QGP signals in small systems

Non-Perturbative and Topological Aspects of QCD
May 28th, 2024

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GAČR CZECH SCIENCE FOUNDATION This work was supported by a grant from The Czech Science Foundation, grant number: 23-07499S

Creation of quark-gluon plasma in large systems

Quark-gluon plasma (QGP) = **deconfined strongly-interacting** QCD matter with color degrees of freedom

CMS LHCb ALICE ATLAS EXPERIMENT

Collectively expanding

Signatures:
modification of momentum and angular distributions

Measurements:
anisotropic flow

Thermalised medium

Signatures:
modification of hadronisation
thermal photon radiation

Measurements:
particle yields
particle spectra

Dense & deconfined medium

Signatures:
parton energy loss
quarkonia dissociation

Measurements:
nuclear modification factor

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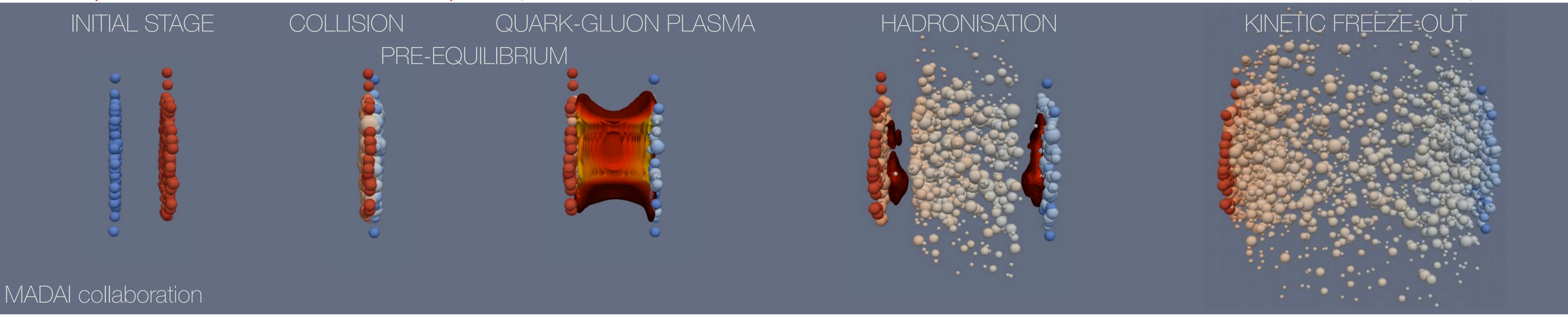
initial state effects ⟷ final state effects



0 — 1 — 10 — 100 — 10^{15} — t (fm/c)

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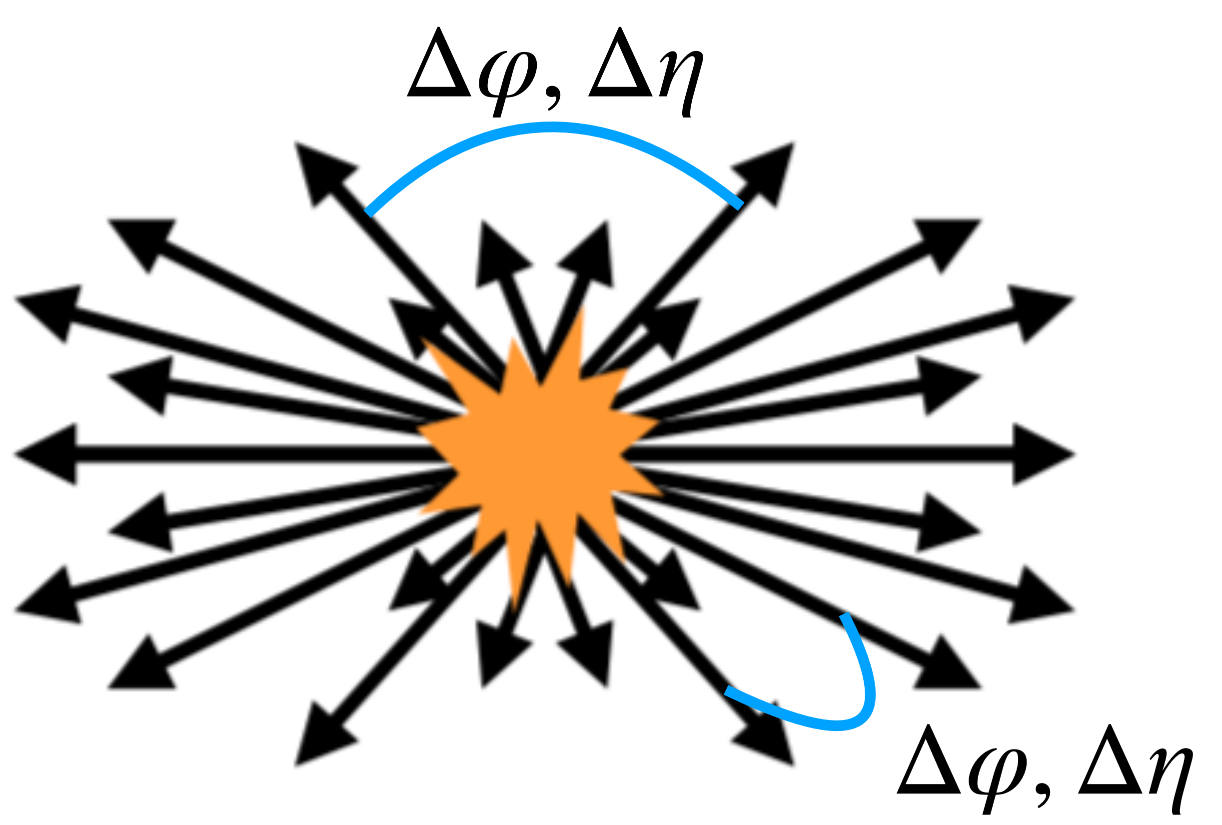
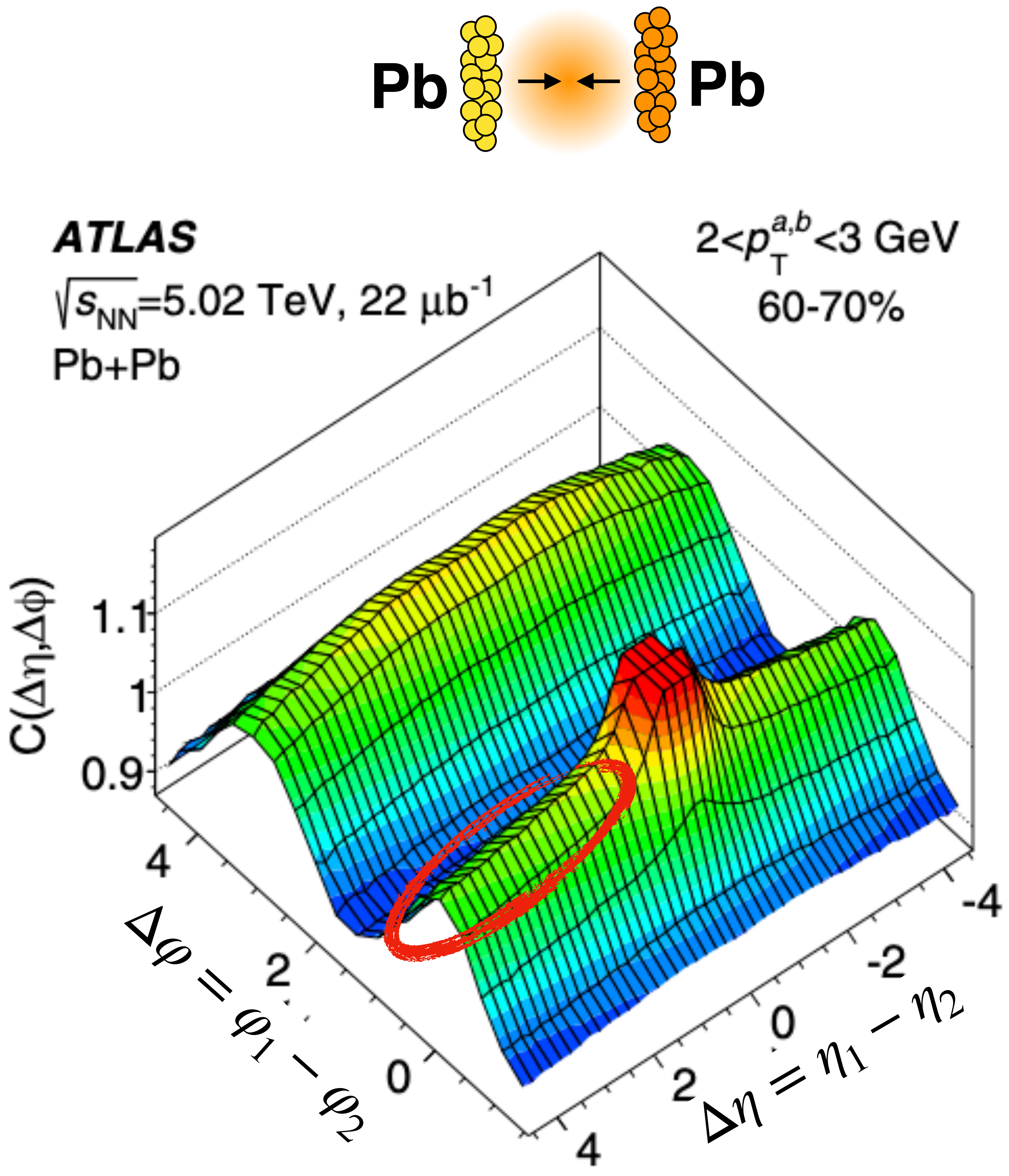
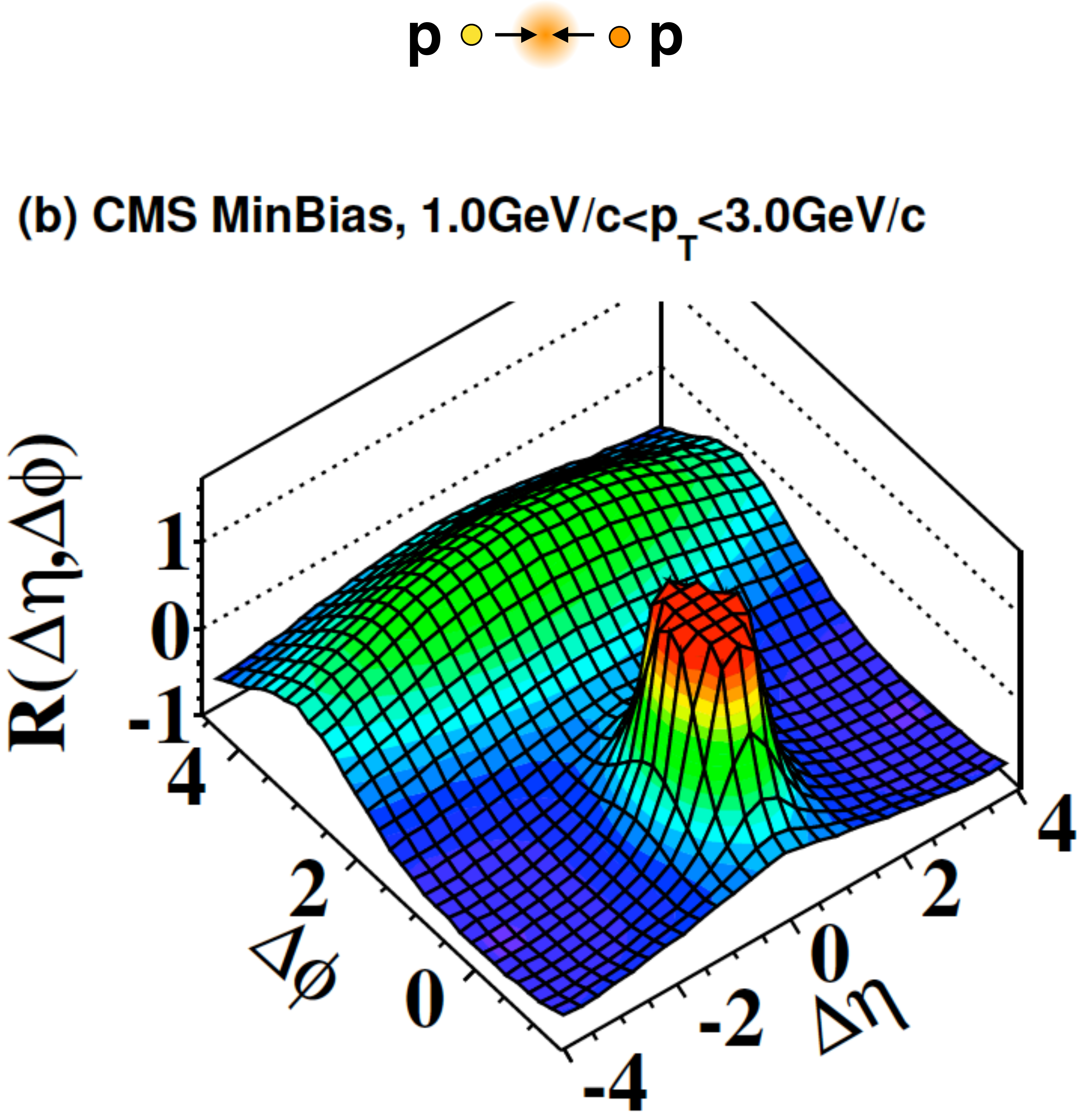
Near-side ridge: consequence of QGP





ATLAS, EPJC 78 (2018) 997



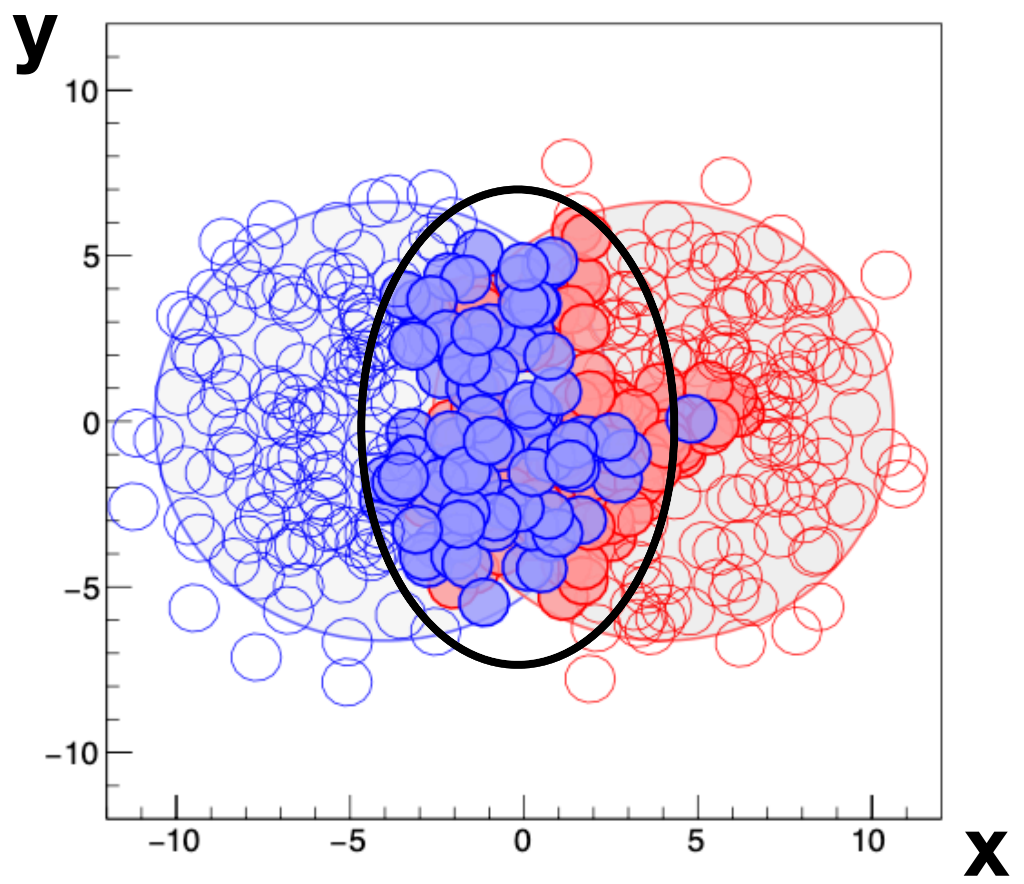
CMS, JHEP09 (2010) 091

Near-side long-range ridge in azimuthal correlations between two particles

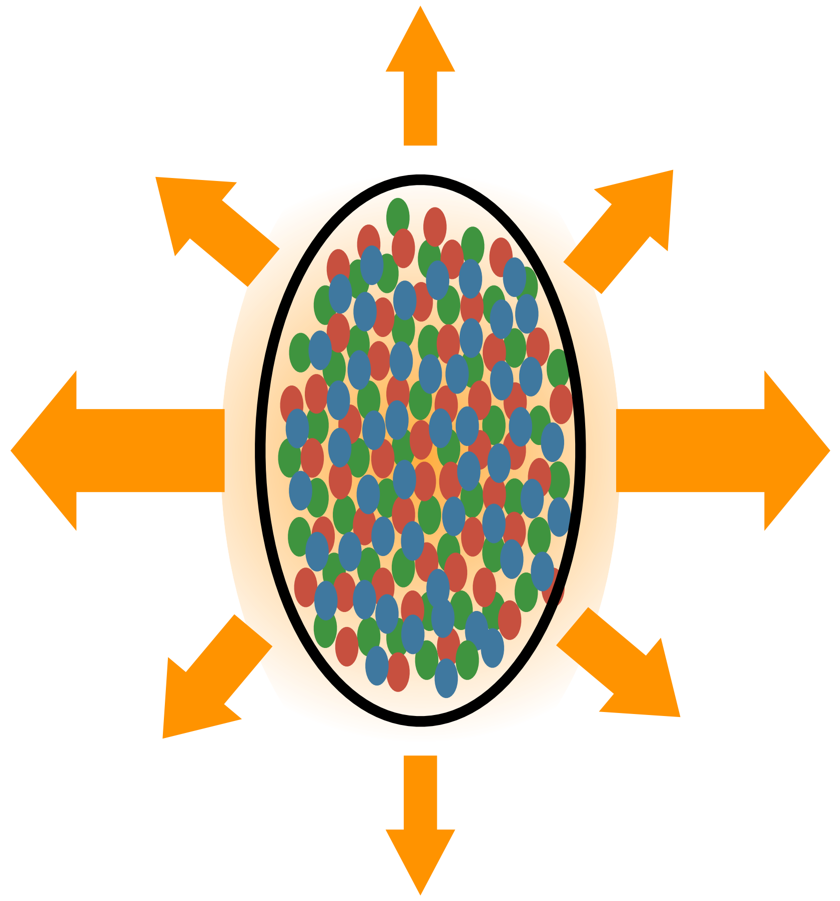
Direct consequence of **the presence of the QGP**

Anisotropic flow: response to geometry

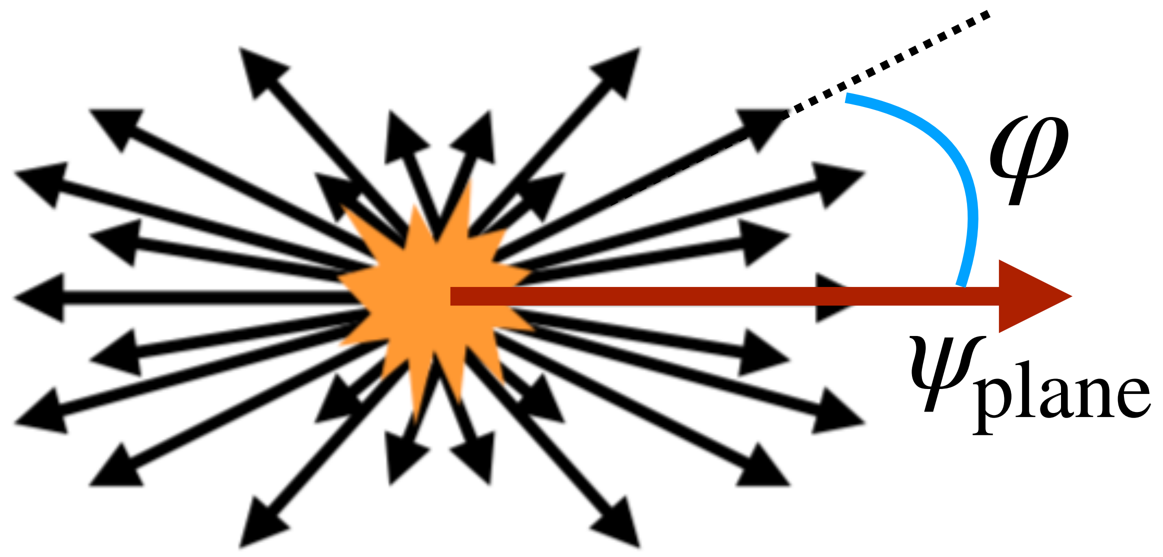
1 Initial spatial asymmetry



2 collectively expanding medium



3 Particles are emitted with preferred direction



4 Angular modulation of their distribution

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

anisotropic flow

Quantifies how strong is particle correlation with symmetry plane Ψ_n

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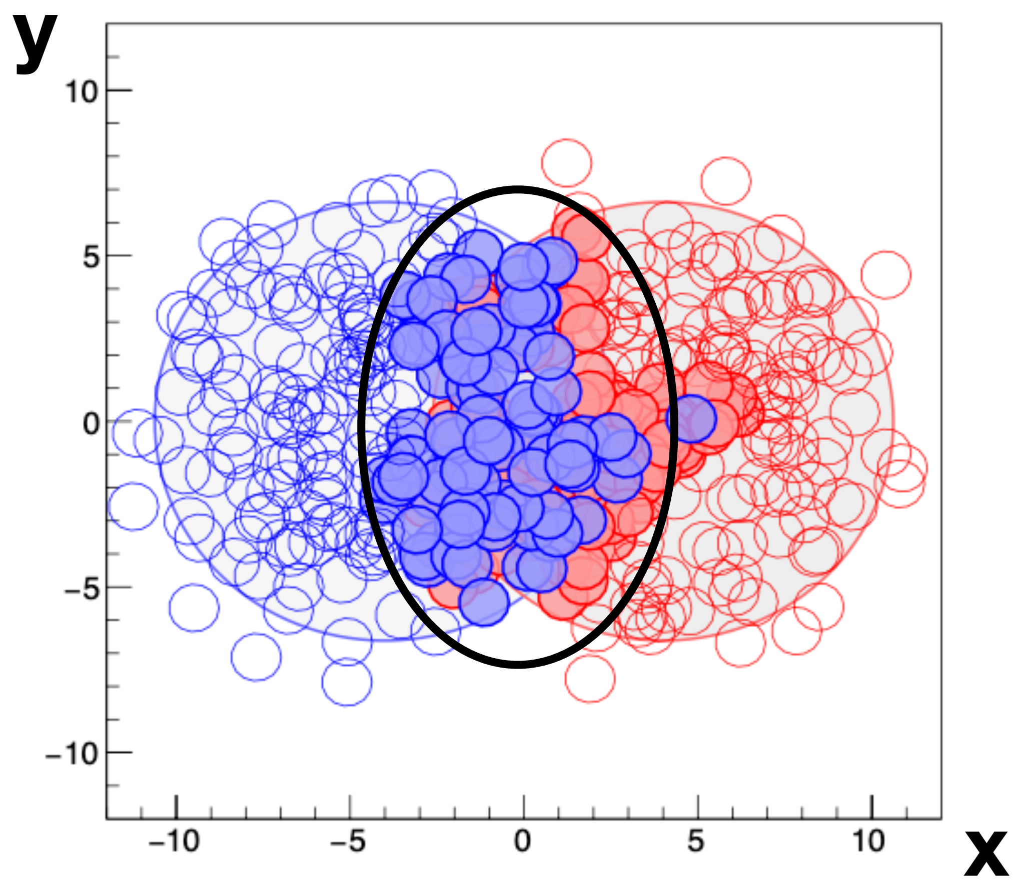

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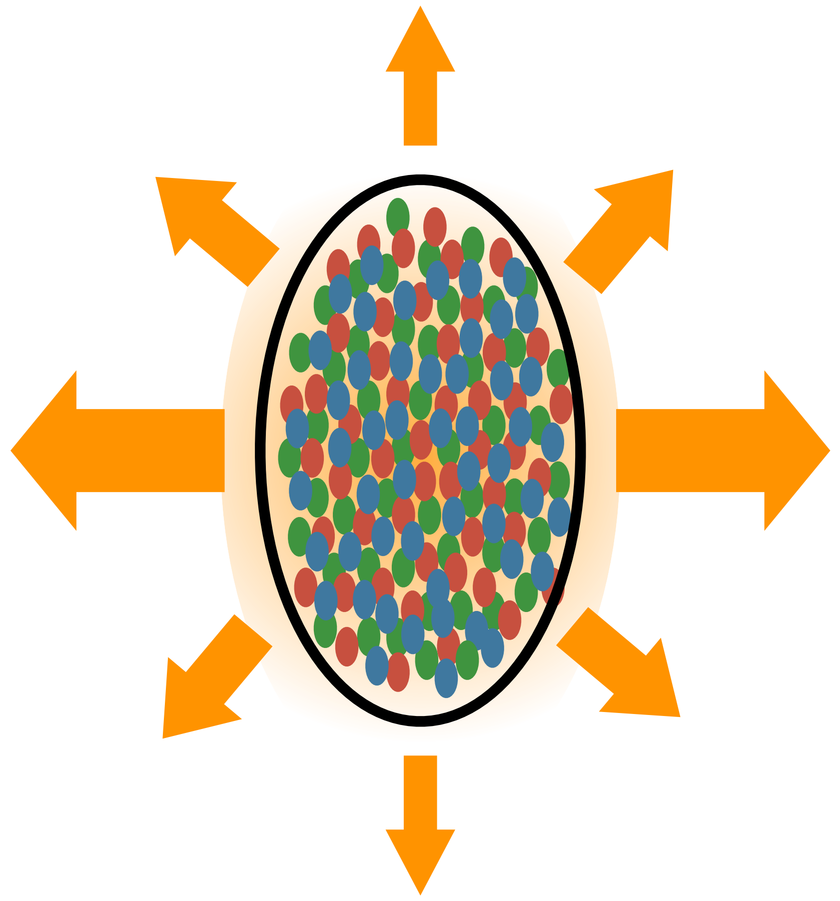

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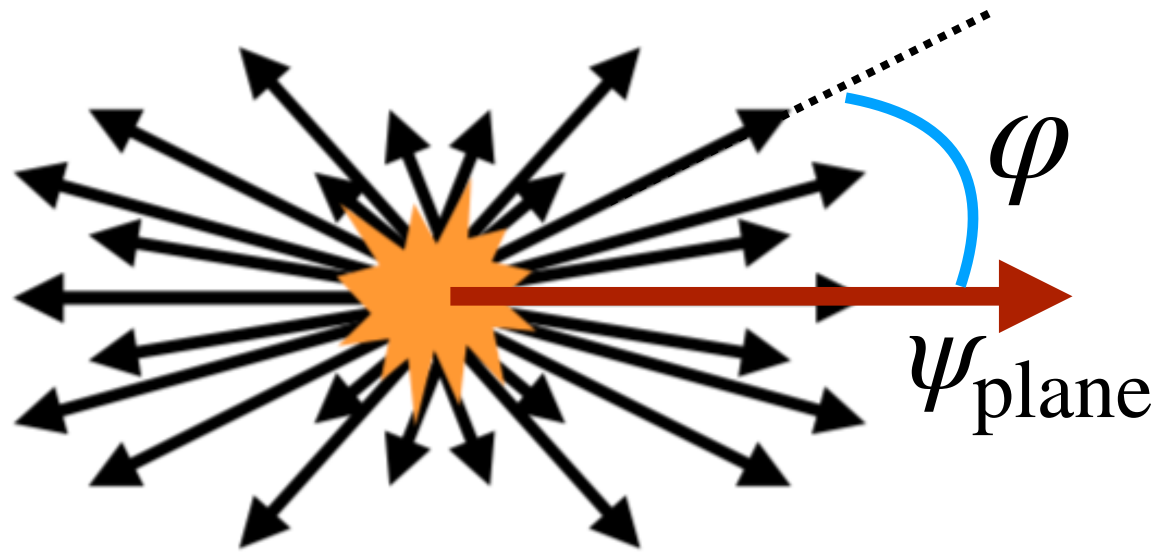

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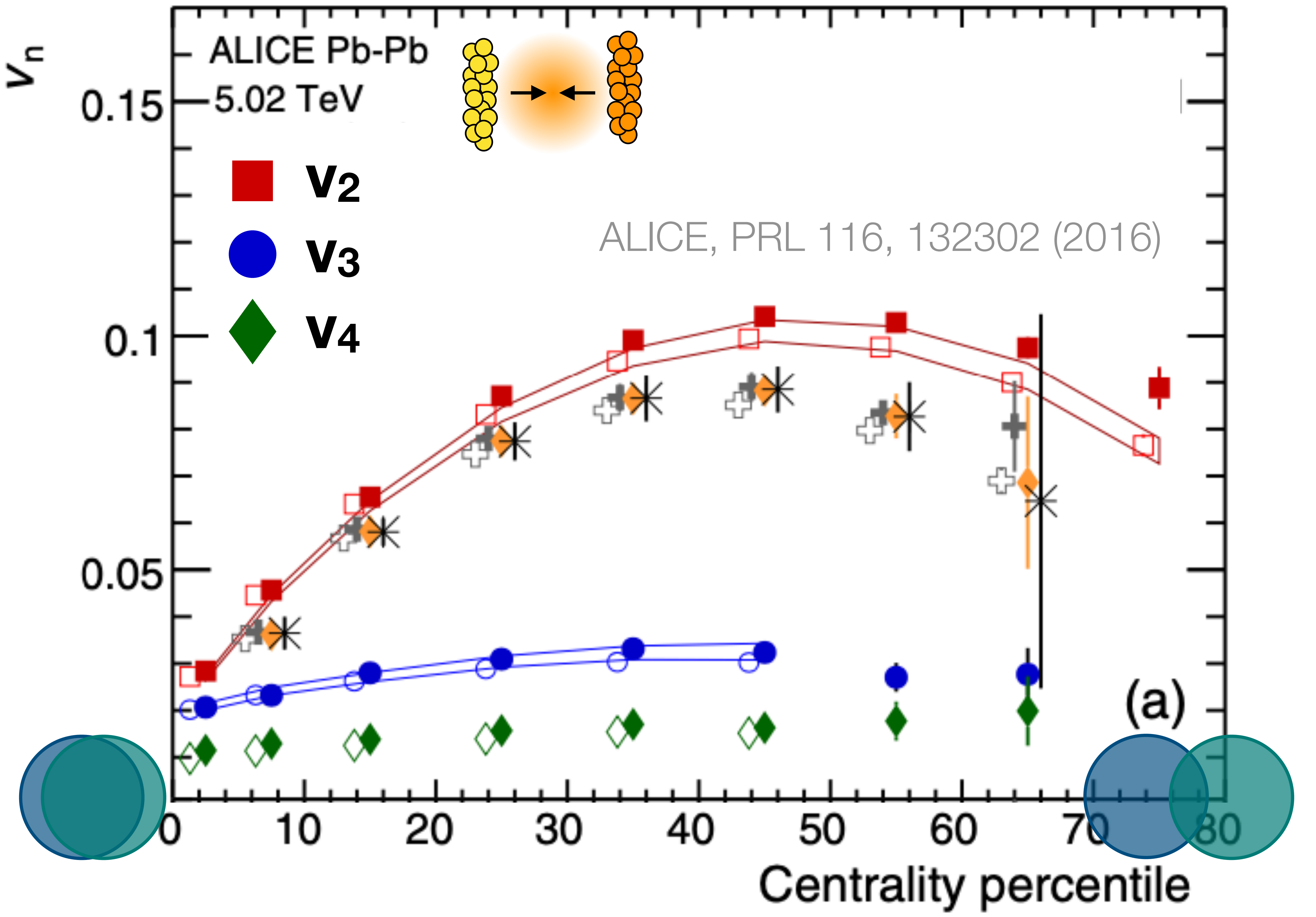
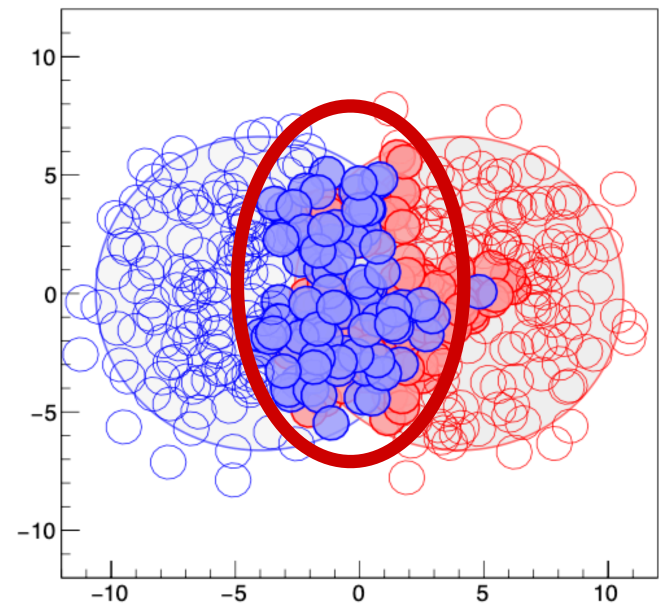
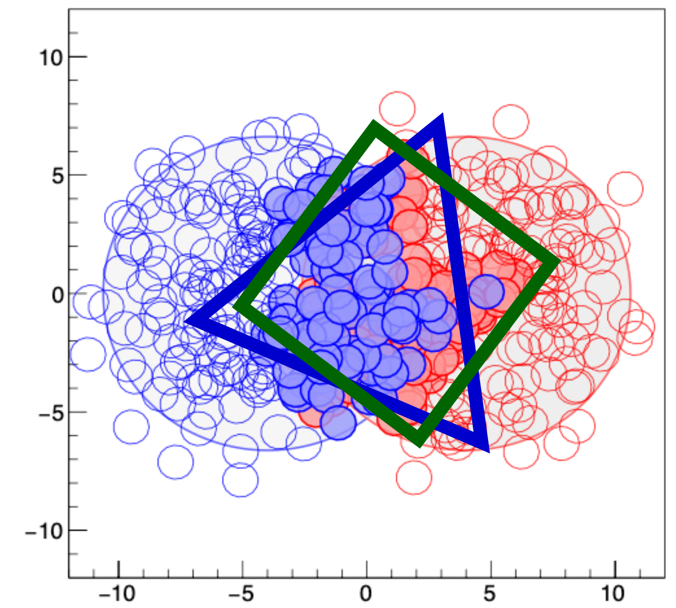


v_2 ← elliptical geometry



v_3, v_4 ← geometry fluctuations



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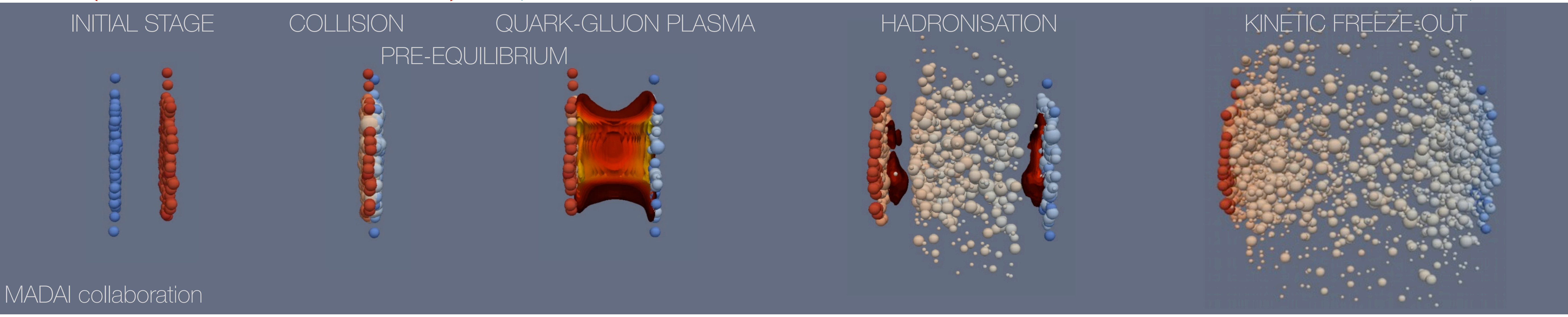

