Signatures of collectivity in small systems

Wei Li (Rice University)

Initial Stages, May 23, 2016

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What is collectivity?

a group of entities that share a common property

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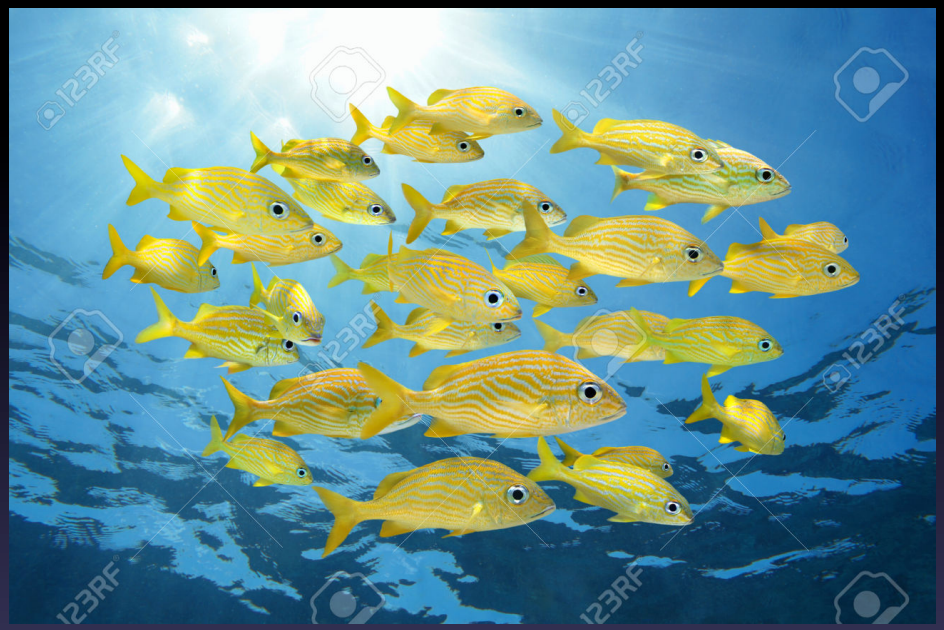

Collectivity ⟷ Emergent phenomena of a many-body **interacting** system

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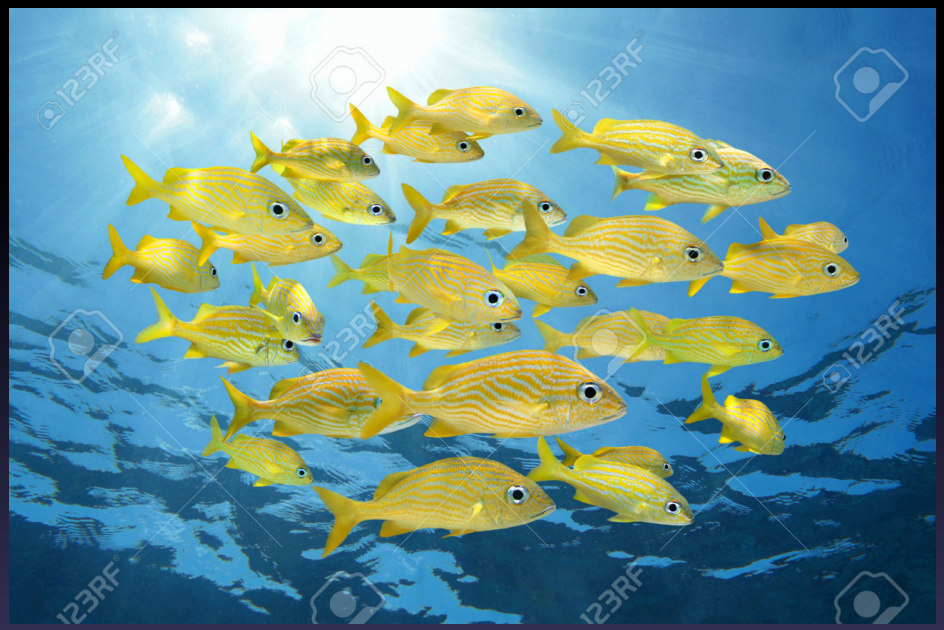
a group of entities that share a common property

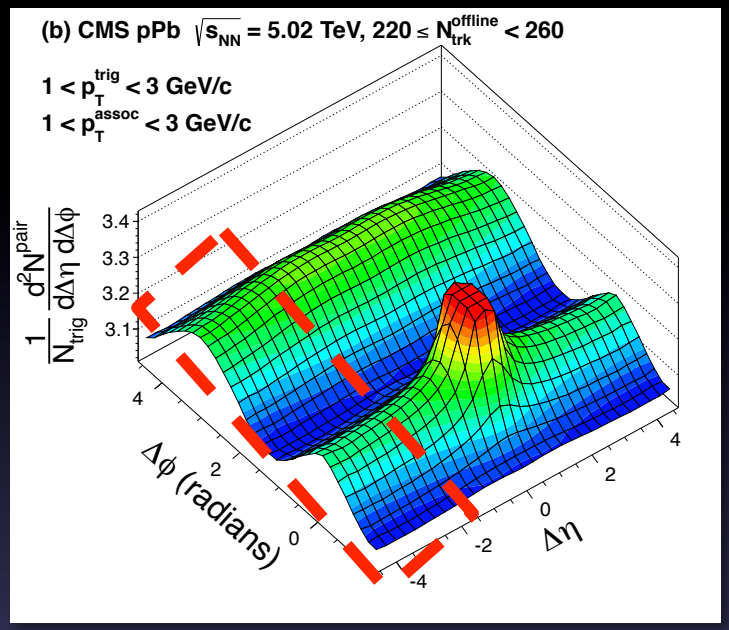


Collectivity ⟷ Emergent phenomena of a many-body **interacting** system

What is the **mechanism** driving the collectivity?

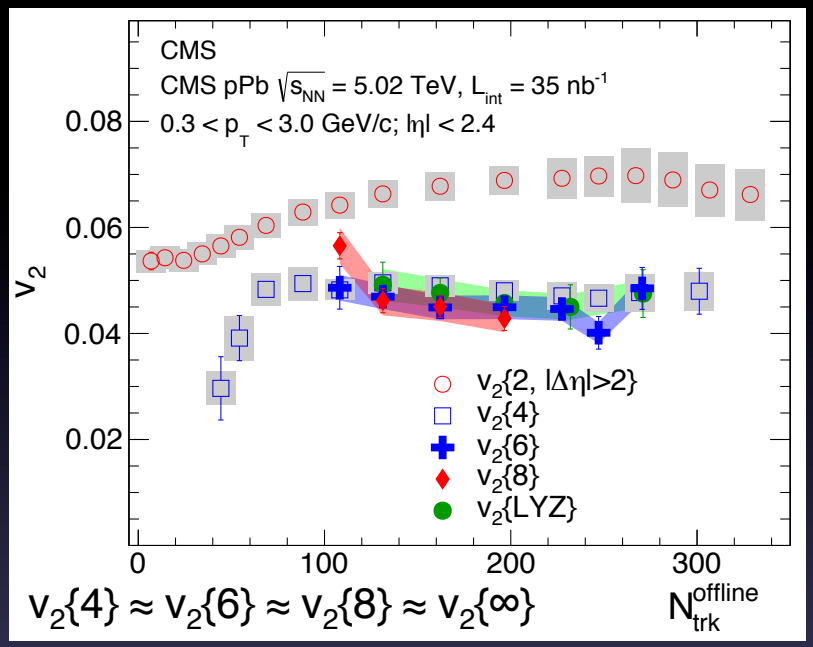
Emergent phenomena in pA and AA

Long-range



PLB 724 (2013) 213

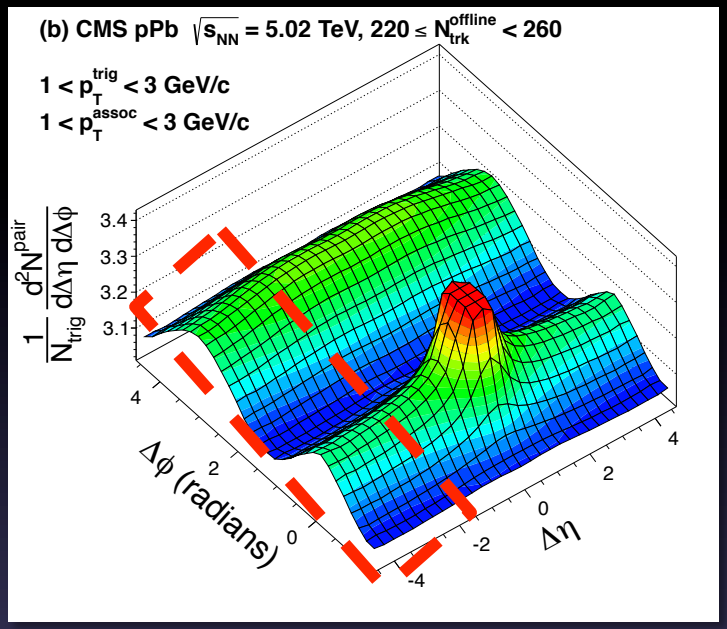
Collective



PRL 115 (2015) 012301

Emergent phenomena in pA and AA

Long-range ➡ *Initial stage* *Collective*



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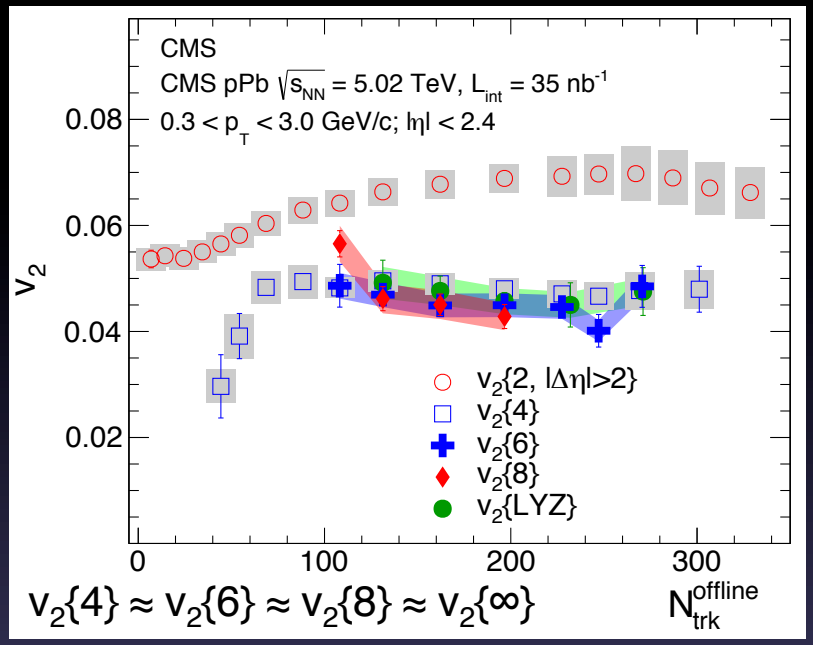

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Emergent phenomena in pA and AA

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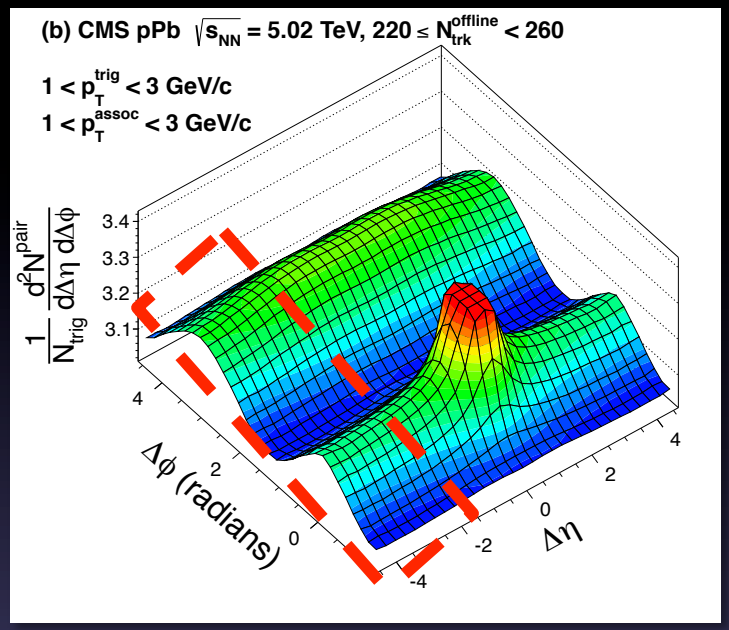

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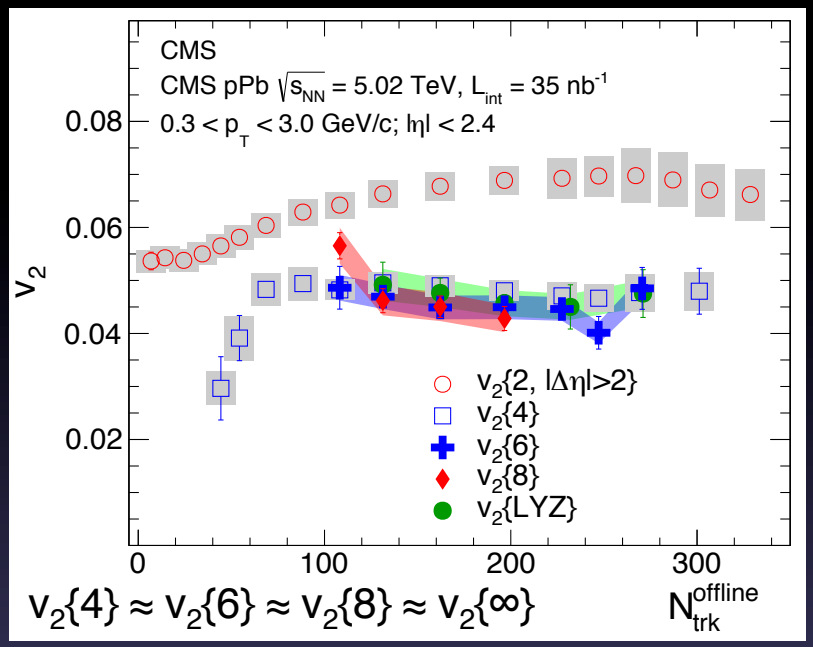
Collective ➡ *Interactions*



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Emergent phenomena in pA and AA

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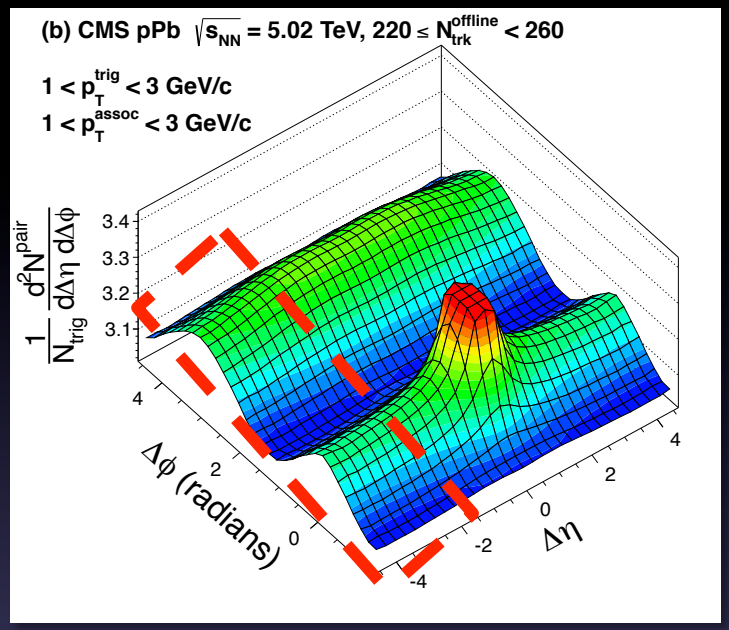

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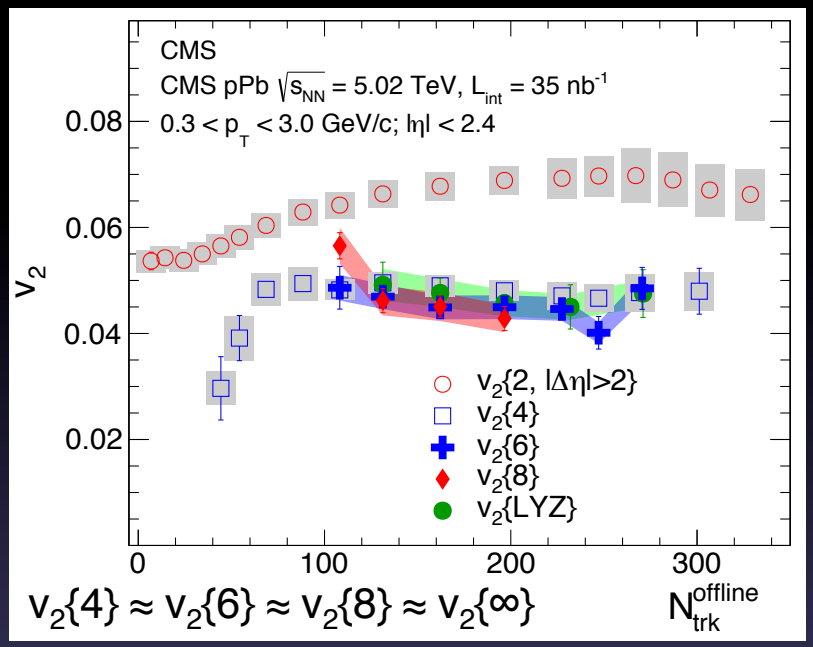

PRL 115 (2015) 012301

Two scenarios

Initial spatial ε_s
+ final interactions
(hydro., transport)

v.s.

Initial momentum ε_p
from initial interactions
(CGC glasma, etc.)

“Perfect” fluid paradigm in AA systems

Long-range collectivity in AA (large)

✧ Described by nearly ideal ($\eta/s \rightarrow 0$) hydrodynamics

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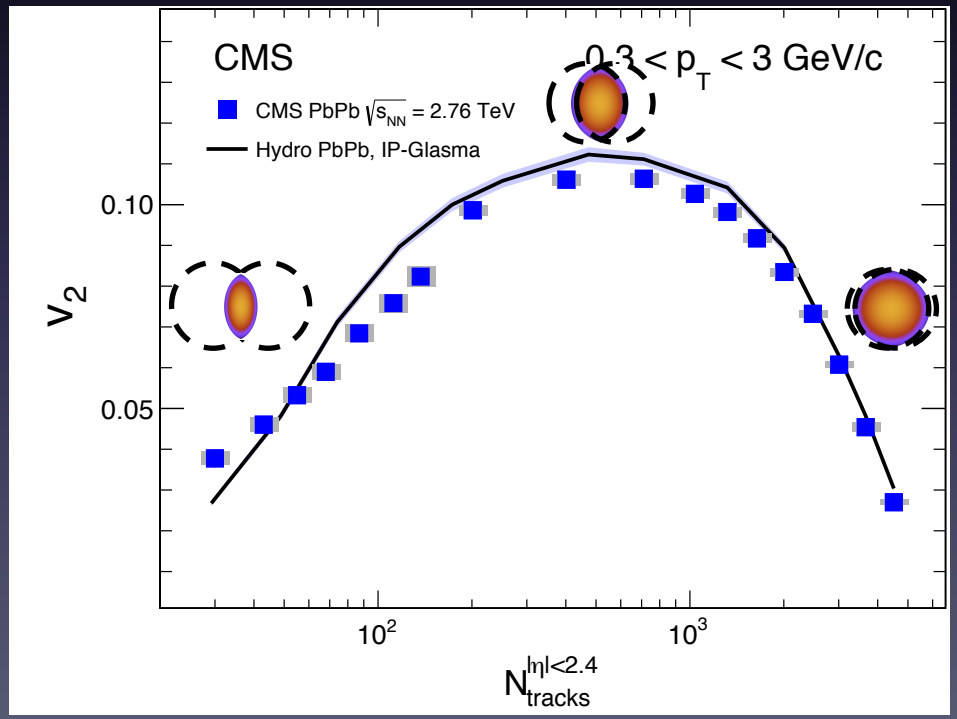

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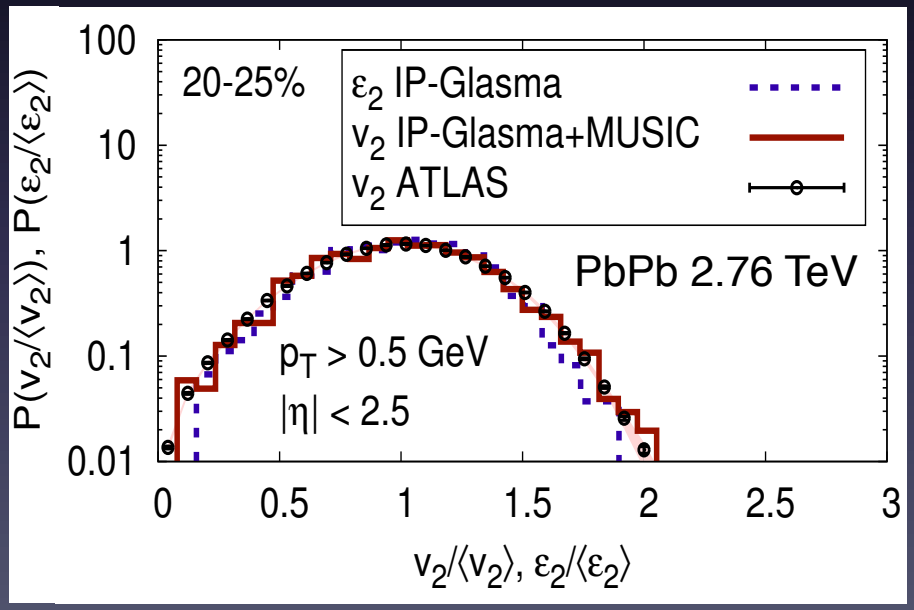

on event-by-event basis!

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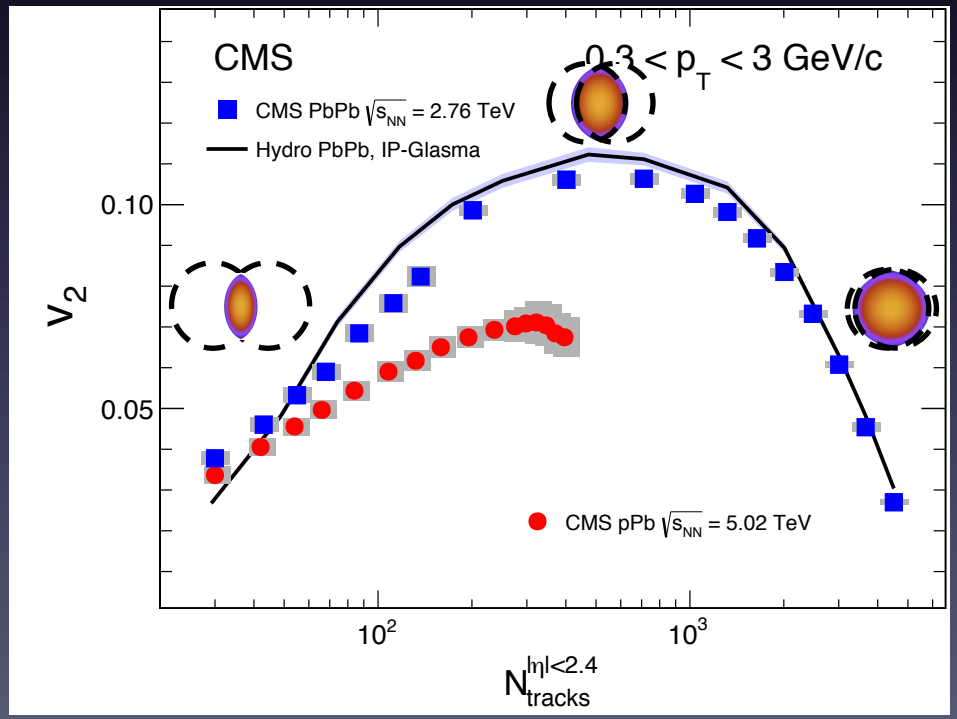

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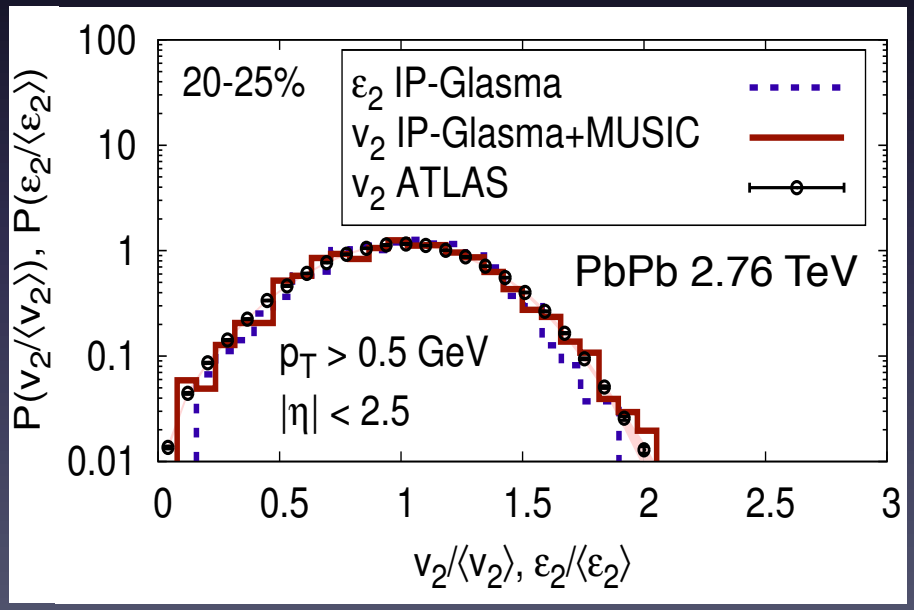
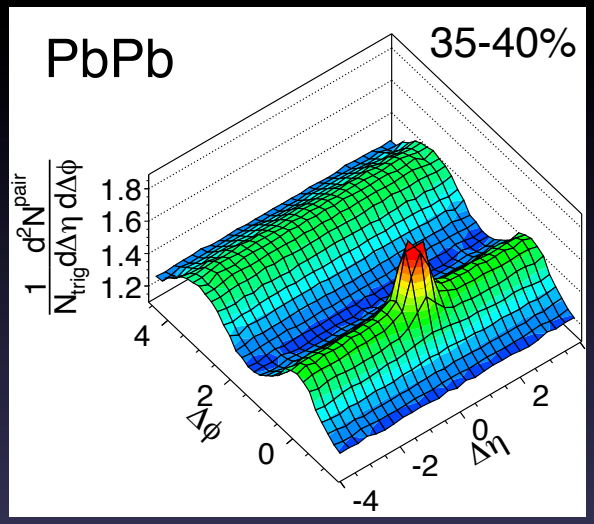
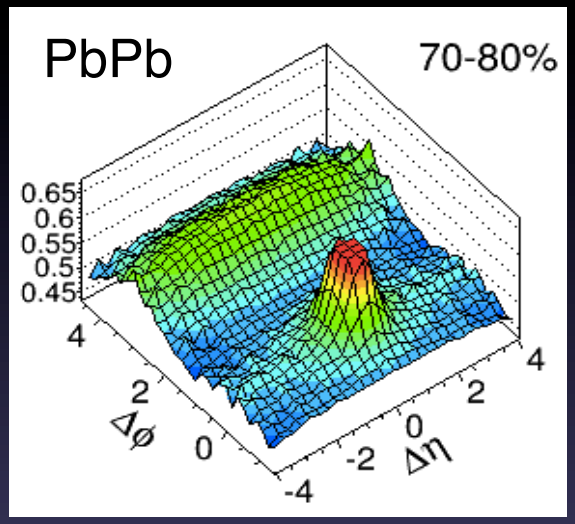


on event-by-event basis!

