Charm quarks from production to hadronisation in heavy–ion collisions

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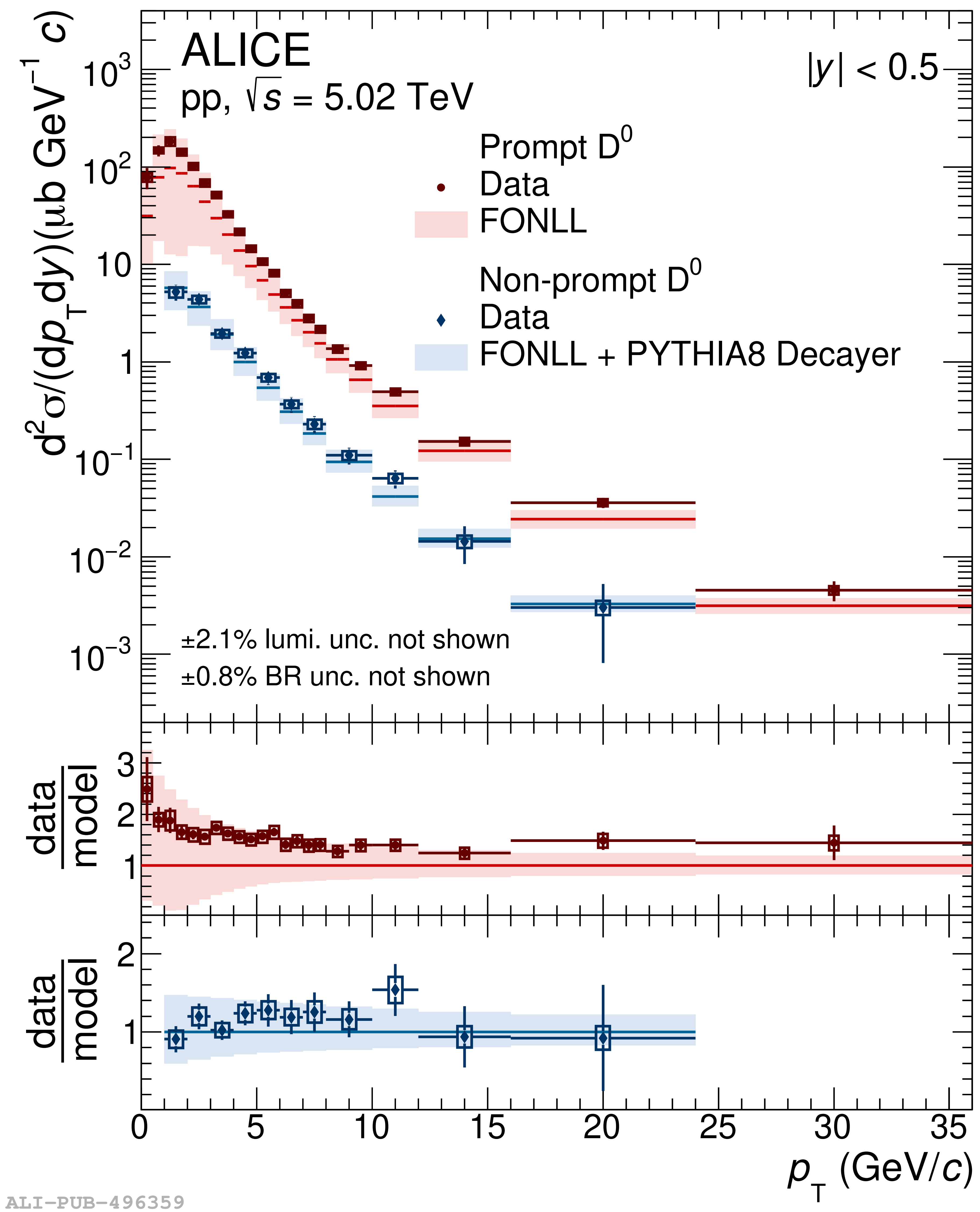
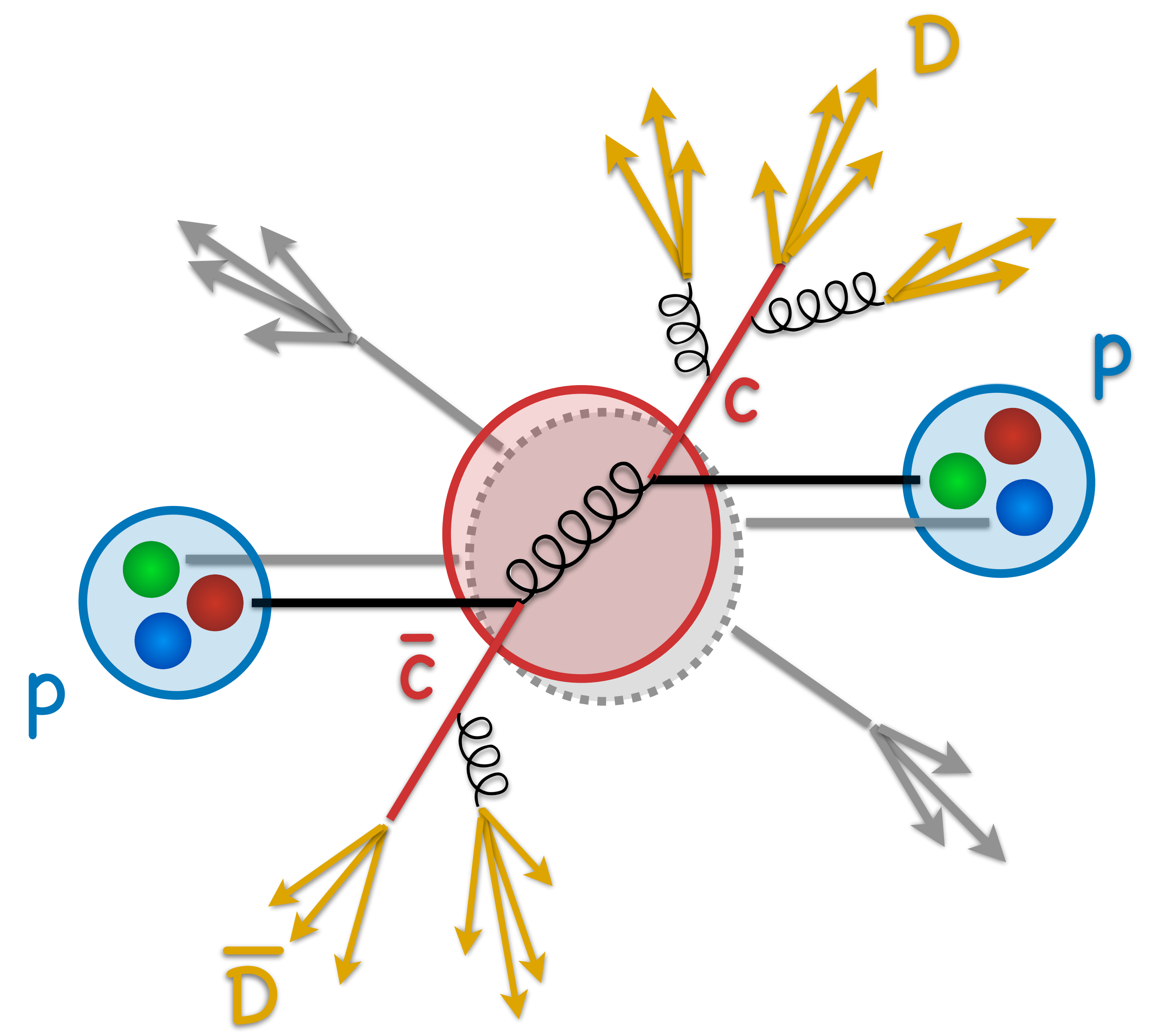
Production of heavy quarks in proton–proton collisions



ALICE, JHEP 05 (2021) 220

- Charm and beauty quarks are produced in hard-scattering processes
- perturbative QCD calculations based on the factorisation theorem



$$\sigma_{hh\rightarrow Hh} = \mathrm{PDF}(x_a, Q^2)\ \mathrm{PDF}(x_b, Q^2) \otimes \sigma_{ab\rightarrow q\bar{q}} \otimes D_{q\rightarrow h}(z_q, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

Fragmentation functions (non perturbative)

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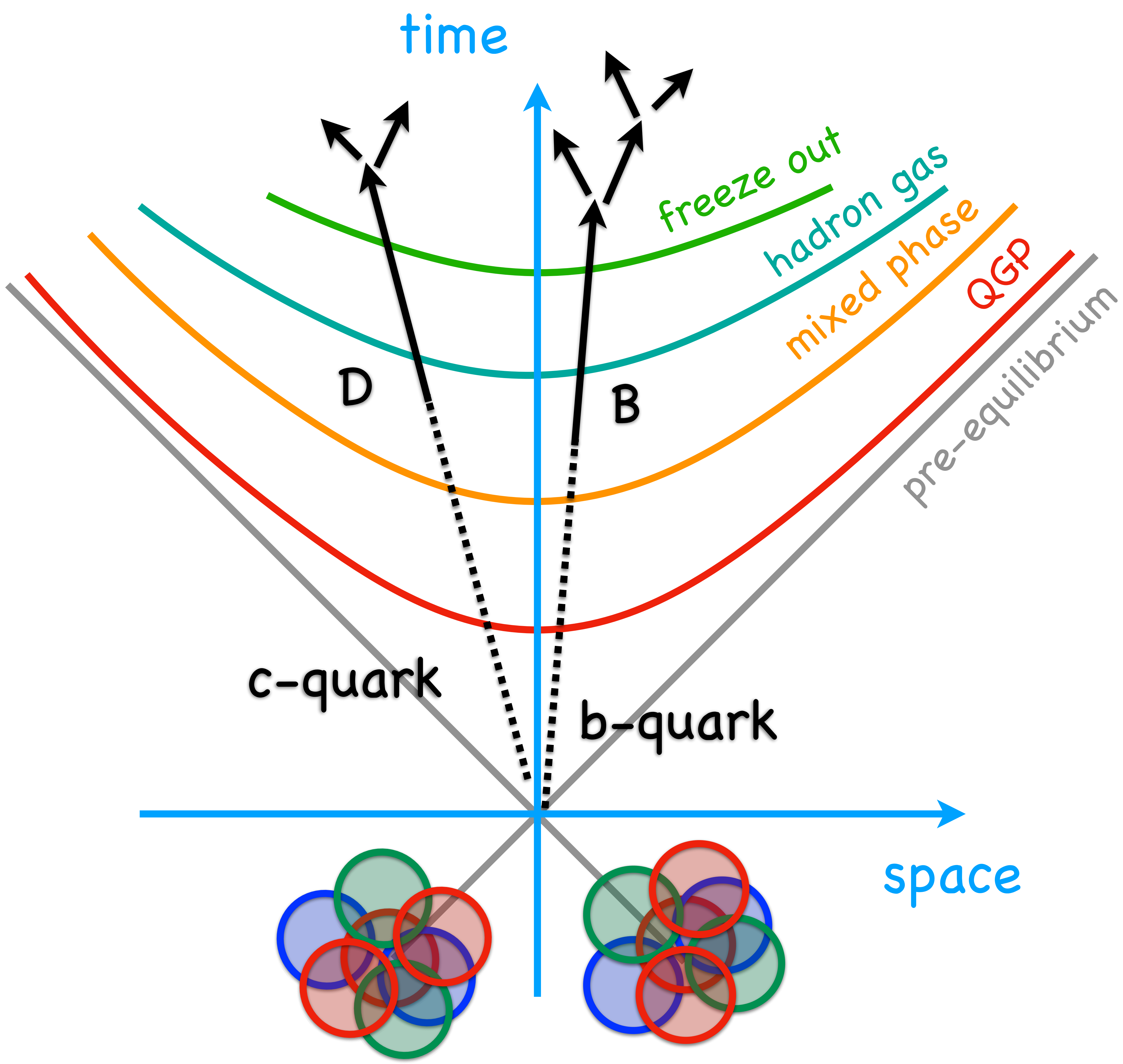


- Lattice QCD calculations predict a phase transition from the ordinary nuclear matter to a *quark–gluon plasma* (QGP)
  - ➡ very high energy density $\varepsilon > 15$ GeV/fm^3
  - ➡ after a pre-equilibrium phase expands hydrodynamically
- Heavy quarks: produced in shorter time scales than QGP
  - ➡ $\tau_{\mathrm{HF}} \lesssim \hbar/m \approx 0.05\text{-}0.1$ fm/c depending on p_{T}
  - ➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) ≈ 0.3 fm/c

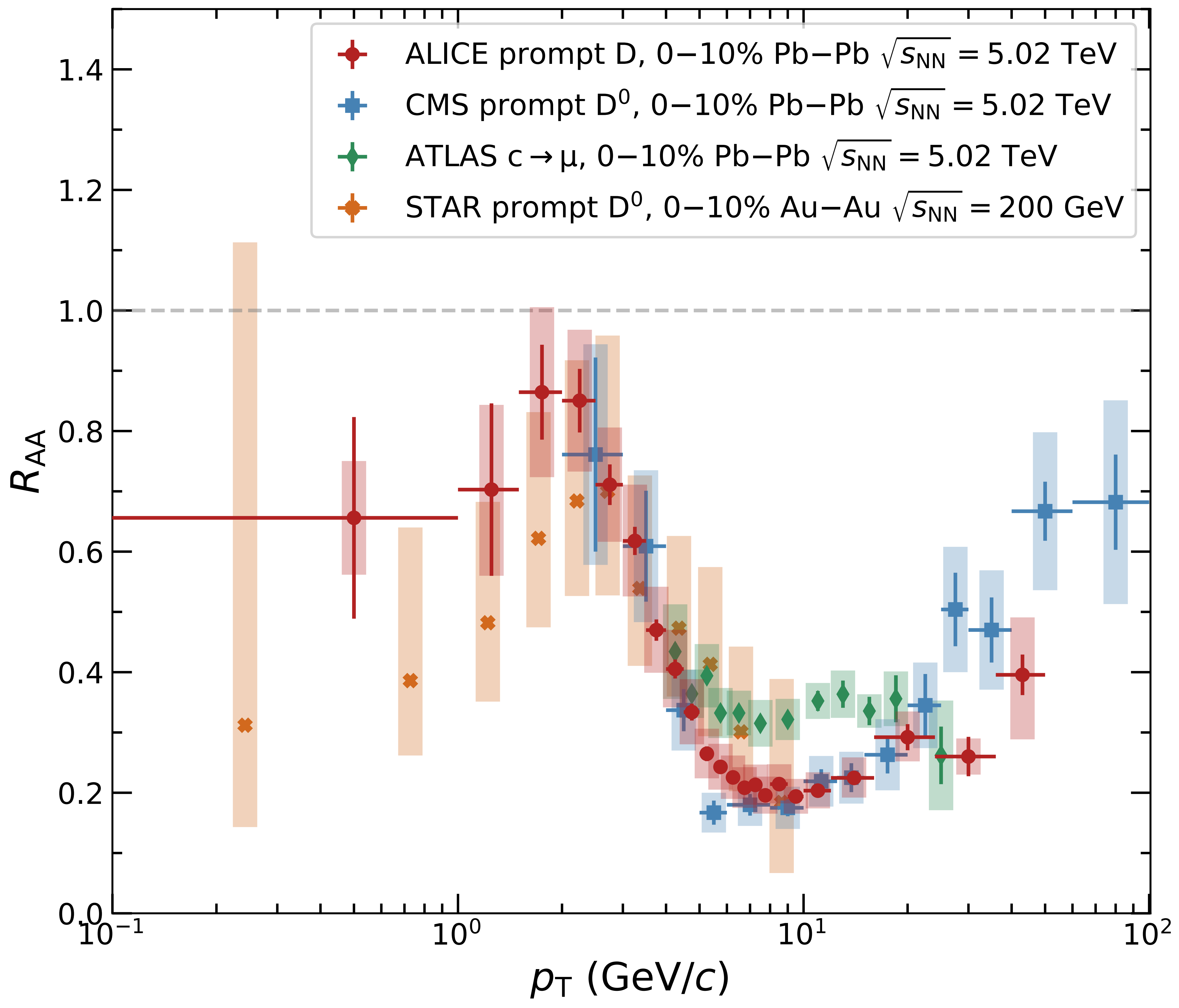
PRC 89 (2014) 034906

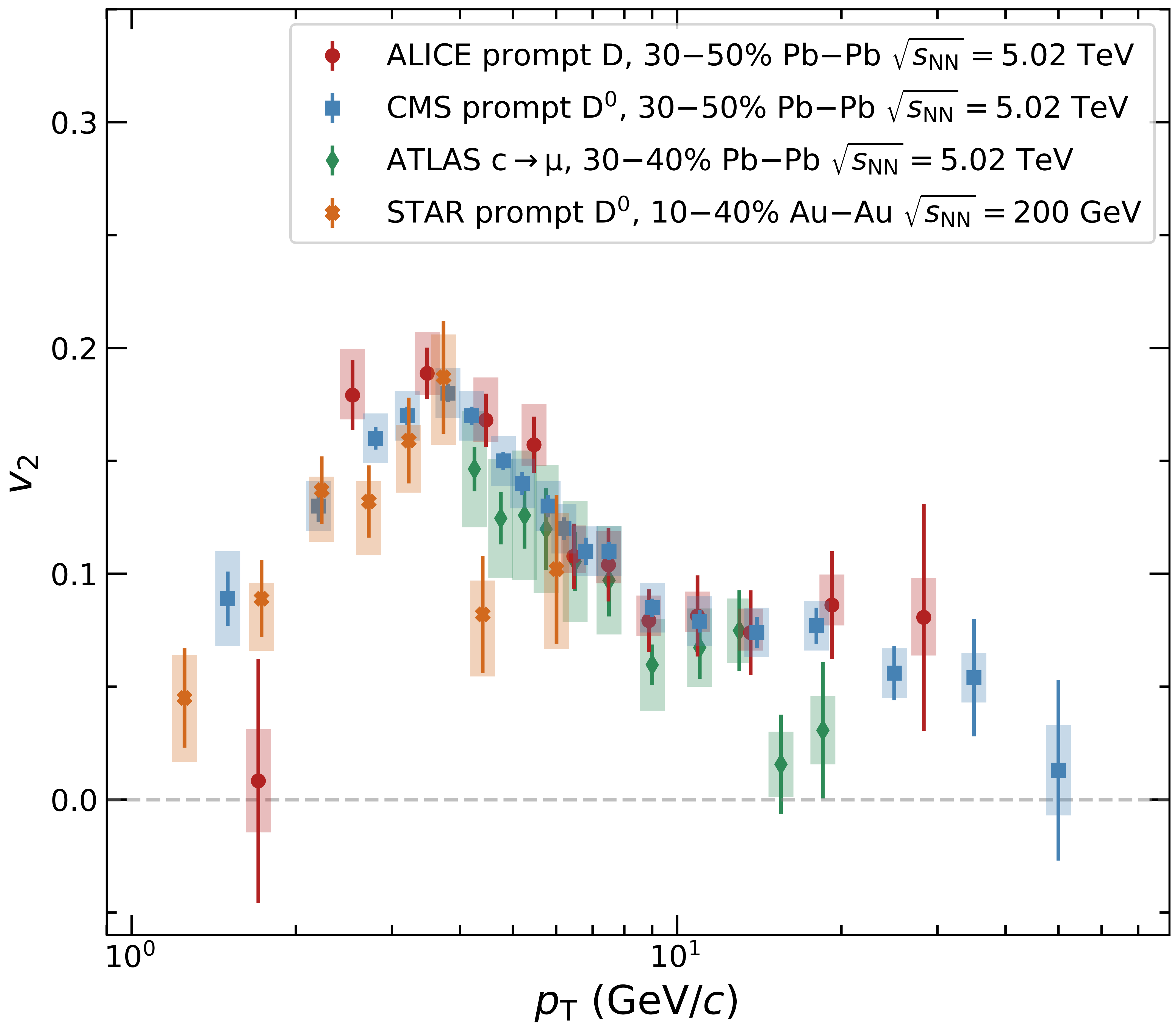
- Low-p_{T}:
  - ➡ Multiple elastic collisions with the medium constituents
    - ▸ Diffusion (Brownian) motion
    - ▸ Possible (partial) thermalisation in the medium
- High-p_{T}:
  - ➡ Radiative energy loss (gluon emission)
    - ▸ Study properties of in-medium energy loss

The main observables

Nuclear modification factor $R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \cdot dN_{pp}/dp_T}$

Elliptic flow $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$





ALICE, JHEP 01 (2022) 174
ALICE, PLB 813 (2021) 136054
ATLAS, PLB 829 (2022) 137077
ATLAS, PLB 807 (2020) 135595
CMS, PLB 782 (2018) 474
CMS, PLB 816 (2021) 136253
STAR, PRC 99 (2019) 34908
STAR, PRL 118 (2017) 212301

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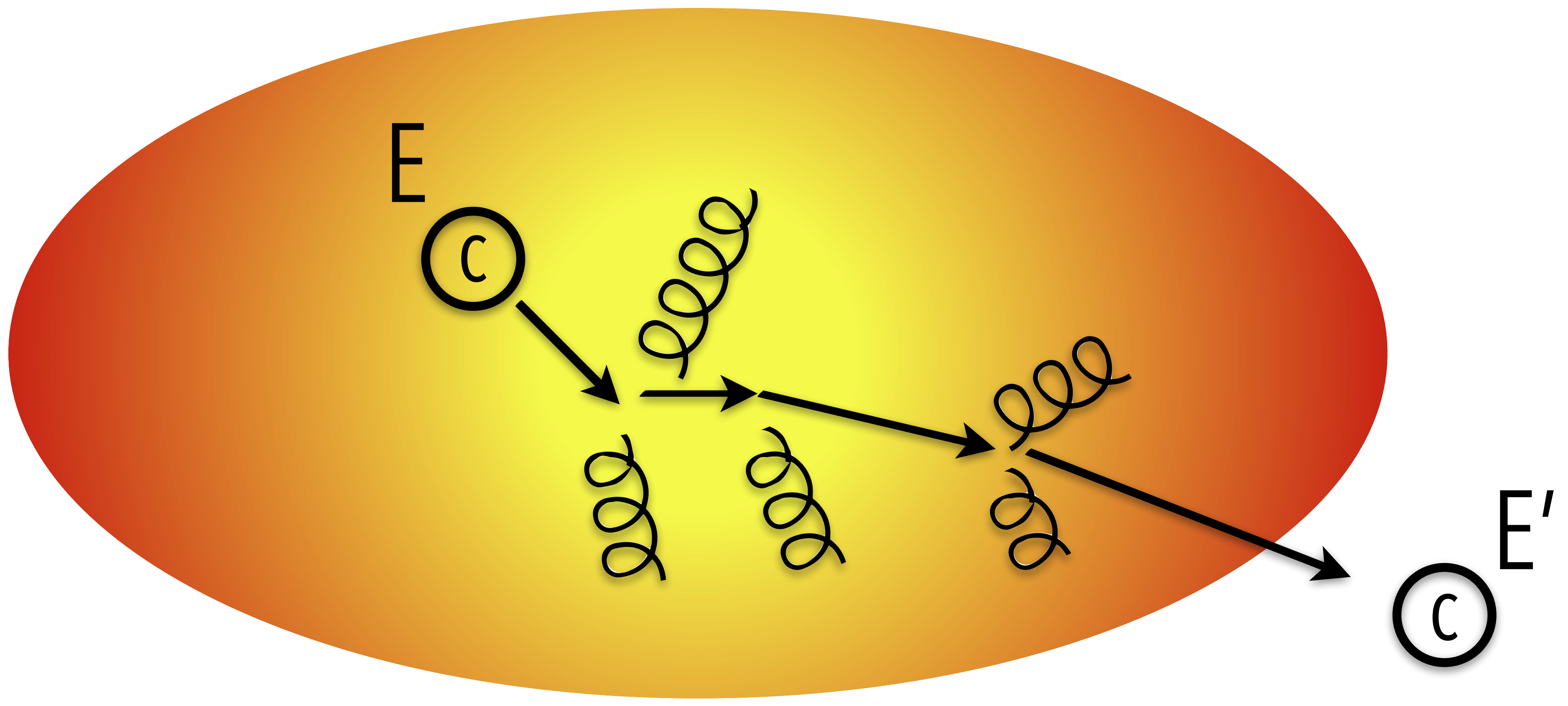
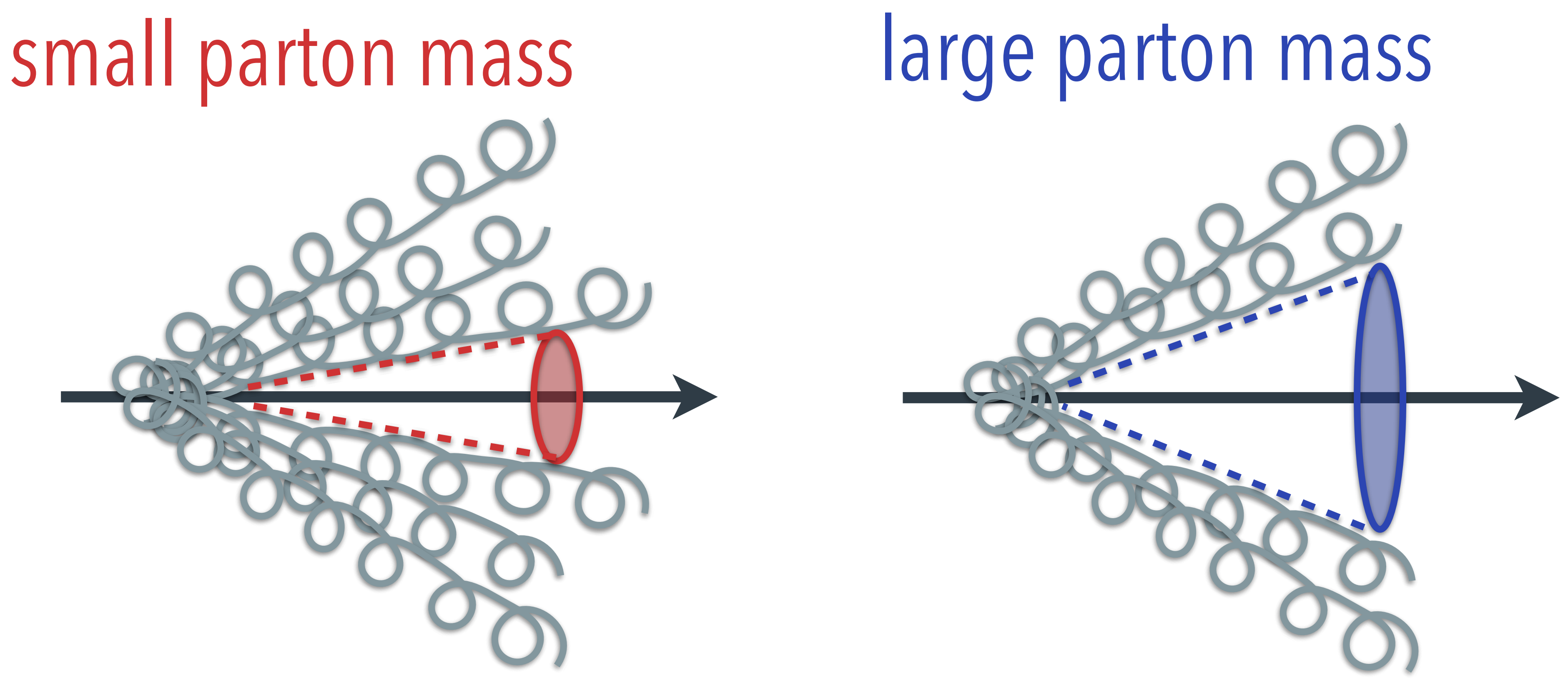
- Dominant effect: energy loss of charm and beauty quarks in the medium
- Goal: study the colour-charge and quark-mass dependence of the in-medium energy loss





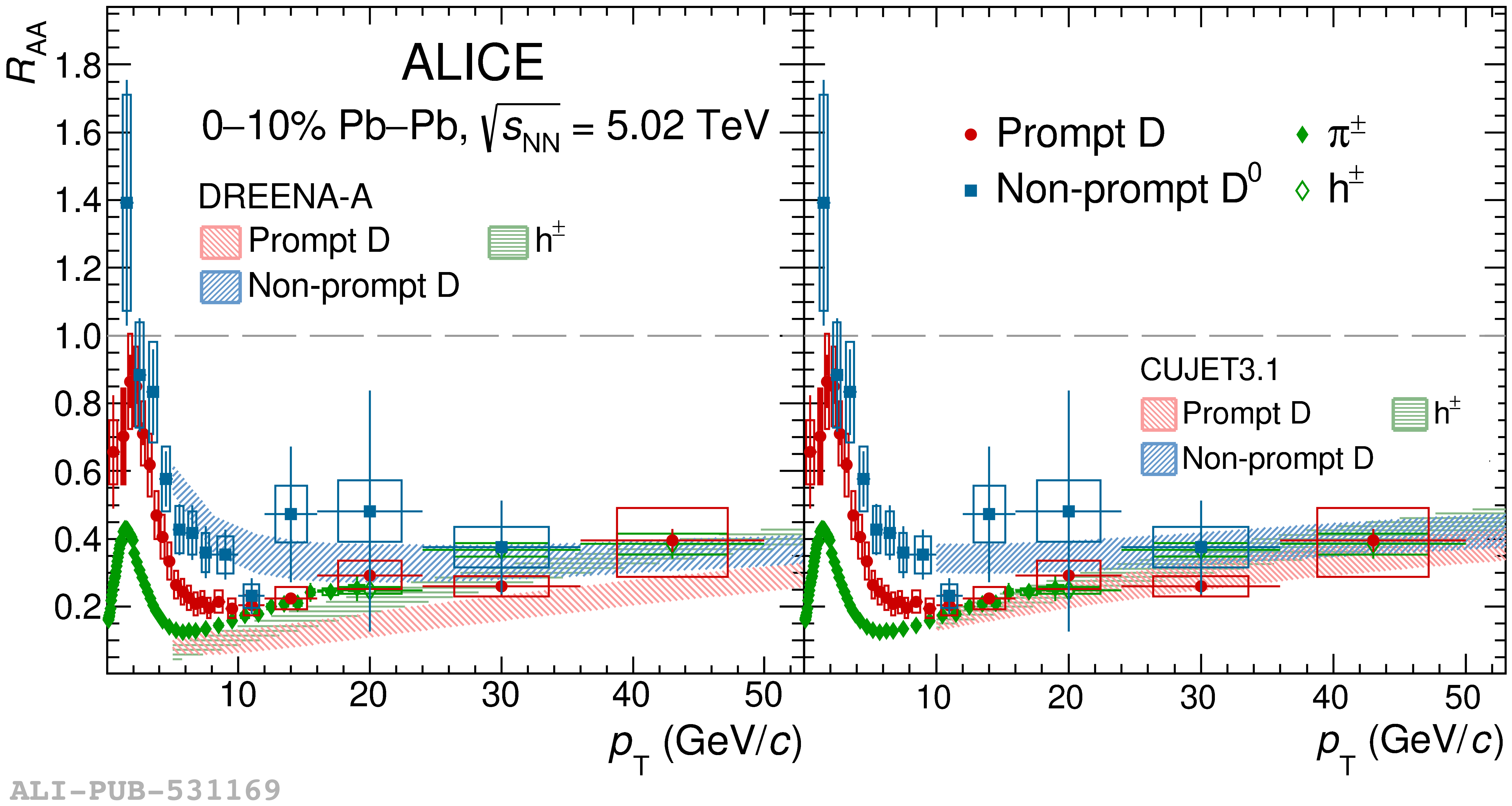
Dead cone effect: gluon radiation suppressed at angles smaller than $\vartheta < m/E$

$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

- L^2 → Path traversed in the medium
- $\hat{q}$ → Transport coefficient (average of the square of the transverse momentum exchanged with the QGP per unit mean free path)
- α_s → Strong coupling constant
- C_R → Casimir factor = 3 for gluons and 4/3 for quarks

The high-p_T regime

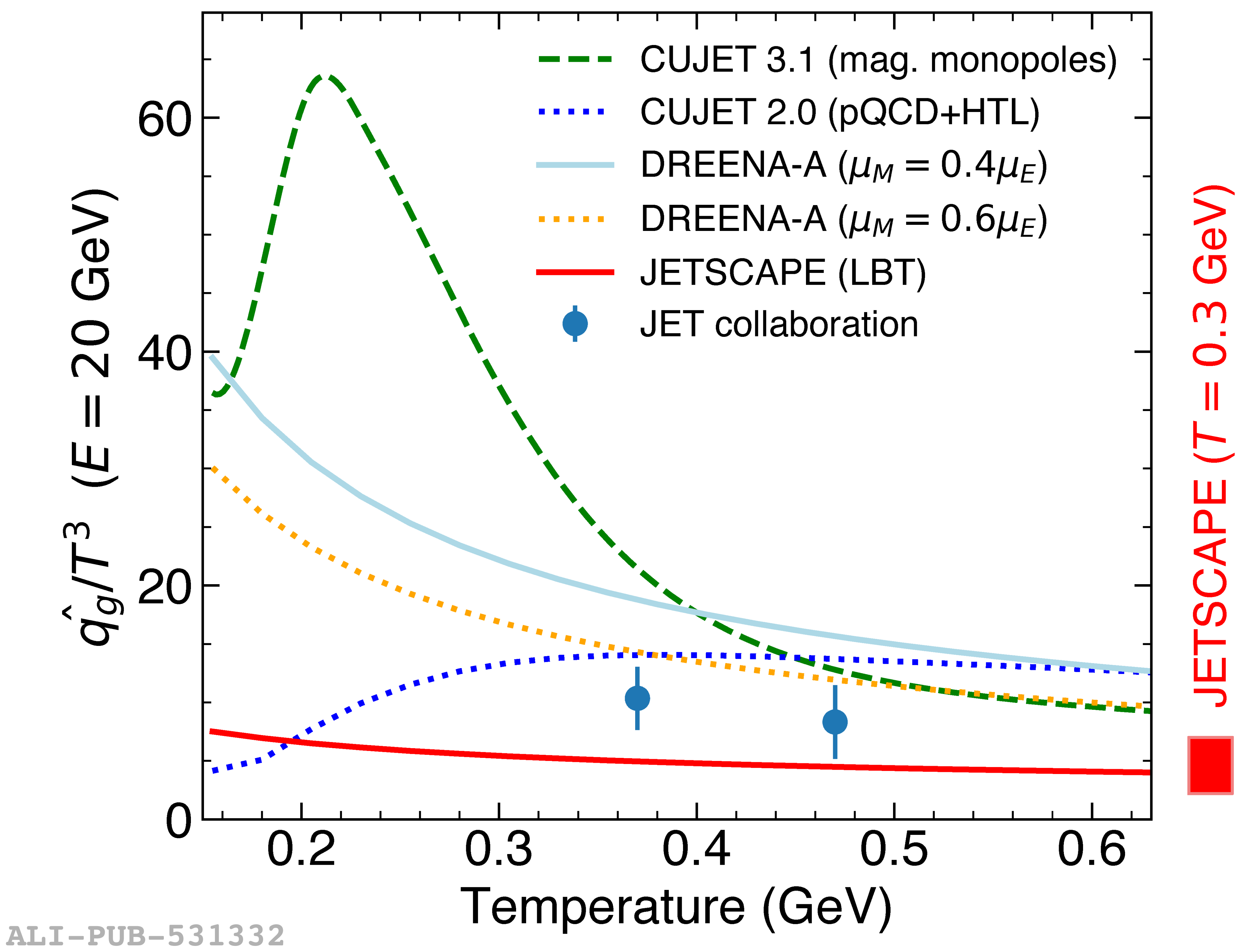
ALICE, arXiv: 2211.04384



- Hierarchy of suppression as expected from dead cone effect

$$R_{AA}(b) > R_{AA}(c) \gtrsim R_{AA}(light)$$

ALICE, arXiv: 2211.04384



- Data-to-model comparison seems to favour the scenario of weak coupling for high temperatures
- Less constraints for models at low temperatures
  - ➡ Different observables needed

- Models based on the charm-quark transport on a hydrodynamically expanding QGP
  - ➡ Typical momentum transfers in scatterings between charm quarks and medium constituents (heat bath) are small
  - ➡ Charm quarks undergo soft and incoherent collisions → Brownian motion
  - ➡ Boltzmann equation can be reduced to a Langevin or Fokker-Plank equation

$$\frac{\partial}{\partial t} f_{\mathrm{Q}}(t, \mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) \cdot f_{\mathrm{Q}}(t, \mathbf{p}) + \frac{\partial}{\partial p^j} \left[B^{ij}(\mathbf{p}) \cdot f_{\mathrm{Q}}(t, \mathbf{p}) \right] \right\}$$

- In case of a medium in thermal equilibrium
  - ➡ $A^i(\mathbf{p}) = A(\mathbf{p}) p_i$ friction
  - ➡ $B^{ij}(\mathbf{p}) = B_0(p) \cdot P_{ij}^{\perp}(\mathbf{p}) + B_1(p) \cdot P_{ij}^{\parallel}(\mathbf{p})$ momentum broadening

- Brownian motion of heavy quarks in QGP governed by the coupling of heavy quarks to the medium
  - ➡ Spatial diffusion coefficient

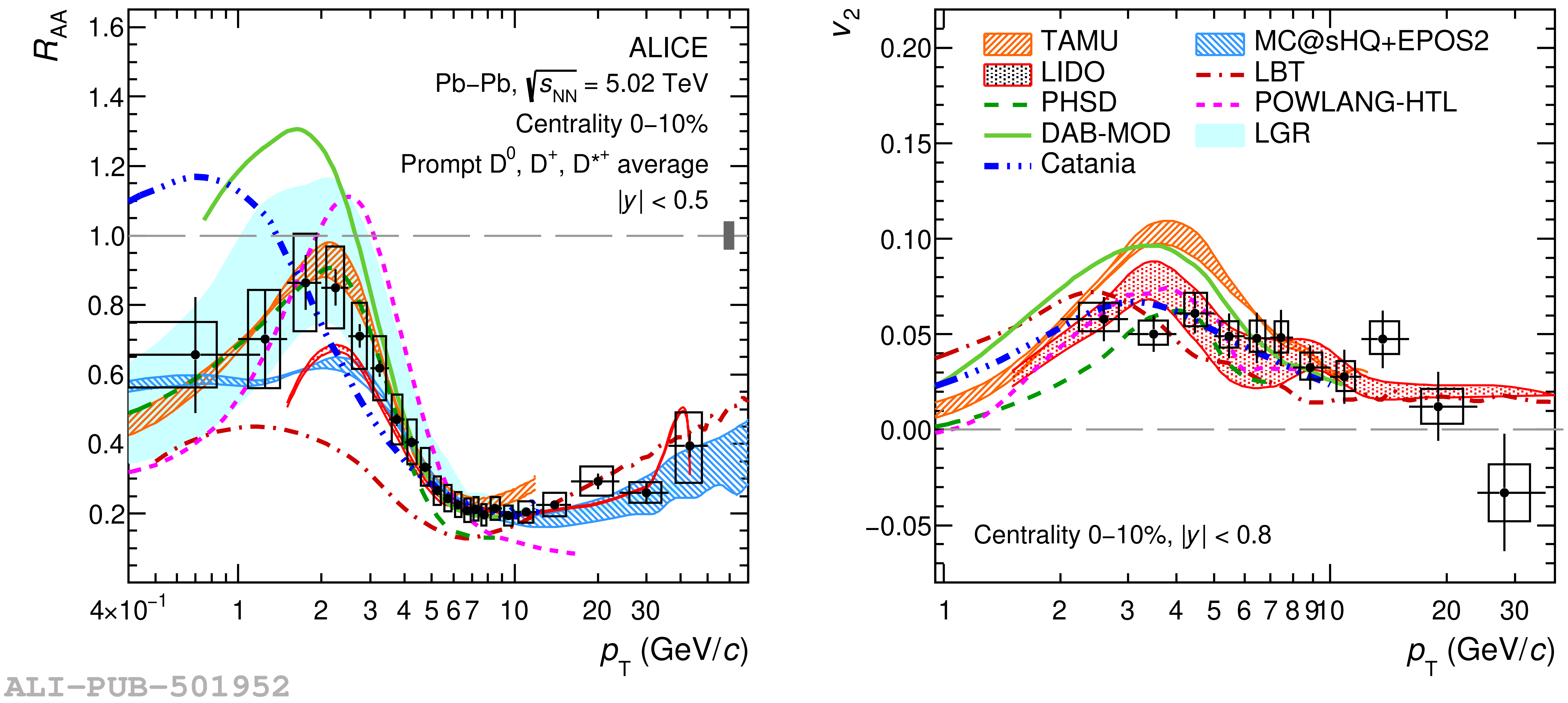
$$D_s = \frac{T}{m_{\mathrm{charm}} A(p=0)}$$

→ Related to the thermalisation time of the charm quark

$$\tau_{\mathrm{charm}} = (m_{\mathrm{charm}}/T) \cdot D_s$$

Approximately $A(p=0) \propto 1/m_{\mathrm{charm}}$

ALICE, JHEP 01 (2022) 174



- Additional model ingredients
  - ➡ Initial state conditions
  - ➡ Nuclear PDFs
  - ➡ Hadronisation via different mechanisms
  - ➡ Hadronic phase

TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: arXiv:1912.08965
LIDO: PRC 98 (2018) 064901
PHSD: PRC 93 (2016) 034906
Catania: PLB 805 (2020) 135460
POWLANG: EPJC (2019) 79:494
LBT: PRC 94 (2016) 014909
DAB-MOD: arXiv:1906.10768

