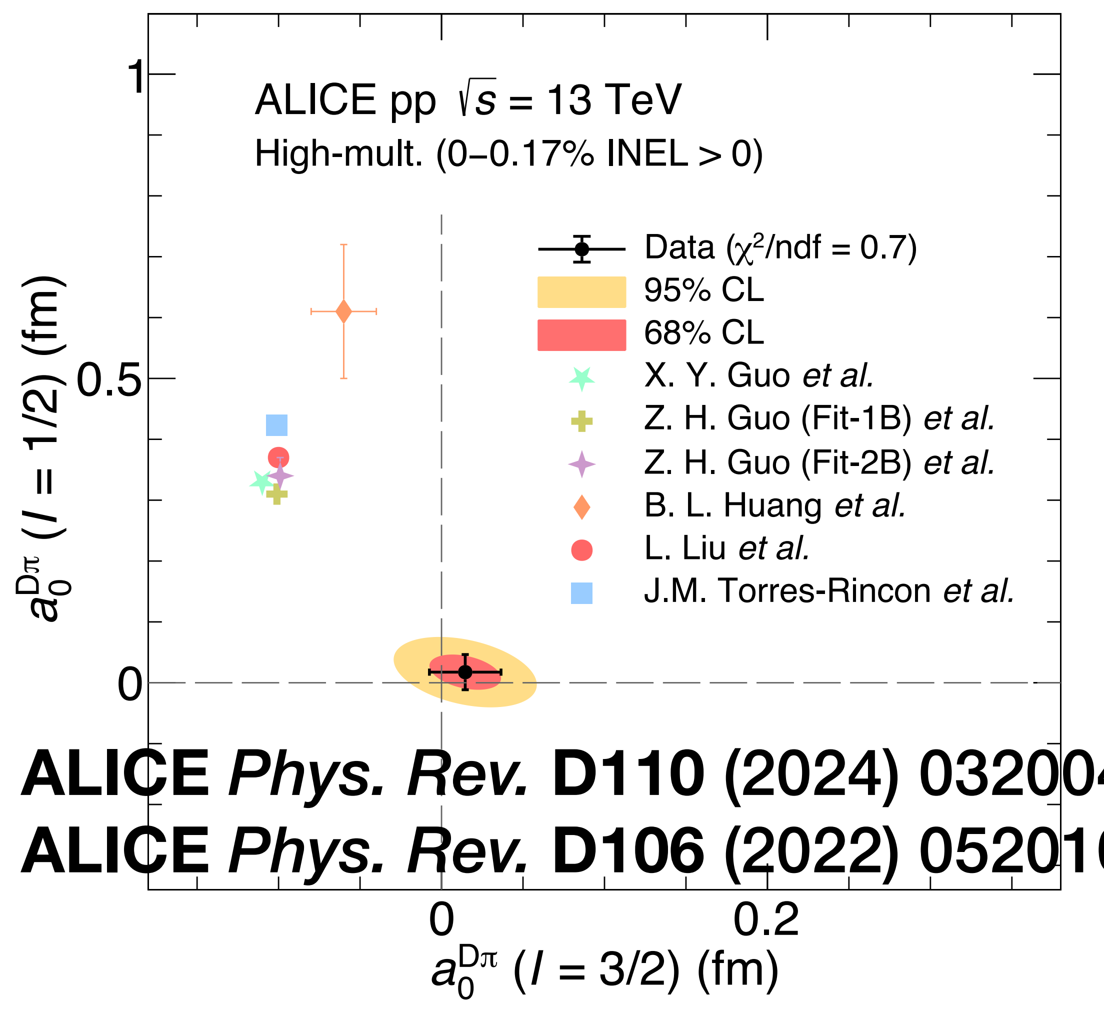
ALICE *Phys. Rev.* D110 (2024) 032004
ALICE *Phys. Rev.* D106 (2022) 052010



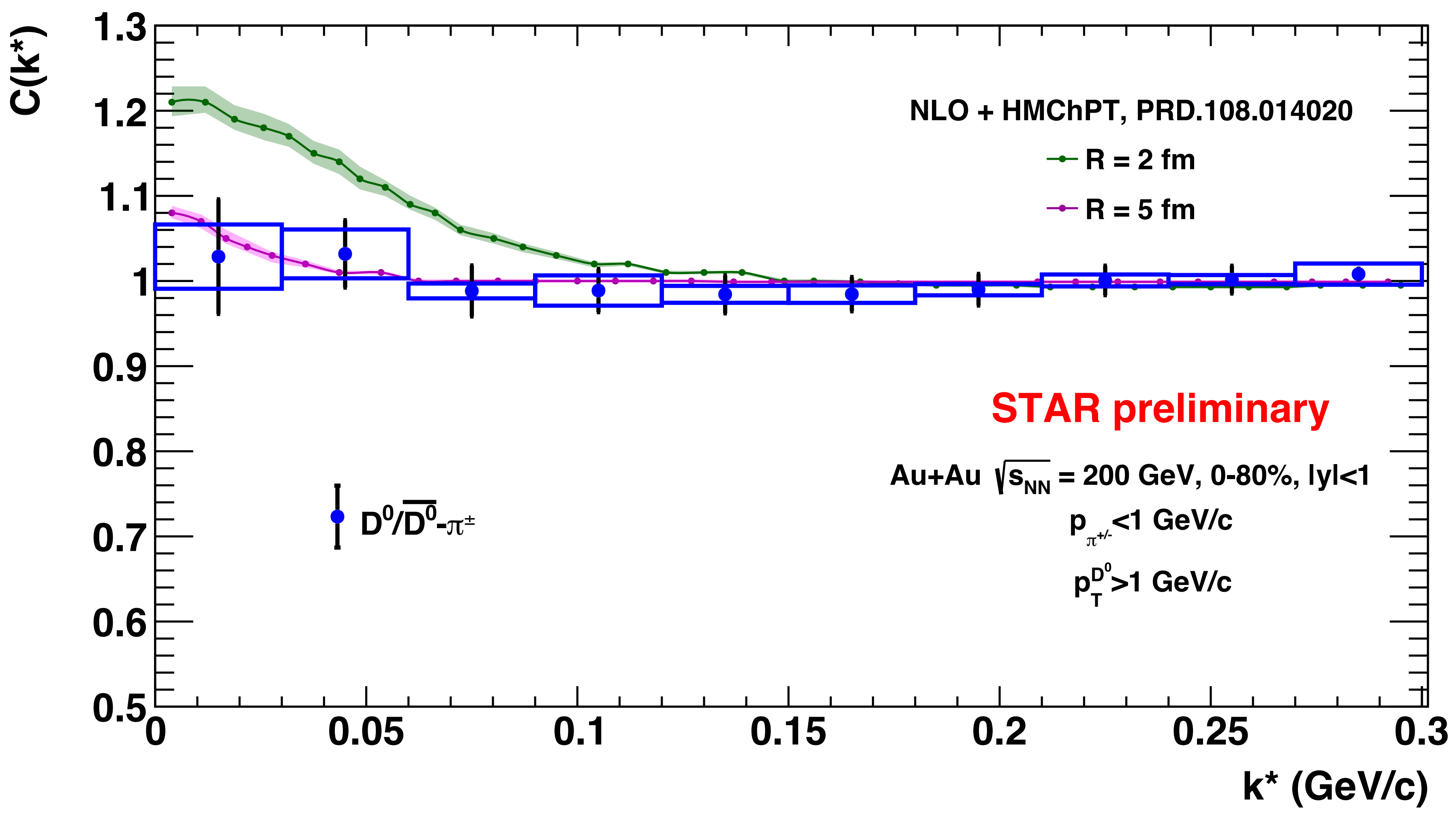
Is there strong nuclear force between D and light hadrons?

More open questions…





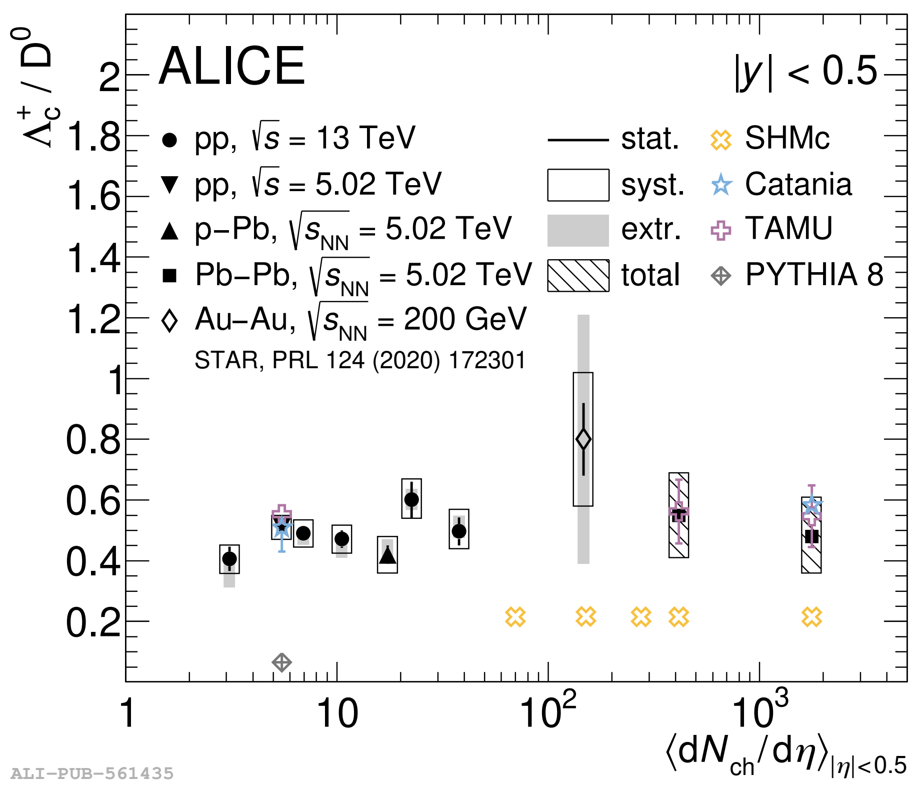
ALICE *Phys. Rev.* D110 (2024) 032004
ALICE *Phys. Rev.* D106 (2022) 052010

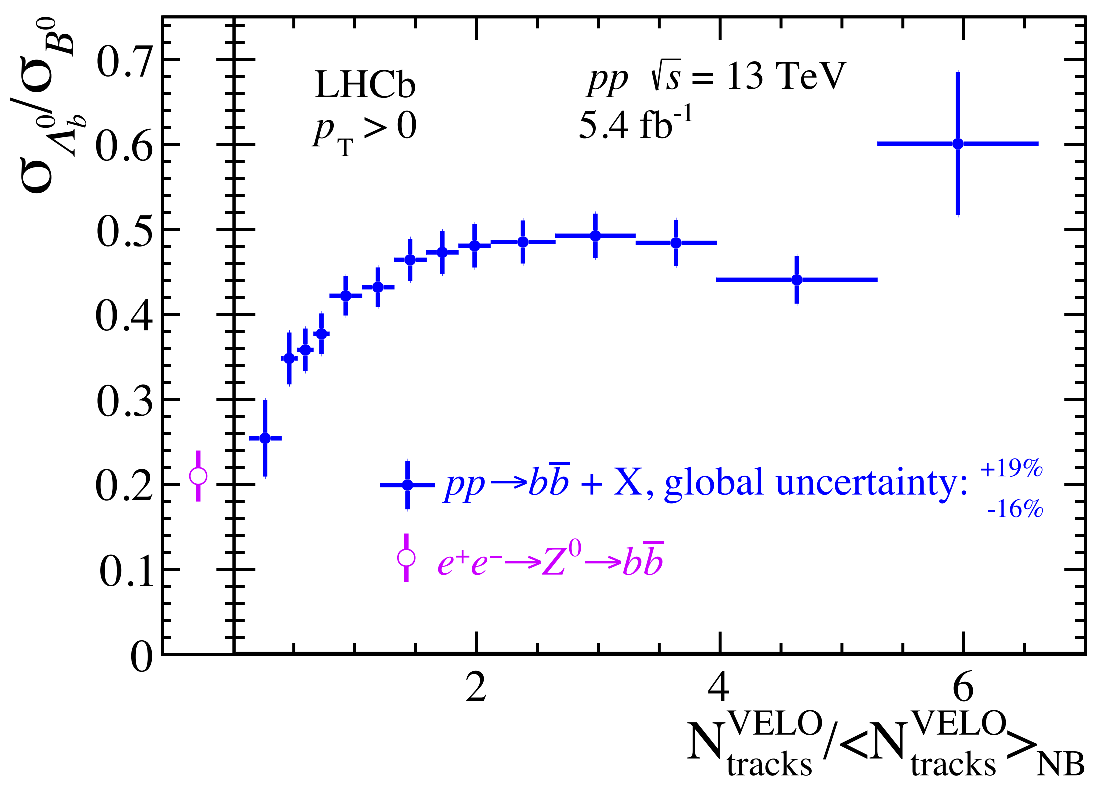


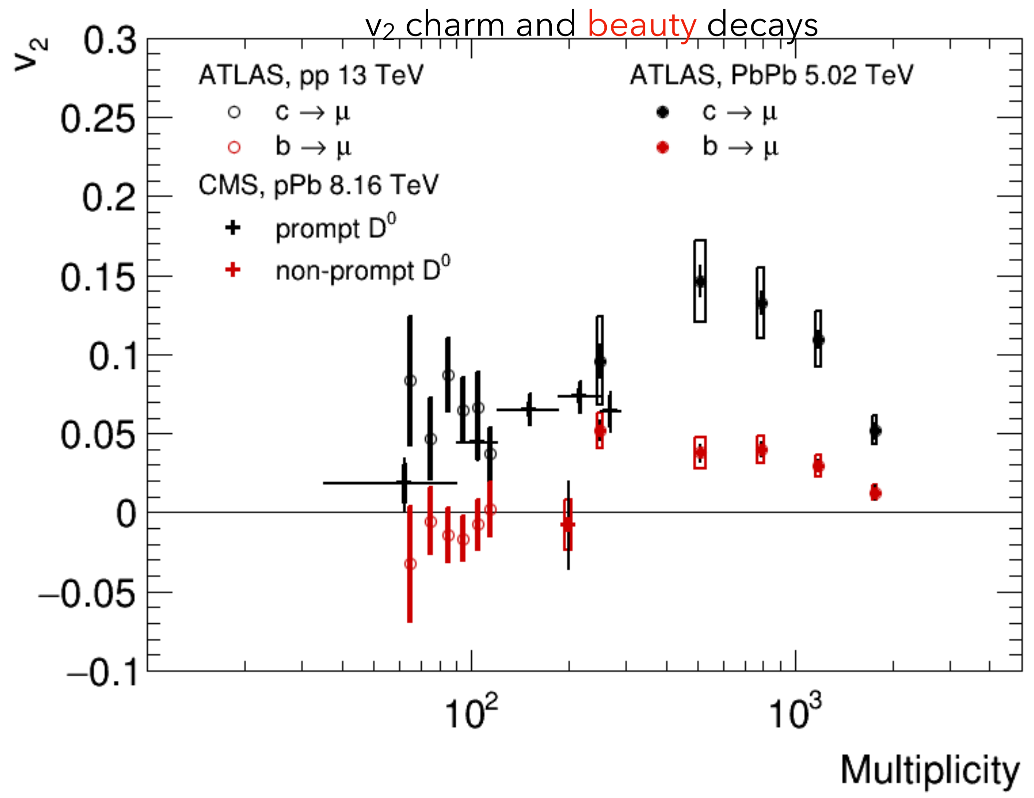
Is there strong nuclear force between D and light hadrons?