Collectivity diminishing as *L* decreases





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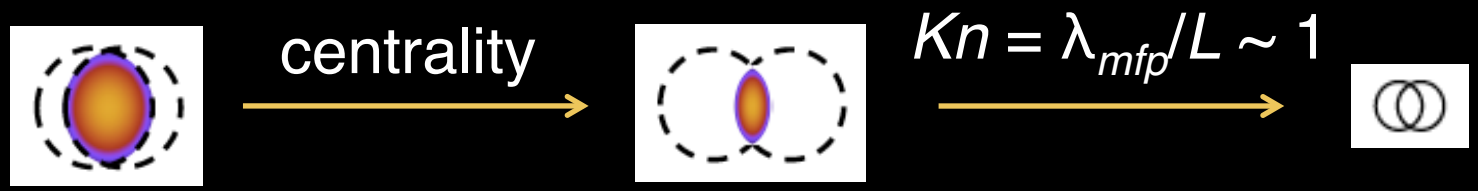

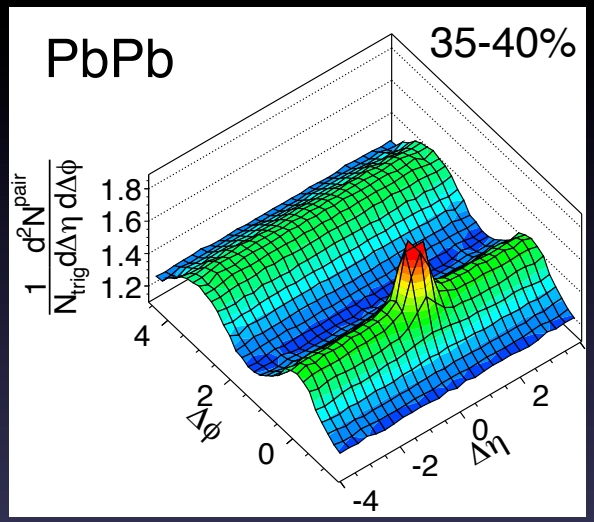

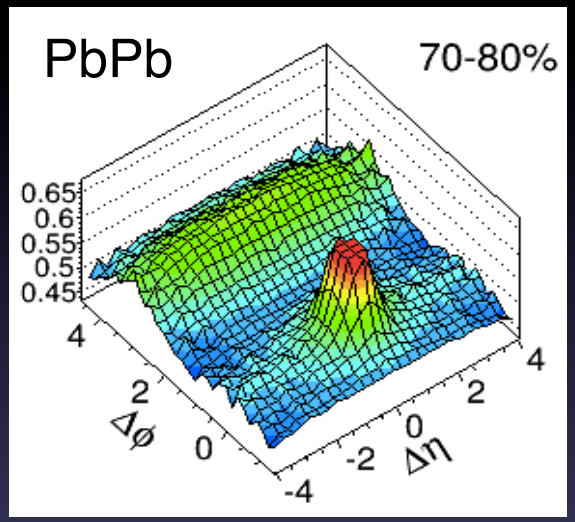

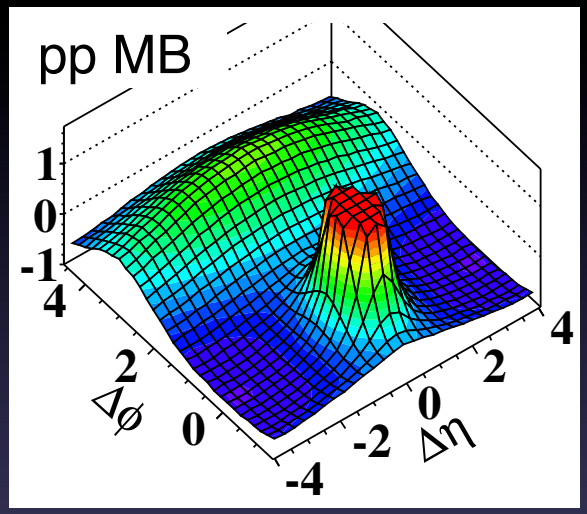

No QGP fluid expected in “small” systems (pp, pA)!

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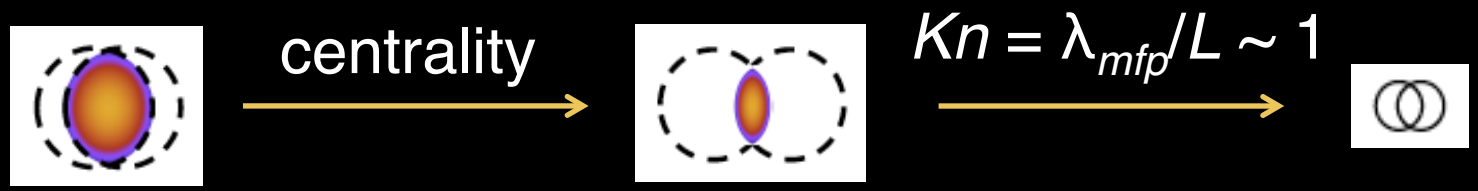

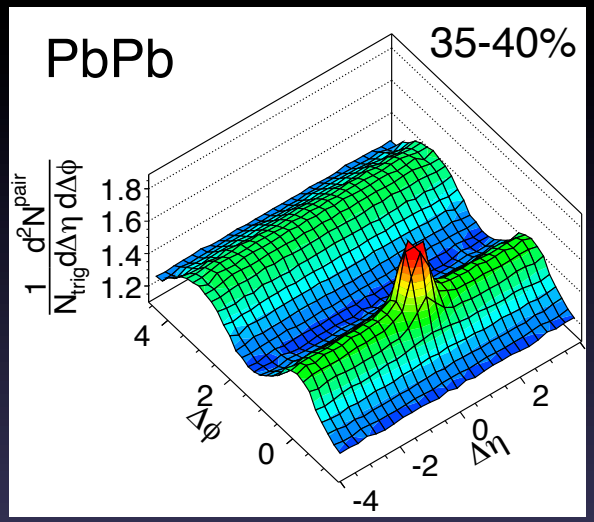

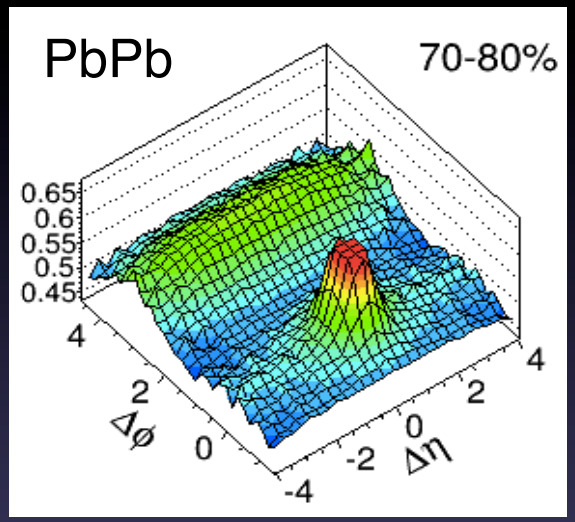

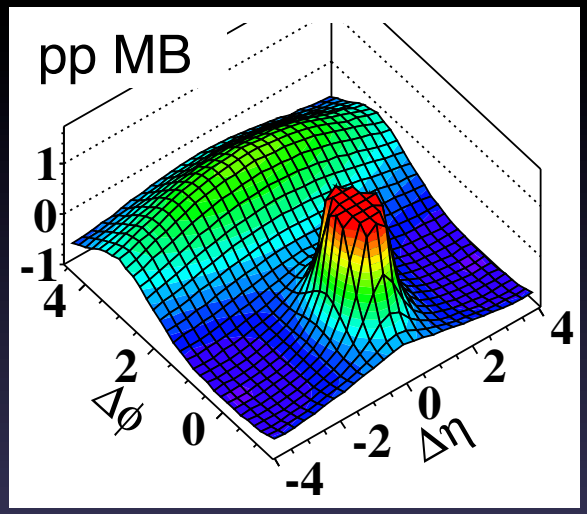

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But what if making it denser (reducing $\boldsymbol{\lambda_{mfp}}$)?

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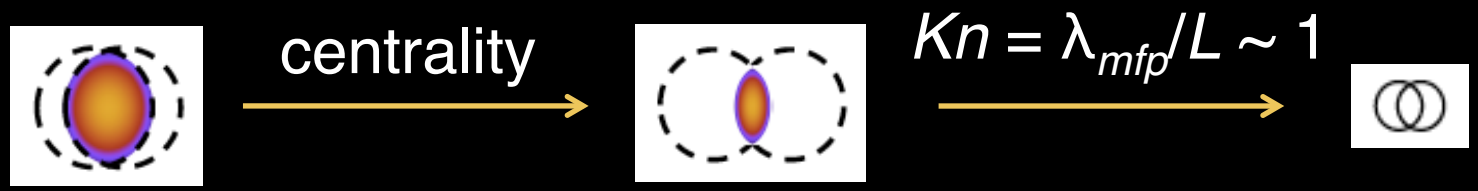

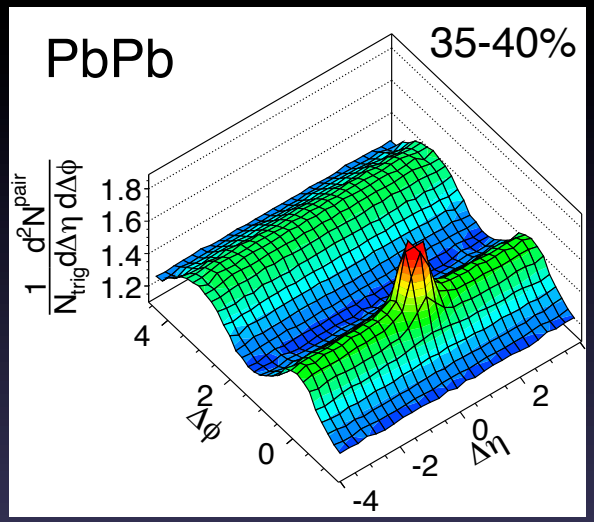

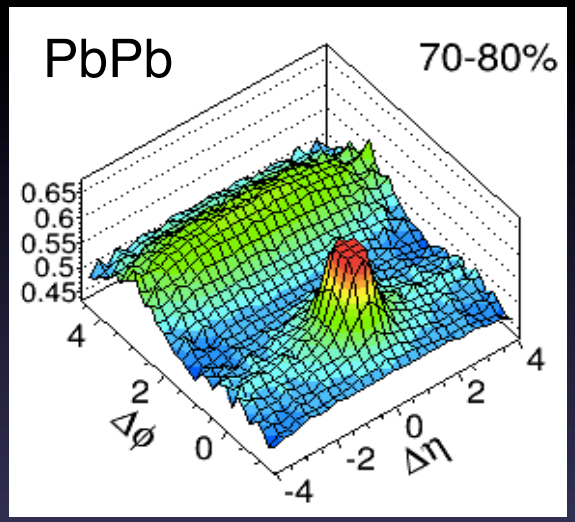

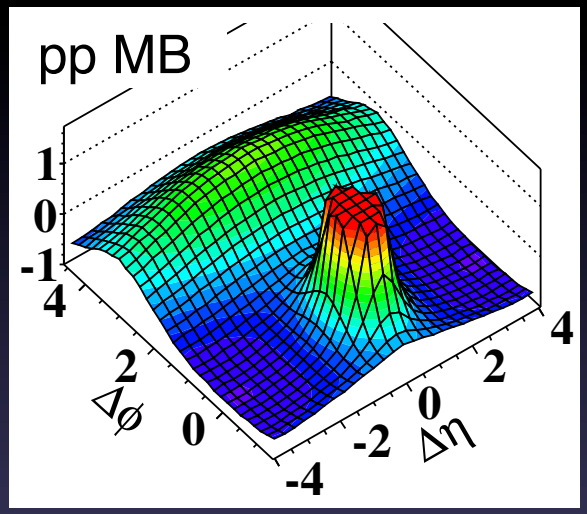

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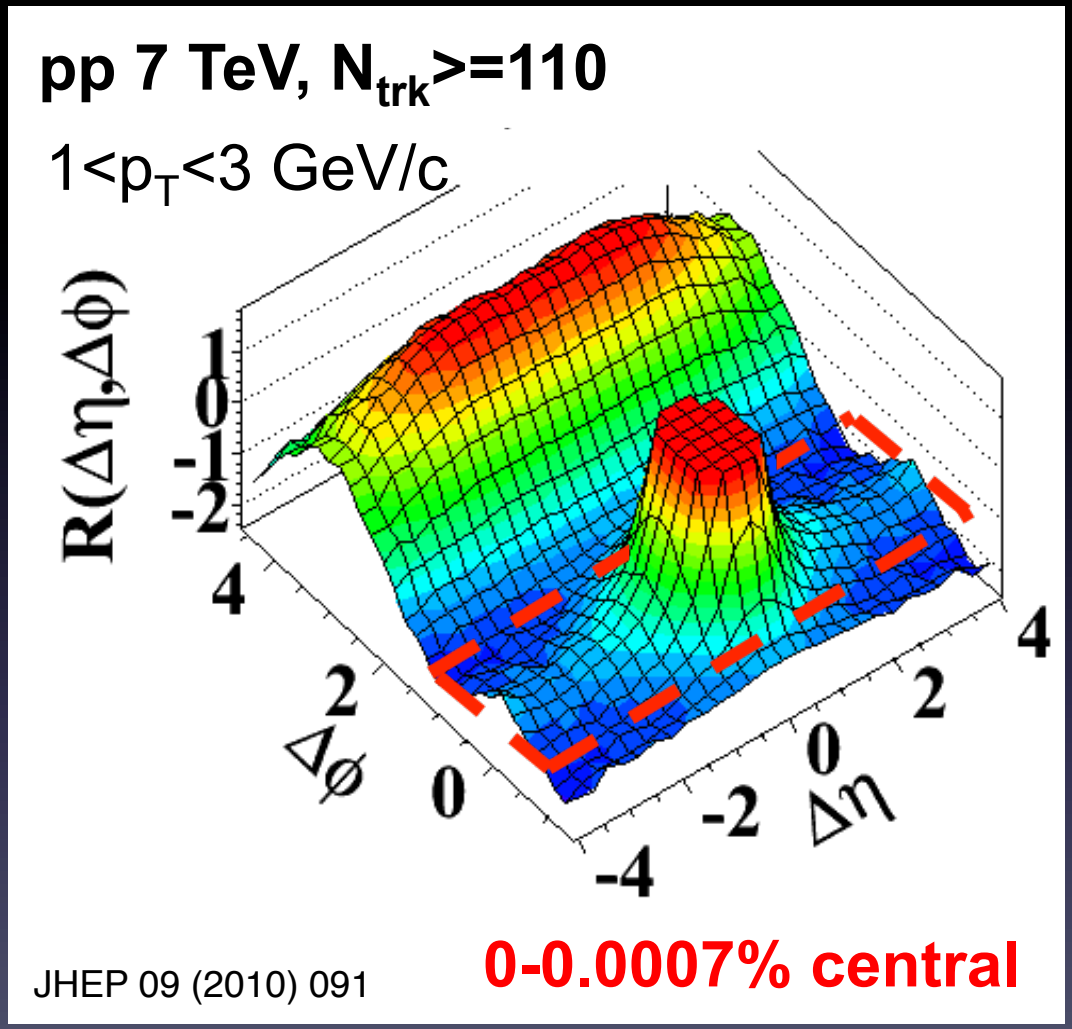
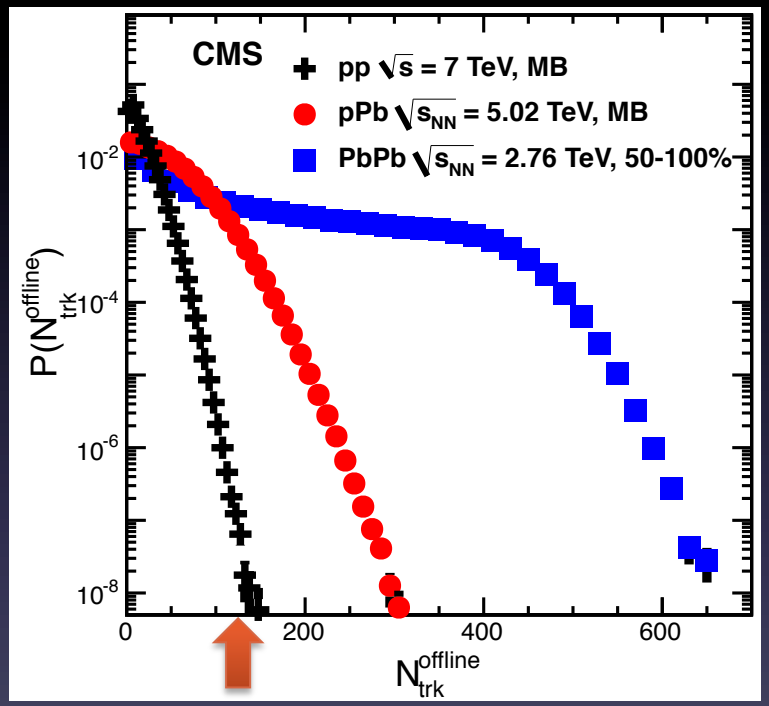
But what if making it denser (reducing $\boldsymbol{\lambda_{mfp}}$)?

➔ a smaller but hotter QGP fluid?!

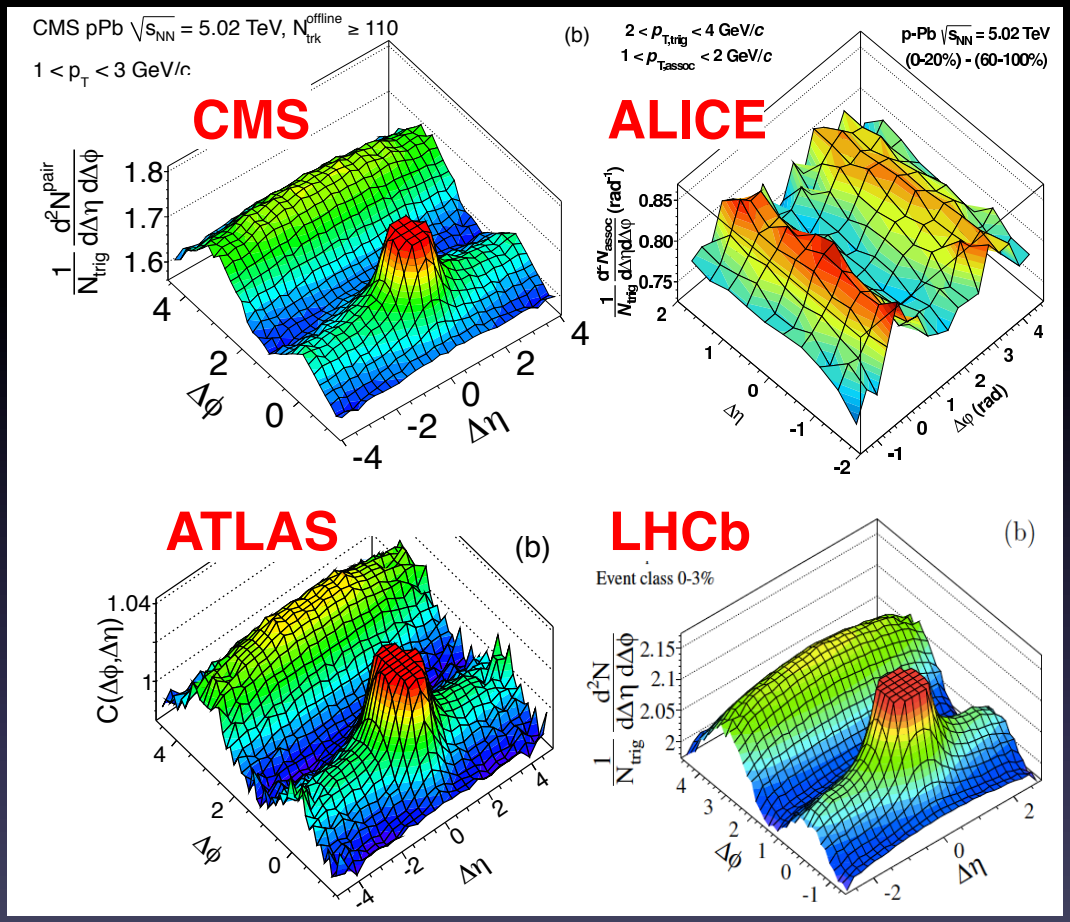
The “ridge” in pp





Mini-QGP fluid (L ~ 1 fm) in pp?