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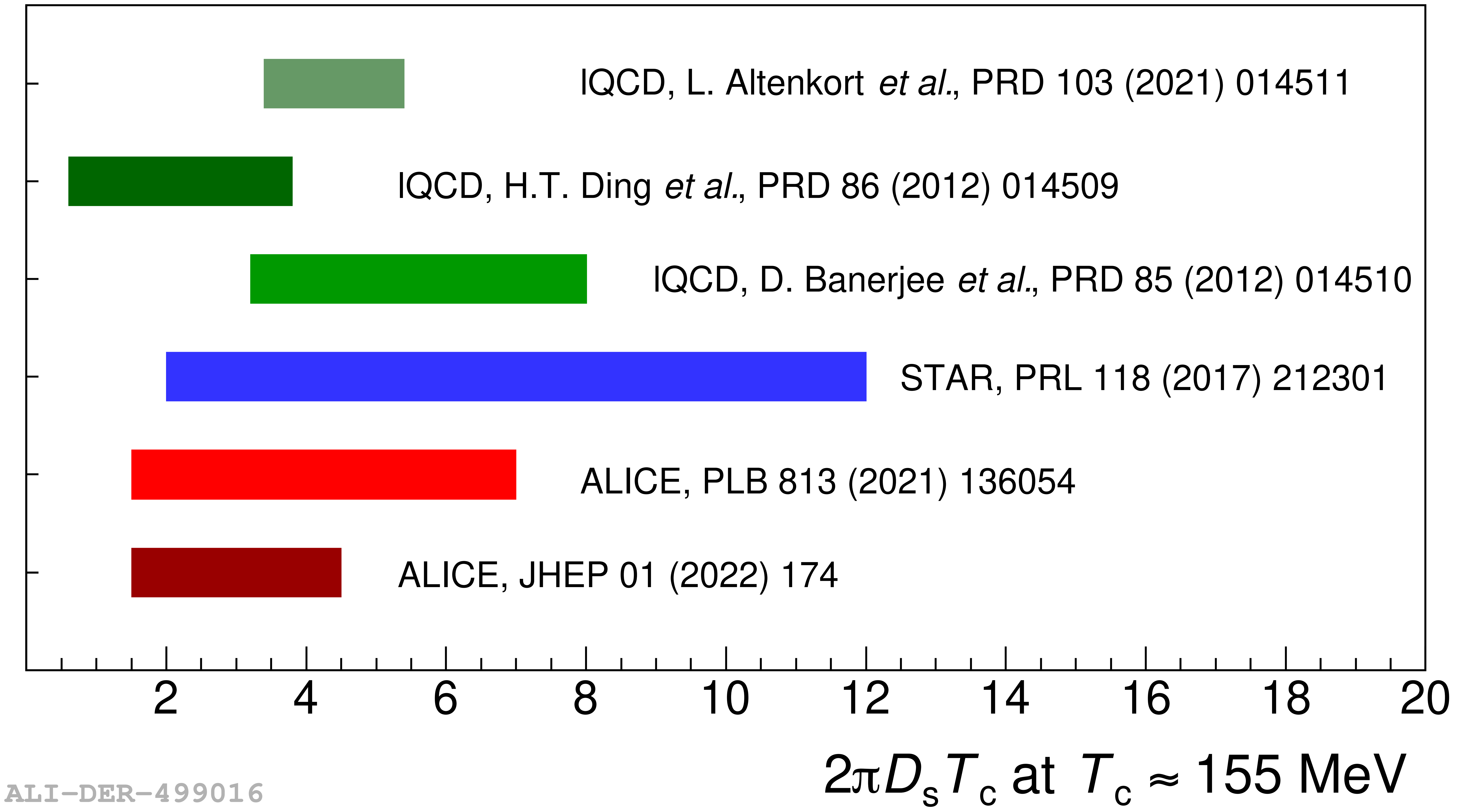
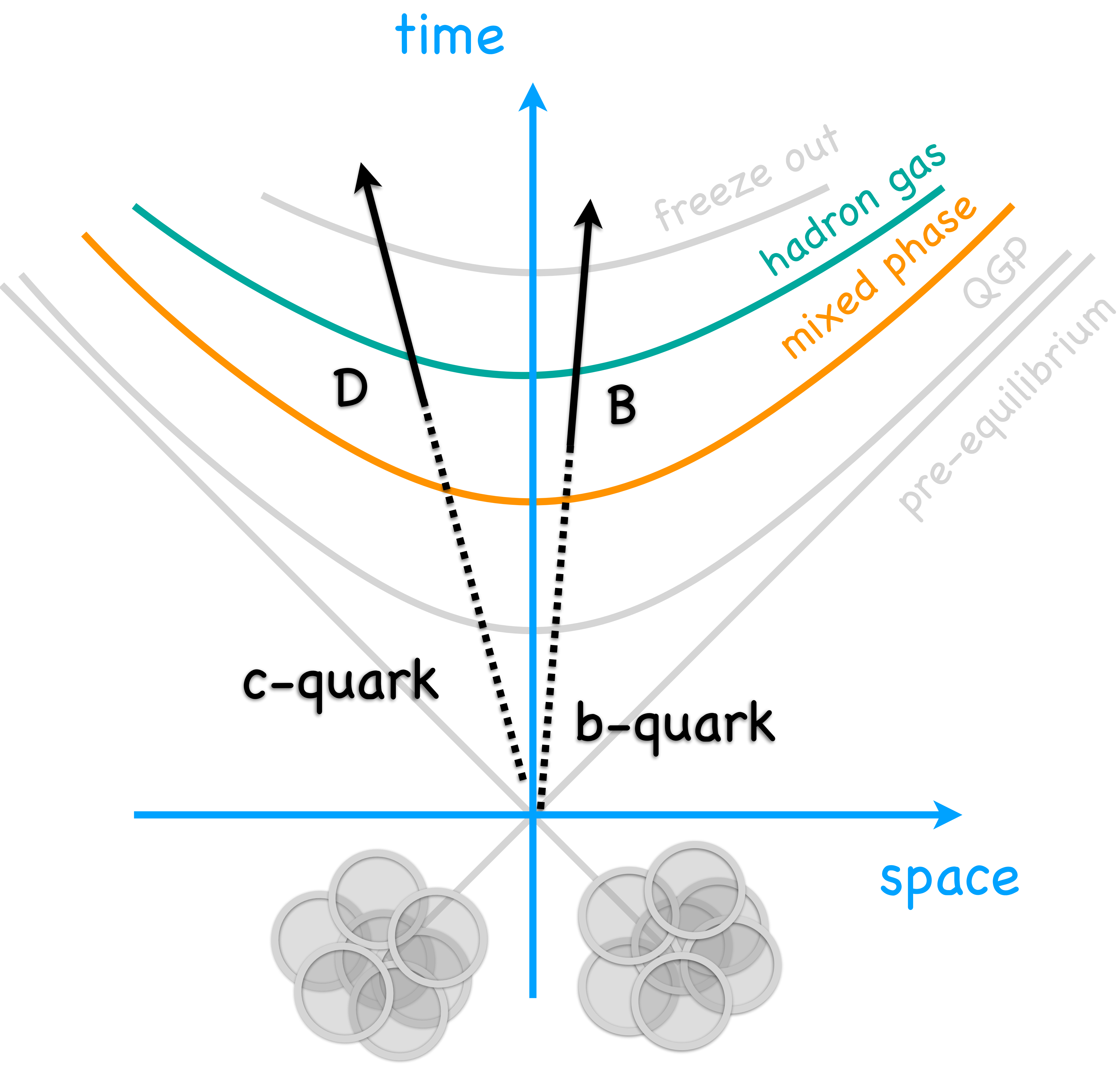
ALICE, JHEP 01 (2022) 174



- Interval of spatial diffusion coefficient obtained by considering the values used in the transport models that reproduce the data
  - ➡ $2.5 < 2\pi D_s T_c < 4.5$ which corresponds to $2 < \tau_{\rm charm} < 6$ fm/c
  - ➡ Indicates a thermalisation time of the charm quark comparable with the QGP lifetime
  - ➡ Compatible with values obtained with QCD calculations on lattice

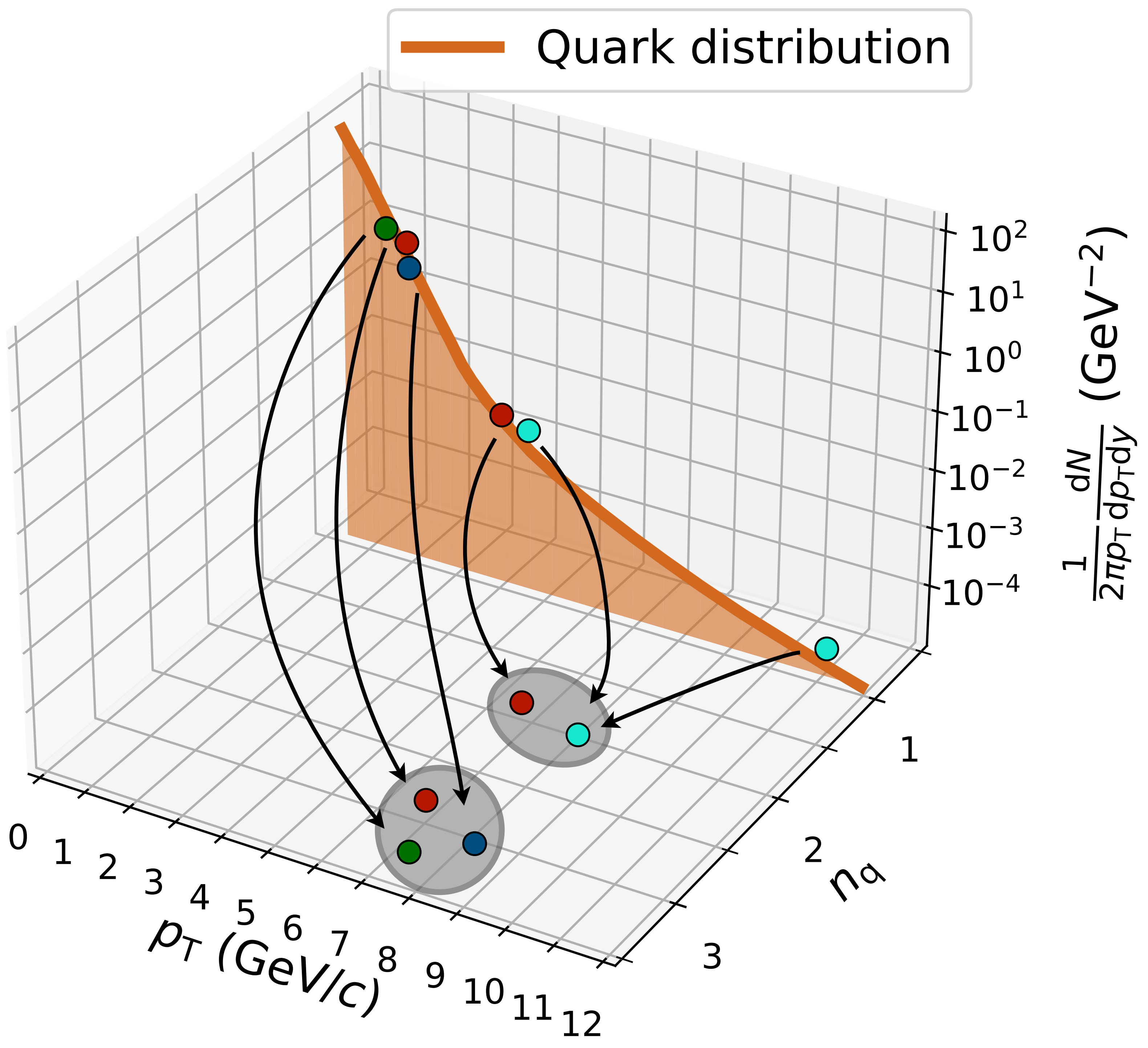
- Can we state that the transport coefficient in a model that describes the data is correct?

- Hadronisation expected to be modified in presence of the colour-deconfined medium



(i) Fragmentation $D_{q\rightarrow h}(z_q, Q^2)$
- A fraction of the parton momentum z_q is taken by the hadron
- Can be modified by energy loss in the QGP

(ii) Recombination/coalescence
- Partons close in phase space can recombine
- Enhances baryon-to-meson ratio at intermediate p_T



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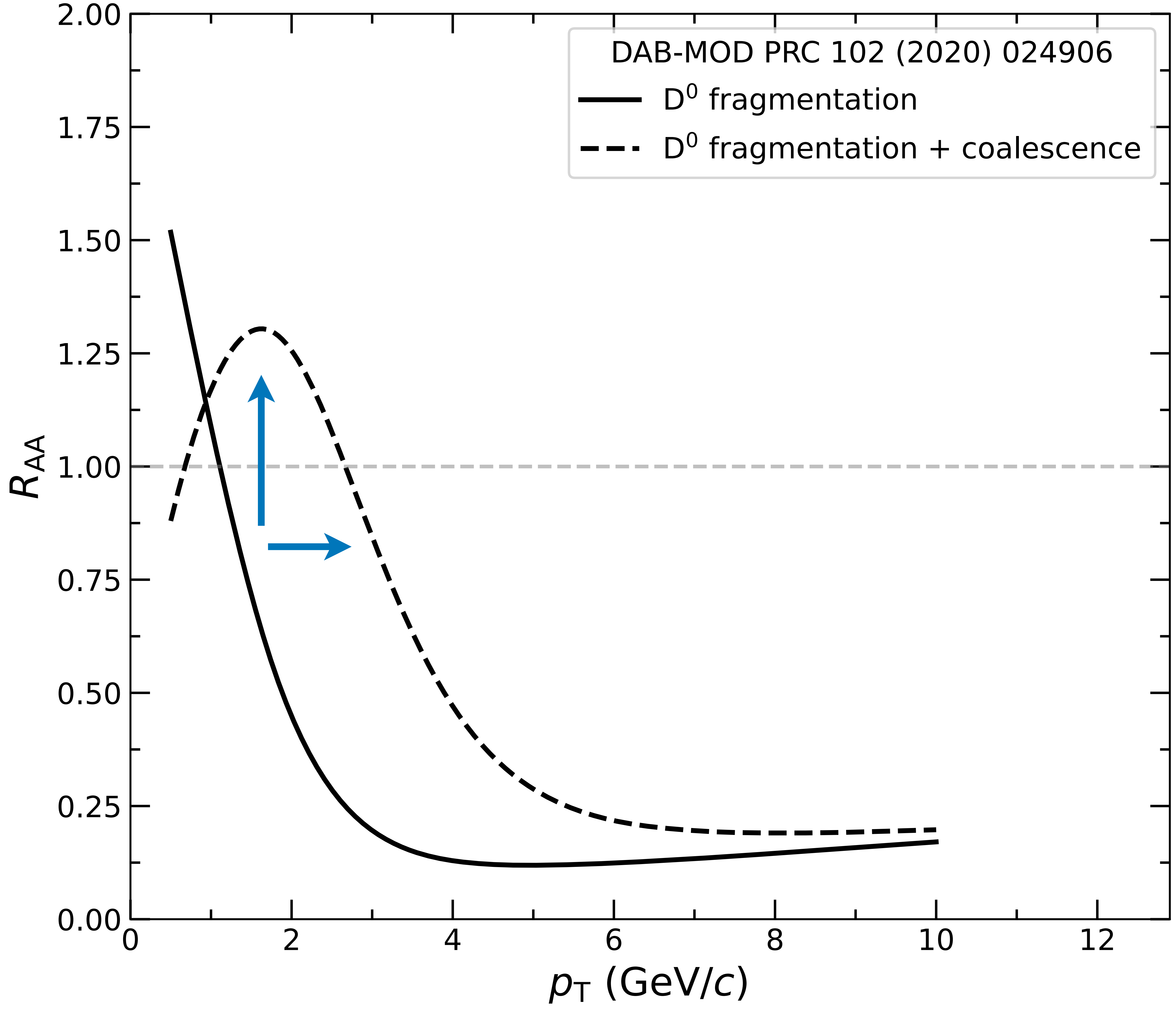
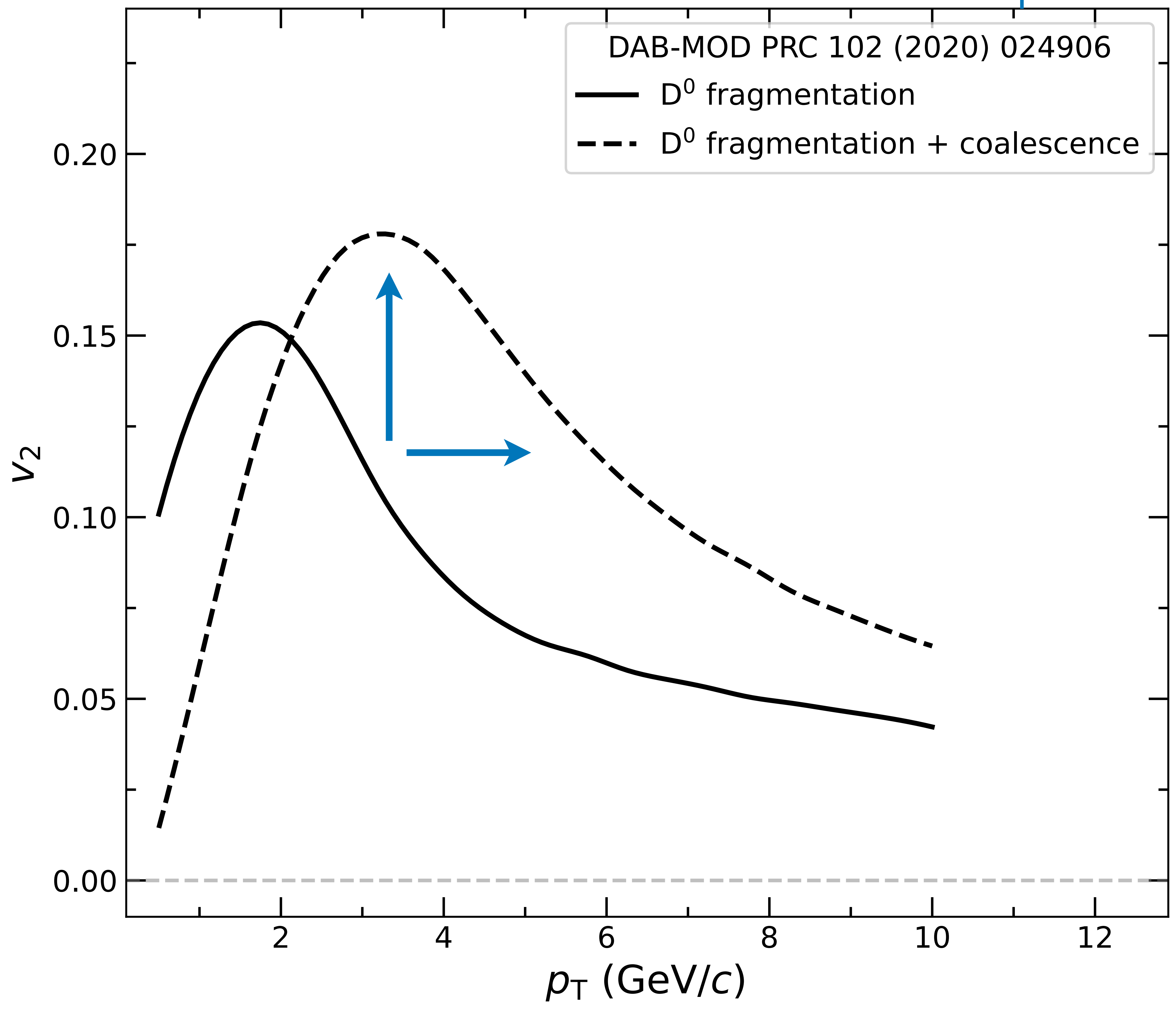
Nuclear modification factor R_{AA}



Elliptic flow



R. Katz et al, PRC 102 (2020) 024906

- Formation of a peak structure at intermediate p_T

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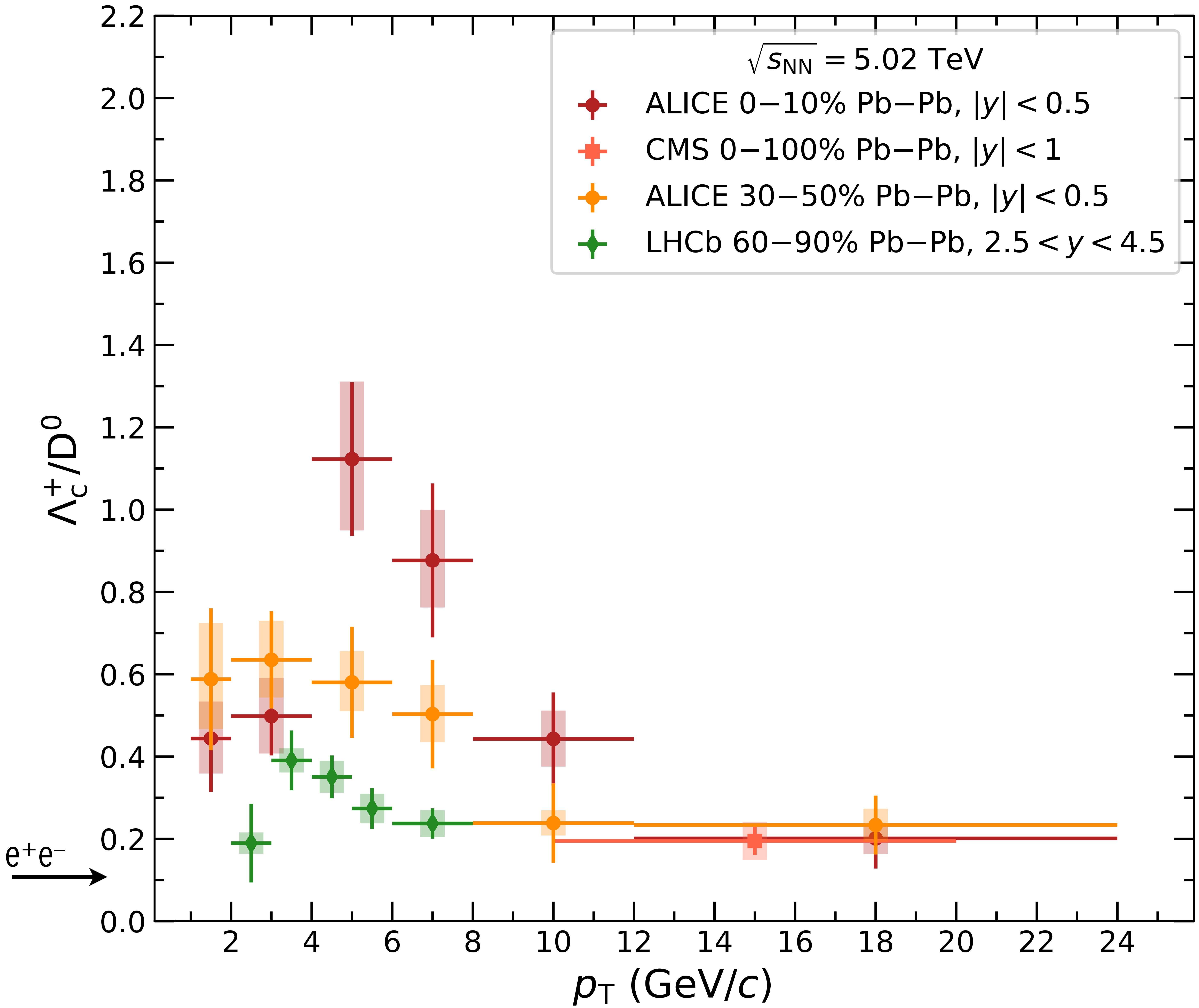
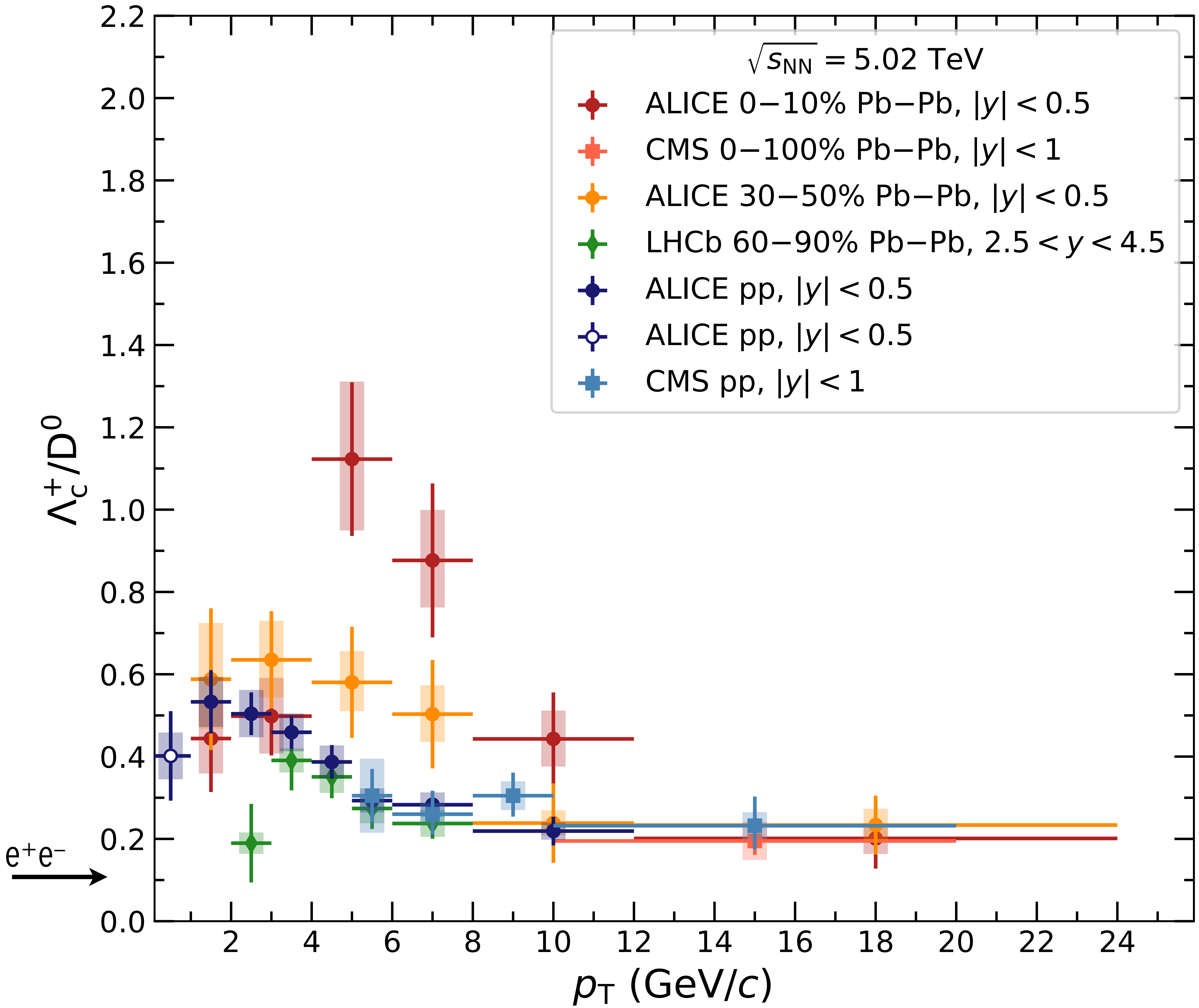


- Λ_c^+/D^0 ratio largely enhanced compared to e^+e^- and ep collisions
- Λ_c^+/D^0 ratio higher in more central collisions at intermediate p_T
  - ➡ Higher probability of hadronisation via coalescence?
  - ➡ Radial flow?
  - ➡ Interplay of radial flow and coalescence?

ALICE, arXiv:2112.08156
CMS, PLB 803 (2020) 135328
ALICE, arXiv:2112.08156
LHCb, arXiv:2210.06939

Charm-quark baryonisation



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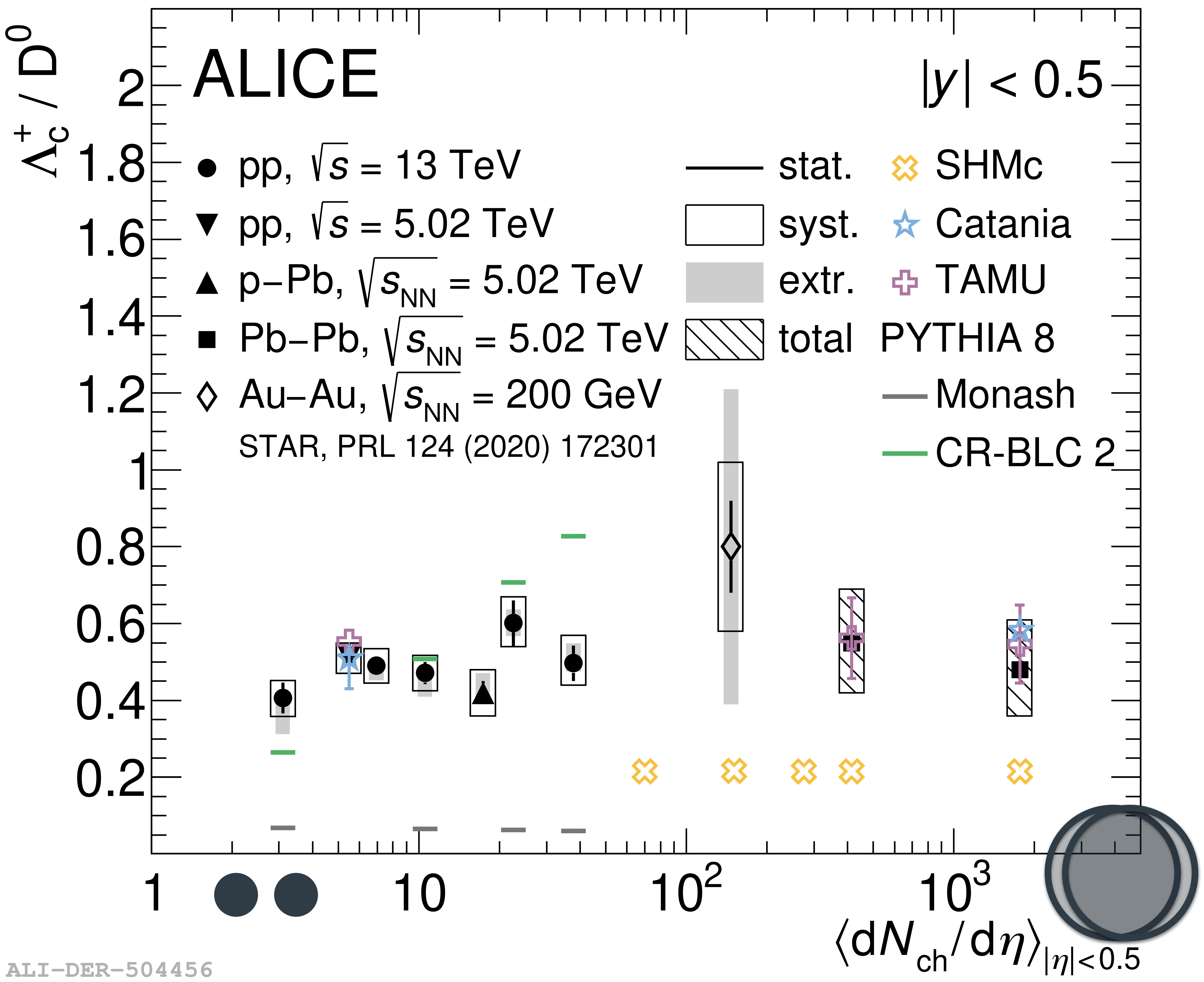
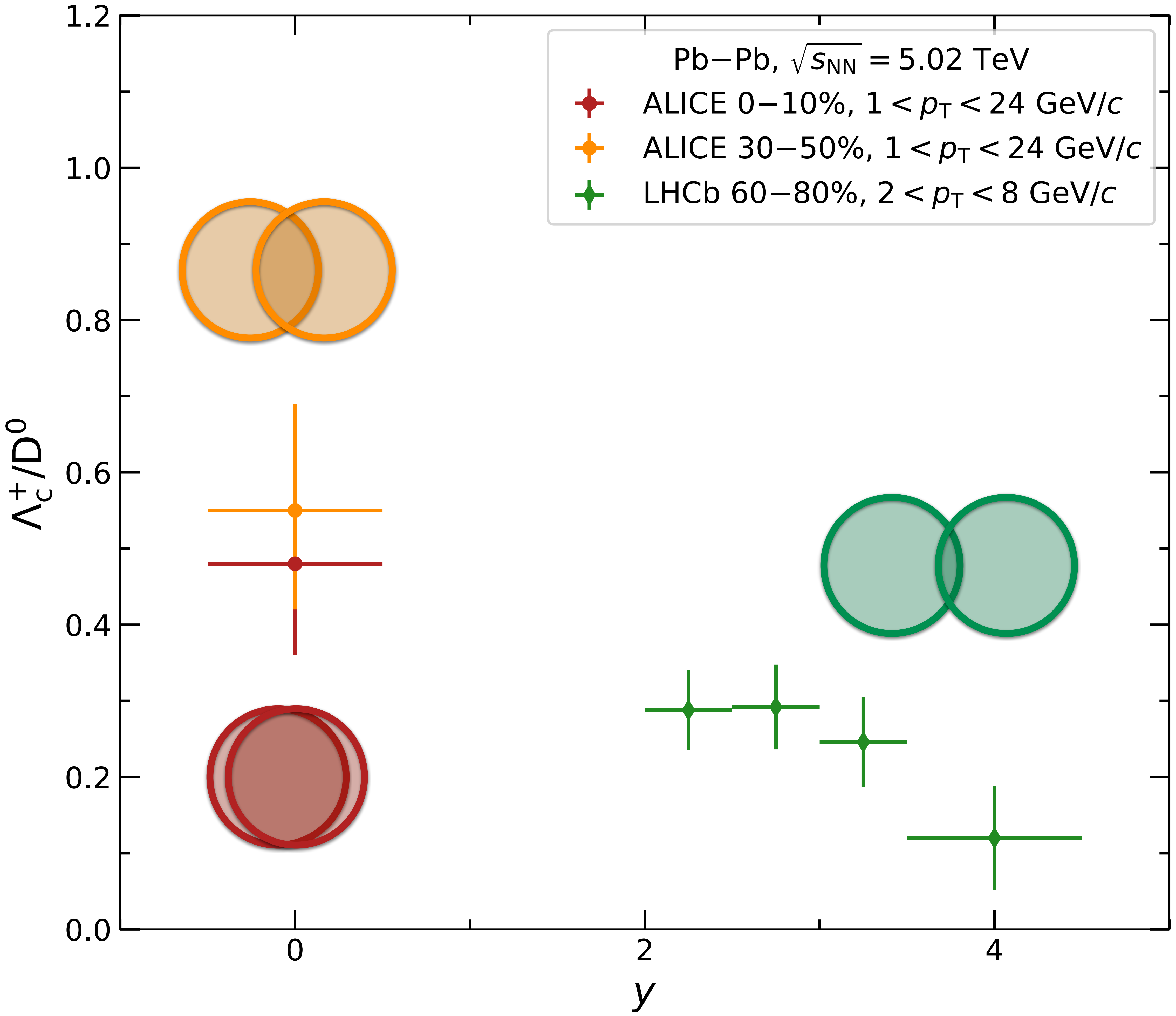
ALICE, arXiv:2112.08156
CMS, PLB 803 (2020) 135328
ALICE, arXiv:2112.08156
LHCb, arXiv:2210.06939
ALICE, PRL 127 (2021) 20, 202301
ALICE, arXiv:2211.14032
CMS, PLB 803 (2020) 135328



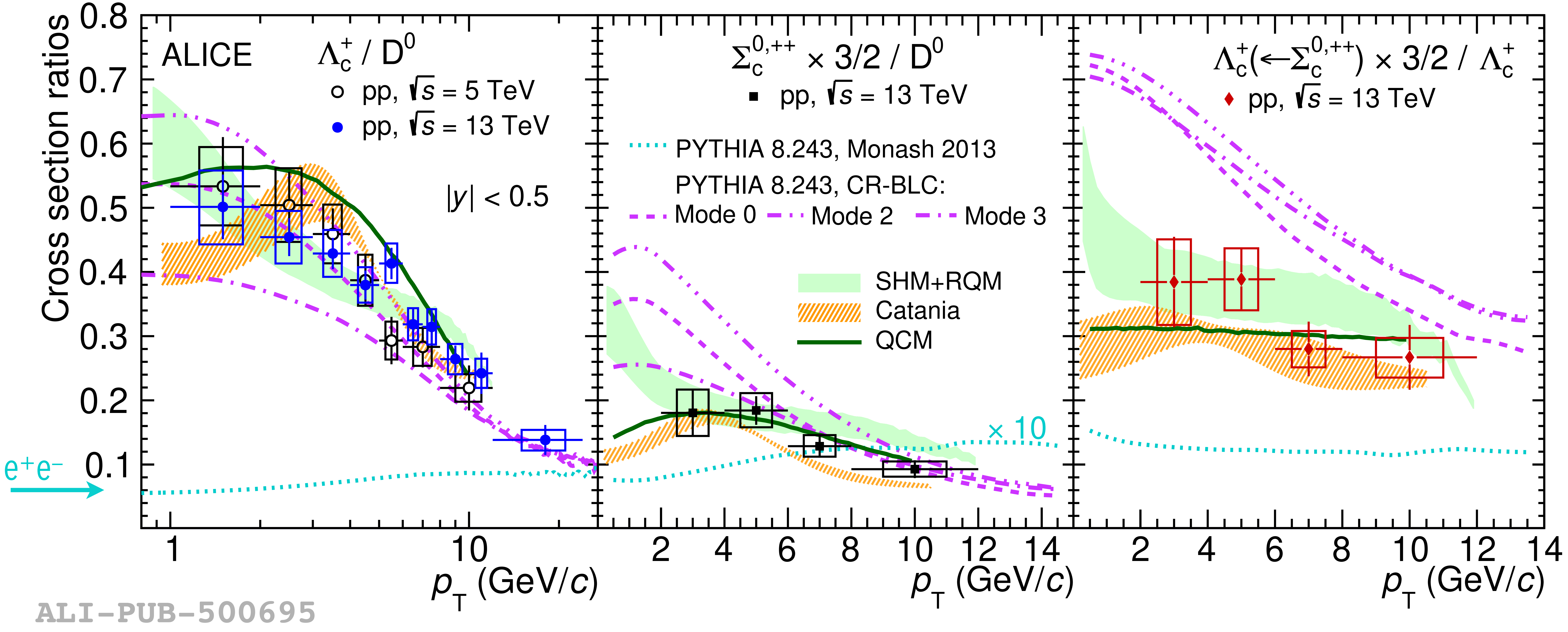


ALICE, PLB 829 (2022) 137065 STAR, PRL 124 (2020) 172301

ALICE, arXiv:2112.08156 LHCb, arXiv:2210.06939

- No indication of modification of p_T-integrated Λ_c^+/D^0 ratio from pp to Pb–Pb collisions
- Possible hint of rapidity dependence

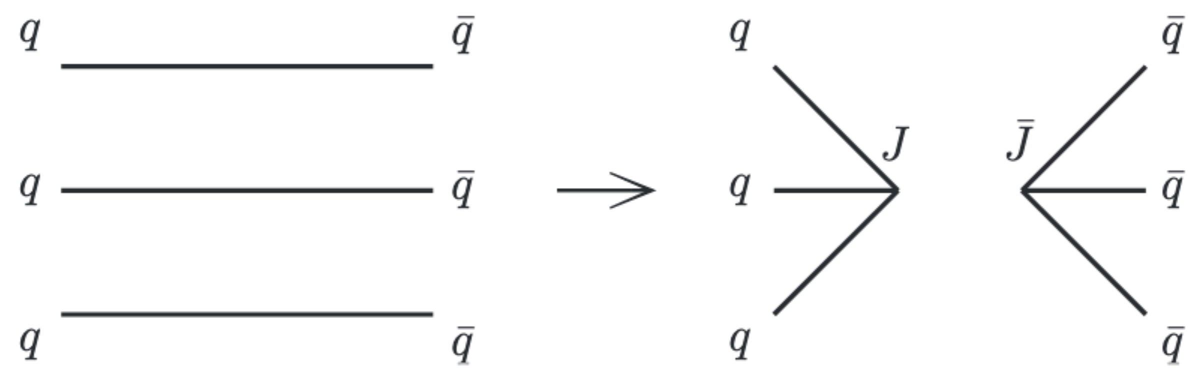
Charm baryon enhancement in pp collisions



- Ground and excited charm baryons enhanced compared to e⁺e⁻ collisions

ALICE, PRL 128 (2022) 012001

- Color Reconnection (PYTHIA8)
  - J.P. Christiansen, P. Z. Skands, JHEP 08 (2015) 003

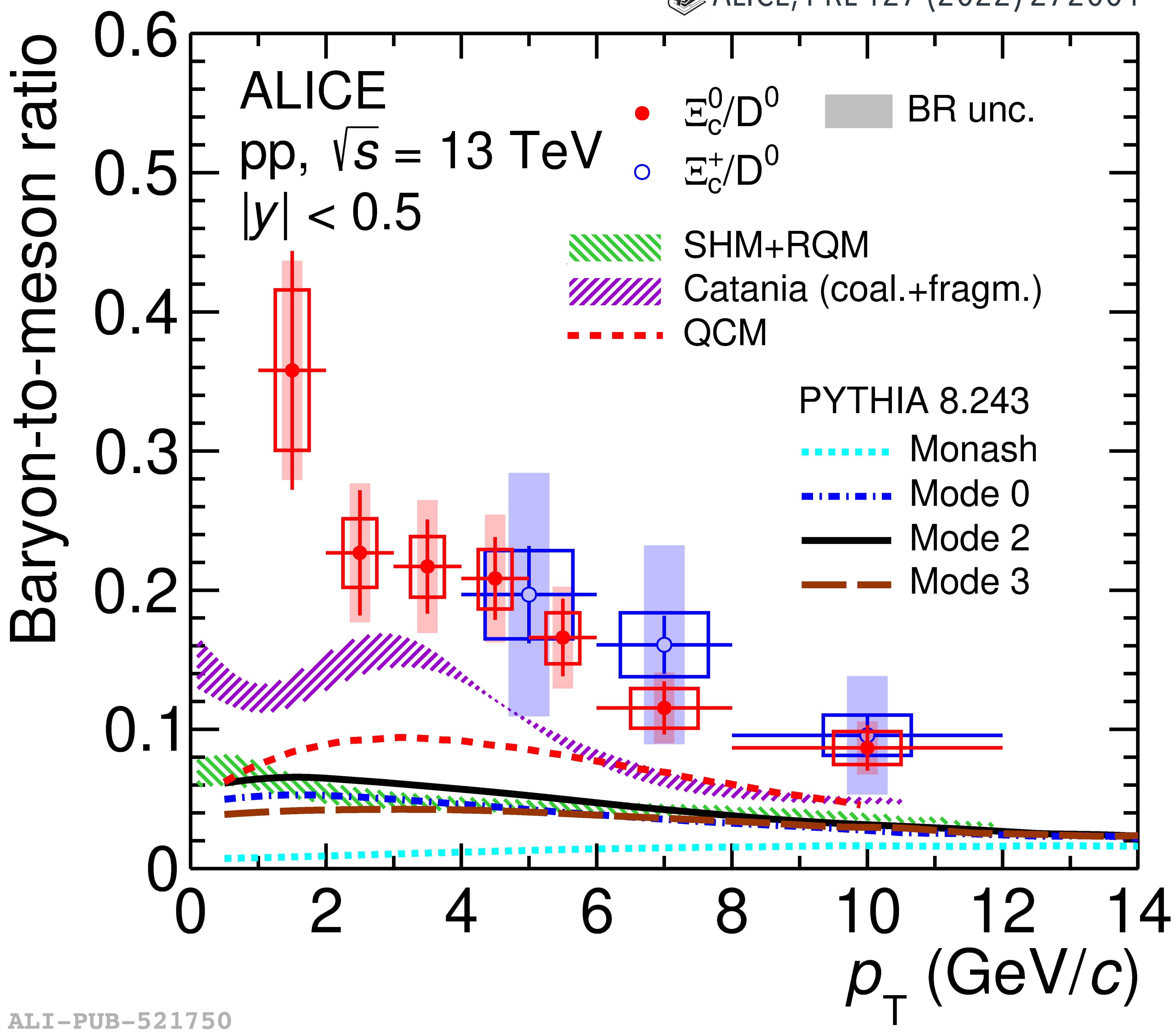


(c) Type III: baryon-style junction reconnection

- Quark coalescence (+fragmentation)
  - V. Minissale, S. Plumari, V. Greco PLB 821 (2021) 136622
  - J. Song, H. Li, F.-l. Shao et al EPJC (2018) 78: 344