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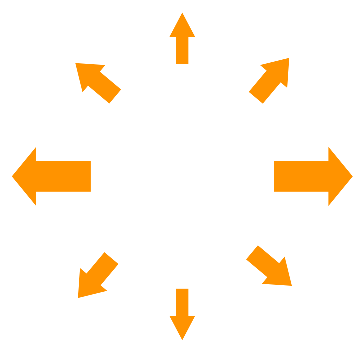
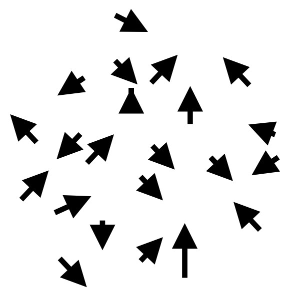
QGP expansion and hadronisation



Collective anisotropic medium expansion

+

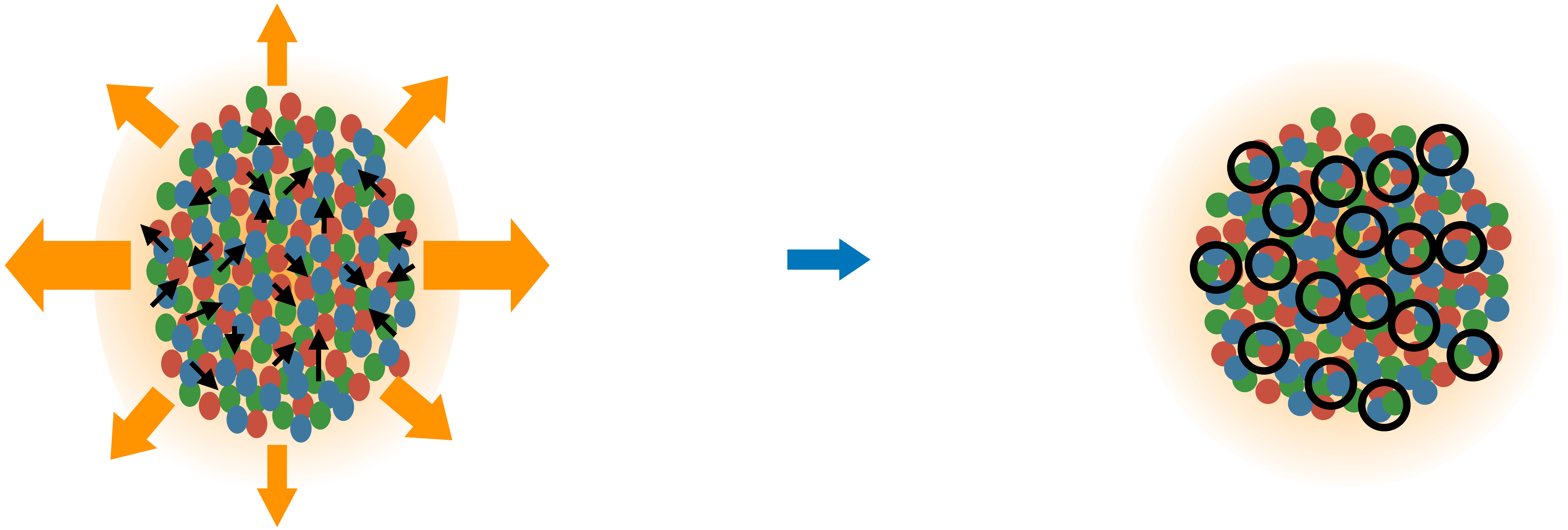


Thermal isotropic medium expansion

➡ constituents **flow with similar velocity**

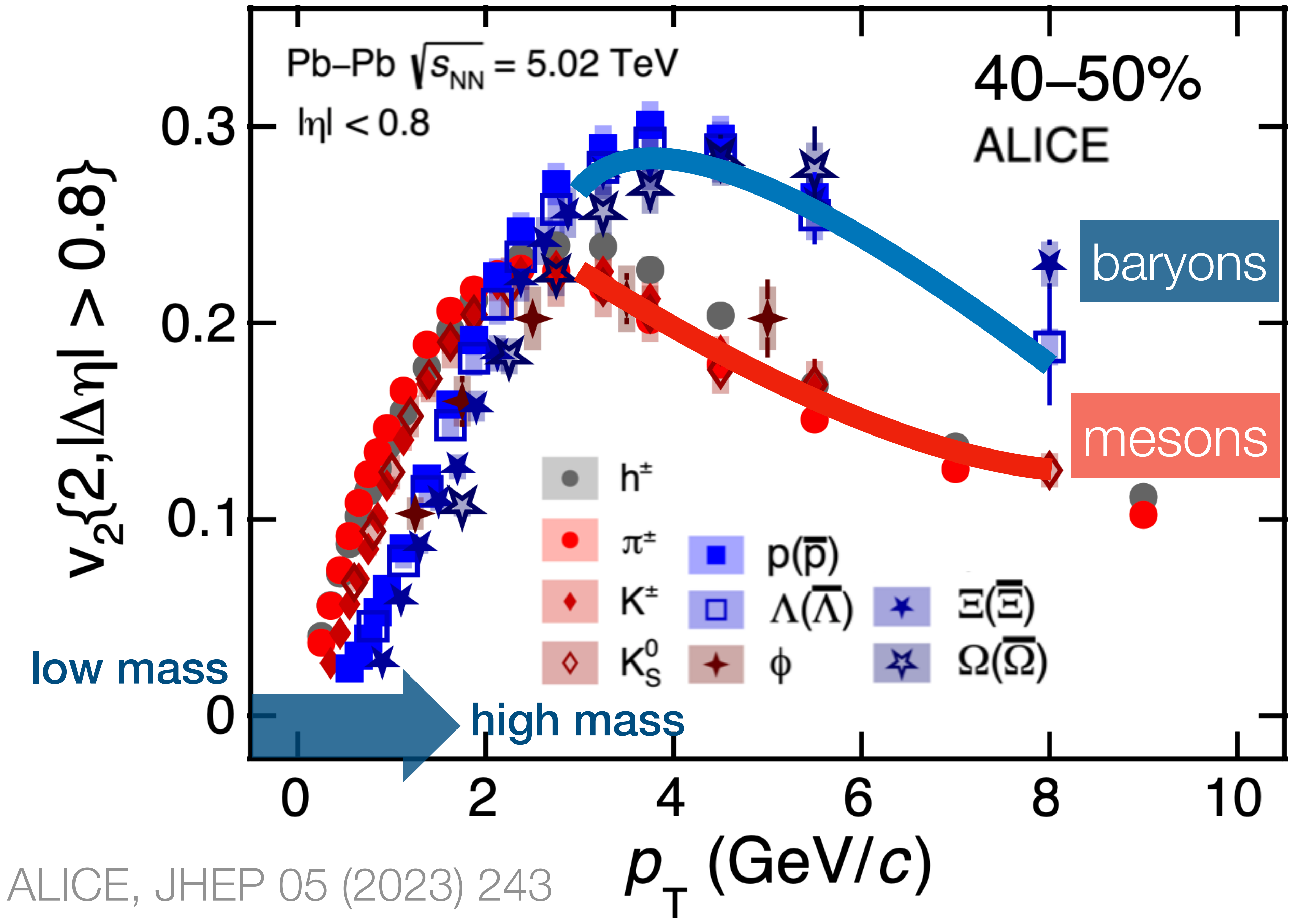
Modified hadron formation mechanism

➡ near-by partons **coalesce into hadrons**



Interplay of these effects results in **mass-dependent** momentum distributions

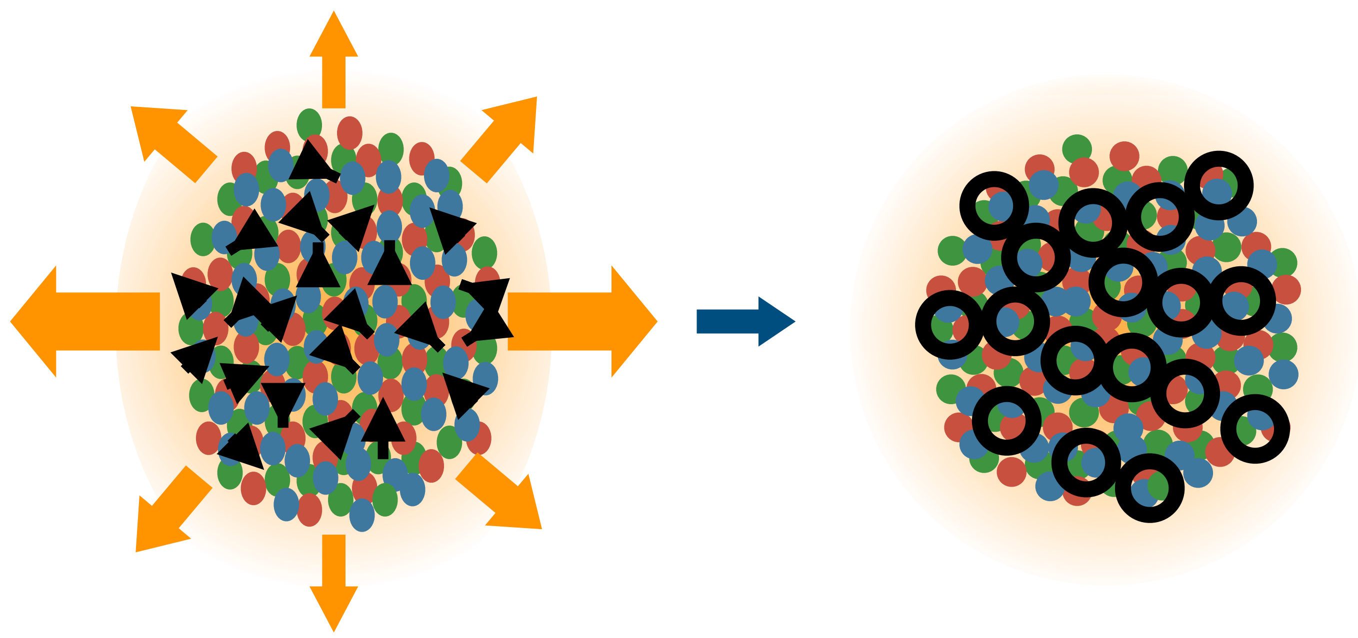
Mass dependence of momentum distributions



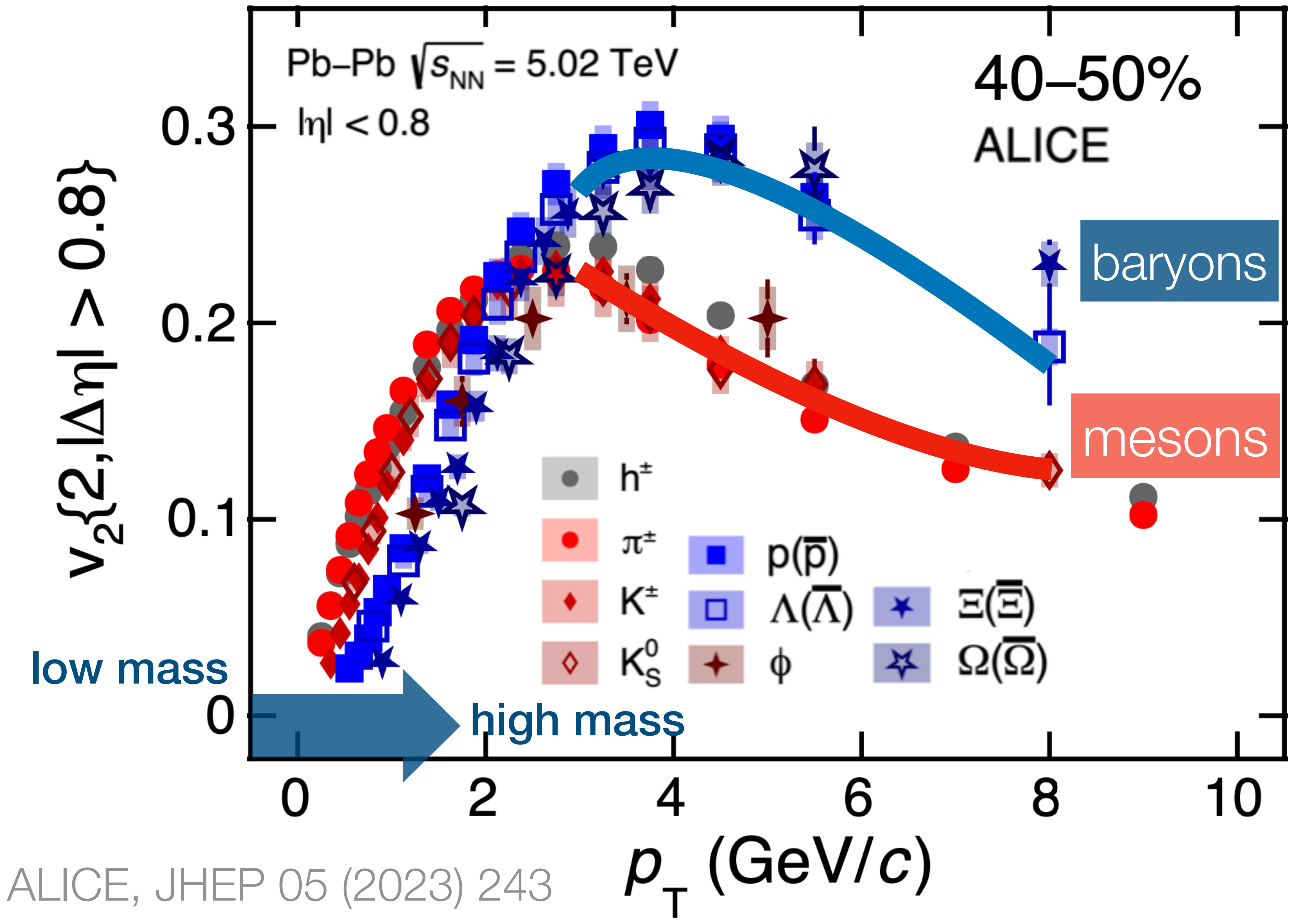
ALICE, JHEP 05 (2023) 243

- Interplay of radial and anisotropic expansion → **mass ordering**
- Intermediate-p_T: **coalescence** → **particle-type grouping**

➡ **Partonic collectivity:** deconfined medium where partons flow



Mass dependence of momentum distributions



ALICE, JHEP 05 (2023) 243

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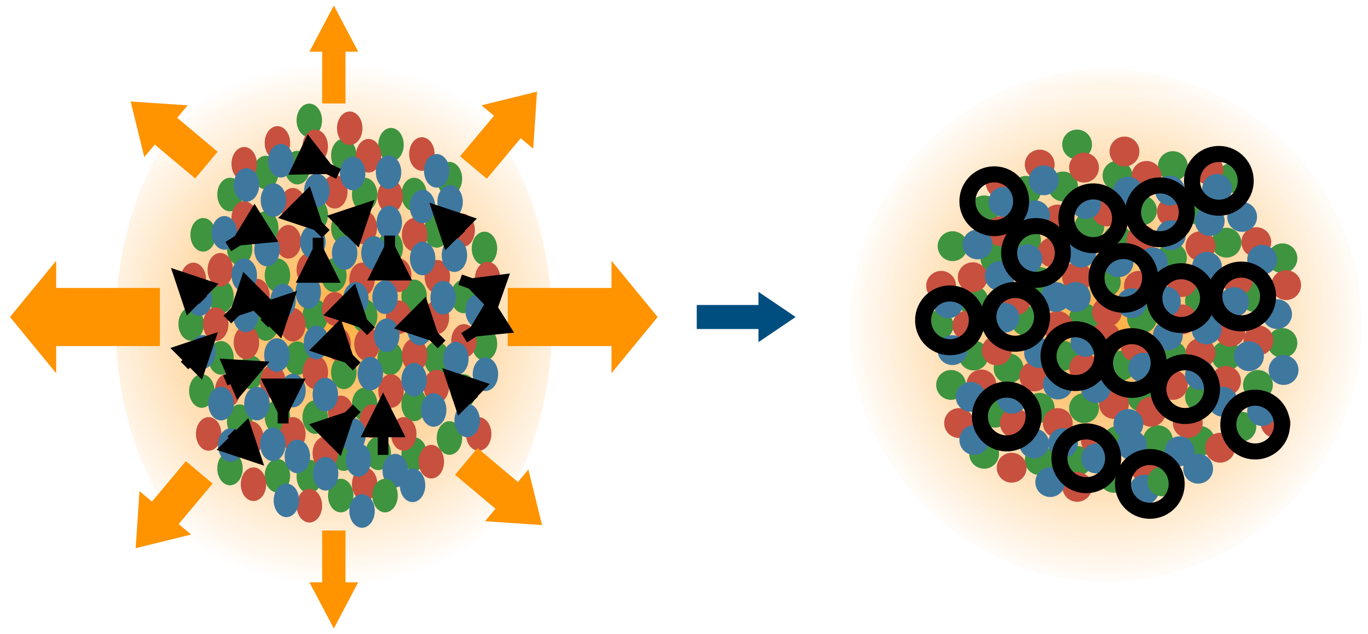
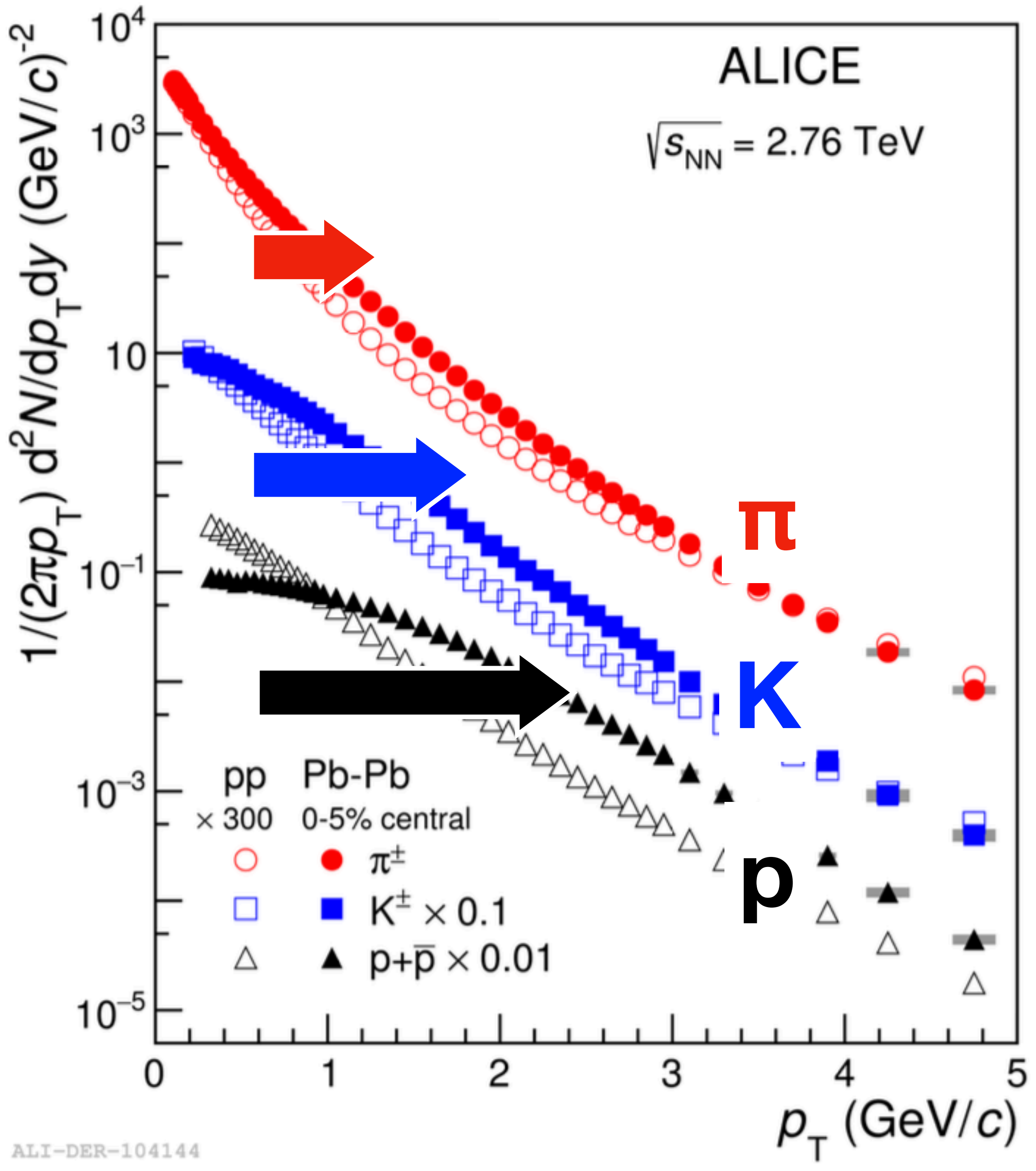
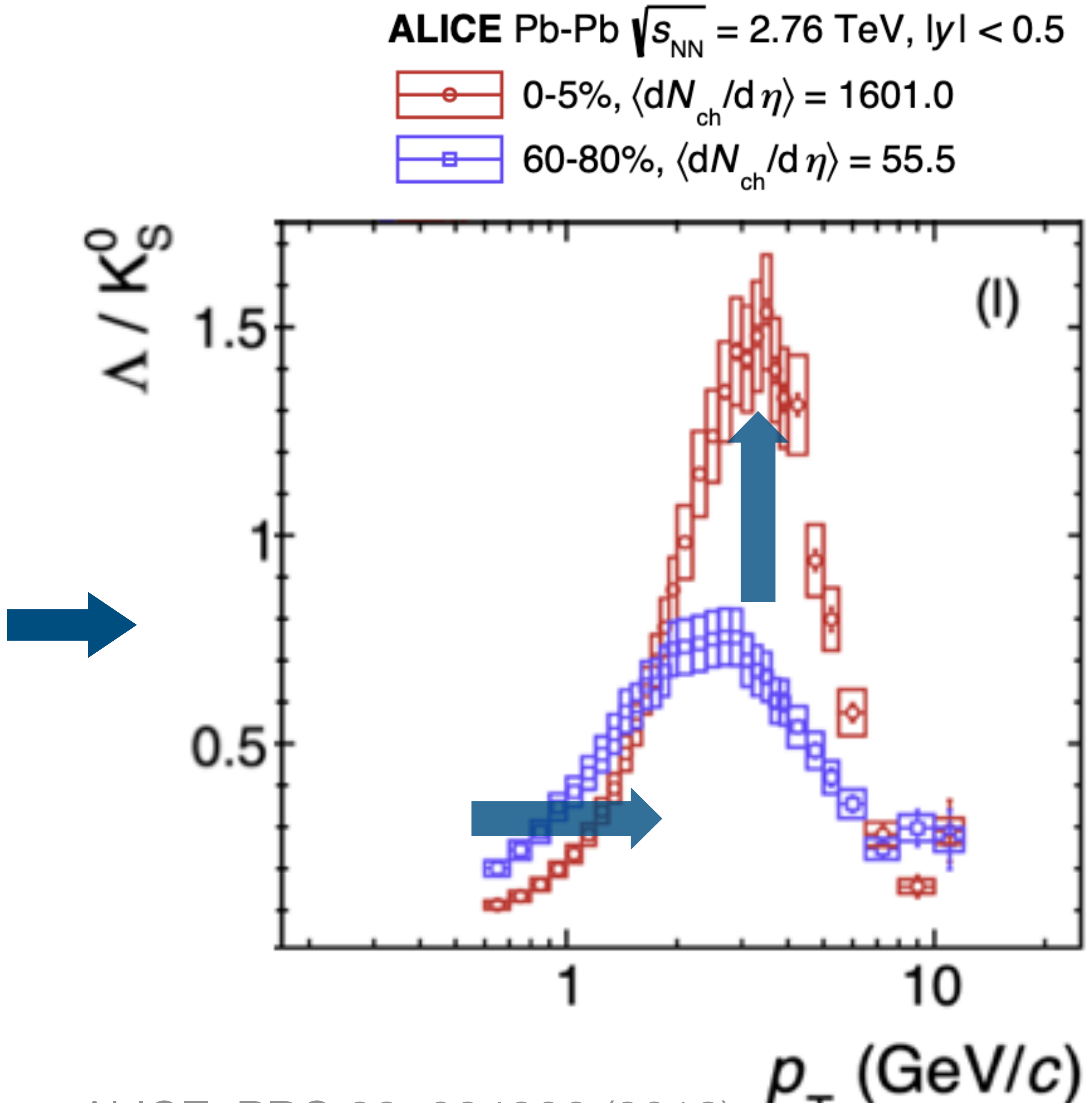


- **Baryon enhancement**: interplay of radial expansion and coalescence





ALICE, PRC 99, 024906 (2019)

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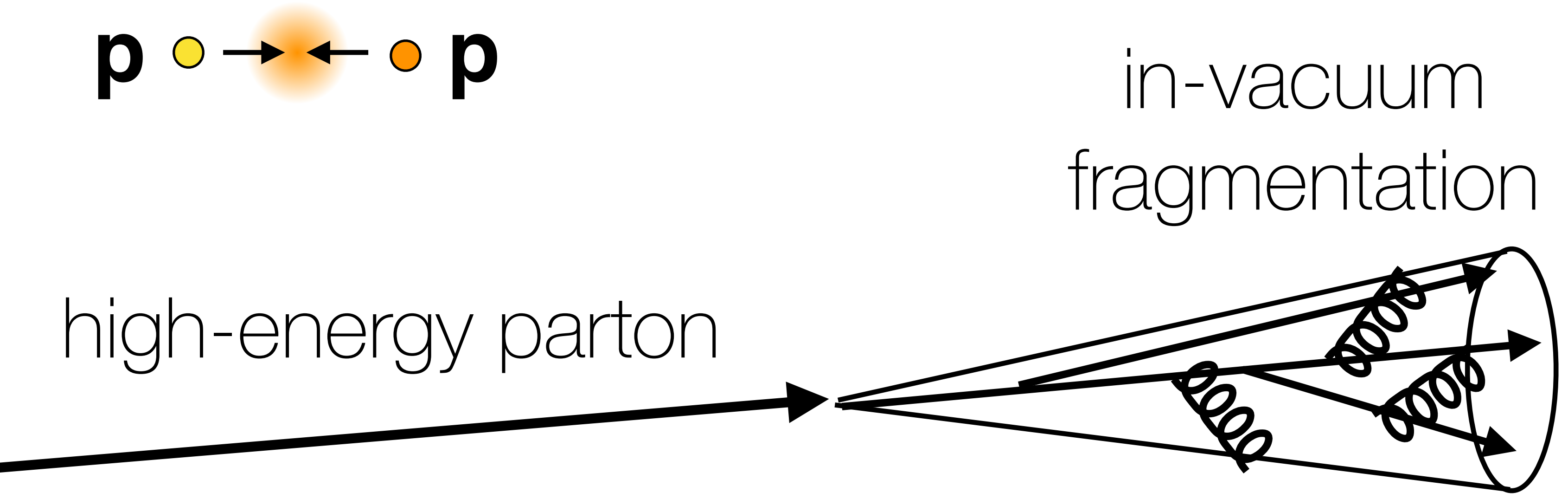
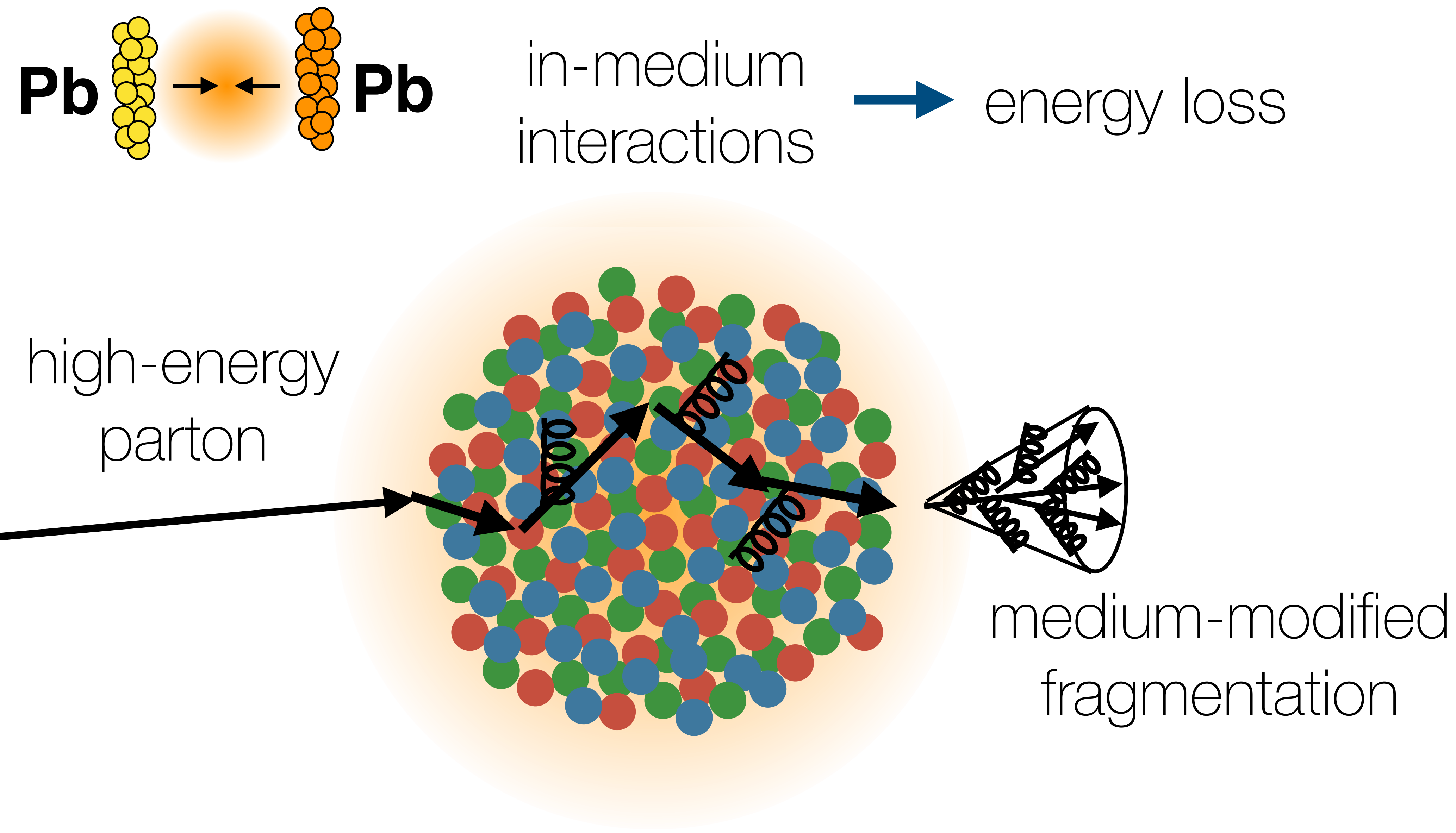
Parton energy loss in the QGP





