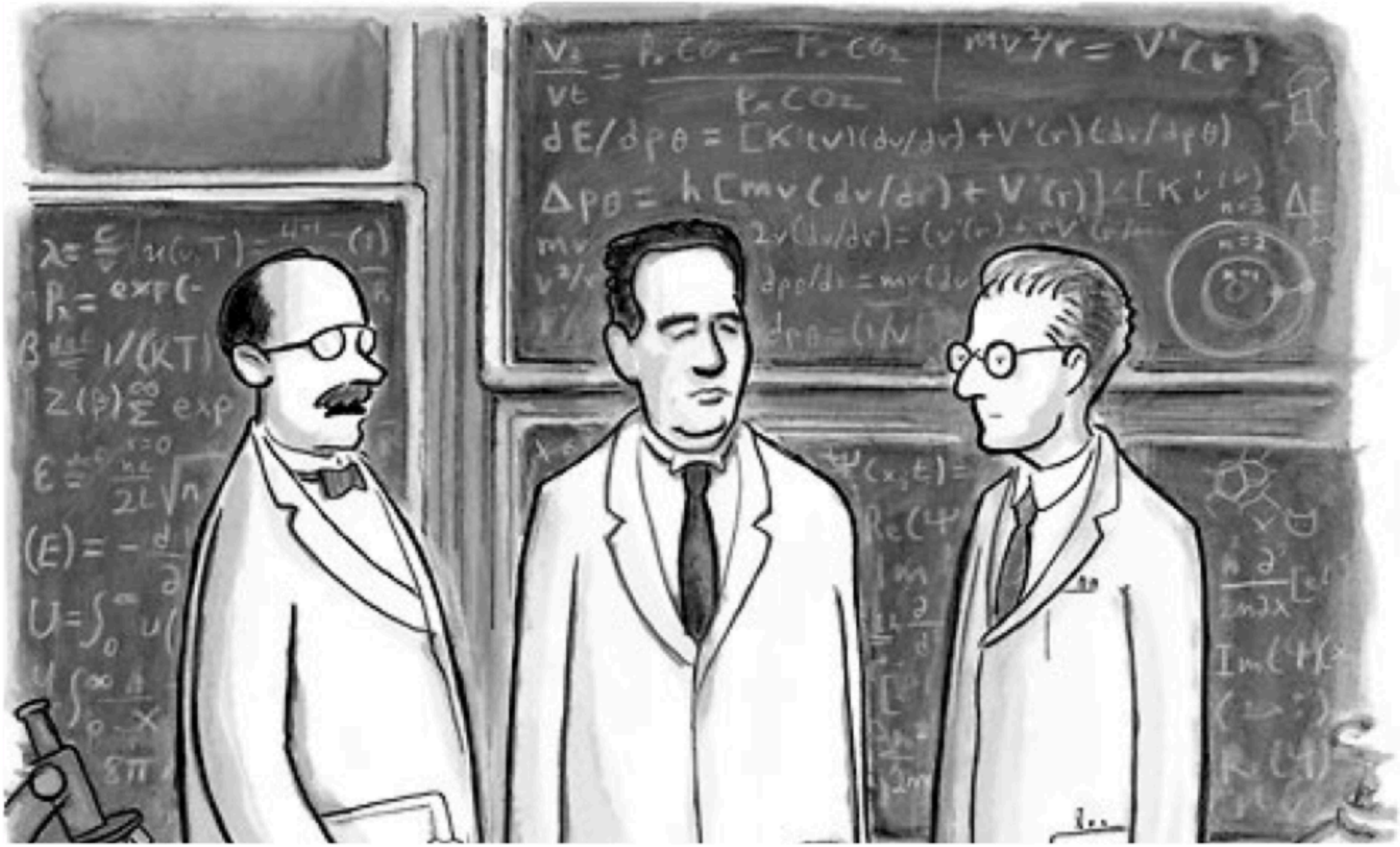
Is a QGP fluid created in pp/pA and why it's a question of importance?

– some perspectives on the key questions

Wei Li
Rice University

Workshop on Collectivity in Small Collision Systems
Copenhagen, Denmark, May 9 – 11



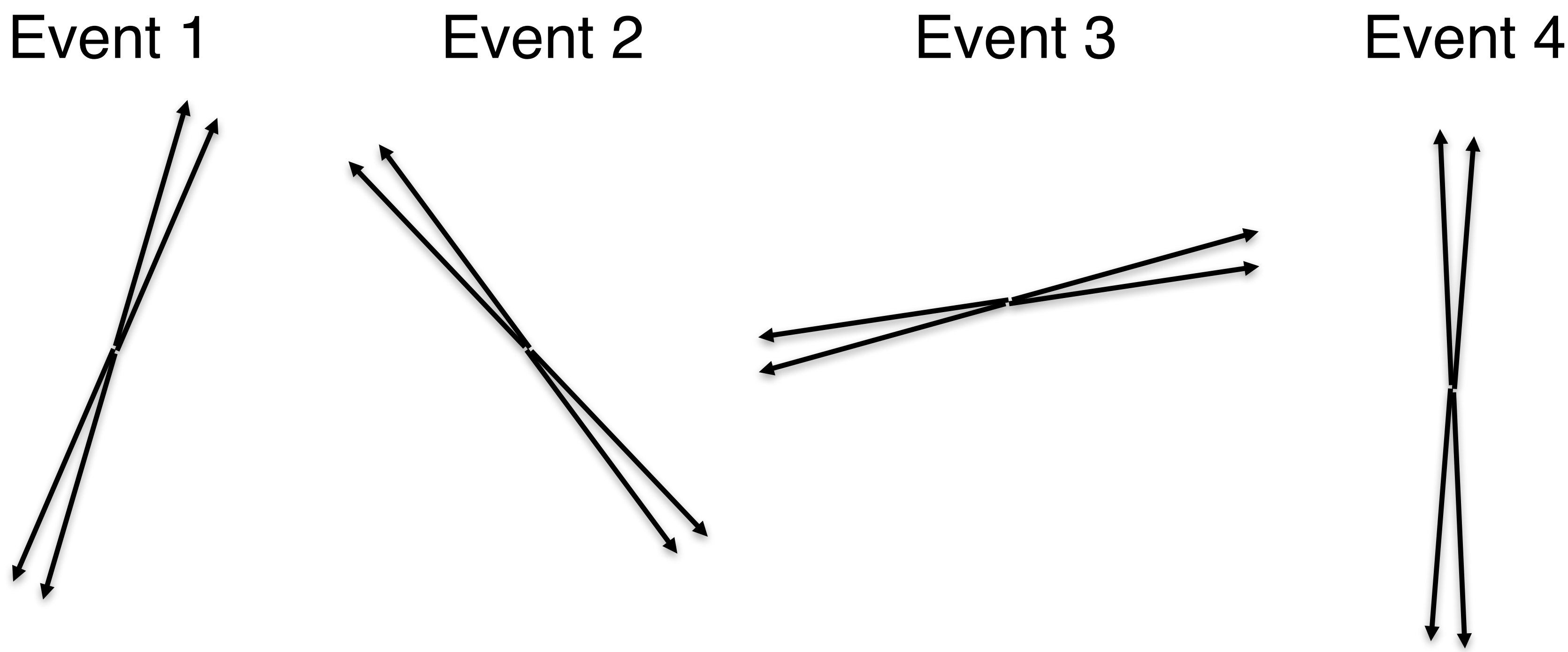
Is there collectivity in small systems? Copenhagen interpretation @

Workshop on Collectivity in Small Collision Systems

Let's address this first!

What is collective and what is not?

Collectivity can be defined to arbitrarily low N_{trk} ($\geq$2)



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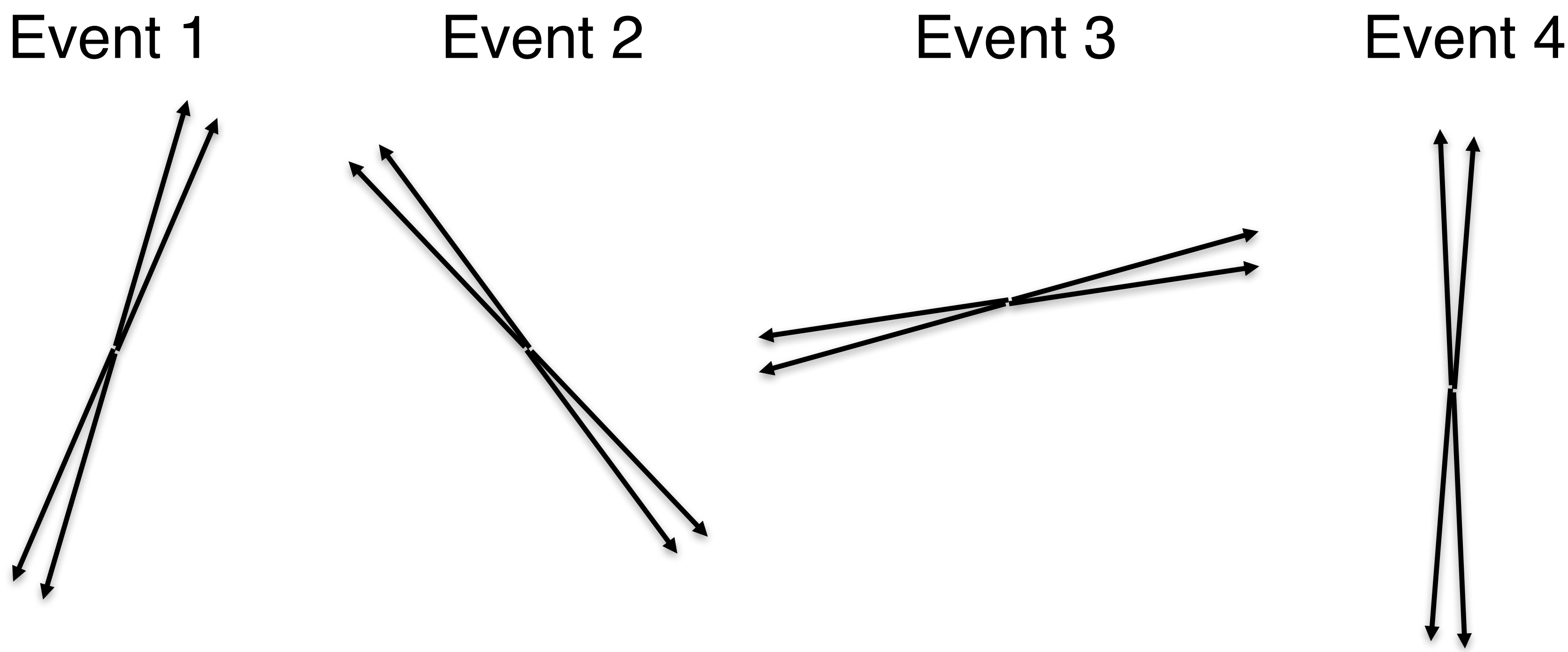


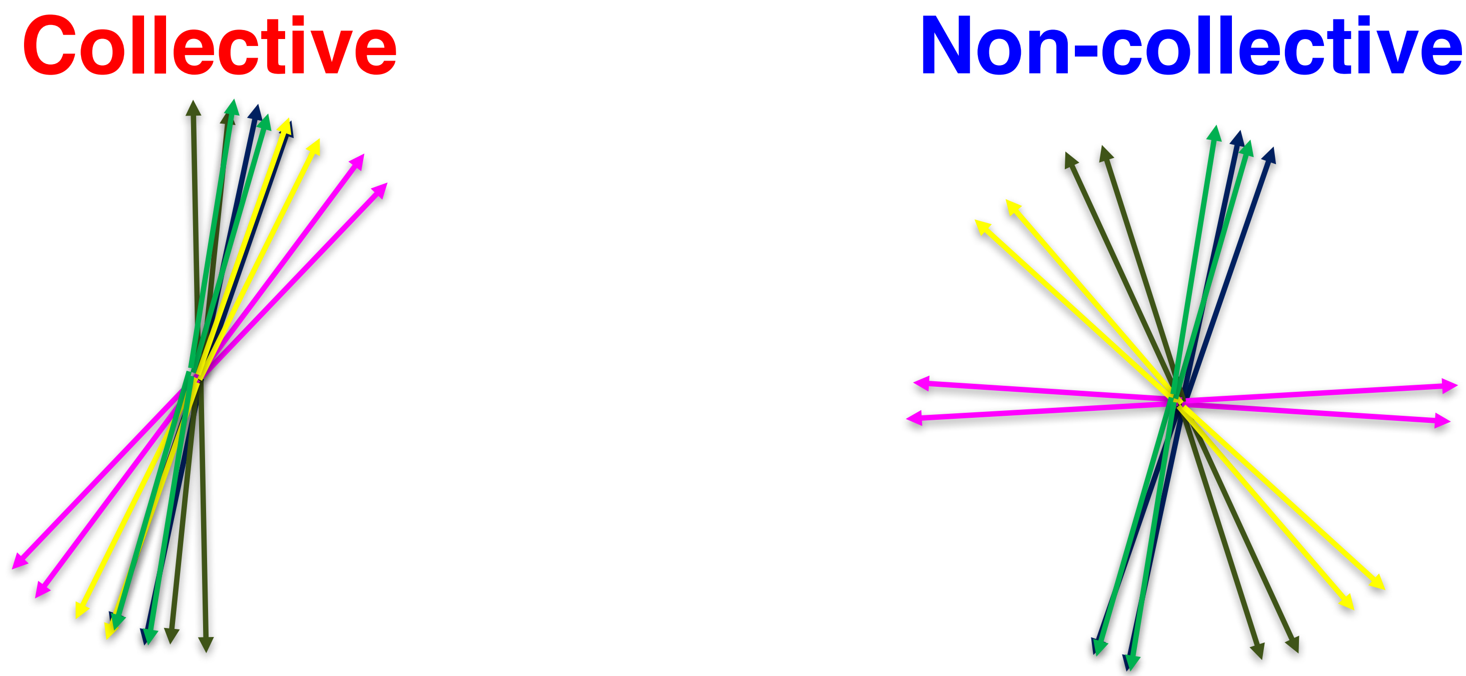
but indistinguishable from "trivial" pQCD processes

Not very interesting!

What is collective and what is not?