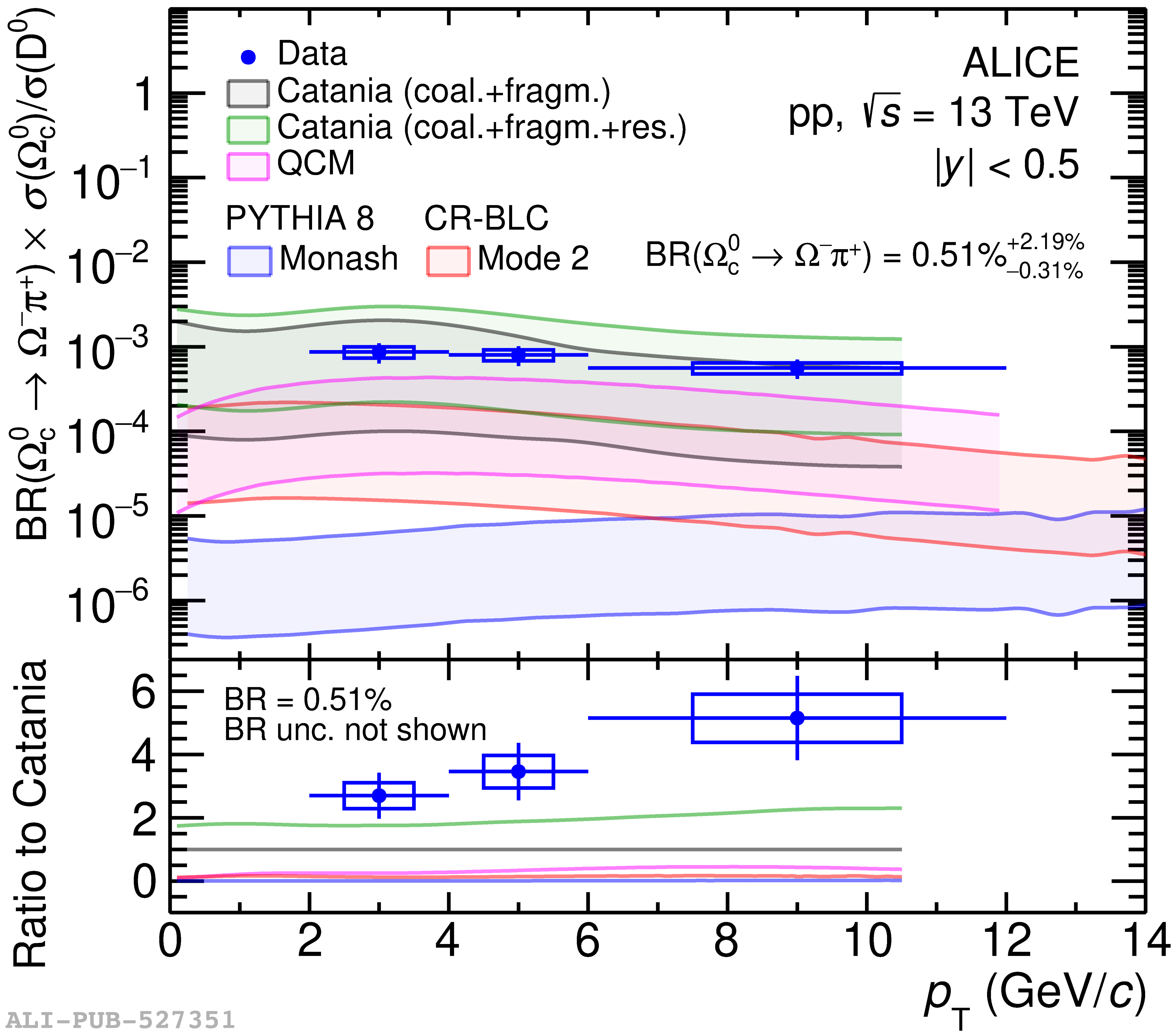
- Statistical hadronisation model with augmented set of charm-baryon excited states from lattice QCD — M. He, R. Rapp, PLB 795 (2019) 117-121

ALICE, PRL 127 (2022) 272001



ALI-PUB-521750

ALICE, arXiv:2205.13993

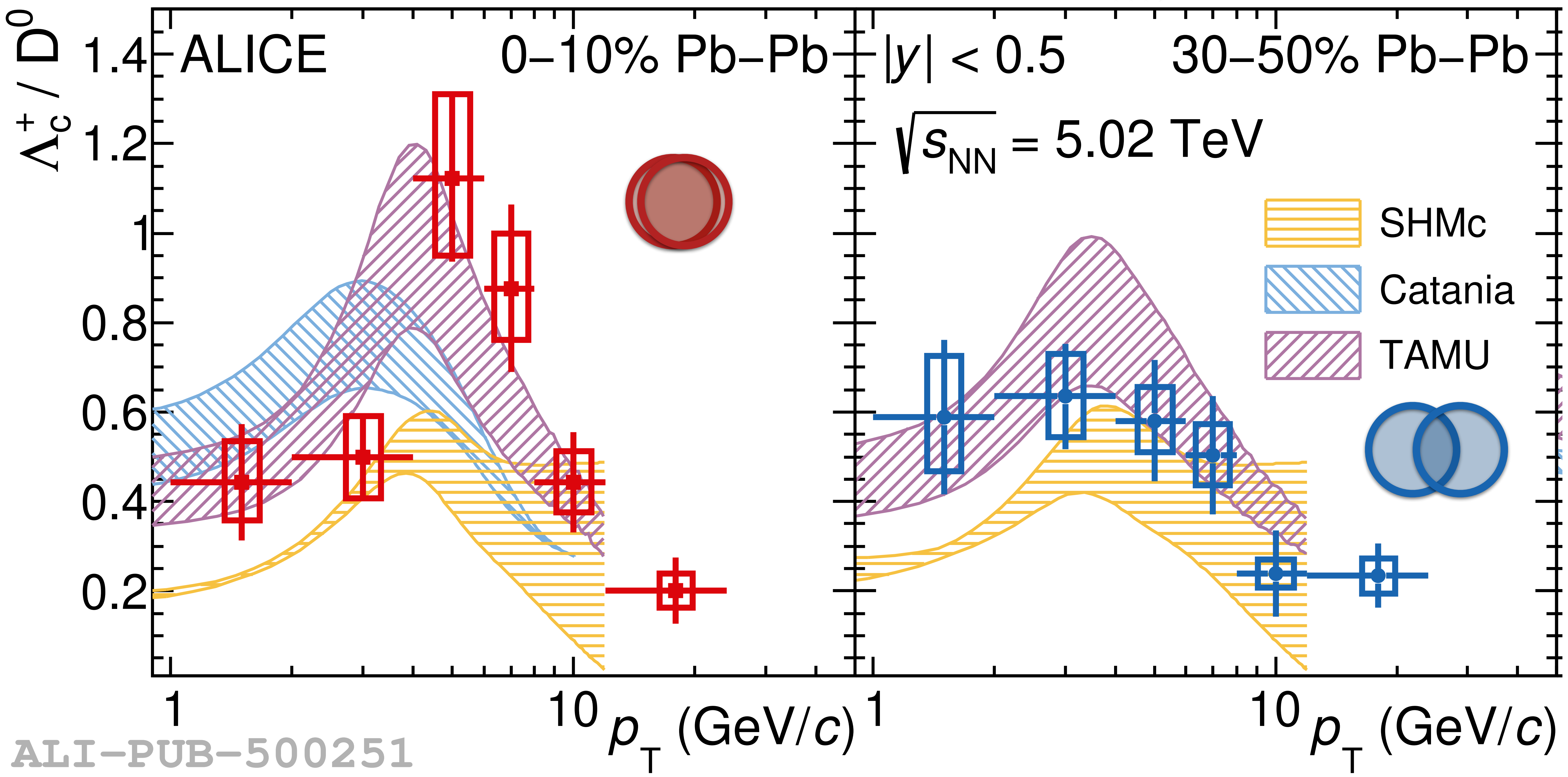


ALI-PUB-527351

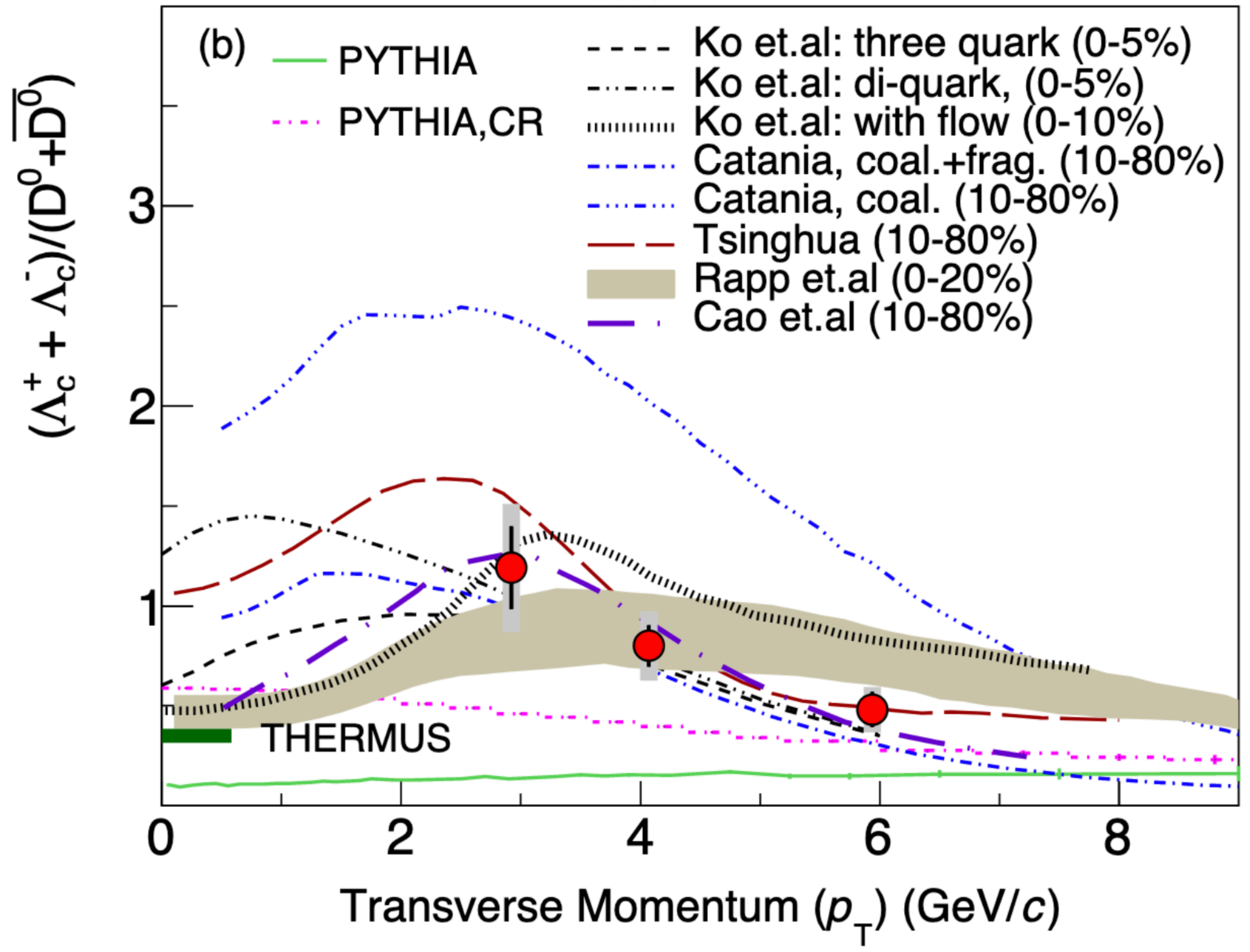
- Models do not reproduce charm-strange baryons

Charm baryon enhancement in heavy–ion collisions

ALICE, arXiv:2112.08156

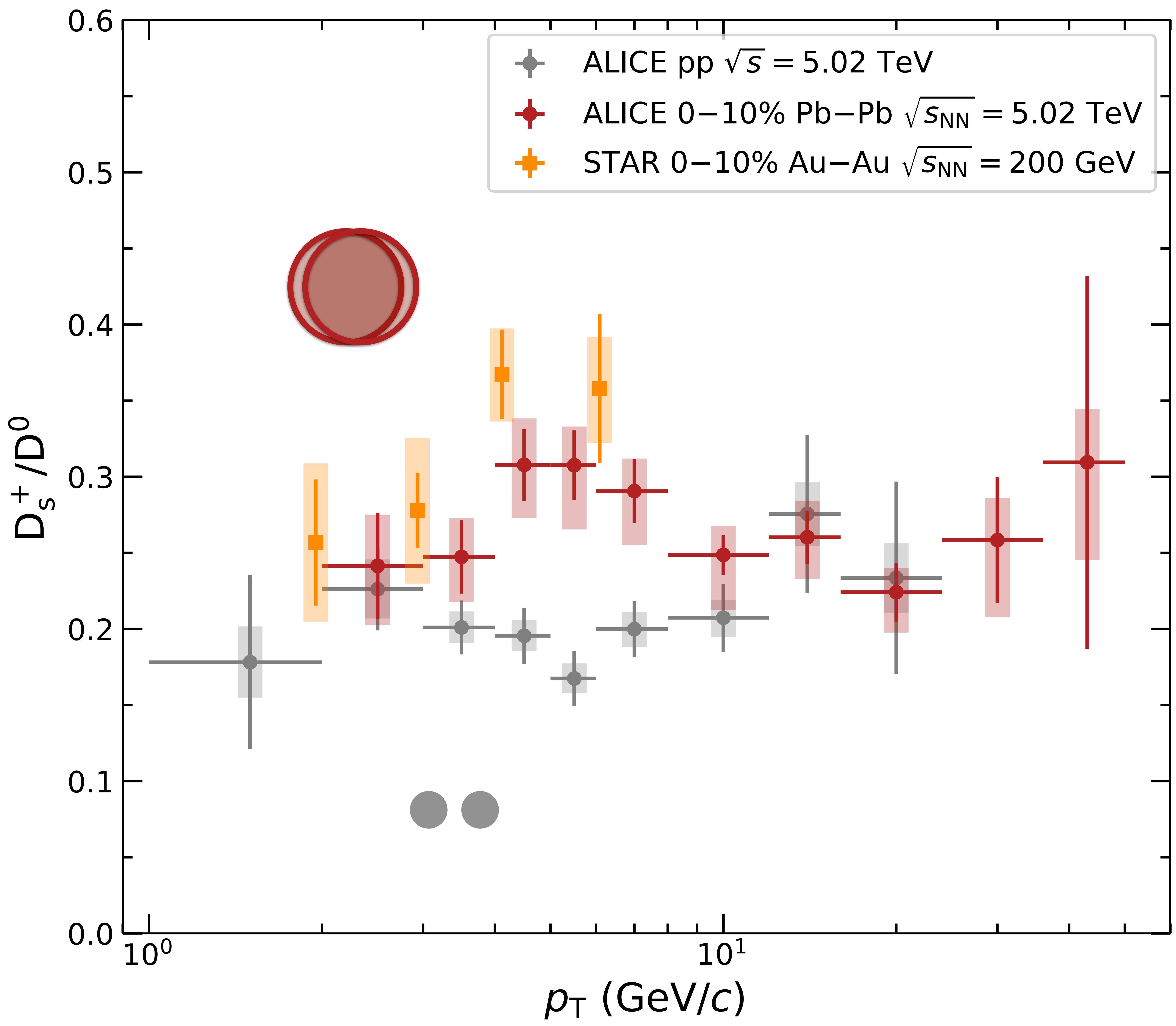


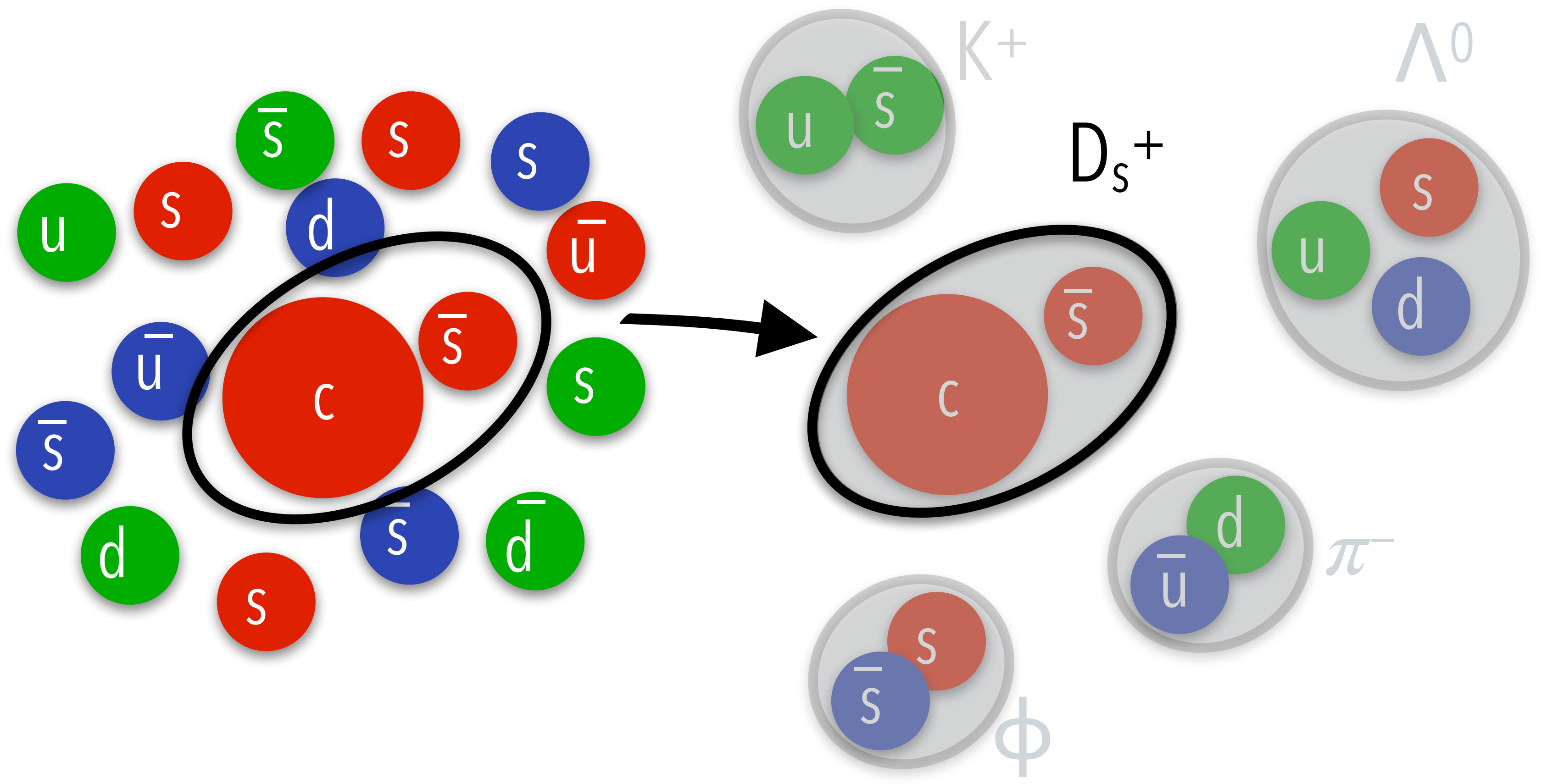
STAR, PRL 124 (2020) 172301



- Coalescence implementations:
  - Instantaneous Catania, EPJC (2018) 78:348
    Cao et al, PLB 807 (2020) 135561 Ko et al, PRC 101 (2020) 024909
  - Resonance Recombination model TAMU, PRL 124 (2020) 042301
  - Sequential recombination Tsinghua, arXiv:1805.10858
- Statistical hadronisation (no enhanced baryon states):
  - Input charm cross section from pp measurements, hydro-based spectrum for core and a pp scaled spectrum for corona SHMc, JHEP 07 (2021) 035
  - Alternative implementation THERMUS, CPC 180 (2009) 84

ALICE, PLB 827 (2022) 136986 STAR, PRL 127 (2021) 092301





- Abundant production of strange quarks in the QGP (strangeness enhancement)
- Hadronisation via recombination (at least partial thermal equilibrium required)
  - ➡ strange hadrons expected to be enhanced
- Strange-to-nonstrange ratio higher in Pb–Pb than pp in charm sector
  - ➡ Also modification of the p_T distribution

ALICE, JHEP 05 (2021) 220

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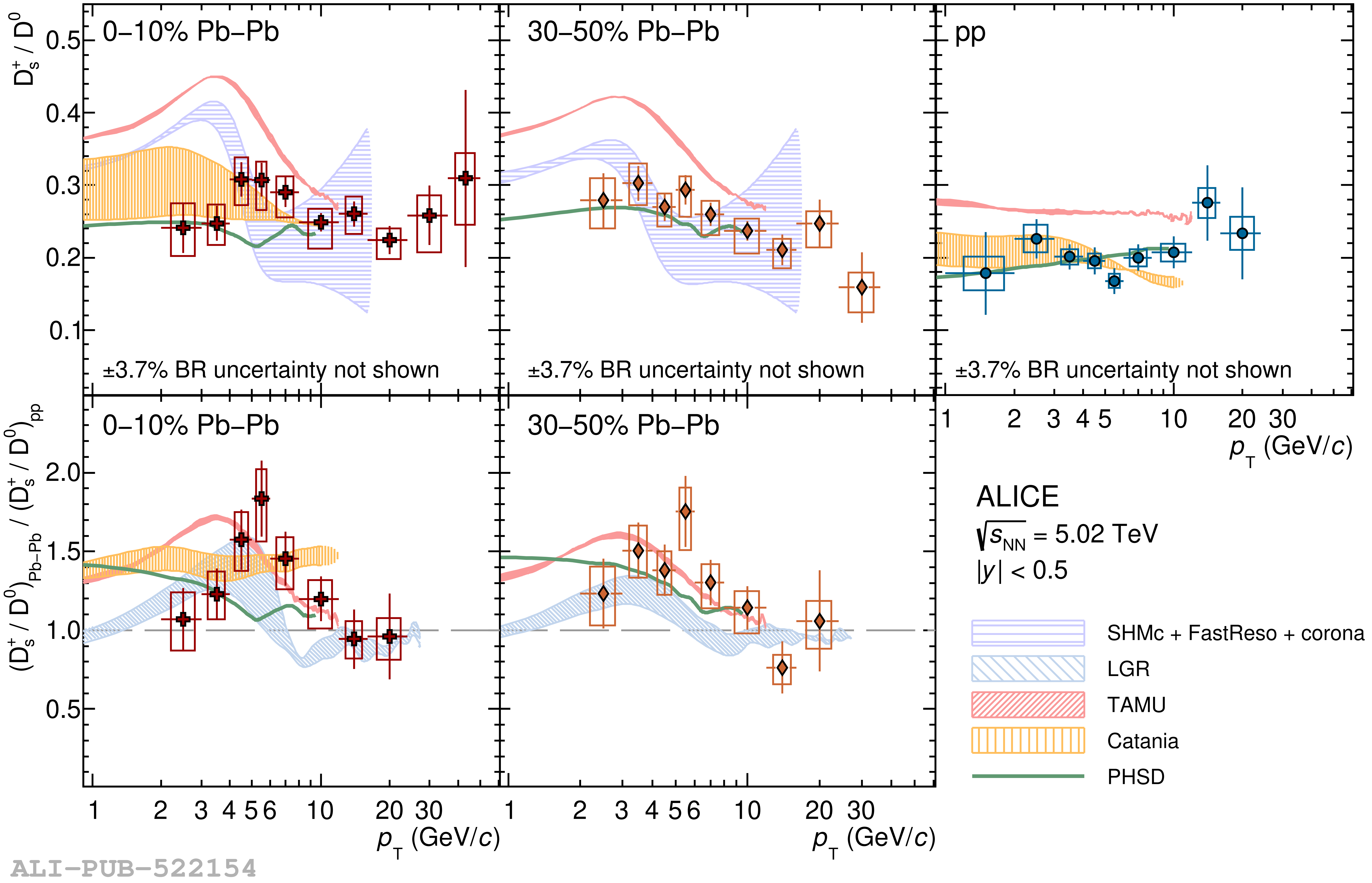

ALICE, PLB 827 (2022) 136986

- Enhancement of strange-to-nonstrange production ratio in Pb–Pb collisions with respect to pp collisions typically well described by models, but absolute value still challenging to be reproduced

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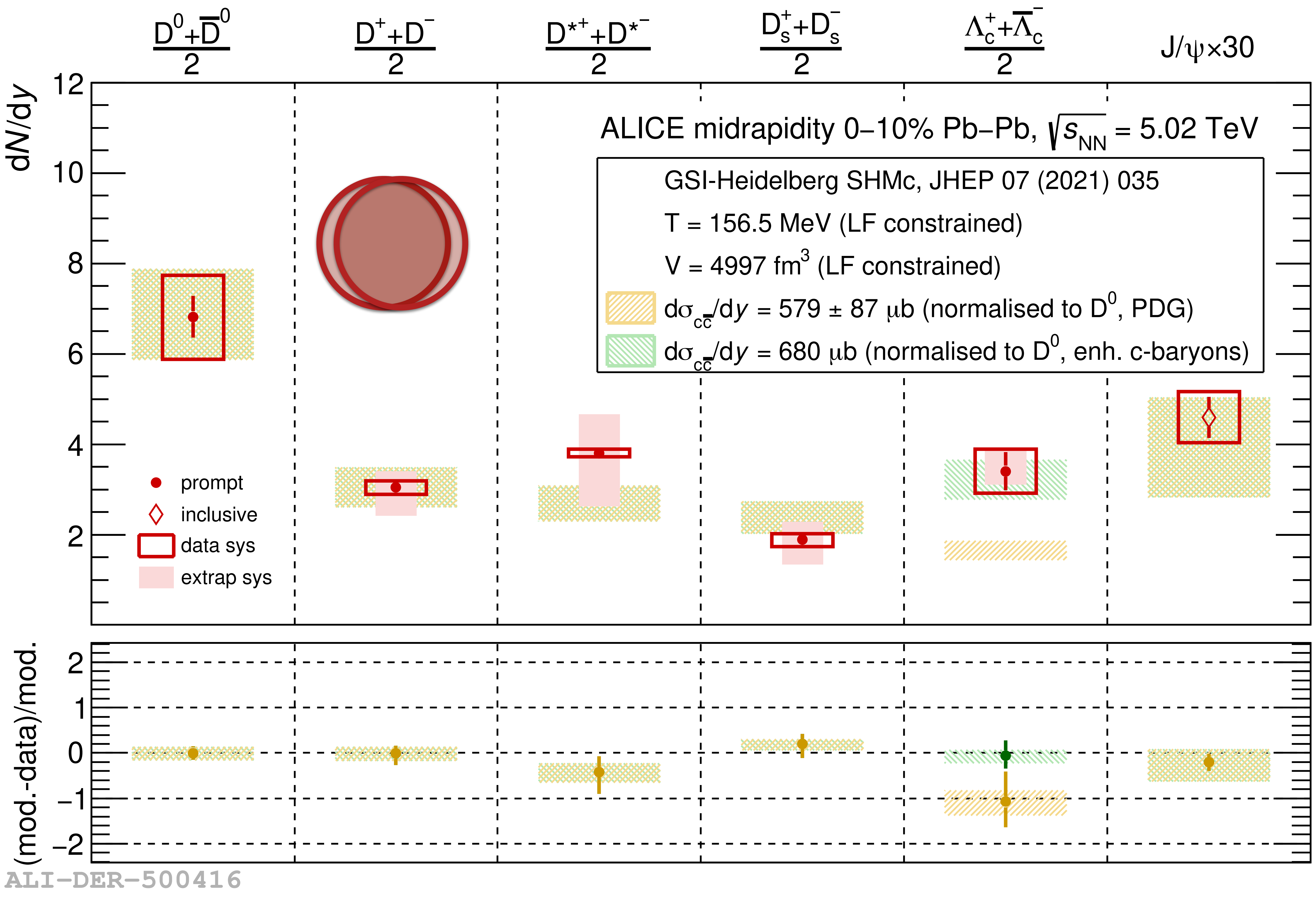
- Assumptions:
  - ➡ Charm quarks created in initial hard scatterings (thermal production negligible) and survive the entire evolution
  - ➡ They reach thermal equilibrium and hadronise at the phase boundary

$$N_{c\bar{c}}^{\mathrm{dir}} = \frac{1}{2} g_c V \left\{ \sum_i n_{D_i} + .. \right\} + g_c^2 V \left\{ \sum_i n_{J/\psi_i} + .. \right\}$$

Charm fugacity factor, constrained from measurements of charm production cross sections in pp collisions



- Charm-hadron abundances described by SHM
  - ➡ Λ_c^+ underestimated if no enhanced set of excited baryon states
  - ➡ Indication of charm quark thermalisation in the QGP

SHMc, JHEP 07 (2021) 035
ALICE, JHEP 01 (2022) 174
ALICE, PLB 827 (2022) 136986
ALICE, arXiv:2112.08156

Statistical hadronisation model – a beauty parenthesis

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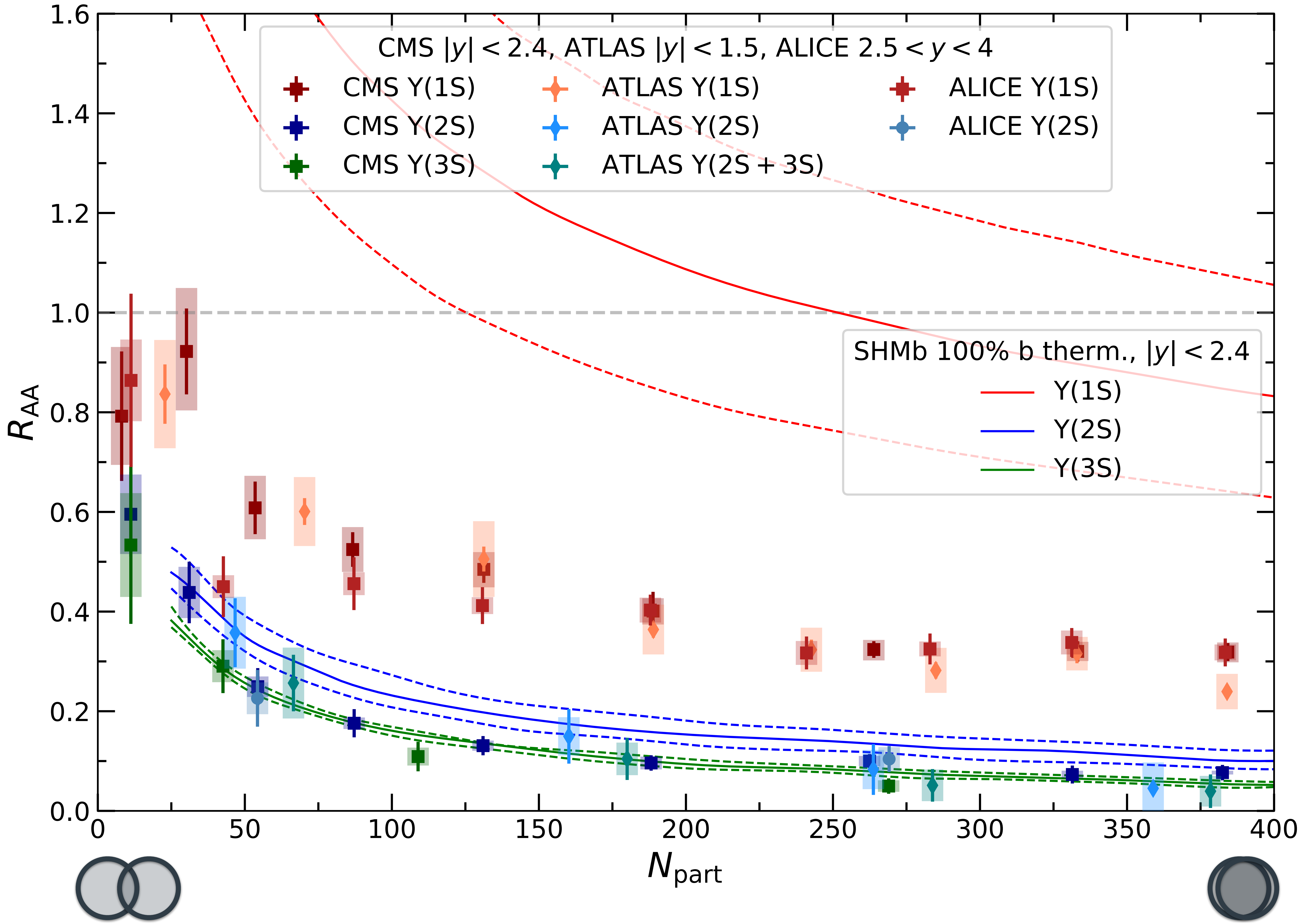
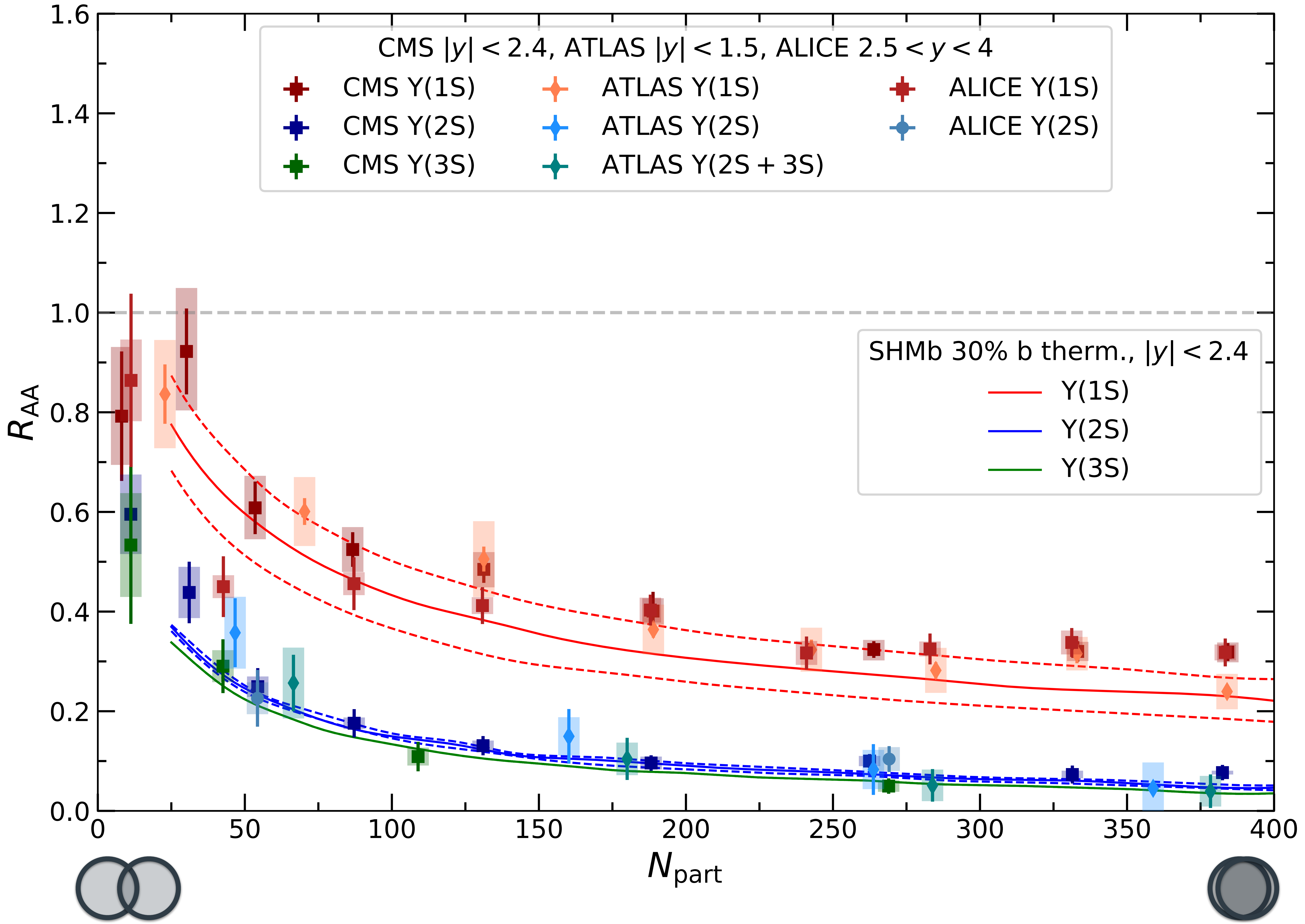


- Υ largely overestimated by SHM if 100% of beauty quarks assumed to be thermalised in the QGP
  - ➡ Do beauty quarks reach thermal equilibrium?
  - ➡ Υ elliptic flow compatible with zero within large uncertainties

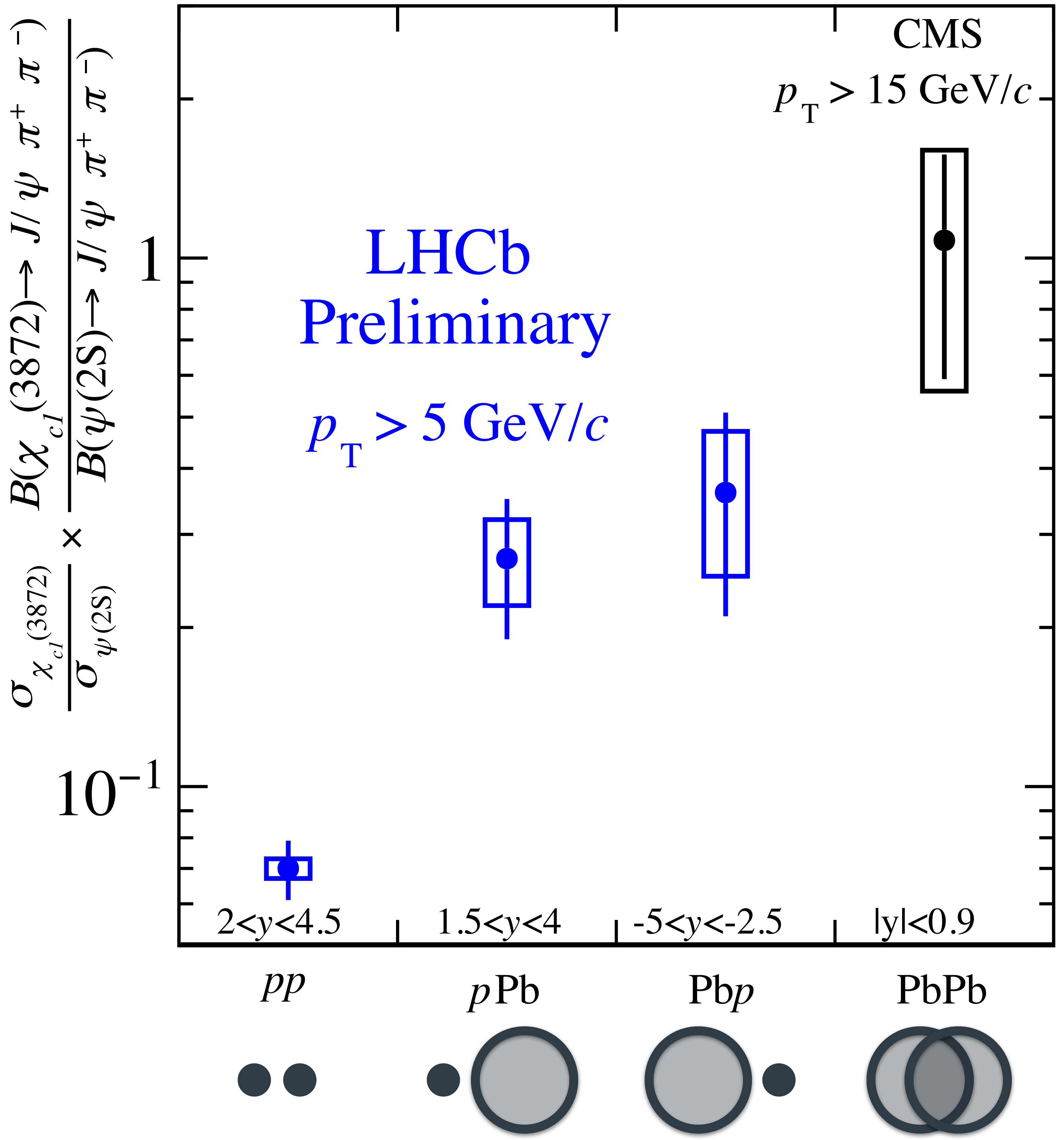
ALICE, PLB 822 (2021) 136579
ATLAS, arXiv:2205.03042
CMS preliminary, CMS-PAS-HIN-21-007

Statistical hadronisation model – a beauty parenthesis



- Υ described by SHM if 30% of beauty quarks assumed to be thermalised in the QGP
  - ➡ Beauty quarks likely reach partial thermalisation
- Υ(1S), Υ(2S), and Υ(3S) yields depend differently on thermalisation fraction
  - ➡ Ratios sensitive to degree of thermalisation

