Probing the quark–gluon plasma with heavy-flavour hadrons

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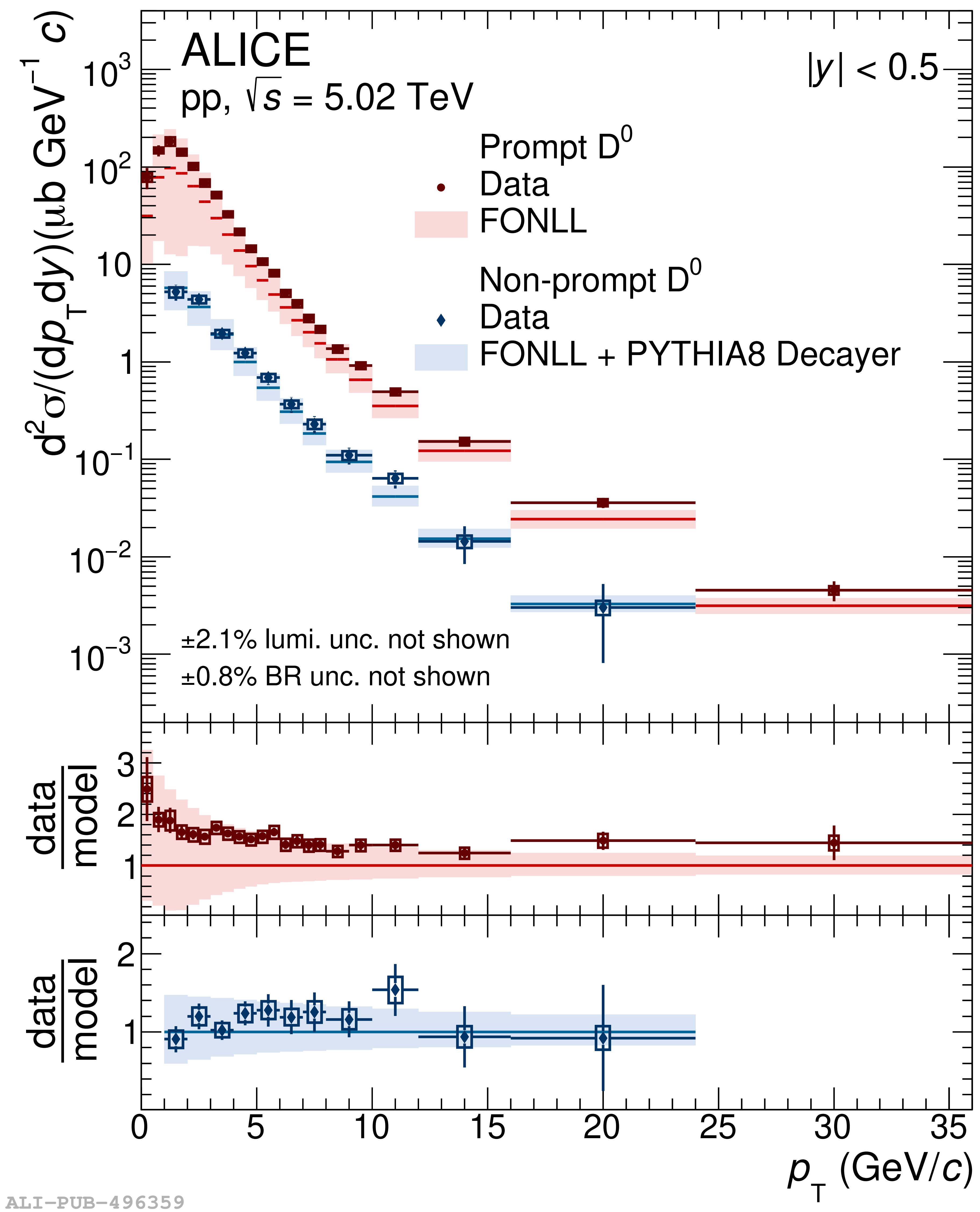
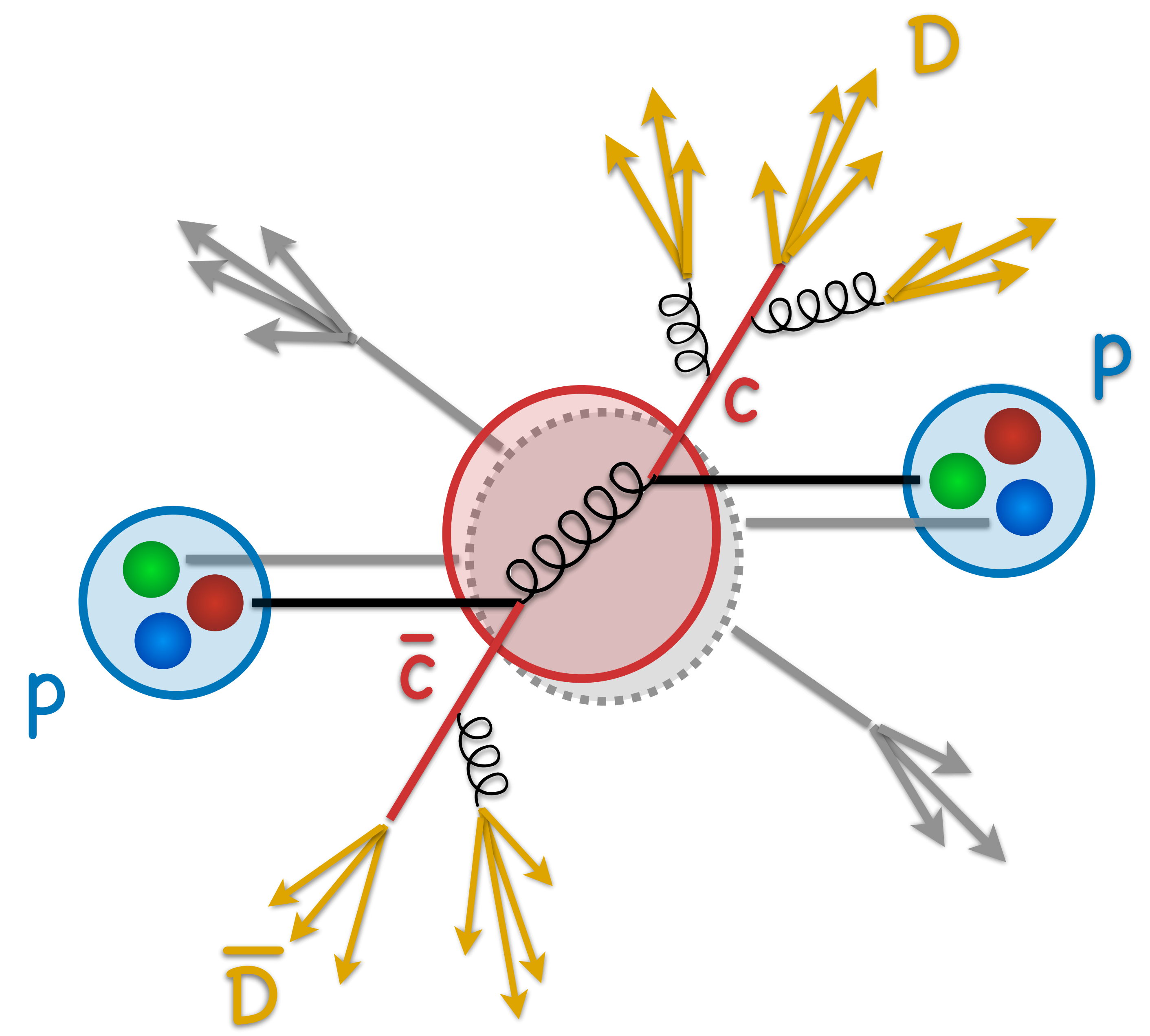
Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics
Wuhan | 19–24/10/2024

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



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

Parton distribution functions (non perturbative)

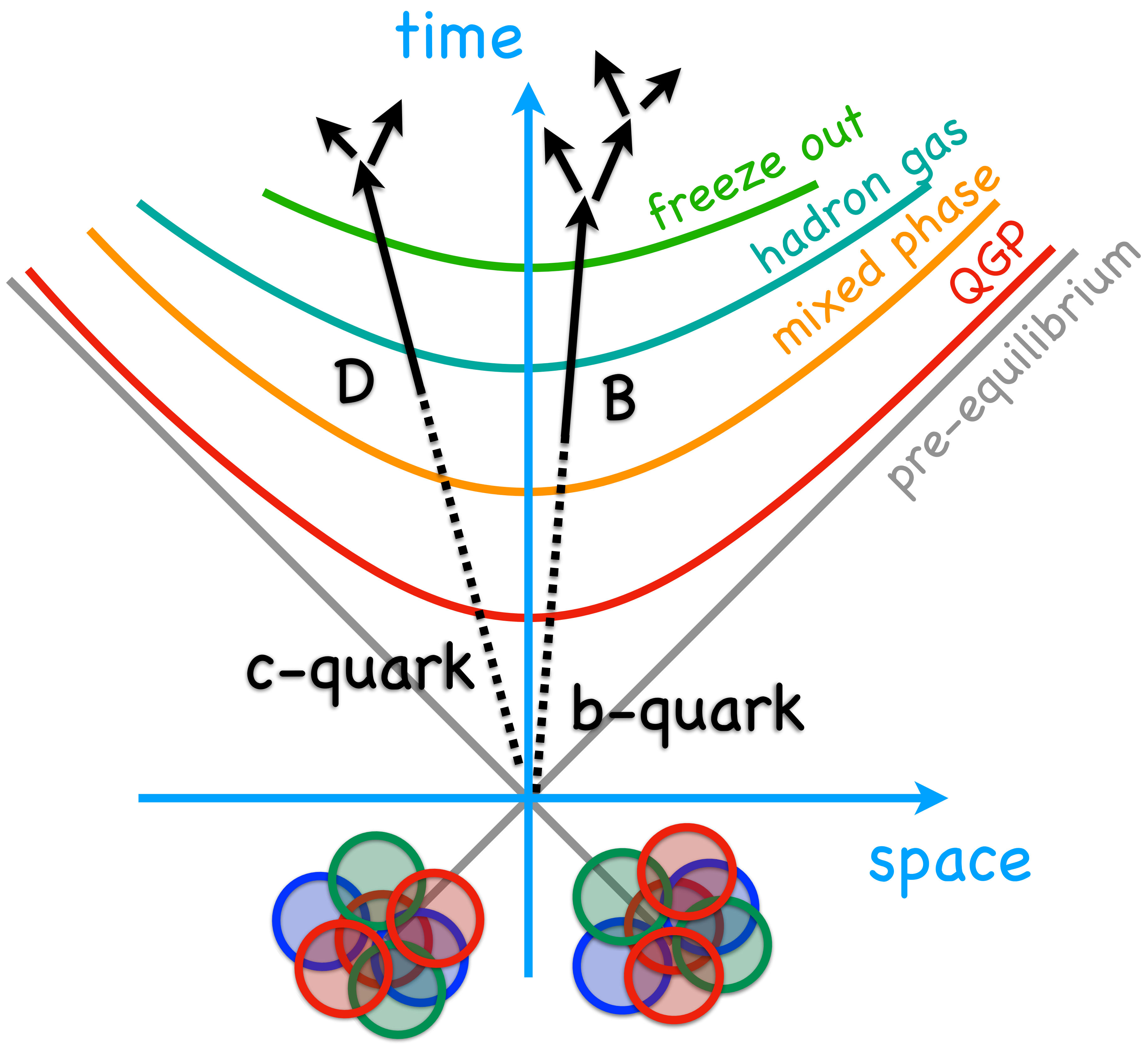
Partonic cross section (perturbative)

Fragmentation functions (non perturbative)

Heavy quarks in the quark–gluon plasma

- Heavy quarks: produced in shorter time scales than the quark–gluon plasma formation (QGP)
  - ➡ $\tau_{\mathrm{HF}} \lesssim \hbar/m \approx$ 0.05-0.1 fm/c depending on p_{T}
  - ➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) $\approx$ 0.3 fm/c

PRC 89 (2014) 034906



- Low-p_{T}: multiple elastic collisions with the medium constituents
  - ➡ Diffusion motion and possible (partial) thermalisation in the medium
- High-p_{T}: radiative energy loss (gluon emission)
  - ➡ Study properties of in-medium energy loss

- Momentum and angular distributions of HF hadrons
  - ➡ Study interactions of heavy-quarks with the medium
- Hadrochemistry: baryons and strange hadrons
  - ➡ Study hadronisation from the medium
- Vector meson polarisation:
  - ➡ Study initial strong magnetic fields
- Strong interaction of heavy-flavour hadrons with light hadrons:
  - ➡ Study the impact of hadronic phase on heavy-ion observables

- Small systems: heavy-ion like effects
  - ➡ Flow, baryons-to-meson ratio modification

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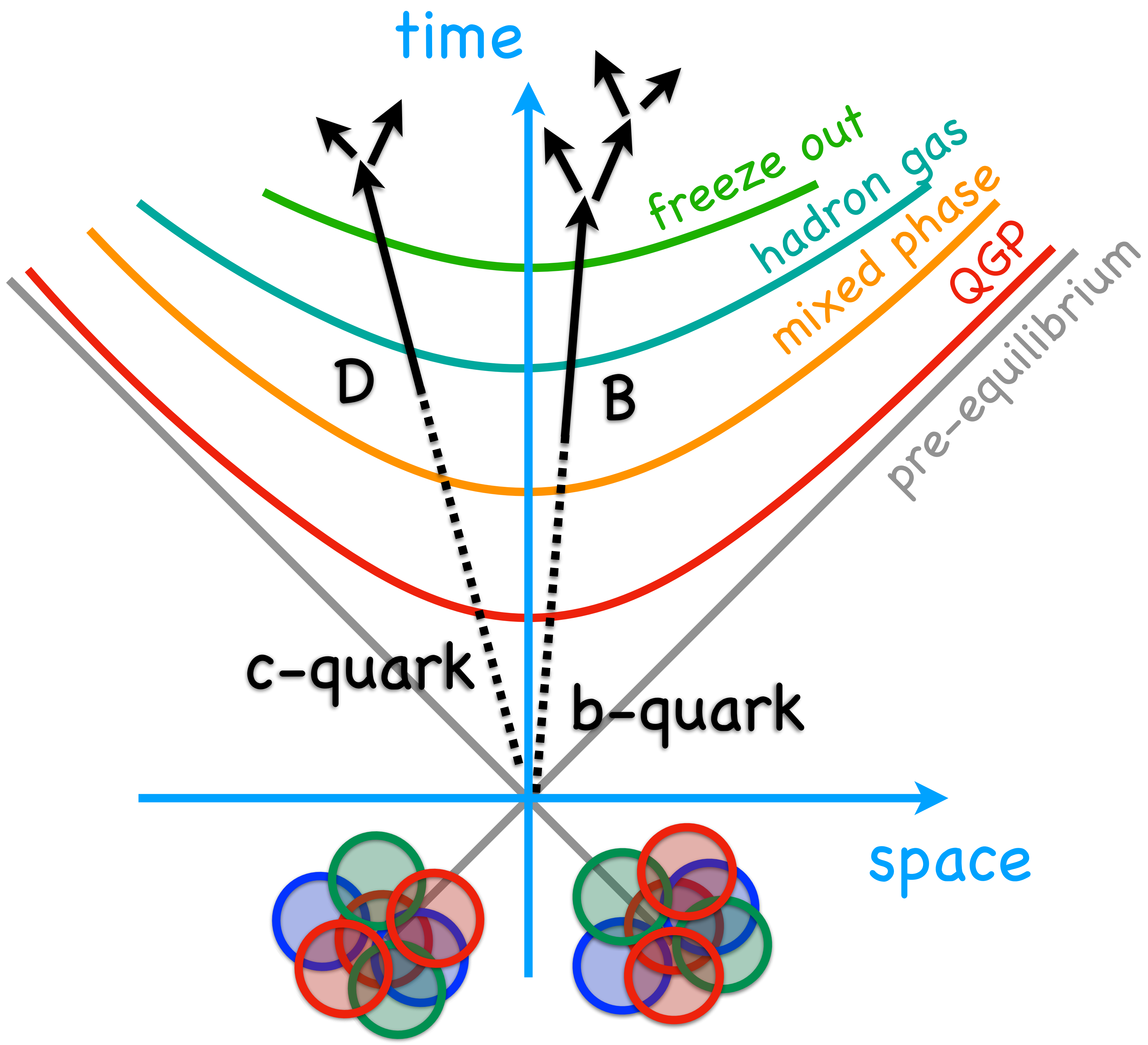

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- Models based on the heavy-quark transport on a hydrodynamically expanding QGP
  - ➡ Typical momentum transfers in scatterings between heavy quarks and medium constituents (heat bath) are small
  - ➡ Heavy quarks undergo soft and incoherent collisions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

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

- 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

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

→ Related to the thermalisation time of the heavy quark quark

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

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

The high-p_T regime

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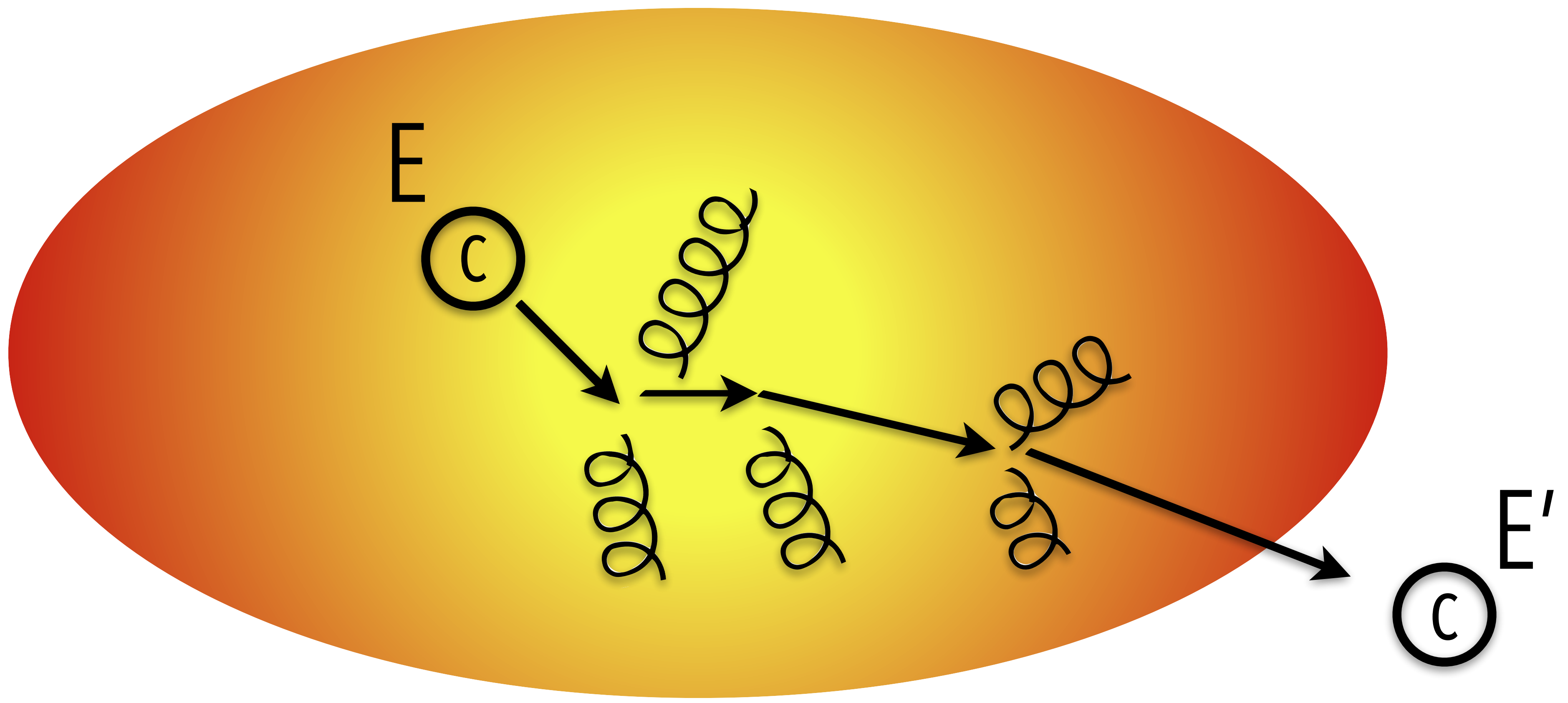
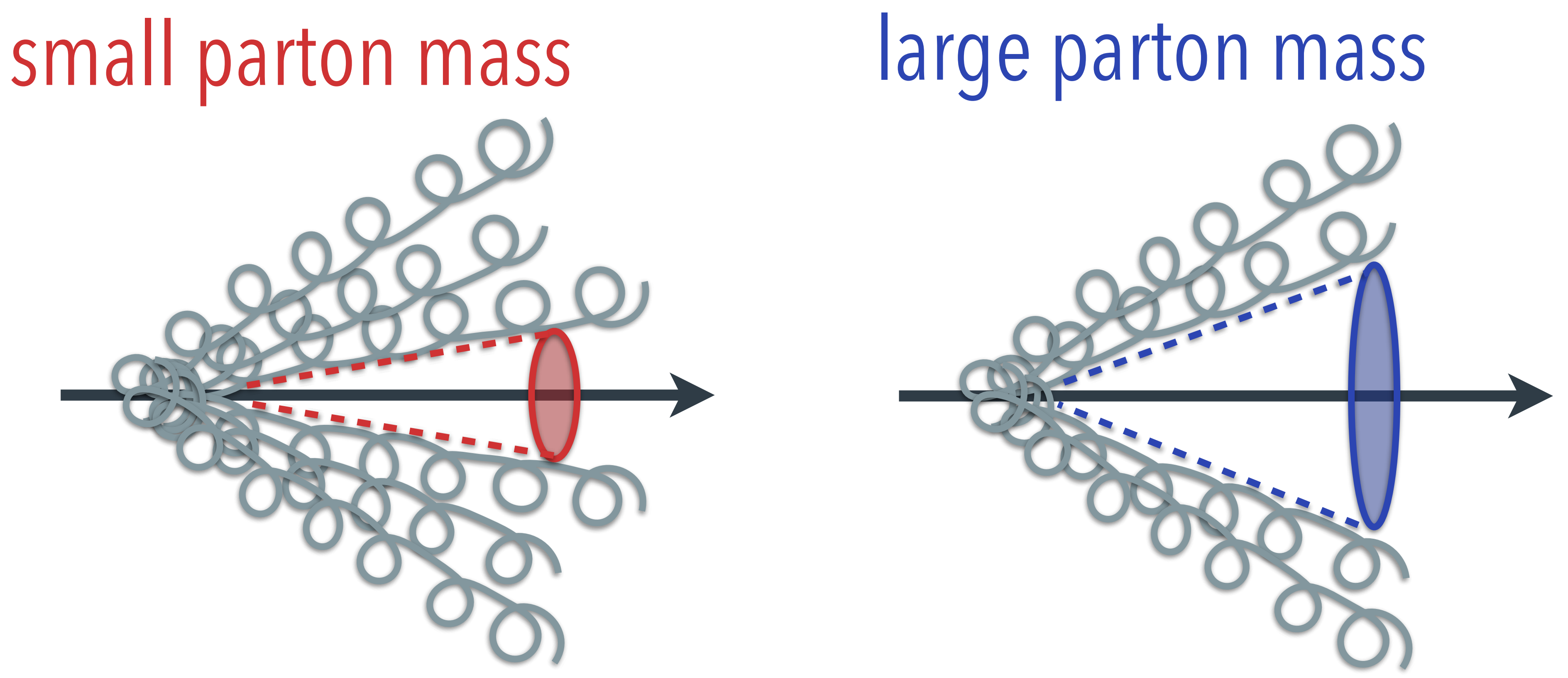
- Dominant effect: energy loss of charm and beauty quarks in the medium
- Goal: study the colour-charge and quark-mass dependence of the in-medium energy loss





