Recent Results on Heavy Flavor production

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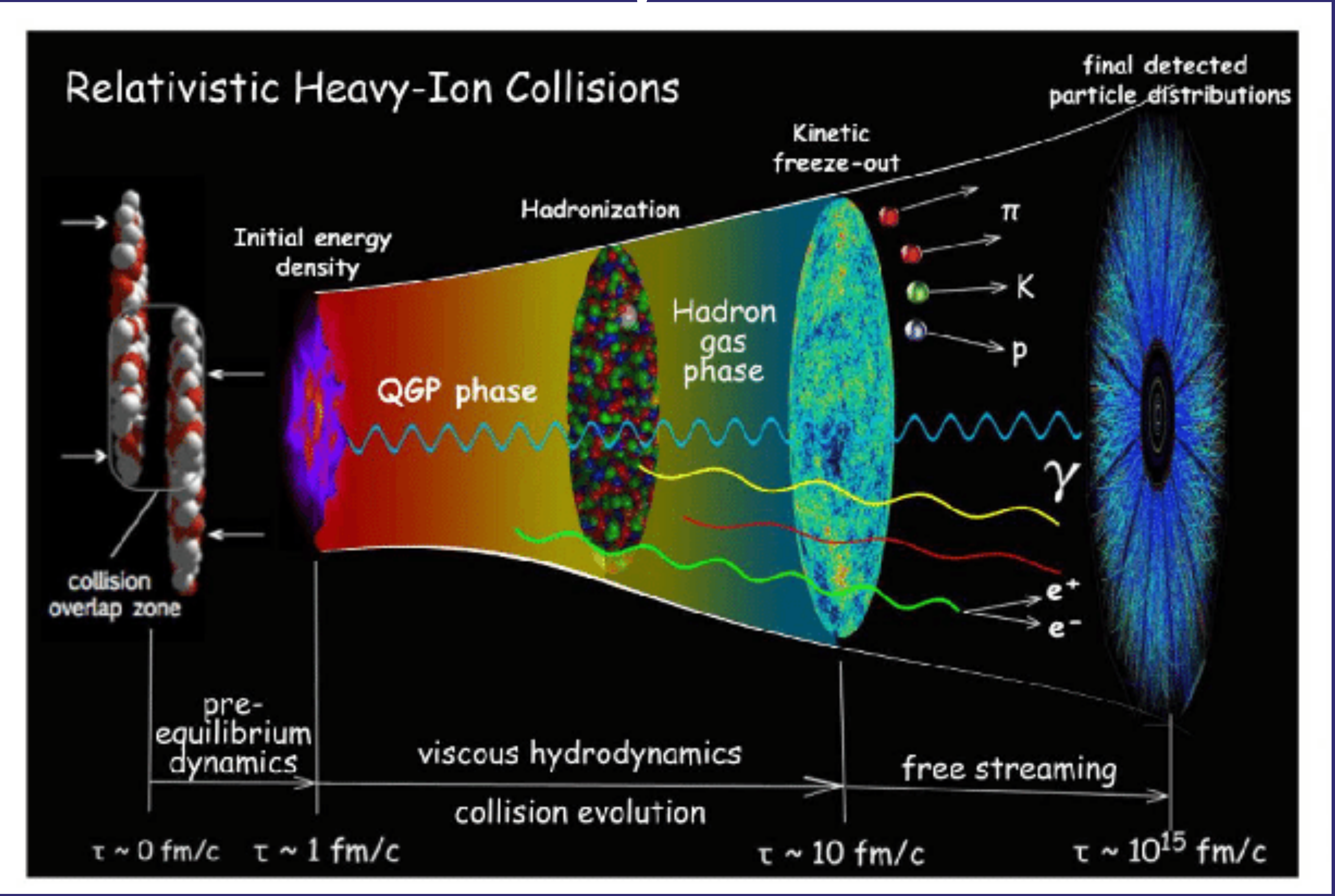
Relativistic Heavy Ion collisions



Finding a Good Probe

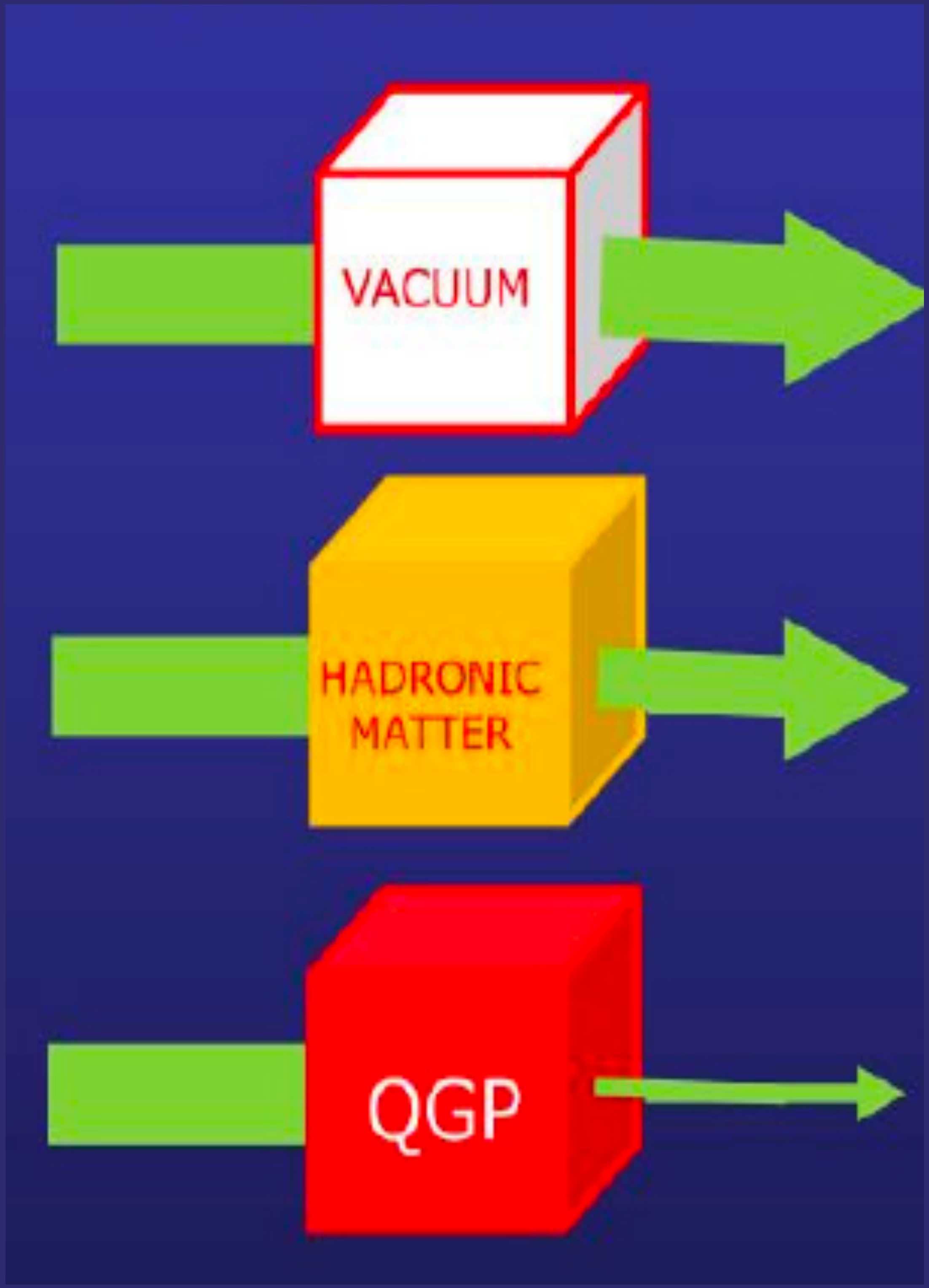
How to study medium ?

Using a probe produced early in the collision evolution so that it is there before the matter to be probed.

Well understood in pp collision.
Slightly affected by hadronic matter.
Strongly affected by the deconfined medium

How to calibrate medium ?

Using another probe not affected by the hot matter.
Using collision systems where new physics is absent.



Which probes ?

Hard probes : jets, heavy flavour

Heavy Flavors (I)

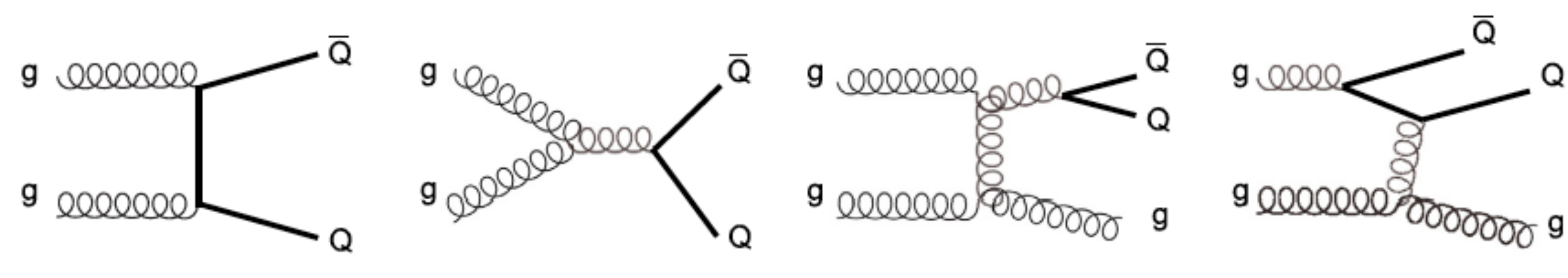
Heavy flavour : Charm and Beauty

Mass: m_c (~ 1.3 GeV/c^2), m_b (~ 4.5 GeV/c^2)

Produced in initial hard scattering process.

Short formation time

$\tau < \tau_{QGP} \sim 0.1 - 1$ fm/c



flavor production

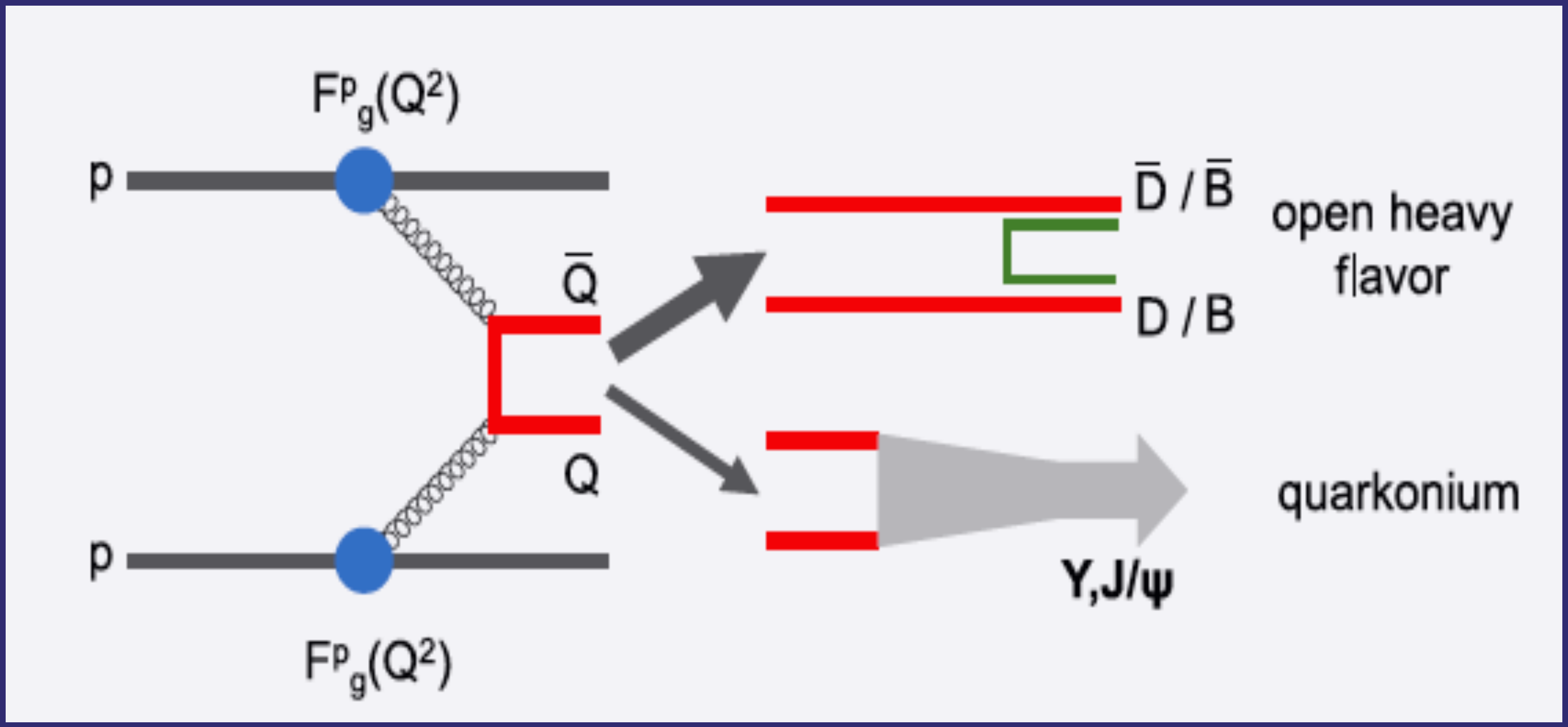
gluon splitting

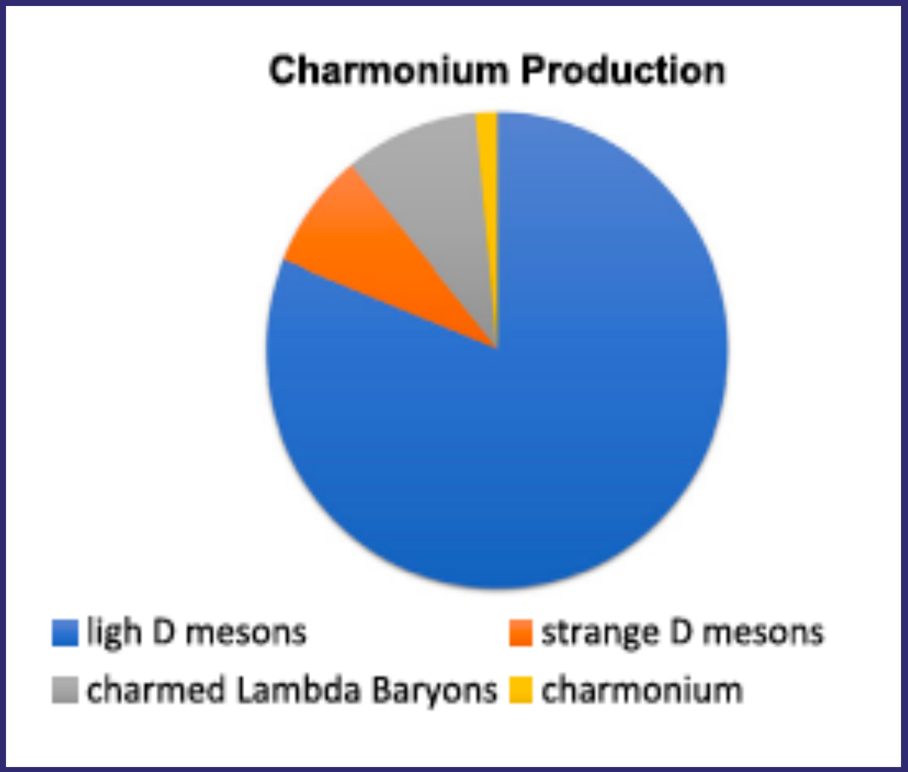
flavor excitation

Heavy Flavors (II)

Open Heavy Flavor
(Open charm ,Open beauty)

Quarkonia
(Charmonium and bottomnium)





Why Heavy Quarks ?

Dominantly produced in very initial stages with large energy-momentum transfer

Initial production is well described by pQCD

Heavy quarks scattering cross-sections are small compared to light quarks

Sensitive to medium properties during expansion

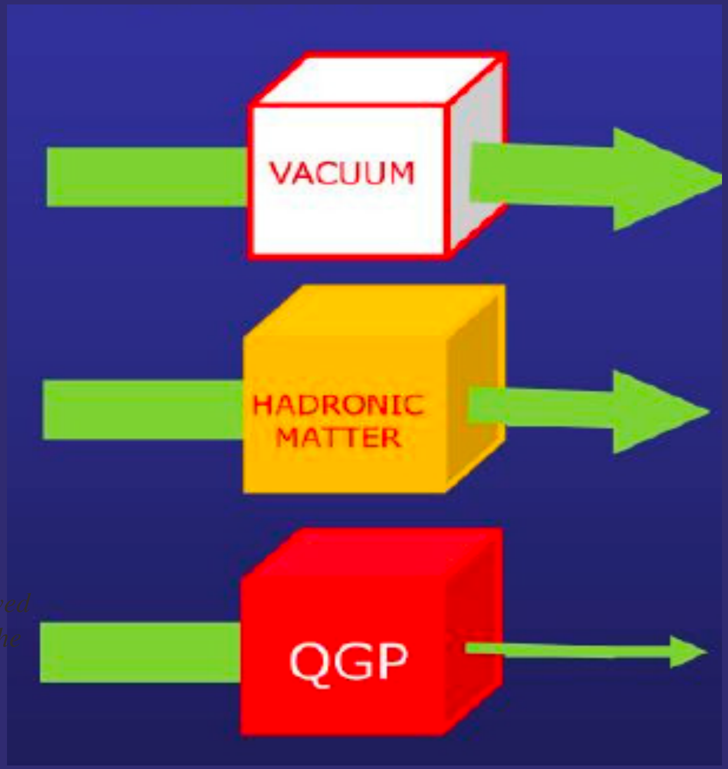
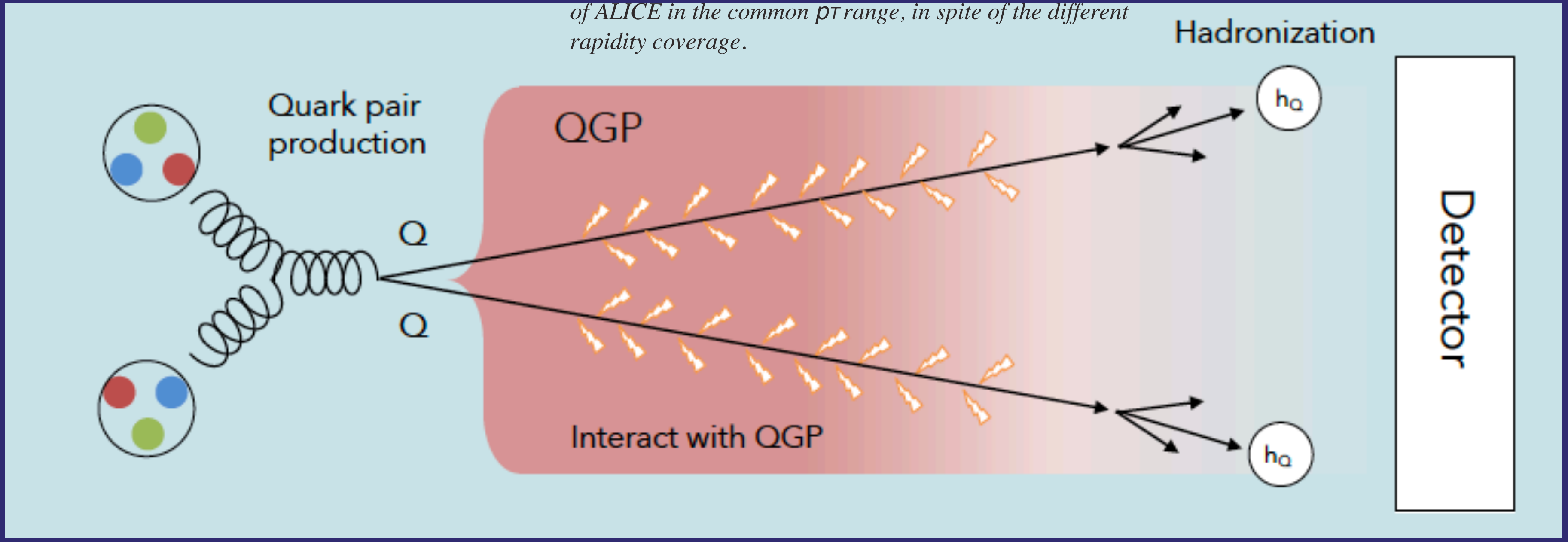
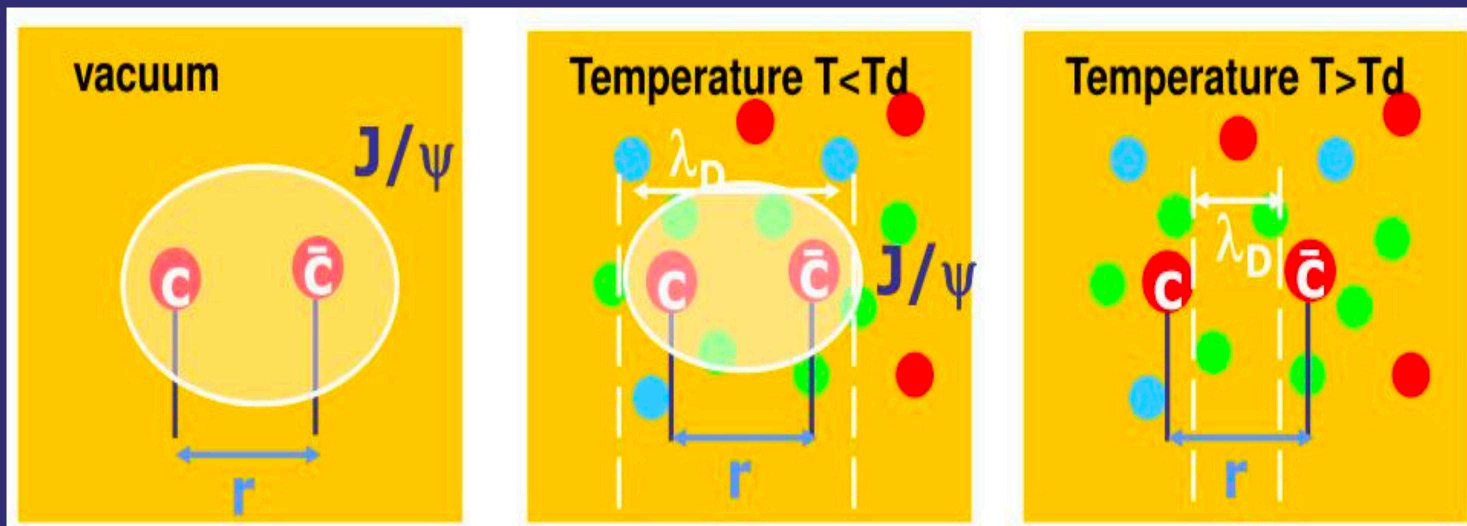


Figure 3 shows the ψ.2S.R_{AA}, compared with the corresponding result for the J=ψ [46], as a function of p_T. The corresponding CMS measurements [48] in the region jyj < 1.6 and 6.5 < p_T < 30 GeV=c are also reported. The main feature is an increase of the nuclear modification factor at low p_T, similar to what was observed for the J=ψ and understood as a direct consequence of the recombination process of charm and anticharm quarks. The strong suppression of the ψ.2S. (R_{AA} ~ 0.15 at p_T . 10 GeV=c) persists up to p_T ; 30 GeV=c as shown by the CMS data, that agree within uncertainties with those of ALICE in the common p_T range, in spite of the different rapidity coverage.