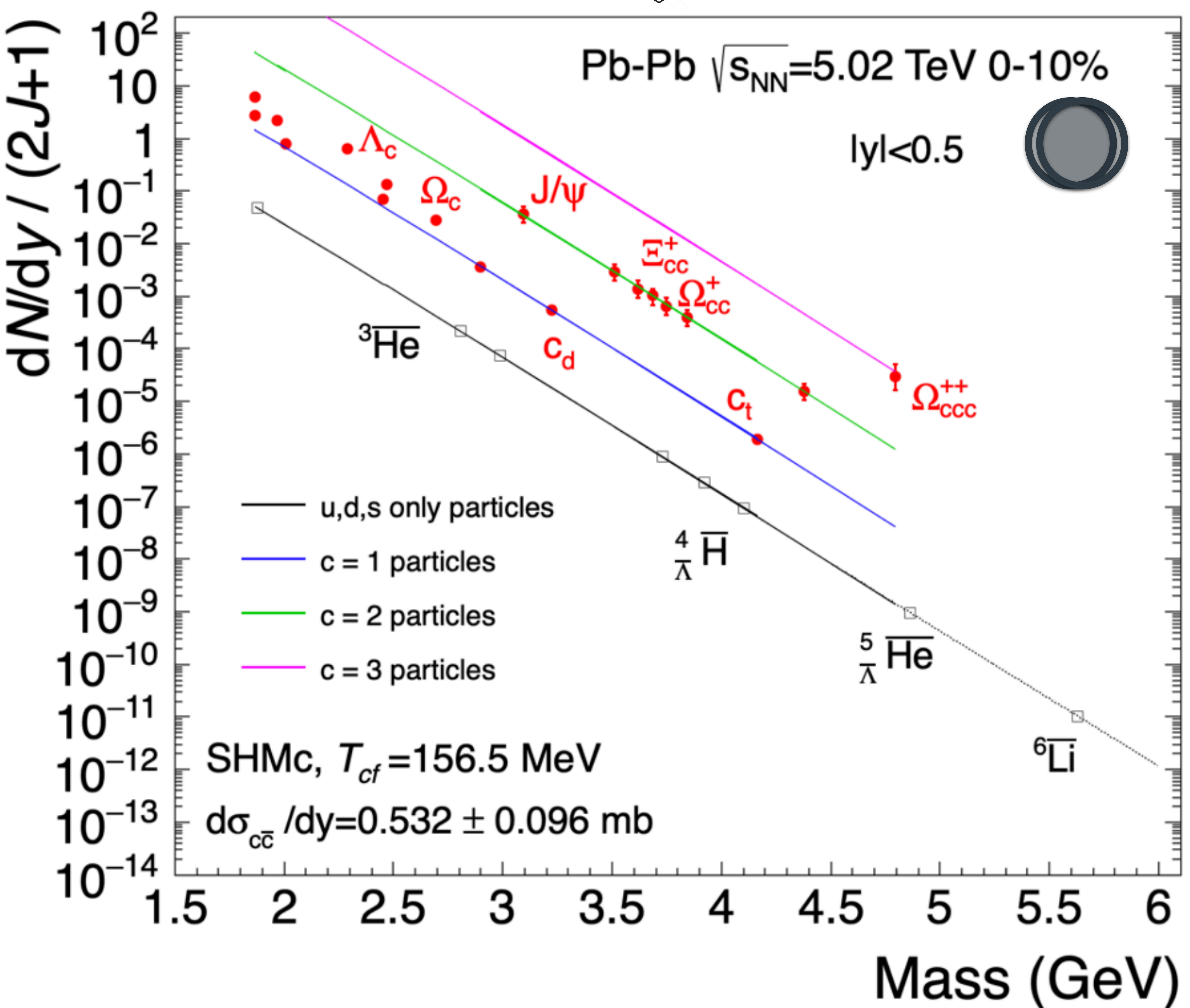
ALICE, PLB 822 (2021) 136579
ATLAS, arXiv:2205.03042
CMS preliminary, CMS-PAS-HIN-21-007



- In case of hadronisation via recombination exotic $c\bar{c}$ states expected to be enhanced in heavy-ion collisions compared to pp collisions
  - ➡ Yield of $c\bar{c}$ states depends on binding energy and size
  - ➡ Crucial to measure low p_T (bulk of production)

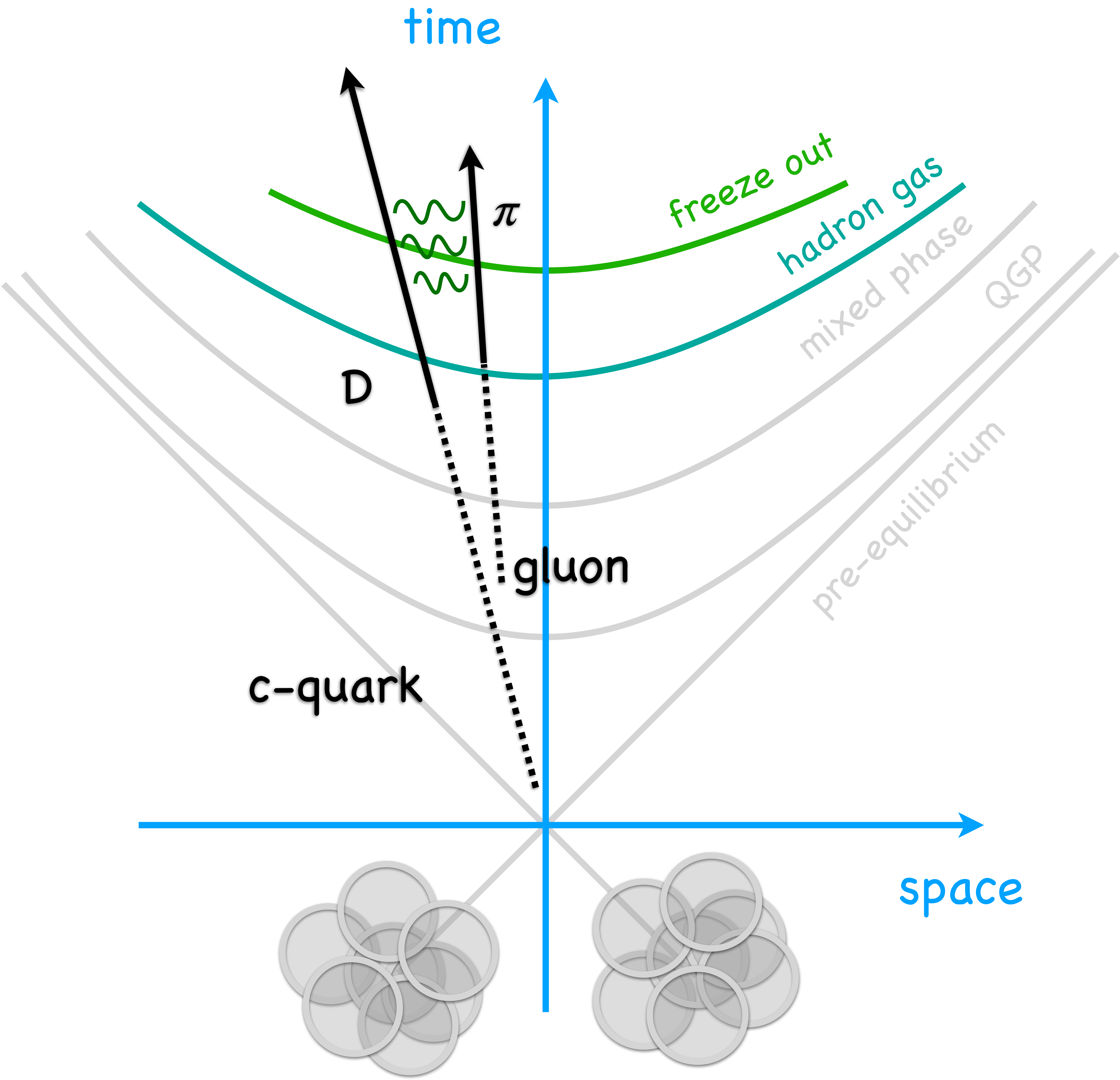
CMS, PRL 128 (2022) 032001
LHCb preliminary, LHCb-CONF-2022-001

ALICE 3 LOI, CERN-LHCC-2022-009



- Multicharm states production in single-parton scattering strongly disfavoured compared to single-charm hadrons in pp collisions
  - ➡ Expected significant enhancement in heavy-ion collisions
- SHM: emergence of unique pattern due to g_c^n dependence

Charm hadrons in the hadronic phase

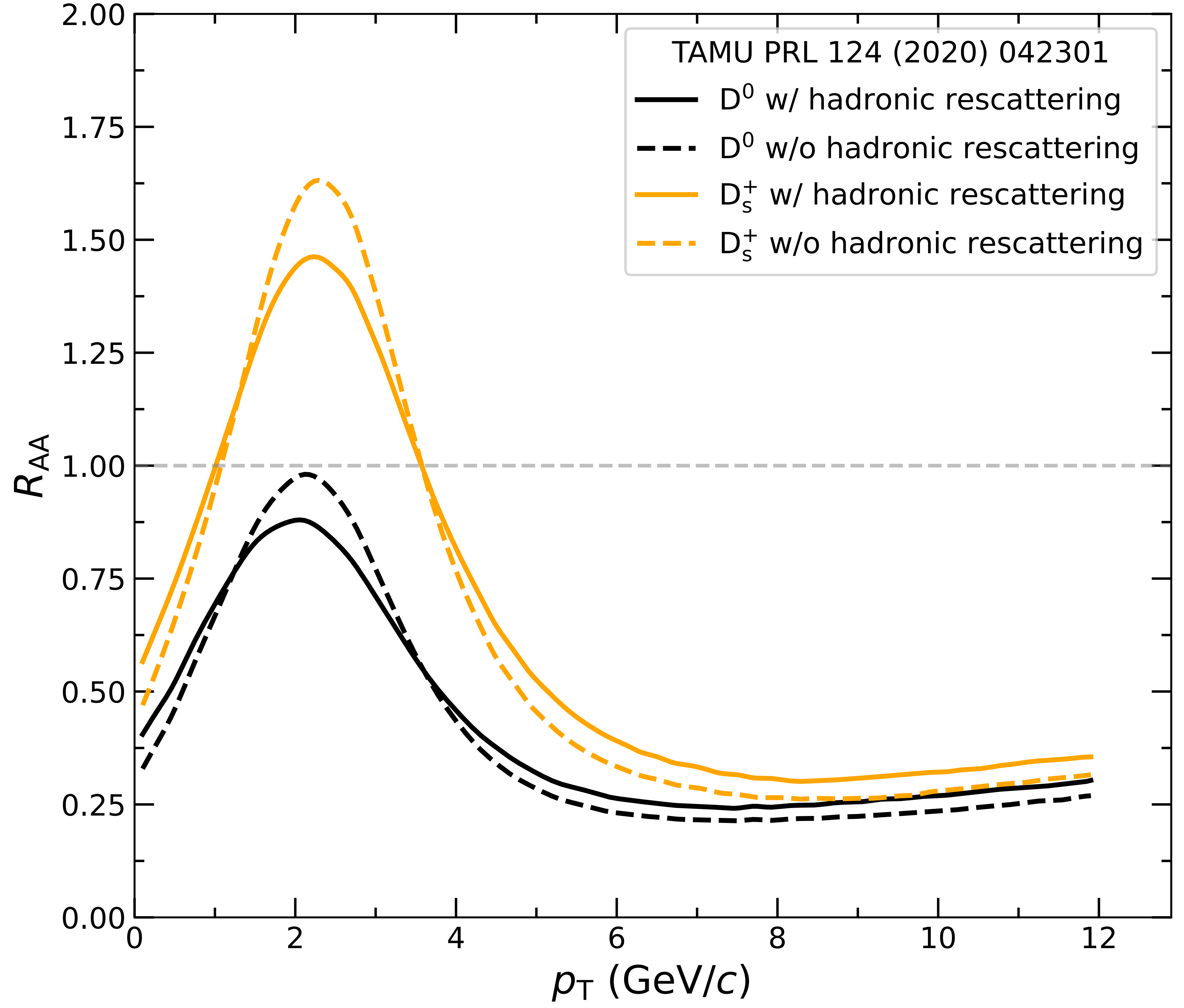


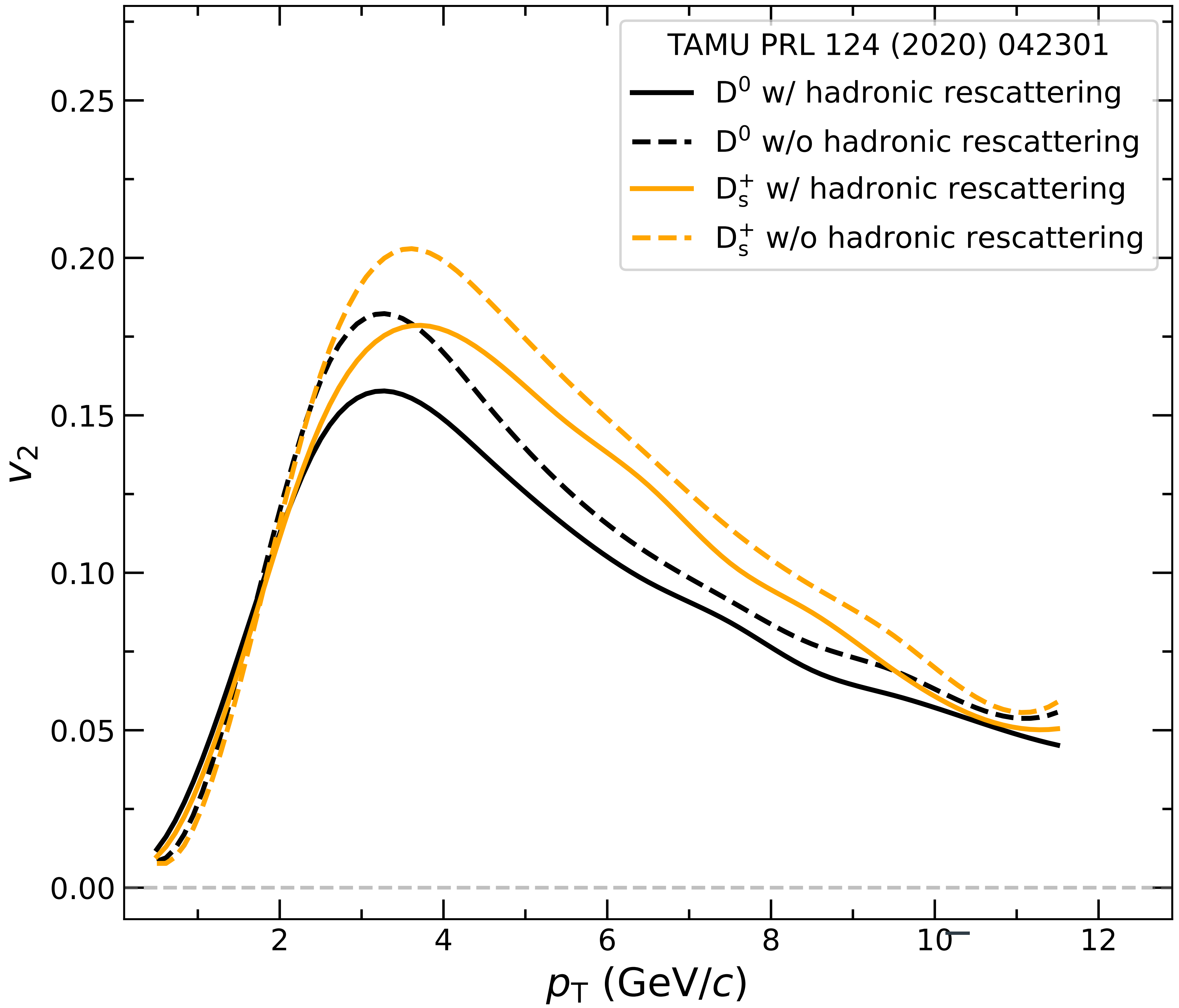
- After the hadronisation, charm quarks hadrons might still interact with the light hadrons produced
  - ➡ How much does the hadronic phase influence the heavy–ion observables?

Nuclear modification factor R_{AA}

M. He, R. Rapp, PRL 124 (2020) 042301

Elliptic flow





- In the TAMU model the scattering lengths used for πD and KD are:
  - ➡ $a_{\pi D}(I=3/2) = -0.10$ fm M. He et al, PLB 701 (2011) 445–450
  - ➡ $a_{KD}(I=1) = -0.22$ fm

➡ No experimental constraints!

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The study of the residual strong interactions

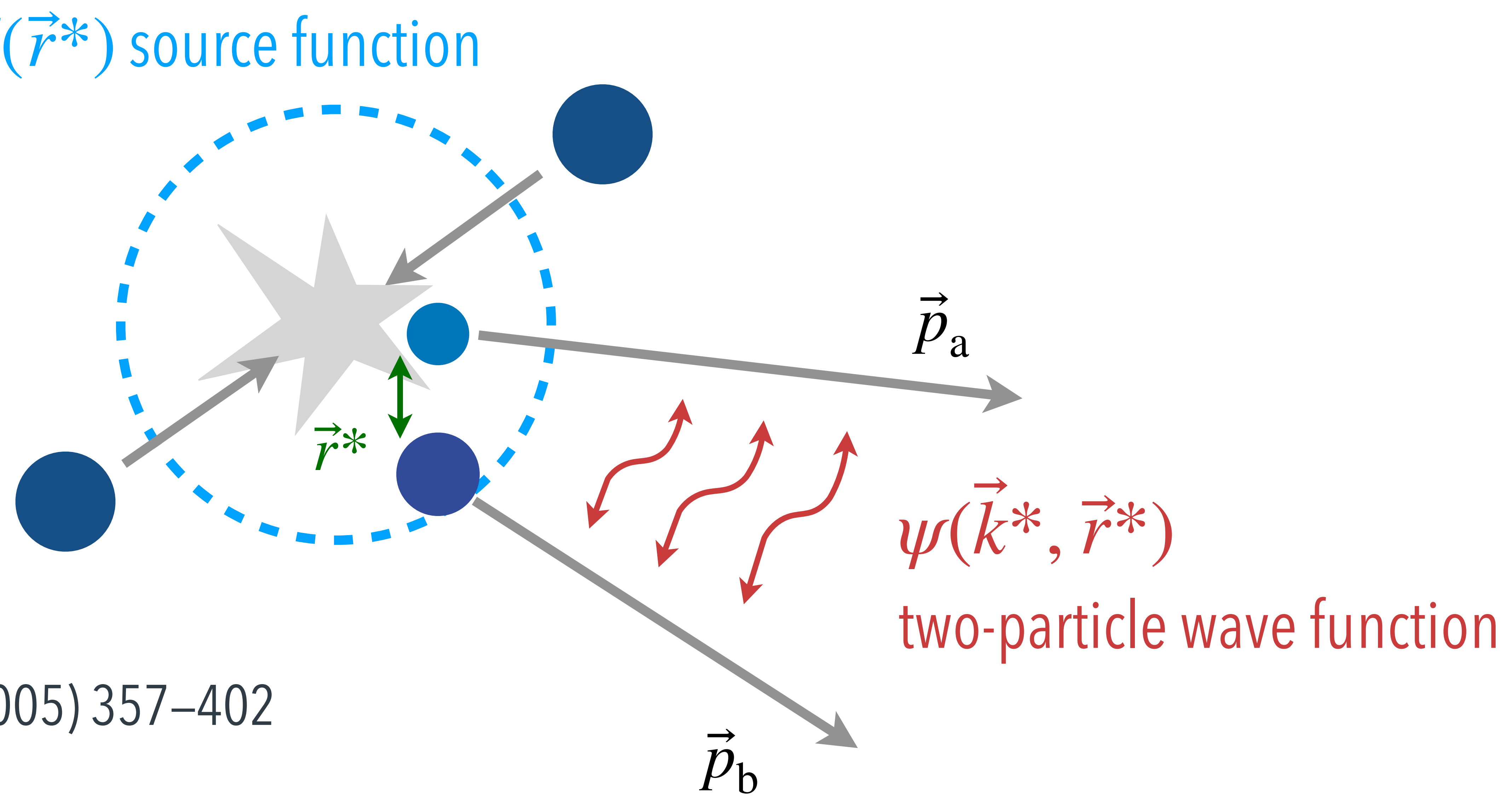
- Femtoscopy technique: based on the correlation function (CF)

Experiment | Theory

$$C(k^*) = \mathcal{N}\frac{N^{\text{pairs}}_{\text{same}}(k^*)}{N^{\text{pairs}}_{\text{mixed}}(k^*)} = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,\mathrm{d}^3r^*$$

Koonin-Pratt equation

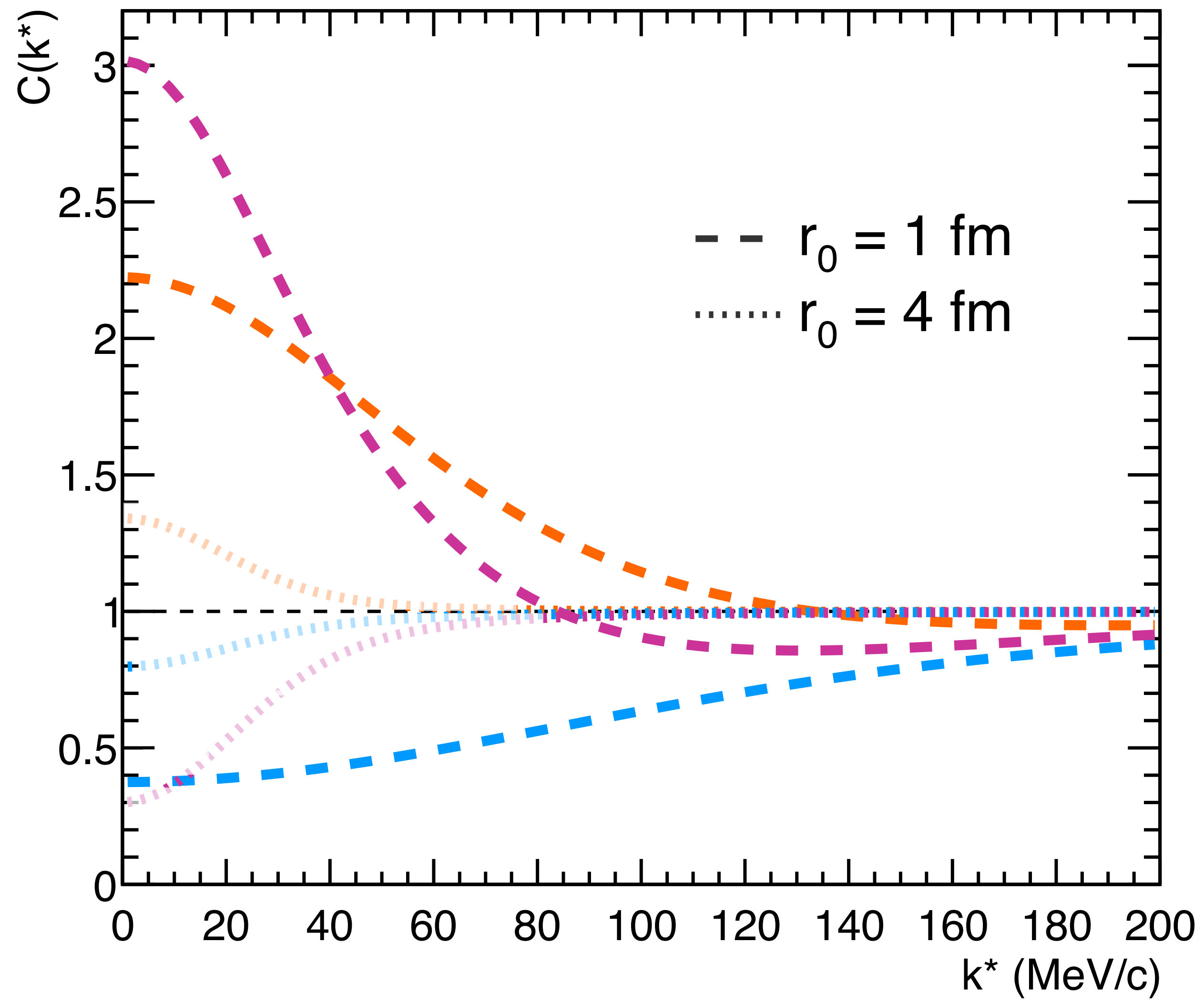
M.Lisa, S. Pratt et al, Ann. Rev. Nucl. Part. Sci. 55 (2005) 357–402



where $\vec{k}^* = \frac{\vec{p}^*_a - \vec{p}^*_b}{2}$ is in the rest frame of the particle pair

- ➡ Relative wave function sensitive to interaction potential
- ➡ Emitting source: hypersurface at kinematic freeze out of final-state particles

- ➡ $C(k^*)$ most sensitive to strong interaction when the source size ~1 fm



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

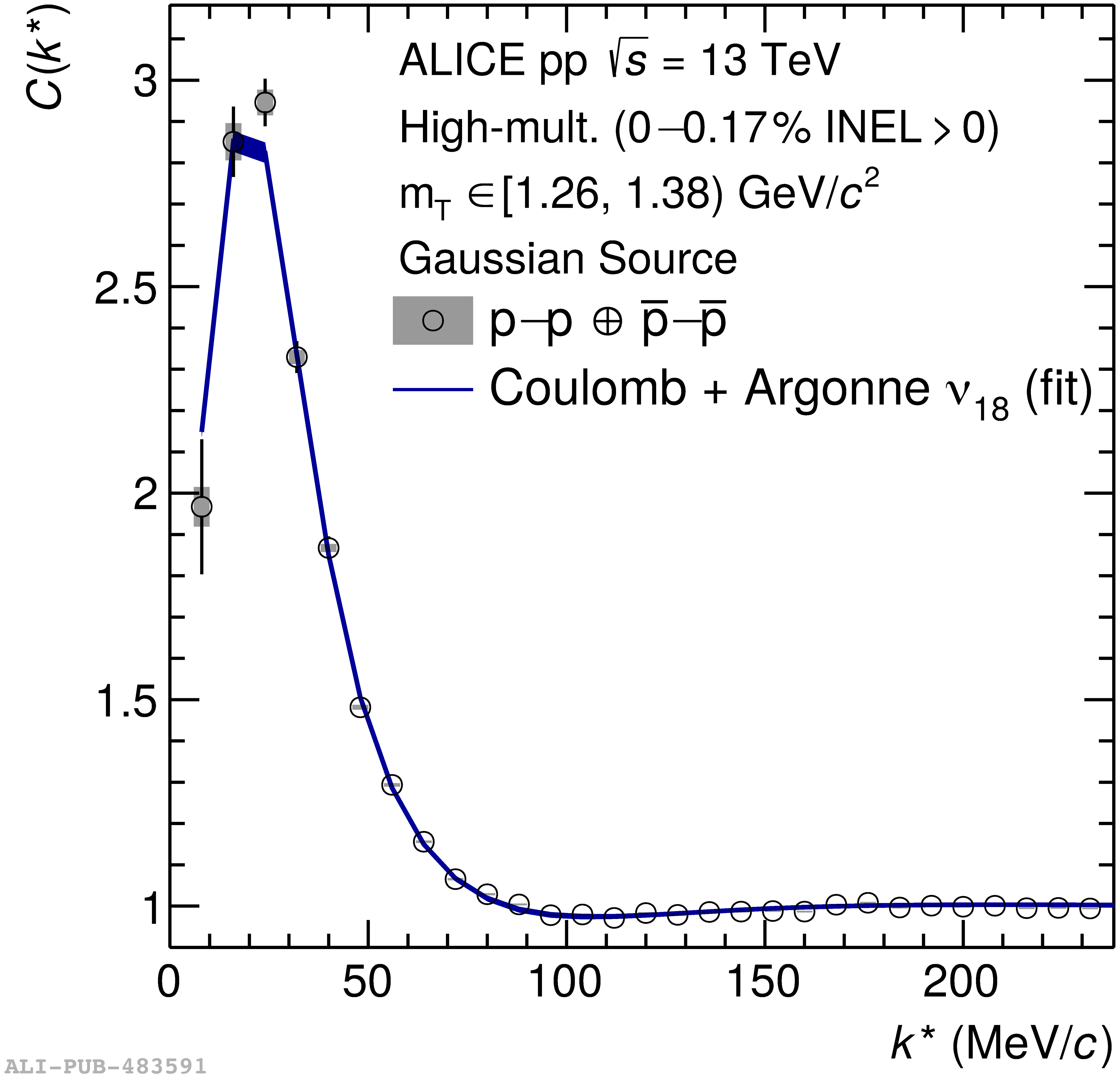
Attractive potential $C(k^*) > 1$

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

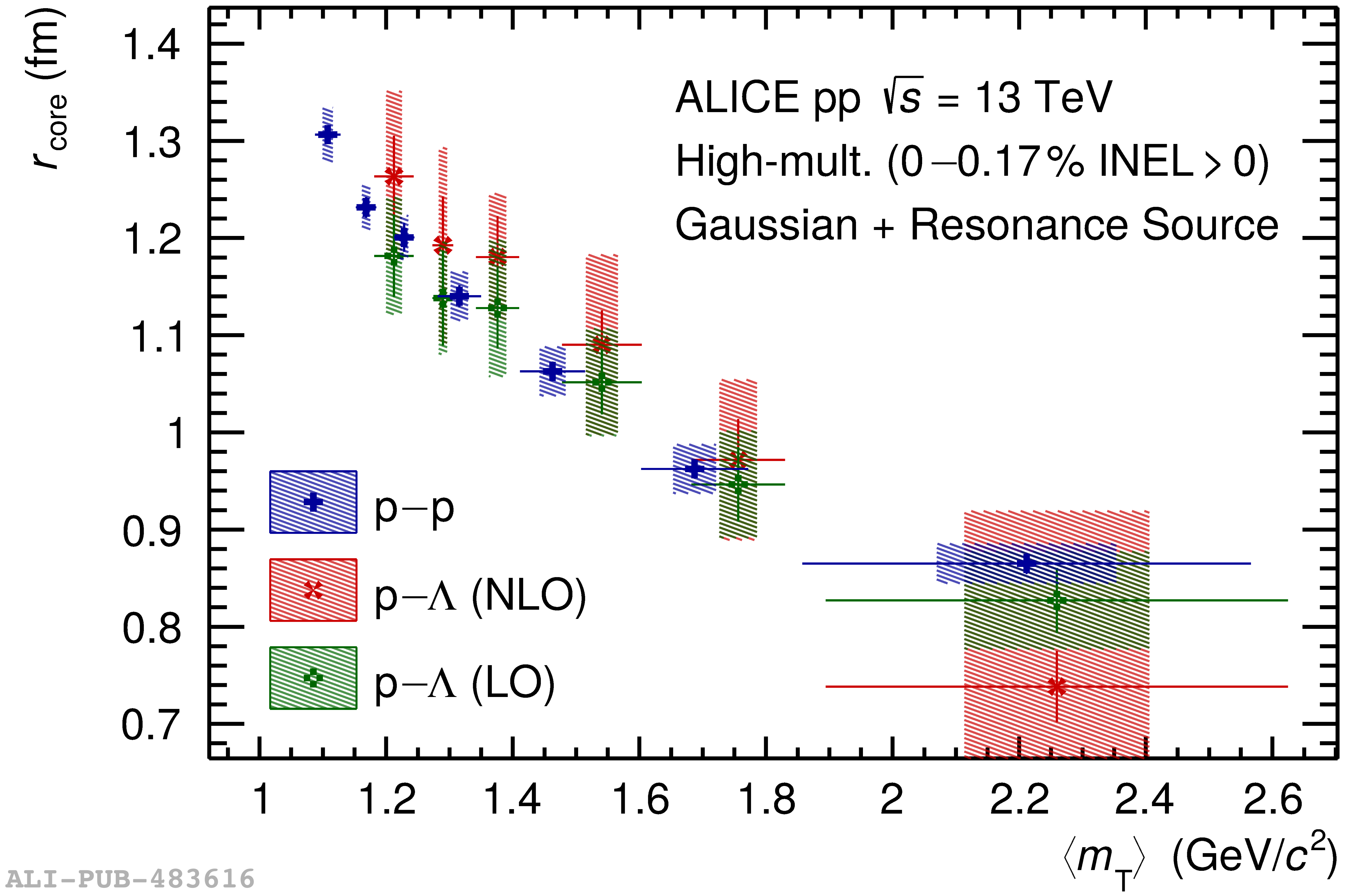
Bound-state formation $C(k^*) <> 1$

L. Fabbietti, V. Mantovani Sarti, O. Vázquez Doce, Annu. Rev. Nucl. Part. Sci. (2021) 71:377–402

Calibrating the emitting source



ALICE, PLB 811 (2020) 135849



- Fit correlation functions of p–p and p–Λ pairs
  - ➡ Interaction precisely described
  - ➡ Gaussian source with radius as free parameter
  - ➡ Universal m_T scaling found

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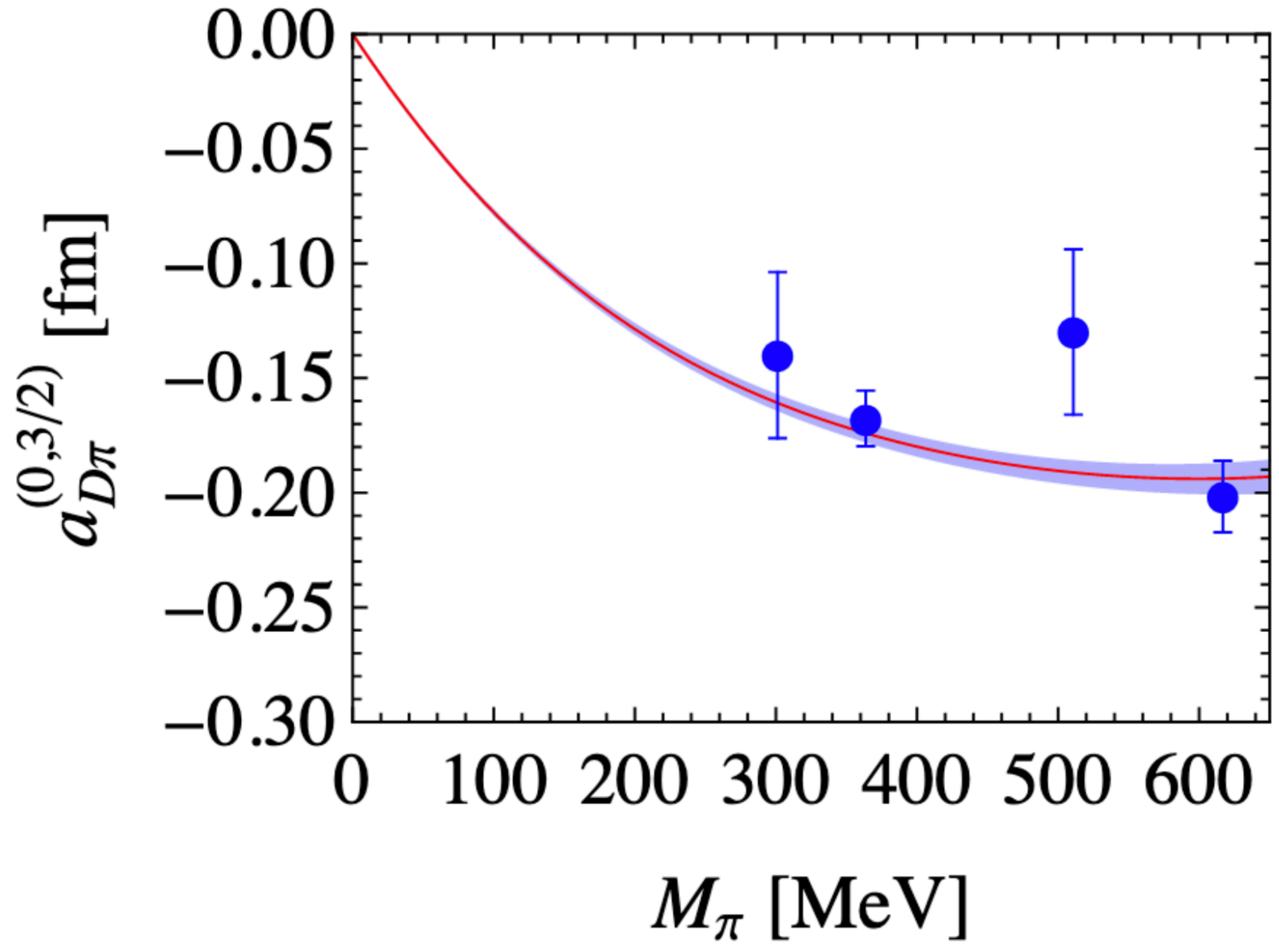
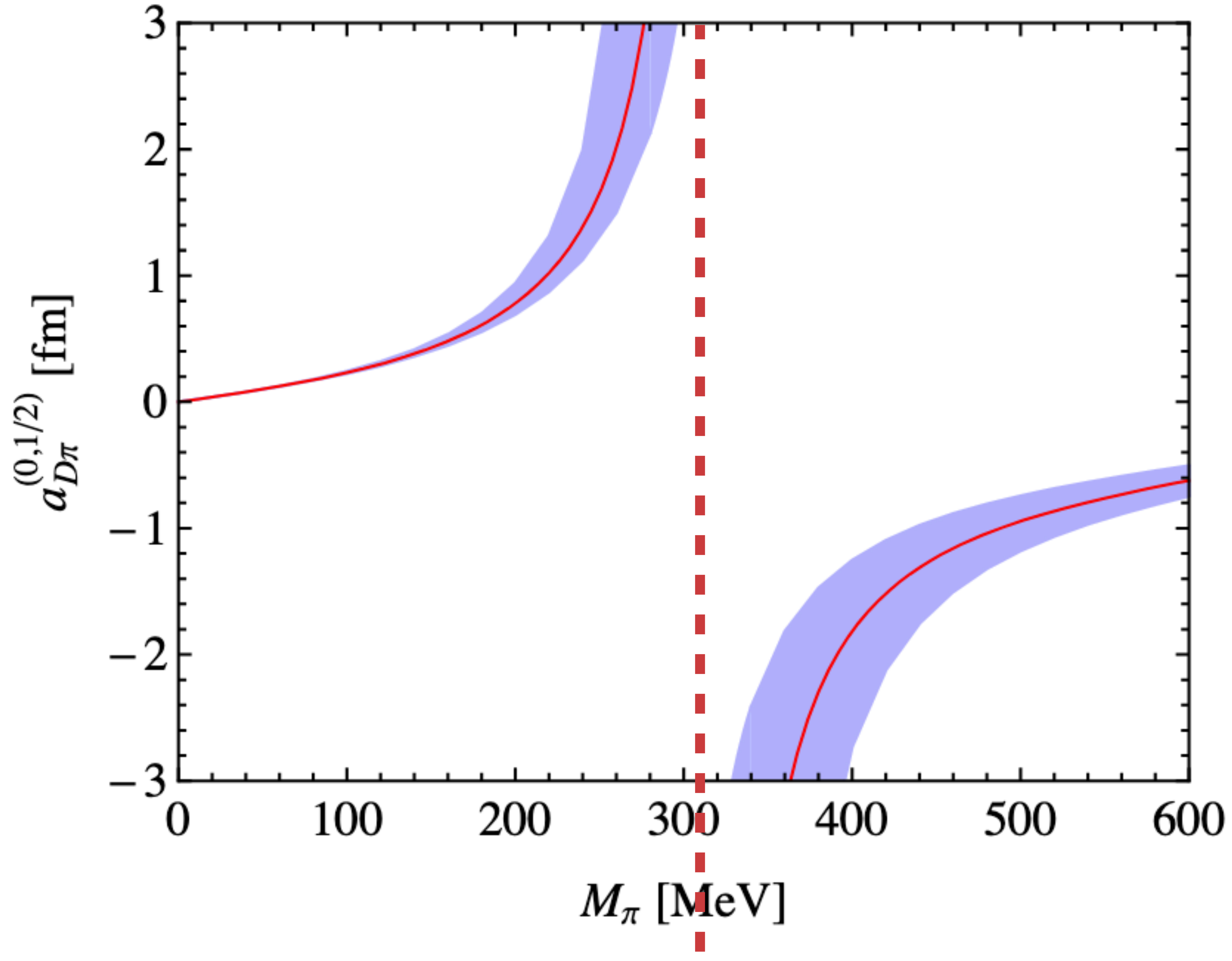
- πD interaction: predictions of scattering lengths derived from lattice QCD calculations
  - ➡ ~0.1-0.5 fm: very small compared to other interactions (light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ No constraints from data
  - ➡ For pions I=3/2 channel more constrained than I=1/2 channel