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

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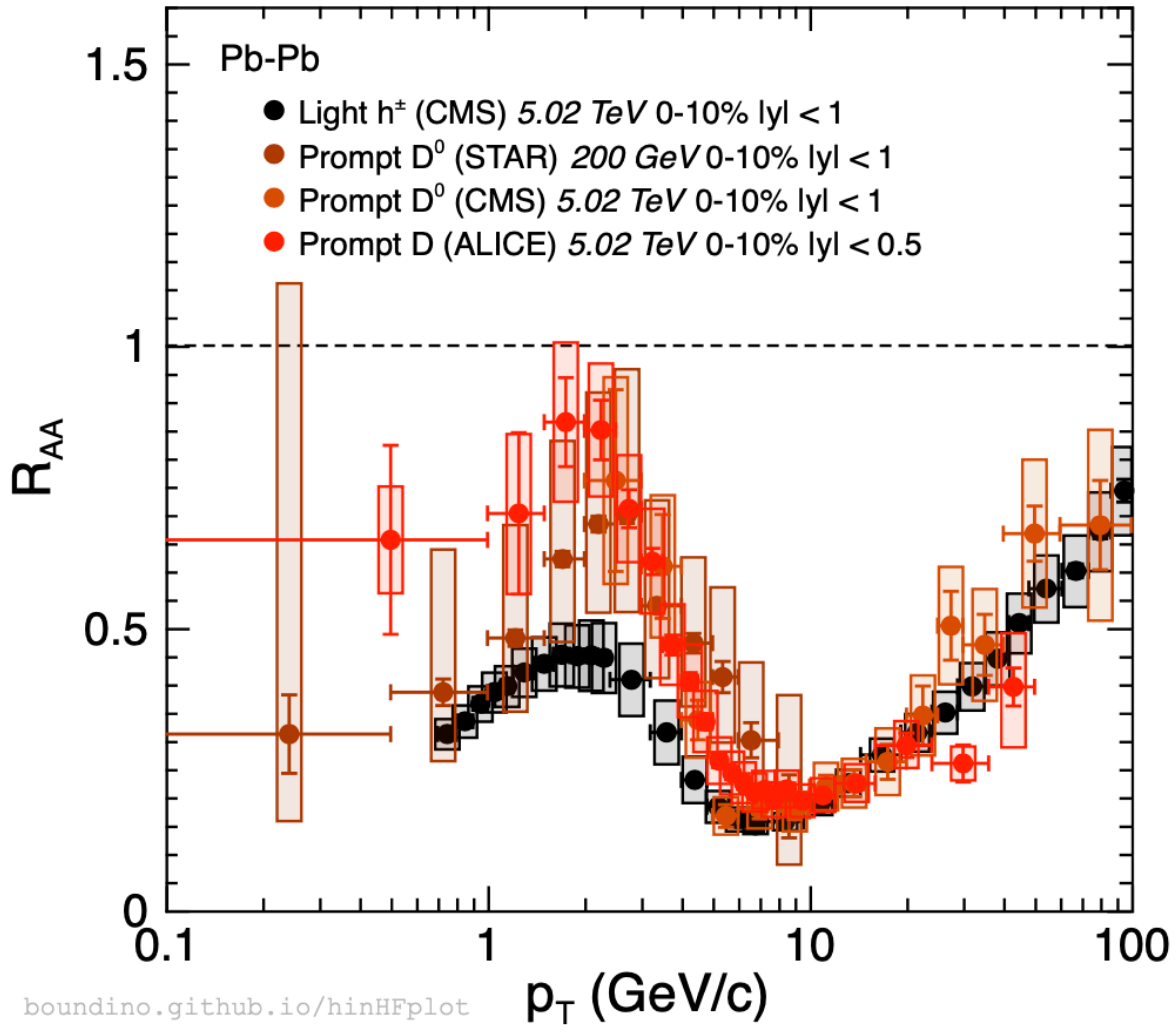
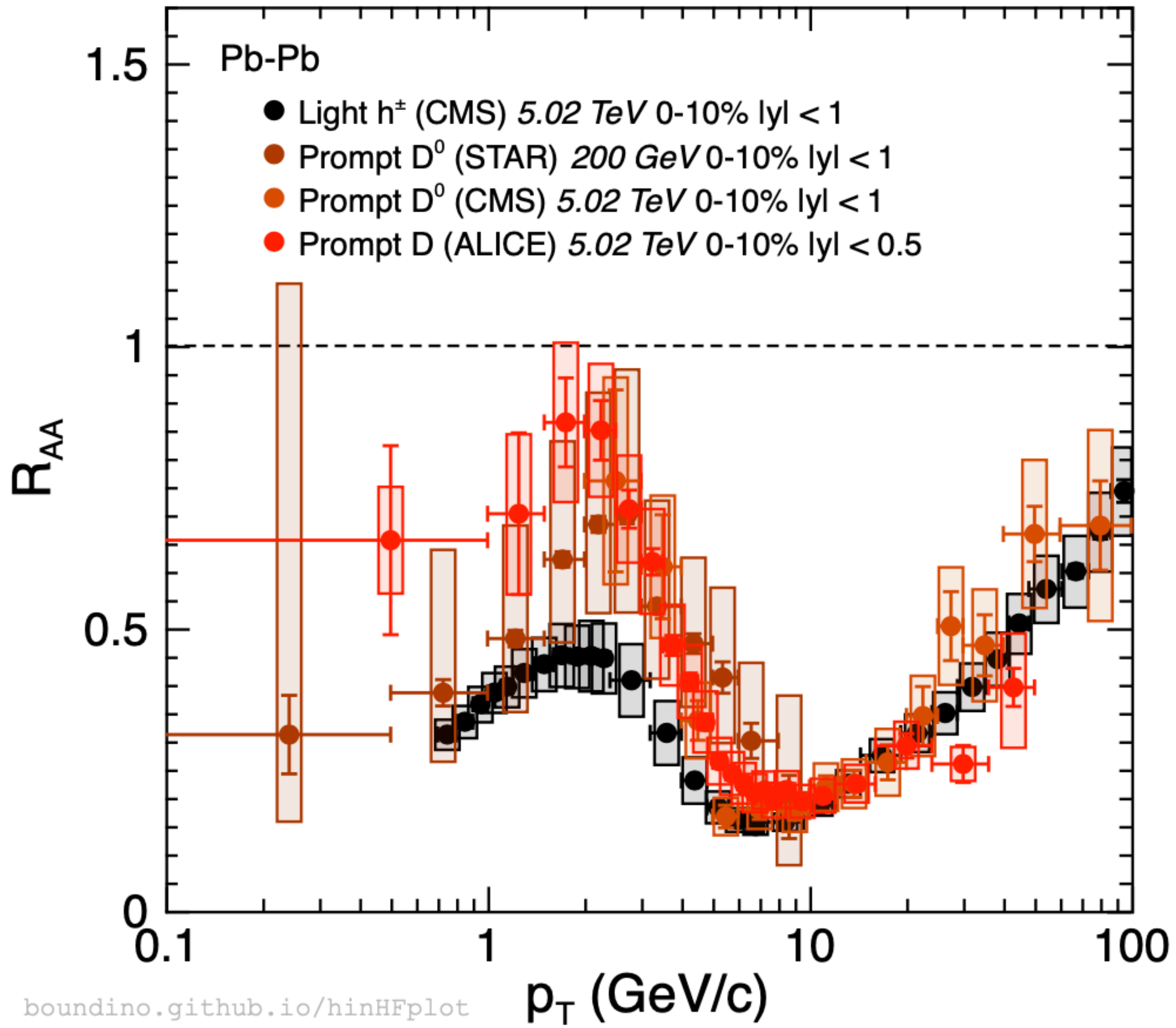


- $p_{\mathrm{T}} < 6\text{–}8$ GeV/c: $R_{\mathrm{AA}}(\mathrm{D}) > R_{\mathrm{AA}}(\pi^{\pm})$
  - ➡ Nuclear PDFs
  - ➡ Collisional energy loss
  - ➡ Radial flow
  - ➡ Hadronisation via recombination
- $p_{\mathrm{T}} > 8$ GeV/c: $R_{\mathrm{AA}}(\mathrm{D}) \approx R_{\mathrm{AA}}(\pi^{\pm})$ ➡ Radiative energy loss

CMS, JHEP 04 (2017) 039
CMS, PLB 782 (2018) 474
ALICE, JHEP 01 (2022) 174
STAR, PRC 99 (2019) 034908

Measurements of charm-hadron nuclear modification factor



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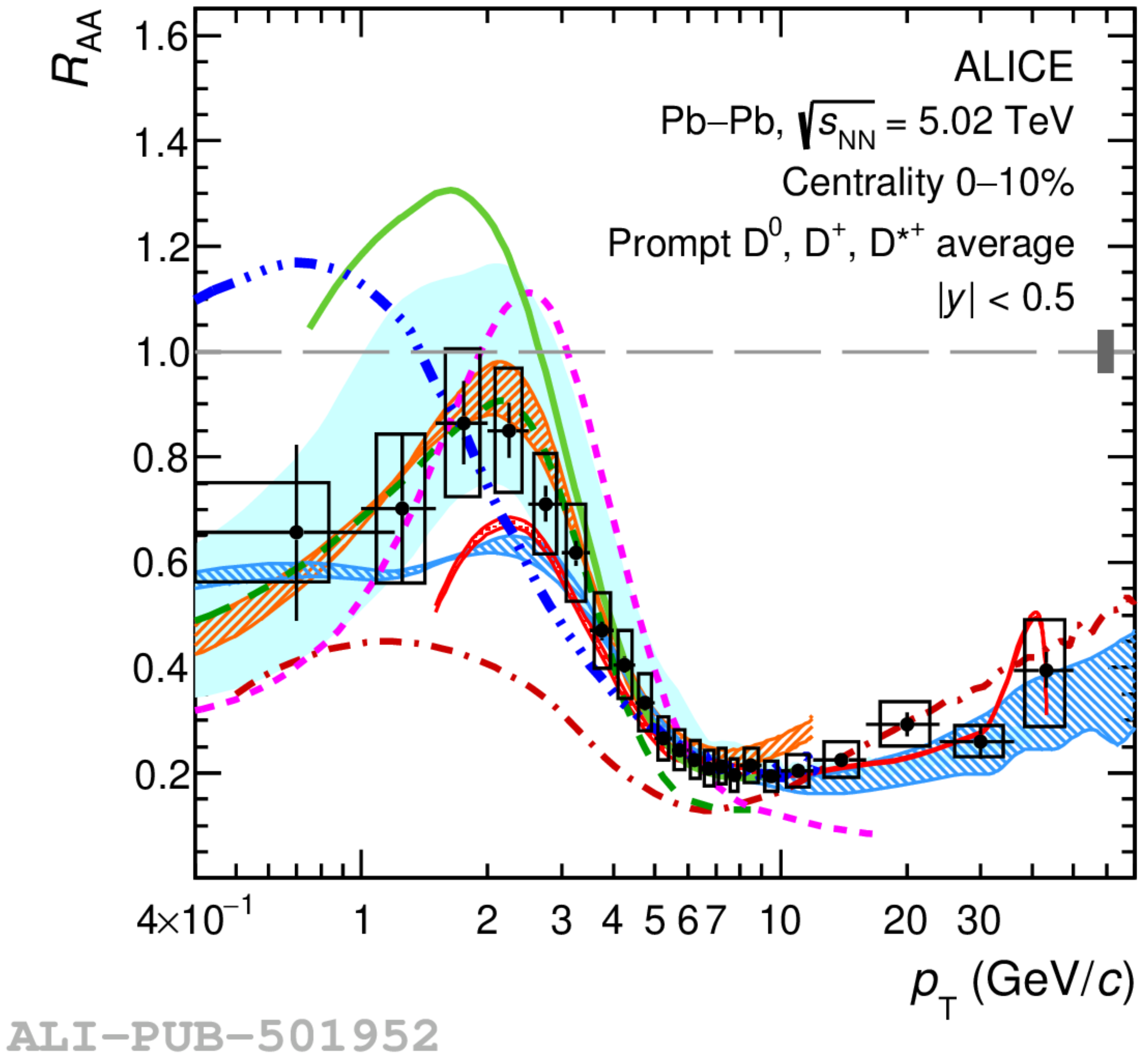
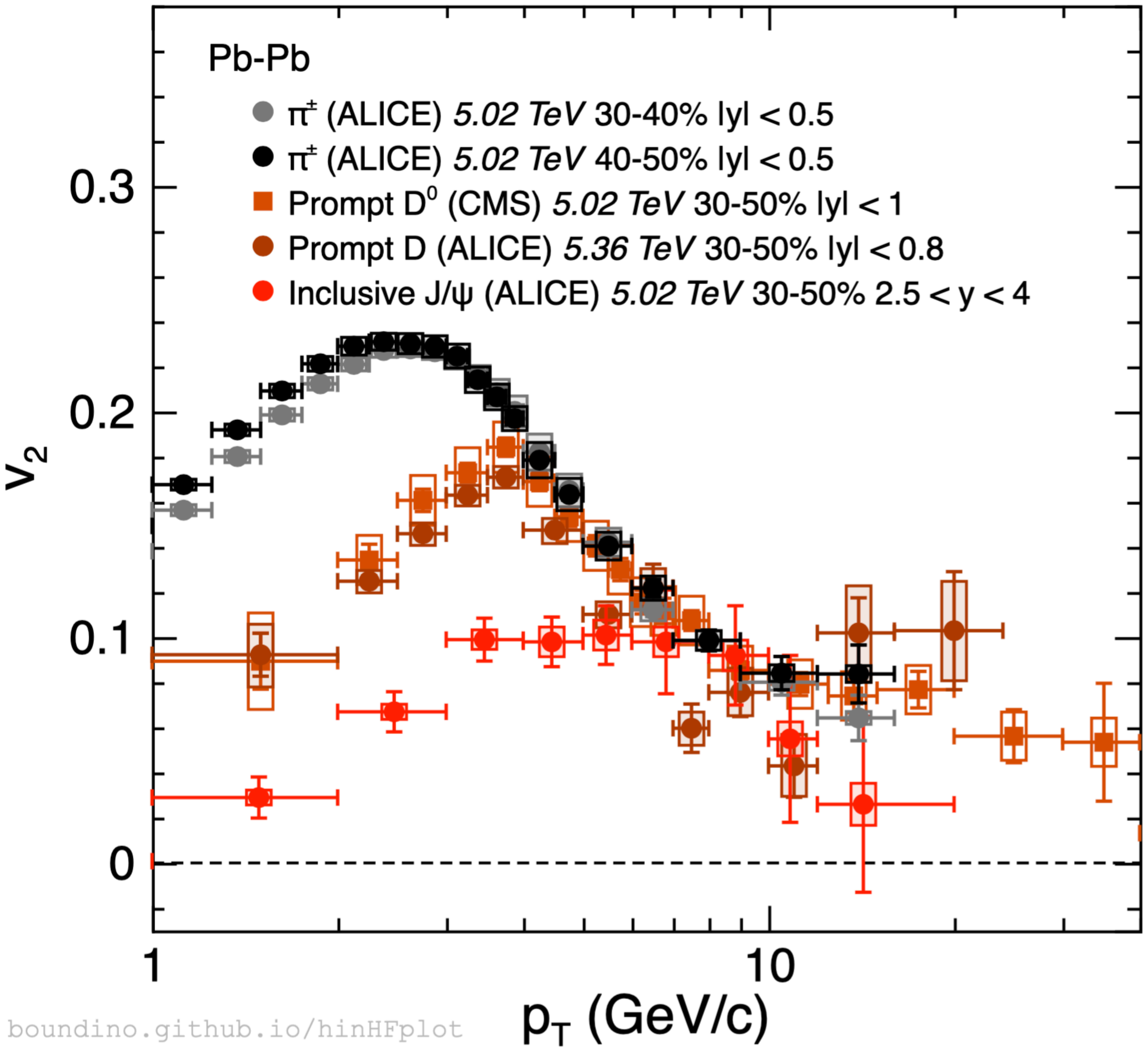


ALICE, JHEP 01 (2022) 174

Reasonably described by models implementing the heavy-quark transport in a hydrodynamically expanding QGP

CMS, JHEP 04 (2017) 039
CMS, PLB 782 (2018) 474
ALICE, JHEP 01 (2022) 174
STAR, PRC 99 (2019) 034908



ALICE. JHEP 09 (2018) 006
CMS, PLB 816 (2021) 136253
ALICE Preliminary
ALICE, JHEP 10 (2020) 141

- $p_T < 3$ GeV/c: $v_2(\pi^{\pm}) > v_2(\mathrm{D}) > v_2(\mathrm{J}/\psi)$
  - ➡ mass hierarchy due to hydrodynamic expansion indicates that the charm quark is likely to reach at least a partial thermalisation in the QGP
- $3 < p_T < 6$ GeV/c: $v_2(\pi^{\pm}) \approx v_2(\mathrm{D}) > v_2(\mathrm{J}/\psi)$
  - ➡ elliptic flow of D mesons similar to that of pions due to the hadronisation via recombination with light quarks from the medium
- $p_T > 6$ GeV/c: $v_2(\pi^{\pm}) \approx v_2(\mathrm{D}) \approx v_2(\mathrm{J}/\psi)$
  - ➡ elliptic flow originates from path-length dependent energy loss in the medium