How to understand the HF spin alignment in HIC?

How to understand the similarity cross systems?



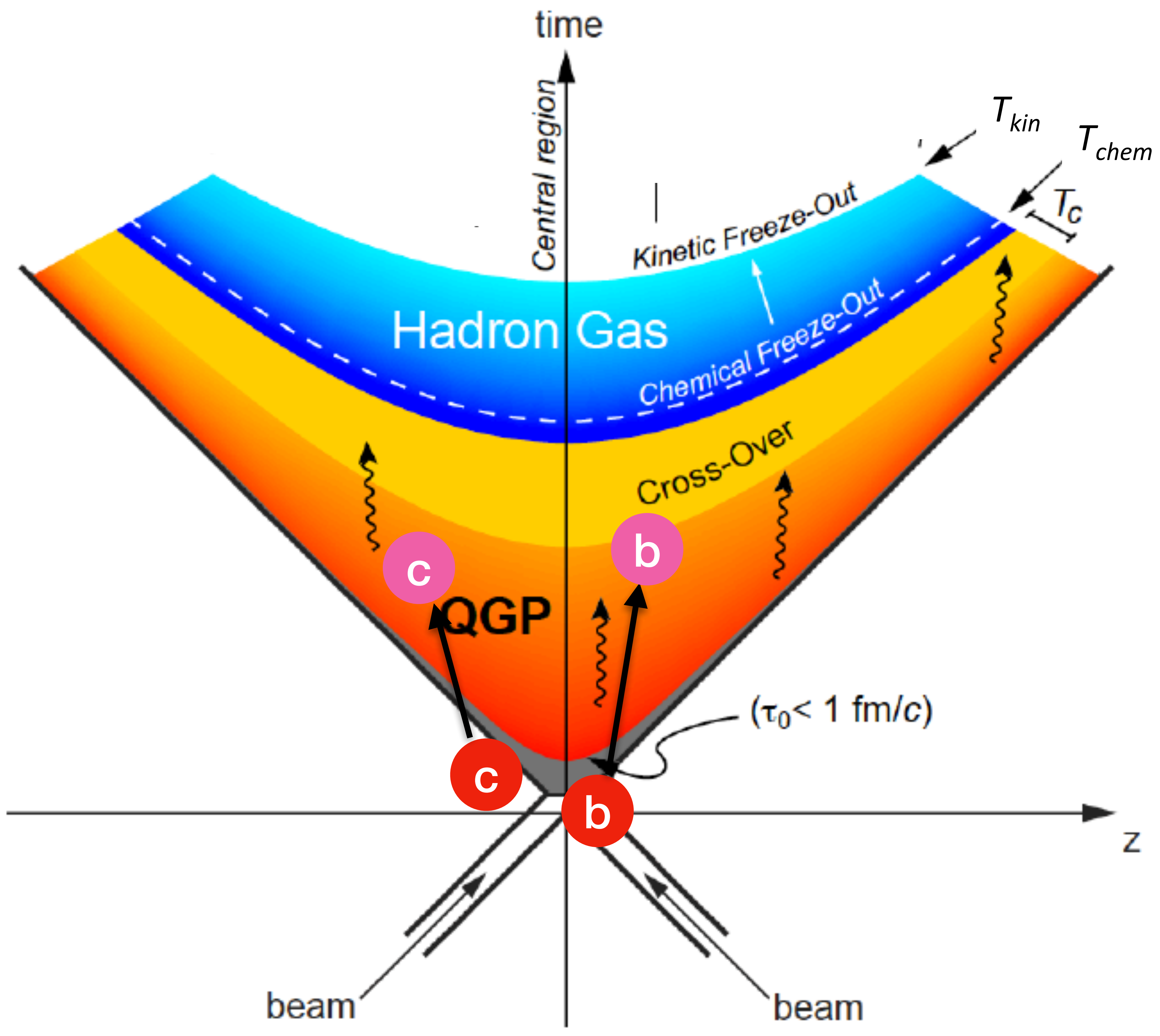




Backup

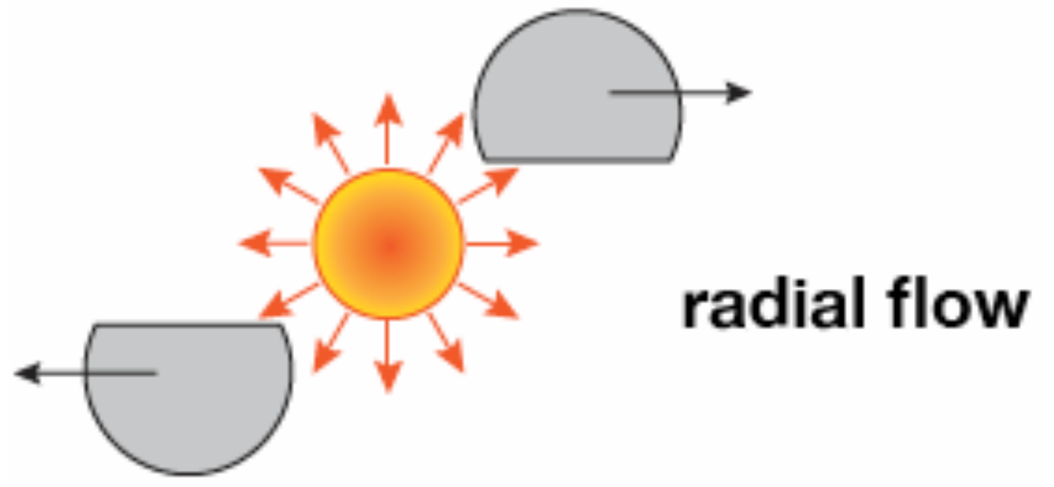
Heavy quarks: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation



Collective expansion

- ➡ Radial flow



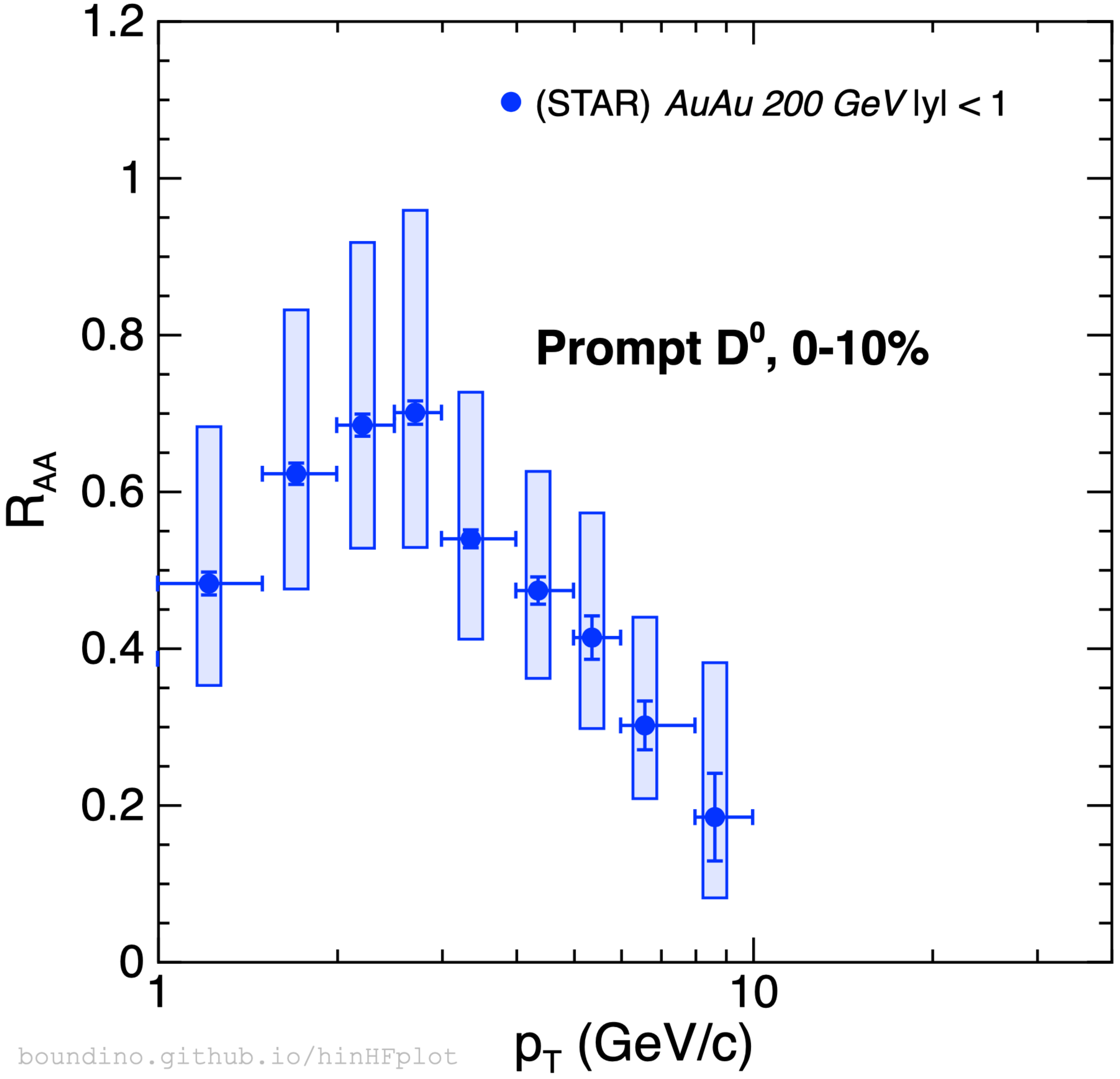
- ➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

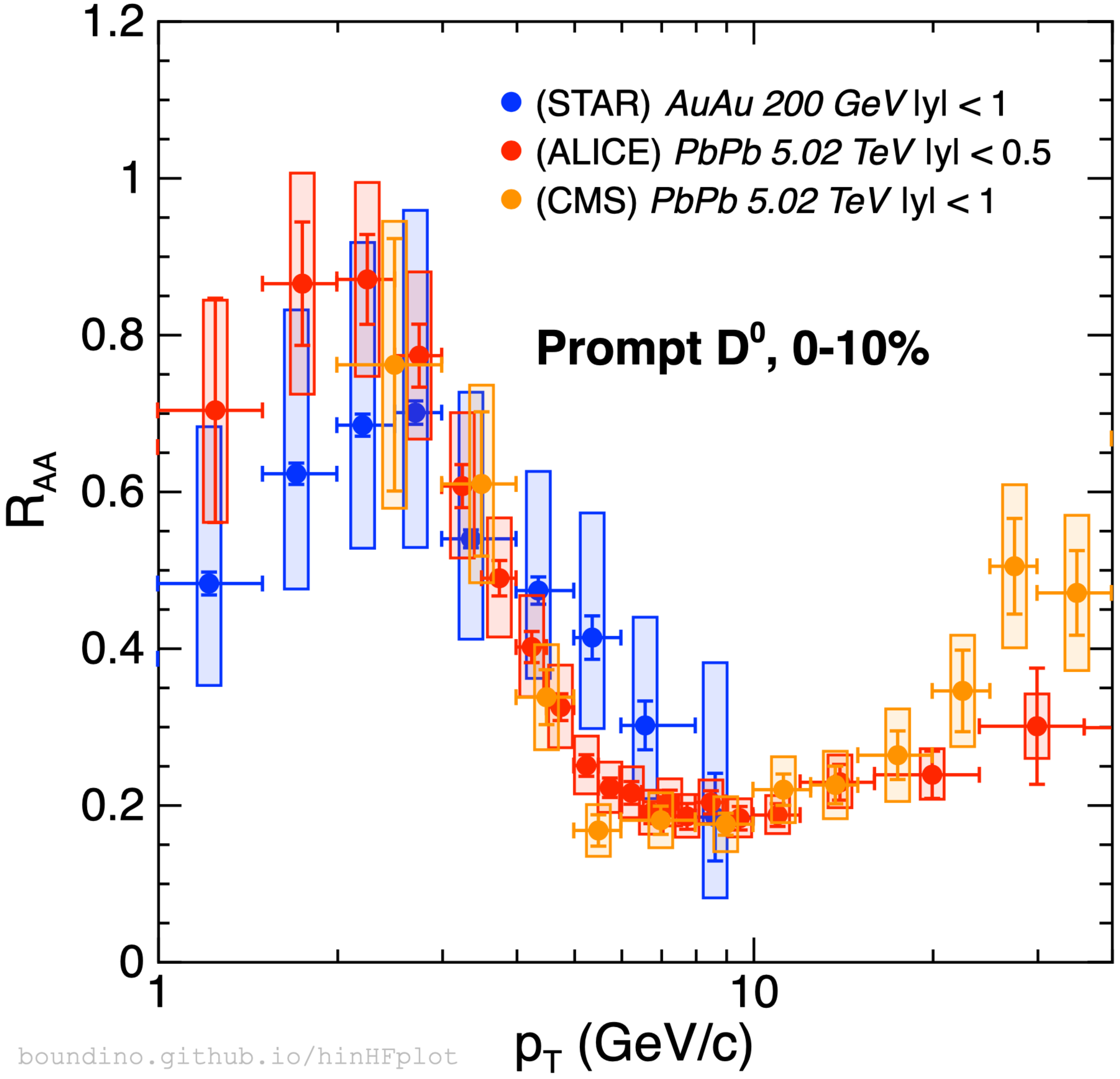
p_0: initial momentum
β: flow velocity
m: particle mass