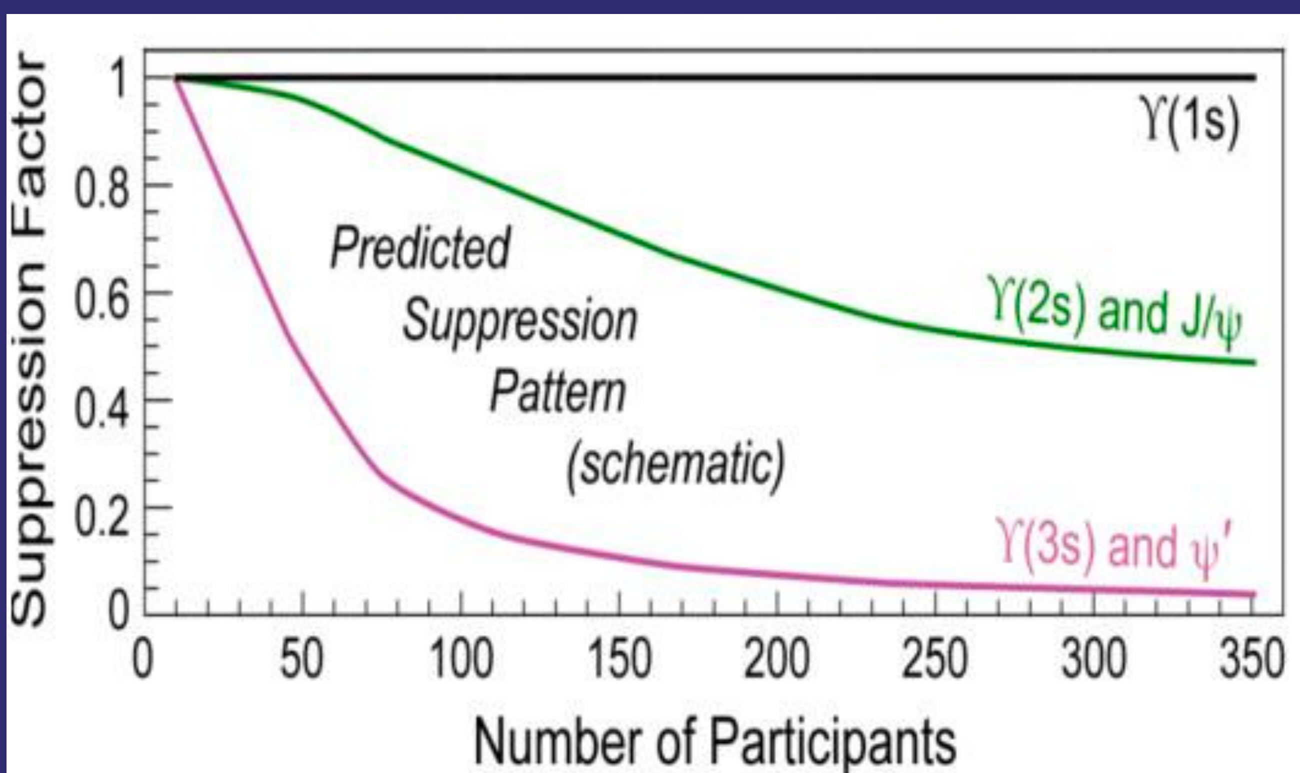
Cleanest probes for early tomography

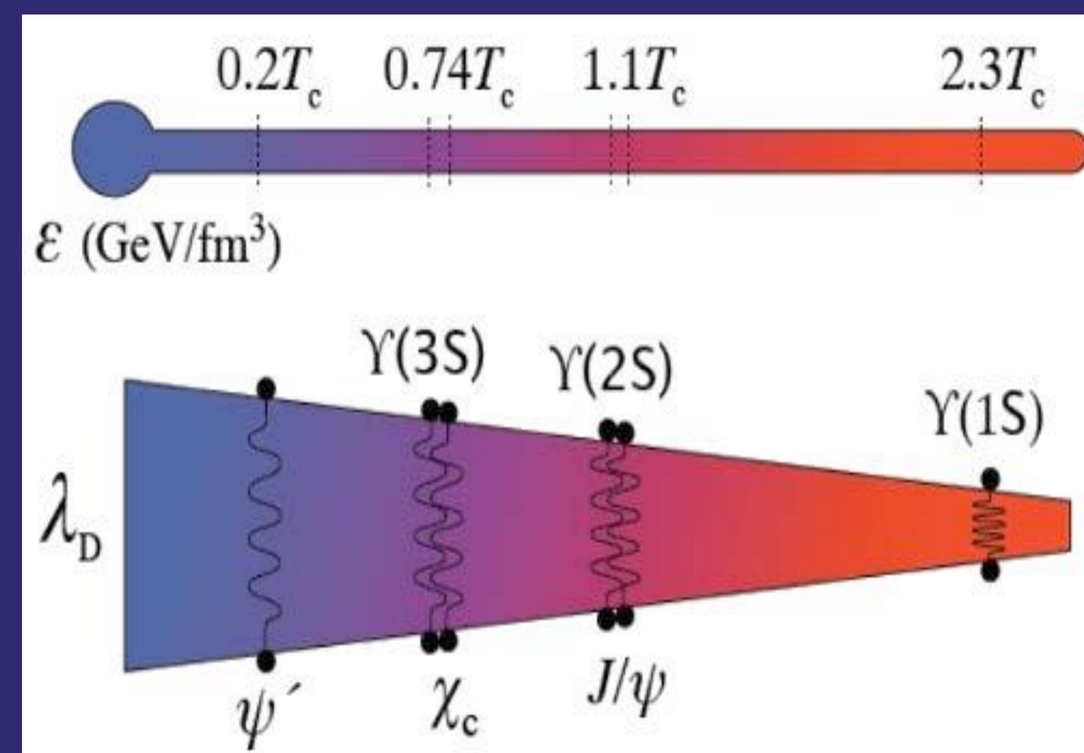
Sequential Suppression of Quarkonia

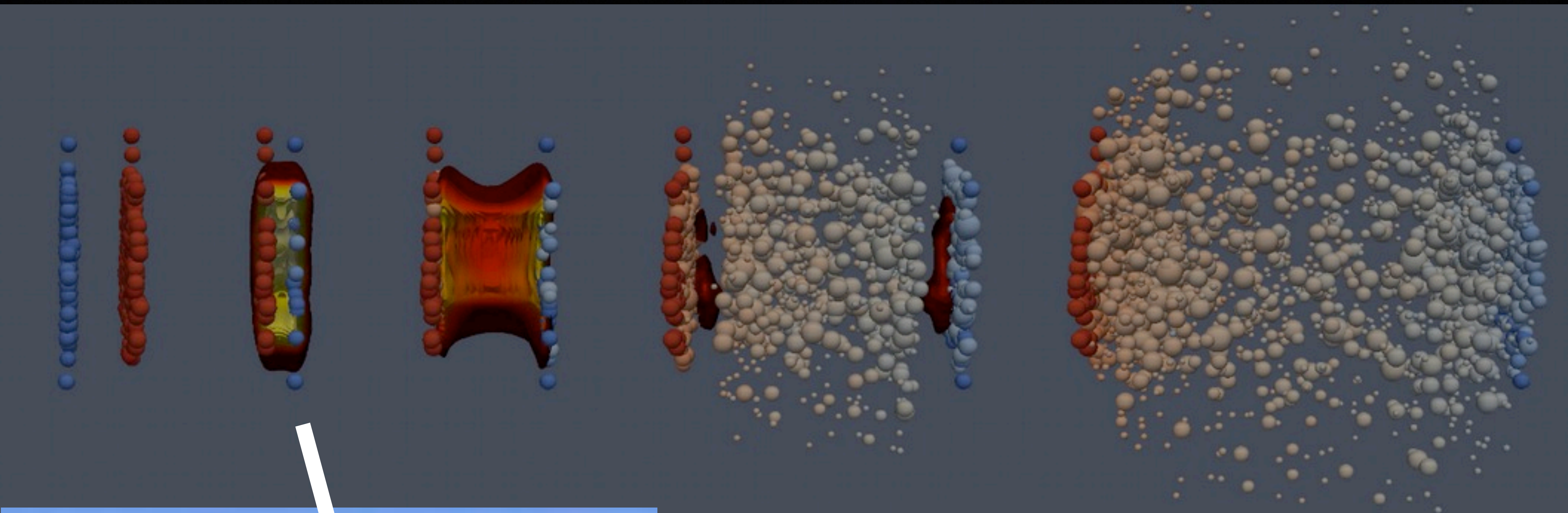


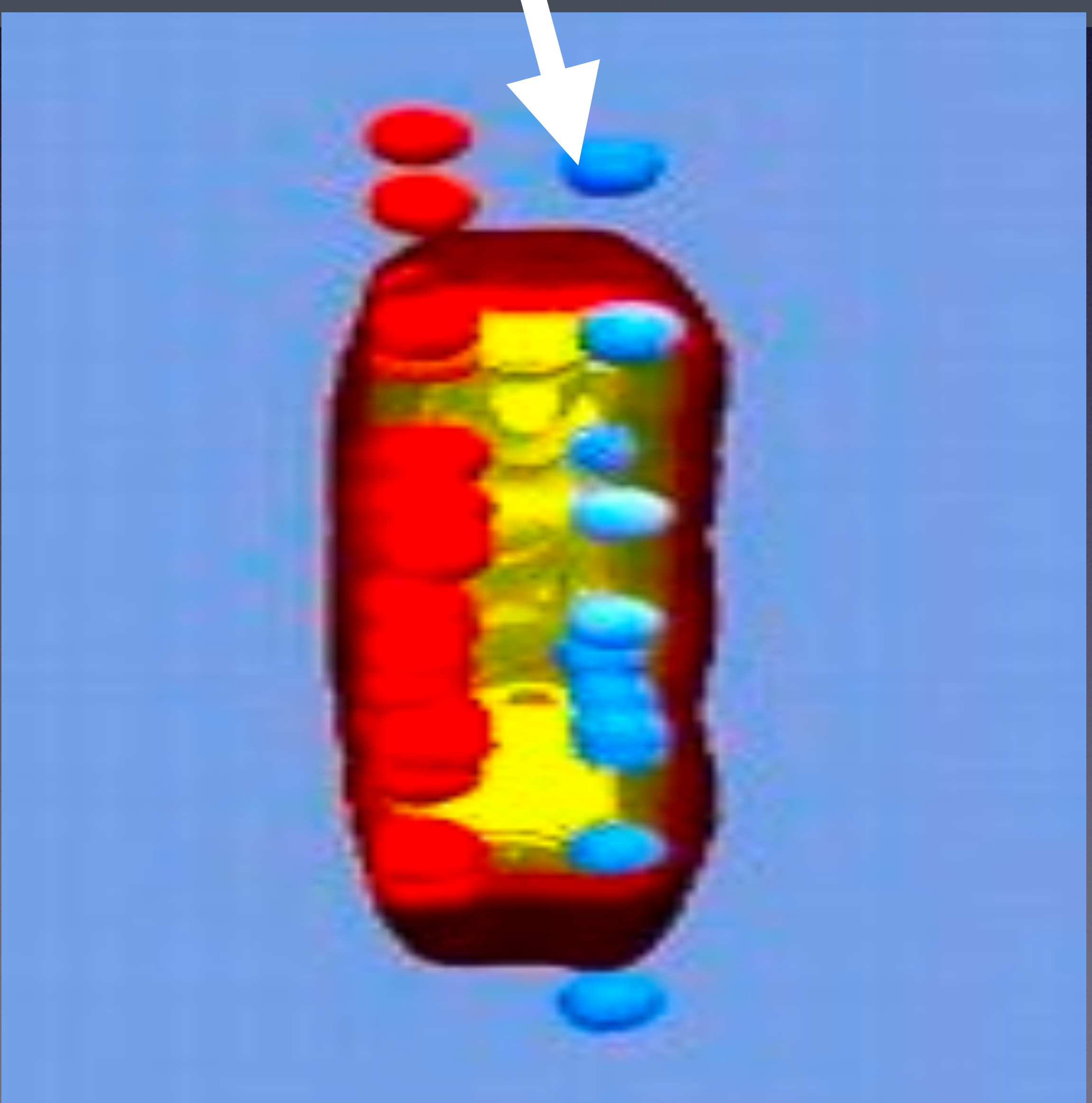
state	J/ψ	χ_c	$\psi(2S)$
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_o(fm)	0.25	0.36	0.45

state	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78



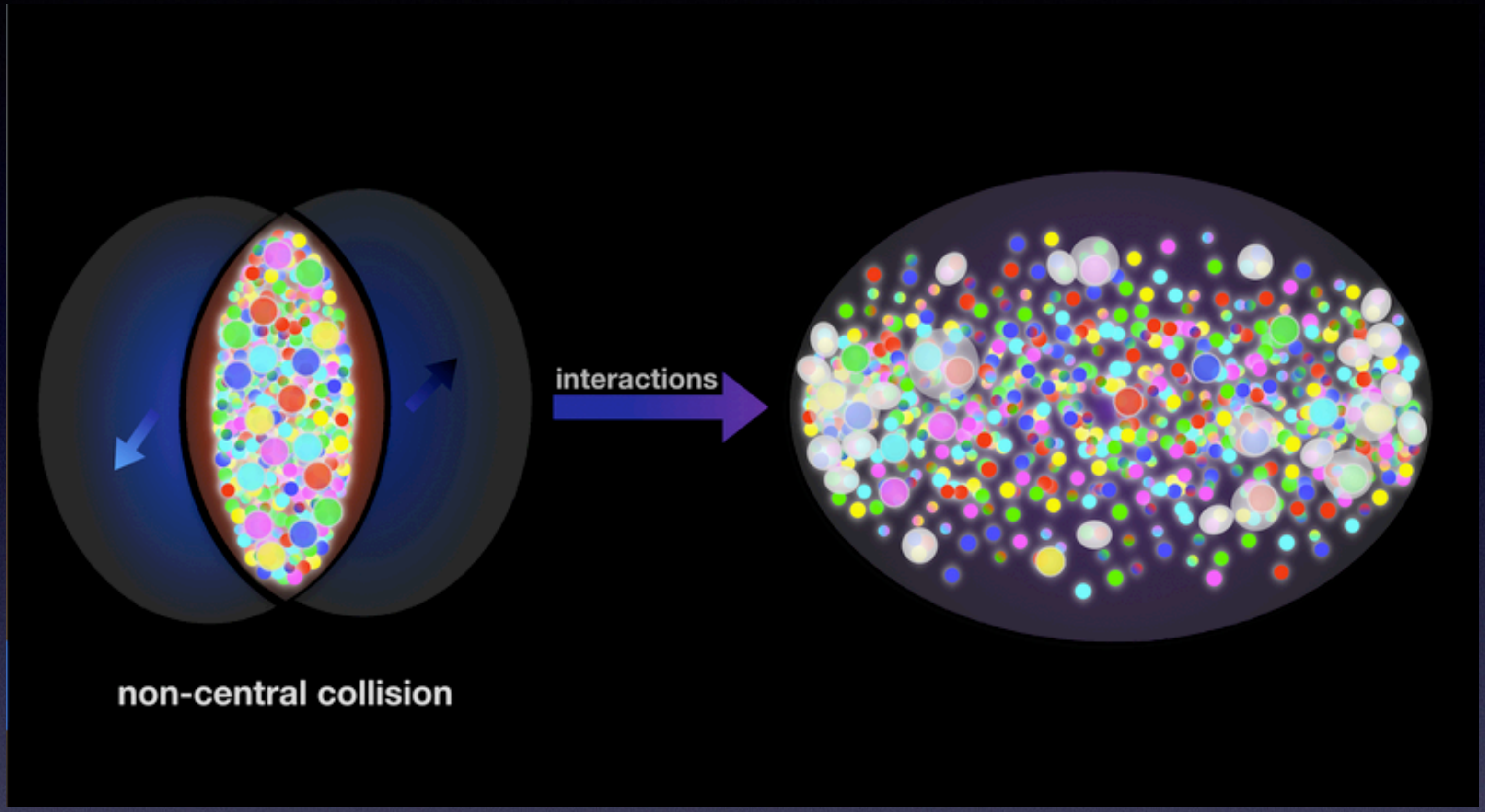






Initial stages

Explore initial state with Flow coefficients

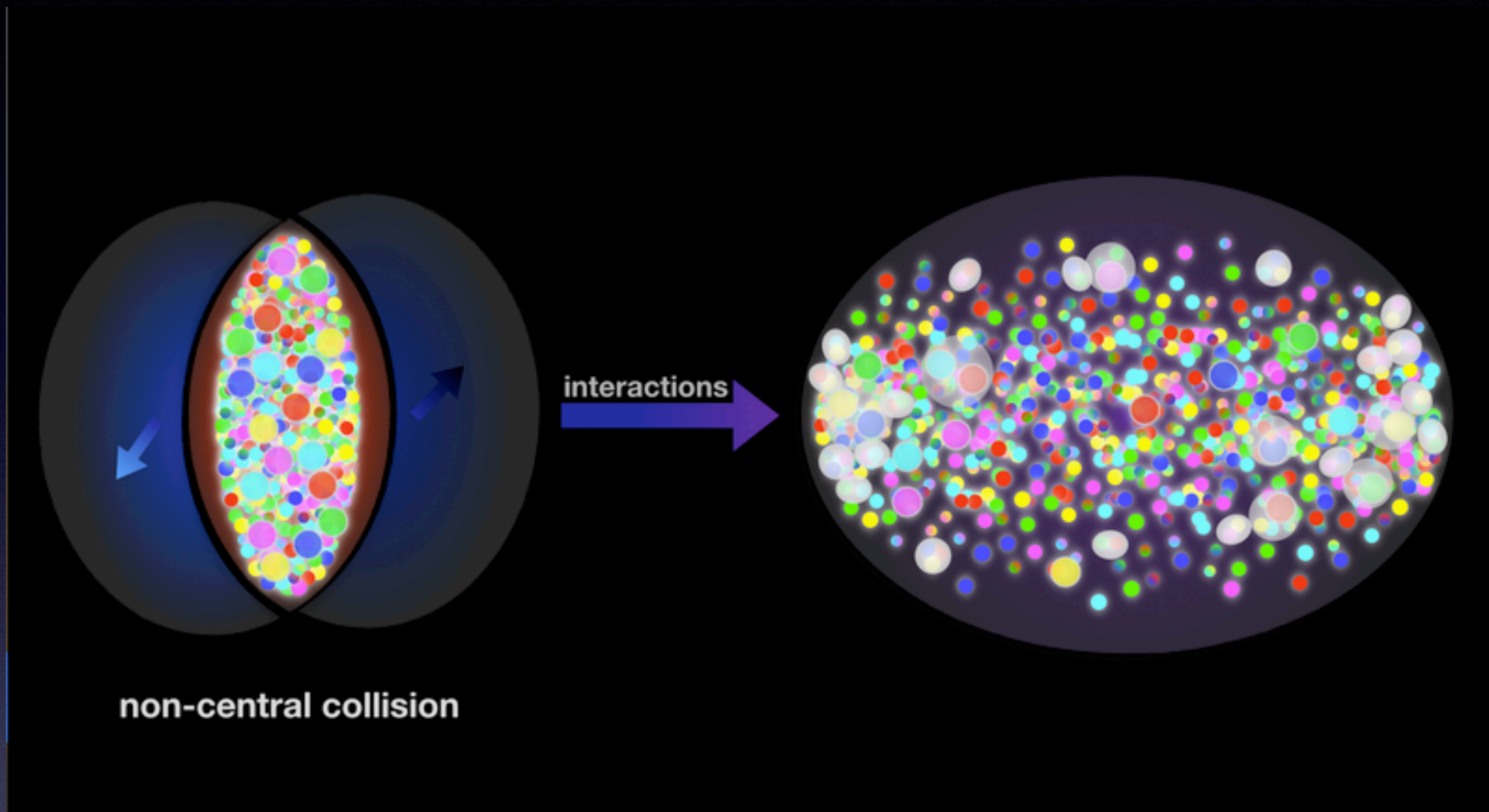


For non-central heavy ion collisions, overlap region is ellipsoid in shape.

Pressure gradient is largest along the shorter axis.

Initial spatial anisotropy manifests in final state momentum anisotropy

Explore initial state with Flow coefficients



For non-central heavy ion collisions, overlap region is ellipsoid in shape.

Pressure gradient is largest along the shorter axis.