The “ridge” tsunami in pPb at the LHC



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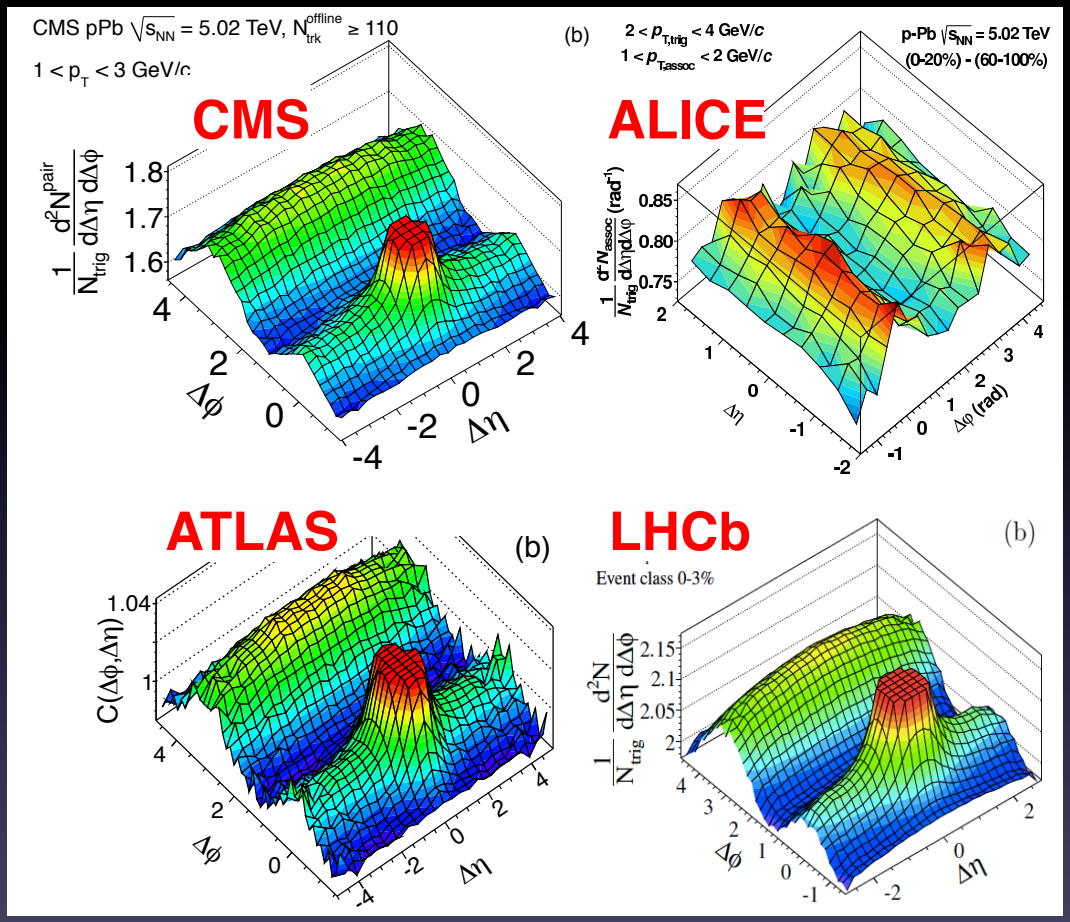
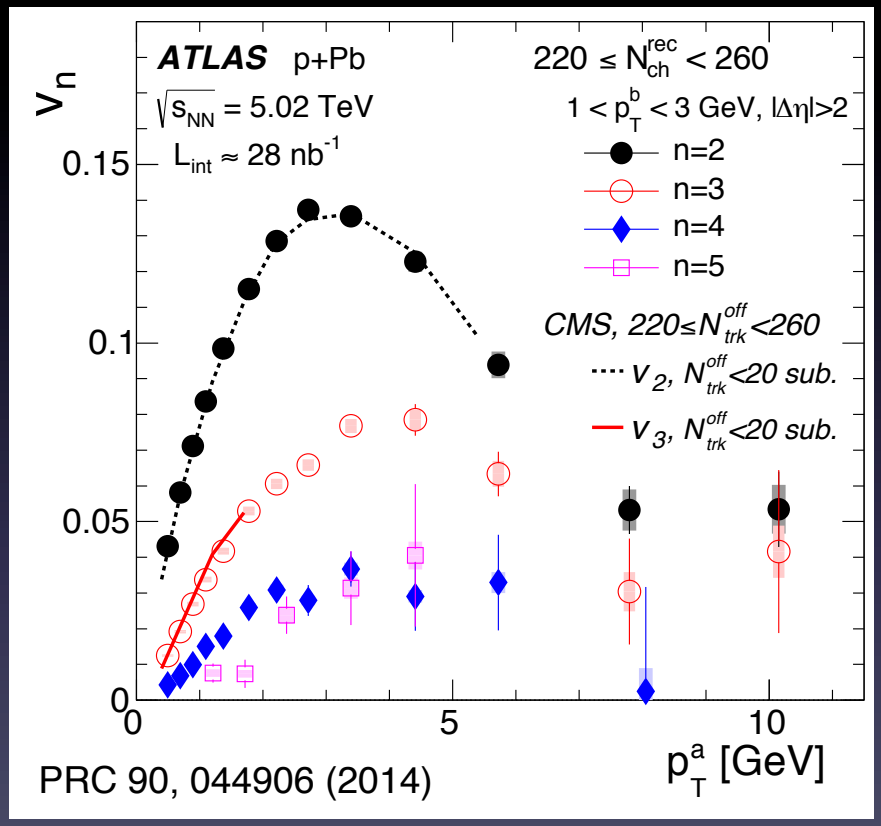


“Flow” analysis



What is the origin of “ridge” in small systems?

How small a QCD fluid can be?

Smallness is relative

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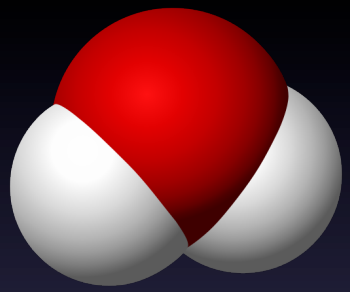
"Absolute smallness" only w.r.t. a fundamental scale



Smallest scale of QED fluid

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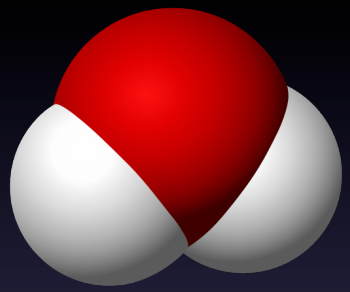

Smallest scale of QED fluid

Is there a fundamental scale in QCD?

- Not obvious with point-like partons ($\lambda_{mfp} \sim 1/T$)
- "Quasi-particles" of sQGP?

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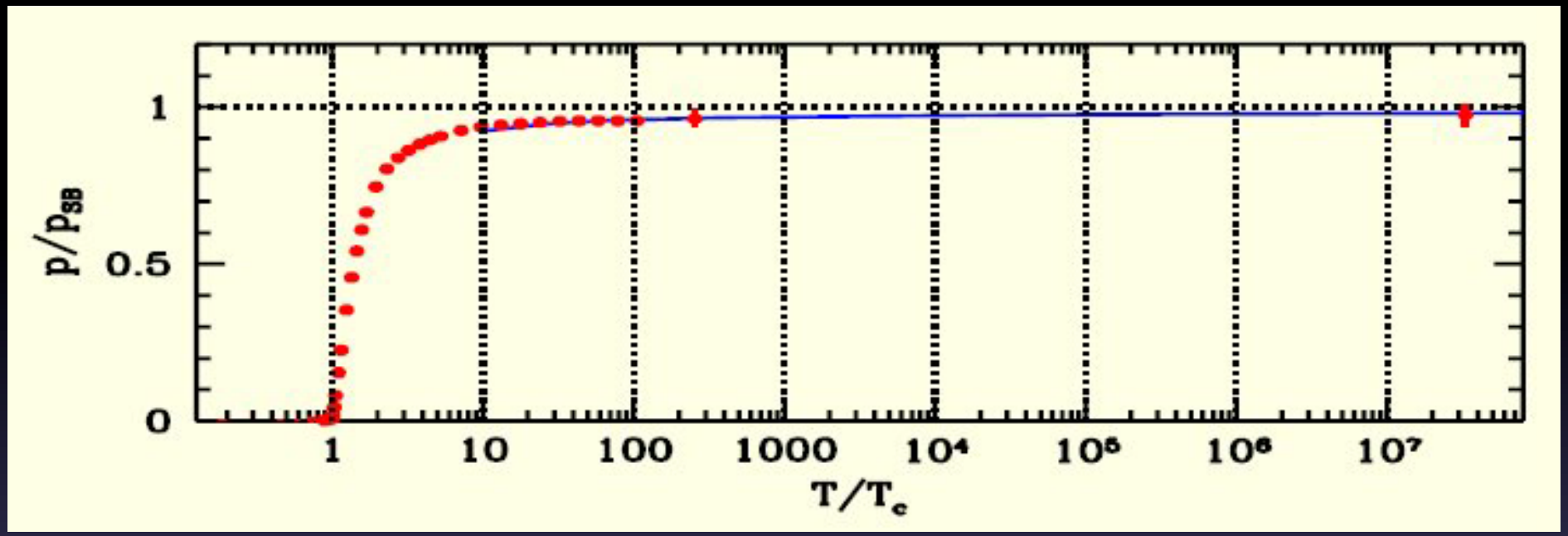


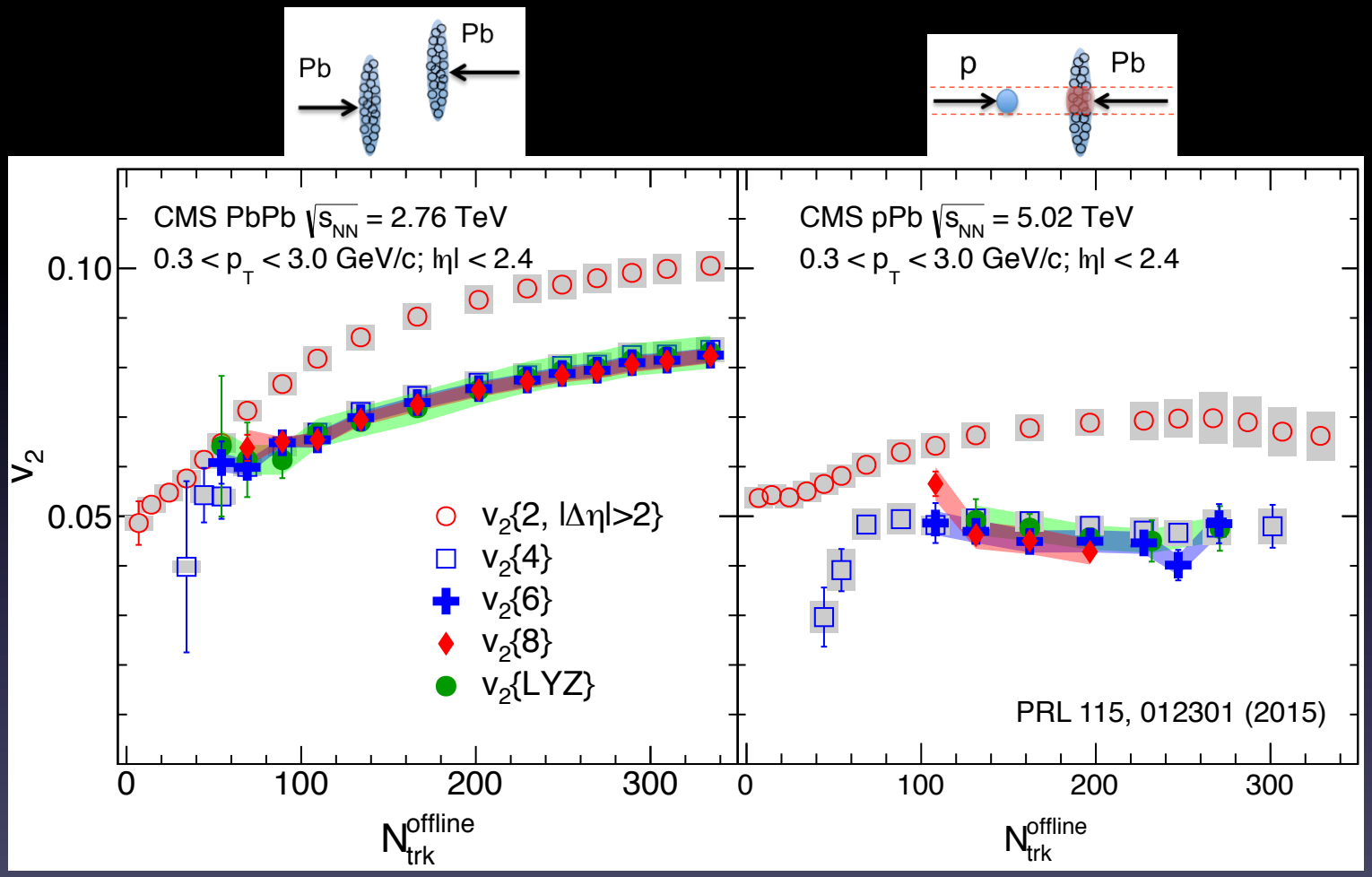
Endrodi et al., 0710.4197

$$\varepsilon \sim \frac{N_{trk}}{V}$$

Weakly-coupled regime reachable in principle, but not in practice

HM pp and pA well in the "fluid" regime

Evidence of collectivity ("big" and "small")



✧ $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

Striking similarities between "big" and "small"

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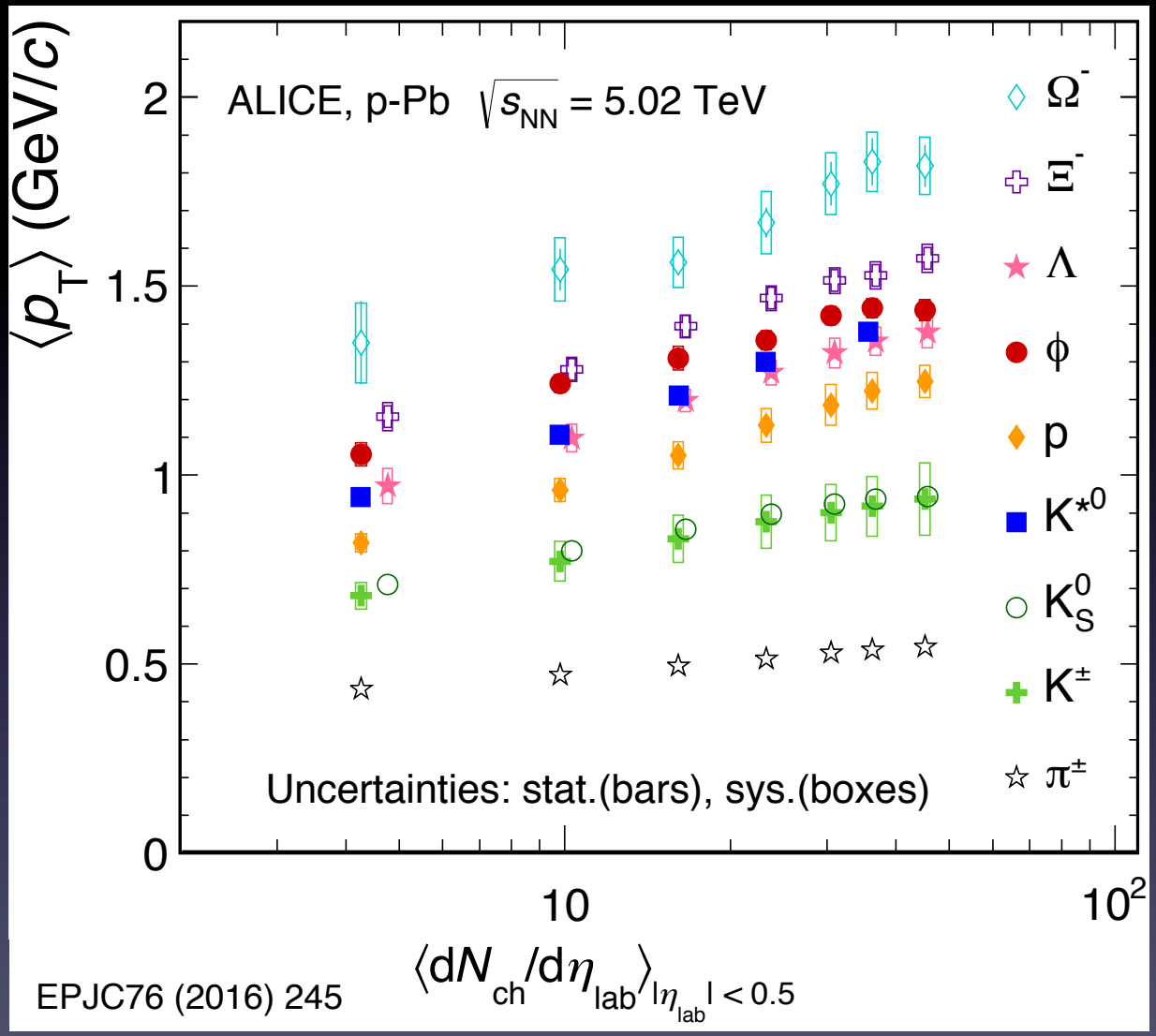

EPJC76 (2016) 245

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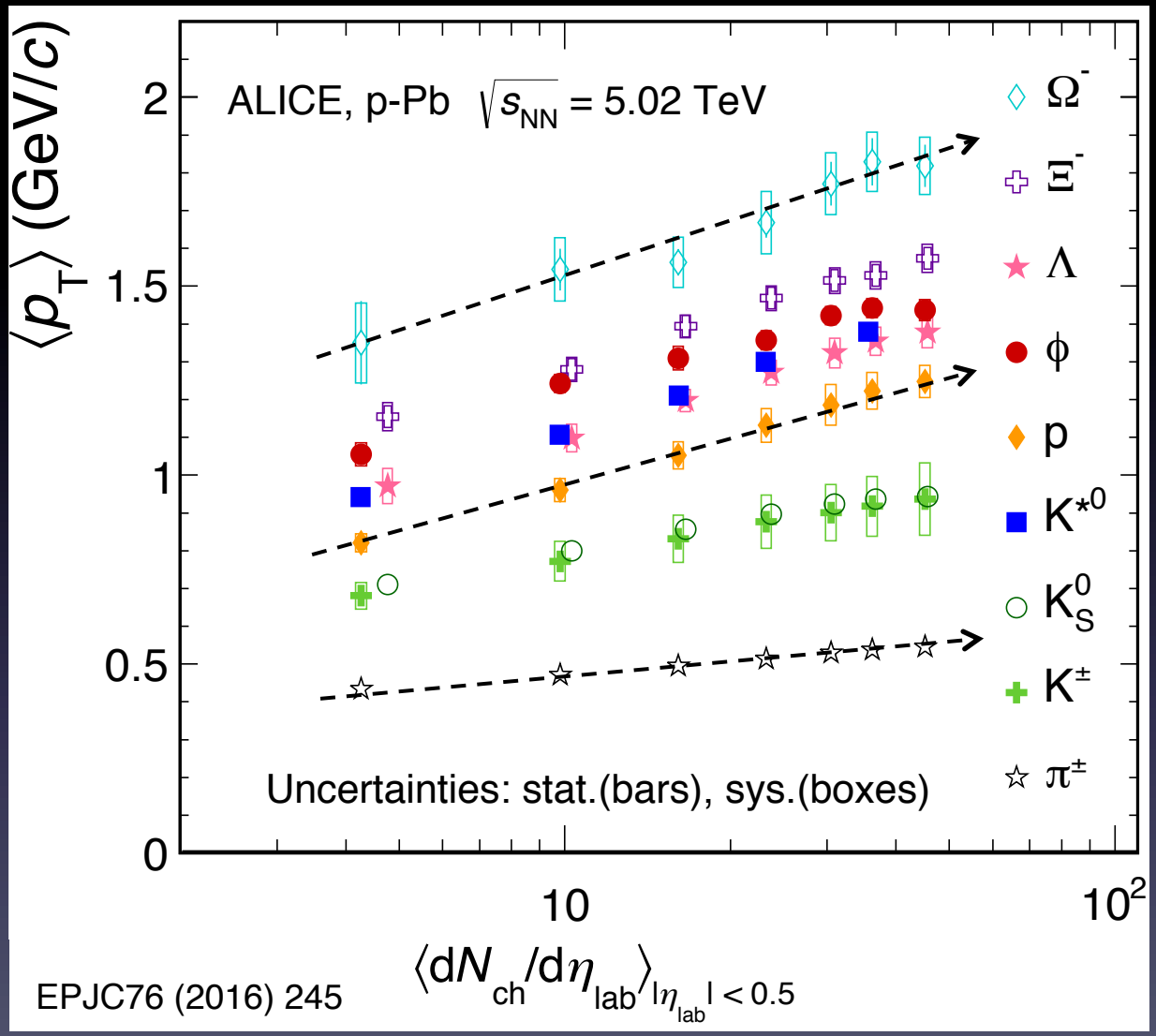

Faster increase in $\langle p_T \rangle$ for heavier species

($\Delta\langle p_T \rangle \sim m\langle \beta_T \rangle$)

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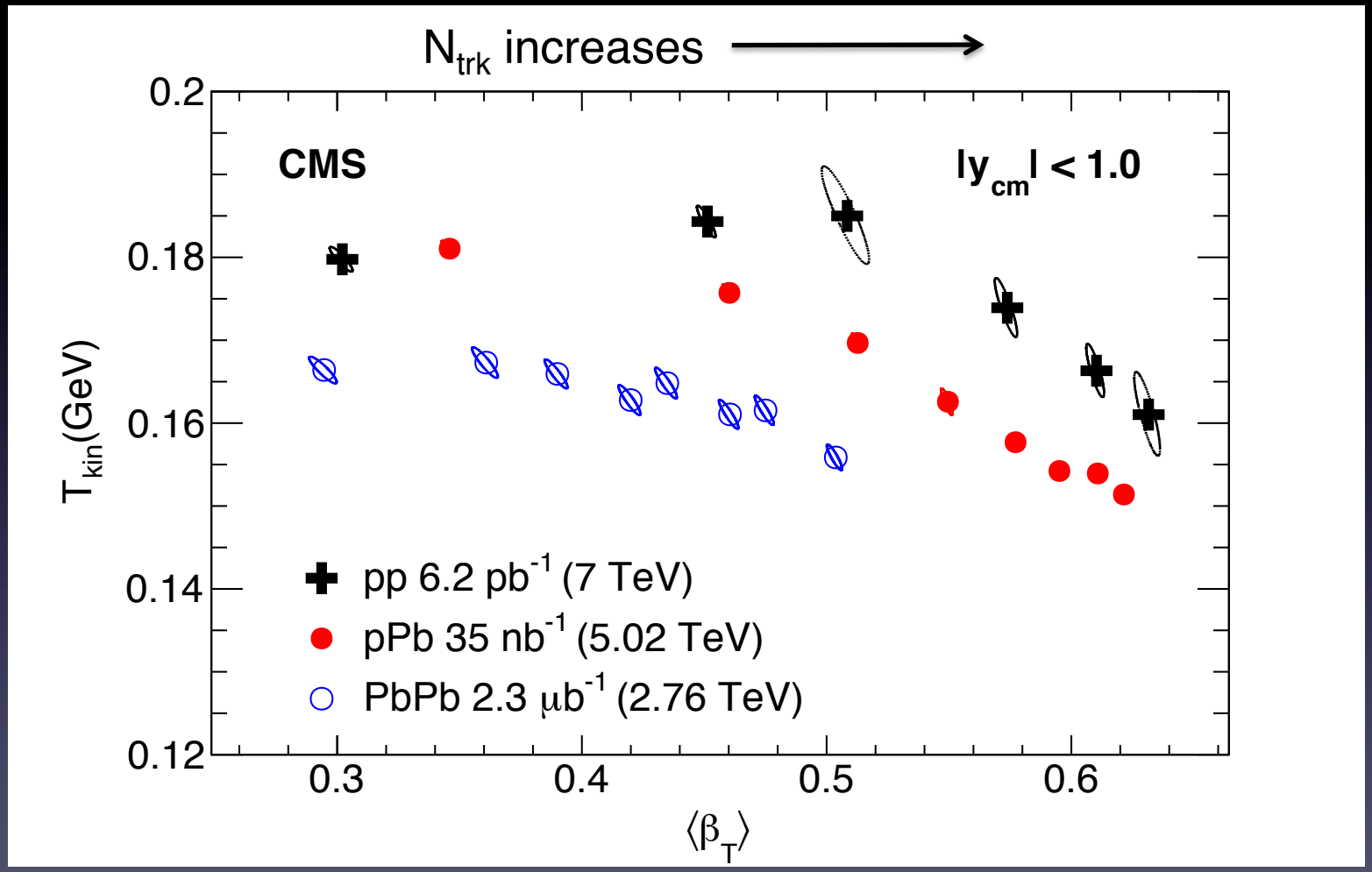
Simultaneous Blast-Wave fits to K_0^s, Λ and Ξ^-



