Study of heavy-quark transport properties with ALICE

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Why heavy quarks as QGP probes?

Heavy-quark mass (charm and beauty) large compared to the scales characterising the QGP:

$m_Q >> \Lambda_{QCD}$ **and** $m_Q >> T_{QGP}$

As consequence:

✦production restricted to **initial hard-scattering processes**

production time of $c\bar{c}(b\bar{b})$ pair at rest:

$\tau_{prod} = \hbar/4m_{c(b)} \simeq 0.1(0.02)$ fm/c < $\tau_{QGP} \simeq 0.1\text{-}1$ fm/c

✦**Brownian motion** in the QGP at low momenta

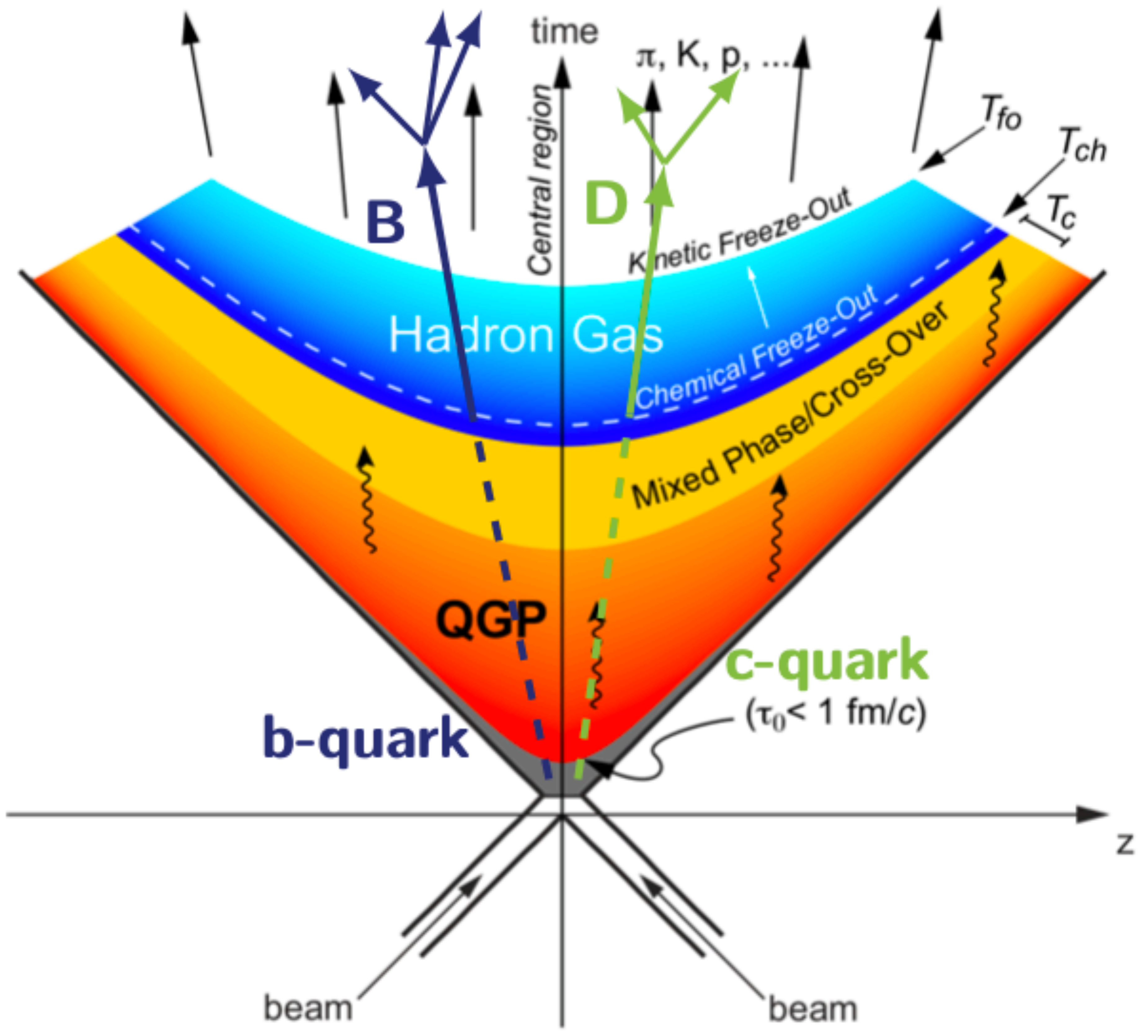
➡ access to the **spatial diffusion coefficient** $\mathbf{2\pi T D_s}$

✦Flavour conserved in strong interactions

➡ **transported through the full system evolution**

✦Long relaxation time τ_Q comparable with the fireball lifetime (~ few fm/c)

➡ **reach partial thermalisation**



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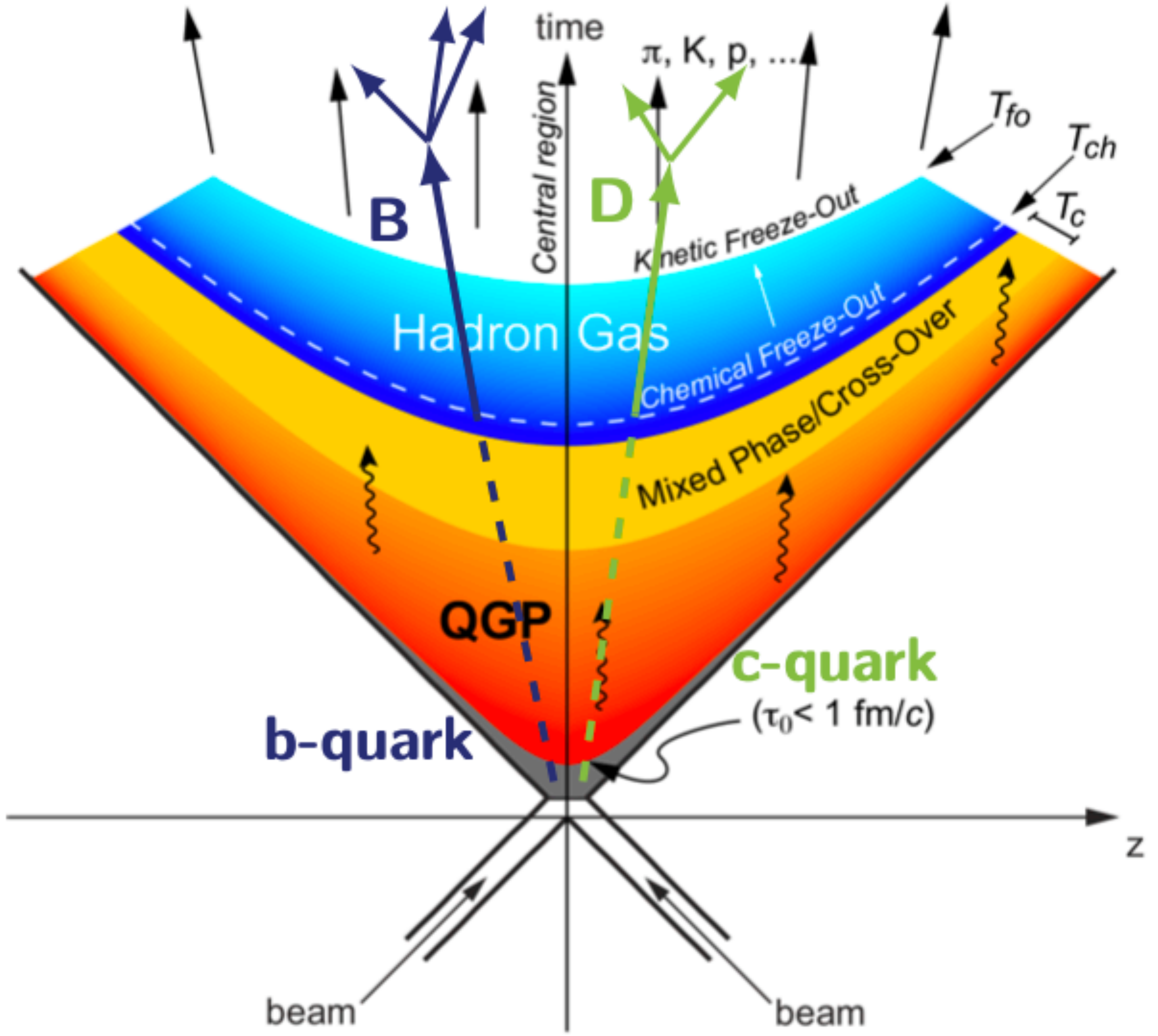


QGP investigations with HQs:

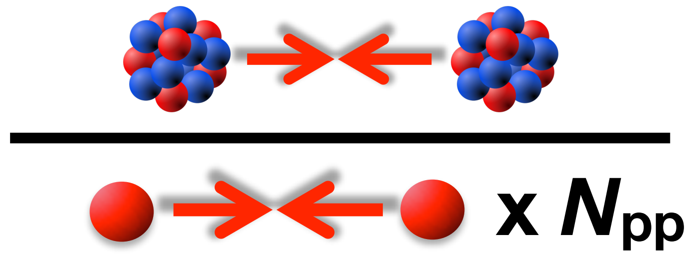
✦**In-medium energy-loss**: colour-charge and quark-mass dependence

✦HQ participation in the collective expansion, **thermalisation** in the medium

✦**Modification of the hadronisation mechanisms** in the medium

In-medium energy loss: D-meson nuclear modification factor

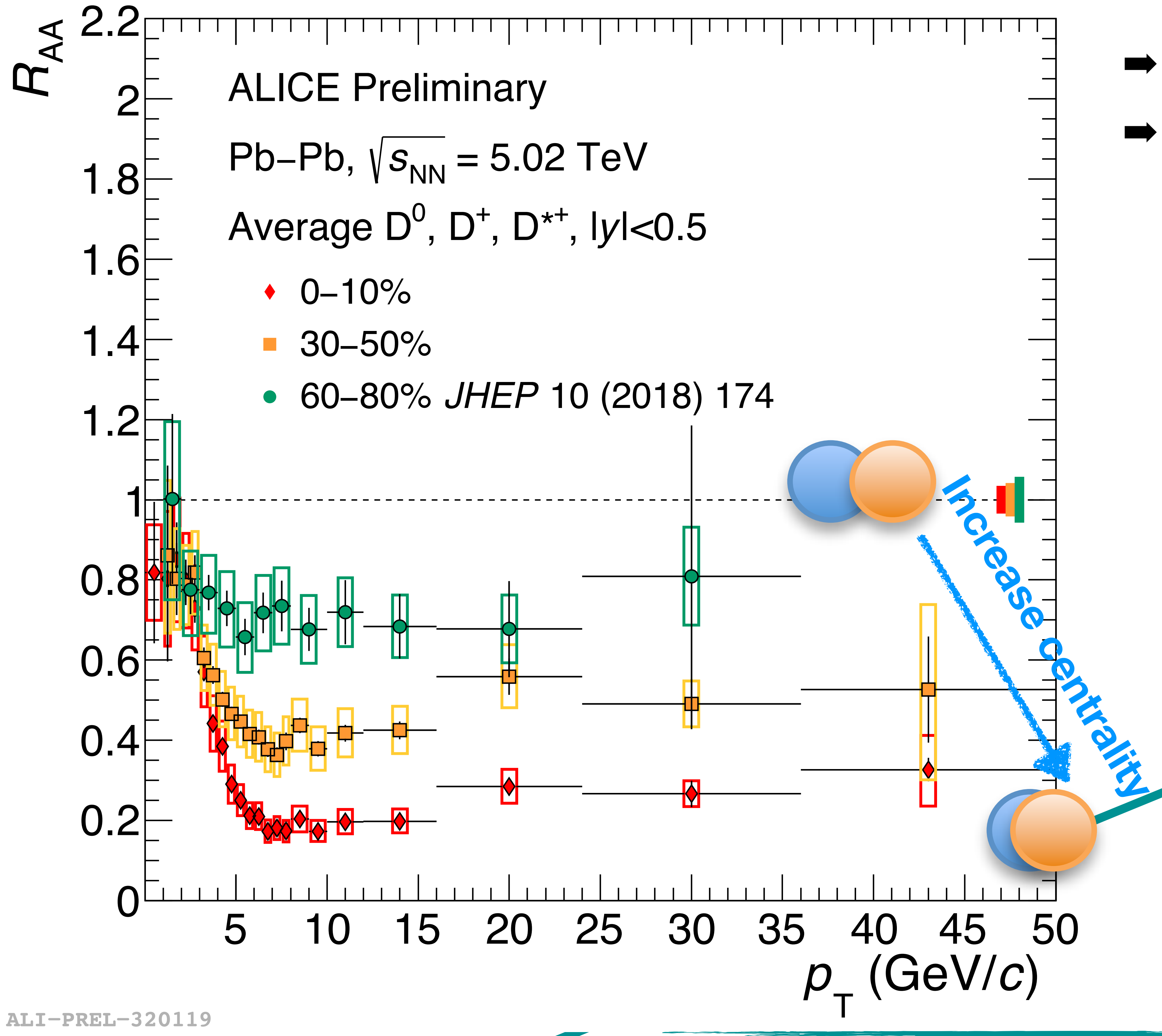
$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} =$$



In-medium energy loss: D-meson nuclear modification factor

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

= (Pb-Pb collision) / (pp collision x N_{pp})



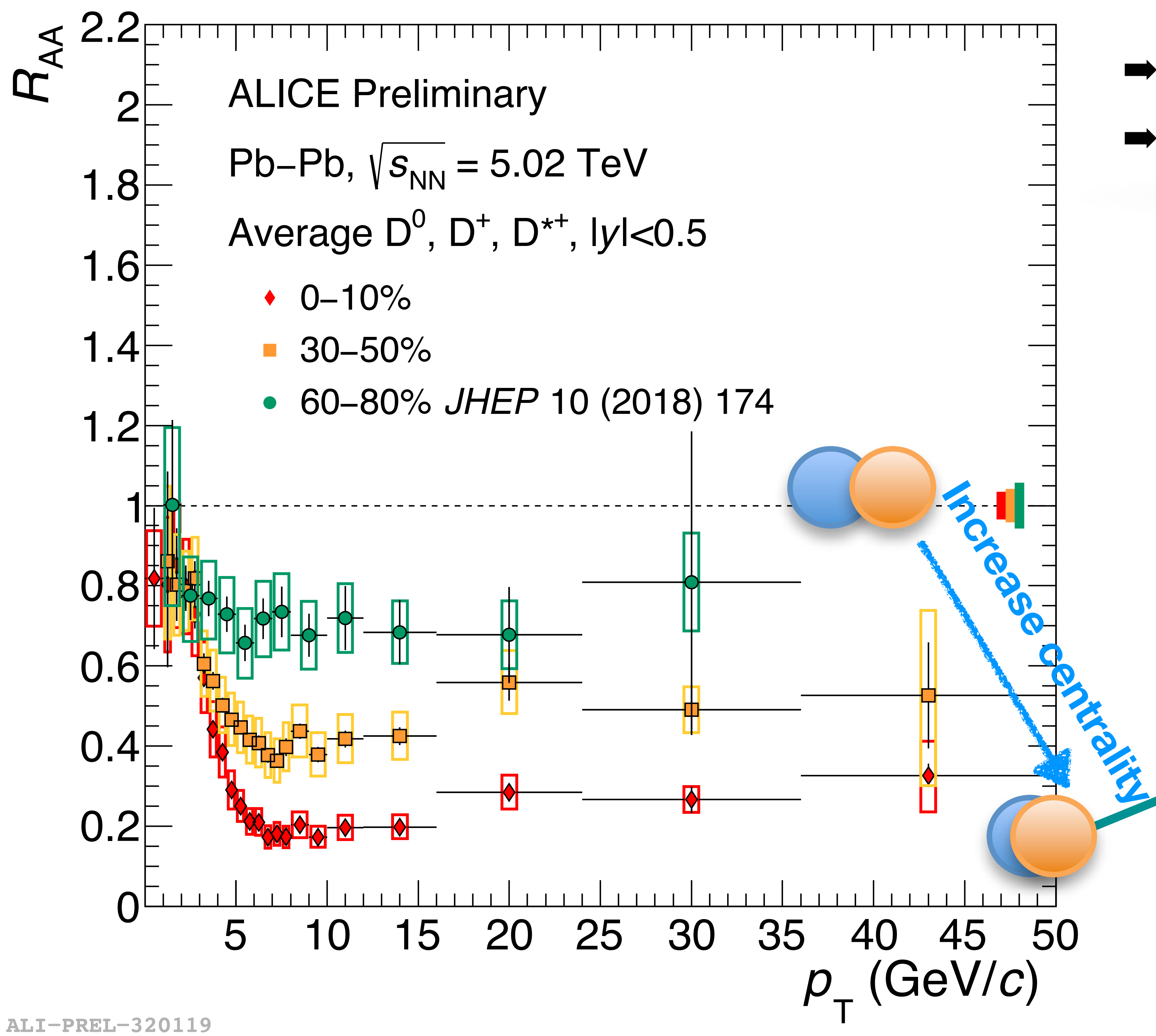
➡ **Strong suppression of D mesons in Pb-Pb collisions**