More about J/ψ ⟶ elliptic flow in talk by X. Bai

Charm-hadron R_{AA} and flow coefficients vs models

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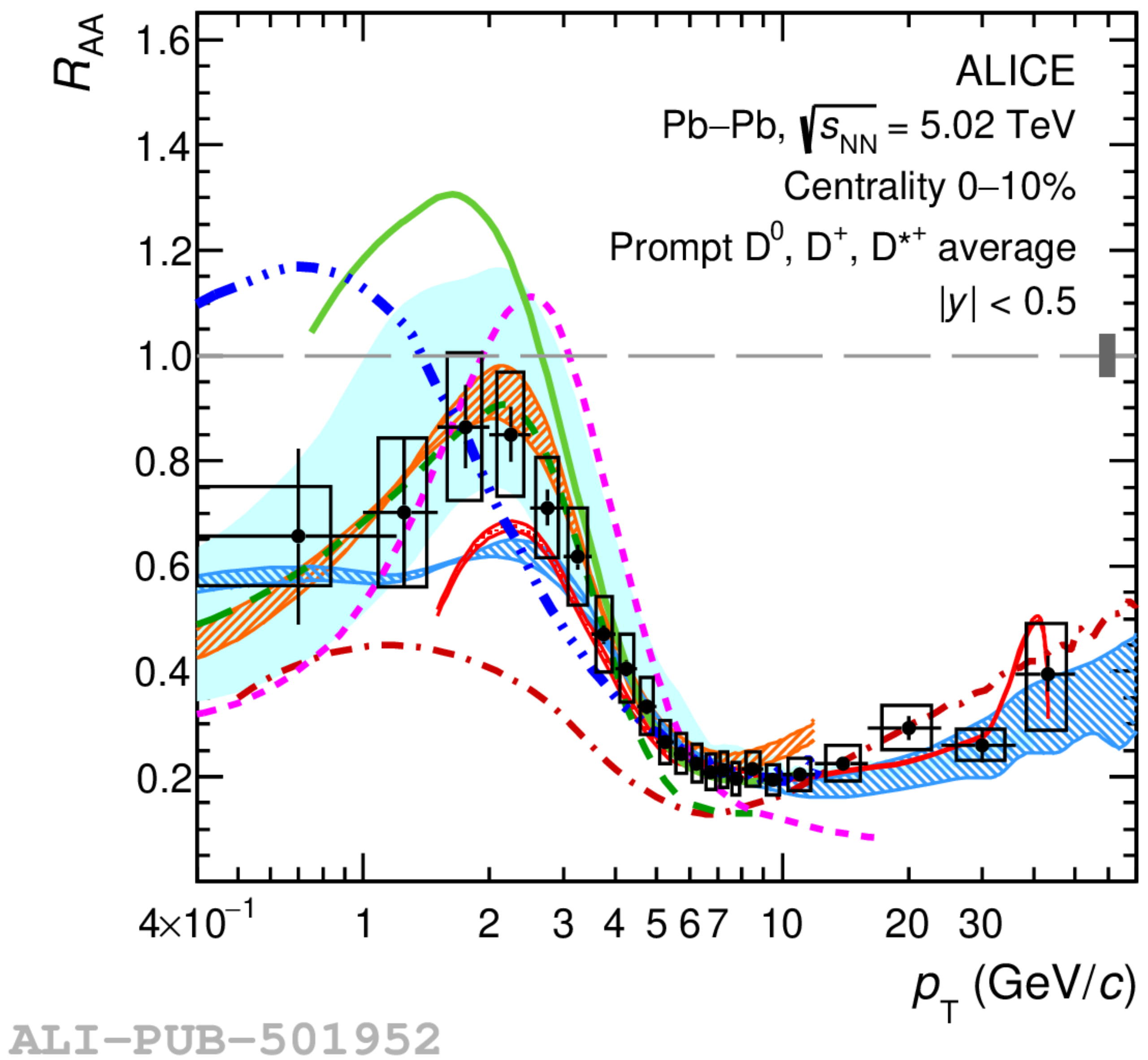
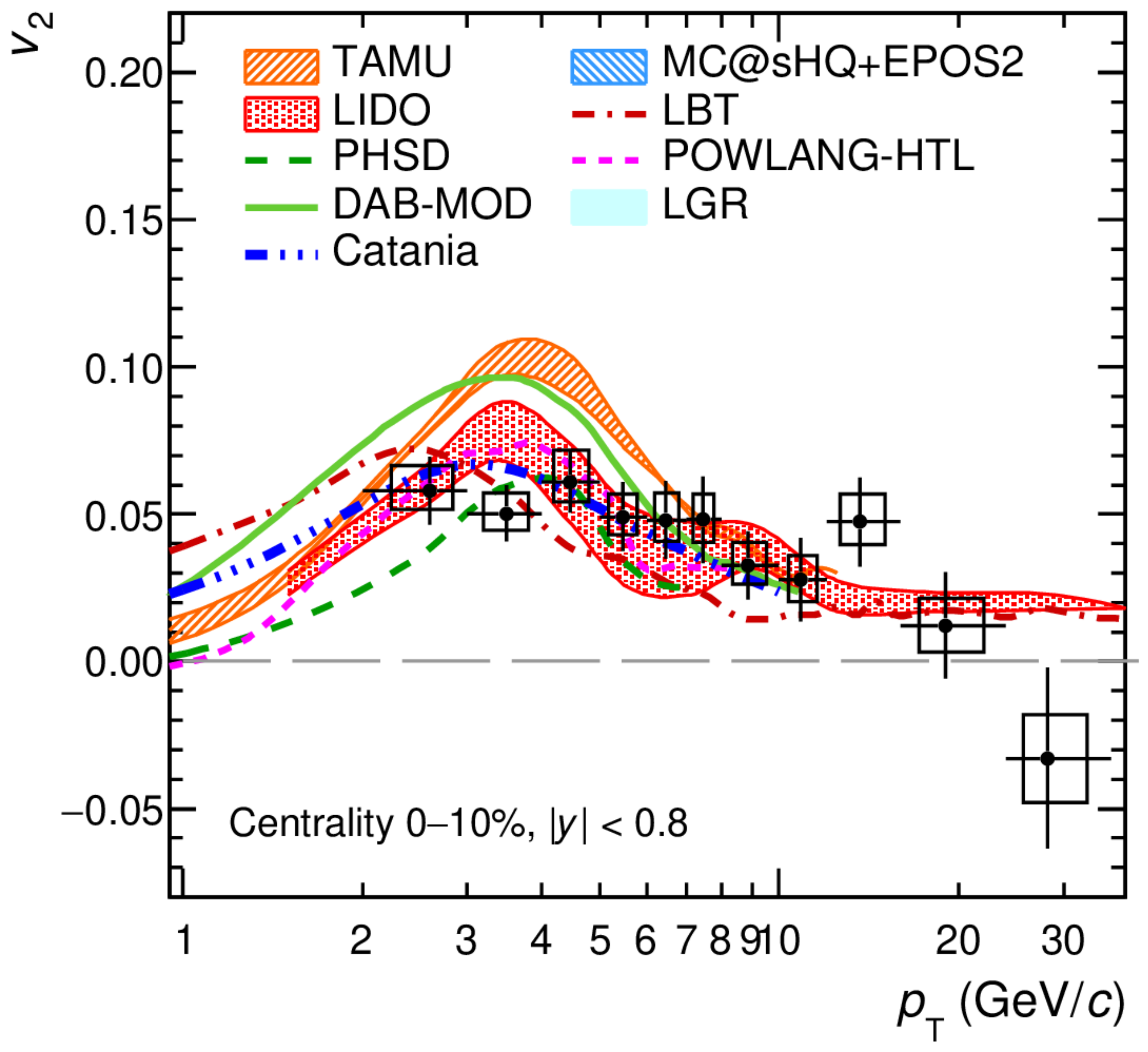
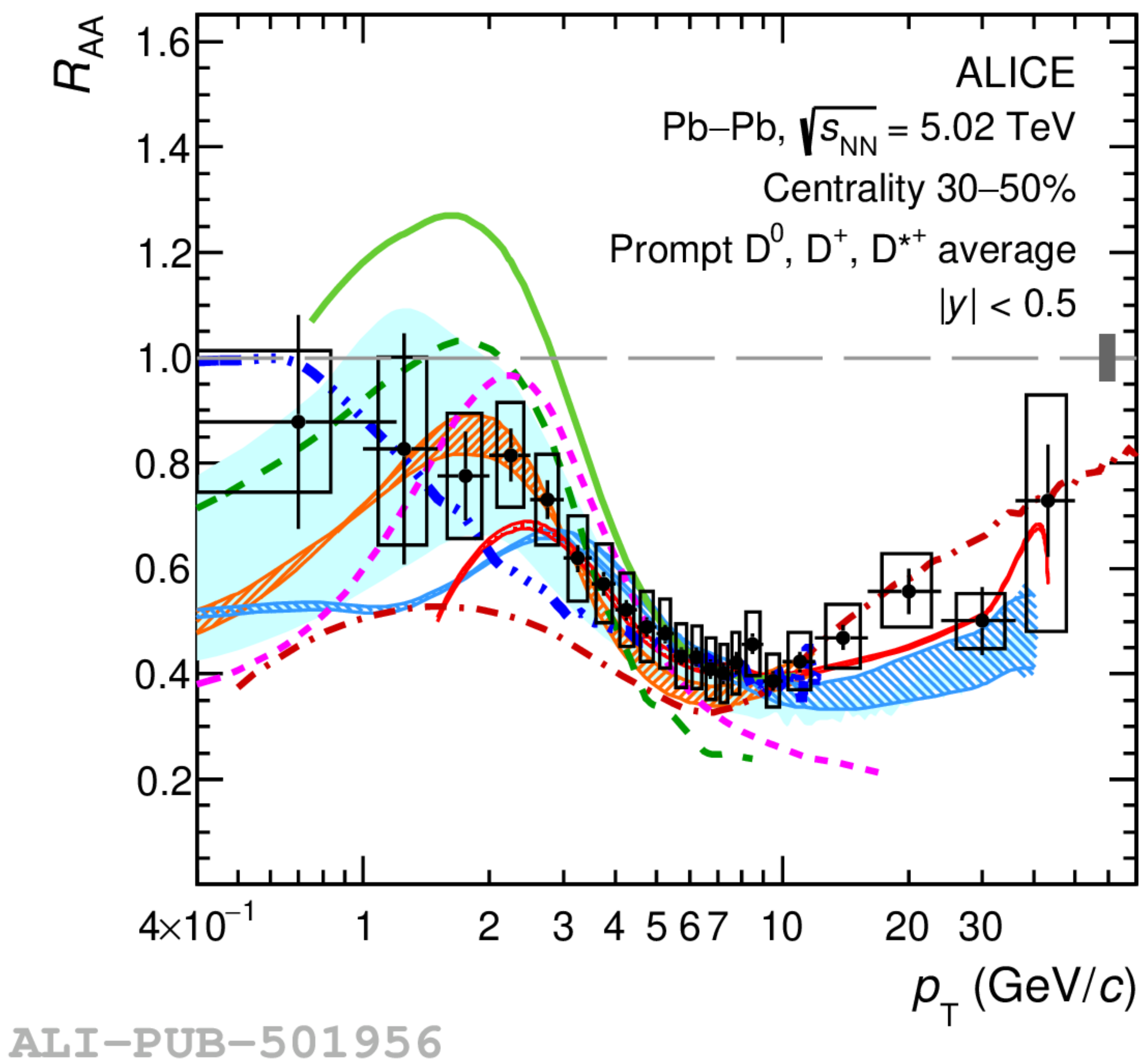
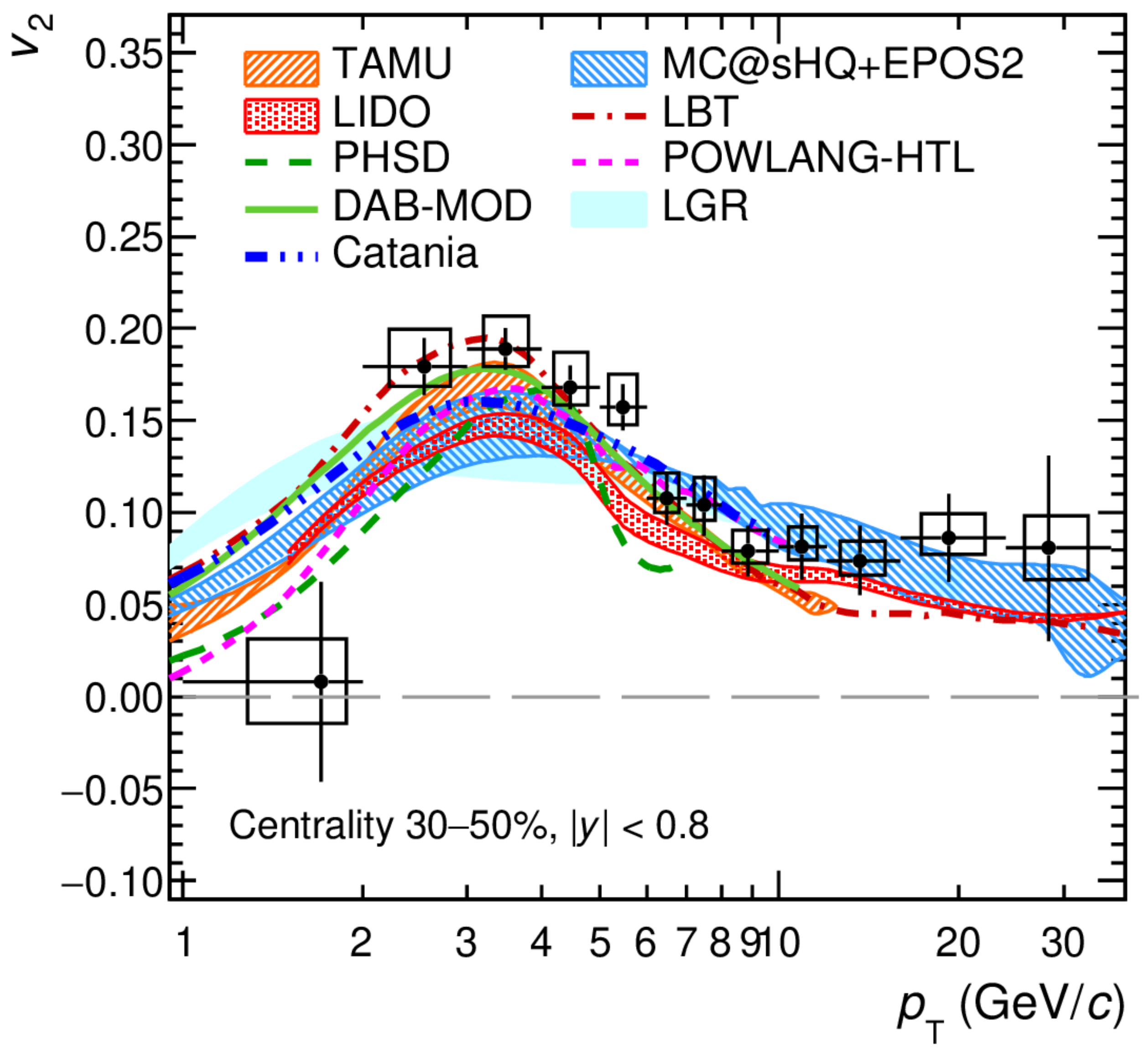




ALI-PUB-501952





ALI-PUB-501956

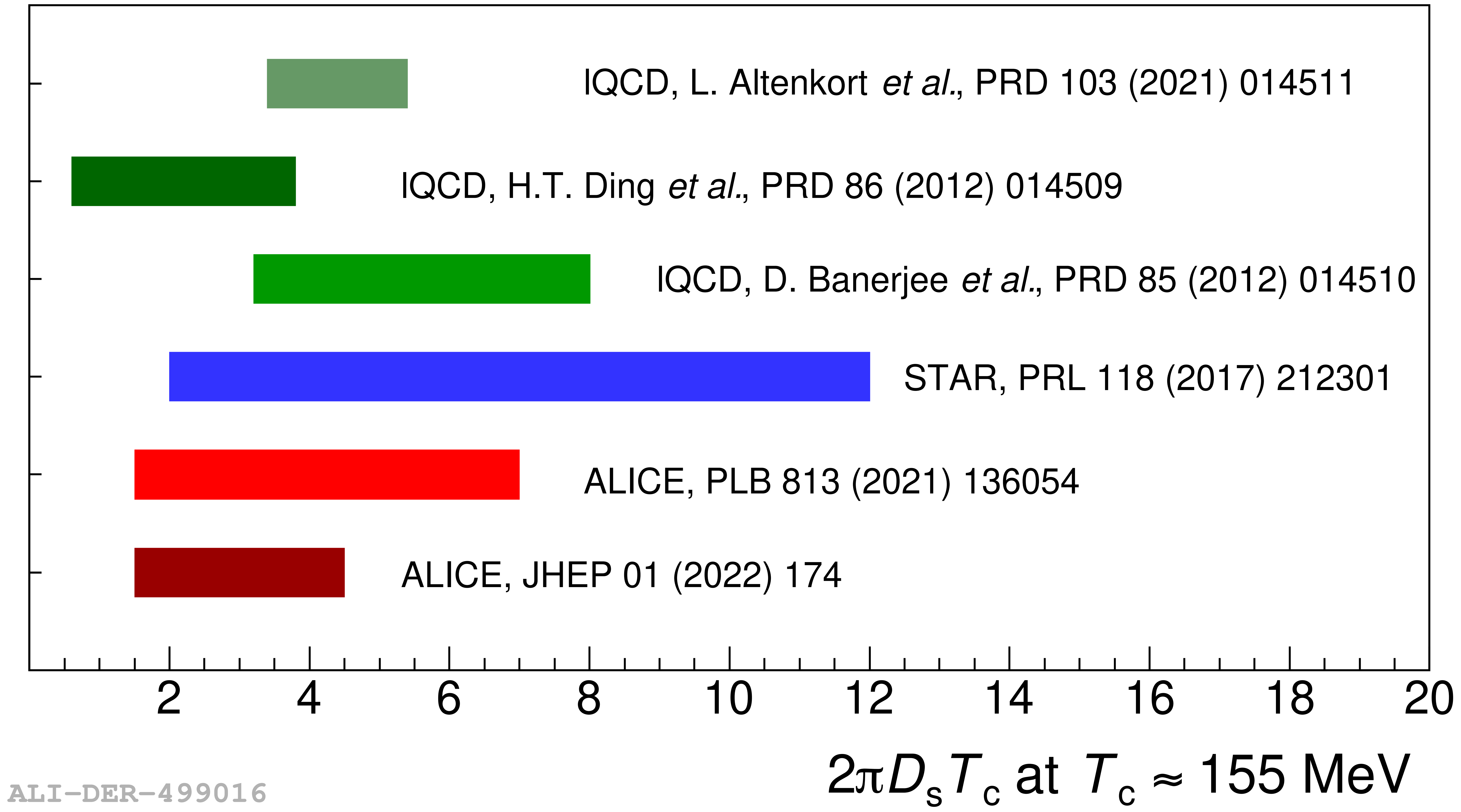
- Models based on the charm-quark transport describe reasonably well the measured elliptic and triangular flow of D mesons
  - ➡ By selecting those that provide a better agreement with data (in terms of χ^2/ndf) it is possible to constrain the charm-quark spatial diffusion coefficient D_s in the QGP

ALICE, JHEP 01 (2022) 174

TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC, 80 7 (2020) 671

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: PRC 102 (2020) 024906

ALICE, JHEP 01 (2022) 174



- Interval of spatial diffusion coefficient obtained by considering the values used in the transport models that reproduce the data
  - ➡ $1.5 < 2\pi D_s T_c < 4.5$ which corresponds to $2 < \tau_{\mathrm{charm}} < 6\ \mathrm{fm}/c$
  - ➡ Indicates a thermalisation time of the charm quark comparable with the QGP lifetime
  - ➡ Compatible with values obtained with QCD calculations on lattice

- Caveat: the spatial diffusion coefficient is not the only parameter that influences the R_{AA} and v_n observables!