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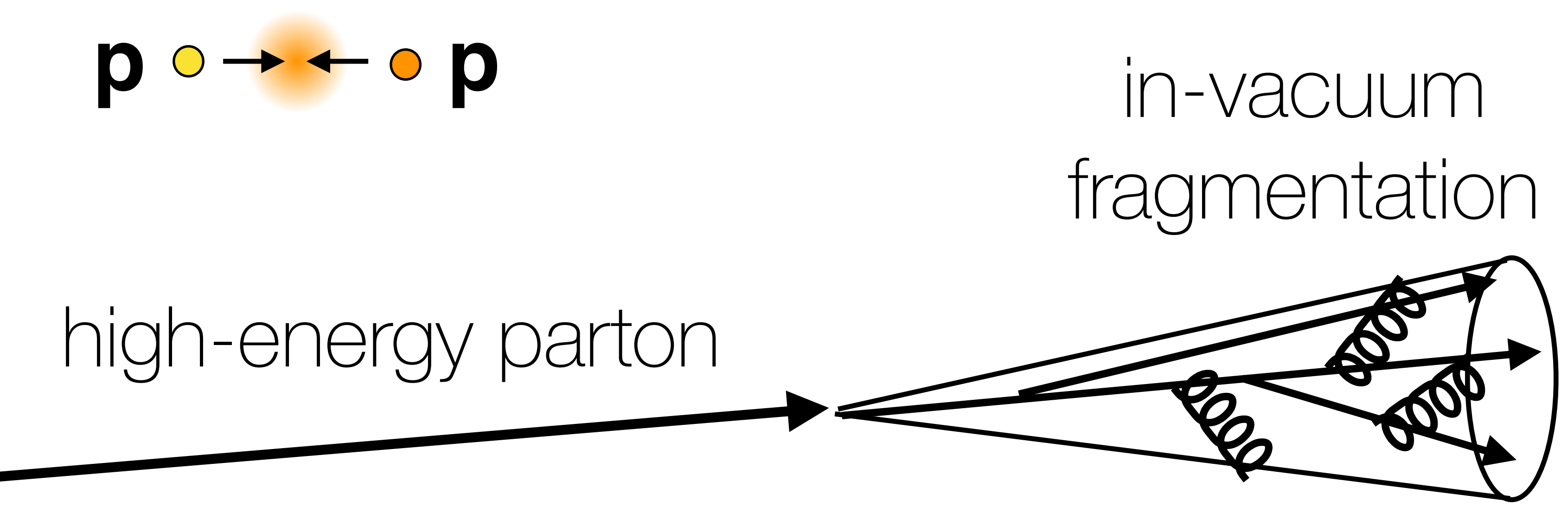
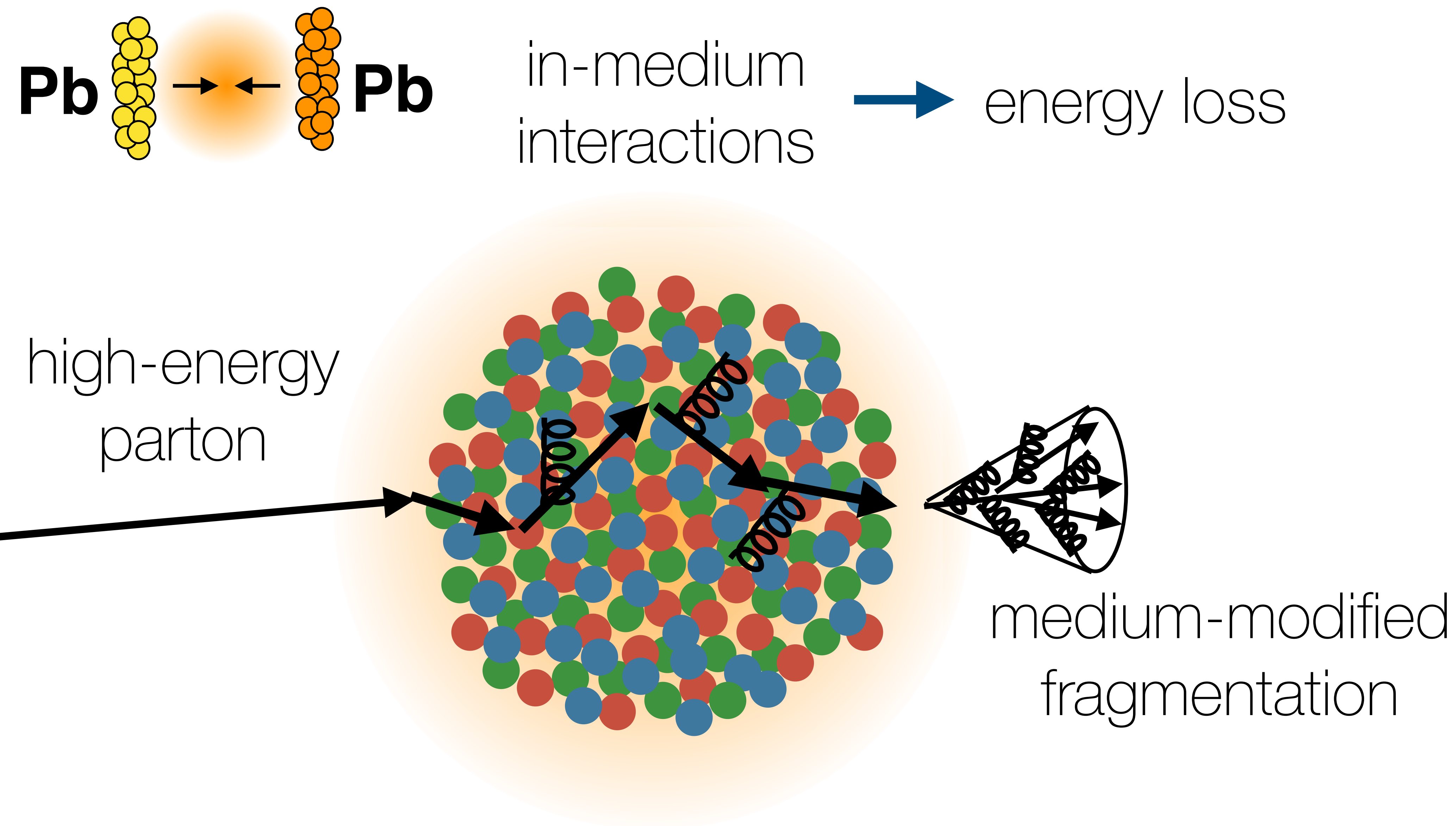


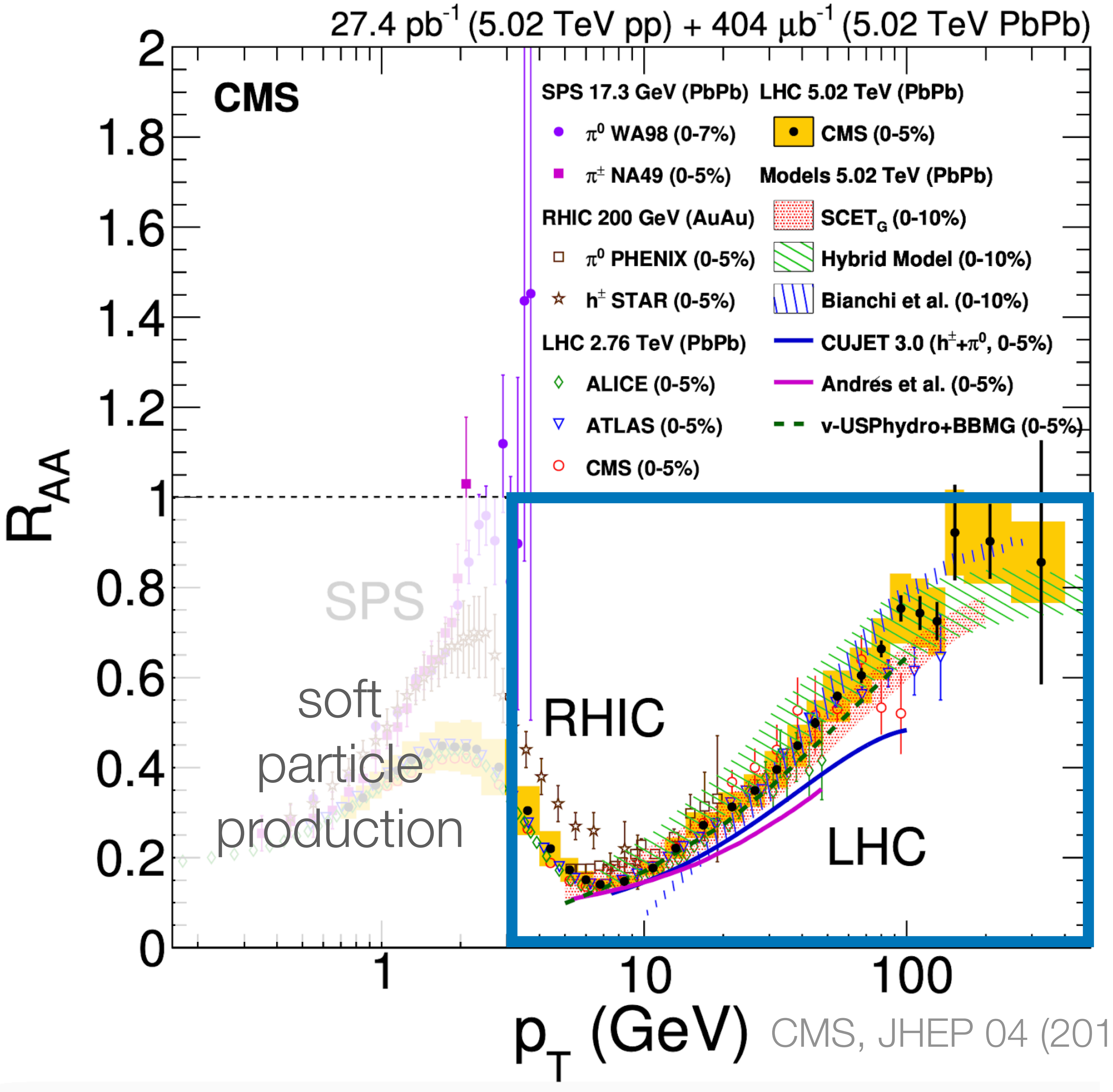
Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \, dN_{pp}/dp_T}$$

$= 1$ no quenching

< 1 **jet quenching**





CMS, JHEP 04 (2017) 039

jet quenching

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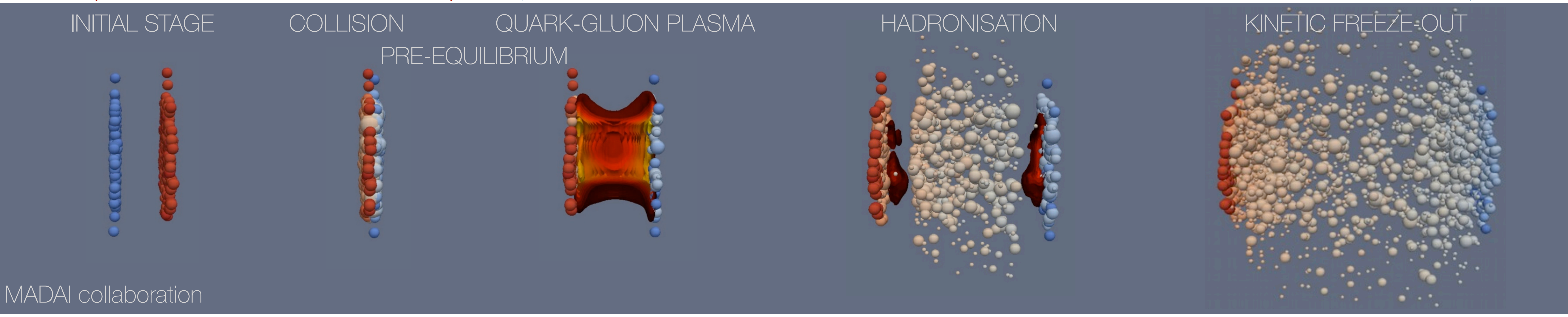

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all these effects ~~are~~ (were) understood as unique signatures of the QGP

w.r.t

baseline represented by vacuum processes in small collision systems

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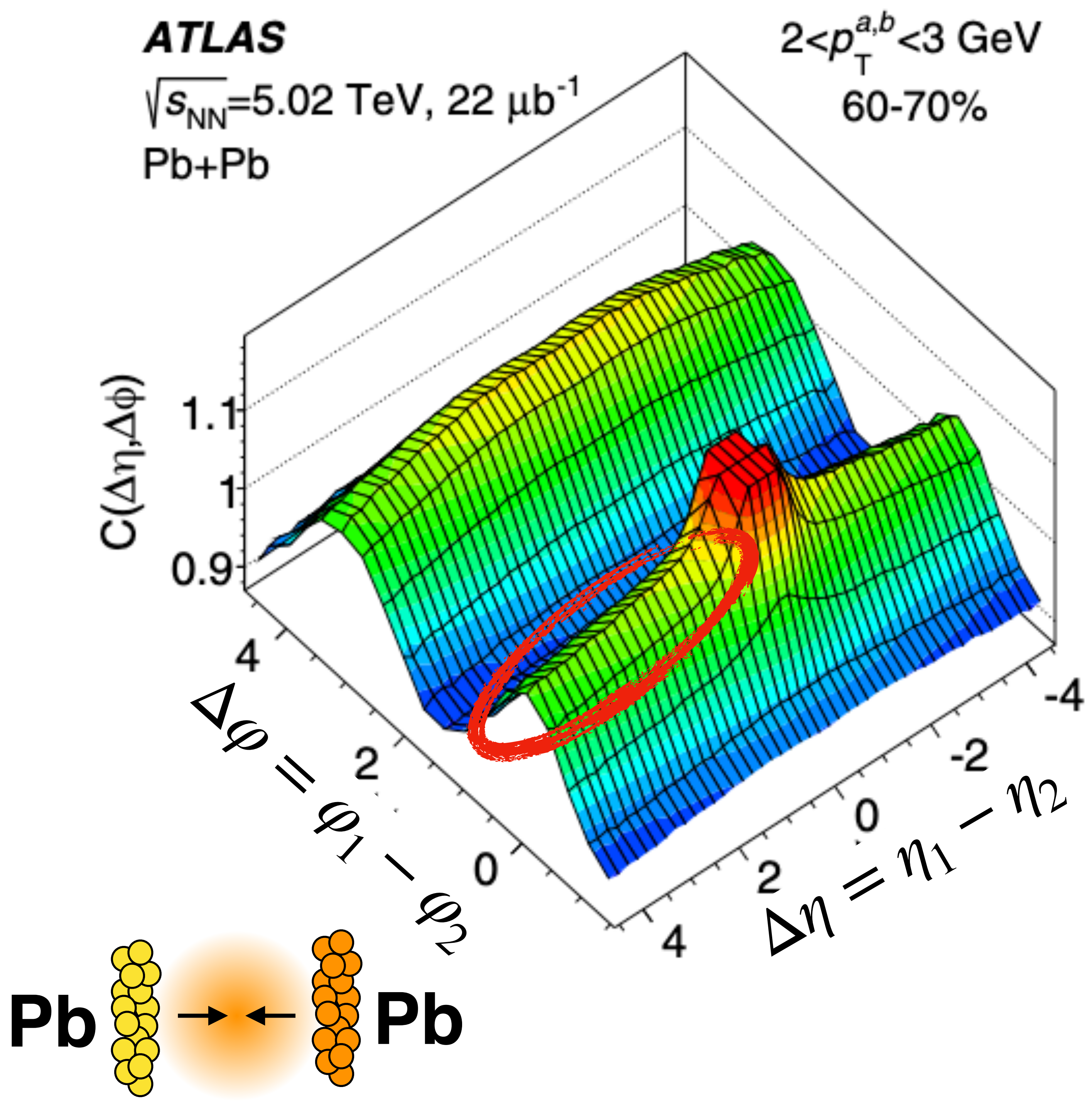
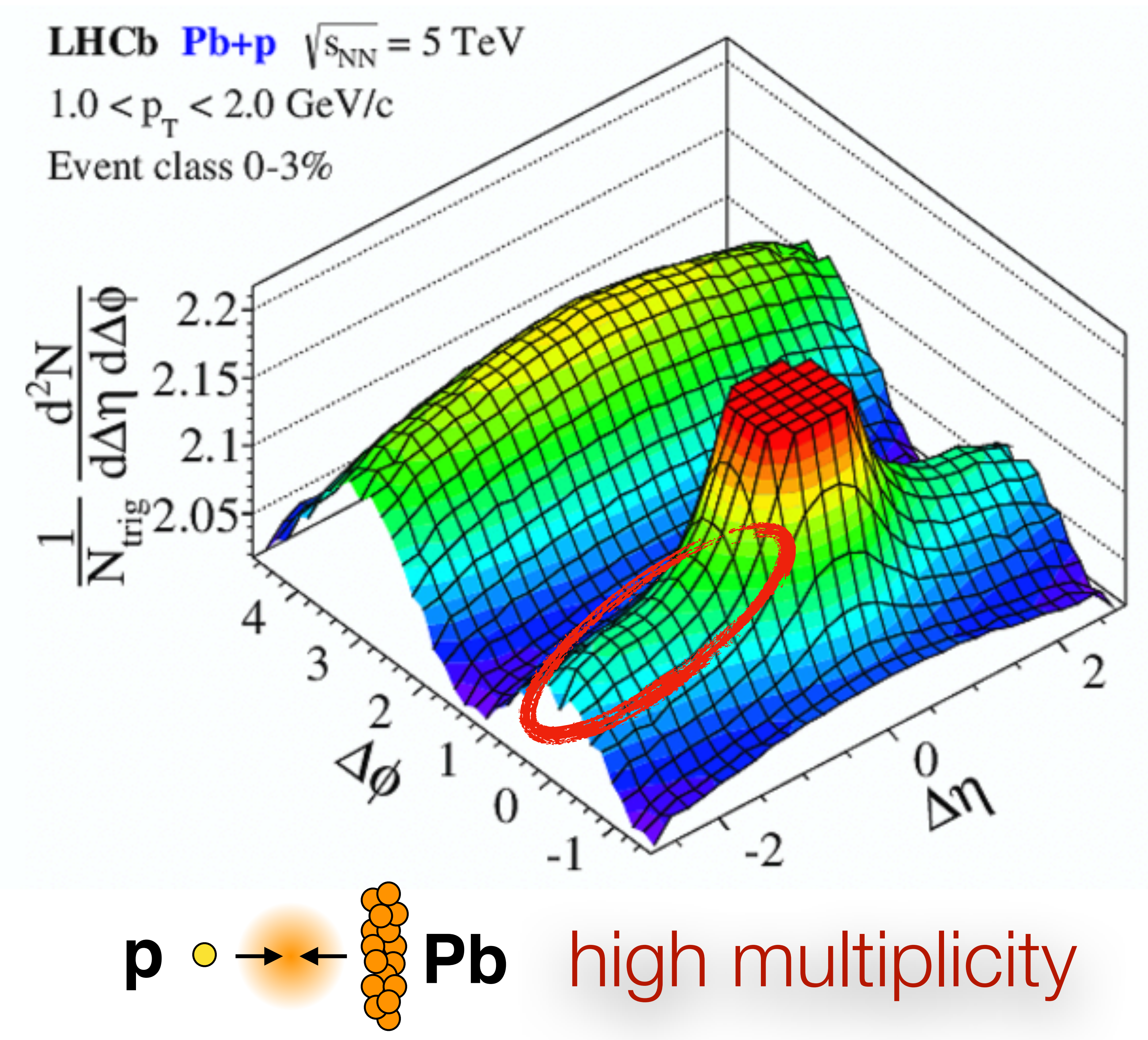
Example: ridge is not unique to Pb-Pb

ATLAS, EPJC (2018) 78:997

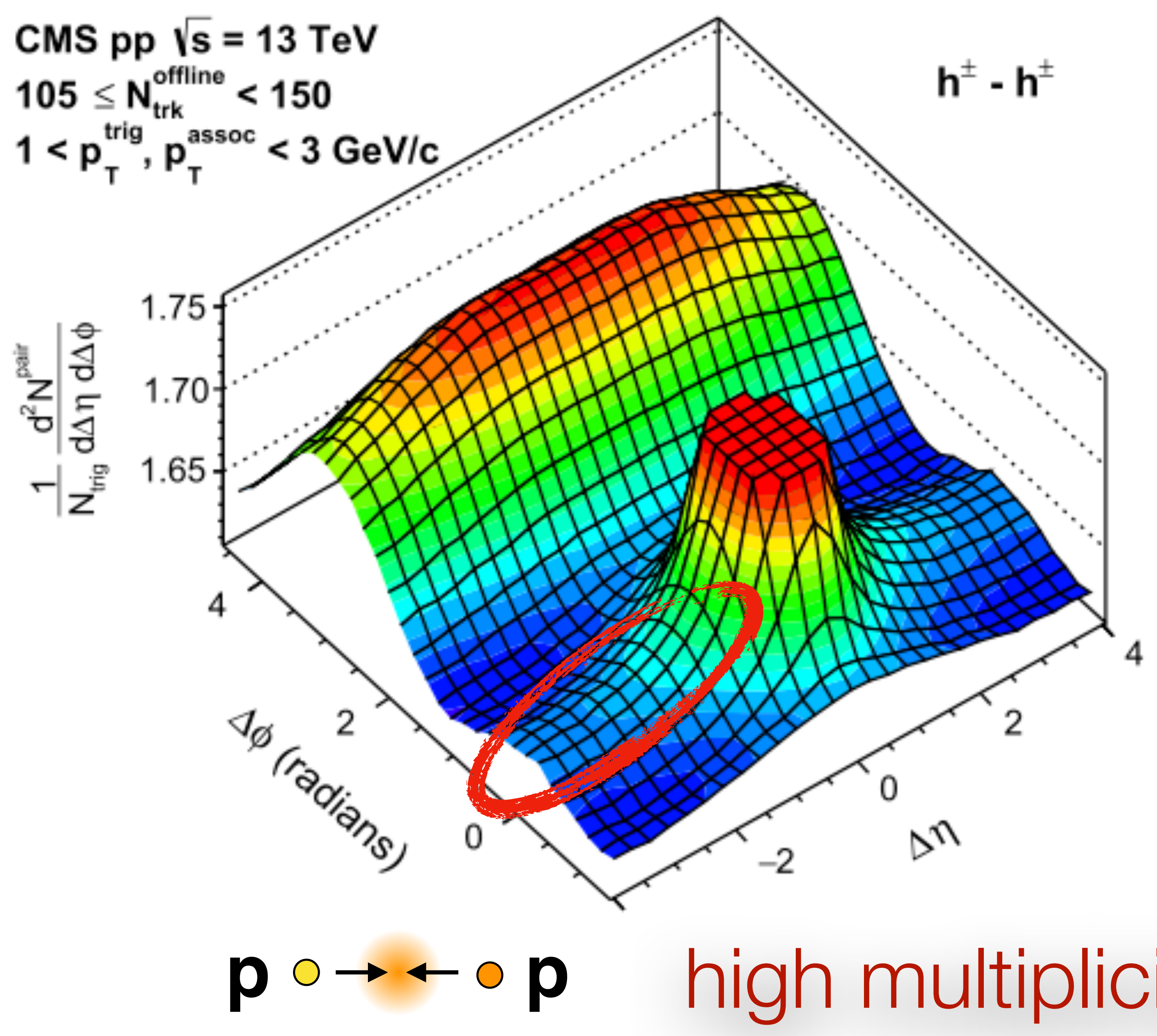


LHCb, PLB 762 (2016) 473



high multiplicity

CMS, PLB 765 (2017) 193



high multiplicity

Ridge observed **universally** across collision systems → What else is universal?

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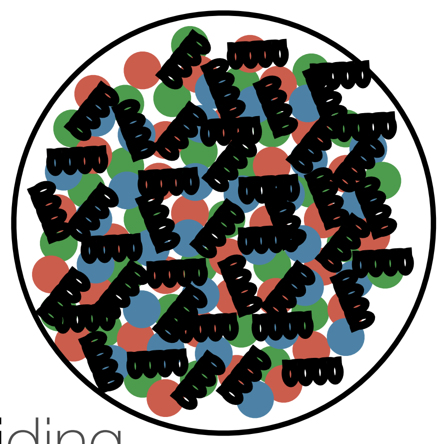
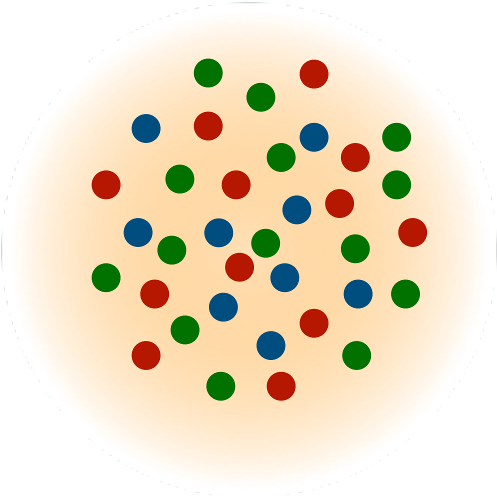


colliding hadron

Initial state
(=before collision)

OR ?



Dilute system
(**few interactions**
in the final state)

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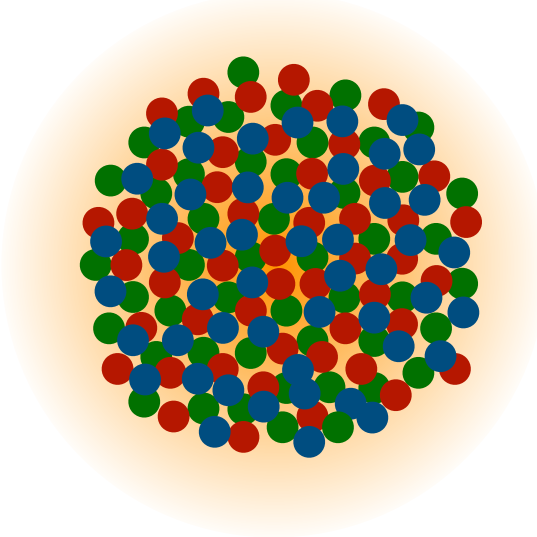
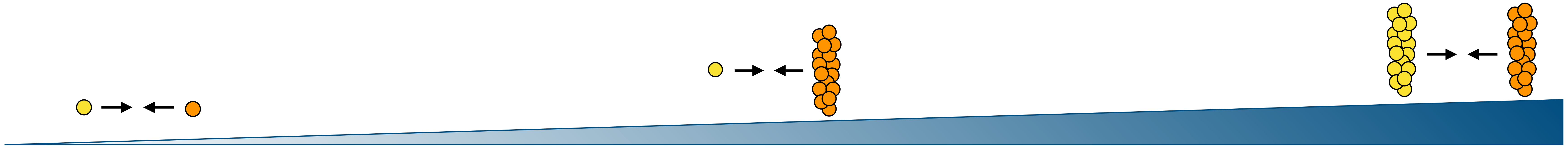


Dense medium
(limit of **many interactions**
in the final state)

low multiplicity



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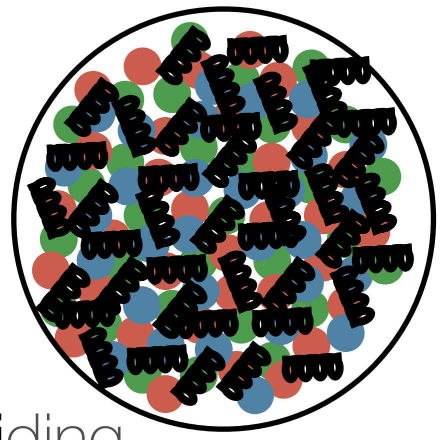

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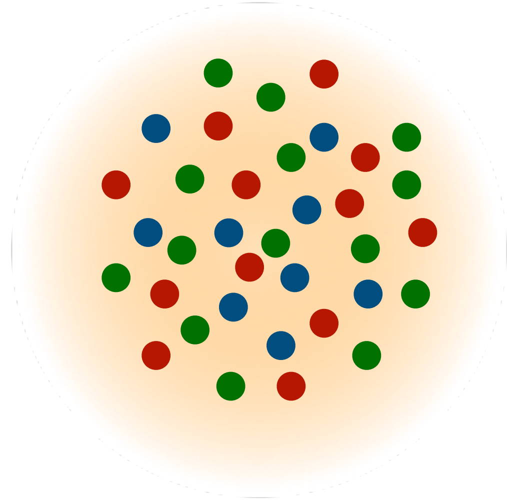

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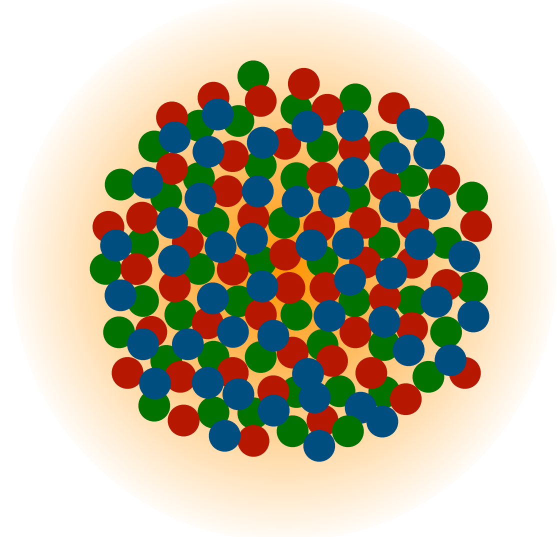

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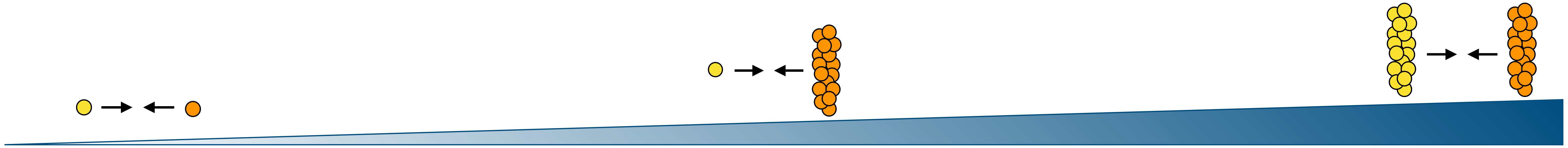

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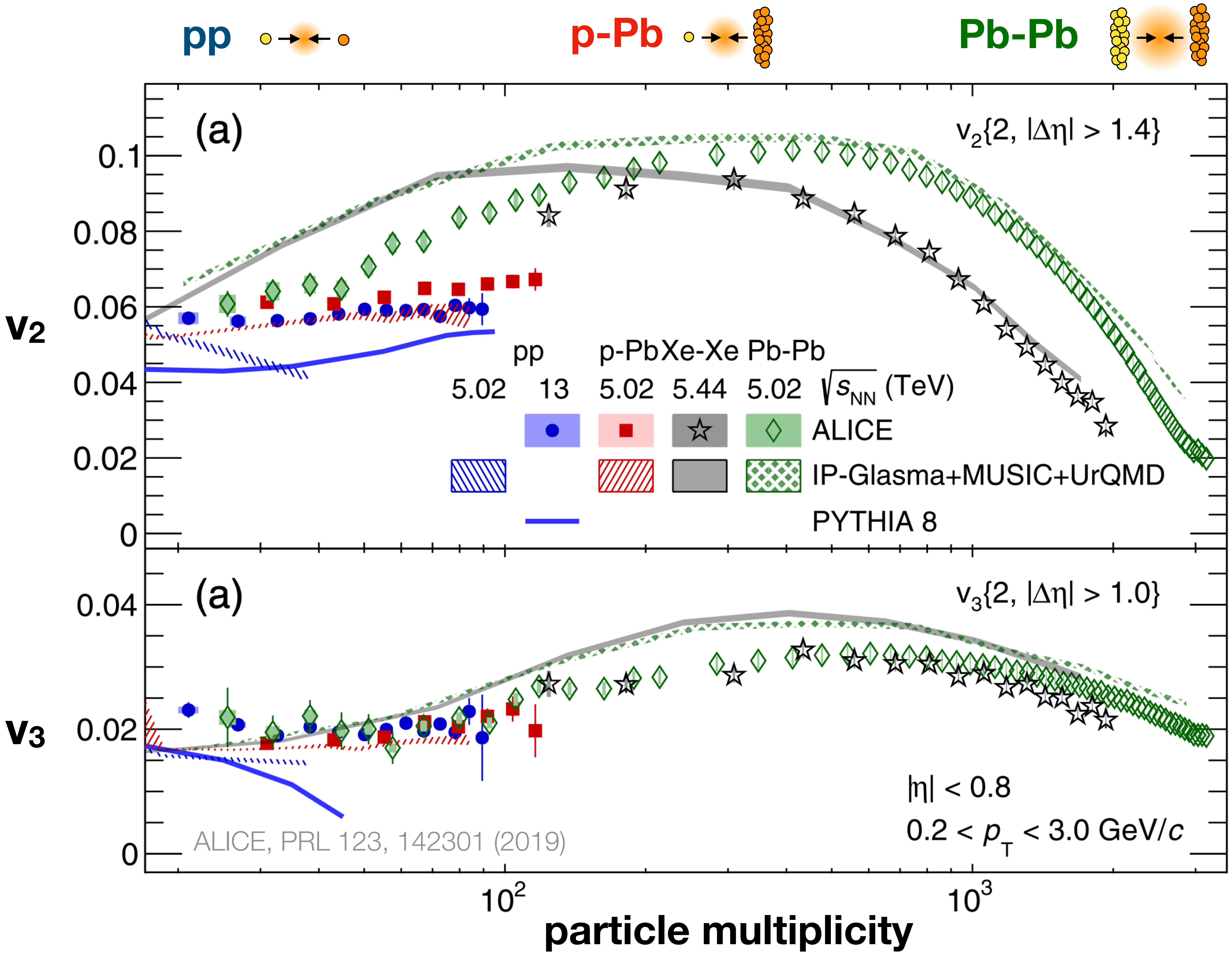
Anisotropic flow in small systems

No sharp turn-off as a function of multiplicity

We do not “switch-off” collectivity ?