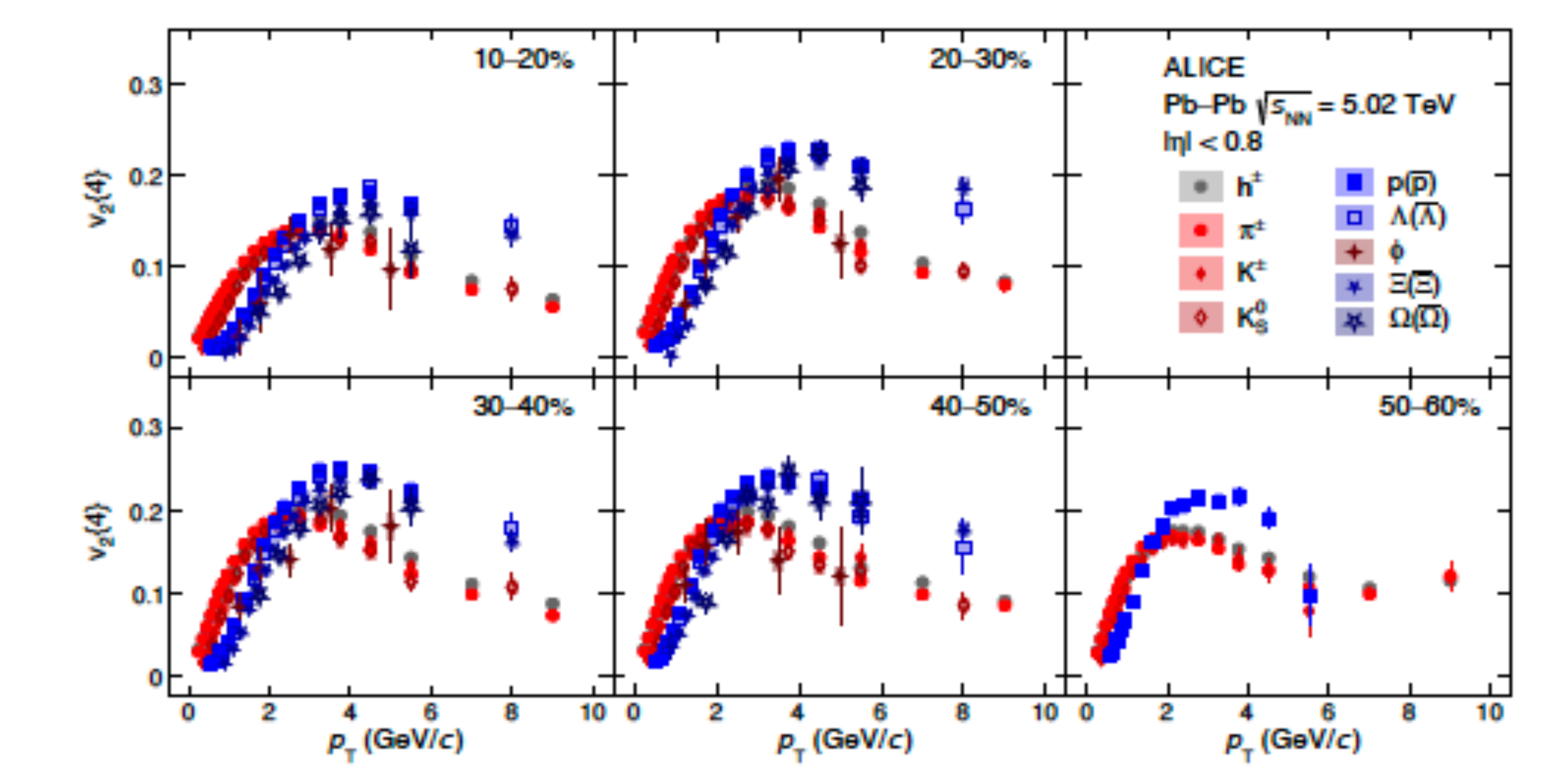
Initial spatial anisotropy manifests in final state momentum anisotropy

$$\frac{dN}{d\phi} \propto 1 + 2\sum v_n cos(n(\phi - \Psi_n))$$

v_2 : **Elliptic flow**

Explore initial state with Flow coefficients (I)

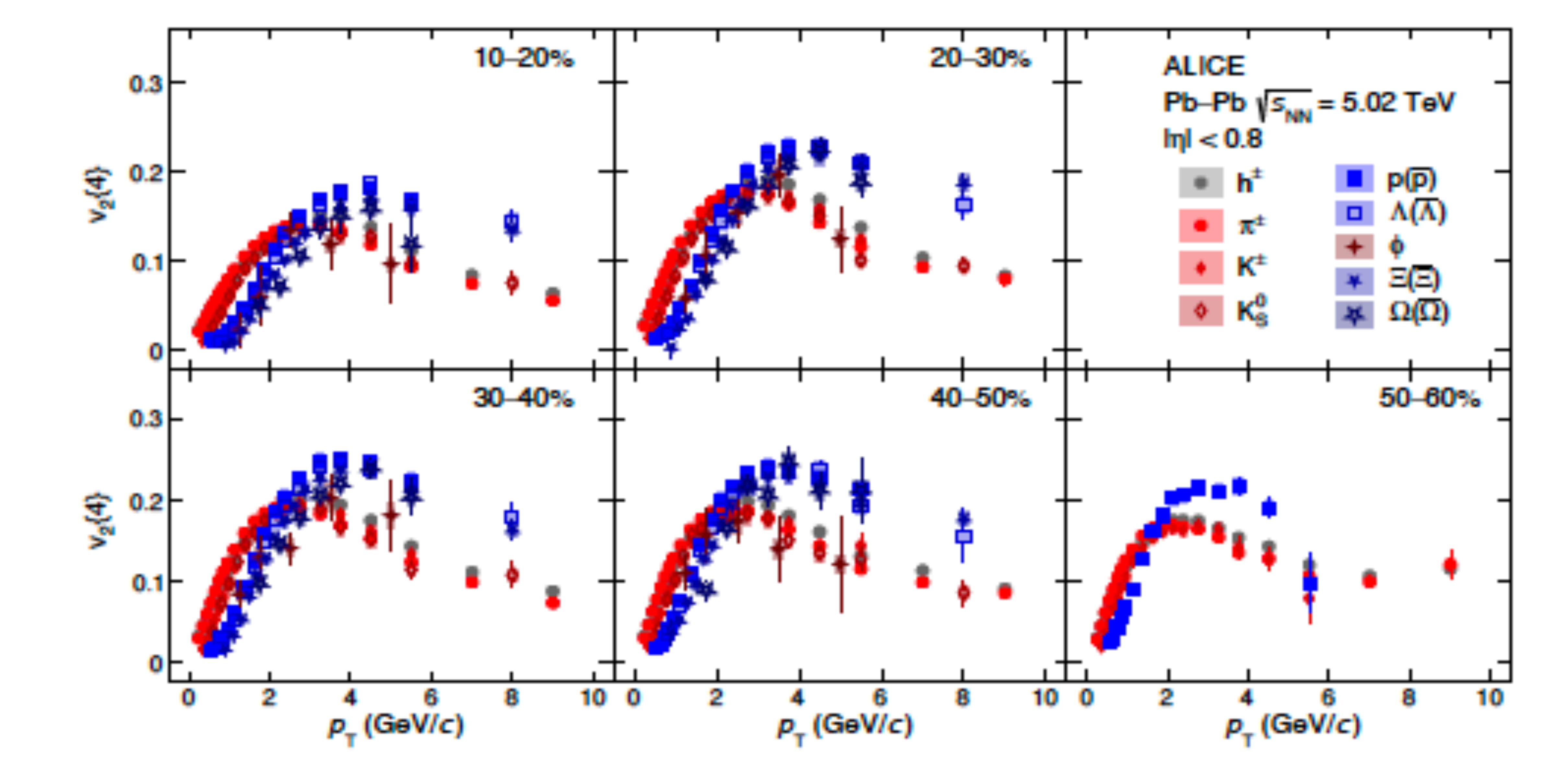
JHEP 05 (2023) 243



Identified particle v_2 measurements using 4-particle cumulants

Explore initial state with Flow coefficients (I)

JHEP 05 (2023) 243

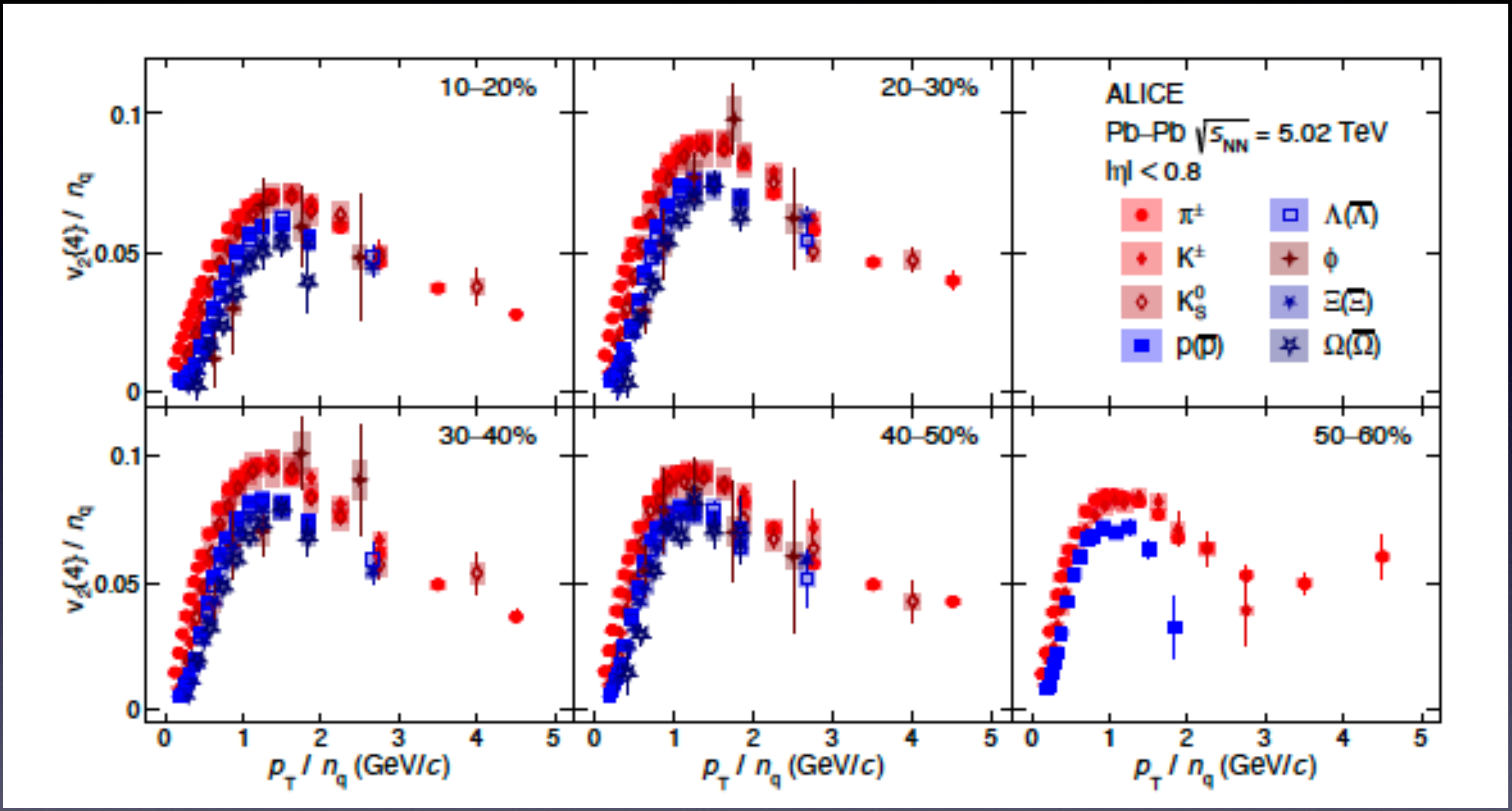


Identified particle v_2 measurements using 4-particle cumulants

Presence of mass ordering and baryon-meson grouping

Explore initial state with Flow coefficients (I)

JHEP 05 (2023) 243



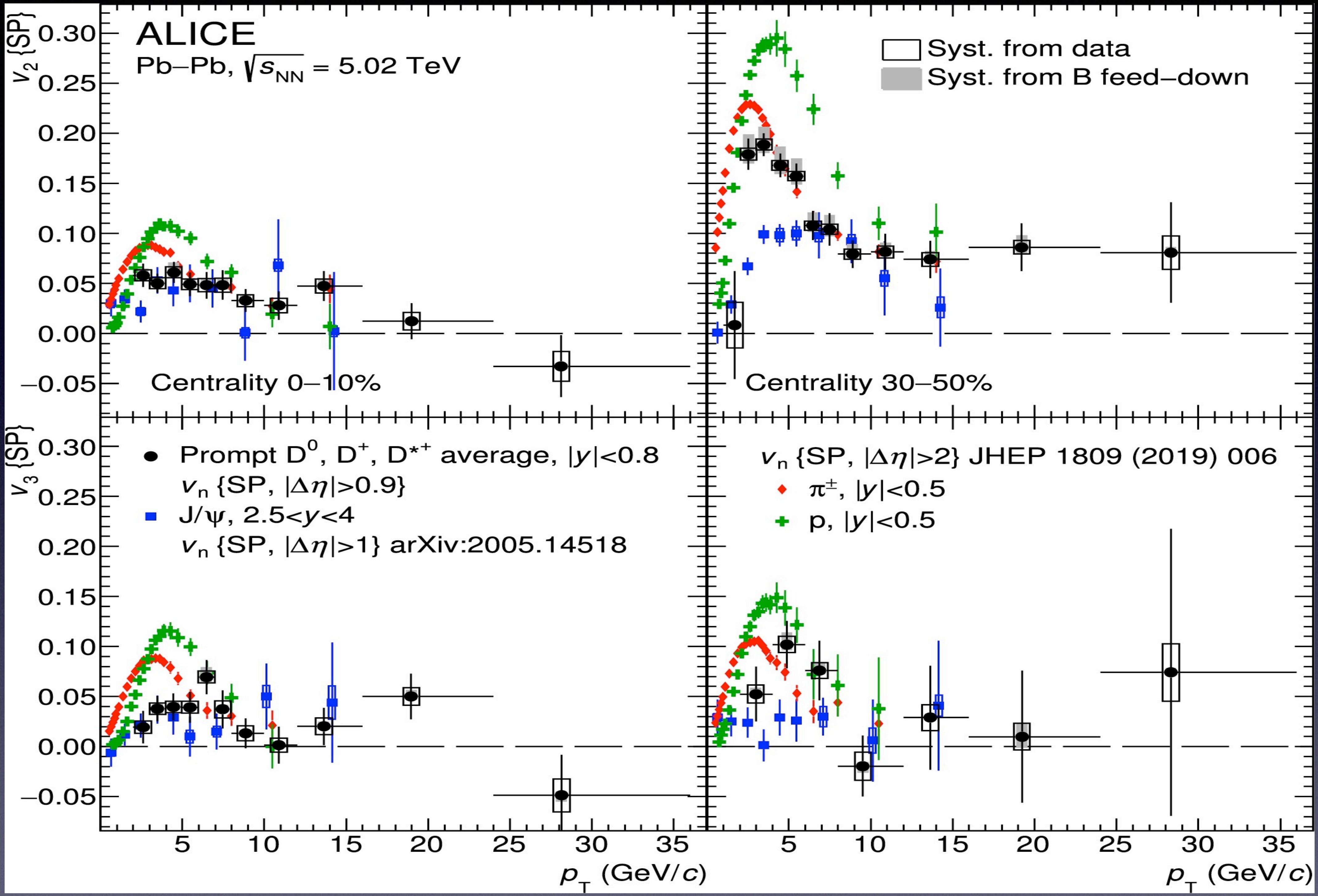
Identified particle v_2 measurements using 4-particle cumulants

Presence of mass ordering and baryon-meson grouping

Approximate NCQ (number of constituent quark) scaling

Explore initial state with Flow coefficients (II)

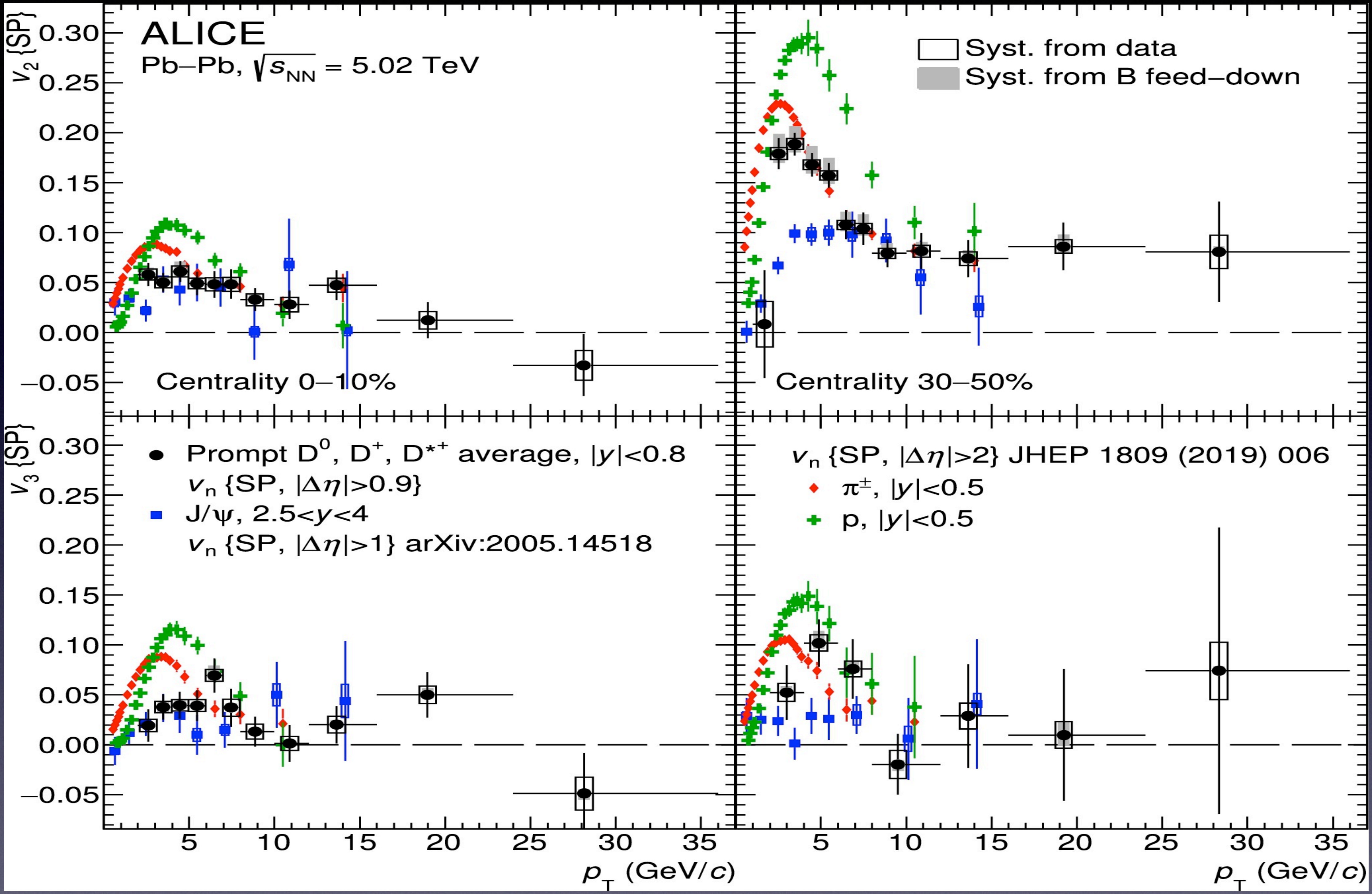
ALICE: Phys.Letts.B 813, 136054 (2021)



D-meson flow increases significantly from central to semi-central collisions.

Explore initial state with Flow coefficients (II)

ALICE: Phys.Letts.B 813, 136054 (2021)

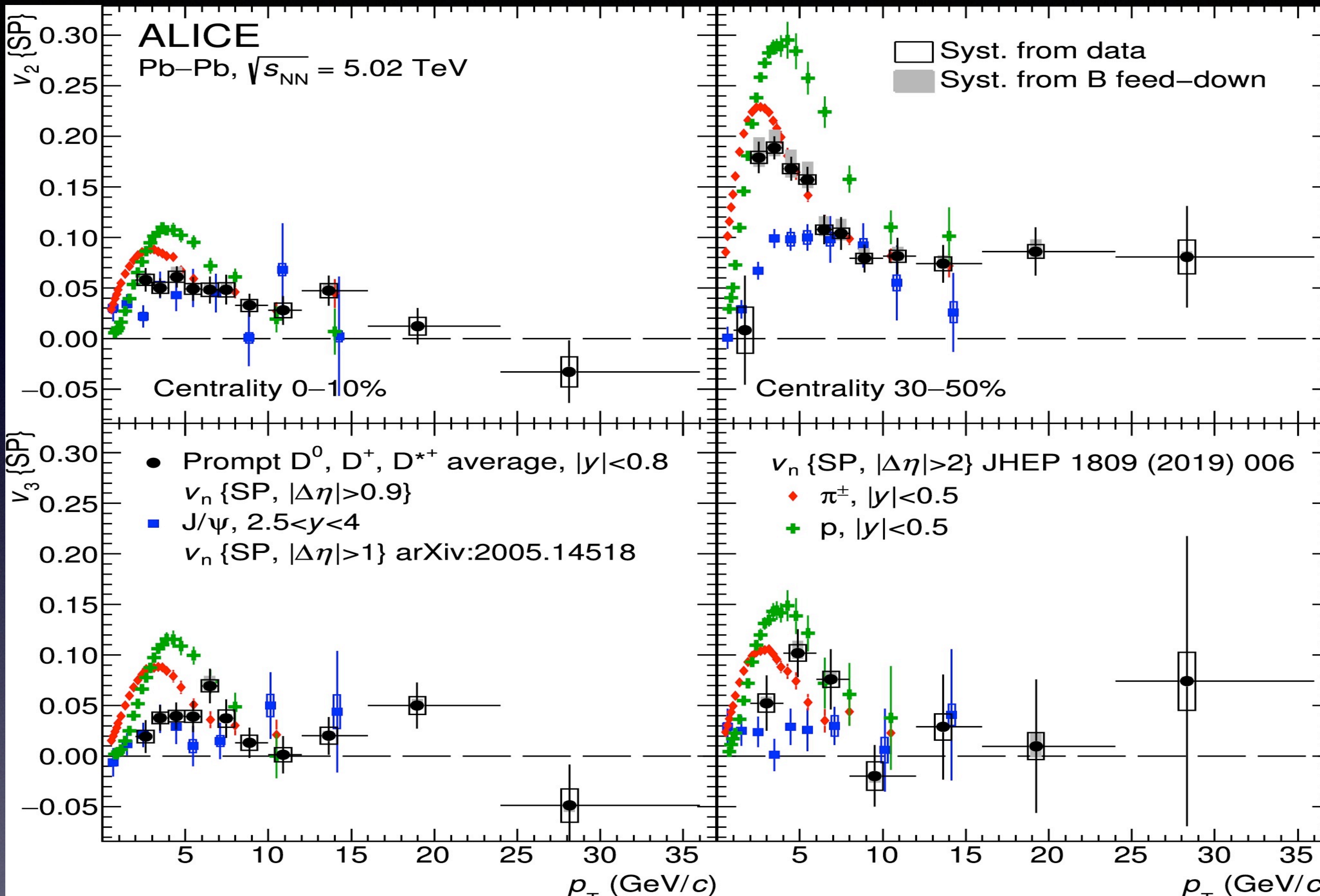


Mass hierarchy observed in the low p_T region

$$v_n(D) < v_n(p) < v_n(\pi)$$

Explore initial state with Flow coefficients (II)