➡ Increasing suppression with centrality

Strong energy loss of charm quarks in the medium

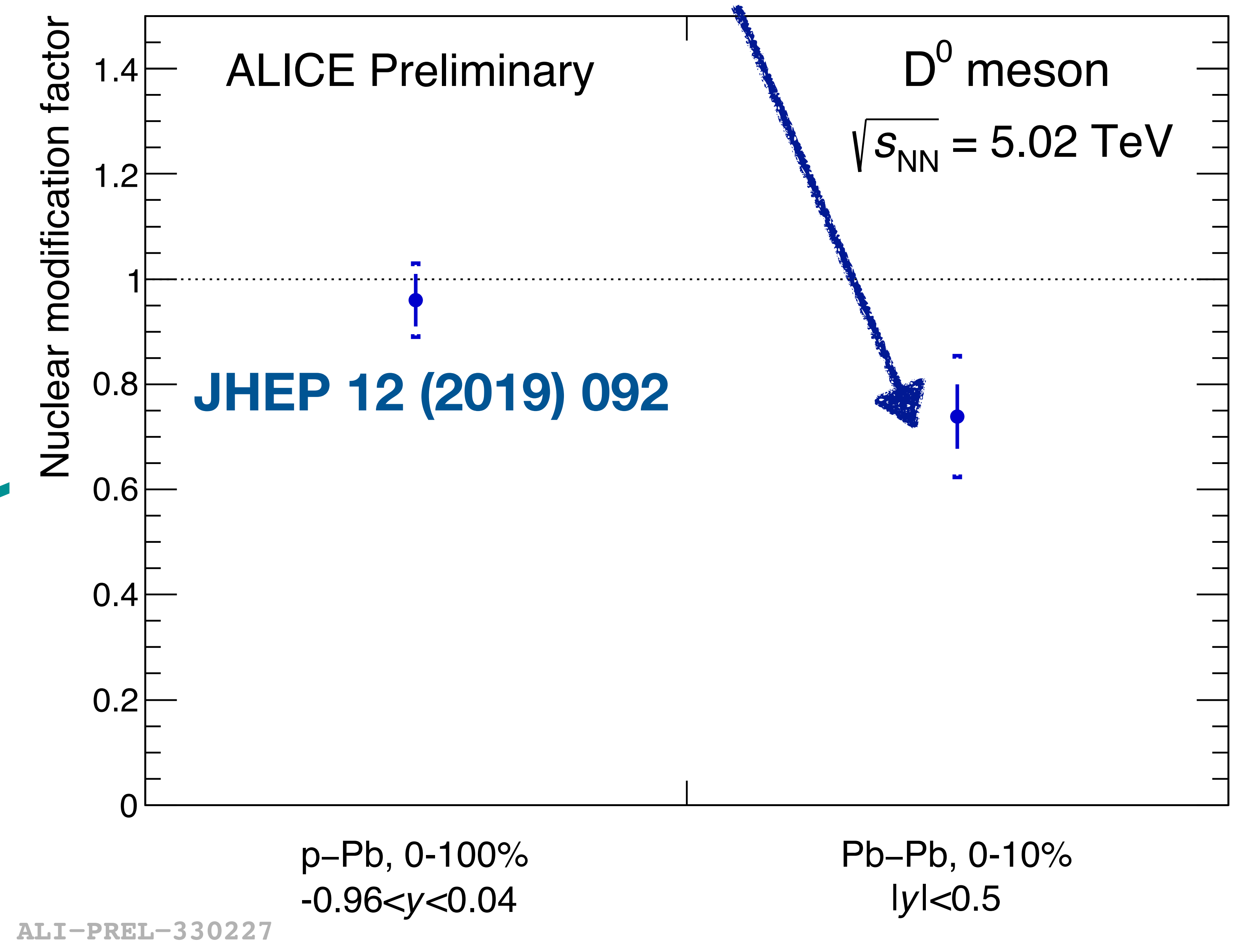
In-medium energy loss: D-meson nuclear modification factor

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{\text{Pb–Pb}}{\text{pp} \times N_{pp}}$$



- ➡ **Strong suppression of D mesons in Pb-Pb collisions**
- ➡ Increasing suppression with centrality

D^0 R_{AA} measured down to $p_T = 0$ ➞ p_T-integrated R_{AA}



Hint of p_T-integrated D^0 $R_{AA} < 1$ and $R_{pPb} = 1$:
modification of the hadronisation in Pb-Pb collisions?

In-medium energy loss: light vs heavy quarks

✦Quark-mass and colour-charge dependence studied comparing **D mesons** and **light hadrons**

$$\Delta E(\text{ch. part}) > \Delta E(\text{D}) > \Delta E(\text{B}) \overset{?}{\rightarrow} R_{\text{AA}}(\text{ch. part}) < R_{\text{AA}}(\text{D}) < R_{\text{AA}}(\text{B})$$

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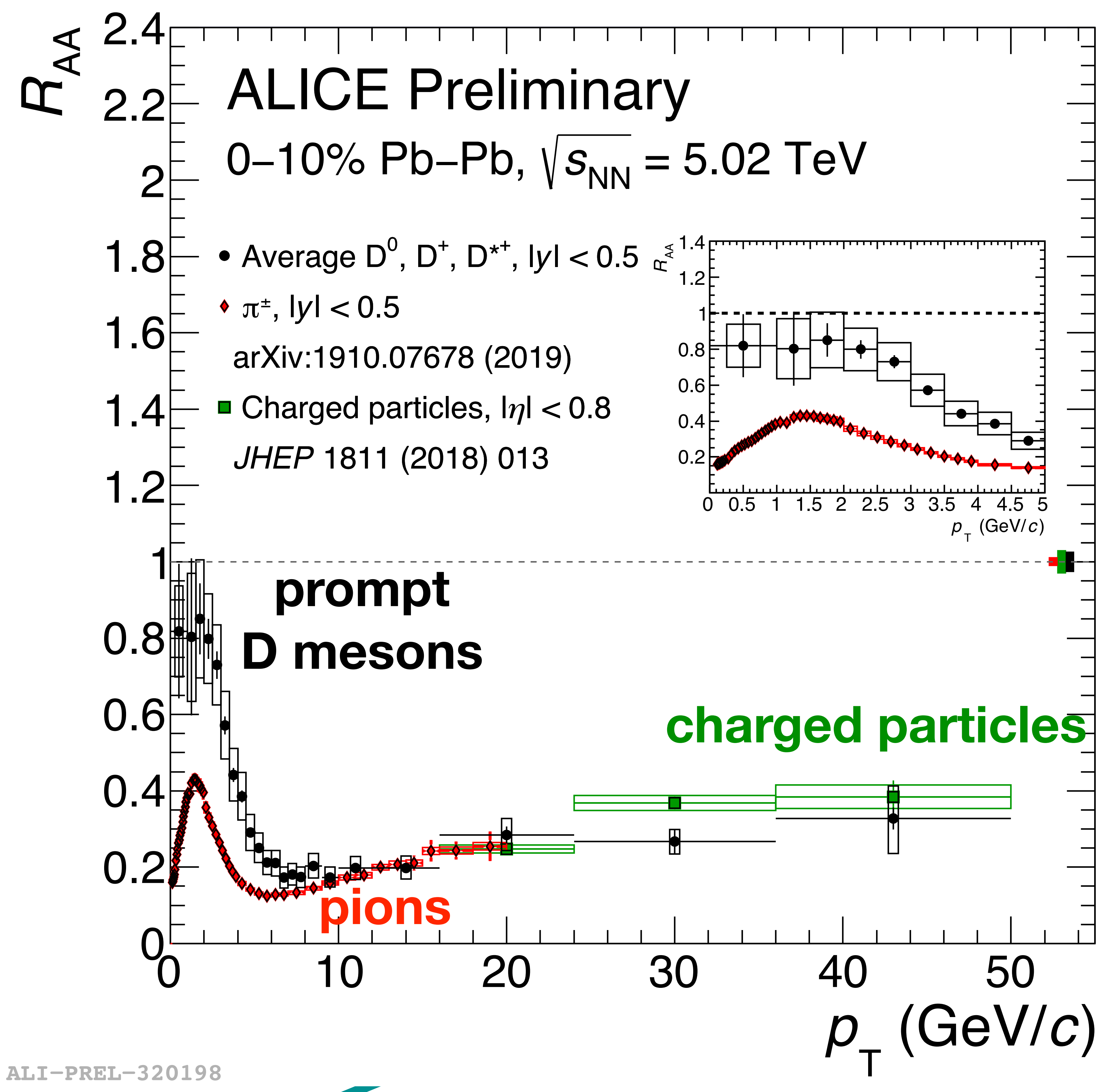

✦**R_{AA}(D) > $R_{AA}(\pi)$ for p_T < 10 GeV/c**

✦**Comparable R_{AA} for p_T > 10 GeV/c**

➡Interpretation not straightforward:

possible mass and Casimir factor effects, shadowing, interplay between different p_T spectra of charm, light quarks and gluons, and different fragmentation fractions

In-medium energy loss: charm vs beauty quarks

ΔE(ch. part) > ΔE(D) > ΔE(B) $\xrightarrow{?}$ R_{AA}(ch. part) < R_{AA}(D) < R_{AA}(B)

In-medium energy loss: charm vs beauty quarks

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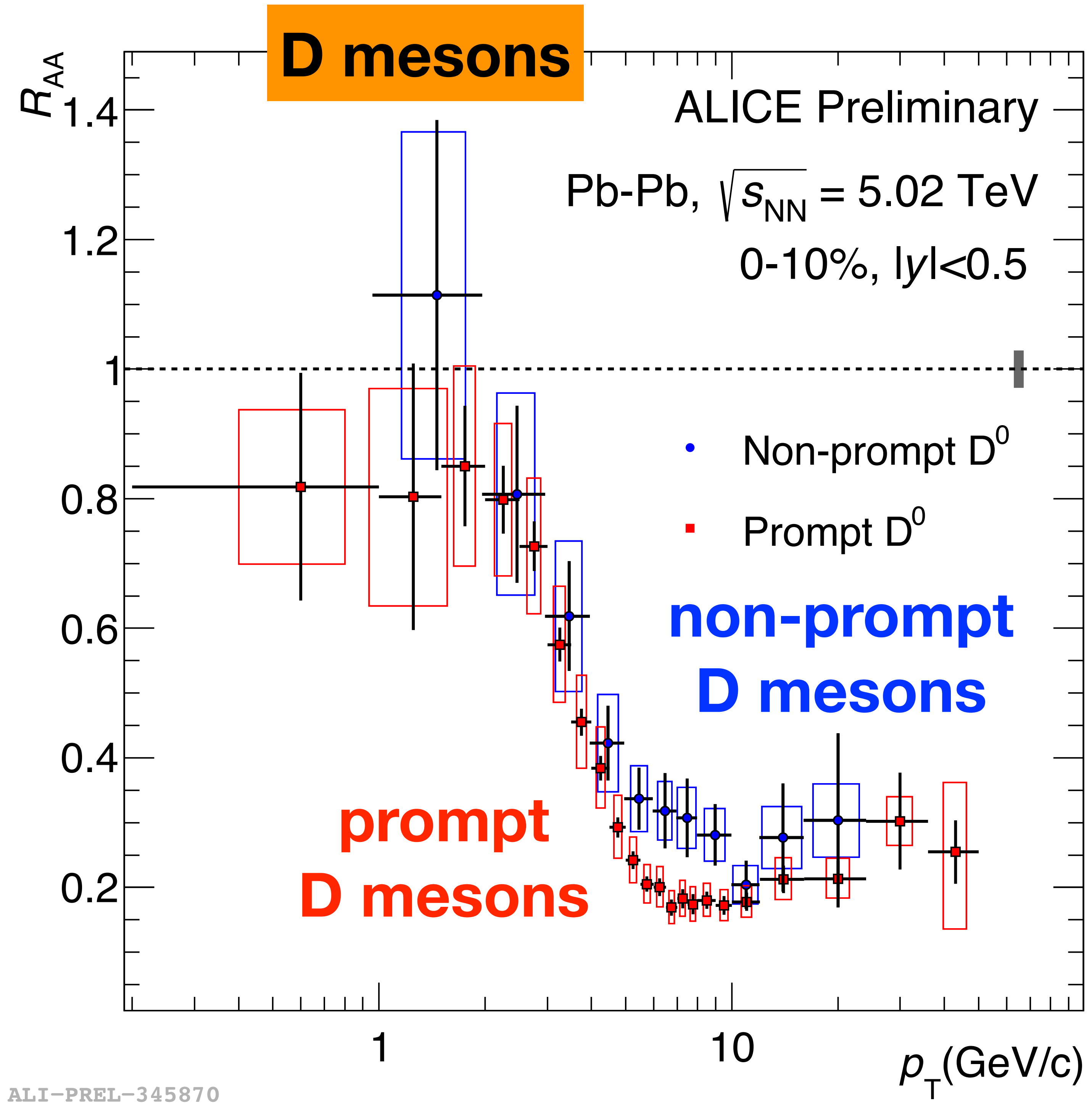
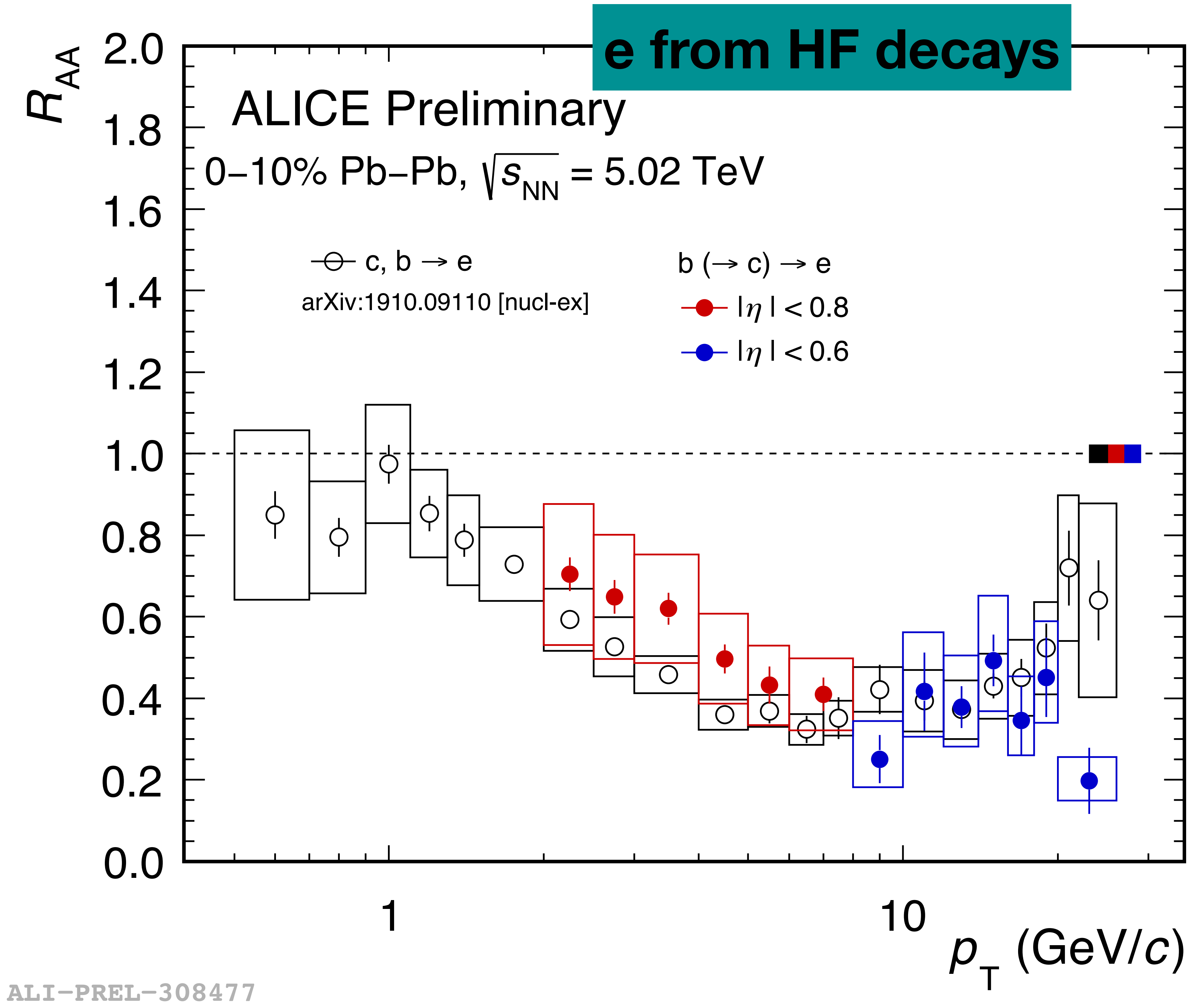




