ALICE results based only on my experiences

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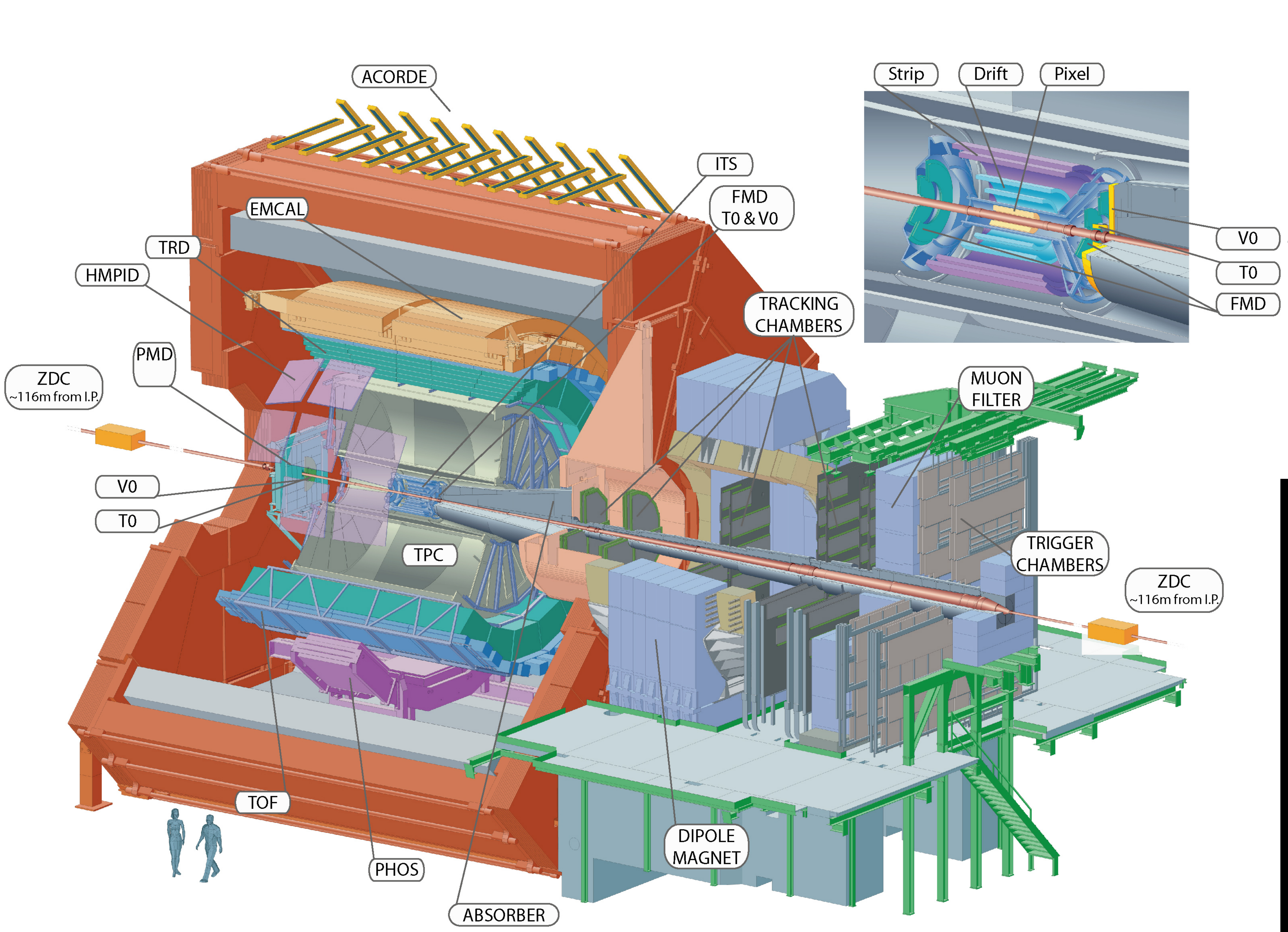
华中师范大学

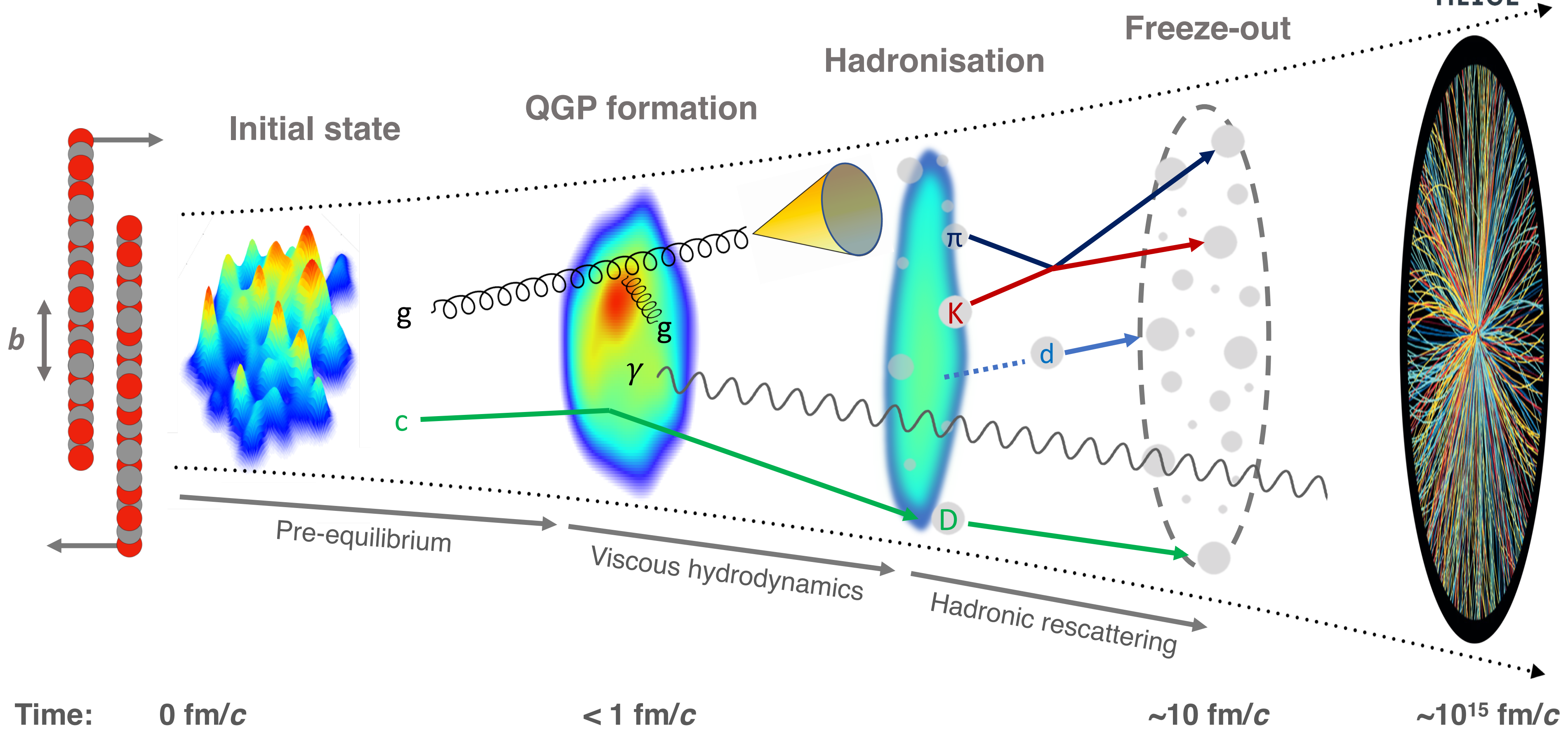
极端核物质前沿研讨会

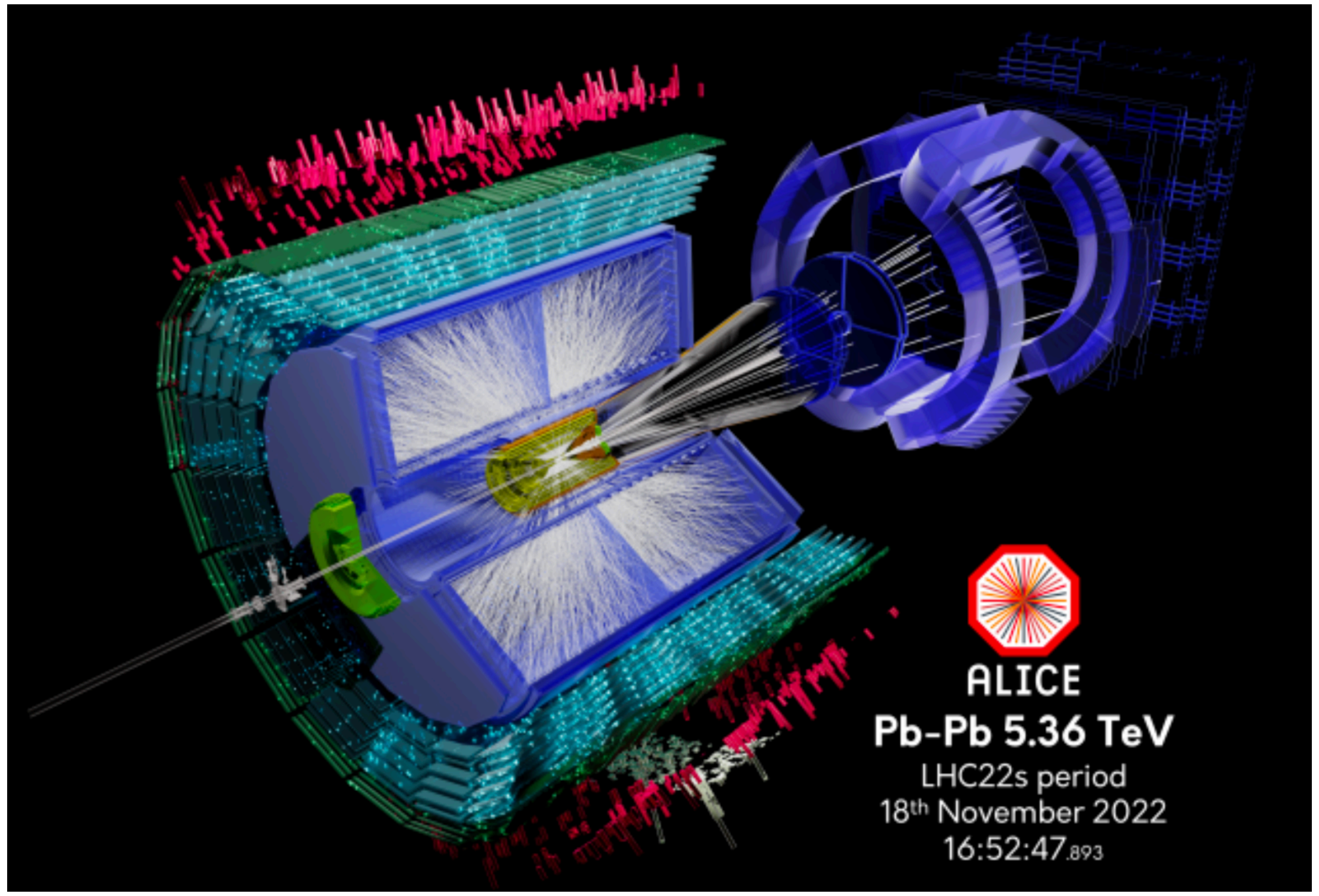
湖北 · 宜昌 2026年4月24–28日

ALICE experiment at the LHC

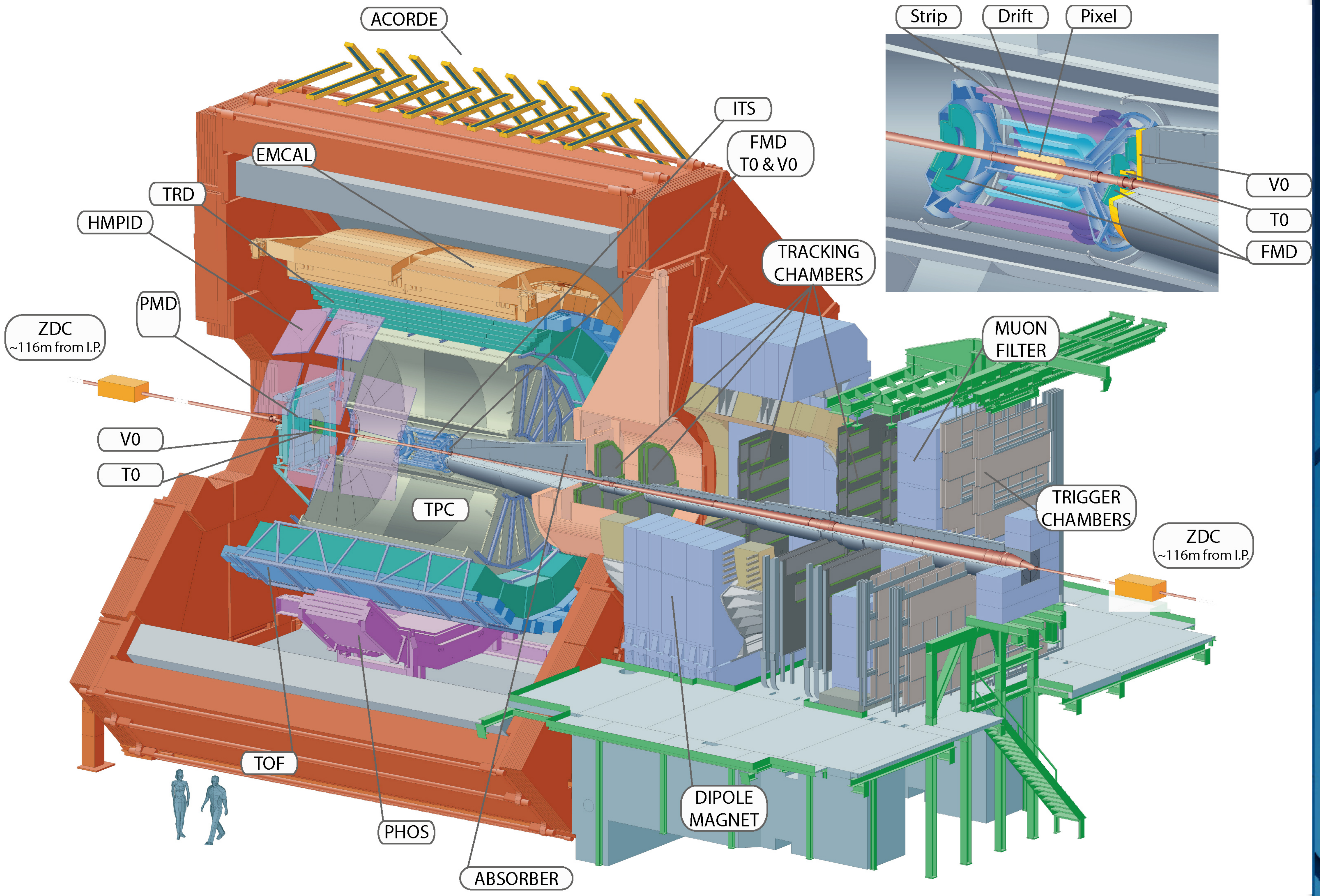


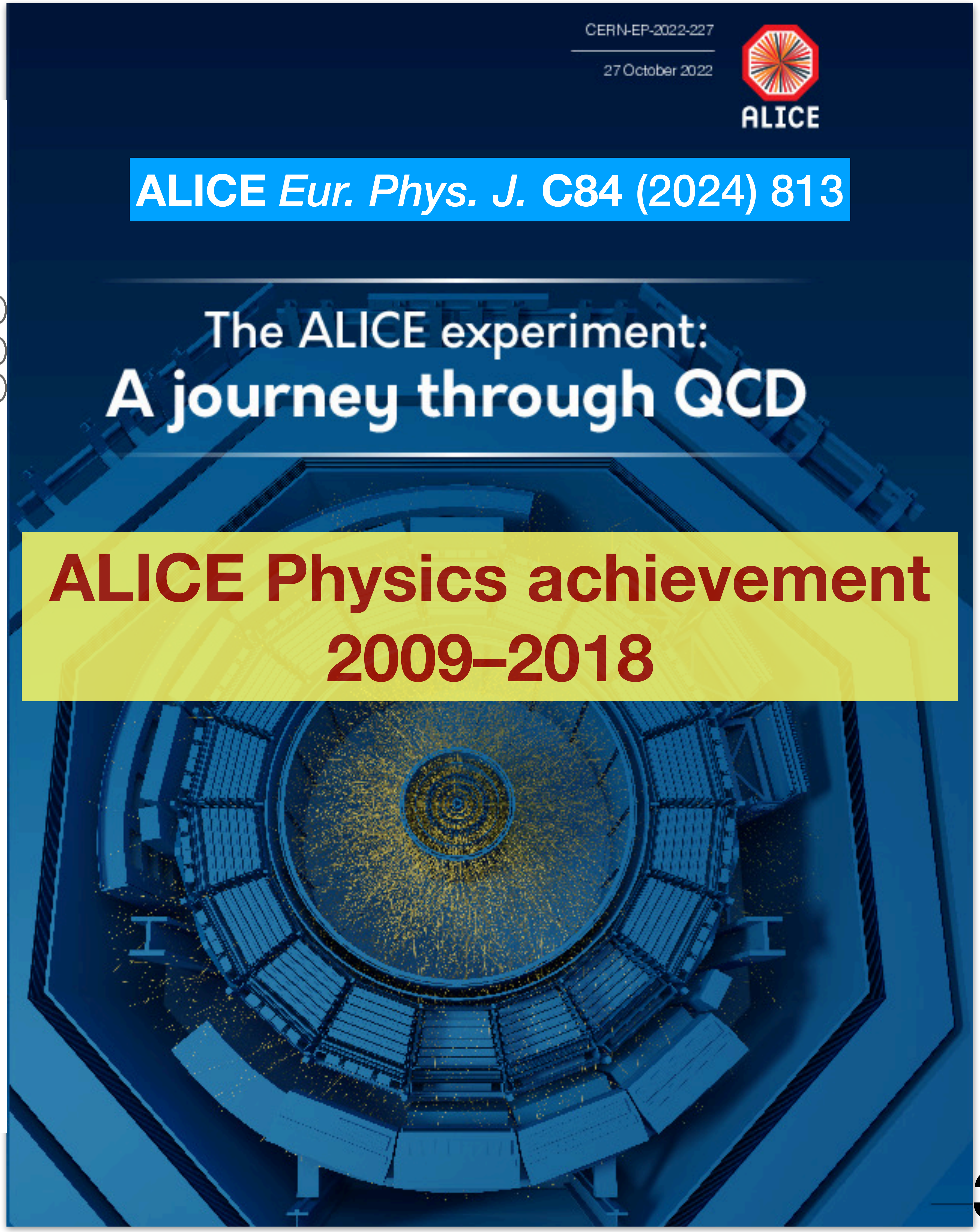
ALICE *Eur. Phys. J.* C84 (2024) 813





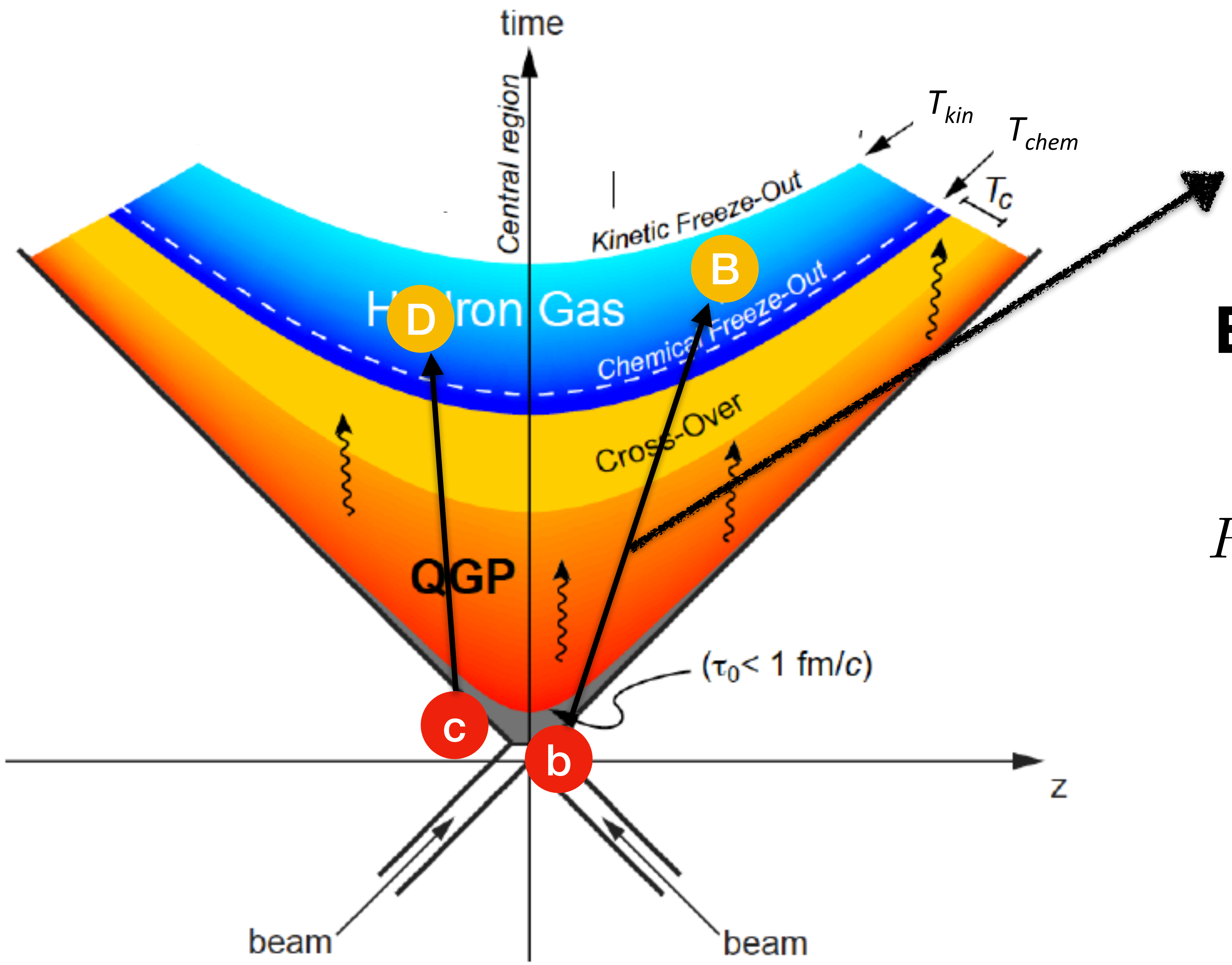
Journey through QCD

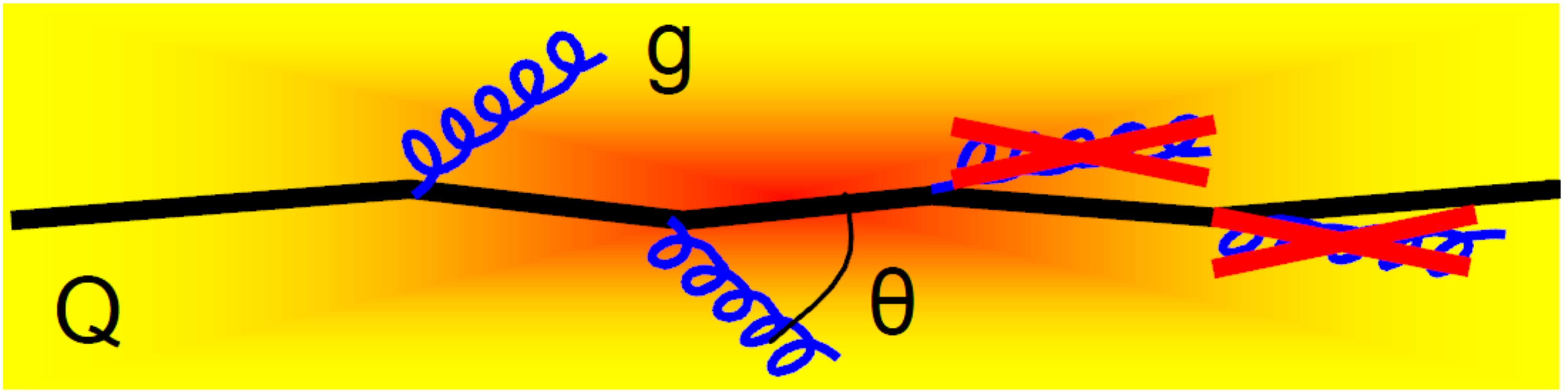




Heavy quarks: QGP tomography

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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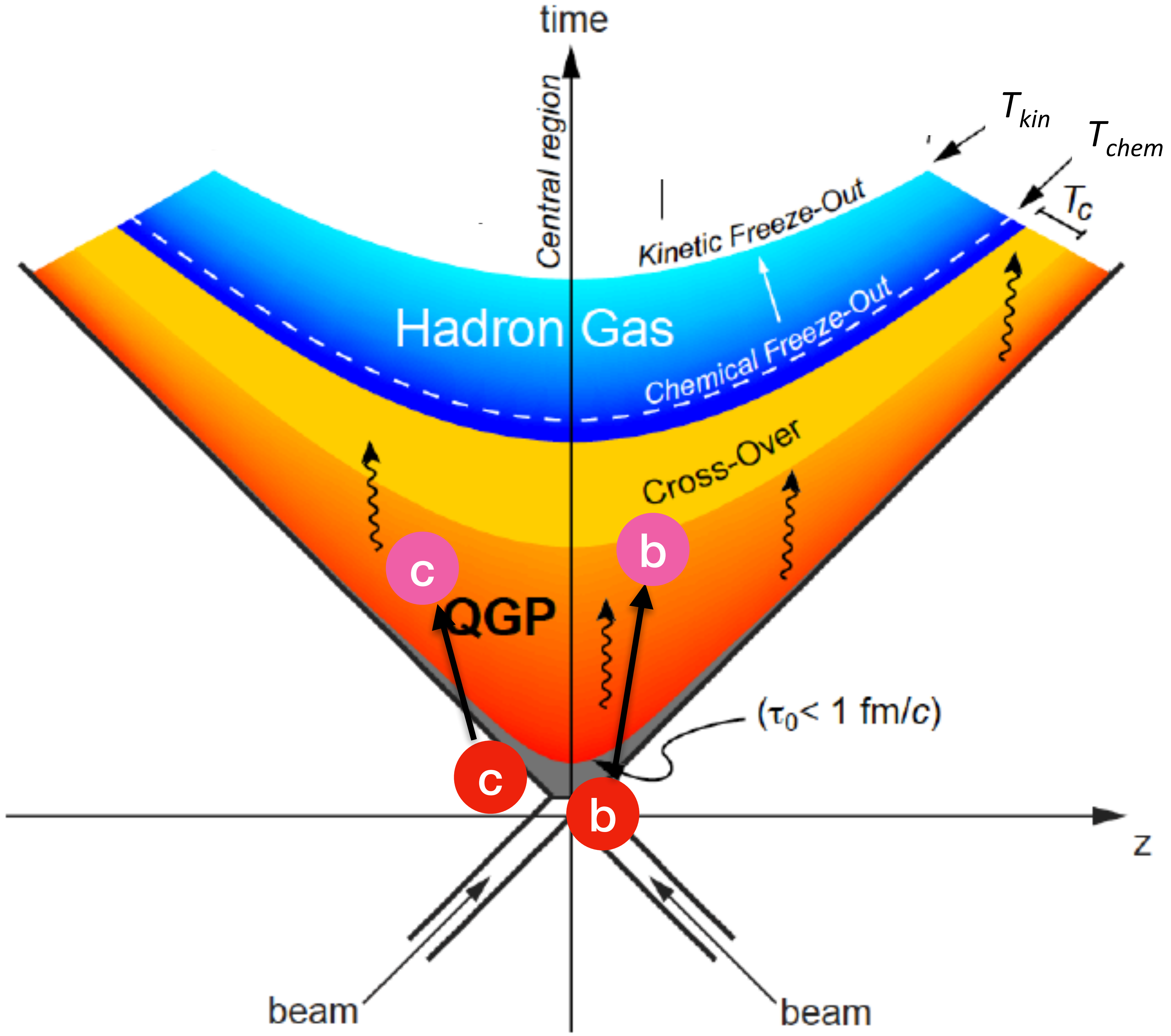
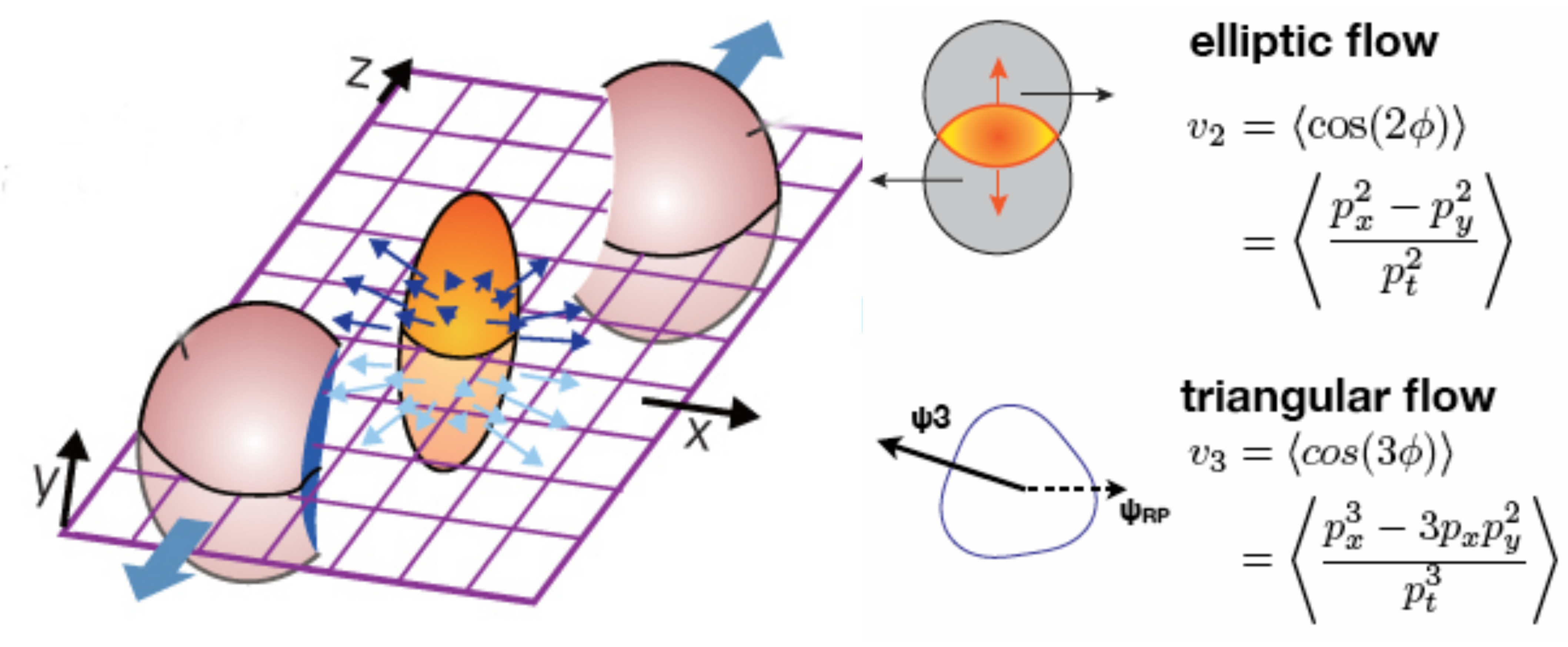