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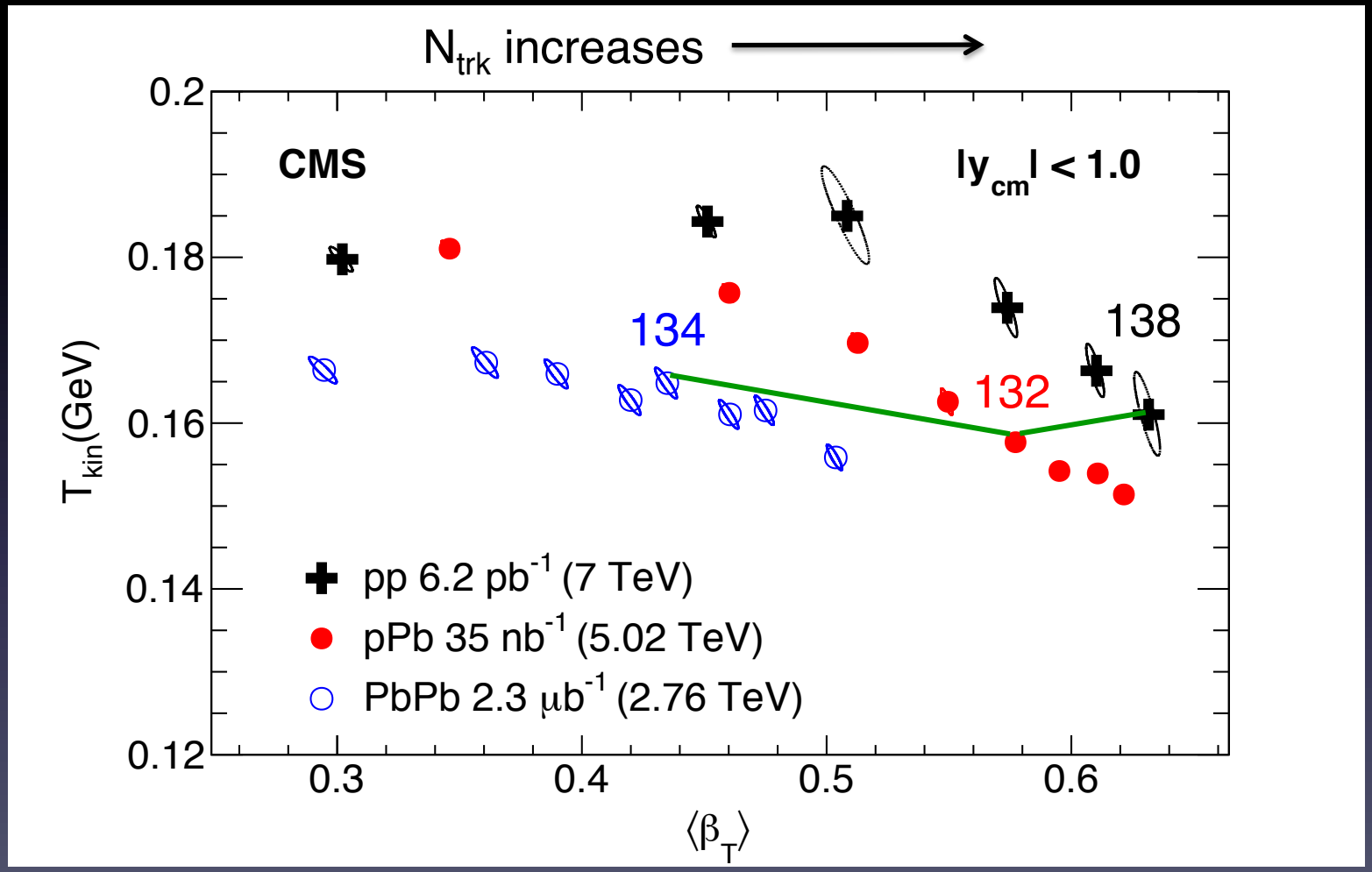
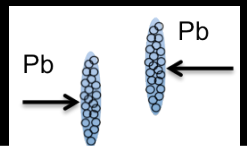
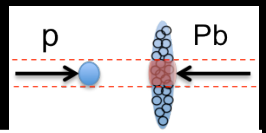


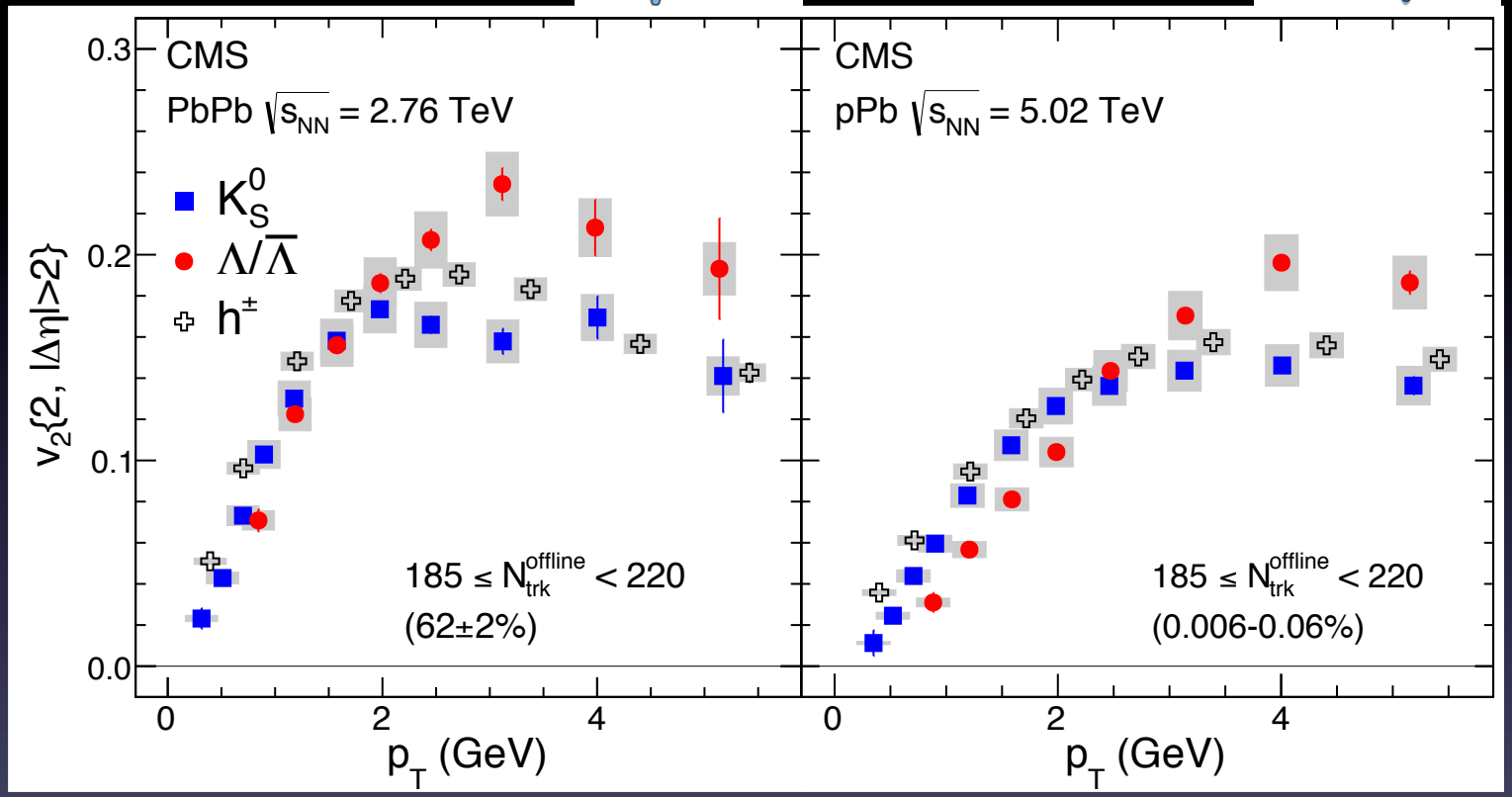
Stronger velocity boost for smaller system

Evidence of collectivity ("big" and "small")

PLB 742 (2015) 200







Larger mass splitting of v_2 in pPb

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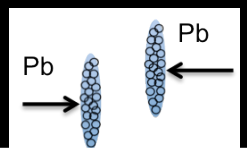

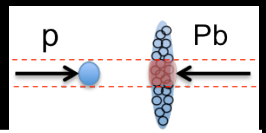

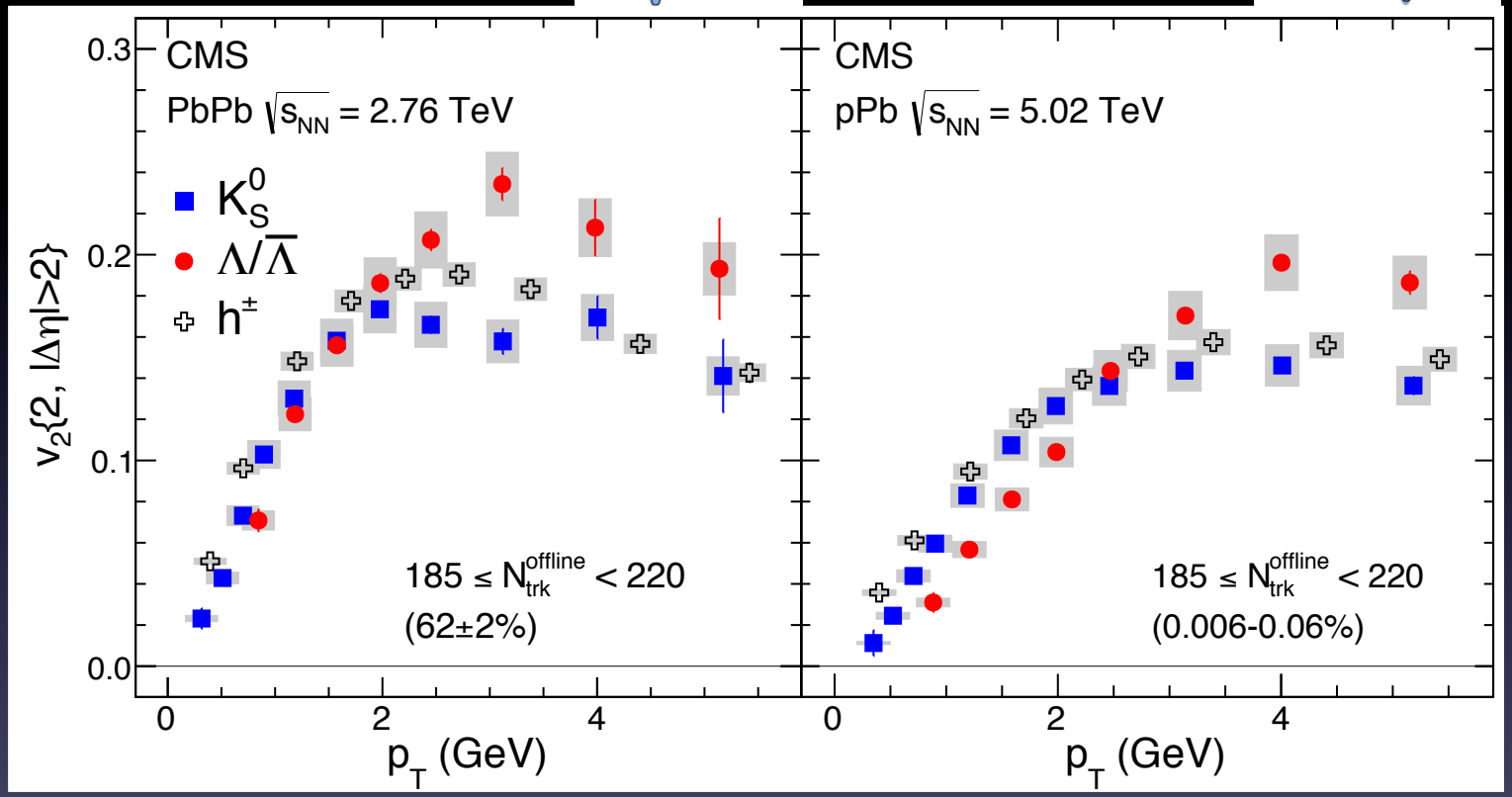

Larger mass splitting of v_2 in pPb

At a similar N_{trk},

smaller hydro. system more explosive!?

Shuryak, Zahed, PRC 88, 044915 (2013)

Clear evidence of collectivity observed, similar for both “small” and “large” systems

- ✓ Multi-particle correlation $v_n\{m\}$
- ✓ Mass dependence of spectra and v_n
- ✓ HBT radii v.s. k_T and N_{trk}
- ✓ …

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- ✧ Data consistent with “hydro-like” scenario
- ✧ Not obvious “small” and “large” fluids behave differently

➡ Accept or discard QGP fluid paradigm altogether

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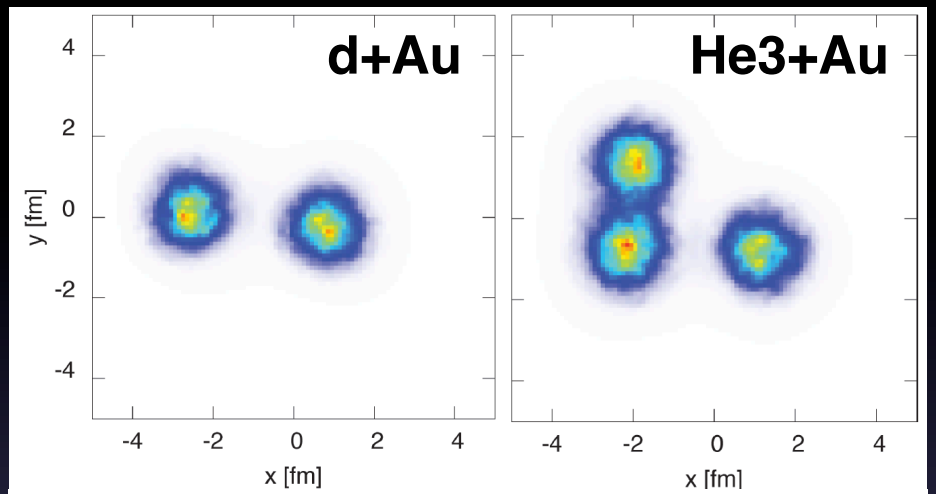
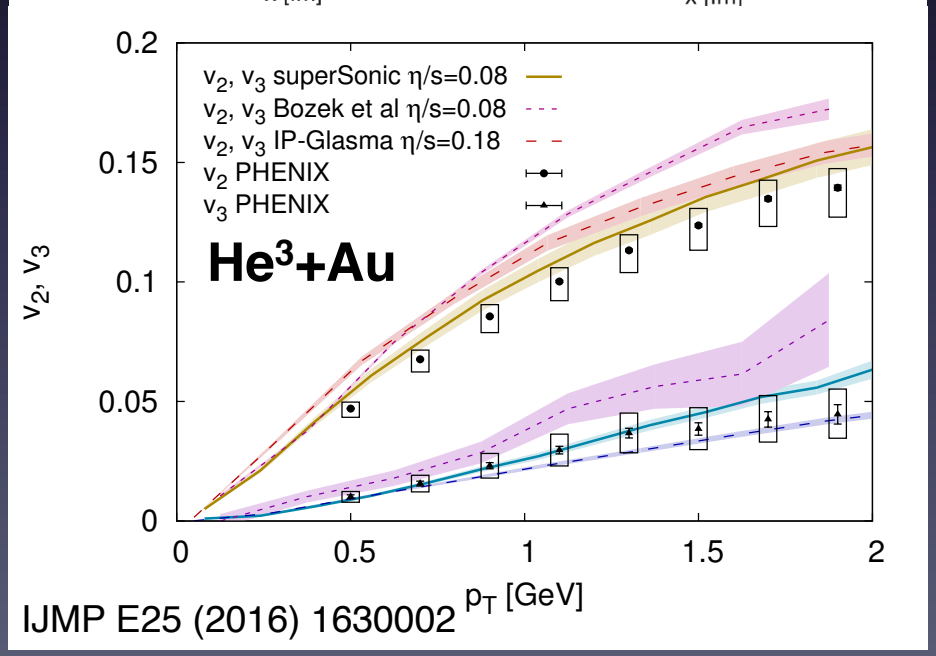
Connection to geometry in small systems?

“Smallness” is not the limitation

For A_1 (A_2) ≥ 2, hydro models agree





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Glauber geometry dominates

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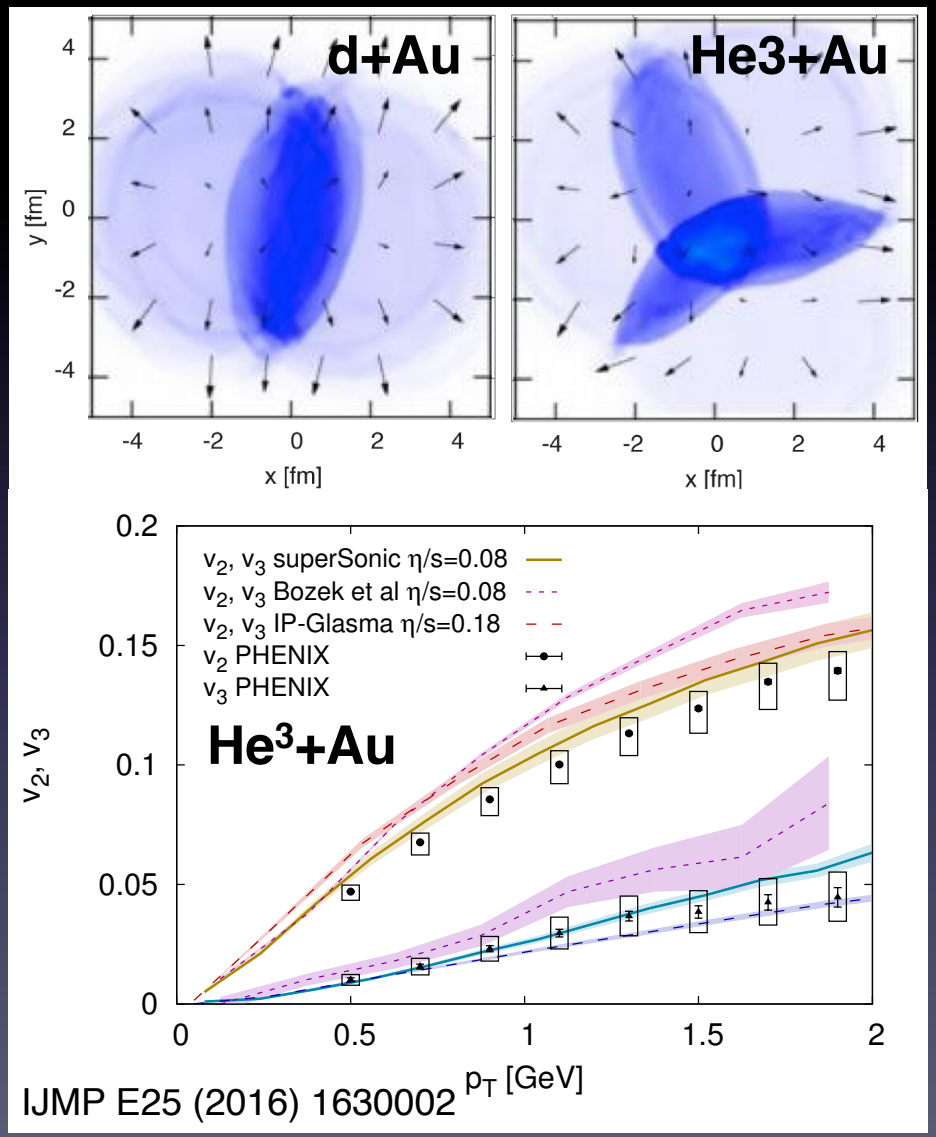

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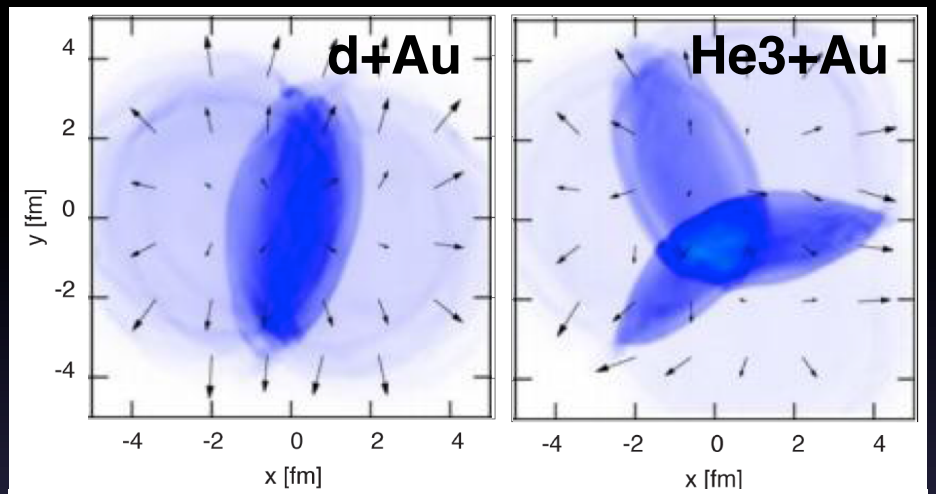
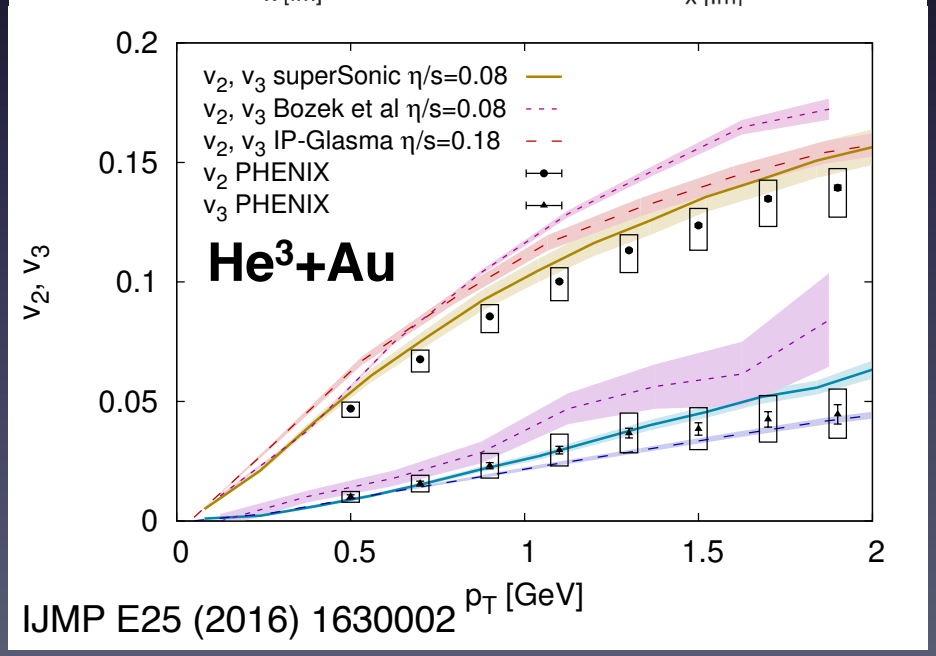
“Smallness” is not the limitation

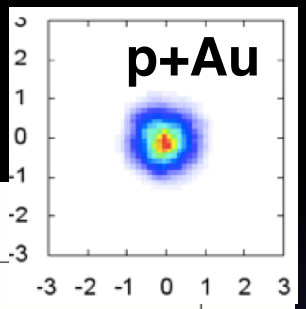
For A_1 (A_2) ≥ 2, hydro models agree

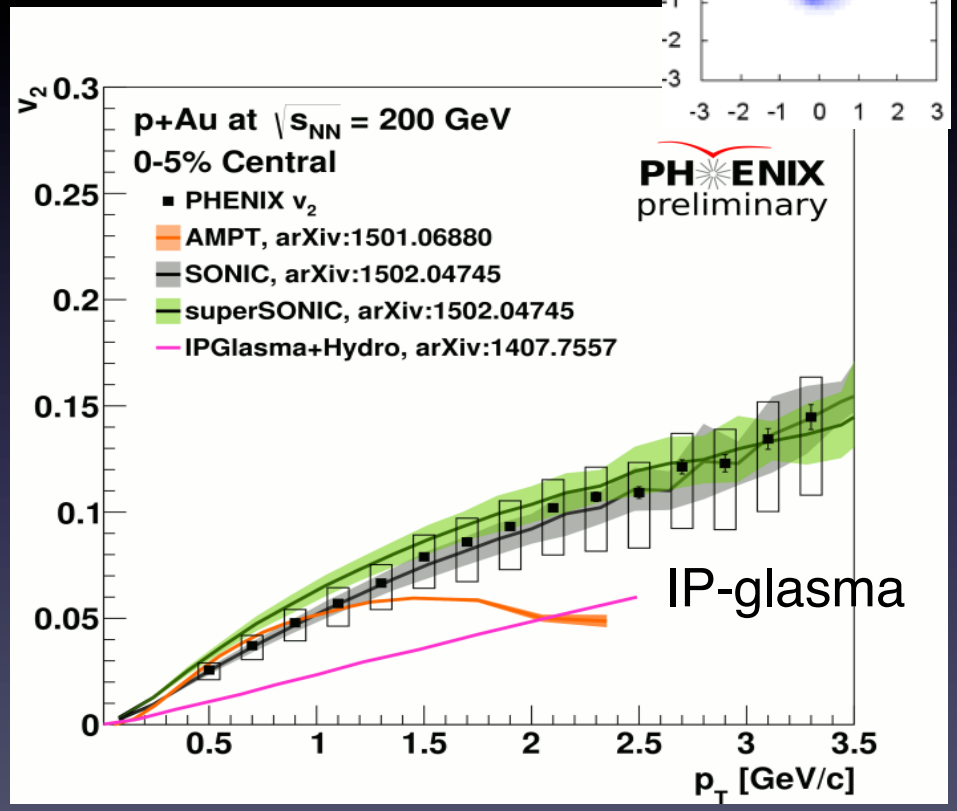




IJMP E25 (2016) 1630002

But if A_1 (A_2) = 1





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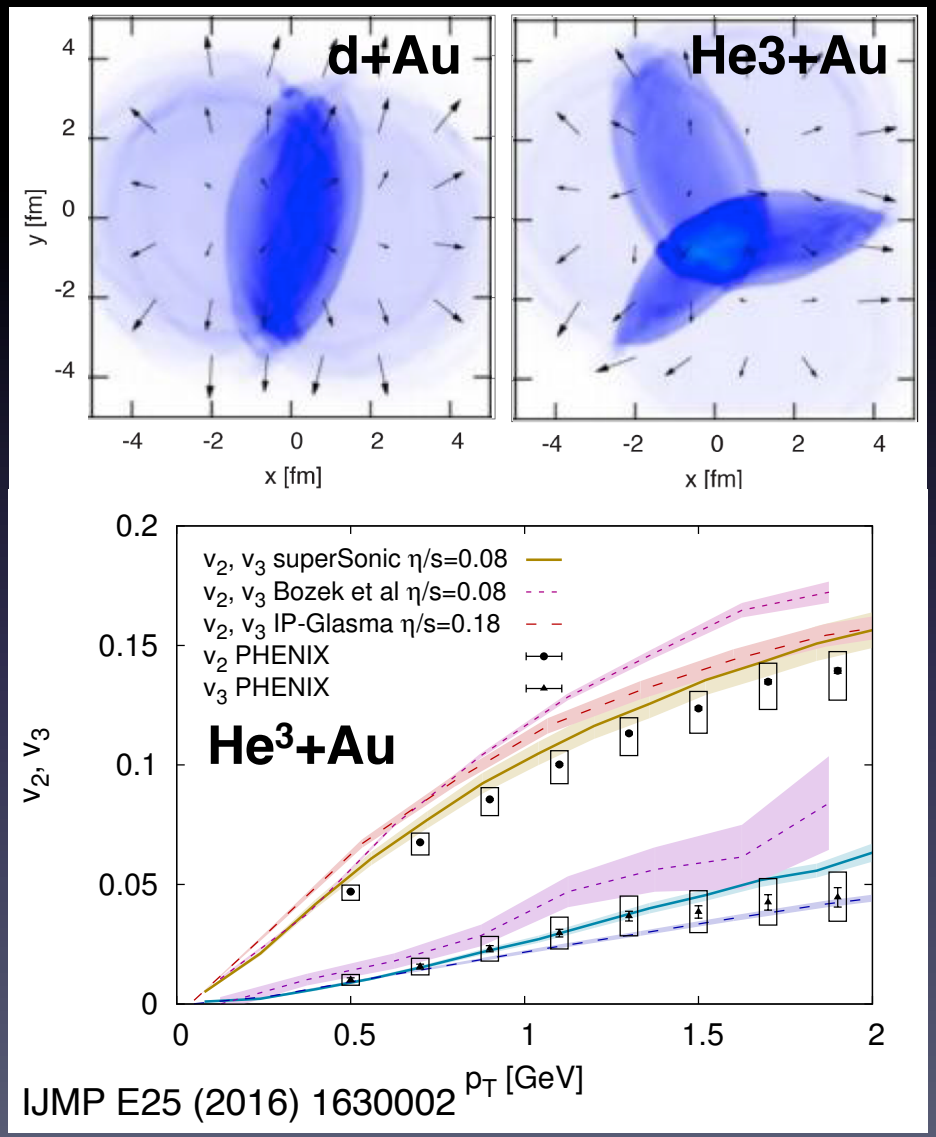