More interested in **multi-particle** collectivity:

"High" Multiplicity >> cluster size



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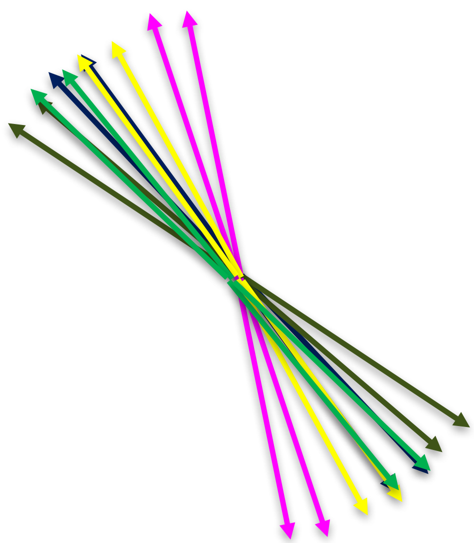
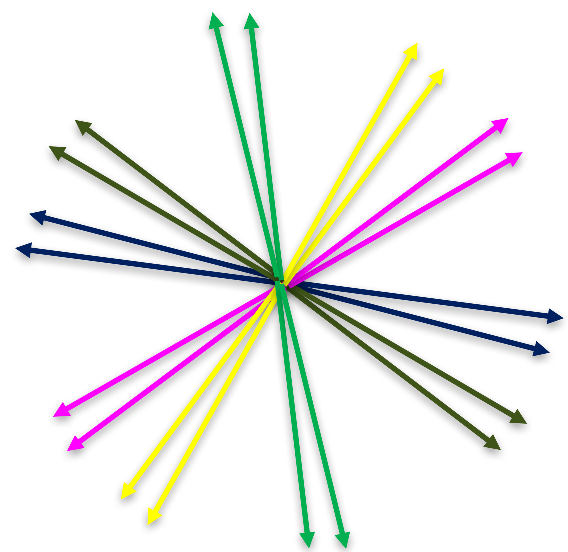


Non-collective



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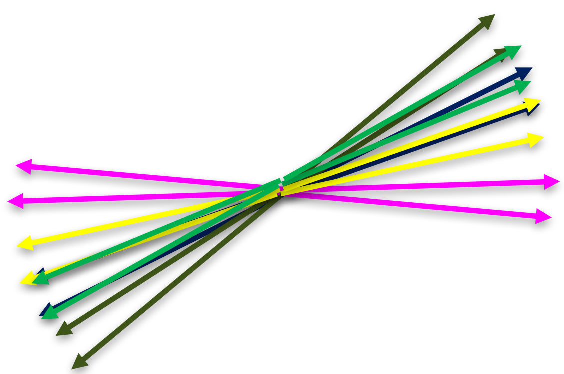

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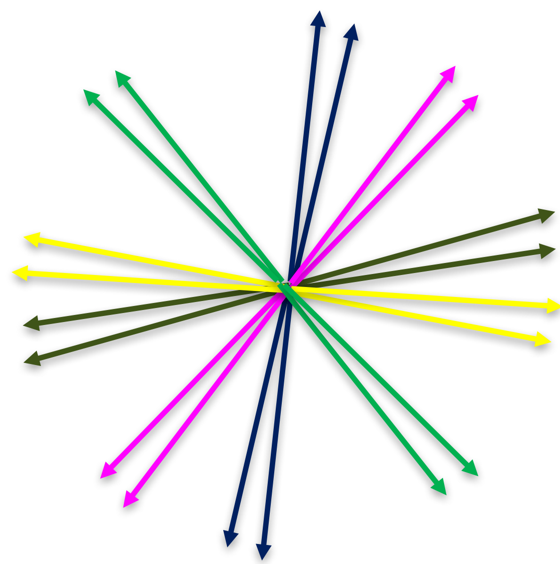

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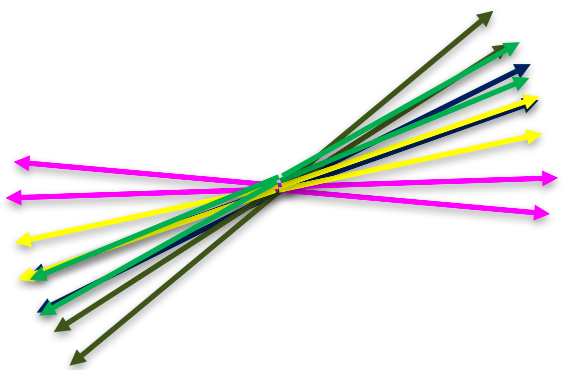

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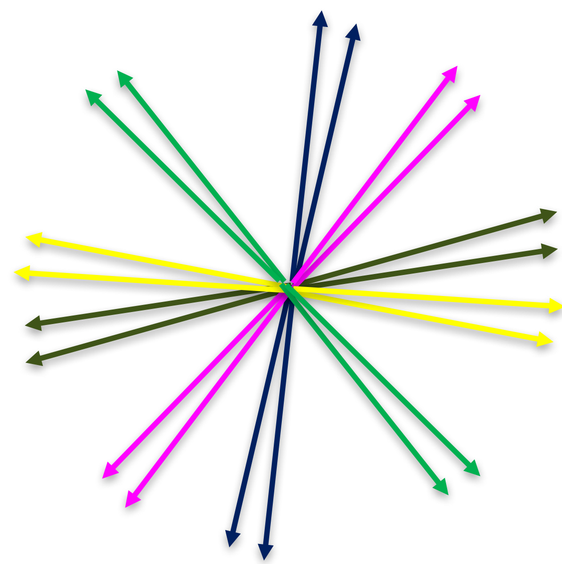

Cumulants designed to suppress few-body correlations

$v_2\{2\} \approx v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

$(c_2\{2\}>0,\ c_2\{4\}<0,\ c_2\{6\}>0,\ c_2\{8\}<0)$

→ A strong evidence for collectivity

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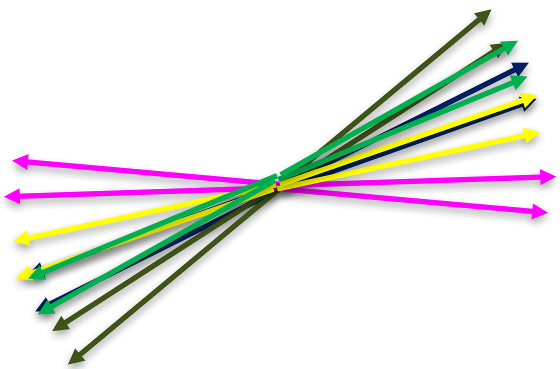

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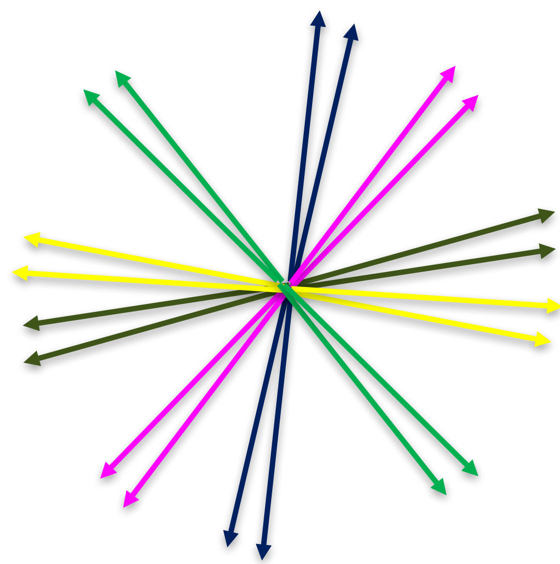

“Right” sign and mag. of $c_2\{m\} \rightarrow$ likely collective

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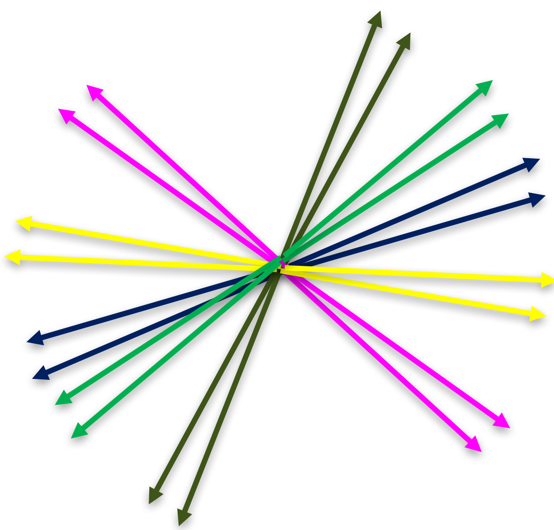

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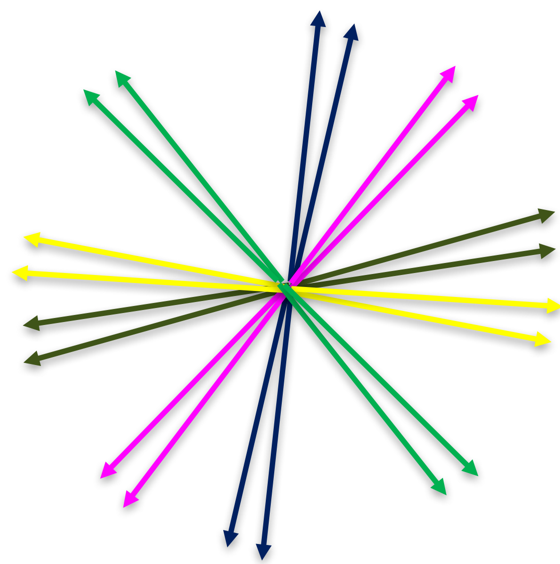

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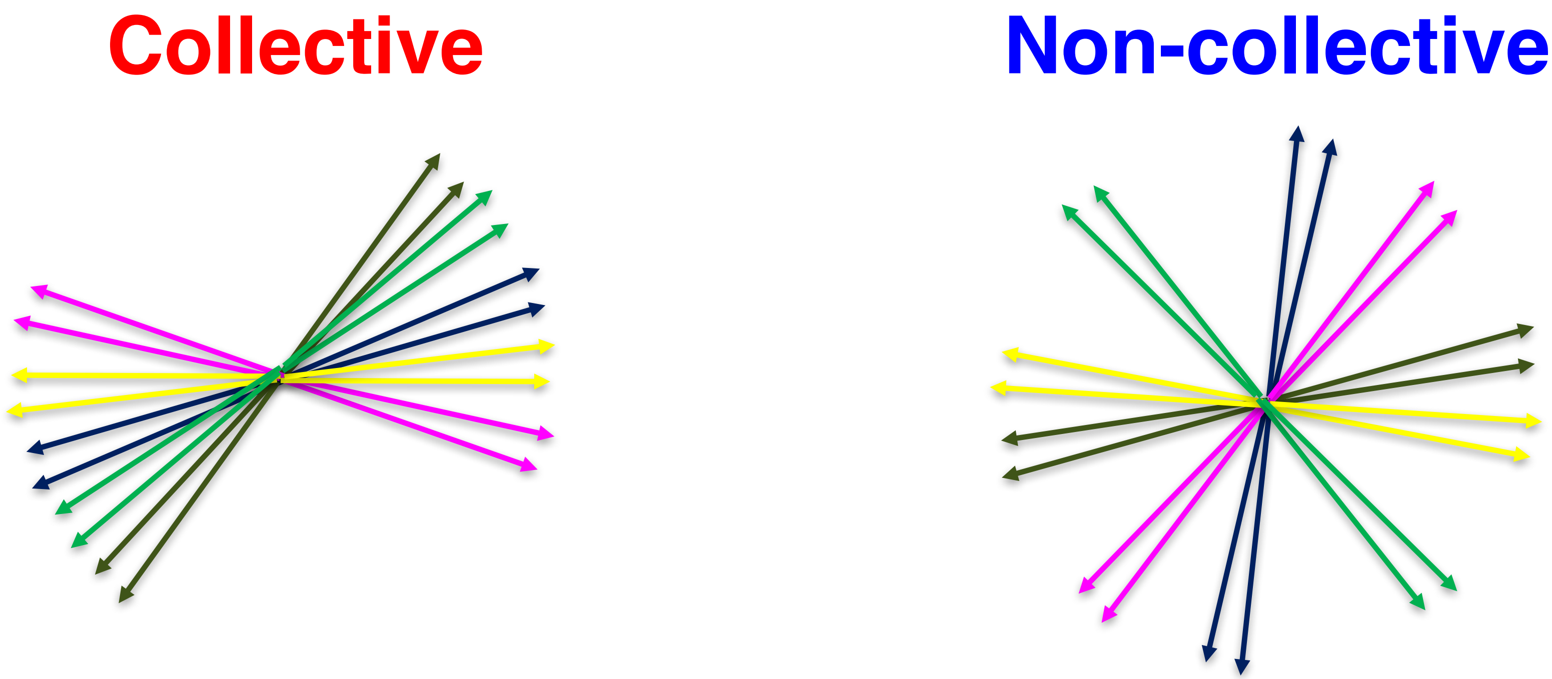

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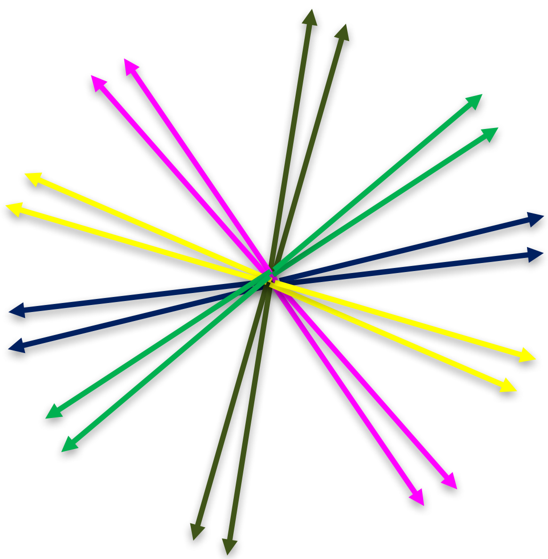