Collective expansion

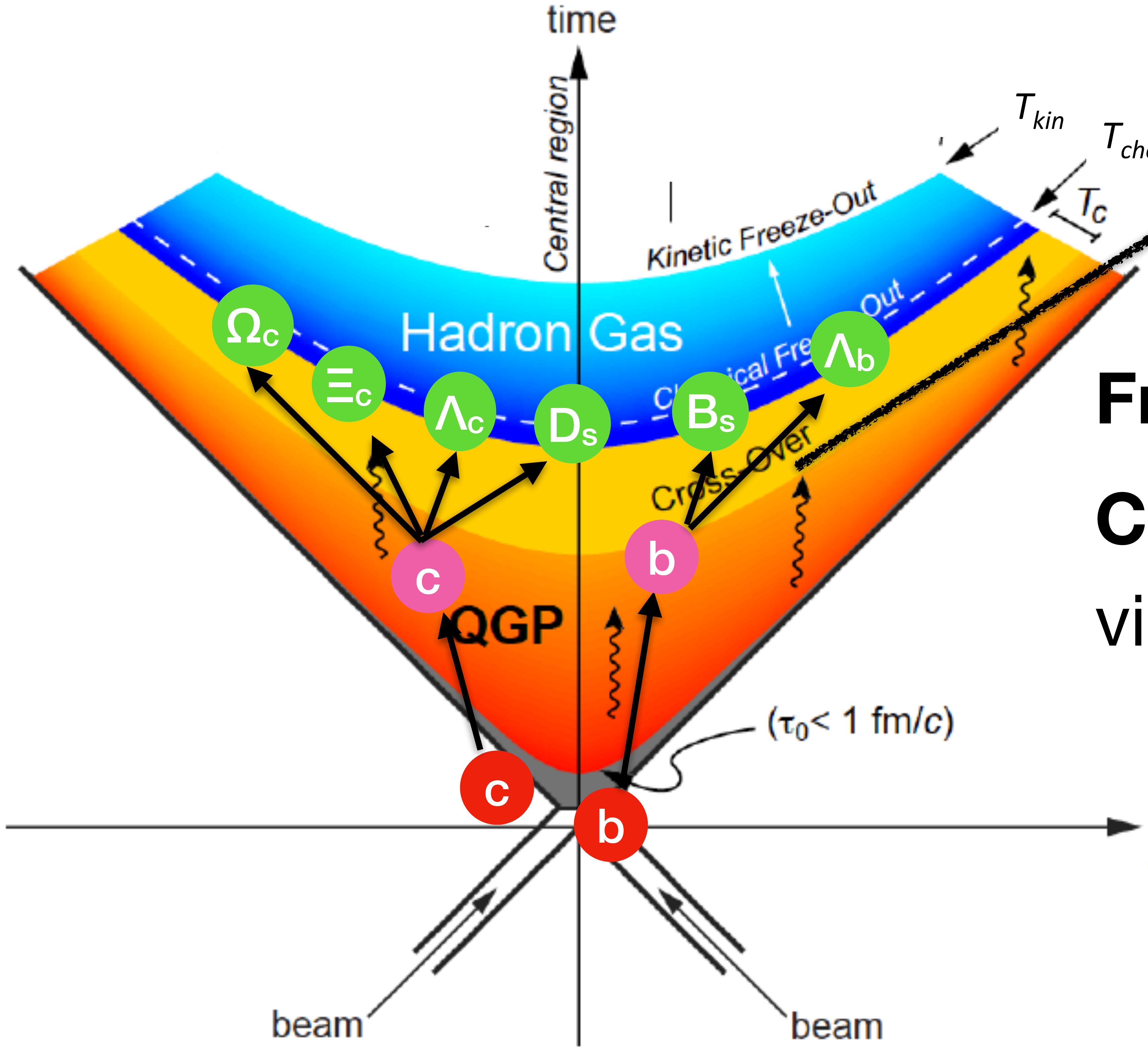
➡ Anisotropic flow

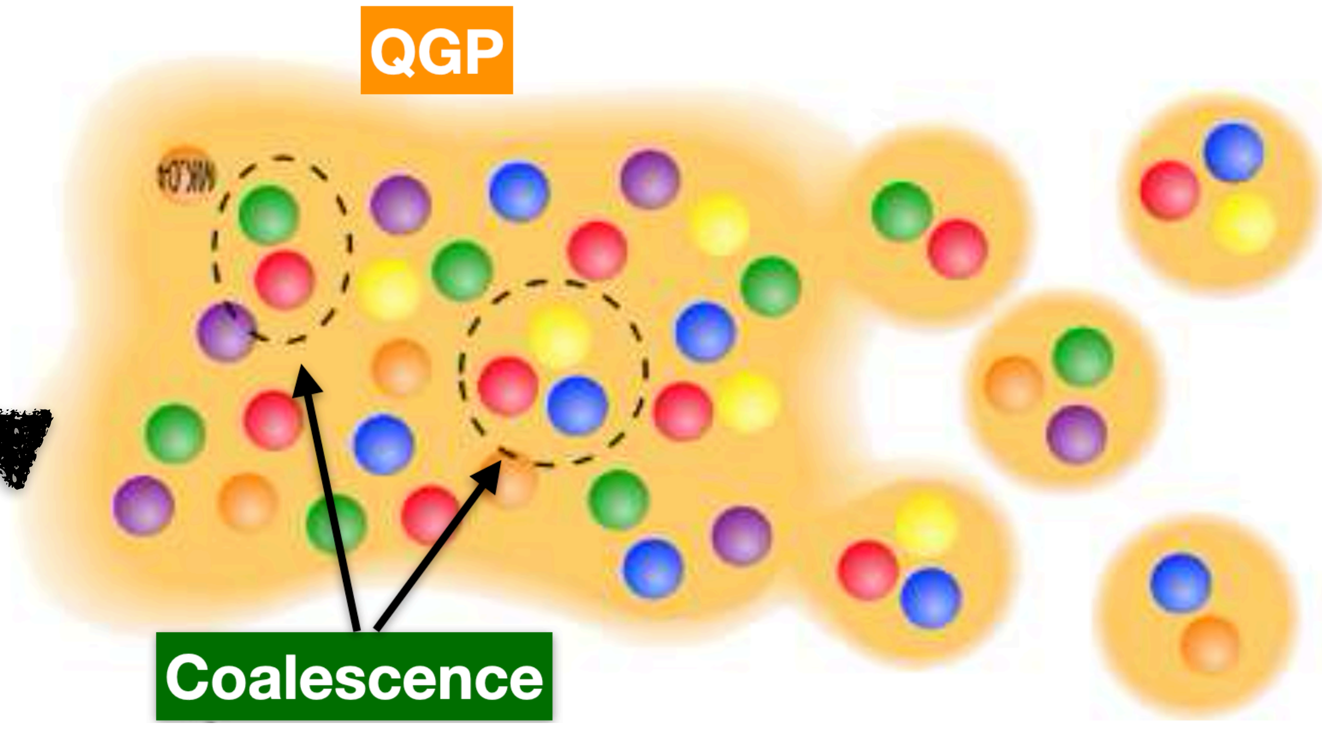


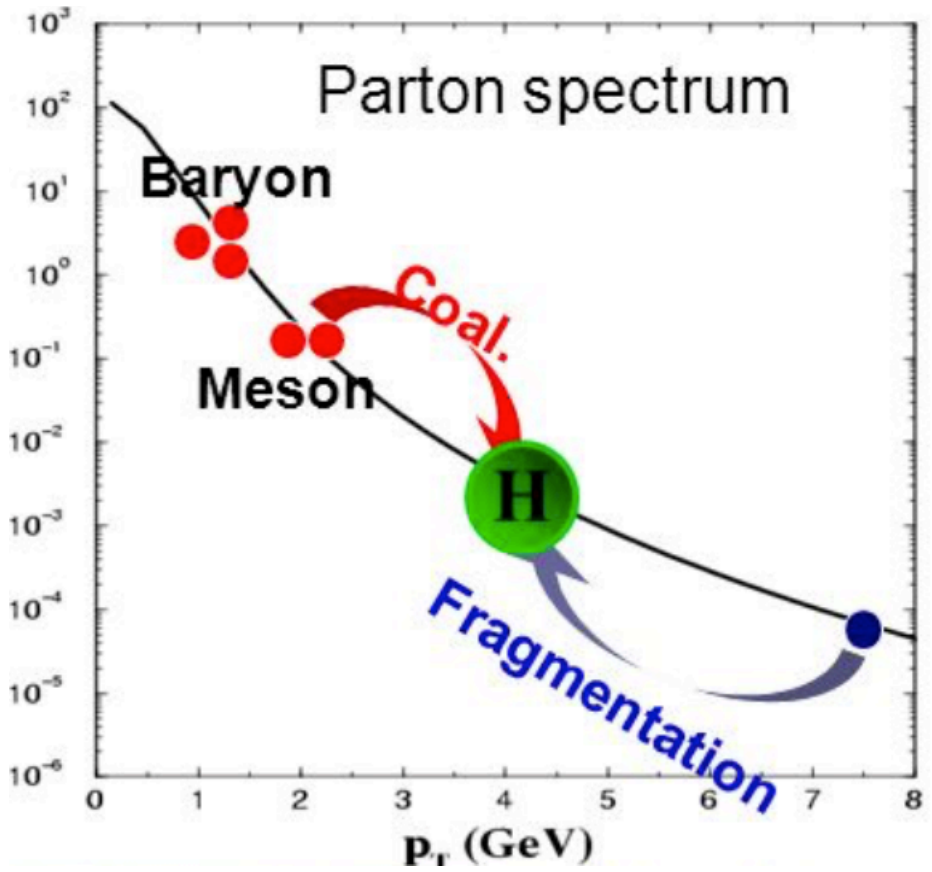
➡ Results in complex azimuthal structure of final-state particles

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

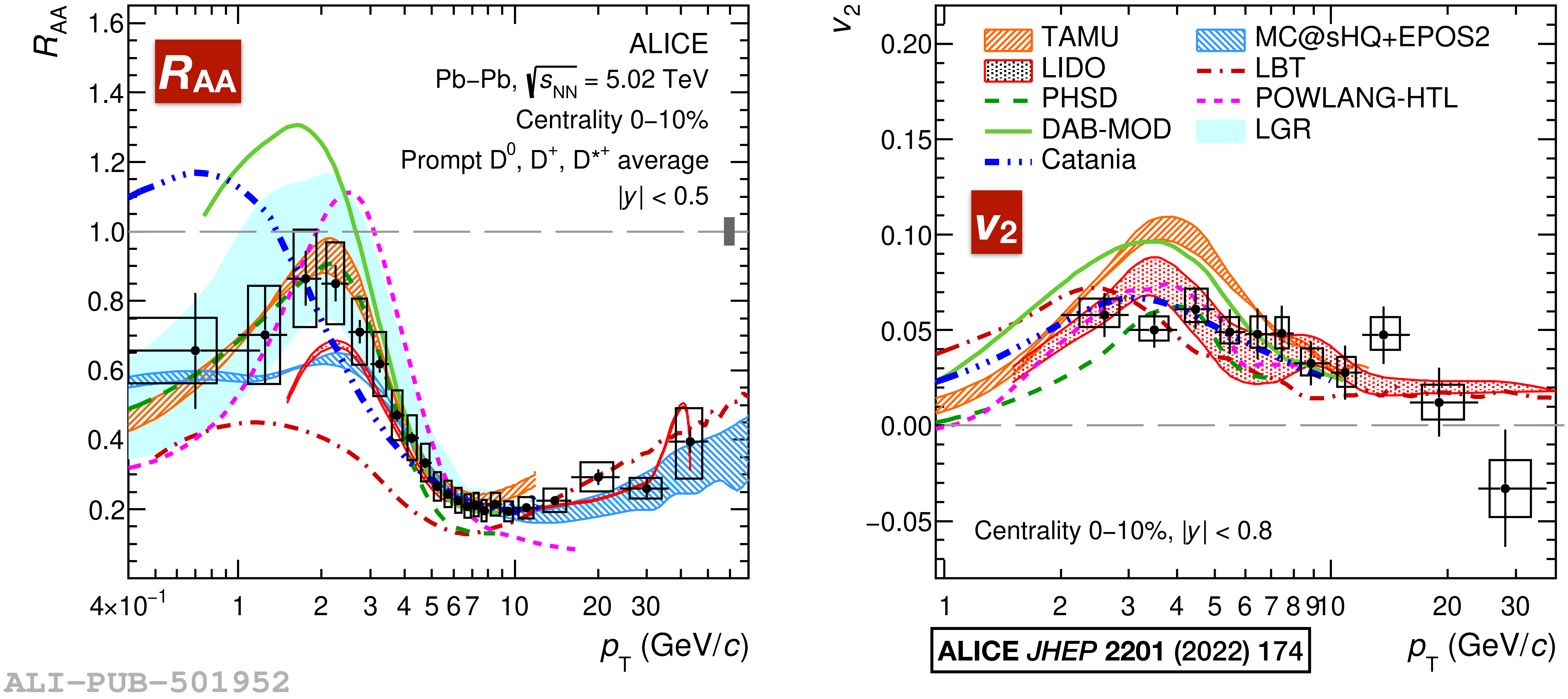
Coalescence/recombination — hadron formation via (di-)quark combination in the QGP medium

➡ $p_{T,hadron} \simeq n\, p_{T,parton}$, n = 2 (meson), 3 (baryon)

➡ Sensitive to baryon and meson species

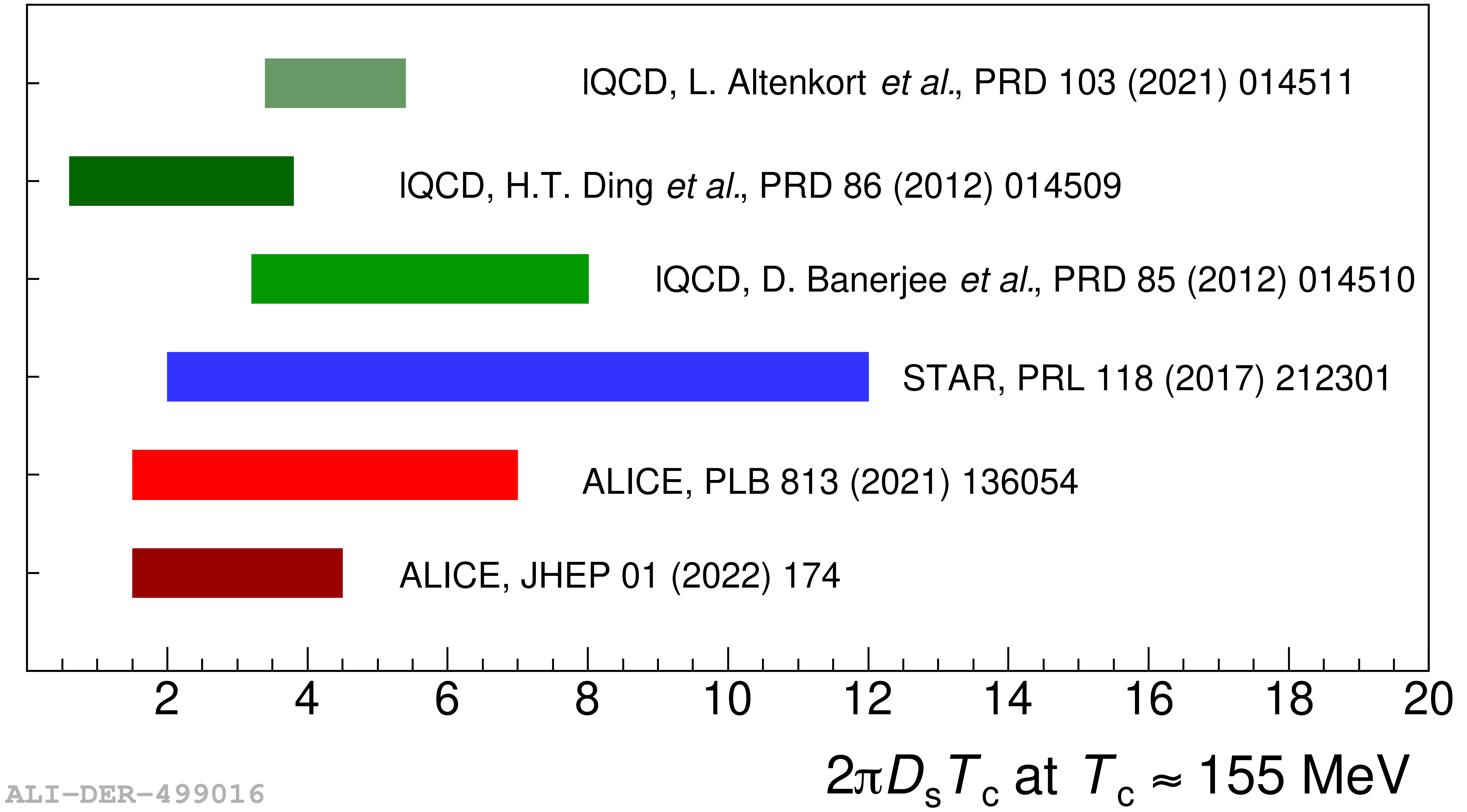
➡ Baryons from lower momenta partons (denser)

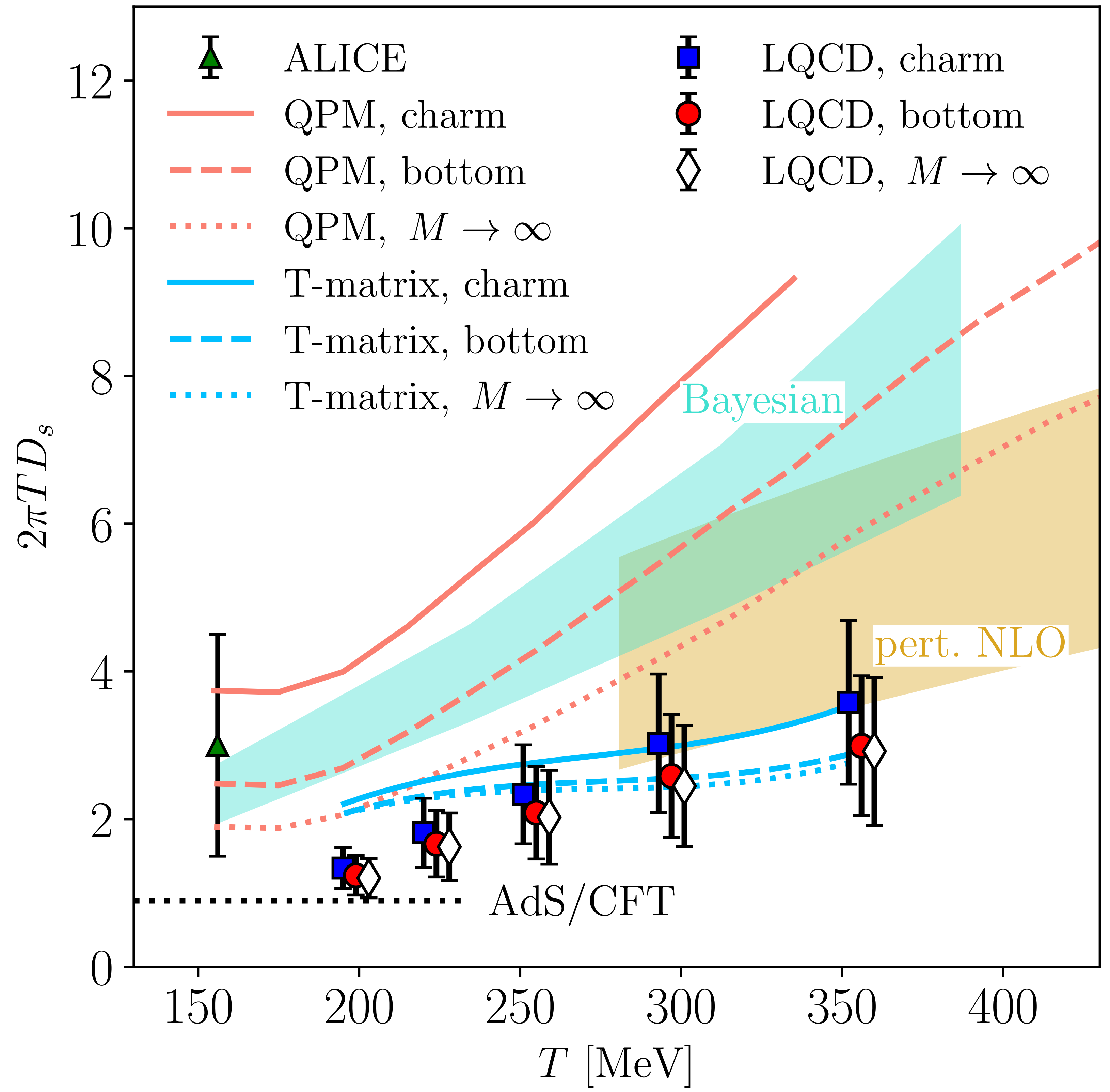
Charm quark transport



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

Charm quark transport



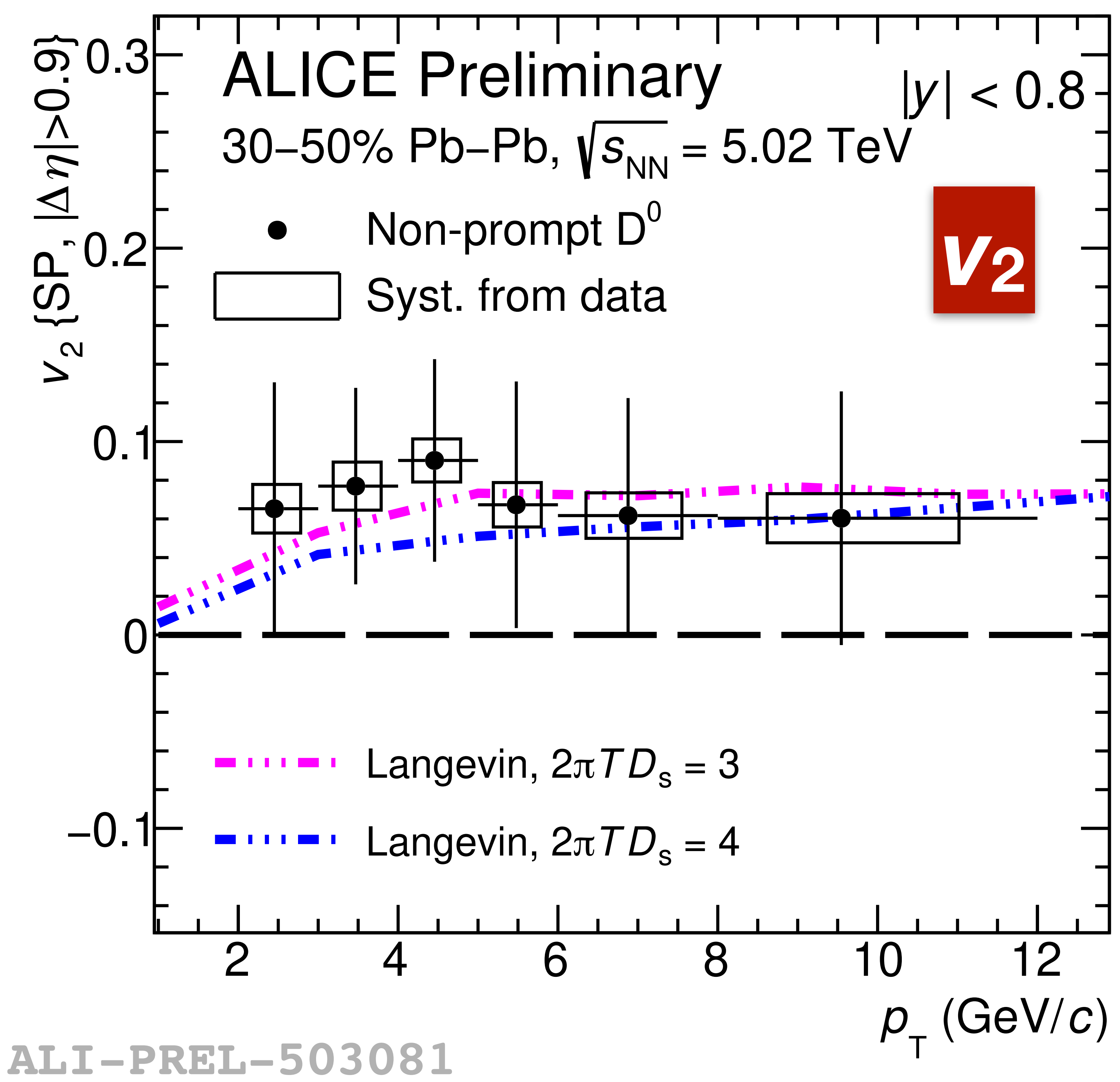


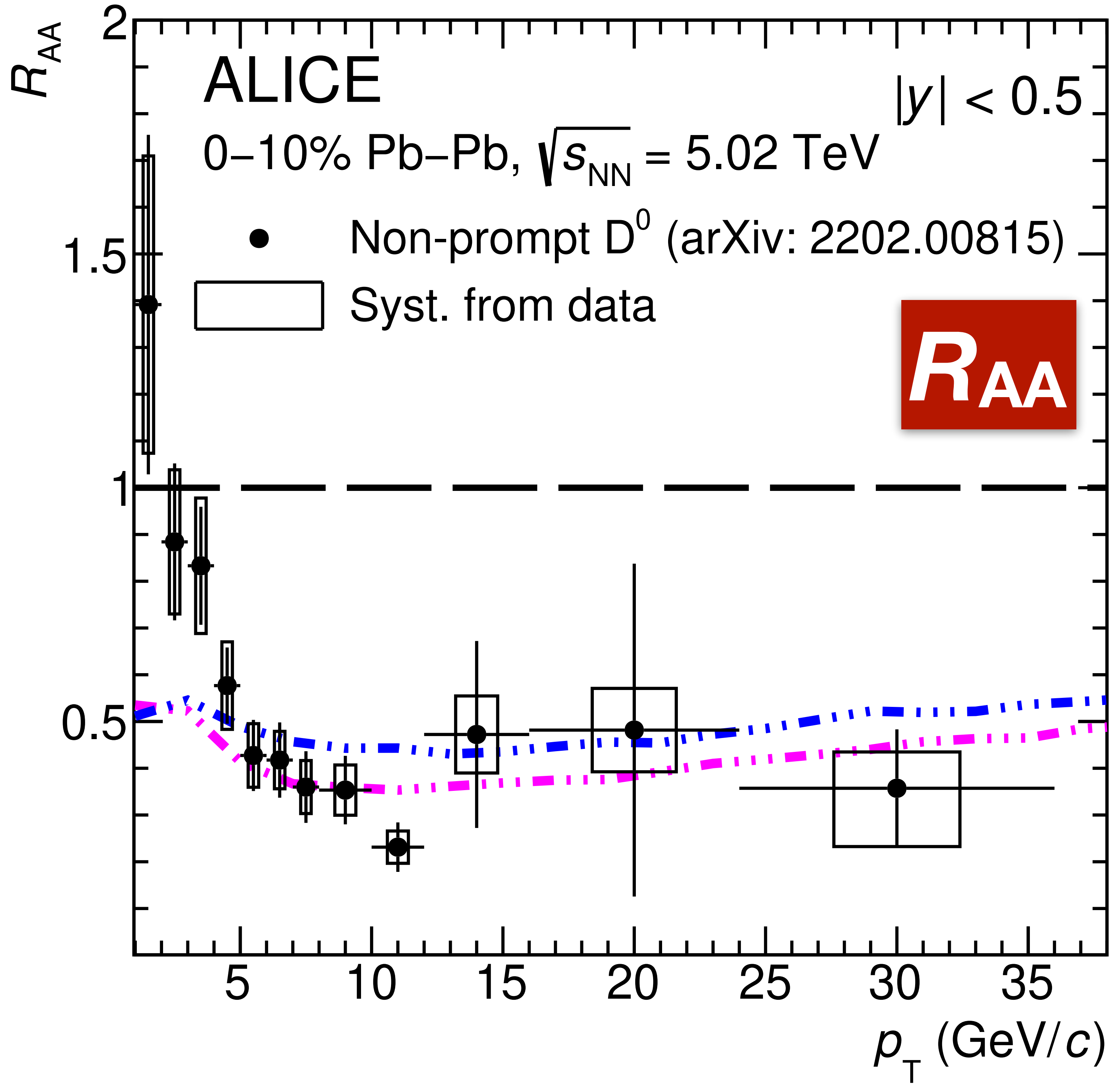
Hot QCD ***Phys. Rev. Lett.*** **132 (2024) 051902**

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

➡ Indicate charm may thermalize in the medium

Beauty quark transport



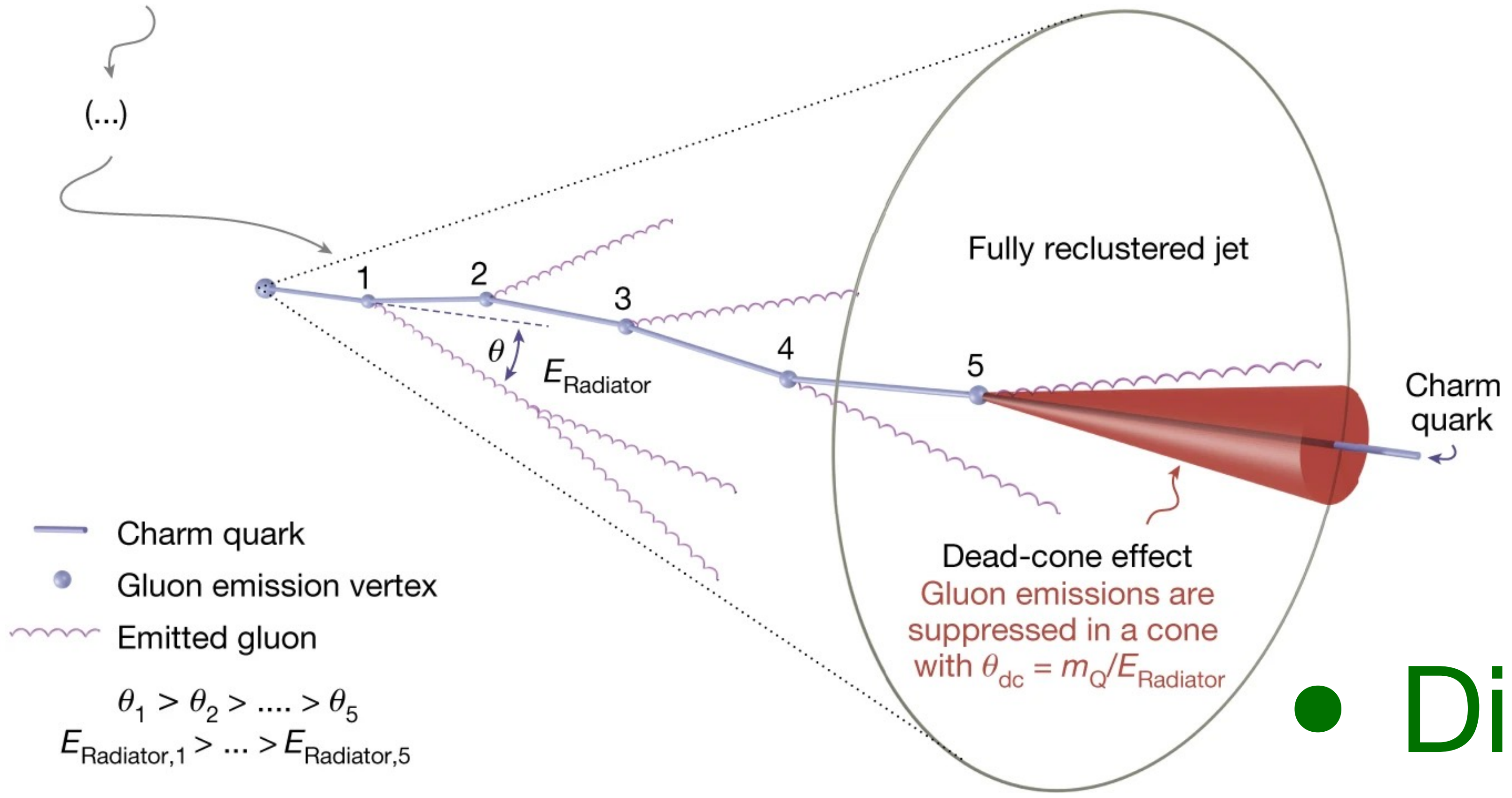


- Beauty particle R_{AA} and v_2 measured via non-prompt D^0 by ALICE
- Conclusion is similar to the measurements of B mesons, non-prompt J/Ψ and B meson semileptonic decays by ATLAS and CMS

- 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 $\tau_{beauty} \propto m_{beauty} D_s \gtrsim \tau_{medium}$ ($m_{beauty} \approx 3\, m_{charm}$)

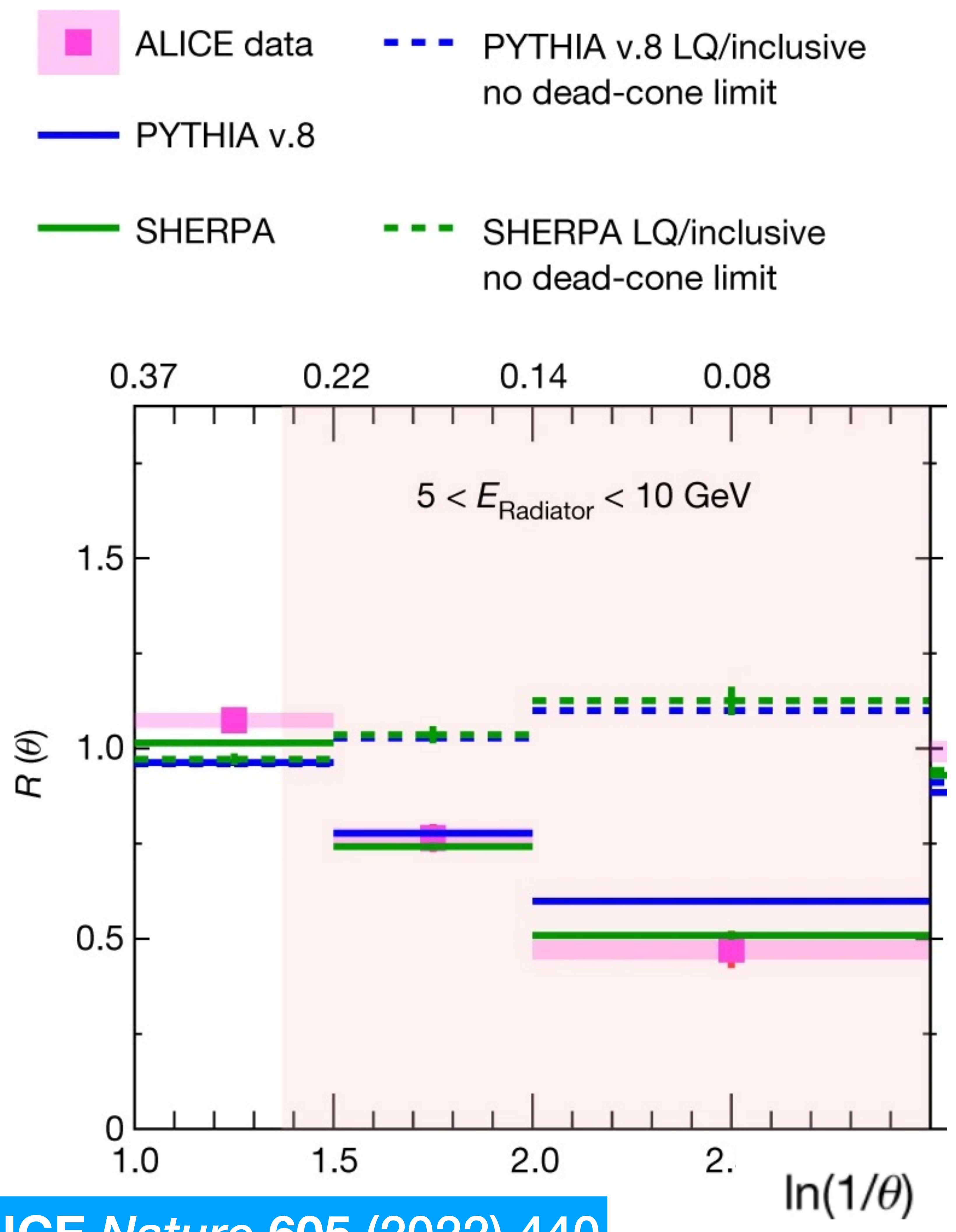
➡ What is thermalization DOF of beauty in the QGP medium?