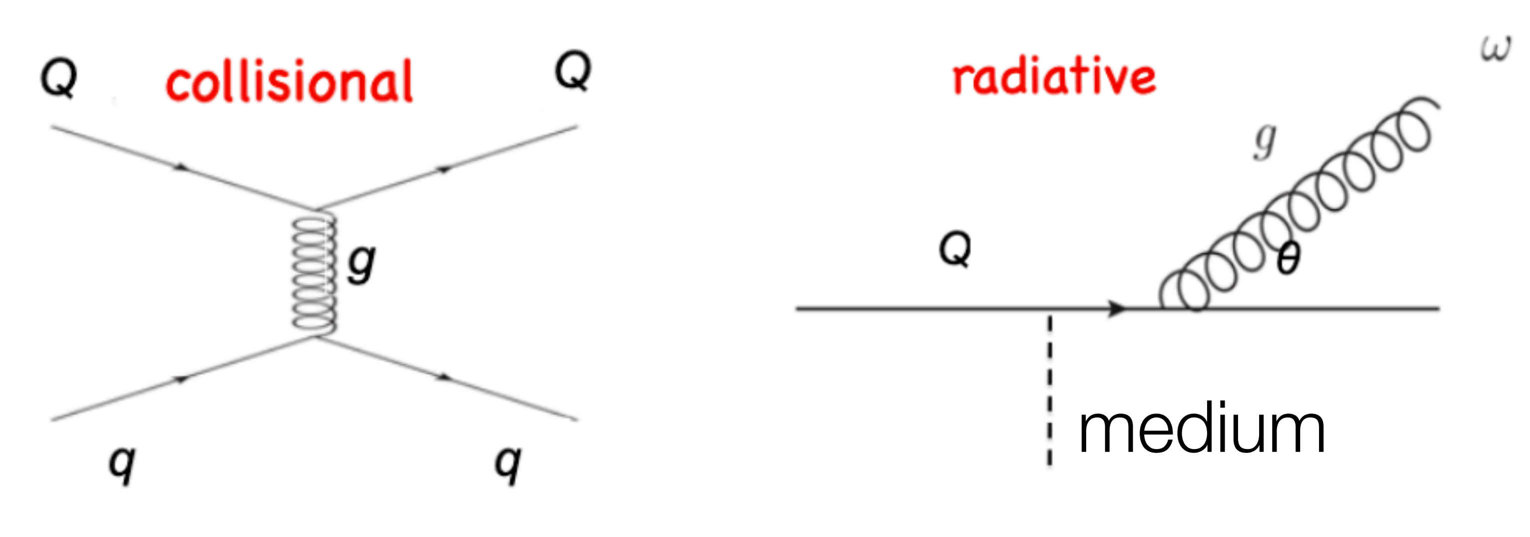
- ✦ R_{AA} (c→D) < R_{AA} (b→D) at intermediate p_T
- ✦ Hint of R_{AA} (c,b→e) < R_{AA} (b→e) at low p_T, compatible at high p_T where the beauty decay dominate

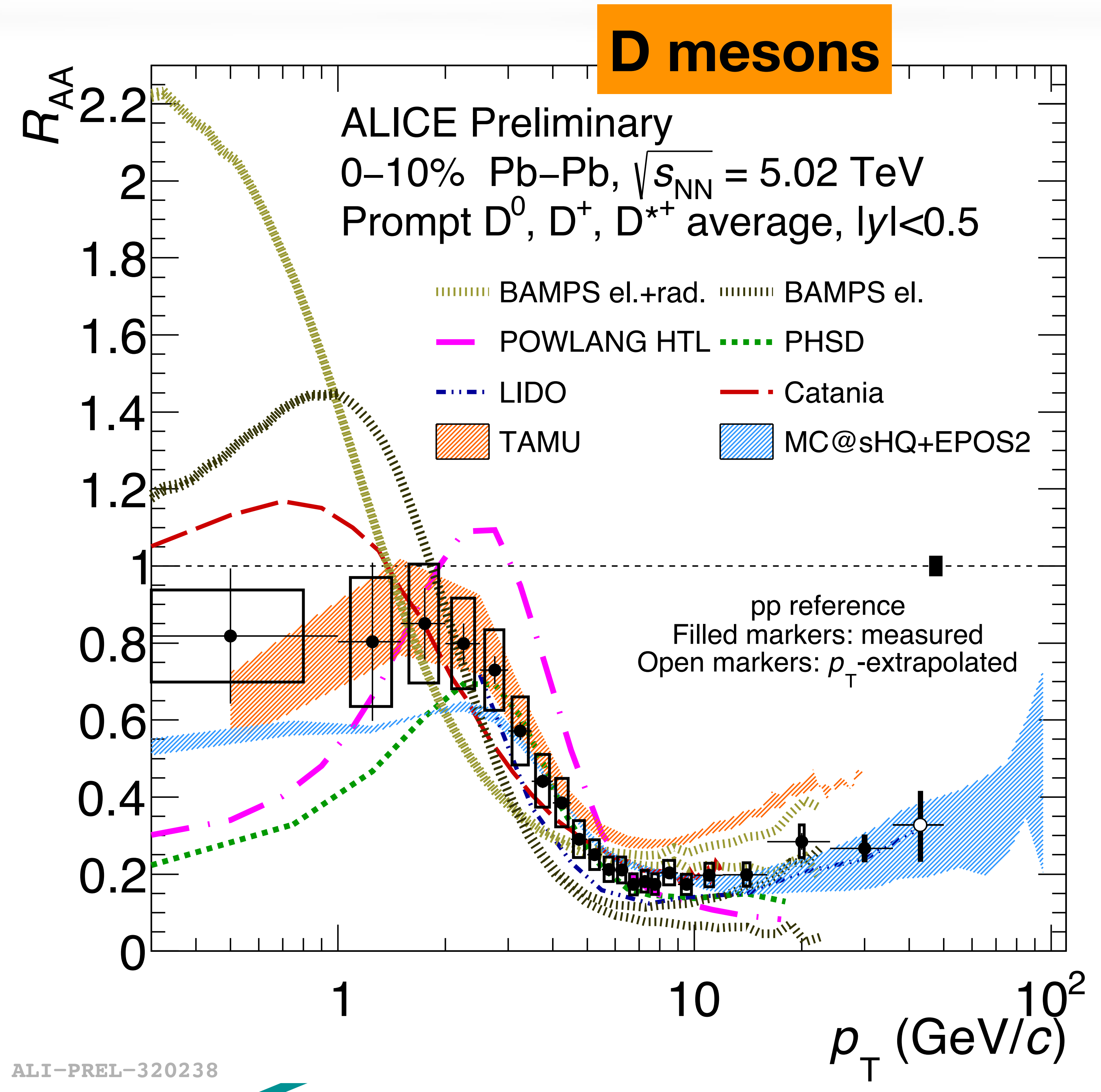
➡ **Parton-mass dependence of the energy loss**

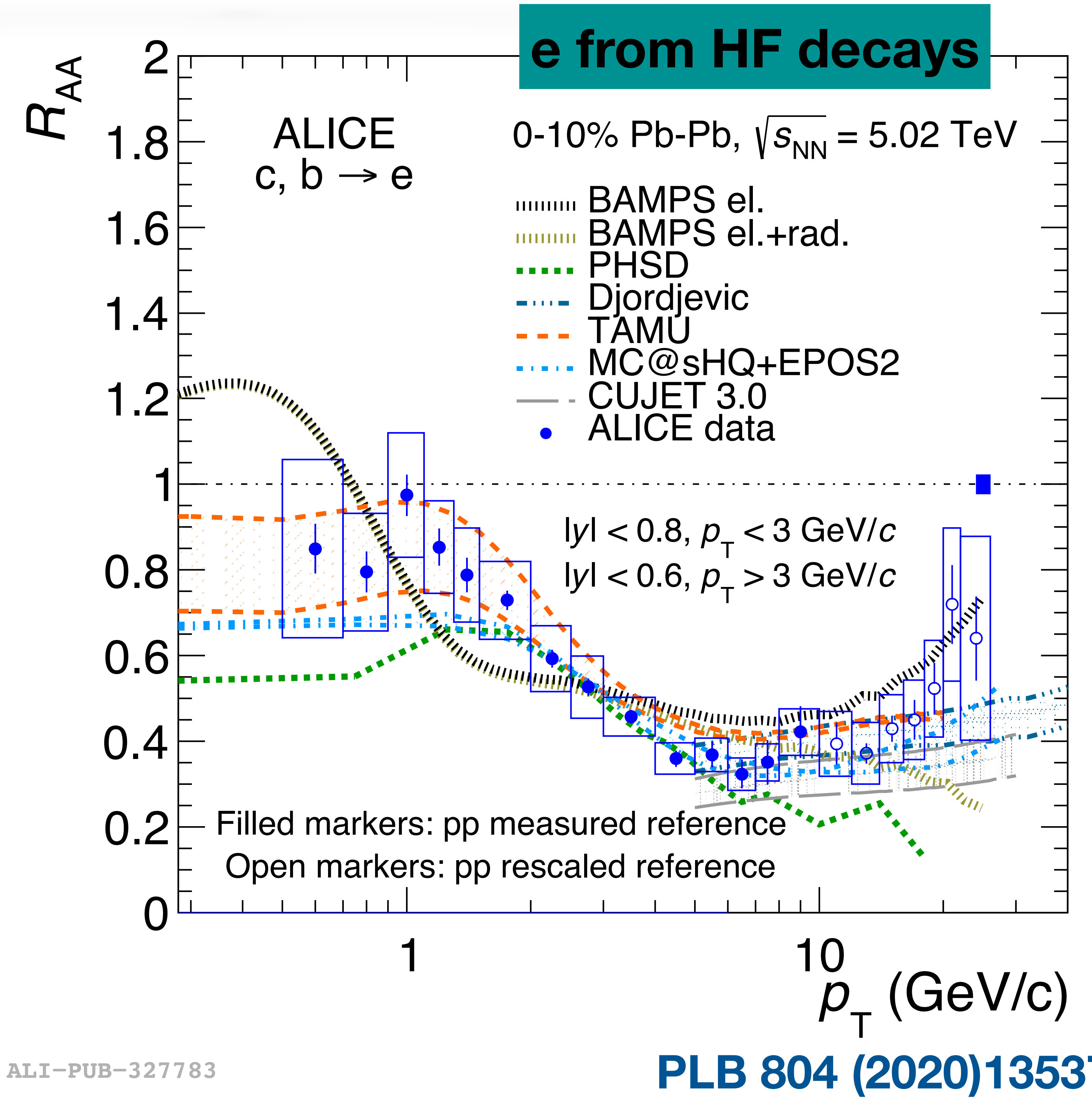
➡ **Dead cone effect**: gluon radiation suppressed for small angles ($\vartheta < m/E$)

Charm quark R_{AA} compared with models

✦Energy loss via **collisional** (dominant at low p_T) and **radiative** (dominant at high p_T) processes







PLB 804 (2020)135377

Interplay of collisional and radiative energy loss + hadronisation via coalescence and fragmentation, hydrodynamic expansion of the medium