- ➡ More pronounced in central collisions
- ➡ Mass dependence

R_{AA} of prompt D mesons

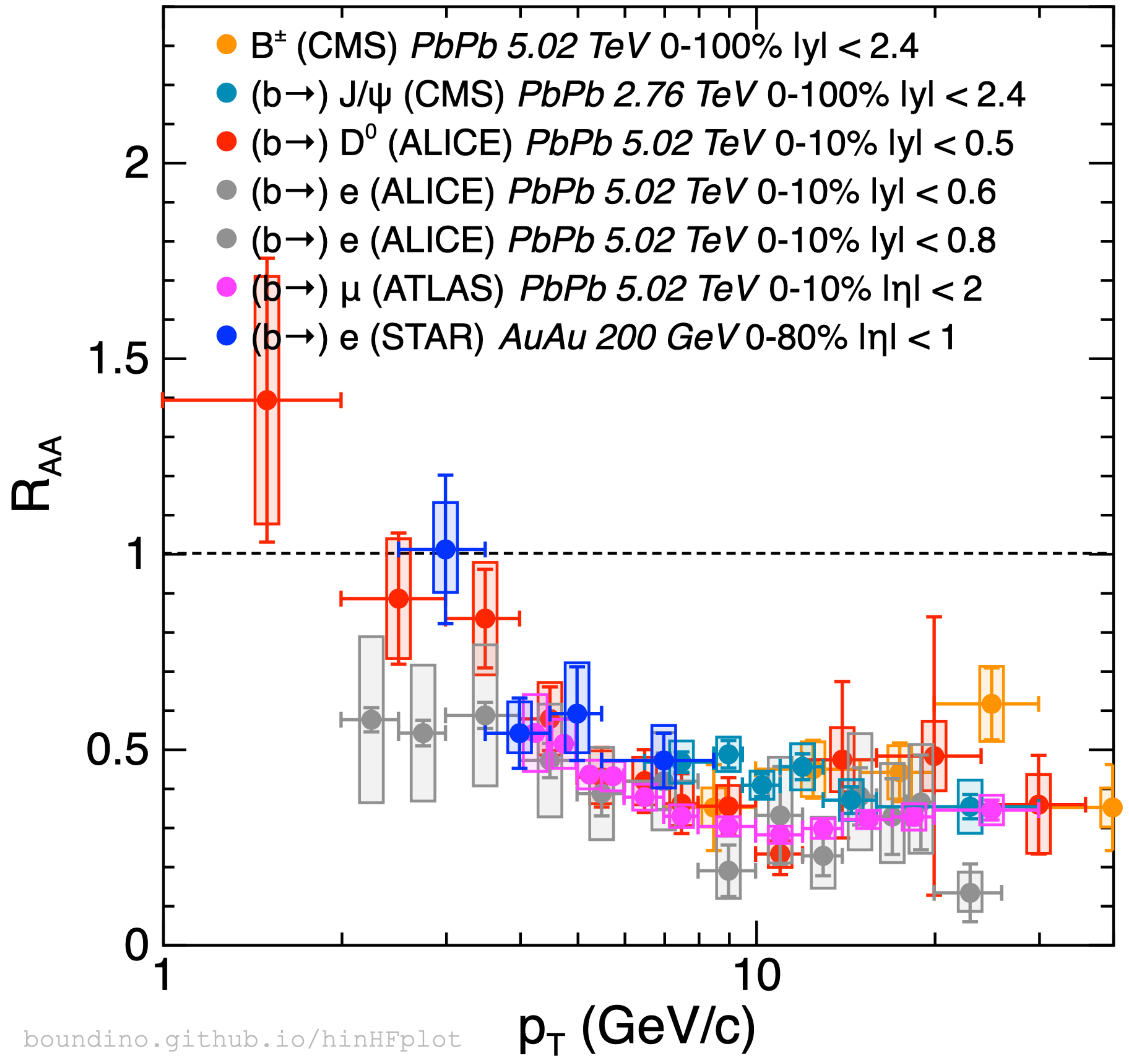


STAR PRC 99 (2019) 034908

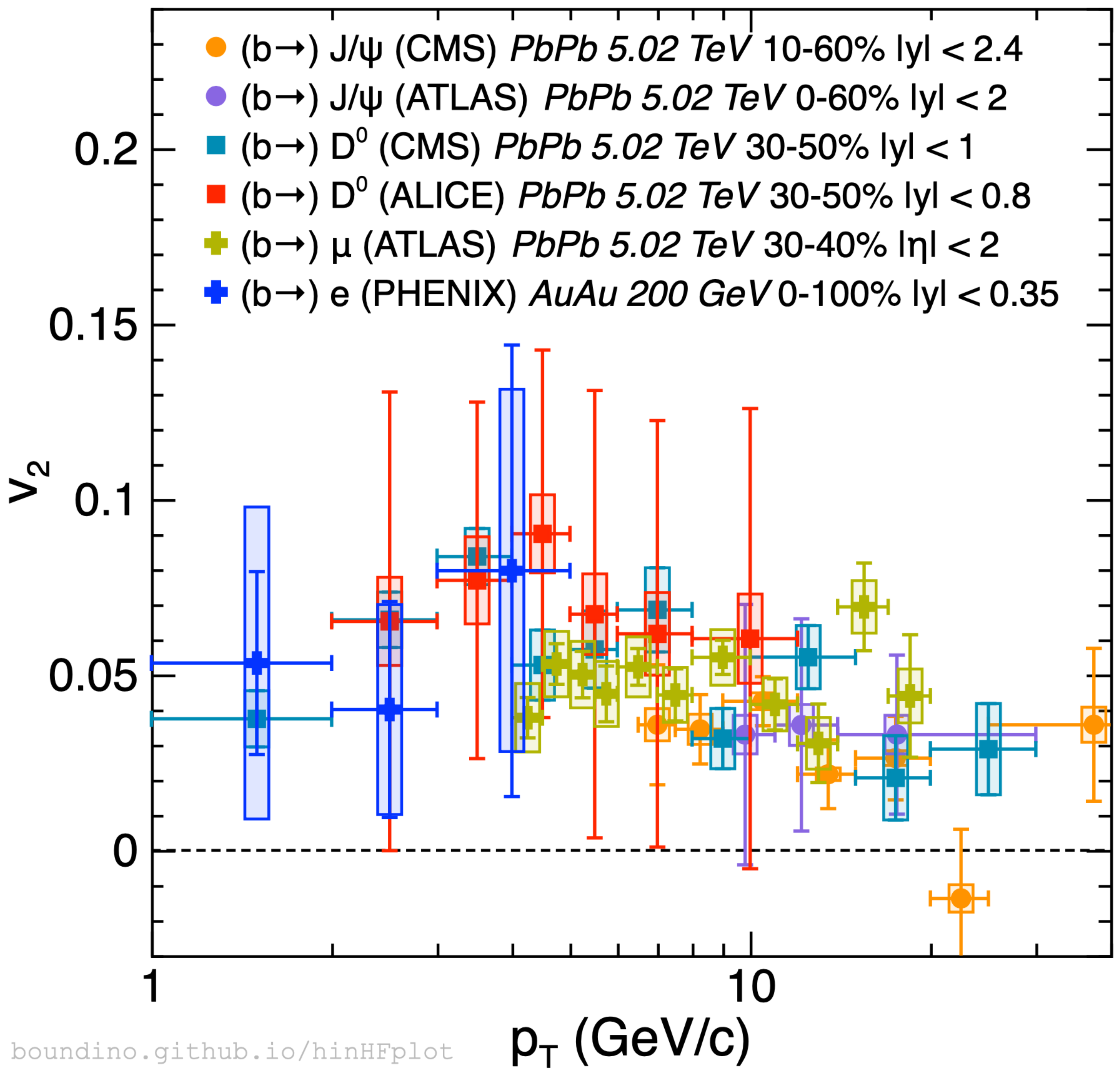


ALICE JHEP 01 (2022) 174
CMS PLB 782 (2018) 474

R_{AA} and v_2 of beauty particles

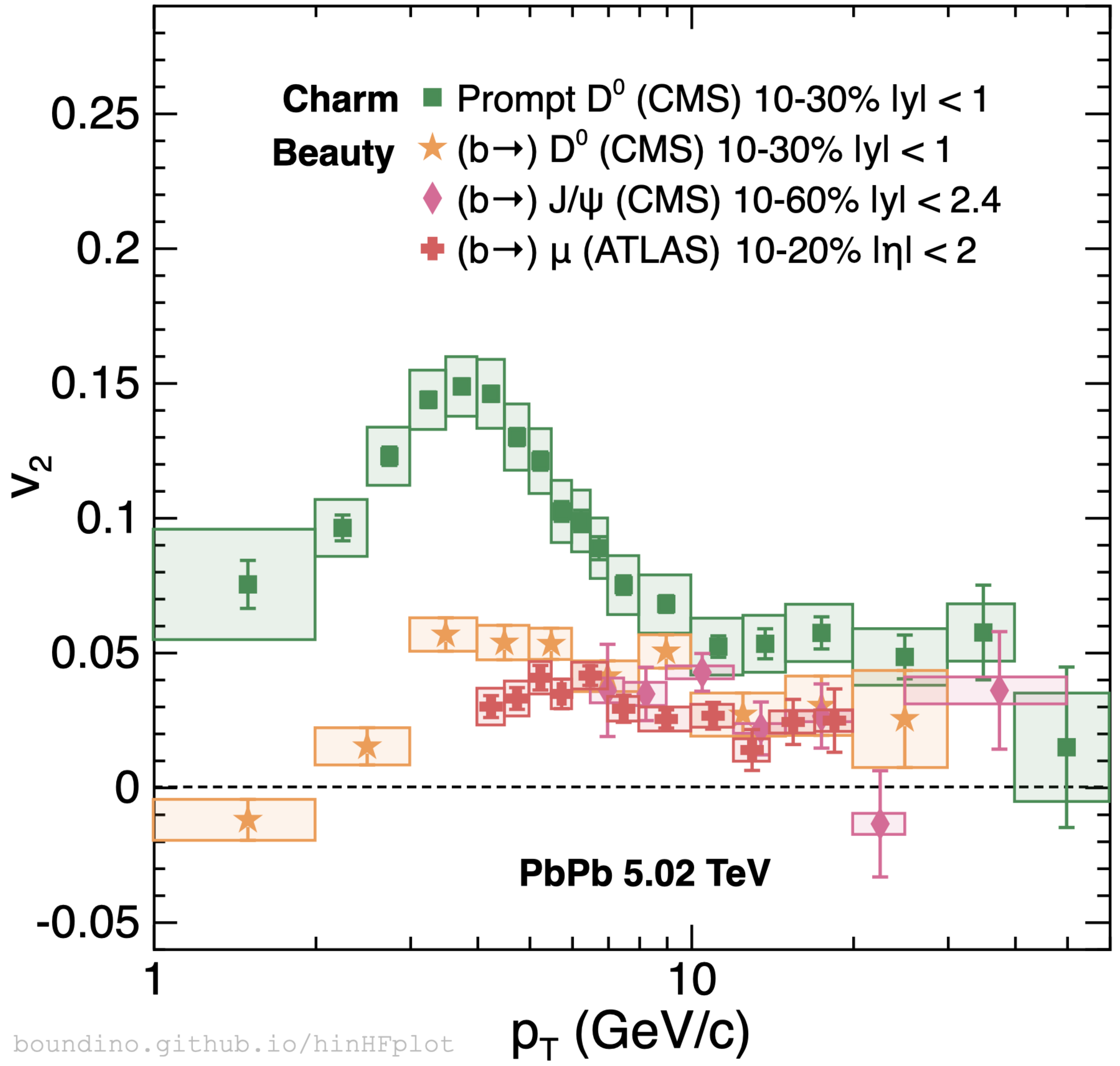


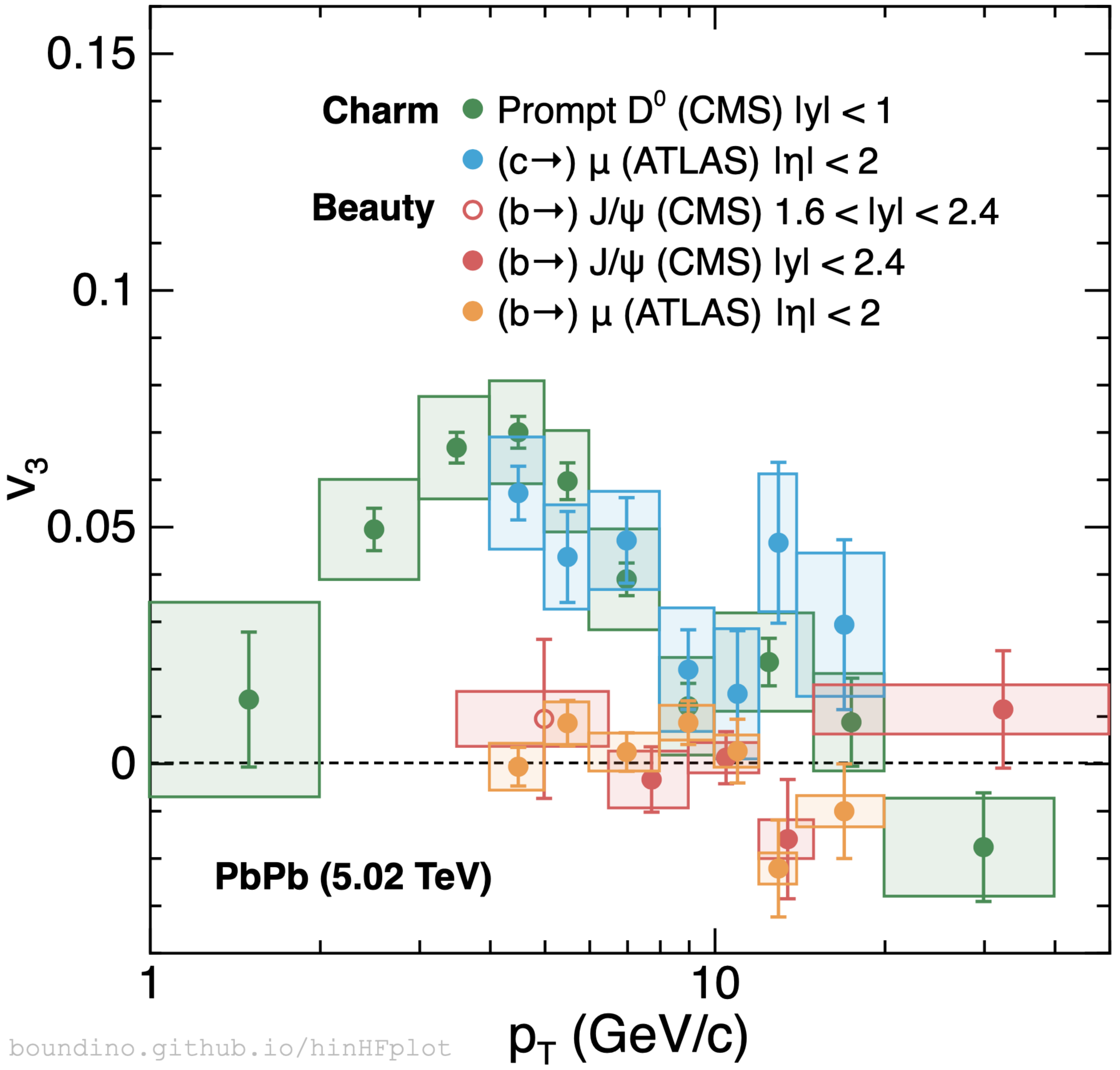
CMS PRL 119 (2017) 152301
CMS EPJC 77 (2017) 252
ALICE JHEP 12 (2022) 126
ALICE PRC 108 (2023) 034906
STAR PRC 108 (2023) 034906