Dead-cone of heavy quark radiation



One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

- Direct observation for charm quarks in pp — QCD vacuum



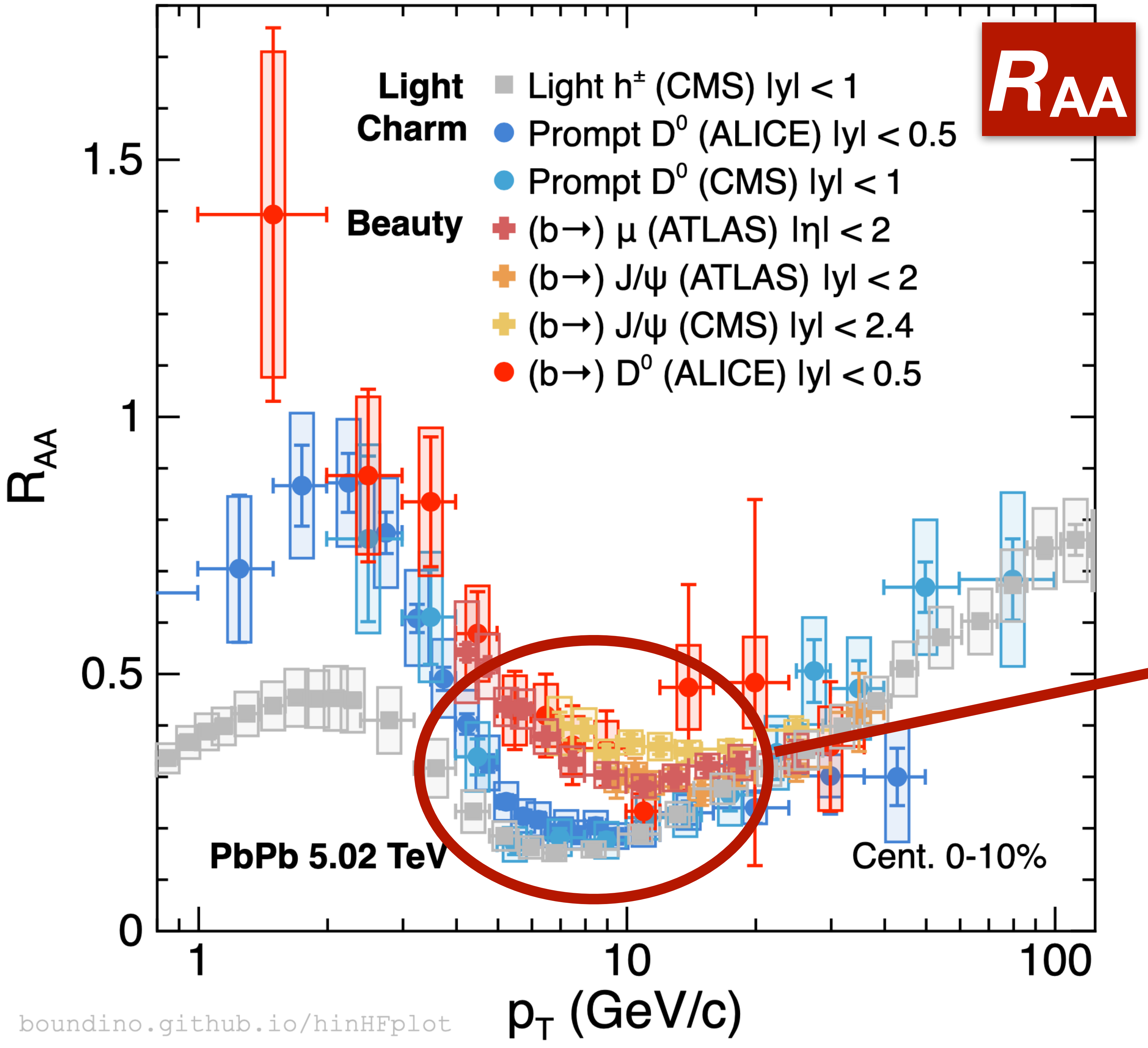
ALICE *Nature* 605 (2022) 440

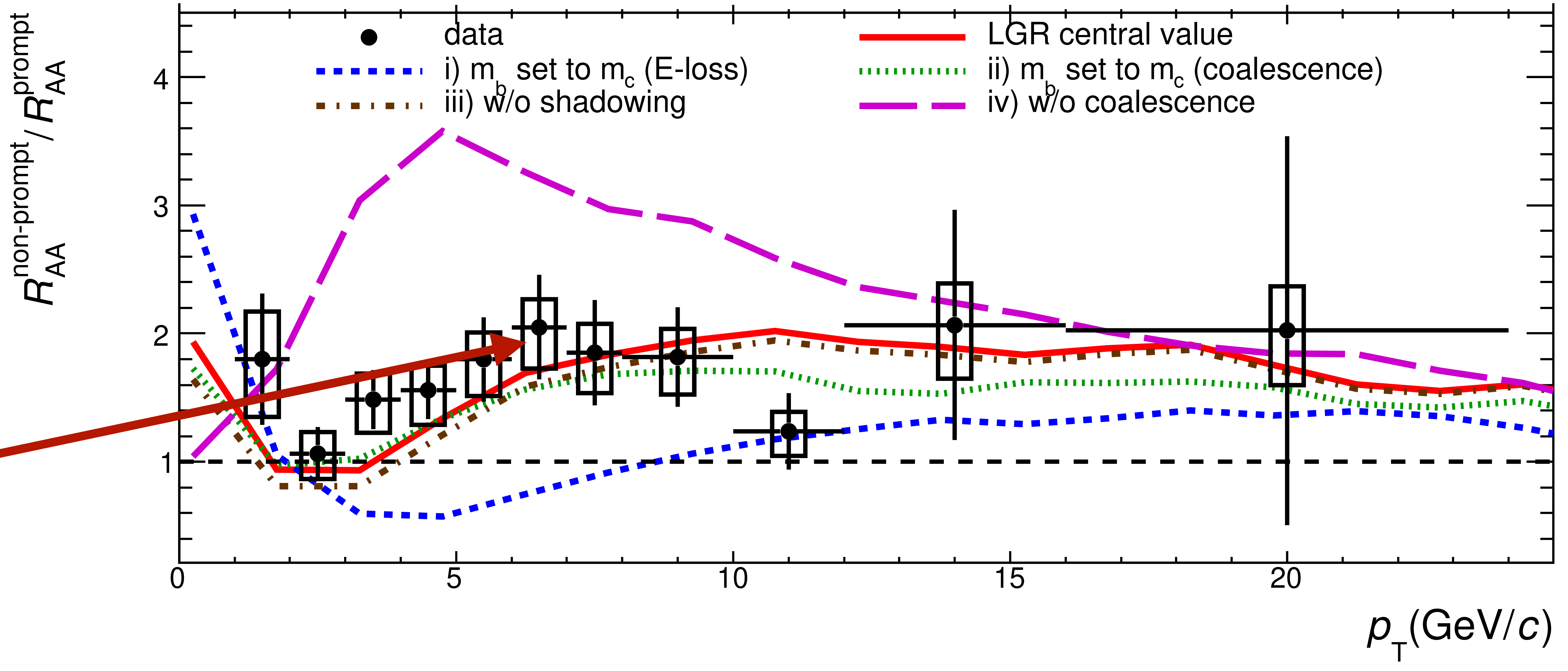
- Whether is it still validated in QCD medium?

➡ Mass dependent heavy quark radiative energy loss

$$\Delta E_{\text{beauty}} < \Delta E_{\text{charm}} \Rightarrow R_{AA}(\text{beauty}) > R_{AA}(\text{charm})$$

Quark mass dependent R_{AA}

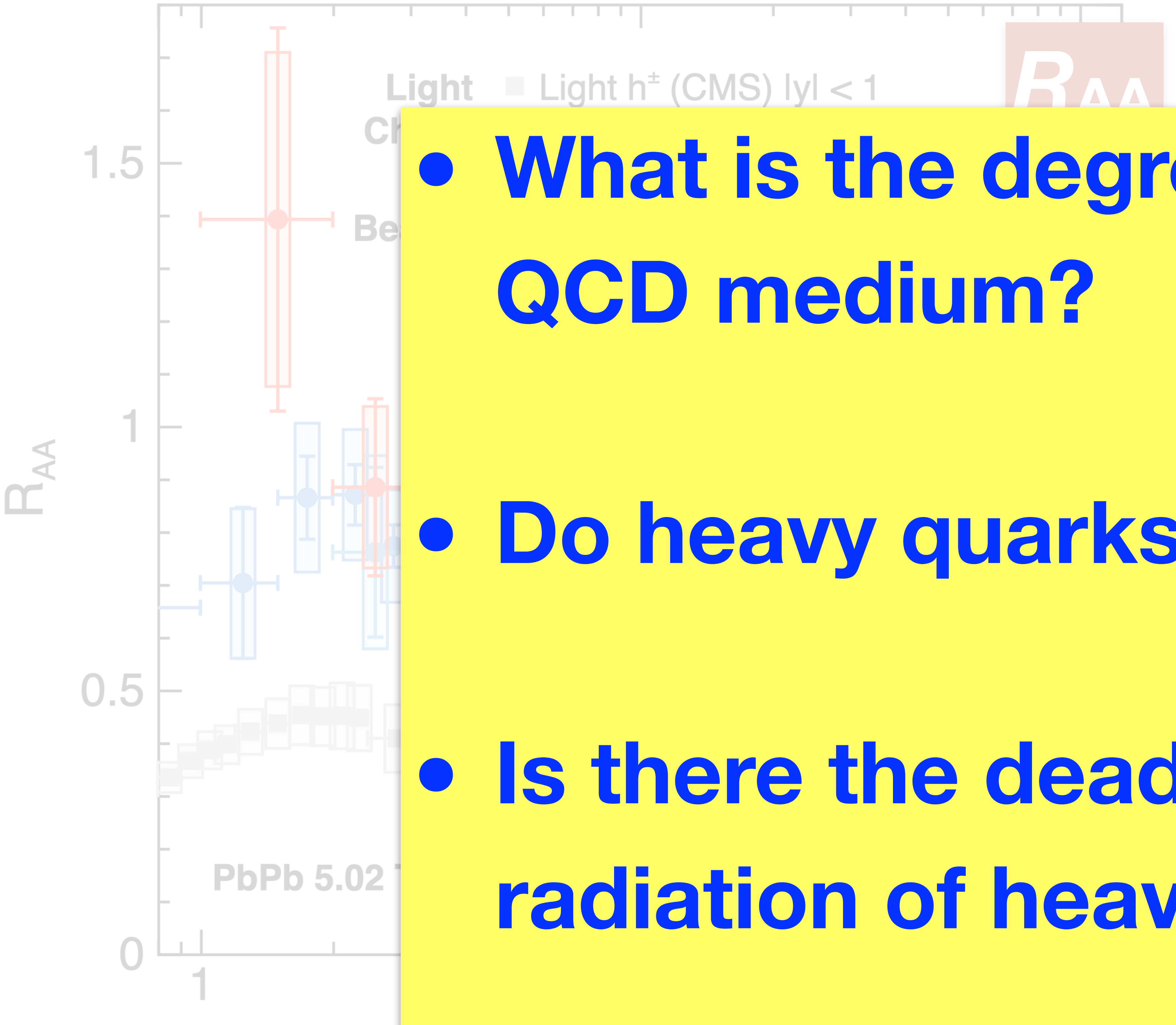




CMS *JHEP* **1704** (2017) 039
CMS *Eur. Phys. J.* **C78** (2018) 509
CMS *JHEP* **2201** (2022) 174
ATLAS *Eur. Phys. J.* **C78** (2018) 762
ATLAS *Phys. Lett.* **B829** (2022) 137077
ALICE *JHEP* **2201** (2022) 174
ALICE *Phys. Lett.* **B782** (2018) 474

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

What do we learn?



- **What is the degree of thermalization of heavy quarks in QCD medium?**

- **Do heavy quarks hadronization via coalescence in QGP?**

- **Is there the dead-cone effect of medium-induced gluon radiation of heavy quarks?**

- **What can we learn more from heavy quarks?**

CMS *JHEP* ...
CMS *Eur. Phys. J.* **C78** (2018) 509
CMS *JHEP* **2201** (2022) 174
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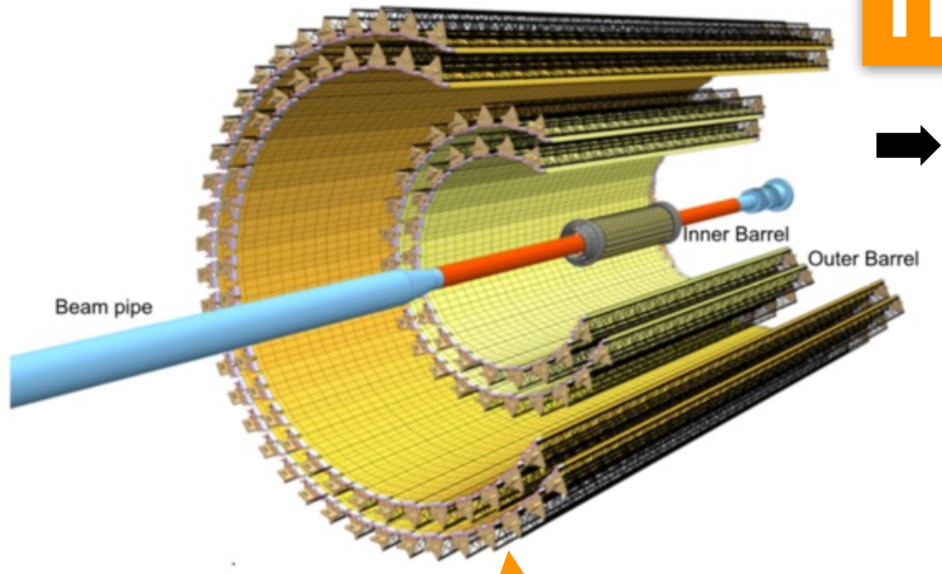
ALICE detector at LHC Run 3

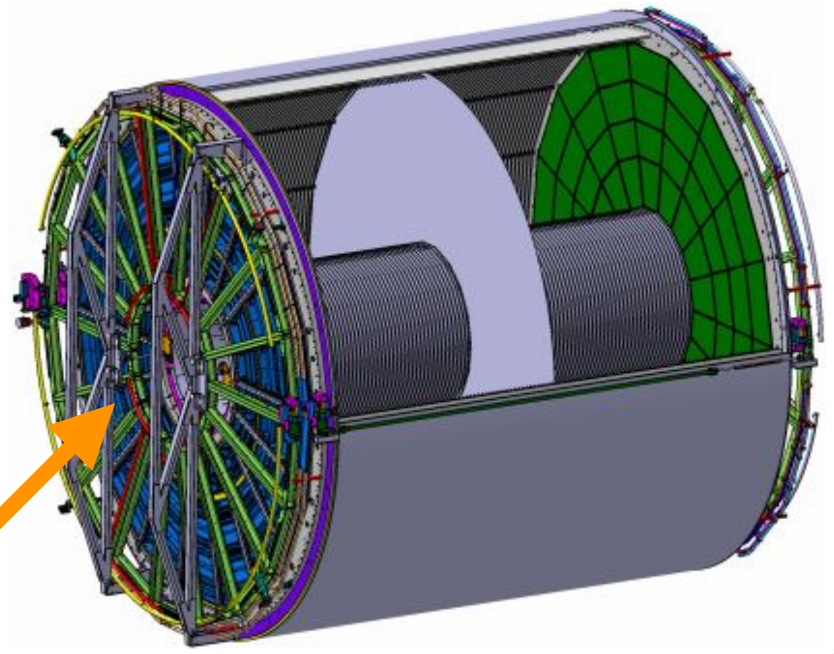


The 2nd generation inner tracking system (ITS2)

➡ 7 layers MAPS detector, the innermost layer closer to interaction point

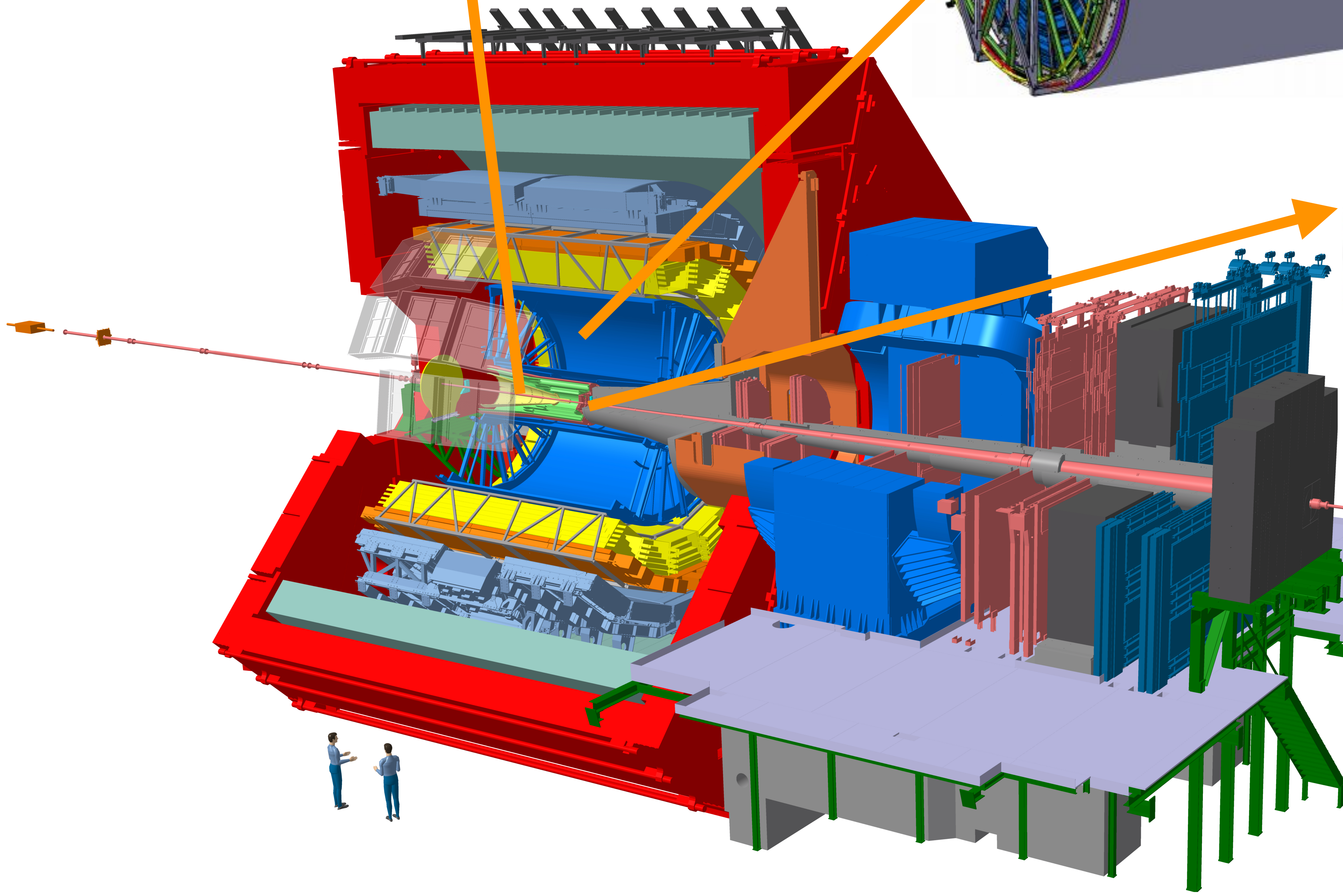
Readout of most detectors are upgraded to allow continuous readout

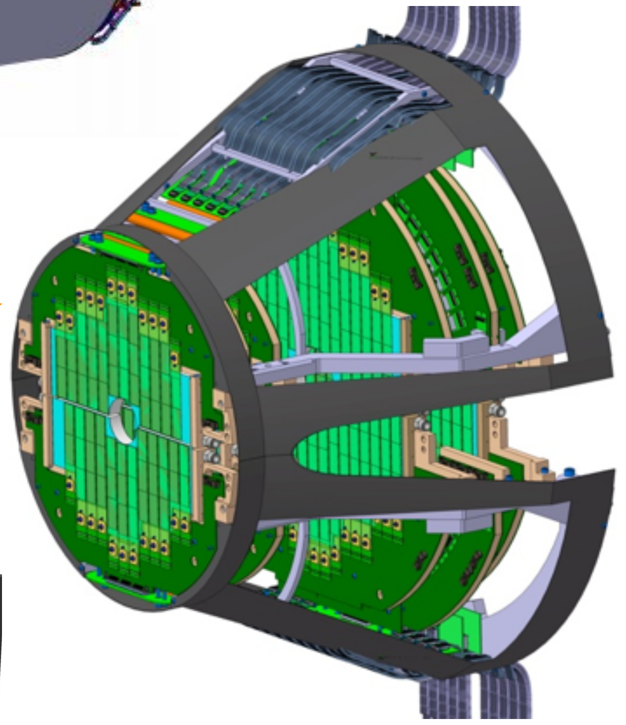
- **pp data taking at 500 kHz**
- **Pb–Pb data taking up to 50 kHz**
- **Improved vertexing**
- **Improved tracking at low p_T**



Time projection chamber (TPC)

➡ New readout: MWPC → GEM



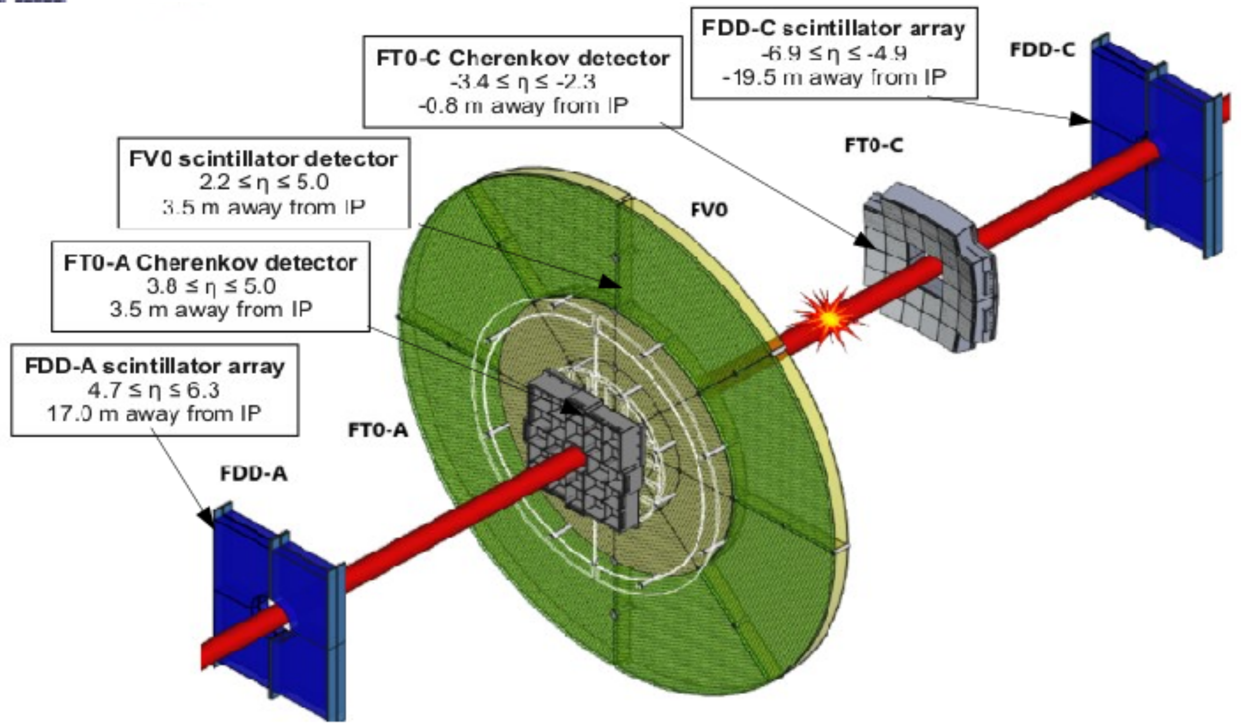


Muon forward tracker (MFT)

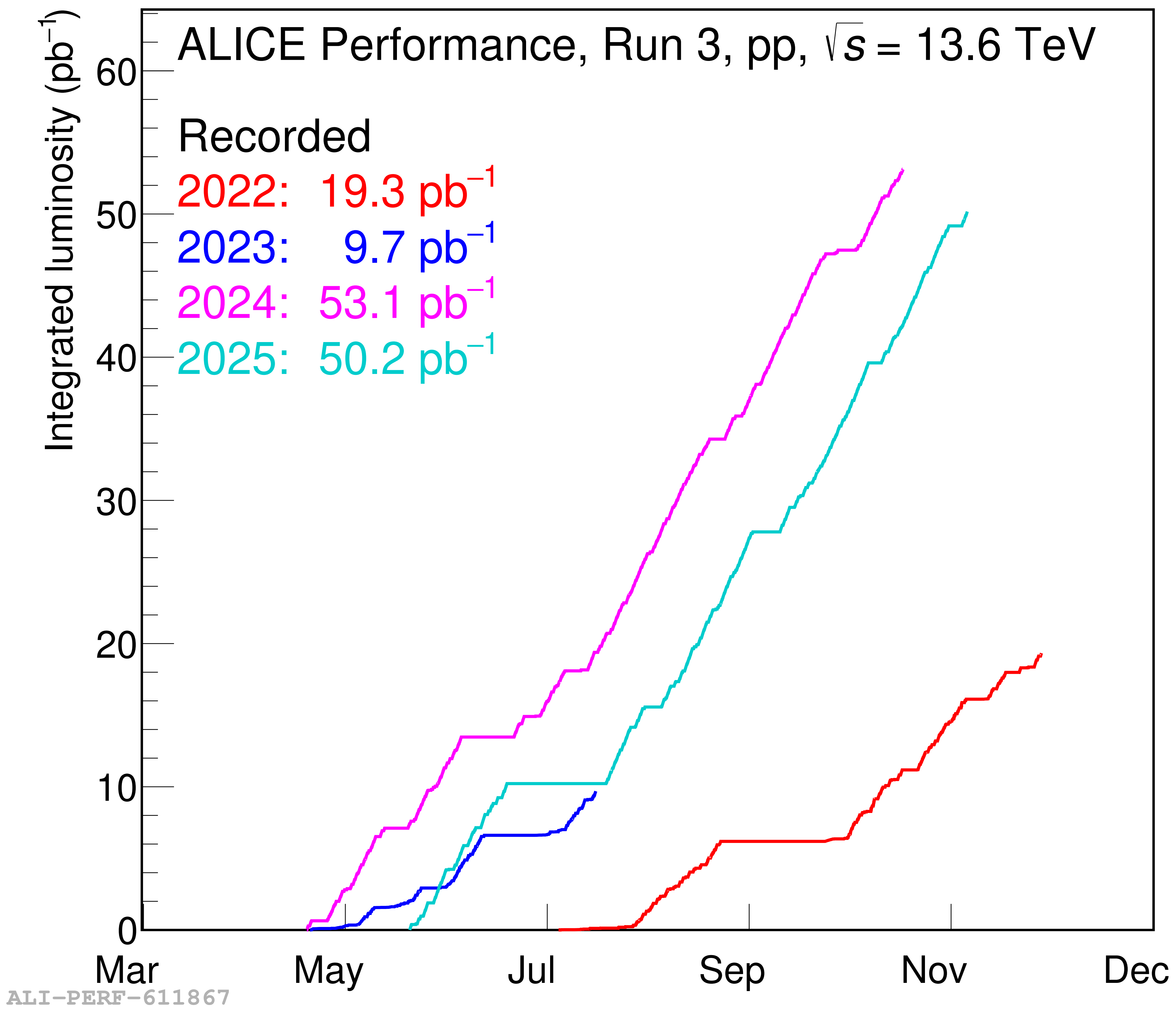
➡ 5 planes of MAPS, vertexing for forward rapidity muons

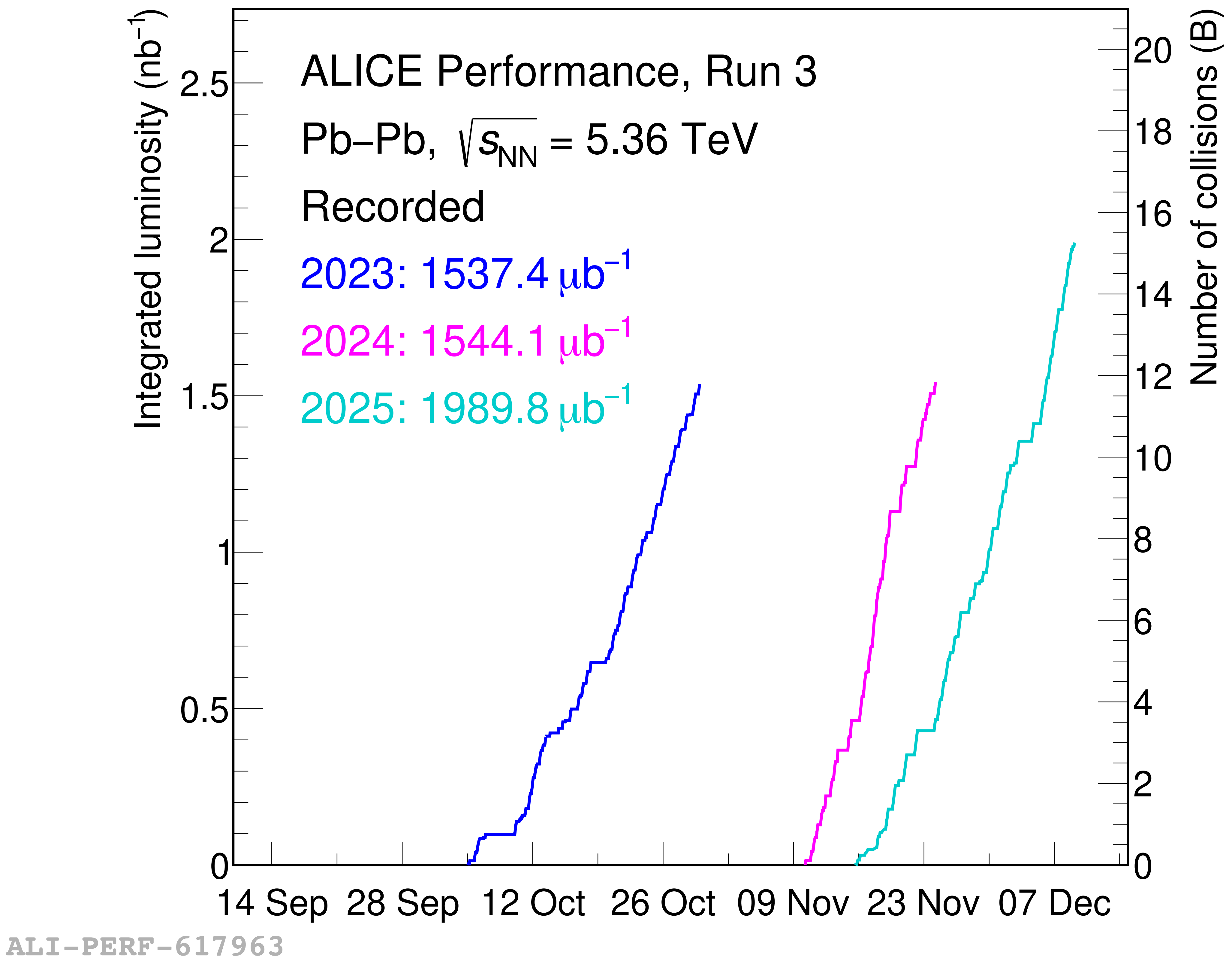
Fast integration trigger (FIT)