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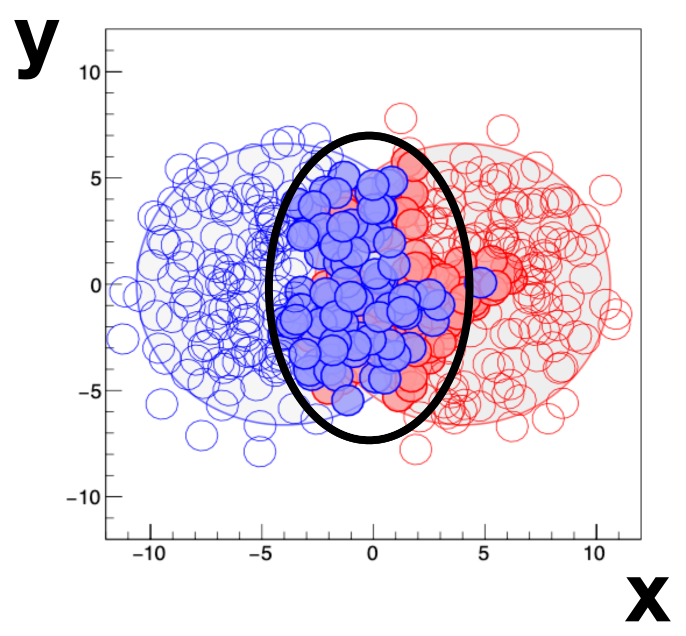
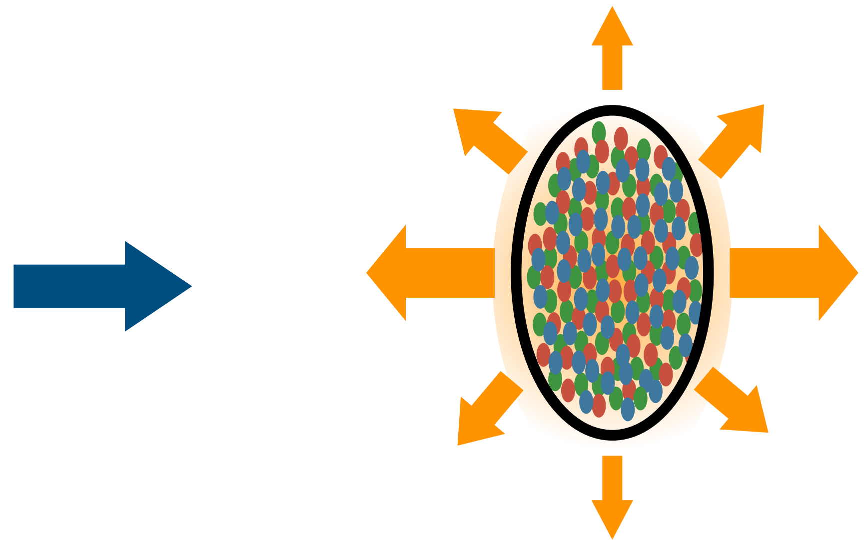
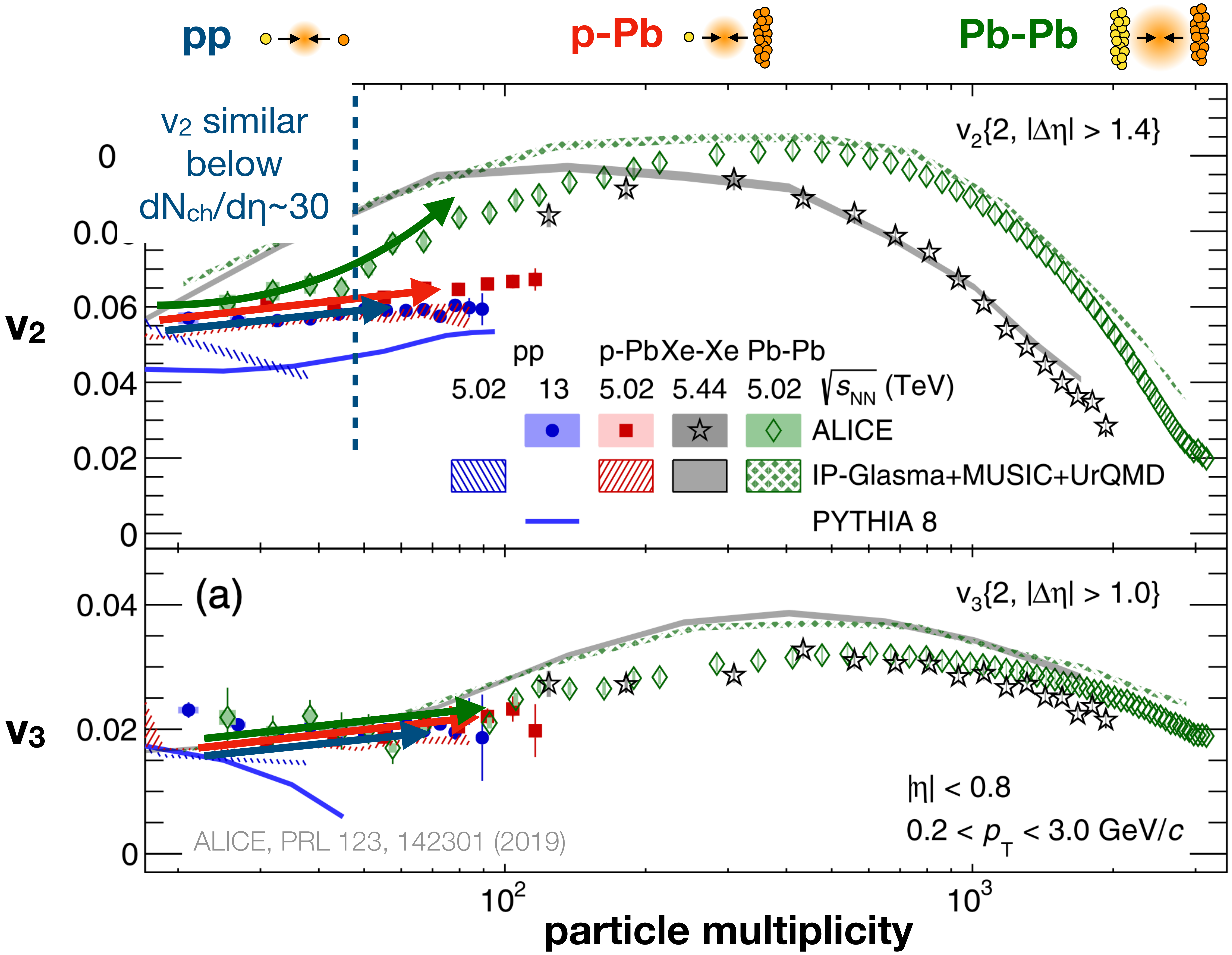
Response to initial geometry

Subnucleon fluctuations important in small systems







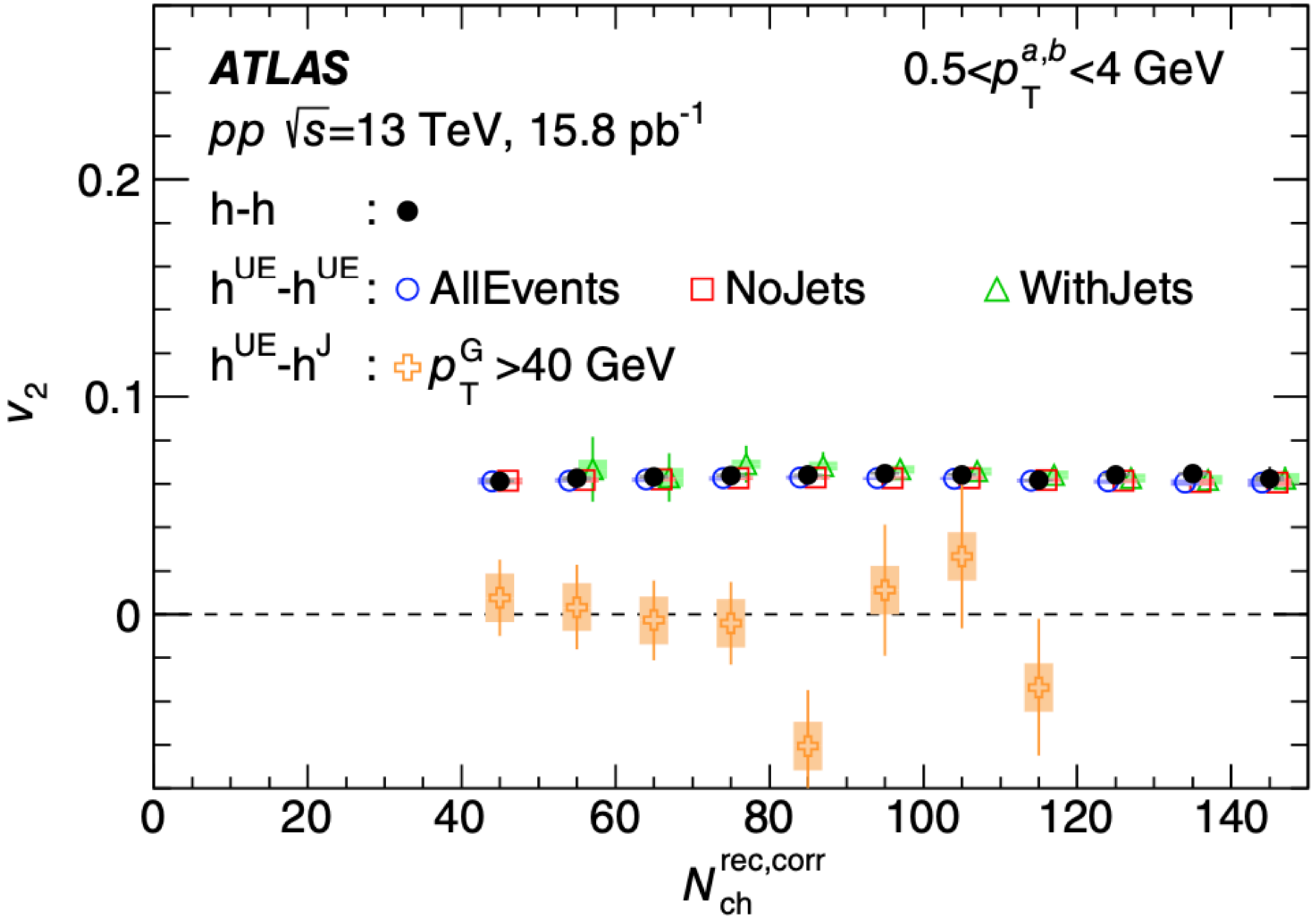
Sensitivity to the presence of jets

Long-range correlations not affected by the presence of hard process

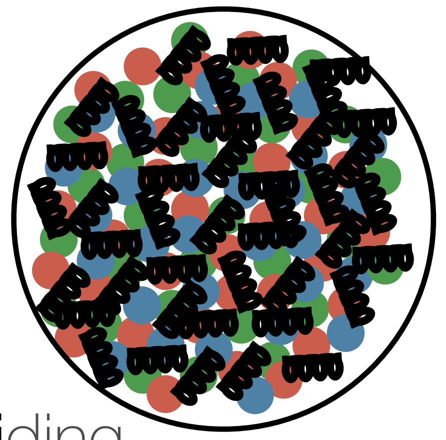
No significant change in v_2 when:

- Removing particles associated with jets
- Selecting events with jets (while removing particles associated with jets)

ATLAS, PRL 131, 162301 (2023)

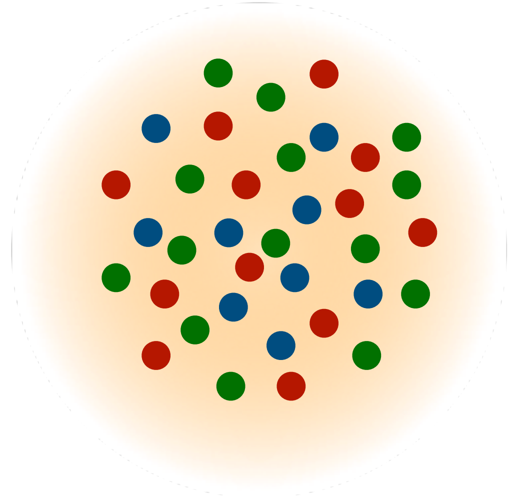


Signatures of QGP in small systems?



Initial state
(=before collision)

OR ?



Dilute system
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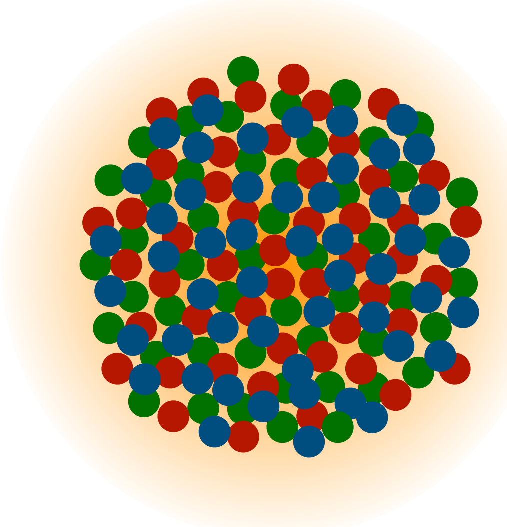

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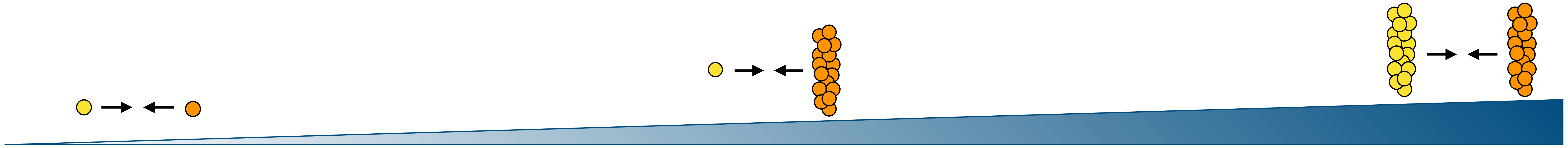

high multiplicity

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Can we ever switch it off?

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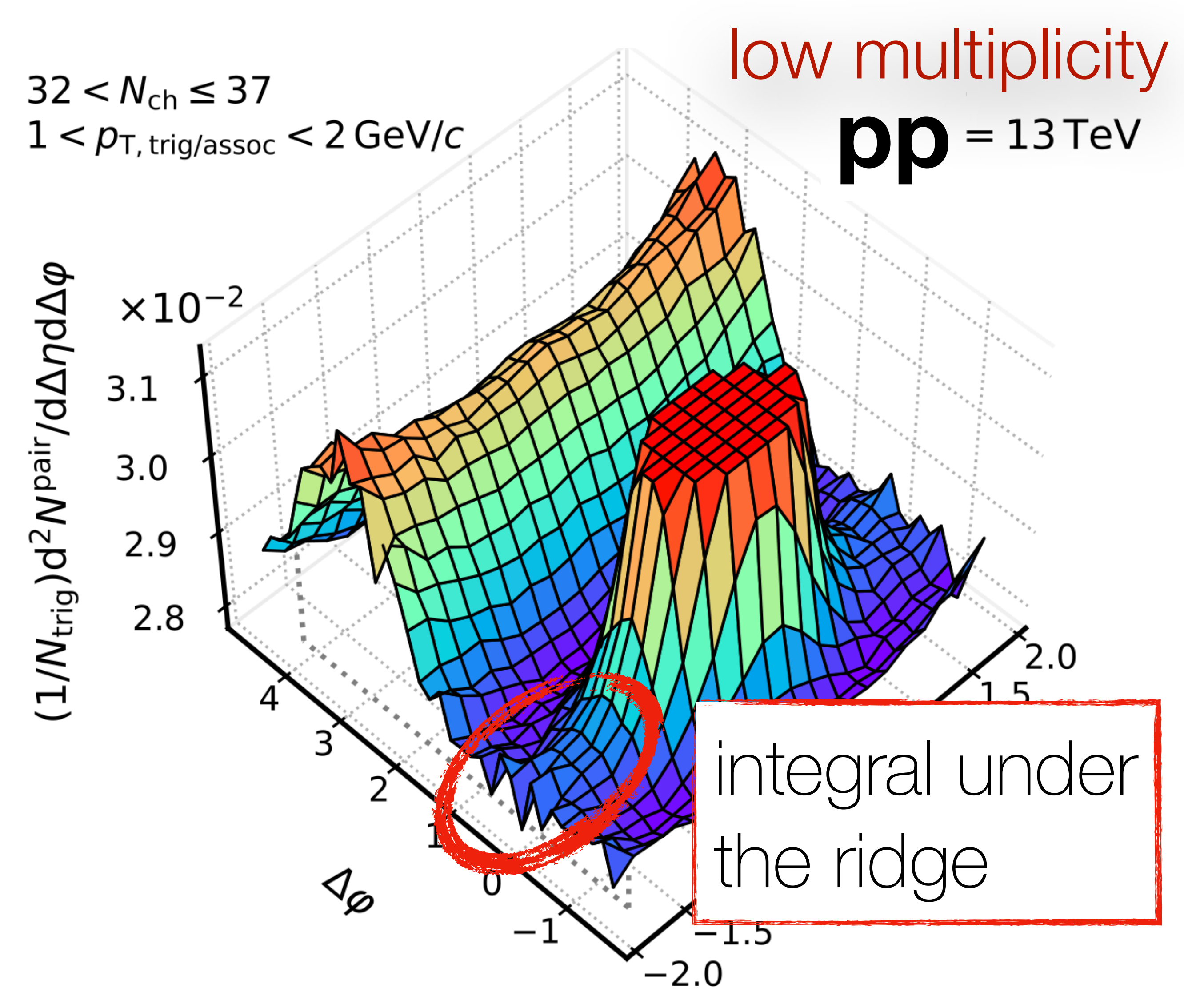
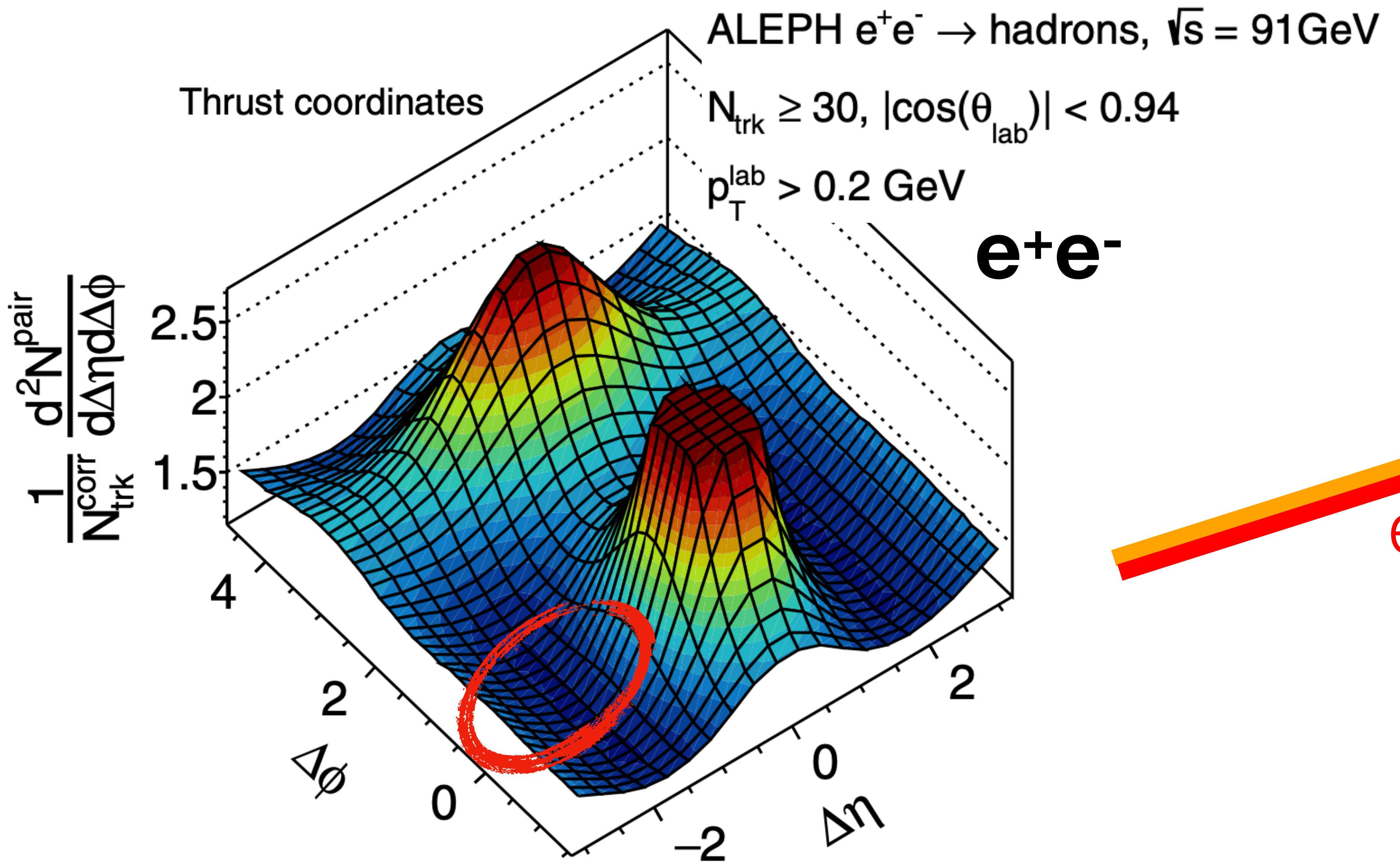
Measurements at the extremes





Near-side long-range ridge yield in pp down to low multiplicity

✅ But **not in e^+e^-** collisions → good, baseline stays a baseline

Note: signs of ridge visible in e^+e^- collisions at high N_{ch} (to be understood)

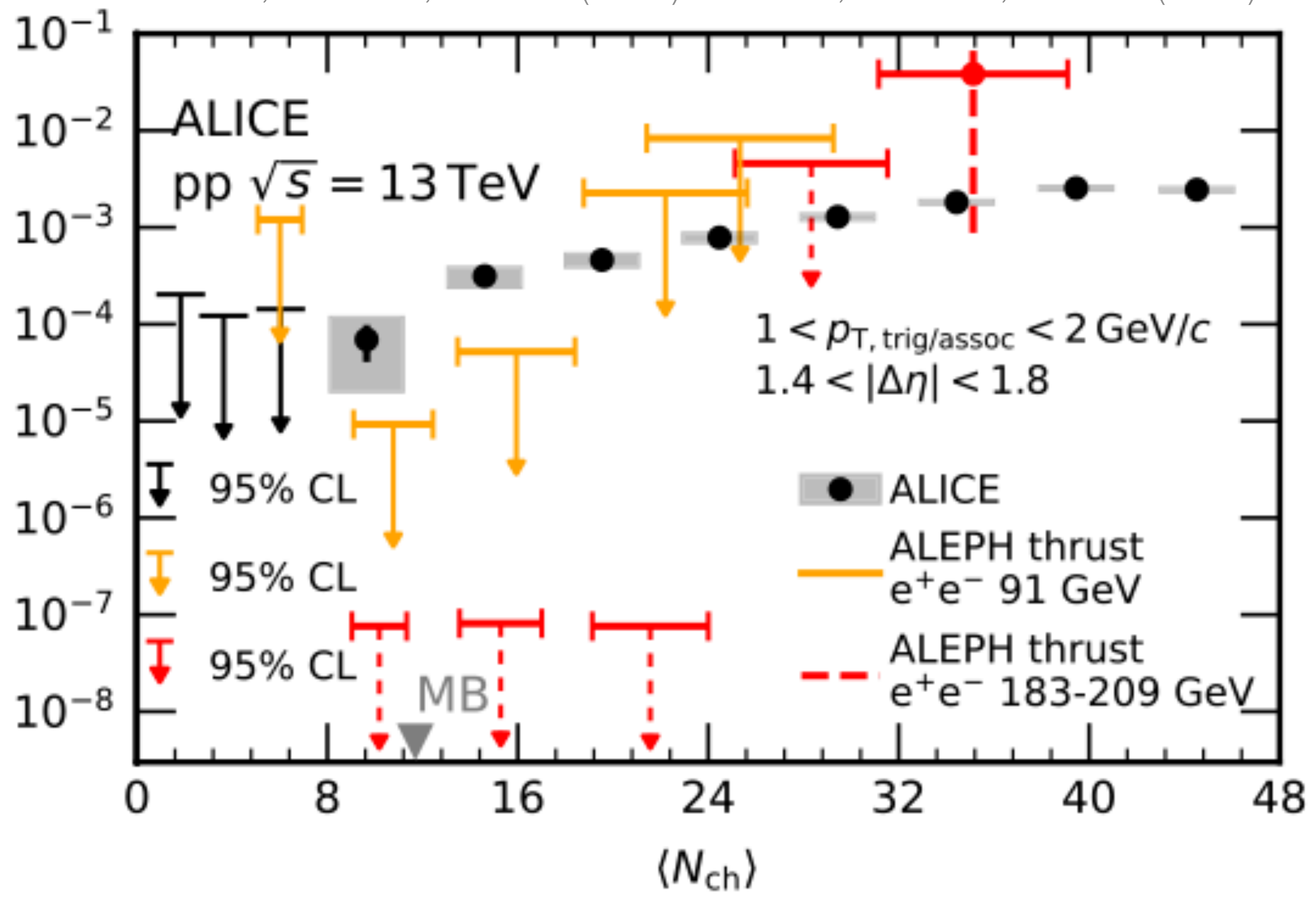
pp collisions

e^+e^- collisions

ALEPH, arXiv: 2312.05084

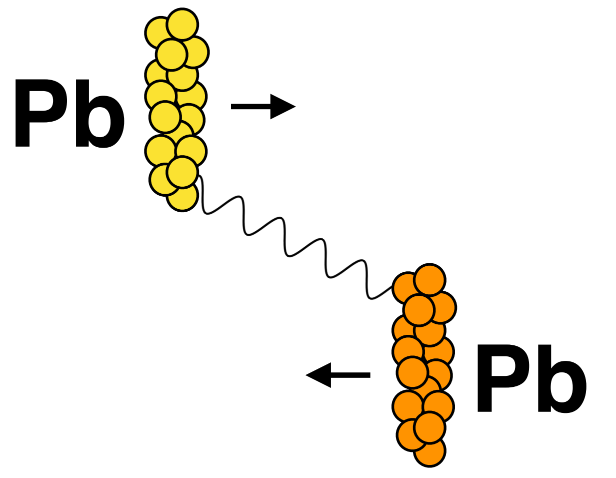
ALEPH, PRL 123, 212002 (2019) ALICE, PRL 132, 172302 (2024)

ridge yield

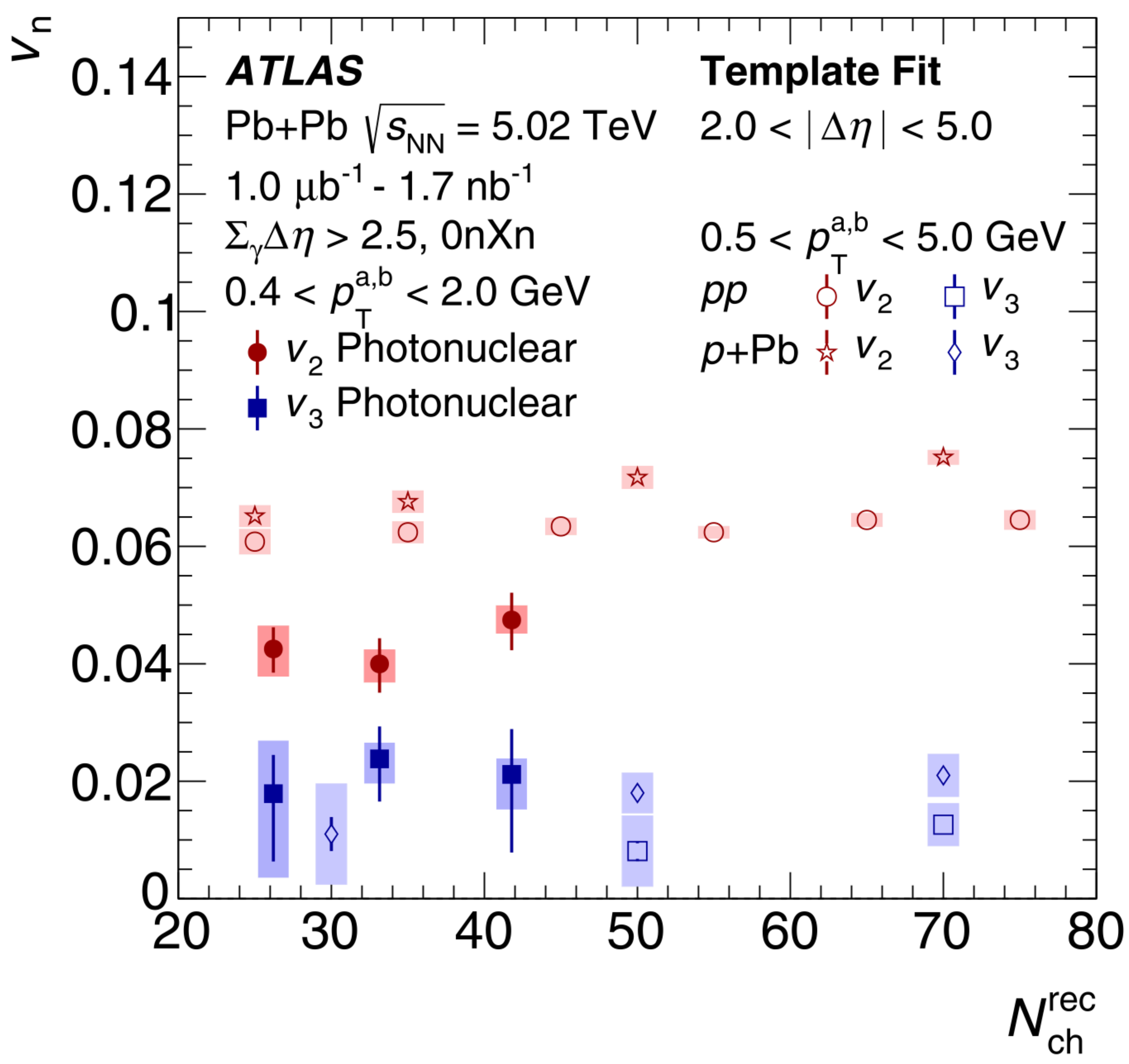


Ultraperipheral collisions to probe the IS effects?

UPC investigate saturation effects in the incoming nucleus
➡ very early collision times



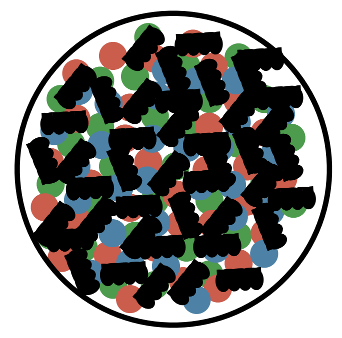
ATLAS, PRC 104, 014903 (2021)



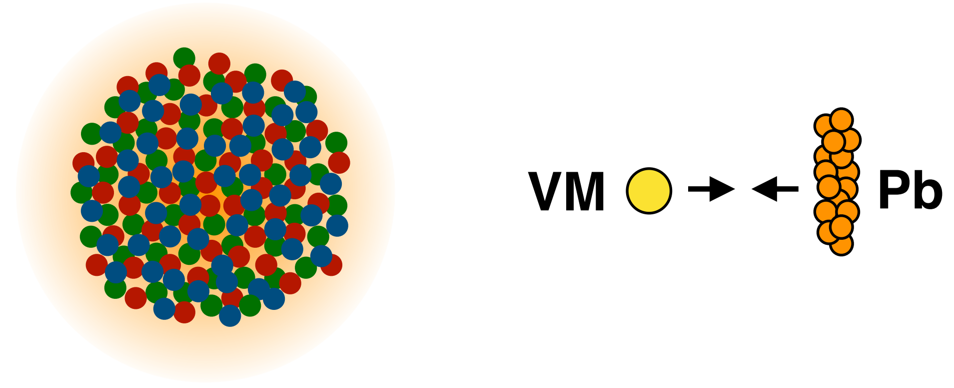
Finite v_2, but with smaller magnitude than in hadron collisions

Effects of the initial state (CGC-like) ?

"Standard flow model": response to geometry ?

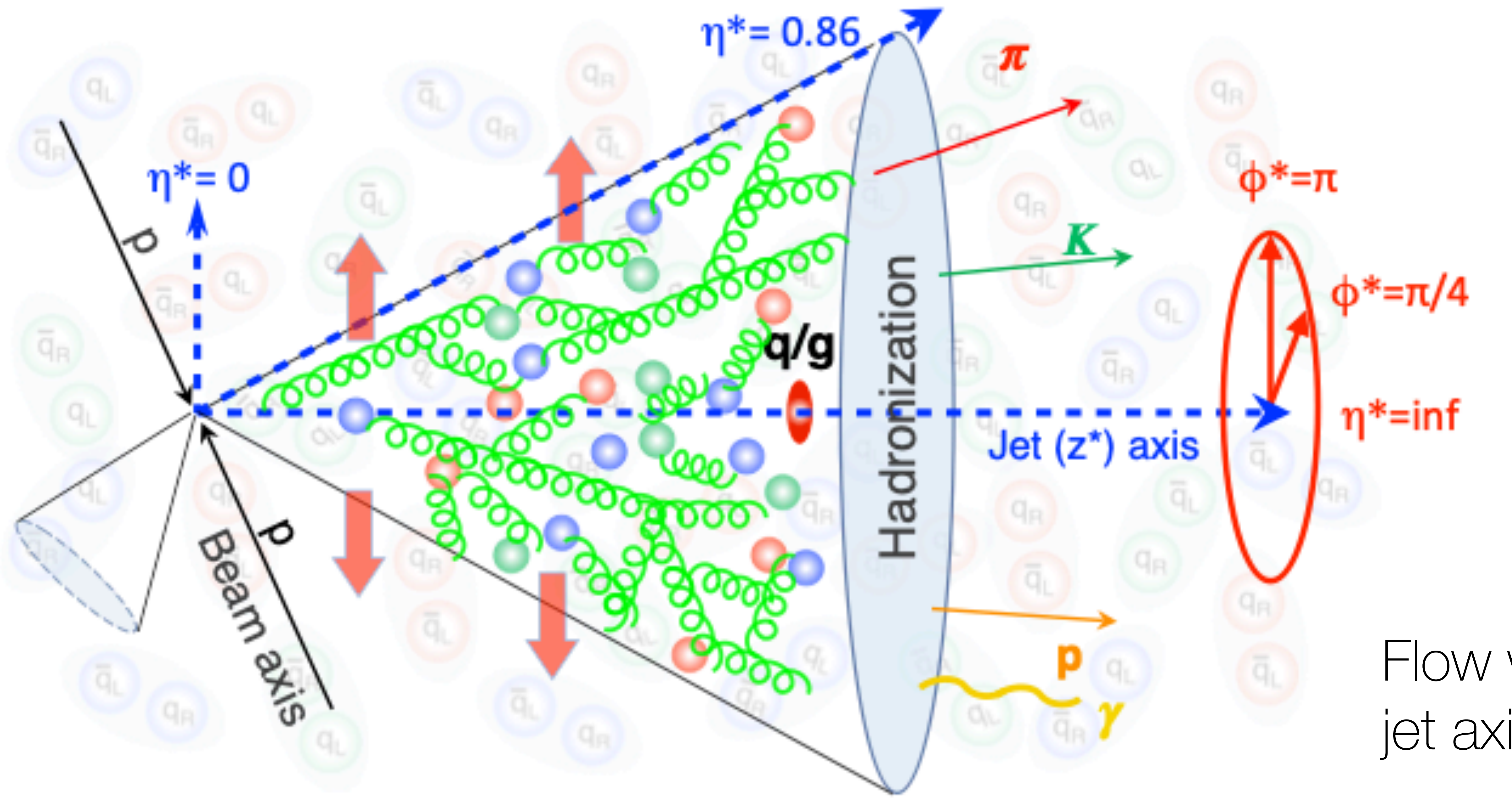


or

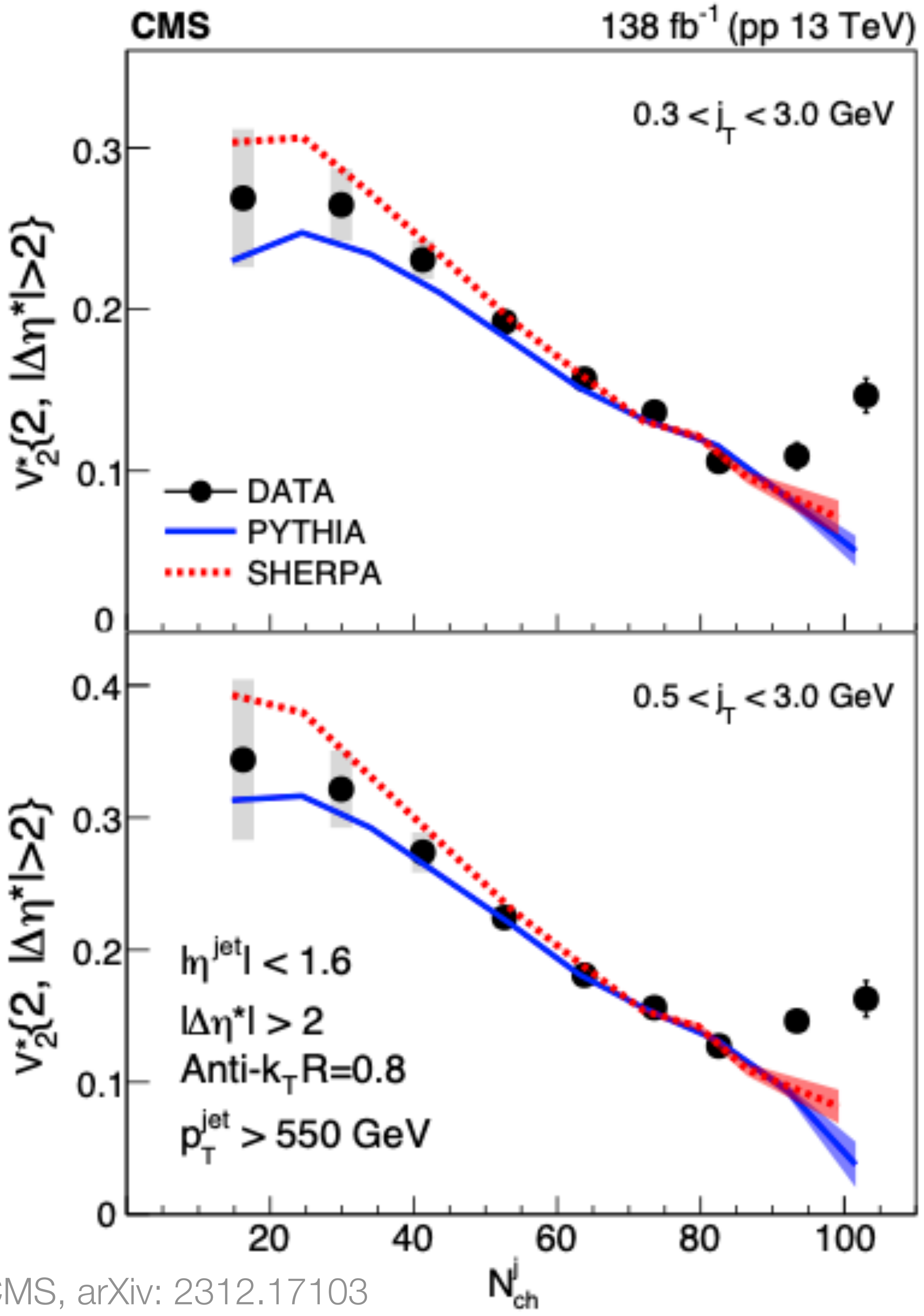


CGC model: Shi et al., PRD 103, 054017 (2021)
Hydro model: Zhao et al., PRL 129 (2022) 252302

Enhanced azimuthal anisotropies in jets?