CMS JHEP 10 (2023) 115
CMS PLB 850 (2024) 138389
ATLAS EPJC 78 (2018) 784
ATLAS PLB 807 (2020) 135595
ALICE EPJC 83 (2023) 1123
PHENIX Preliminary

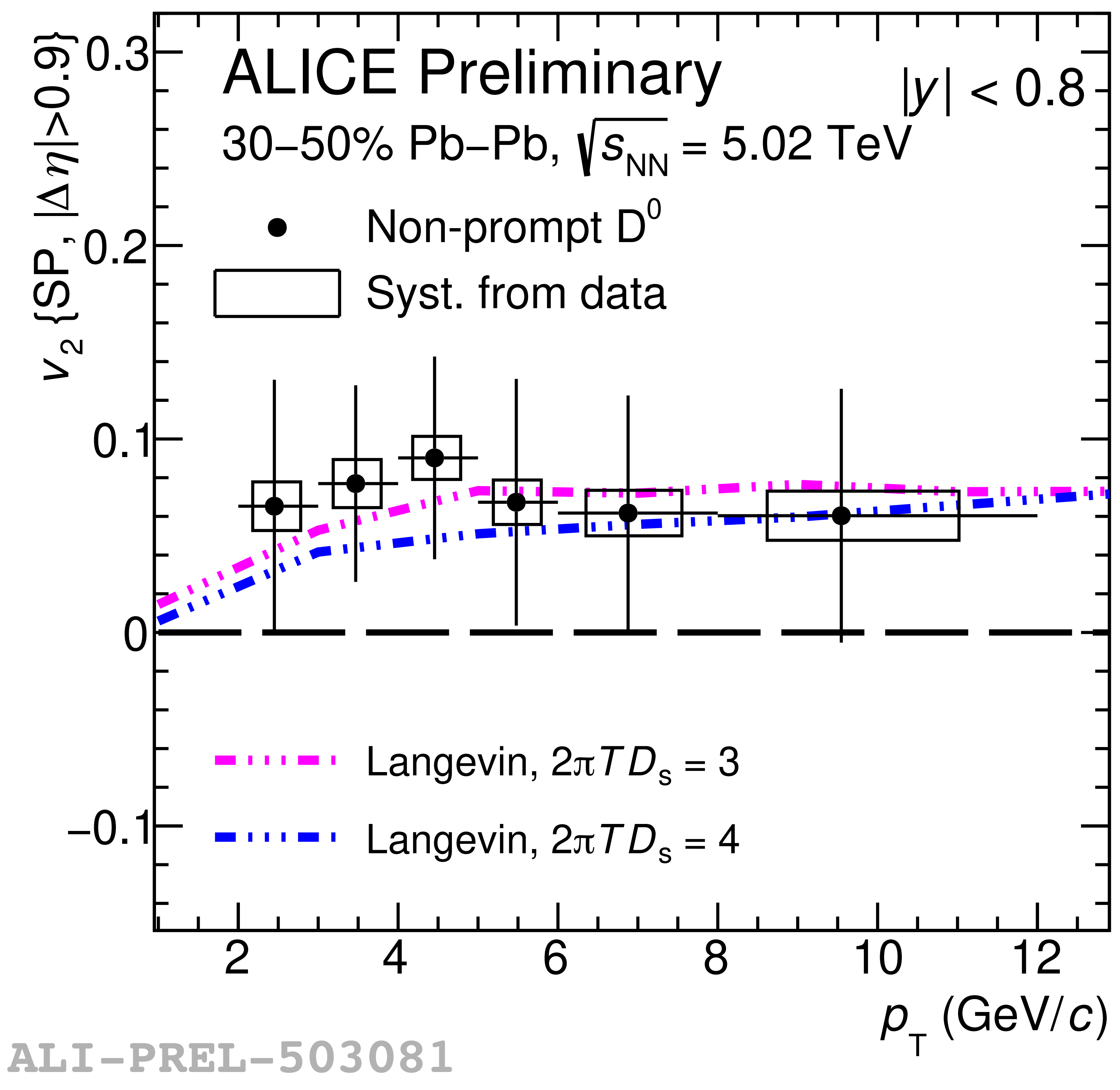
v_2 of beauty particles

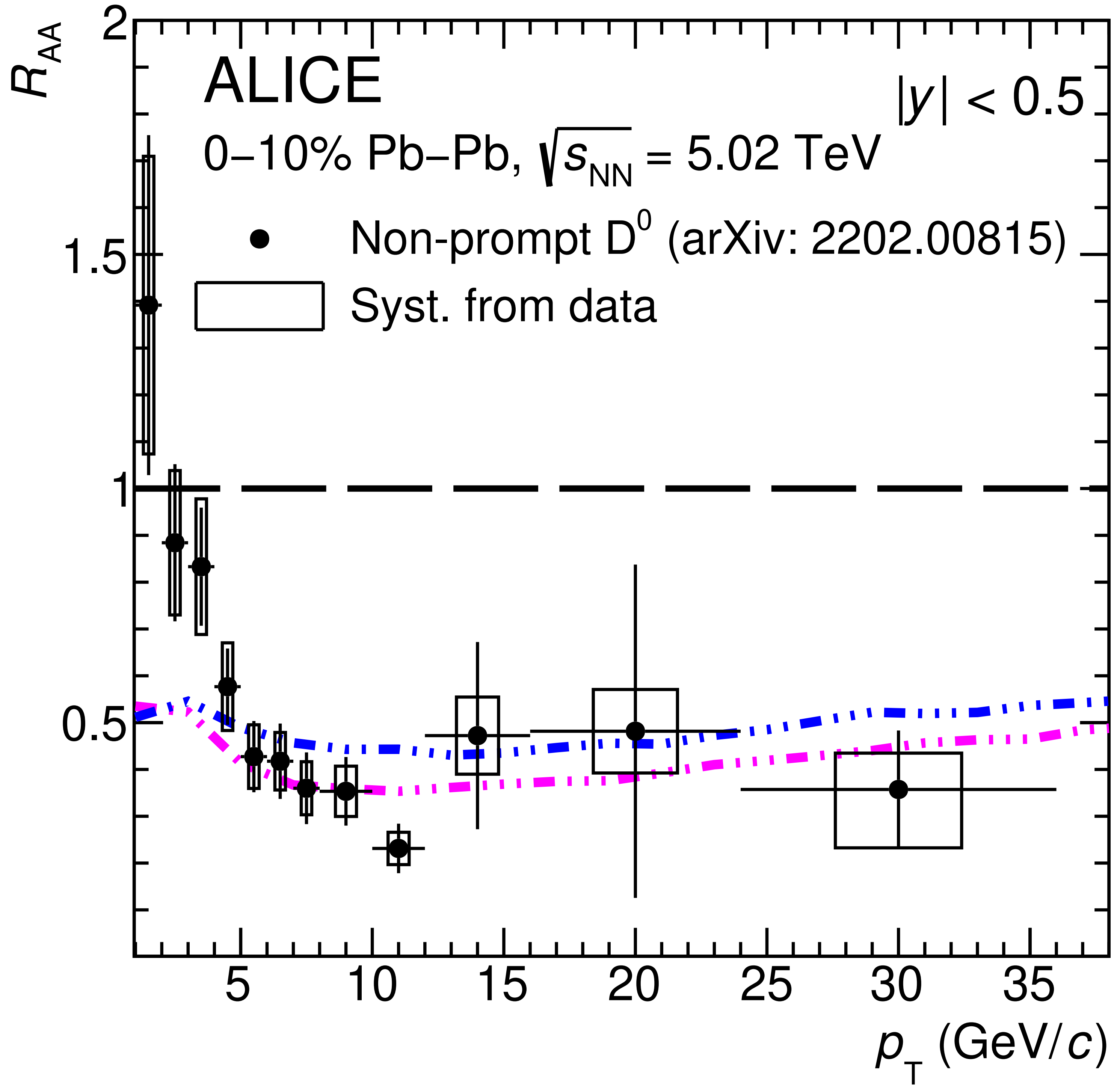




CMS *Phys. Lett.* **B816** (2021) 136253
CMS *Phys. Lett.* **B850** (2024) 138389
CMS *JHEP* **2310** (2023) 115
ATLAS *Phys. Lett.* **B807** (2020) 135595
ALICE *Eur. Phys. J.* **C83** (2023) 1123

Beauty quark transport



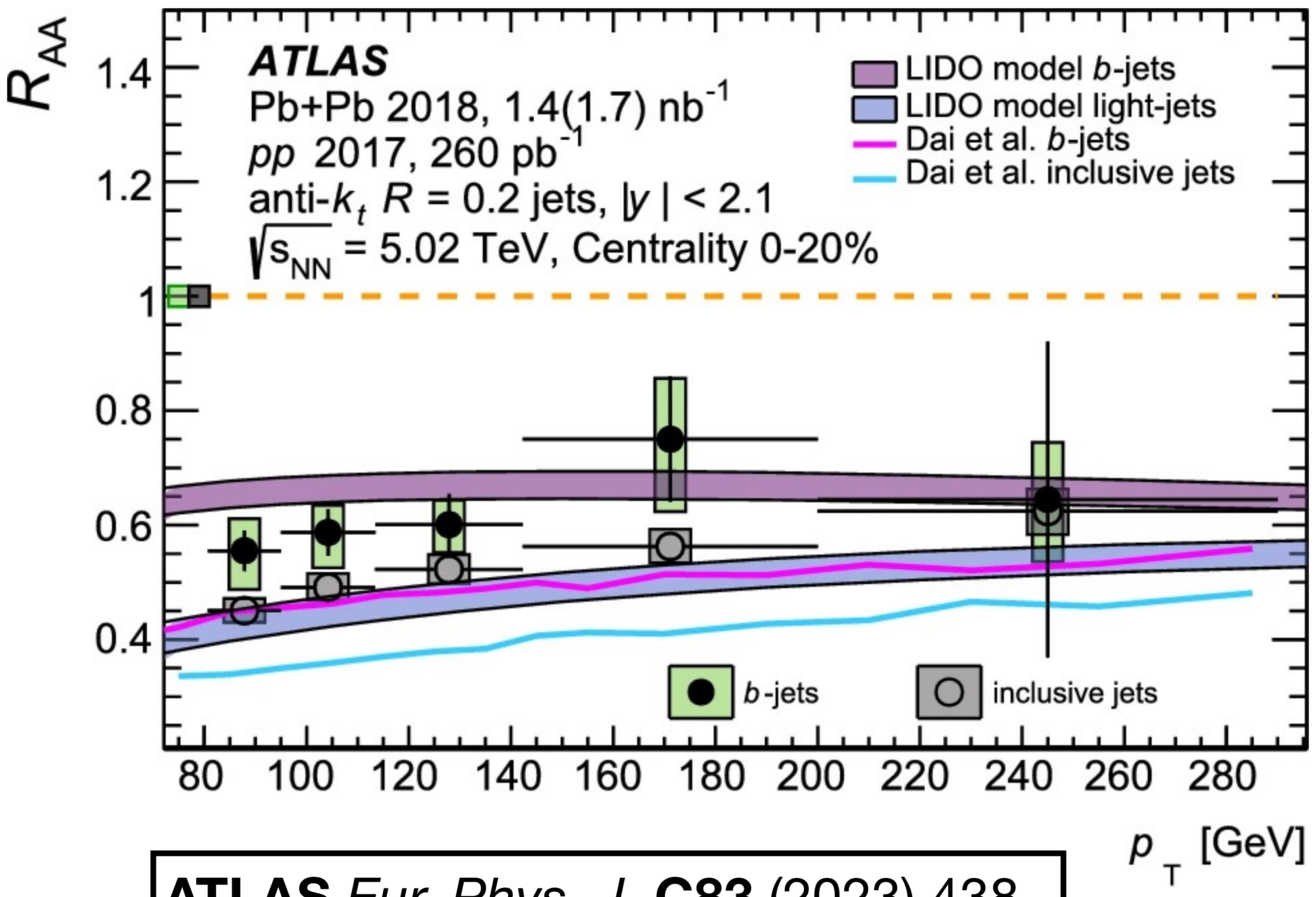


- Beauty particle R_{AA} and v_2 measured via non-prompt D^0 by ALICE
- Conclusion is similar to the measurements of B mesons, non-prompt J/Ψ and B meson semileptonic decays by ATLAS and CMS