➡ Event trigger, characterization, and online luminometer,



ALICE date taking in Run 3





pp: 6.5 trillion MB events

×2000 more than Run 1+2

Pb–Pb: 40 billion MB events

×110 more than Run 1+2

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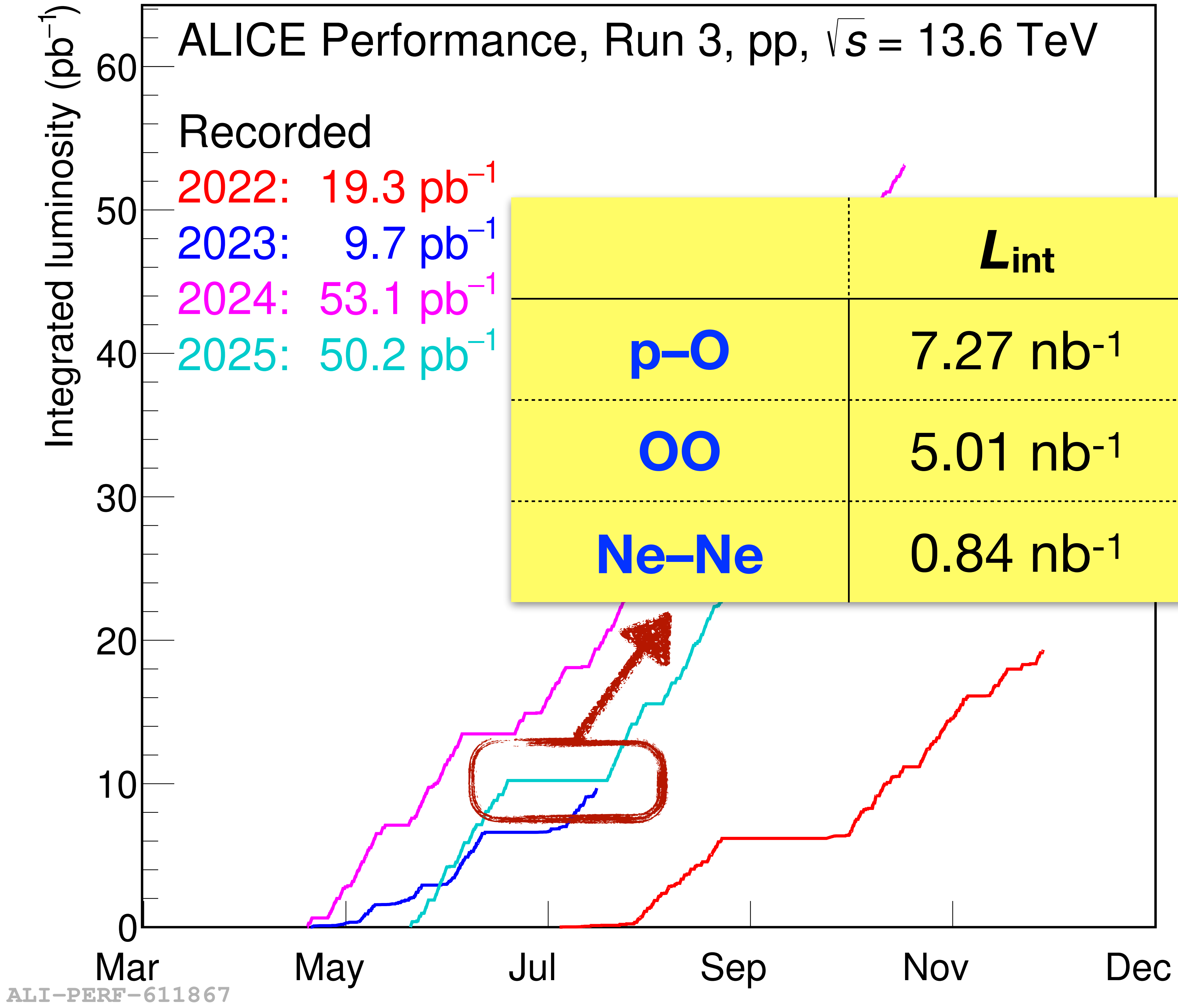
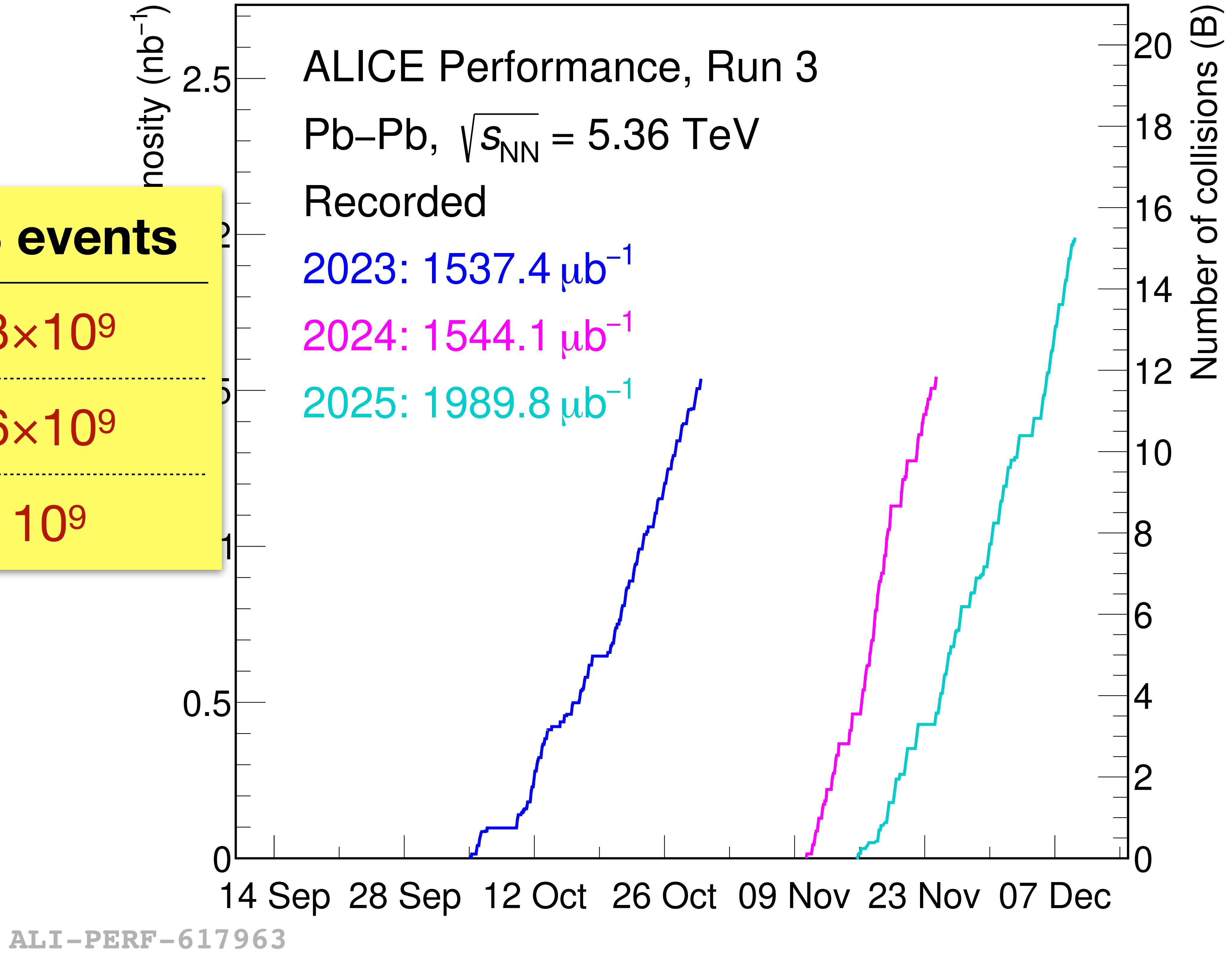


	L_{int}	MB events
p–O	7.27 nb^{-1}	3×10^9
OO	5.01 nb^{-1}	6×10^9
Ne–Ne	0.84 nb^{-1}	10^9



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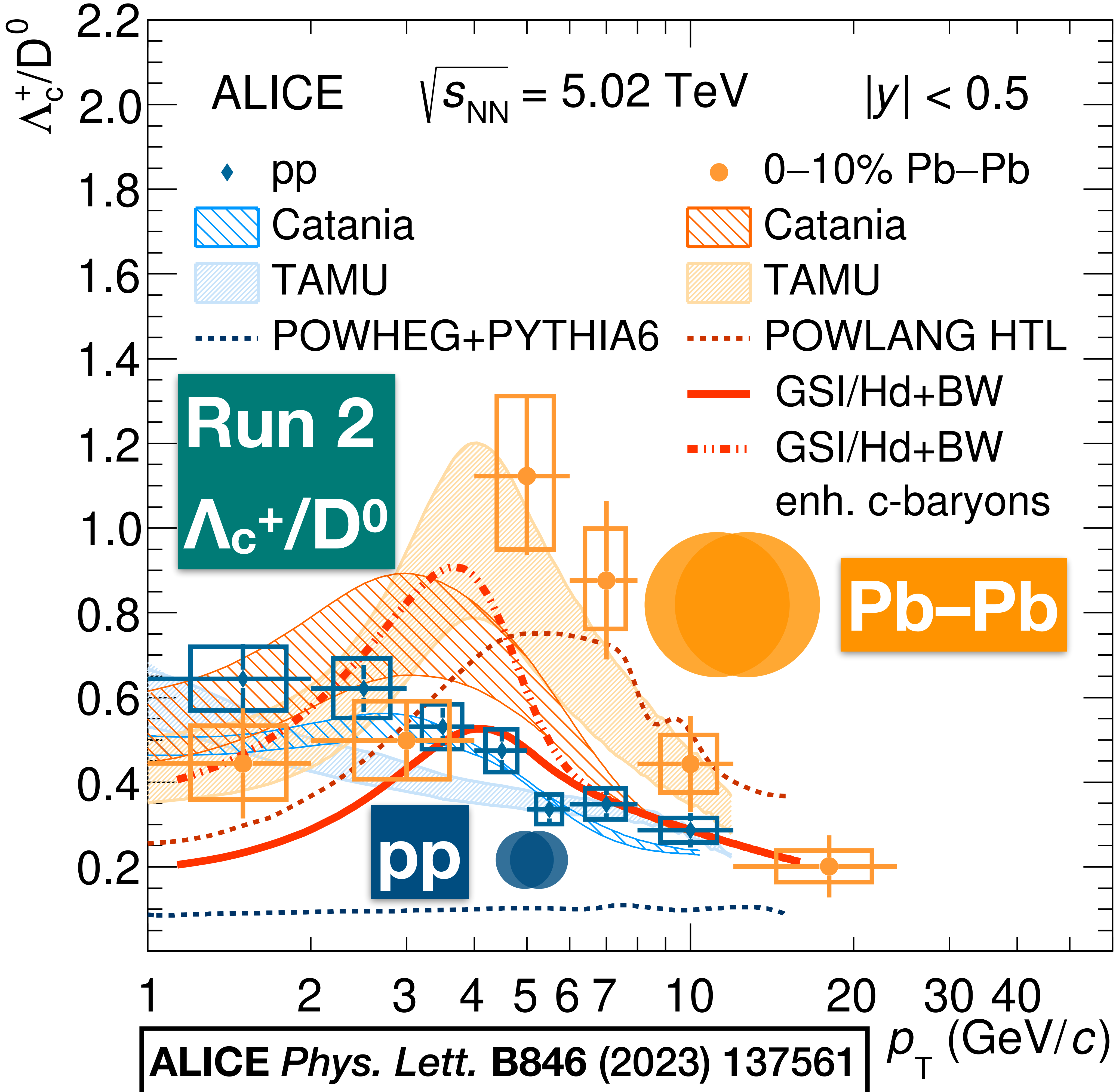
Constrain on hadronizaton?

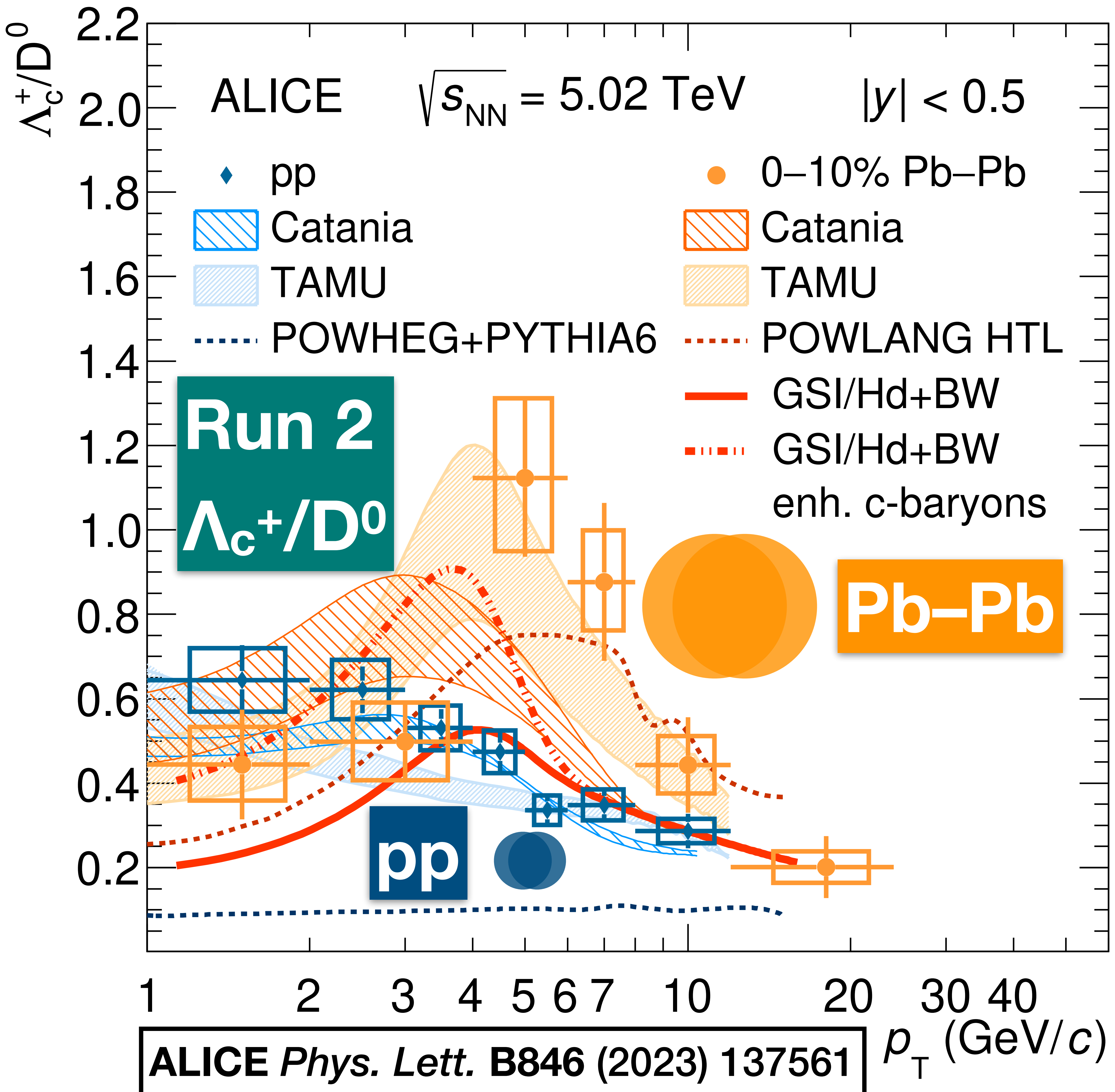


ALICE *Phys. Lett.* **B846** (2023) 137561
ALICE *Phys. Lett.* **B839** (2023) 137796

Interplay between hadronization and energy loss

➡ Higher precision and more differential measurements are needed

Constrain on hadronizaton?



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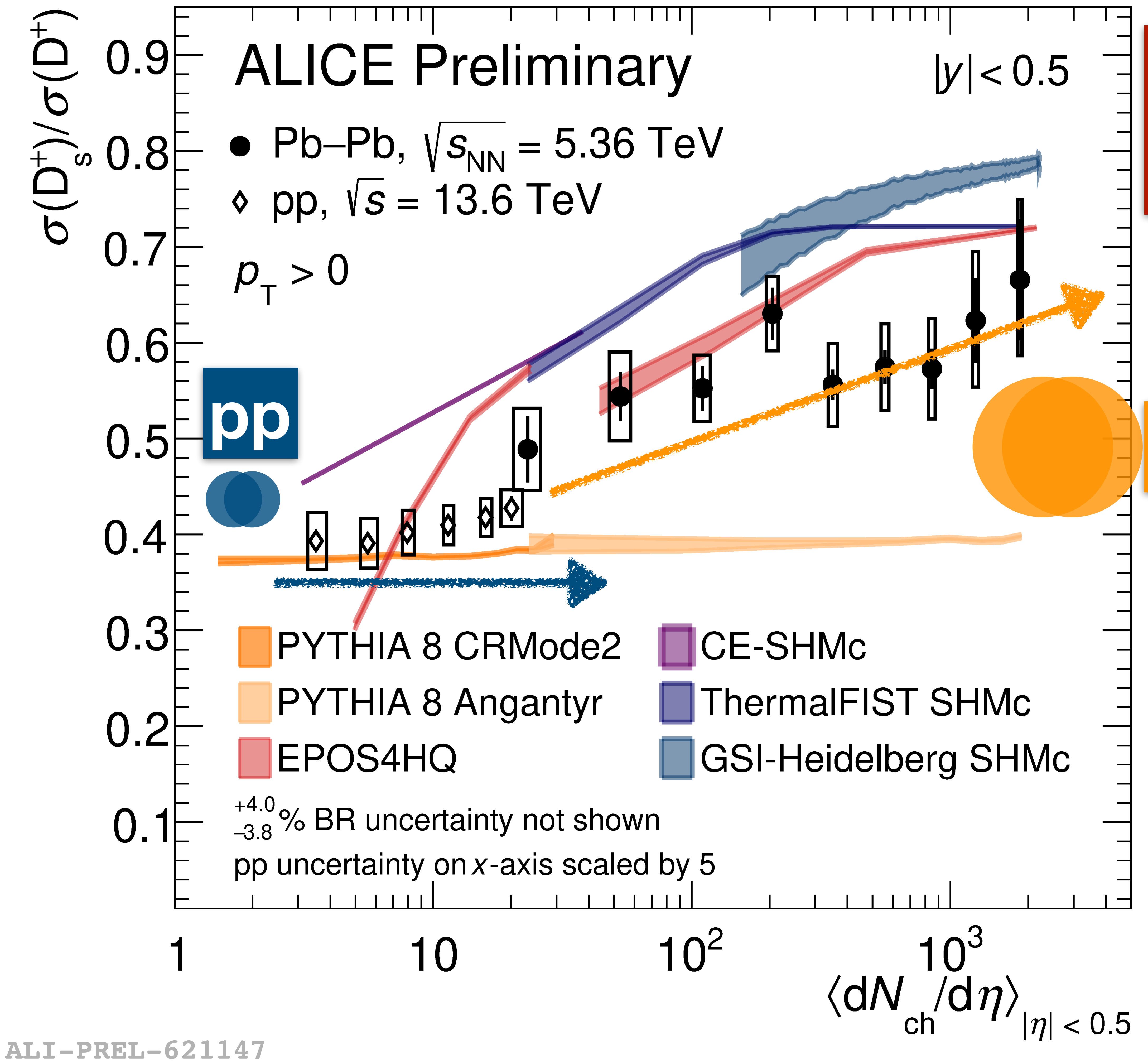
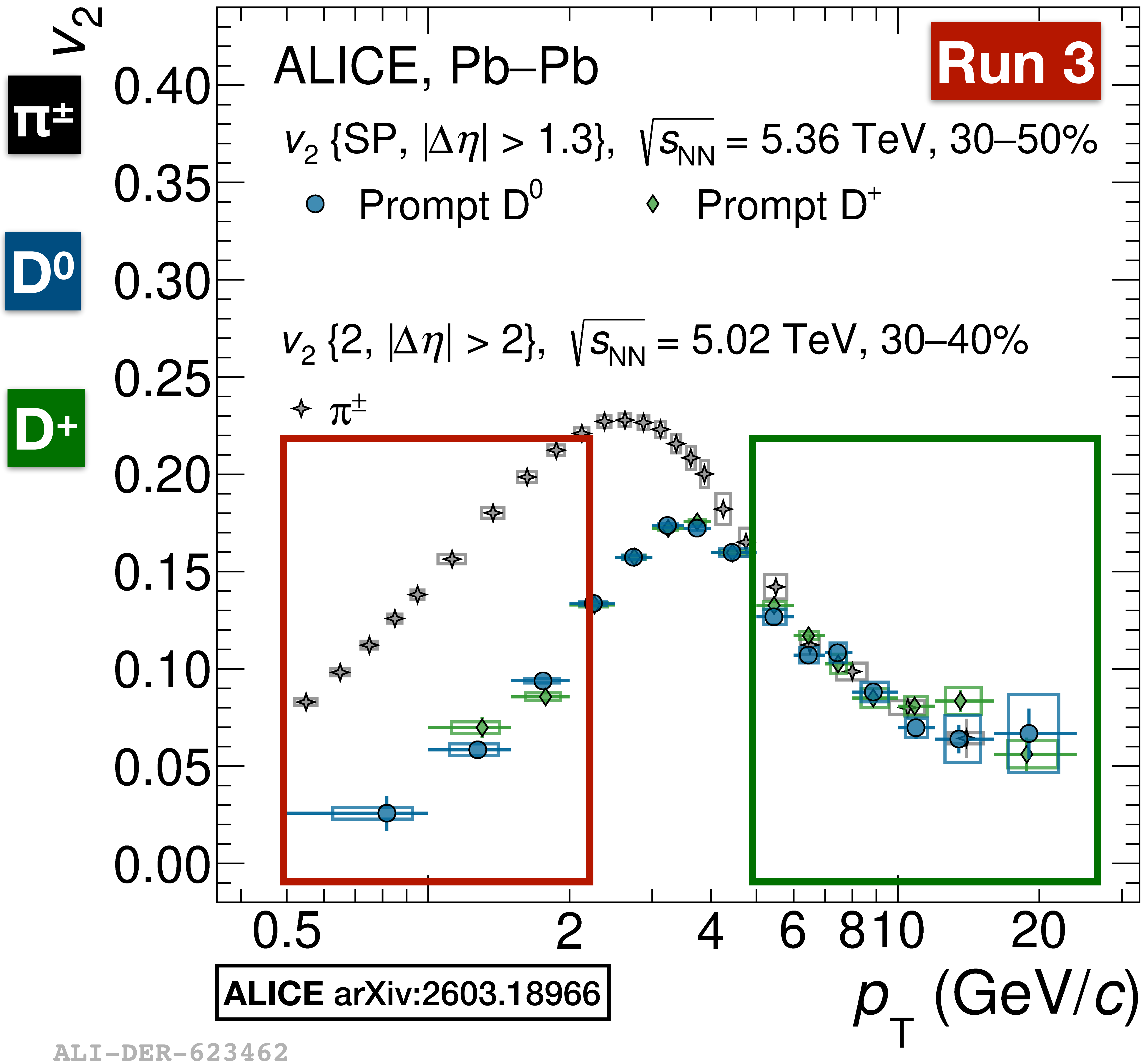


Run 3
D_s^+/D^+

Pb–Pb

Supports hadronisation also via coalescence in the deconfined strangeness-enhanced medium

Charm hadron v_2 in Run 3



Low and intermediate–p_T

$v_2(D^0) \approx v_2(D^\pm) < v_2(\pi^\pm)$

➡ Interplay between radial and elliptic flow

High-p_T

$v_2(D^0) \approx v_2(D^+) \approx v_2(\pi^\pm)$

➡ Path-length dependent energy loss

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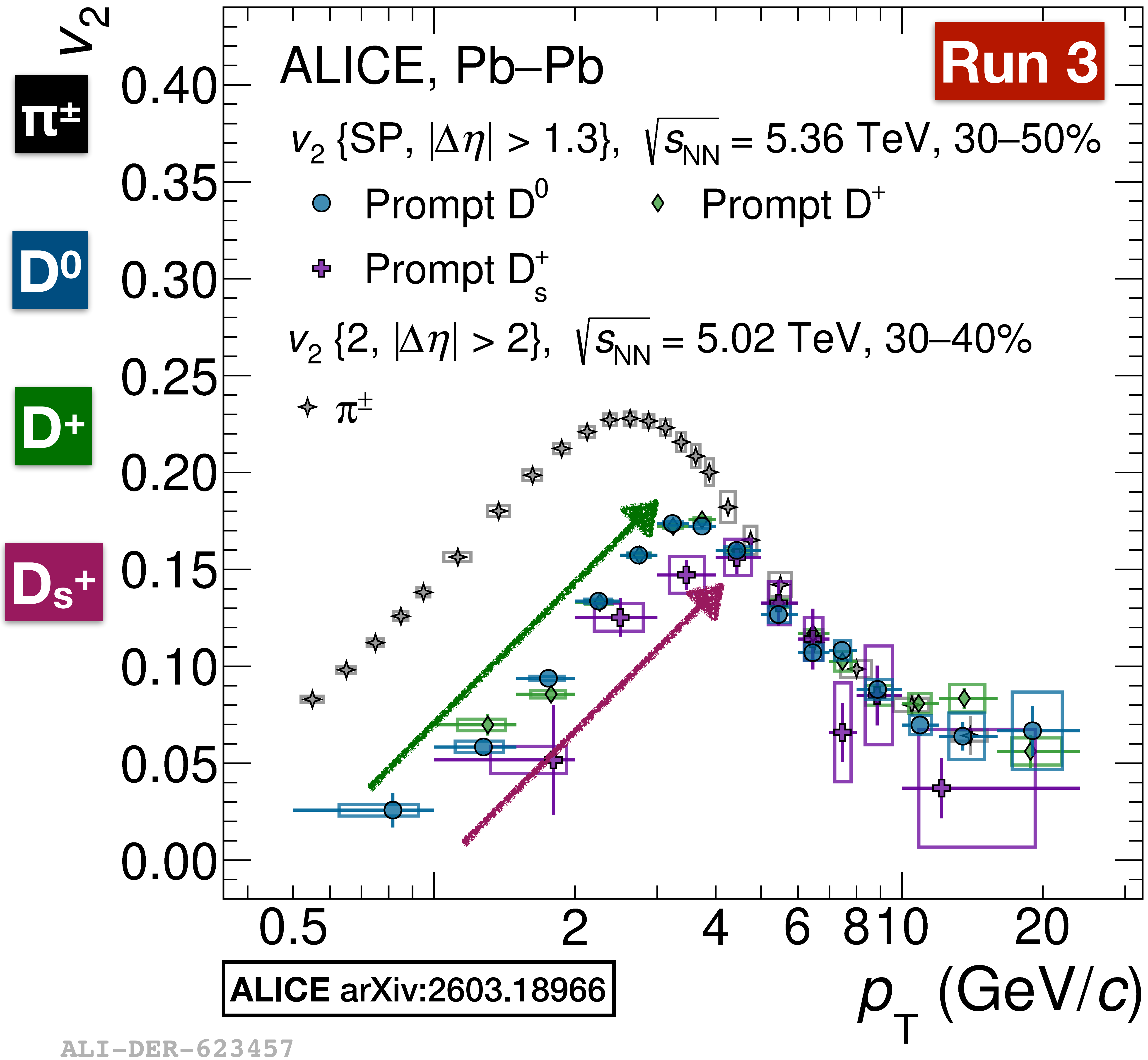

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$v_2(D_s^{\pm}) < v_2(D^0) \approx v_2(D^{\pm}) < v_2(\pi^{\pm})$

➡ Interplay between radial and elliptic flow

➡ D_s^+ early kinetic freeze-out

Fries *et al. Phys. Rev. Lett.* **110** (2013) 112301

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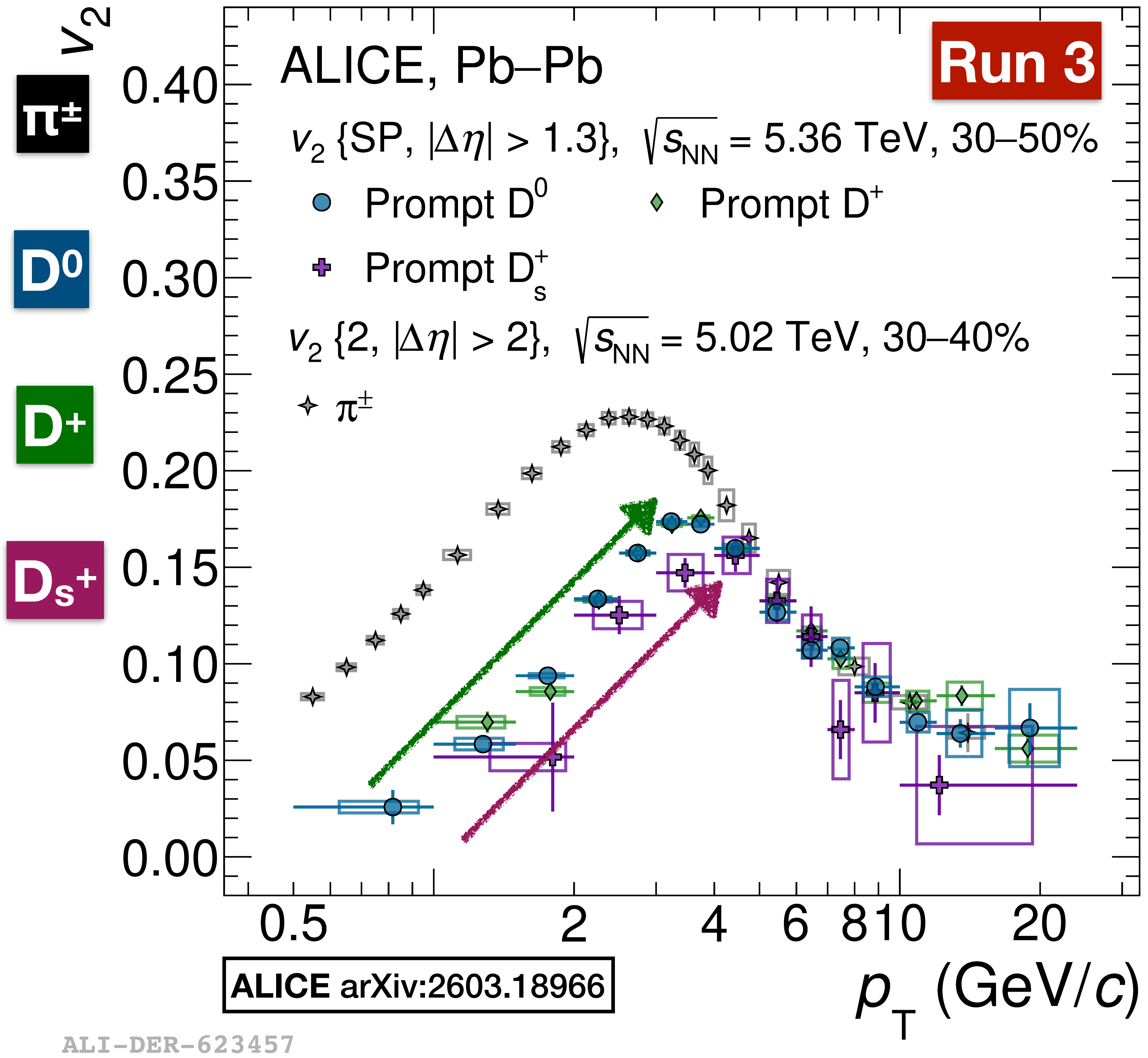