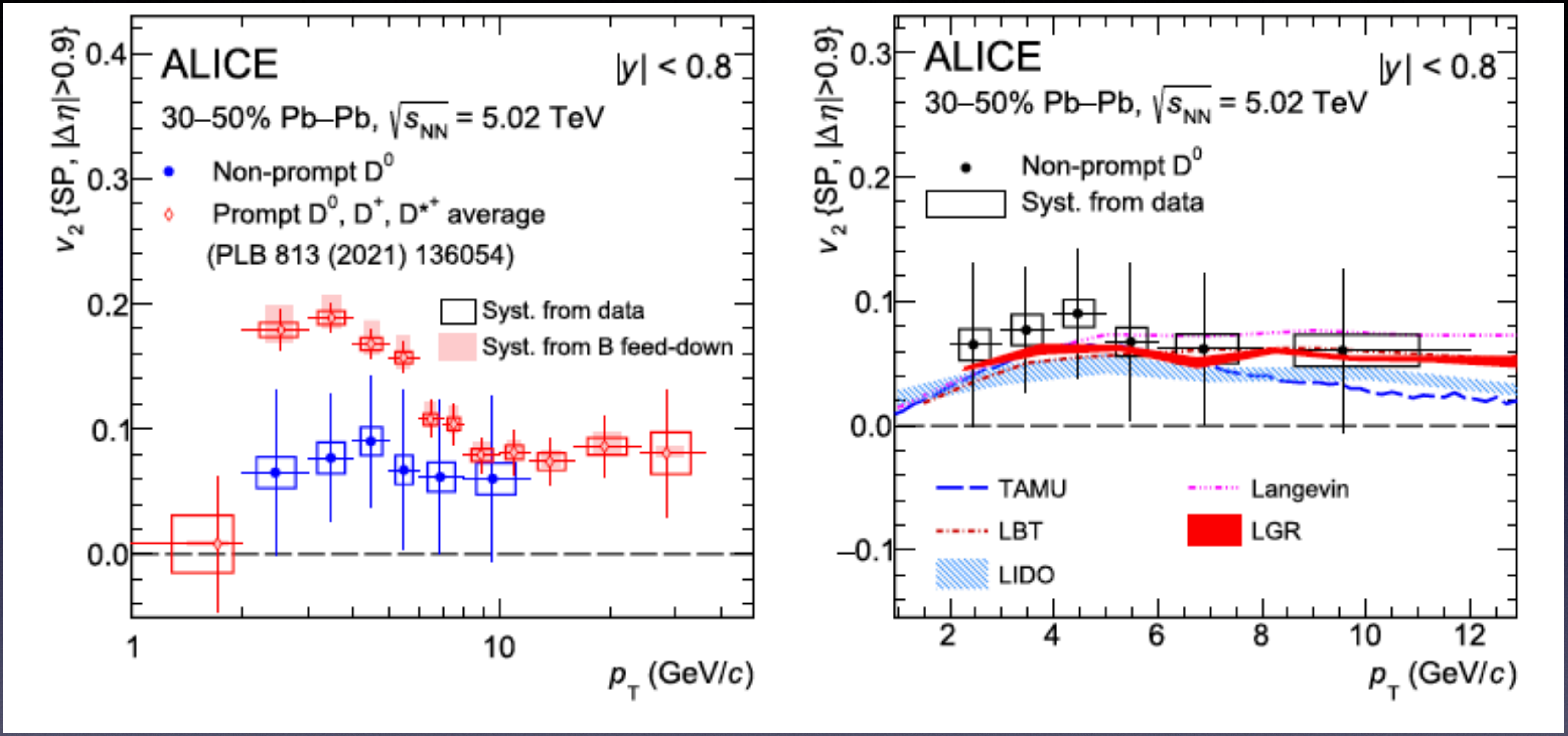
ALICE: Phys.Letts.B 813, 136054 (2021)



Quark coalescence in the intermediate p_T region as D meson flow comparable to pions

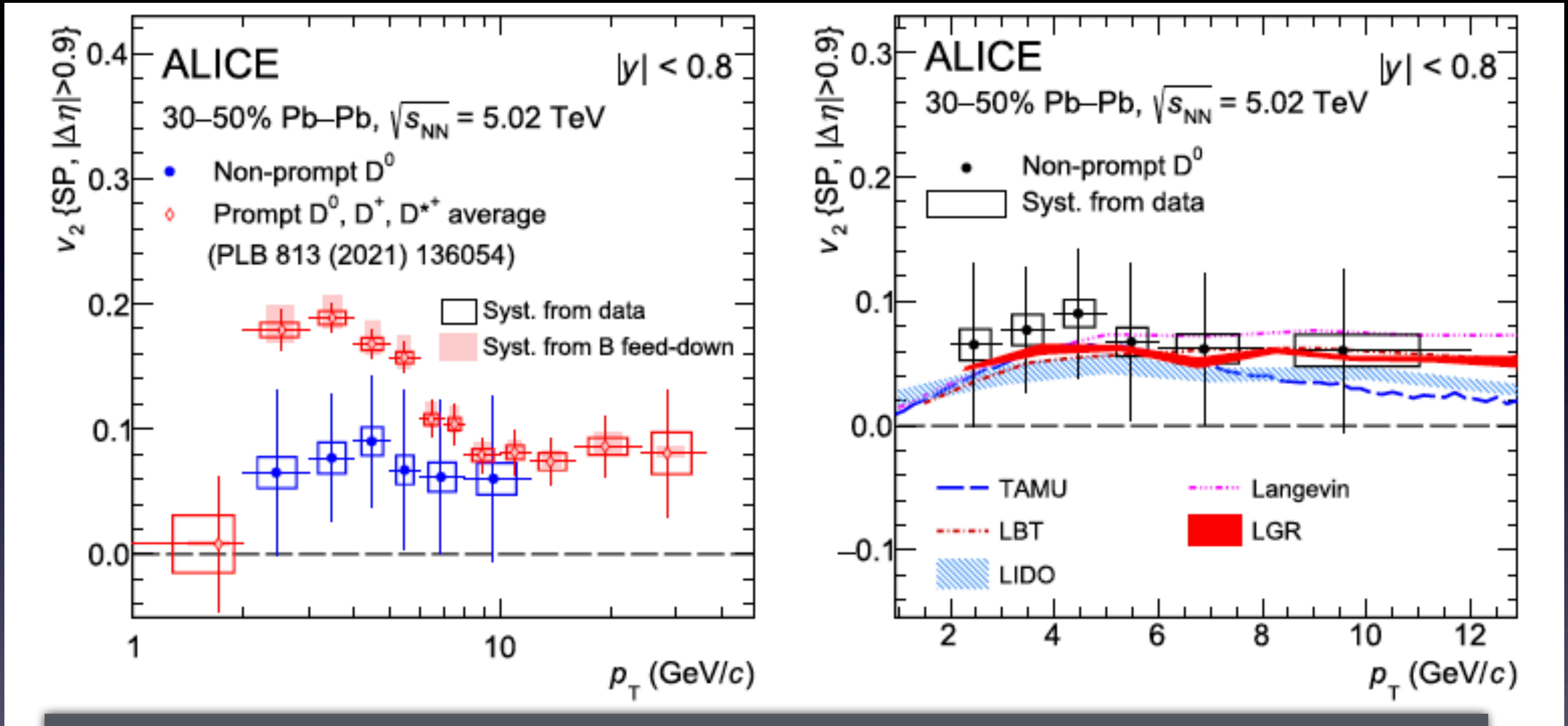
Explore initial state with Flow coefficients (II)

Eur. Phys. J. C (2023) 83:1123 .



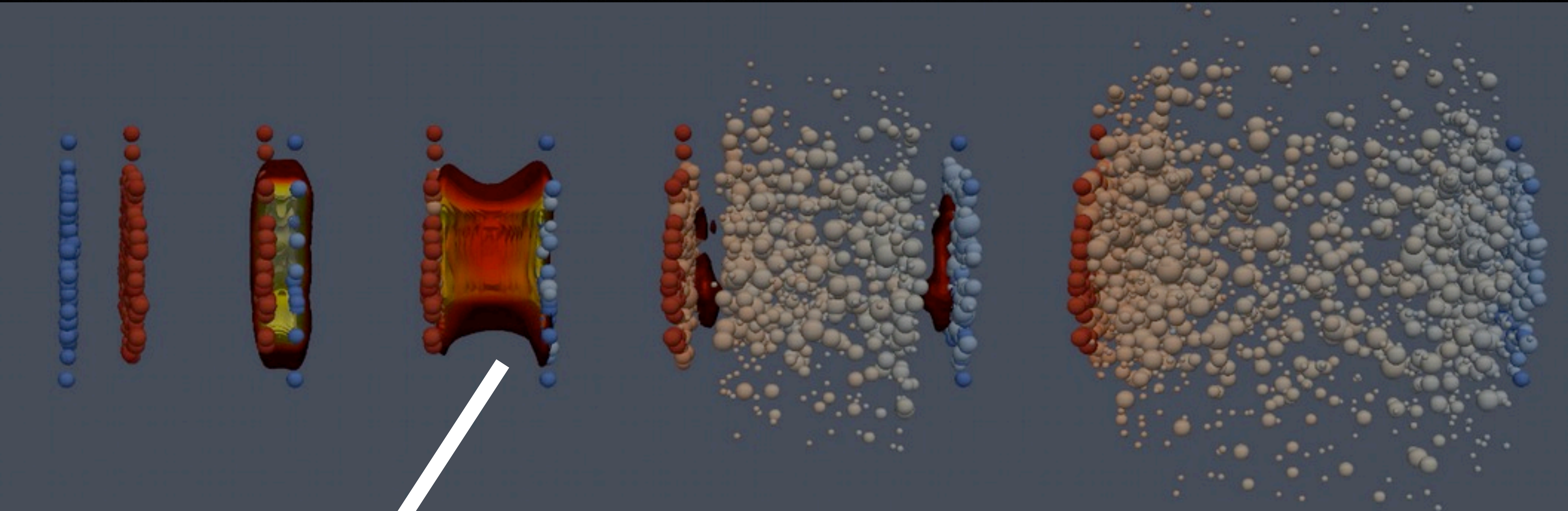
Explore initial state with Flow coefficients (II)

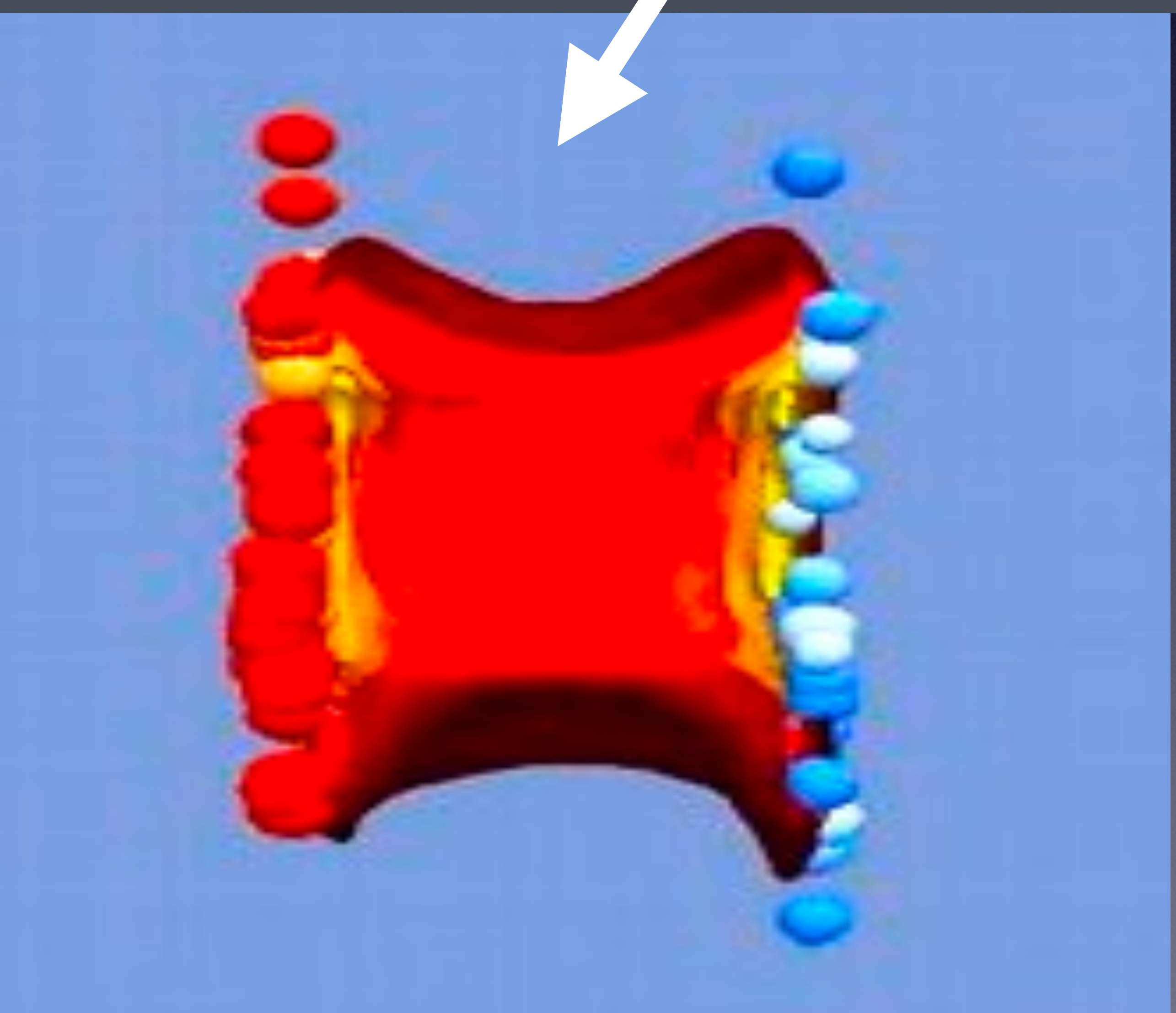
Eur. Phys. J. C (2023) 83:1123 .



Magnitudes of flow coefficients are lower for non-prompt D0.

Suggests mass-hierarchy in quark interactions with QGP.





Hot Medium properties

Explore medium with R_{AA}

R_{AA} : Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$

Explore medium with R_{AA}

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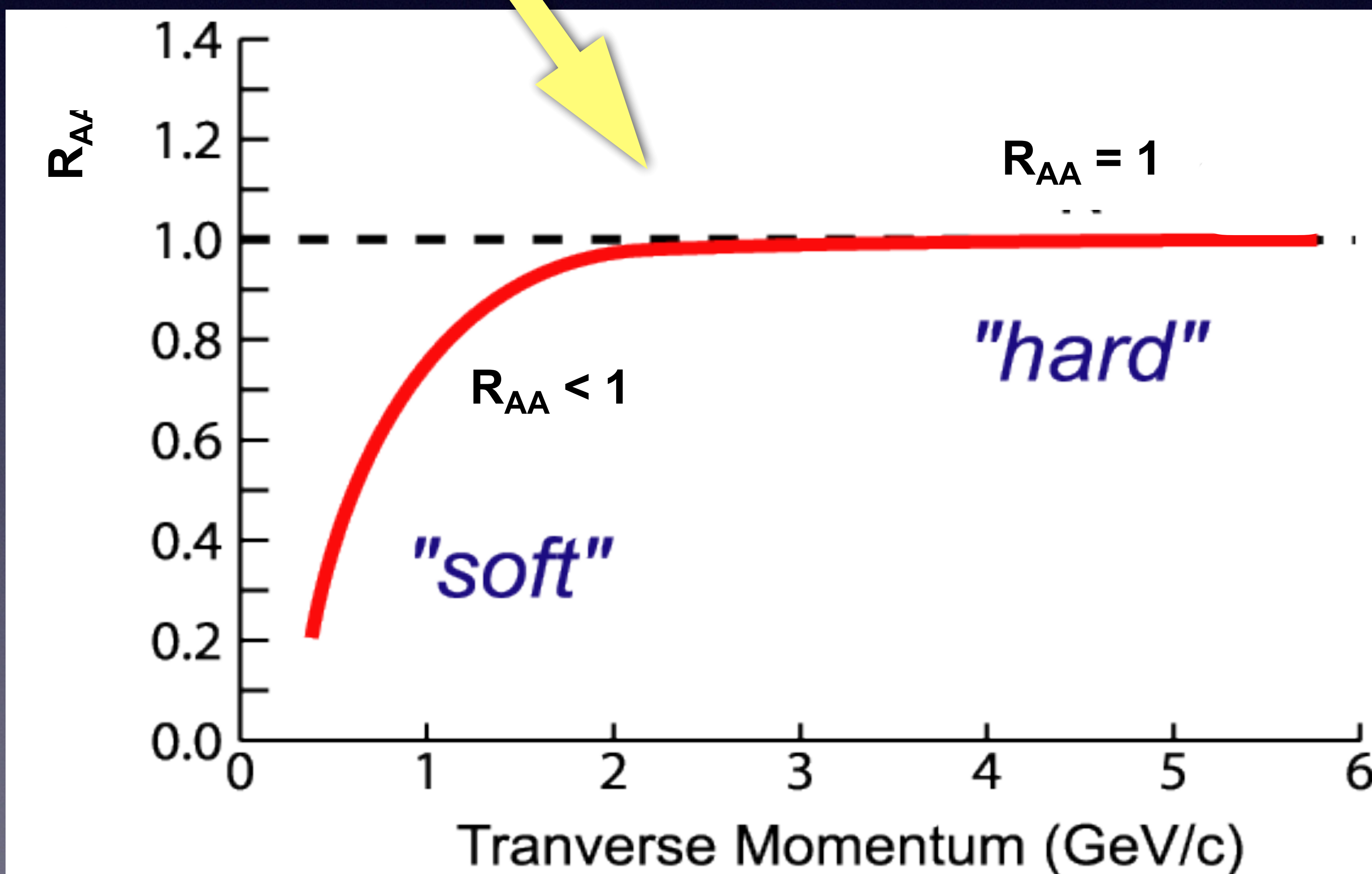
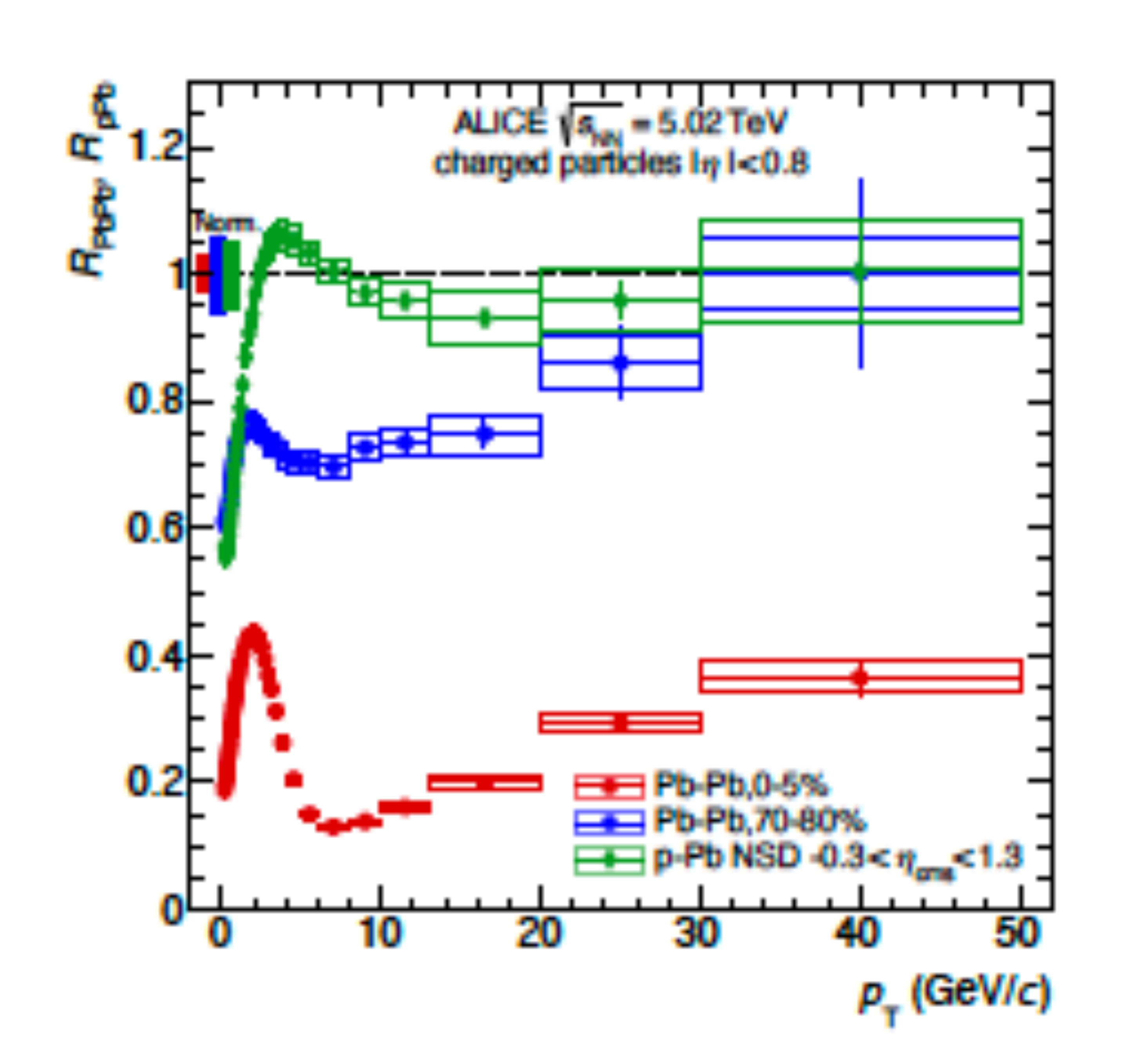