Flow with respect to jet axis

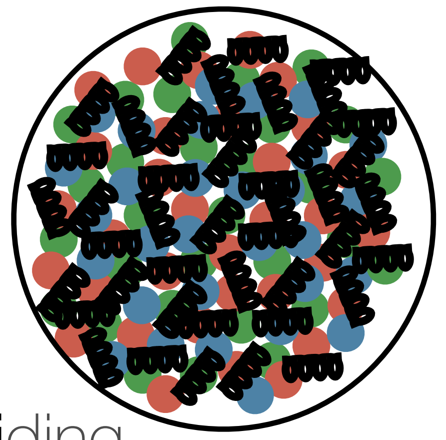


CMS, arXiv: 2312.17103

Unexpected enhanced correlations in high-multiplicity jets

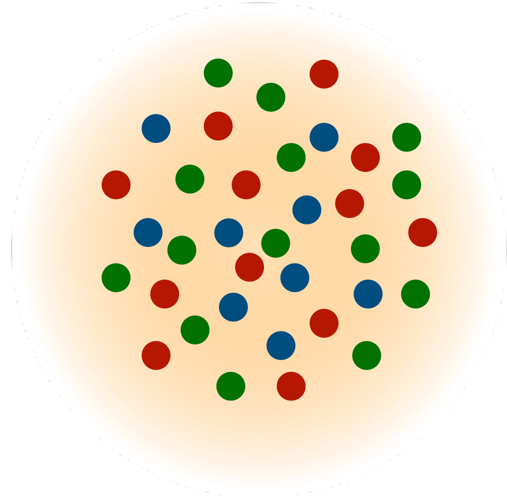
Is it just a corner of phase space not yet captured by particle-production models, or new effects ?

Signatures of QGP in small systems?



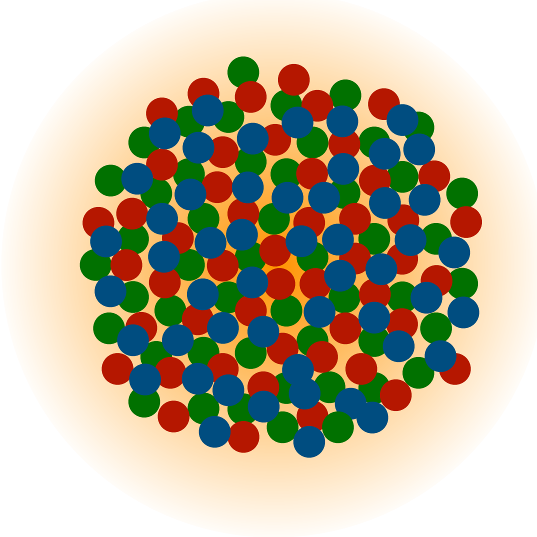
Initial state
(=before collision)

OR ?



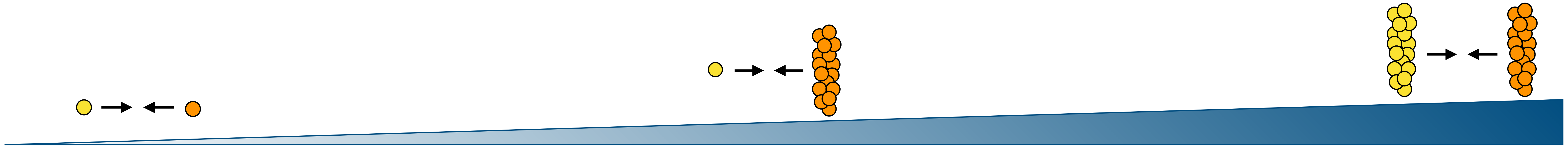
Dilute system
(**few interactions**
in the final state)

OR ?



Dense medium
(limit of **many interactions**
in the final state)

low multiplicity



high multiplicity

✅ **Collectively expanding**

Signatures:
modification of momentum and angular distributions

Measurements:
anisotropic flow

Thermalised medium

Signatures:
modification of hadronisation
thermal photon radiation

Measurements:
particle yields
particle spectra

?

Dense & deconfined medium

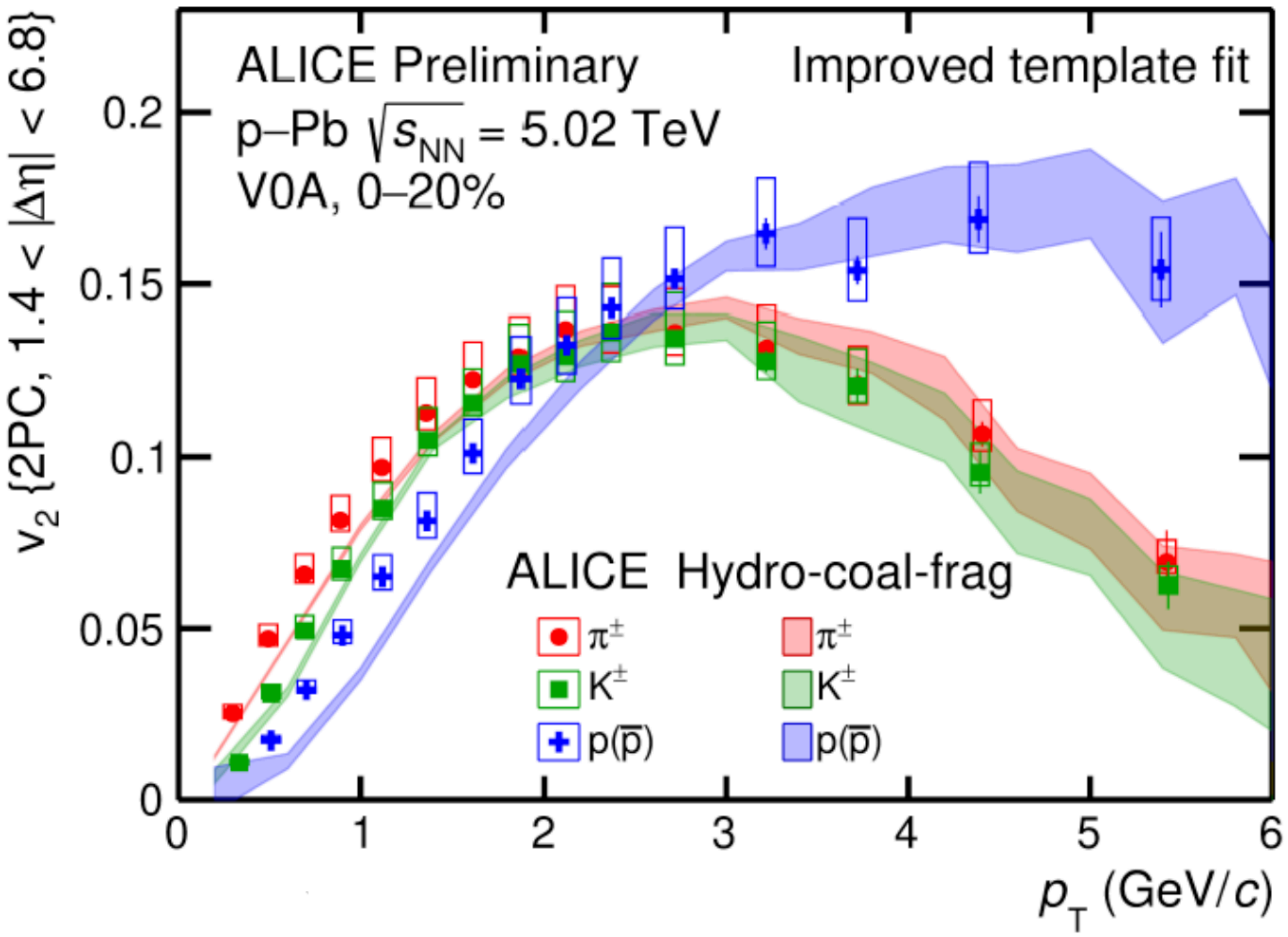
Signatures:
parton energy loss
quarkonia dissociation

Measurements:
nuclear modification factor

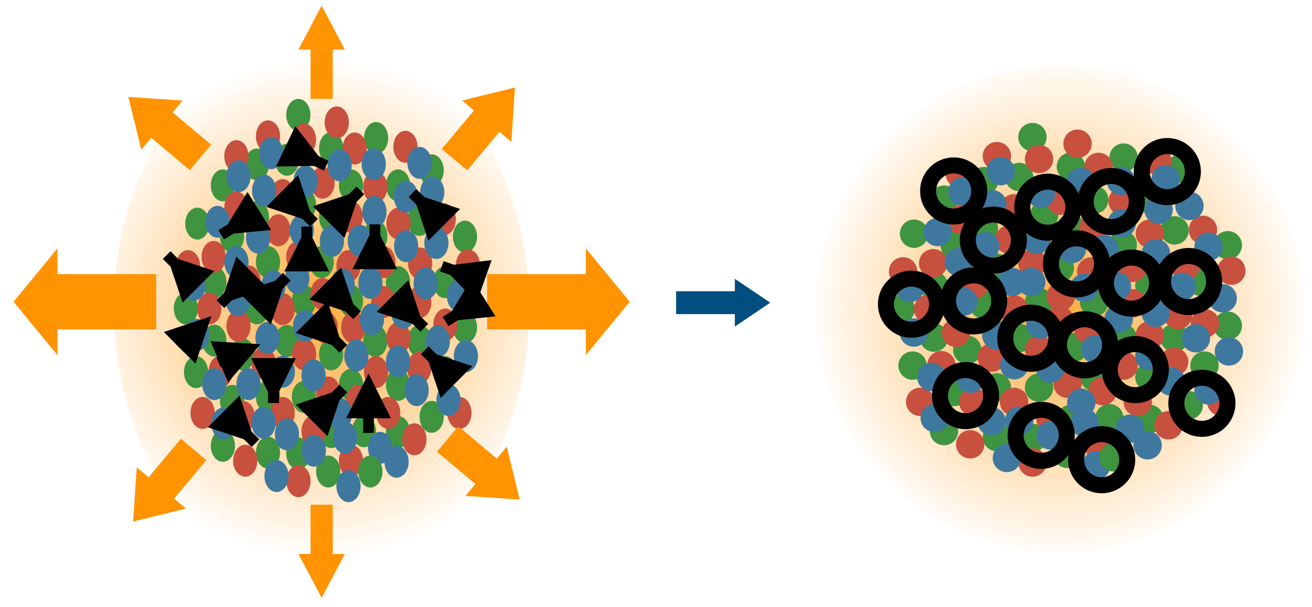
?

Hadron species dependence of flow in p-Pb/pp

ALICE, Quark Matter 2022



Collectively expanding medium
➡ constituents flow with similar velocity, and coalesce into hadrons



Mass ordering

Particle-type grouping

One of the most prominent **signatures of partonic** (deconfined) **medium**

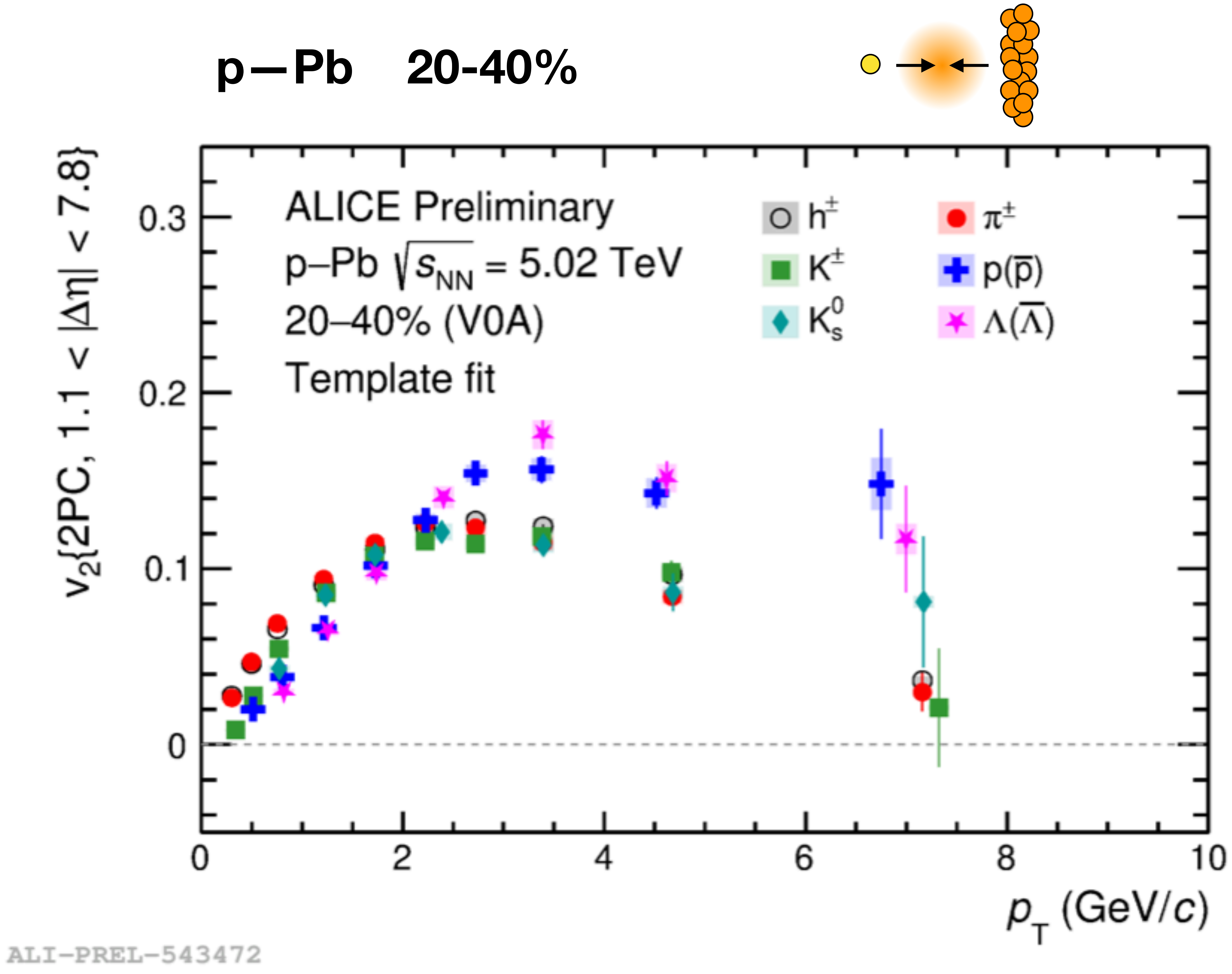
Again: how low in N_{ch} do we observe this?

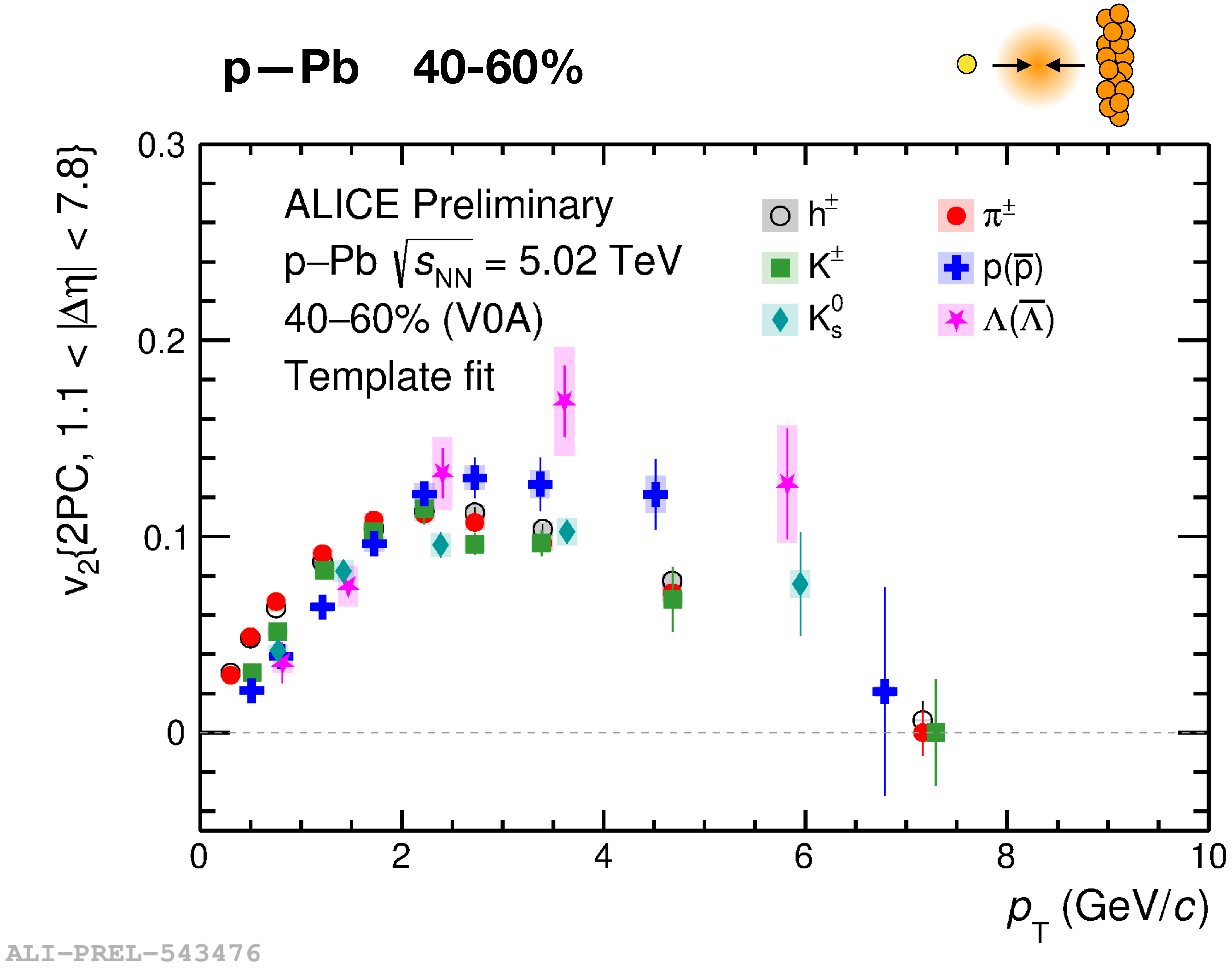
PID flow down to low multiplicity in pPb

Features of partonic collectivity remain
at smaller multiplicities

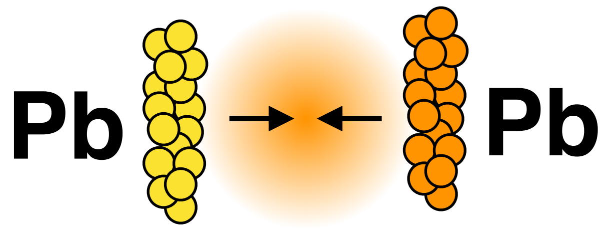
What about pp, e^+e^- ?

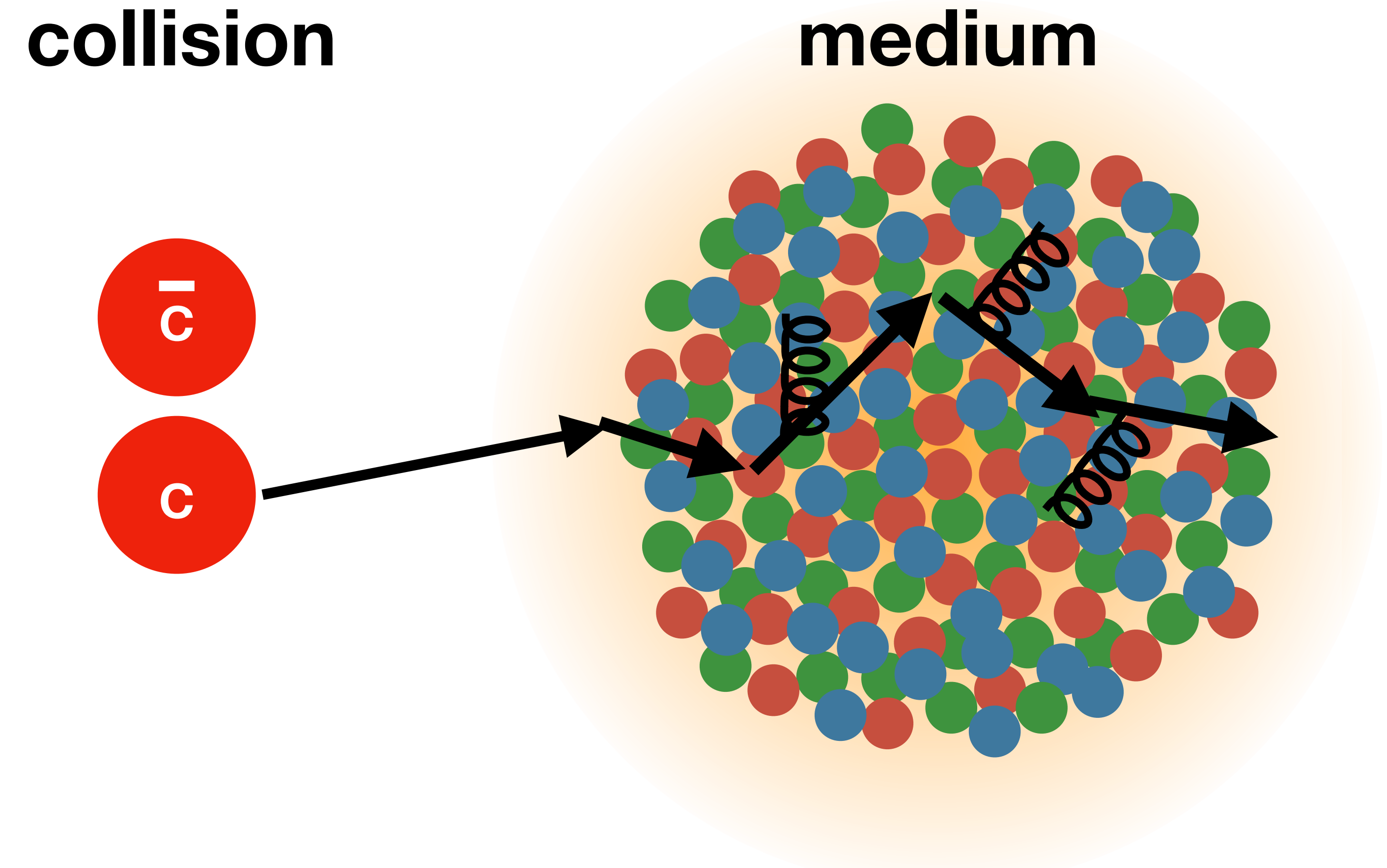
Hint: check talks at SQM :)





Even charm flows in small systems ?





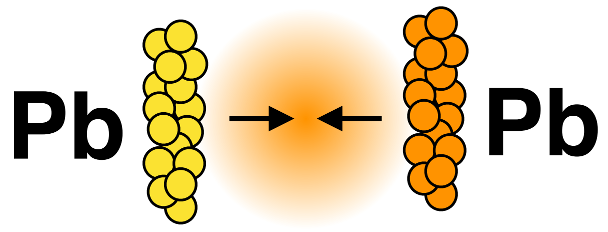
created in vacuum
during early
hard scatterings

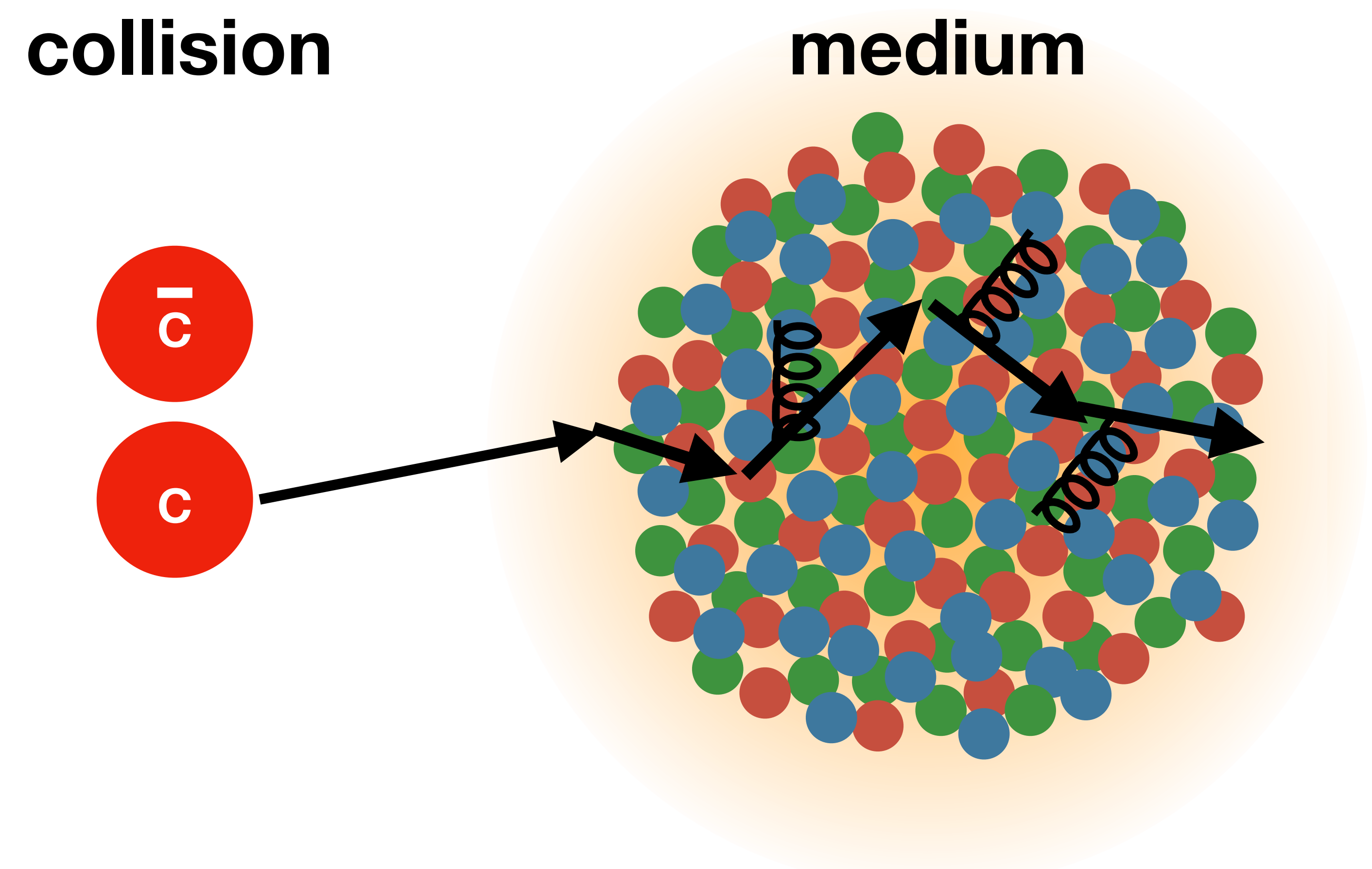
(partially) equilibrated
with the medium
via interactions

if heavy quark
participates in
the collective expansion
of the medium

➡ $v_2 > 0$

Even charm flows in small systems ?





created in vacuum during early hard scatterings

(partially) equilibrated with the medium via interactions

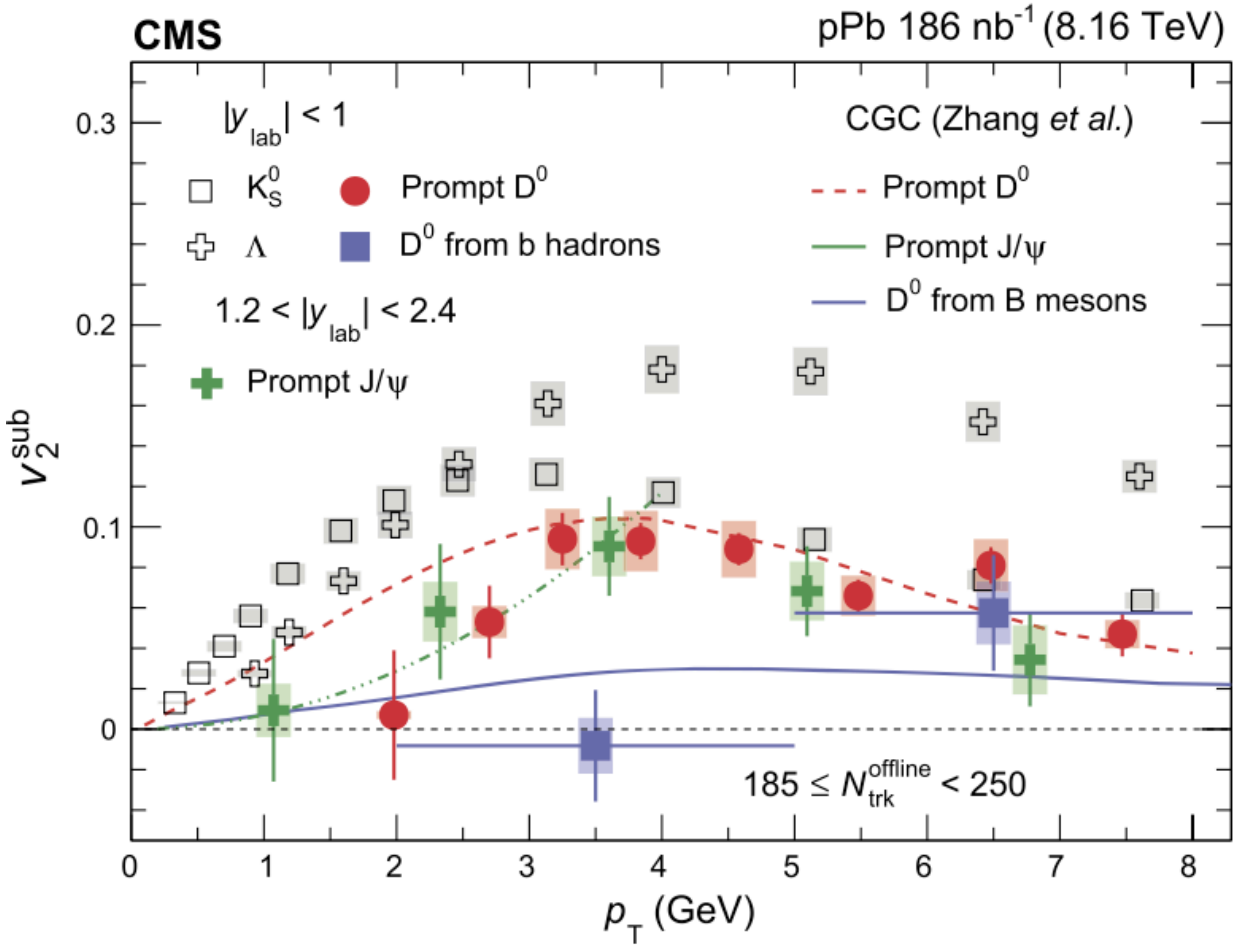
if heavy quark **participates in the collective expansion** of the medium ➡ $v_2 > 0$

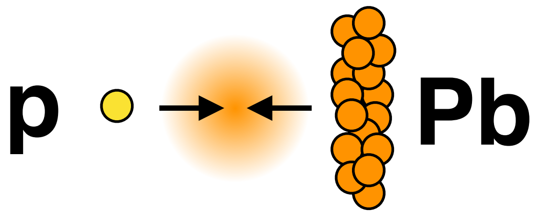
Nonzero v_2 of charm hadrons in pp and p—Pb

Sign of thermalisation with (some) medium ?

Left-over from initial state effects ?

CMS, PLB 813 (2021) 136036



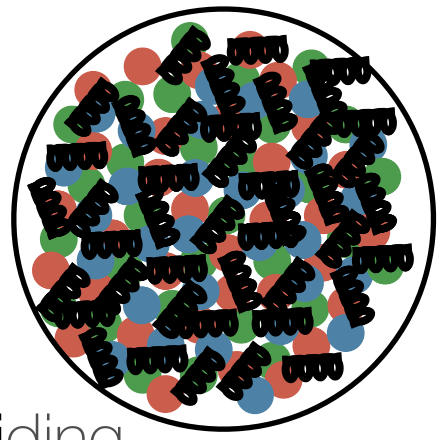


$v_2(D^0)$

$v_2(J/\Psi)$

What about charm baryons? Grouping effect?
Measurements at low N_{ch} ?