Only collisional energy loss in: POWLANG, BAMPS el, TAMU

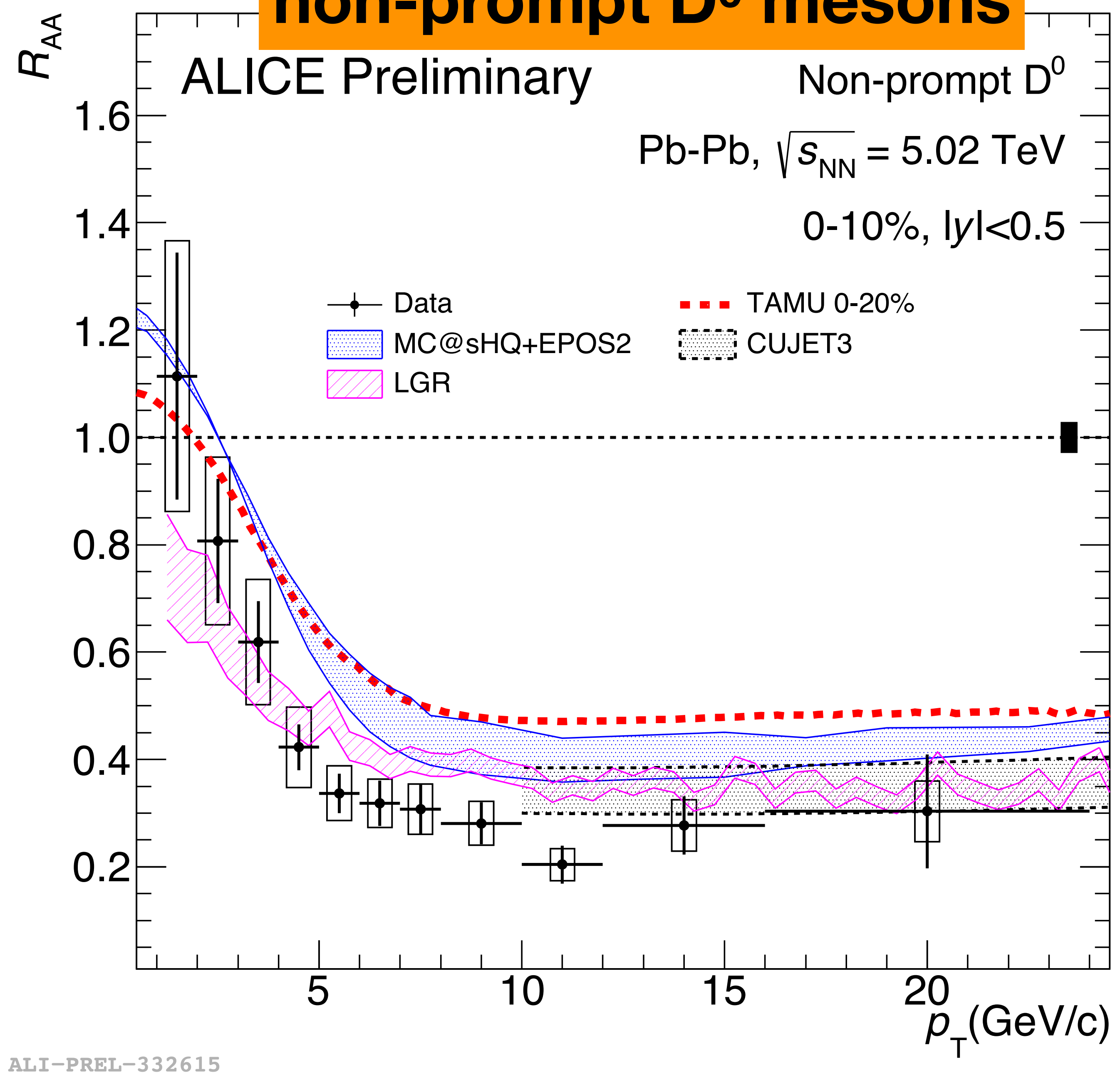
→determination of onset of radiative contributions by deviations from experimental data at a certain p_T

Collisional and radiative contributions in: PHSD, MC@sHQ+EPOS2, BAMPS el+rad, Djordjevic, LIDO, Catania

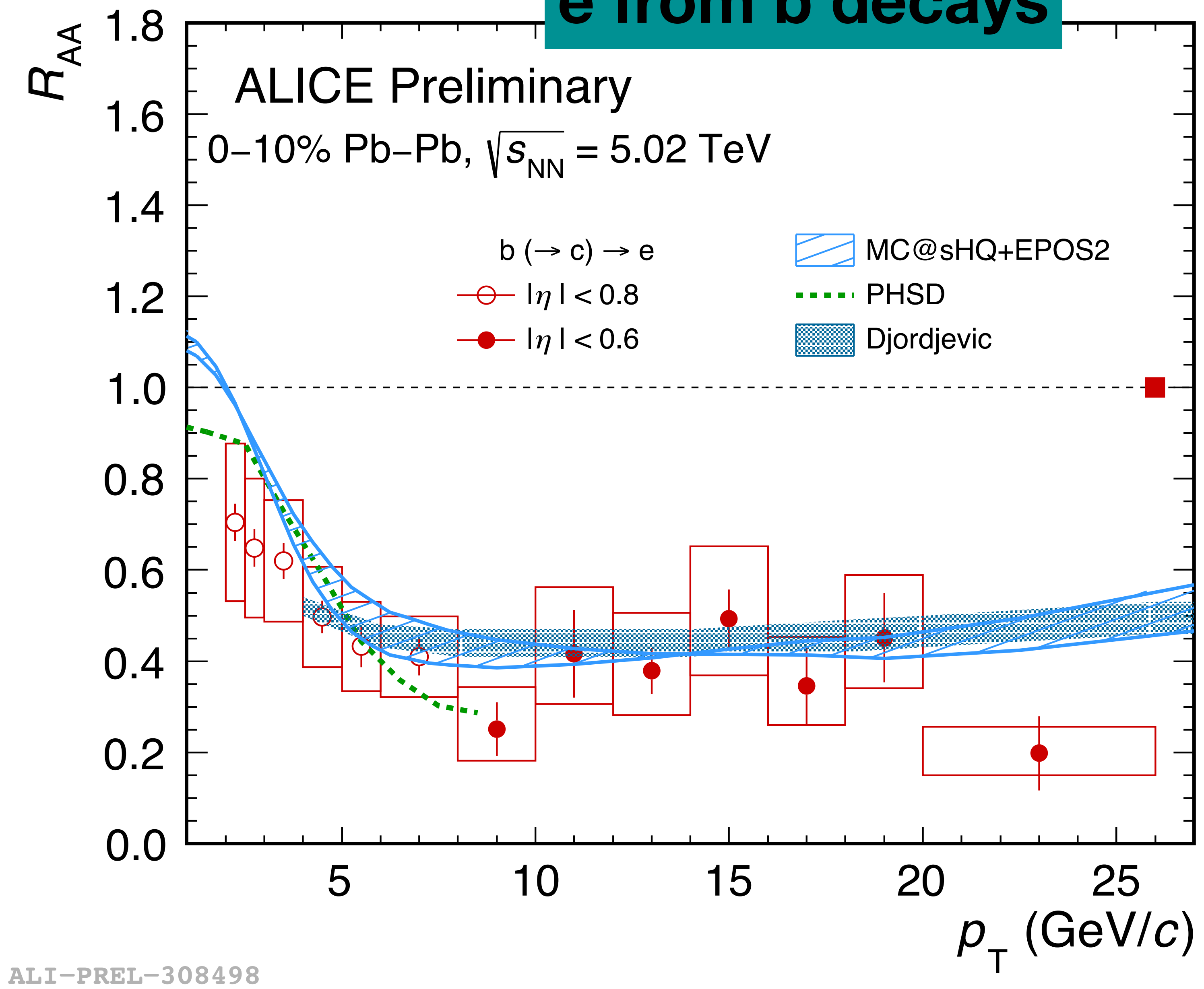
Quark recombination in: TAMU, POWLANG, PHSD, MC@sHQ, LIDO, Catania

Beauty quark energy loss compared with models

non-prompt D^0 mesons

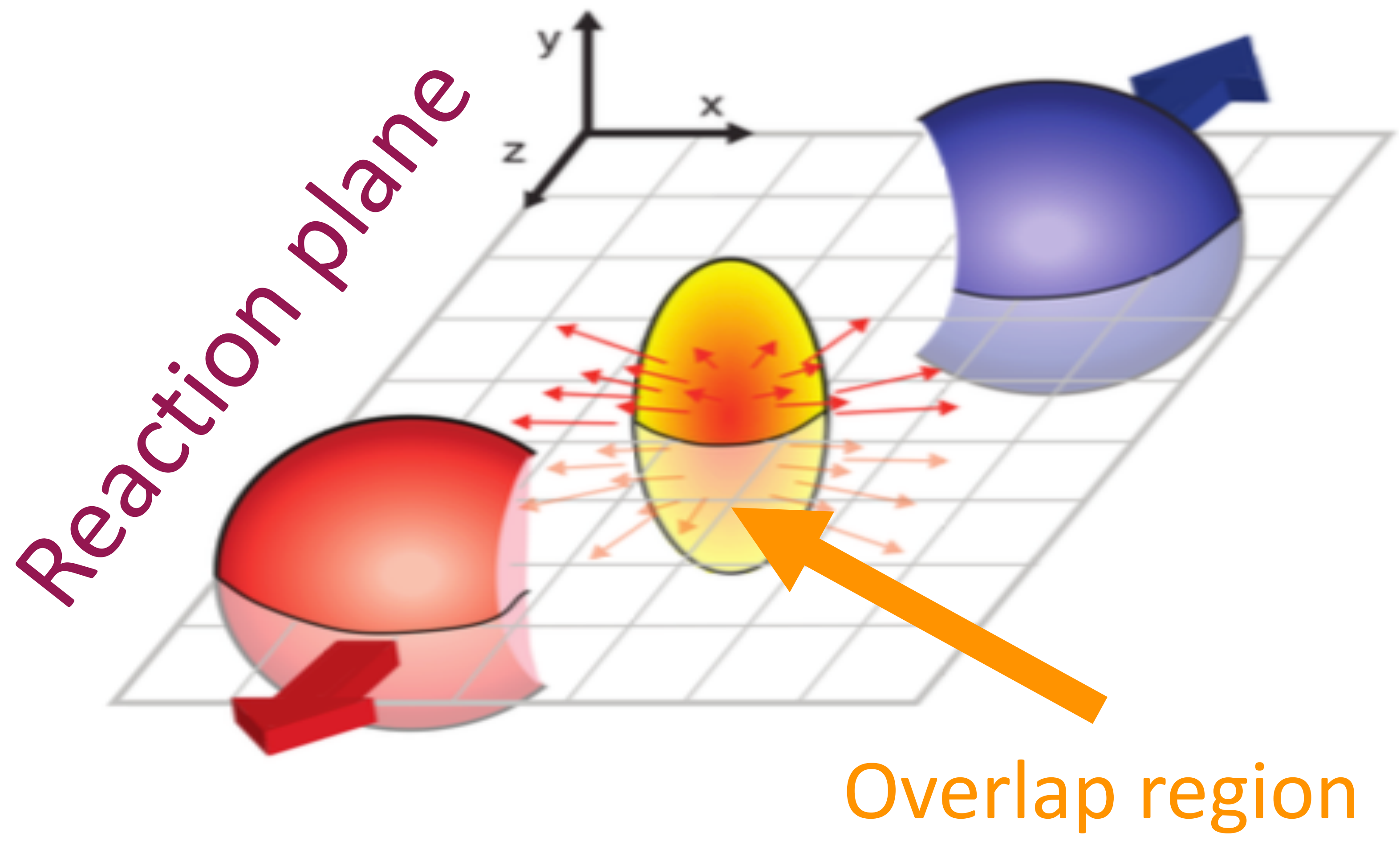


e from b decays



✦ Theoretical models including collisional and radiative energy loss can describe the data within uncertainties

Azimuthal anisotropies of heavy-flavour particles



- ✦ **Initial spatial anisotropy transferred into final anisotropy in momentum via collective interactions**
- ✦ **Expressed via the Fourier decomposition of the azimuthal distribution of particle momenta**

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_n))\right)$$

Flow coefficients

n^{th} symmetry plane

$$v_n = \langle \cos(n(\varphi - \Psi_n)) \rangle$$

Elliptic flow (v_2):

✦**low p_T**: sensitive to the participation of the HQ in the collective motion and thermalisation

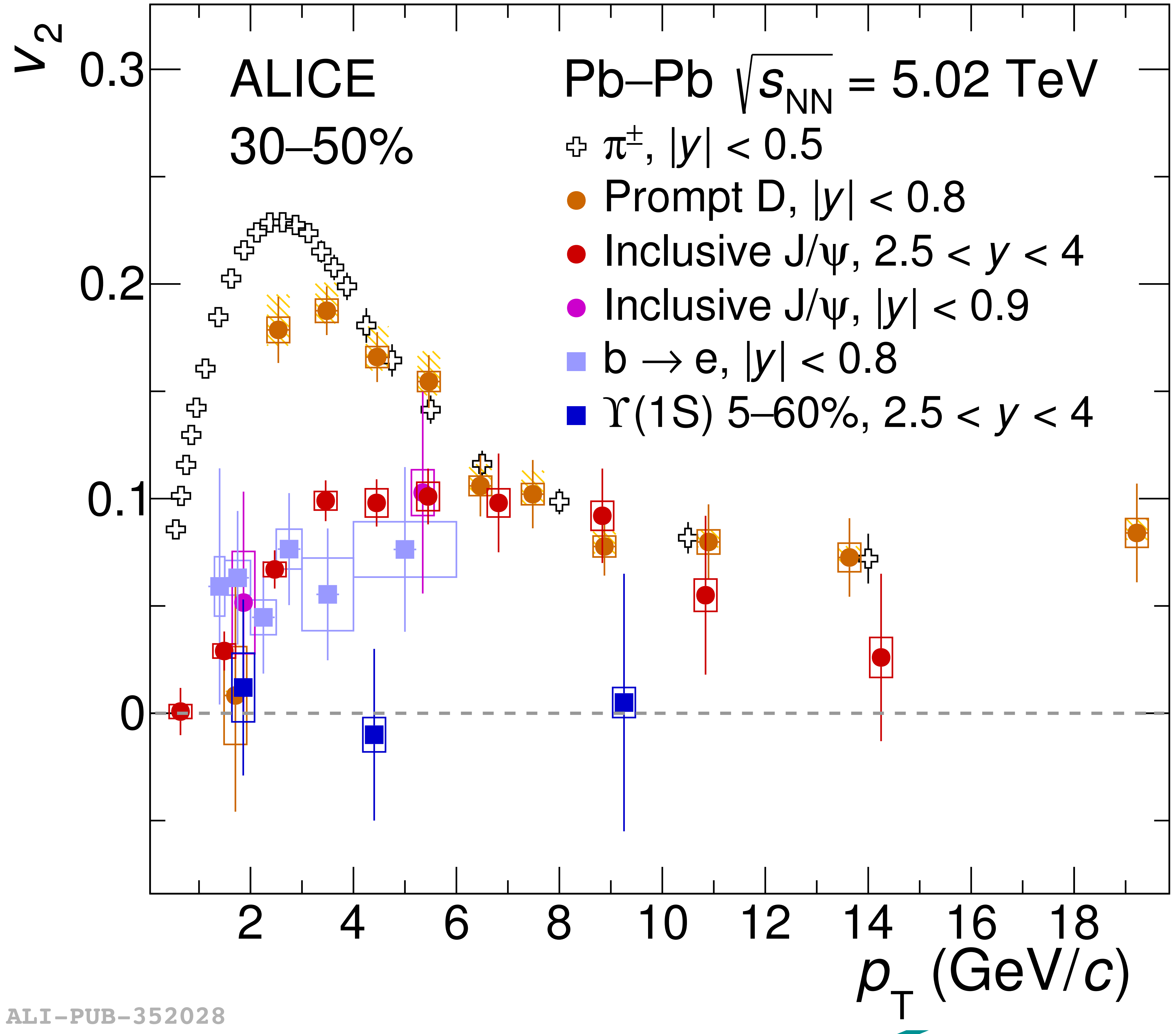
✦**high p_T**: sensitive to path-length dependence of energy loss