IJMP E25 (2016) 1630002

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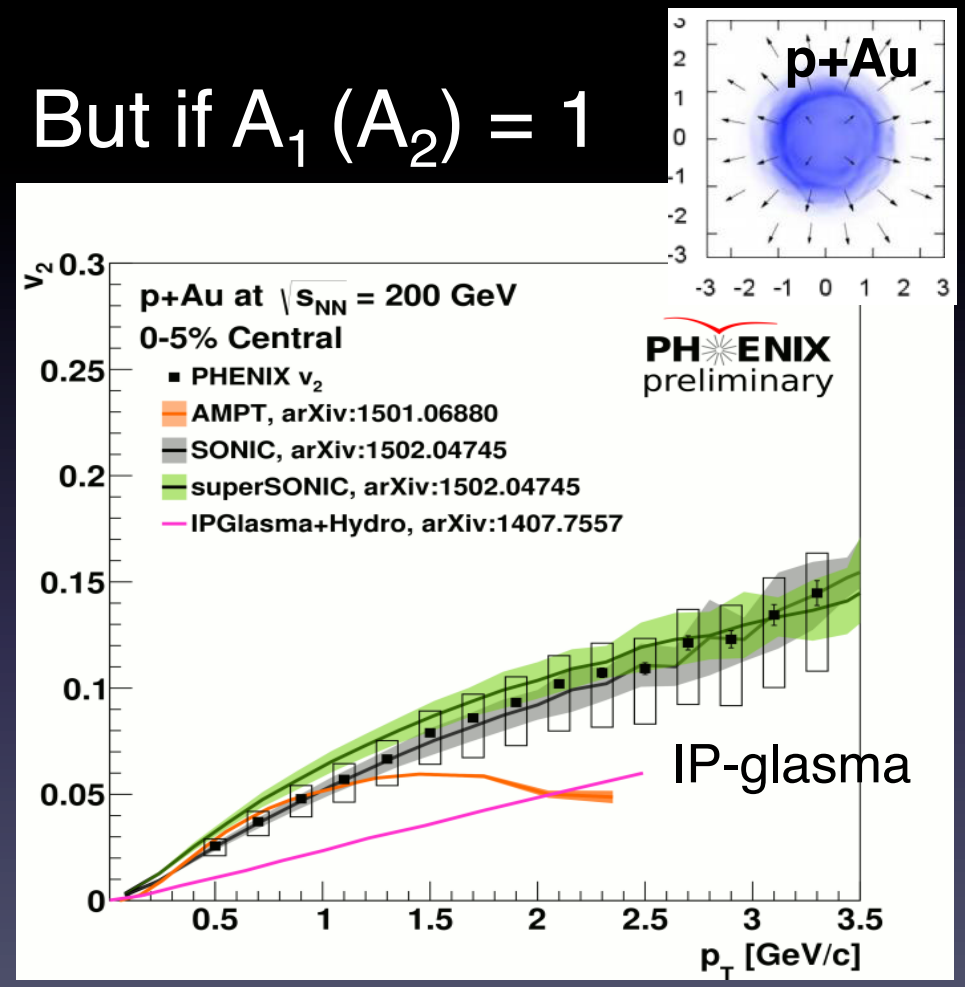

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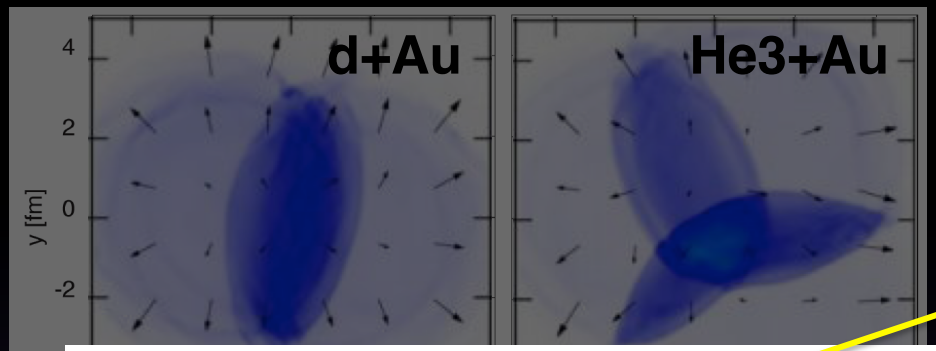

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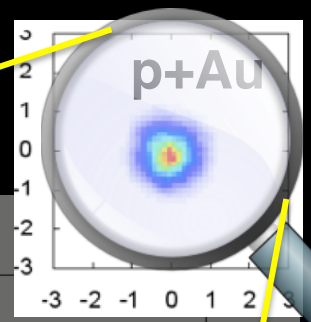
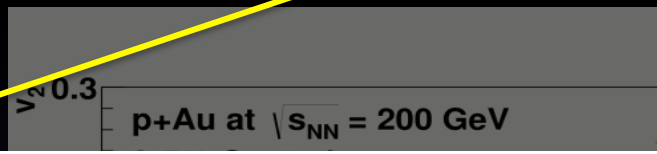
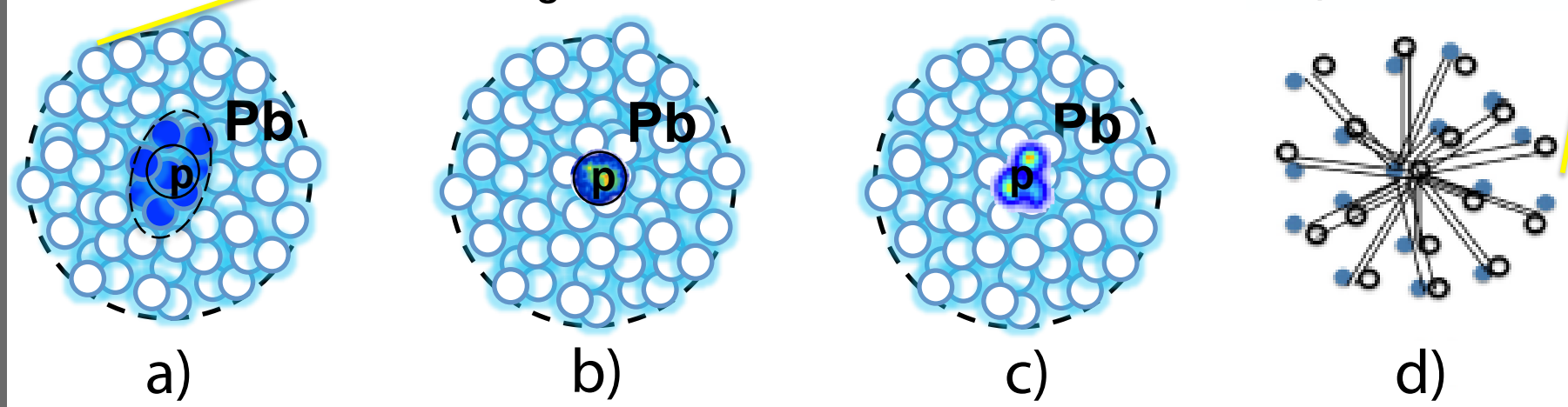




Models of initial states in pA collisions

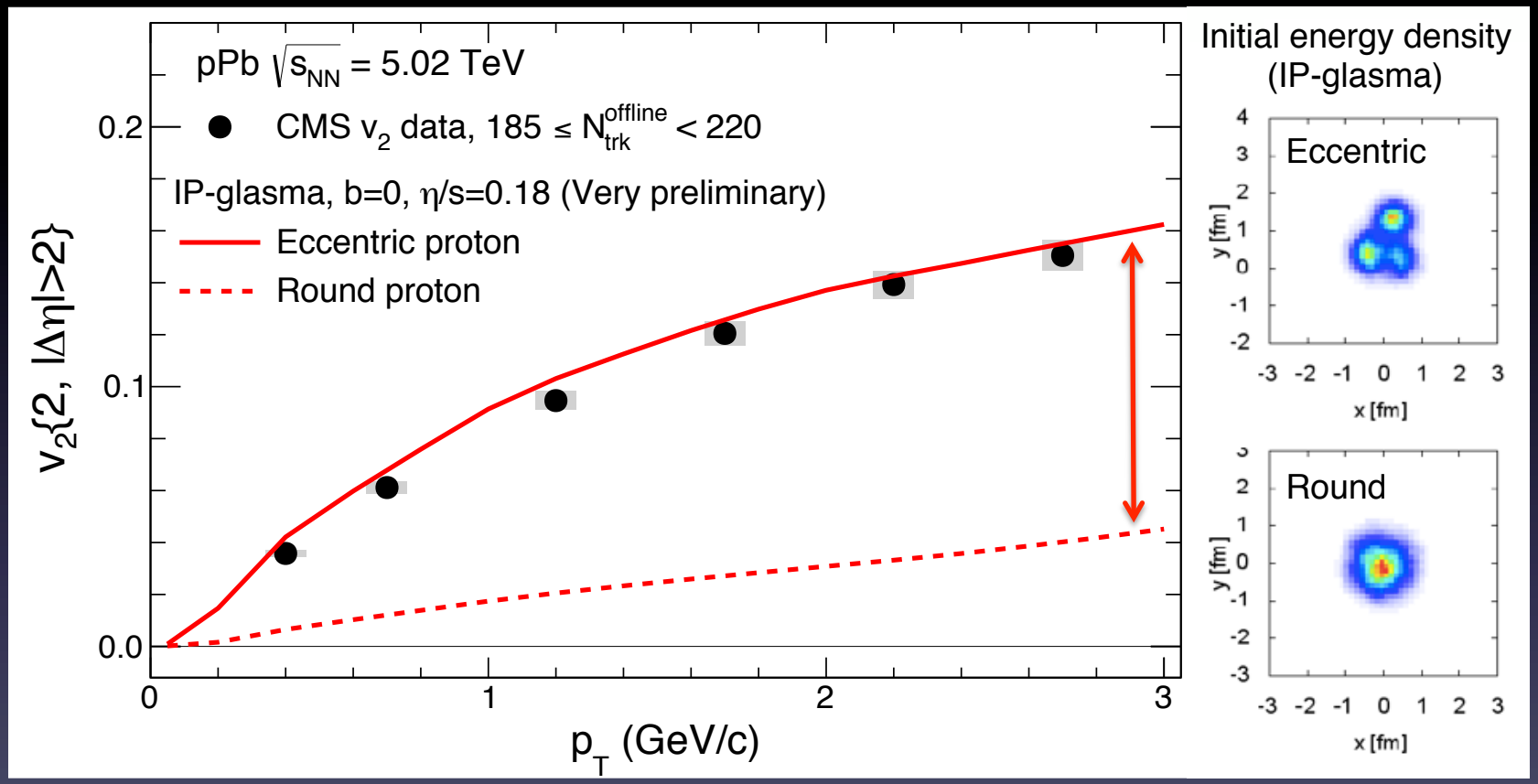


In pA, the unknown is the *“Shape”*

Glauber geometry dominates

“Smallness” is not the limitation

Shape of a proton relevant for describing v_n in pA



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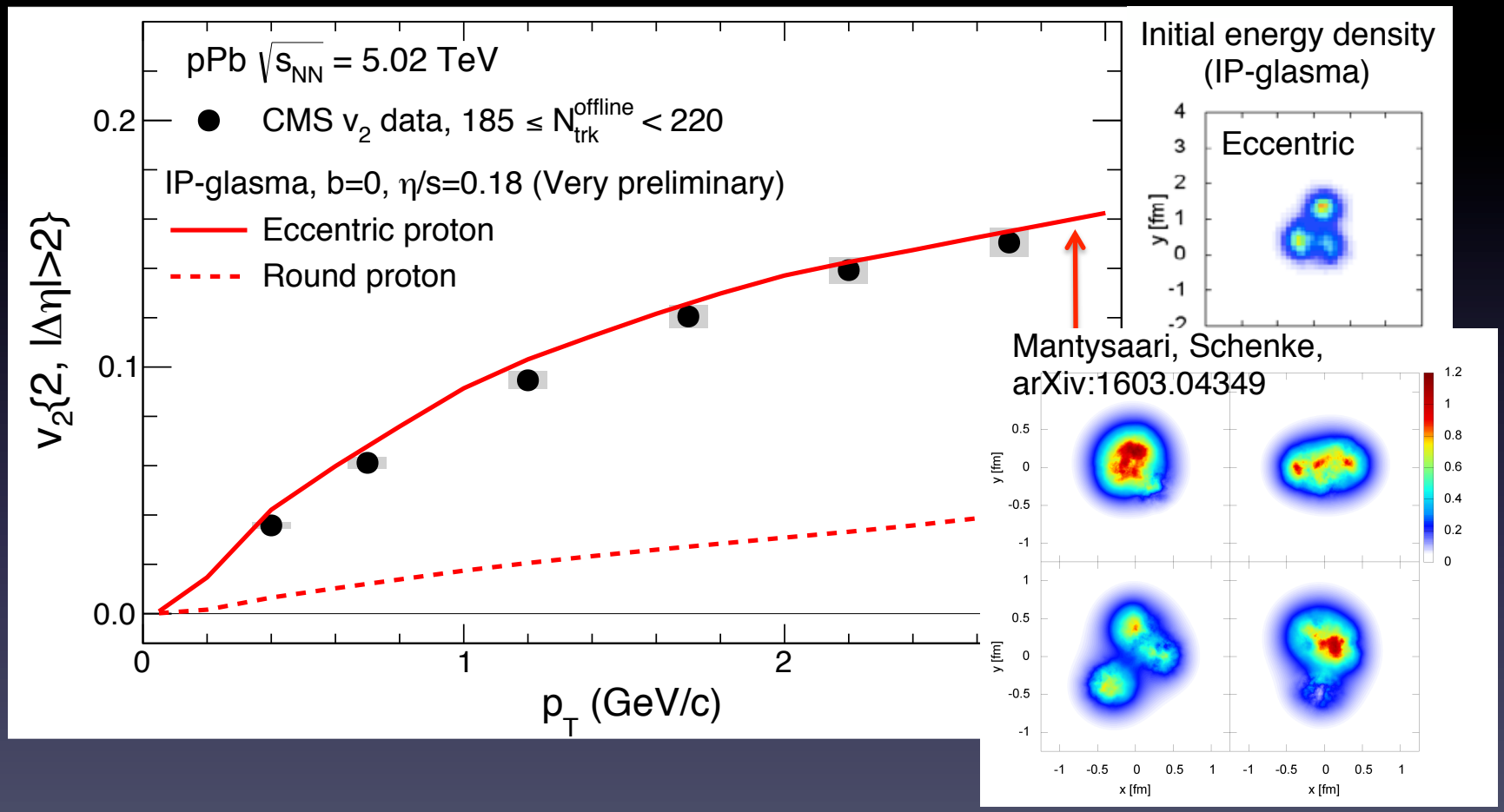
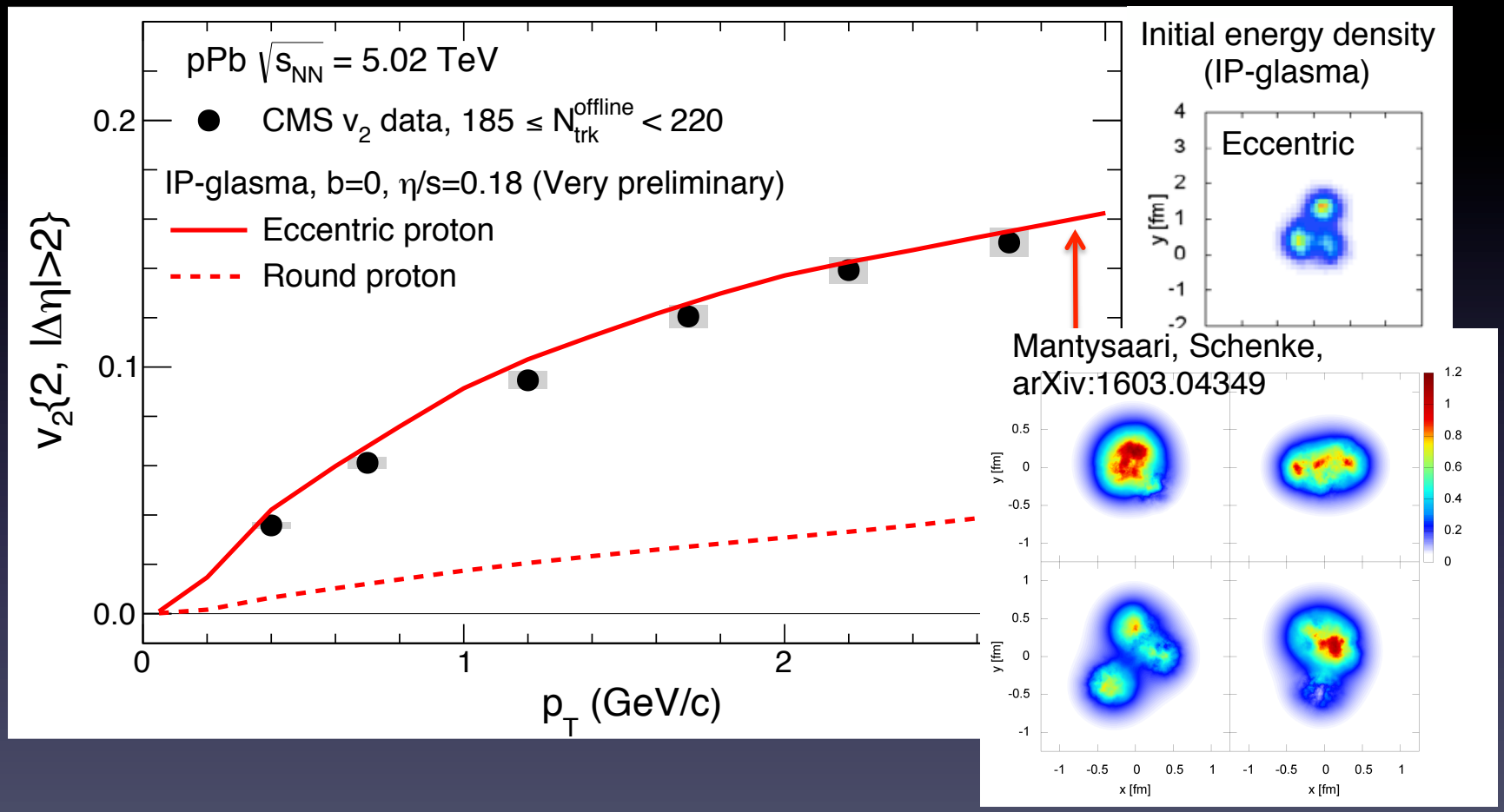


What is the image of a proton in yoctoseconds?

“Smallness” is not the limitation

Shape of a proton relevant for describing v_n in pA

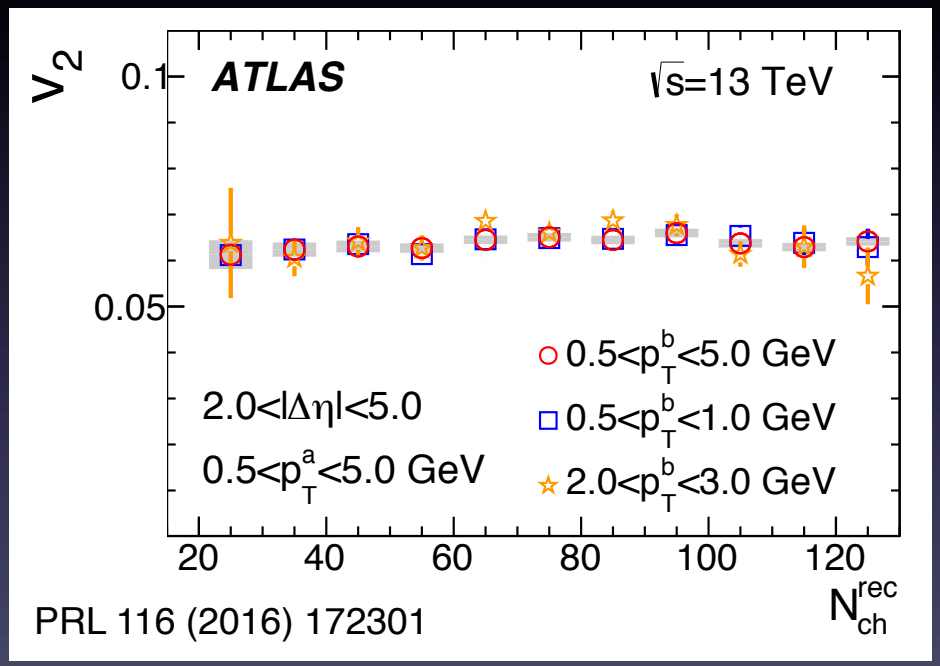


What is the image of a proton in yoctoseconds?