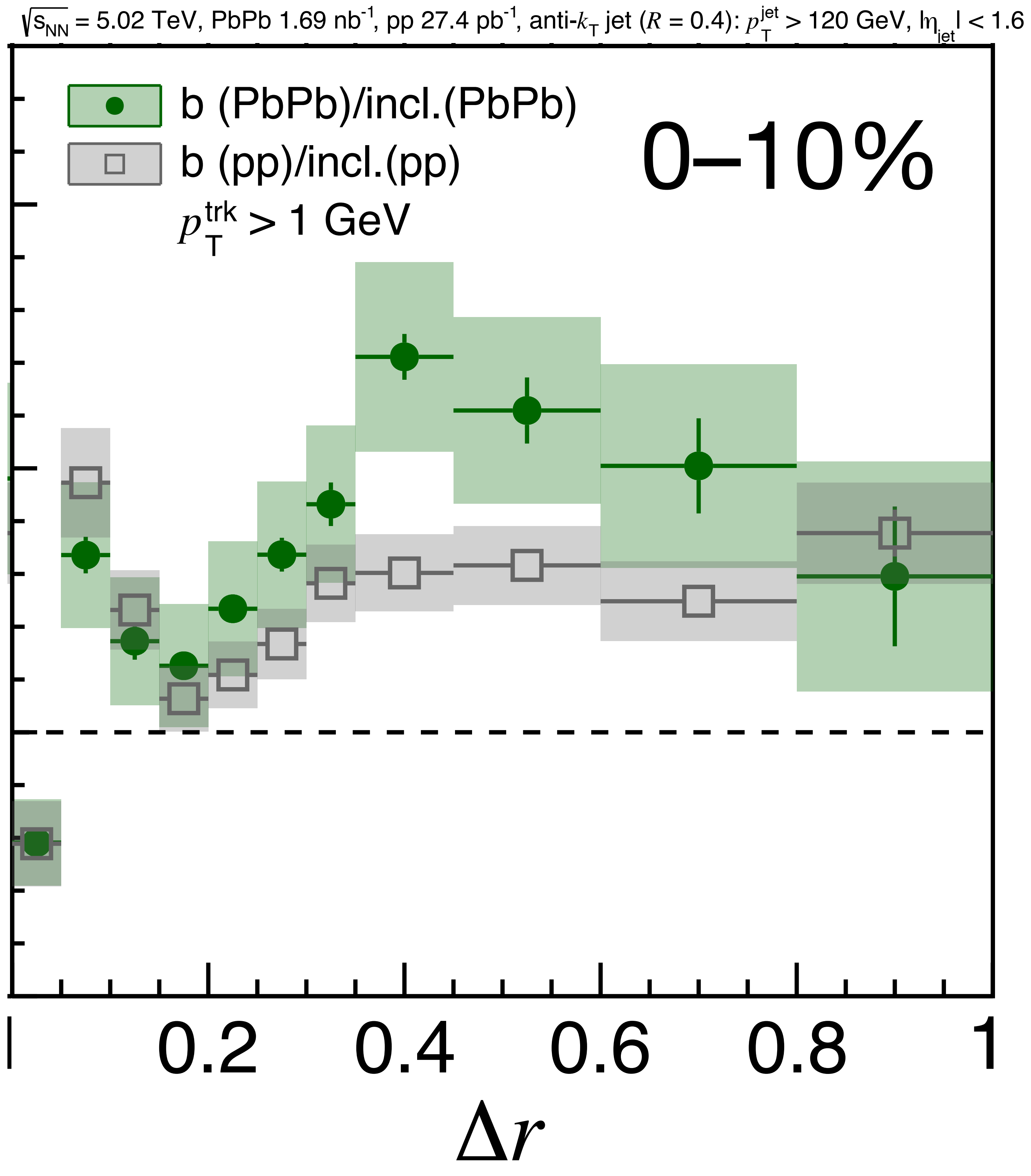
- D_s obtained in beauty sector is similar to that in charm sector ($2\pi D_s \approx 1.5$–4.5 for charm)
- Indicate $\tau_{beauty} \propto m_{beauty} D_s \gtrsim \tau_{medium}$ ($m_{beauty} \approx 3\, m_{charm}$)

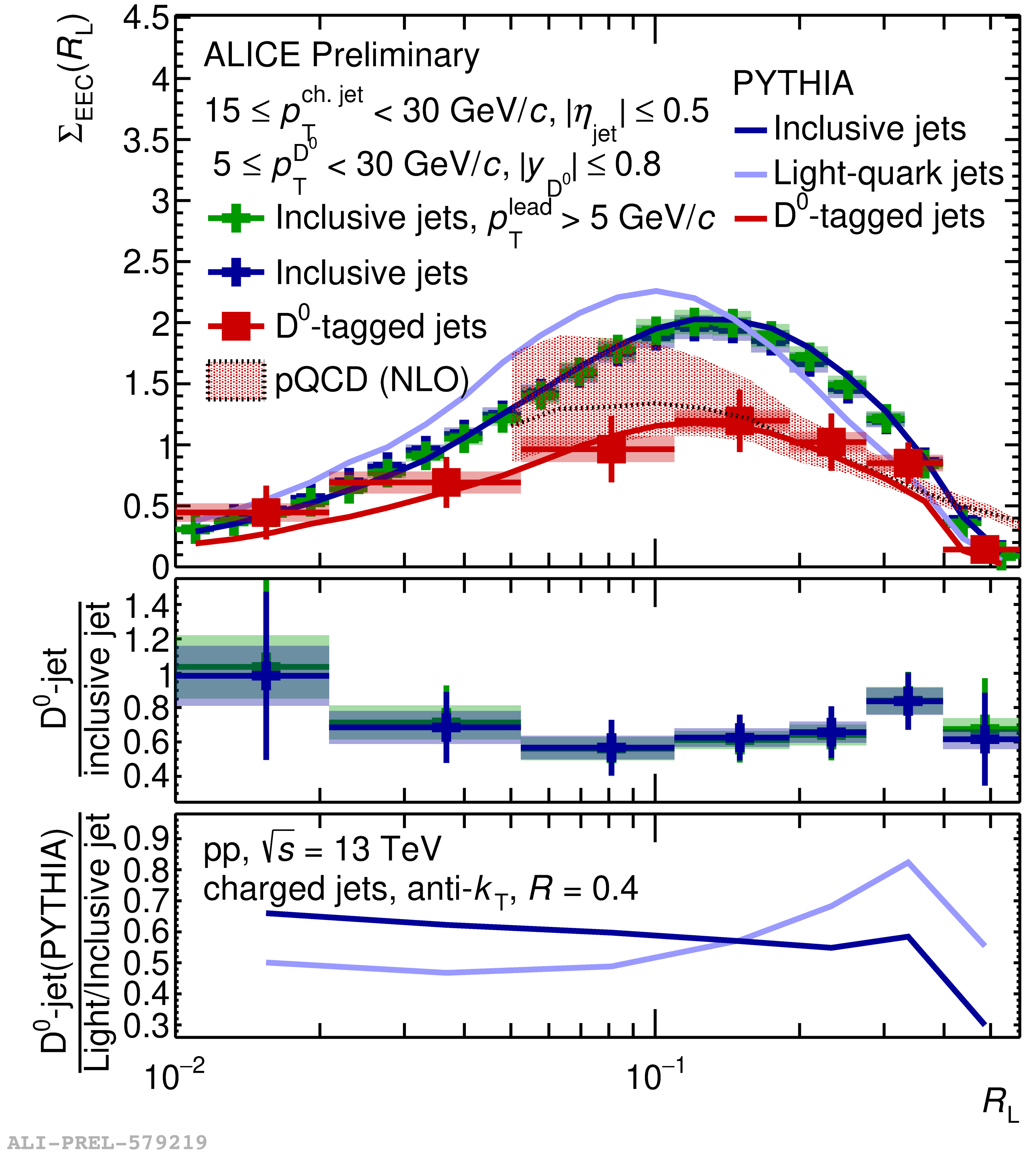
➡ What is thermalization DOF of beauty in the QGP medium?

HF jet production



ATLAS *Eur. Phys. J.* **C83** (2023) 438
CMS *Phys. Lett.* **B844** (2023) 137849