Estimates of the spatial-diffusion coefficient - bayesian analyses

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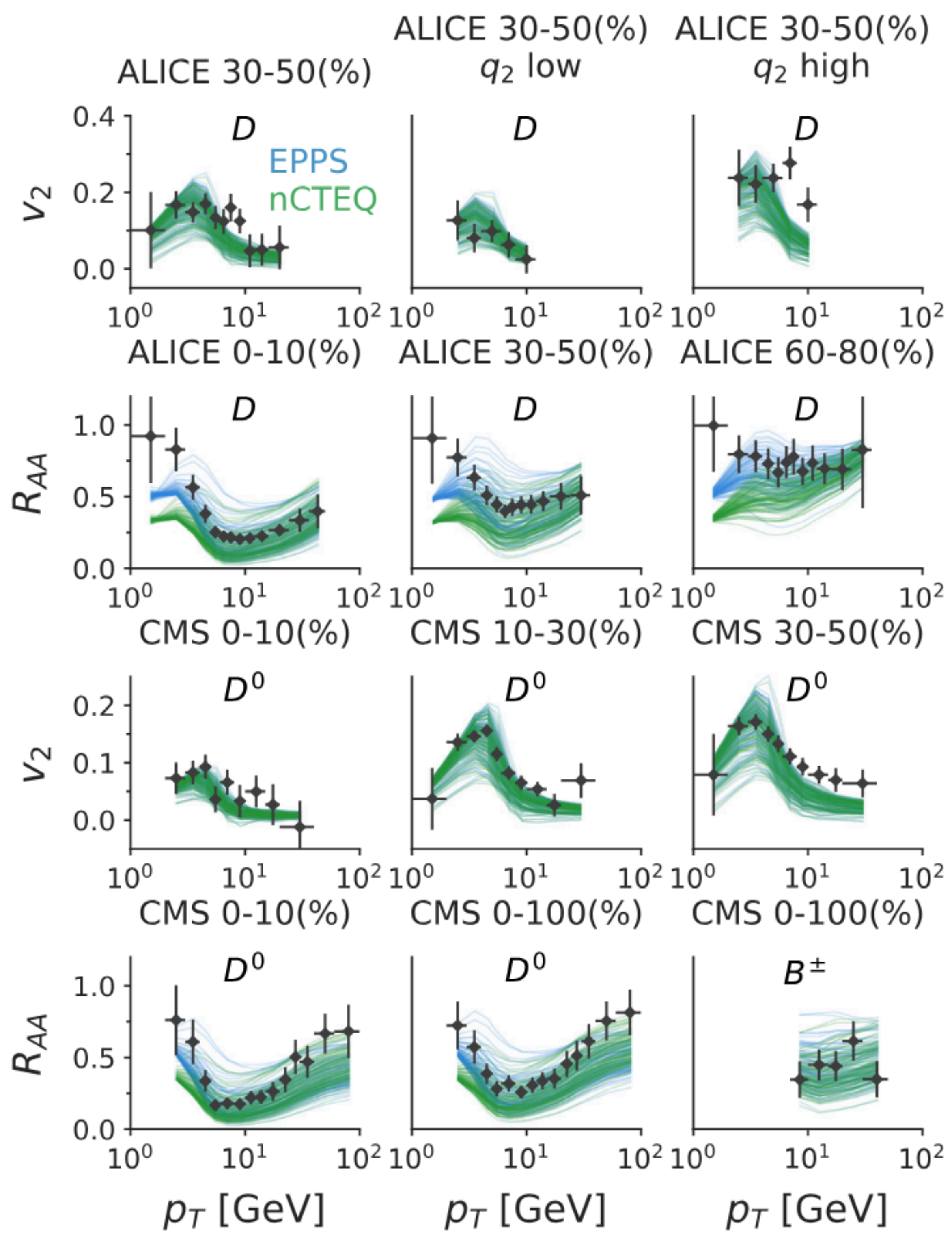
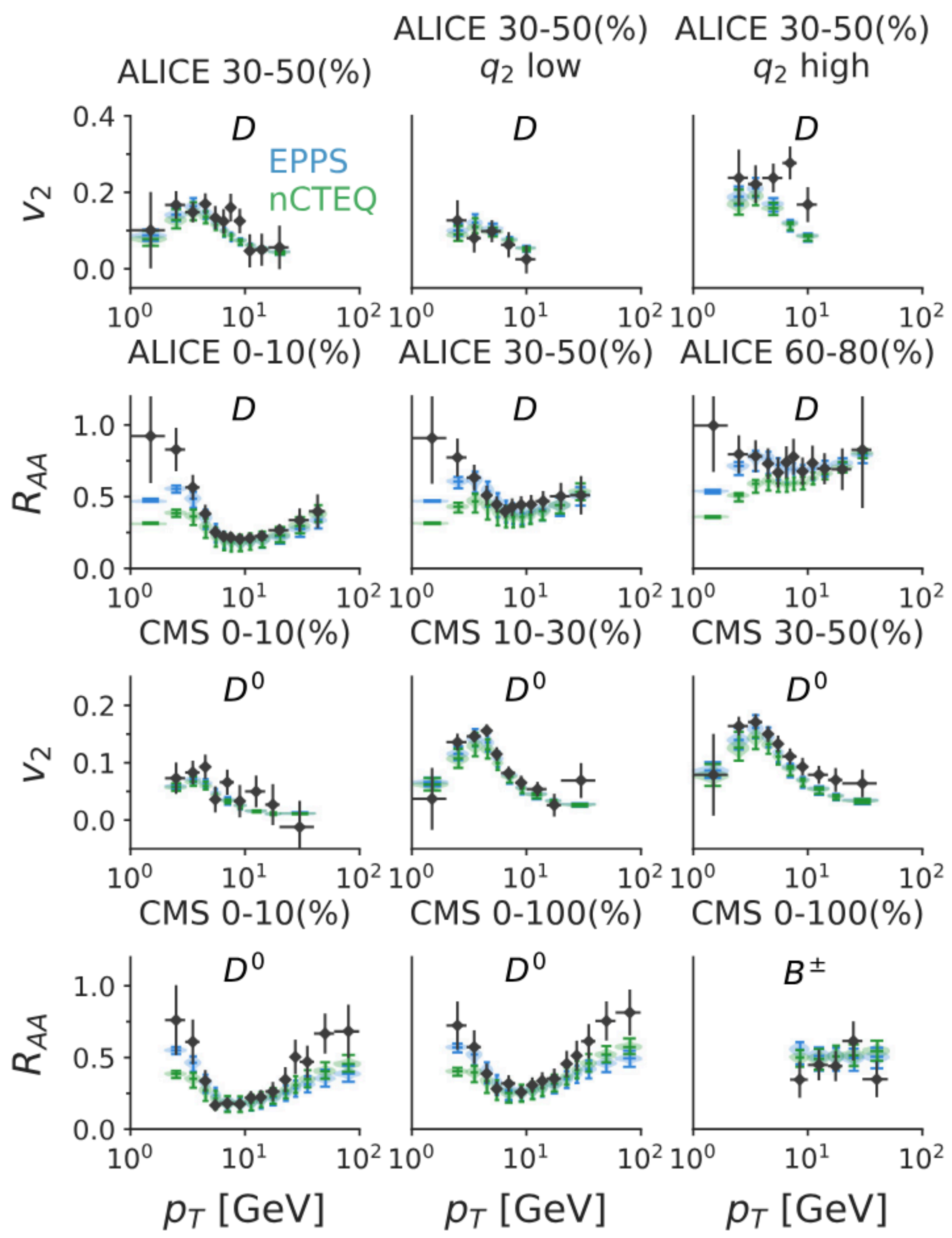
Prior distributions

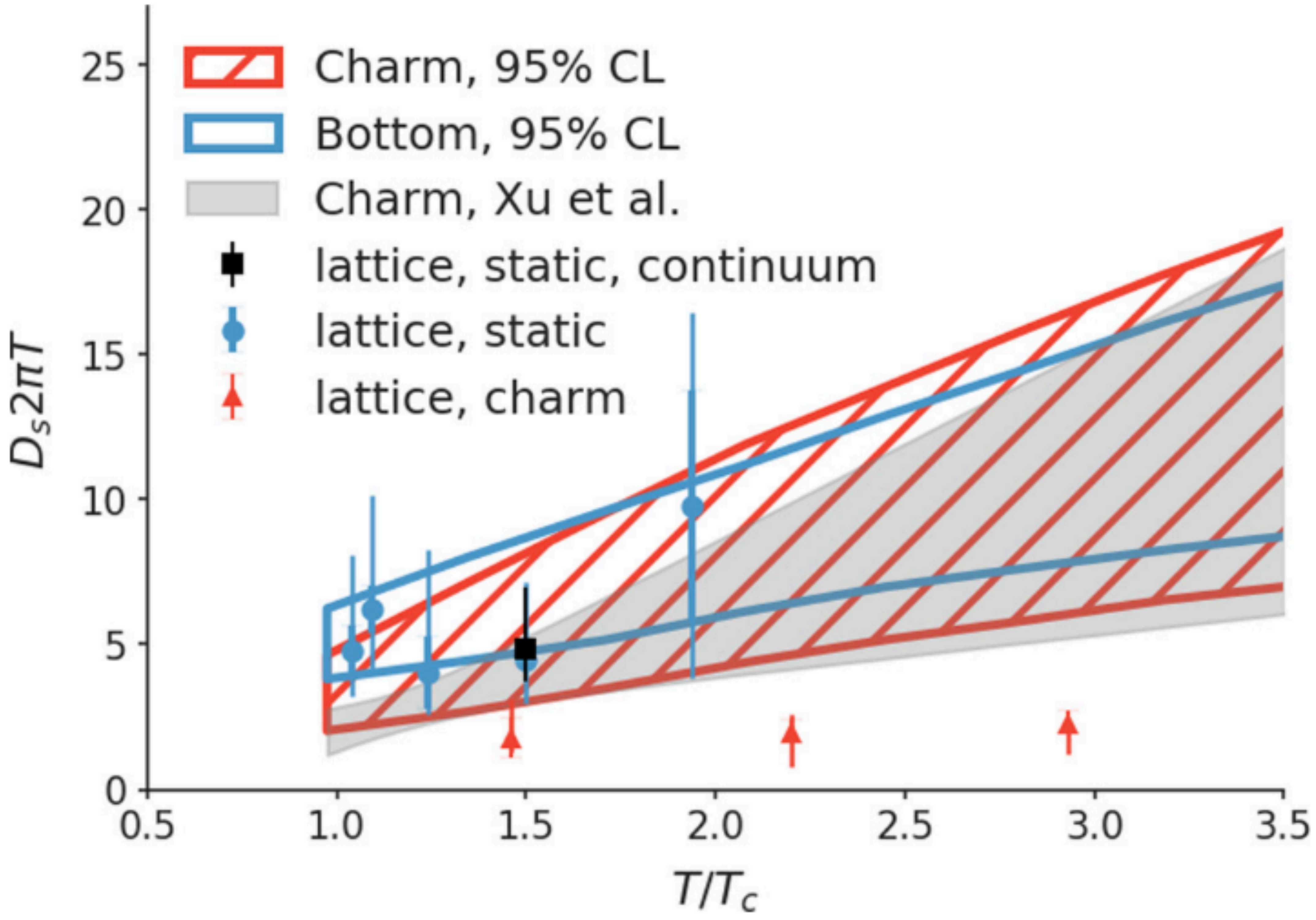


Posterior distributions



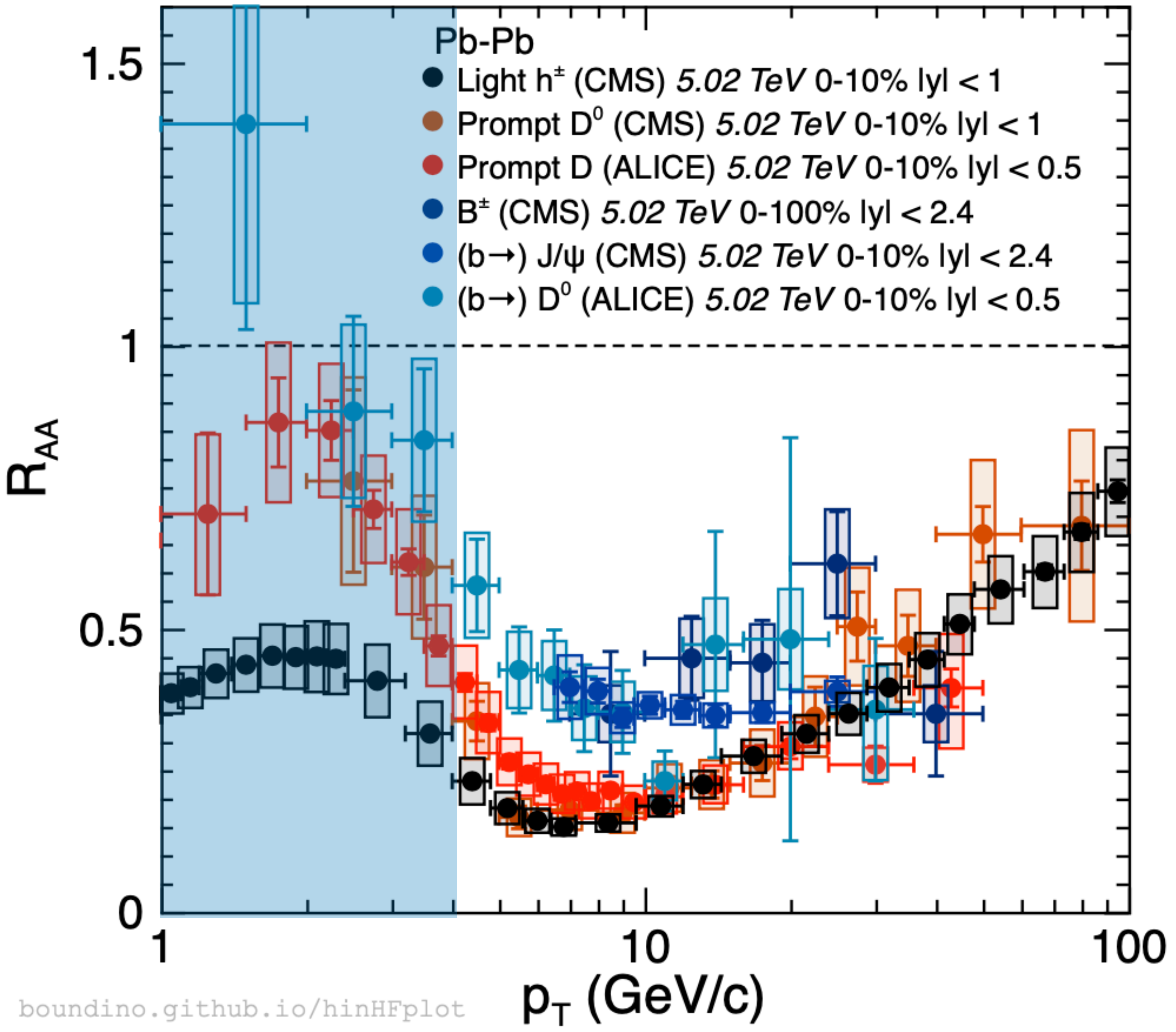
W. Ke et al, PRC 98 (2018) no.6, 064901

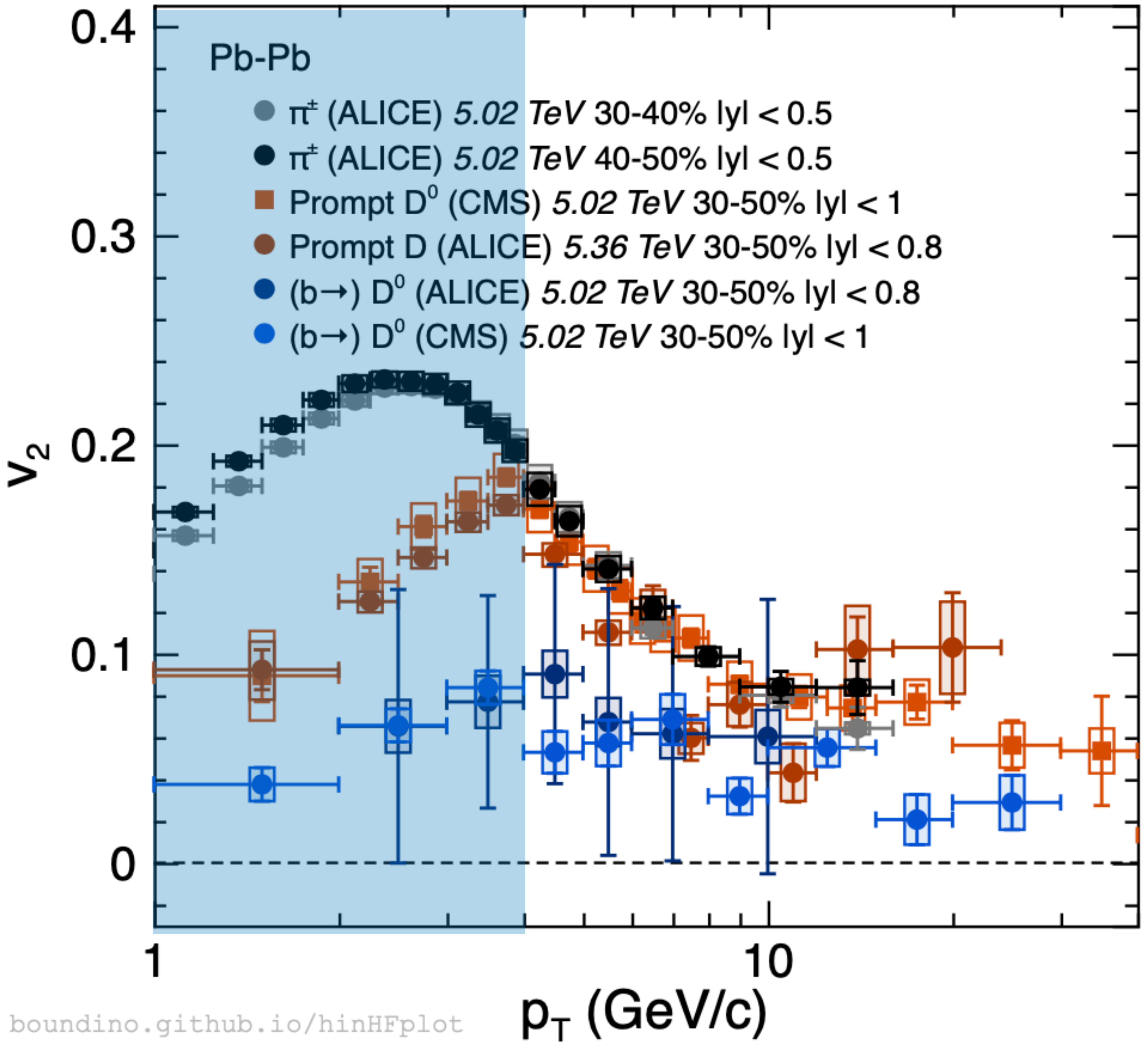
- To have a proper determination of the spatial diffusion coefficient, a global (e.g. bayesian) analysis of several measurements is needed



- Posterior distribution of the heavy-quark spatial diffusion coefficient
  - ➡ Compatible between charm and beauty
  - ➡ Still large uncertainty (beauty ~ charm even if many less and less precise observables) → beauty crucial to constrain D_s

Measurements of beauty-hadron nuclear modification factor and flow





- $p_T < 3$–4 GeV/c:
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CMS, PLB 816 (2021) 136253
ALICE Preliminary
CMS, PLB 850 (2024) 138389
ALICE, EPJC 83 (2023) 1123