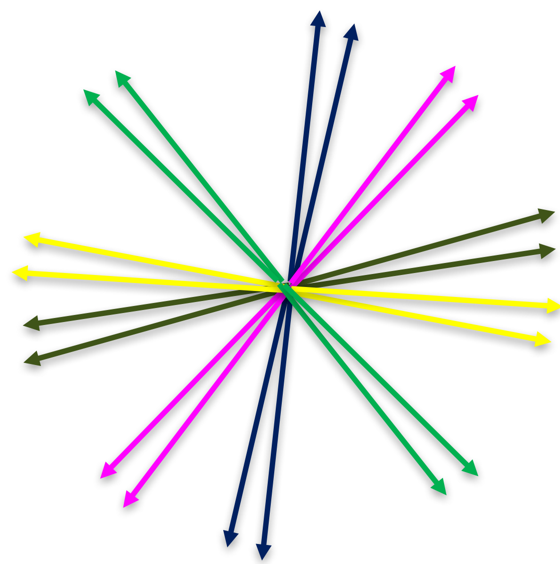

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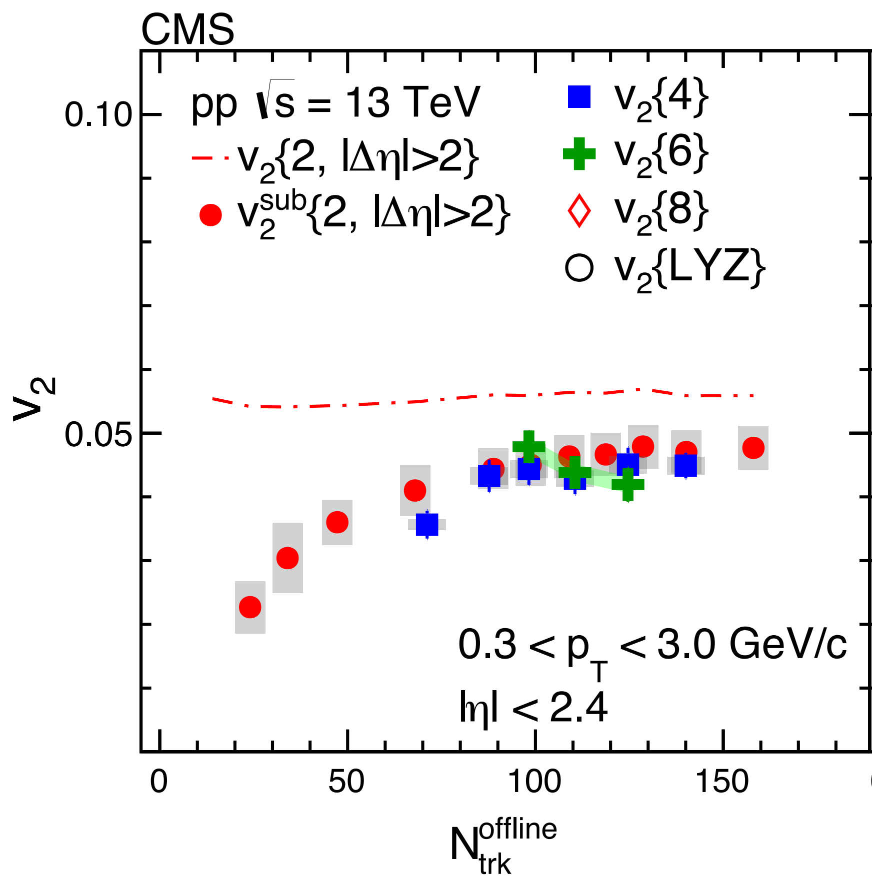
Collectivity seen in "HM" small systems

Evidence for collectivity in pp collisions at the LHC

The CMS Collaboration * Physics Letters B 765 (2017) 193–220



$v_2\{4\} \approx v_2\{6\} \approx \ldots$
Multiplicity independent

Collective anisotropies at high multiplicity

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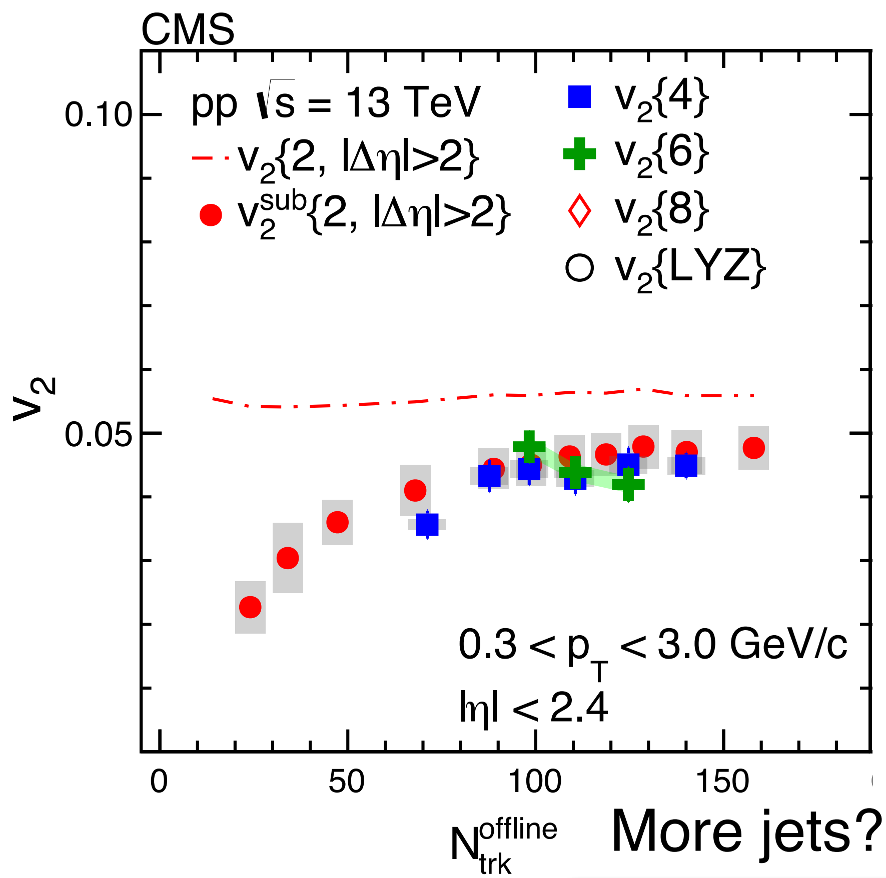


More jets?

$v_2\{4\} \approx v_2\{6\} \approx \dots$
Multiplicity independent

Collective anisotropies at high multiplicity

very hard jets (>10 GeV): rare

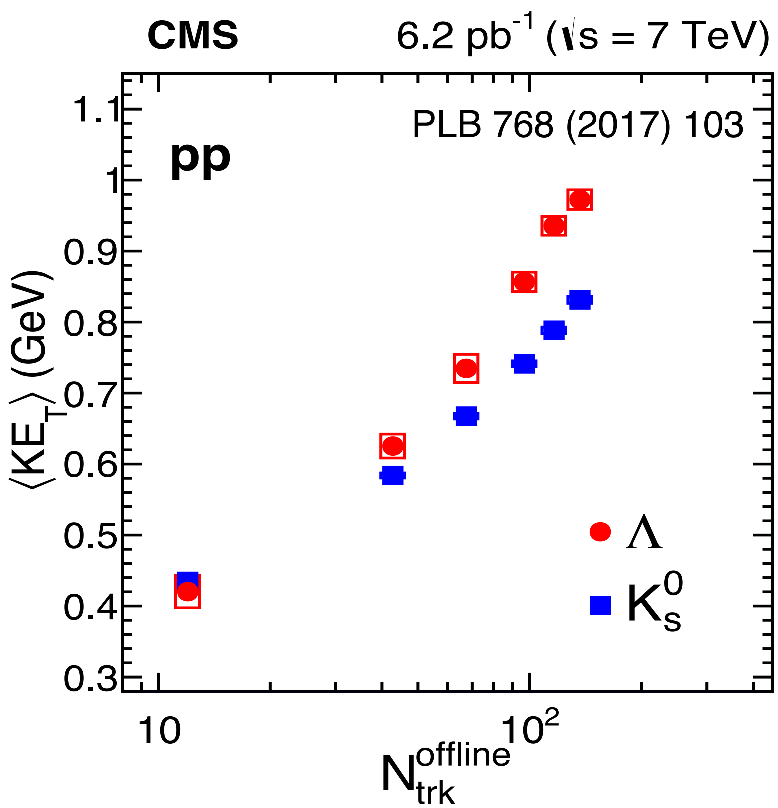
semi-hard (< a few GeV): interact and flow

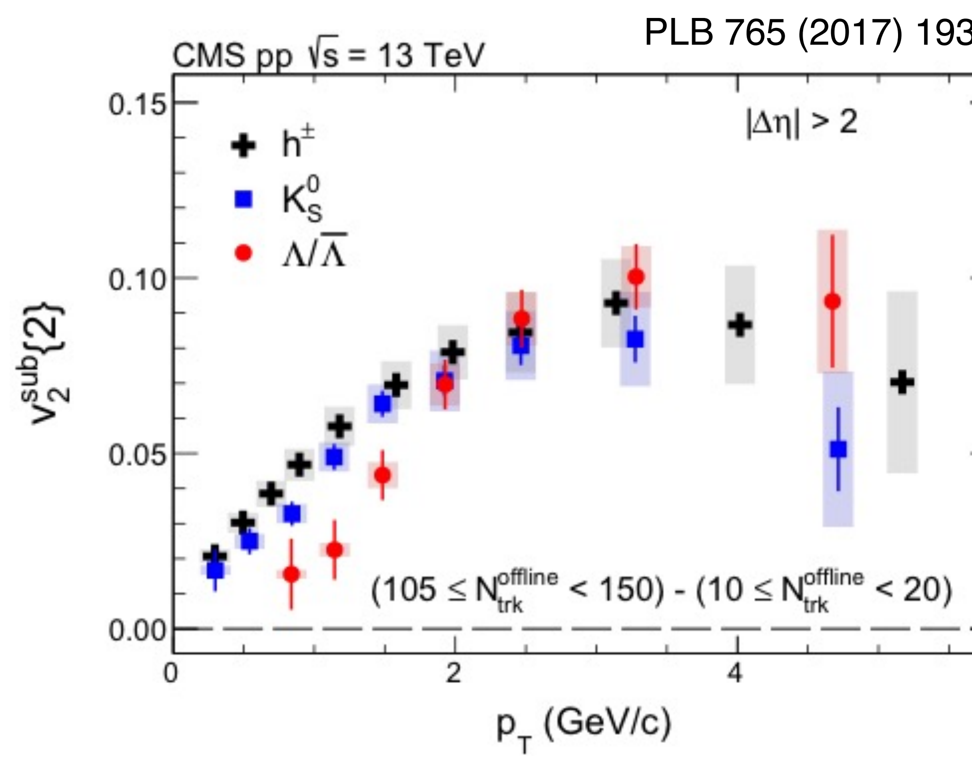
Collectivity seen in "HM" small systems

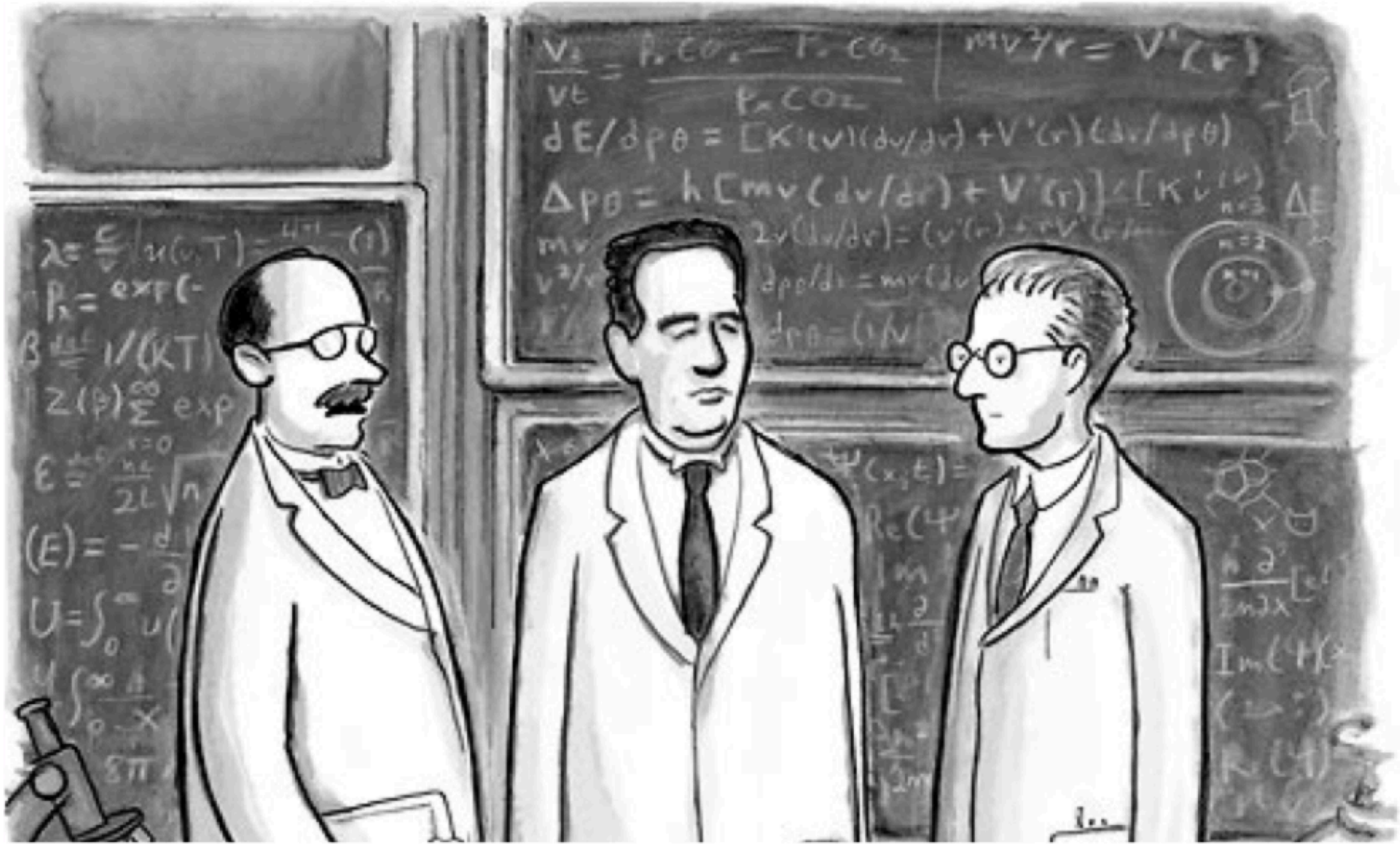
More evidence of collectivity in pp …

Mass-proportional splitting

➡ **Radial collective emission** of a moving source







Is there collectivity in small systems? Copenhagen interpretation @ ***Workshop on Collectivity in Small Collision Systems***

Ample experimental data consistent with novel **collective** **long-range** correlations in small systems

Have we created a tiny QGP fluid?

"Hydrodynamic" scenario

Initial spatial ε_s at $\tau=0$

\+ Pressure gradient
(**final-state** interactions)

Feasibly, and it is the accepted paradigm in AA

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Initial momenta ε_p at $\tau \leq 0$ by **initial** interactions

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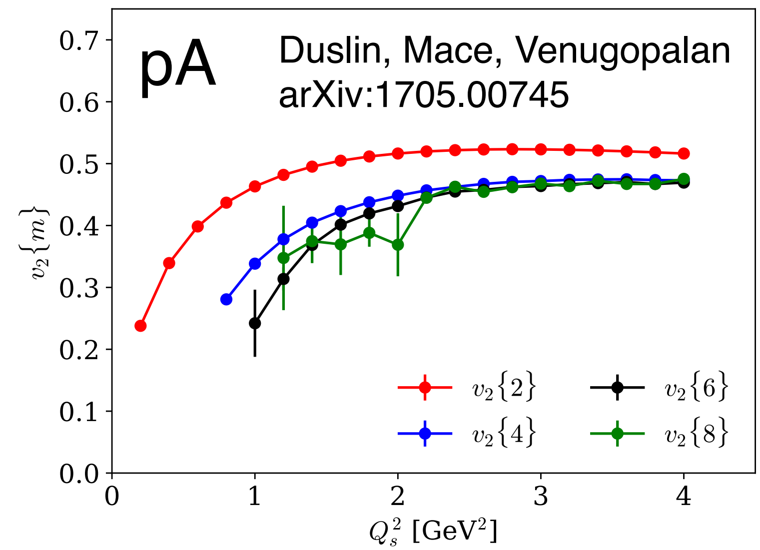
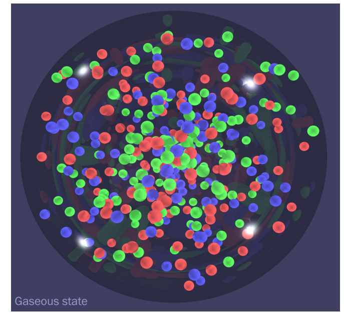
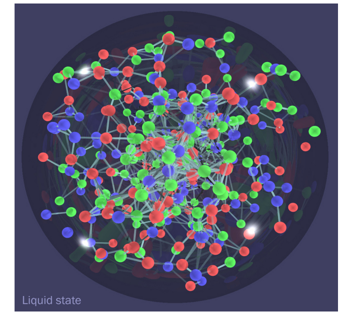


The fact that this behavior is reproduced in a simple initial state model is a proof of principle that it is not unique to interpretations of collectivity arising from the hydrodynamic response of the system to the n-th moments of m particle spatial eccentricities [44, 45]. For a

Have we created a tiny QGP fluid?





RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

Monday, April 18, 2005

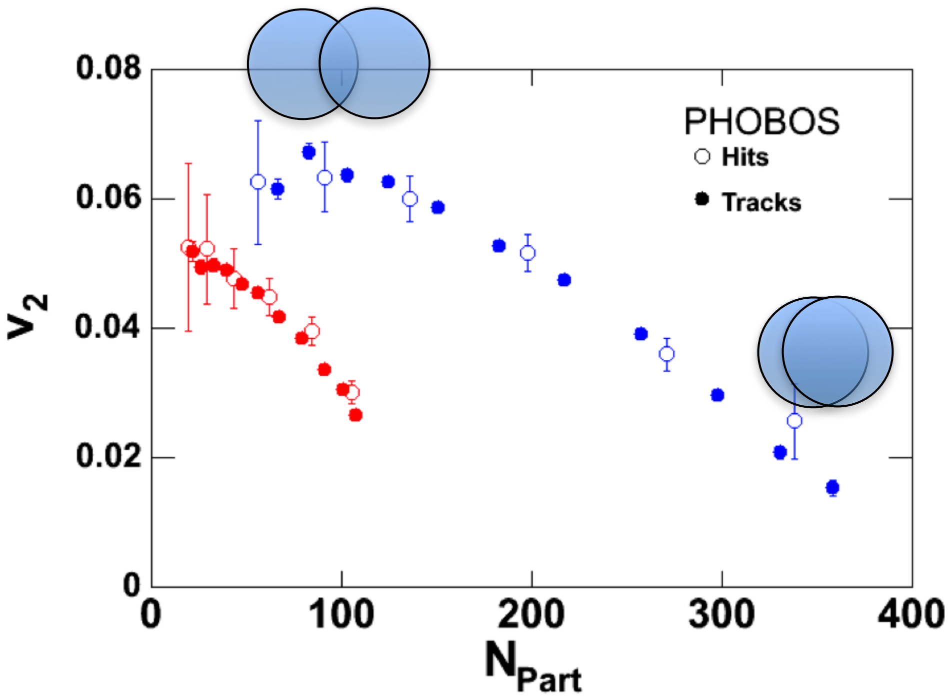
TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

Why we aren't debating "Hydro" vs "CGC" in AA?

What does it still take to reach a consensus on the origin of collectivity in small systems (pp/pA)?

“Perfect” fluid paradigm in AA

- **Geometry (ε_s) at work!**



Centrality dependence

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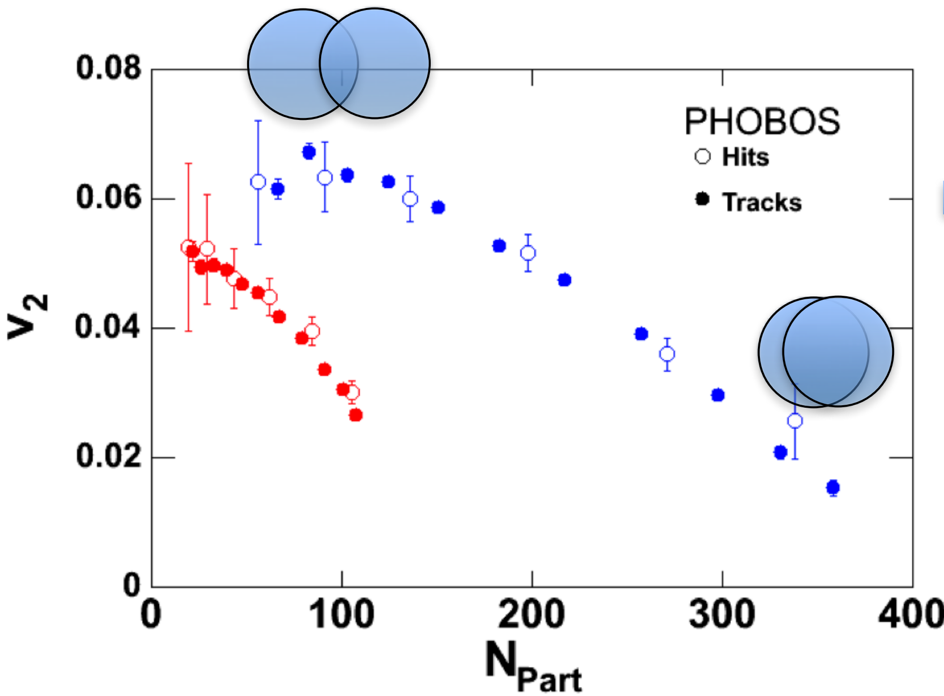
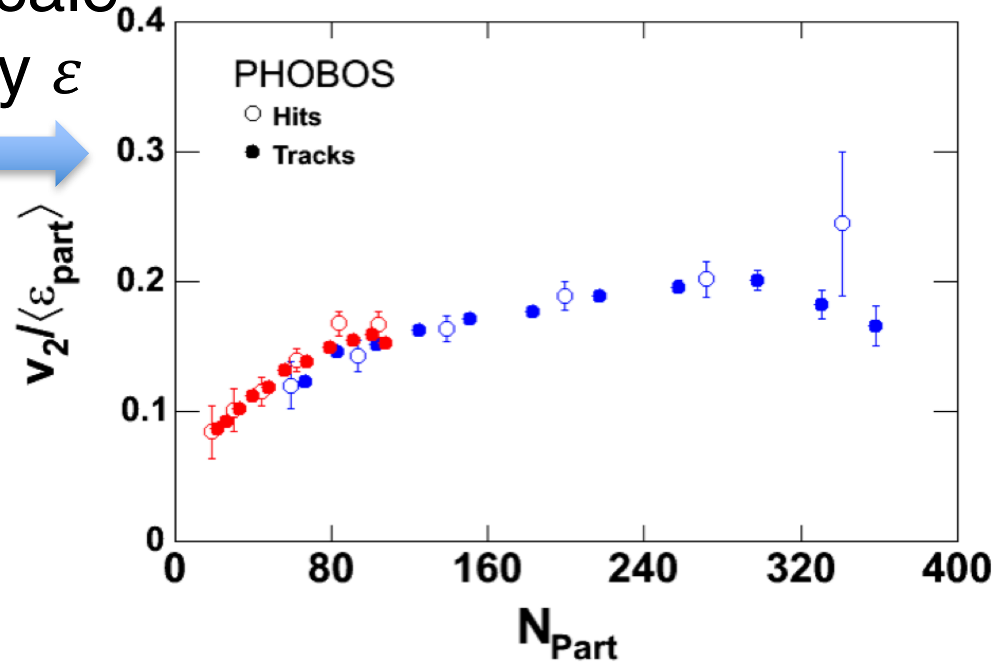


Centrality dependence

scale by ε



CuCu vs AuAu scaling

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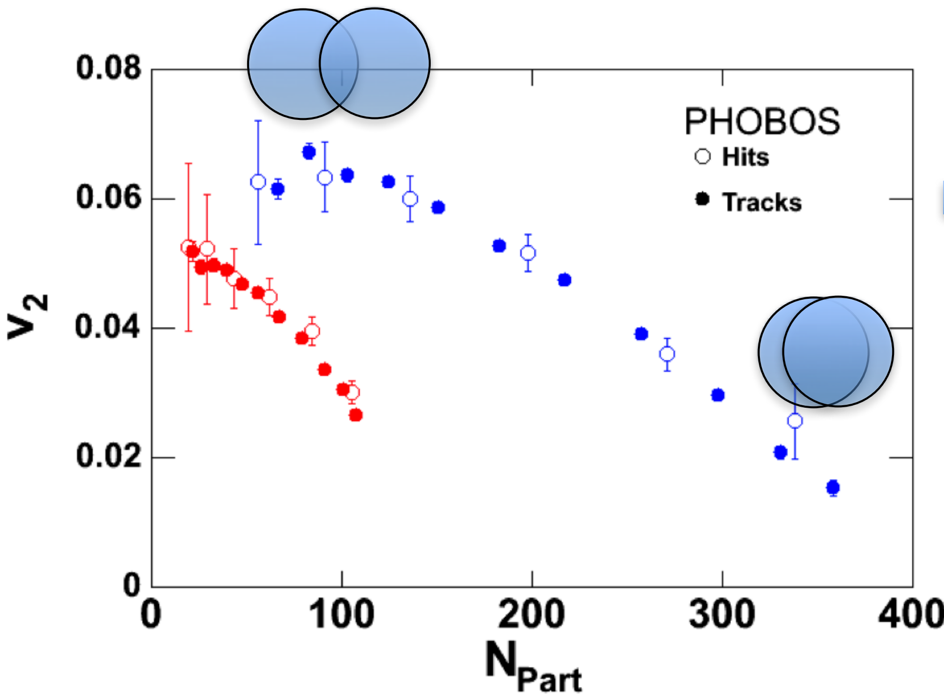

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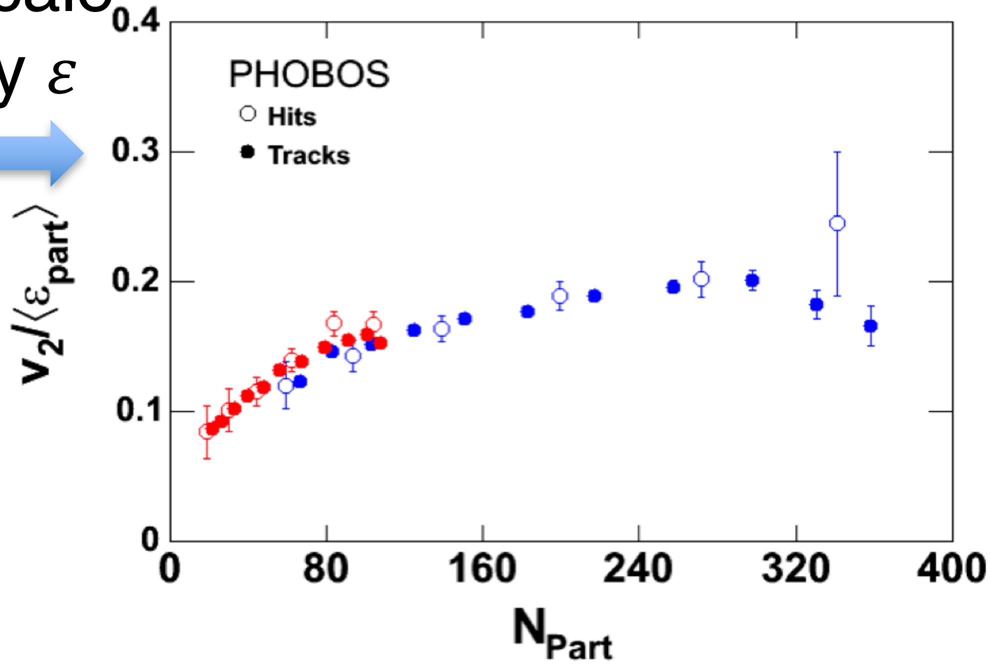

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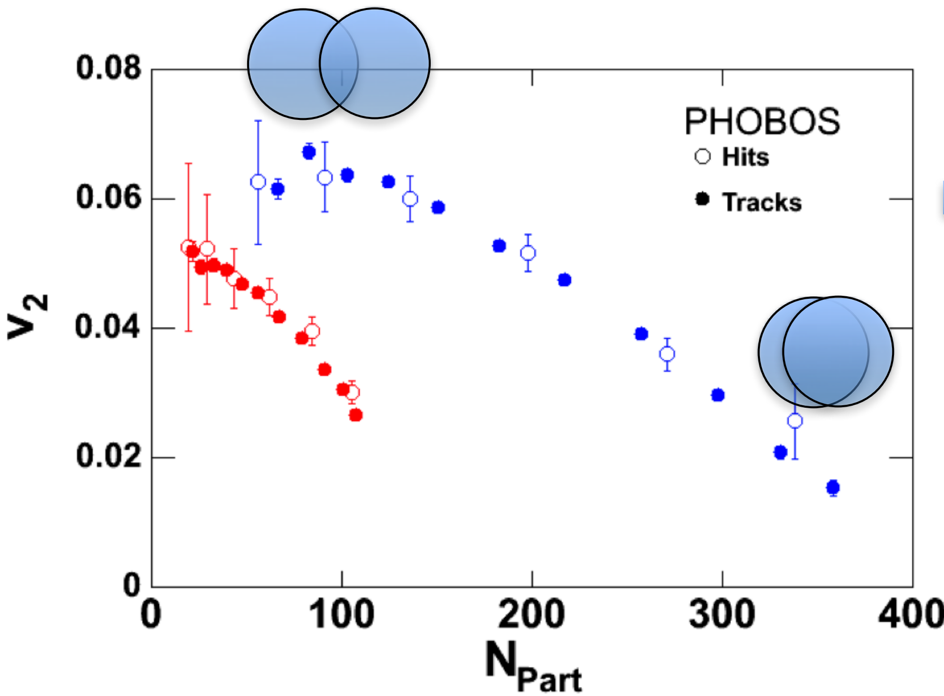