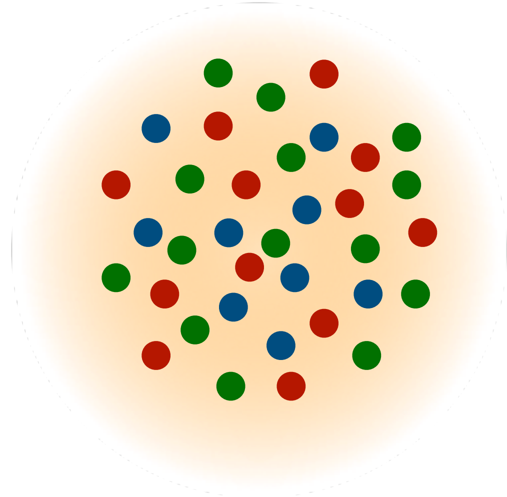
Signatures of QGP in small systems?



colliding hadron

Initial state
(=before collision)

OR ?



Dilute system
(**few interactions**
in the final state)

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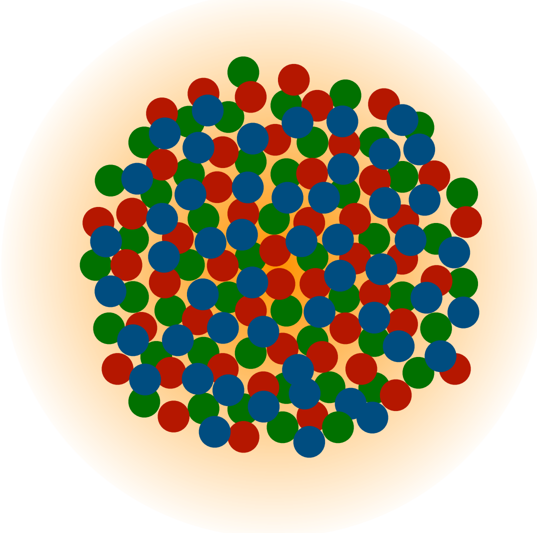

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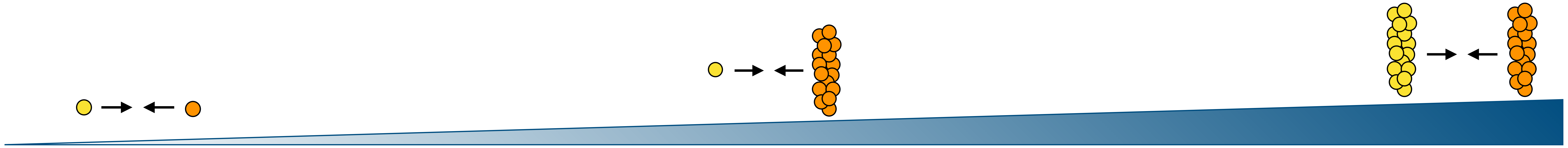

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thermal photon radiation

Measurements:
particle yields
particle spectra

Dense & deconfined medium

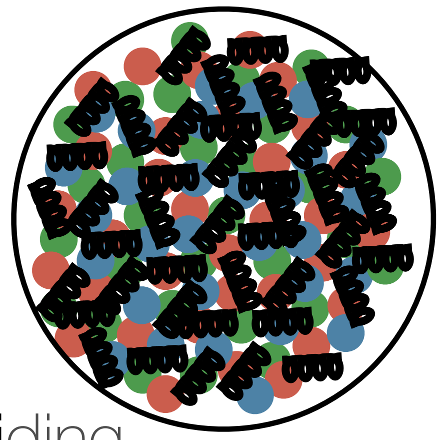
Signatures:
parton energy loss
quarkonia dissociation

nts:
cation factor

?

More about this topic in the next talk

Signatures of QGP in small systems?



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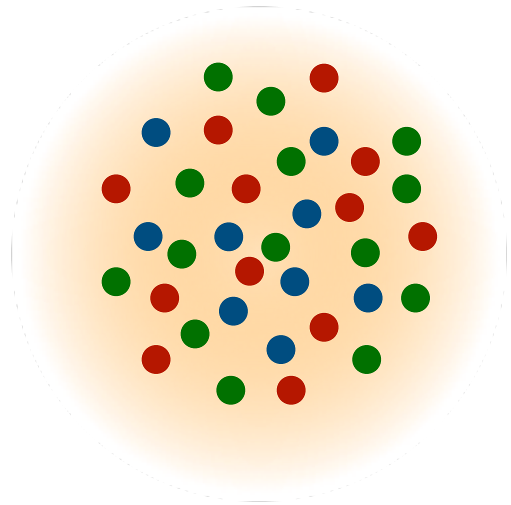

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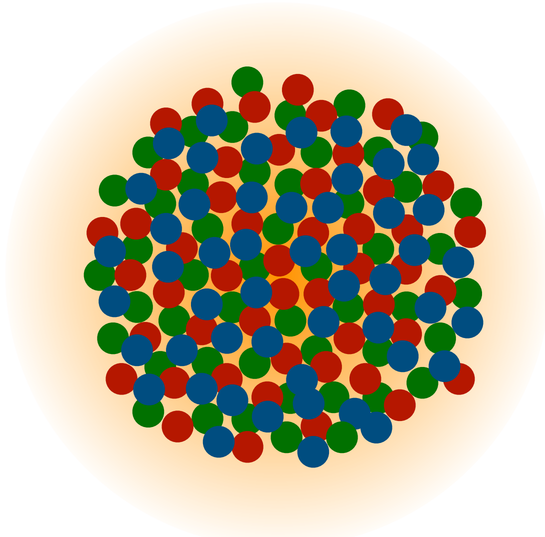

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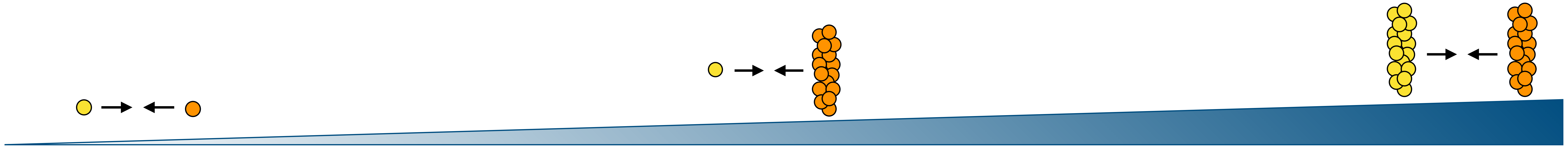

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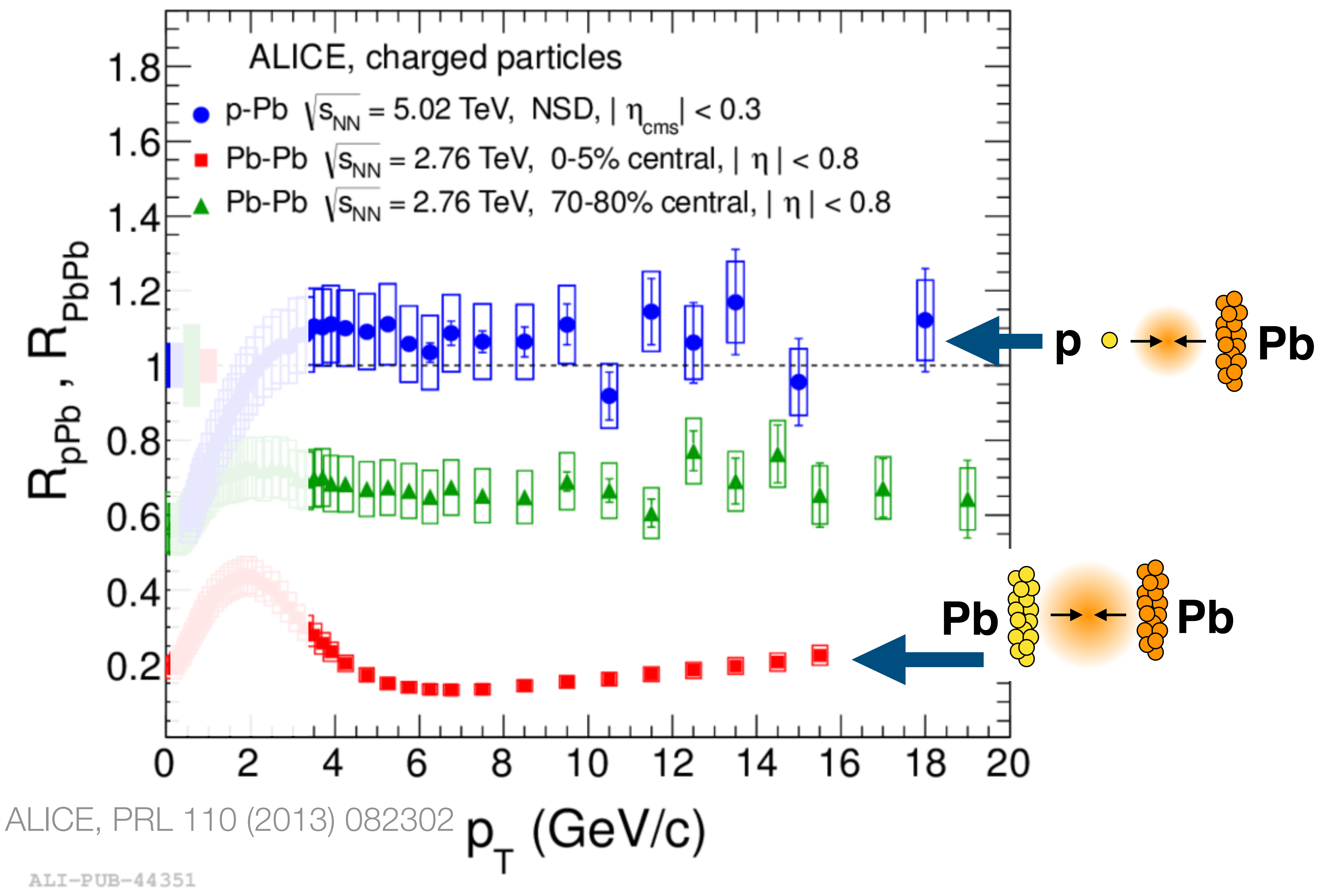
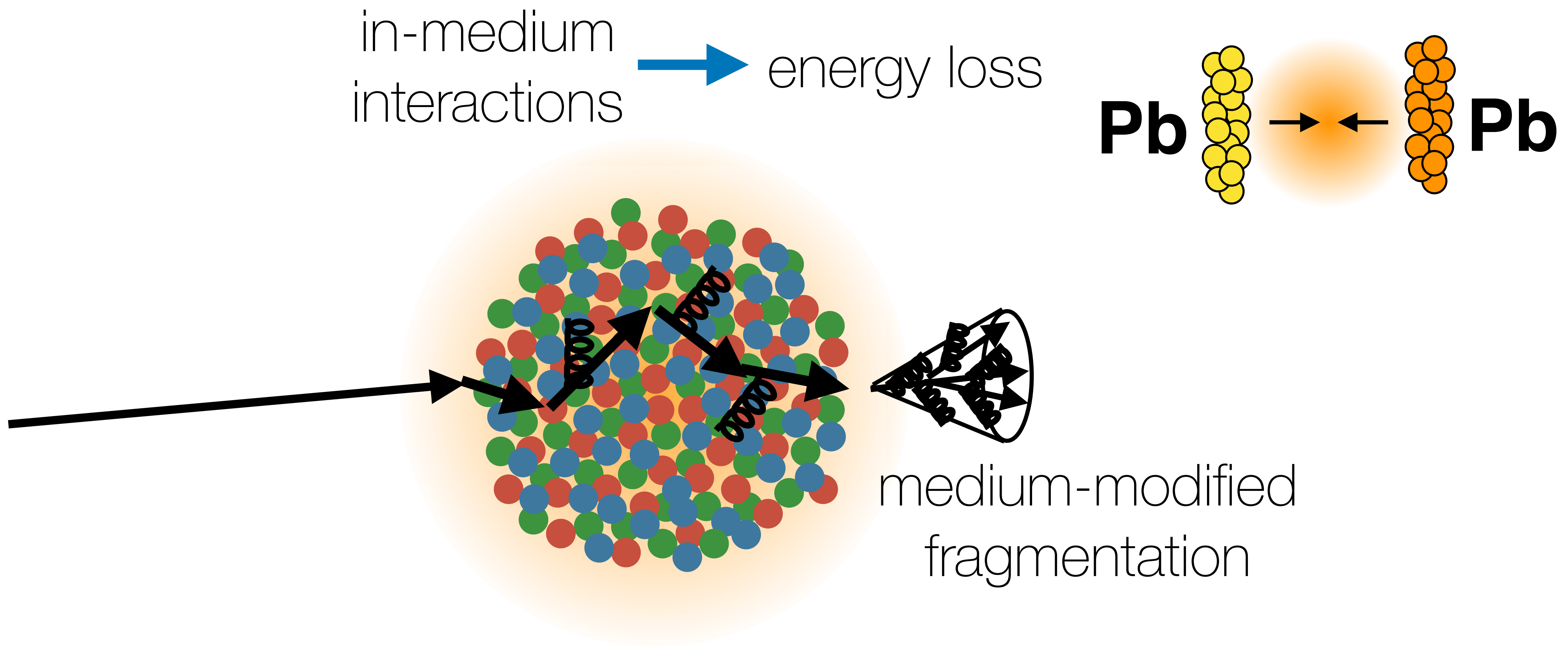
Parton energy loss in p-Pb collisions?



ALICE, PRL 110 (2013) 082302



Absence of suppression in p—Pb collisions

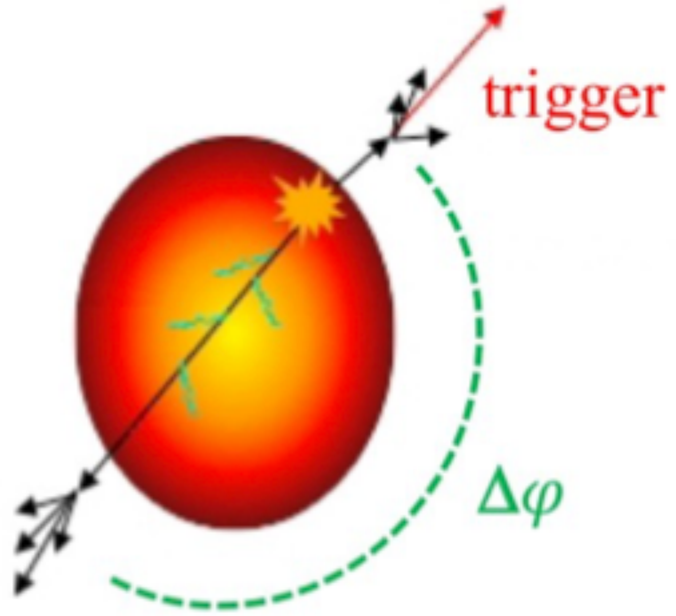
Does it mean absence of parton energy loss in small systems?

Note: both ALICE and ATLAS observe non-zero v_2 of (mini)-jets and high-p_T hadrons

ALICE, arXiv: 2212.12609
ATLAS, EPJC (2020) 80:73

Other way to address parton energy loss

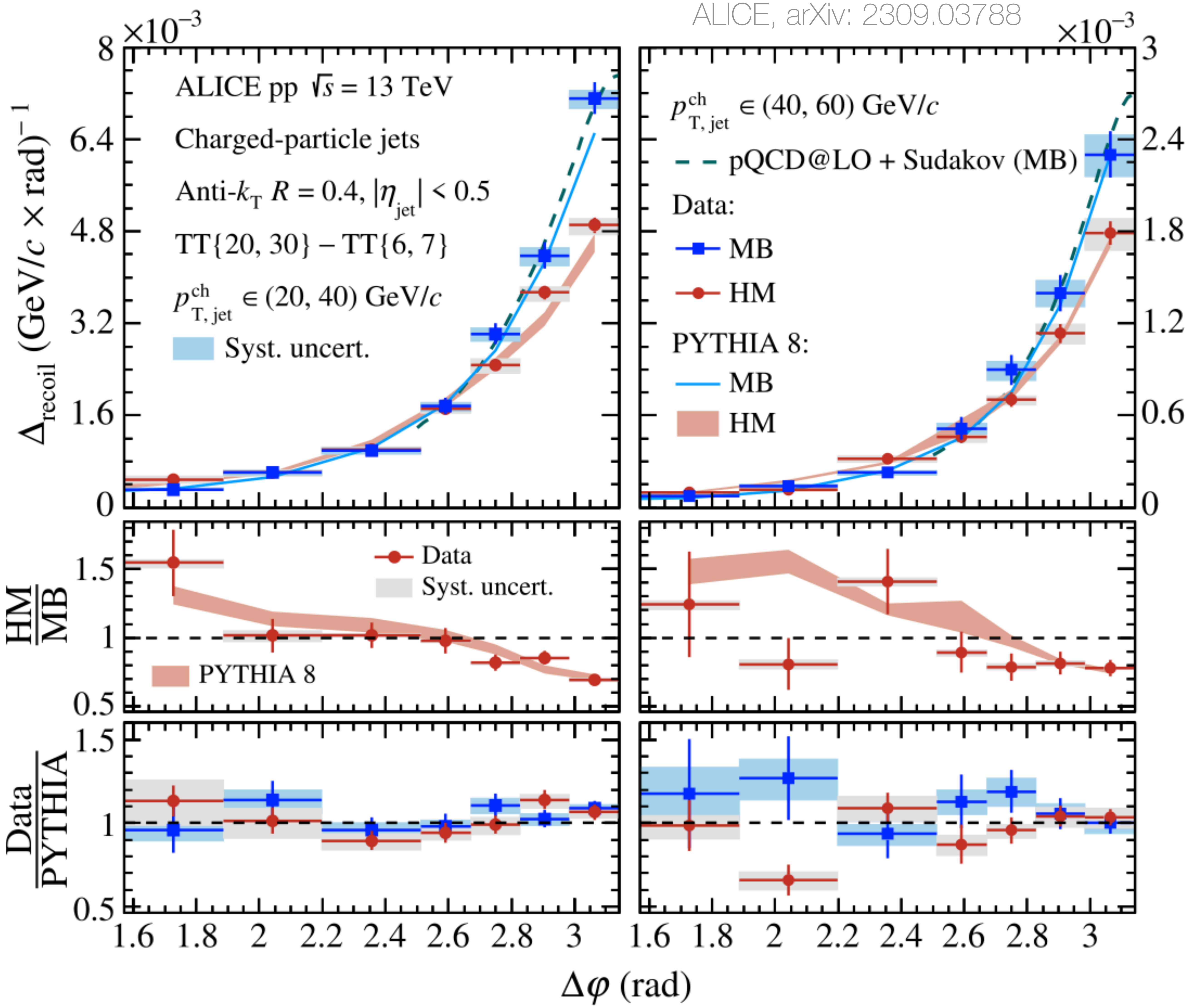
hadron - jet acoplanarity



looking at broadening/suppression of the recoiling jet w.r.t. trigger high-p_T hadron

$$\Delta_{\mathrm{recoil}}(p_{\mathrm{T}},\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\Delta\varphi}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}_{\mathrm{Sig}}} - c_{\mathrm{Ref}}\times\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{jet}}}{\mathrm{d}p^{\mathrm{ch}}_{\mathrm{T,jet}}\mathrm{d}\Delta\varphi}\Bigg|_{p_{\mathrm{T,trig}}\in\mathrm{TT}_{\mathrm{Ref}}}$$

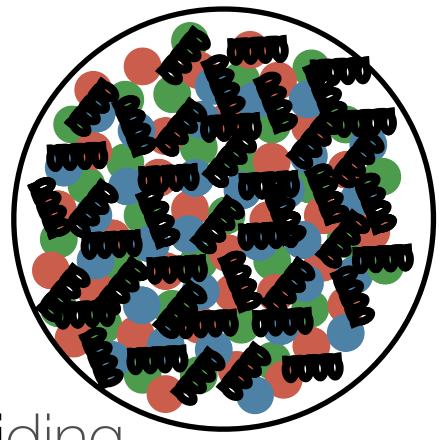
ALICE, arXiv: 2309.03788



No confirmation of parton energy loss yet

The effect is reproduced with PYTHIA Monash

Signatures of QGP in small systems?



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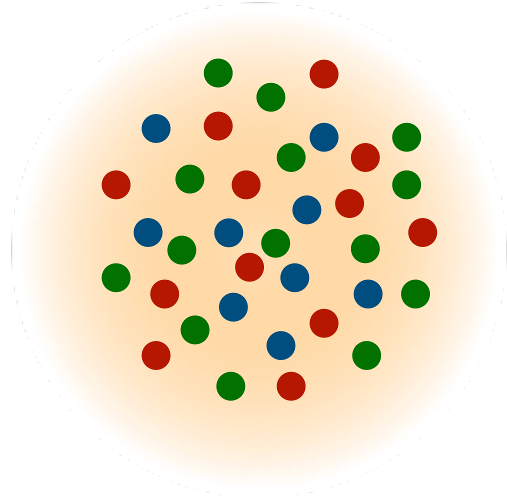

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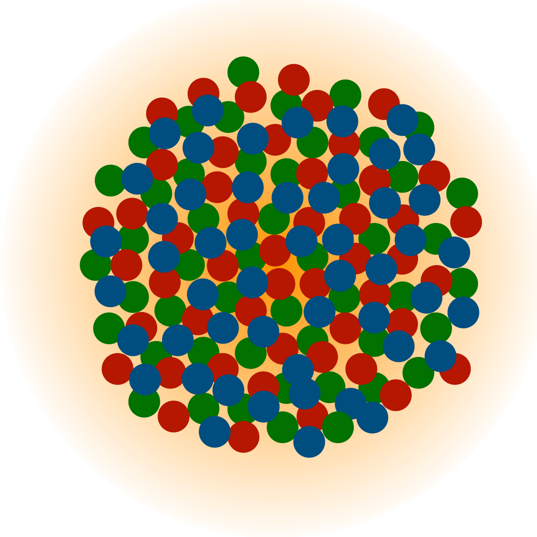

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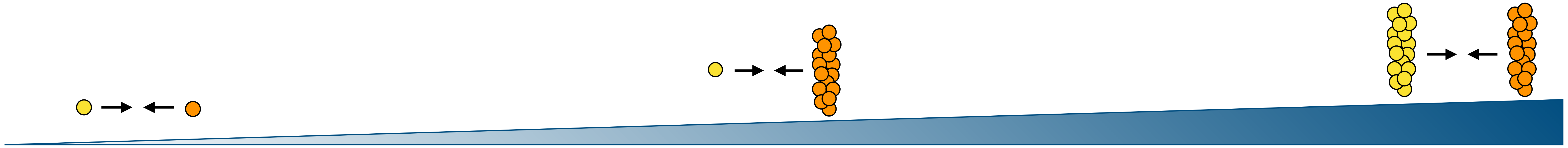

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particle yields
particle spectra

Dense & deconfined medium

Signatures:
~~parton energy loss~~
quarkonia dissociation

Measurements:
nuclear modification factor

?

How sure are we about the QGP hypothesis?

Standard heavy-ion paradigm of flow:

initial geometry (fluctuating nucleon/subnucleon distributions) ➡ **final state interactions** (strings, partons, hadrons, …) ➡ **collective correlations** (flow)

Is the underlying physics of ***small & dilute*** in essence the same as in ***large & dense?***

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Is the underlying physics of ***small & dilute*** in essence the same as in ***large & dense?***

NO Alternative explanations **(initial gluon momentum correlations** - CGC) ruled out / not dominant

→ Such correlations may vanish very quickly, or are excluded from measurements by applying $\Delta\eta$ gaps

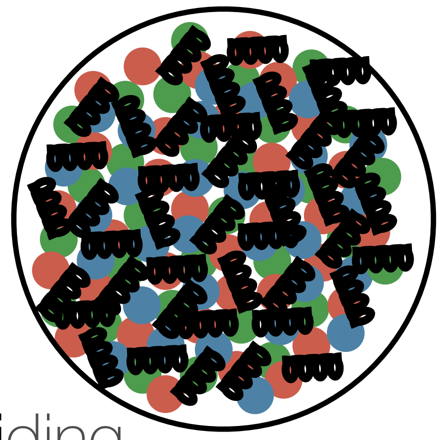
Schenke, Schlichting, Singh, PRD 105, 094023 (2022)

seems to be the preferrable option (?) **YES** Flow built as a **response to initial geometry**

→ But, does this mean that we accept hydro-like picture down to minimum bias pp collisions?

→ Hydrodynamics has its limitations

The big picture of small systems



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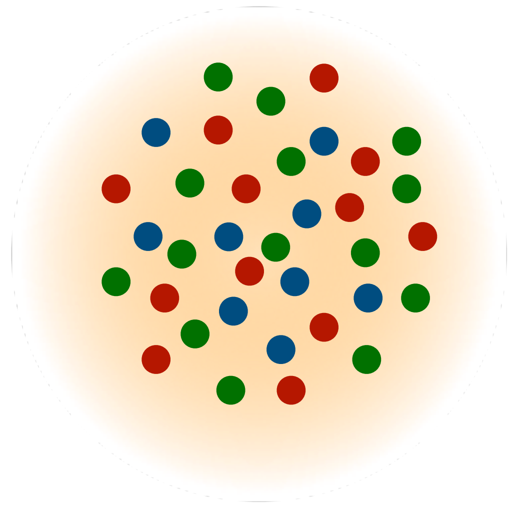

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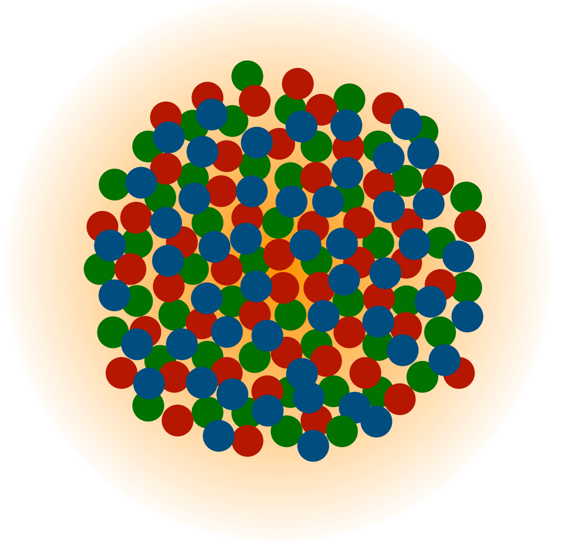

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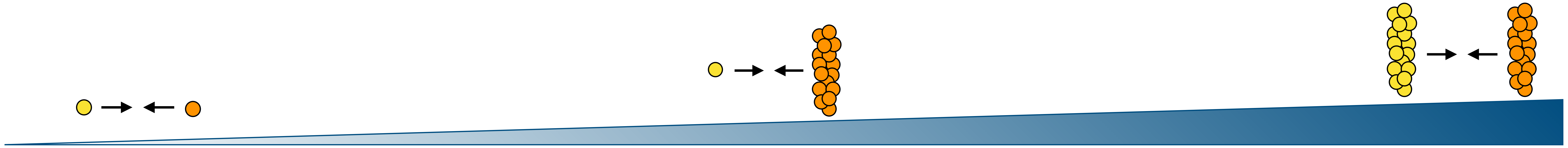


high multiplicity

How do other phenomena fit into the picture?

… should we expect jet quenching?

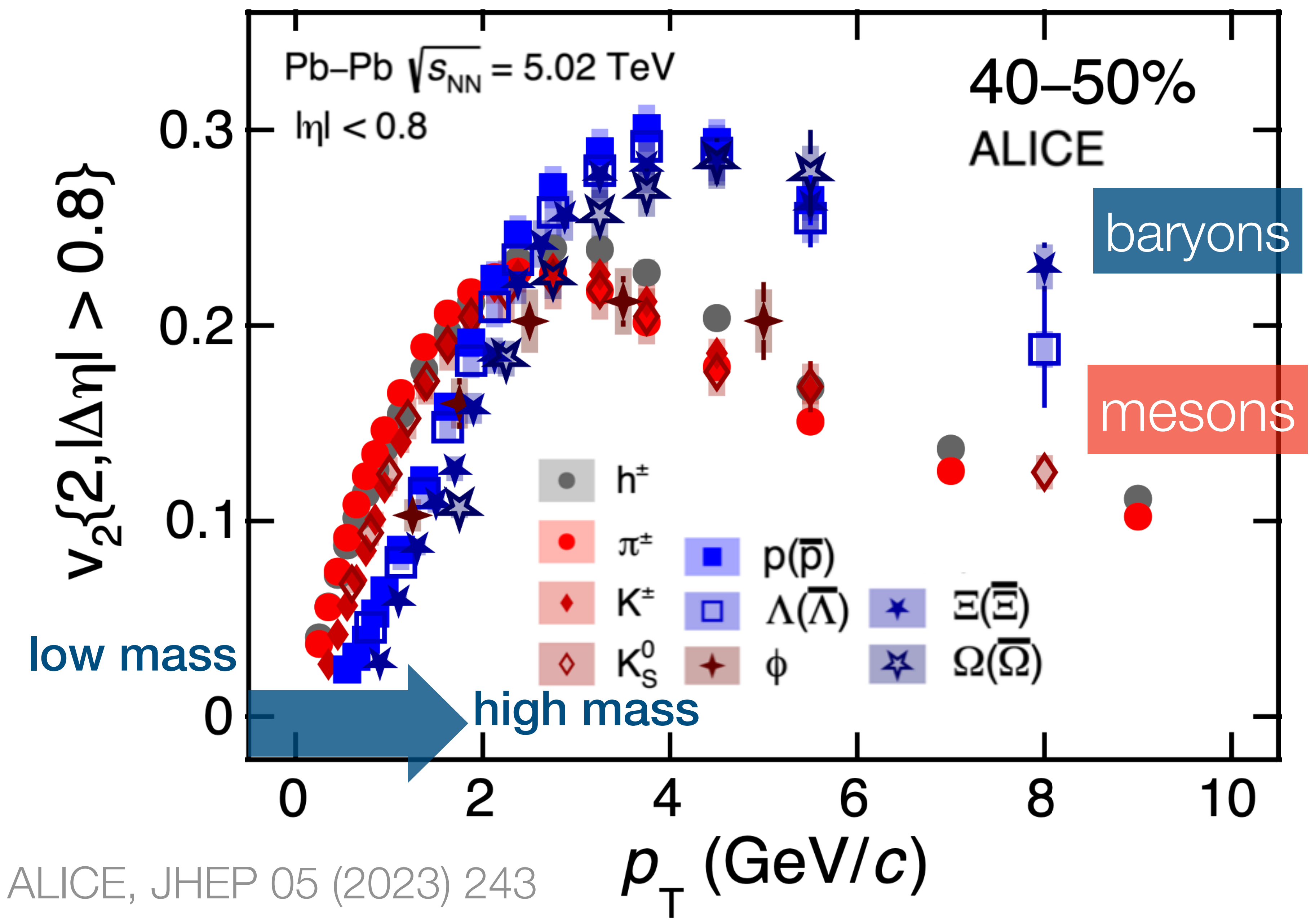
… should we expect to see any thermal radiation?

… should we expect to see any quarkonia dissociation?

Can we reach a unified picture of QCD collectivity across system size?