Measurements of beauty-hadron nuclear modification factor and flow

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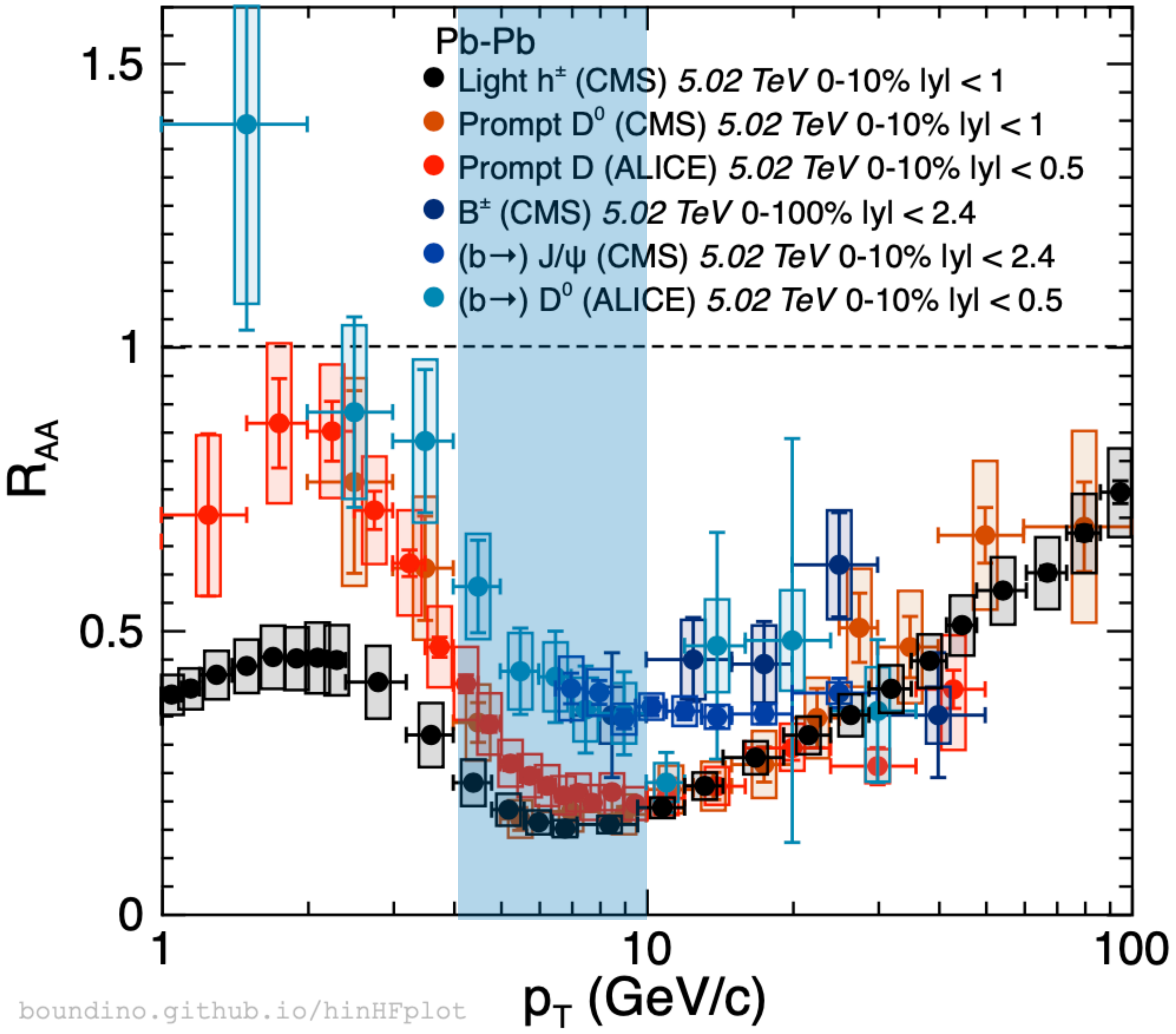

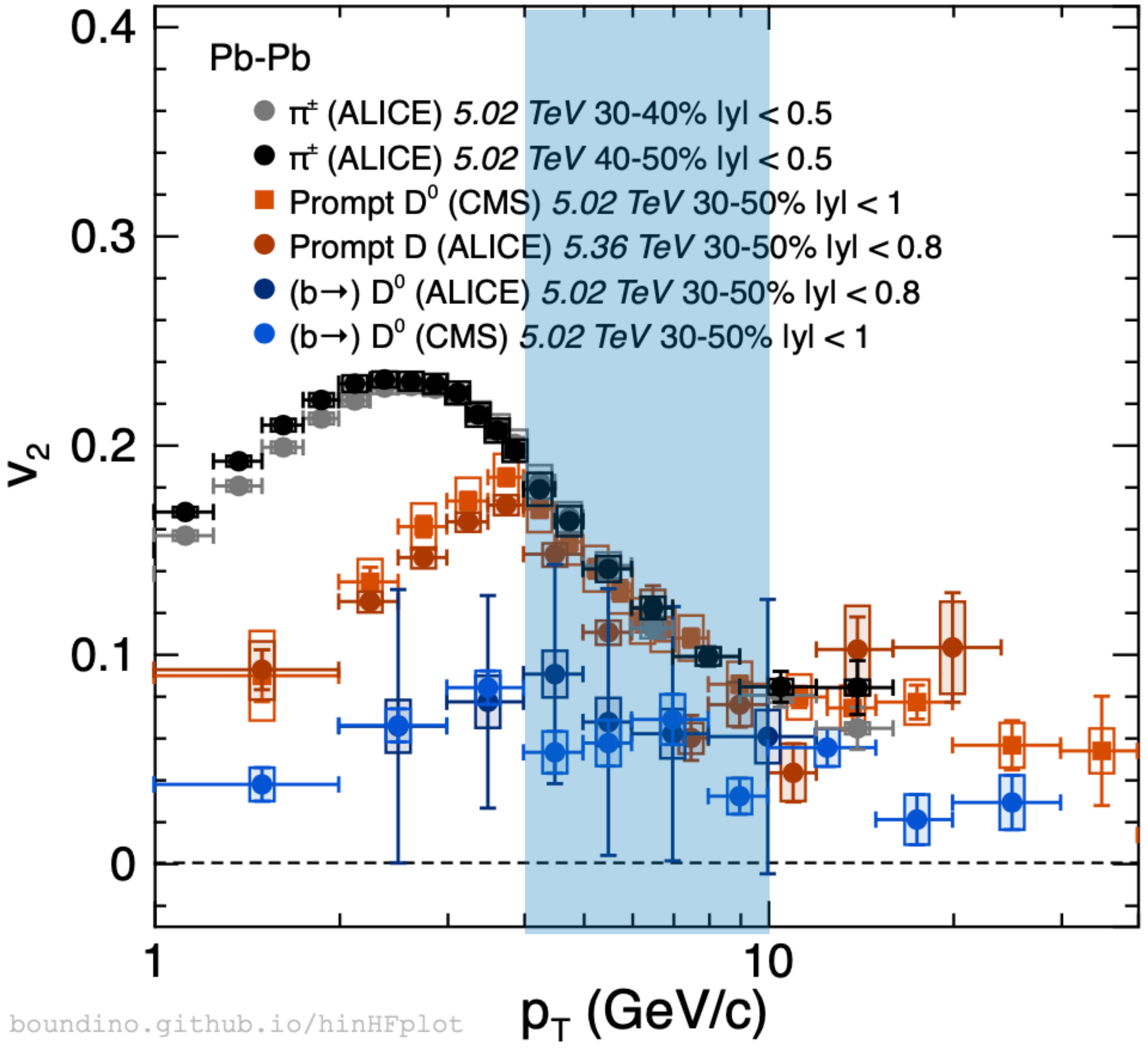

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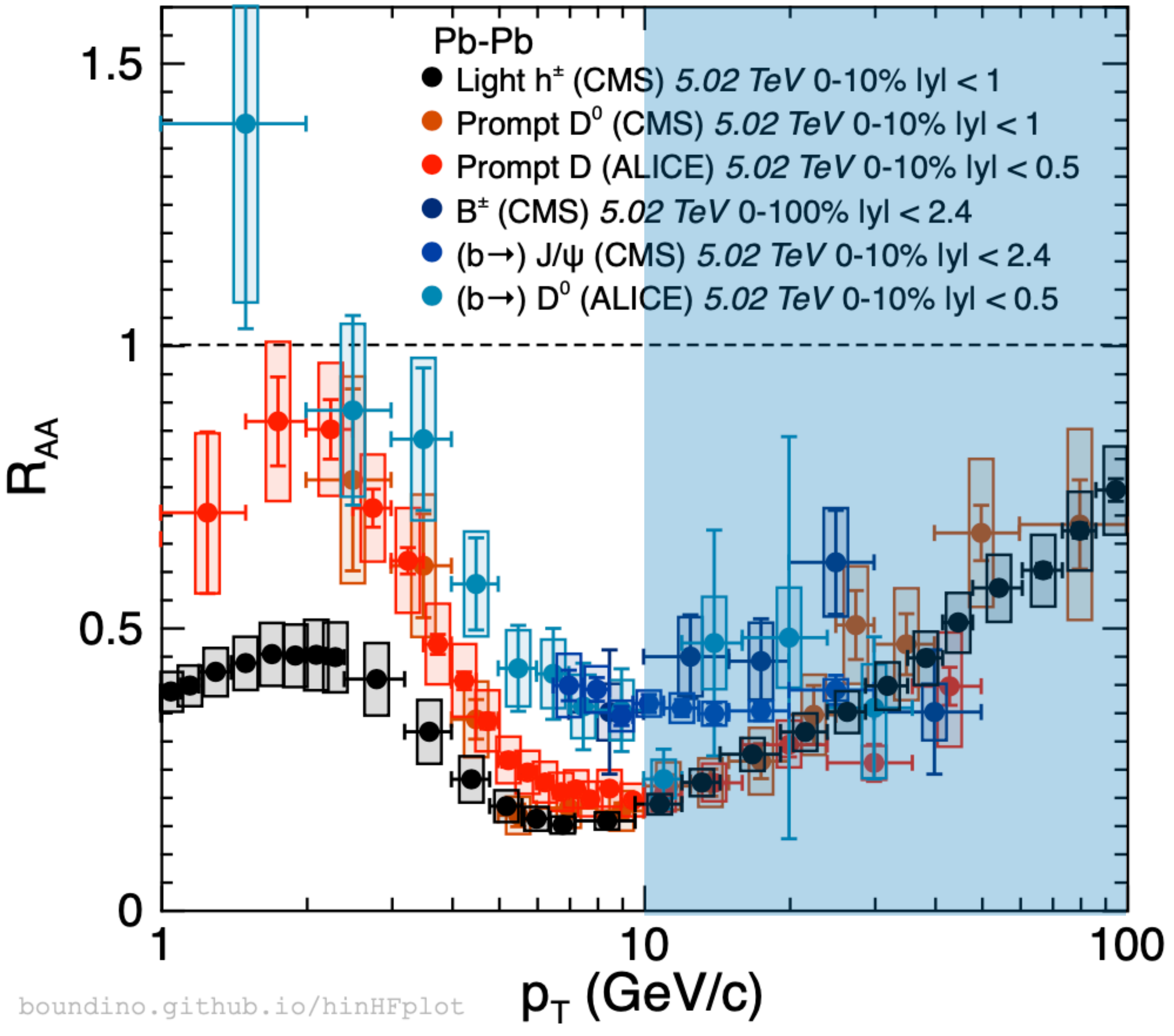

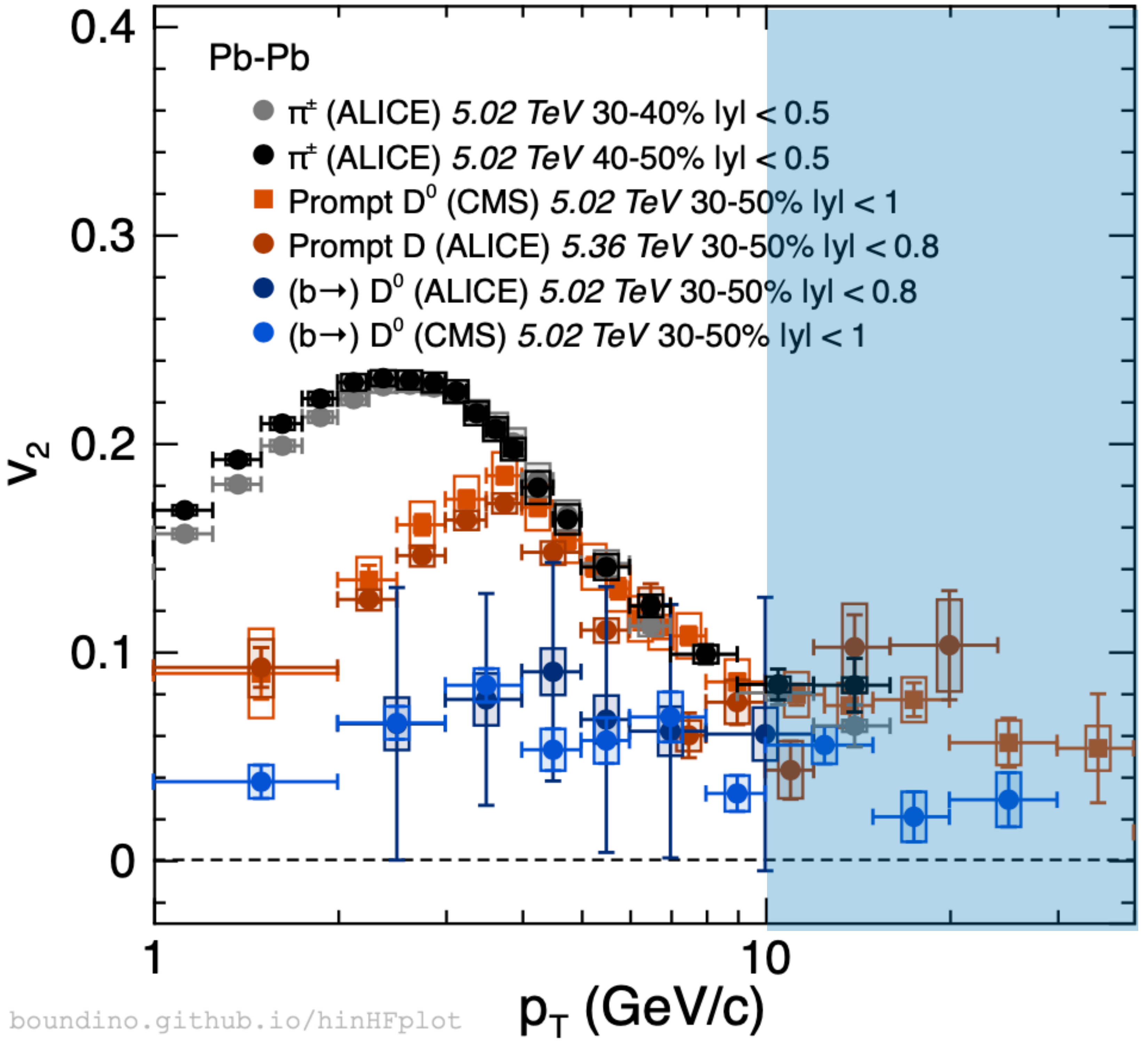

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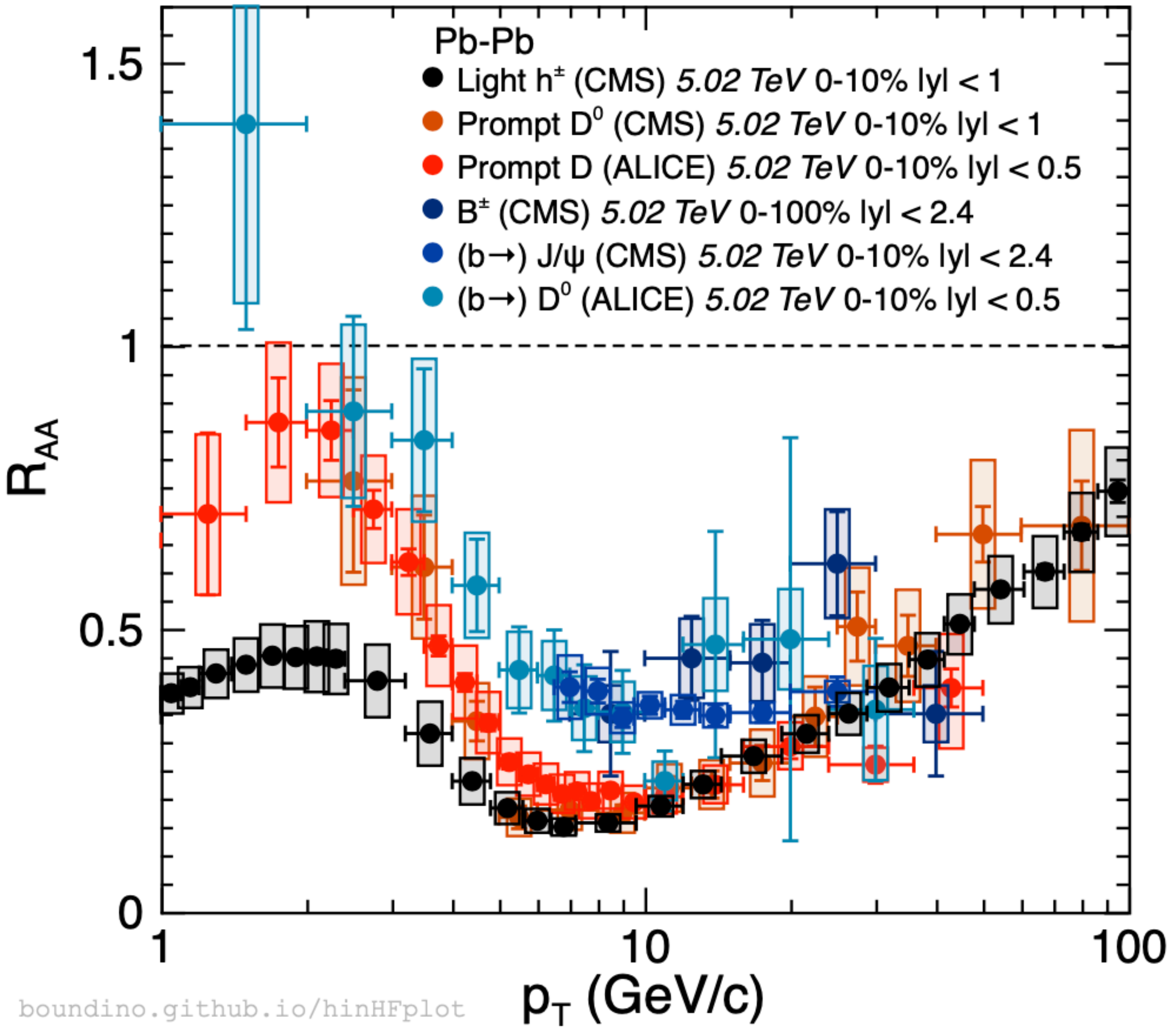

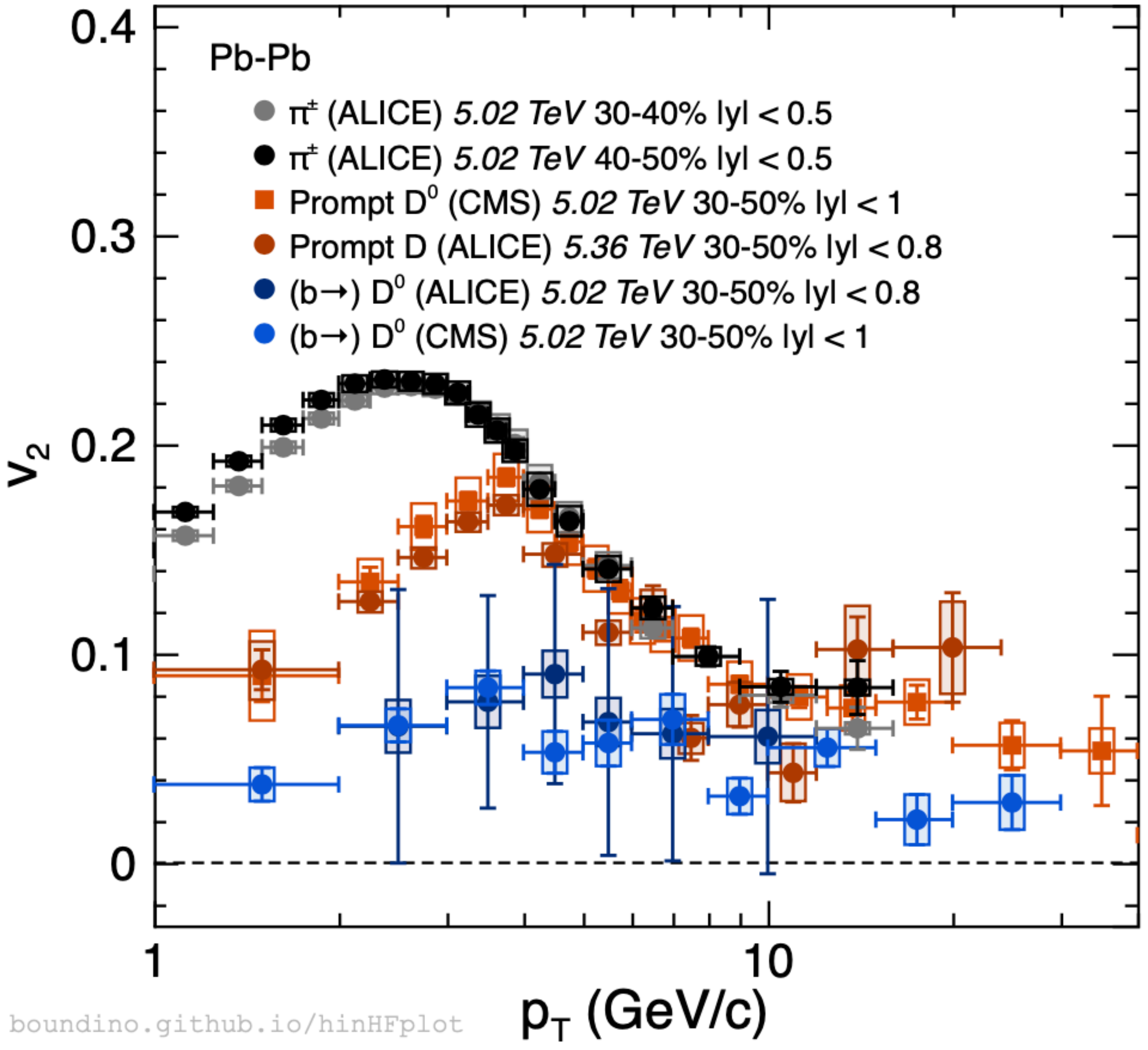

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- Most of the measurements related to beauty currently indirect via non-prompt charm hadrons (only B fully reconstructed from CMS for $p_T > 7$ GeV/c)
  - ➡ Possible effects due to decay kinematics (shift in p_T)
  - ➡ Need of properly modelling to extract physics message