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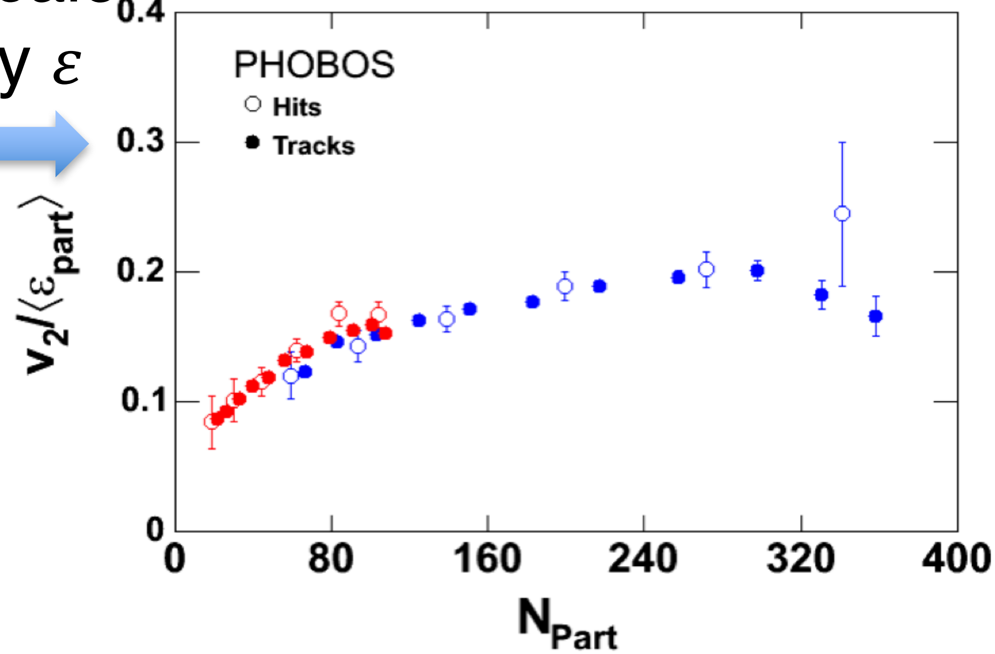

CuCu vs AuAu scaling

- **Pressure driven**

Indirectly, jet quenching → opaque, strong rescattering

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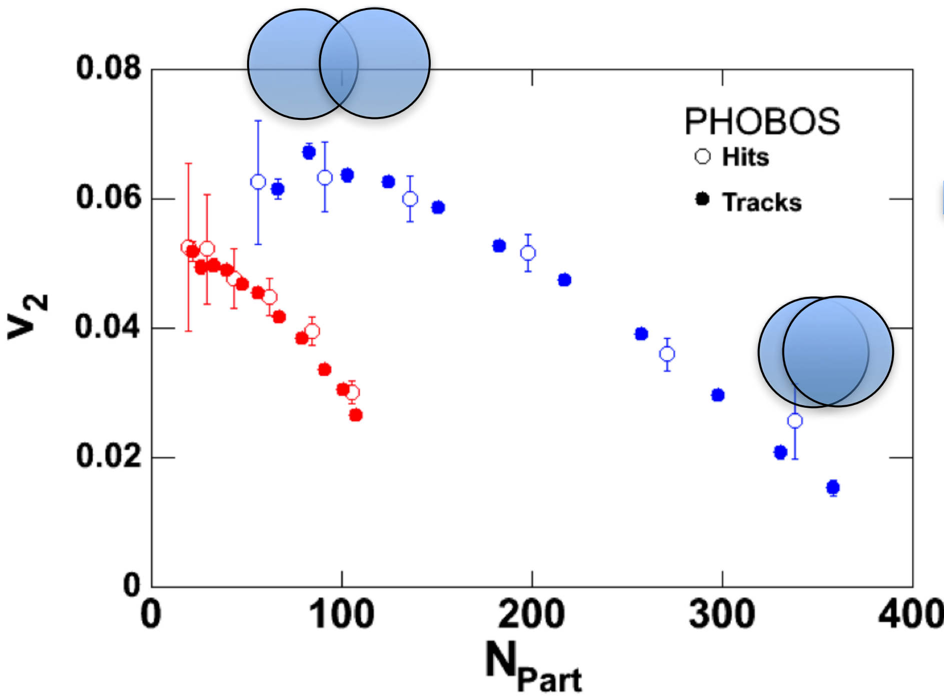

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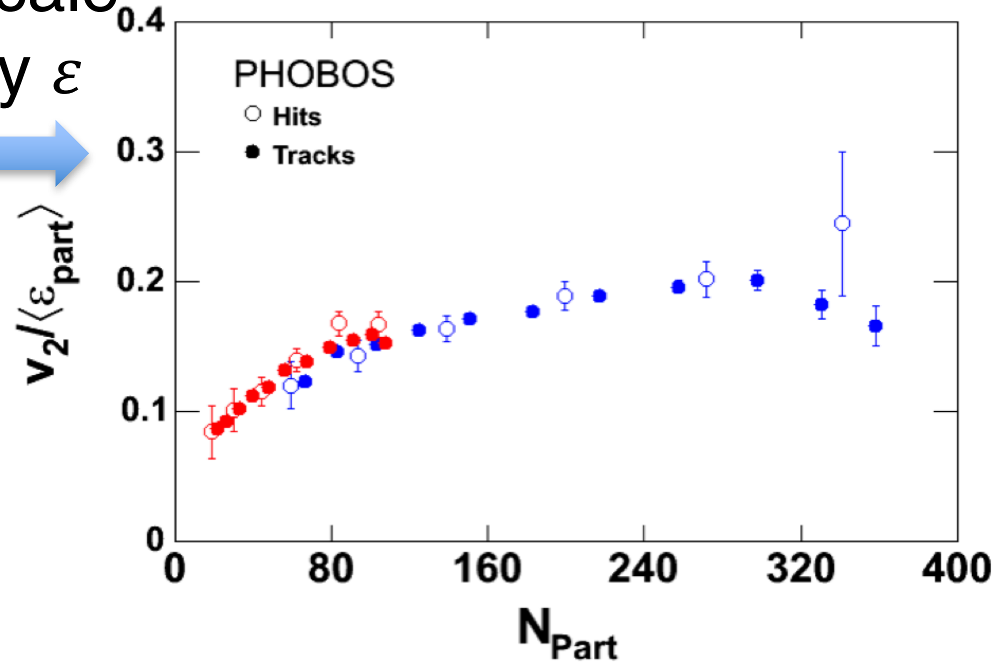

Centrality dependence

CuCu vs AuAu scaling

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Indirectly, jet quenching → opaque, strong rescattering

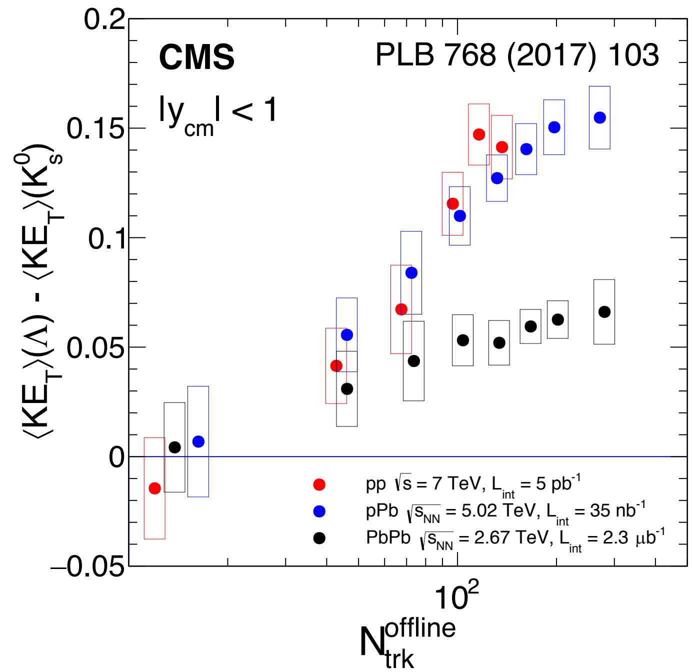
Both not fully established in small systems yet

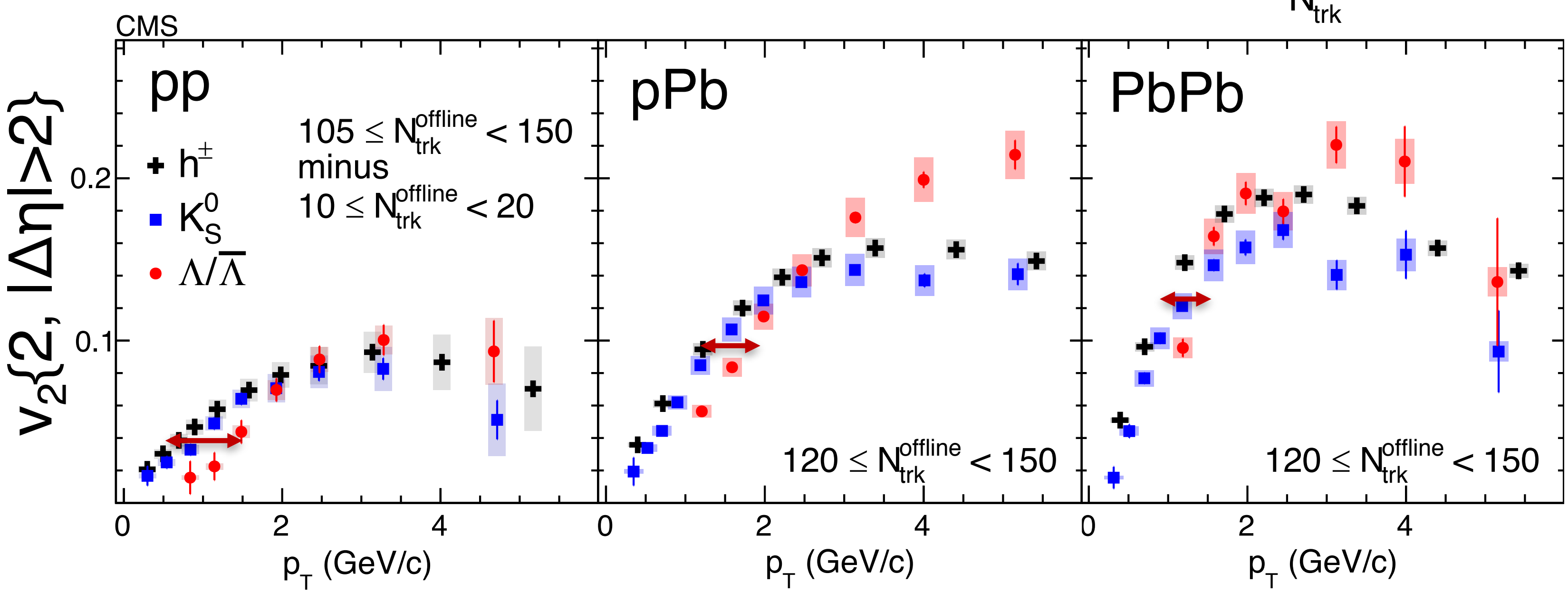
Pressure driven in pp/pA?

Evidence for pressure driven

$$\langle \beta_T \rangle_{pp} > \langle \beta_T \rangle_{pPb} > \langle \beta_T \rangle_{PbPb}$$

smaller initial size and more explosive?





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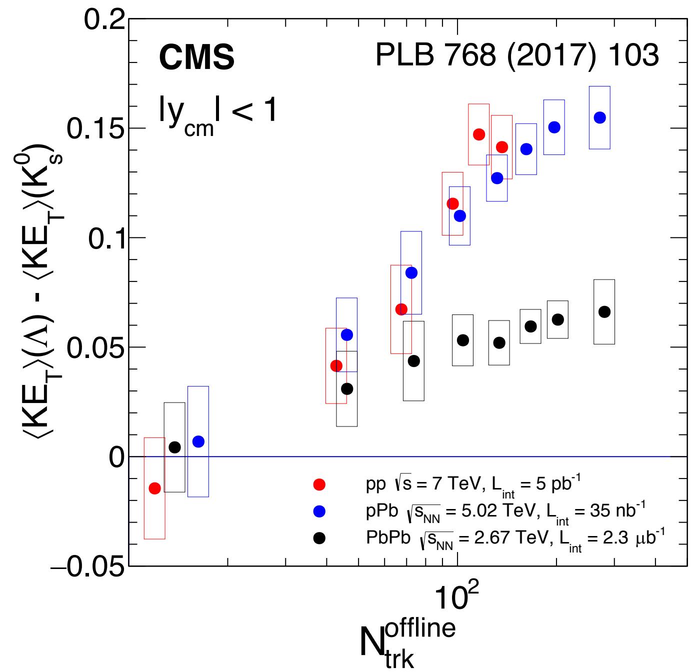
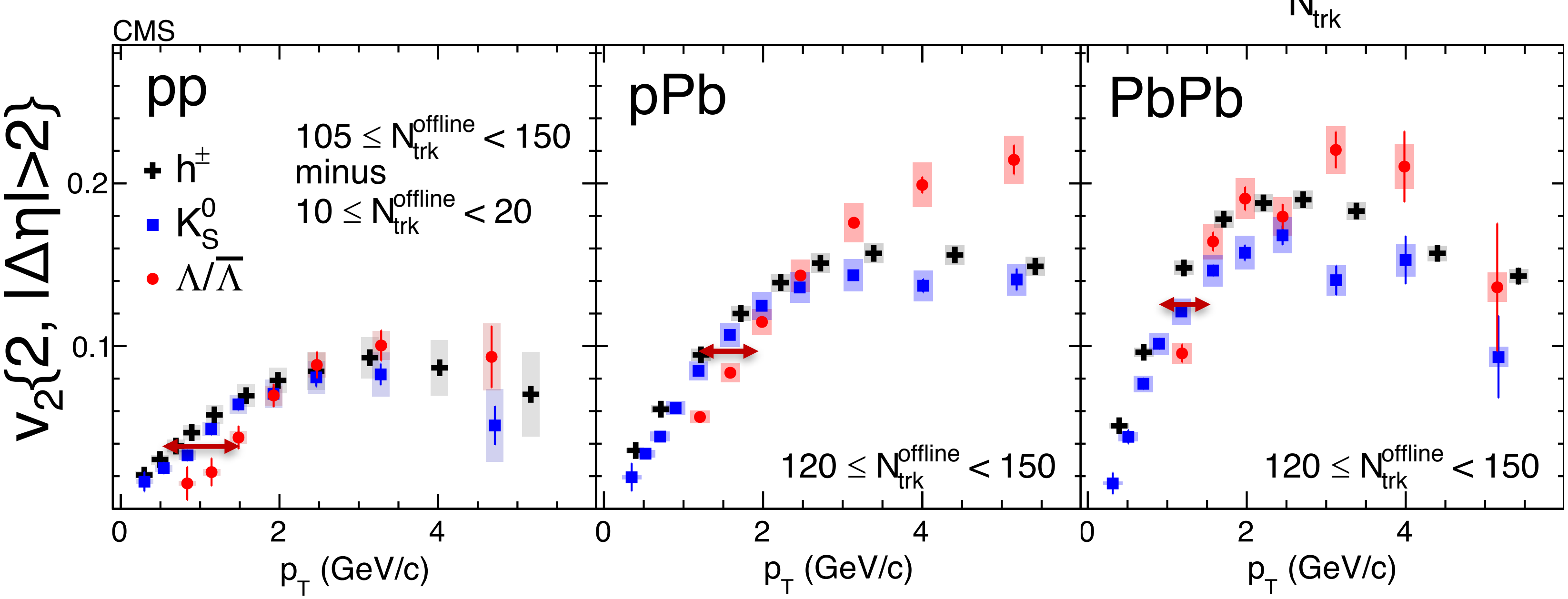