Explore medium with R_{AA} : light flavours

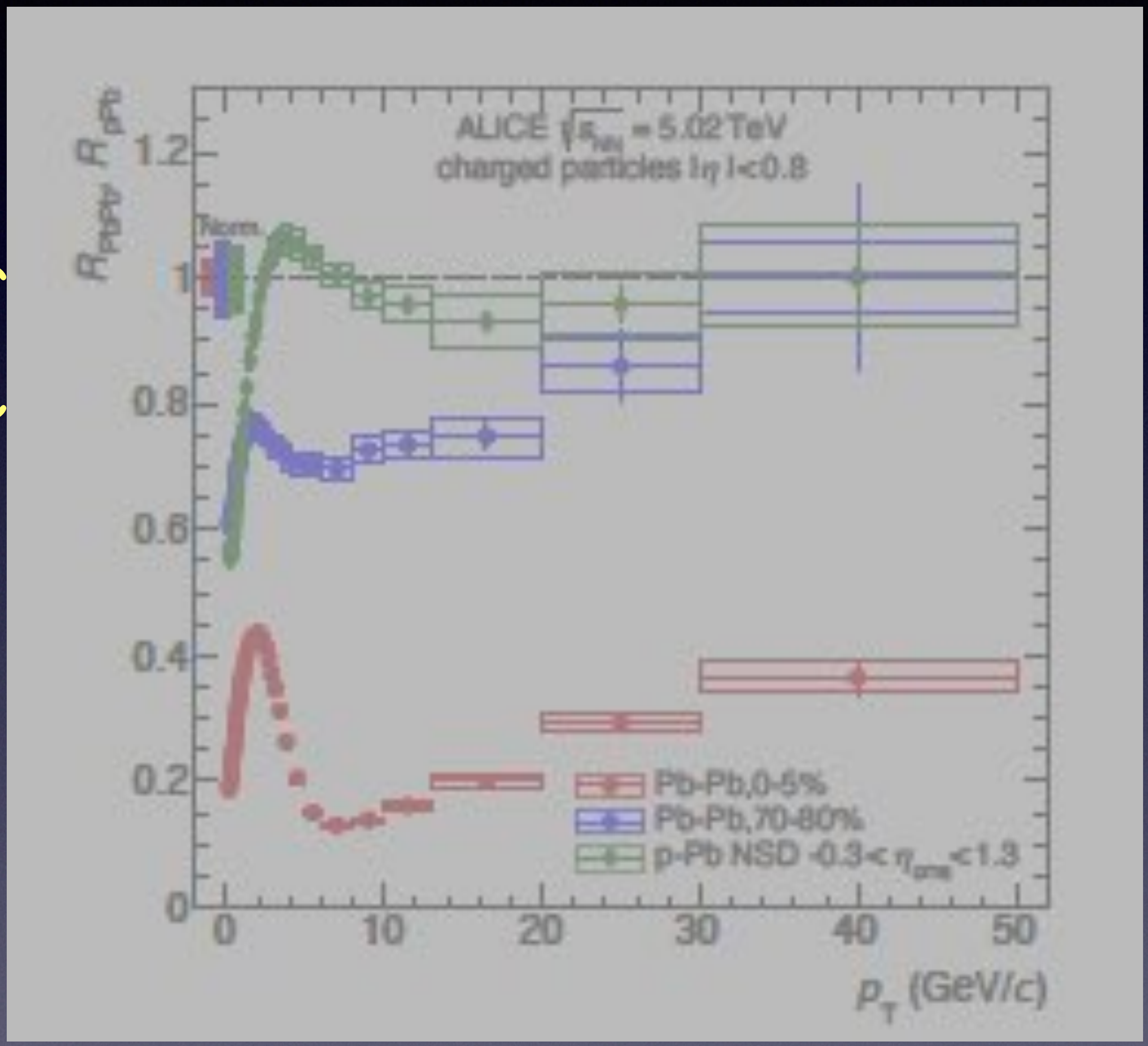
JHEP 1811 (2018) 013



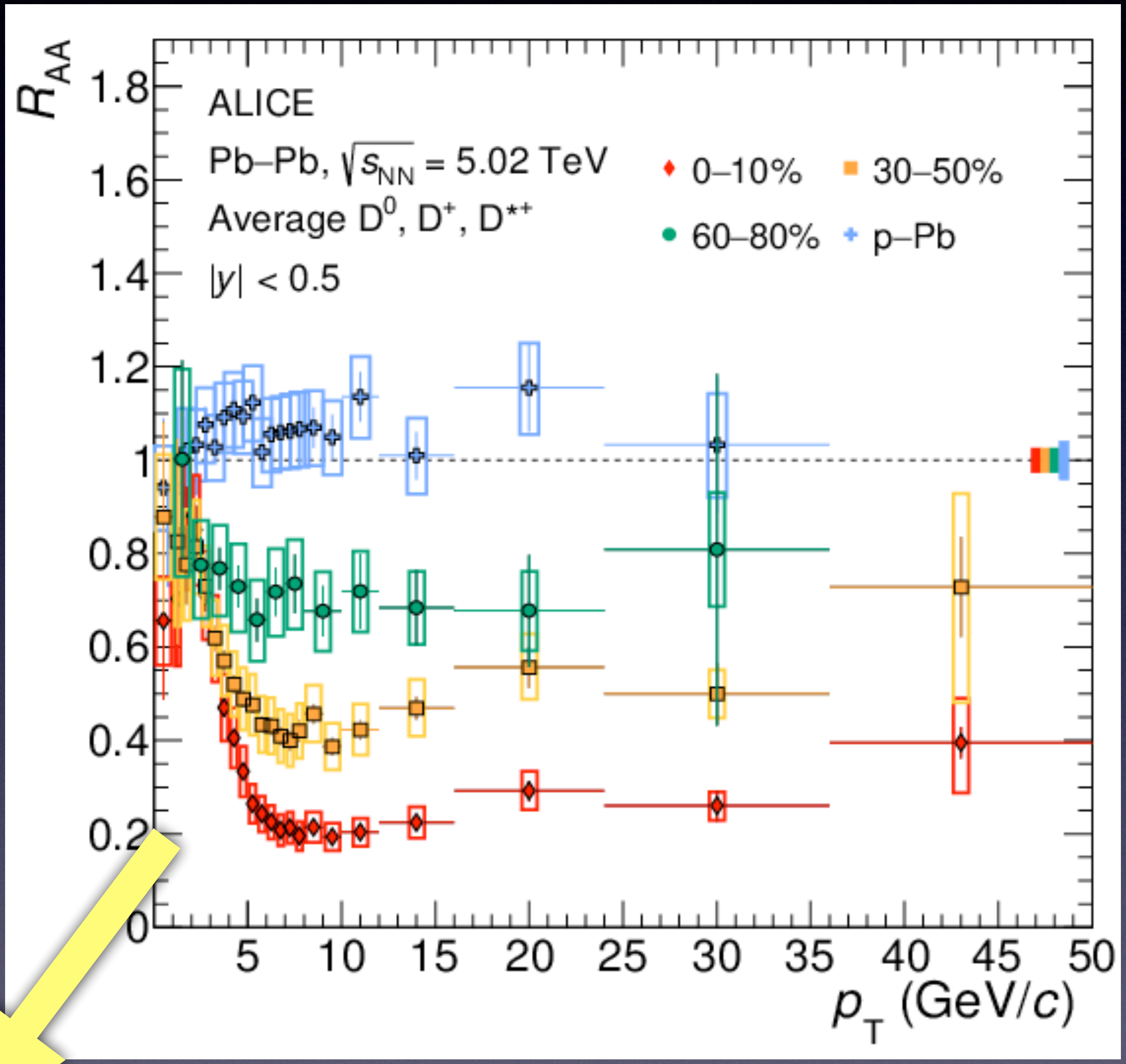
R_{AA} shows a strong centrality dependence

Explore medium with R_{AA} (II): heavy quarks

JHEP 1811 (2018) 013



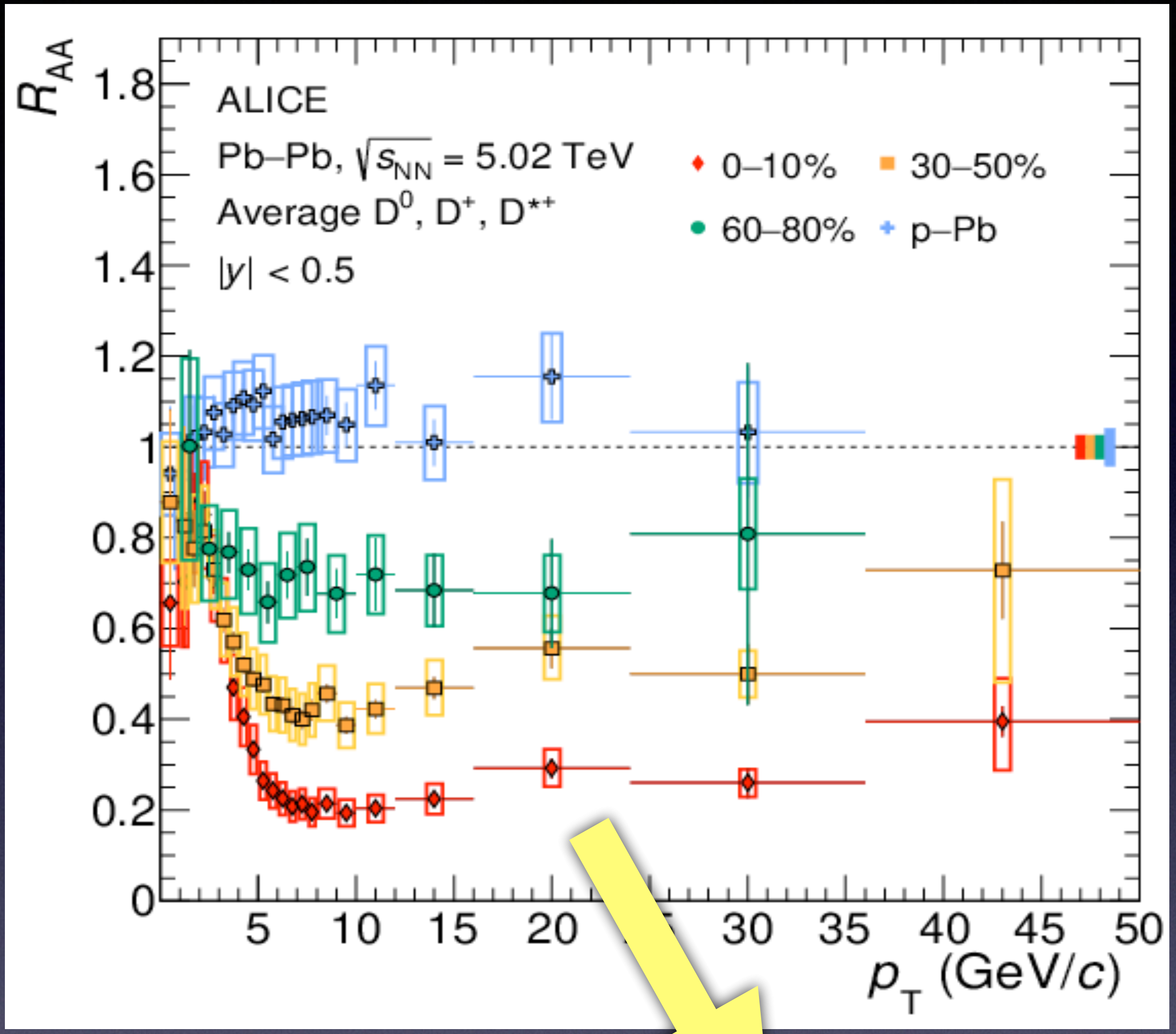
JHEP 174 (2022) 01



R_{AA} of D mesons shows a strong centrality dependence

Explore medium with R_{AA} (II): heavy quarks

JHEP 174 (2022) 01

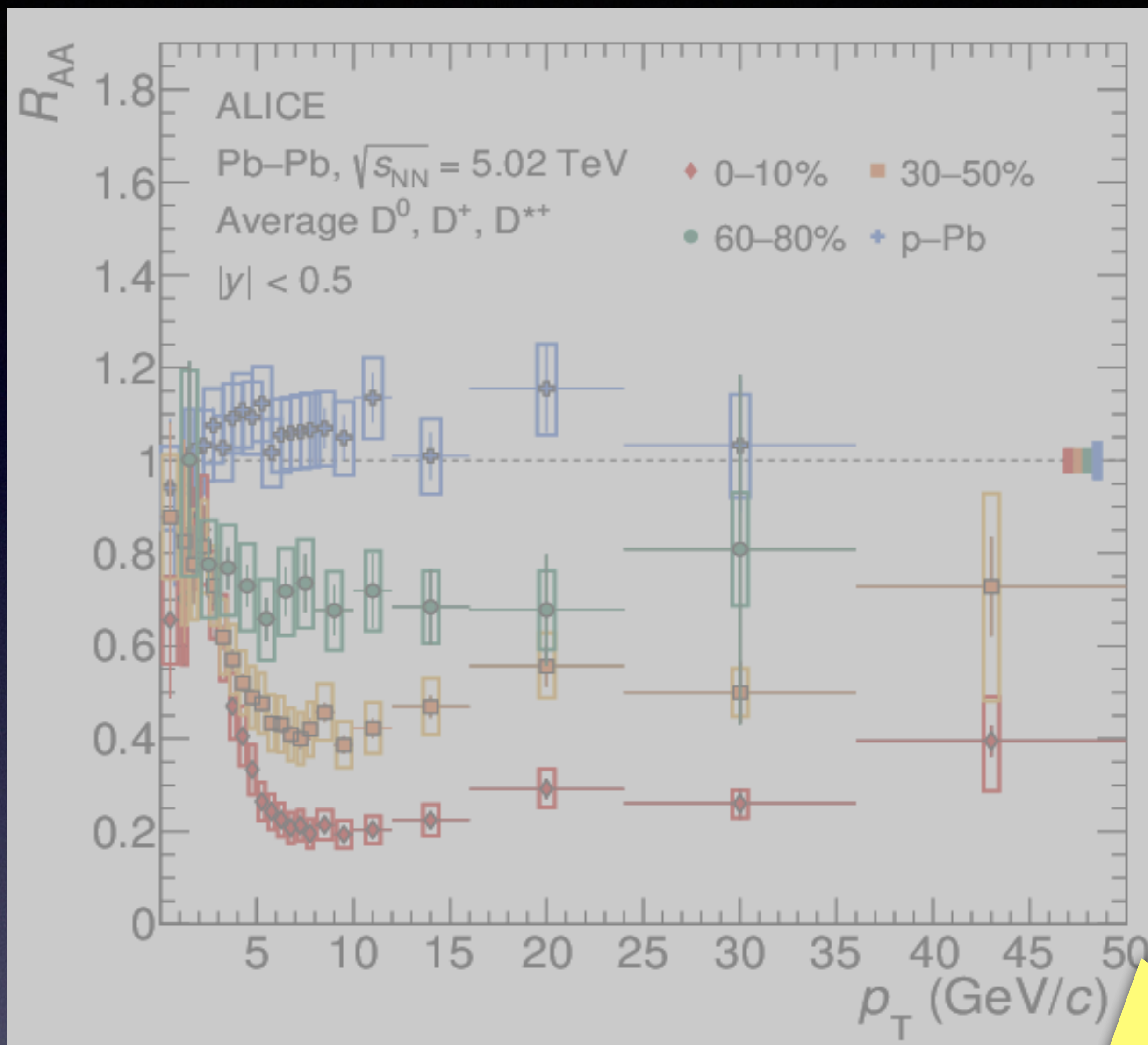


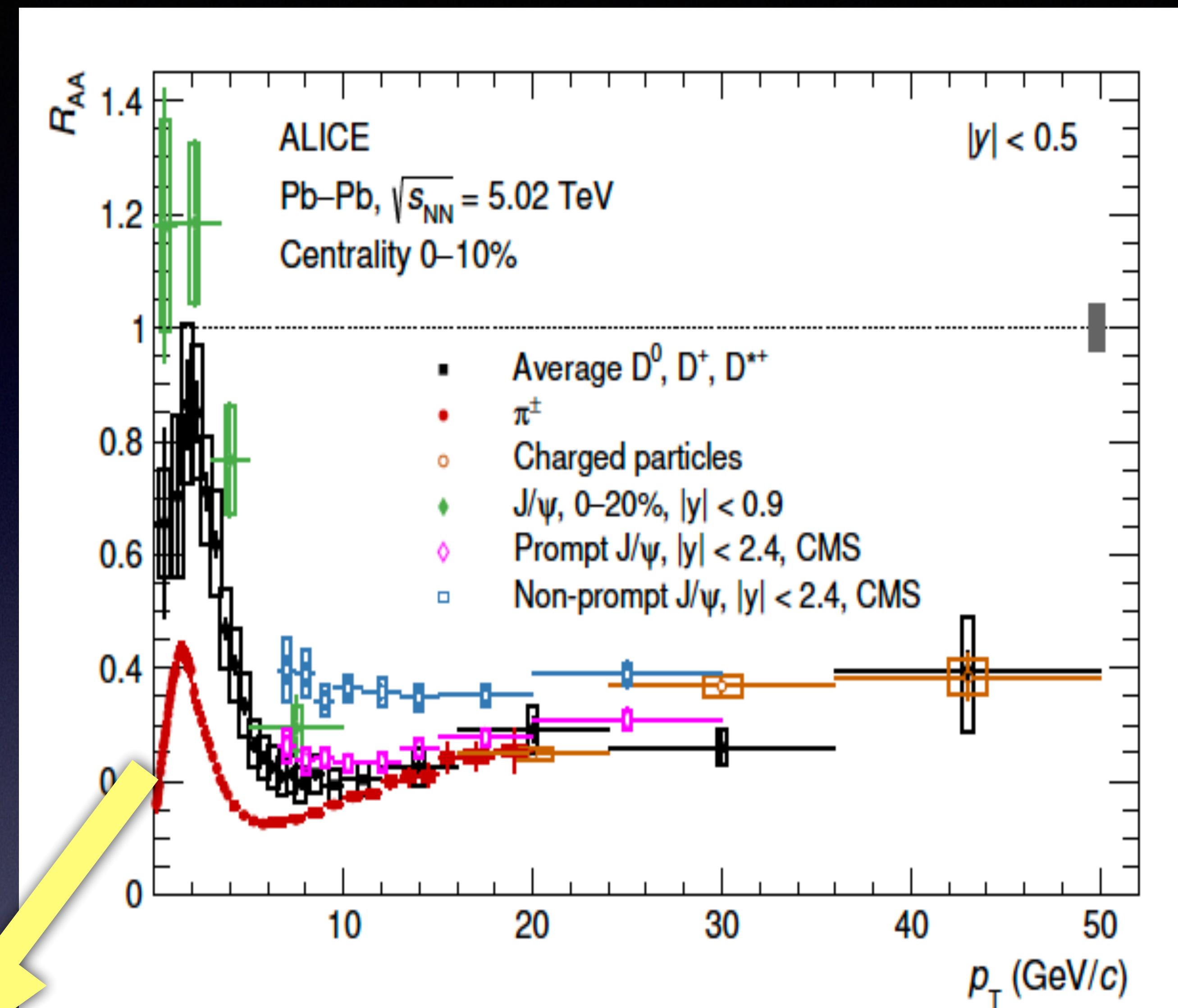
Suppression increases from peripheral to central collisions

Suppression observed in Pb-Pb collisions due to final state effects induced by the medium