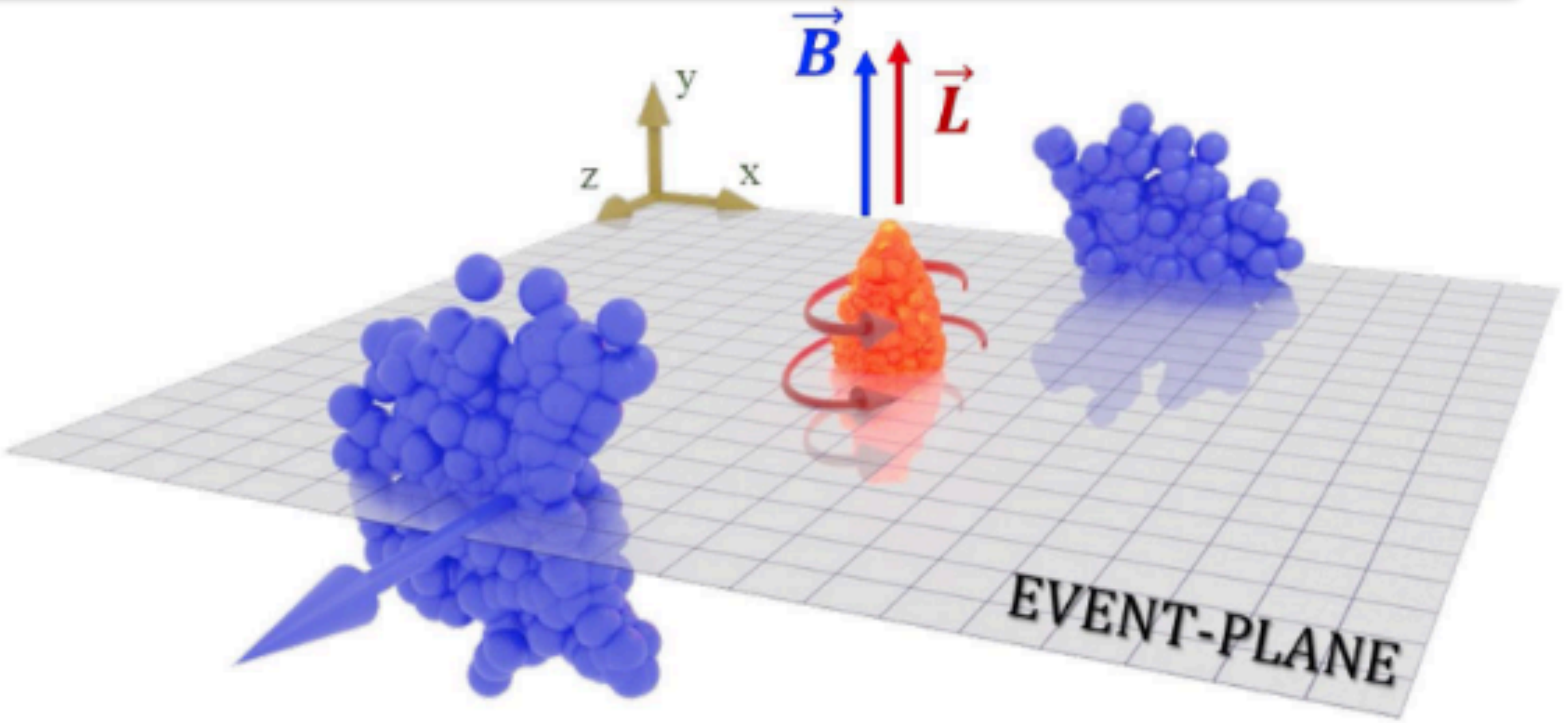


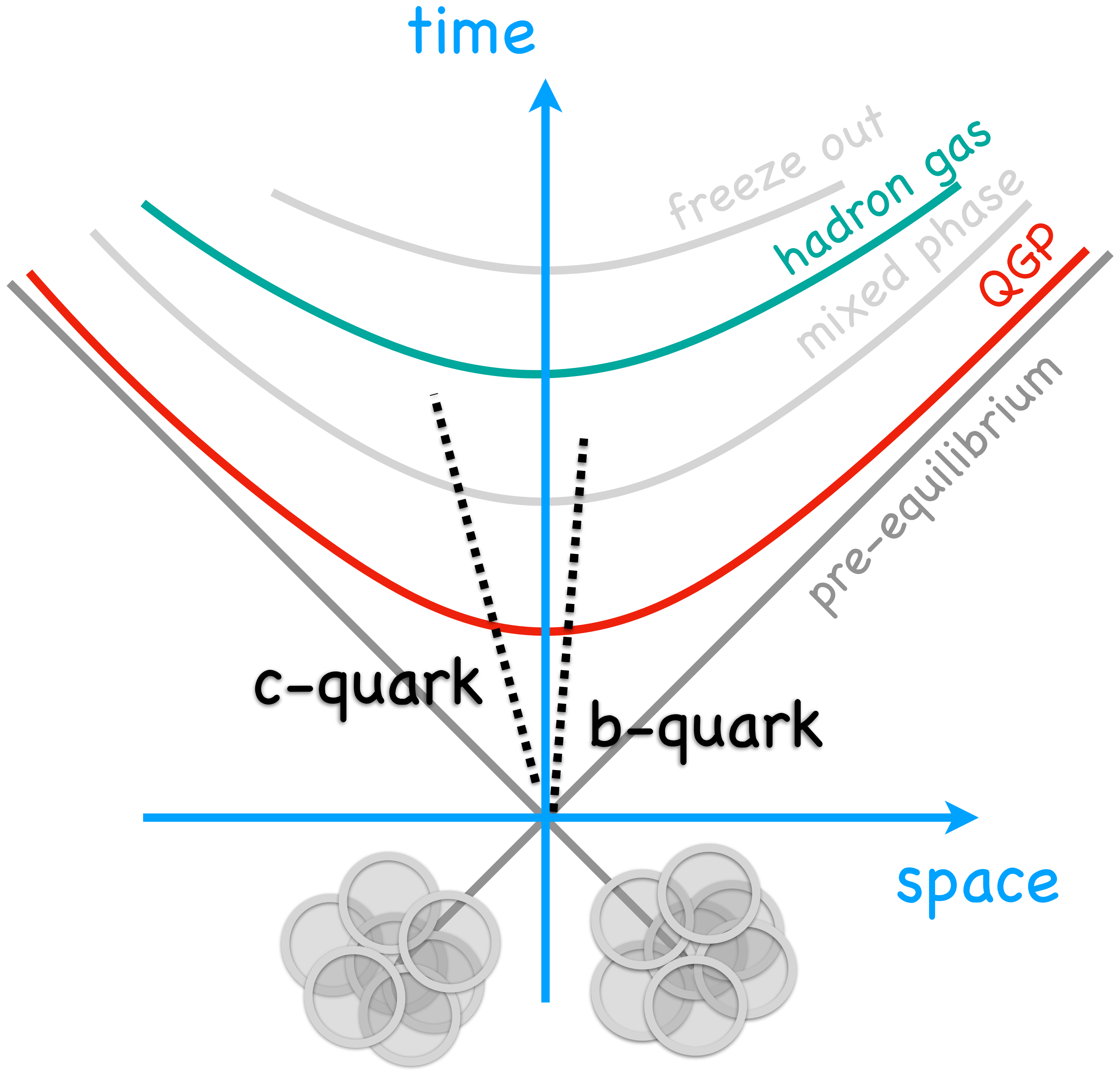


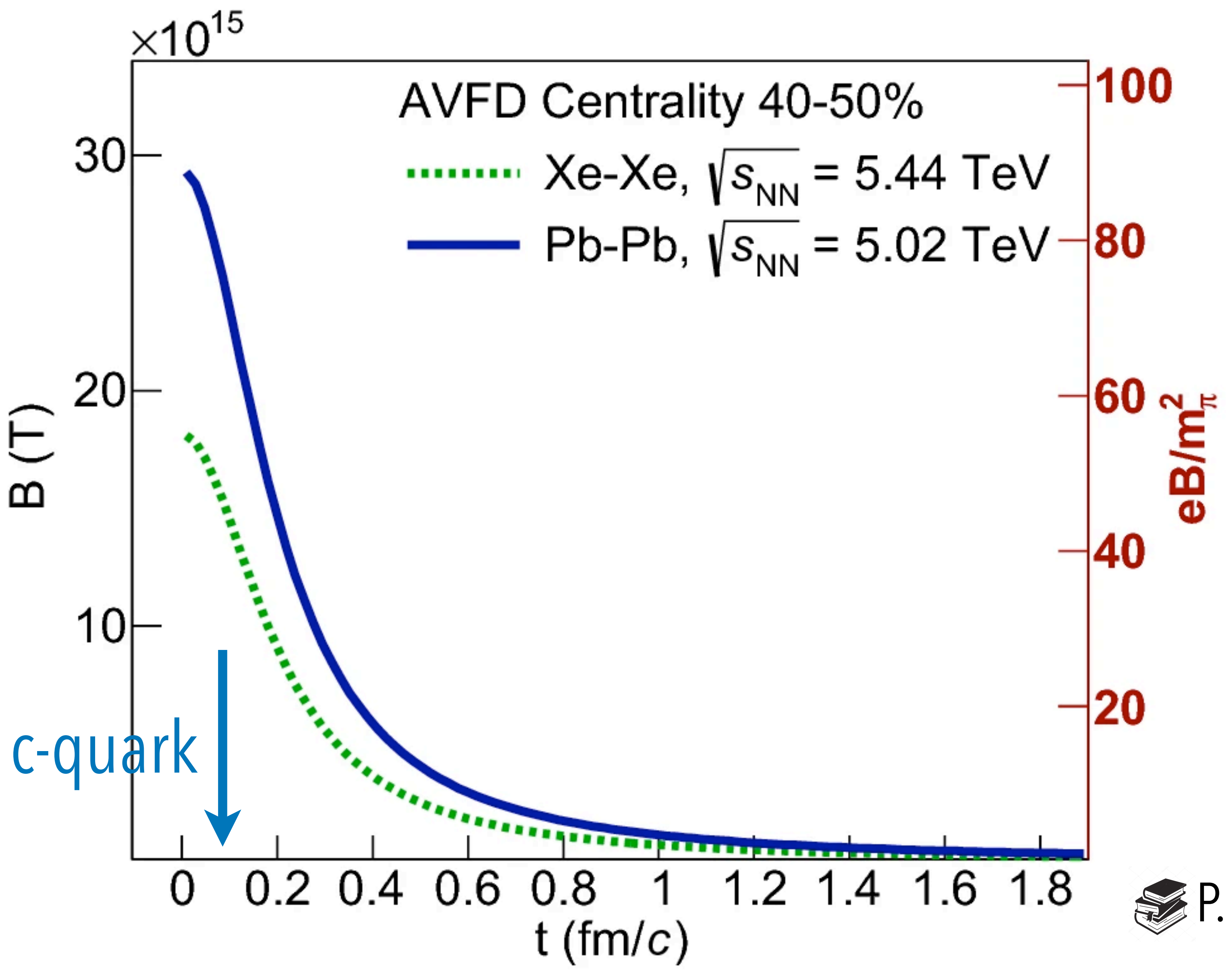
HF spin alignment

- Non-central heavy-ion collisions
  - ➡ Large angular momentum due to the medium rotation is predicted 📚 Becattini et al, PRC 77 (2008) 024906
  - ➡ Huge initial magnetic field (B ~ 10^{14} T) is expected to be formed

📚 Kharzeev et al, NPA 803 (2008) 227-253





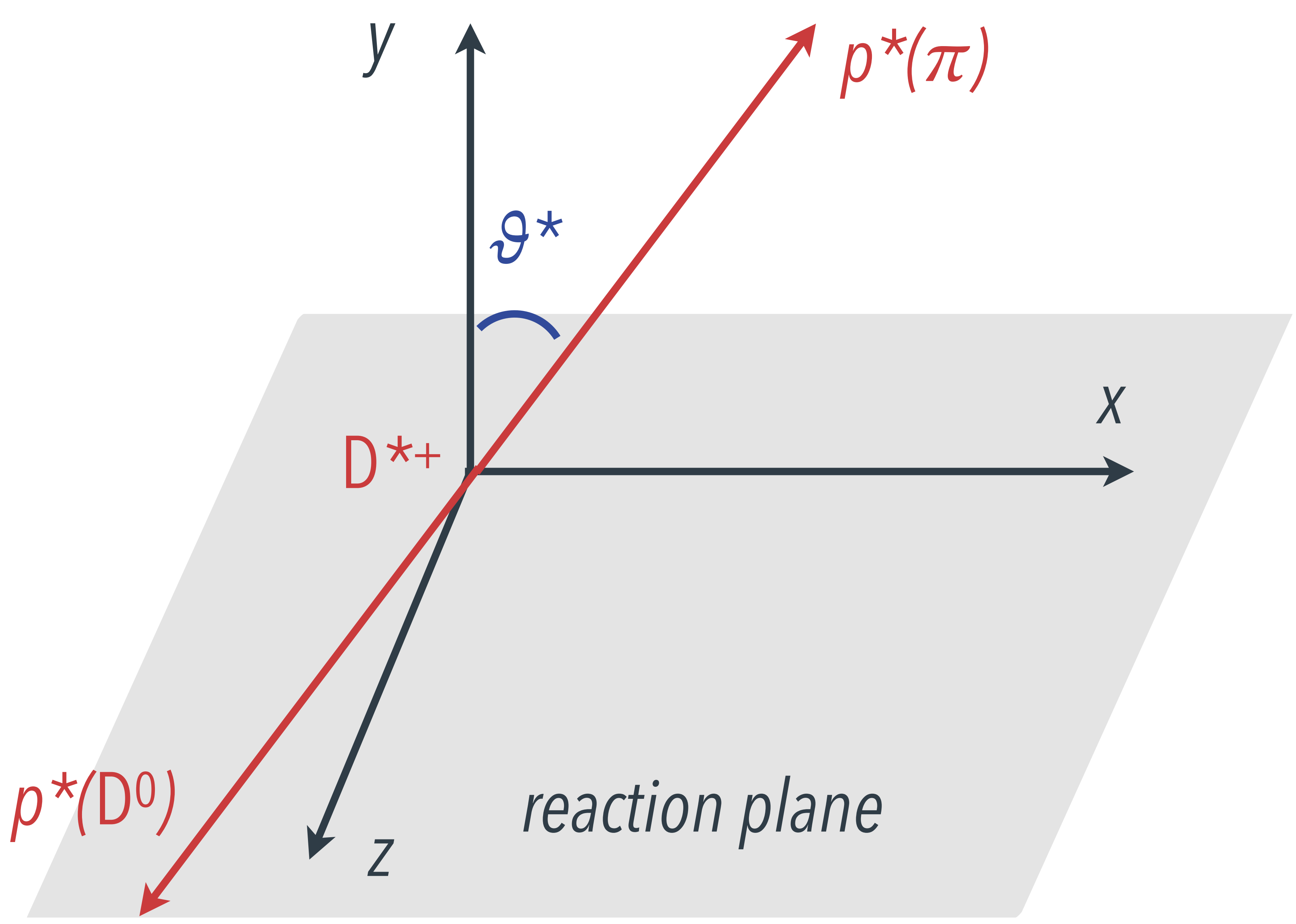


- Charm quarks are produced in the initial stage of the collision and hence are expected to be more sensitive to the magnetic field

📚 P. Christakouglu et al, EPJC 81 (2021) 717

HF spin alignment

- Spin alignment of vector mesons can be studies via the angular distribution of their decay products in the mother rest frame with respect to a quantisation axis



$$\frac{\mathrm{d}N}{\mathrm{d}\cos\vartheta*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\vartheta*$$

ρ_{00} is the spin-density matrix element indicating the probability to find the vector meson in the spin 0 state

- ➡ $\rho_{00} = 1/3$ no spin alignment
- ➡ $\rho_{00} \neq 1/3$ spin alignment

- Quantisation axes:
  - ➡ pp collisions: helicity (direction of the vector meson momentum in the laboratory reference system) or production (orthogonal to helicity and beam axes)
  - ➡ Pb–Pb collisions: normal to the reaction plane (direction of angular momentum and magnetic field)

HF spin alignment

- The spin alignment of vector mesons is related to the polarisation of the constituent quarks P_q
  - ➡ It also depends on the hadronisation mechanism

Recombination

$$\rho_{00}^{rec} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} \begin{cases} > 1/3 \text{ if } P_q \cdot P_{\bar{q}} < 0 \\ < 1/3 \text{ if } P_q \cdot P_{\bar{q}} > 0 \end{cases}$$

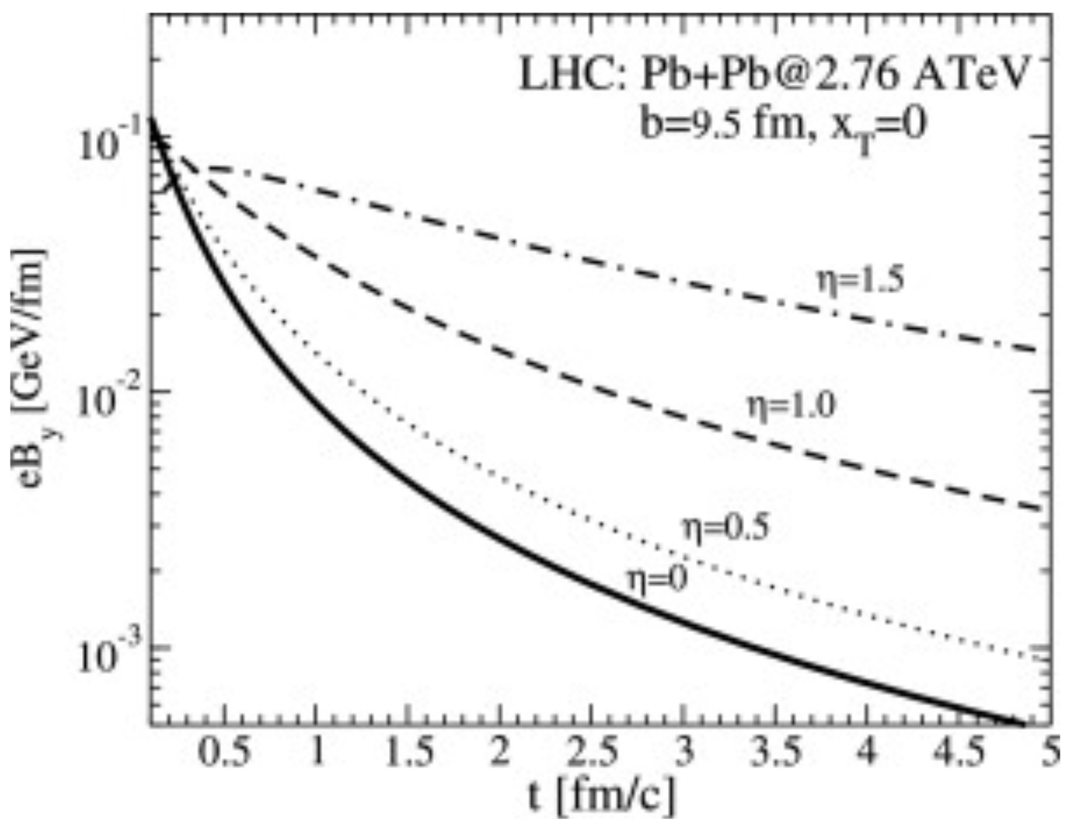
* > 1/3 for neutral mesons, < 1/3 for charged mesons