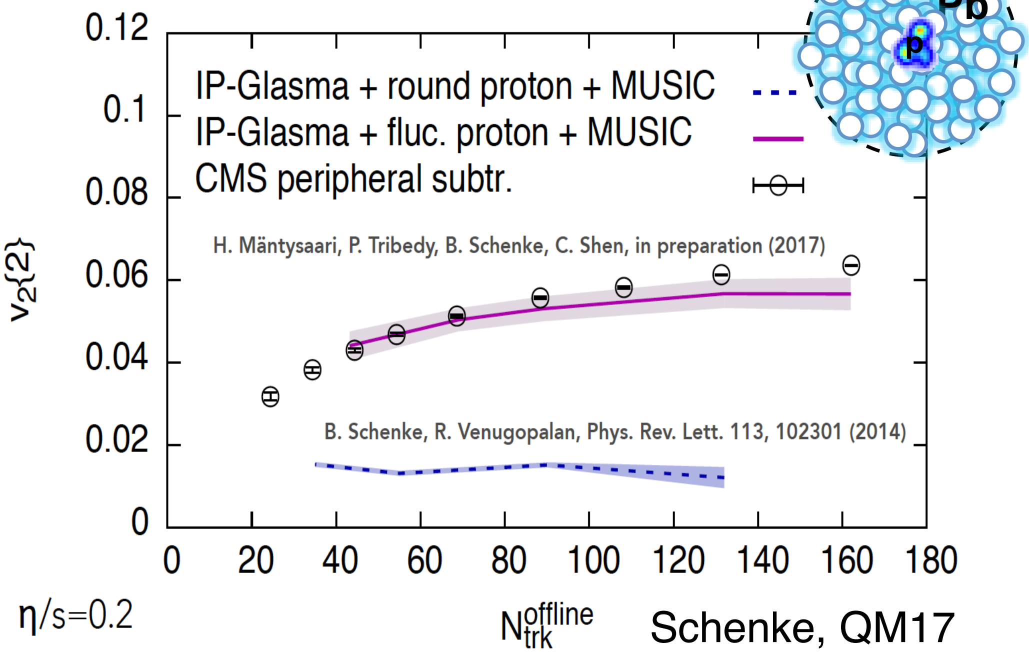


AMPT gets v_2 in a "dilute" limit: how about size dep. of "radial flow"?

Connection to geometry in pp/pA?

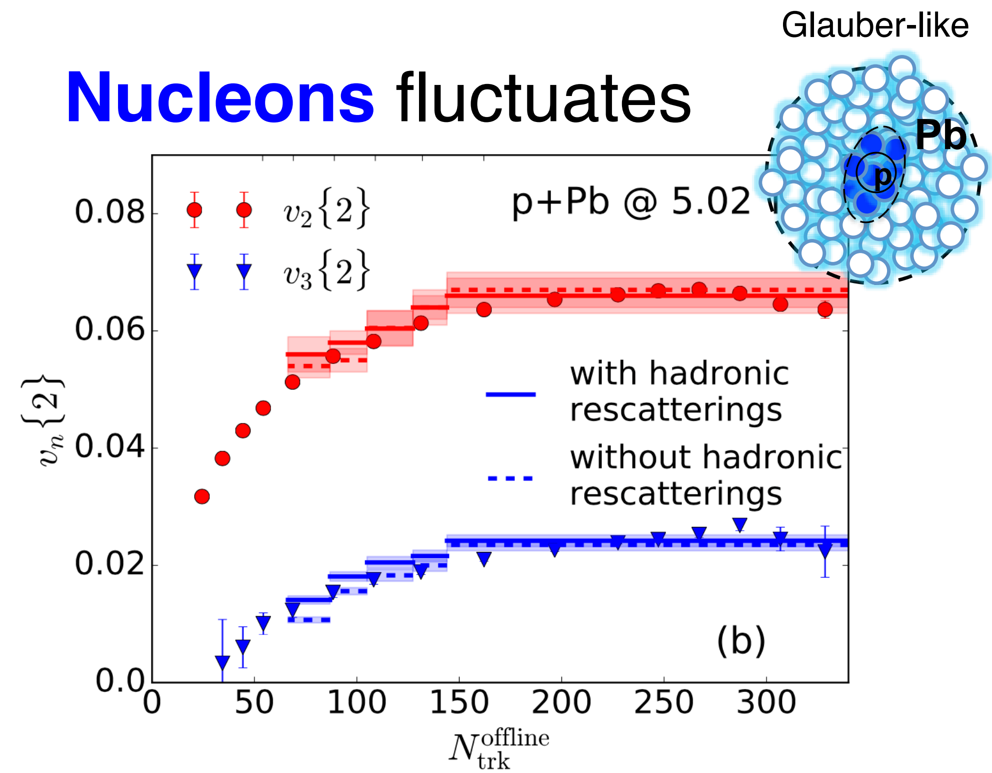
Hydro. fits the data in pA …

Proton fluctuates



Schenke, QM17

Nucleons fluctuates



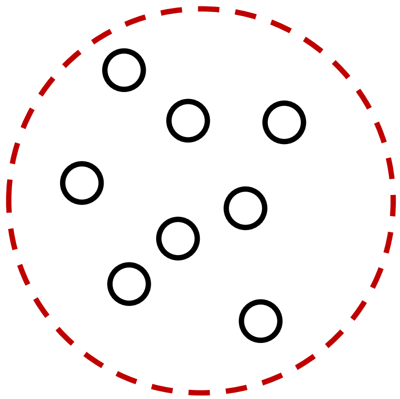
Shen, PRC95 (2017) 014906

- ➢ Large uncertainty in modeling of IS in pp/pA
- ➢ Hard to vary in a controlled way

Connection to geometry in pp/pA?

Universal features of fluctuation-driven ε_n

Yan, Ollitrault, PRL 112, 082301 (2014)



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

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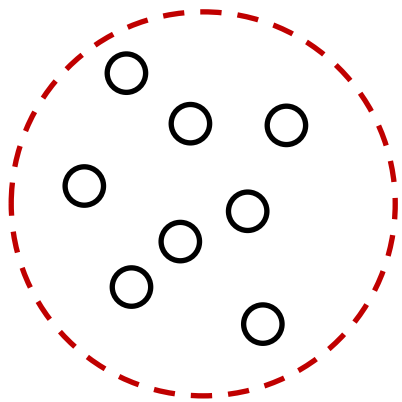

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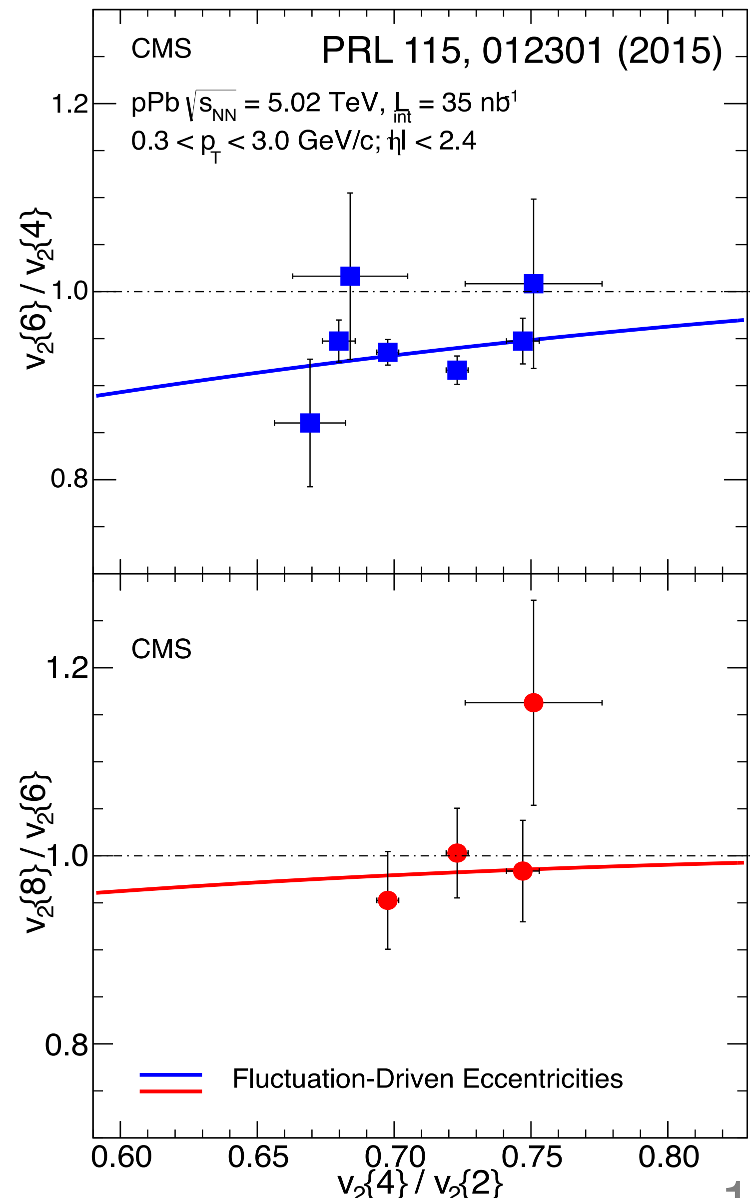
➢ Fine splitting among $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$



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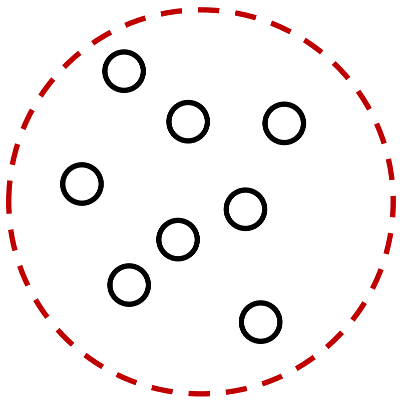
W. Li
LPC, 9/5/16

Yan, Ollitrault, PRL 112, 082301 (2014)



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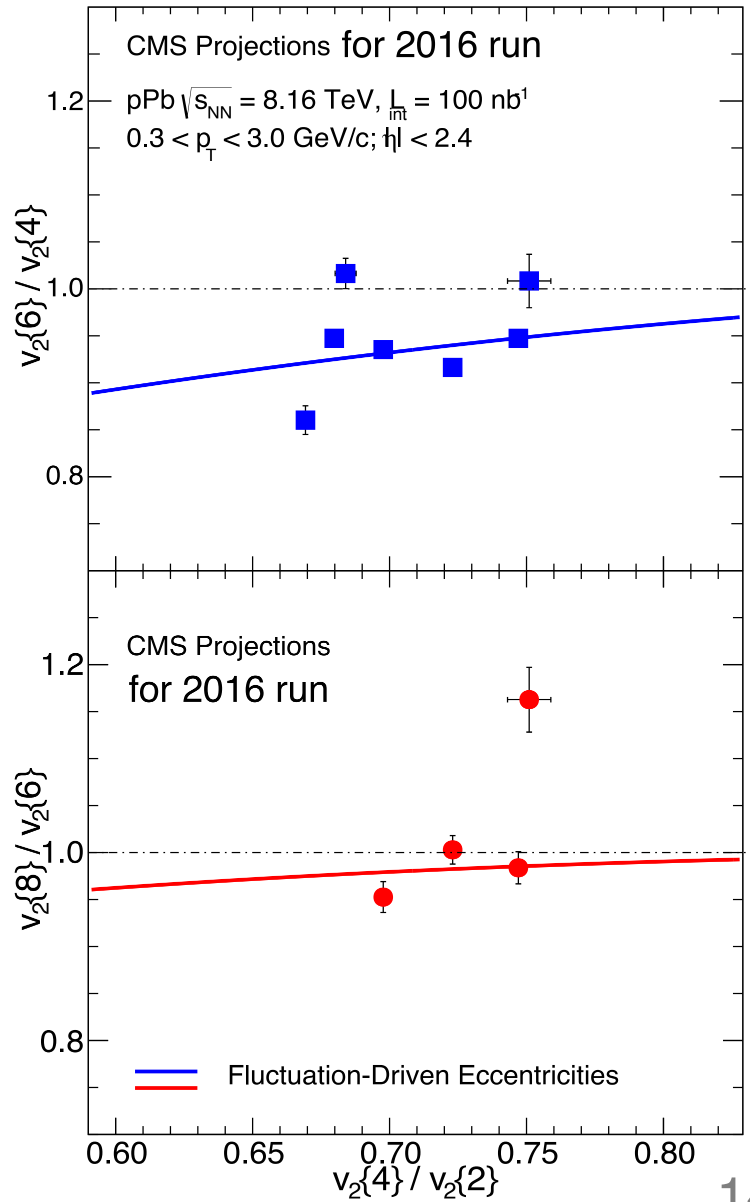

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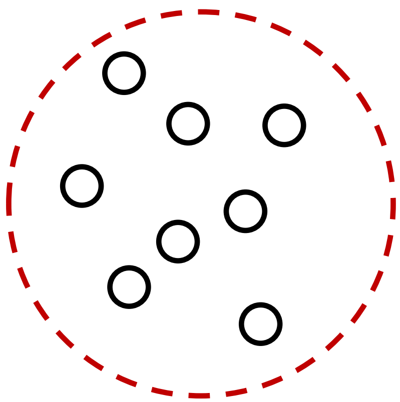