Measurements of beauty-hadron nuclear modification factor and flow

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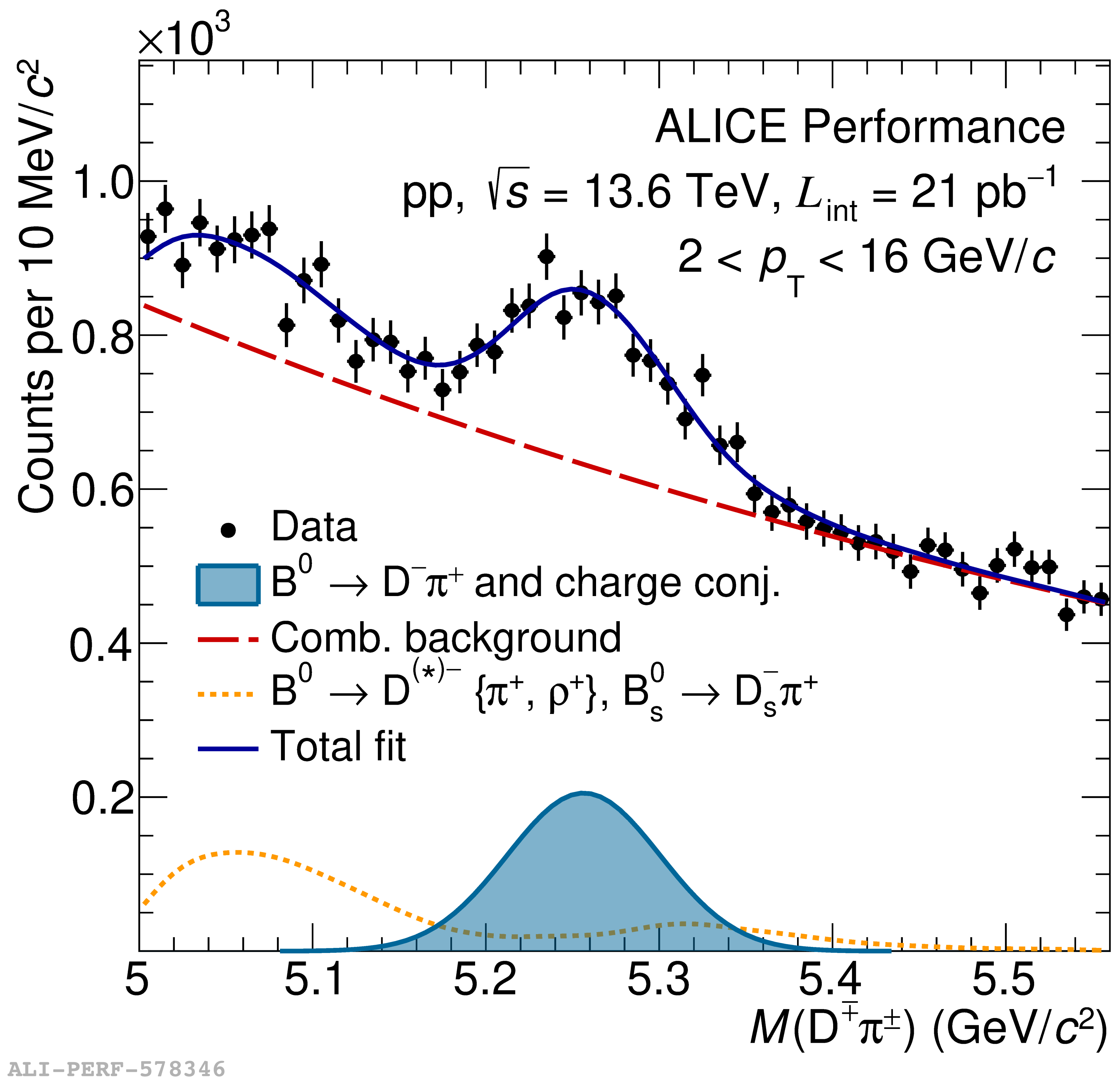

OUTLOOK

Full reconstruction of B hadrons possible in ALICE down to p_T = 2 GeV/c due to large luminosity collected in Run 3

More about ALICE in Run3 in talk by C. Terrevoli

- p_T < 3–4 GeV/c:
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Measurements of fully reconstructed B hadrons

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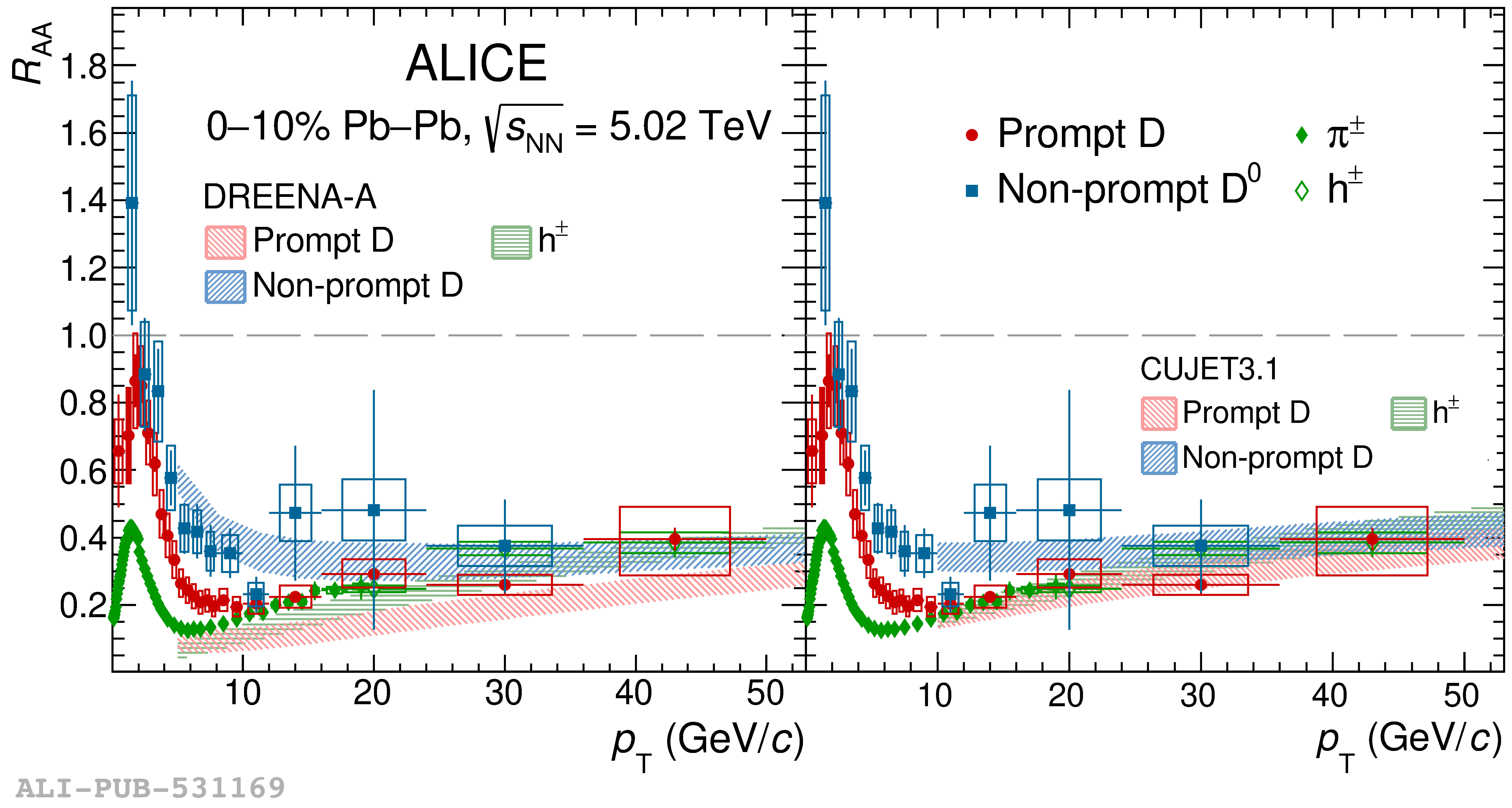
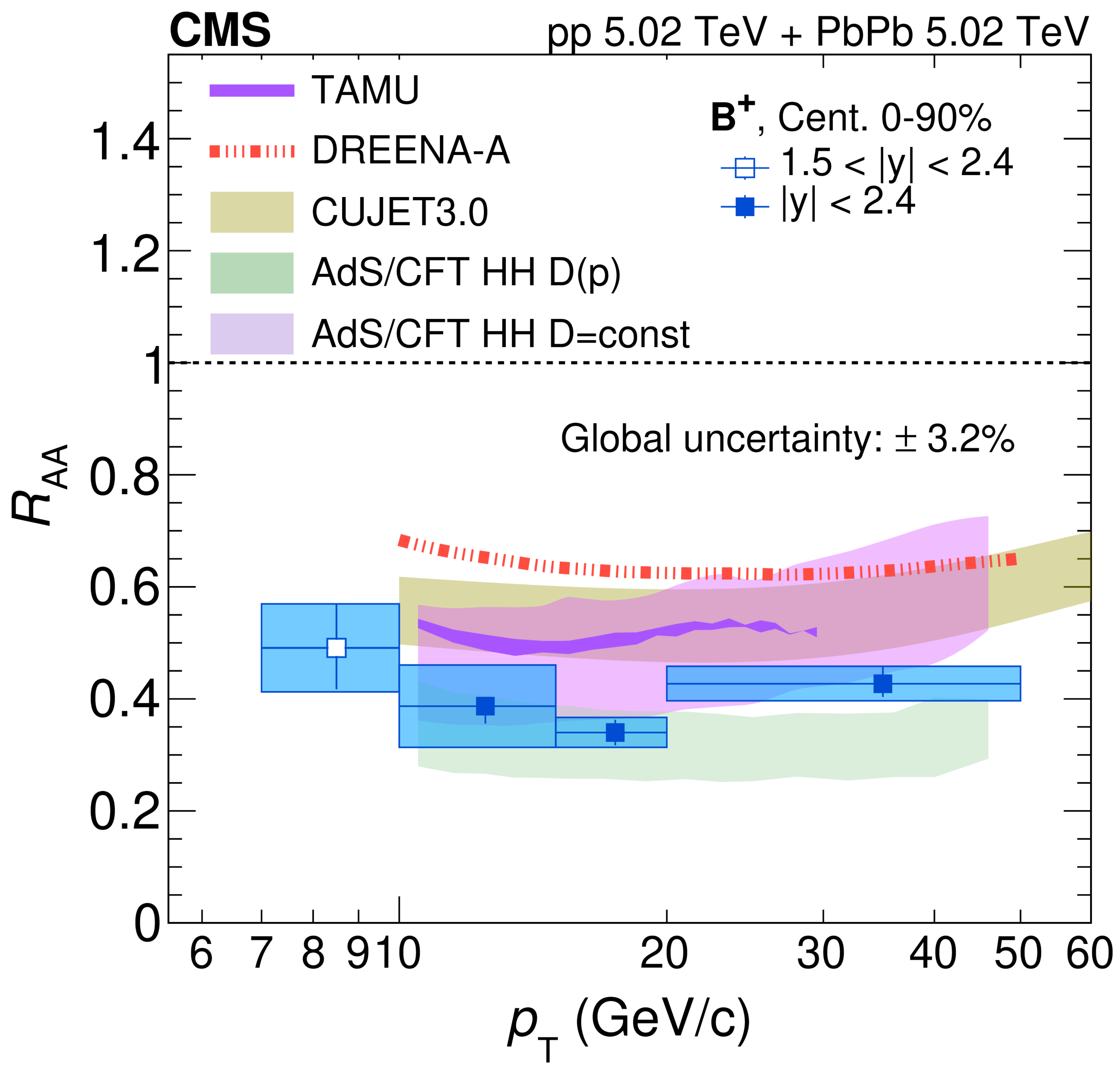
ALICE, EPJC 84 (2024) 813



CMS, arXiv:2409.07258



- Expected hierarchy from dead-cone effect

$$R_{AA}(B) > R_{AA}(D) \gtrsim R_{AA}(\pi^{\pm})$$

- Constrain pQCD inspired models including energy loss via radiative processes

TAMU: PRL 124 (2020) 042301
DREENA-A: Front. Phys. 10 (2022) 957019
CUJET3: CPC 43 (2019) 044101
Ads/CFT: arXiv:1703.05845

Role of hadronisation mechanism on charm and beauty R_{AA}

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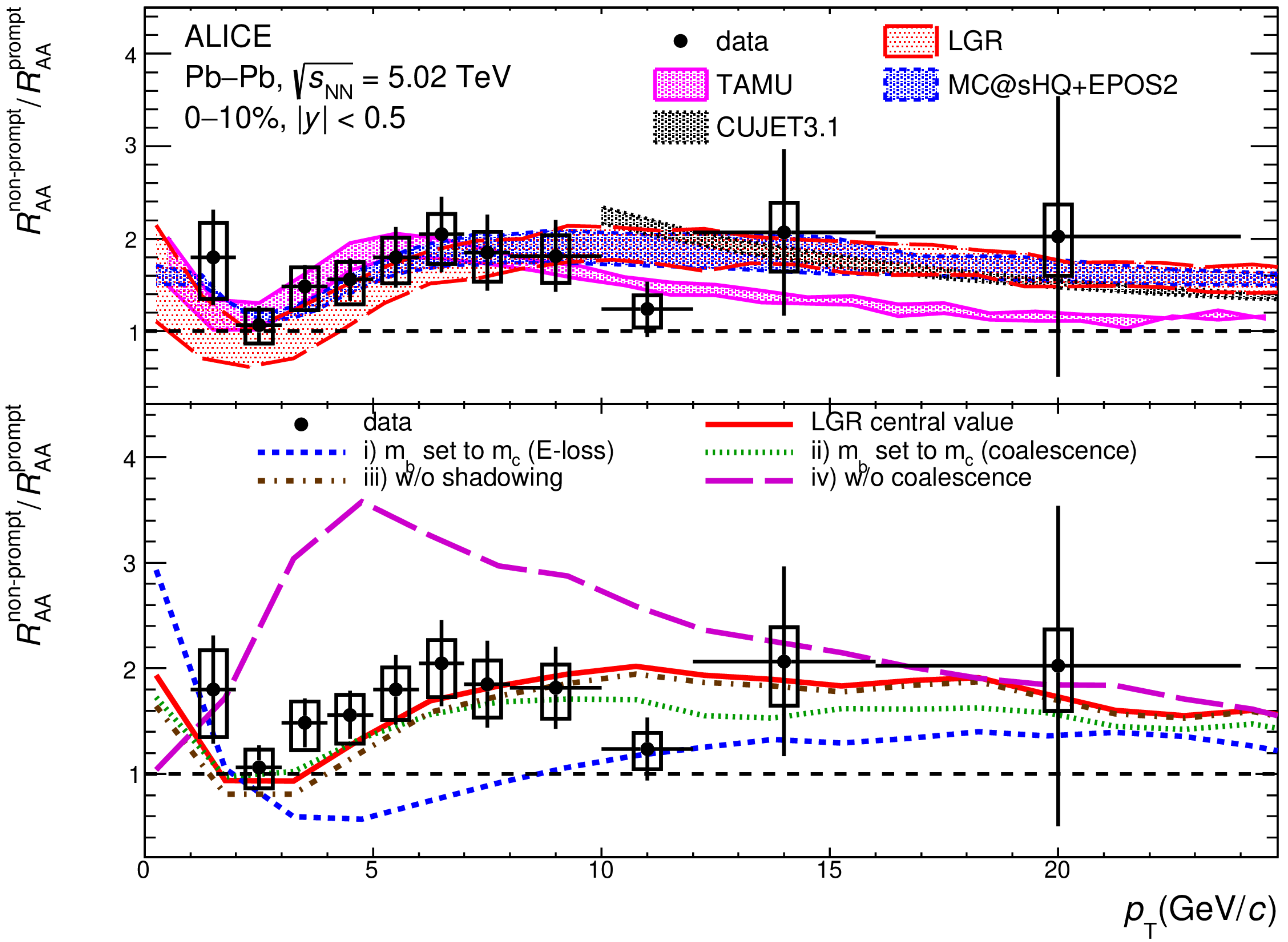
ALICE, JHEP 12 (2022) 126



- Non-prompt / prompt R_{AA} ratio:
  - ➡ CUJET3.1 describes the measurement at high p_T
  - ➡ Models including both collisional and radiative energy loss (LGR, MC@sHQ+EPOS2) describe the measurement in all the full p_T region
  - ➡ More precision needed to verify necessity of radiative energy loss (not included in TAMU)
- Hadronisation via coalescence needed to describe the intermediate p_T region

→ More about HF in hadronisation in talk by A. Rossi

TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC, 80 7 (2020) 671
CUJET3.1: CPC 43 (2019) 044101