Triangular flow (v_3):

✦Originate from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region

✦Sensitive to the ratio fo shear viscosity to the entropy density η/s

Elliptic flow of heavy-flavour particles



- ✦Positive v_2 for prompt D mesons
- ✦Positive v_2 for J/ψ
- ✦Positive v_2 for b→e (significance 3.75σ)
- ✦ϒ(1S) v_2 compatible with zero

JHEP 09 (2018) 006 (pions)
arXiv:2005.11131 (D mesons)
arXiv:2005.14518 (J/ψ)
arXiv:2005.11130 (b→e)
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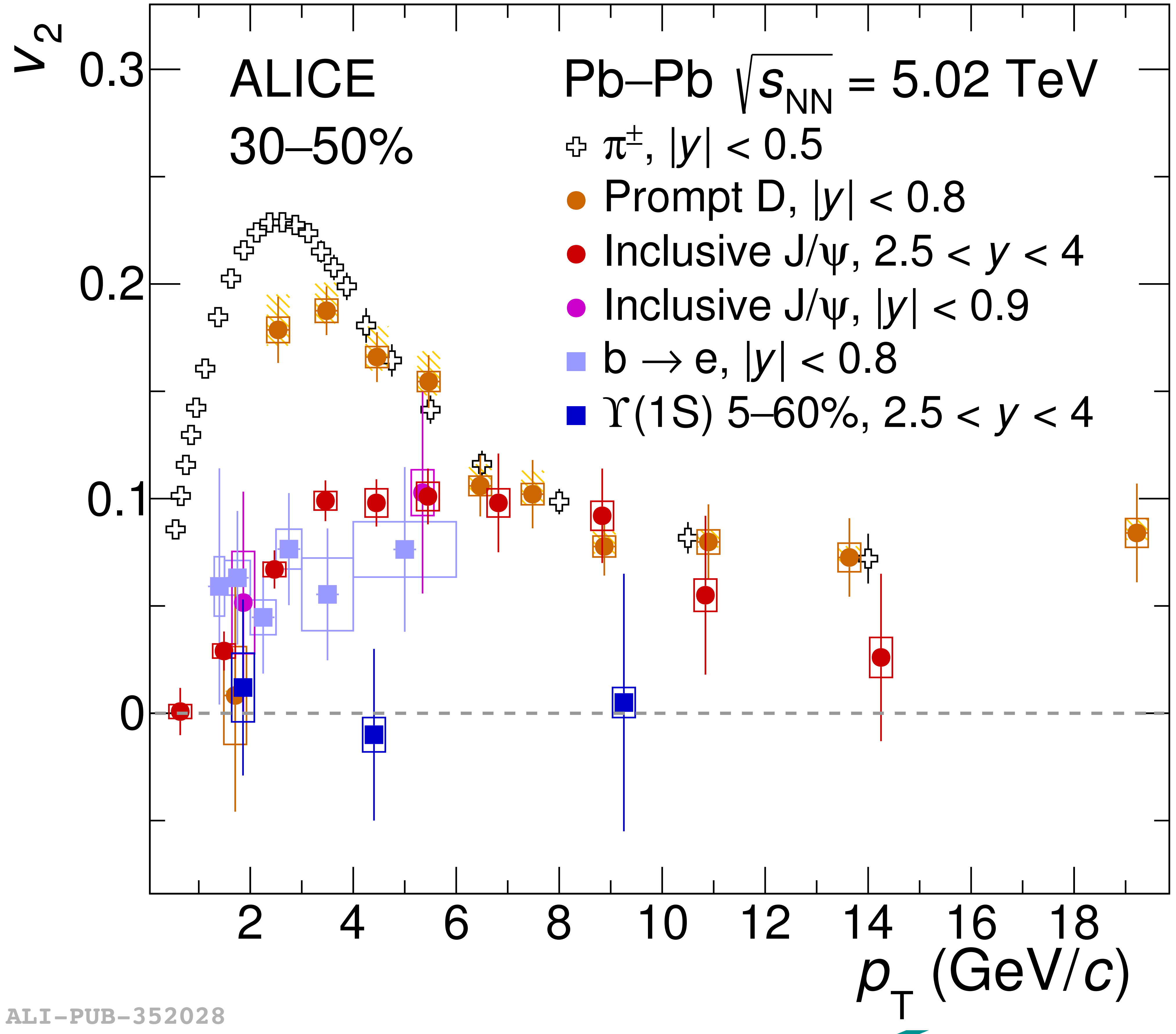

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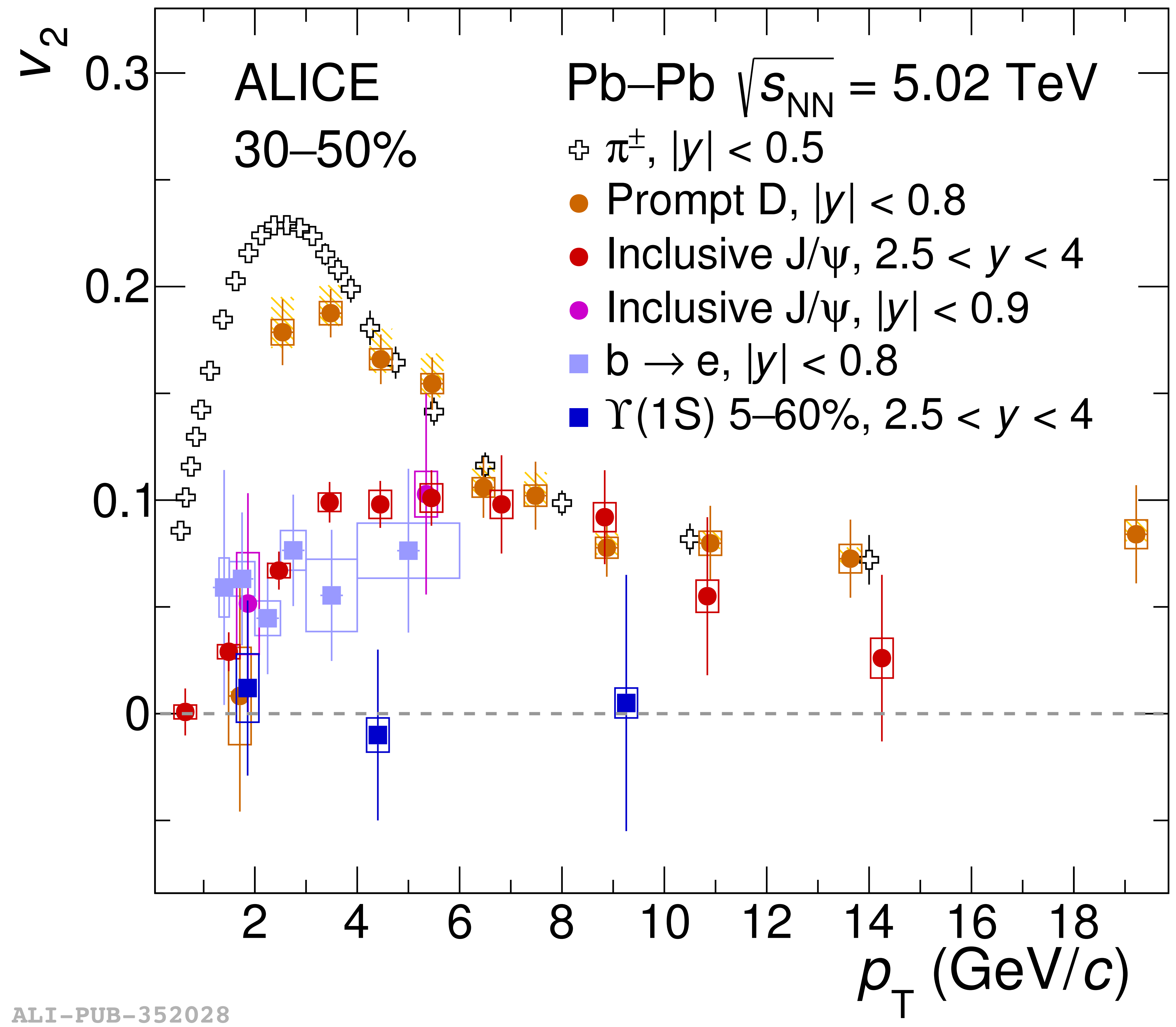
Looking more in details at different p_T regions:

- For $p_T < 3$ GeV/c ➡ **mass ordering**

$\boldsymbol{v_2(\Upsilon(1S)) \lesssim v_2(b \to e) \sim v_2(J/\psi) < v_2(D) < v_2(\pi)}$

Elliptic flow of heavy-flavour particles



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- For 3 < p_T < 6 GeV/c ➡ **charm quark coalescence with flowing light quarks**

v_2(J/ψ)< v_2(D)~v_2(π)

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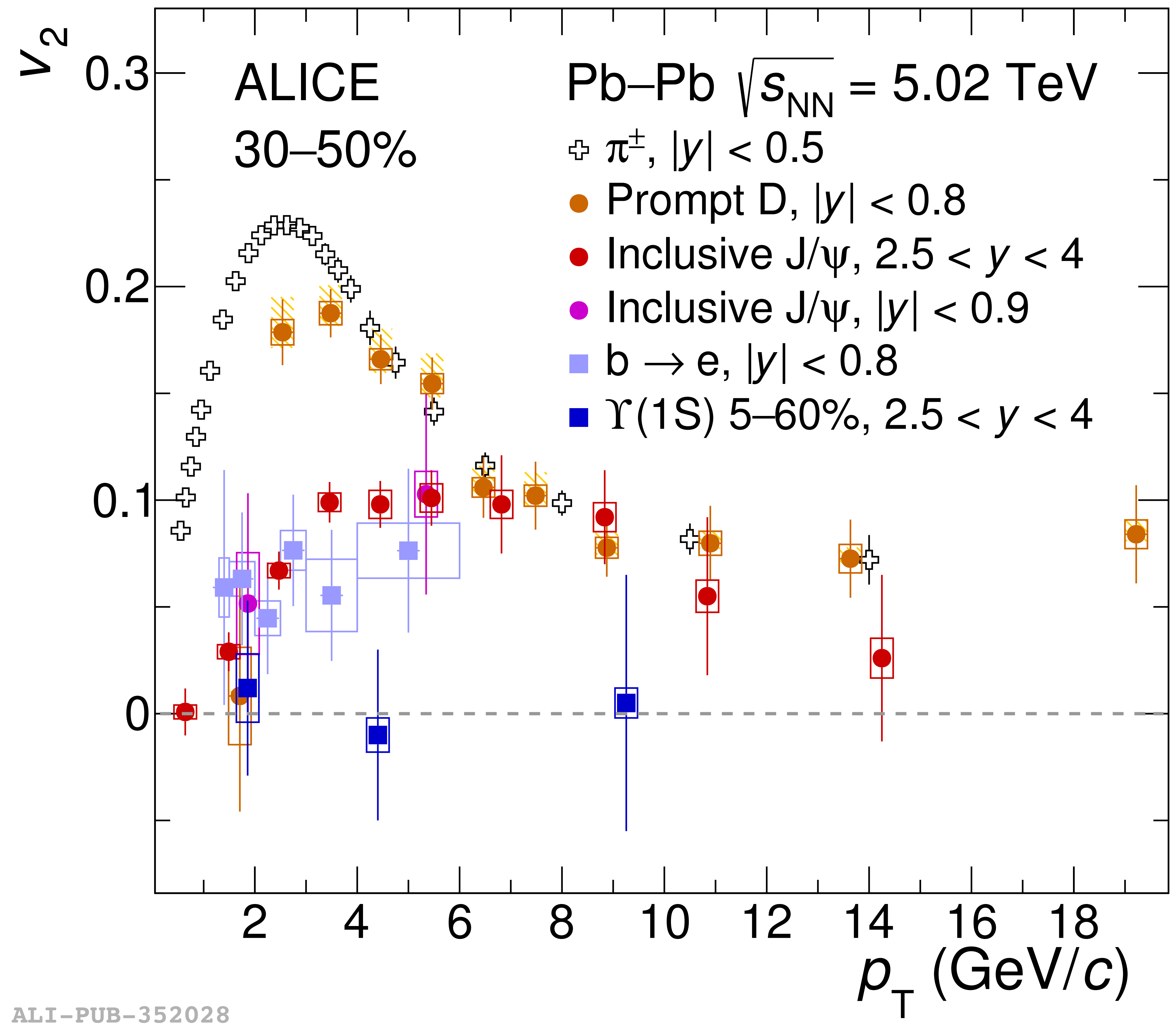

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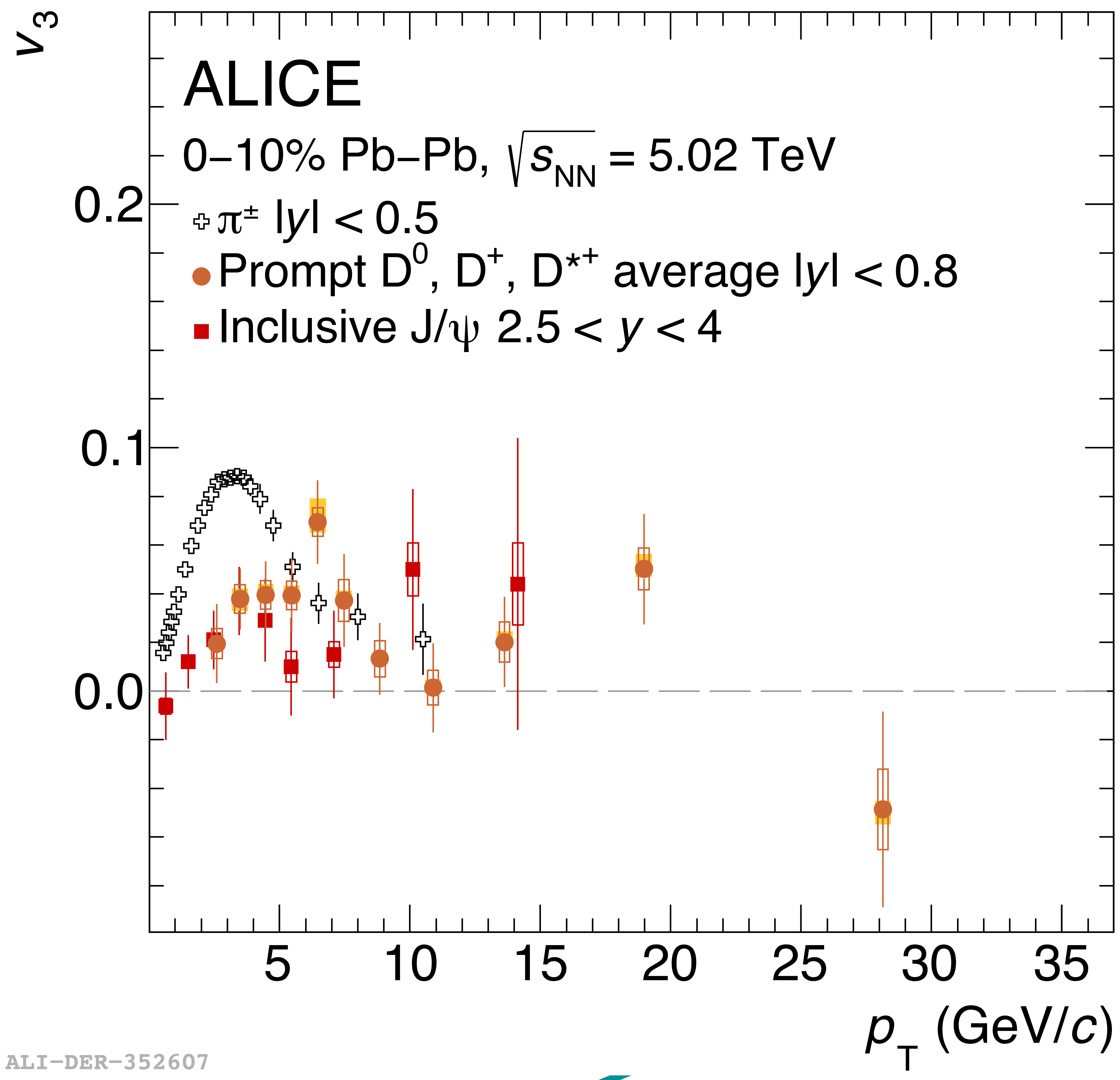
v_2(J/ψ)< v_2(D)~v_2(π)