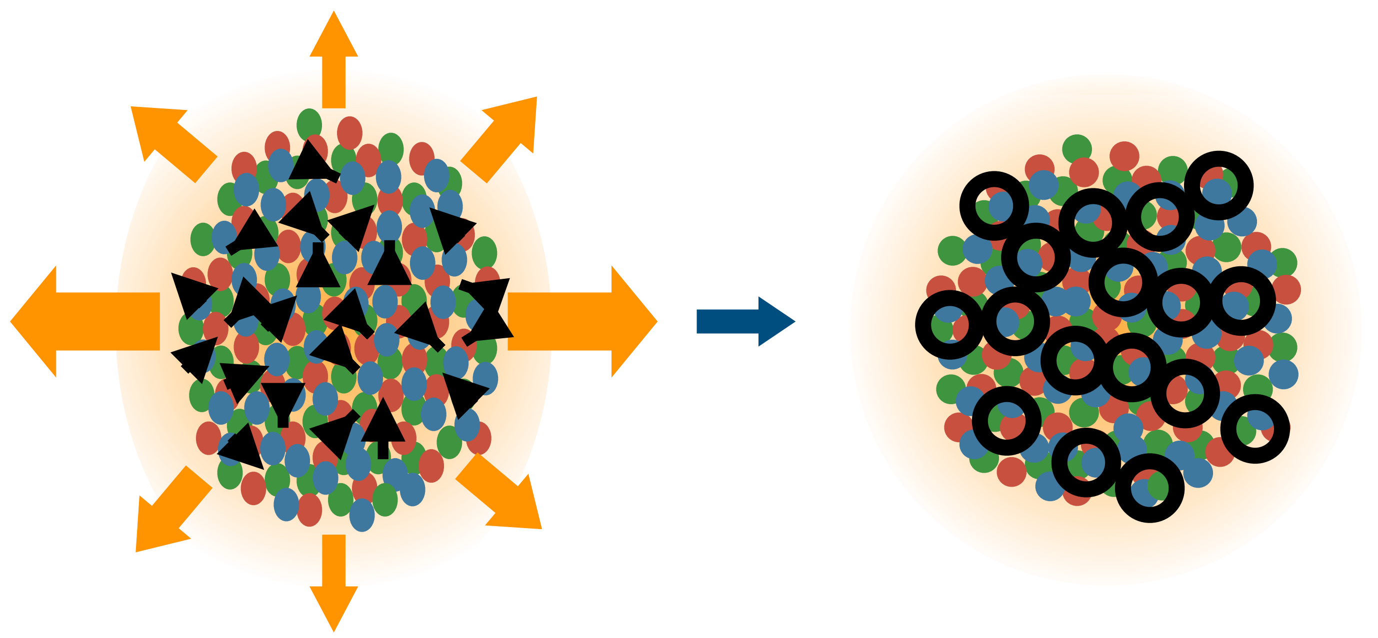
Backup

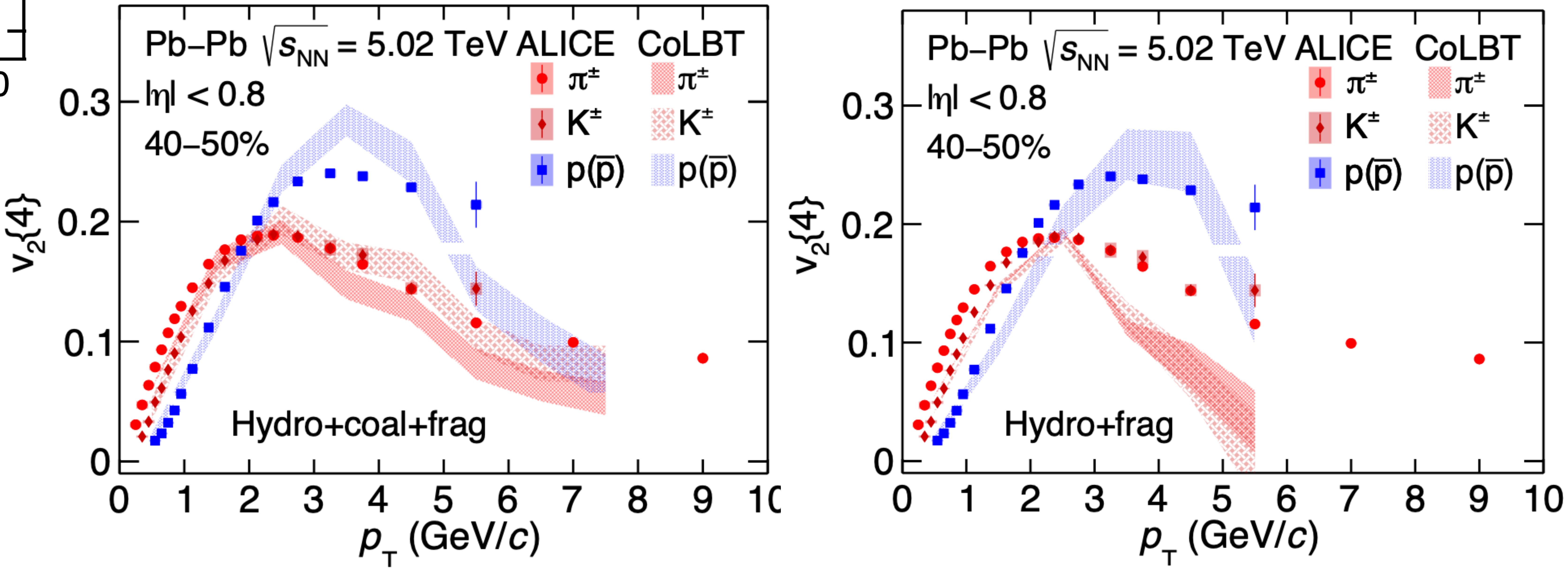
Mass dependence of momentum distributions



ALICE, JHEP 05 (2023) 243

- Anisotropic flow described by model that includes **hydrodynamics** + **coalescence** + fragmentation (at high p_T)
  - Low-p_T: interplay of radial and anisotropic expansion → **mass ordering**
  - Intermediate-p_T: coalescence → **particle-type grouping**





Anisotropic flow in small systems

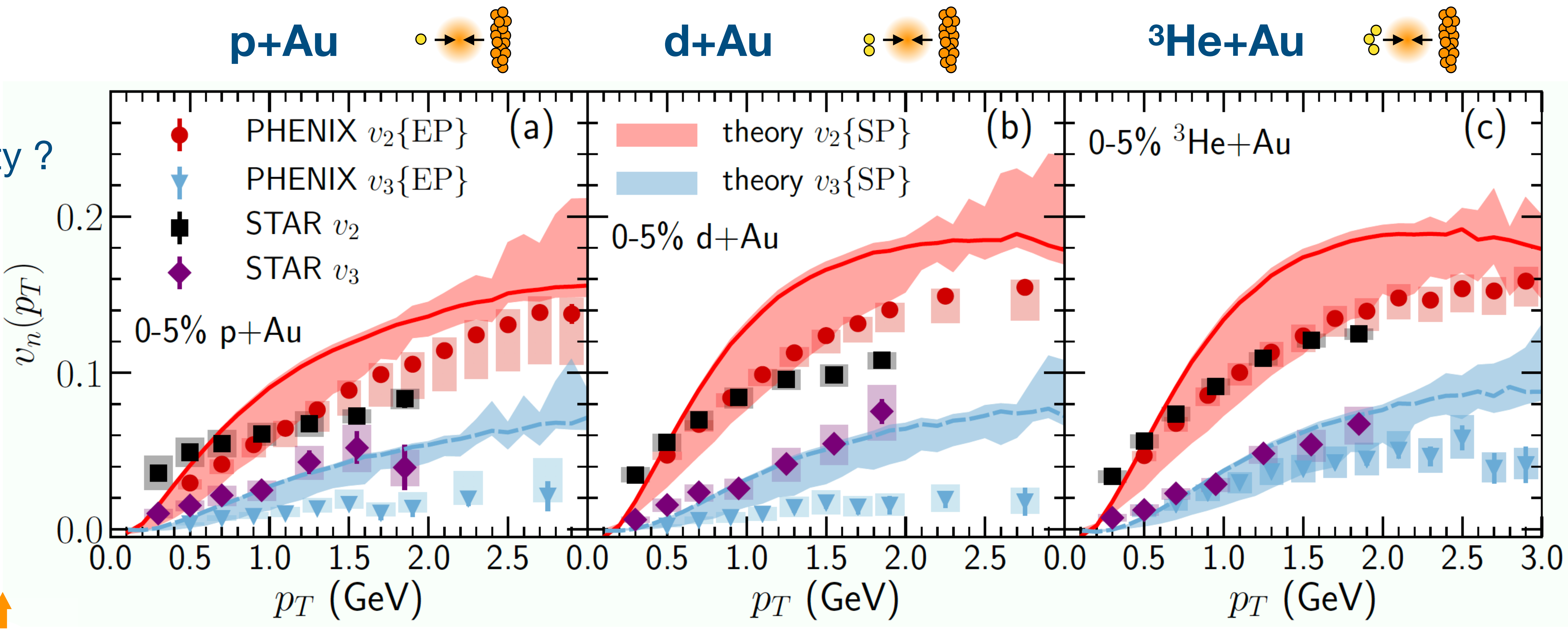
B. Schenke, Ch. Shen, P. Tribedy, PLB 803 (2020) 135322
B. Schenke, QM19

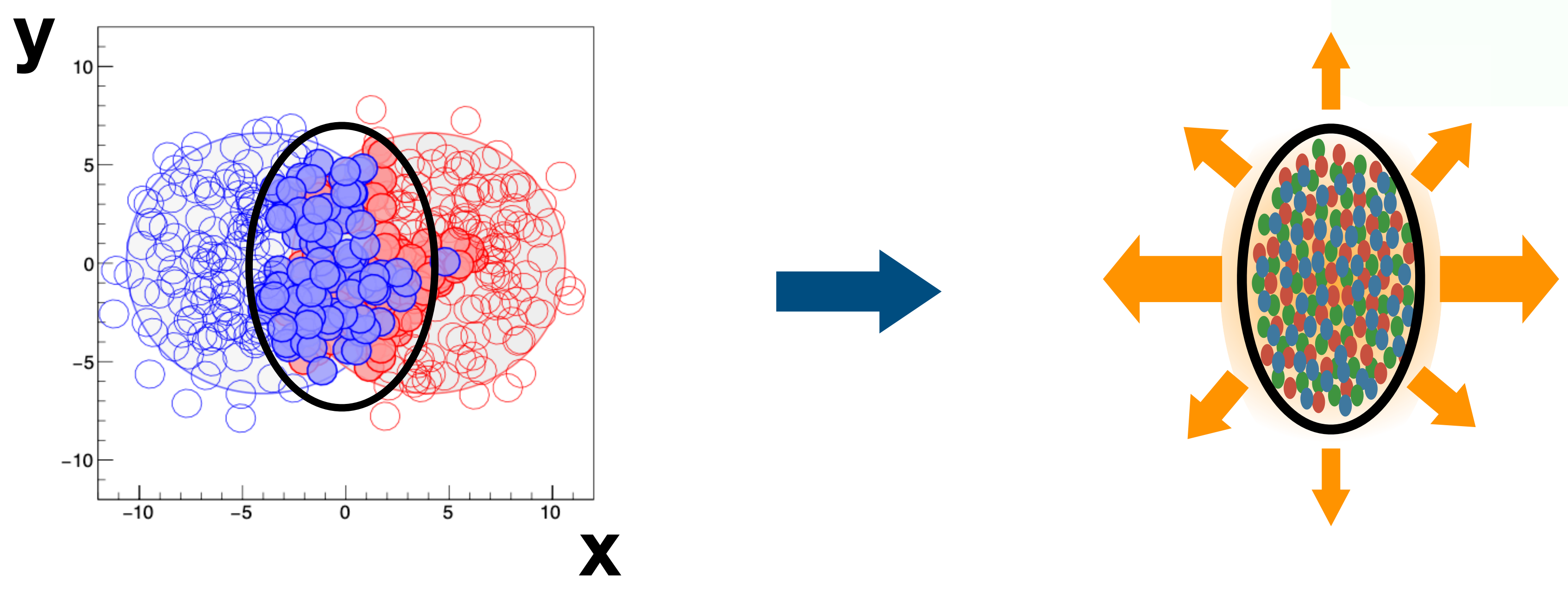
No sharp turn-off as a function of multiplicity

We do not “switch-off” collectivity ?

Response to initial geometry

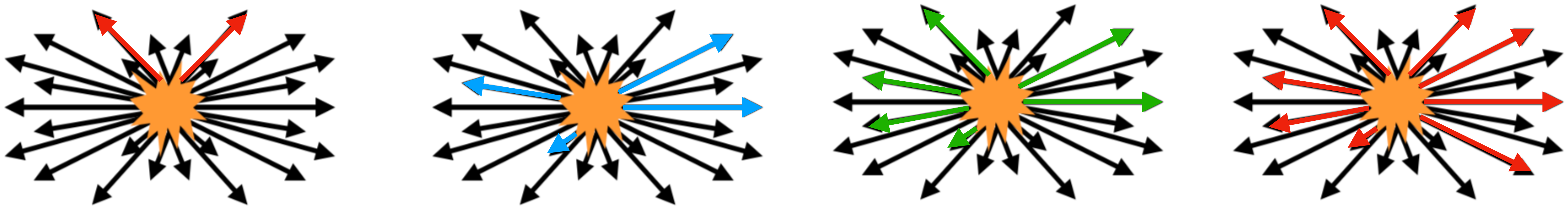
Subnucleon fluctuations important in small systems



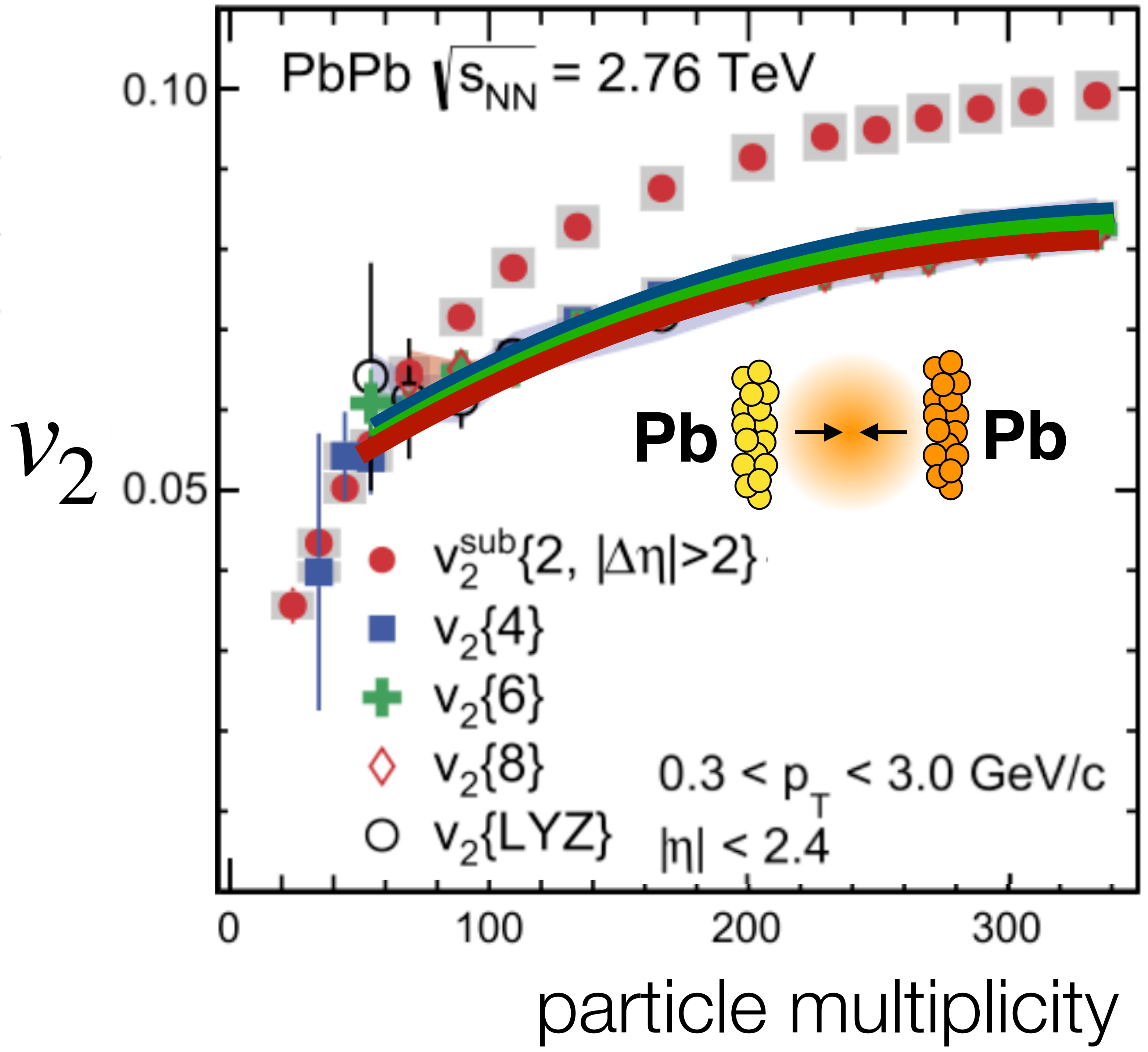


Anisotropic flow in heavy-ion collisions

number of particles used to quantify v_n:



CMS, PLB 765 (2017) 193



$v_2\{2\}$

various processes can give two-particle correlation signal

we focus on multiparticle correlations

$v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

No matter how many particles we use, they will show the same signal

genuine collectivity

Collectivity observed across systems

ATLAS, PRC 97, 024904 (2018)
ALICE, PRL 123, 142301 (2019)

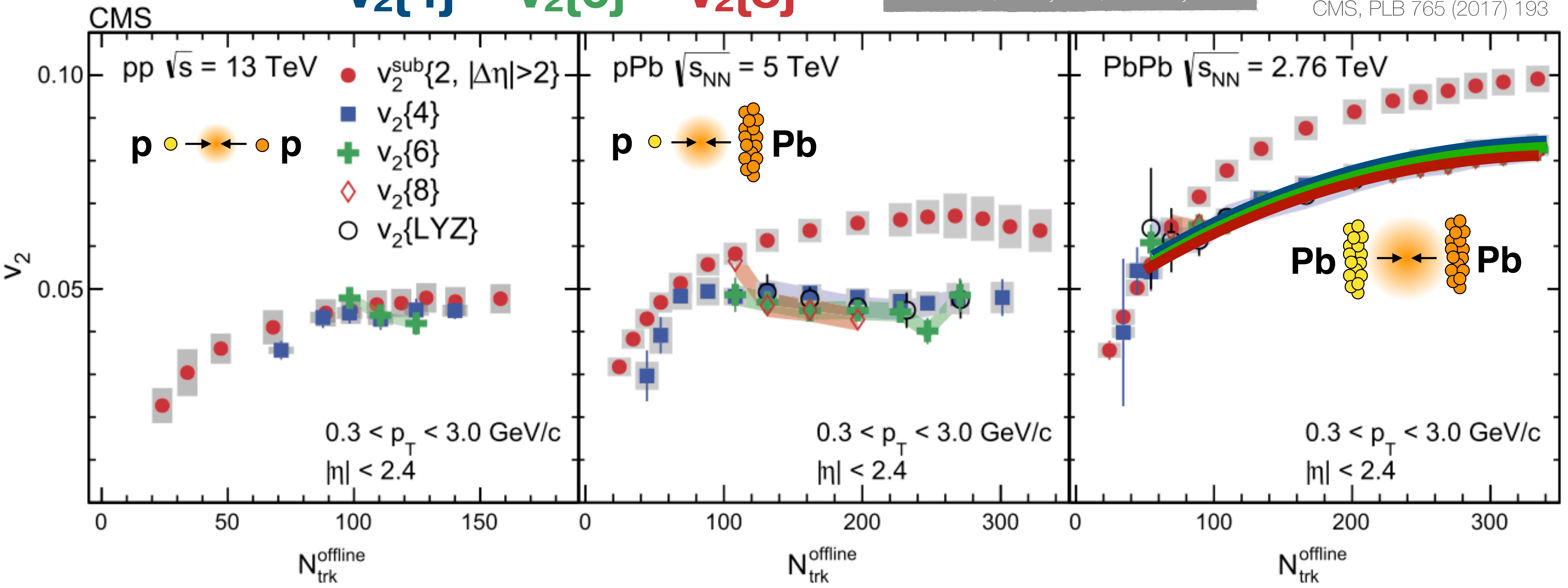
$v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

B. Seidlitz, Heavy Ions, Thursday 14:40

CMS, PLB 765 (2017) 193

Small systems exhibit collective behavior

What is the origin of collectivity?



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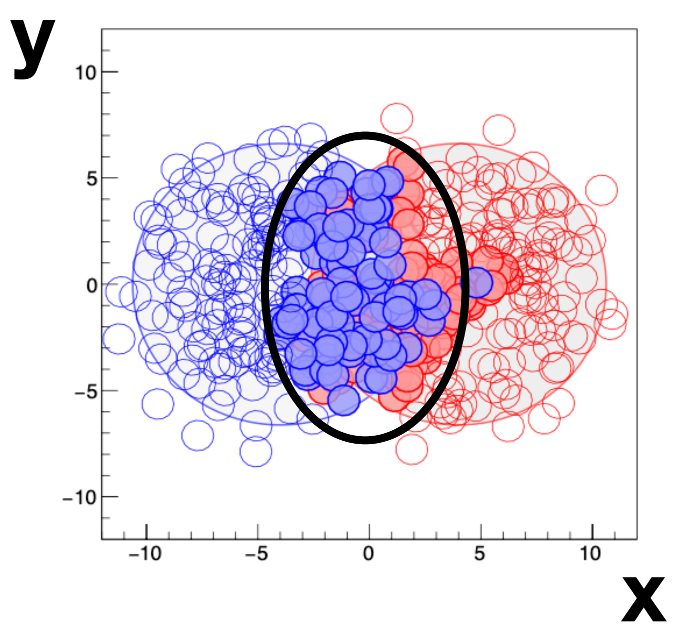
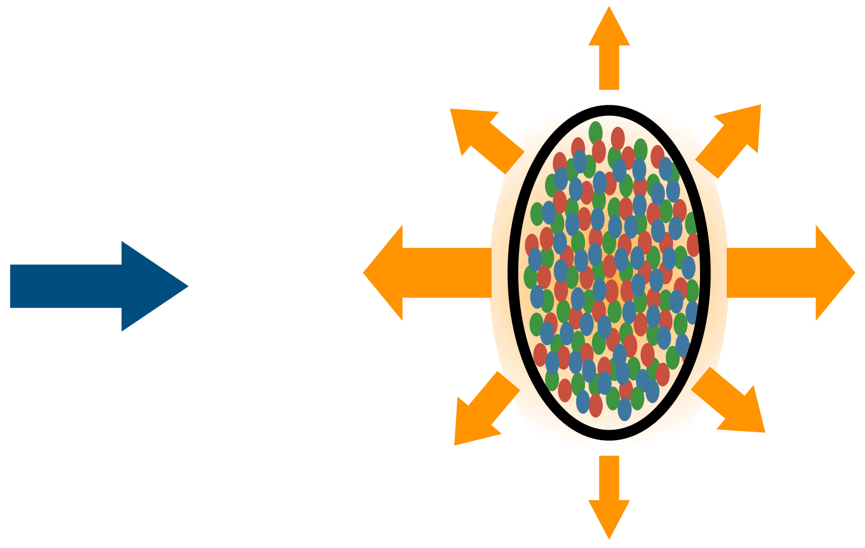
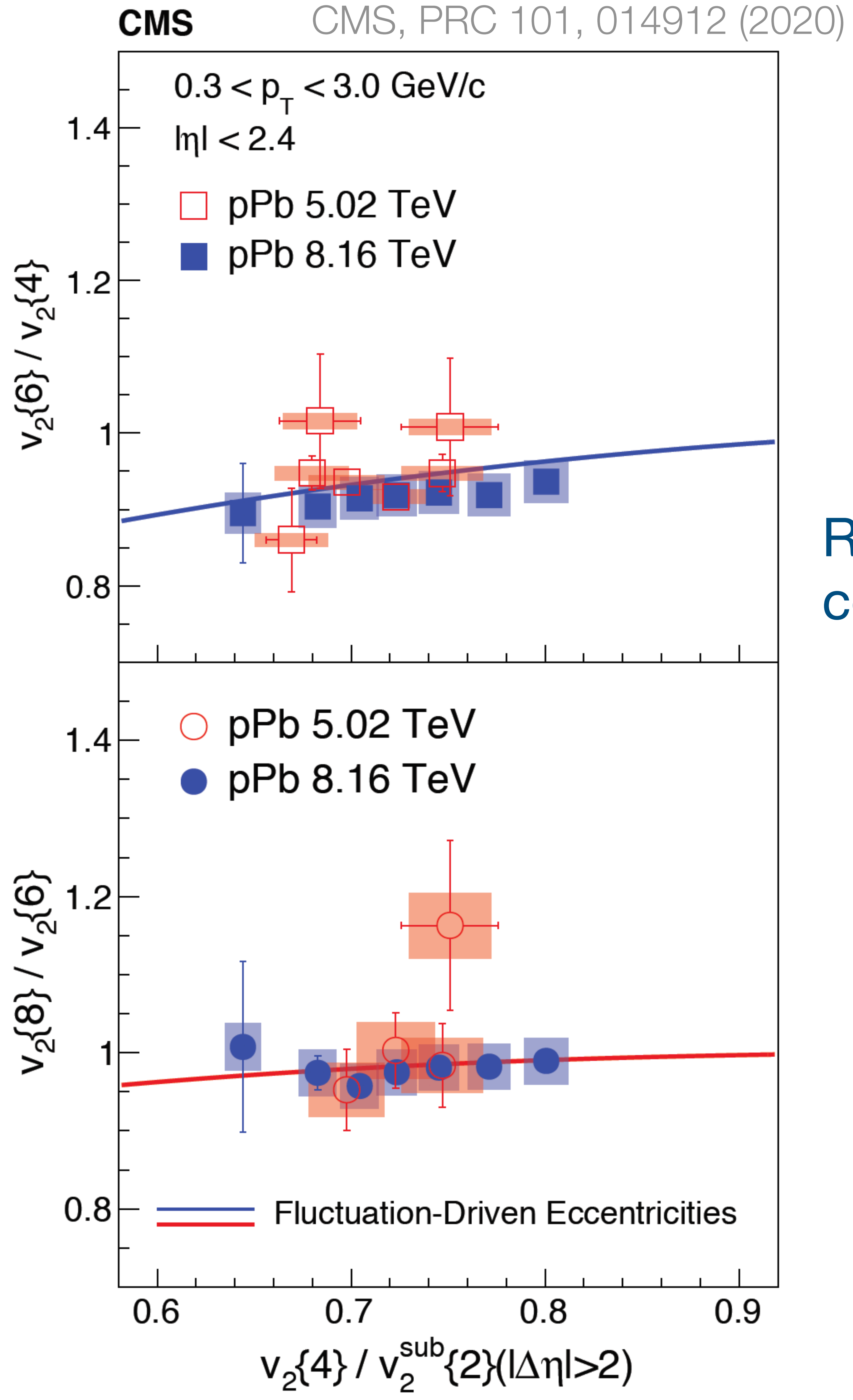


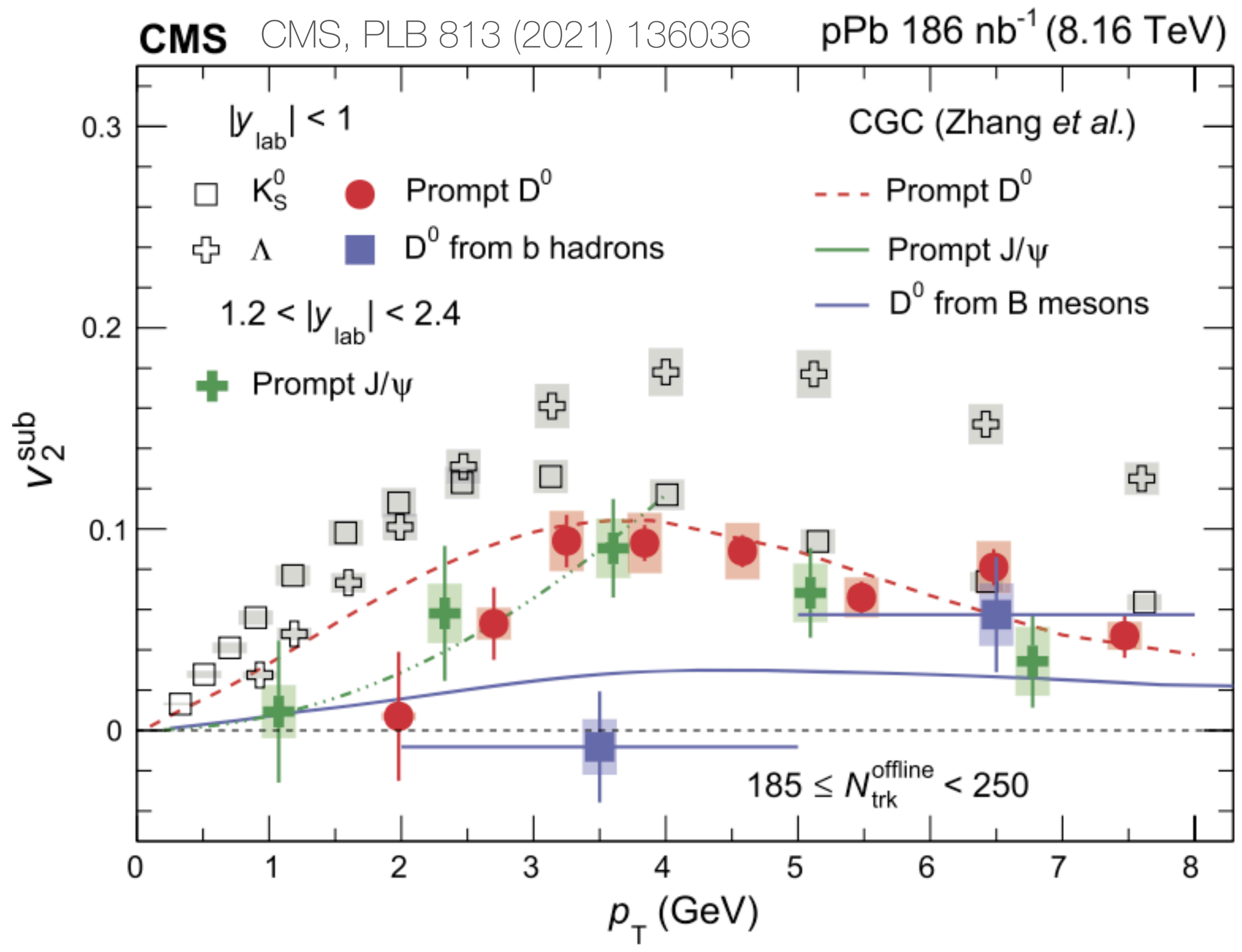


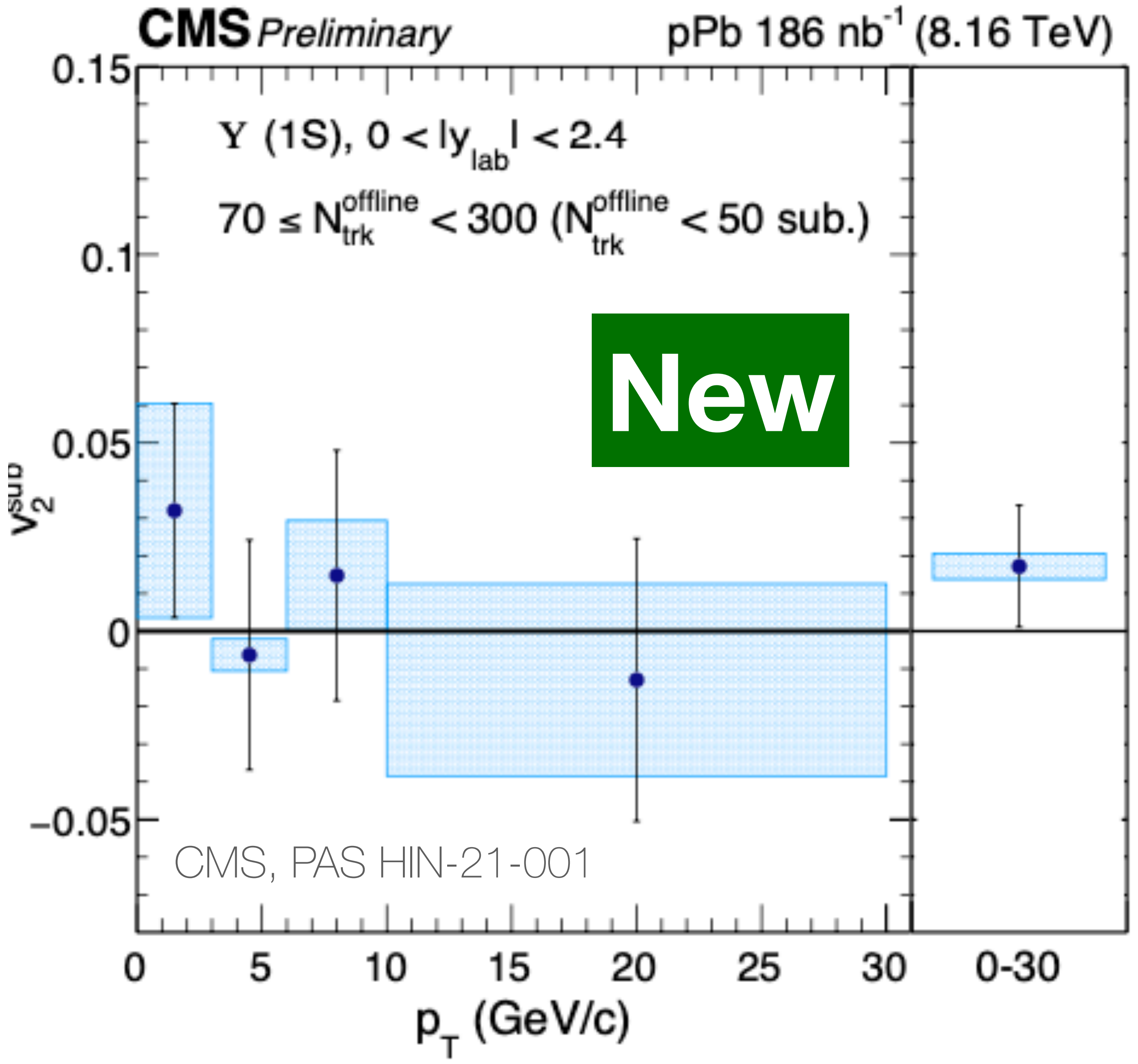


Ratios of multi-particle cumulants consistent with geometry-driven assumption

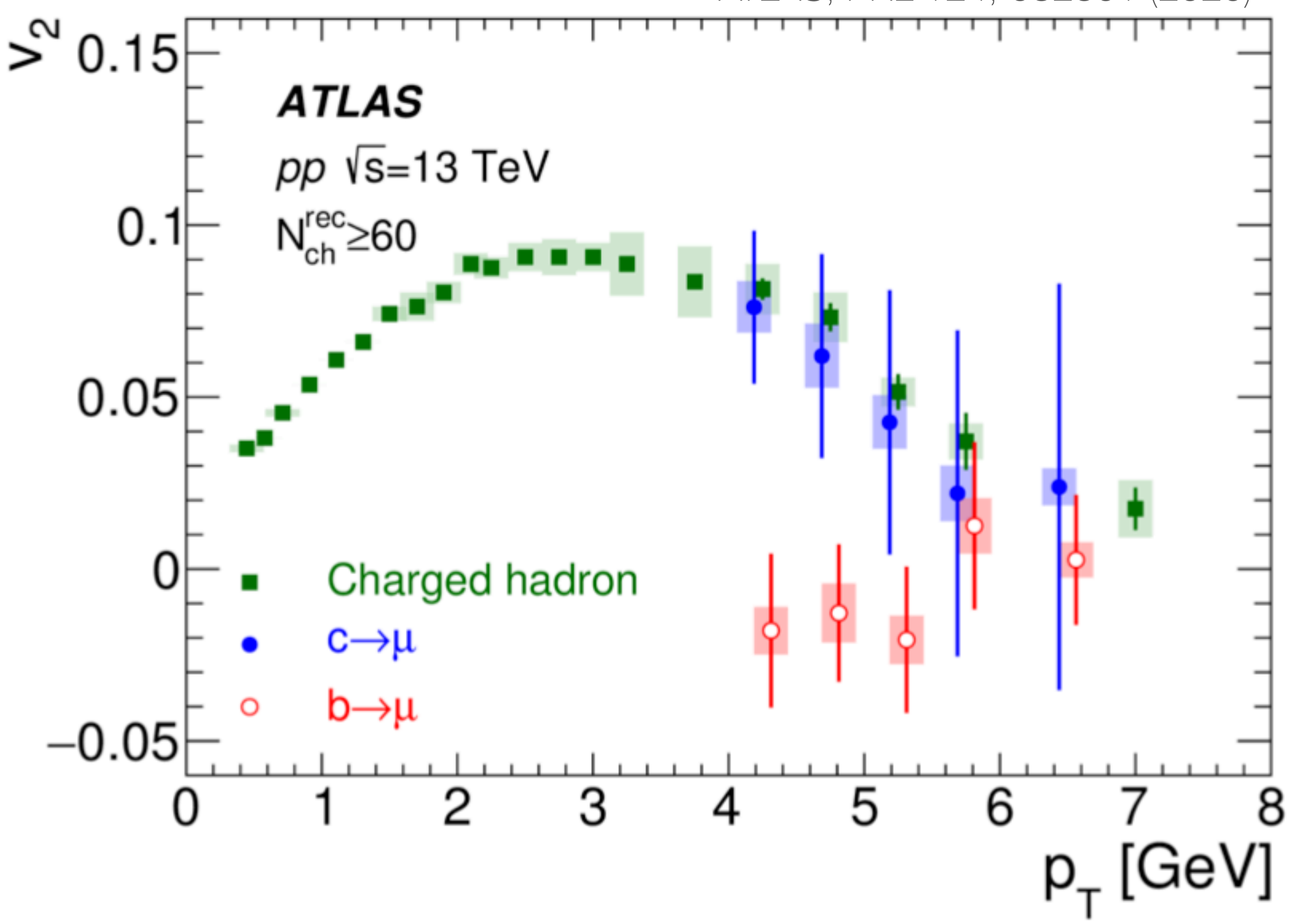
Do heavy quarks flow in small systems?