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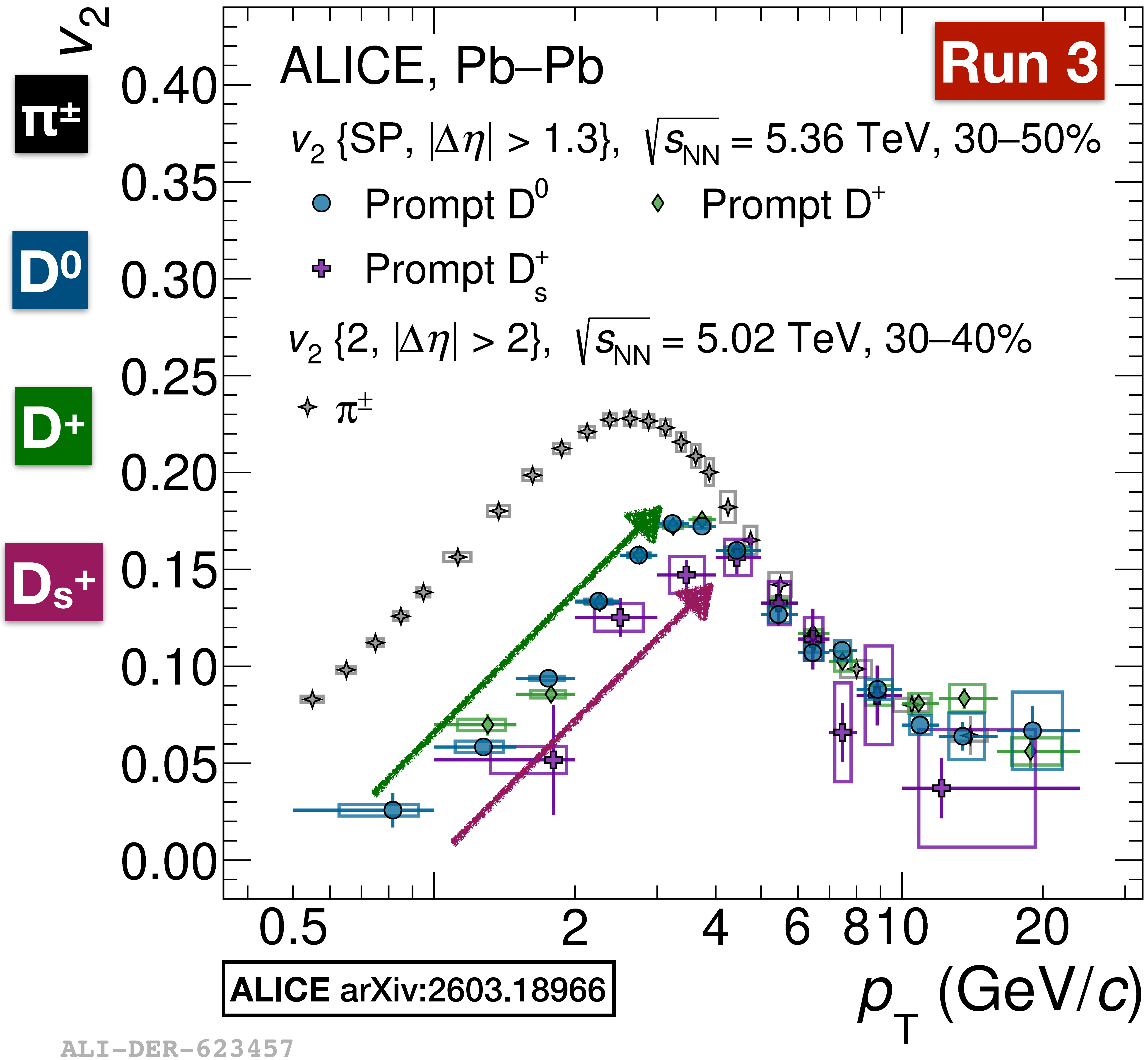

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➡ Sequential hadronization Zhao, Shi, Xu, and Zhuang *Springer Proc. Phys.* **250** (2020) 275

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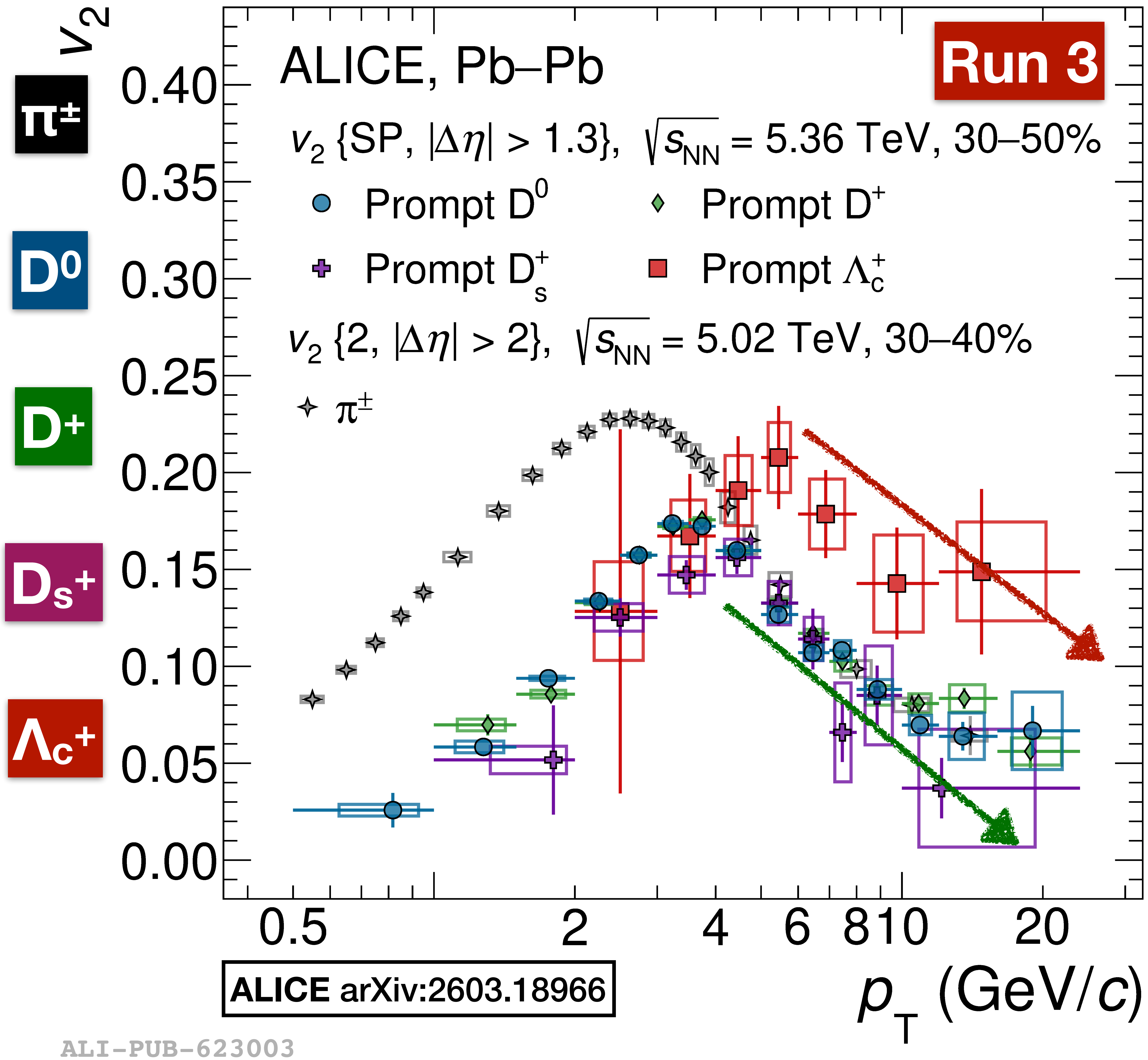

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High-p_T

$v_2(D_s^+) \approx v_2(D^0) \approx v_2(D^+) \approx v_2(\pi^\pm)$

➡ Path-length dependent energy loss

Intermediate and high-p_T

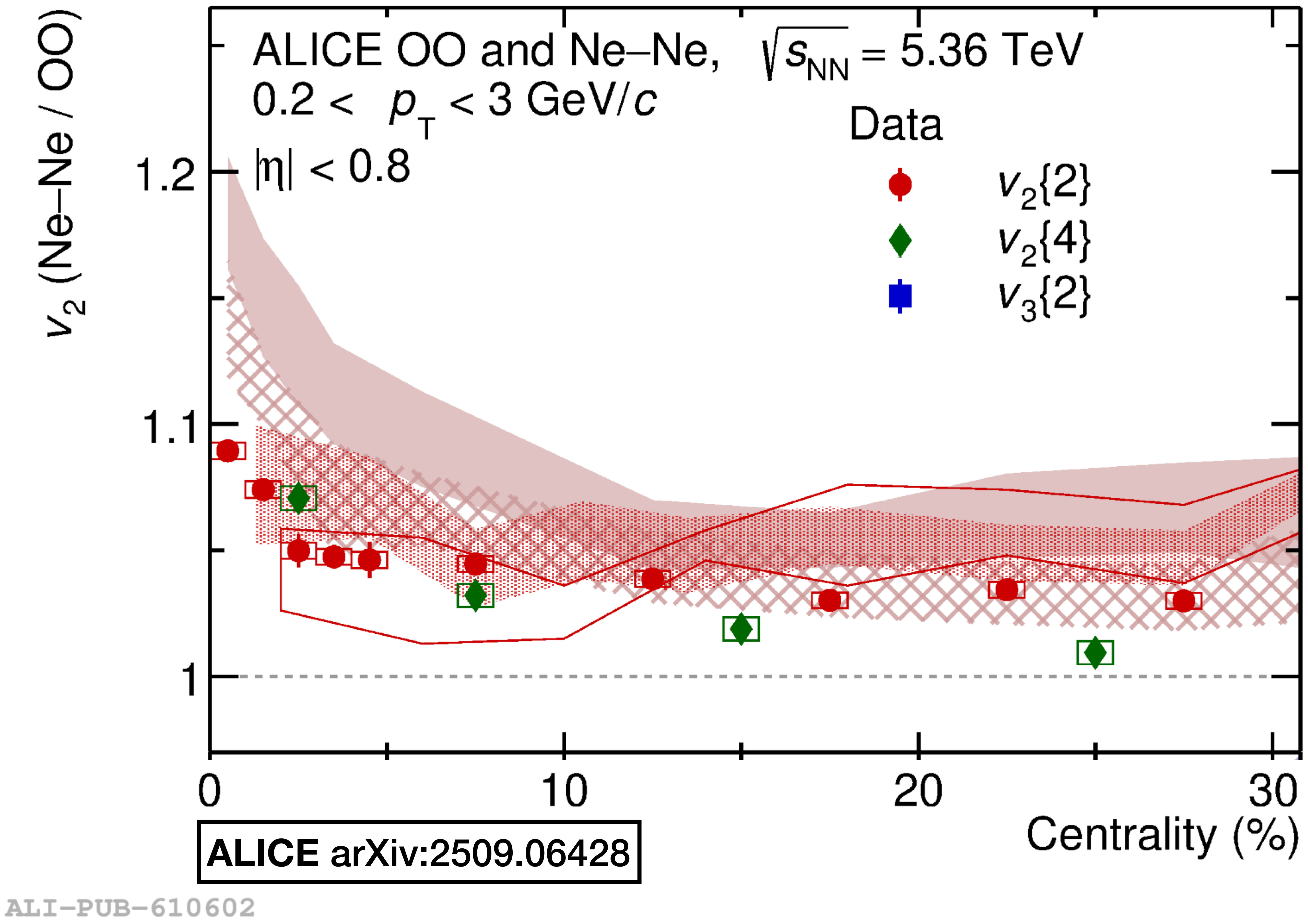
$v_2(\Lambda_c^+) > v_2(D_s^+) \approx v_2(D^0) \approx v_2(D^+) \approx v_2(\pi^\pm)$

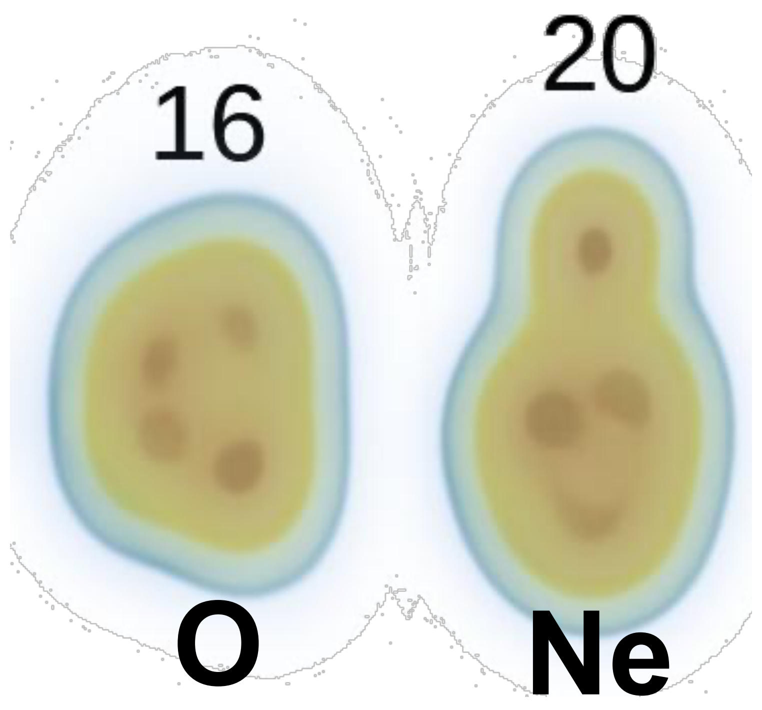
➡ Strong evidence of coalescence

Flow in OO and Ne–Ne collisions

High energy nuclear collisions provide "snap-shoot" for the initial nuclear geometry

S. Zhang, Y.-G. Ma *et al.*, *Phys. Rev.* **C95** (2017) 064904
W.-B. He, Y.-G. Ma *et al.*, *Phys. Rev.* **C94** (2016) 014301

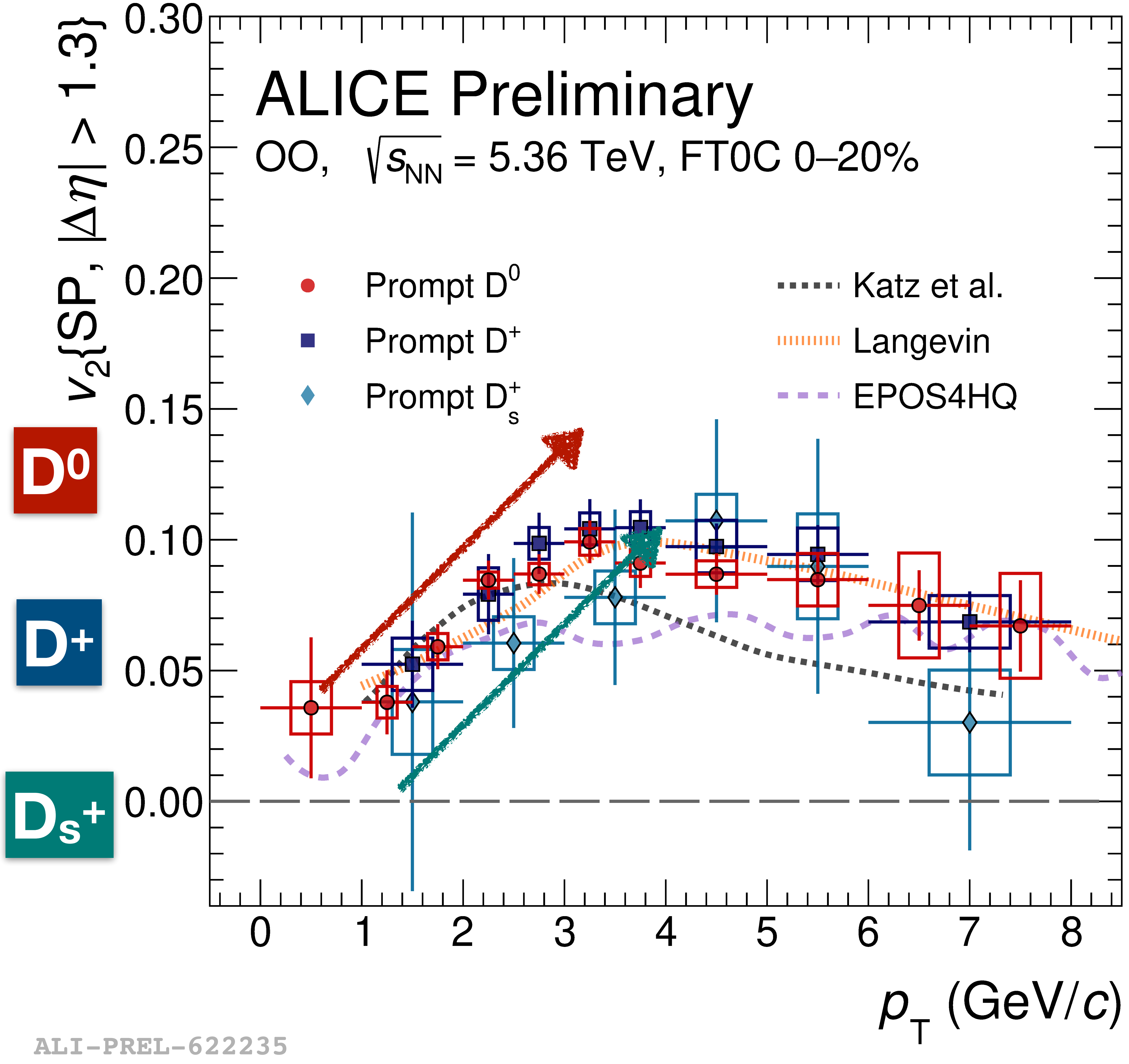




v_2 Ne–Ne/OO ratio enhancement at small centrality

➡ Reveals a deformed shape of ^{20}Ne

Flow of D mesons in OO



Support QGP formation in OO collisions

Hints of $v_2(D_s^+) < v_2(D^{0,+})$ at low-p_T

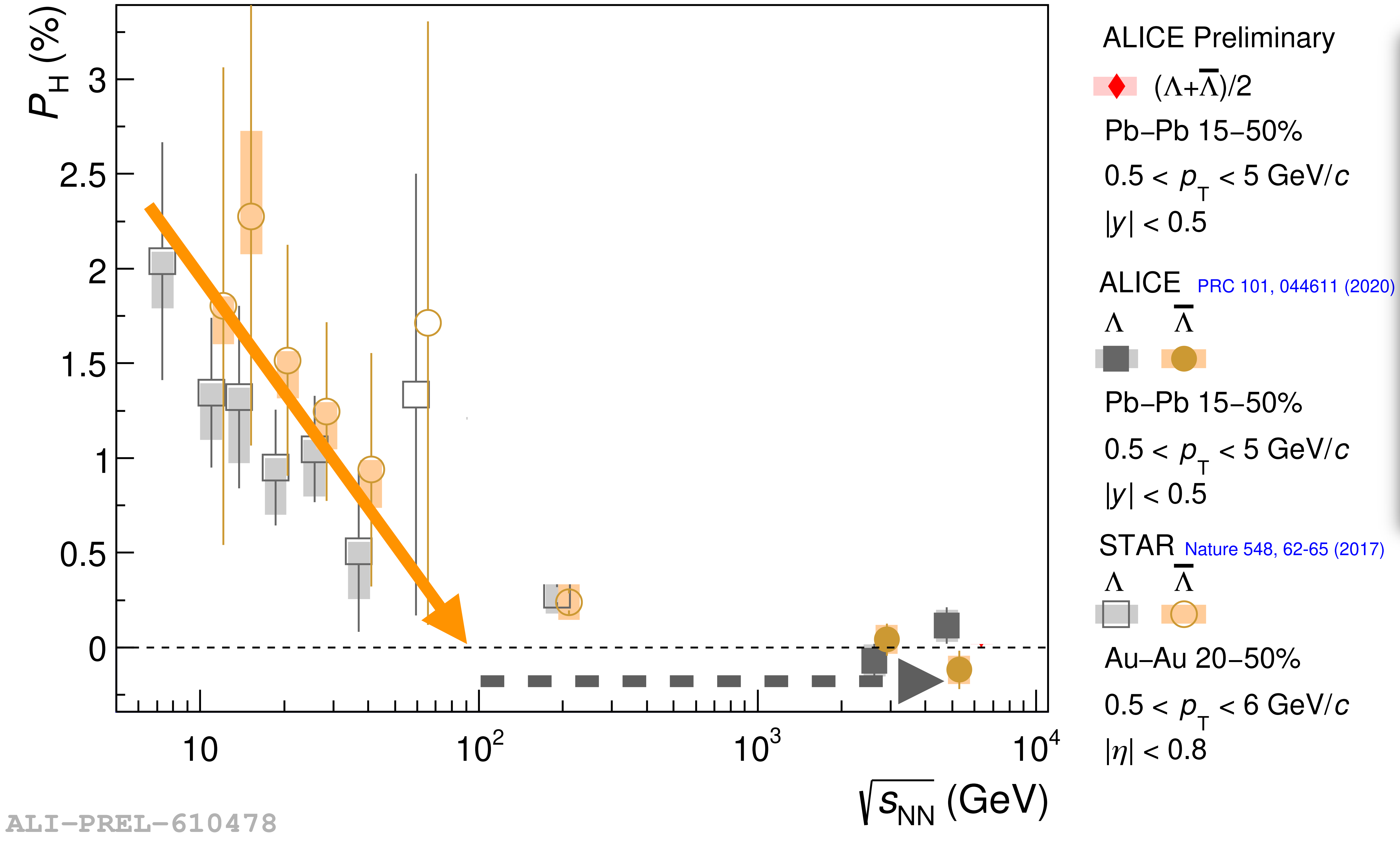
➡ Support sequential hadronization

Zhao, Shi, Xu, and Zhuang

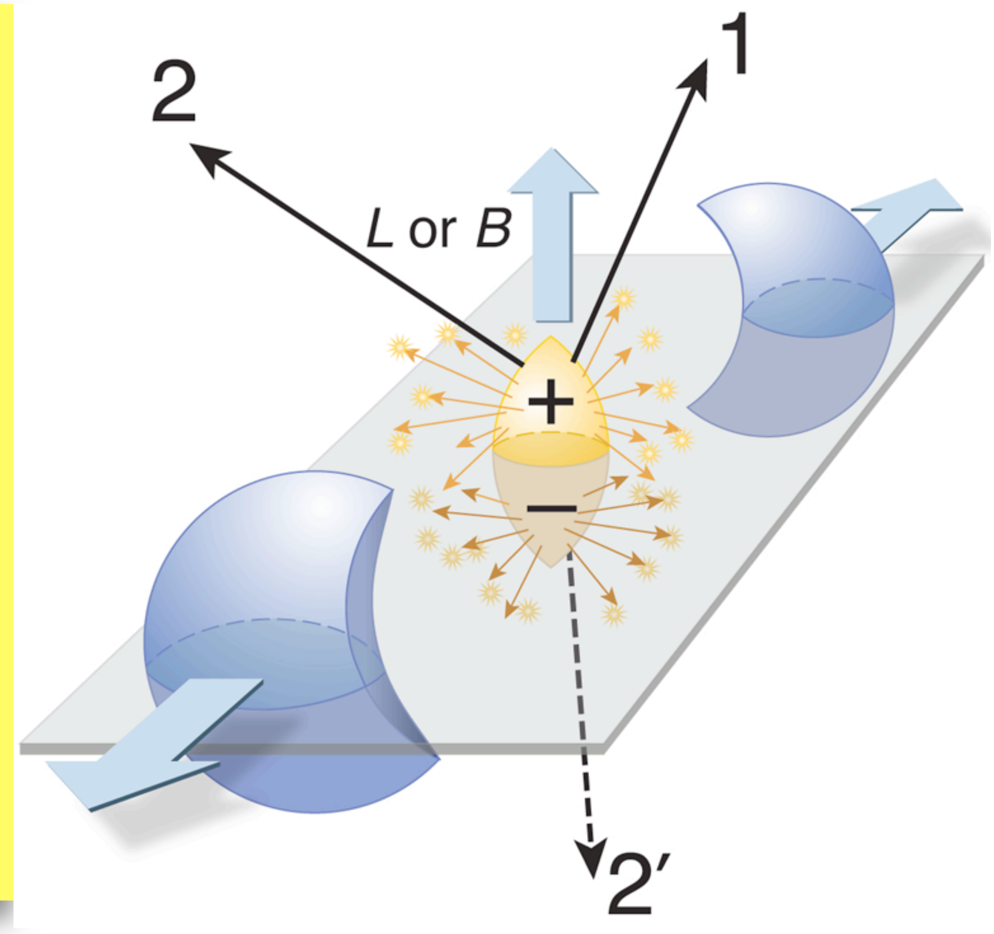
Springer Proc. Phys. **250** (2020) 275

Katz *et al. Phys. Rev.* **C102** (2020) 041901
Langevin: *Eur. Phys. J.* **C81** (2021) 1035
EPOS4HQ: *Phys. Rev.* **C110** (2024) 024909

Global polarization of hyperons



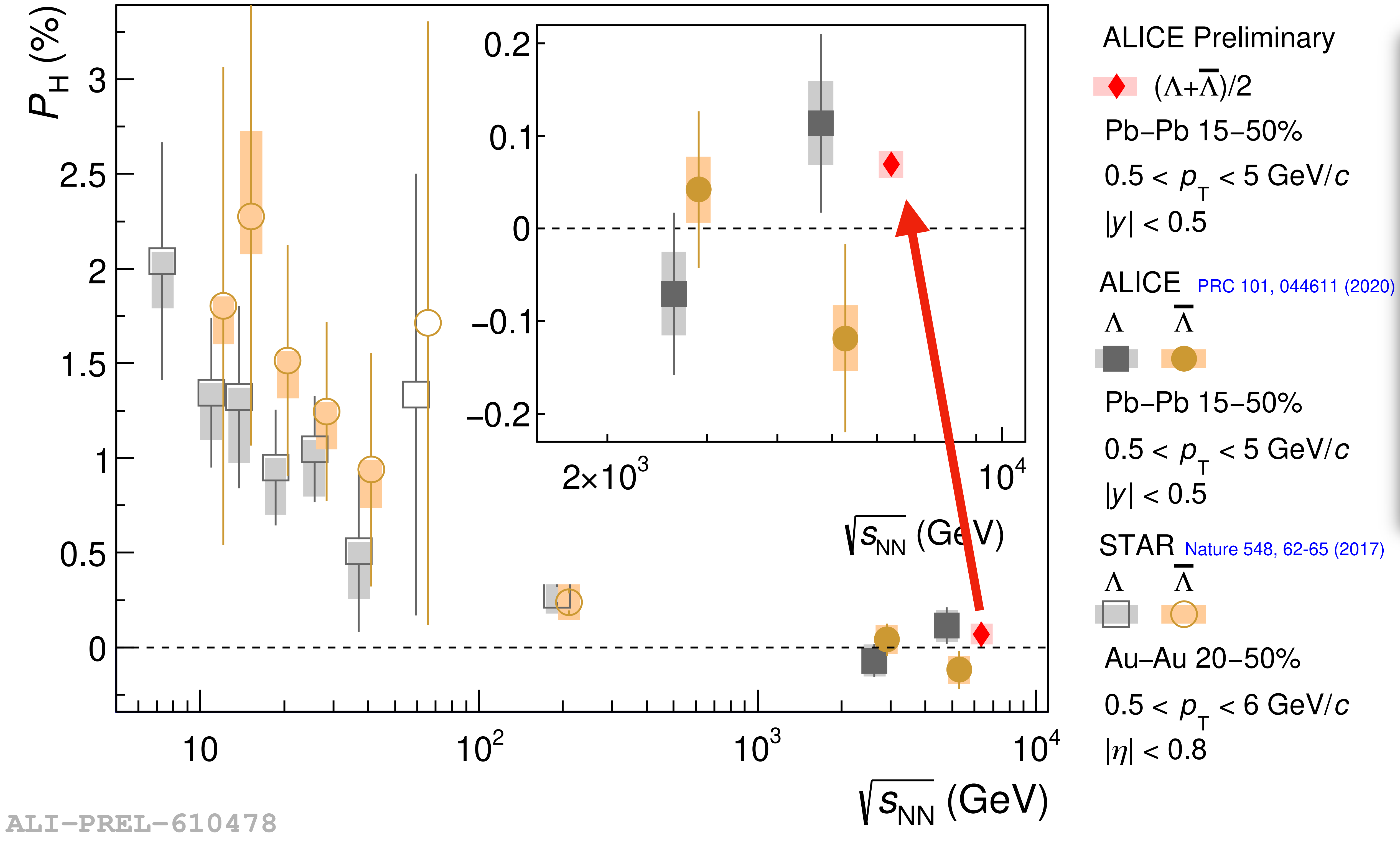
Large orbital angular momentum and strong magnetic fields in non-central collisions induce global polarization



Z.-T. Liang and X.-N. Wang, *Phys. Rev. Lett.* **96** (2006) 039901
Z.-T. Liang and X.-N. Wang, *Phys. Lett.* **B629** (2005) 20
STAR *Nature* **548** (2018) 62 **STAR** *Nature* **614** (2023) 244

➡ LHC Run 1 and 2: Global polarization consistent with zero (large uncertainties)

Global polarization of hyperons



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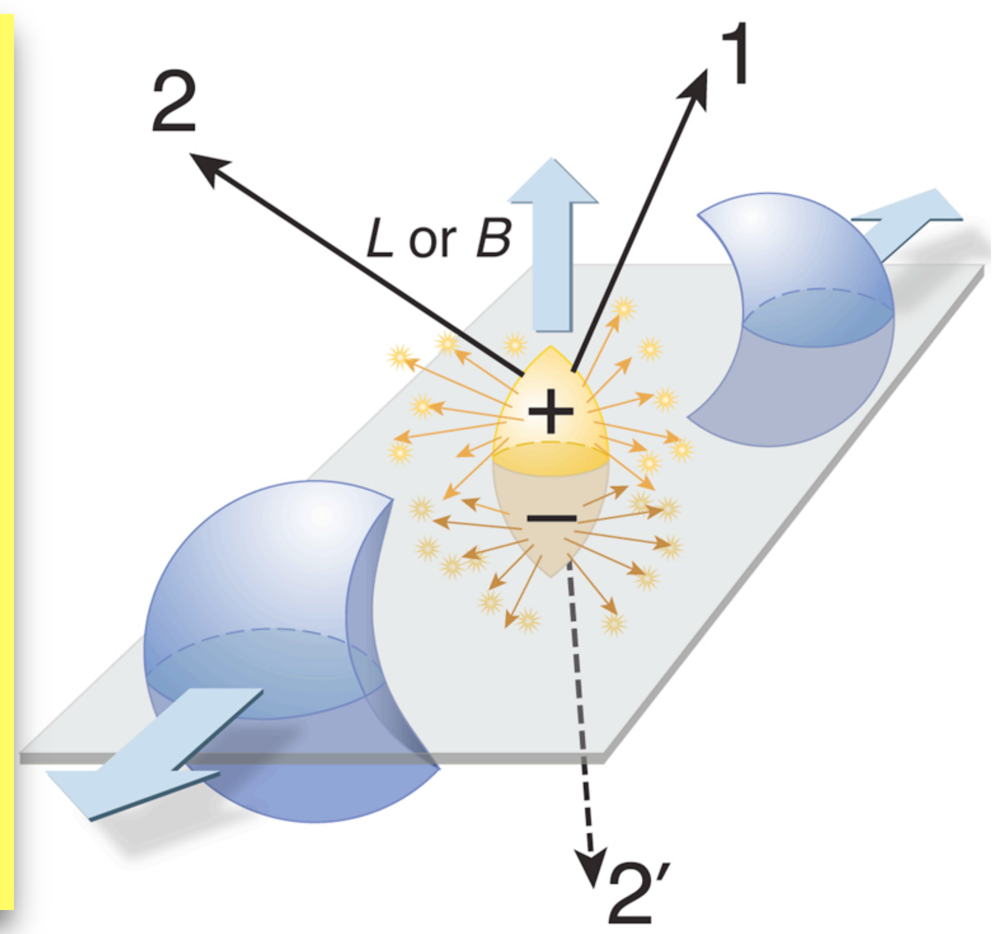

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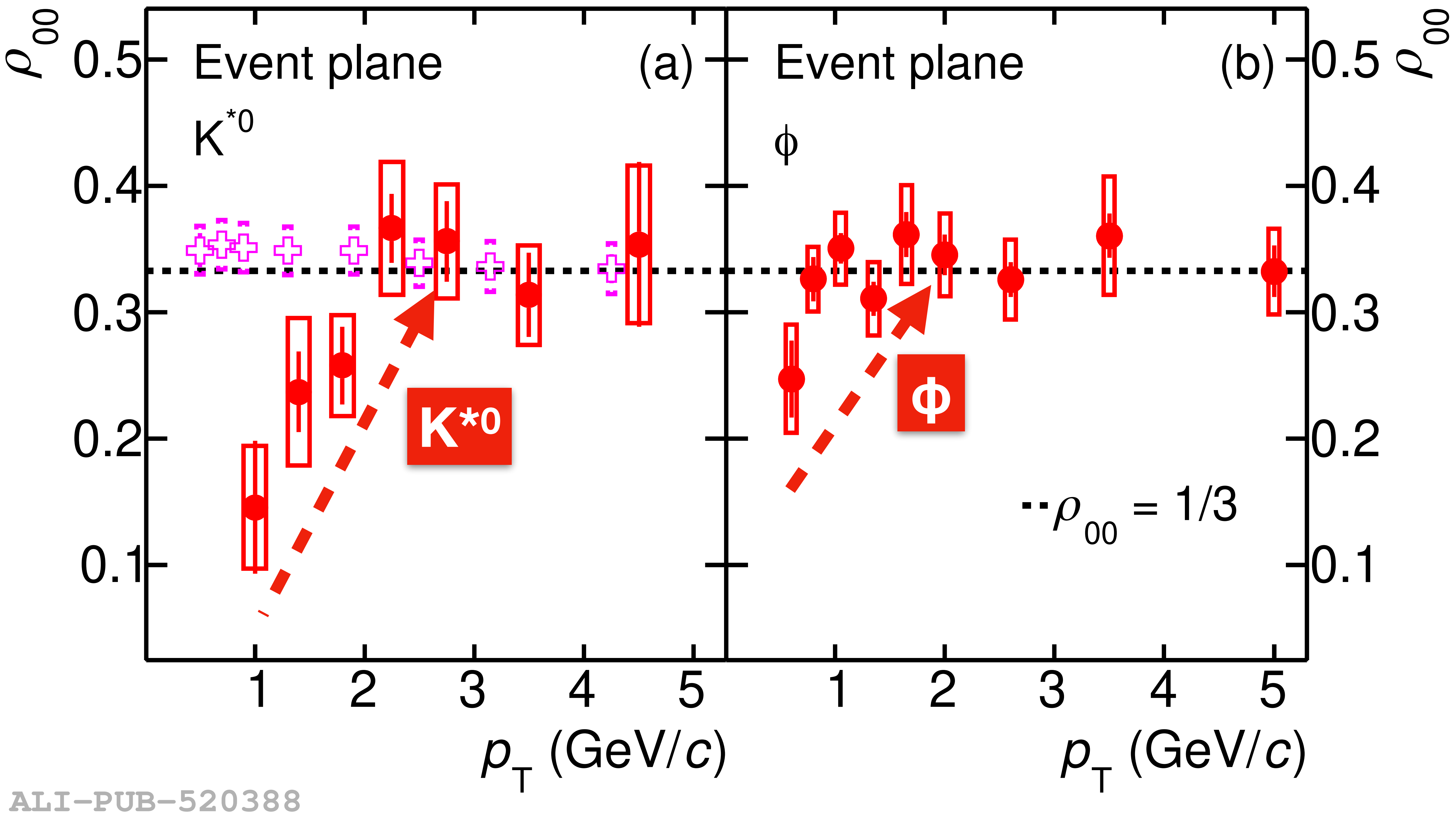
➡ LHC Run 1 and 2: Global polarization consistent with zero (large uncertainties)

➡ New Run 3: First observation of polarized hyperons at LHC energies with 5σ

Efforts ongoing for the measurement of polarization difference between particle and anti-particle, which is sensitive to magnetic field!