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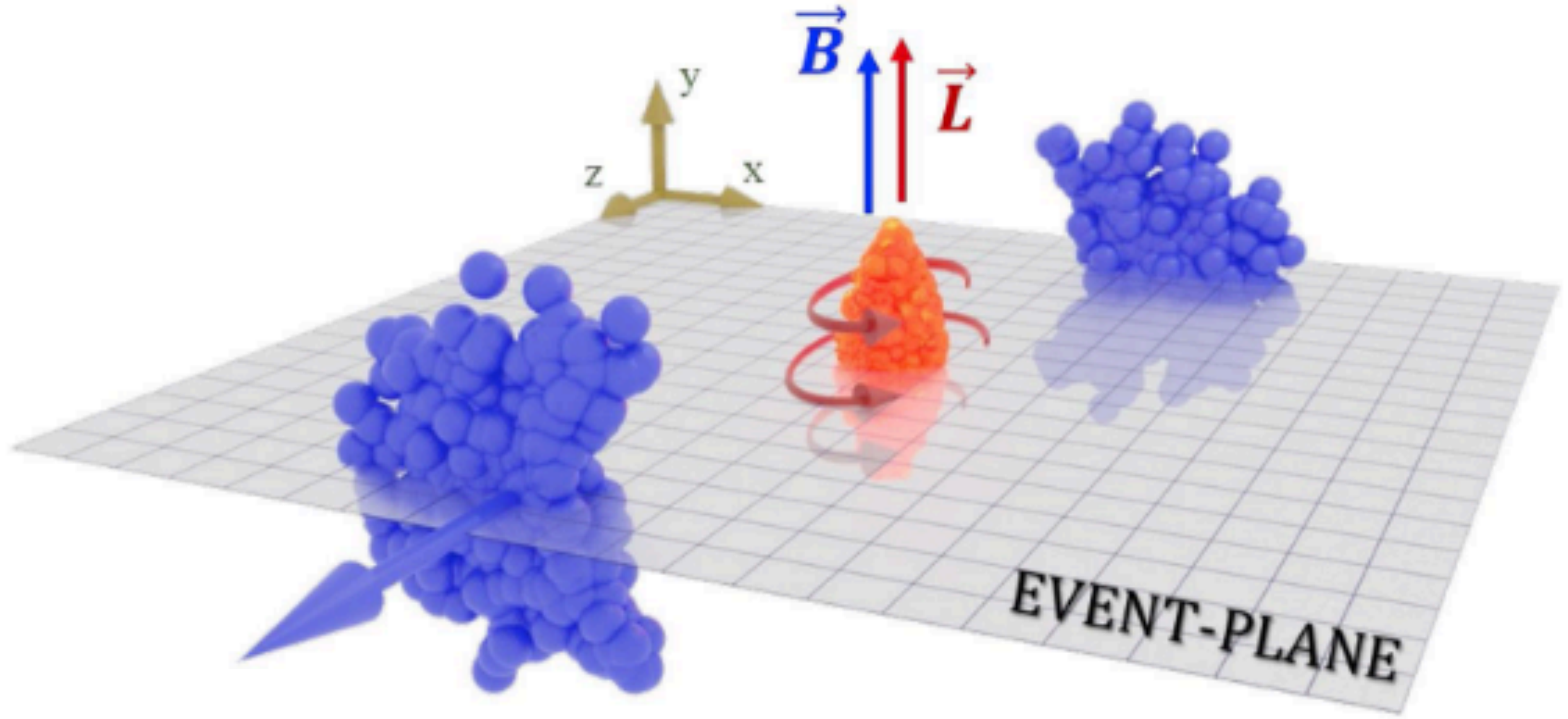
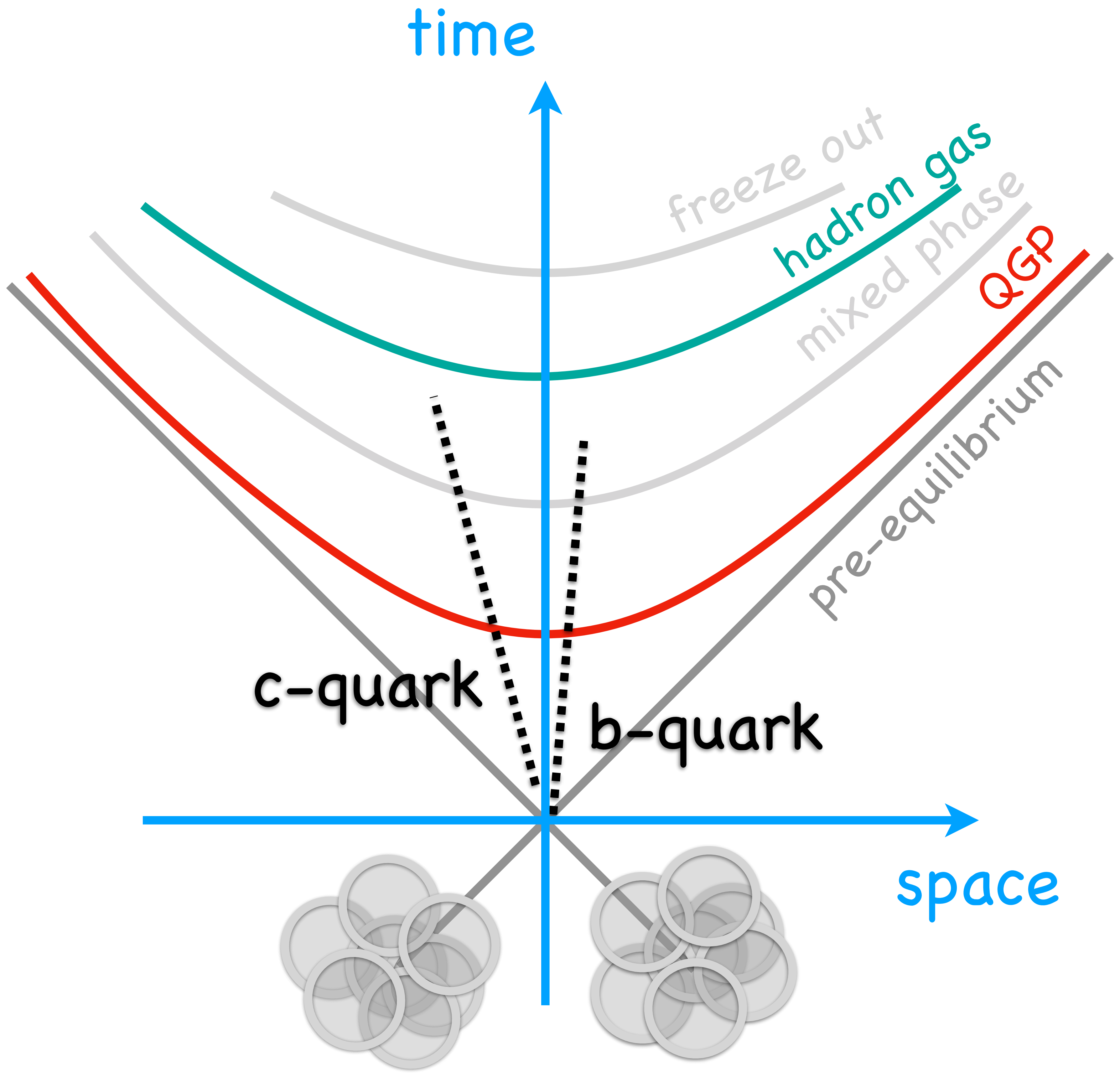
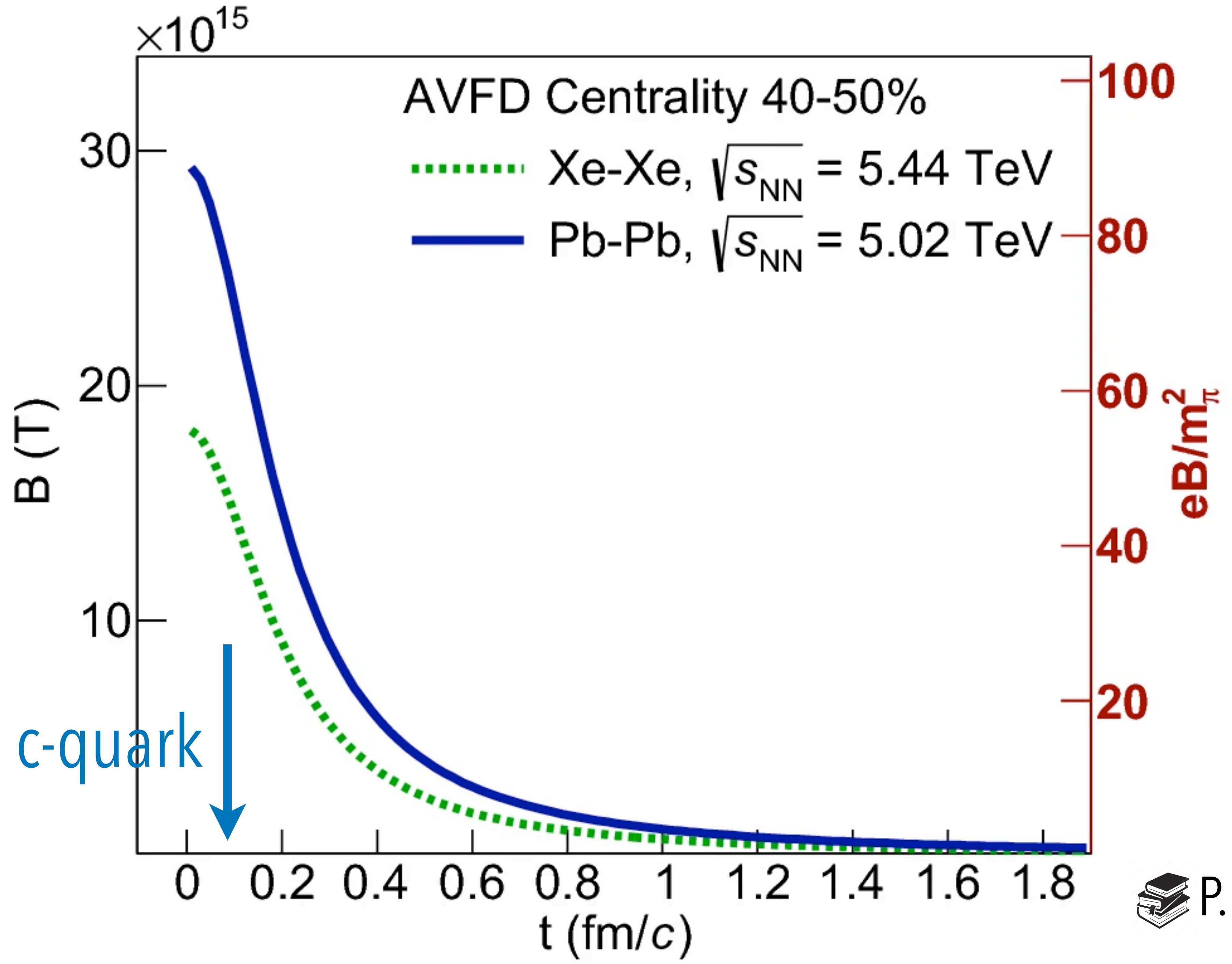
- Non-central heavy-ion collisions
  - ➡ Large angular momentum due to the medium rotation is predicted 📚 Becattini et al, PRC 77 (2008) 024906
  - ➡ Huge initial magnetic field (B ~ 10^{14} T) is expected to be formed

📚 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

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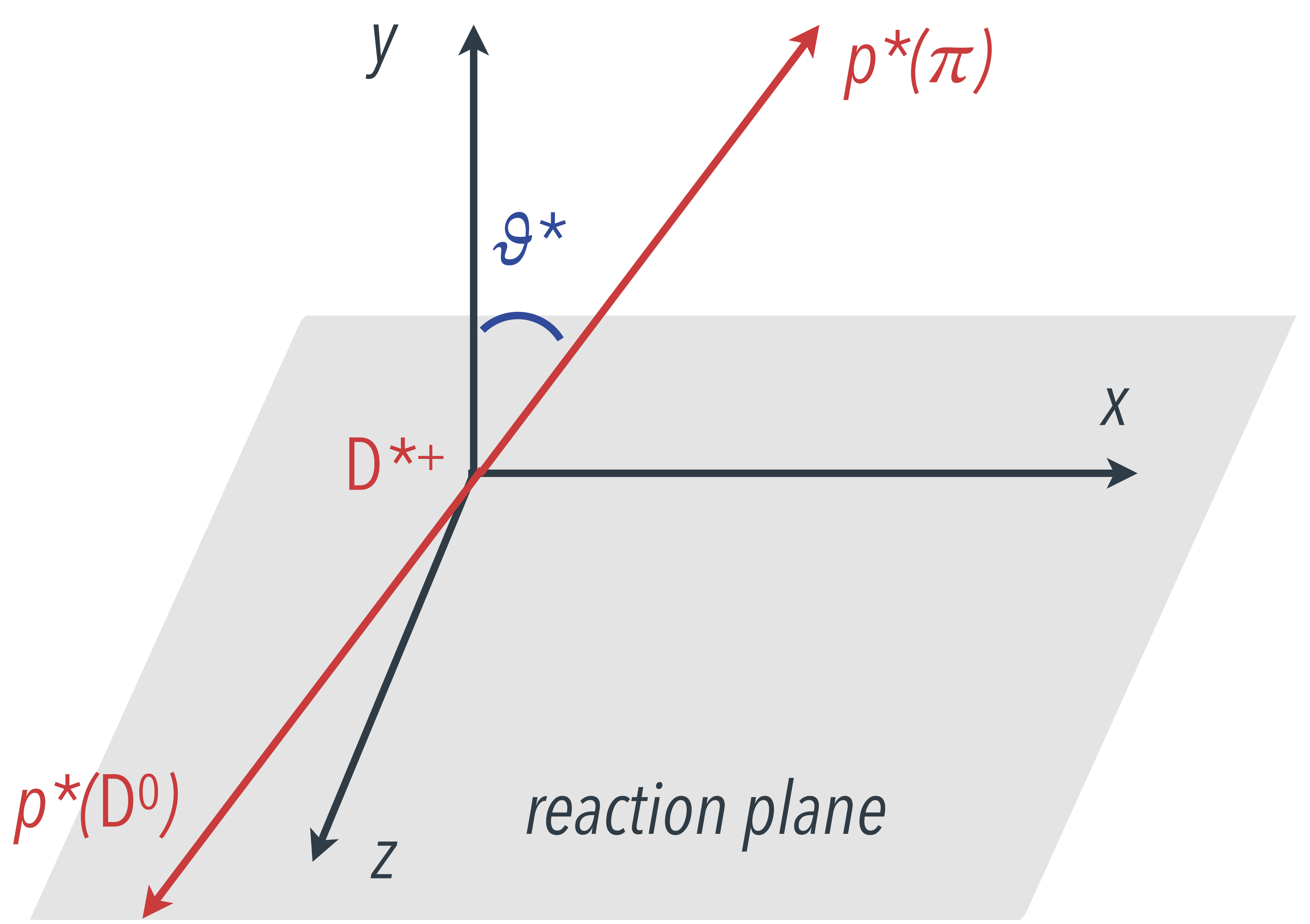
- Spin alignment of vector mesons can be studies via the angular distribution of their decay products in the mother rest frame with respect to a quantisation axis



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

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)

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- 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

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

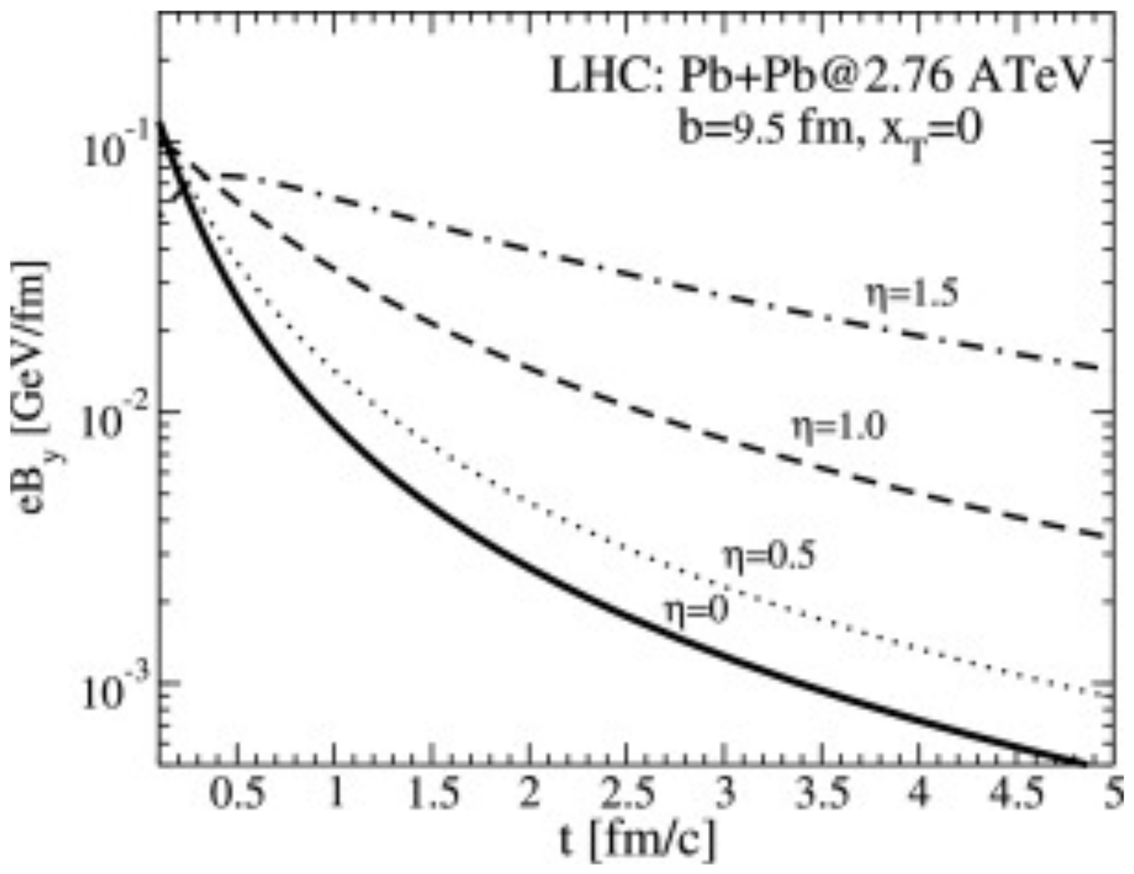
* > 1/3 for neutral mesons, < 1/3 for charged mesons

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

Fragmentation

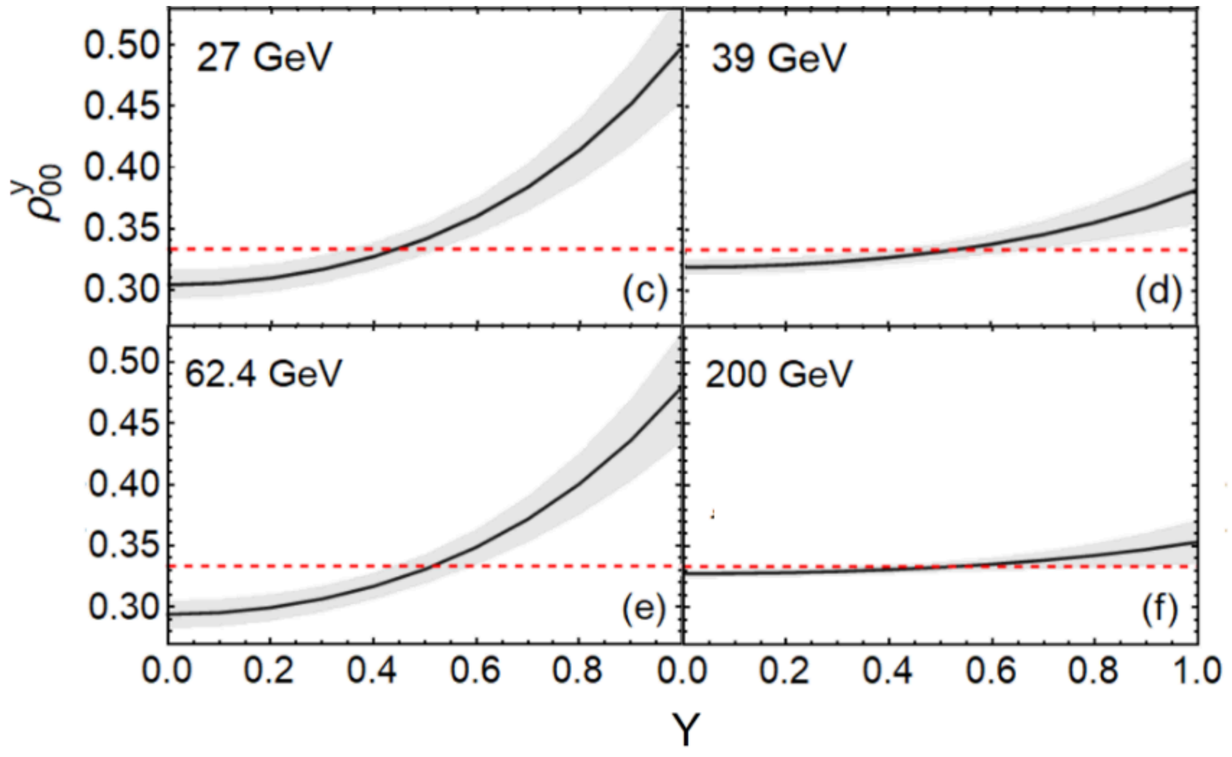
$$\rho_{00}^{frag} = \frac{1 + \beta \cdot P_q^2}{3 - \beta \cdot P_q^2} > 1/3$$