- For p_T > 6 GeV/c: ➡ **consistent with similar path-length dependence of the energy loss for light and heavy quarks**

v_2(J/ψ)~ v_2(D)~v_2(π)

Triangular flow of heavy-flavour particles



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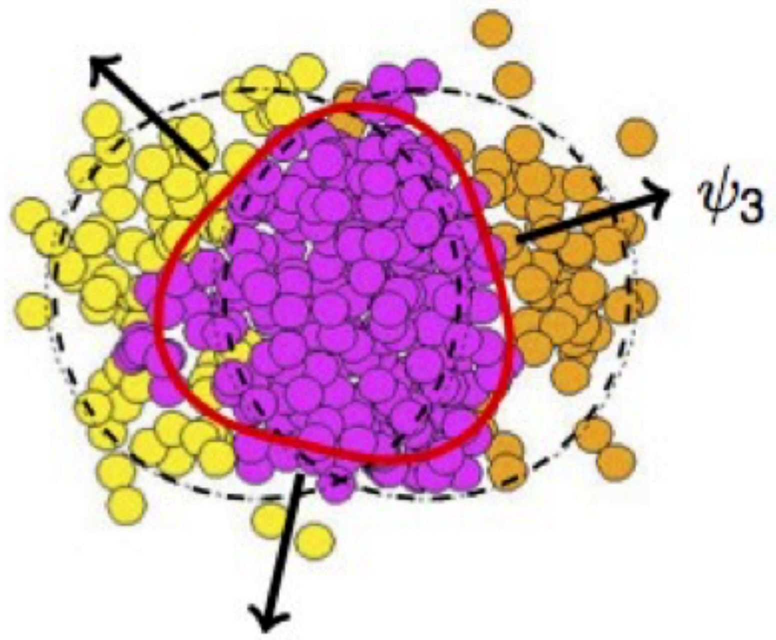
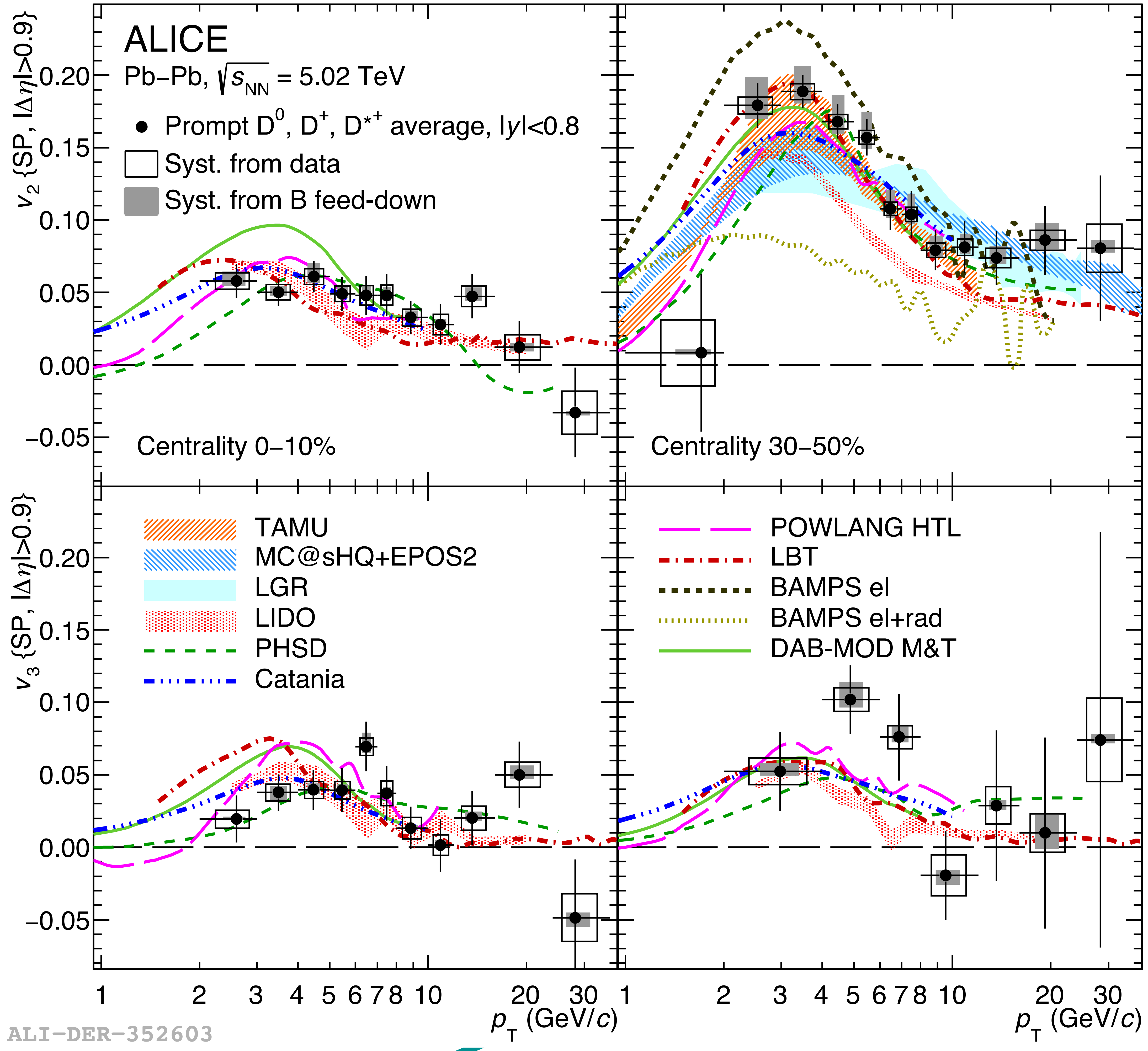
✦Originate from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region



- For p_T < 5 GeV/c: **0 < v_3(J/ψ) ~ v_3(D) < $v_3(\pi)$**

➡**Charm quarks sensitive to initial state fluctuations**

D-meson v_2 and v_3 in transport models



arXiv:2005.11131

All models includes:

- ✓transport of charm quarks in an hydrodynamical expanding medium
- ✓charm-quark energy loss (collisional and/or radiative)
- ✓hadronisation via quark coalescence and fragmentation

Constrain charm spatial diffusion coefficient:

$1.5 < 2\pi T D_s < 7$

for models that describe the data with χ^2/ndf<2

➡**charm thermalisation time: τ_{charm} =3-14 fm/c**

Conclusions

✓ **Strong suppression of heavy-flavour production in central Pb-Pb collisions**

➡ **Mass ordering** of the R_{AA} observed at low/intermediate p_T

➡ **R_{AA} described by several models with different implementation of the charm/beauty-quarks energy loss** (+ hadronisation via coalescence and fragmentation, hydrodynamic expansion of the medium)

✓ **Heavy quarks participate in collective expansion of the system**

➡ Positive D-meson and J/ψ v_2 and v_3

➡ Comparison with models **constraints the charm spatial diffusion** coefficient and the charm quark **thermalisation time** (~ QGP lifetime)

➡ Positive v_2 for electrons from beauty hadron decays: also **beauty quarks partially thermalise**?

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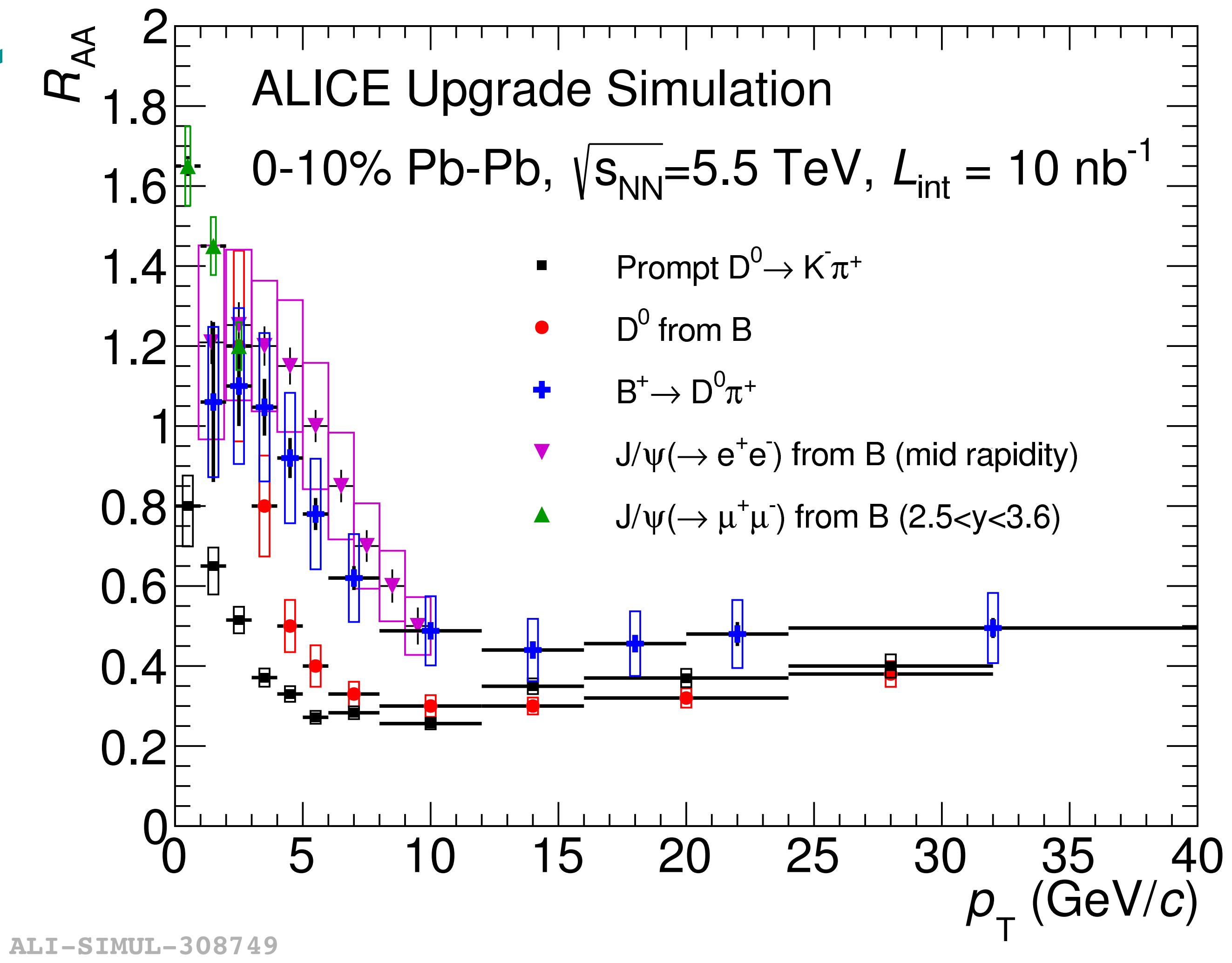
Wide ALICE upgrade program for LHC Run 3 and 4:

➡Investigate deeper the low p_T regime

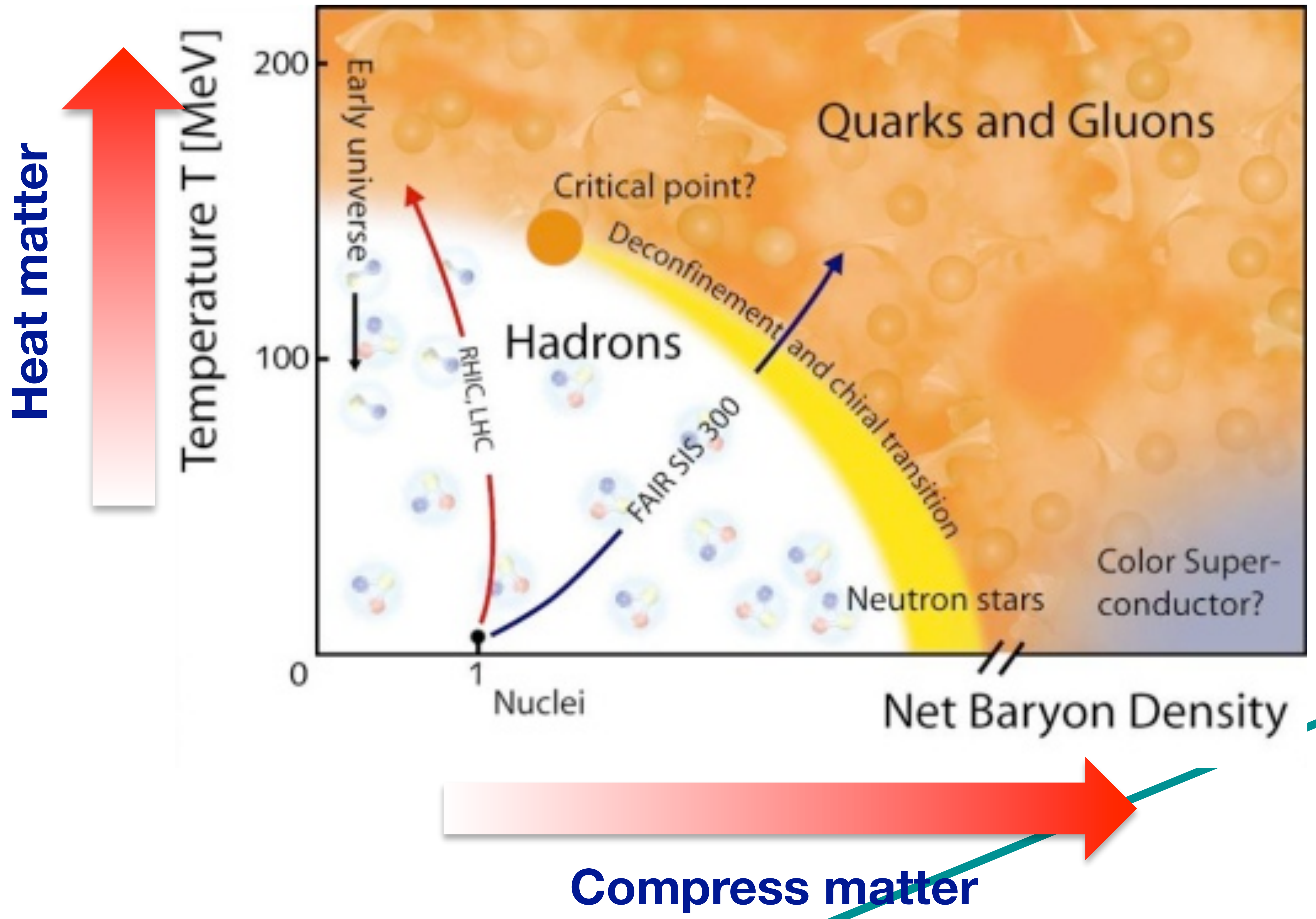
➡Precise measurements of charm mesons and baryons