X.-Y. Guo et al, PRD 98 (2018) 014510





Bound-state pole formation

πD interaction: fit with Lednický-Lyuboshits formula

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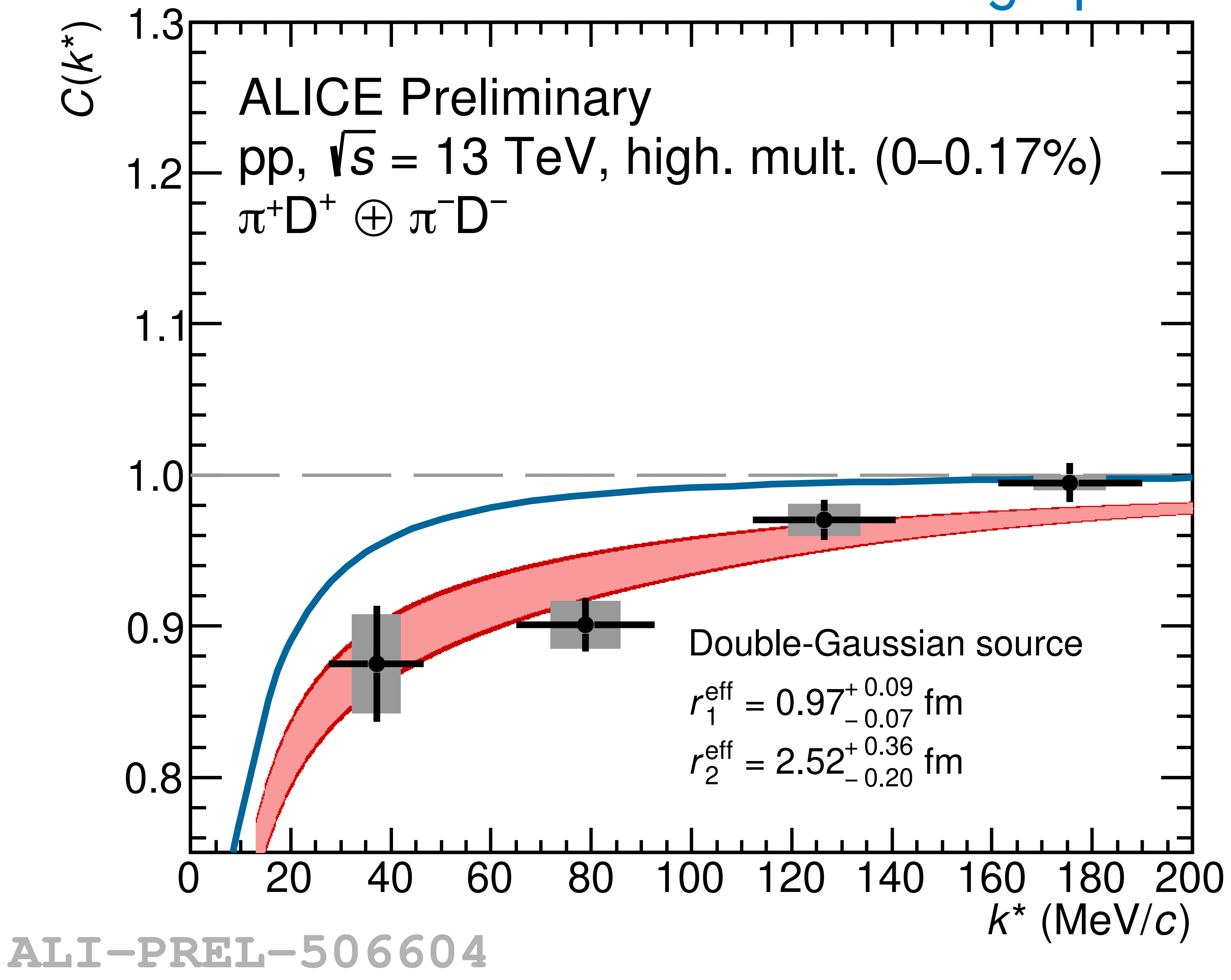
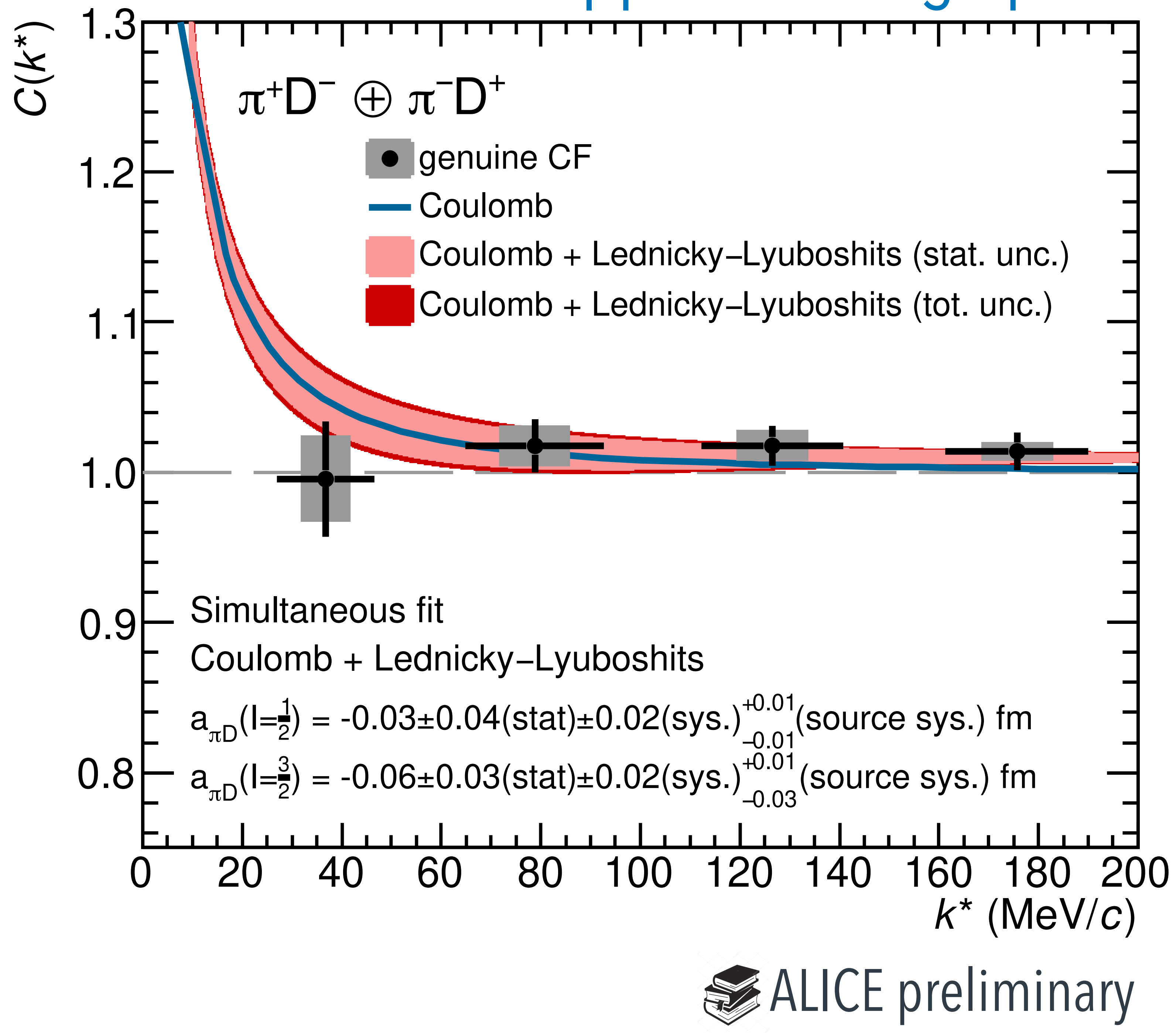
Same-charge pairs

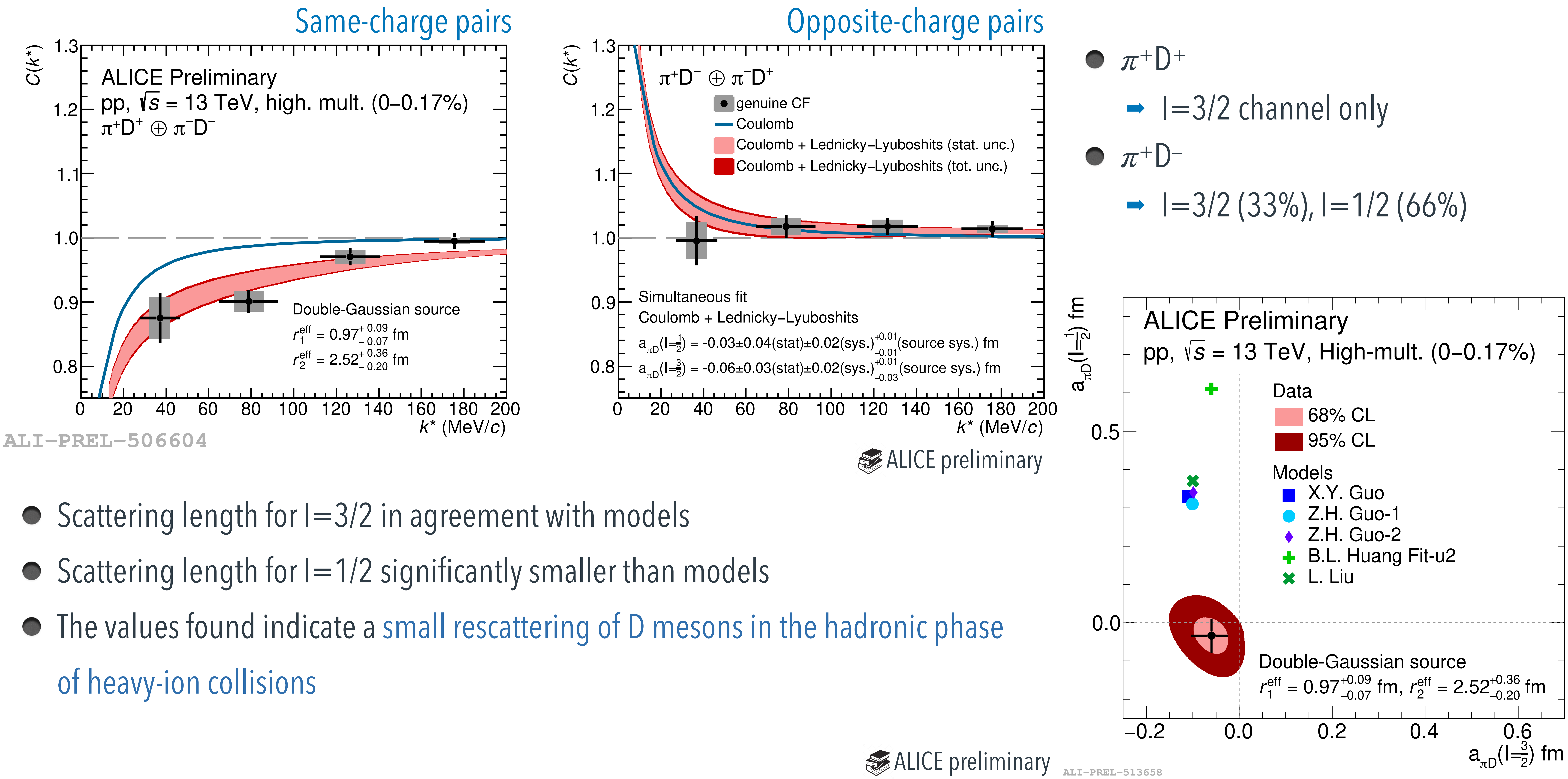


Opposite-charge pairs



- π^+D^+
  - ➡ I=3/2 channel only
- π^+D^-
  - ➡ I=3/2 (33%), I=1/2 (66%)

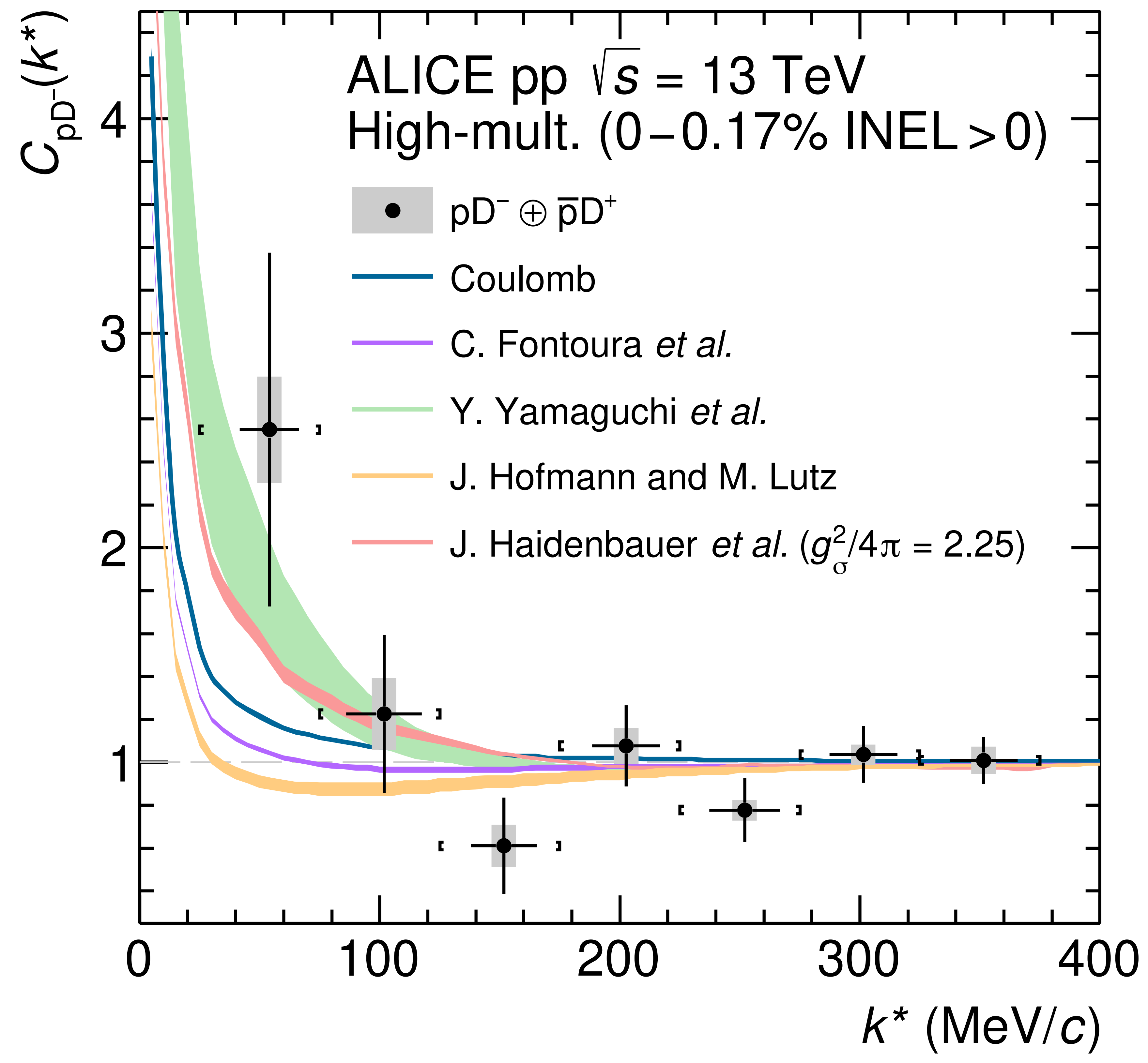
πD interaction: fit with Lednický-Lyuboshits formula

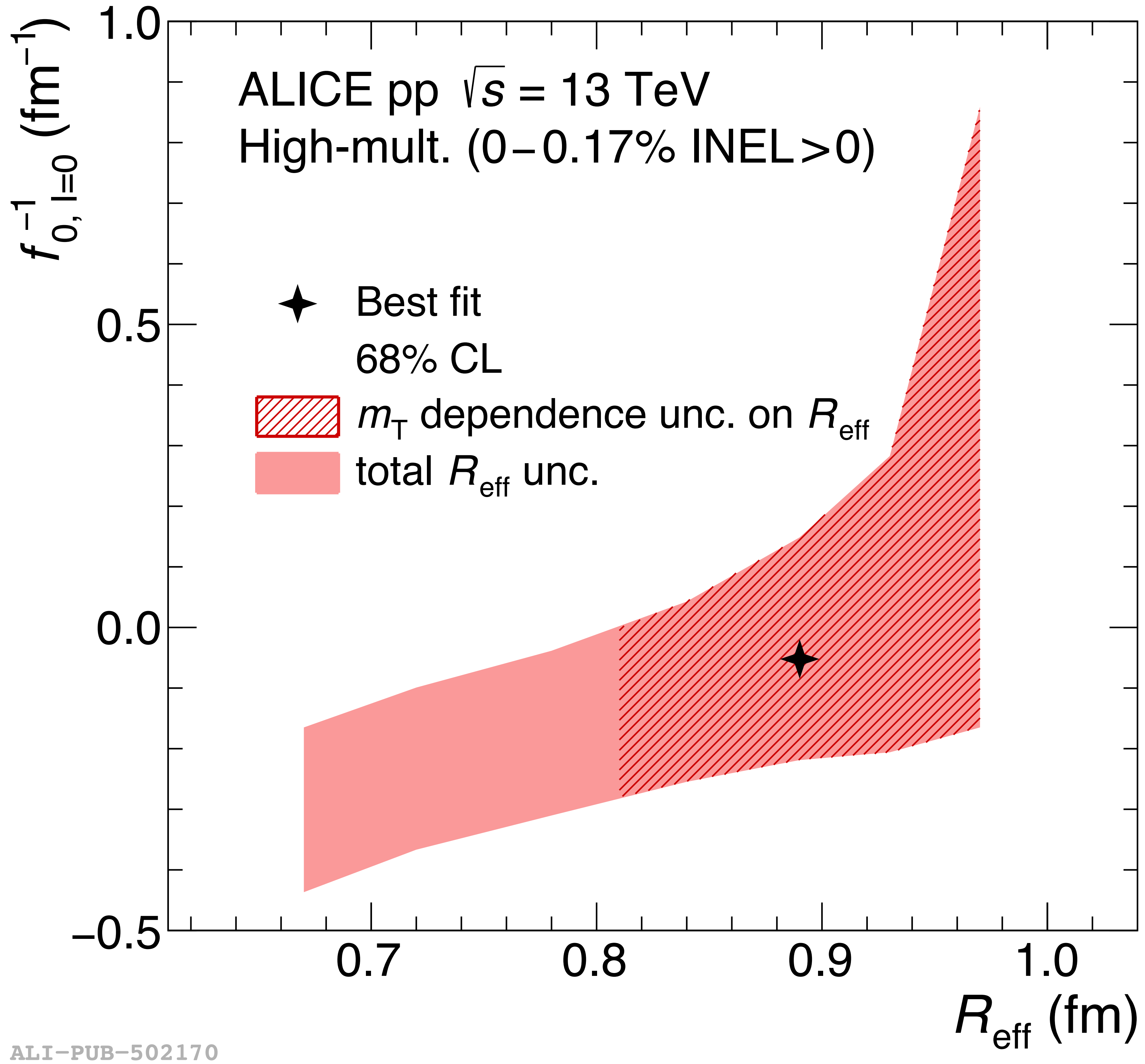


- π^+D^+
  - ➡ I=3/2 channel only
- π^+D^-
  - ➡ I=3/2 (33%), I=1/2 (66%)

- Scattering length for I=3/2 in agreement with models
- Scattering length for I=1/2 significantly smaller than models
- The values found indicate a small rescattering of D mesons in the hadronic phase of heavy-ion collisions

- Small compared to other interactions (scattering lengths light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
- Most of the models predict repulsive interaction
- Possible bound state formation (Yamaguchi et al)





ALICE, PRD 106 (2022) 052010

- Interval of scattering length for isospin I=0 at 68% CL indicates either attractive interaction with or without the formation of a bound state

J. Haidenbauer et al, EPJA 33 (2007) 107–117
J. Hofmann and M. Lutz, NPA 763 (2005) 90–139
Fontura et al, PRC 87 (2013) 025206
Yamaguchi et al, PRD 84 (2011) 014032

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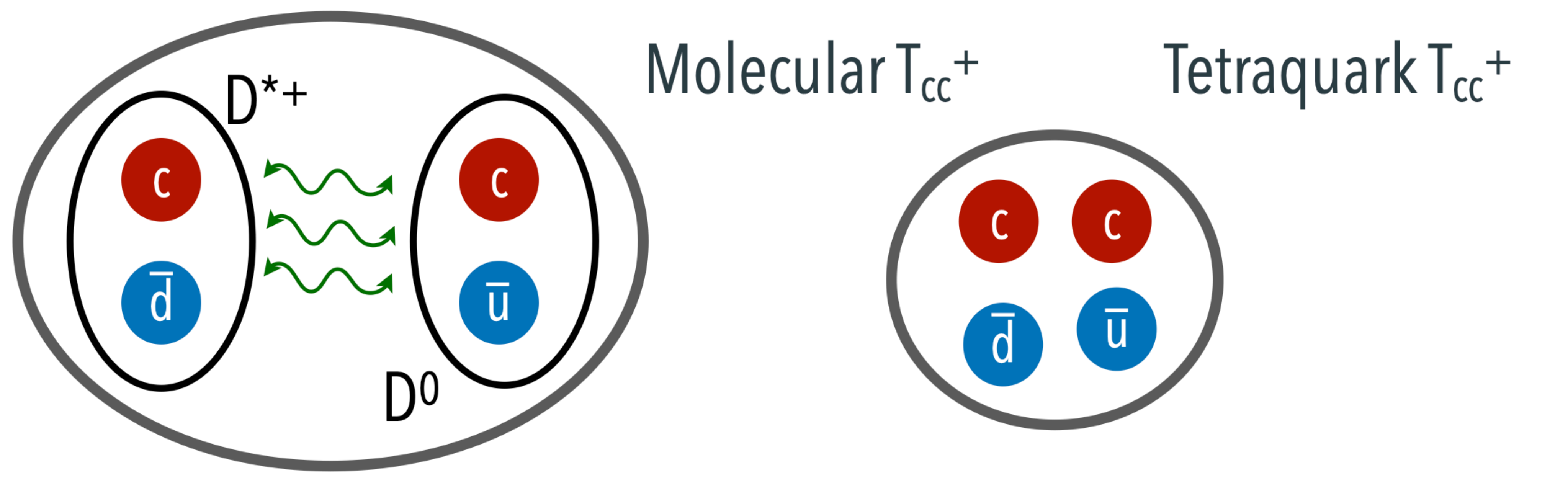
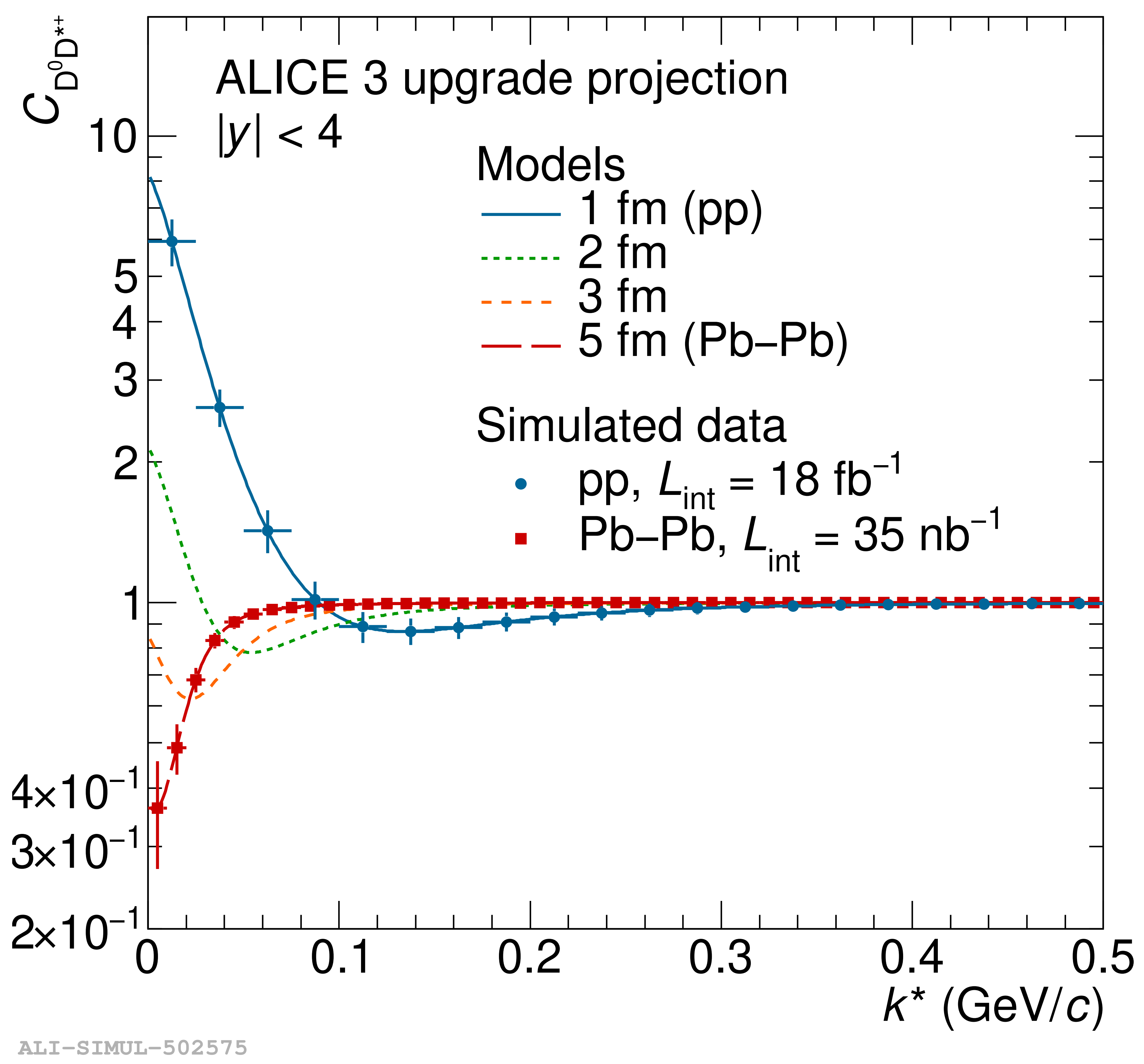
- Charm molecules?

System	I ($J^{P(C)}$)	Candidate
np	0 (1^+)	deuteron
ND	0 ($1/2^-$)	$\Lambda_c(2765)$
ND*	0 ($3/2^-$)	$\Lambda_c(2940)$
ND	0 ($1/2^-$)	$\Sigma_c(2800)$
$D^*\bar{D}$	0 (1^{++})	X(3872)
D*D	0 (1^+)	T_{cc}
$D_1\bar{D}$	0 (1^{--})	Y(4260)
$D_1\bar{D}^*$	0 (1^{--})	Y(4360)
$\Sigma\bar{D}$	1/2 ($1/2^-$)	$P_c(4312)$
$\Sigma\bar{D}^*$	1/2 ($1/2^-$)	$P_c(4457)$
$\Sigma\bar{D}^*$	1/2 ($3/2^-$)	$P_c(4440)$

Fang-Zheng Peng et al, Phys. Rev. D 105, 034028 (2022)





- Interplay between system size and scattering length
  - ➡ Size-dependent modification of $C(k^*)$ in presence of a molecular state

ALICE3 LOI, CERN-LHCC-2022-009

Summary and conclusions

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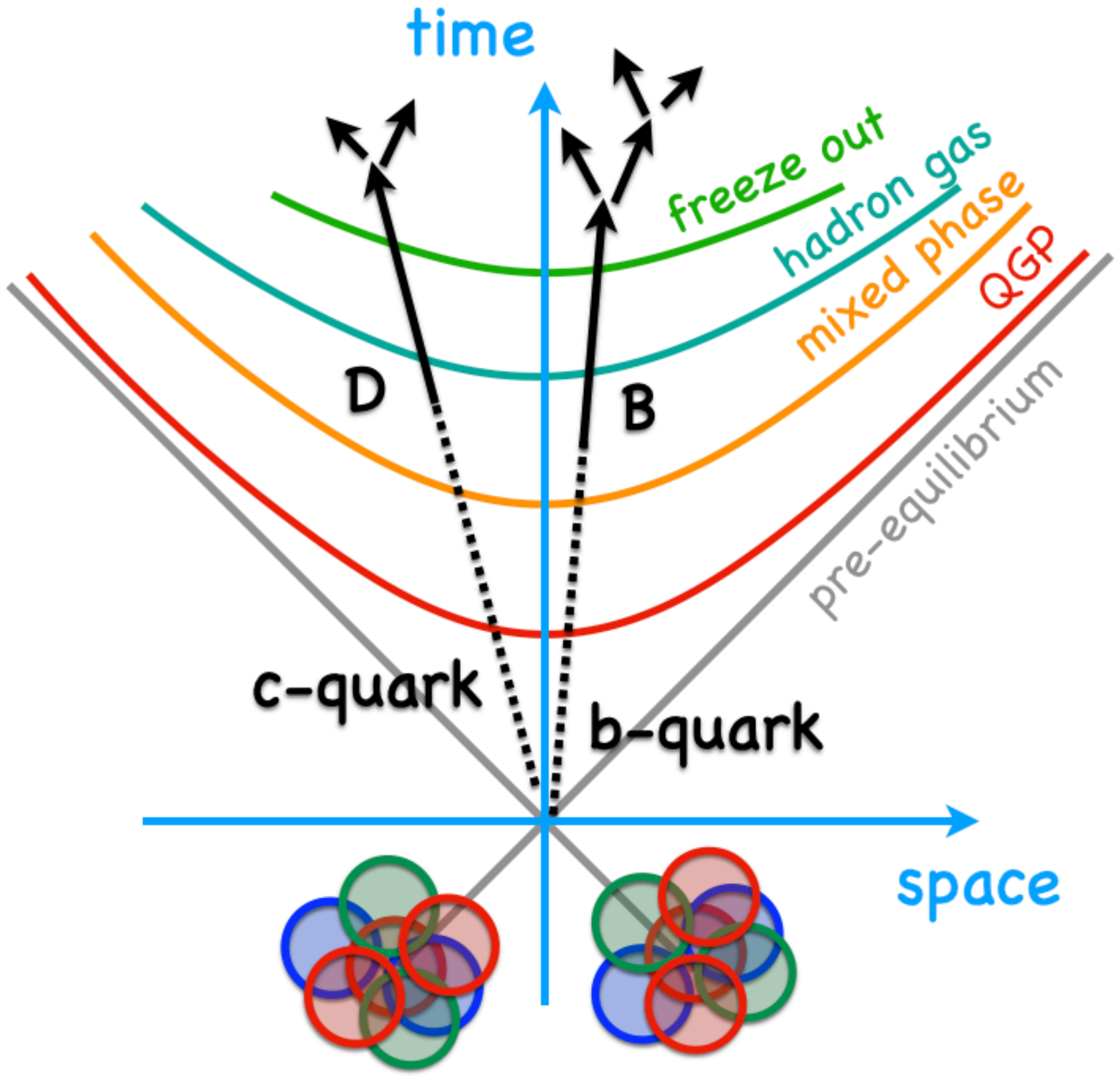
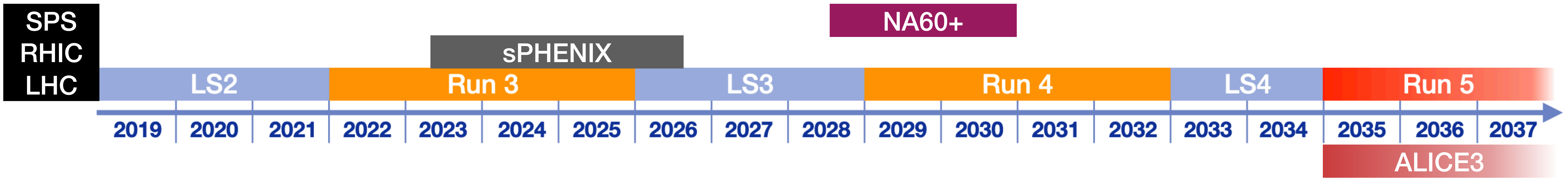
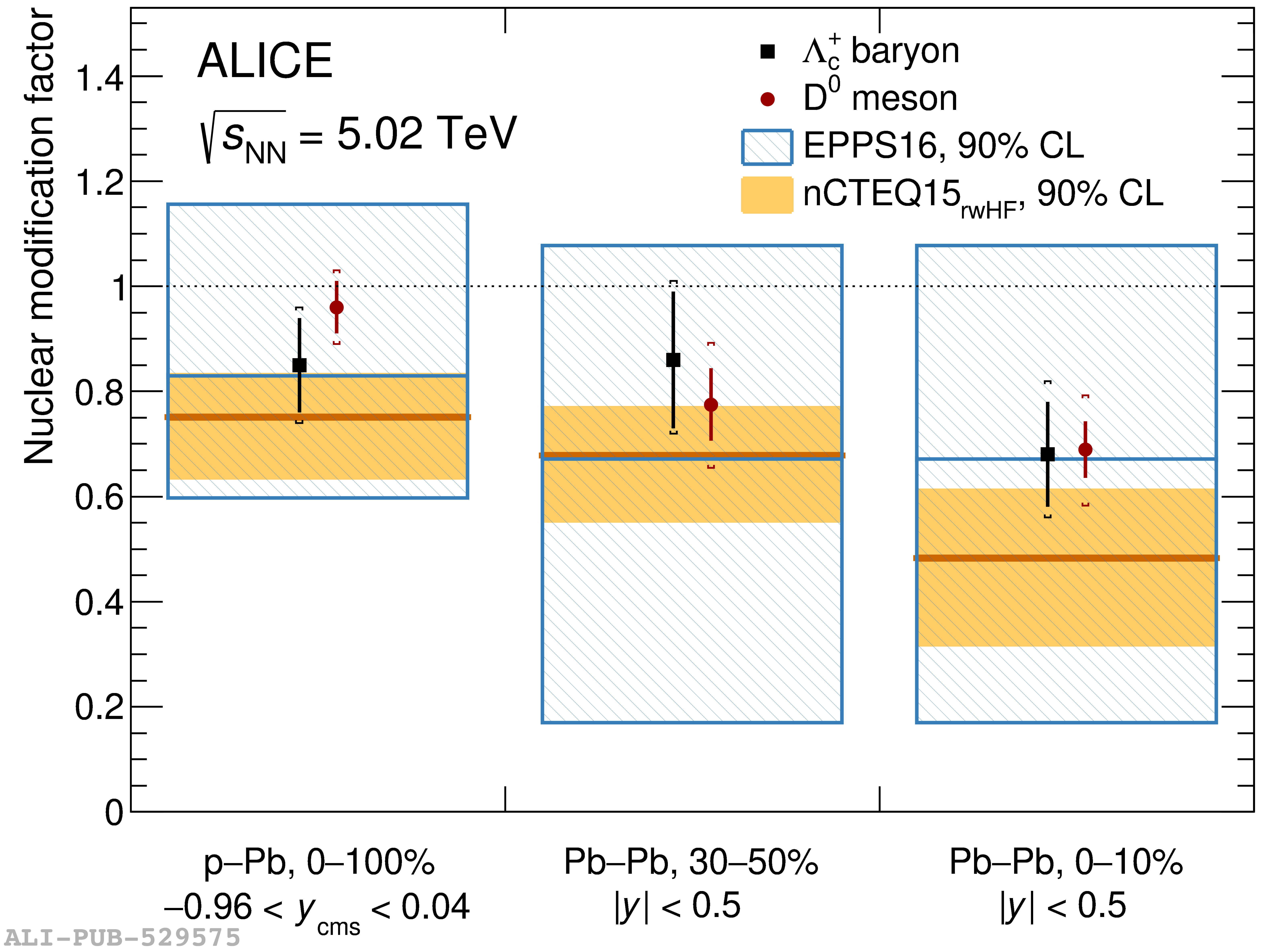
- Heavy quarks are very good probes of the QGP
  - ➡ Comparison with models useful to extract transport coefficients
  - ➡ Precise estimates: understanding of all the other model ingredients necessary
- Experimental observables to study their interaction with QGP constituents
  - ➡ Baryon-to-meson and strange-to-nonstrange ratios and production of quarkonia and multi-charm/beauty states: hadronisation from the QGP
  - ➡ Study residual strong interaction with femtoscopy: hadronic rescattering
- Future heavy-ion runs crucial to better understand HF interactions with the QGP





ADDITIONAL SLIDES

pT-integrated R_{AA} of D^0 and Λ_c^+



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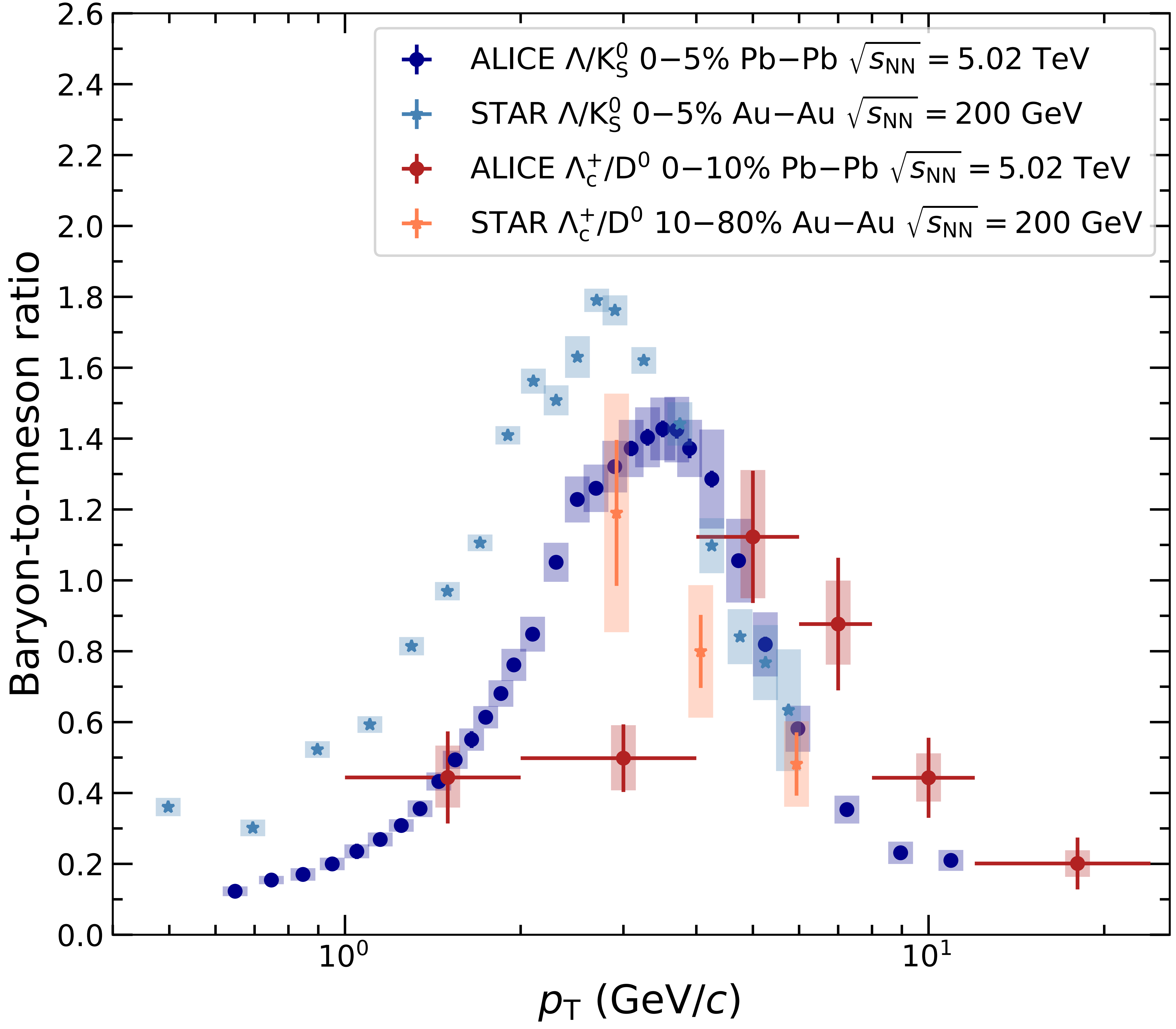

- Harder p_T distribution of baryon-to-meson ratio at LHC compared to RHIC
  - ➡ Stronger radial flow