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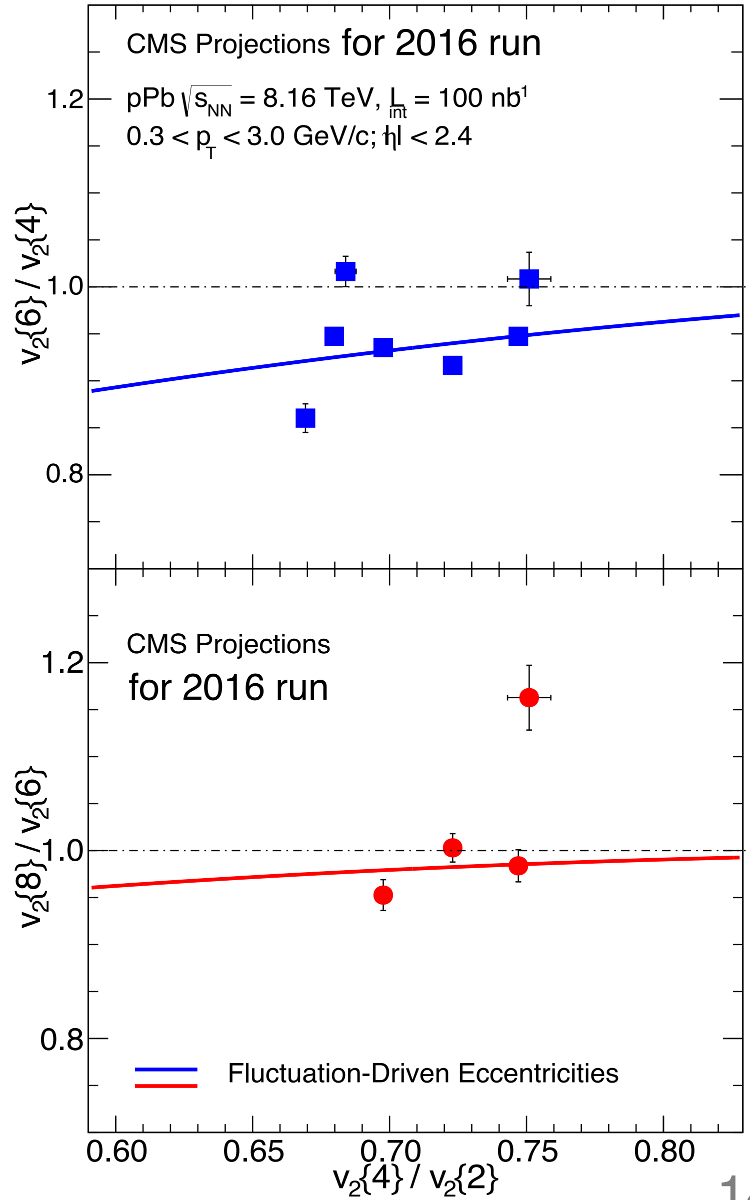
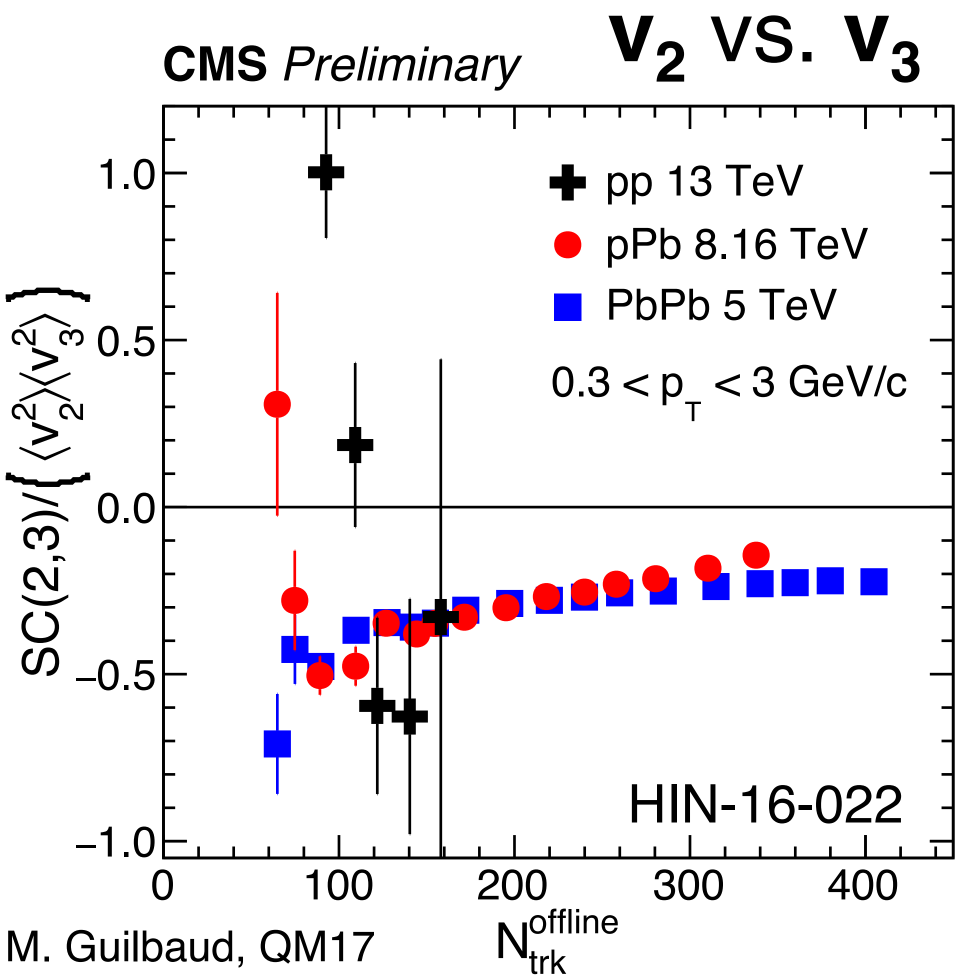


Predictions:

- Fine splitting among $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$
- $\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{v_3\{4\}}{v_3\{2\}}$

Connection to geometry in pp/pA?

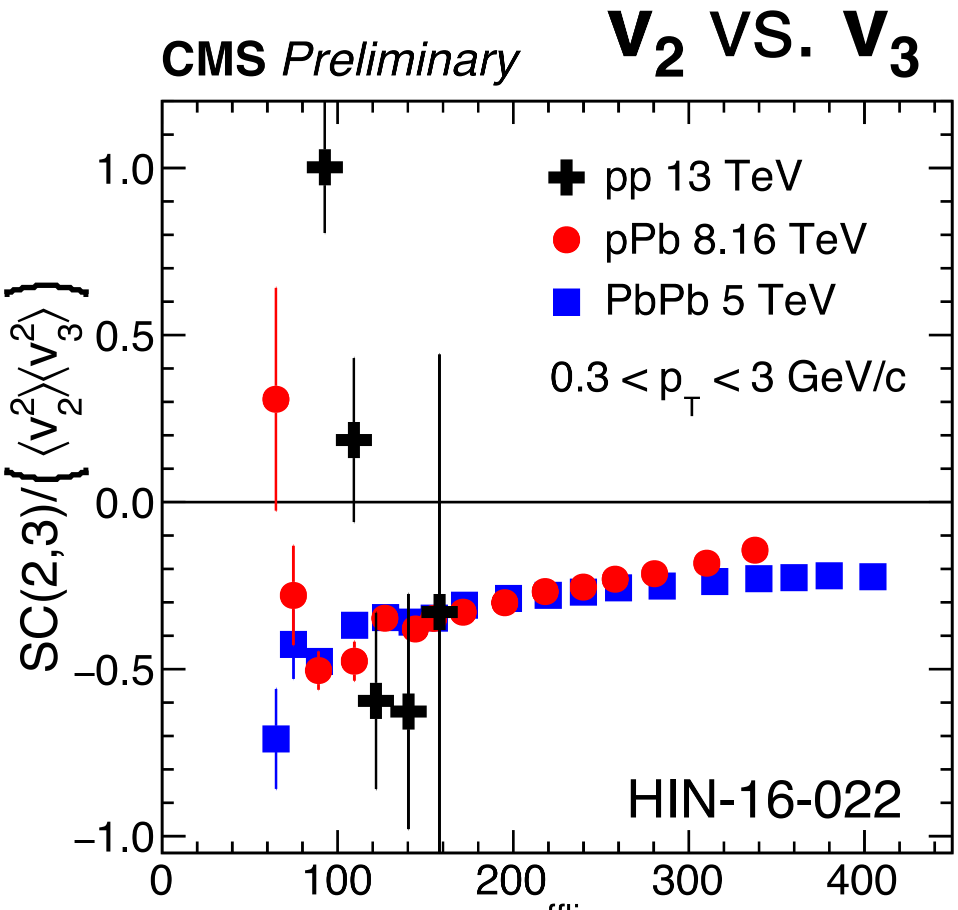
Symmetric cumulants



- Naturally explained by initial geometry
- A challenge to initial interaction models?

Connection to geometry in pp/pA?

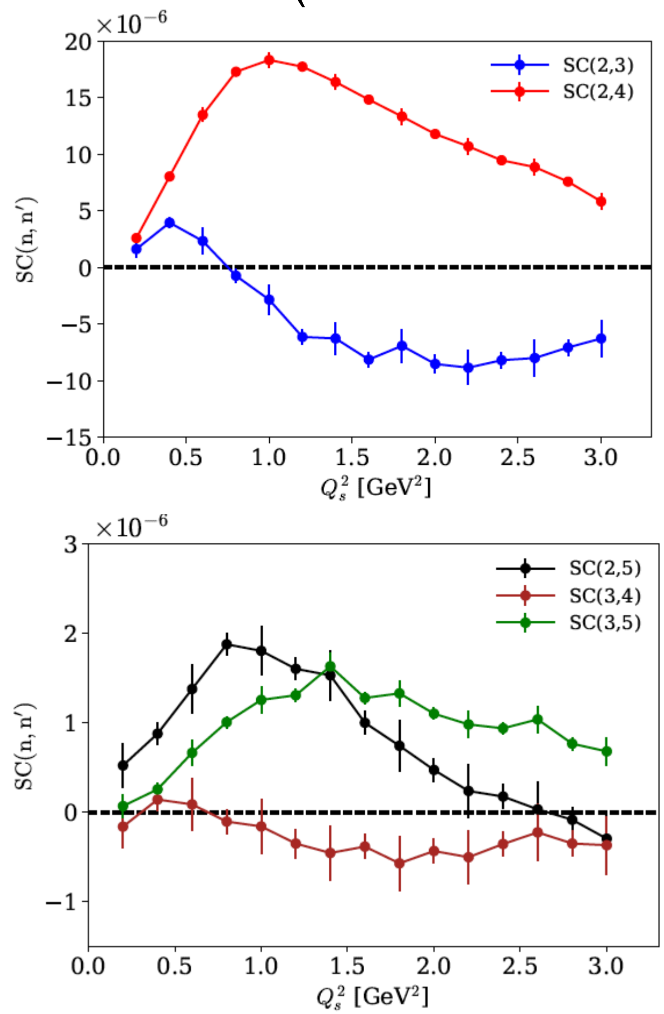
Symmetric cumulants



M. Guilbaud, QM17

But …

Color domains (arXiv:1705.00745)



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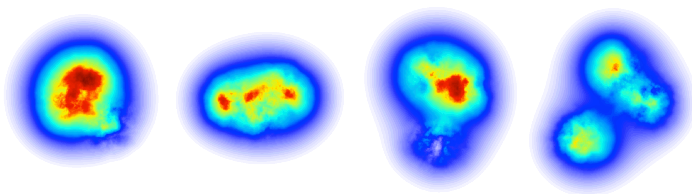
QGP fluid in pp/pA: why important?

1. Proton size and shape fluctuations

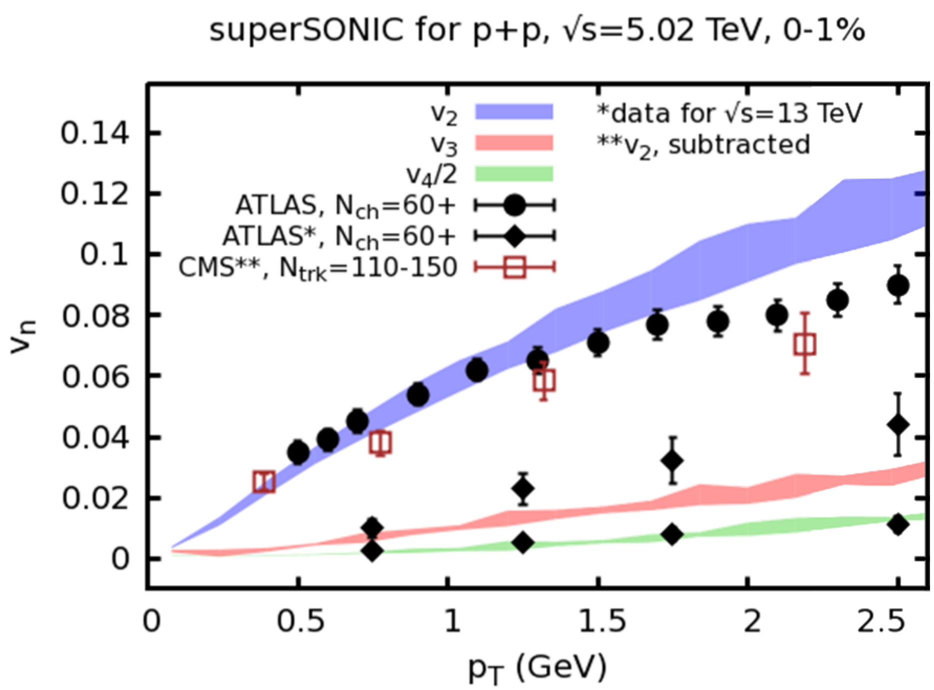


Mantysaari, Schenke,
PRL 117, 052301 (2016)

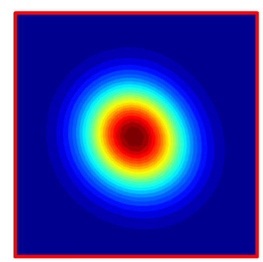
Lots of interests

P. Bożek, W. Broniowski, M. Rybczyński, PRC94 (2016) 014902
K. Welsh, J. Singer, U.W. Heinz, PRC94 (2016) 024919
R. D. Weller and P. Romatschke arXiv:1701.07145
P. Bozek, W. Broniowski, arXiv:1701.09105
D. McGlinchey, J.L. Nagle, D.V. Perepelitsa, PRC94 (2016) 024915

pp is the ultimate test



Smooth proton



Weller, Romatschke
arXiv:1701.07145

SC(v2,v3) should be very small?

QGP fluid in pp/pA: why important?