Explore medium with R_{AA} (II): heavy quarks

JHEP 174 (2022) 01

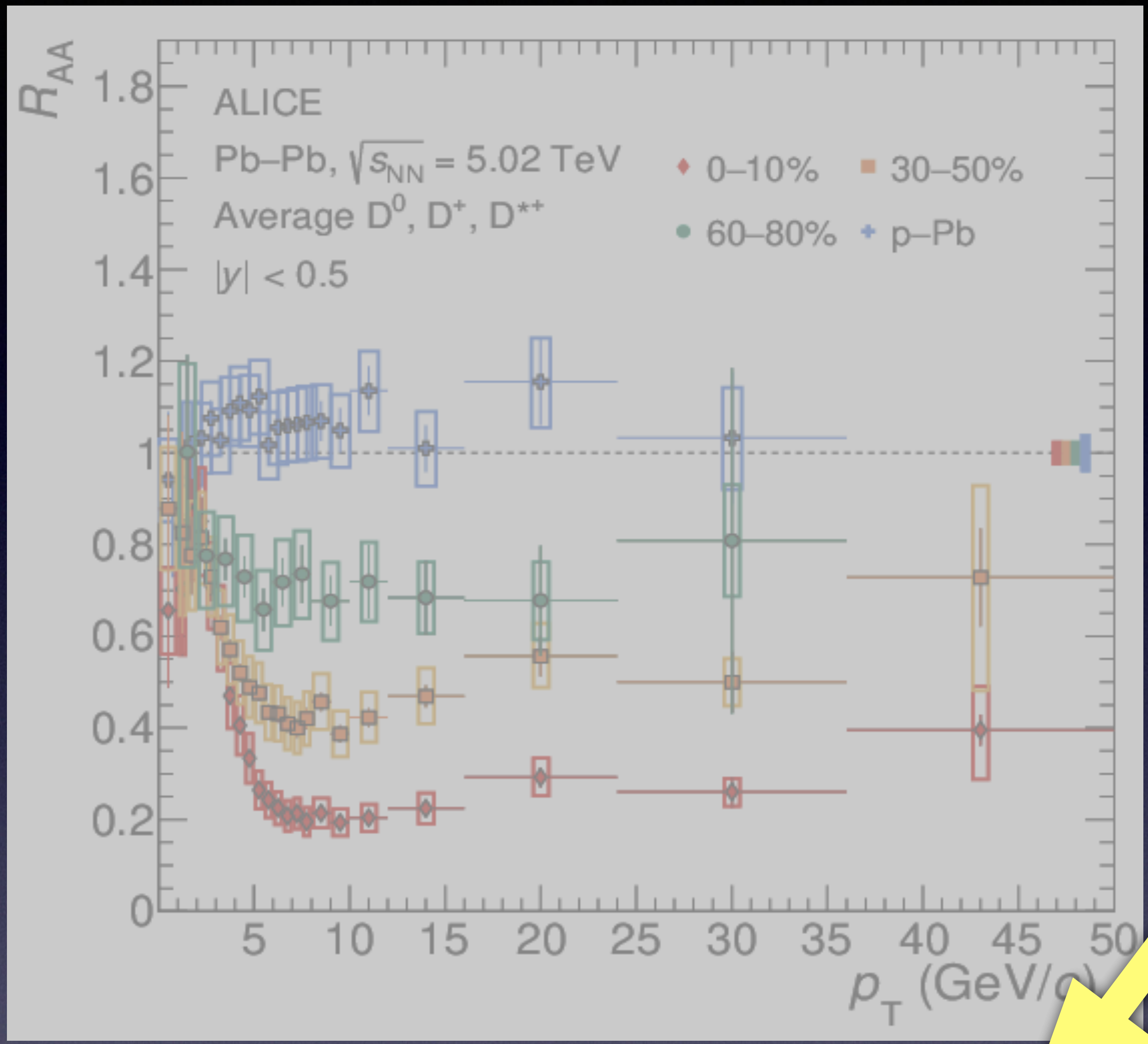


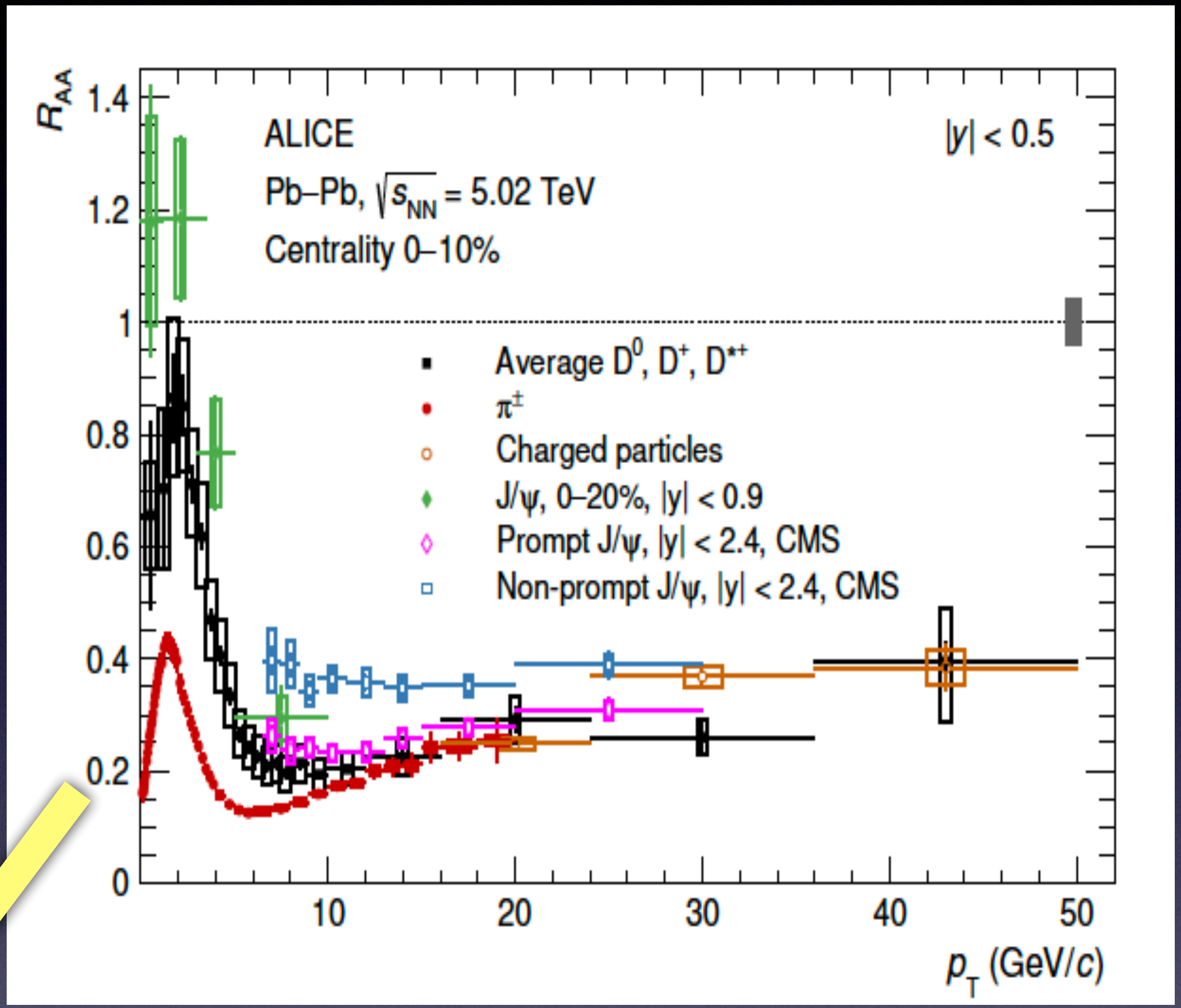


Different R_{AA} of D mesons and light flavored mesons

Explore medium with R_{AA} (II): heavy quarks

JHEP 174 (2022) 01



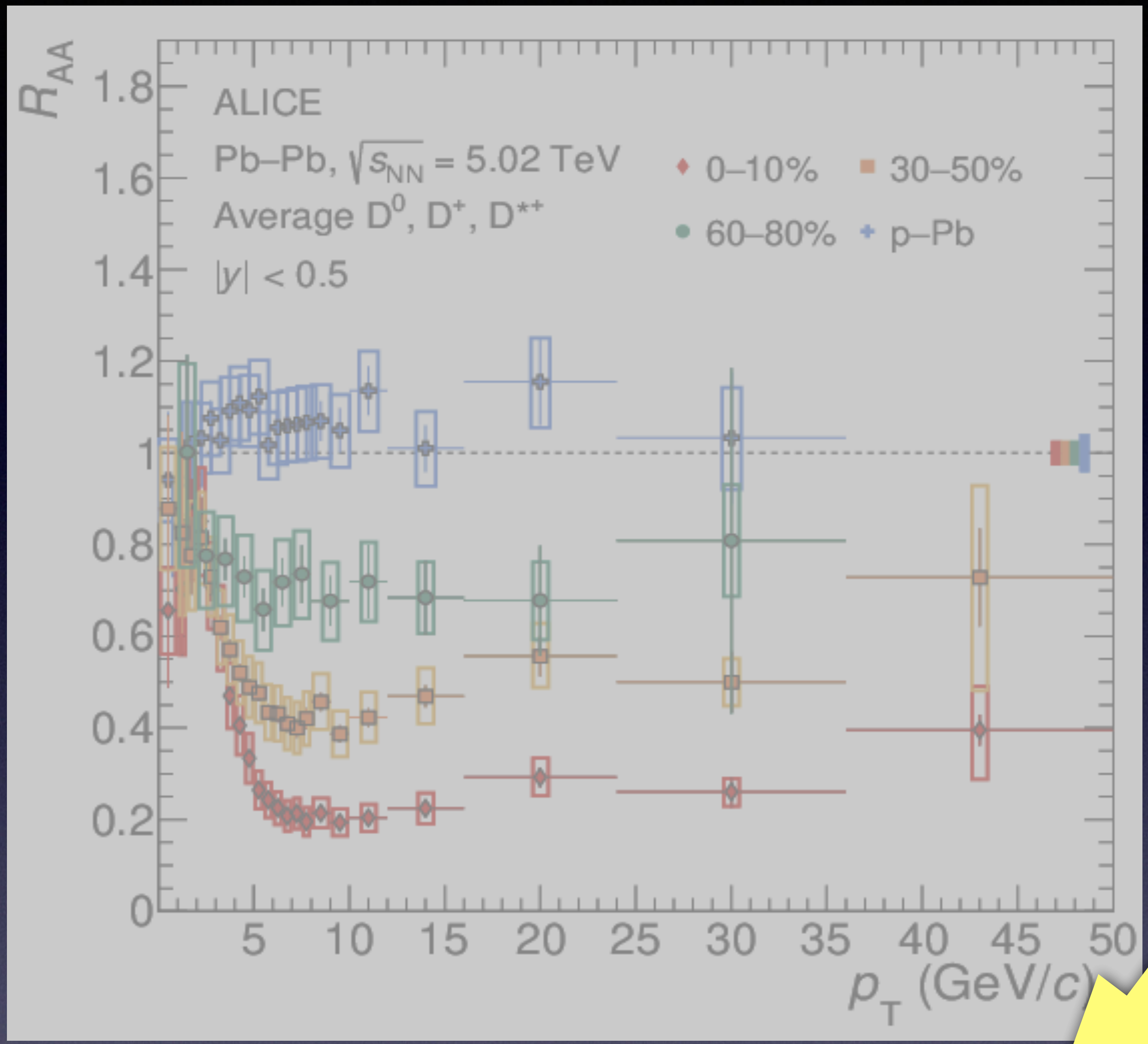


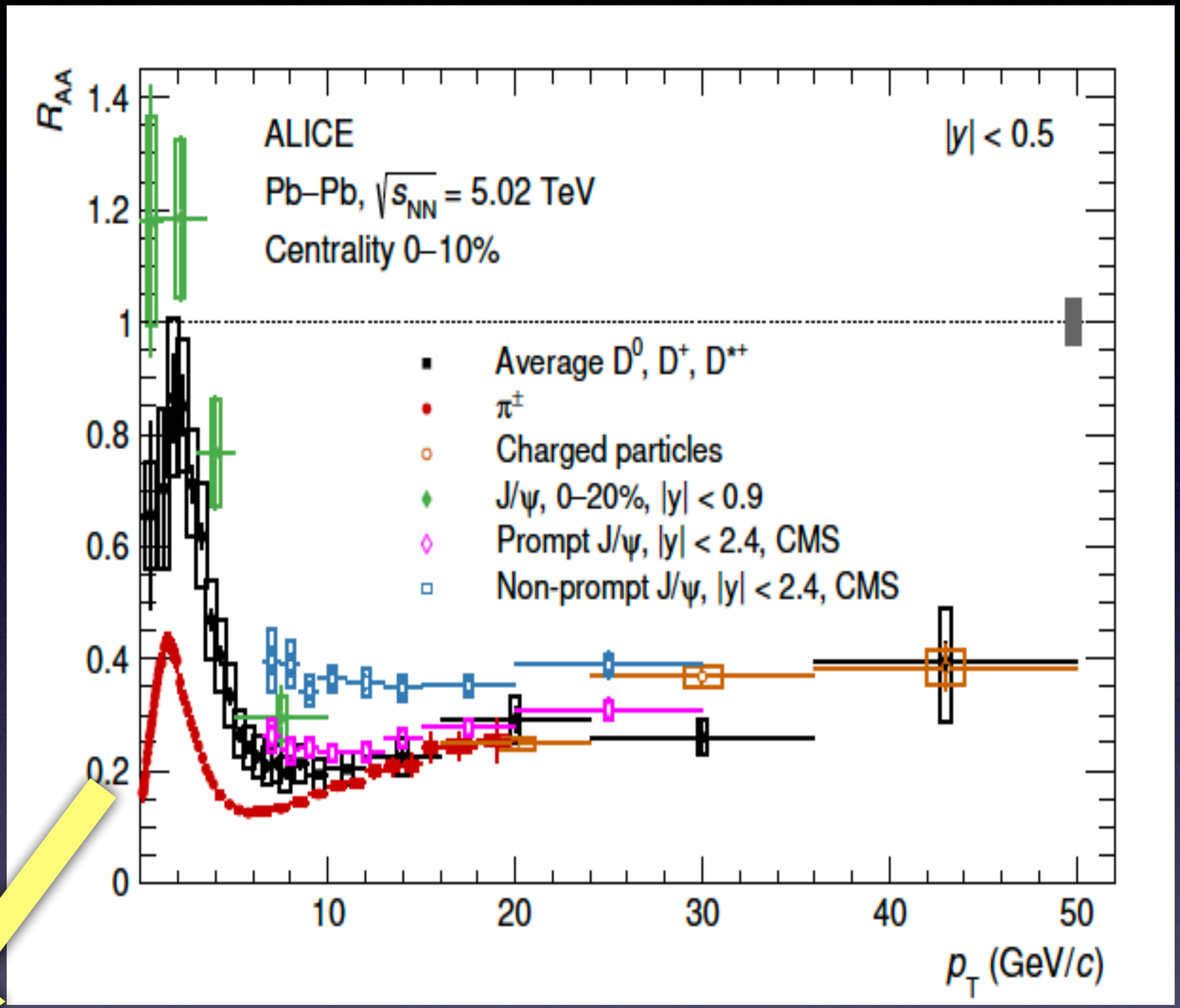
Different R_{AA} of D mesons and light flavored mesons

R_{AA} of D mesons and prompt J/Ψ signals interplay of different QGP effects in charm sector.

Explore medium with R_{AA} (II): heavy quarks

JHEP 174 (2022) 01



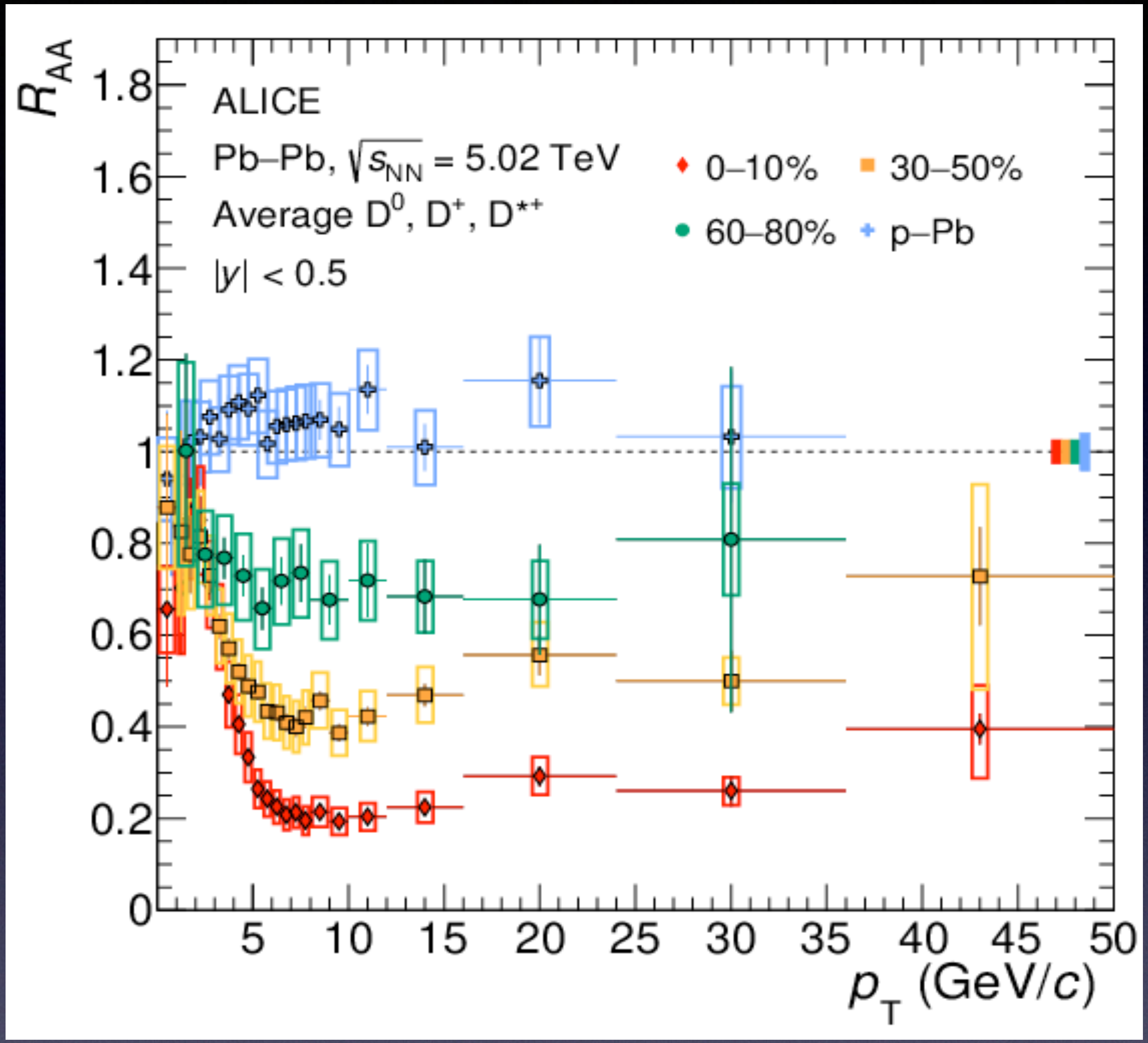


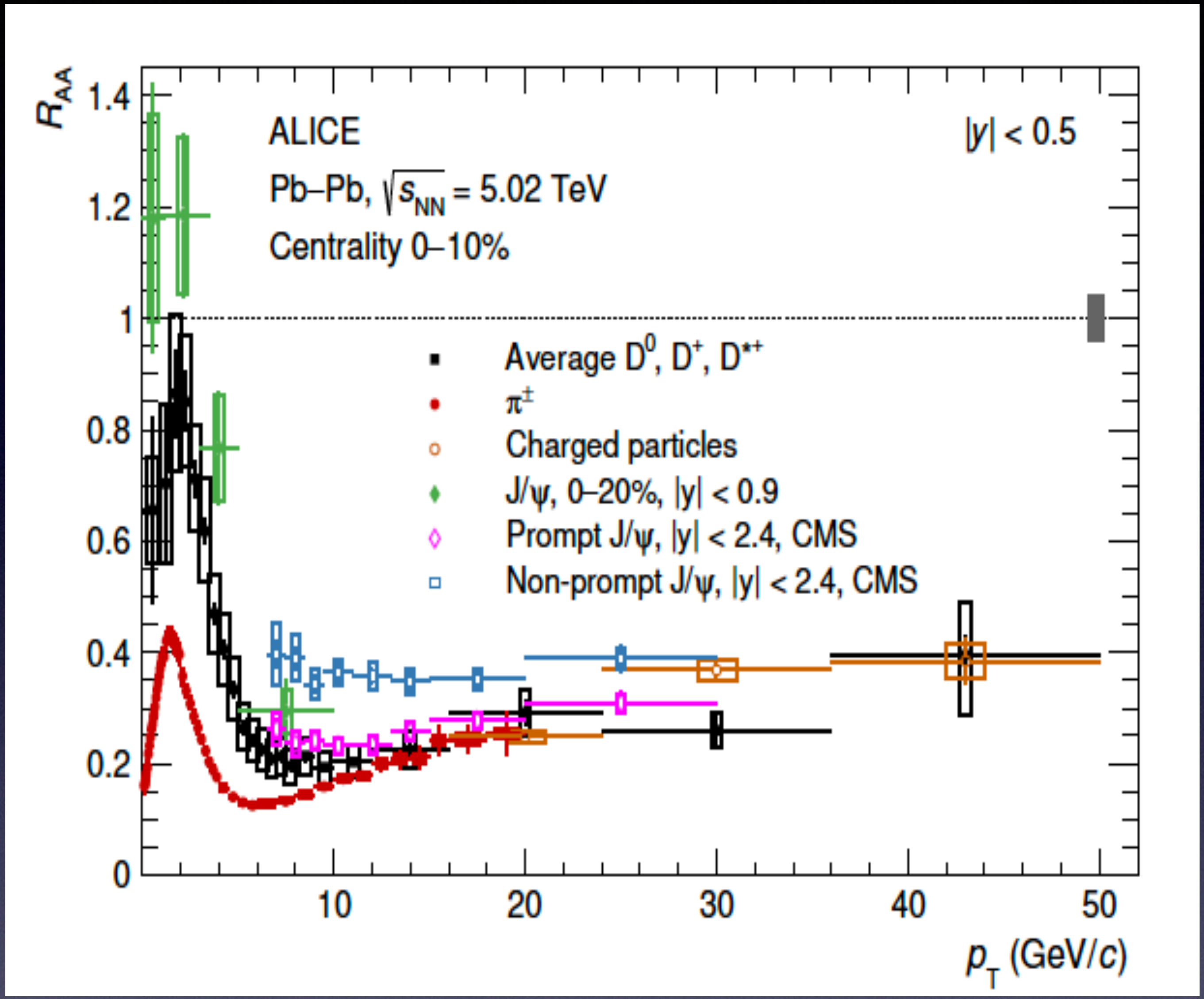
Different R_{AA} of D mesons and light flavored mesons

R_{AA} of D mesons and prompt J/Ψ signals interplay of different QGP effects in charm sector.

Different R_{AA} of D mesons and non-prompt J/Ψ from beauty hadron decays signals quark mass dependence of in-medium energy loss .