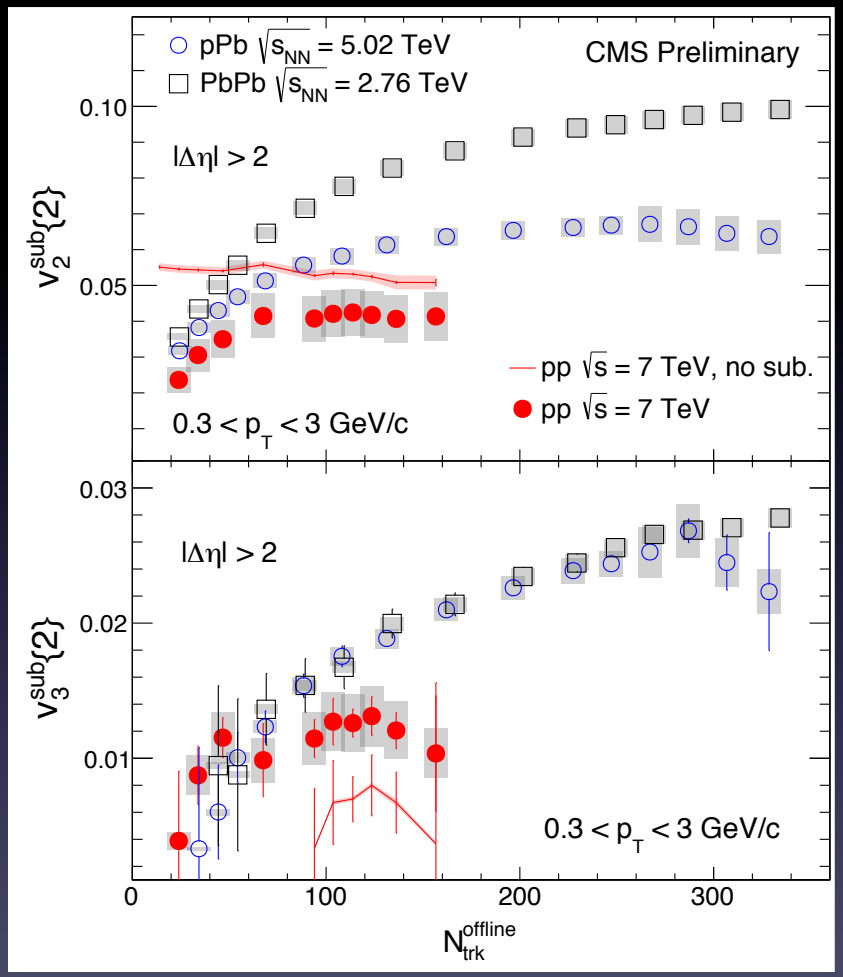
exciting opportunity, well connected to EIC physics

IS of small system: (I) v_n in pp

Ridge and v_n in pp



PRL 116 (2016) 172302, CMS-PAS-HIN-15-009



$v_3 > 0$ in pp – the "shape" of a proton must fluctuate

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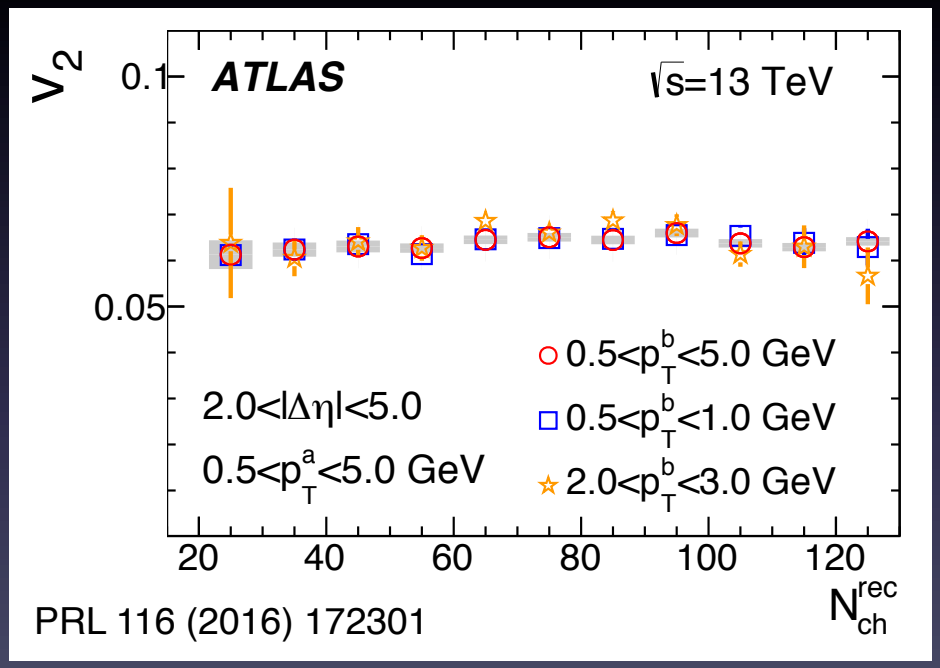
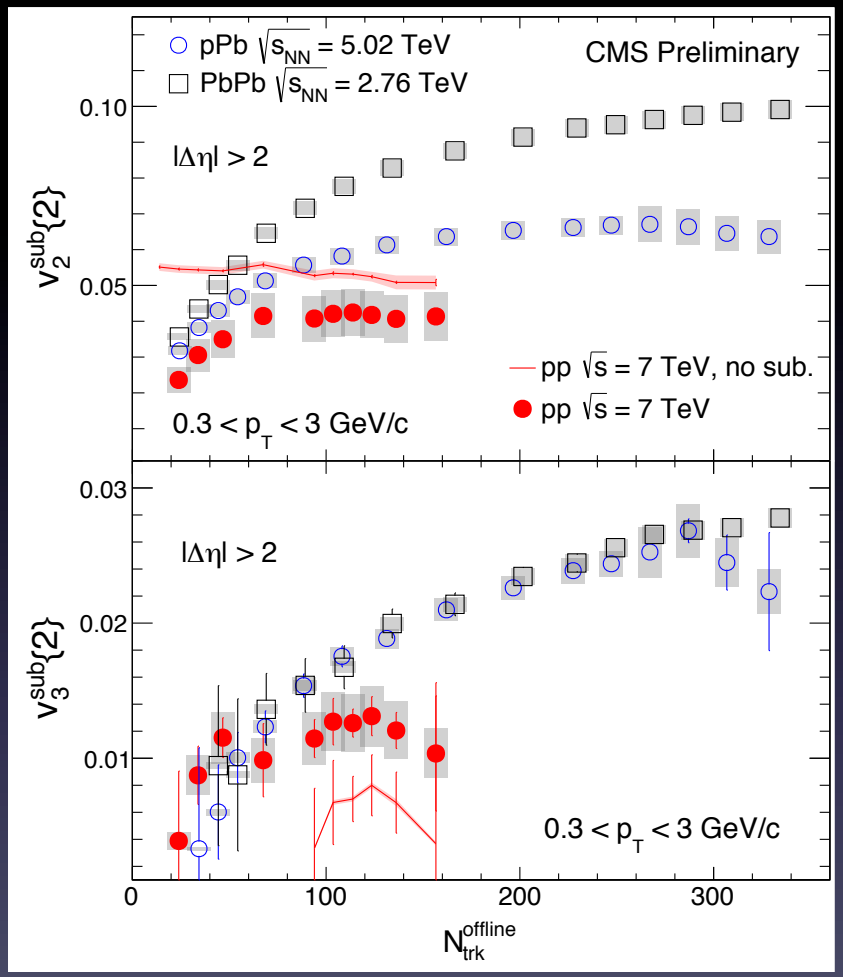


PRL 116 (2016) 172301

PRL 116 (2016) 172302, CMS-PAS-HIN-15-009



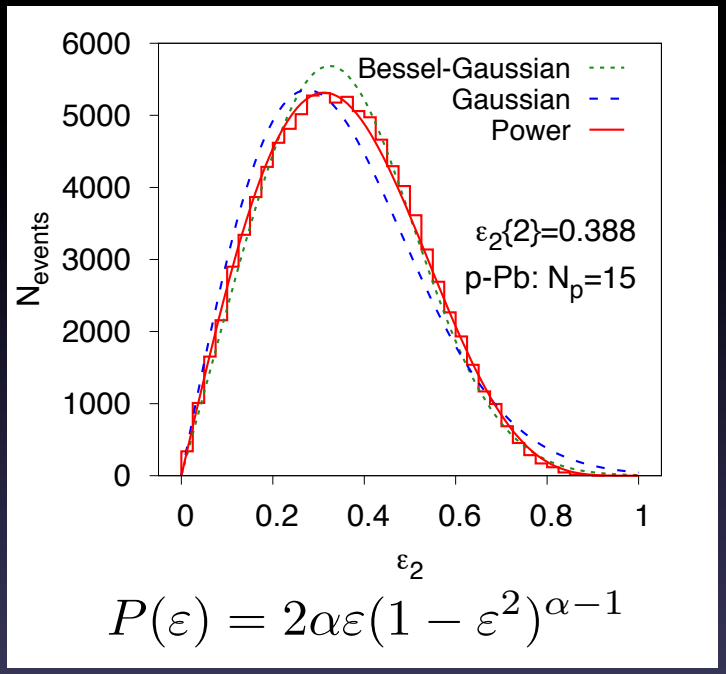
$v_3 > 0$ in pp – the "shape" of a proton must fluctuate

Strongly constrained by pp + pPb data

IS of small system: (II) cumulant $v_n\{m\}$

Fluctuation-driven ε_n

Yan, Ollitrault, PRL 112, 082301 (2014)



Cumulants

$\varepsilon_2\{m\}$

(m = 2, 4, 6, 8 …)

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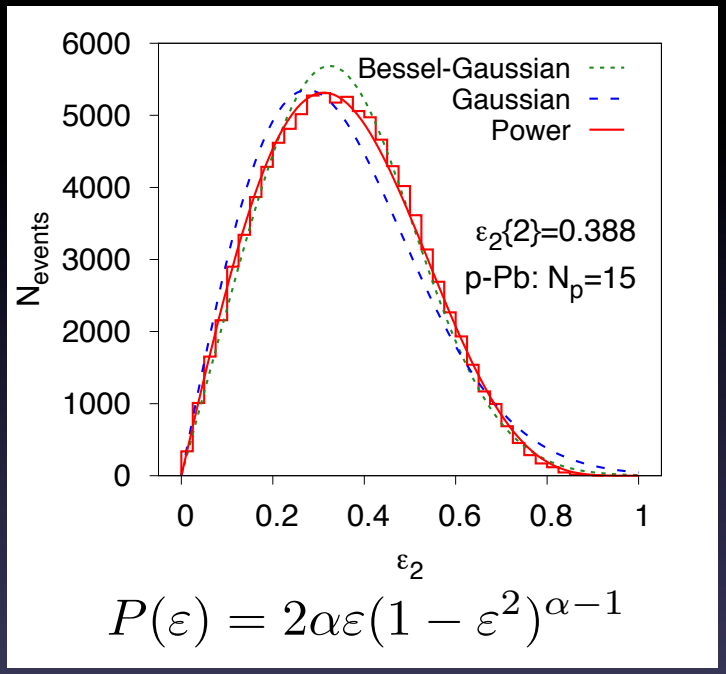

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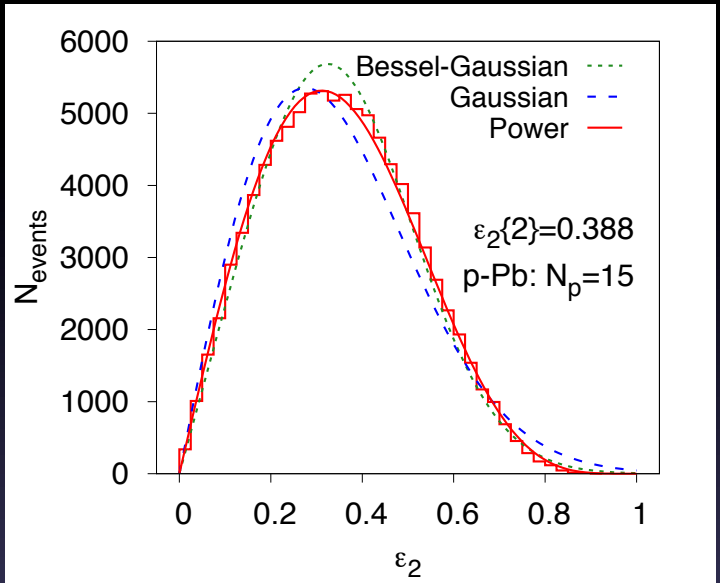

$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$

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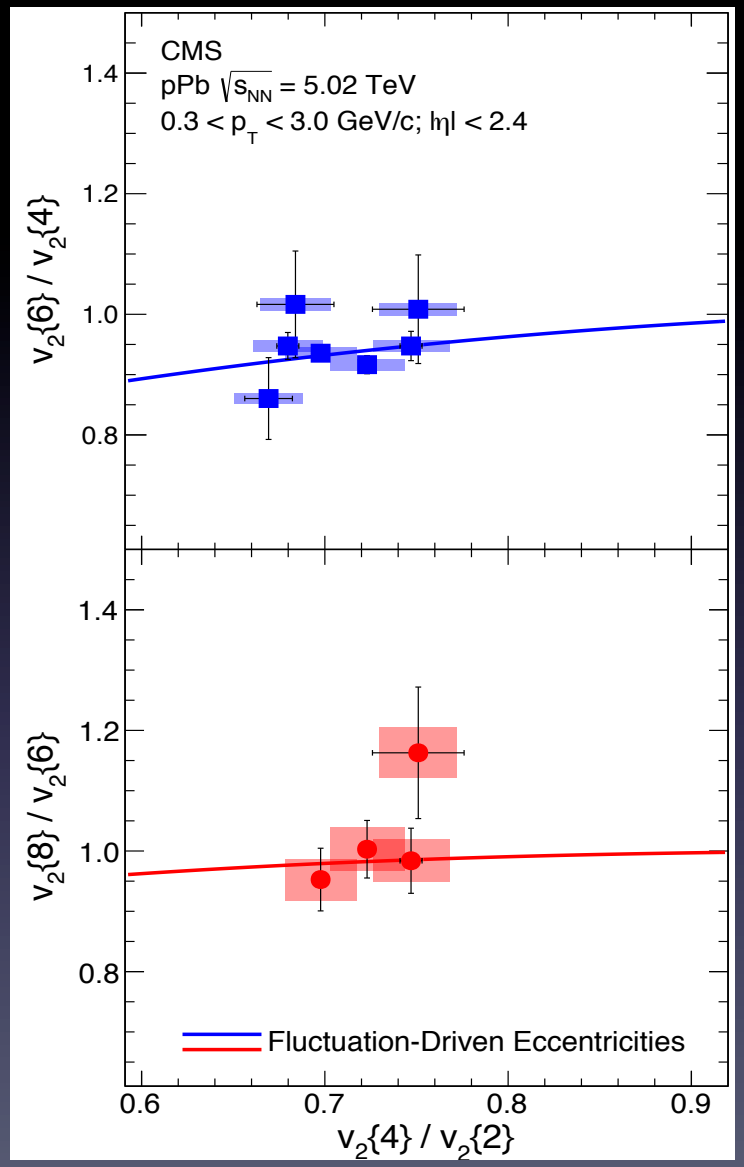
PRL 115, 012301 (2015)



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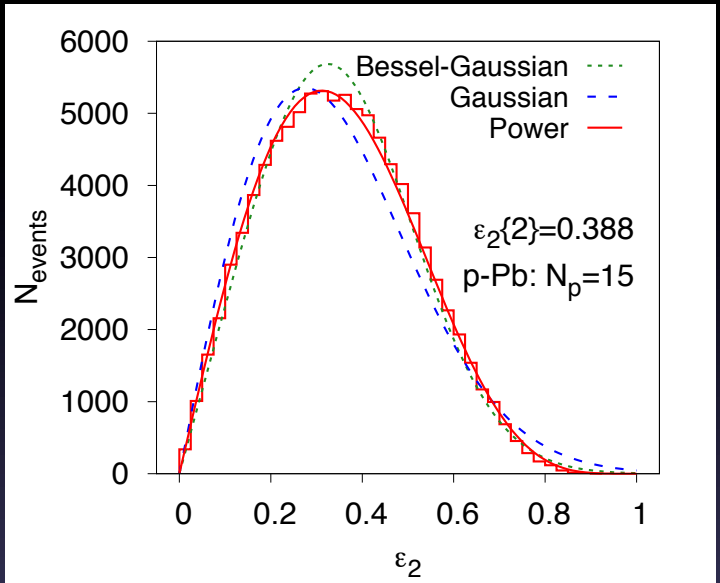

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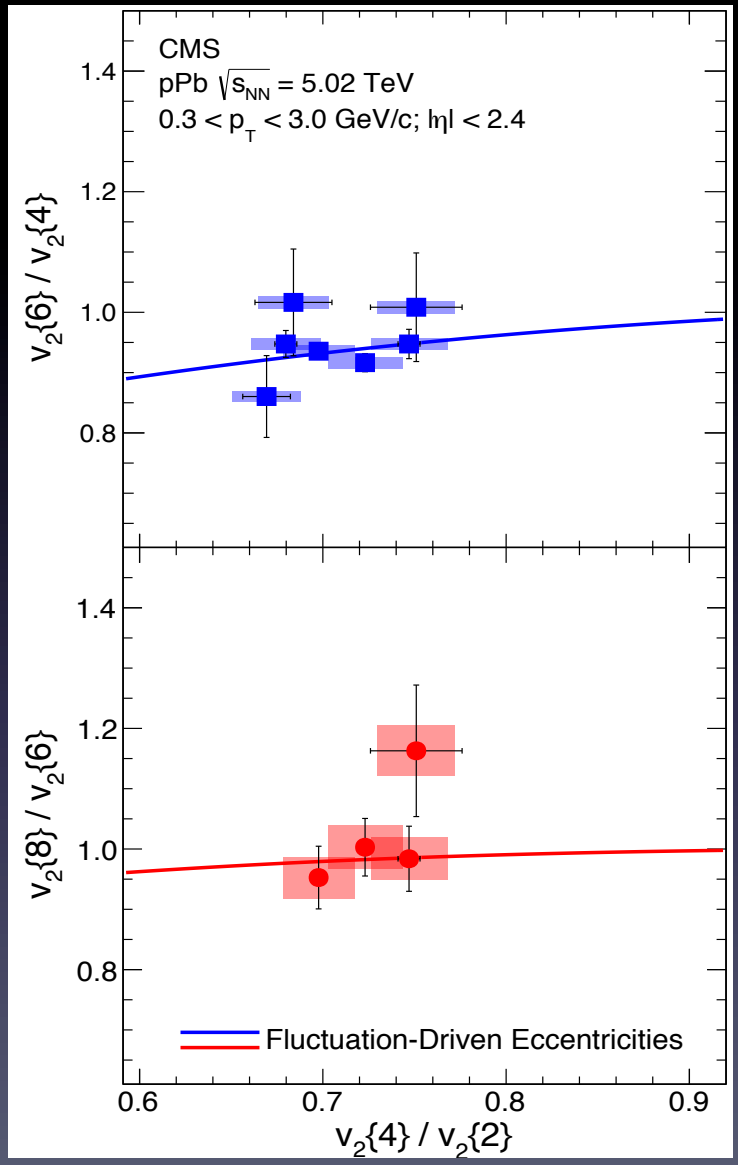

Cumulants

$$\varepsilon_2\{m\} \xrightarrow{\text{Hydro.}} v_2\{m\}$$

(m = 2, 4, 6, 8 …)

Hydrodynamic model is very testable!

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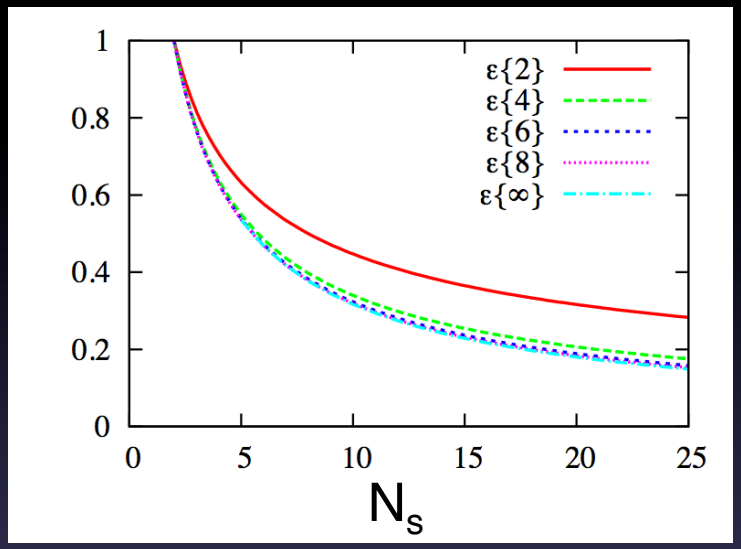
Fluc.-driven ε_n determined by # of sources (N_s)



Yan, Ollitrault, PRL 112, 082301 (2014)

$$\frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} = \left(\frac{2}{1+N_s/2}\right)^{1/4}$$

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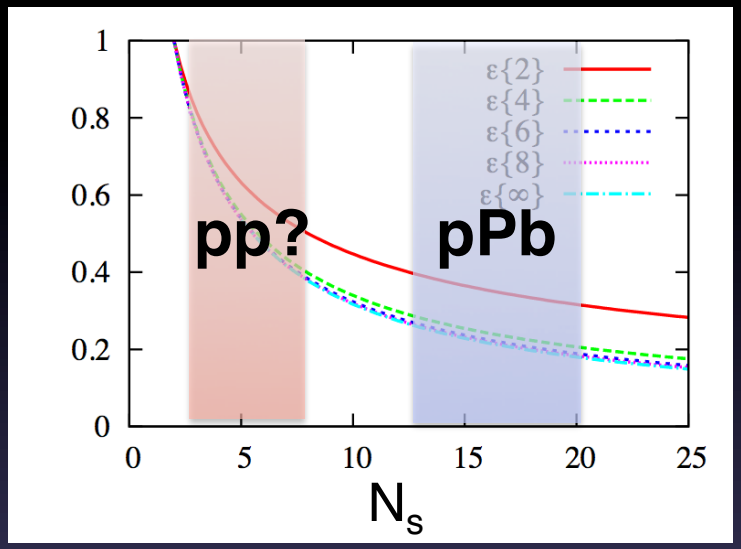

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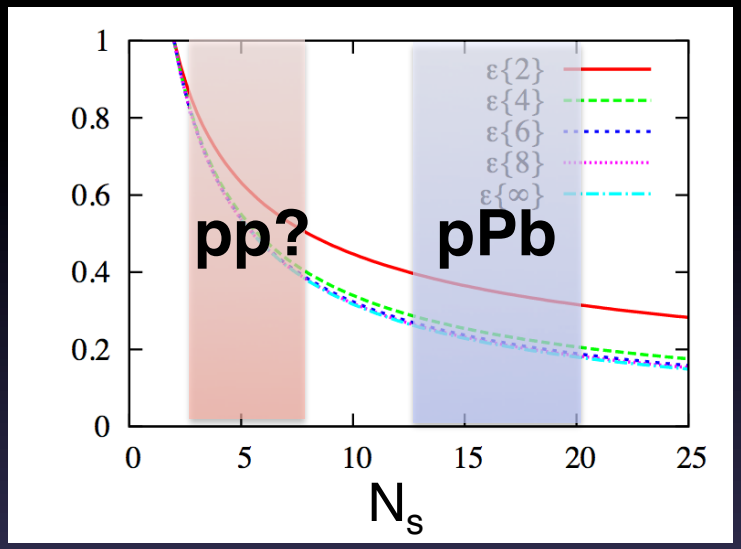

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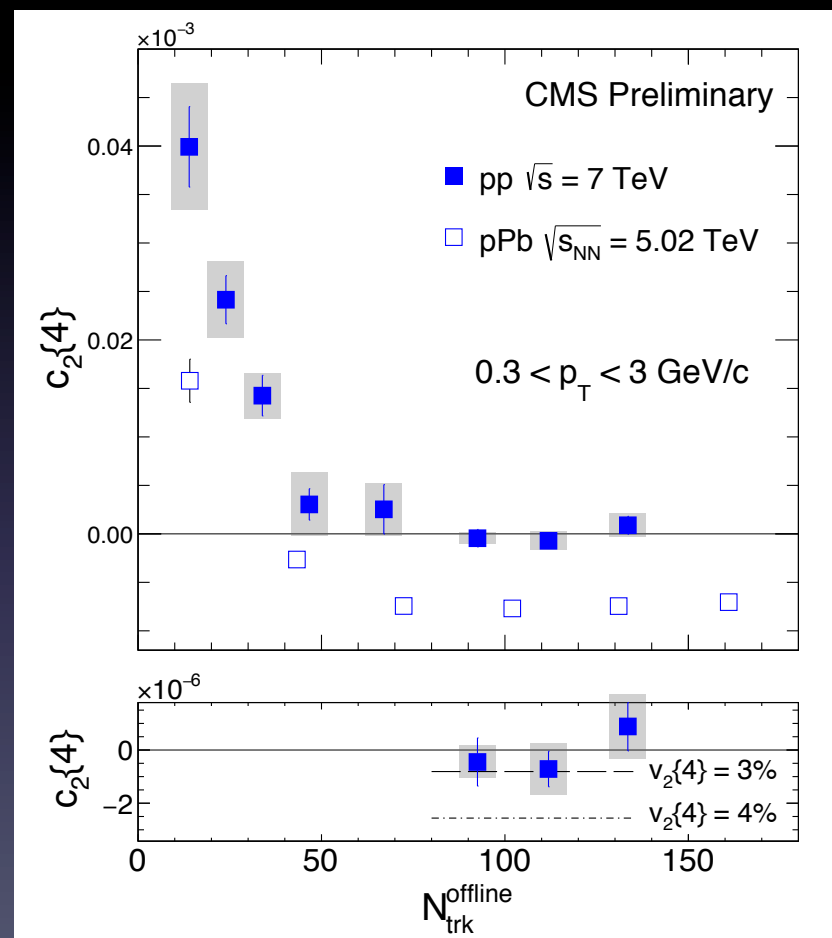
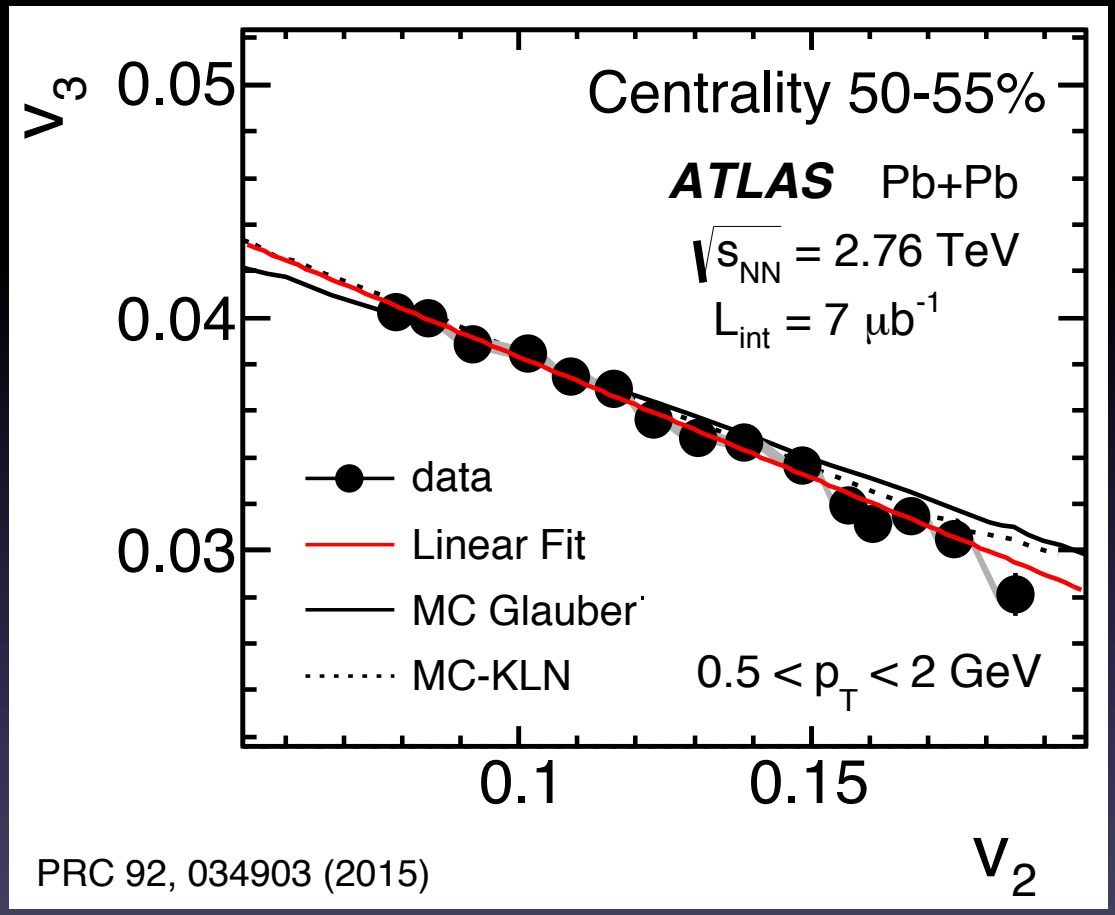
CMS-PAS-HIN-15-009



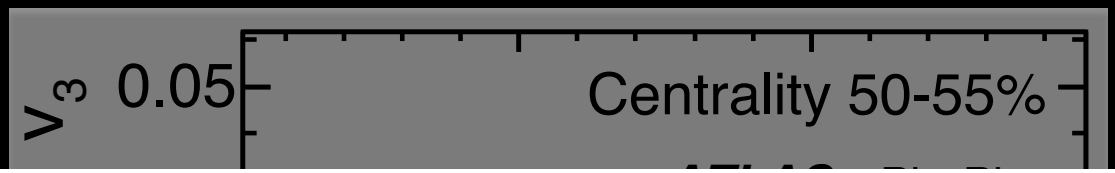
See experimental talks for new results later!