➡Access to measurements of beauty-strange mesons and beauty-baryon production and flow



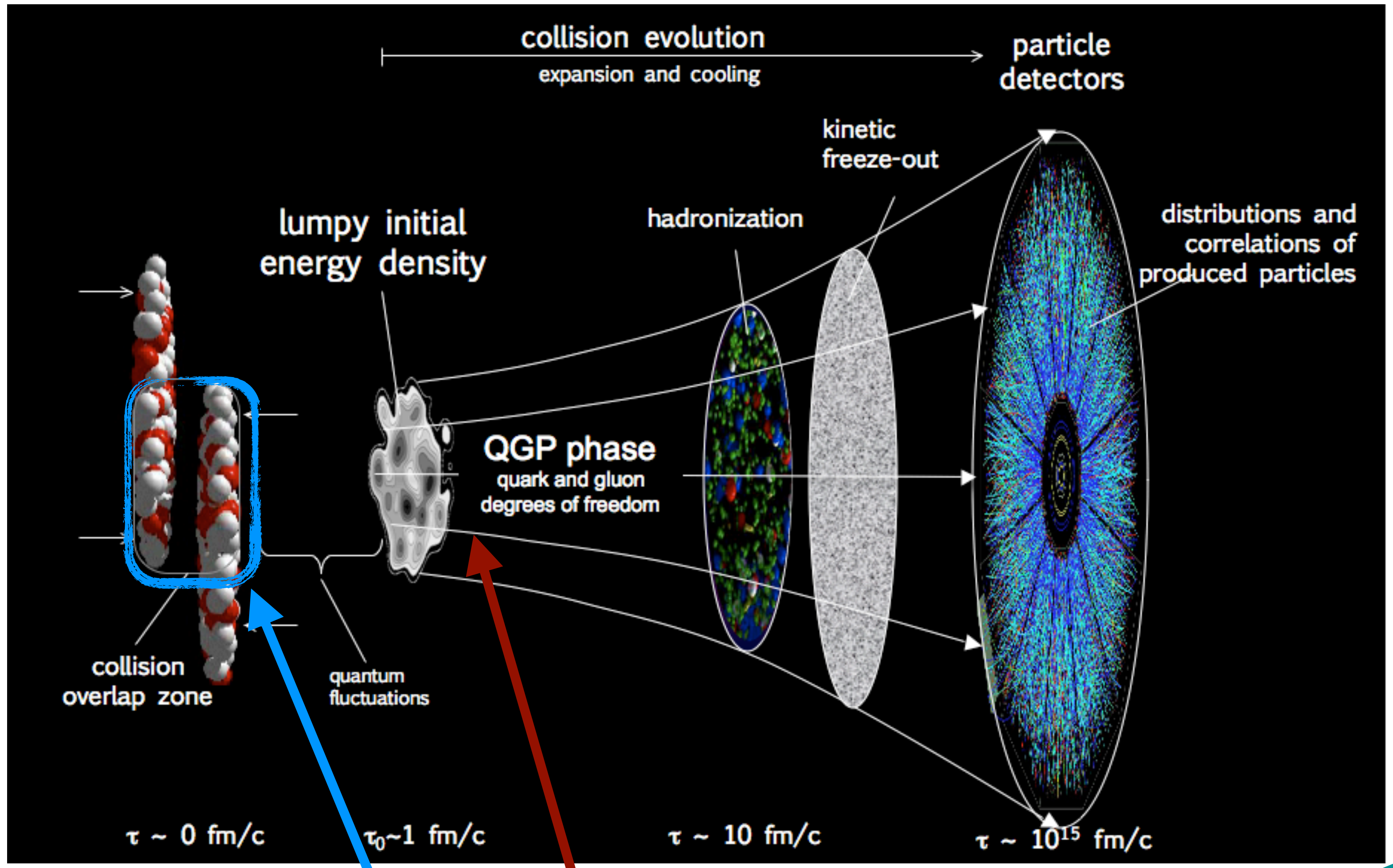
Back-up slides

Creating hot and dense matter in the laboratory



Collisions of relativistic heavy nuclei create the conditions for the phase transition from ordinary matter to a **strongly interacting, deconfined medium**: the **Quark-Gluon Plasma (QGP)**

Nuclear collisions and QGP expansion



- **Pre-thermal processes**
scattering of incoming quarks and gluons

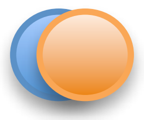
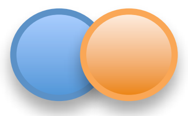
- **Thermalisation** (t~1 fm/*c* = 3*10^{-24} s)
Equilibrium is established

- **QGP expansion and cooling** (t~10 fm/*c*)
Described by an almost perfect fluid dynamics

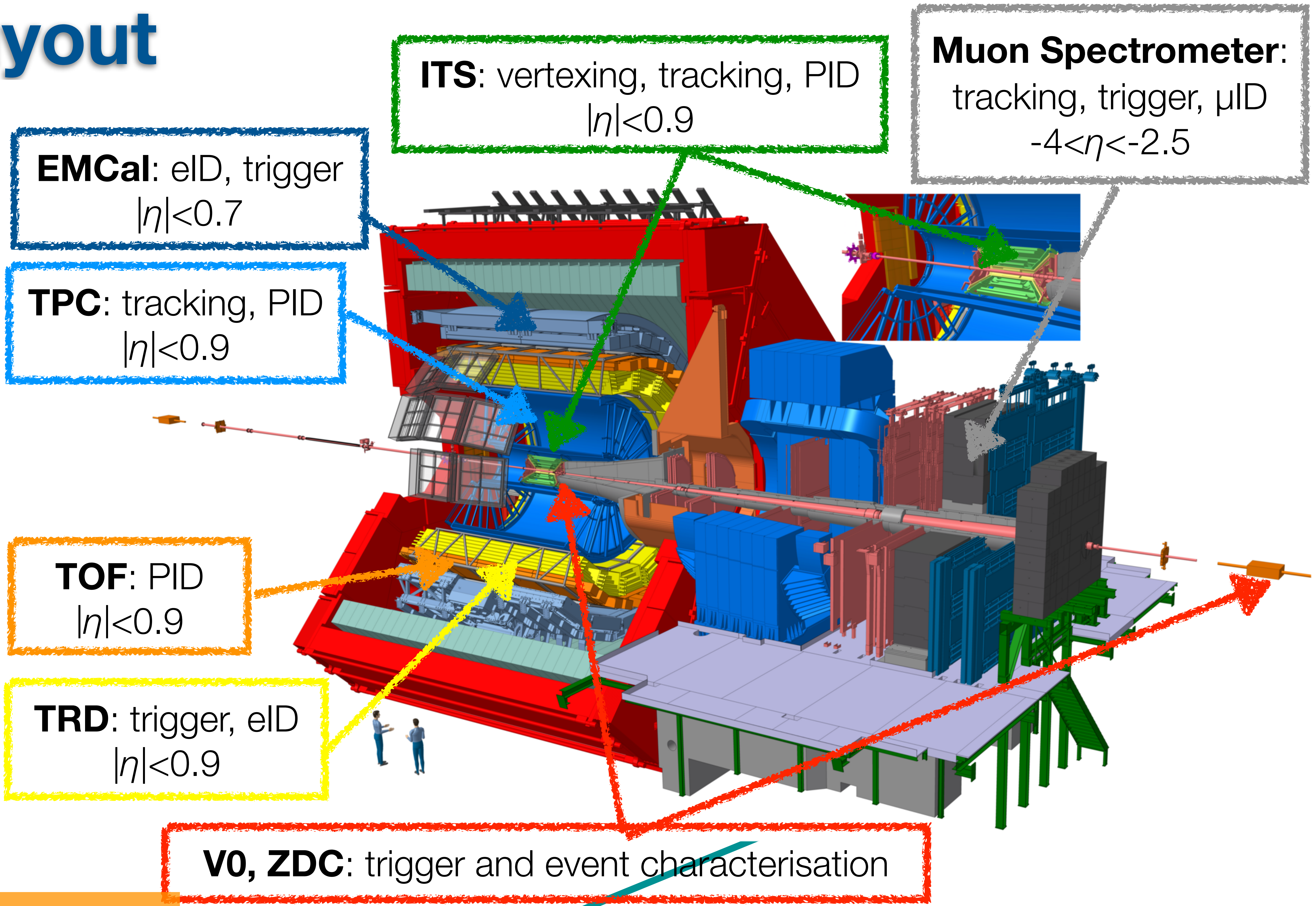
- **Hadronisation, Chemical freeze-out**
Inelastic interactions cease, particle abundances frozen

- **Kinetic freeze-out**
Elastic interactions cease, particle dynamics (spectra) frozen

Conditions similar to the Universe ~10 μs after the Big Bang

Collision overlap zone:
Full overlap -> **“central”** collisions 
Non-complete overlap -> **“peripheral”** collisions 

ALICE layout



Fully reconstructed D and Λ_c hadronic decays

$D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \Phi\, \pi^+ \rightarrow K^-K^+\pi^+$

$\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow K_0^s\, p$

$\Xi_c^+ \rightarrow \pi^+K^-p$, $\Xi_c^+ \rightarrow \pi^+\pi^+\Xi^-$, $\Xi_c^0 \rightarrow \pi^+\Xi^-$