Explore medium with R_{AA} (II): heavy quarks



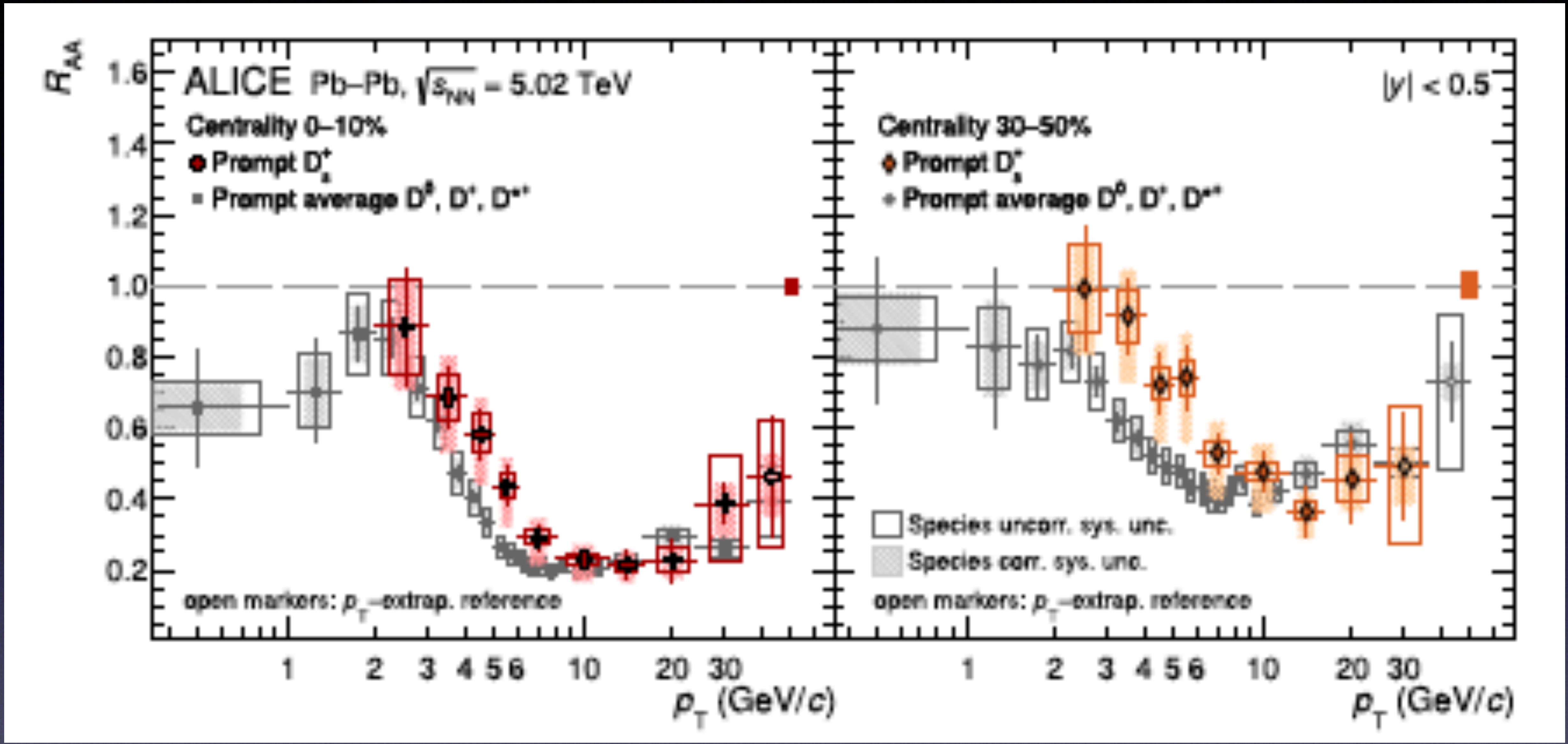


Suppression increases from peripheral to central collisions

Suppression observed in Pb-Pb collisions due to final state effects induced by the medium

Explore medium with R_{AA} (II) : heavy+strange

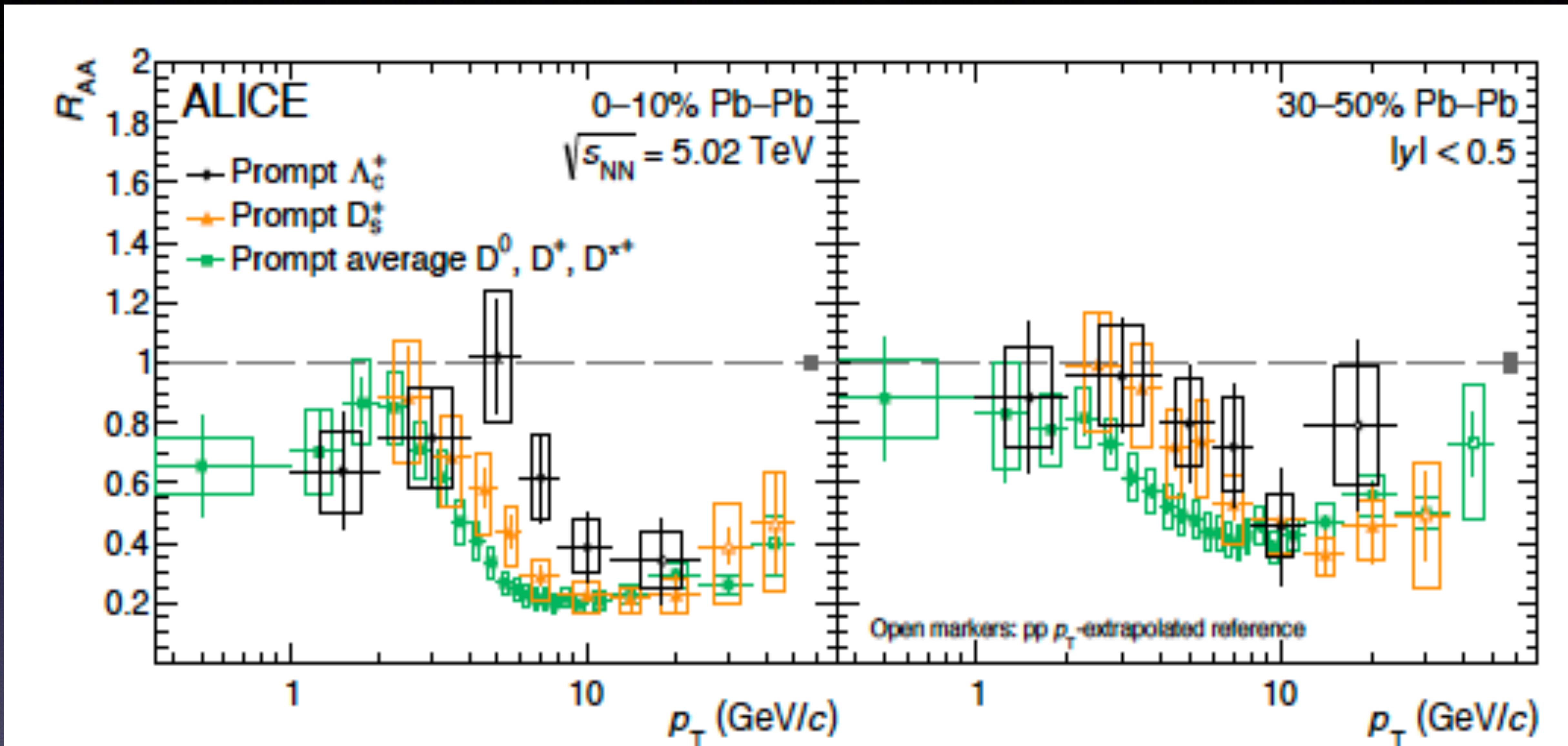
Phys. Lett. B 827 (2022) 136986



Strong suppression of $D_S{}^+$ reaching a minimum at p_T ~ 10 GeV/c

Explore medium with R_{AA} (II) : heavy+strange

Phys. Lett. B 839 (2023) 137796

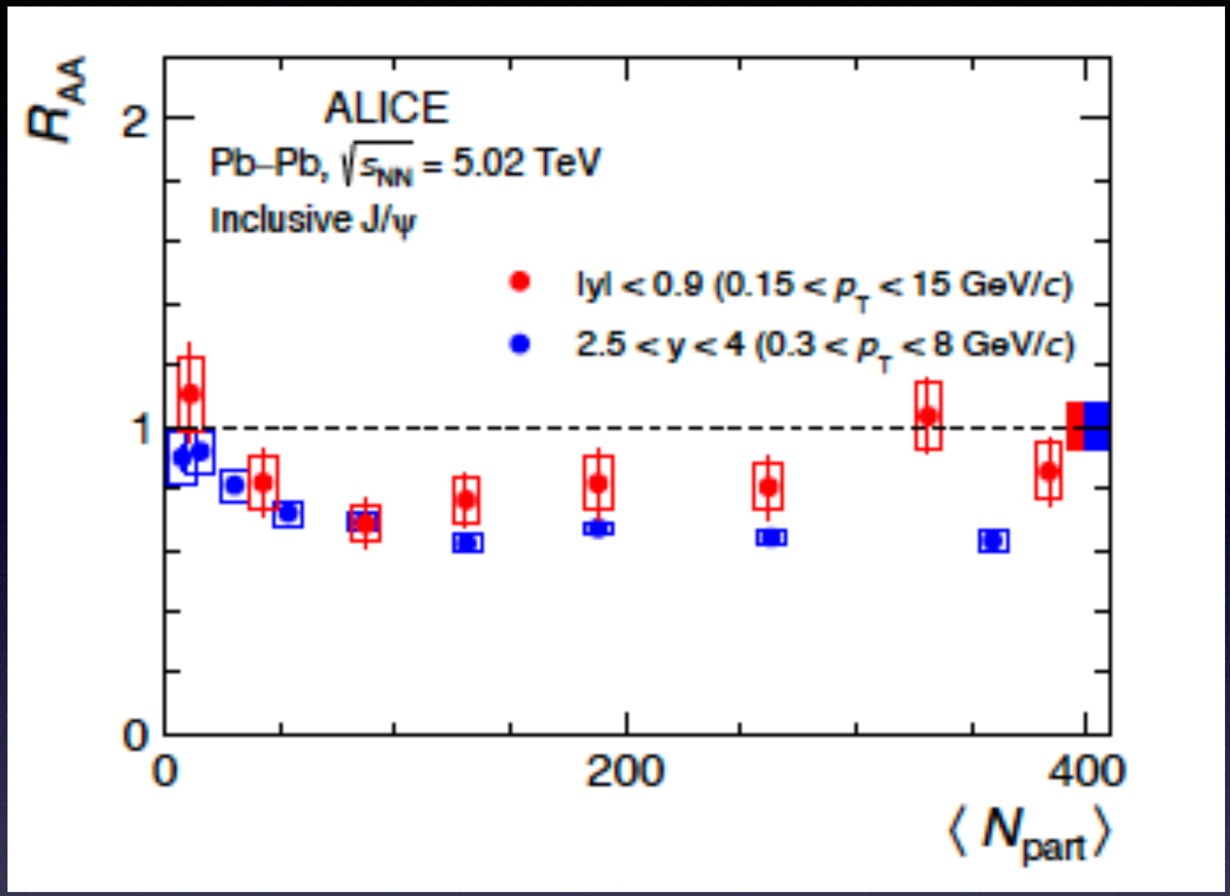


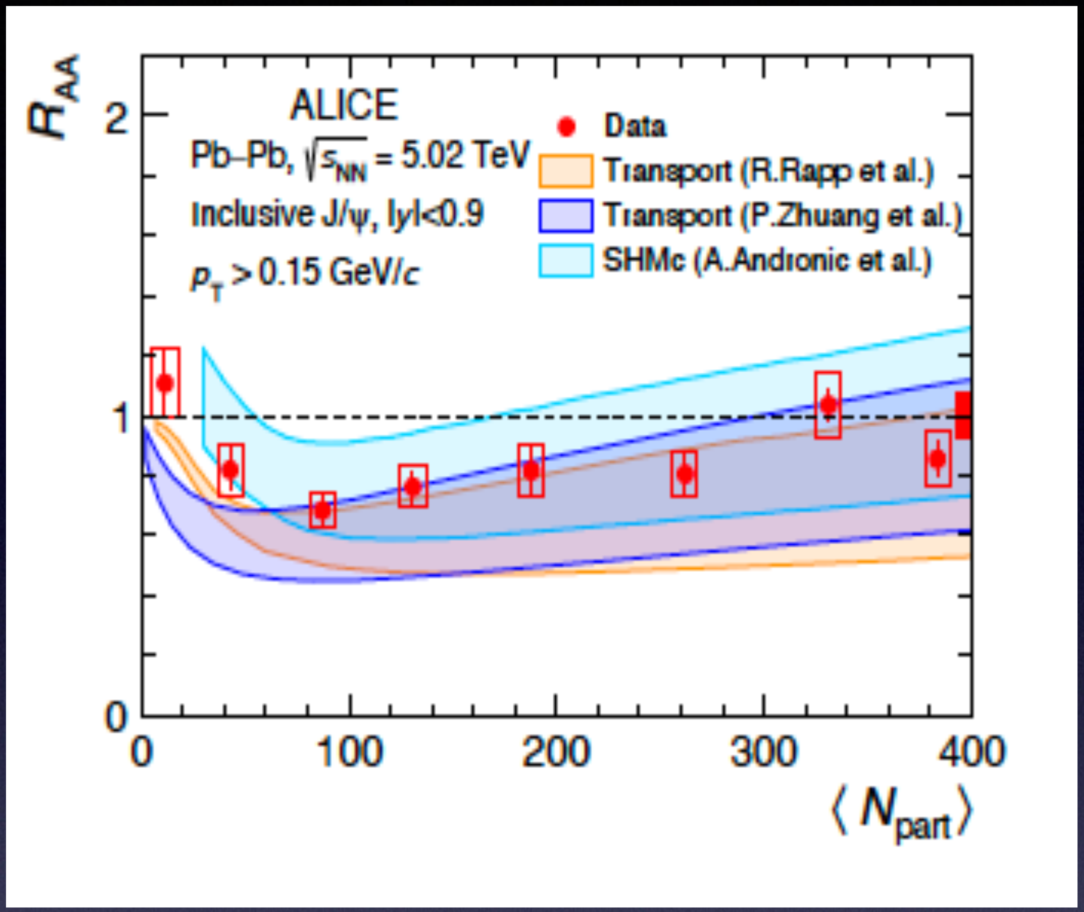
Suppression of Λ_c^+ at p_T > 6 GeV/c

Hierarchy R_{AA} (Λ_c) > R_{AA} (D_S) > R_{AA}(D) for pT > 4.5 GeV

Explore medium with R_{AA} (II) : J/Ψ

PRL 132, 042301 (2024)

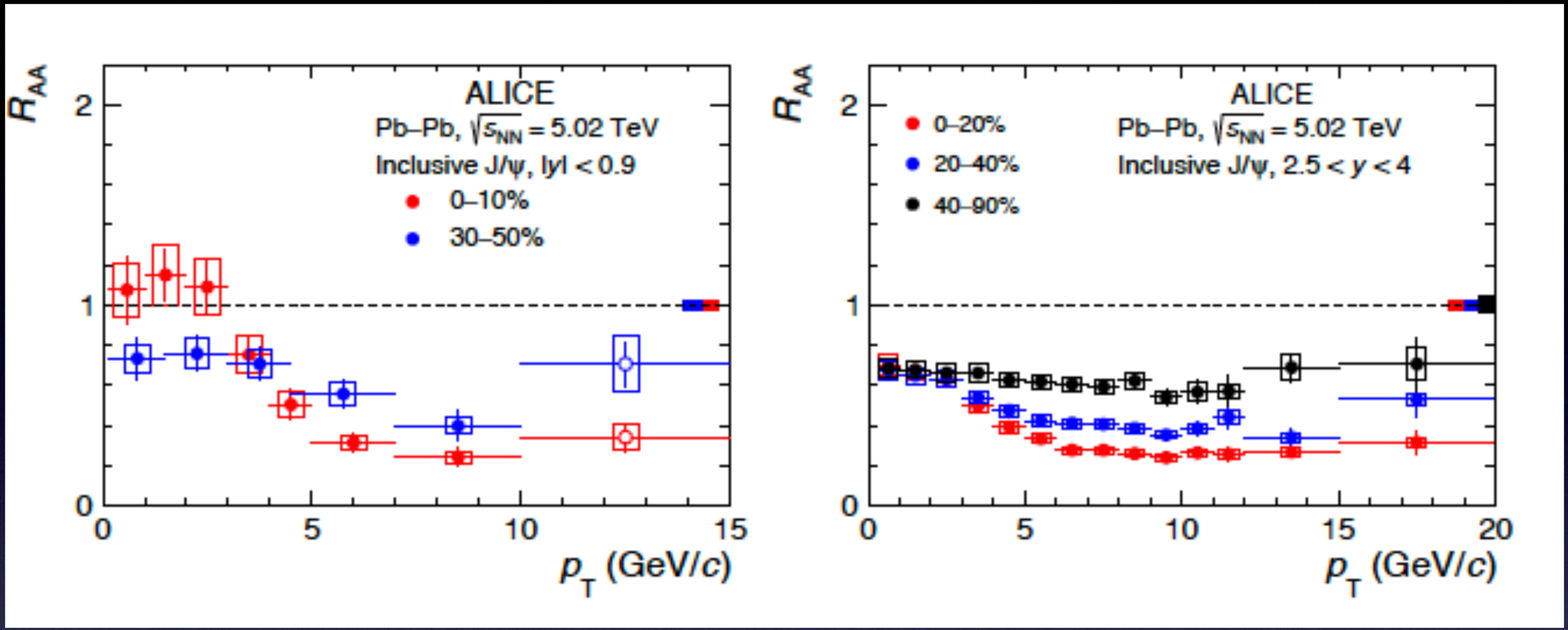




The values at midrapidity are larger than those measured at forward rapidity.

Explore medium with R_{AA} (II) : J/Ψ

Phys. Lett. B 849 (2024) 138451

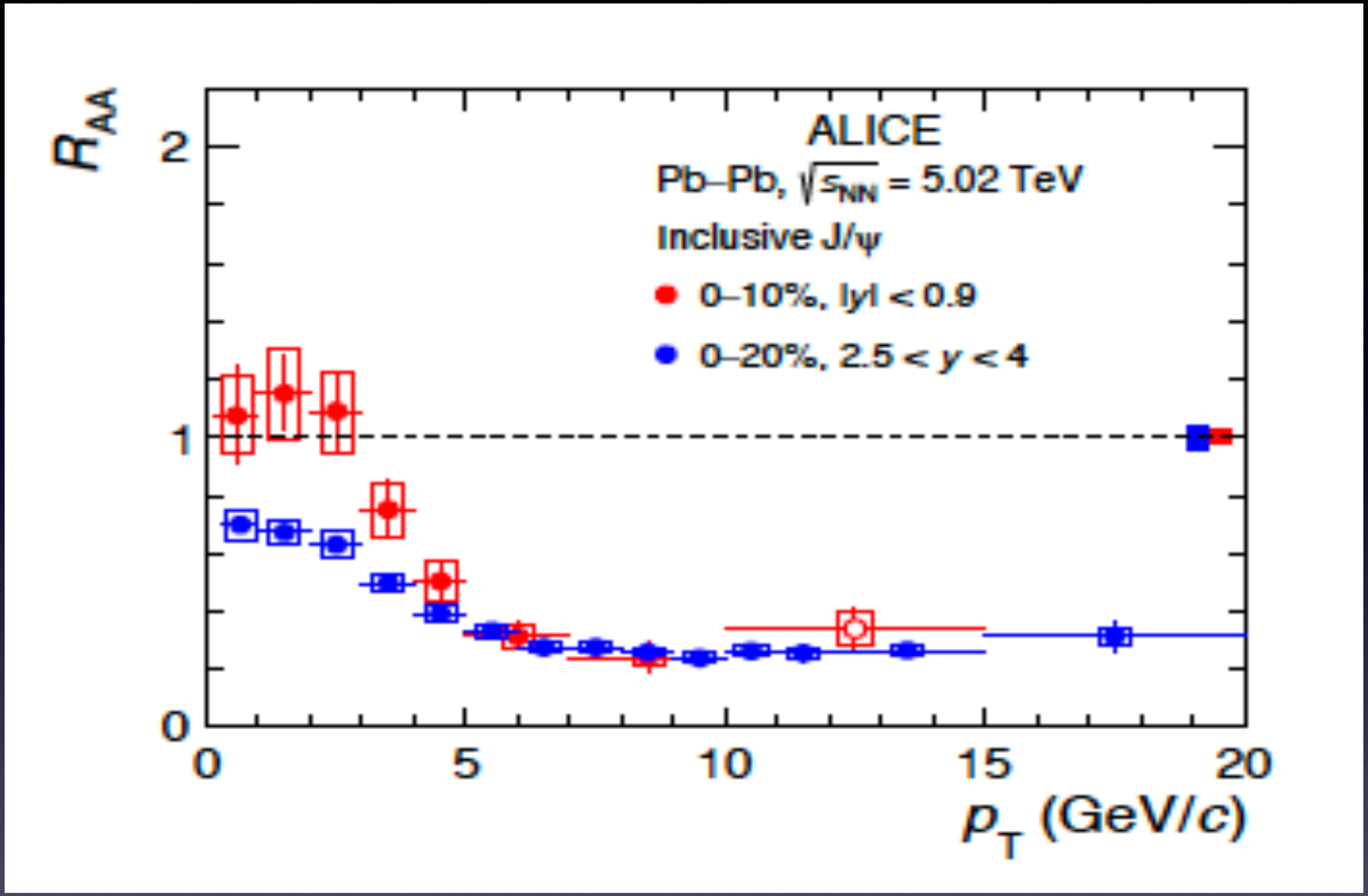


R_{AA} values are relatively large at low p_T (p_T < 5 GeV/c), in contrast with the strong suppression in the p_T > 5 GeV/c range, for central and semi-central collisions.

A weaker p_T dependence of the R_{AA} values is observed from central to peripheral collisions, up to a constant R_{AA}, within uncertainties. in the 40–90% centrality interval at forward rapidity.

Explore medium with R_{AA} (II) : J/Ψ

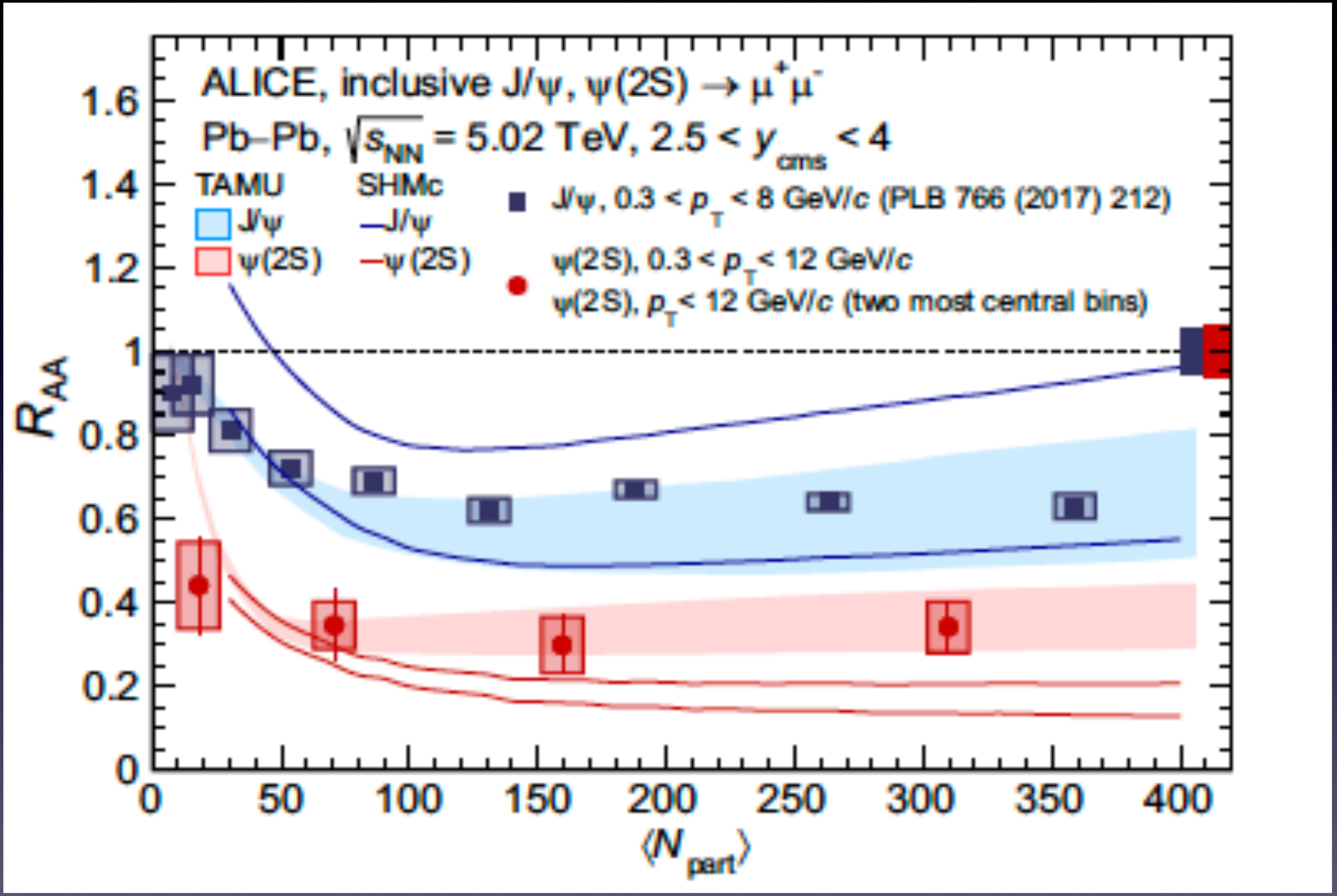
Phys. Lett. B 849 (2024) 138451



The R_{AA} is higher at midrapidity with respect to forward rapidity at low p_T (p_T < 3 GeV/c), supporting the picture of quarkonium production via coalescing charm quarks.
The two measurements converge to similar values at higher p_T suggesting a weaker dependence on rapidity for the suppression effects.