Baryon enhancement in pp collisions

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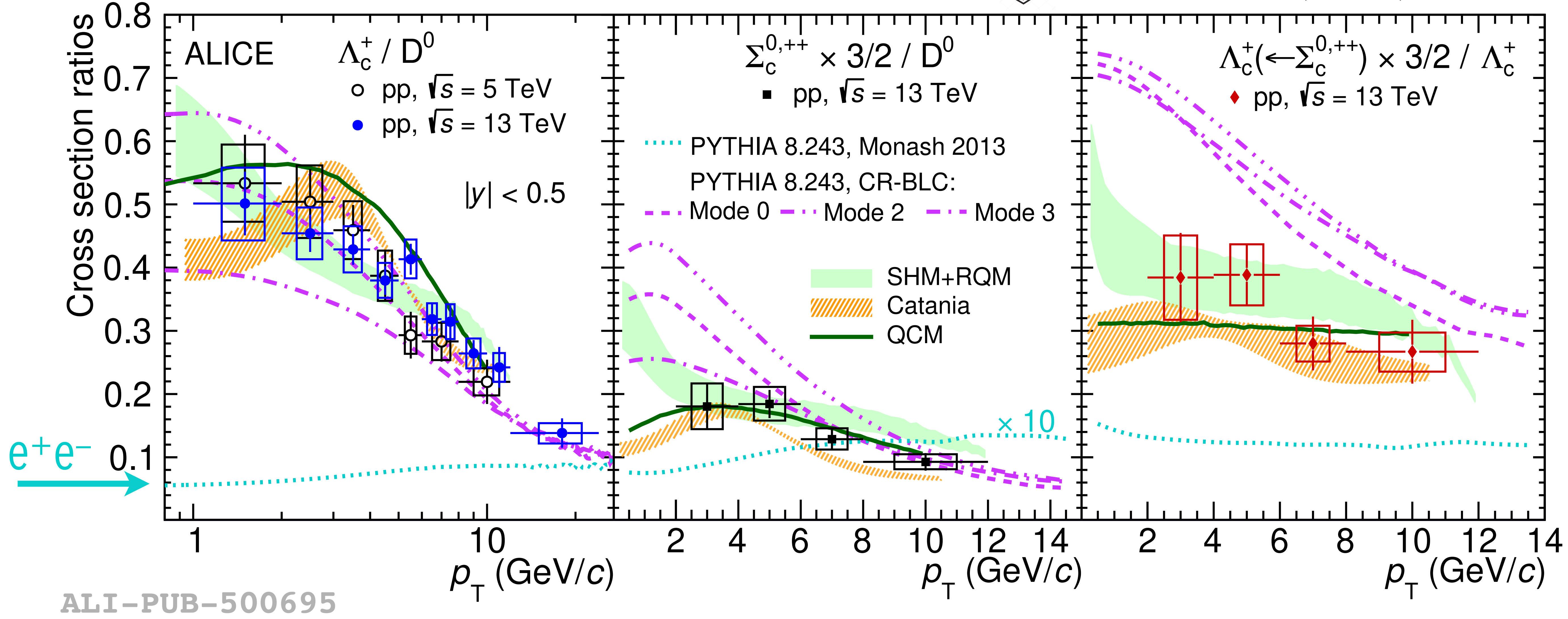
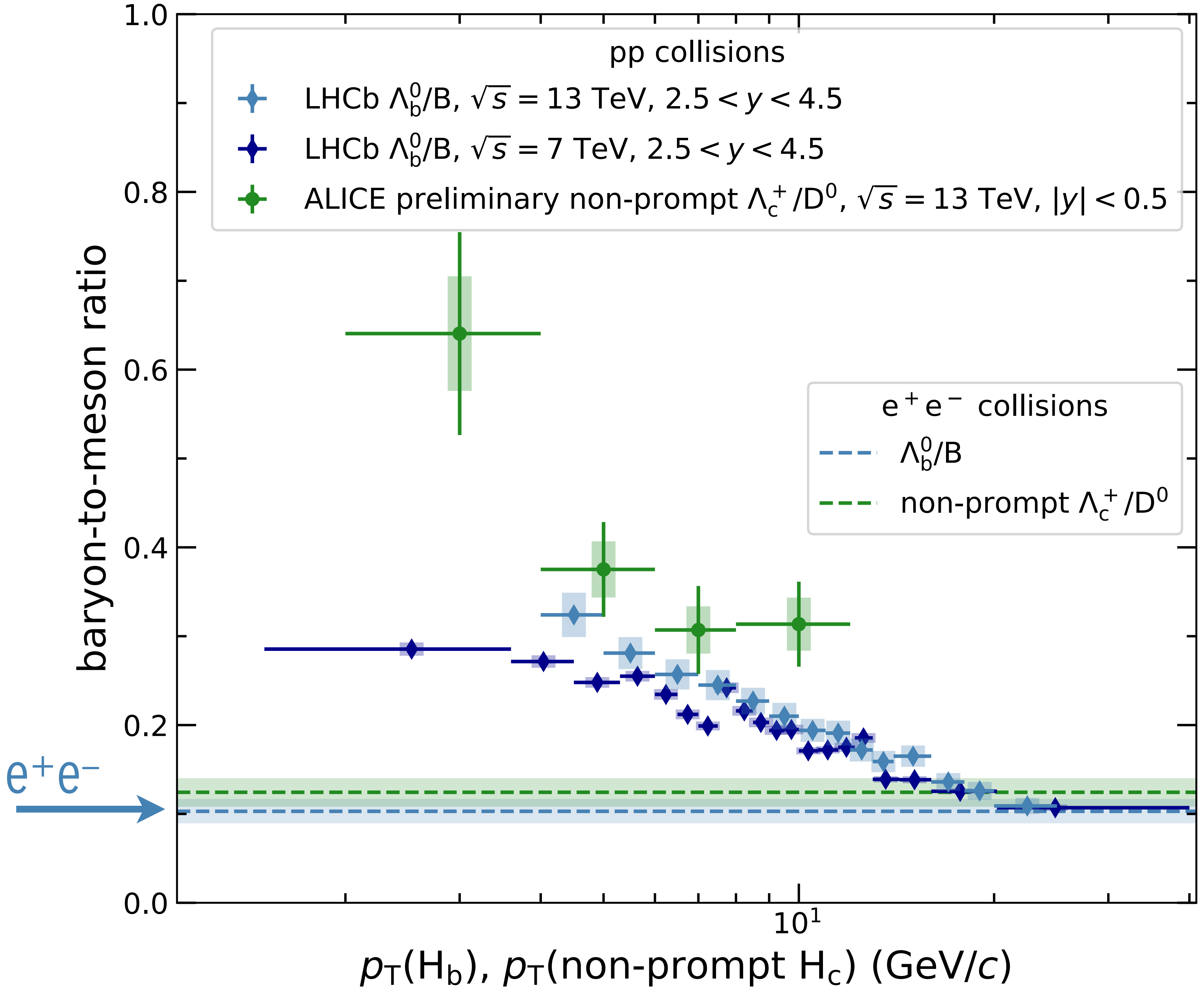
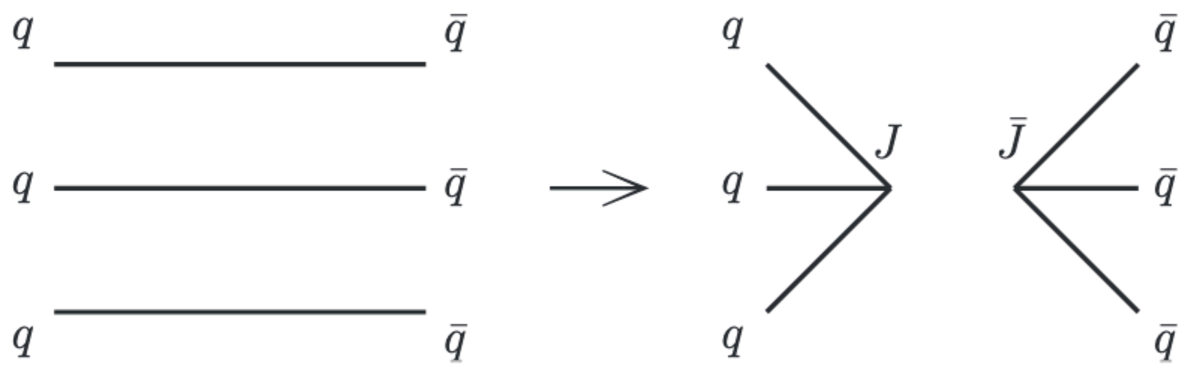
ALICE, PRL 128 (2022) 012001



- Ground and excited charm baryons enhanced compared to e+e− collisions
- **Similar enhancement observed in the beauty sector**



- Color Reconnection (PYTHIA8)
  - J.P. Christiansen, P. Z. Skands, JHEP 08 (2015) 003



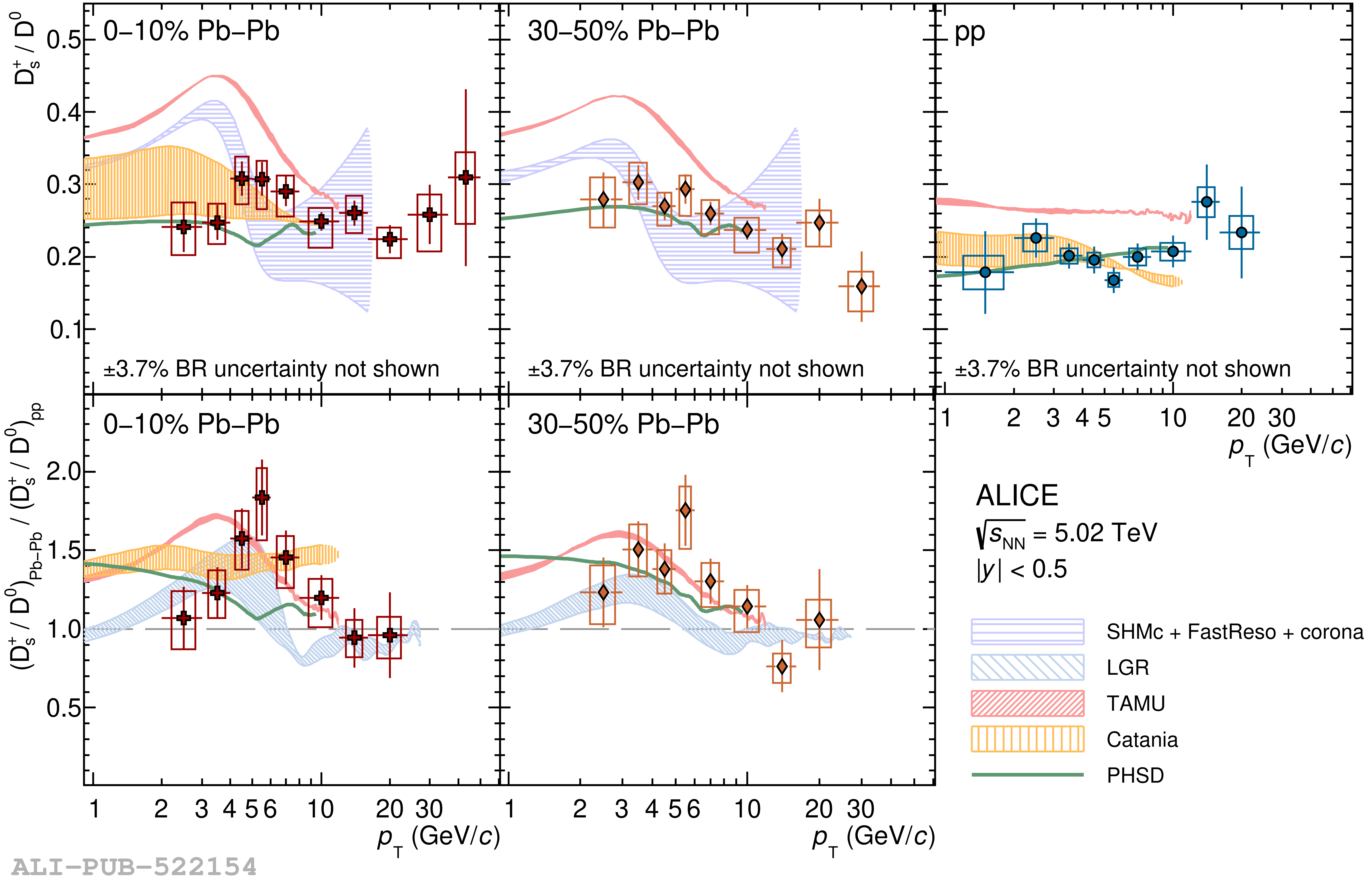
(c) Type III: baryon-style junction reconnection

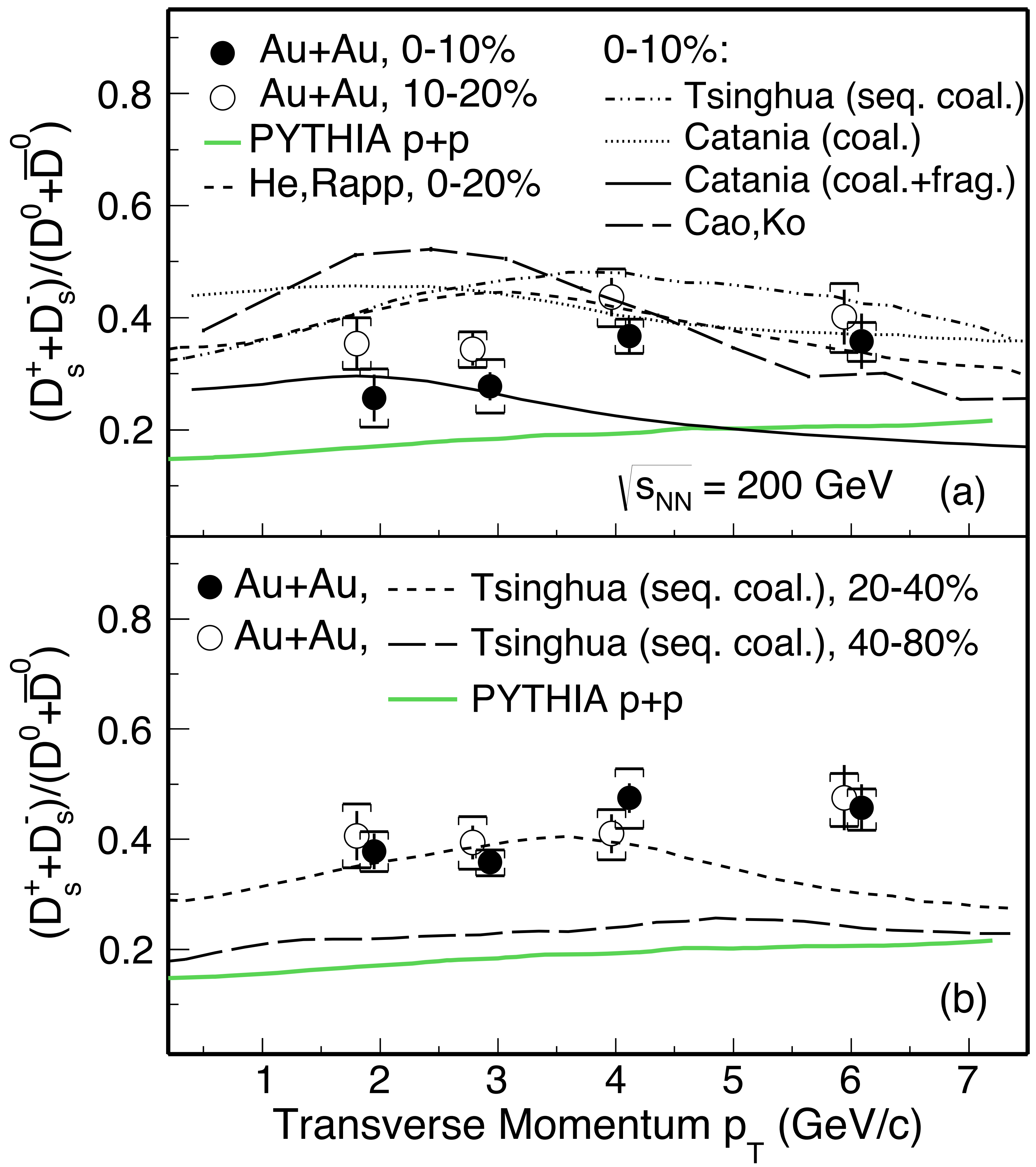
- Quark coalescence (+fragmentation)
  - V. Minissale, S. Plumari, V. Greco PLB 821 (2021) 136622
  - J. Song, H. Li, F.-I. Shao et al EPJC (2018) 78: 344
- Statistical hadronisation model with augmented set of charm-baryon excited states from lattice QCD — M. He, R. Rapp, PLB 795 (2019) 117-121

LHCb, JHEP 08(2014)143
LHCb, PRD 100 (2019) 3, 031102
ALICE, preliminary

e+e−
PDG, PTEP 8 (2020) 083C01
EPJC 75 (2015) 19

D_s^+/D^0 in Pb–Pb collisions compared with models





D_s^+/D^0 and Λ_c^+/D^0 in pp collisions as a function of multiplicity

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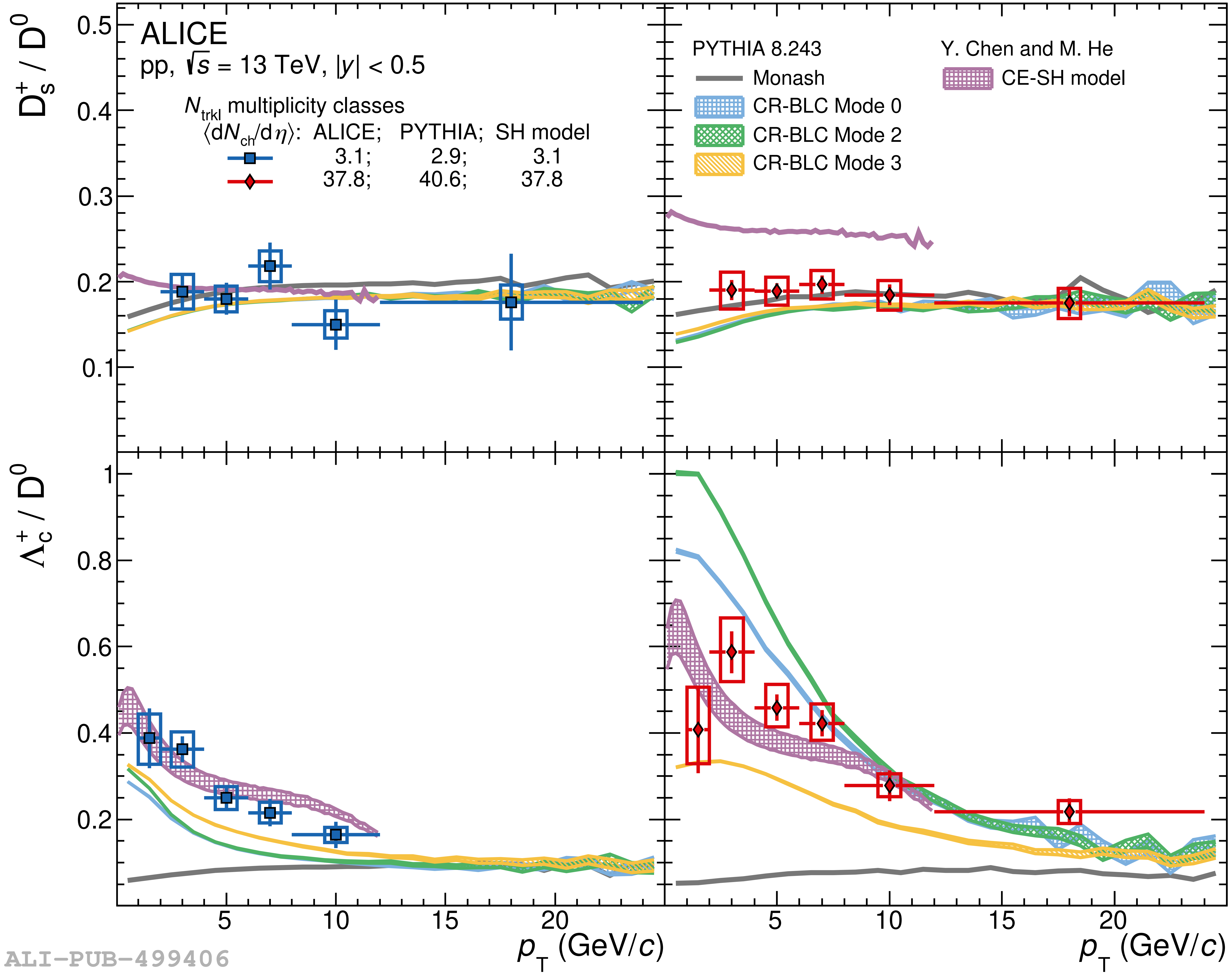

- Significant modification of the p_T dependence of the Λ_c^+/D^0 ratio as a function of multiplicity in pp collisions
- No multiplicity dependence observed for D_s^+/D^0 in pp collisions

ALICE, PLB 829 (2022) 137065

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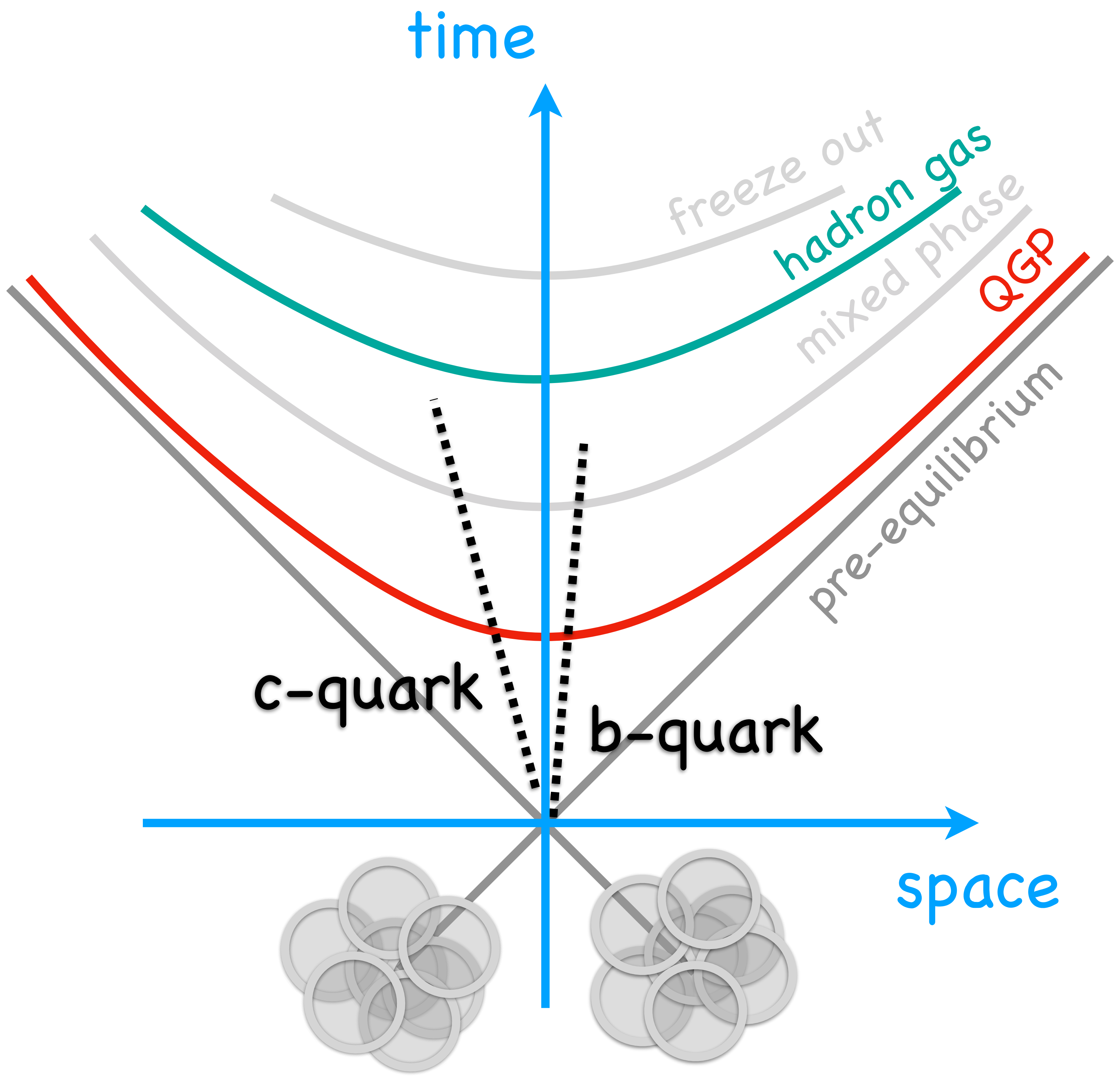
- Non-central heavy-ion collisions
  - ➡ Large angular momentum due to the medium rotation is predicted
  - ➡ Huge initial magnetic field ($B \sim 10^{14}$ T) is expected to be formed

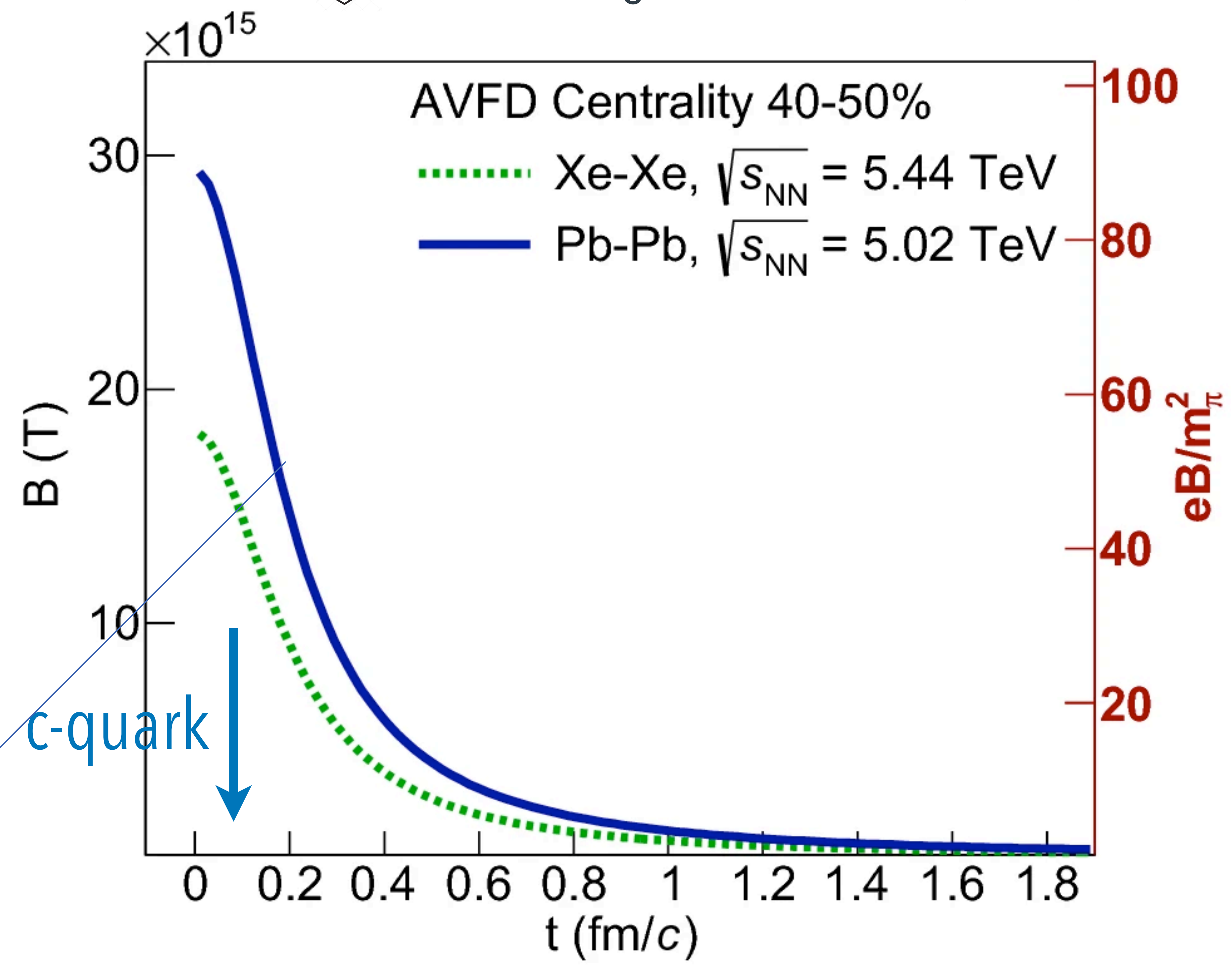
Becattini et al, PRC 77 (2008) 024906

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

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



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



- Quark-coalescence model Y.-G. Yang et al, PRC 97 (2018) 034917
  - ➡ Spin alignment:

$$\rho_{00}(\omega, B) = \frac{1}{3} - \frac{1}{9}(\beta\omega)^2 - \frac{1}{9}\beta^2\frac{Q_1 Q_2}{m_1 m_2}B^2$$

no polarisation   angular momentum   magnetic field

J/ψ polarisation in heavy-ion collisions

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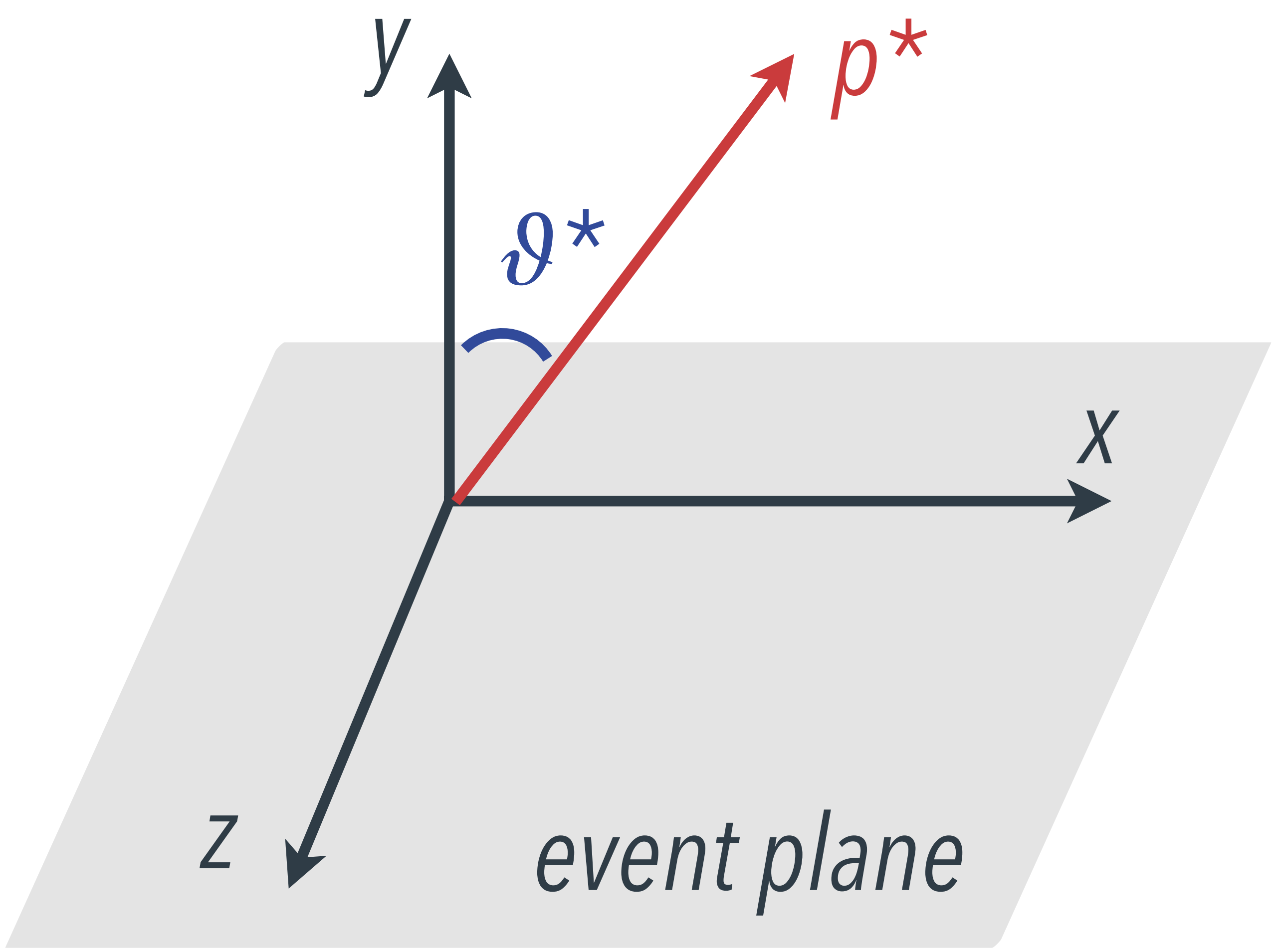


- Polarisation of J/ψ mesons studied with respect to event plane

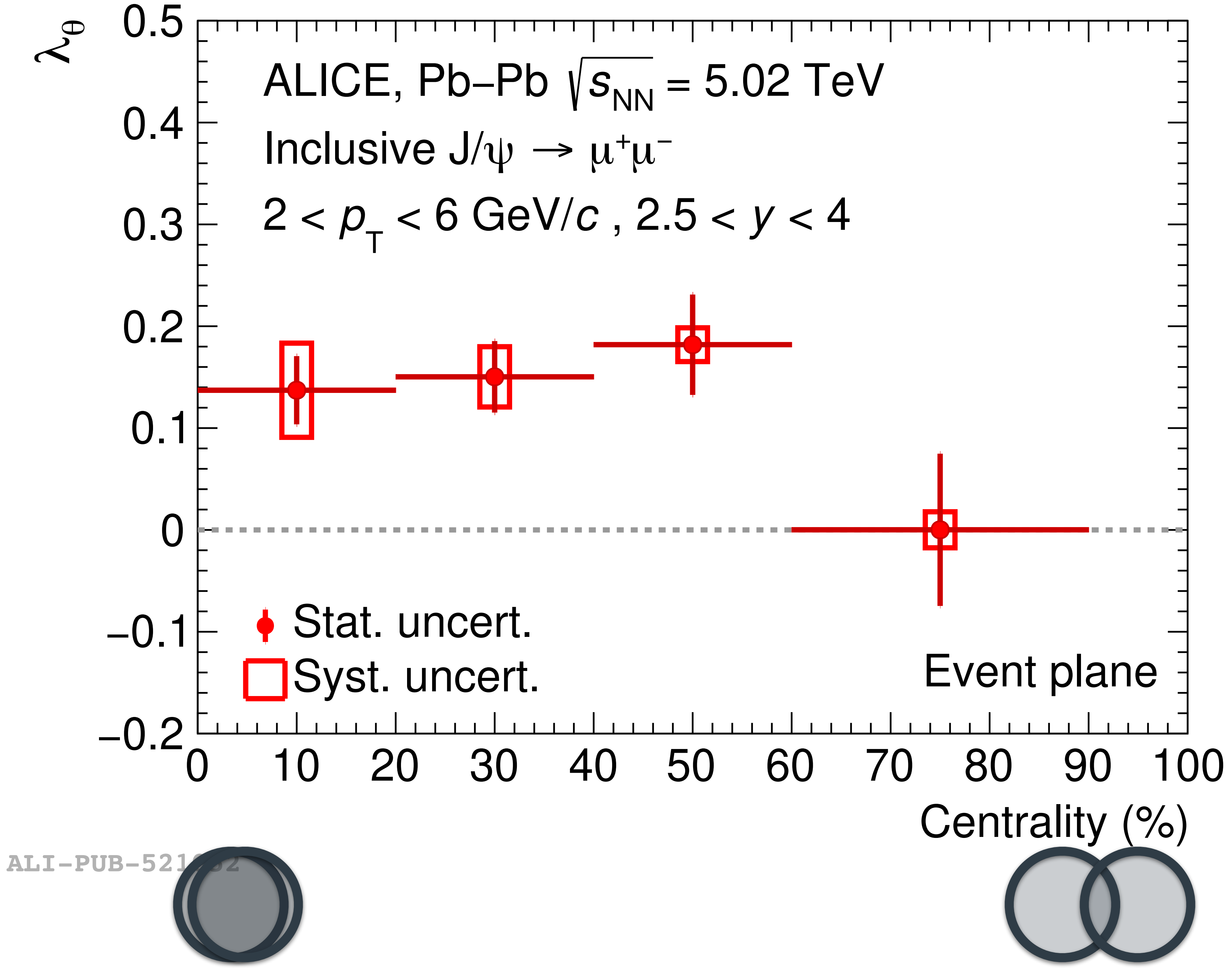
$$W(\theta) \propto \frac{1}{1+3\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$$

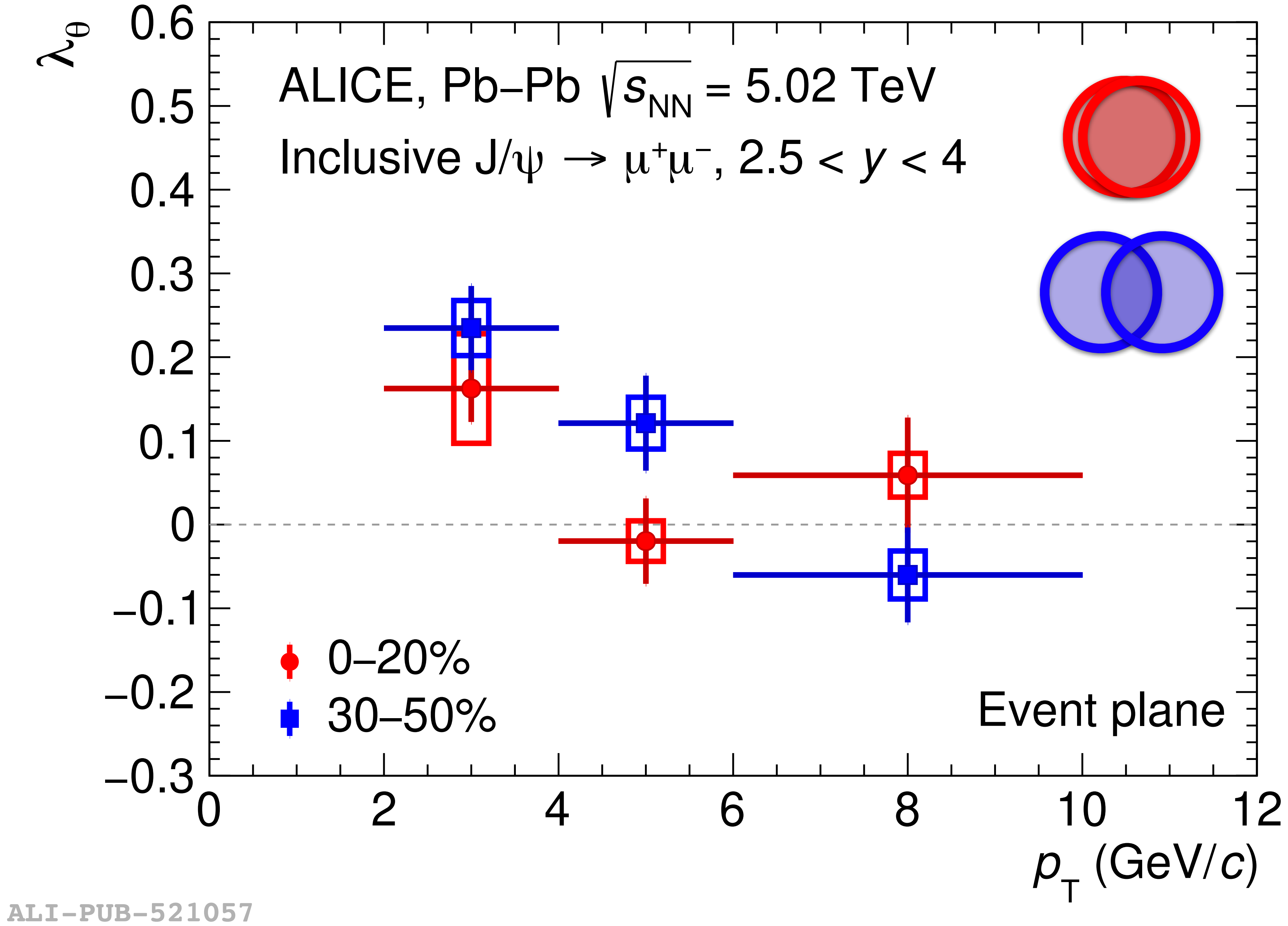
Can be related to the spin-density matrix element ρ_{00}

$$\lambda_\theta \propto (3\rho_{00}-1)/(1-\rho_{00})$$

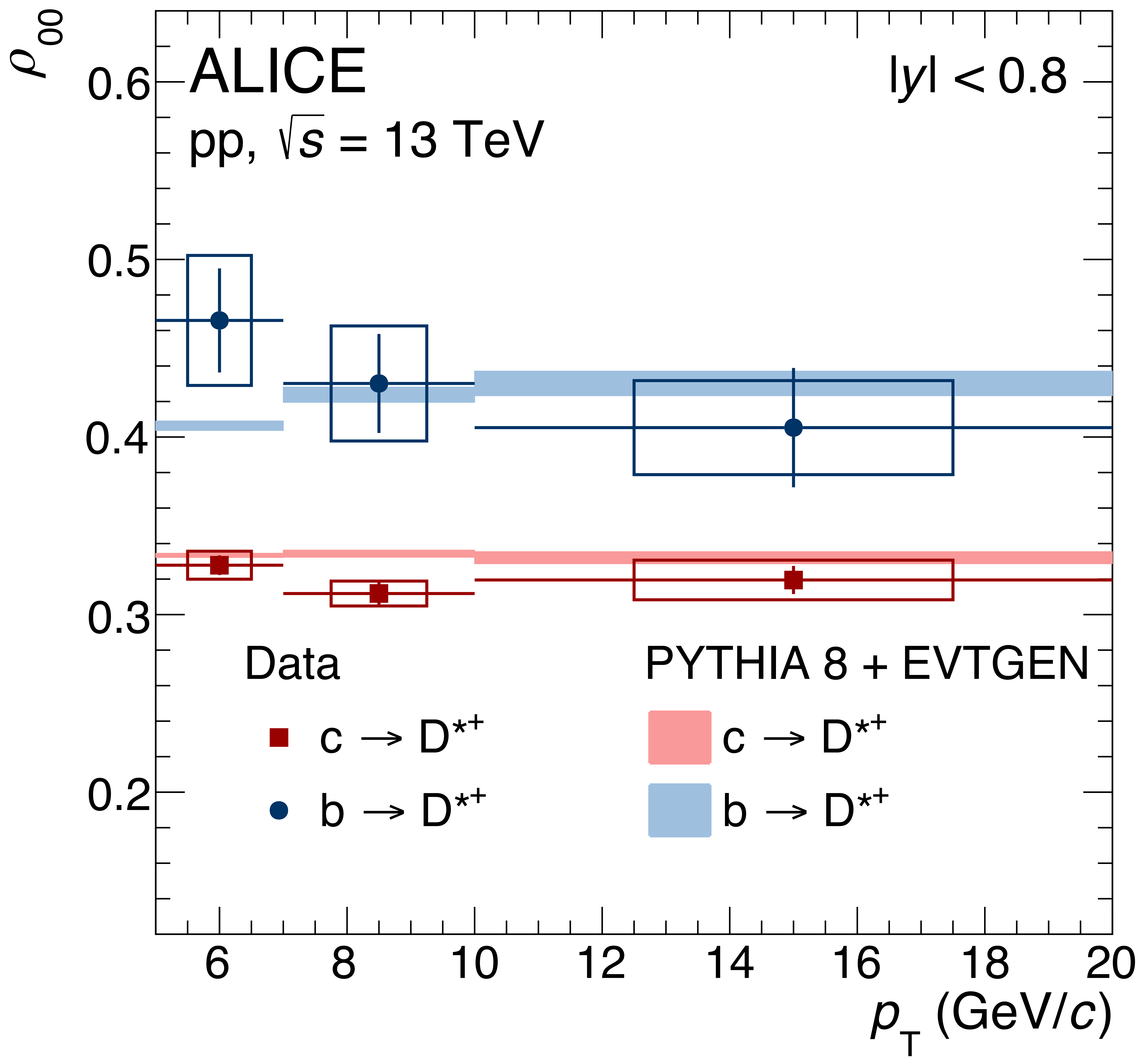
- Evidence of J/ψ polarisation with respect to event plane
  - ➡ Opposite direction that of light vector mesons

$$\lambda_\theta^{J/\psi} > 0,\ \rho_{00}^{\phi,K^{*0}} < 1/3$$





ALICE, arXiv:2204.10171



- Spin alignment of prompt and non-prompt charm vector mesons with respect to helicity axis in pp collisions
  - ➡ Prompt D^{*+} compatible with no polarisation
  - ➡ Non-prompt D^{*+} $\rho_{00} > 1/3$ (helicity conservation in $\mathrm{B} \to \mathrm{D}^{*+}\mathrm{X}$ decays)

- Measurement of D^{*+} vector mesons in heavy-ion collisions crucial to complete the picture for c-quark