Spin alignment of vector mesons

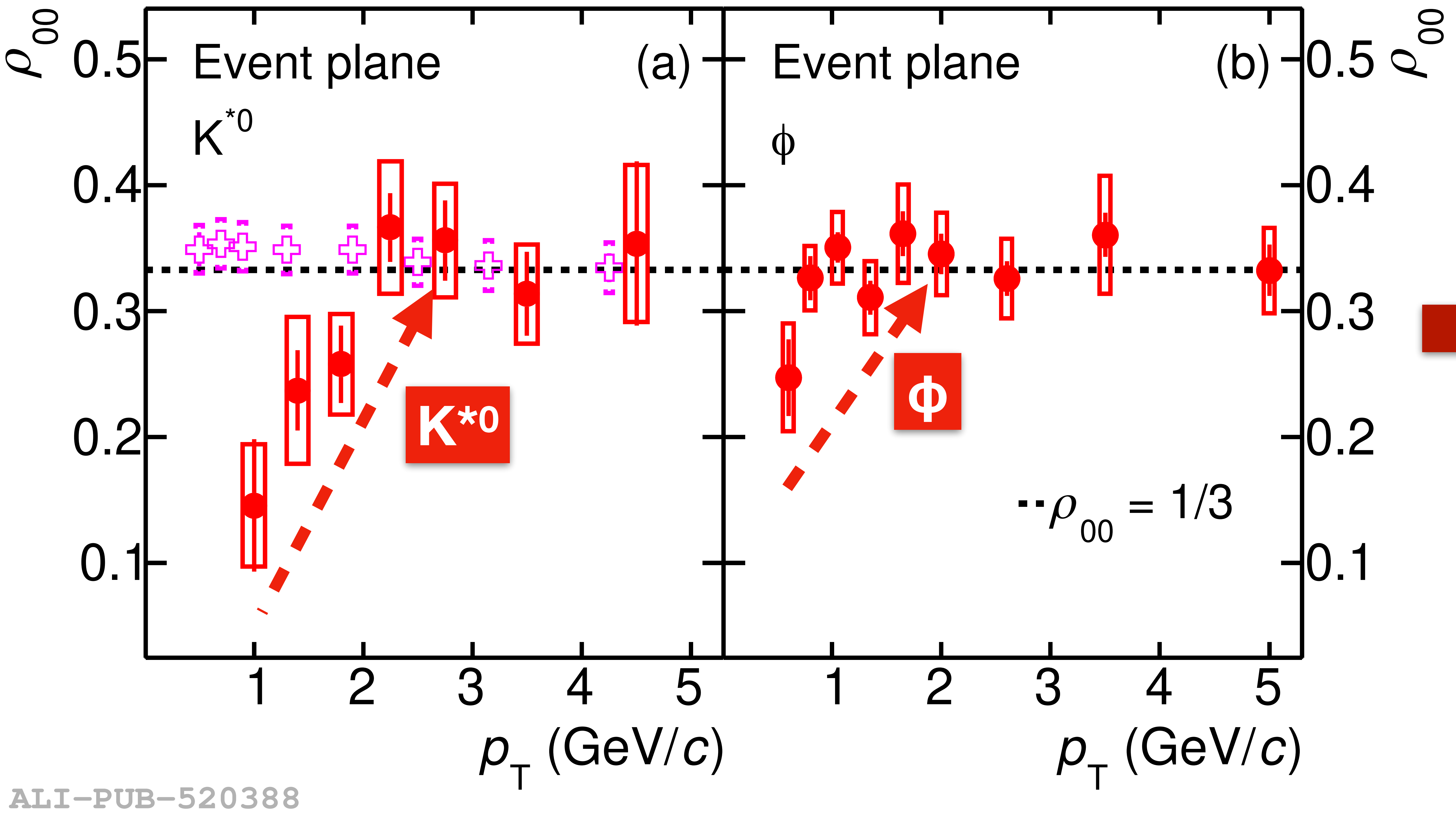
ALICE *Phys. Rev. Lett.* **125** (2020) 012301



Not consistent with early direct extrapolation from Λ measurements

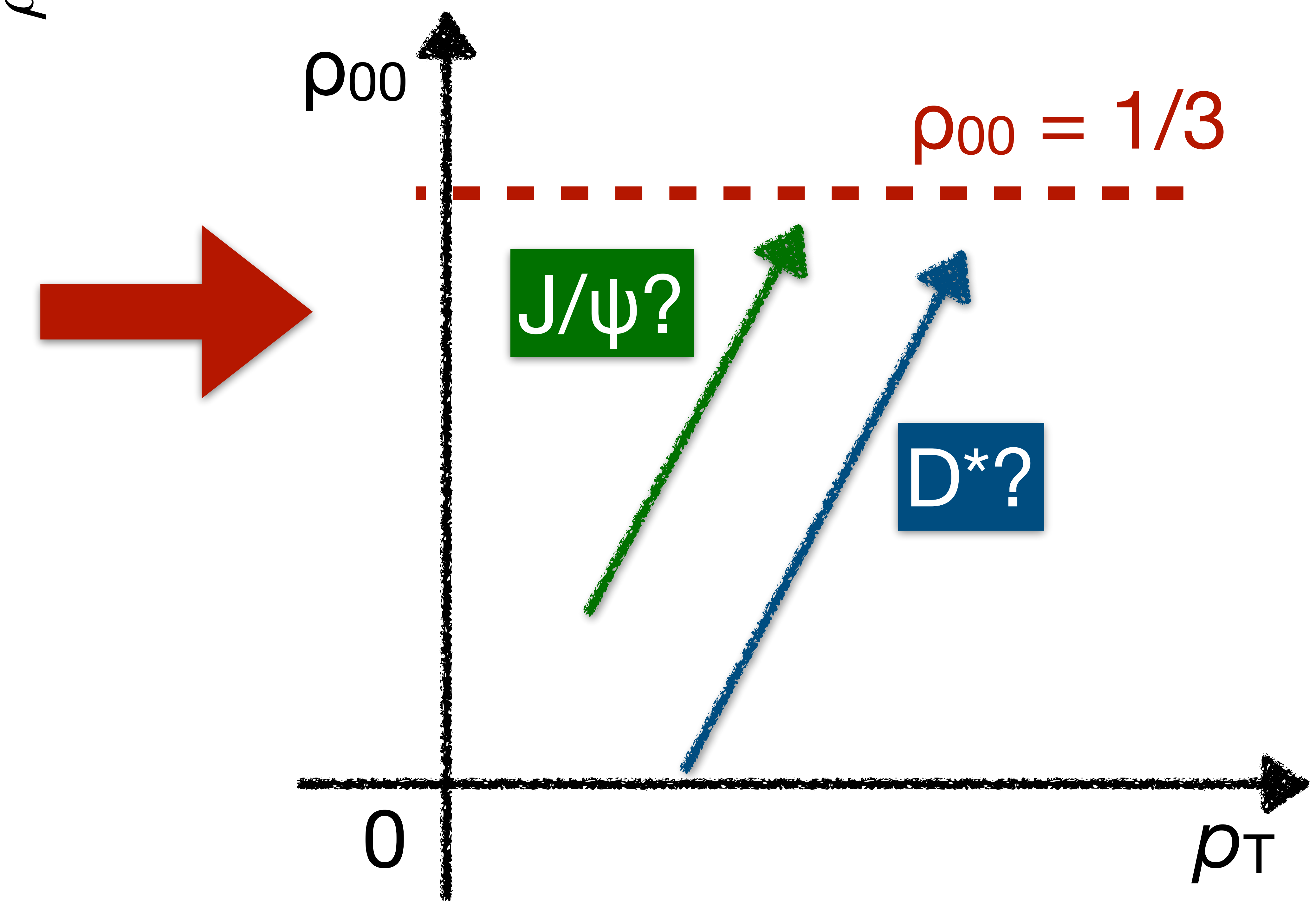
Spin alignment of vector mesons

ALICE *Phys. Rev. Lett.* **125** (2020) 012301



Not consistent with early direct extrapolation from Λ measurements

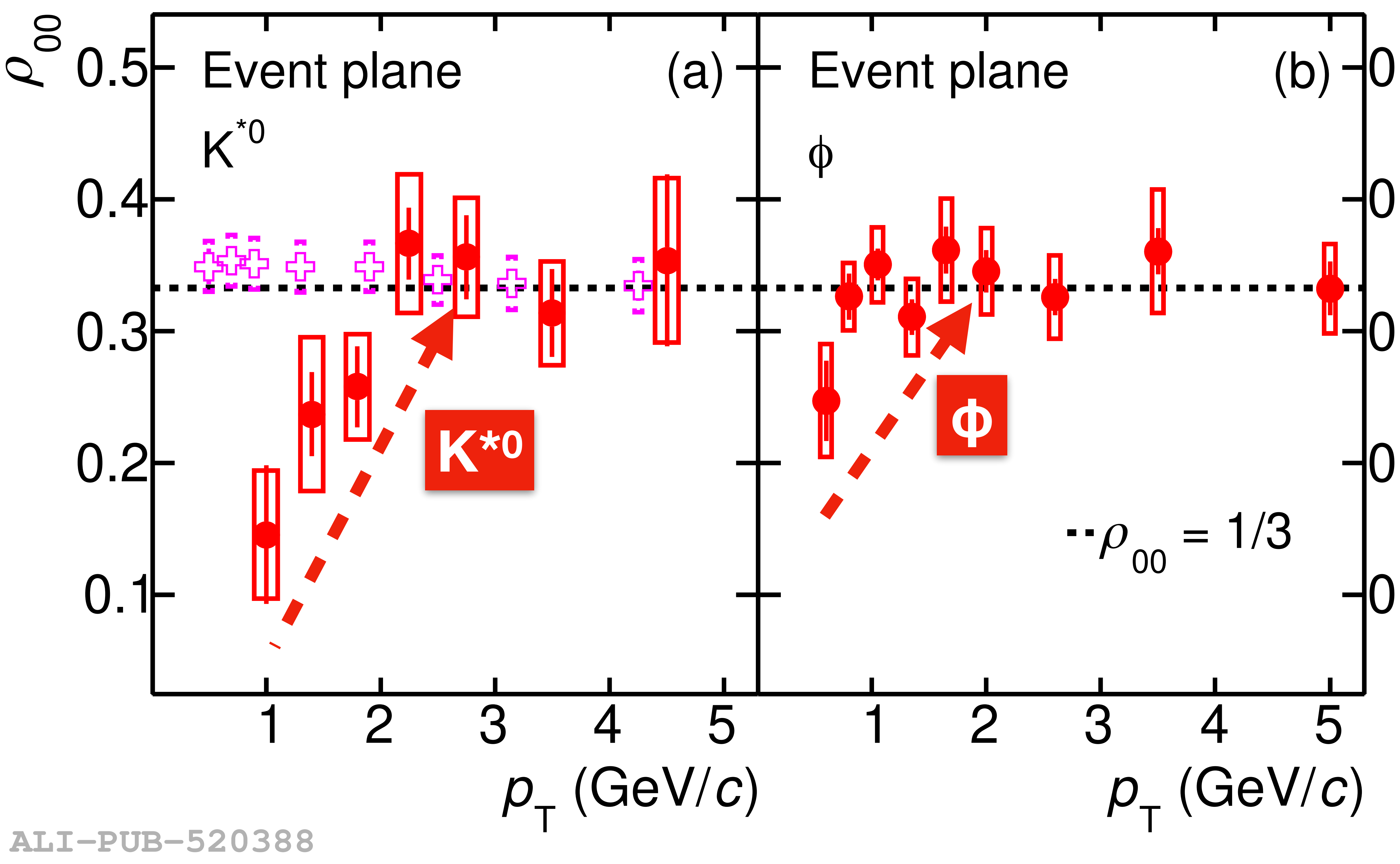
Prediction at heavy-quark sector



Would a similar trend show at heavy-quark sector?

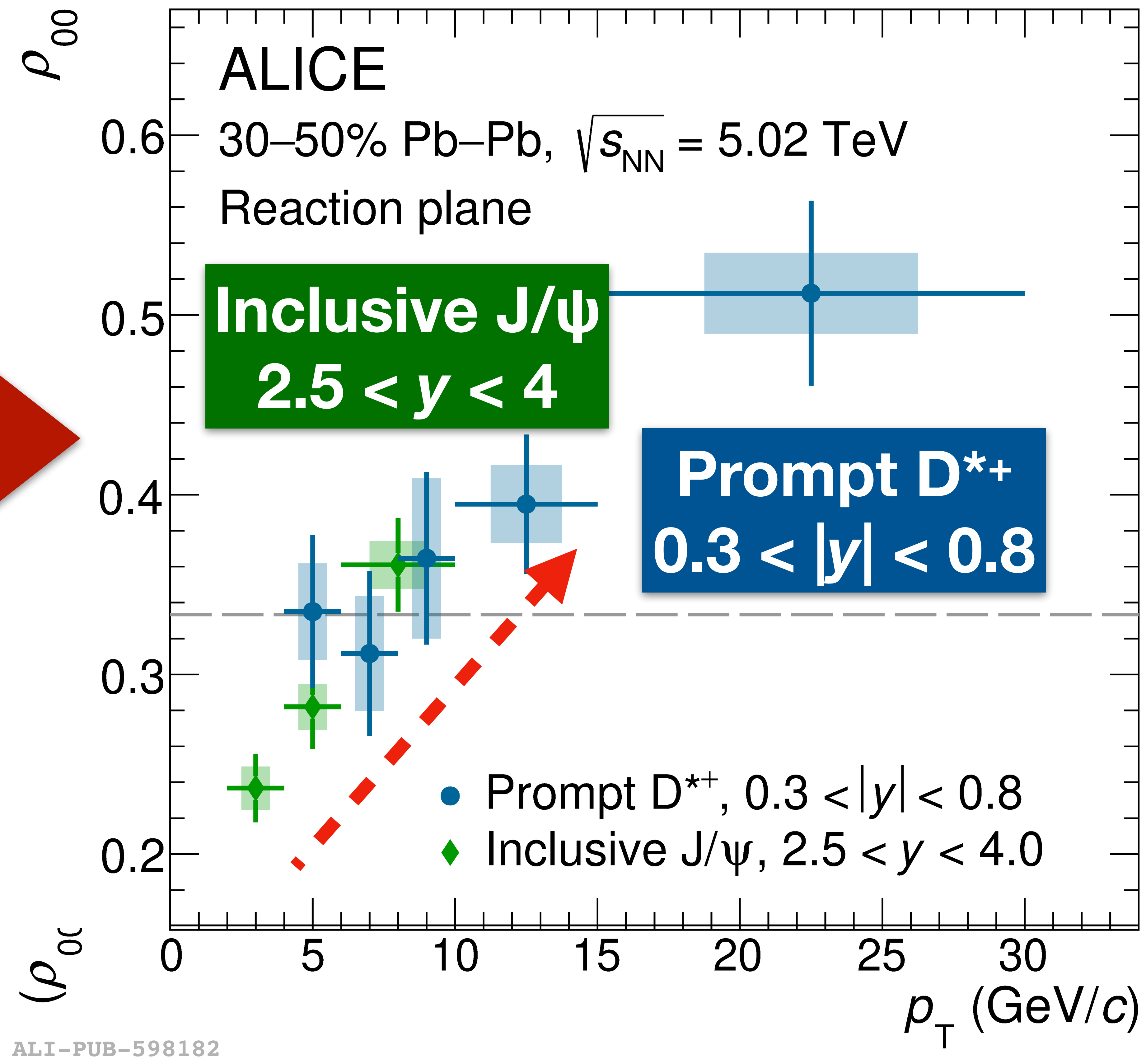
Spin alignment of vector mesons

ALICE *Phys. Rev. Lett.* **125** (2020) 012301



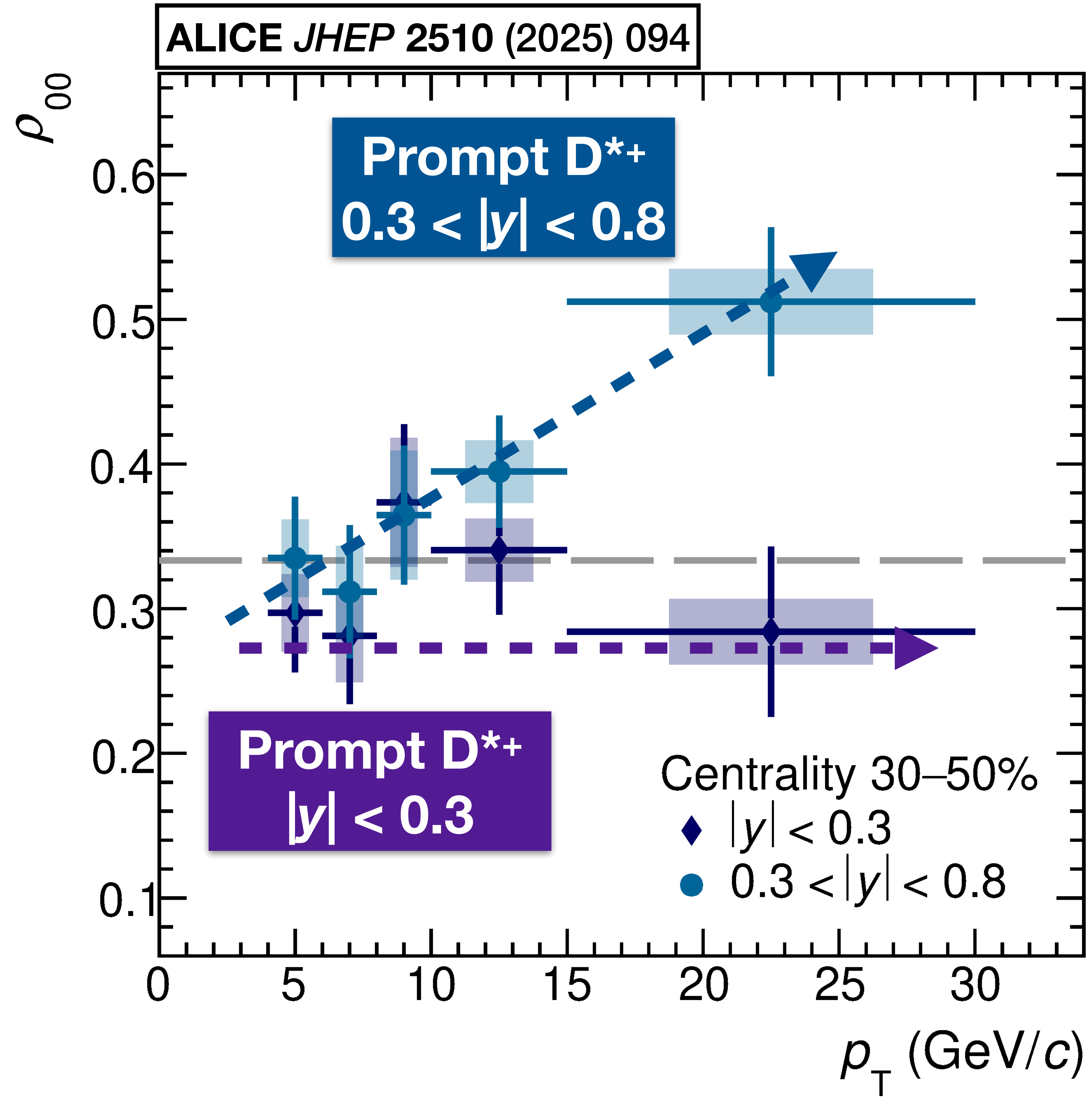
Not consistent with early direct extrapolation from Λ measurements

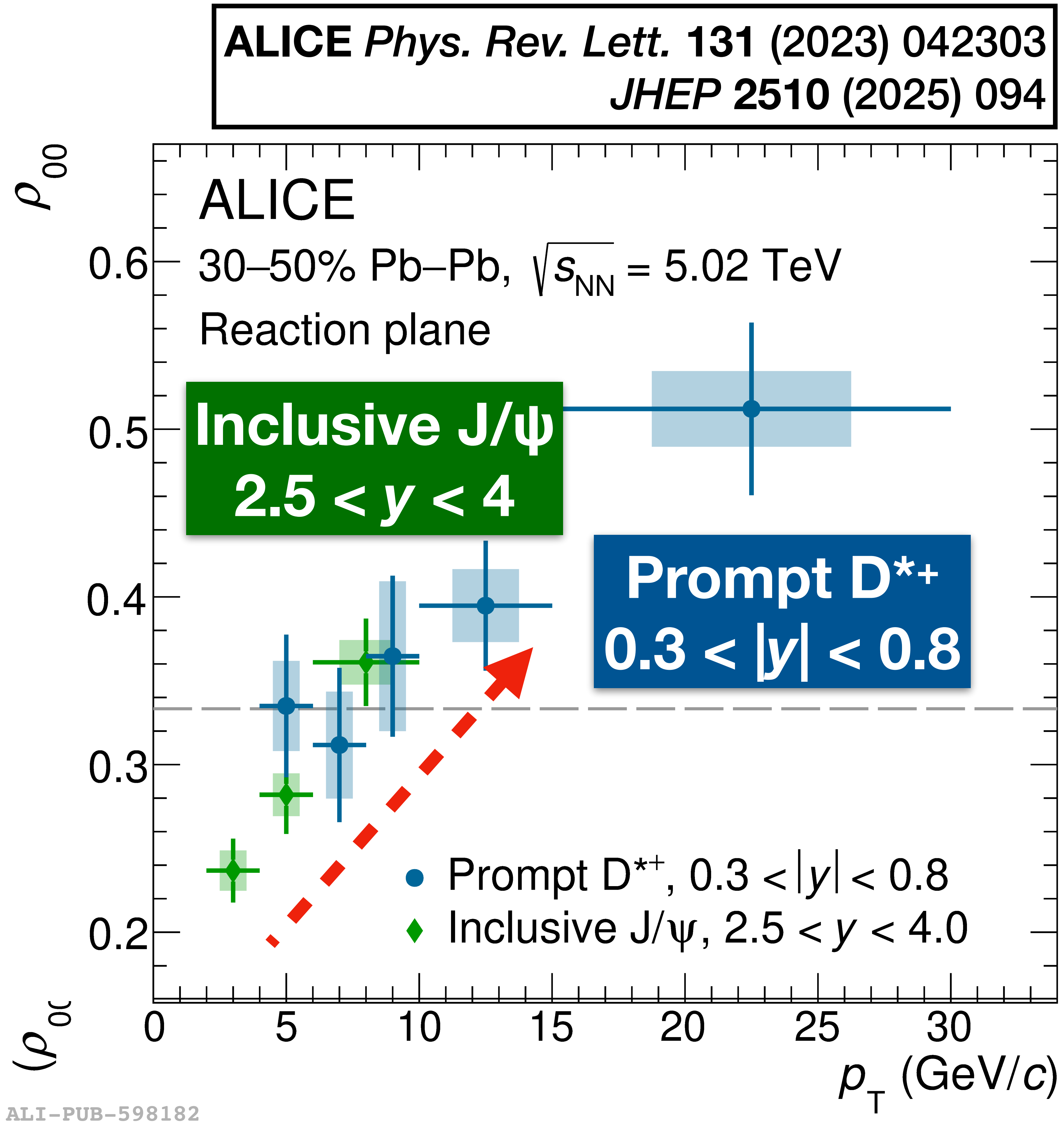
ALICE *Phys. Rev. Lett.* **131** (2023) 042303
JHEP **2510** (2025) 094