Explore medium with R_{AA} (II) : Ψ(2S)

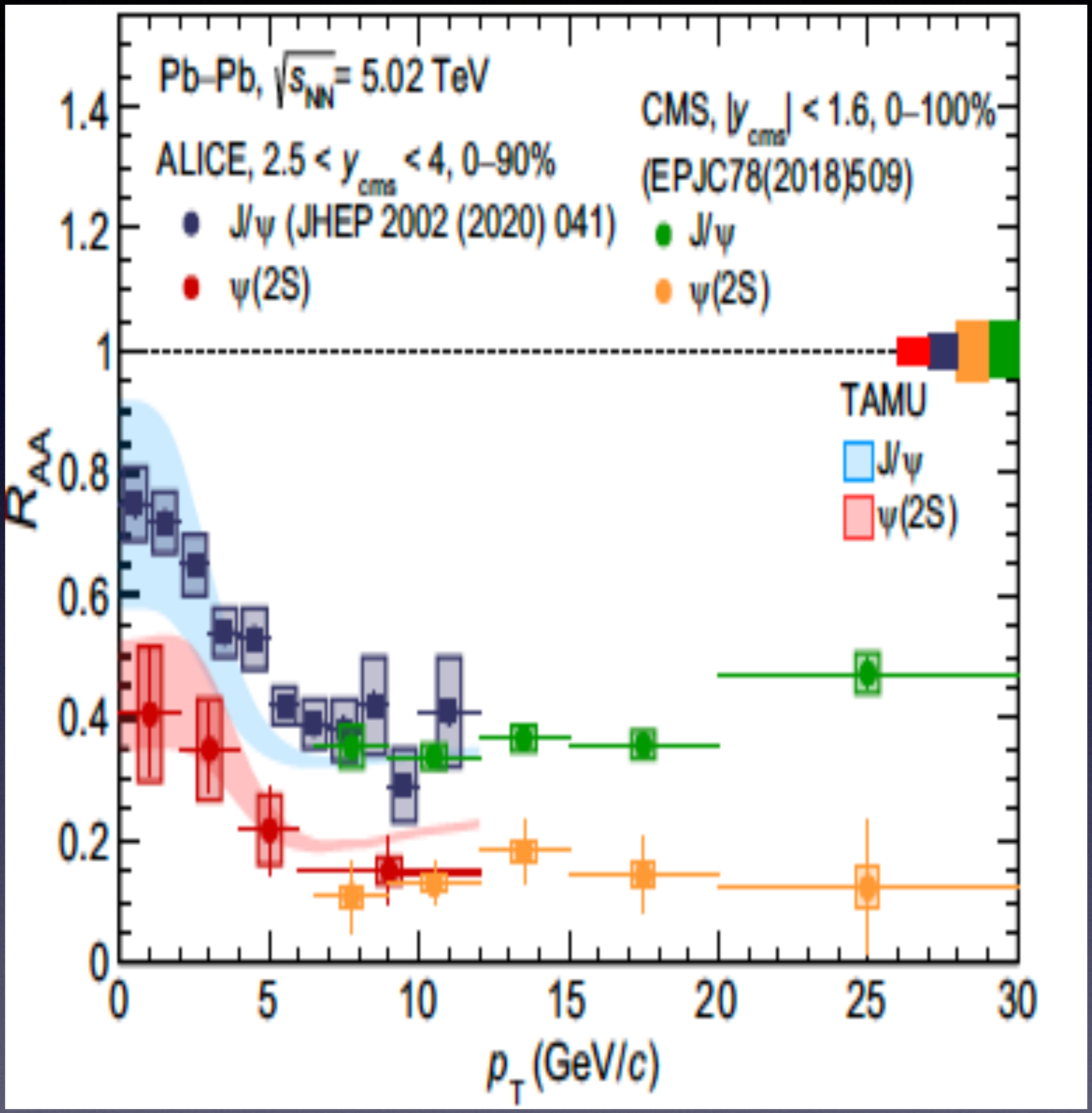
PRL 132, 042301 (2024)



Stronger suppression of Ψ(2S) compared to J/Ψ

Explore medium with R_{AA} (II) : $\Psi(2S)$

PRL 132, 042301 (2024)

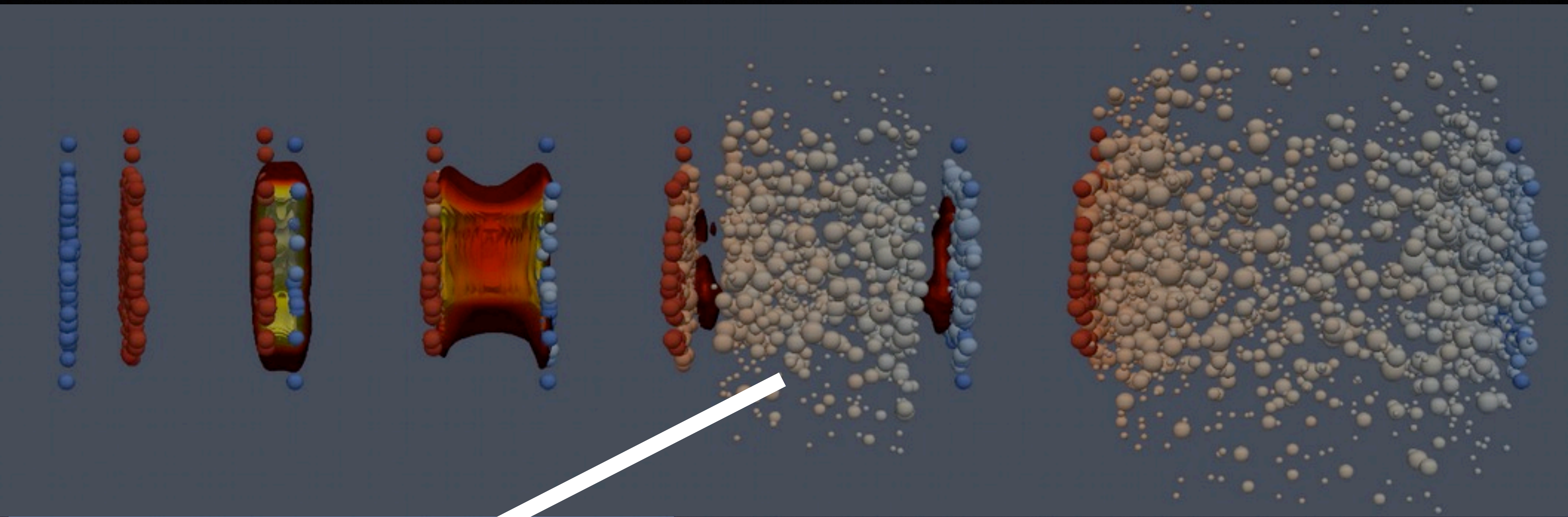


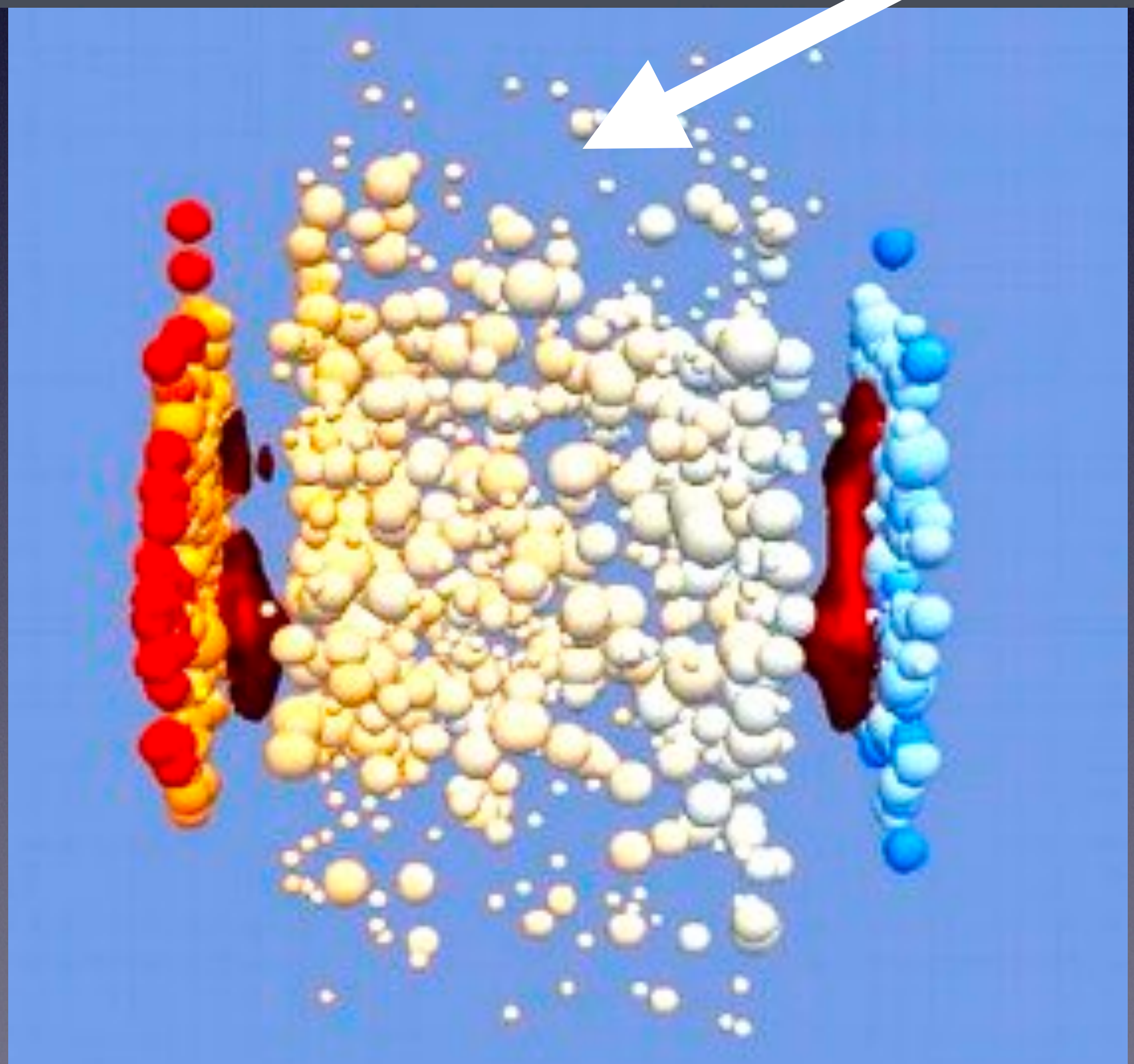
Stronger suppression of $\Psi(2S)$ compared to J/Ψ

Increasing trend of RAA towards low p_T for $\Psi(2S)$

Compatible with midrapidity CMS results in common p_T range.

p_T dependence of RAA reproduced by TAMU

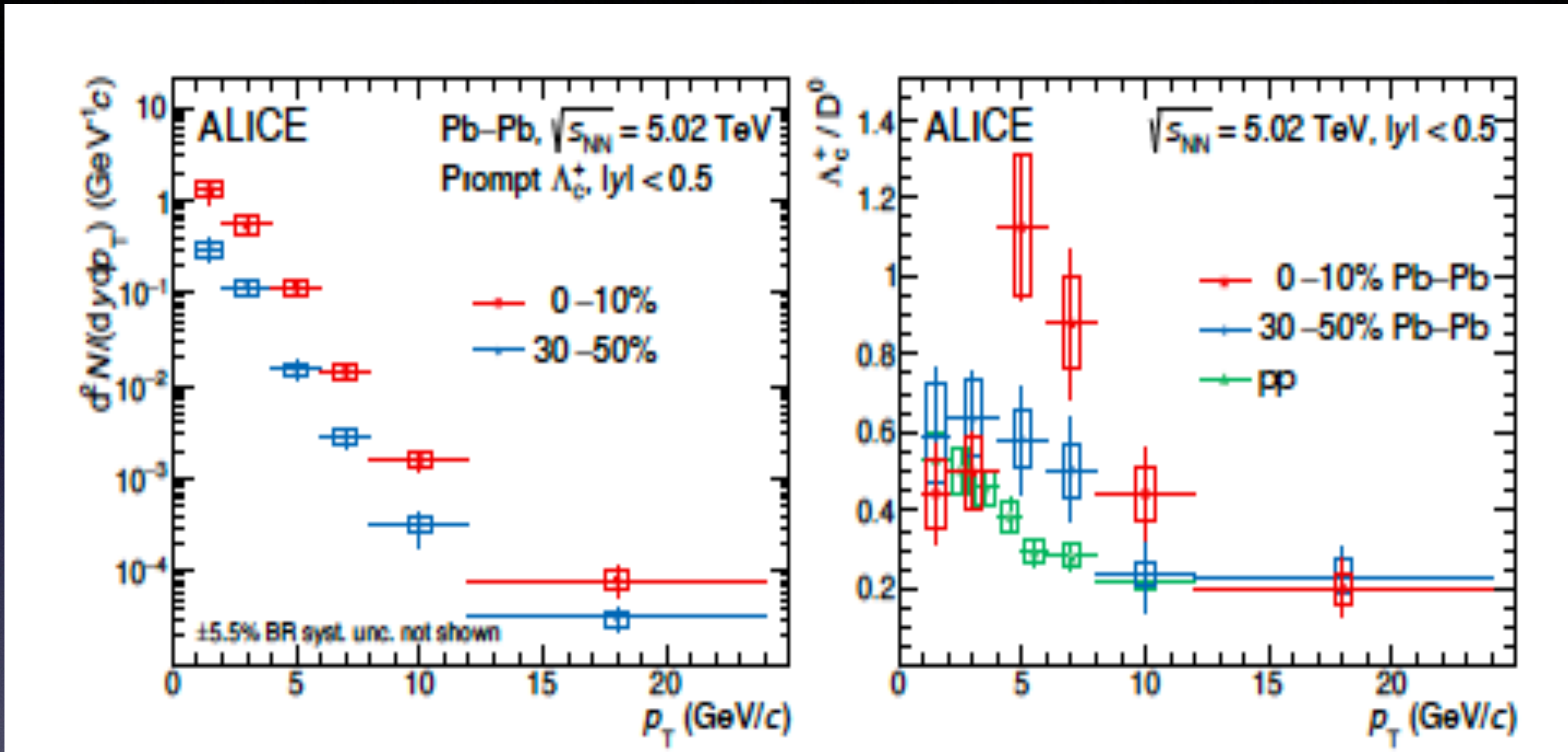




Hadronization

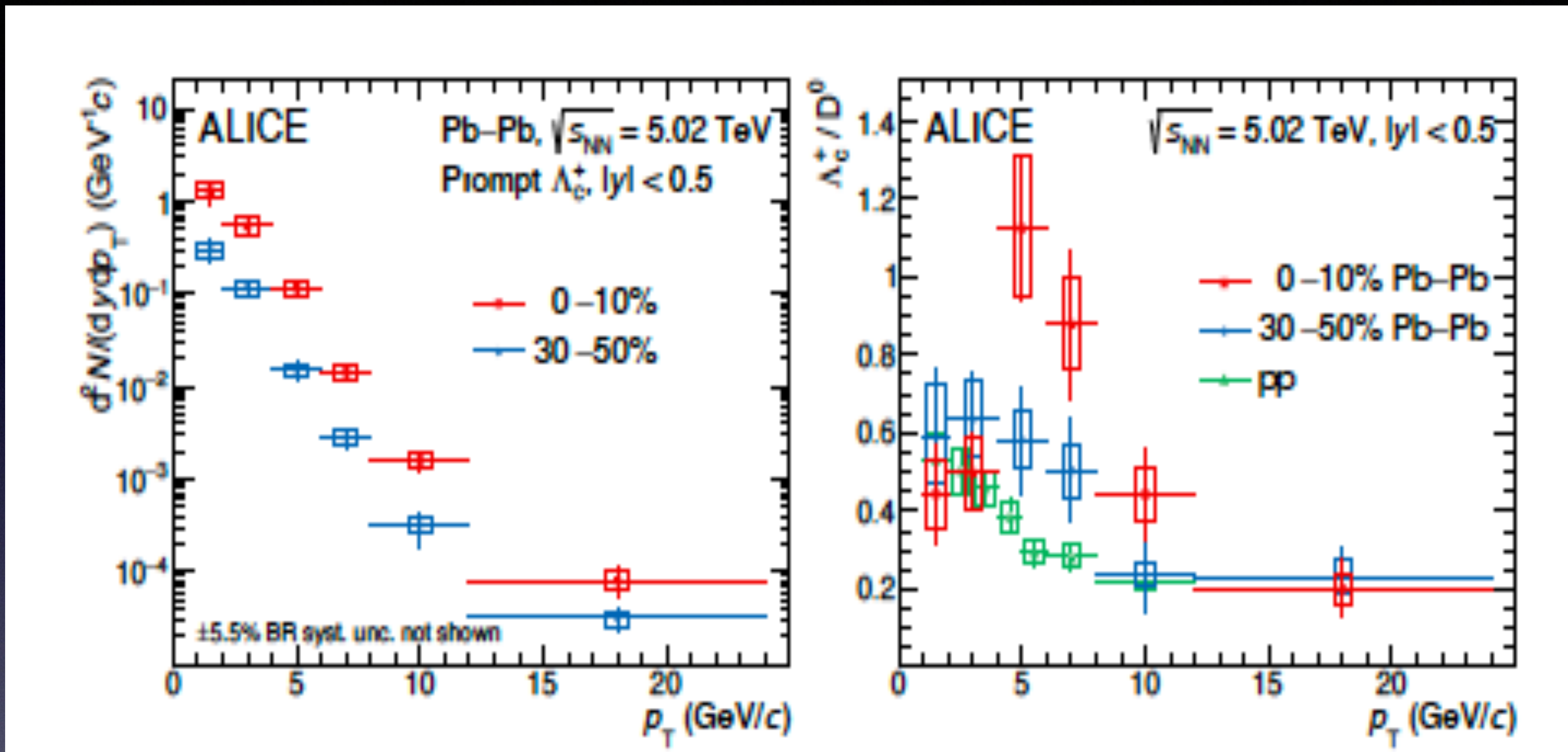
Baryon to meson anomaly in charm sector

Phys. Lett. B 839 (2023) 137796



Baryon to meson anomaly in charm sector

Phys. Lett. B 839 (2023) 137796

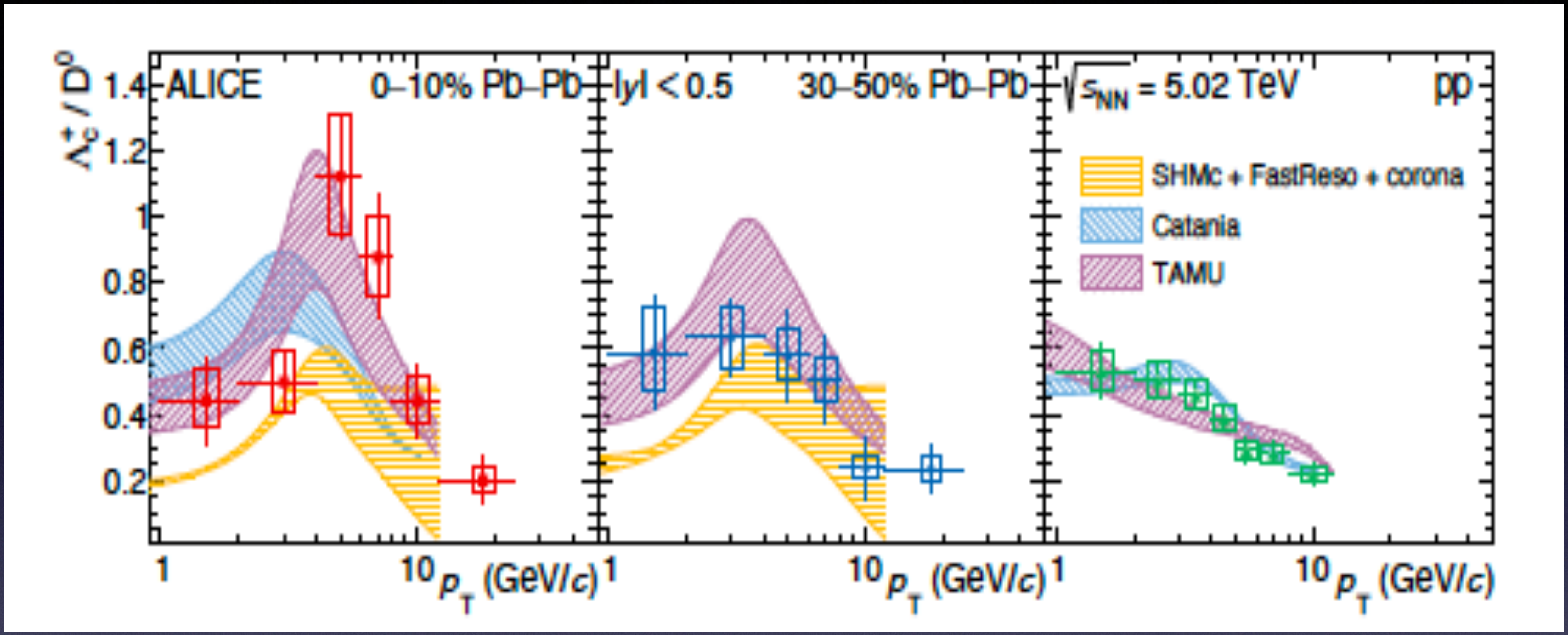


Enhancement of Λ_c/D^0 at intermediate p_T.

This observation is similar to that observed for light flavour sector

Baryon to meson anomaly in charm sector

Phys. Lett. B 839 (2023) 137796



Ratio increases from pp to central Pb-Pb collisions

Compatible with theoretical models that include both fragmentation and coalescence mechanism of hadronization.

Summary

Heavy ion collisions are our door to study the properties of strong interactions at very high energy densities.

The various facilities from a few GeV to a few TeV centre of mass energies provided a lot of results which demonstrates a strong sensitivity to the properties of the medium.

The medium formed in such collisions has the characteristics foreseen for a quark gluon plasma, behaves like a fluid and has spectacular effects on hard probes such as heavy flavor.

The vibrant experimental programs with precision measurements have been answering long standing questions driving heavy ion physics to the multi messenger era.