ALICE, arXiv:2212.06588

Heavy-quark hadronisation and strangeness enhancement

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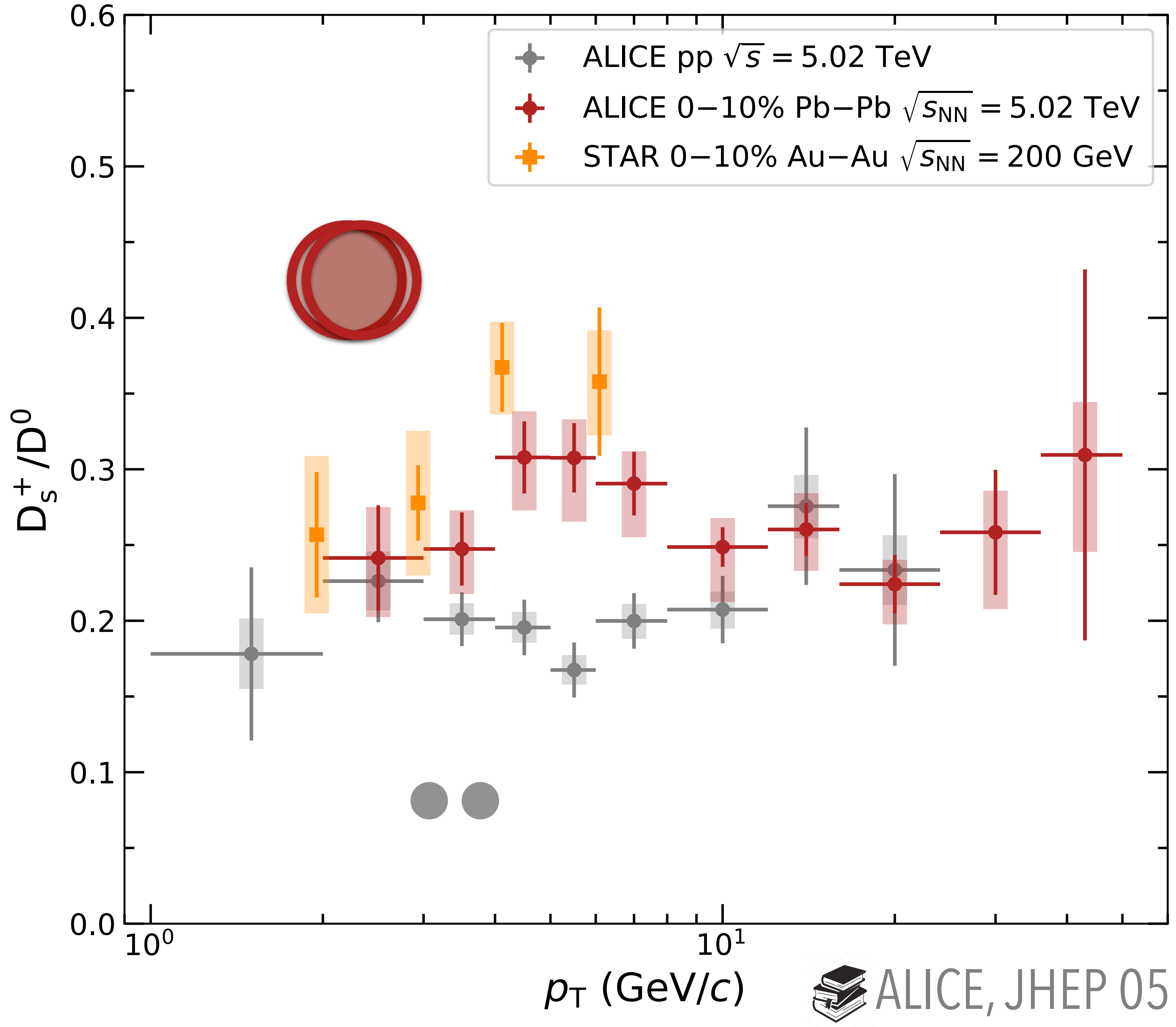
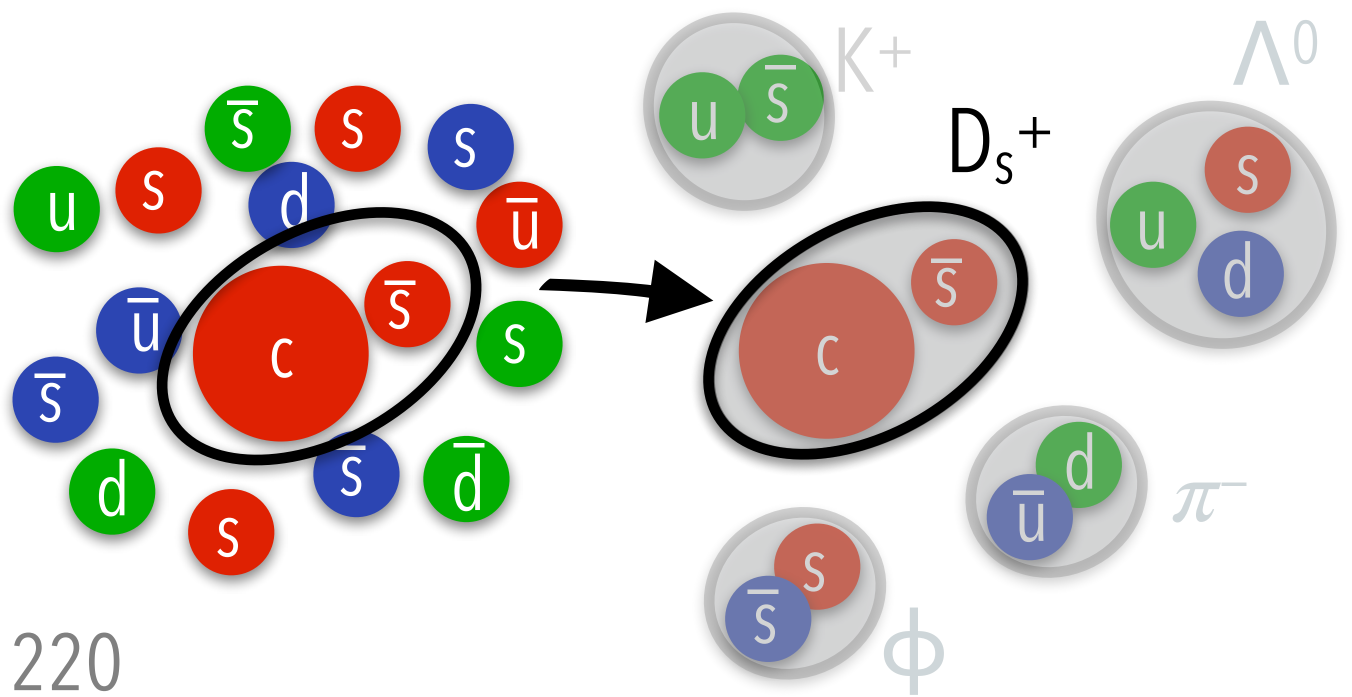
ALICE, PLB 827 (2022) 136986 STAR, PRL 127 (2021) 092301

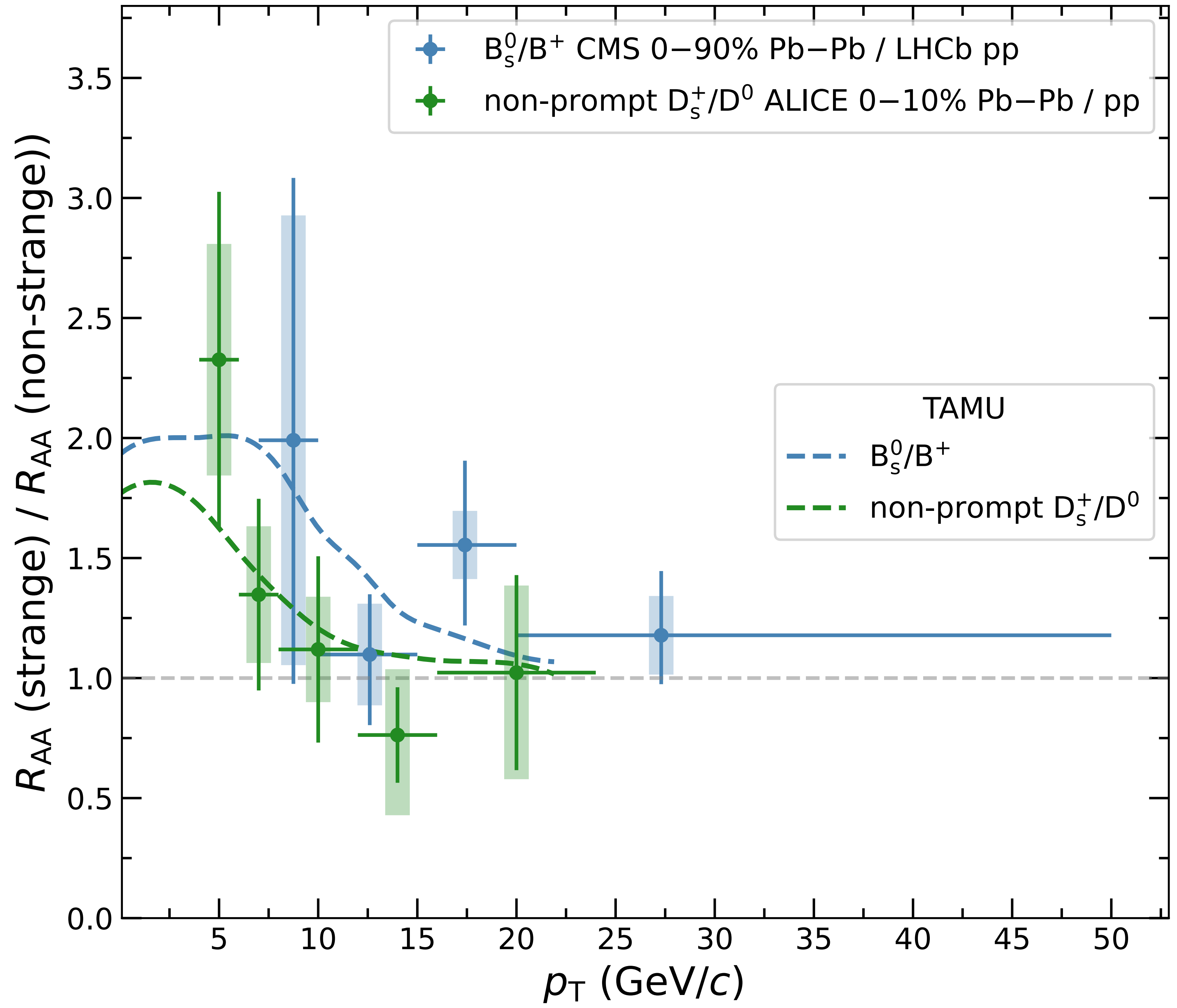


ALICE, JHEP 05 (2021) 220

- Abundant production of strange quarks in the QGP (strangeness enhancement)
- Hadronisation via recombination → strange hadrons expected to be enhanced
  - ➡ (Partial) thermal equilibrium required
- **Strange-to-nonstrange ratio higher in Pb–Pb than pp in charm sector**

ALICE, arXiv:2204.10386
CMS, PLB 829 (2022) 137062
LHCb, PRL 124 (2020) 122002

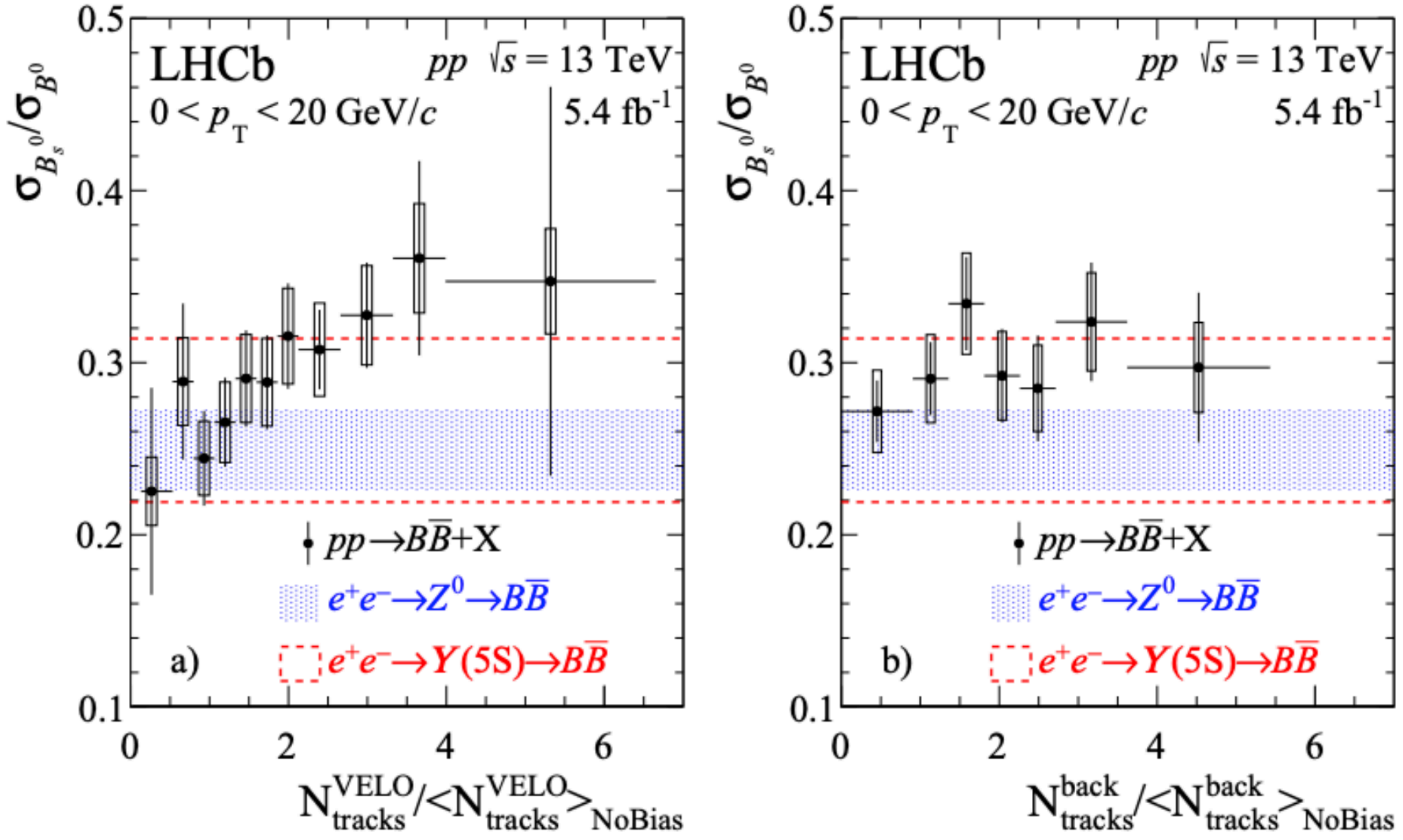




TAMU, PLB 735 (2014) 445–450

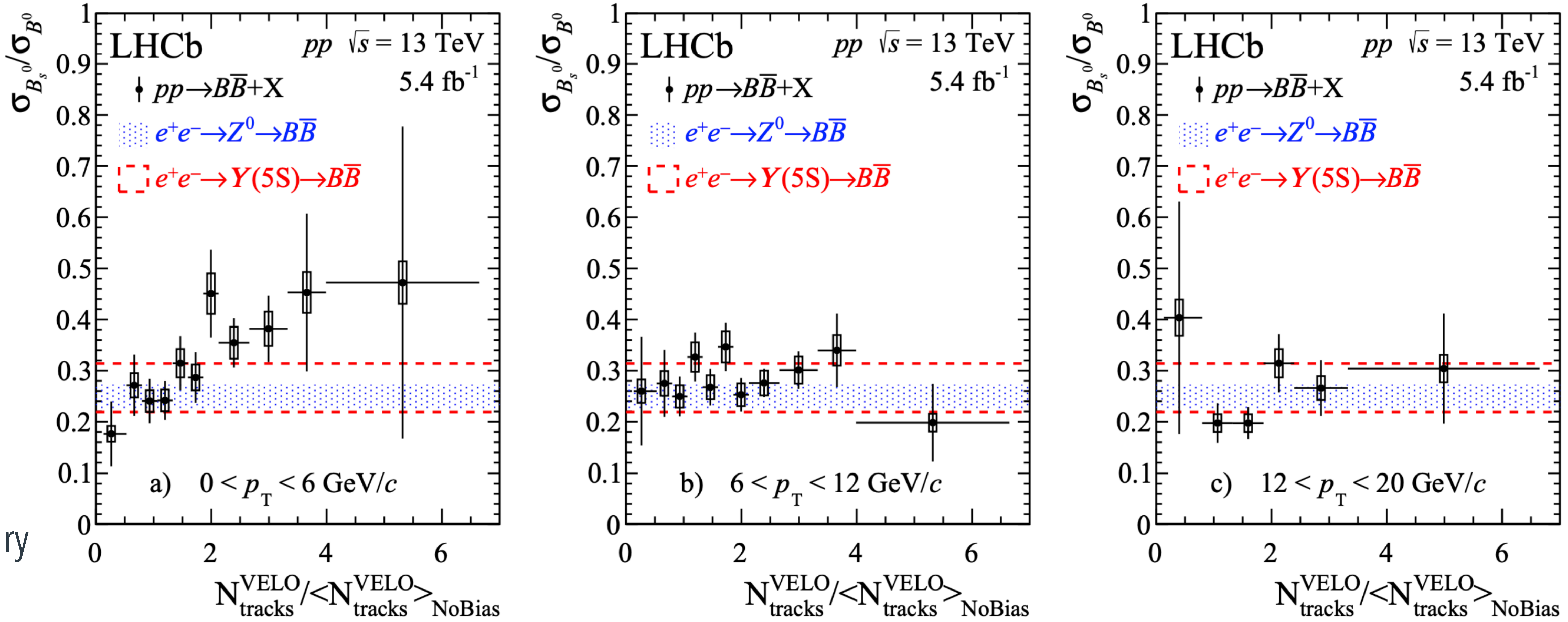
- Measurements in the beauty sector compatible with transport models implementing strangeness enhancement and hadronisation via recombination
  - ➡ **Do beauty quarks reach (partial) thermalisation?**
- Current data precision limited: also compatible with no enhancement scenario
  - ➡ Next LHC runs crucial to study the beauty sector

B_s^0/B^0 in pp collisions as a function of multiplicity



- Multiplicity dependence of B_s^0/B^0 in pp collisions
  - ➡ Significant in case of charged-particle multiplicity measured in the same rapidity range of B mesons
  - ➡ Not observed if charged-particle multiplicity measured with large pseudorapidity gap wrt B mesons

- Multiplicity dependence at low p_T only



LHCb, preliminary

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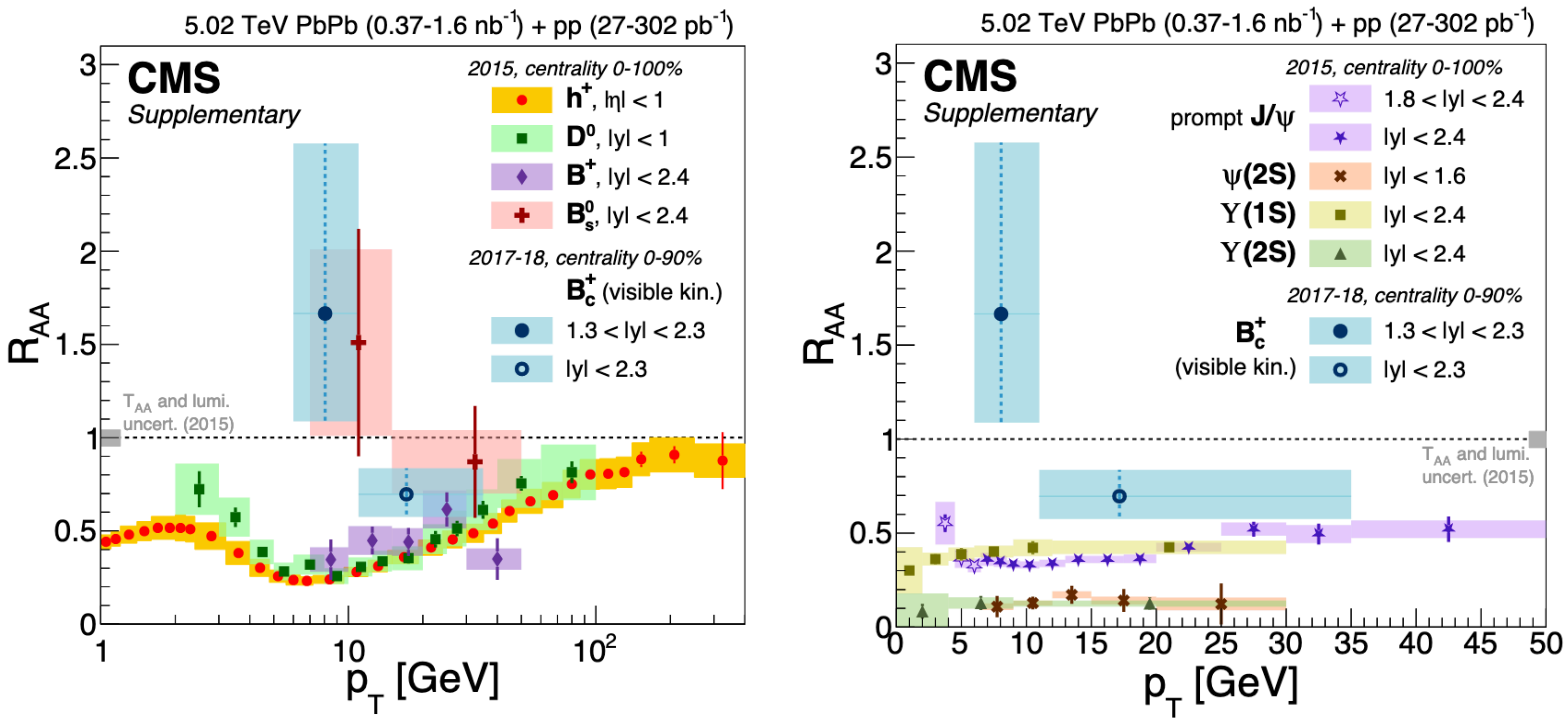
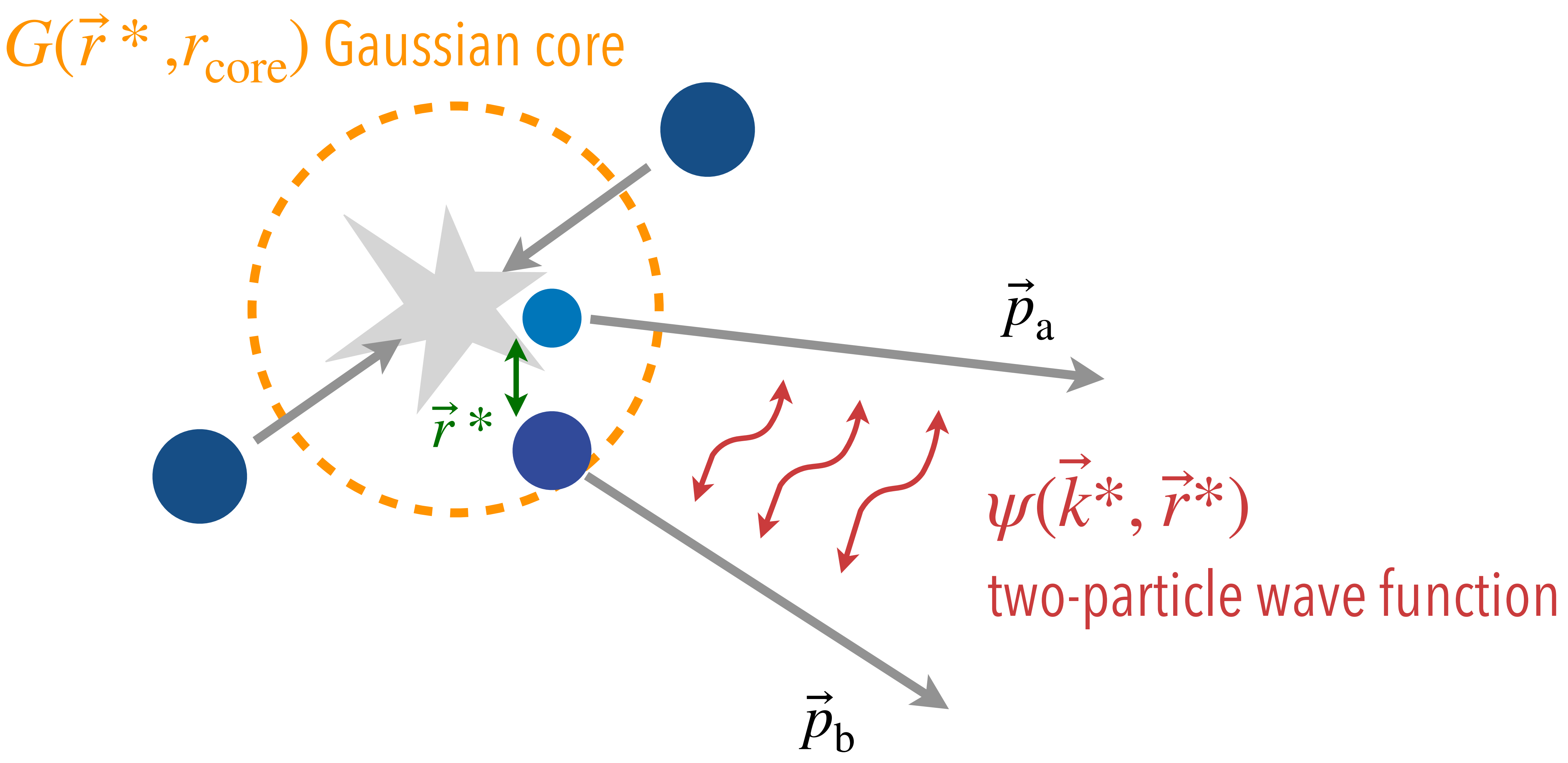


- Hint of $R_{AA}(B_c^+) \sim R_{AA}(B_s^0) > R_{AA}(B)$ and $R_{AA}(B_c^+) > R_{AA}(\Upsilon, J/\psi, \psi)$

$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,\mathrm{d}^3r^*$$

➡ Emitting source: hypersurface at kinematic freezout of final-state particles



- Described with a Gaussian core

$$G(r^*, r_{\rm core}(m_{\rm T})) = \frac{1}{(4\pi r_{\rm core}^2(m_{\rm T}))^{3/2}} \cdot \exp\left(-\frac{r^{*2}}{4r_{\rm core}^2(m_{\rm T})}\right)$$

$$C(\vec{k}^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,\mathrm{d}^3r^*$$

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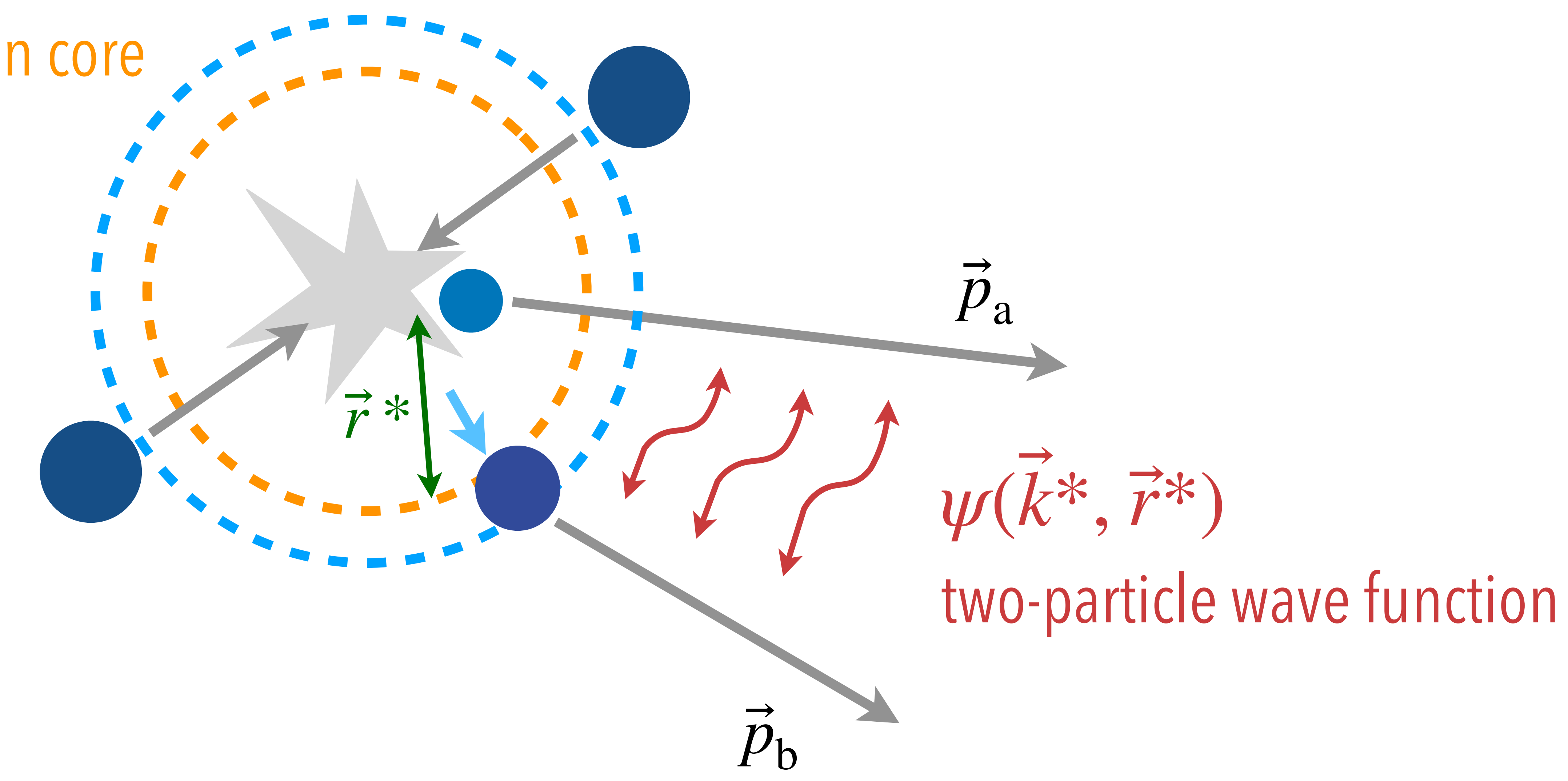
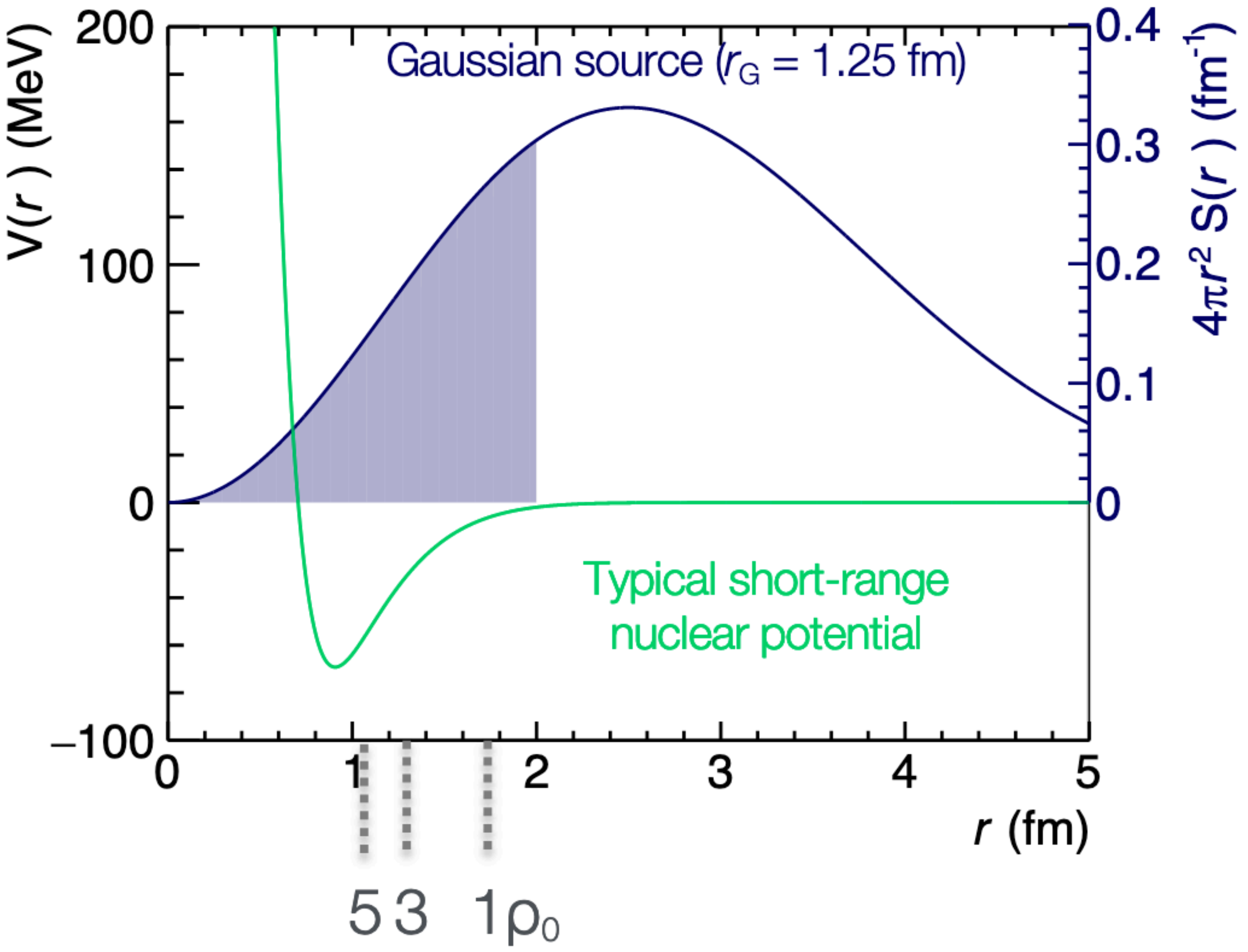


- Described with a Gaussian core

$$G(r^*, r_{\rm core}(m_{\rm T})) = \frac{1}{(4\pi r^2_{\rm core}(m_{\rm T}))^{3/2}} \cdot \exp\left(-\frac{r^{*2}}{4r^2_{\rm core}(m_{\rm T})}\right)$$

- Short-lived strongly decaying resonances effectively enlarge it

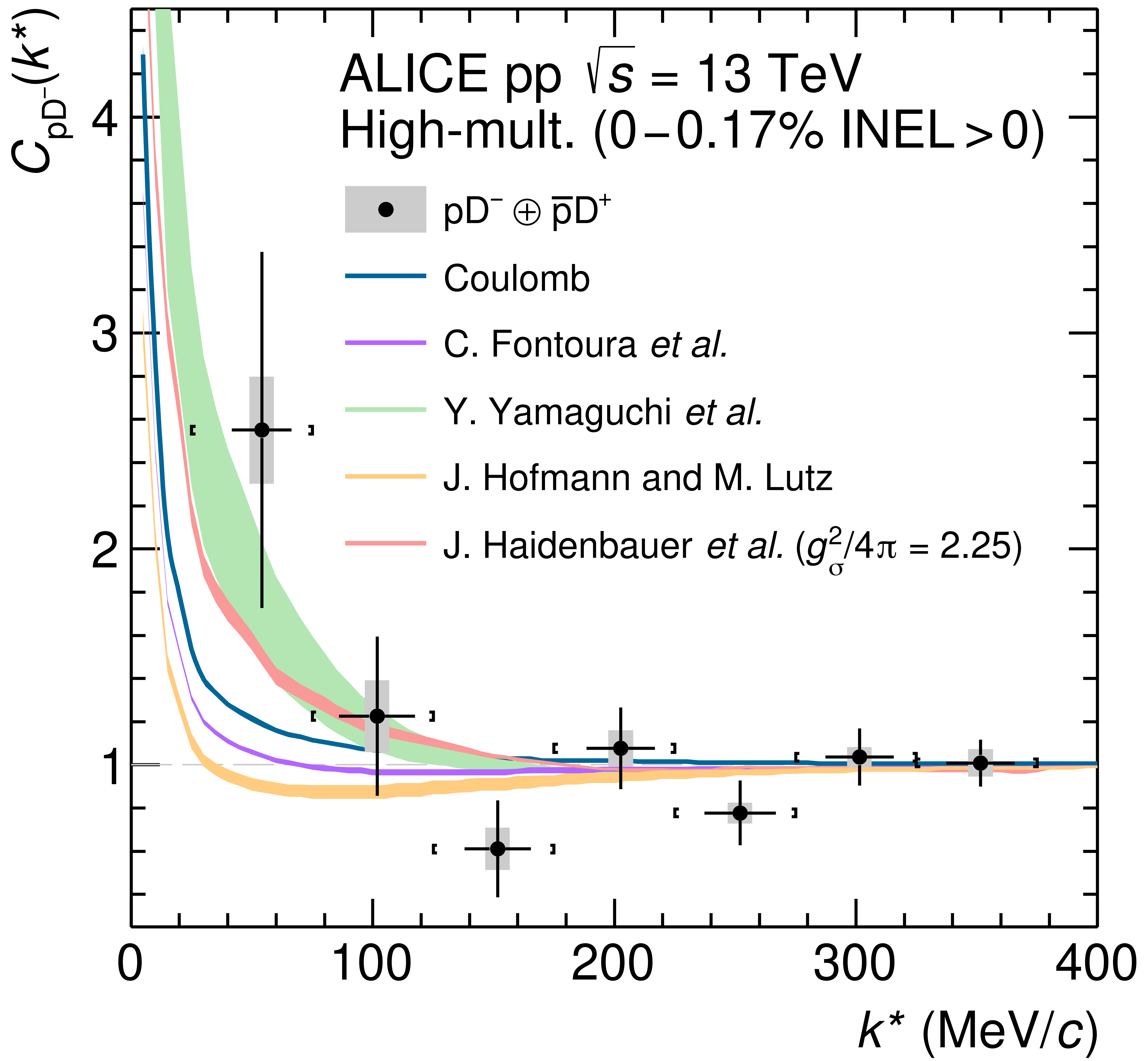
$$E(r^*, M_{\rm res}, \tau_{\rm res}, p_{\rm res}) = \frac{1}{s}\exp\left(-\frac{r^*}{s}\right) \quad \text{with} \quad s = \beta\gamma\tau_{\rm res} = \frac{p_{\rm res}}{M_{\rm res}}\tau_{\rm res}$$



- Typical range of nuclear potential around 1-2 fm
  - ➡ study of strong interaction among hadrons not possible with larger sources
  - ➡ proton–proton and proton–nucleus collisions are the ideal laboratory to study the strong interaction

N$\bar{\text{D}}$ interaction

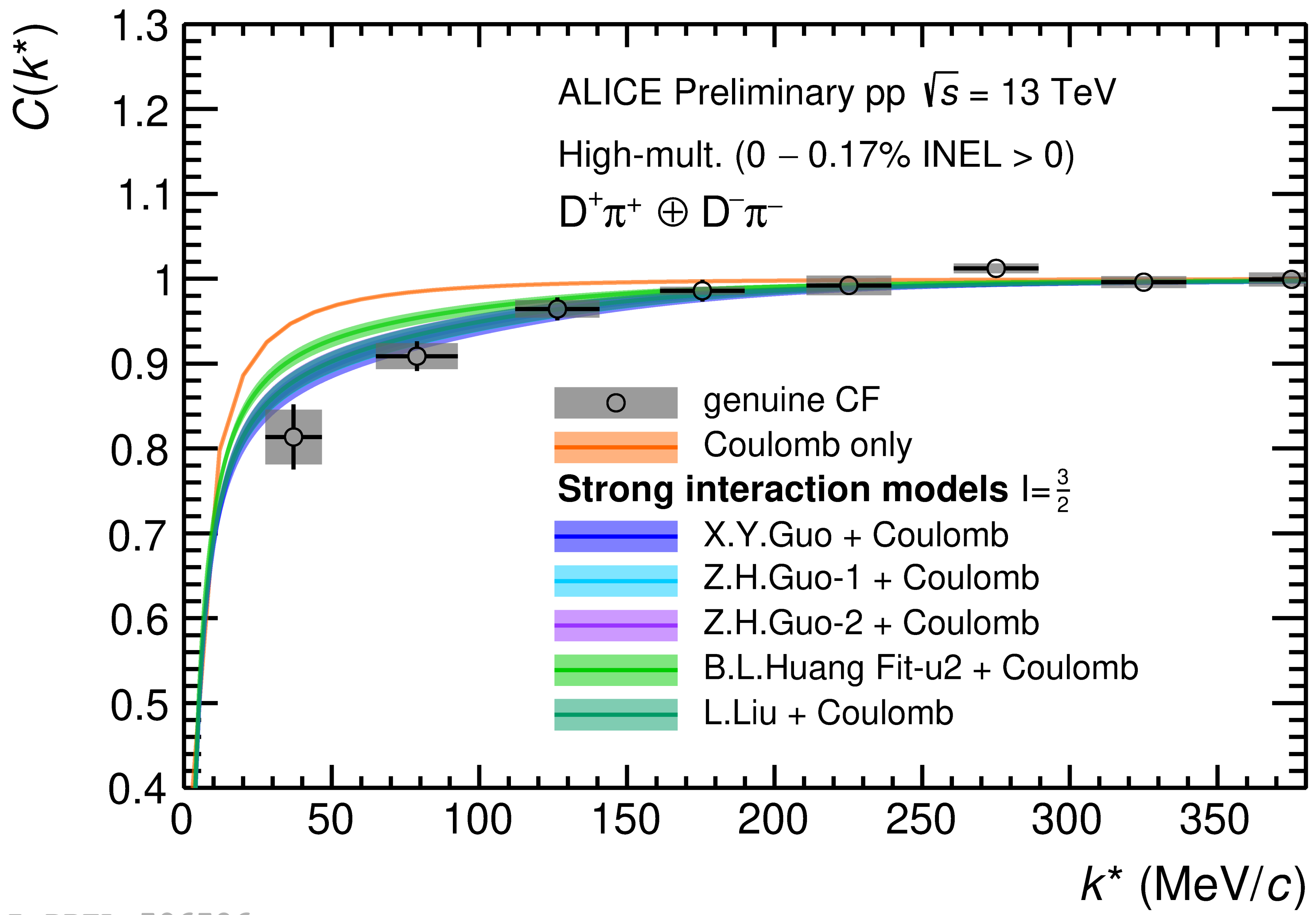
- pD⁻
  - ➡ Typically very small compared to other interactions (light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ Most of the models predict repulsive interaction
  - ➡ Possible bound state formation (Yamaguchi et al)
- Data compatible with Coulomb only interaction, but comparison slightly improves when also attractive strong interaction is considered