Z.-T. Liang et al, PLB 629:20-26, 2005

Fragmentation

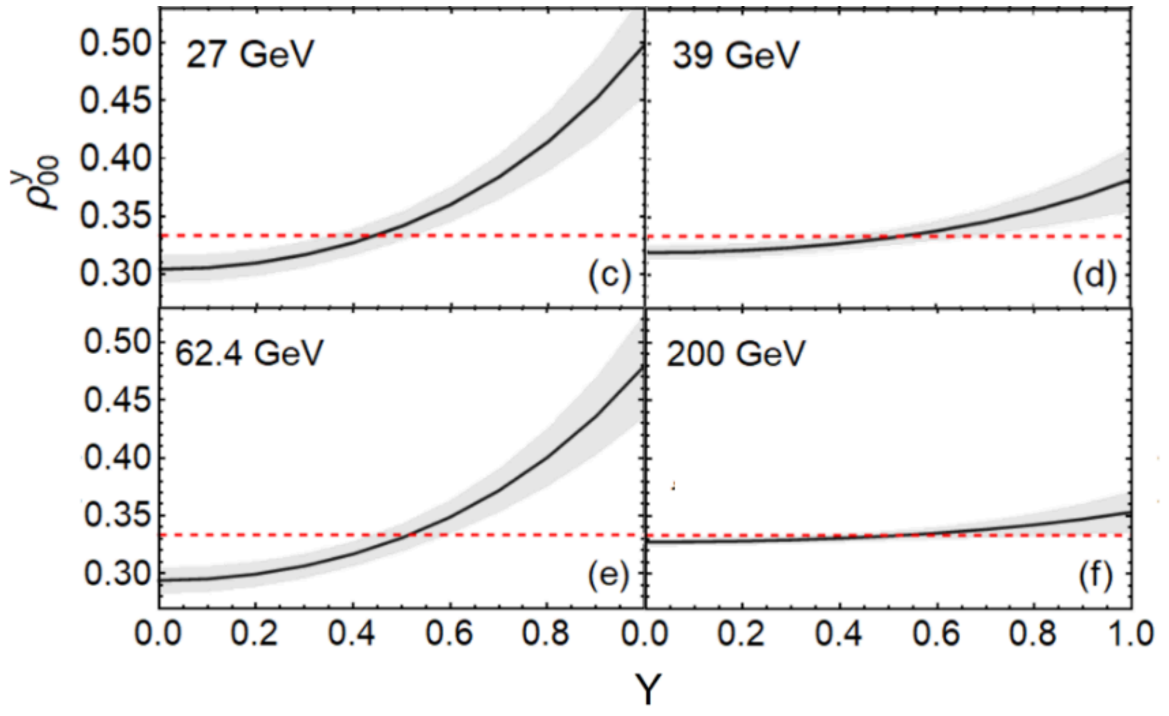
$$\rho_{00}^{frag} = \frac{1 + \beta \cdot P_q^2}{3 - \beta \cdot P_q^2} > 1/3$$

- rapidity dependence expected:



In case of B-field induced polarisation due to the decrease in time, less steep at forward rapidity

S.K. Das et al, PLB 768 (2017) 260



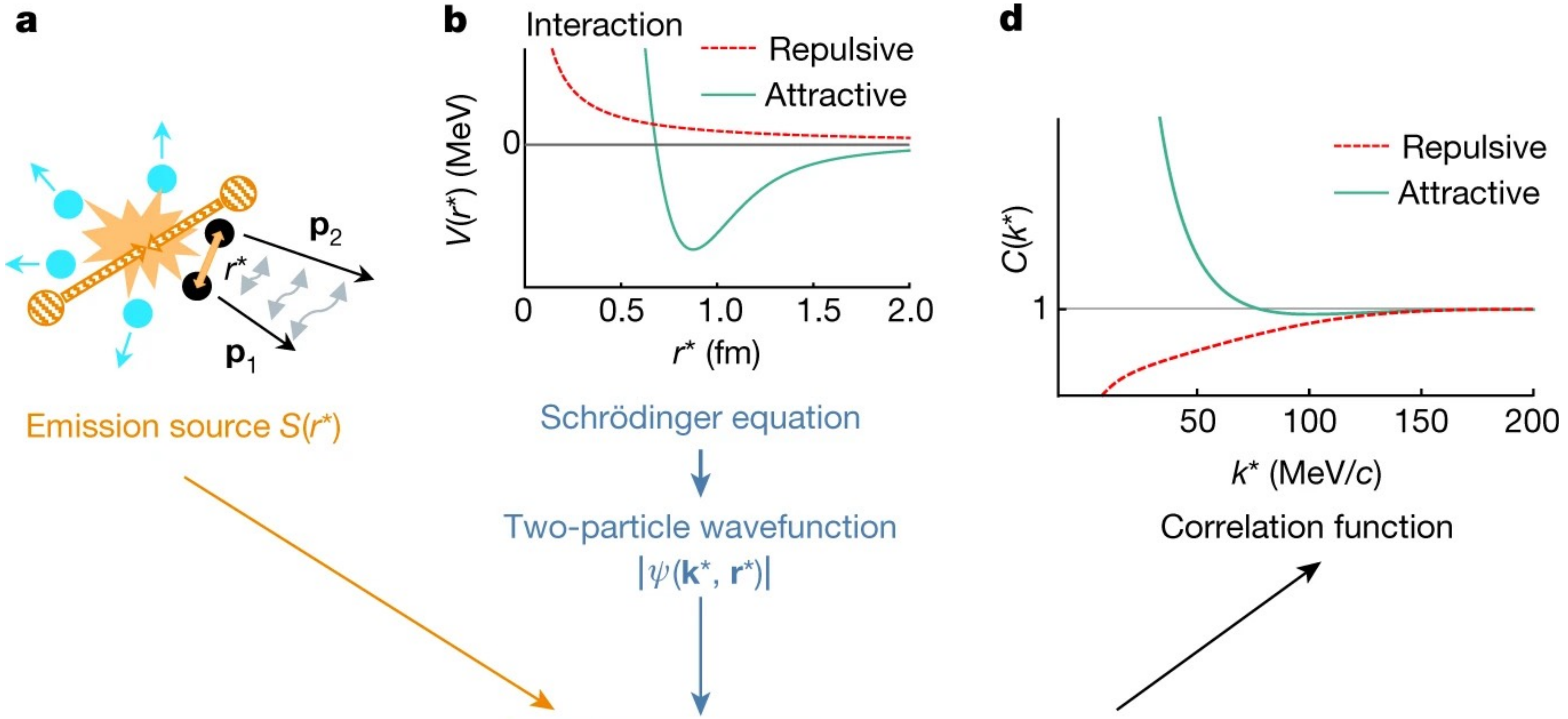
Also possible in case of vector-meson field, for thermalised polarised quarks recombining in the QGP

X.L. Sheng et al, arXiv: 2308.14038

- Increase with p_T also expected because of earlier production for high momentum quarks (magnetic field) and in effective-field theory models which predict a polarisation due to the angular momentum transferred via quark recombination

S. Gupta, arXiv:2307.12250

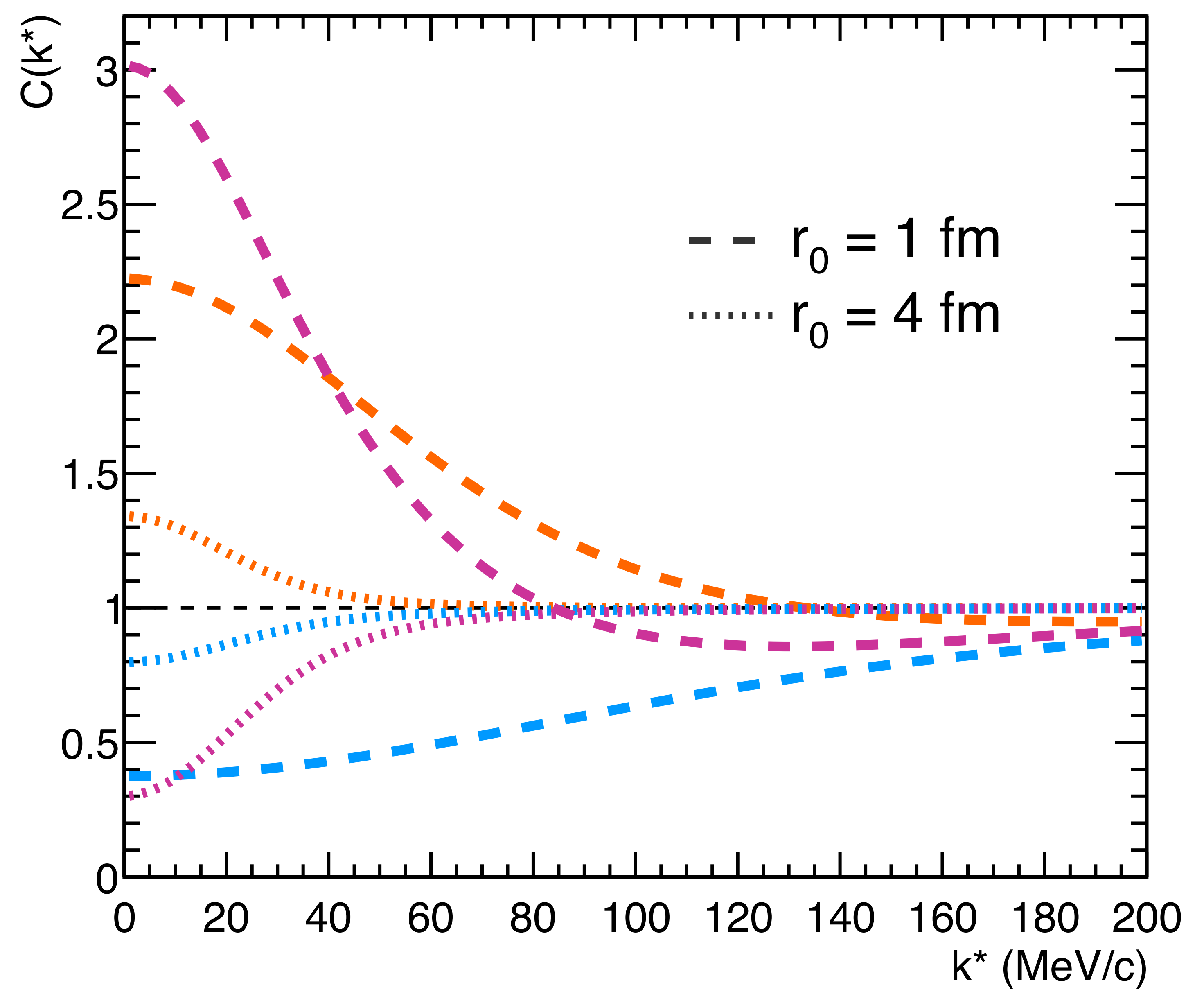
Femtoscopy



c

$$C(k^*) = \int S(r^*)|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2 d^3r^* = \xi(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Ann. Rev. Nucl. Part. Sci. **71** (2021) 377



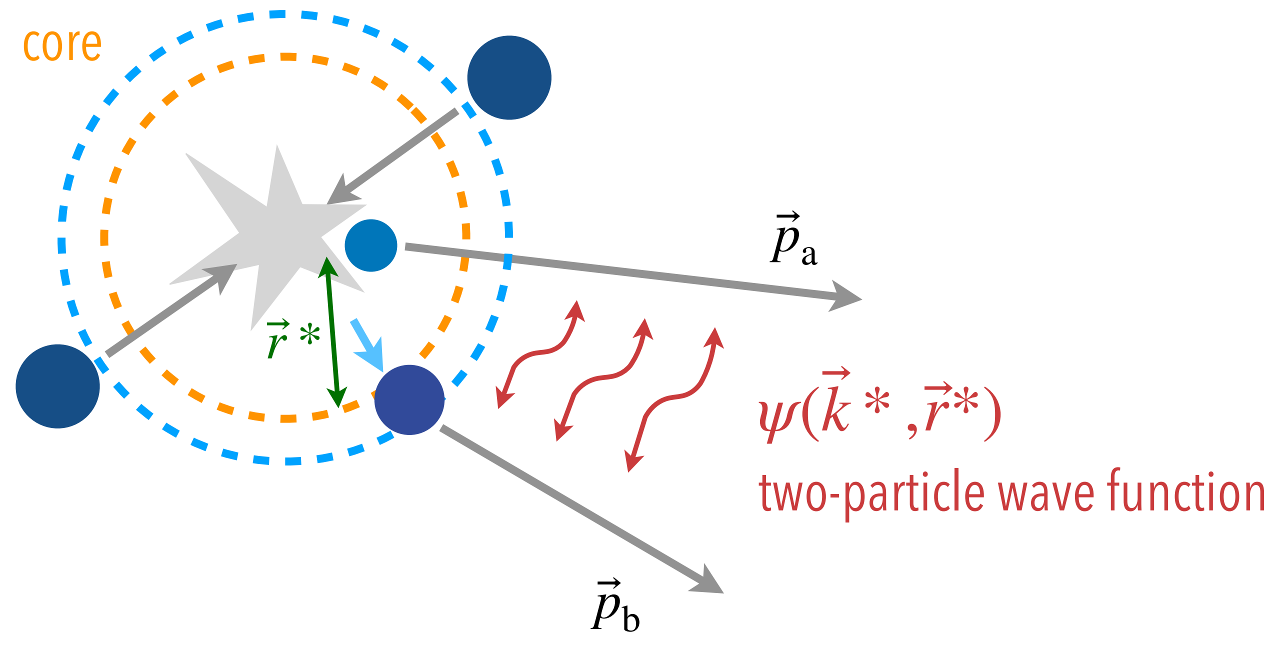
- Further constraints on the residual strong interaction between NN, YN and YY
- Important input of EoS of neutron stars