IS of small system: (III) v_n correlations

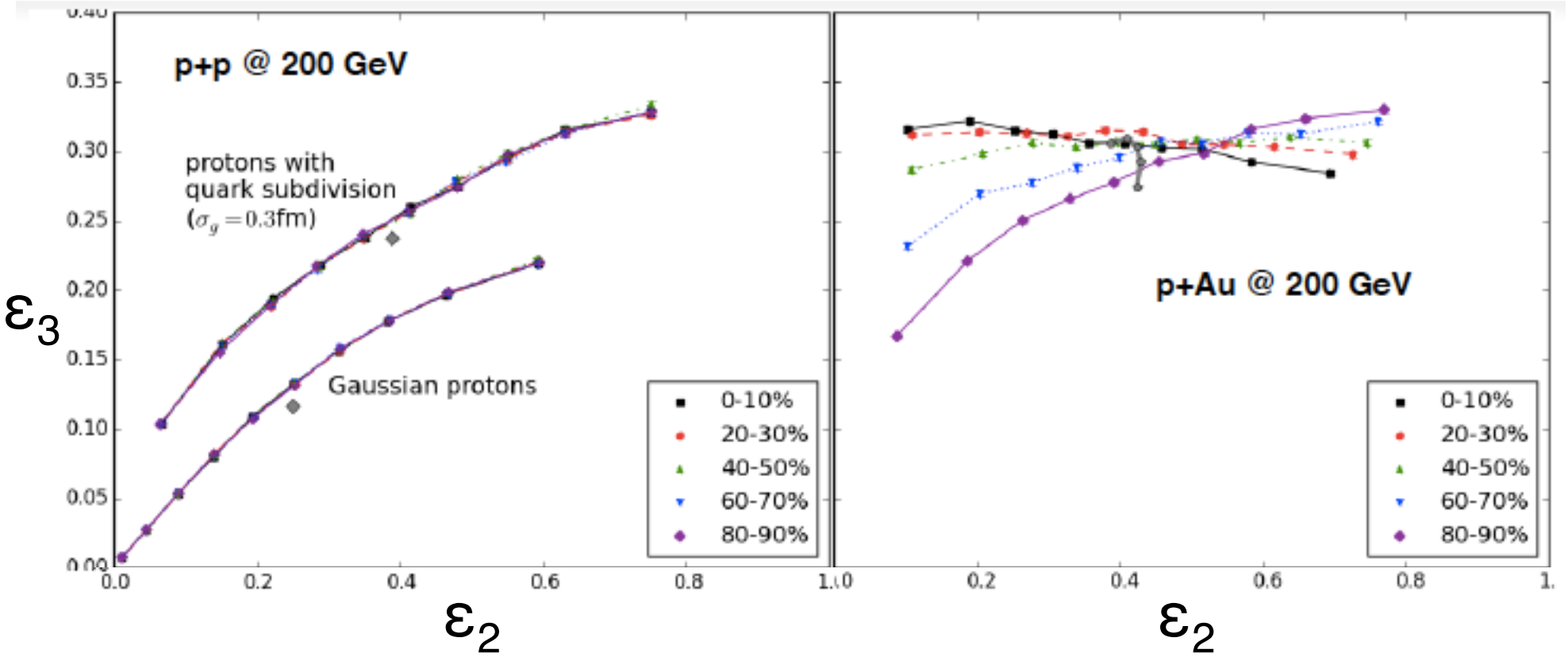


$v_2 - v_3$ correlation in AA from initial-state geometry

IS of small system: (III) v_n correlations



Uli's prediction, EIC users meeting 2016



Is it there in pp/pA systems?

IS of small system: (IV) factorization

Flow factorization breaking/PCA

$$V_{n\Delta}(p_T^a,\eta^a;p_T^b,\eta^b) \neq v_n(p_T^a,\eta^a)\times v_n(p_T^b,\eta^b)$$

(two-particle) (single-particle)

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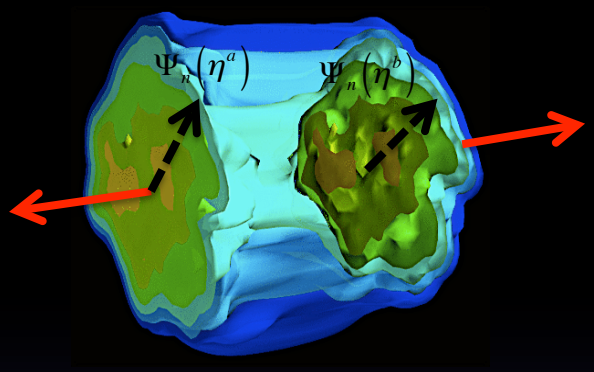

– caused **by "lumpiness"** of the initial state

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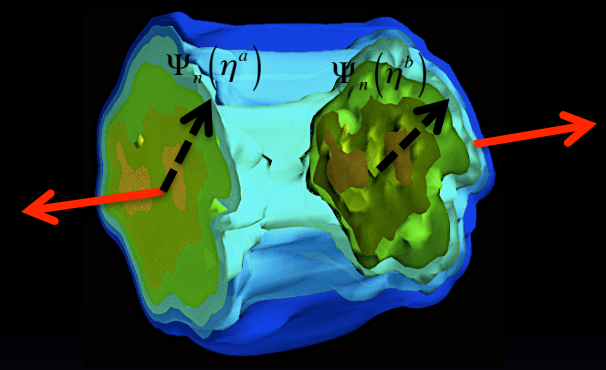

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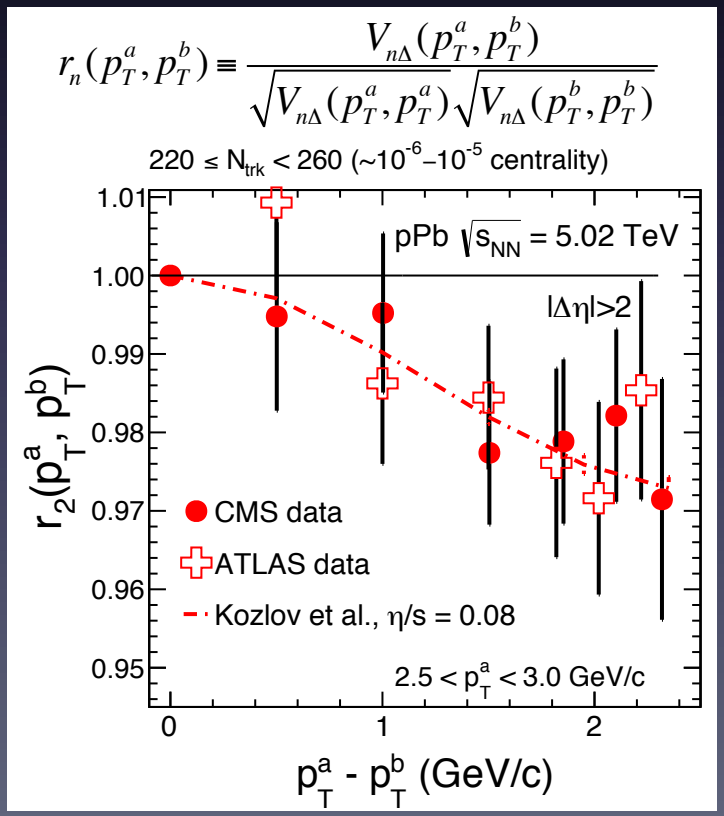
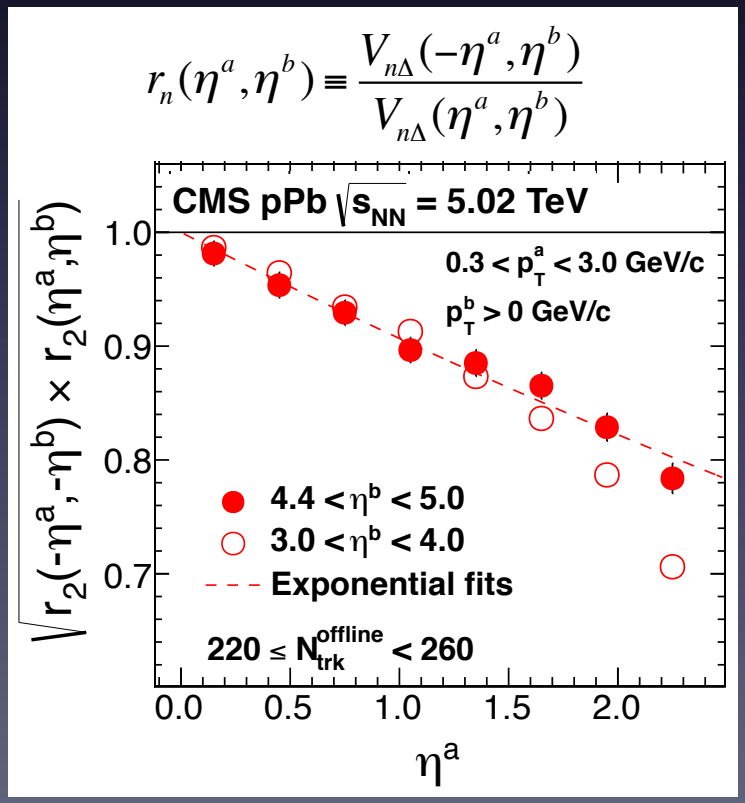
PRC 90, 044906 (2014), PRC92, 034911 (2015)





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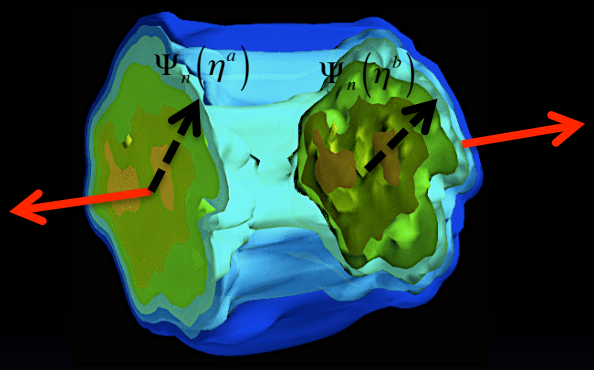

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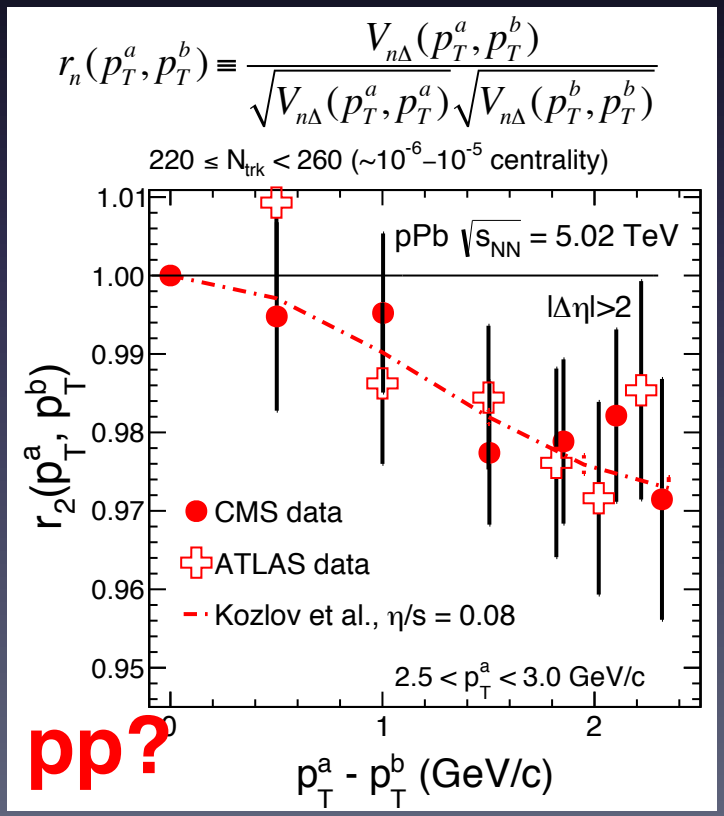

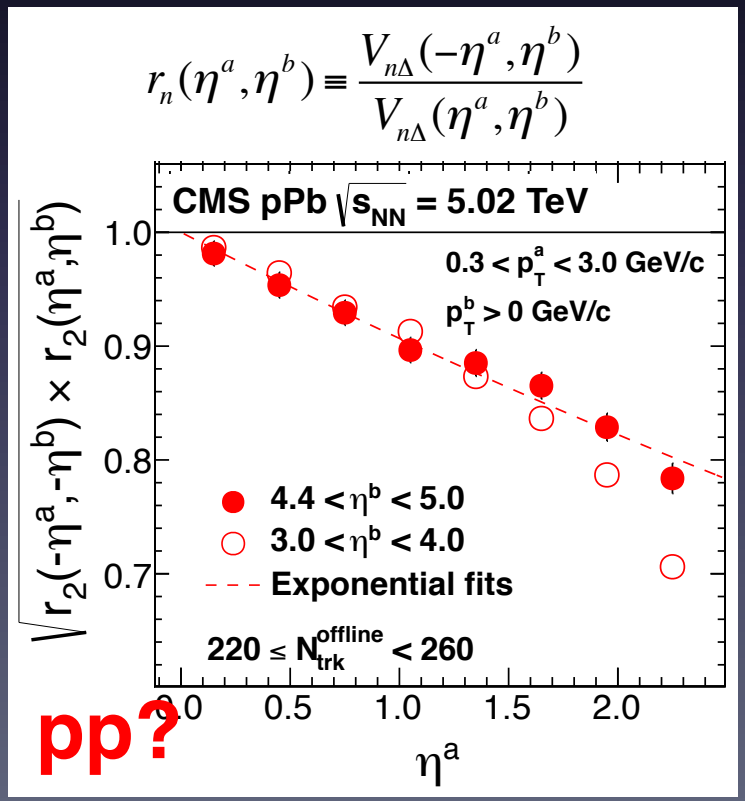

Summary

Clear evidence of *long-range, collective* phenomena in HM QCD systems

Initial spatial ε_s + final interactions

OR

Initial momentum ε_p from initial interactions

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QCD fluid in pp/pA? Connection to initial geometry is the key ingredient to be established in the future

Unique opportunity in pp/pA of probing fluctuations of proton substructure – *Test of fundamental QCD*

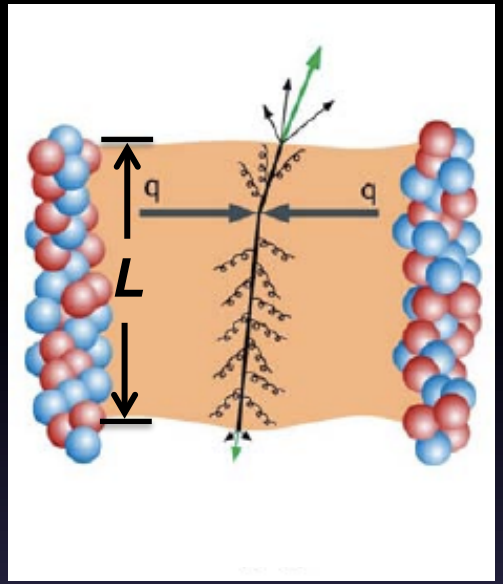
➡ Potential connection to future EIC program!

Backup

Jet quenching in small systems (?)

If ridge is flow → strongly interacting

→ **presence of jet quenching?**



In small system at fixed N_{trk}

L ↓ but $\hat{q}$ ($\sim T^3$) ↑

$$\Delta E \sim \alpha_s(T)\hat{q}(T)L^2$$

Who wins?

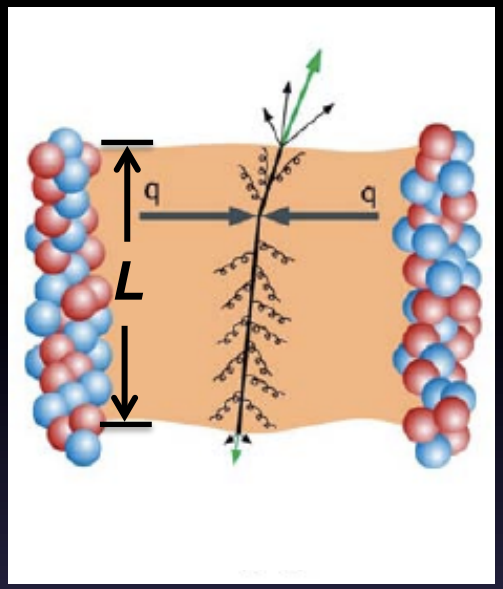
$$s \sim T^3$$
$$s \sim \frac{N_{trk}}{\pi L^2}$$

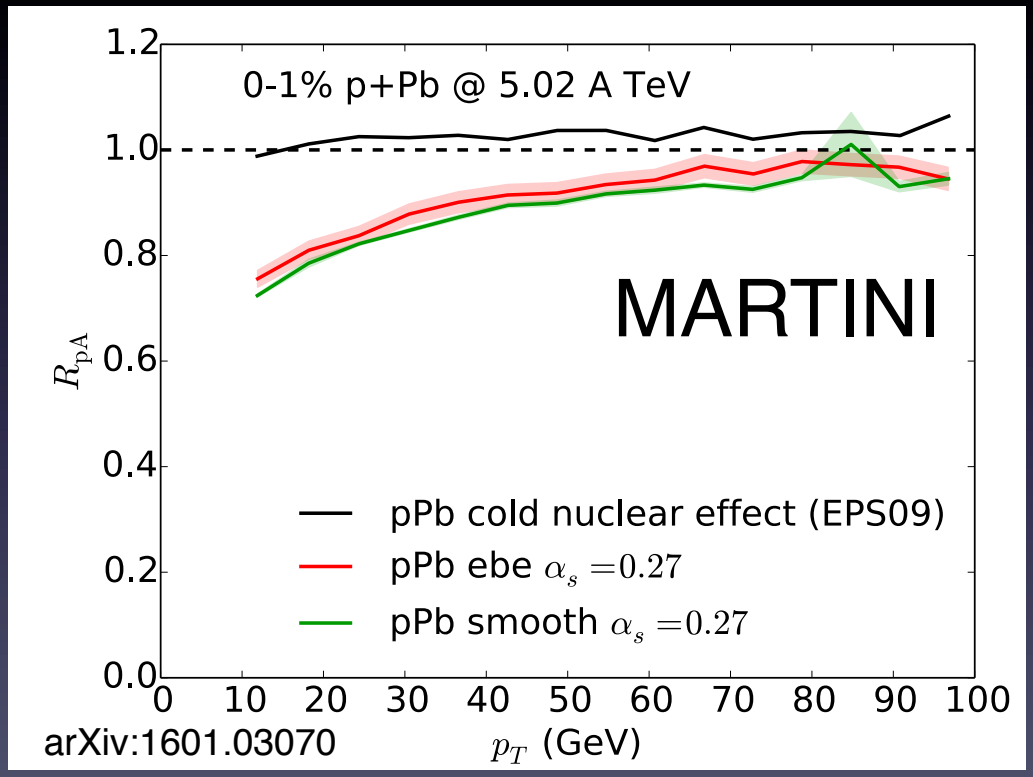
Roughly balanced

Jet quenching in small systems (?)

If ridge is flow ➔ strongly interacting

➔ presence of jet quenching?