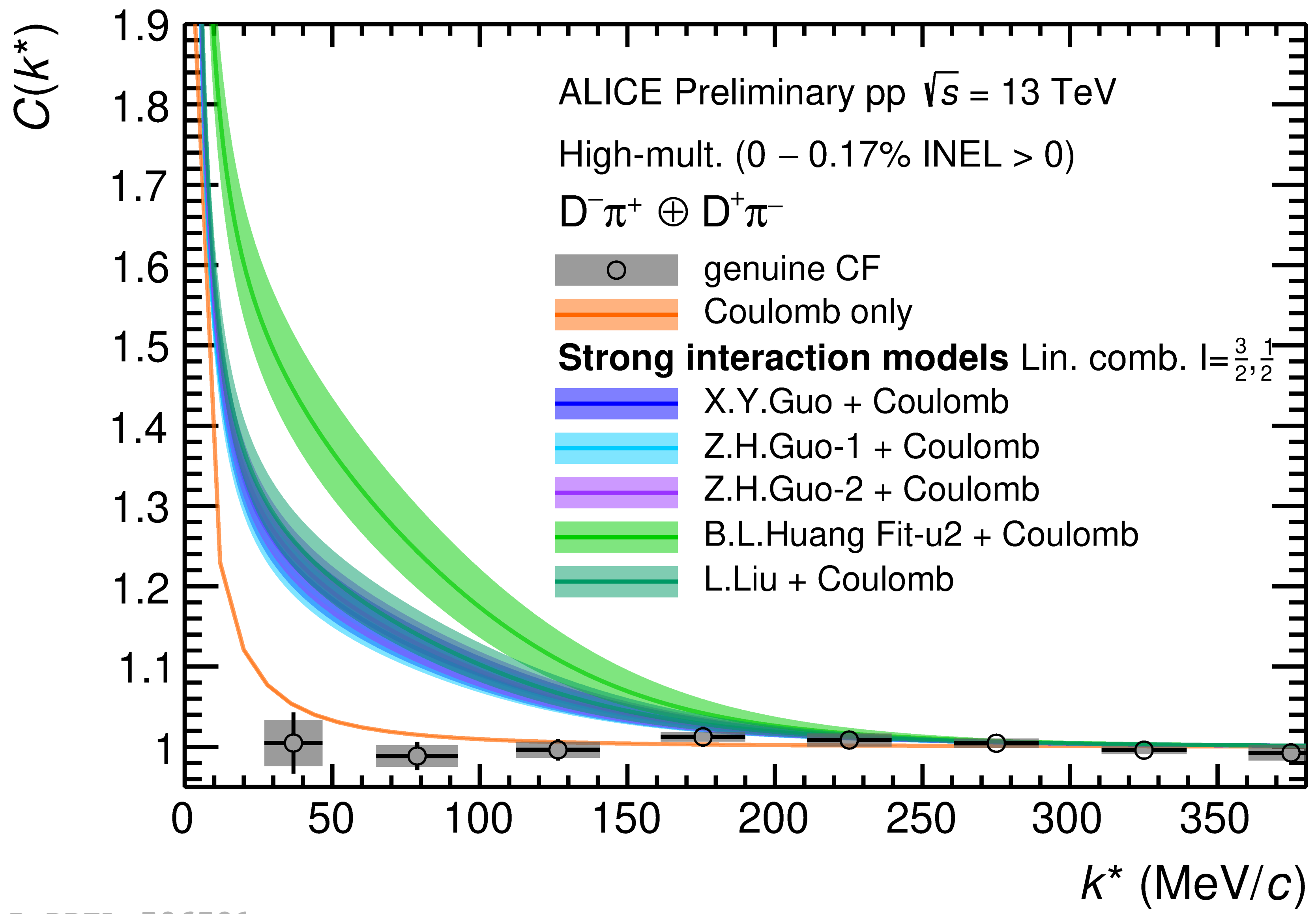
ALI-PUB-502166

J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107–117
J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90–139
Fontura et al, Phys. Rev. C 87 (2013) 025206
Yamaguchi et al, Phys. Rev. D84 (2011) 014032
ALICE, arXiv: 2201.05352

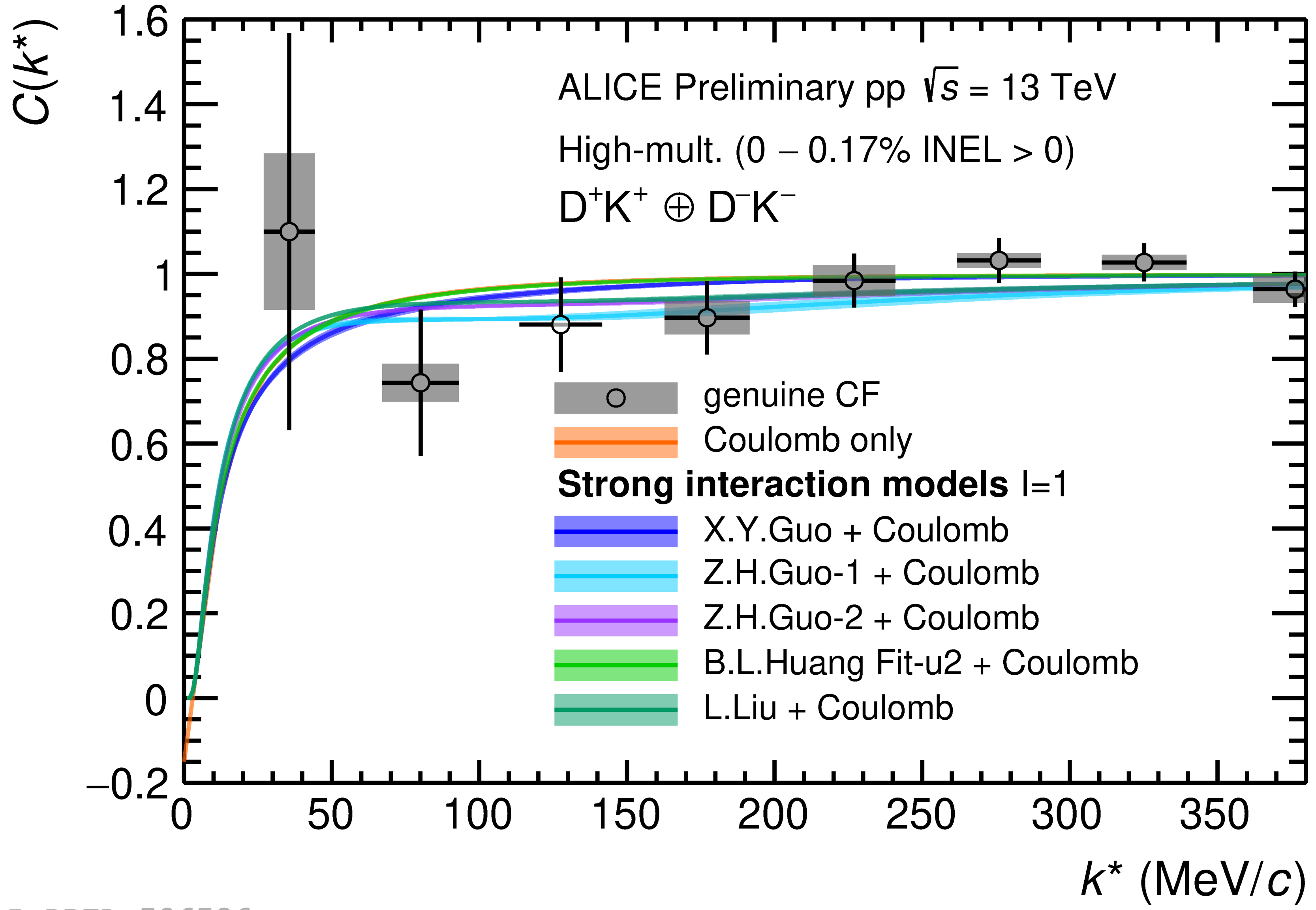
πD and KD interactions



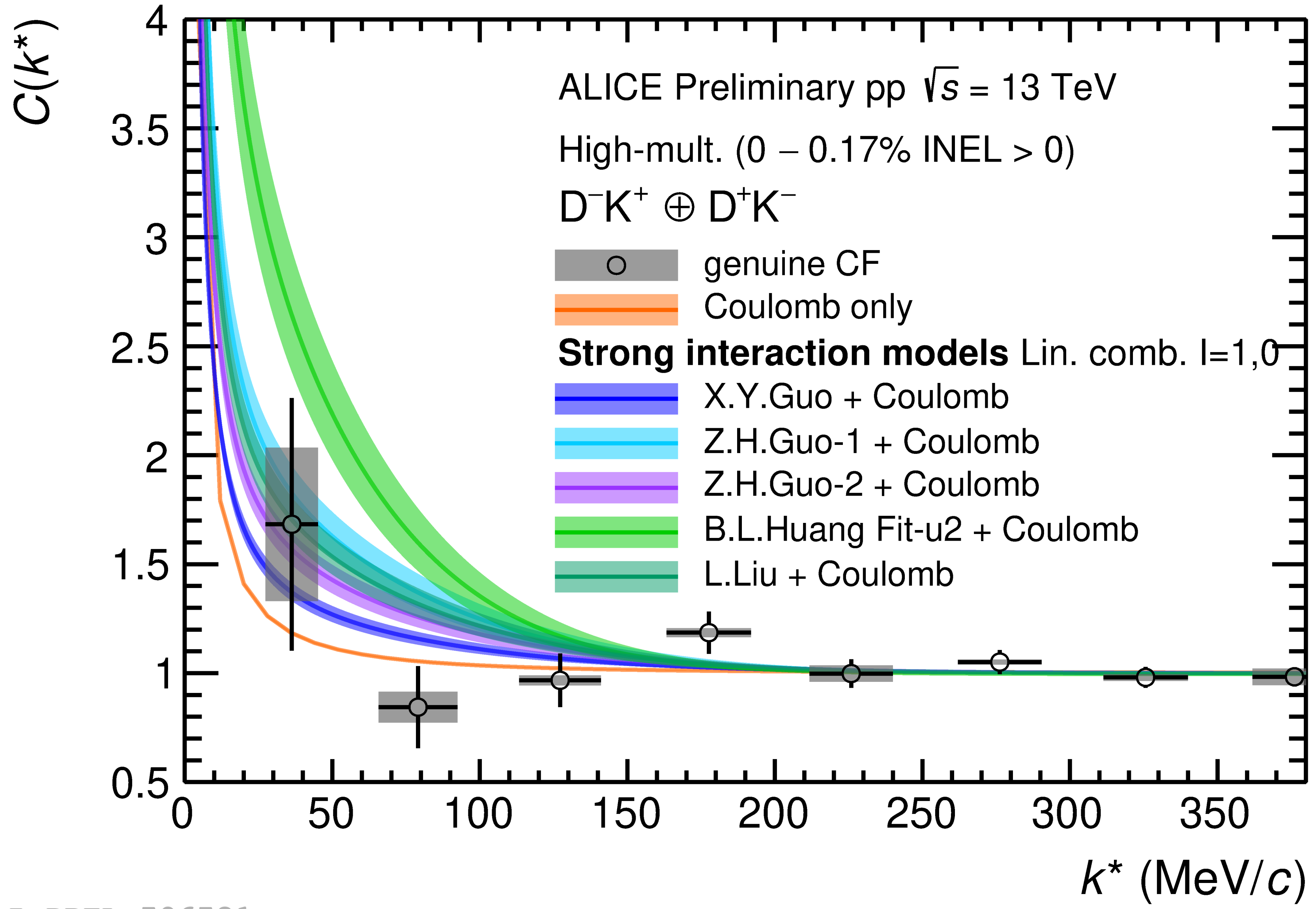
ALI-PREL-506596



ALI-PREL-506591



ALI-PREL-506586



ALI-PREL-506581

- Models agree with data in case of same-charge CF
- Models overestimate data in case of opposite-charge CF

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

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- Charm molecules?

System	I ($J^{P(C)}$)	Candidate
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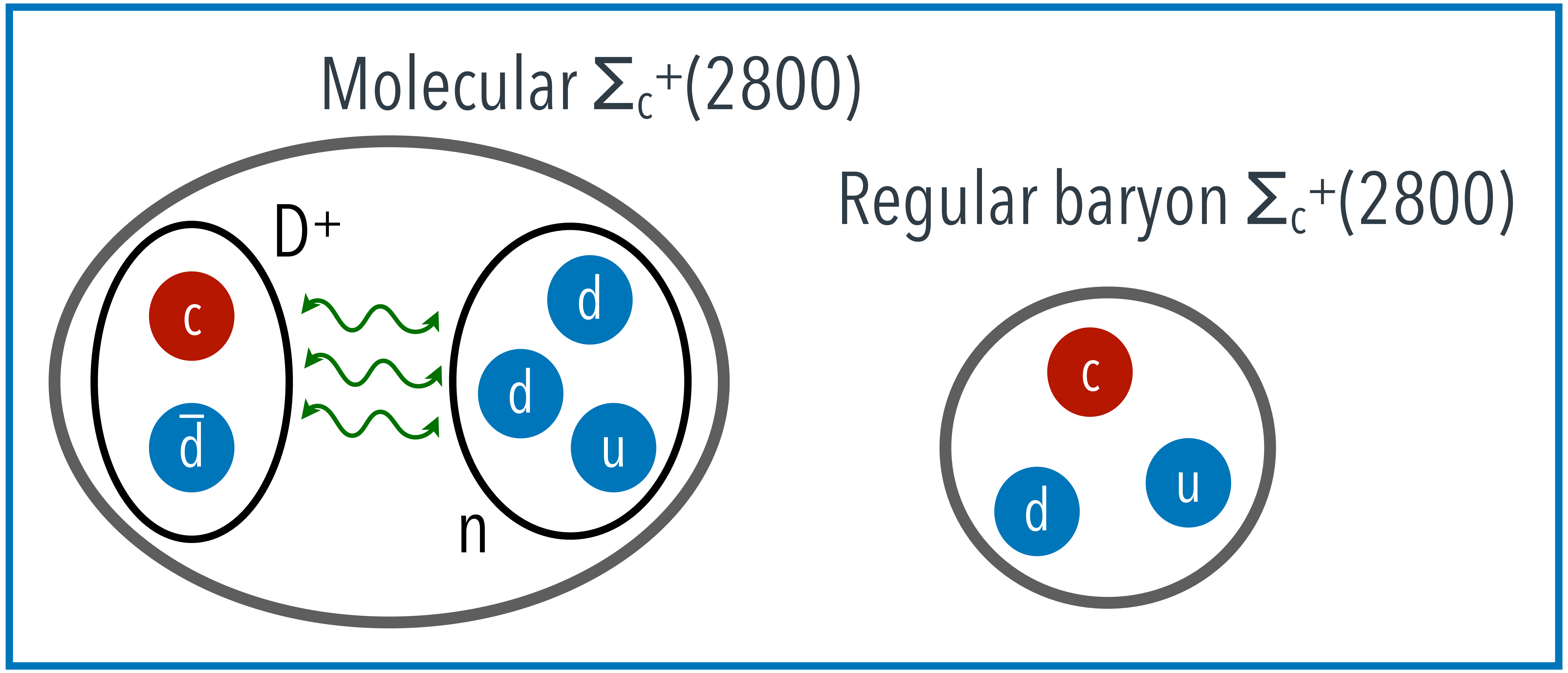
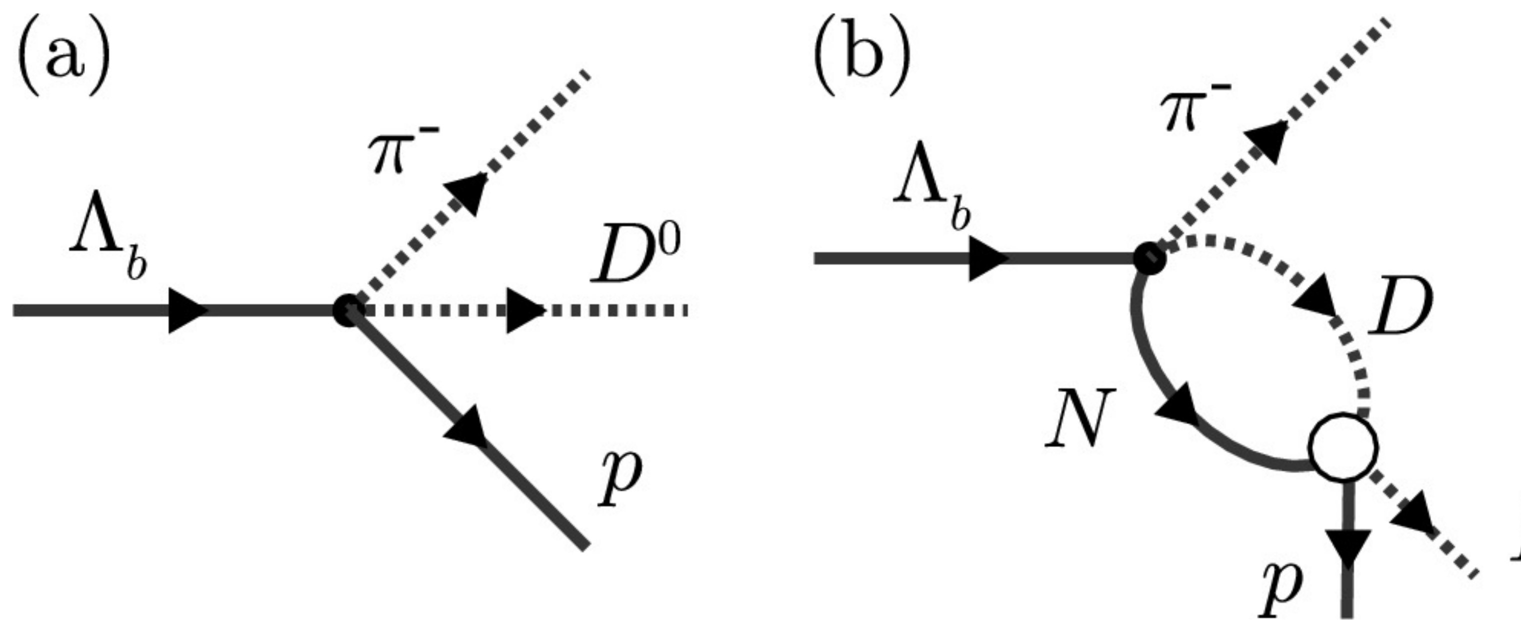
ND*	0 ($3/2^-$)	$\Lambda_c(2940)$
ND	0 ($1/2^-$)	$\Sigma_c(2800)$
$D^*\bar{D}$	0 (1^{++})	X(3872)
D^*D	0 (1^+)	T_{cc}
$D_1\bar{D}$	0 (1^{--})	Y(4260)
$D_1\bar{D}^*$	0 (1^{--})	Y(4360)
$\Sigma_c\bar{D}$	1/2 ($1/2^-$)	$P_c(4312)$
$\Sigma_c\bar{D}^*$	1/2 ($1/2^-$)	$P_c(4457)$
$\Sigma_c\bar{D}^*$	1/2 ($3/2^-$)	$P_c(4440)$

Fang-Zheng Peng et al, Phys. Rev. D 105, 034028 (2022)

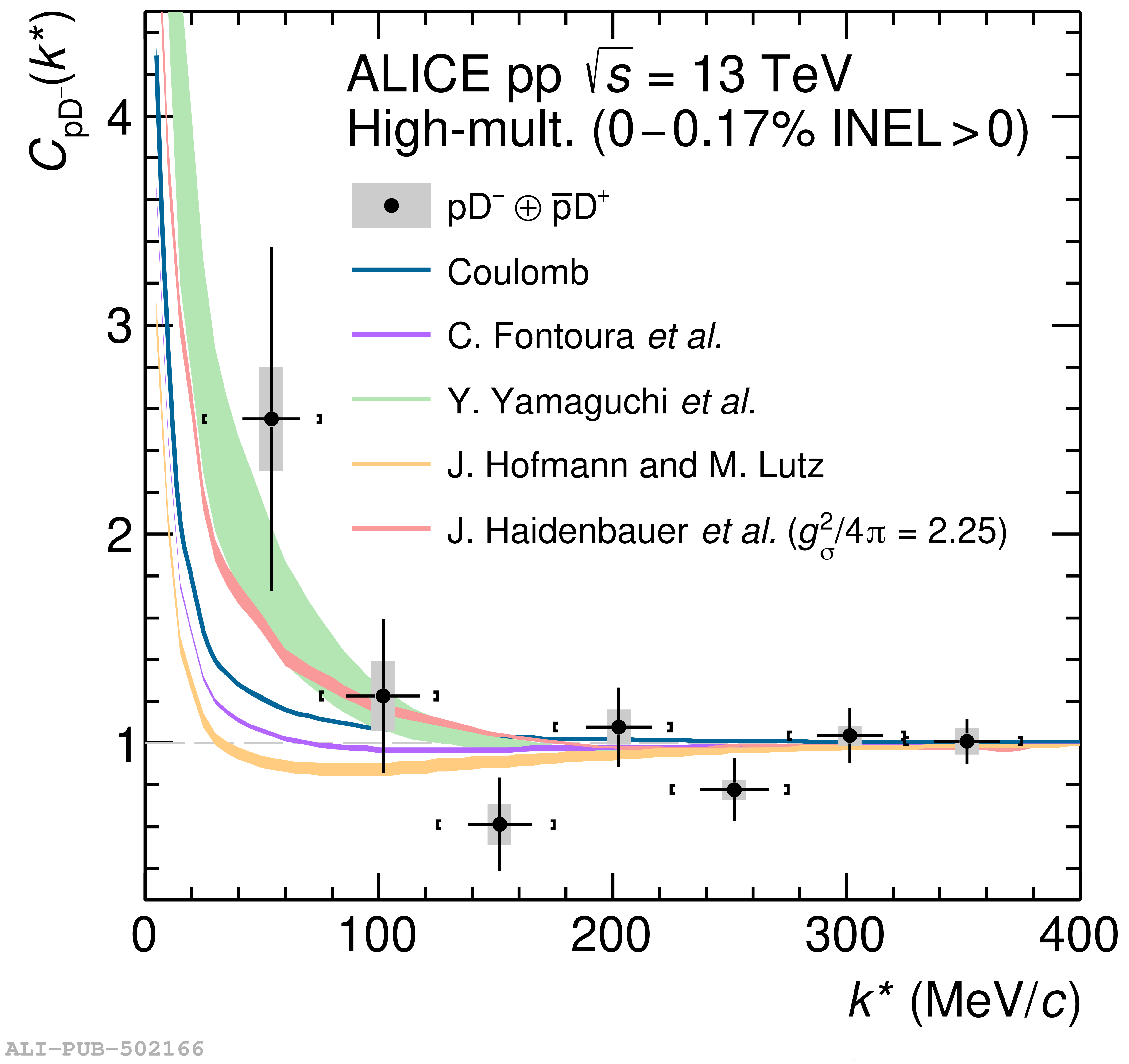


- Proposed as molecular state in J. Haidenbauer et al, Eur. Phys. J. A 47, 18 (2011)
  S. Sakai et al, Phys. Lett. B 808 (2020) 135623



- Molecular states also relevant to explain some beauty-hadron decays

Model	f_0 (I=0) [fm]	f_0 (I=1) [fm]
Haidenbauer $g_\sigma^2/4\pi = 1$ Meson-exchange model	0,14	–0,28
Haidenbauer $g_\sigma^2/4\pi = 2.25$ Meson-exchange model	0,67	0,04
Hofmann and Lutz SU(4) contact interaction	–0,16	–0,26
Yamaguchi meson-exchange on HQ symmetry	–4,38	–0,07
Fontoura Chiral-quark model	0,16	–0,25



J. Haidenbauer et al, Eur. Phys. J. A33 (2007) 107–117
J. Hofmann and M. Lutz, Nucl. Phys. A 763 (2005) 90–139
Fontura et al, Phys. Rev. C 87 (2013) 025206
Yamaguchi et al, Phys. Rev. D84 (2011) 014032

ALICE, arXiv: 2201.05352

πD and KD interactions - scattering lengths in models

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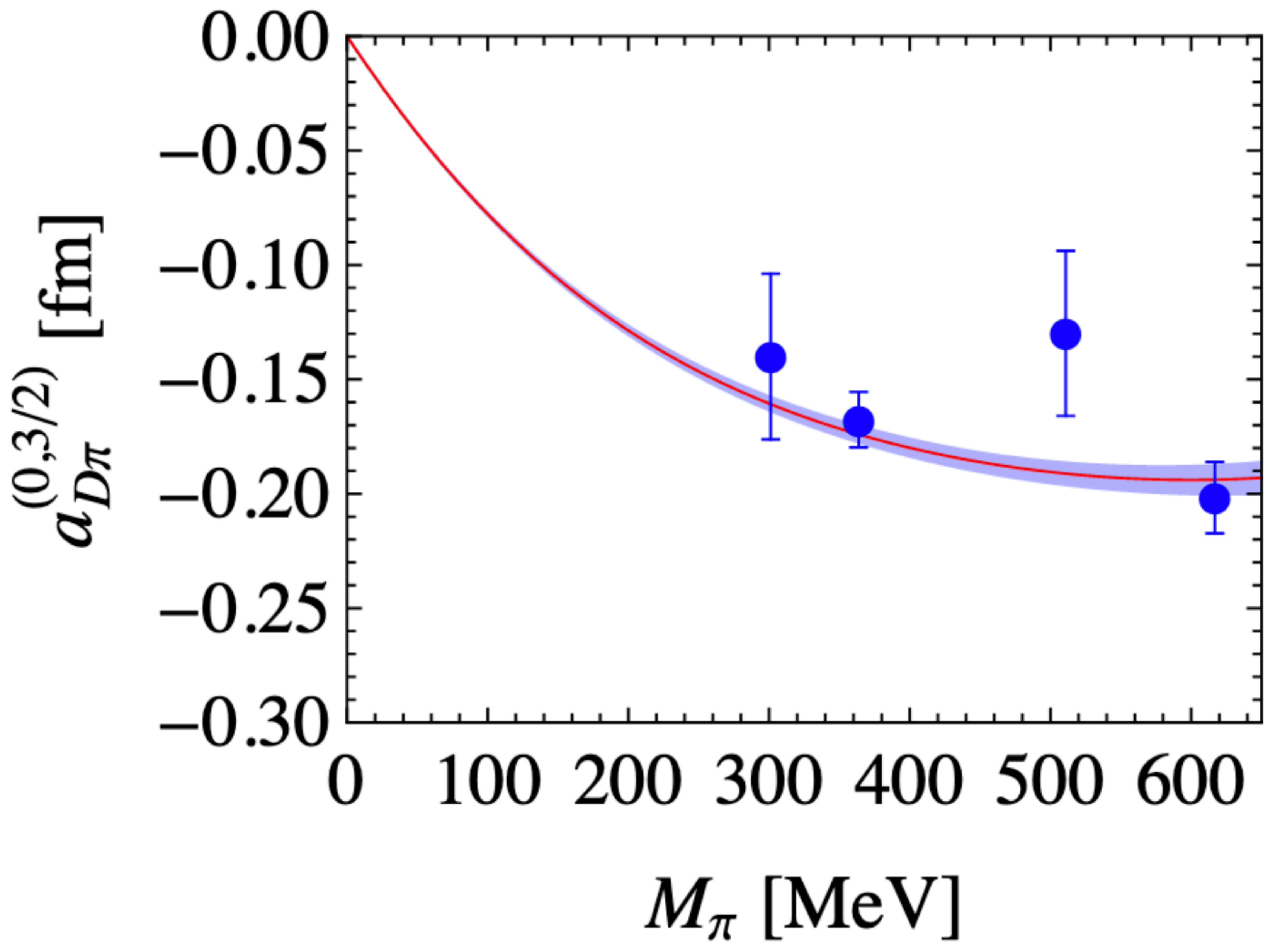
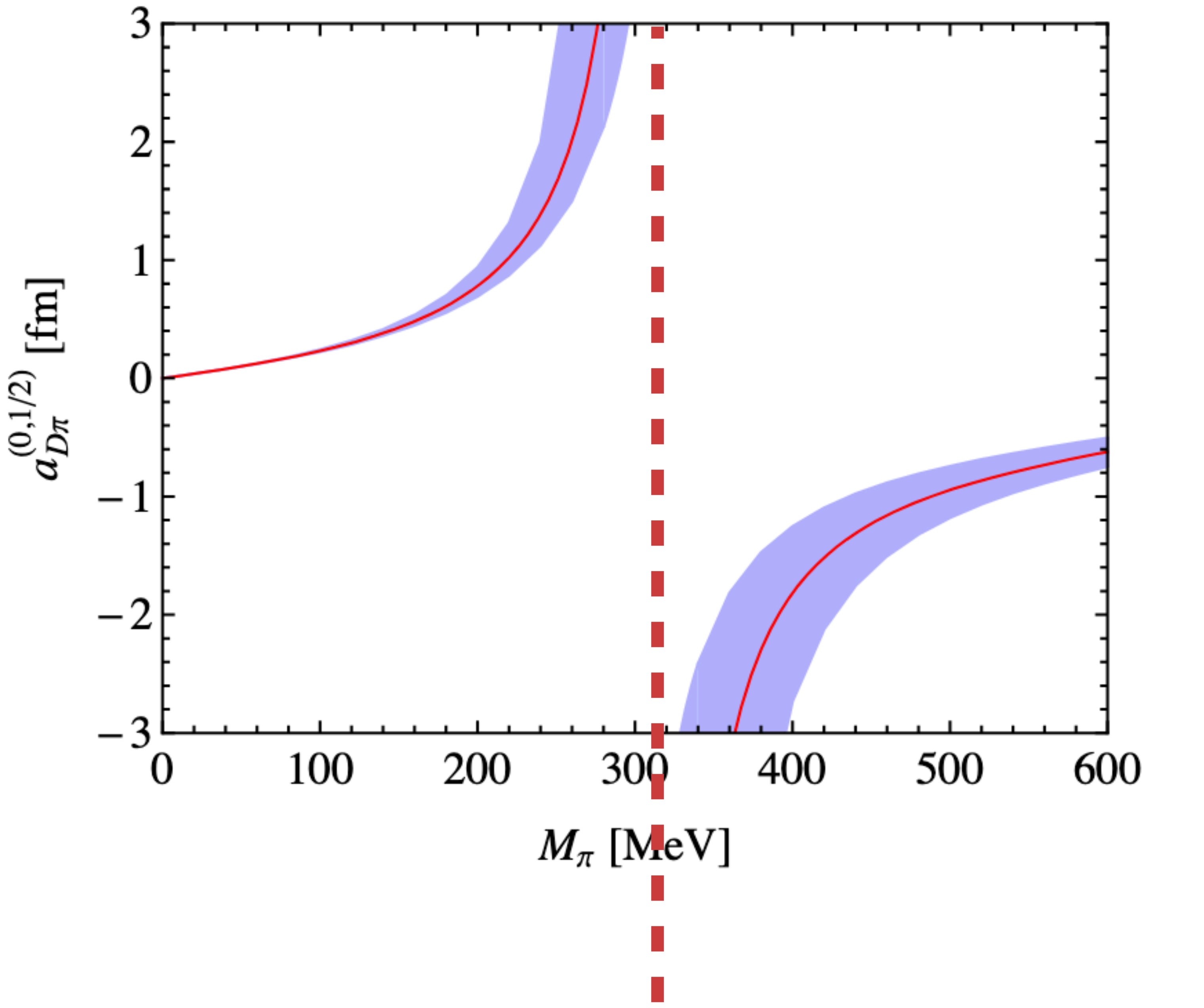
Channel	L. Liu	X.-Y. Guo	Z.-H. Guo-1	Z.-H. Guo-2	B.-L. Huang
Dπ(I=3/2) [fm]	−0,10	−0,11	−0,101	−0,099	−0,06
Dπ(I=1/2) [fm]	0,37	0,33	0,31	0,34	0,61
DK(I=1) [fm]	0,07+i0,17	−0,05	0,06+i0,30	0,05+i0,17	−0,01
D$\bar{K}$(I=0) [fm]	0,84	0,46	0,96	0,68	1,81
D$\bar{K}$(I=1) [fm]	−0,20	−0,22	−0,18	−0,19	−0,24

L. Liu et al, Phys. Rev. D87 (2013) 014508
X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510
B.-L. Huang et al, Phys. Rev. D 105 (2022) 036016
Z.-H. Guo et al Eur. Phys. J. C 79 (2019) 13

- Predictions of scattering lengths derived from lattice QCD calculations
  - ➡ Typically very small compared to other interactions (light-light ~ 7-8 fm, light-strange ~ 1.5 fm)
  - ➡ No constraints from data
  - ➡ For pions I=3/2 channel more constrained than I=1/2 channel



X.-Y. Guo et al, Phys. Rev. D 98 (2018) 014510



Bound-state pole formation

Lednický-Lyuboshits formula

$$C'(k^*) = A_C(k^*)\left\{ 2\left[\frac{1}{4}\left(\frac{|f_C(k^*)|}{r}\right)^2\left[1 - \frac{d_0}{2\sqrt{\pi}r} + \frac{1}{2}(A_C(k^*)-1)^2(1-e^{-4(rk^*)^2})\right] + \right.\right.$$

$$+\mathcal{R}(f_C(k^*))\frac{F_1(2k^*r)}{\sqrt{\pi}r} +$$

$$\left.\left. +\mathcal{I}(f_C(k^*))\left[\frac{F_2(2k^*r)}{2r} + (A_C(k^*)-1)k^*\cos(rk^*)e^{-(rk^*)^2}\right]\right] + 1 \right\}$$

Where

$$f_C(k^*) = \left[\frac{1}{a_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_C}h(k^* a_C) - ik^* A_C(k^*)\right]^{-1}$$

M. Gmitro, J. Kvasil, R. Lednicky, and V.L. Lyuboshits, Czech. J. Phys. B (1986) 36:1281

KD interaction: fit with Lednický-Lyuboshits formula

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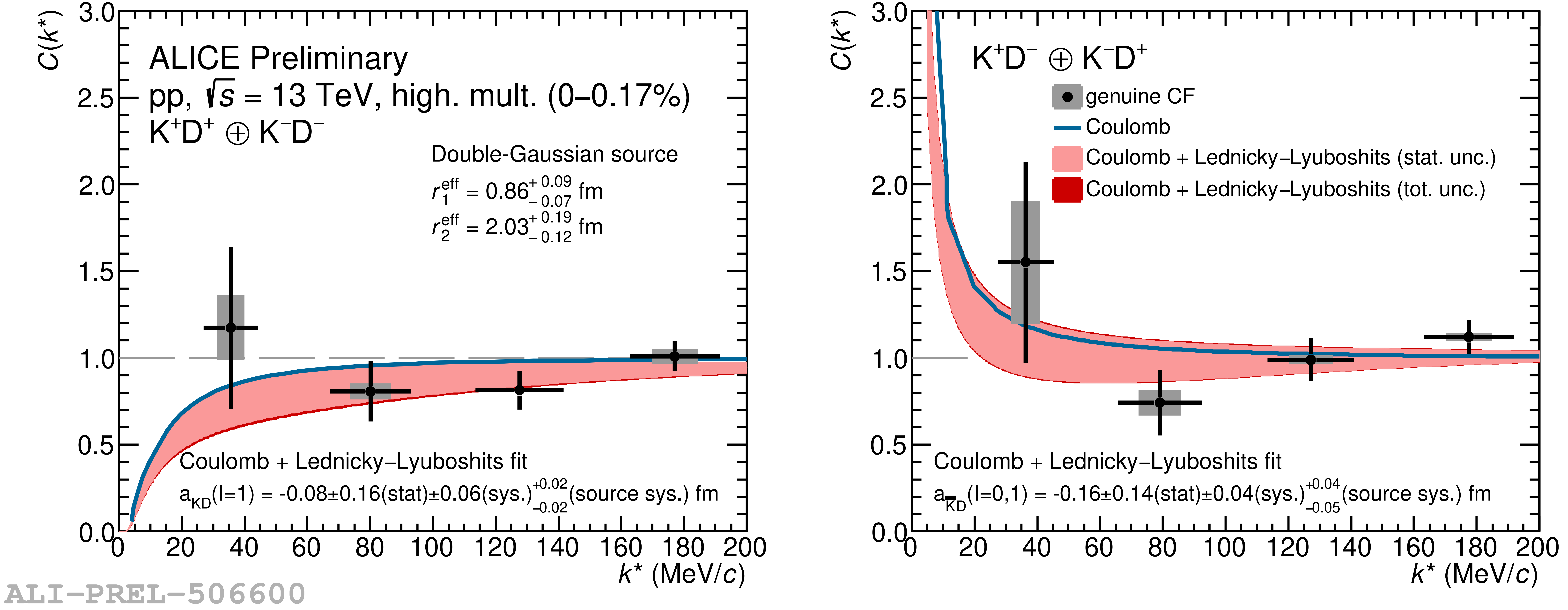
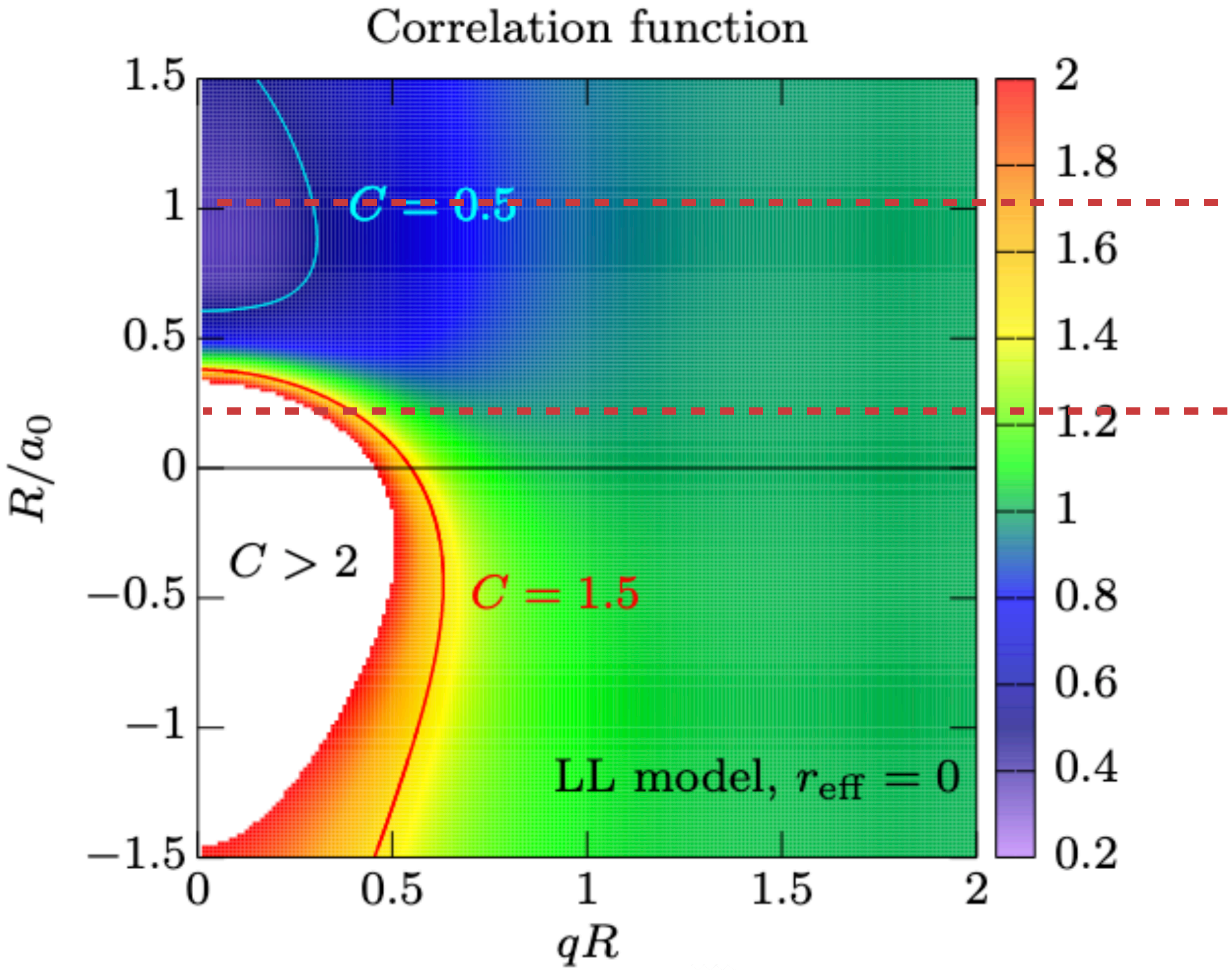
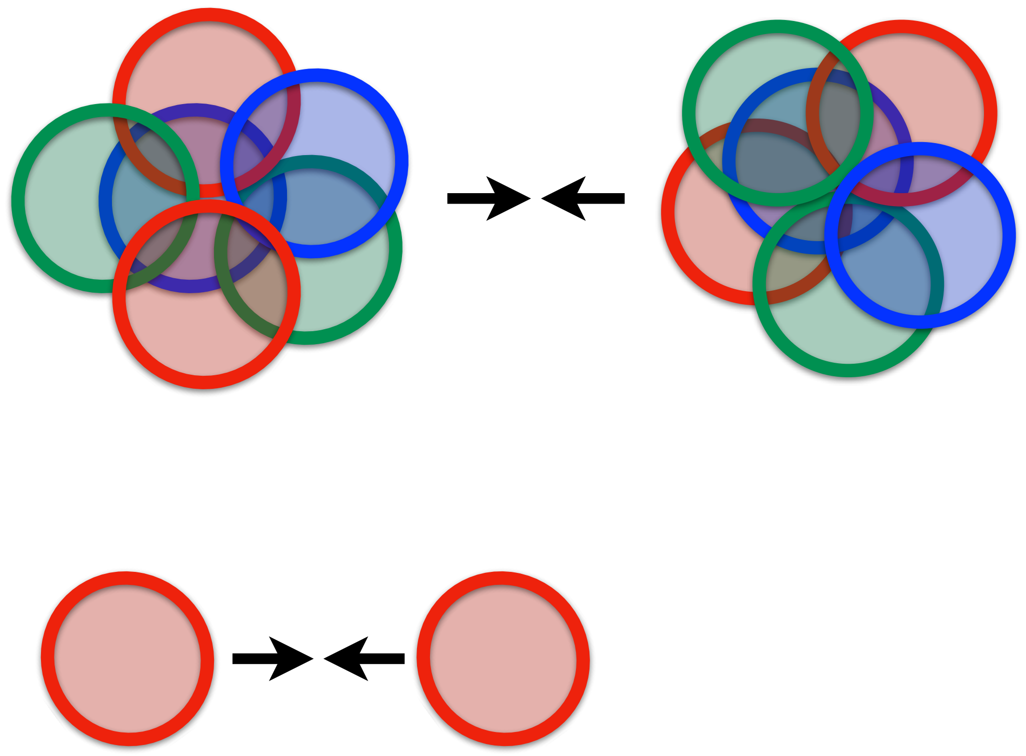


- K^+D^+
  - ➡ I=1 channel only
- K^+D^-
  - ➡ I=0 (50%)
  - ➡ I=1 (50%)

System-size dependence of CF in case of bound-state formation





- Interplay between system size and scattering length
  - ➡ size-dependent modification of the correlation function in presence of a bound state

Yuki Kamyia et al, arXiv:2108.0964

Charm quark production cross section and fragmentation fractions