Absence interaction $C(k^*) = 1$

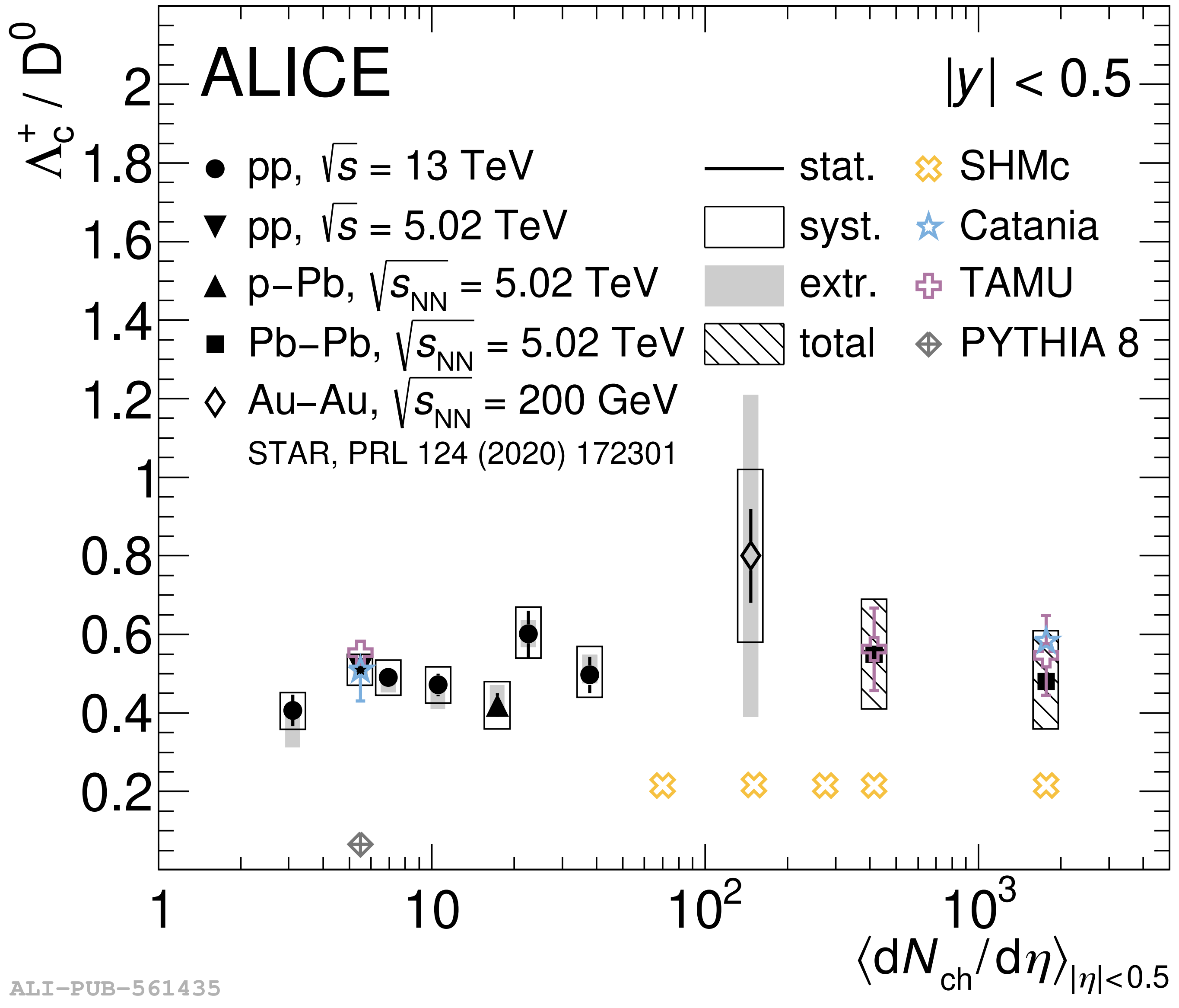
Attractive potential $C(k^*) > 1$

Repulsive potential $C(k^*) < 1$

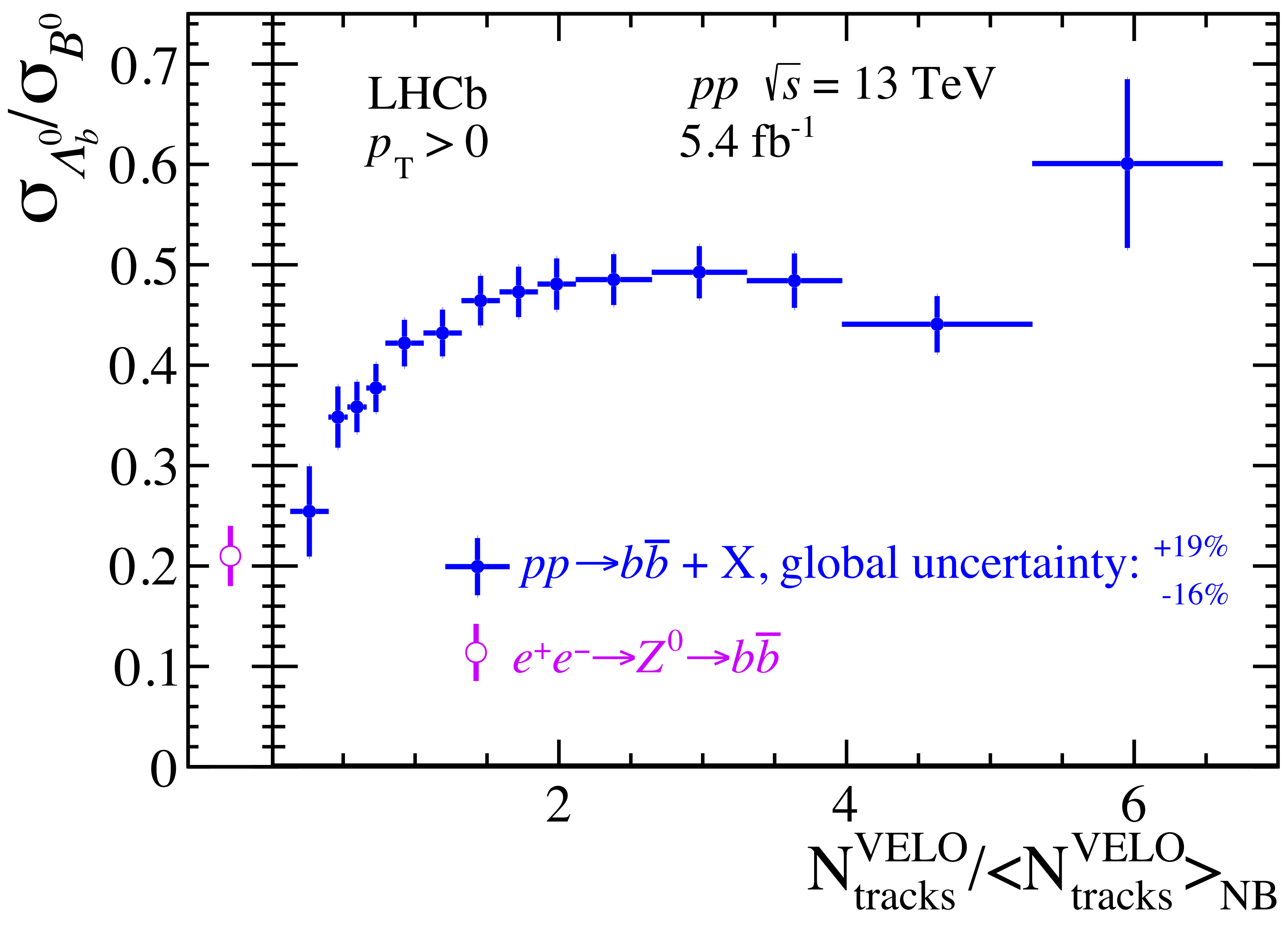
Bound-state formation $C(k^*) \gtreqless 1$



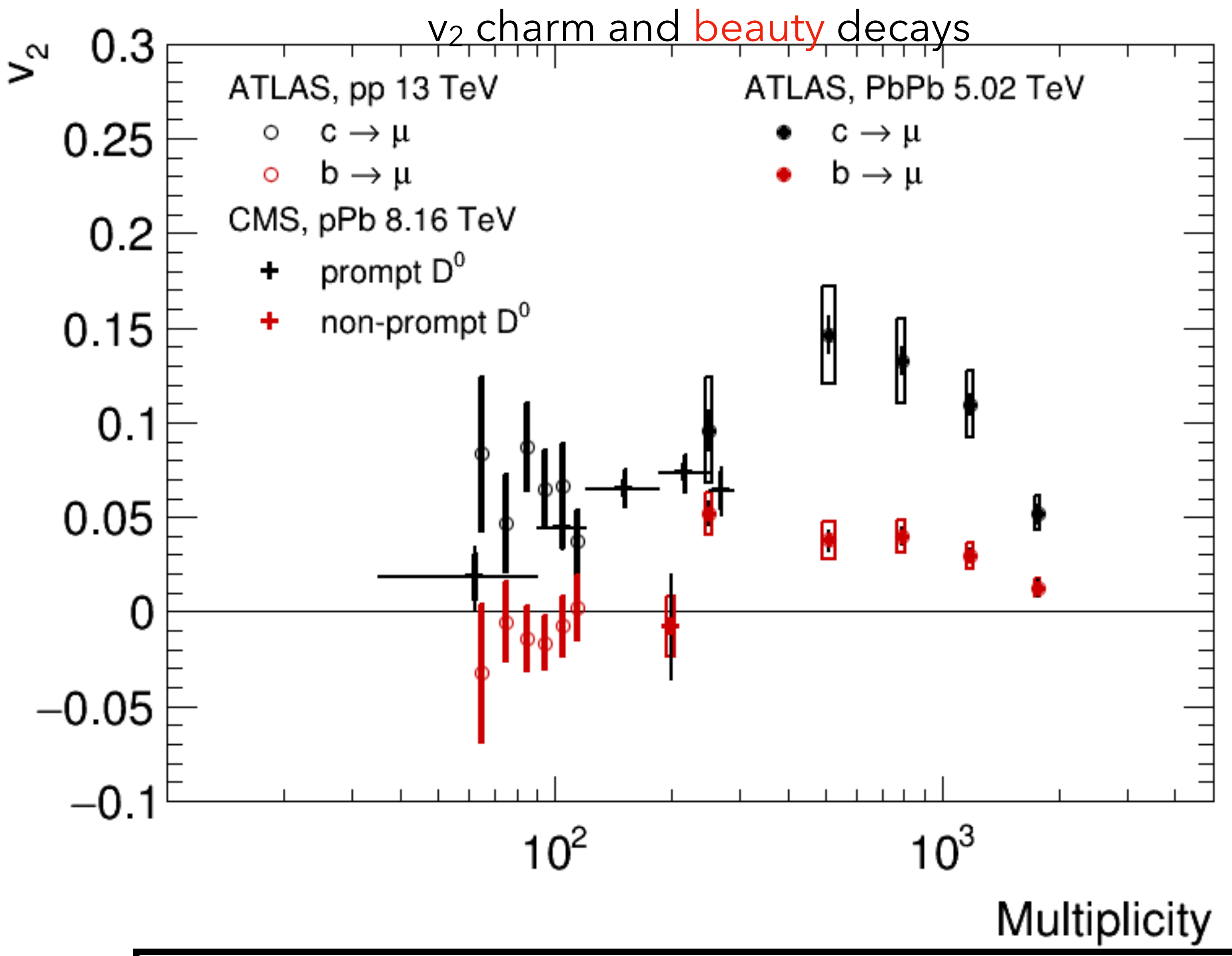
HF production cross system



ALICE ***Phys. Lett.*** **B839 (2023) 137796**

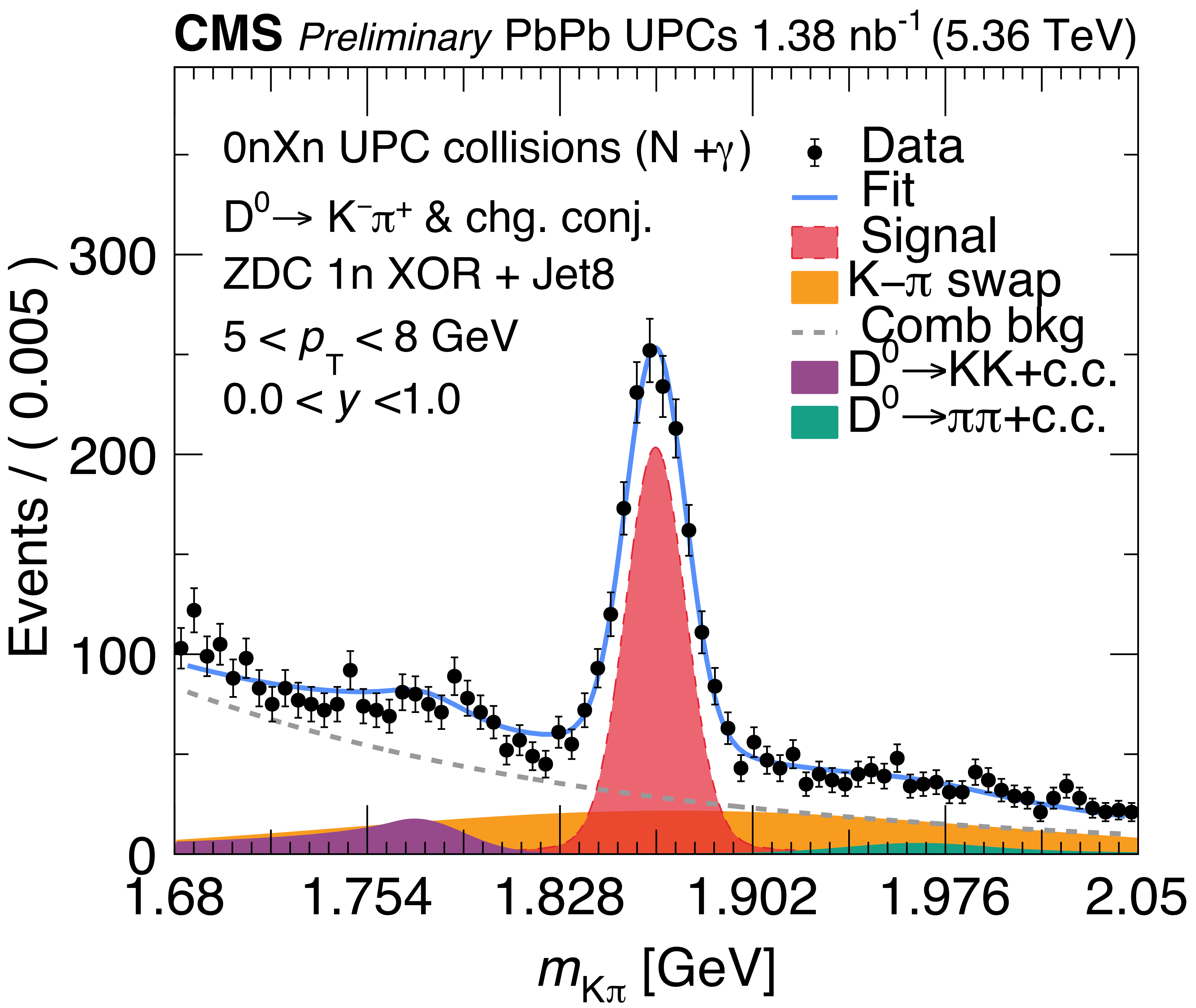


LHCb ***Phys. Rev. Lett.*** **132 (2024) 081901**



STAR, PLB 844 (2023) 138071
ATLAS, pp, PRL 124 (2020) 082301
ATLAS, PbPb, PLB 807 (2020) 135595
CMS, pPb, prompt D^0, PRL 121 (2018) 8, 082301
CMS, pPb, non-prompt D^0, PRL 813 (2021) 136036
ALICE, pPb, JHEP 2019 (2019) 92
LHCb, D^0, arXiv:2205.03936

D meson production in UPC



CMS CMS-PAS-HIN-24-003