$v_2(D^0)$ $v_2(J/\Psi)$ p → ← Pb $v_2(\Upsilon)$



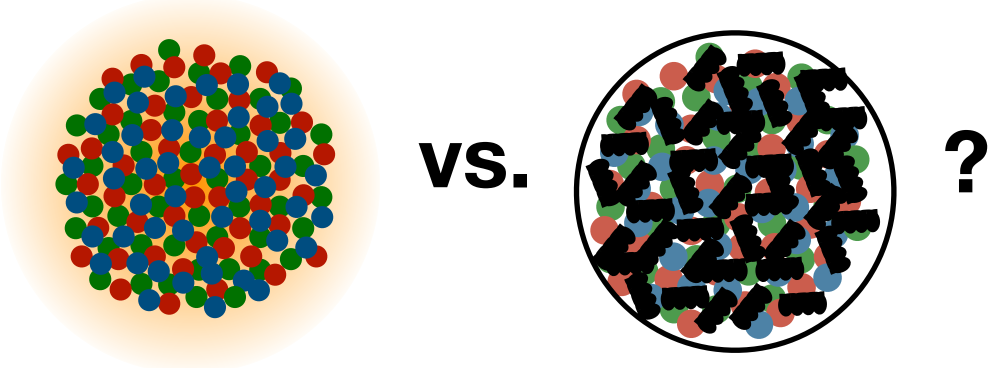


p → ← p $v_2(c)$ $v_2(b)$

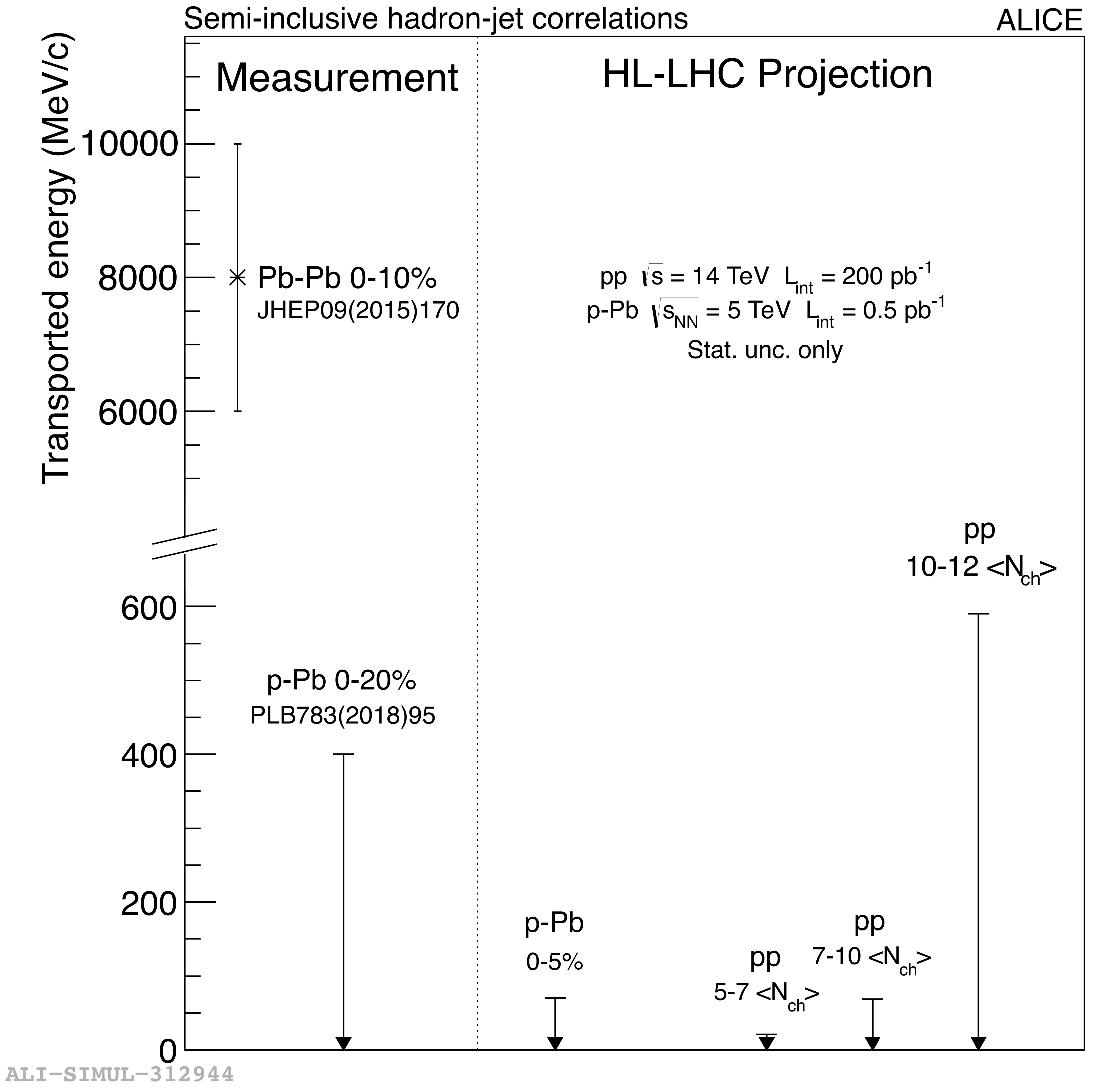


Quantitative description of charm flow with the **initial state model** (though charm and bottom flow predicted to be the same)

Zhang et al., PRD 102, 034010 (2020)



Parton energy loss in p-Pb collisions?



- If there is parton energy loss in small systems, **how big should we expect the signal**?
- Are there other observables with good enough precision to reveal a small signal of parton energy loss?
- **Limits for pp collisions could be set in Run 3**

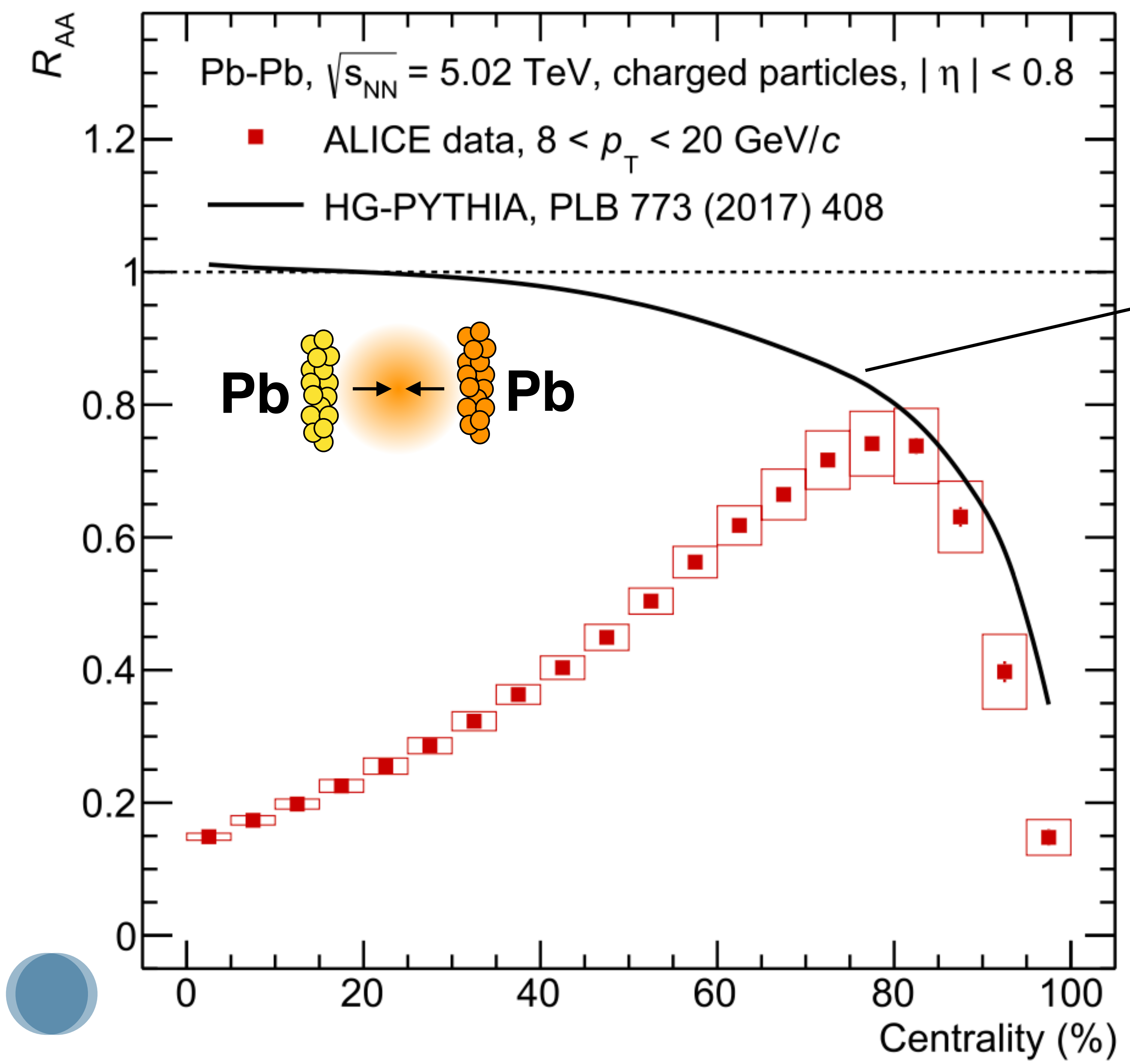
ALICE, JHEP 09 (2015) 170 ALICE, PLB 783 (2018) 95 ALICE-PUBLIC-2019-001

Parton energy loss in peripheral Pb-Pb

$R_{AA} < 1$ observed all the way to the most peripheral Pb-Pb collisions

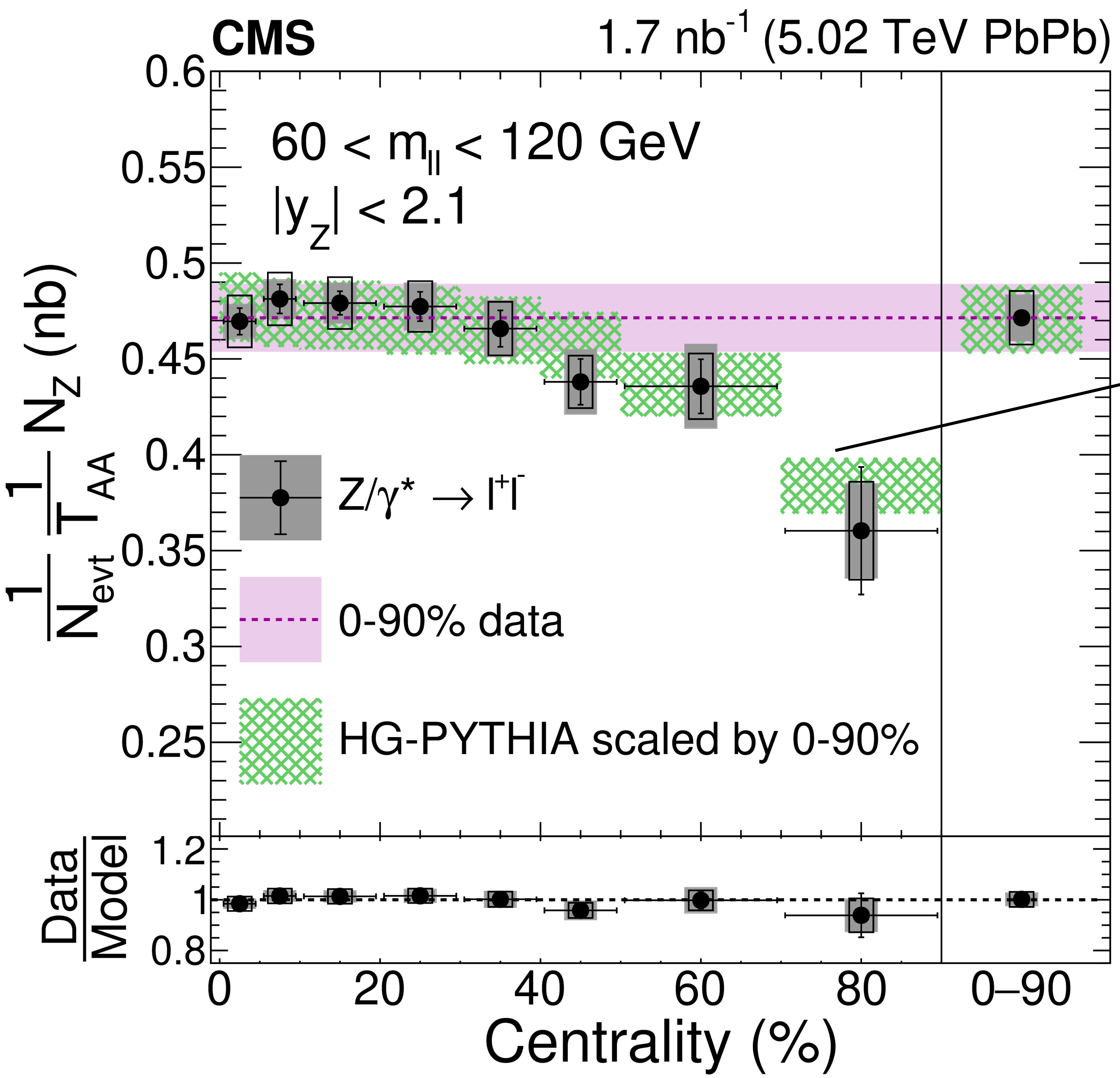
→ Explained by increasing importance of geometry of the overlapping nucleon-nucleon collisions

ALICE, PLB 793 (2019) 420



model without nuclear modification

CMS, PRL 127 (2021) 102002



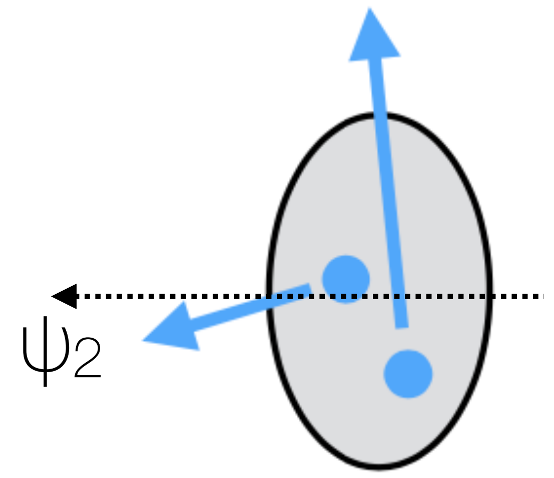
model without nuclear modification

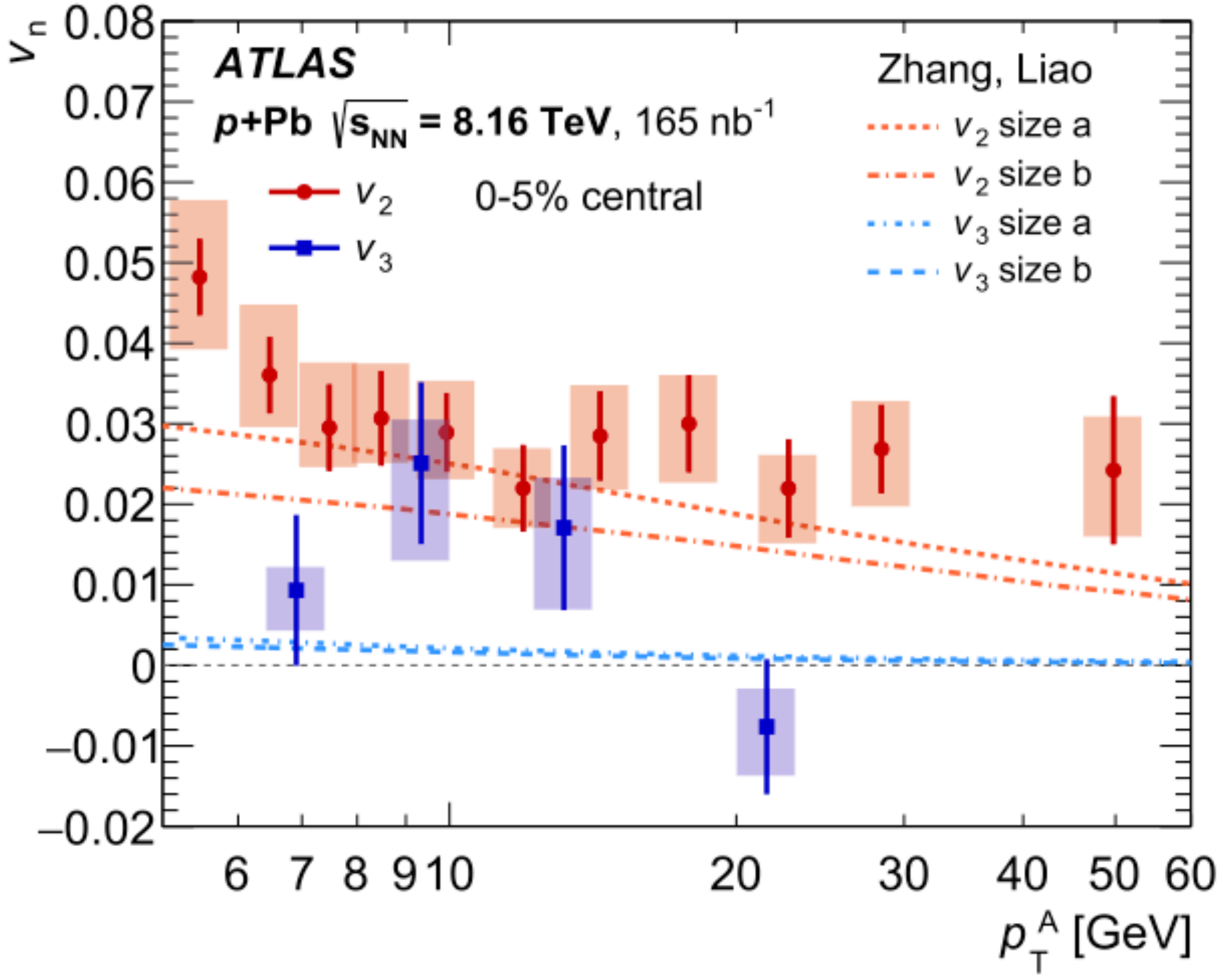
Y. Mao, Heavy Ions, Tuesday 14:42

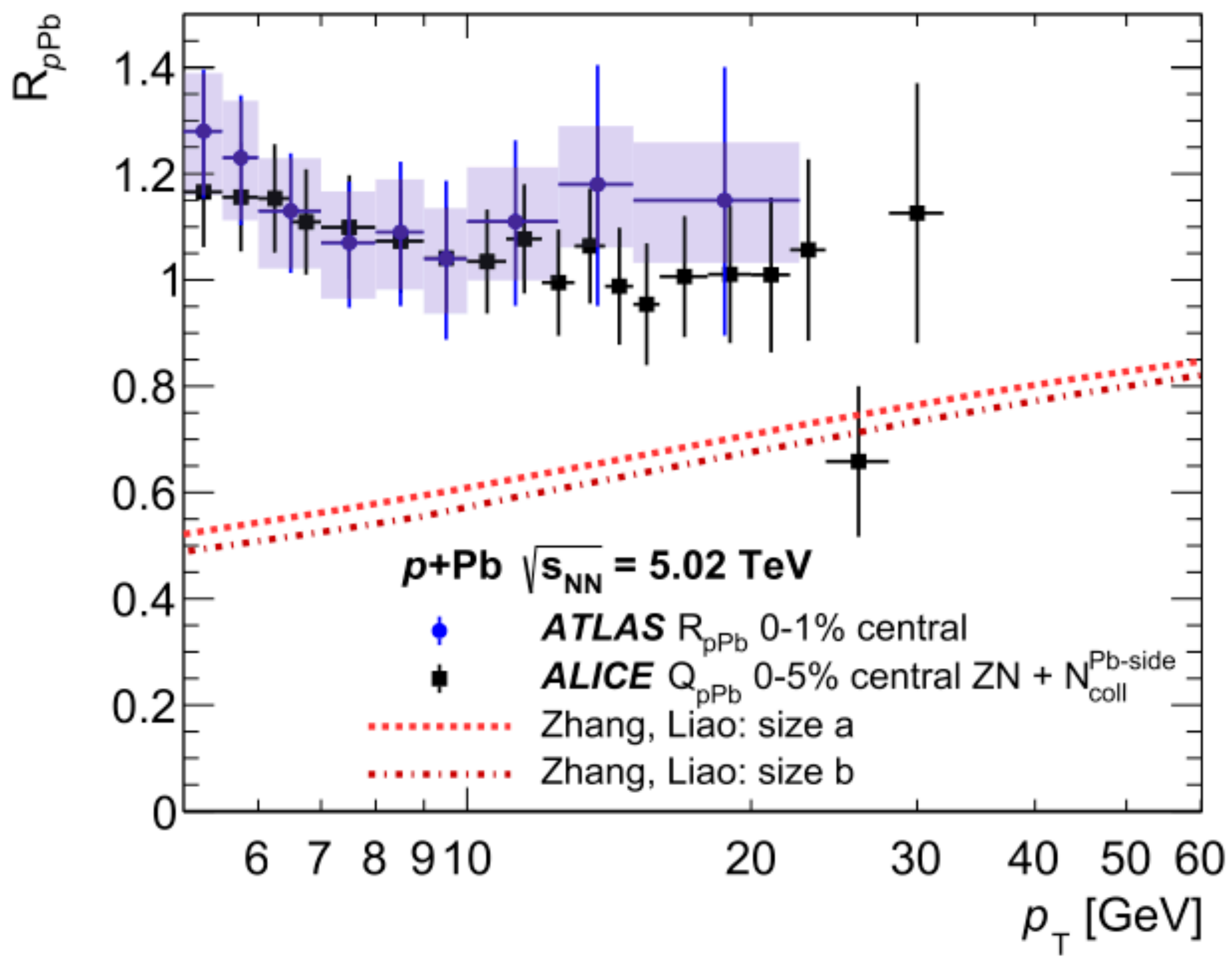
Other way to address parton energy loss

ATLAS, EPJC (2020) 80:73

Non-zero flow at high p_T understood as a consequence of path length dependence of energy loss







Experiment: no suppression in R_{AA}, but finite flow at high p_T

Theory: this magnitude of flow at high p_T should come with a significant jet quenching

EXPERIMENT	THEORY
$v_2(p_T) > 0$	$v_2(p_T) > 0$
$R_{pPb} \approx 1$	$R_{pPb} < 1$

IS effects may be important for flow

Final state effects	Flow = initial geometry + final state interactions
Initial state effects	Flow = initial (gluon) momentum correlations

$$Q(\epsilon_2, V_2) = \frac{Re\langle \vec{\epsilon_2} \cdot \vec{V_2^*} \rangle}{\sqrt{\langle |\vec{\epsilon_2}|^2 \rangle \langle |\vec{V_2}|^2 \rangle}}$$

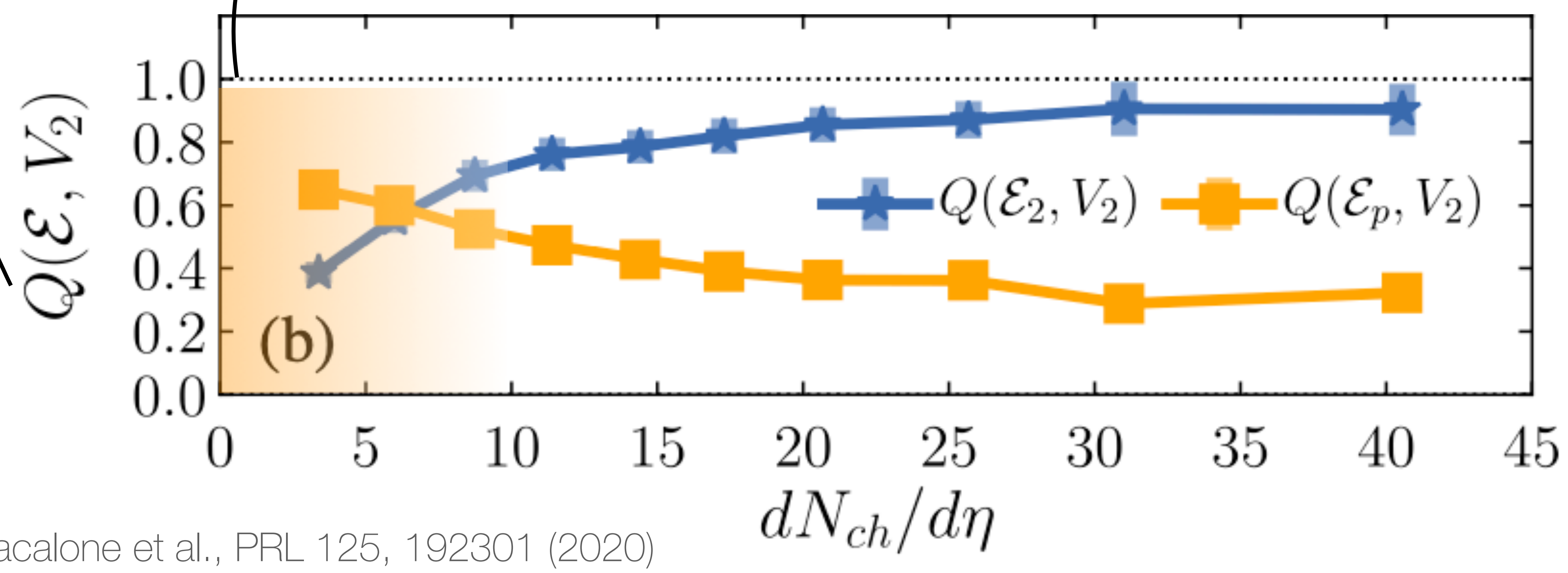
correlation of flow with initial spatial anisotropy

$$Q(\epsilon_p, V_2) = \frac{Re\langle \vec{\epsilon_p} \cdot \vec{V_2^*} \rangle}{\sqrt{\langle |\vec{\epsilon_p}|^2 \rangle \langle |\vec{V_2}|^2 \rangle}}$$

correlation of flow with initial momentum anisotropy

Pearson correlation coefficients

Q = 1 ➡ full correlation



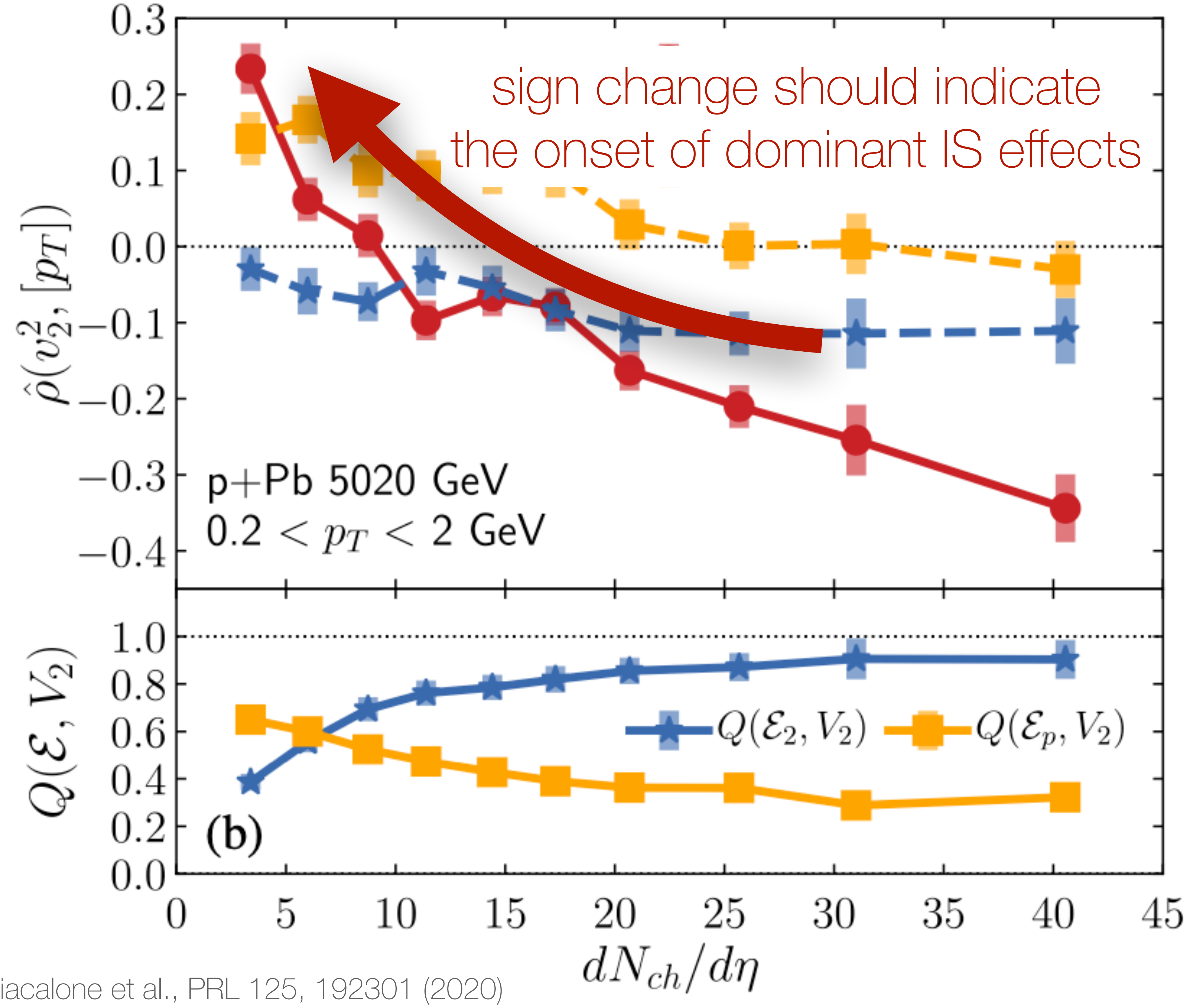
Giacalone et al., PRL 125, 192301 (2020)

Effects of the initial state may become significant below some multiplicity region

Inconclusive results ?

Correlation between flow and mean-p_T

$$\rho(v_2^2, [p_T]) = \frac{\mathrm{Cov}(v_2^2, [p_T])}{\sqrt{\mathrm{Var}(v_2^2)}\sqrt{\mathrm{Var}([p_T])}}$$

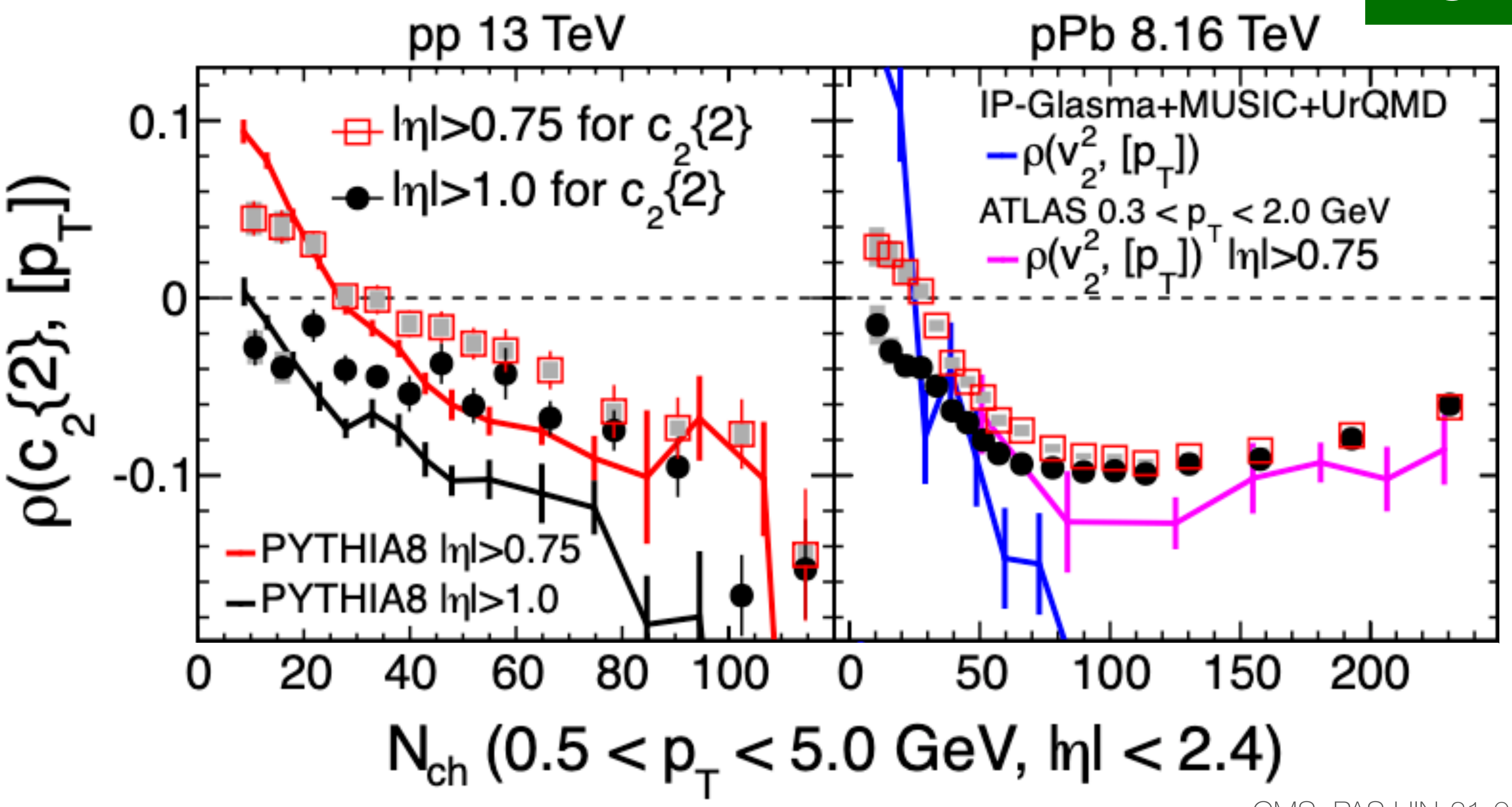


Giacalone et al., PRL 125, 192301 (2020)

Sign change dissapears when large rapidity gap between correlated particles is used to suppress contamination

Caveat: the rapidity separation may also remove the desired effects of the initial state

New



CMS, PAS HIN-21-012