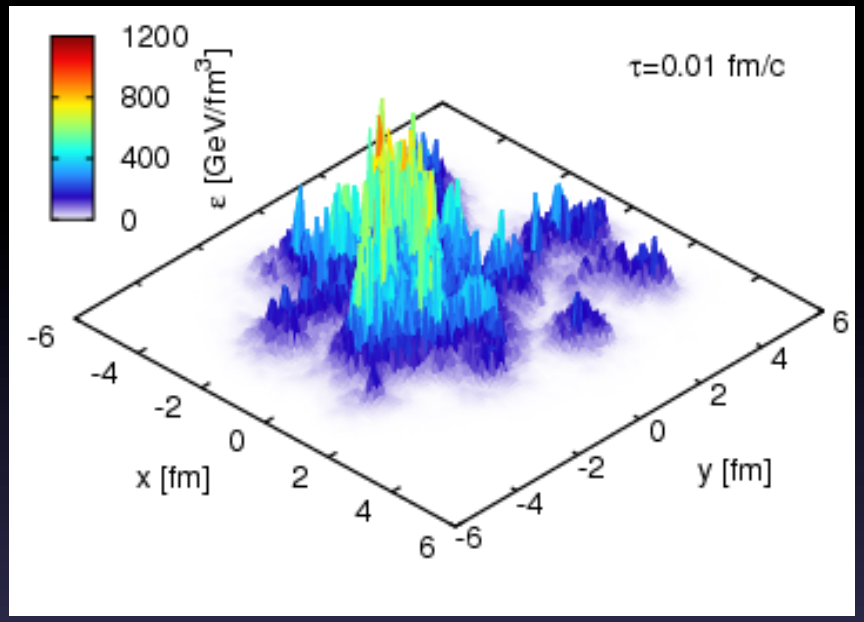


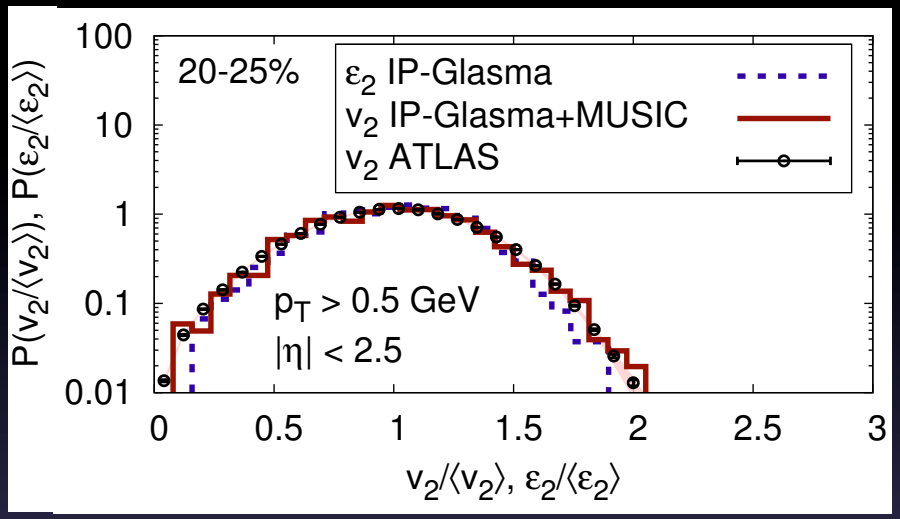


arXiv:1601.03070

Sizable suppression predicted for $p_T \sim$ 10-20 GeV/c

Misconception of IP-glasma model



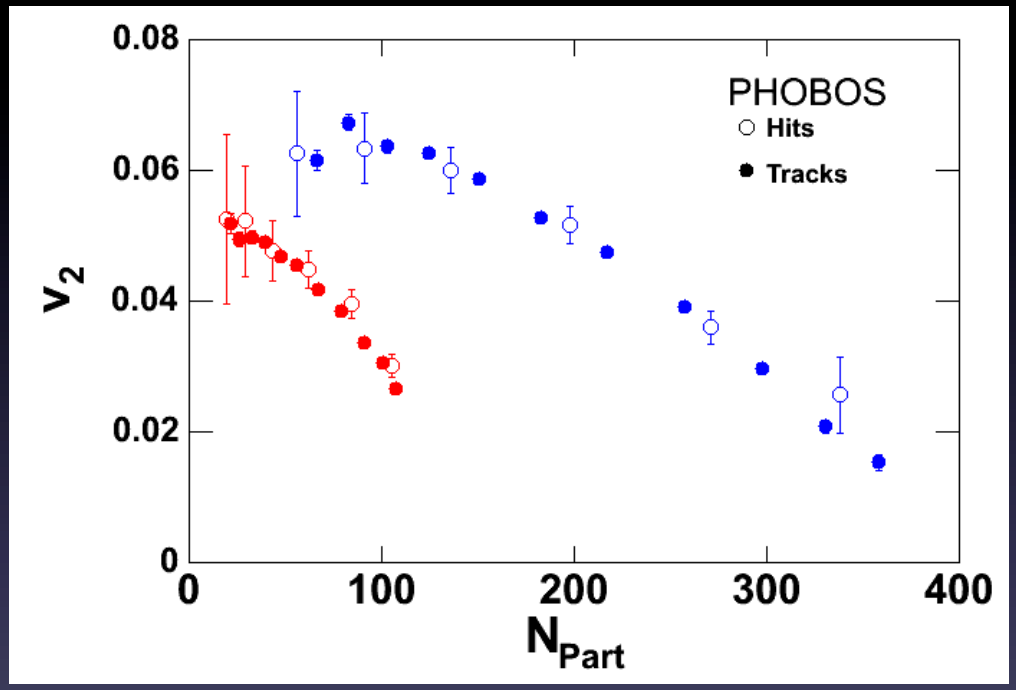


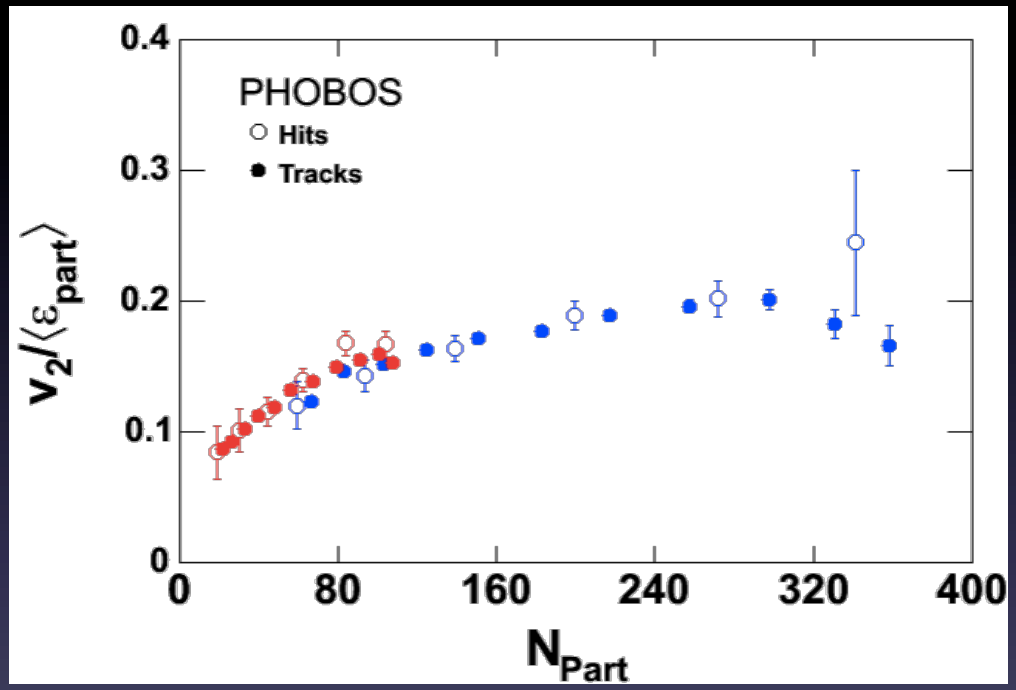
N. B. fluctuation of each N-N energy deposit

AA data NOT sensitive to subnucleonic structure

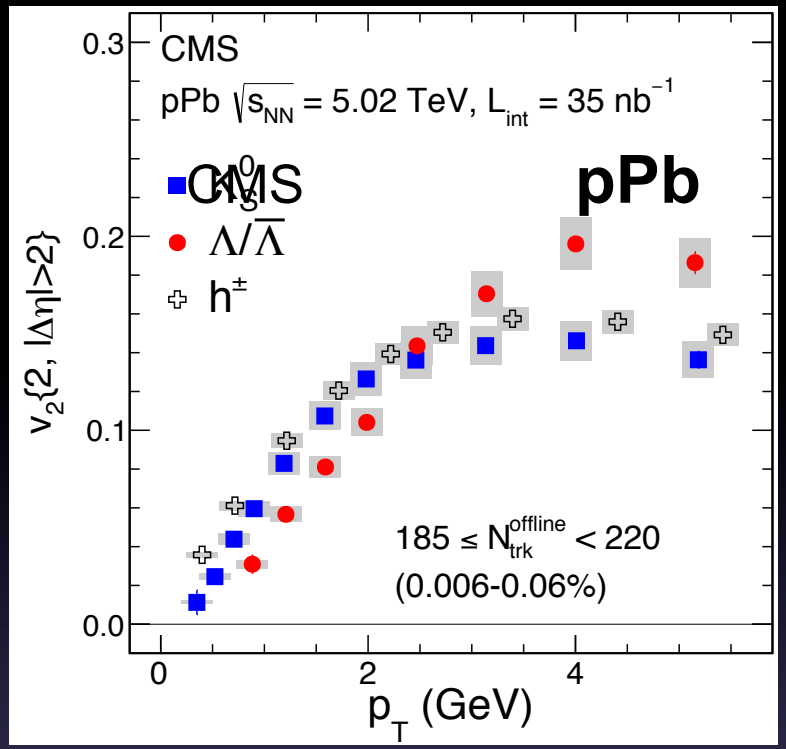
"Lumpiness" of proton can be probed by pA (or pp)

Connection to Geometry





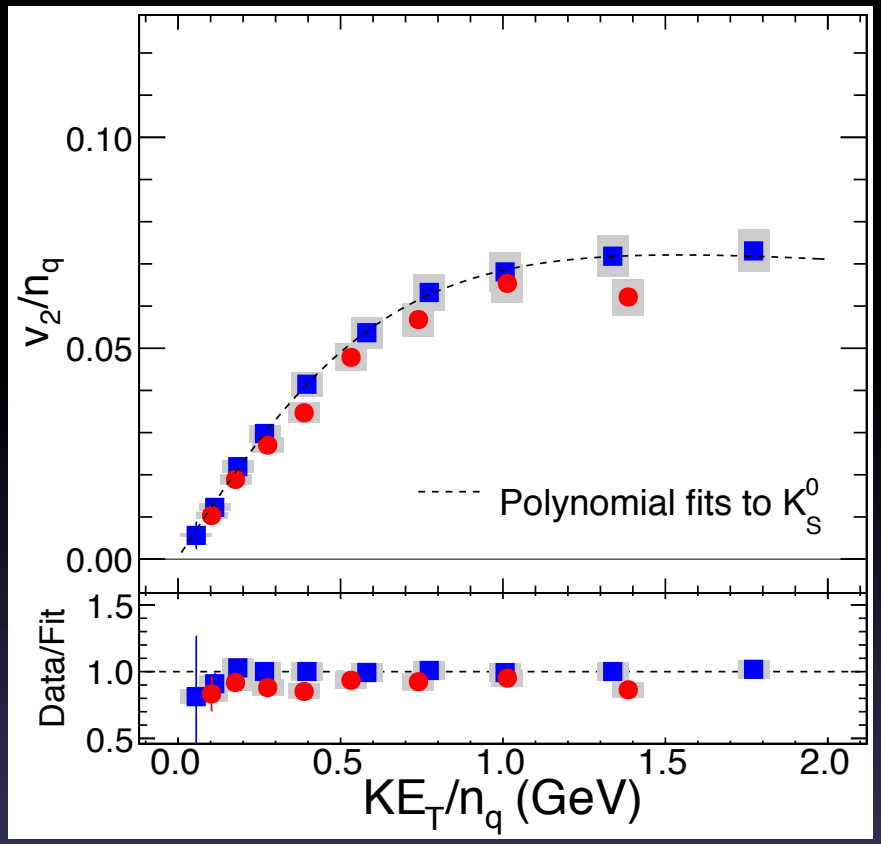
NCQ scaling in pPb system!



Baryon/meson crossing

scaled by n_q

K^0_s (n_q=2)
Λ (n_q=3)

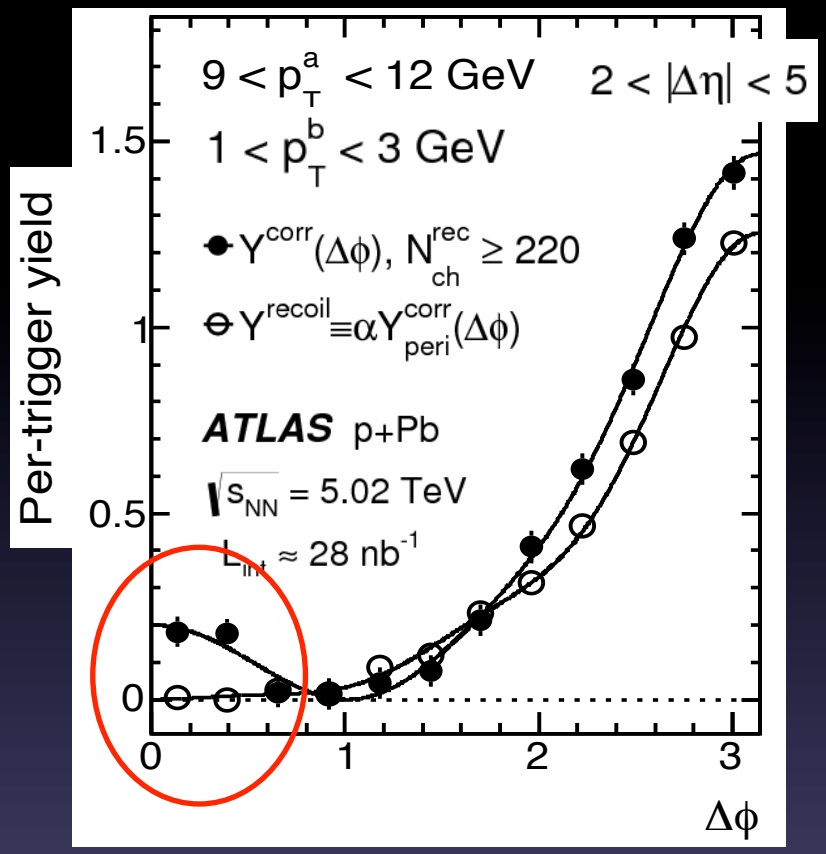


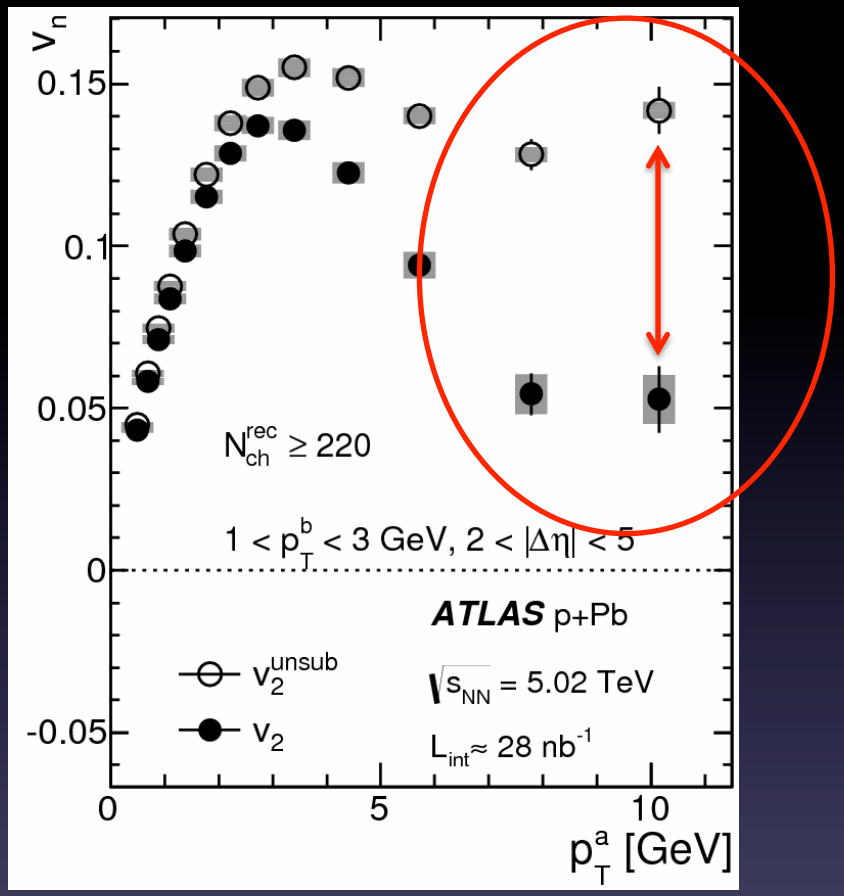
Flow developed at partonic level!?

Expected or surprising in pPb?

Amazing scaling in AA discovered 10 yrs ago in quest of explanations, esp. in light of pPb data

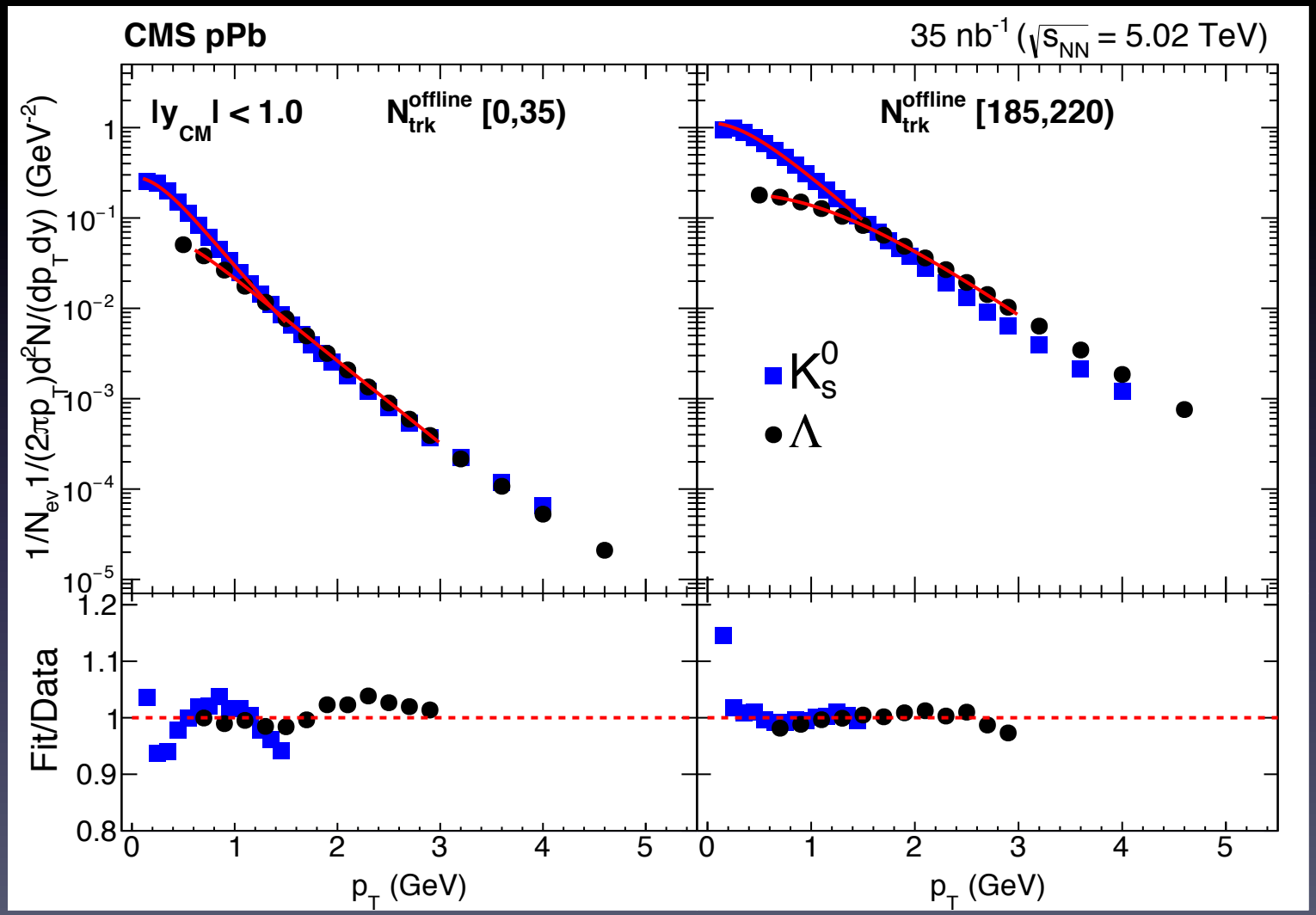
Ridge in pPb persists up to at least several GeV/c

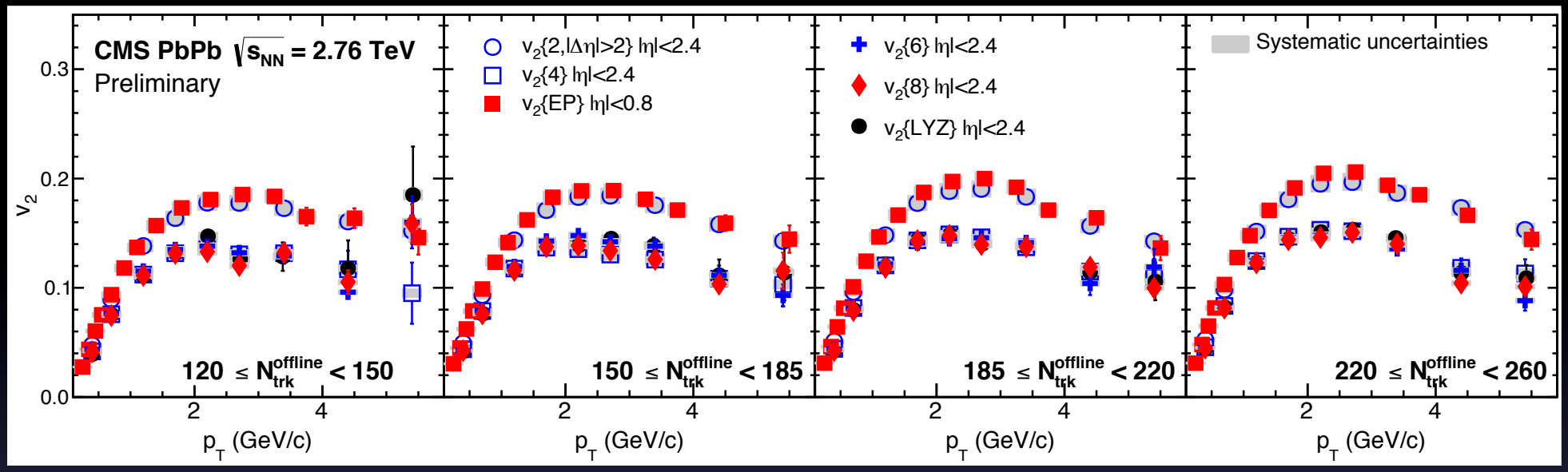


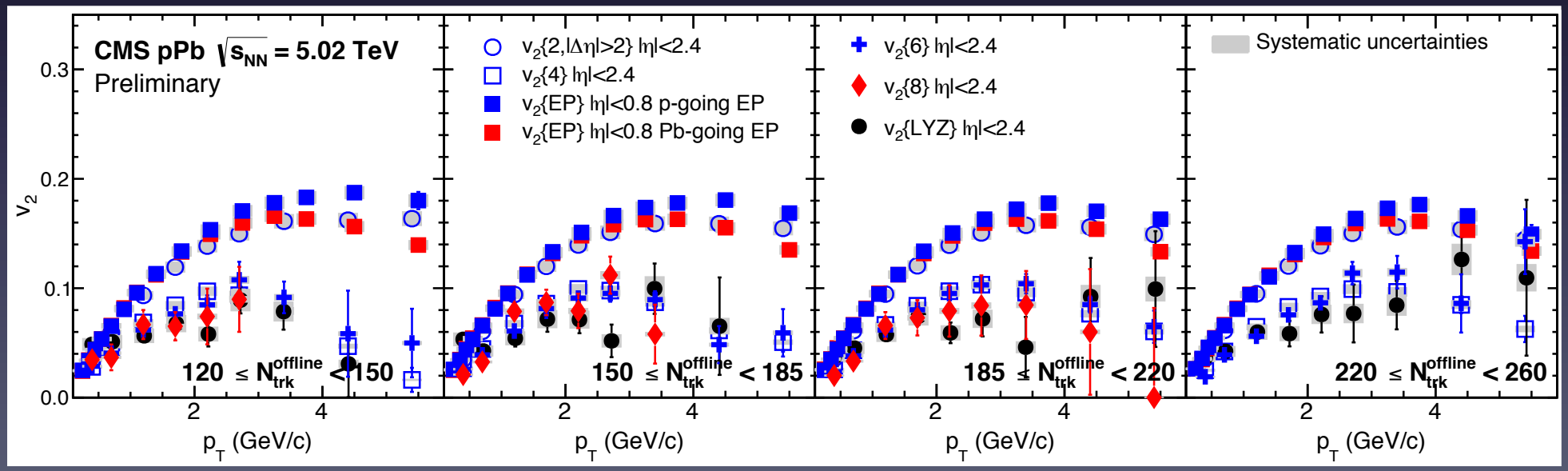


Sizeable $v_2 \sim 5\%$ (after a large subtraction)

Multiparticle correlations to test collectivity of high p_T particles


CMS pPb
35 nb^{-1} ($\sqrt{s_{NN}}$ = 5.02 TeV)
$|y_{CM}| < 1.0$
$N_{trk}^{offline}$ [0,35)
$N_{trk}^{offline}$ [185,220)
K_S^0
Λ
$1/N_{ev}\, 1/(2\pi p_T) d^2N/(dp_T dy)$ (GeV^{-2})
Fit/Data
p_T (GeV)


CMS PbPb √sNN = 2.76 TeV
Preliminary
v2{2,|Δη|>2} |η|<2.4
v2{4} |η|<2.4
v2{EP} |η|<0.8
v2{6} |η|<2.4
v2{8} |η|<2.4
v2{LYZ} |η|<2.4
Systematic uncertainties
v2
pT (GeV/c)
120 ≤ Ntrk offline < 150
150 ≤ Ntrk offline < 185
185 ≤ Ntrk offline < 220
220 ≤ Ntrk offline < 260


CMS pPb √sNN = 5.02 TeV
Preliminary
v2{2,|Δη|>2} |η|<2.4
v2{4} |η|<2.4
v2{EP} |η|<0.8 p-going EP
v2{EP} |η|<0.8 Pb-going EP
v2{6} |η|<2.4
v2{8} |η|<2.4
v2{LYZ} |η|<2.4
Systematic uncertainties
v2
pT (GeV/c)
120 ≤ Ntrk offline < 150
150 ≤ Ntrk offline < 185
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