Quarkonia leptonic decays

$J/\Psi \rightarrow \mu^+ \mu^-$,

$\Psi(2S) \rightarrow \mu^+ \mu^-$

$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow \mu^+ \mu^-$

$J/\Psi \rightarrow e^+ e^-$

Semi-leptonic decays

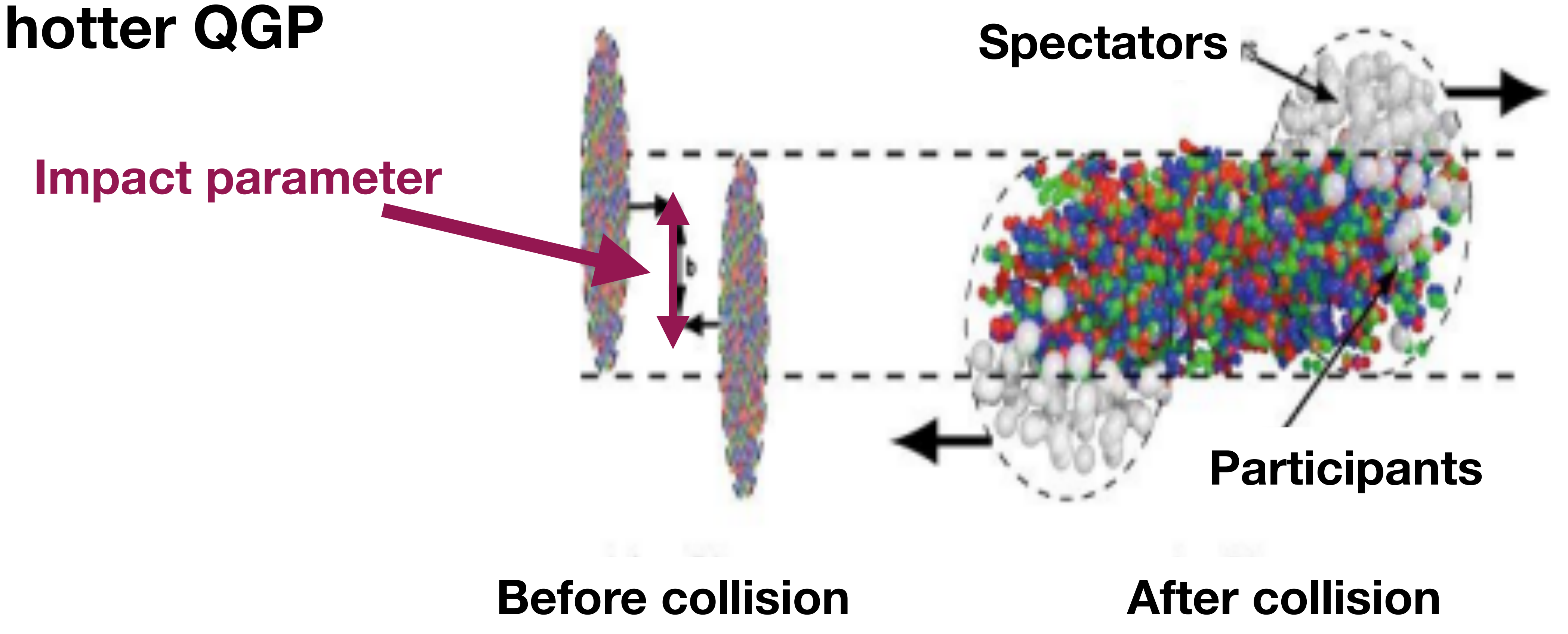
$D, B \rightarrow \mu^\pm X$

$D, B, \Lambda_c^+, \Xi_c^0 \rightarrow e^\pm X$

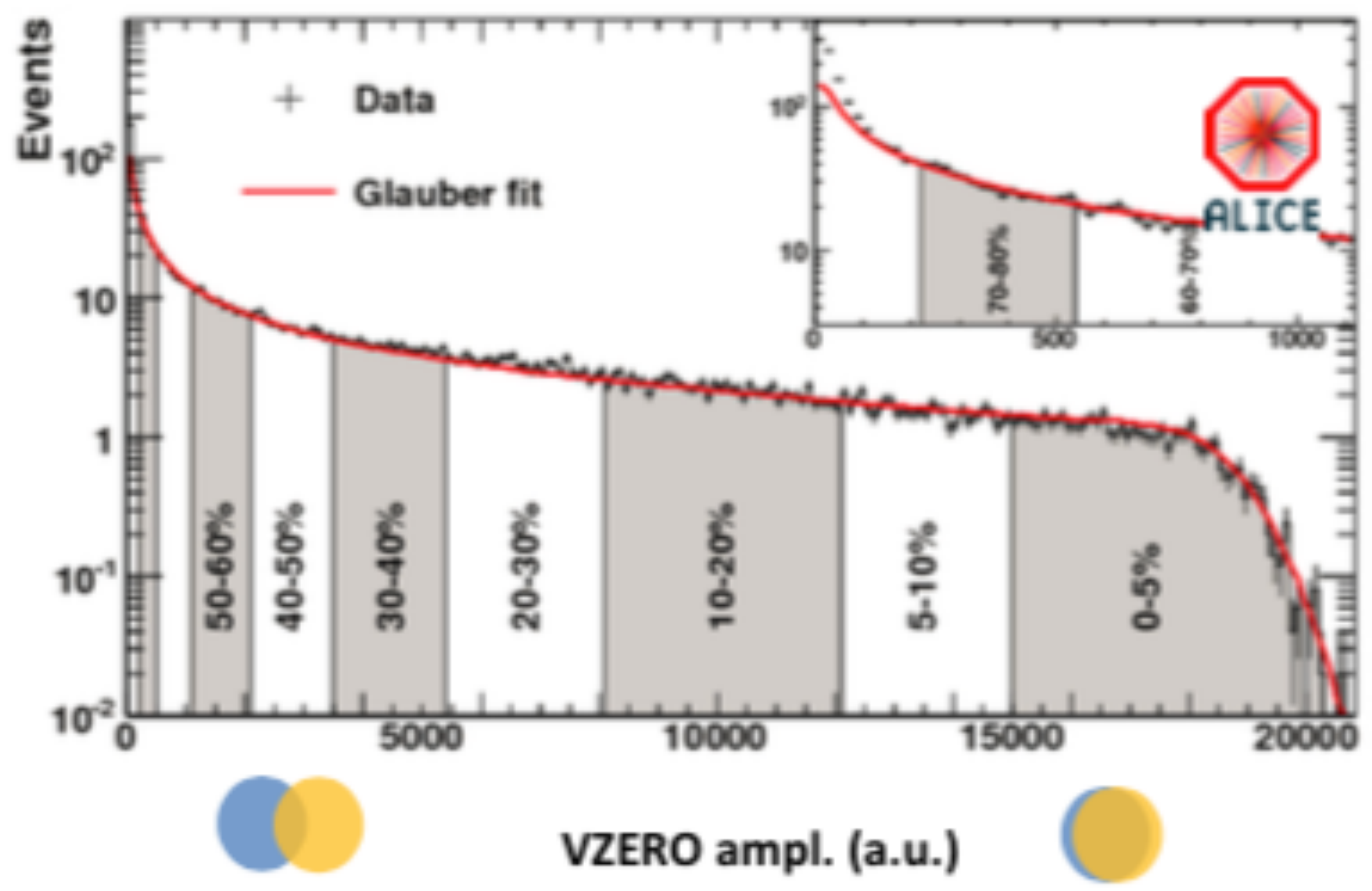
HF-tagged jets

Centrality in AA collisions

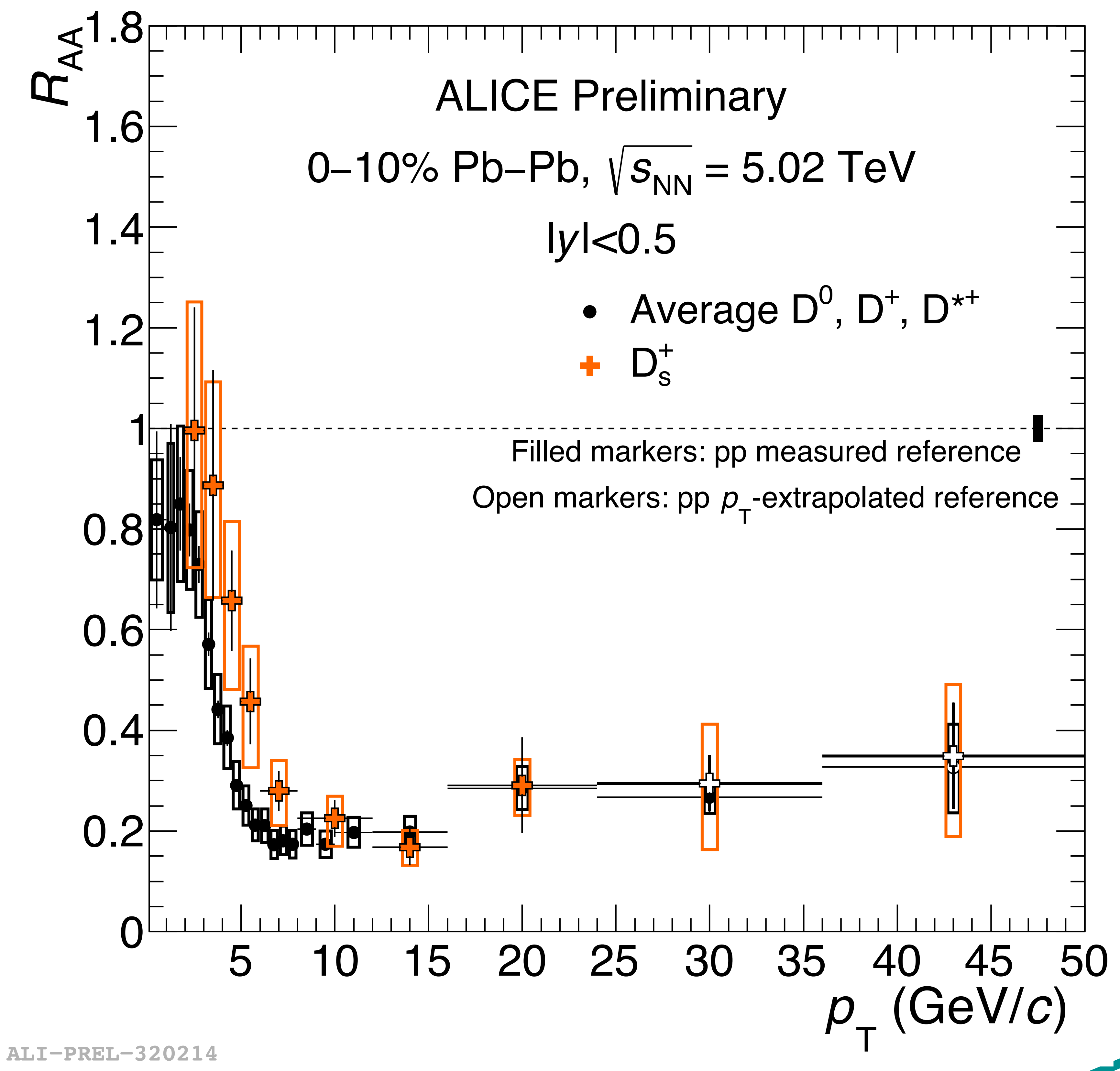
- Ions are large, R~7 fm, collisions occur with random impact parameter that cannot be directly measured
- **Higher centrality -> hotter QGP**



- The impact parameter has to be estimated based on measured quantities: e.g. N_{ch} , E_T , ZDC…
- Glauber model: connects centrality to a number of binary collisions (N_{coll}) and participants (N_{part})



D_s^+ R_{AA}



- ✦ **Hint of less suppression for D_s^+ wrt non-strange D**

Event-Shape Engineering

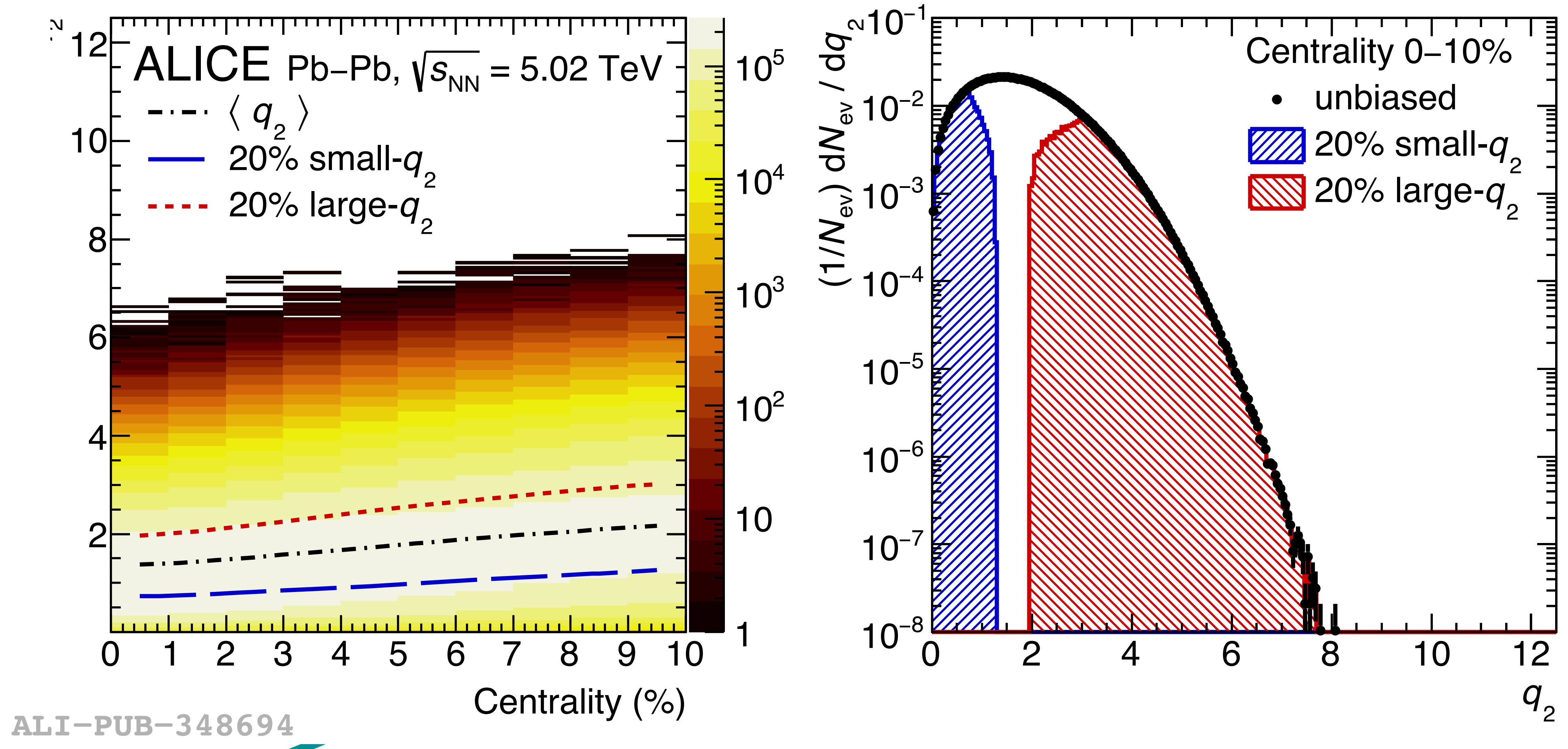
- Events classified on the basis of the eccentricity, according to the magnitude of the second harmonic reduced flow vector q_2

$$q_2 = \frac{|\vec{Q}_2|}{\sqrt{M}}, \qquad Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i, \qquad Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$

20% smallest q_2 — $\langle v_2 \rangle_{\text{small}-q_2} < \langle v_2 \rangle_{\text{unbiased}}$

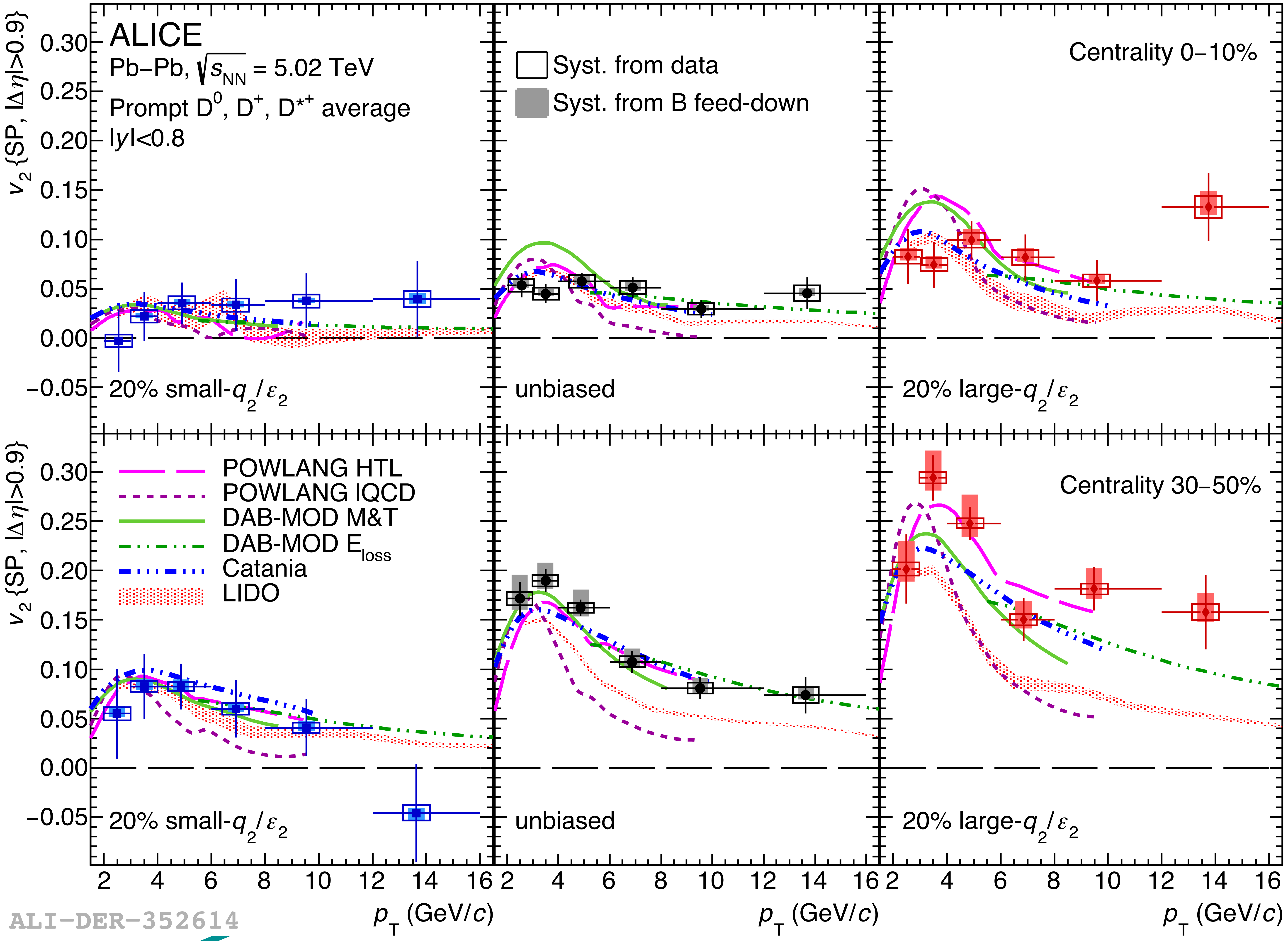
20% largest q_2 — $\langle v_2 \rangle_{\text{large}-q_2} > \langle v_2 \rangle_{\text{unbiased}}$

arXiv:2005.11131



- Elliptic flow for different q_2 samples:
  - ➡ correlation between v_2 of D mesons and soft hadrons
  - ➡ event-by-event fluctuations in the initial state

ESE-selected v2



- D-meson v_2 in ESE-selected sample in 0-10% and 30-50% centrality class
- Results point to a positive correlation between D-meson v_2 and light-hadron v_2
- Models based on charm-quark transport in an hydrodynamically expanding medium reasonably describe the q_2 dependence of elliptic flow

📖 POWLANG: EPJC 79, 494 (2019)
📖 DAB-MOD M&T: PRC 96 064903 (2017)
📖 LIDO: PRC 98 064901 (2018)
📖 CATANIA: PLB 805 135460 (2020)