J/ψ and D^{*+} seems to feature common trend at overlapping p_T

Spin alignment of vector mesons

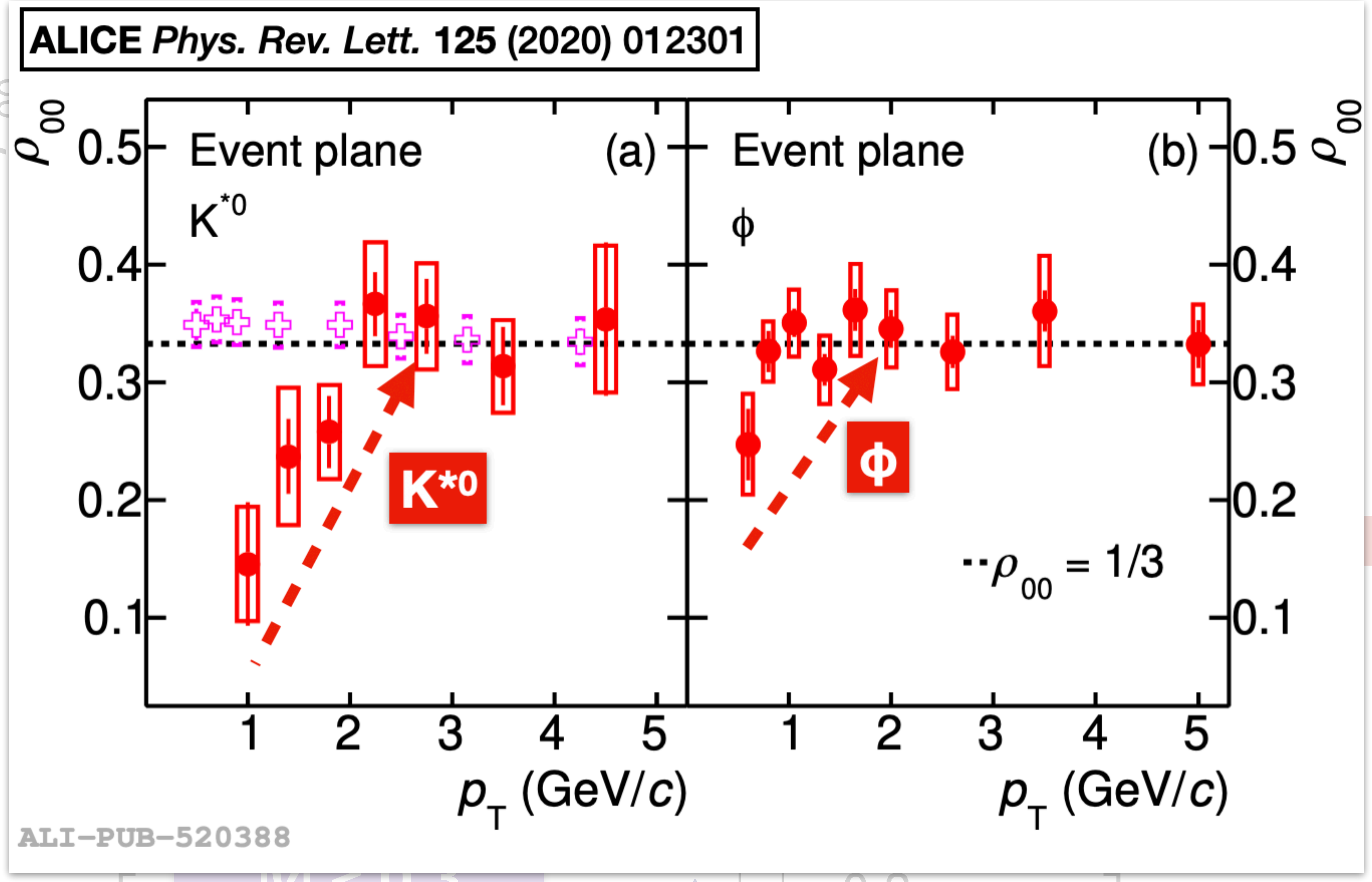


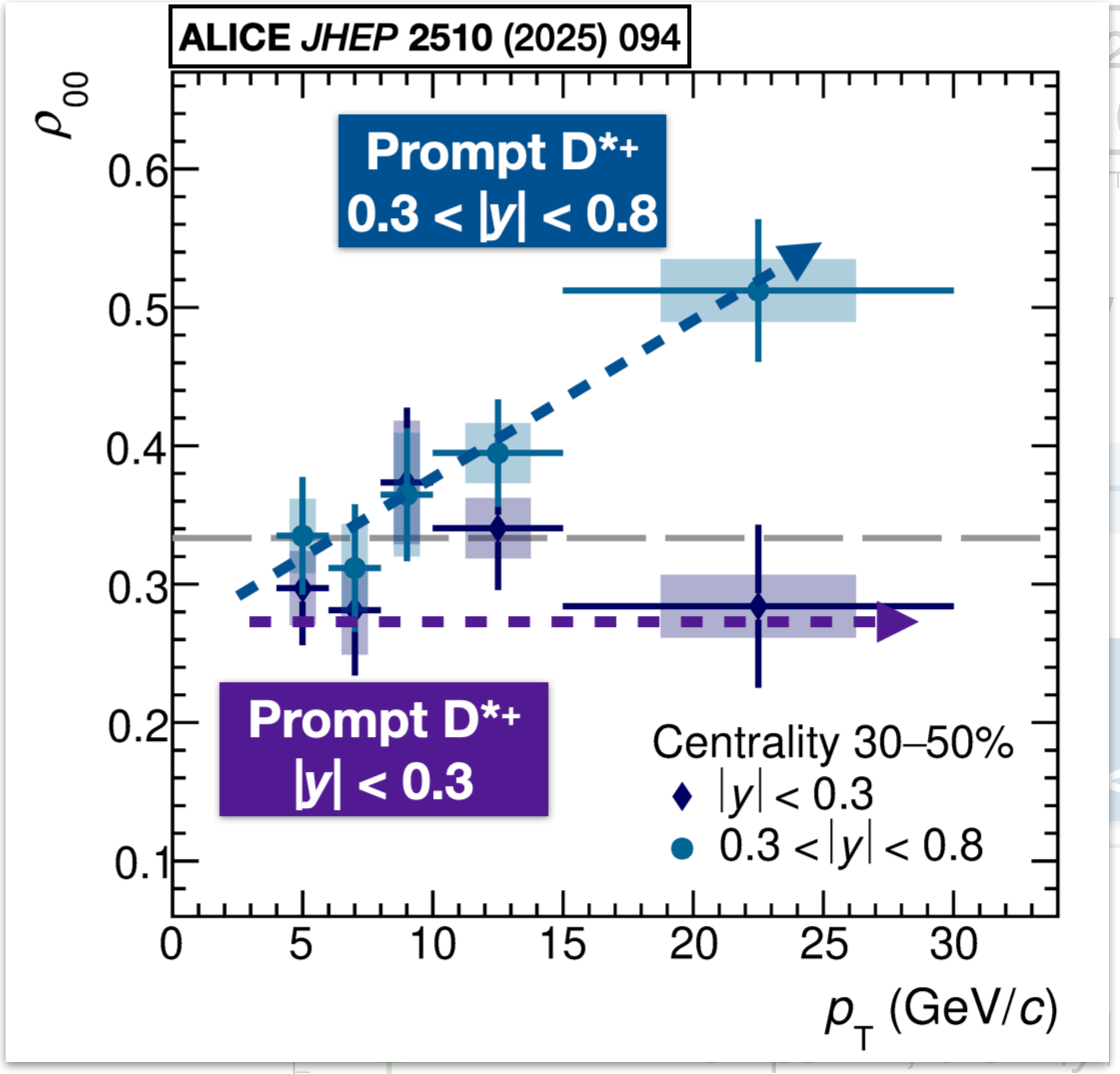


ρ_{00} of D*+ increases with p_T at large rapidity

J/ψ and D*+ seems to feature common trend at overlapping p_T

Advertisement

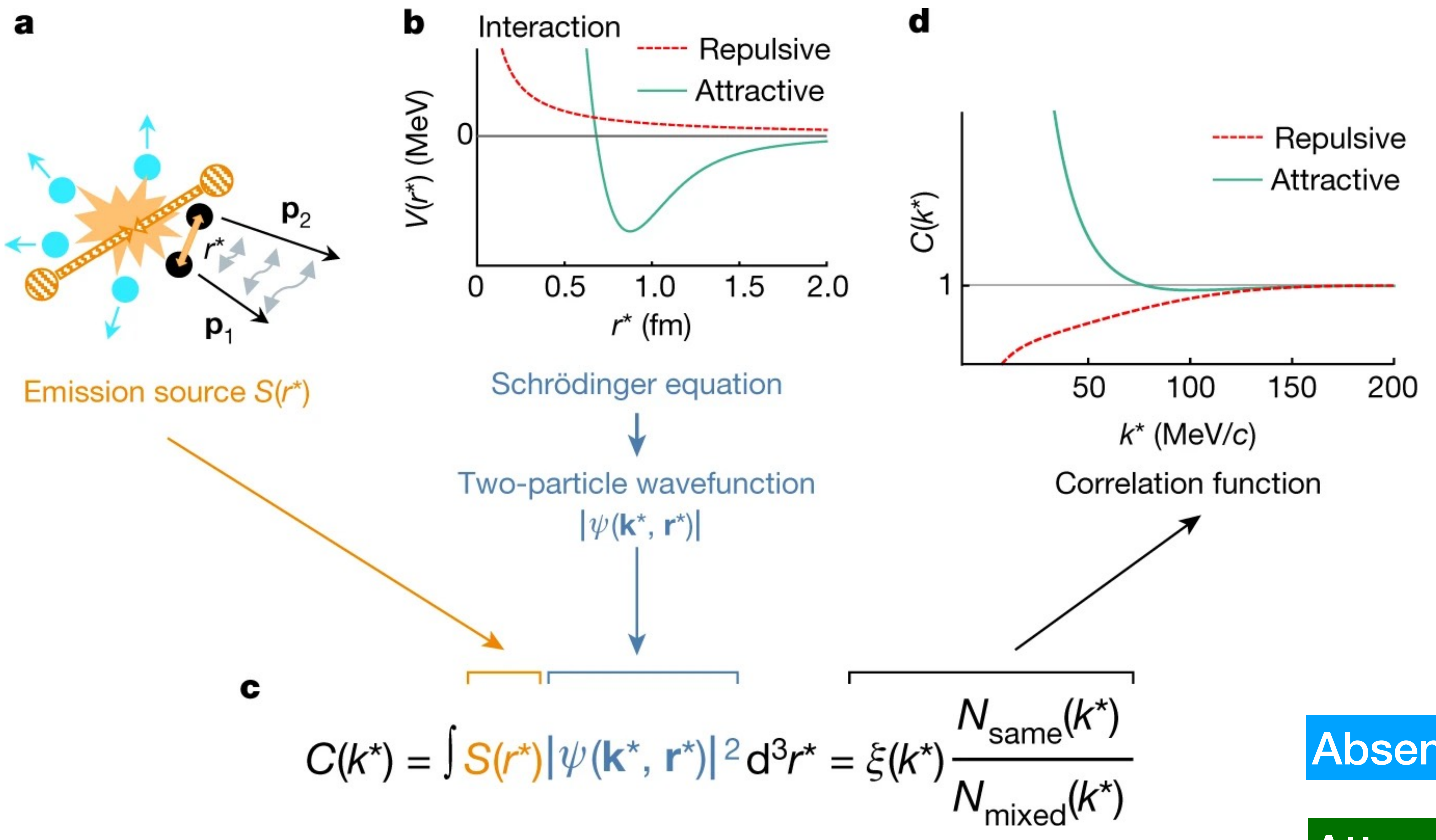




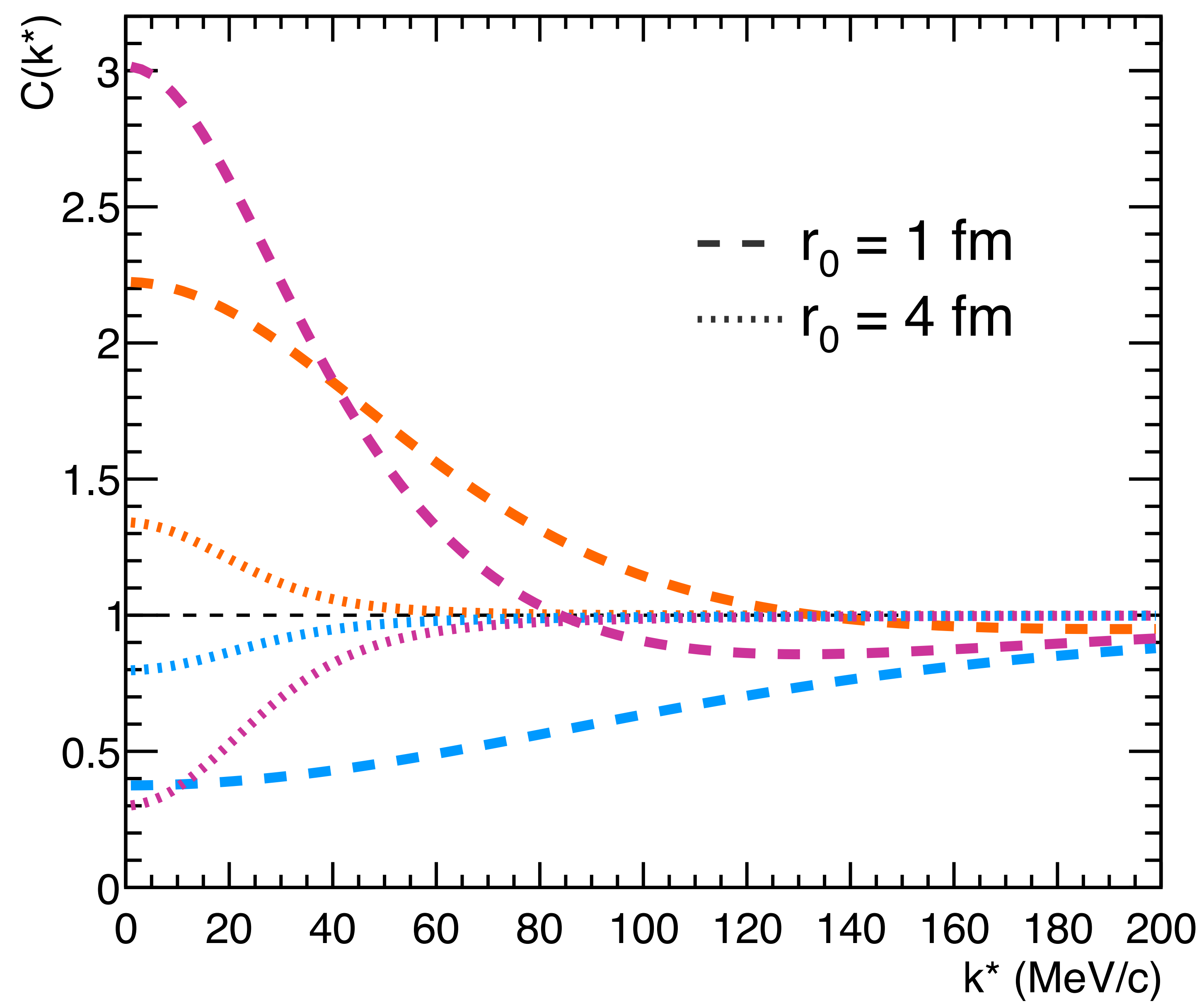
- **What could be the possible explanation for the vector meson spin alignment enhancement?**
- **Why does there seem to be a rapidity dependence on D*+ spin alignment?**

➡ New efforts are ongoing and will be shown in HP'26

Femtoscopy



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

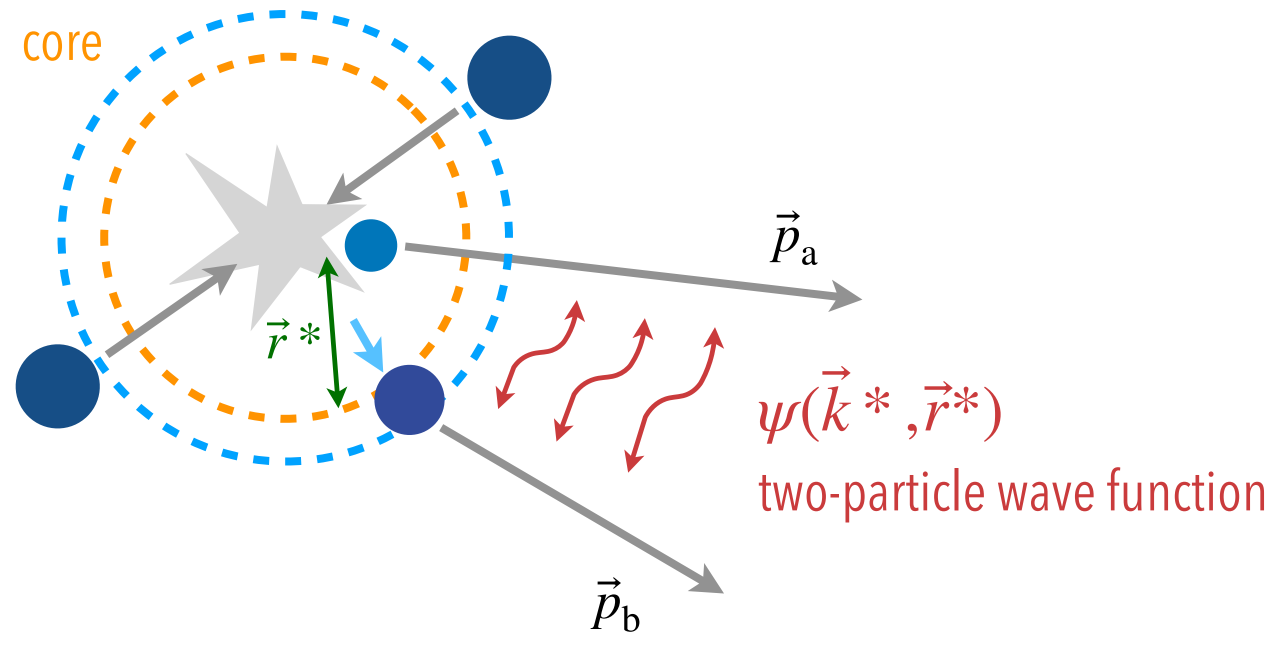


Absence interaction $C(k^*) = 1$

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

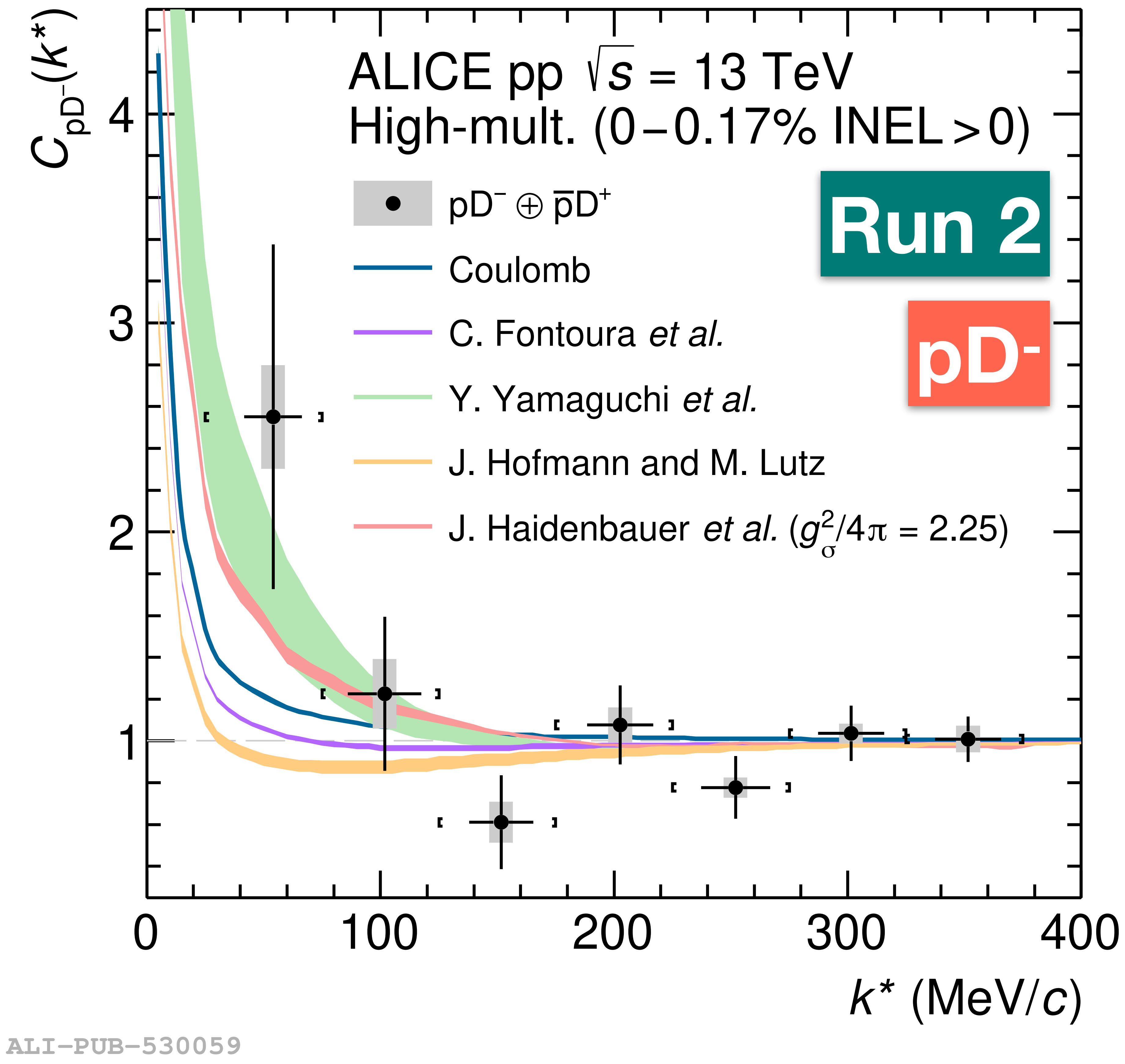
Repulsive potential $C(k^*) < 1$

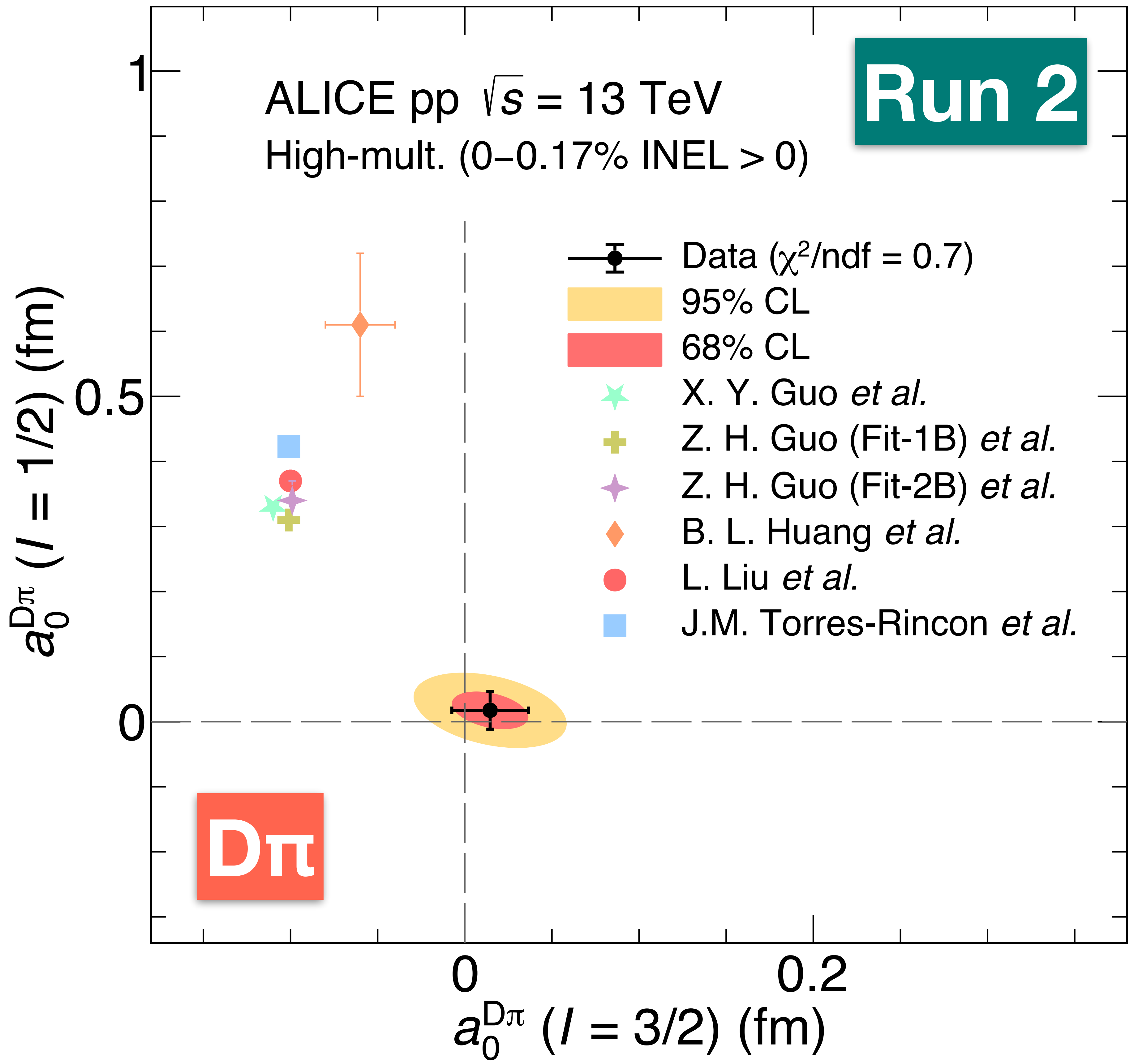
Bound-state formation $C(k^*) \gtreqless 1$



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

pD and πD interactions

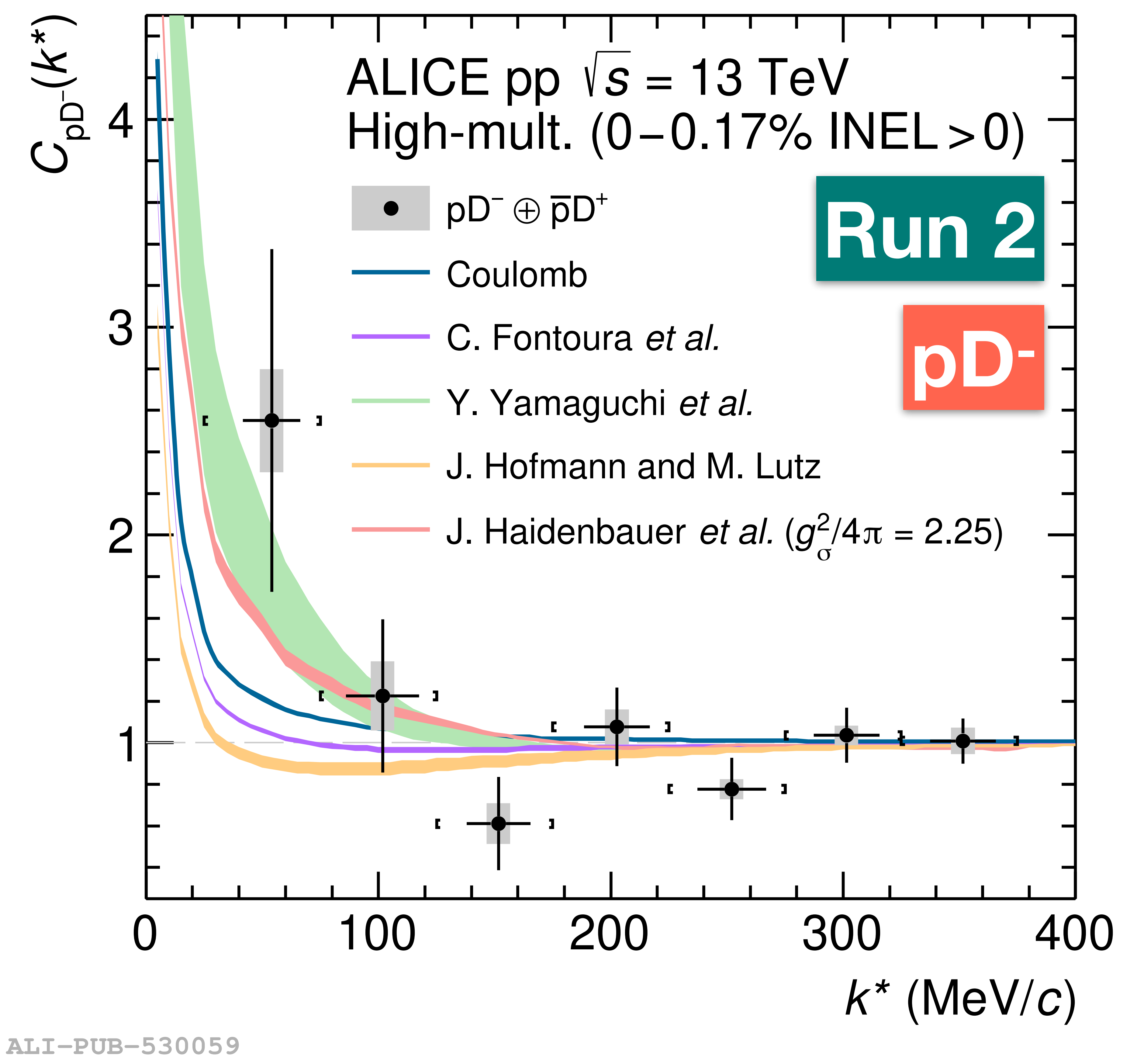


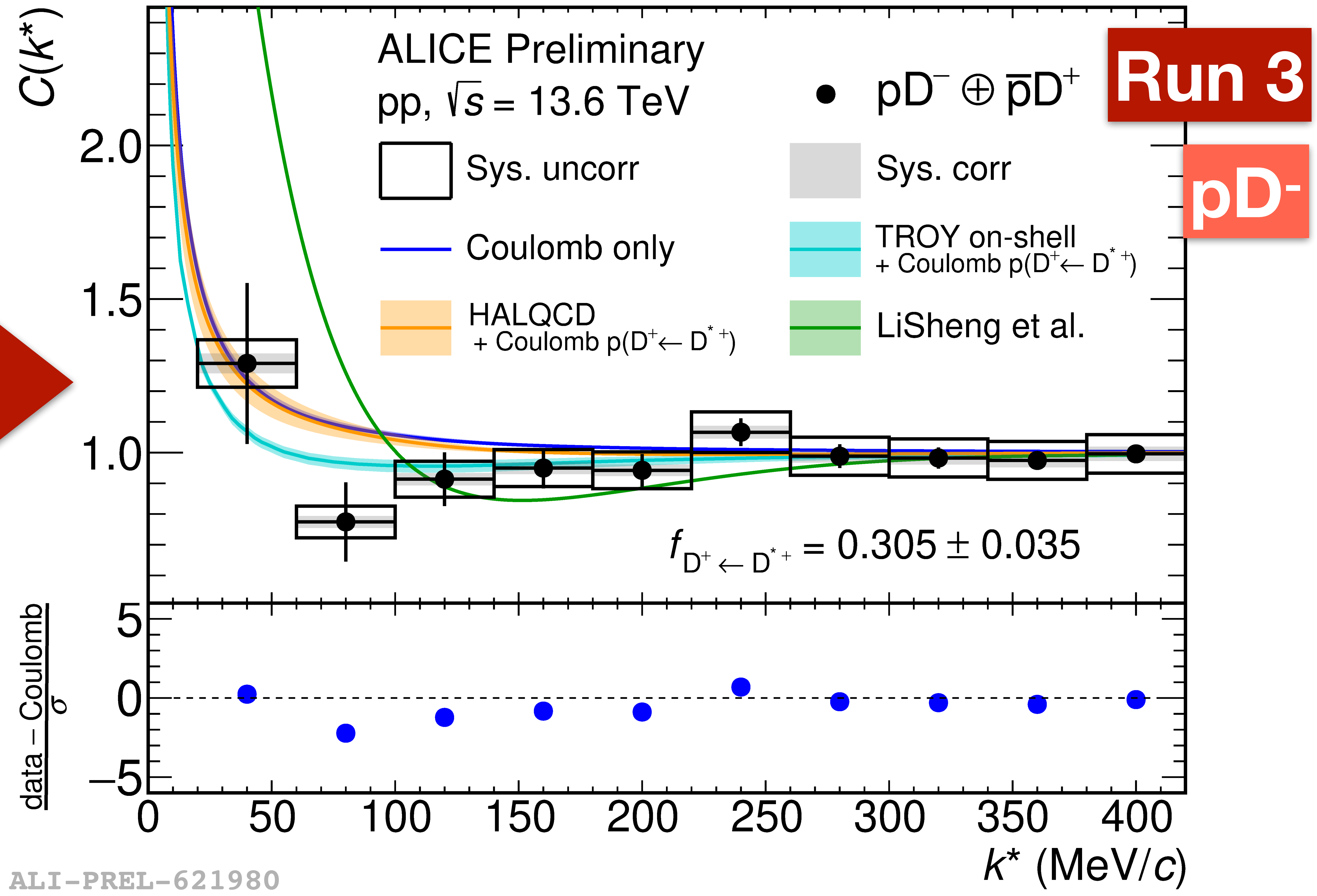


pD⁻ Data compatible with Coulomb only interaction [**ALICE** *Phys. Rev.* **D106** (2022) 052010]

D(*)π Vanishing scattering parameters in both isospin channels [**ALICE** *Phys. Rev.* **D110** (2024) 032004]

pD interactions in Run 3



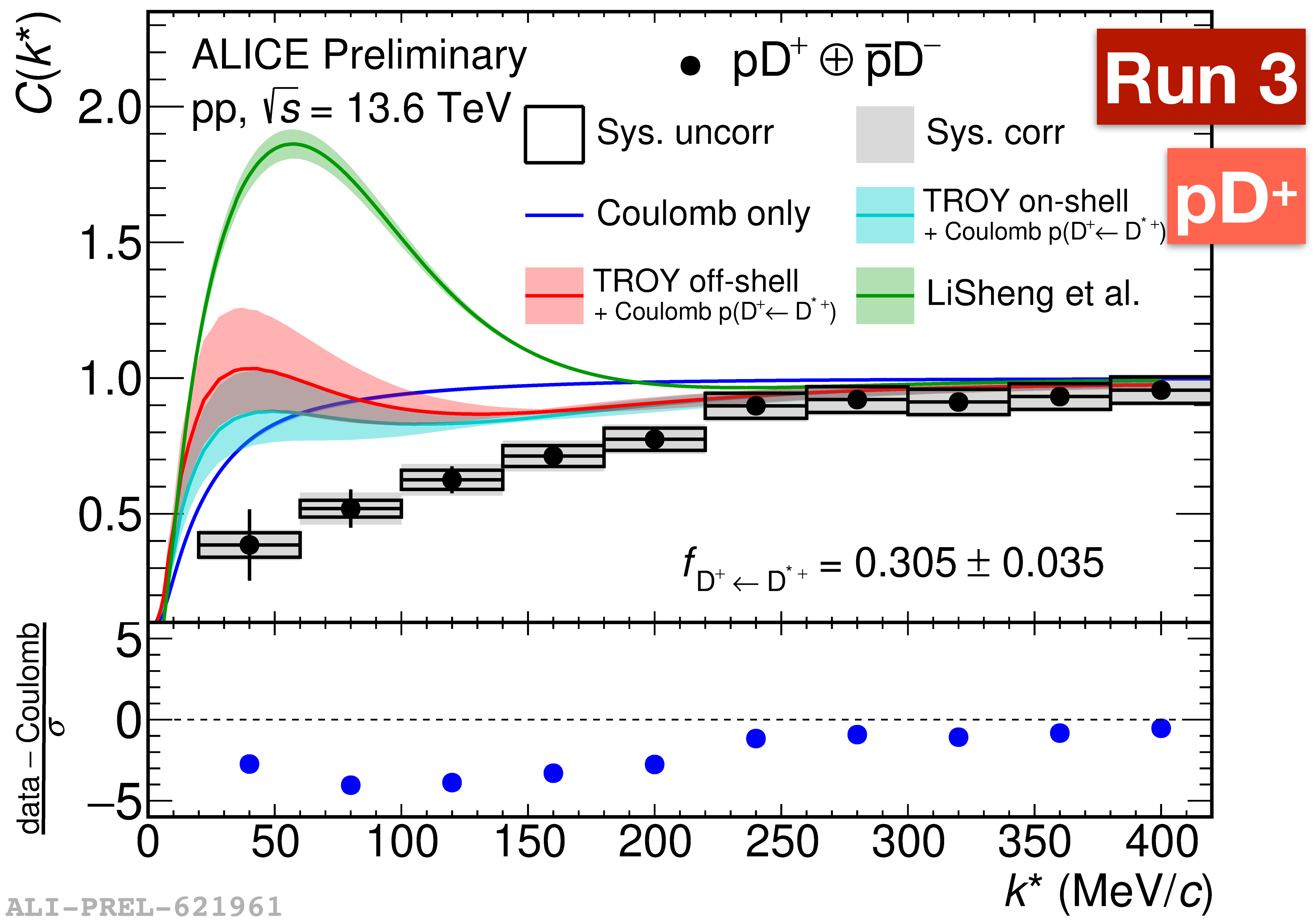


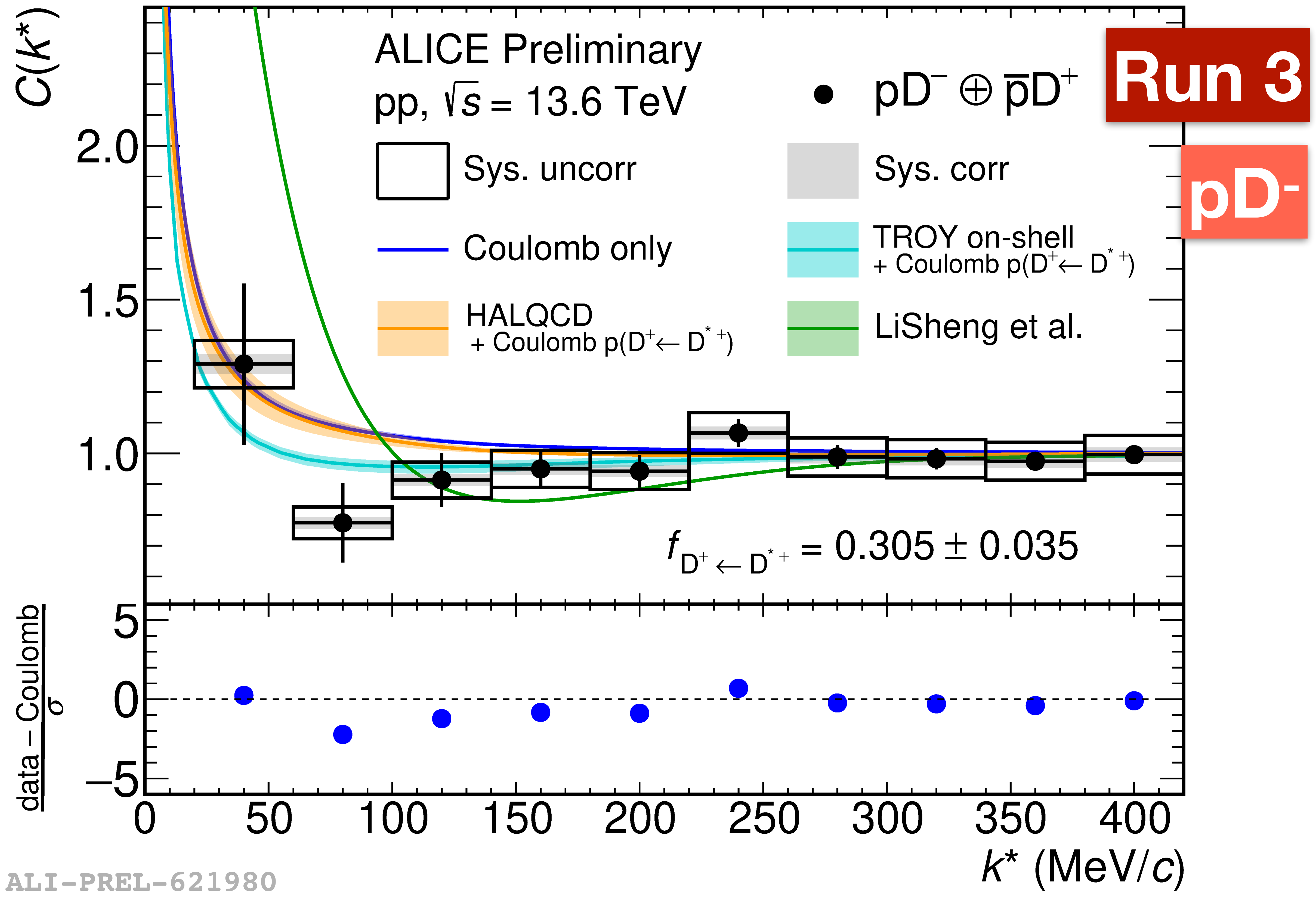
pD- Data compatible with Coulomb only interaction

[**ALICE** *Phys. Rev.* **D106** (2022) 052010]

New pD- in Run 3 Compatible with **Coulomb-only** interaction or **shallow repulsive strong interactions**

pD interactions in Run 3





pD+ Clear deviation from Coulomb-only model

➡ Models include bound state $\Sigma_c^{++}(2800)$

➡ Disfavored by data

New pD- in Run 3 Compatible with **Coulomb-only** interaction or **shallow repulsive strong interactions**

What do we learn?