- 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



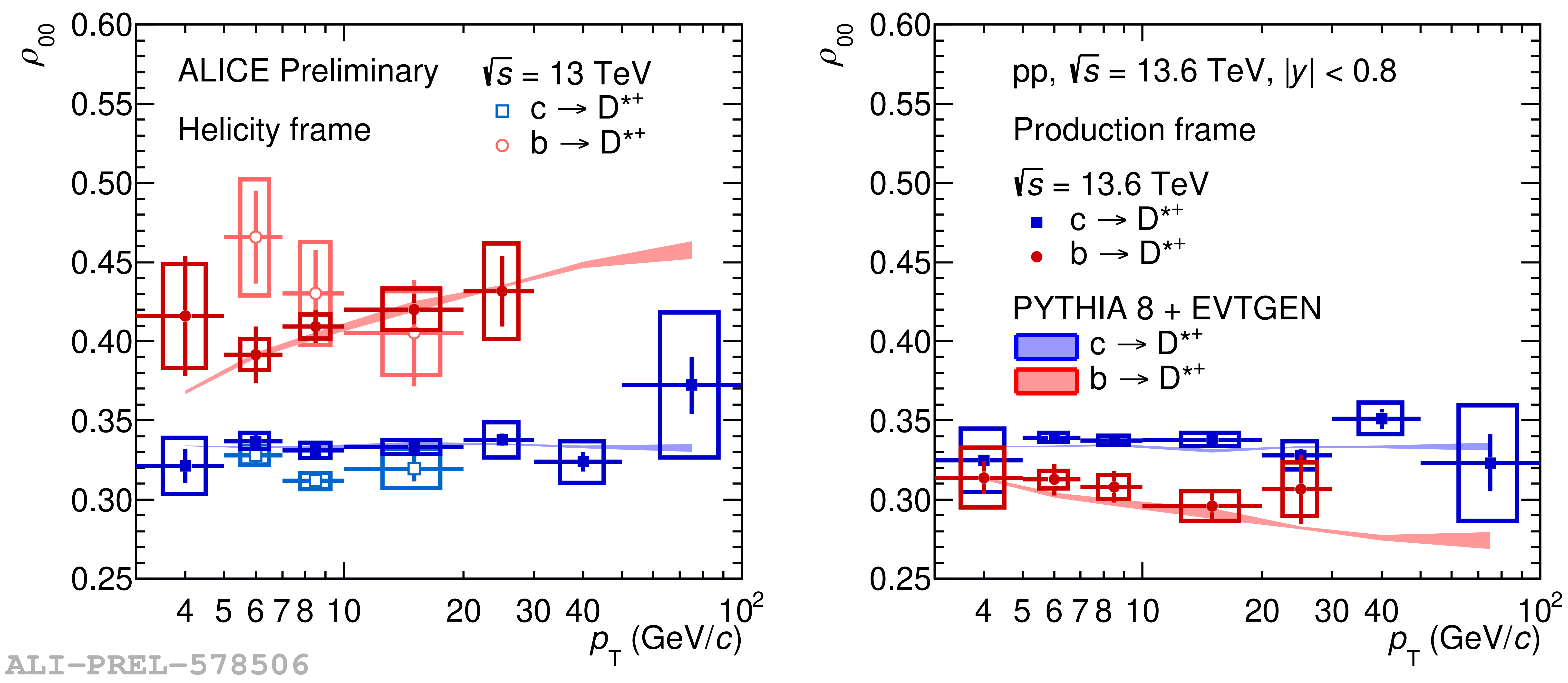
Also possible in case of vector-meson field, for thermalised polarised quarks recombining in the QGP

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

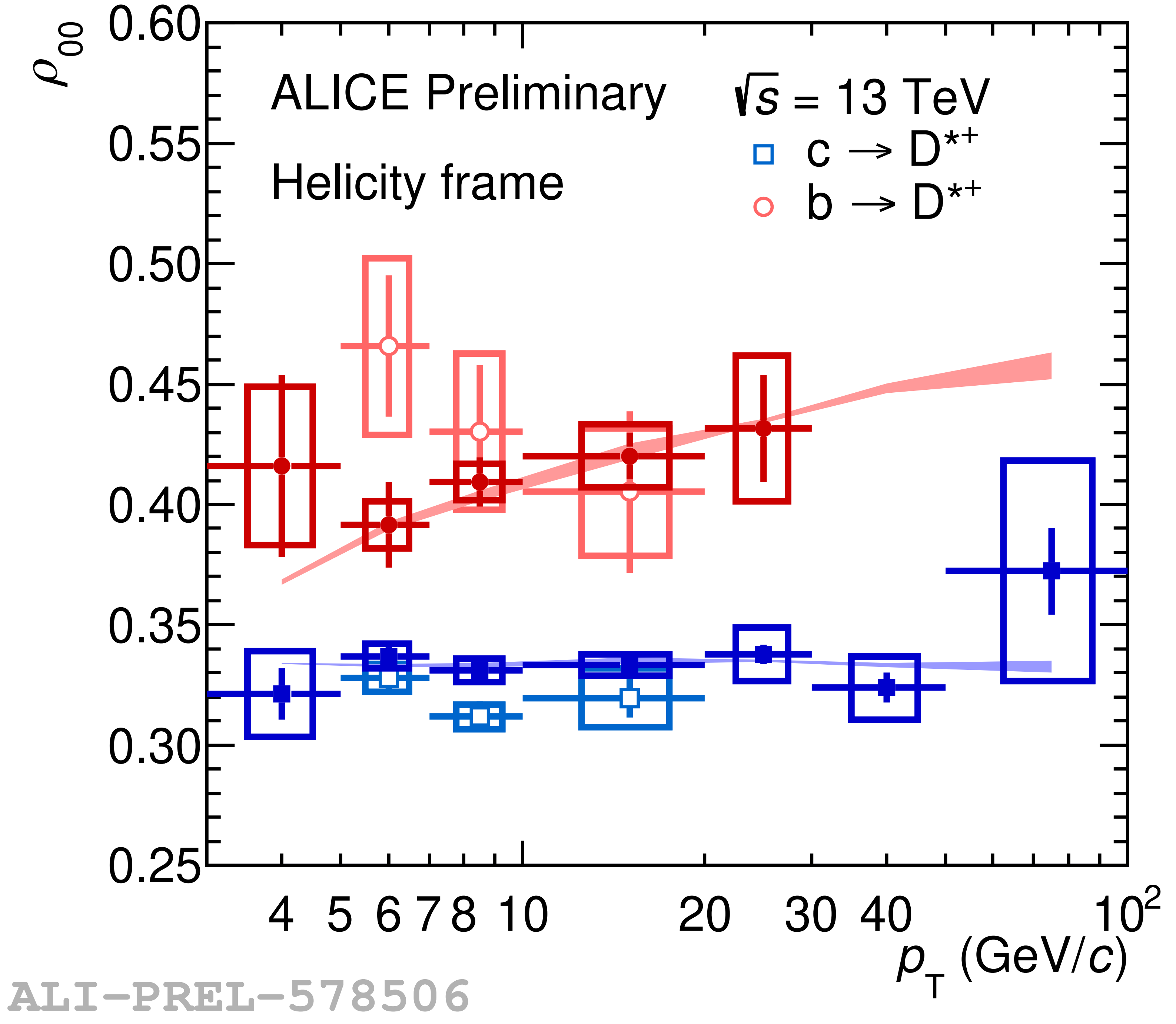
Spin alignment of D*+ mesons in pp collisions

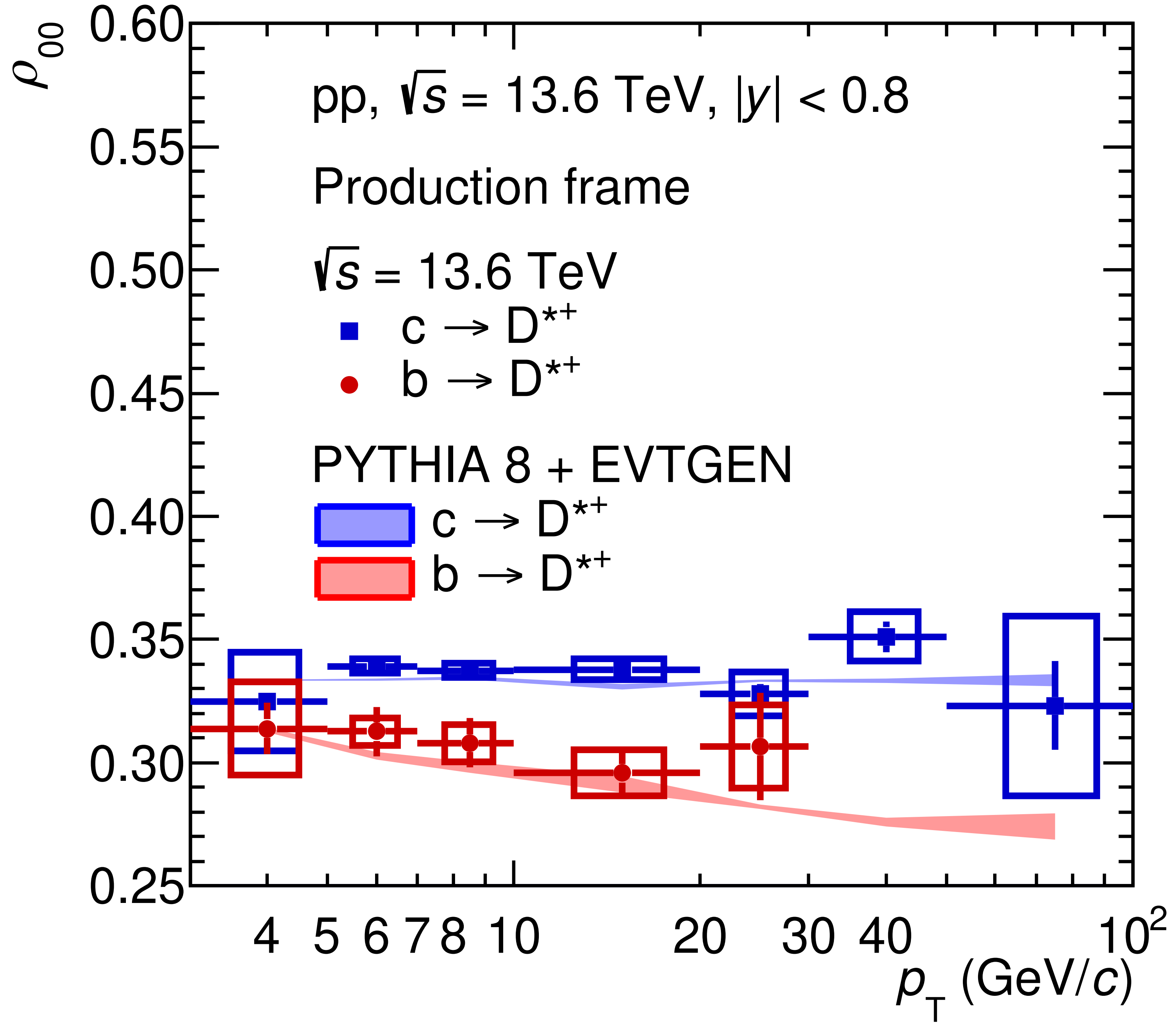


ALICE, PLB 846 (2023) 137920 ALICE Preliminary
PYTHIA8: CPC 191 (2015) 159–177
EVTGEN: NIM A 462 (2001) 152–155

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

Spin alignment of non-prompt charm mesons in pp collisions



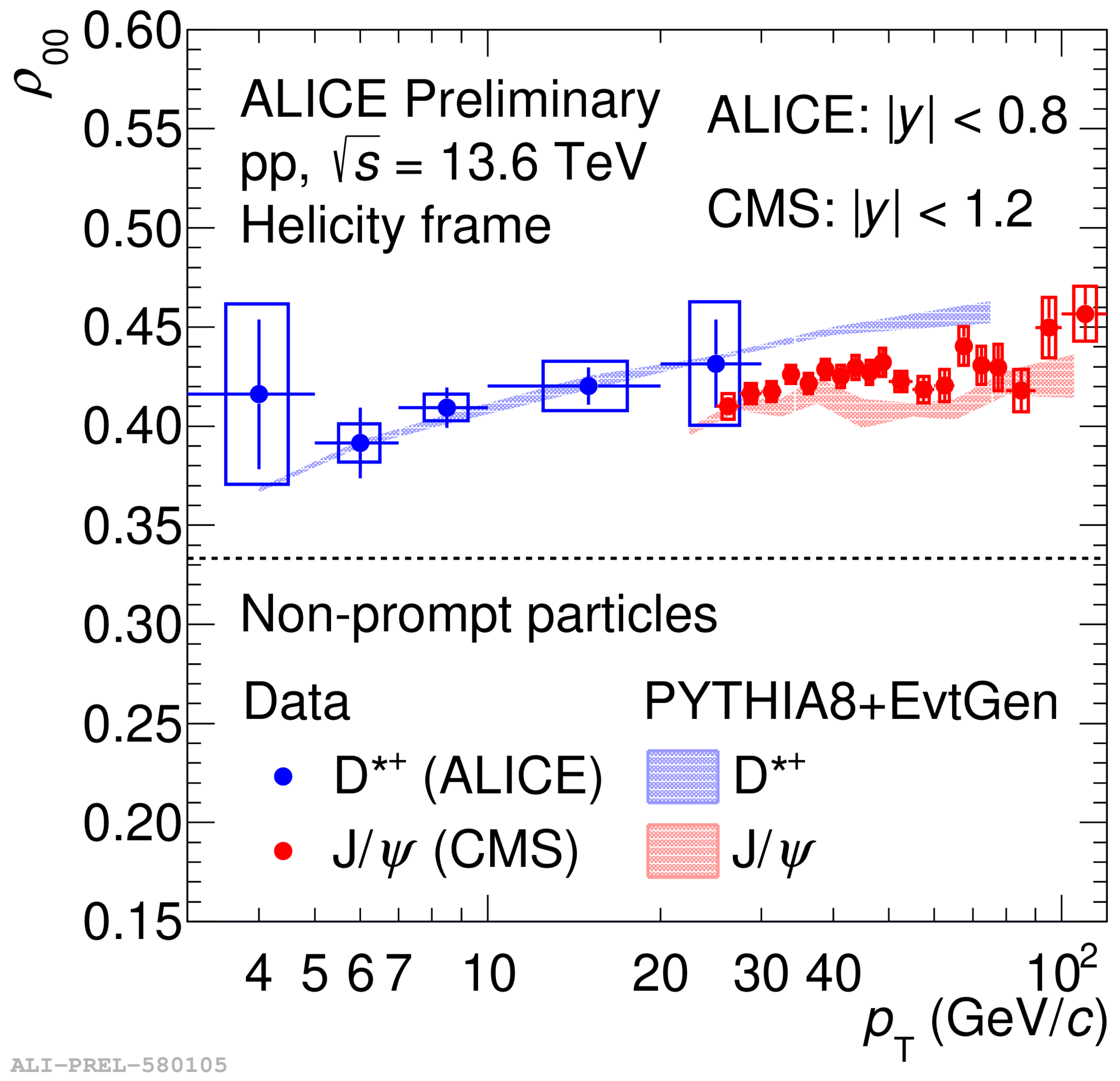


ALICE, PLB 846 (2023) 137920 ALICE Preliminary

PYTHIA8: CPC 191 (2015) 159–177

EVTGEN: NIM A 462 (2001) 152–155

CMS, arXiv:2406.14409



- Baseline: spin alignment of prompt and non-prompt charm vector mesons with respect to helicity and production axes in pp collisions
  - ➡ Prompt D*+ compatible with no polarisation
  - ➡ Non-prompt D*+ ρ_{00} > 1/3 (helicity) < 1/3 (production)
    - helicity conservation in $B \rightarrow D^{*+}X$ decays

- Similar ρ_{00} for non-prompt D*+ and non-prompt J/ψ

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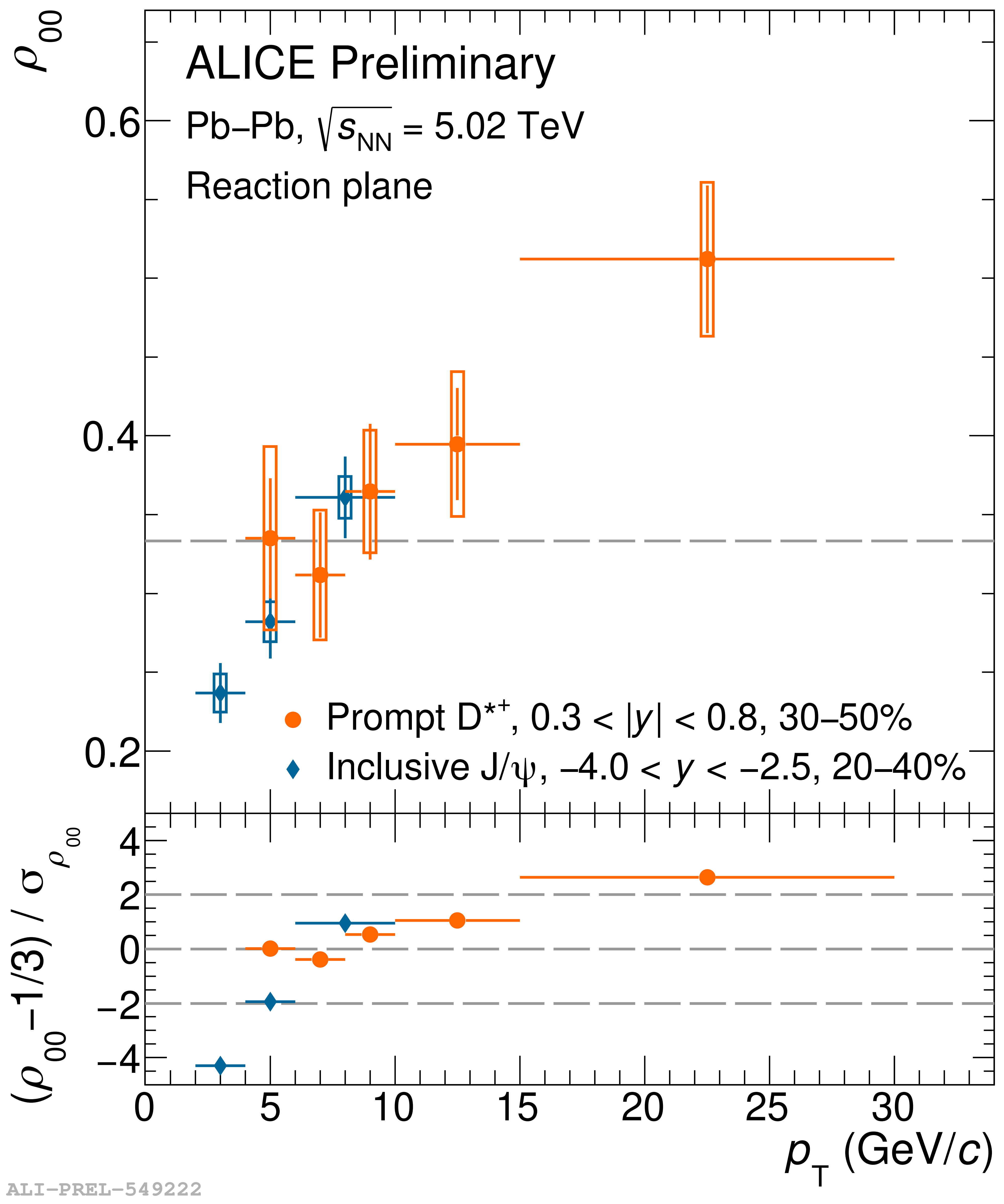

- D^{*+} measurement compatible with polarised charm quarks hadronising via fragmentation
- J/ψ measurement compatible with polarisation due to angular momentum / vector-meson fields and hadronisation via recombination

→ More about J/ψ polarisation in talk by X. Bai

ALICE, PRL 131 (2023) 042303
ALICE Preliminary

Summary and conclusions

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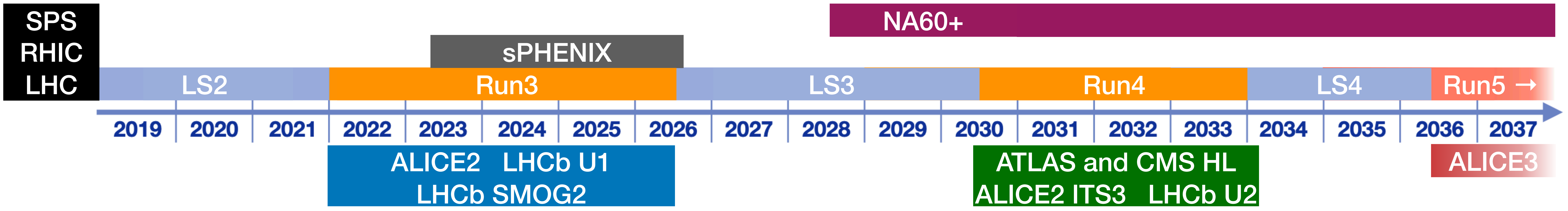
- Hadrons containing heavy quarks are excellent probes of the quark–gluon plasma, which allows us to study:
  - ➡ transport coefficients (i.e. spatial diffusion) and possible thermal equilibrium
  - ➡ colour-charge and quark-mass dependence of energy loss
  - ➡ hadronisation mechanisms
  - ➡ Early magnetic field and angular momentum produced in non-central heavy-ion collisions

- Core of physics programs of current and future heavy-ion experiments

→ See presentations by M. Van Leeuwen, A. Fantoni, A. Marie



ADDITIONAL SLIDES

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- Hint of increasing trend with p_T in midcentral Pb–Pb collisions
- Only in the rapidity interval $0.3 < |y| < 0.8$ → need of more precise and more differential (vs y) measurements