- **What is the degree of thermalization of heavy quarks in QCD medium?**

- **Do heavy quarks hadronization via coalescence in QGP?**

  ➡ **Sequential hadronization is favored**

- **Is there the dead-cone effect of medium-induced gluon radiation of heavy quarks?**

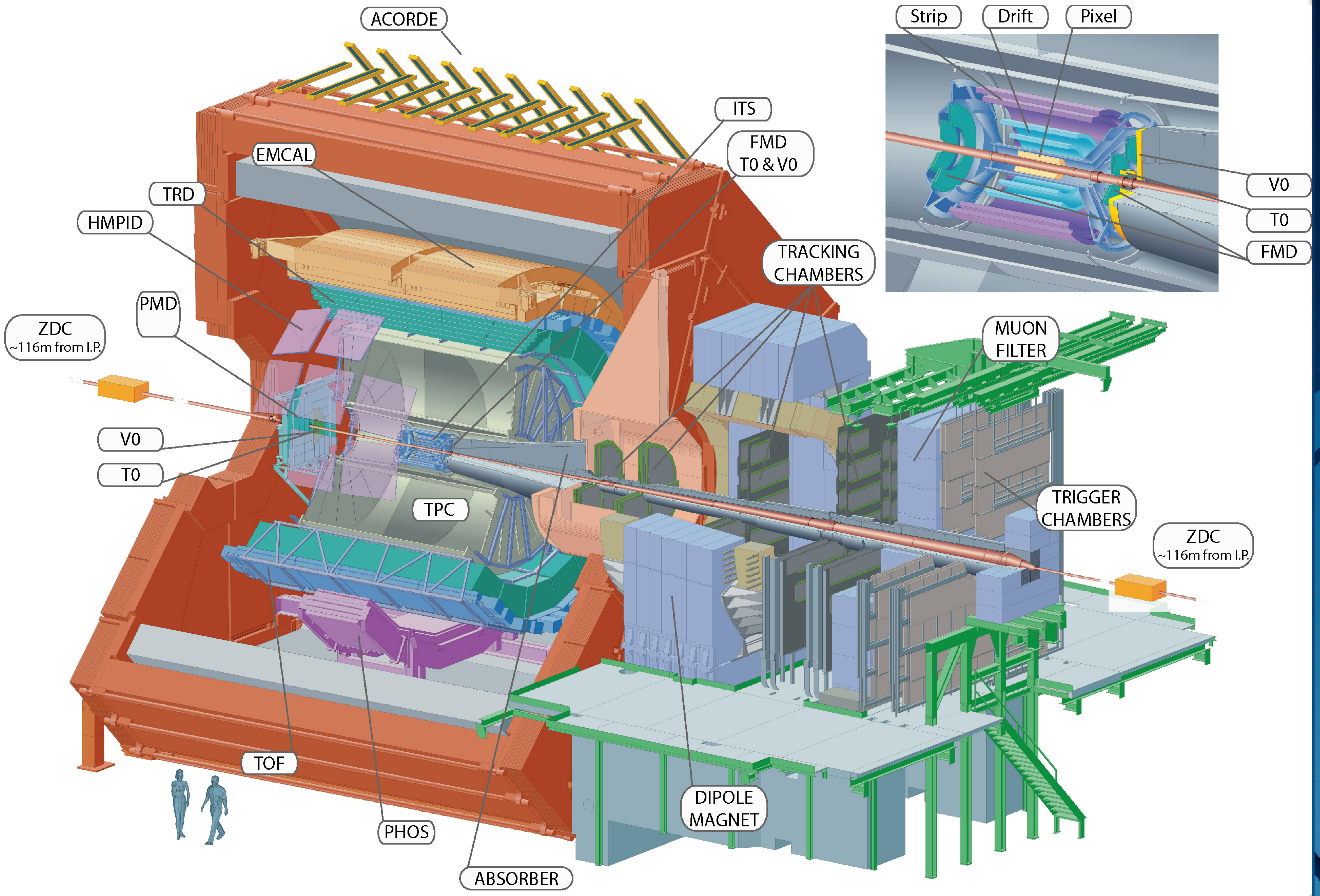
- **What can we learn more from heavy quarks?**

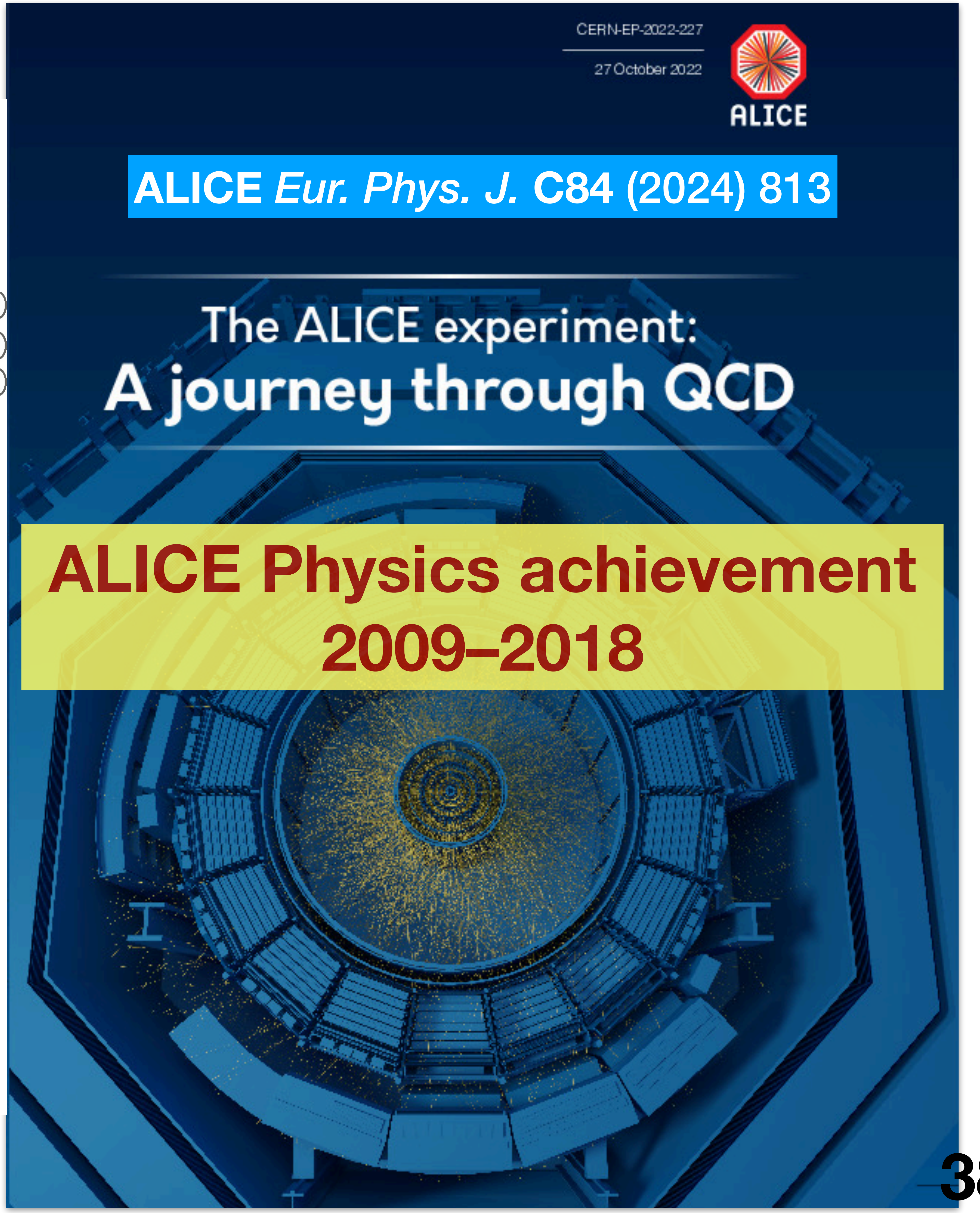
  ➡ **New tool of study spin physics and strong nuclear force**

Thanks for your attention!

Backup

Journey through QCD

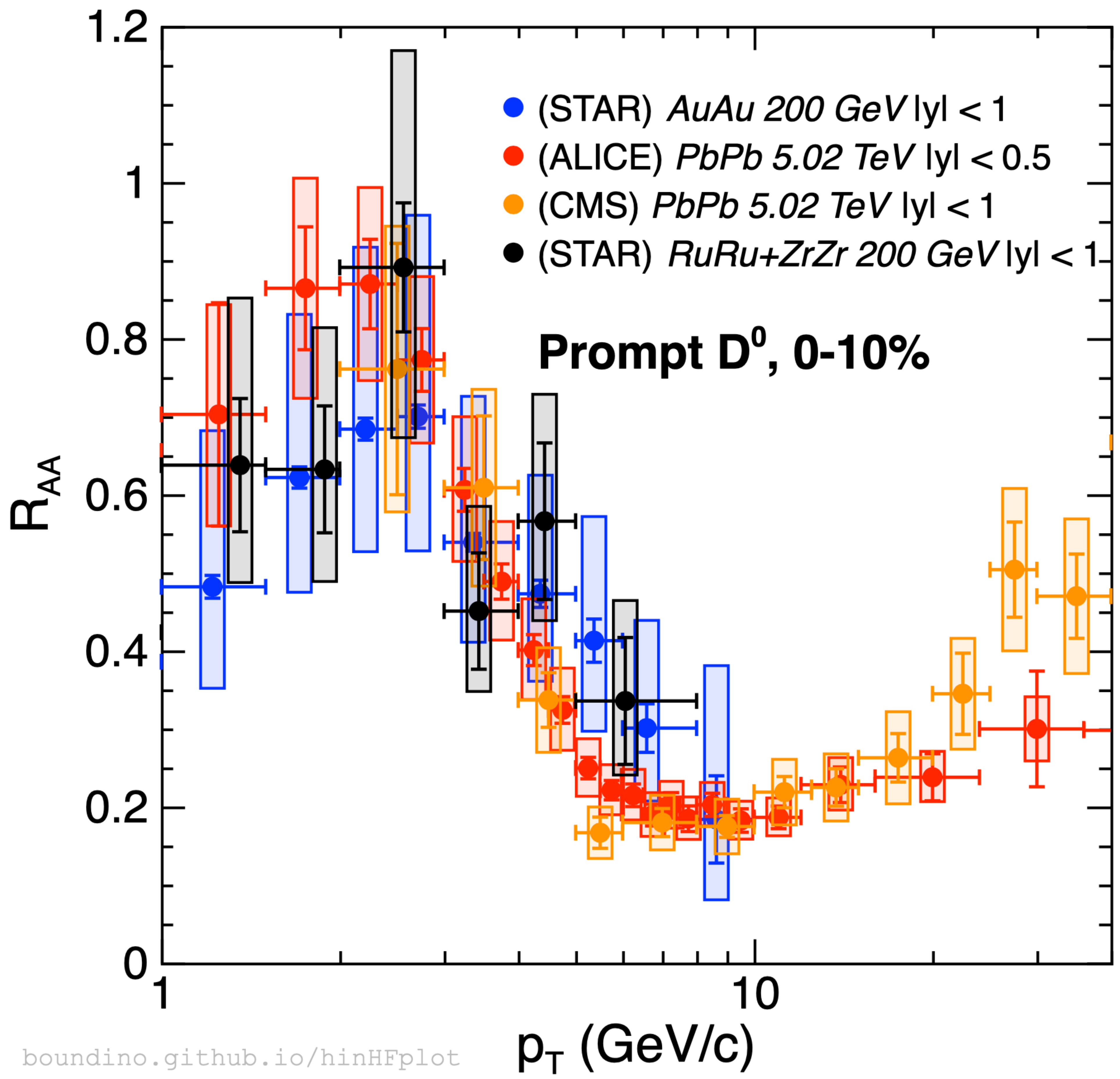




ALICE *Eur. Phys. J.* C84 (2024) 813

ALICE Physics achievement 2009–2018

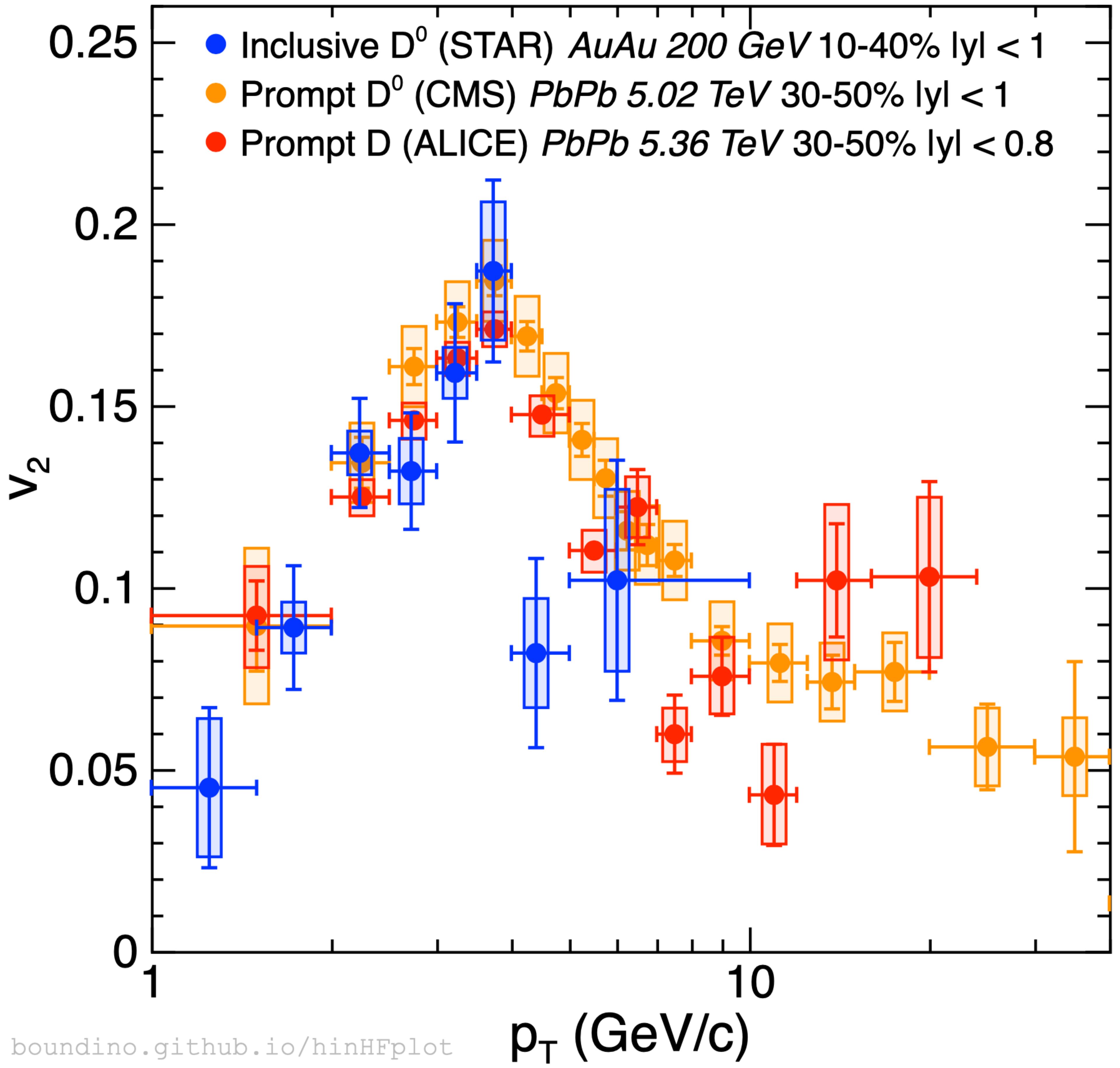
R_{AA} of prompt D mesons



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 (?)

Elliptic flow of D mesons



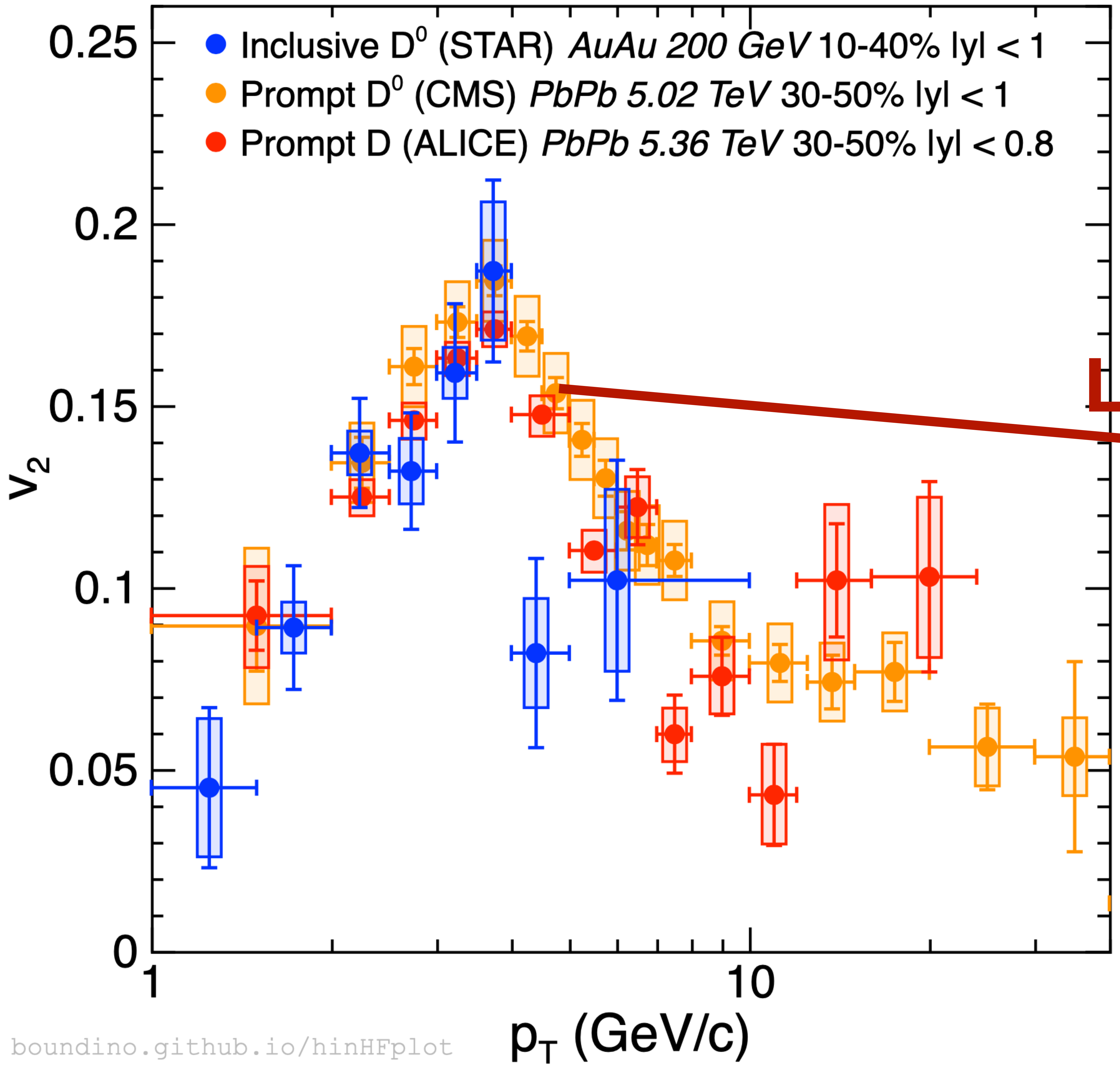
STAR *Phys. Rev. Lett.* **118** (2017) 212301
CMS *Phys. Rev. Lett.* **129** (2022) 022001
CMS *Phys. Lett.* **B816** (2021) 136253
ALICE Preliminary

(Again) similarity between RHIC and the LHC

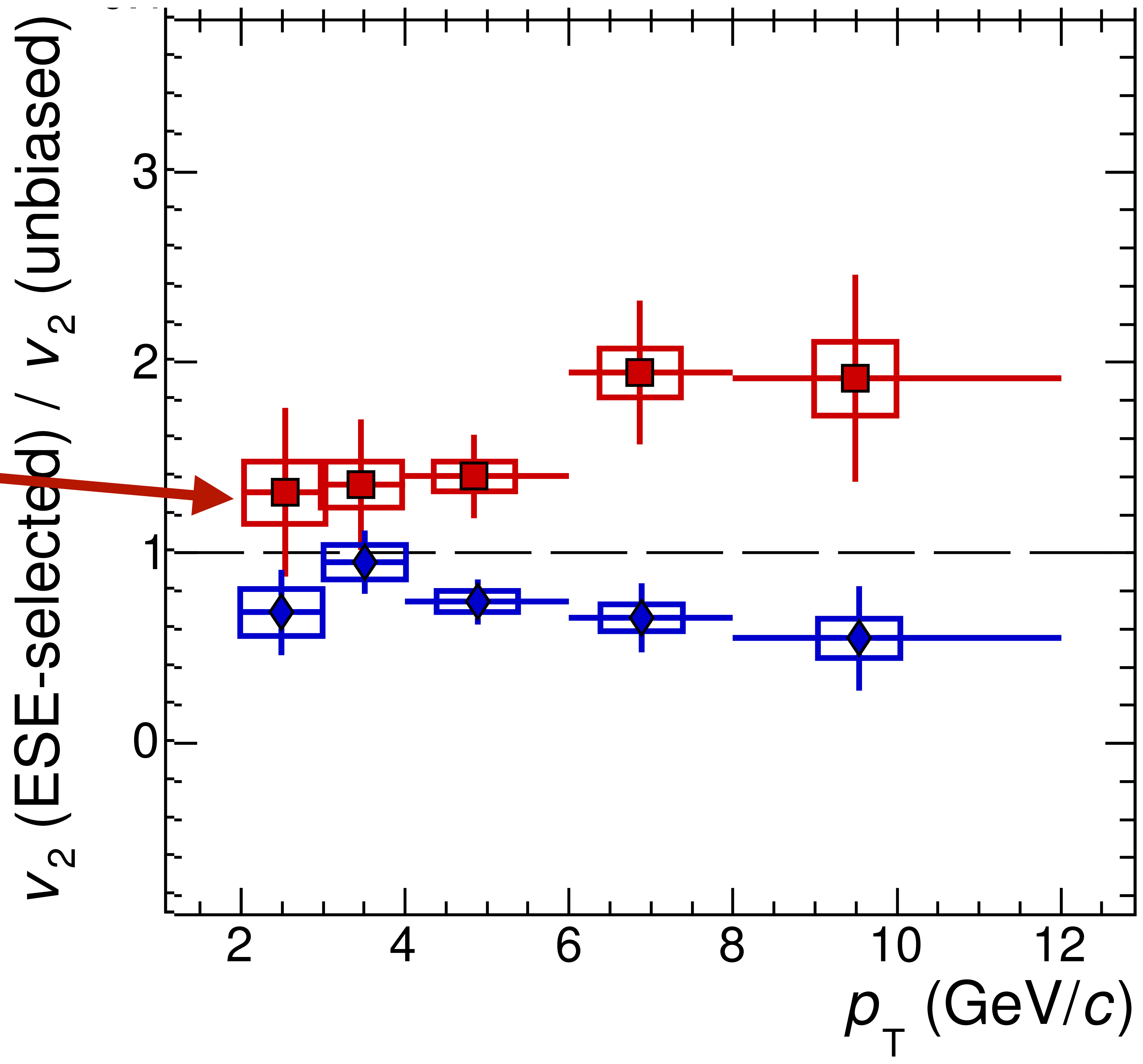
Additional dependence on

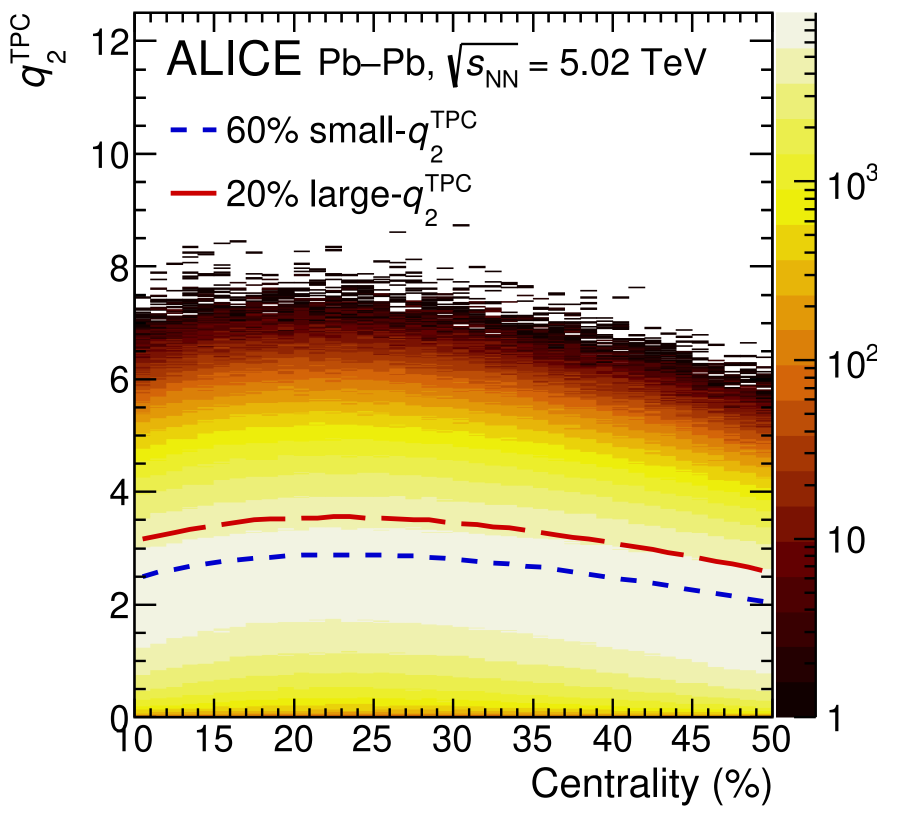
- Initial geometry, fluctuations…
- Medium viscosity
- Hadronic interactions
- …

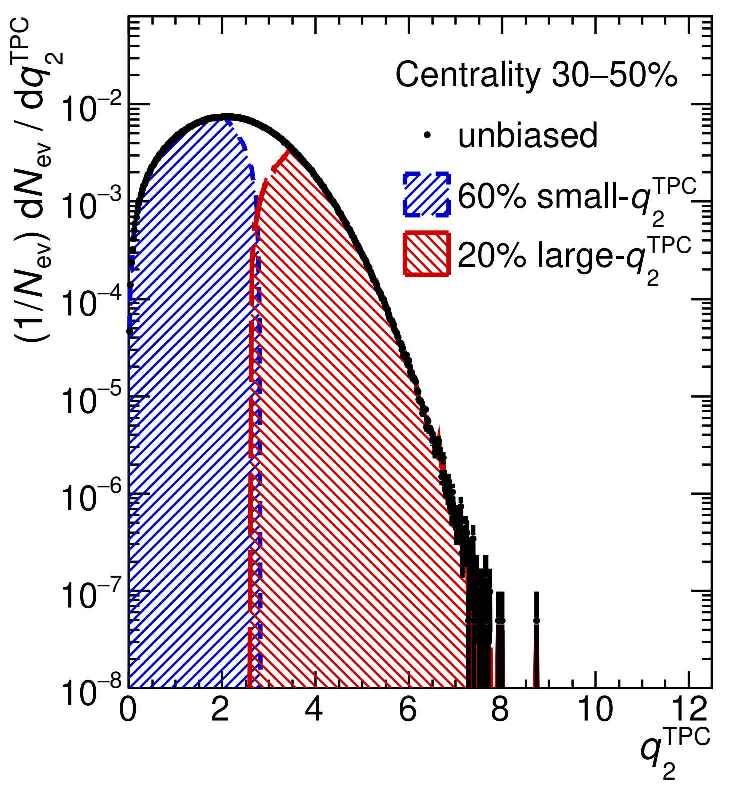
Elliptic flow of D mesons



LHC





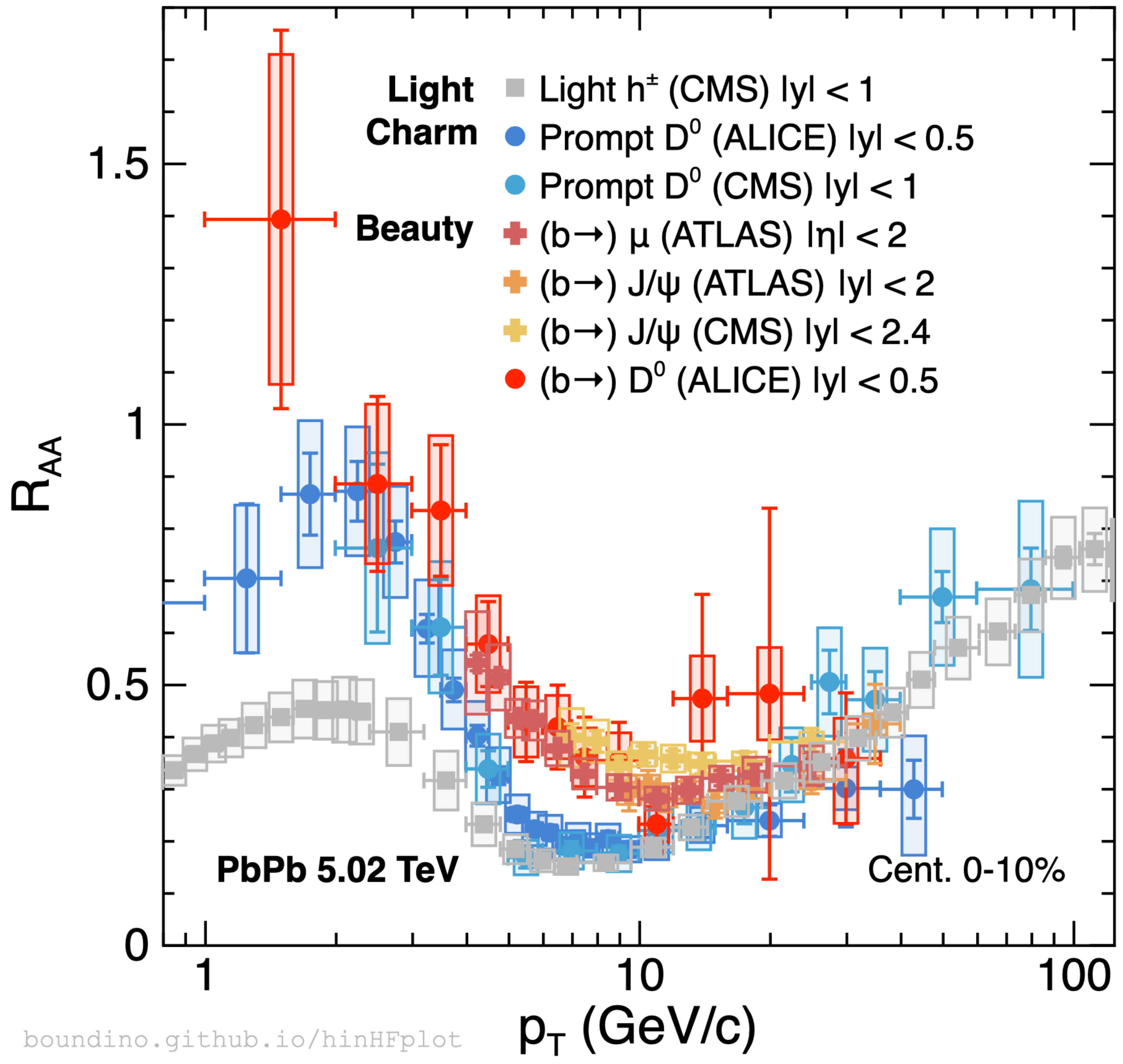


STAR *Phys. Rev. Lett.* **118** (2017) 212301
CMS *Phys. Rev. Lett.* **129** (2022) 022001
CMS *Phys. Lett.* **B816** (2021) 136253
ALICE Preliminary

Clear correlations with eccentricity

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

Quark mass dependent R_{AA}



CMS *JHEP* **1704** (2017) 039
CMS *Eur. Phys. J.* **C78** (2018) 509
CMS *JHEP* **2201** (2022) 174
ATLAS *Eur. Phys. J.* **C78** (2018) 762
ATLAS *Phys. Lett.* **B829** (2022) 137077
ALICE *JHEP* **2201** (2022) 174
ALICE *Phys. Lett.* **B782** (2018) 474