2. Universality of strongly-coupled QCD system
(AA, pA, pp, and even e^+e^-, ep, eA)

Applicability of hydrodynamics

$$L >> \lambda_{m.f.p.}$$

where $\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$

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$$N_{trk} \sim (LT)^3$$

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- How hydro breaks down as a function of N_{trk} may give insights to the fundamental system coupling

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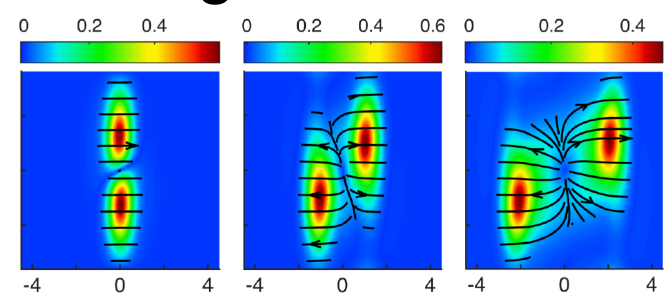
AdS/CFT, $g \to \infty$ P. Chesler



QGP fluid in pp

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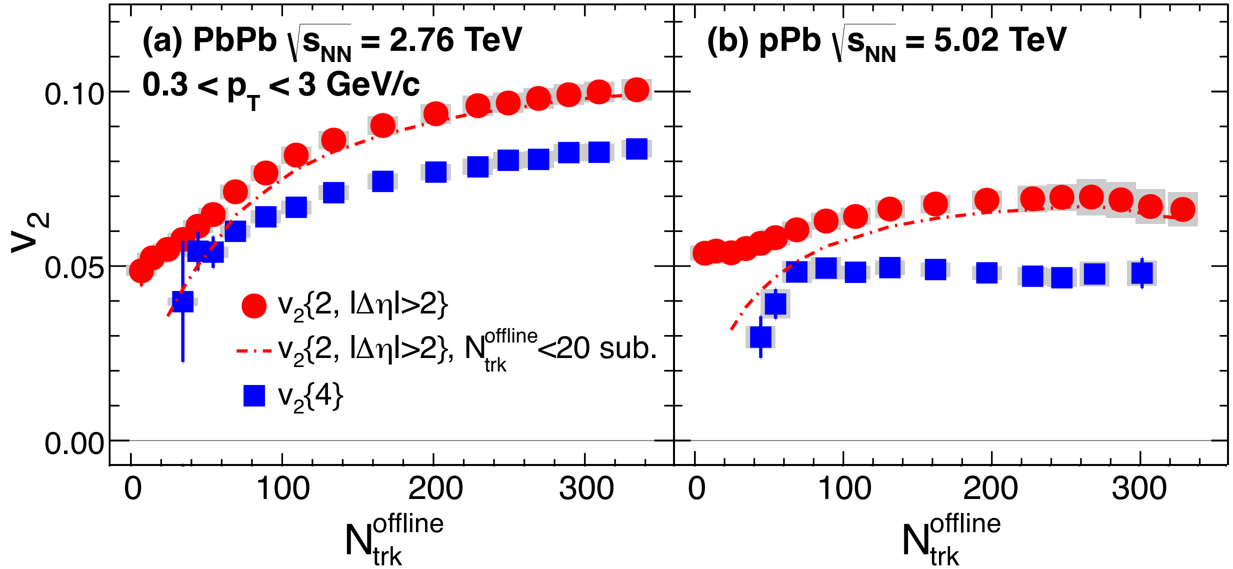
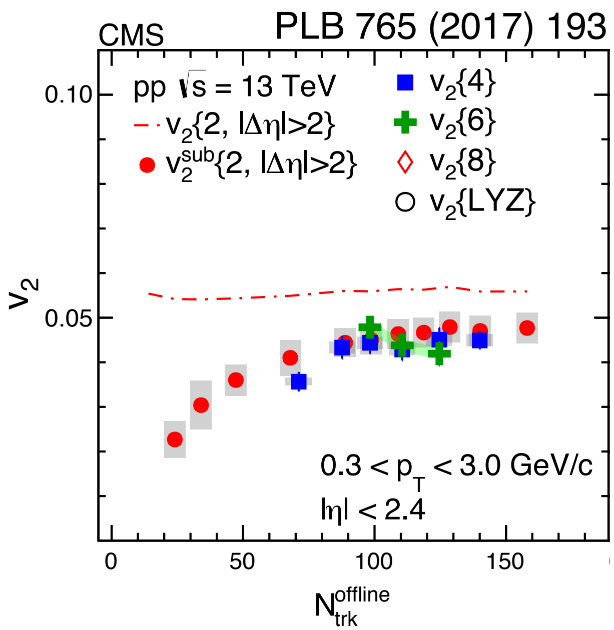
Collectivity toward low multiplicity

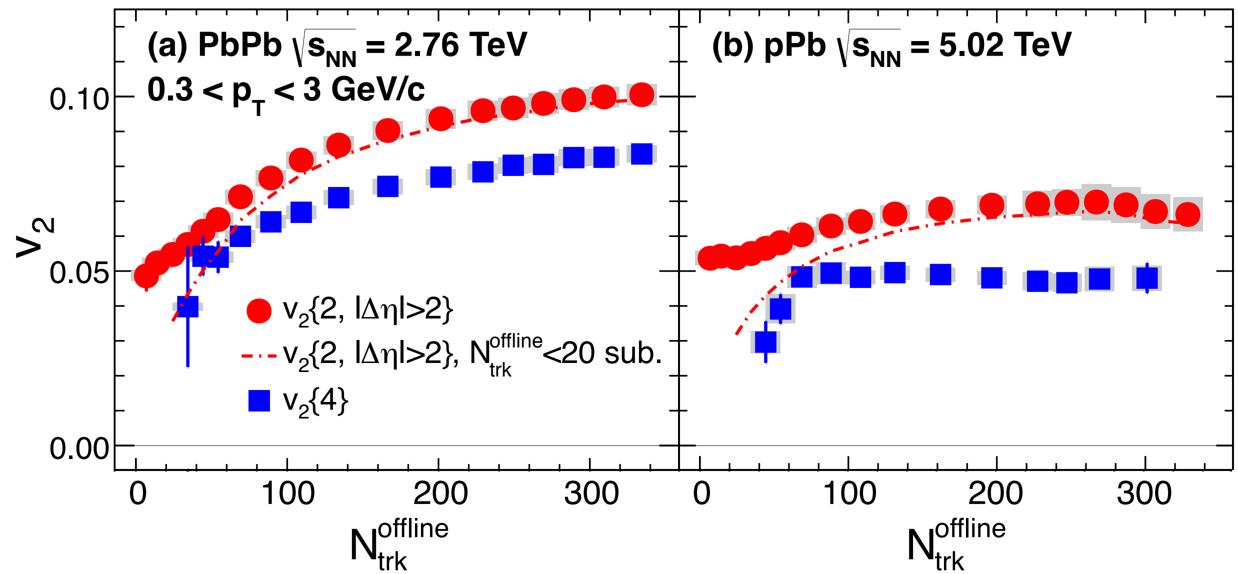


v_2 decreases at low N_{trk} in pPb, PbPb

Collectivity toward low multiplicity



Debatable in pp



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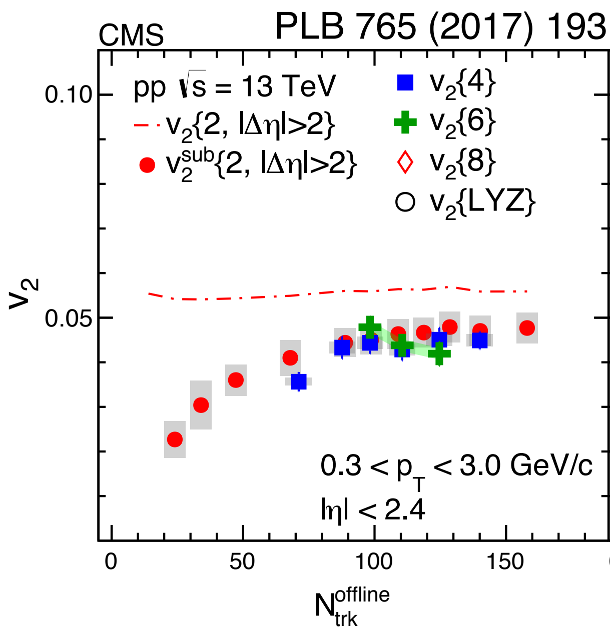
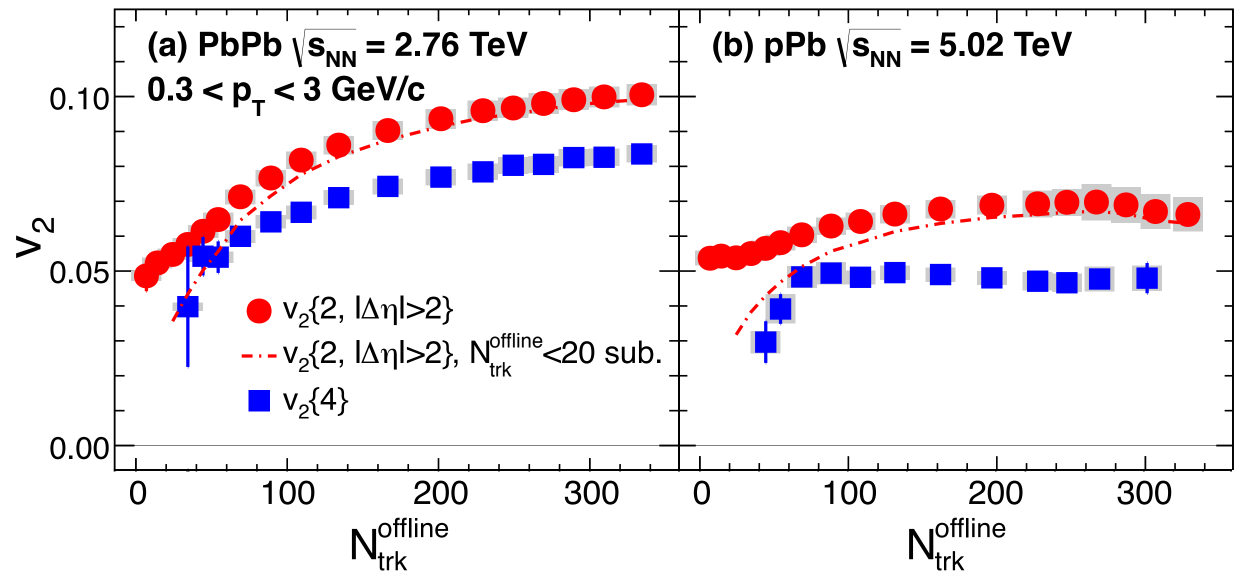


Debatable in pp



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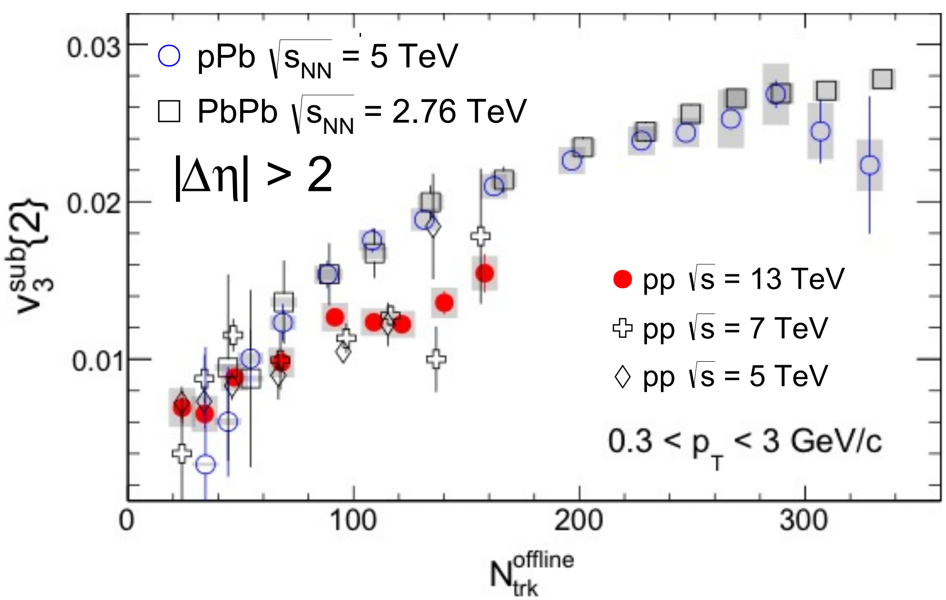
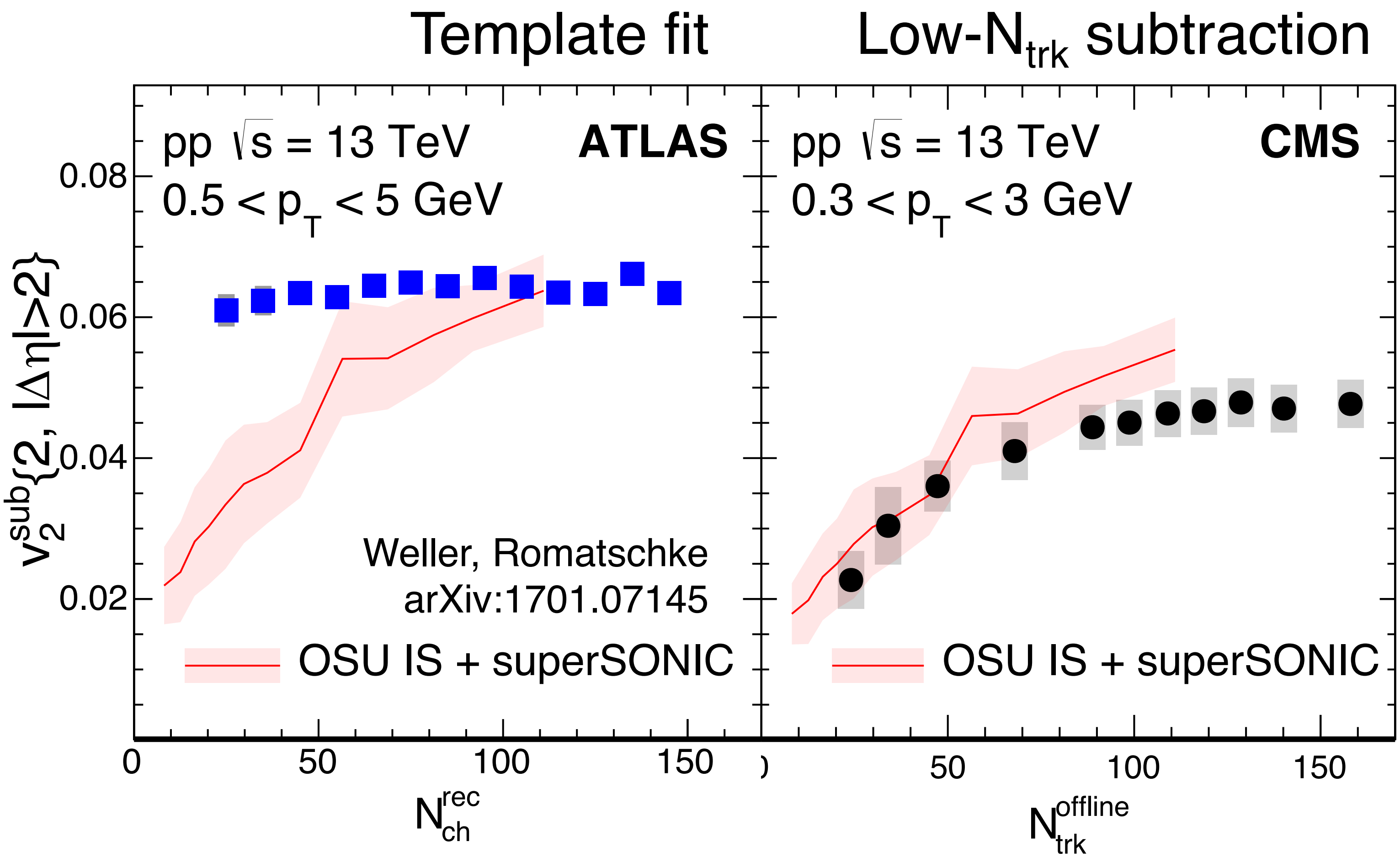


v_3 decreases at low N_{trk} for all systems, regardless of subtraction method

Collectivity toward low multiplicity

Hydro. down to dN/dy ~ 2

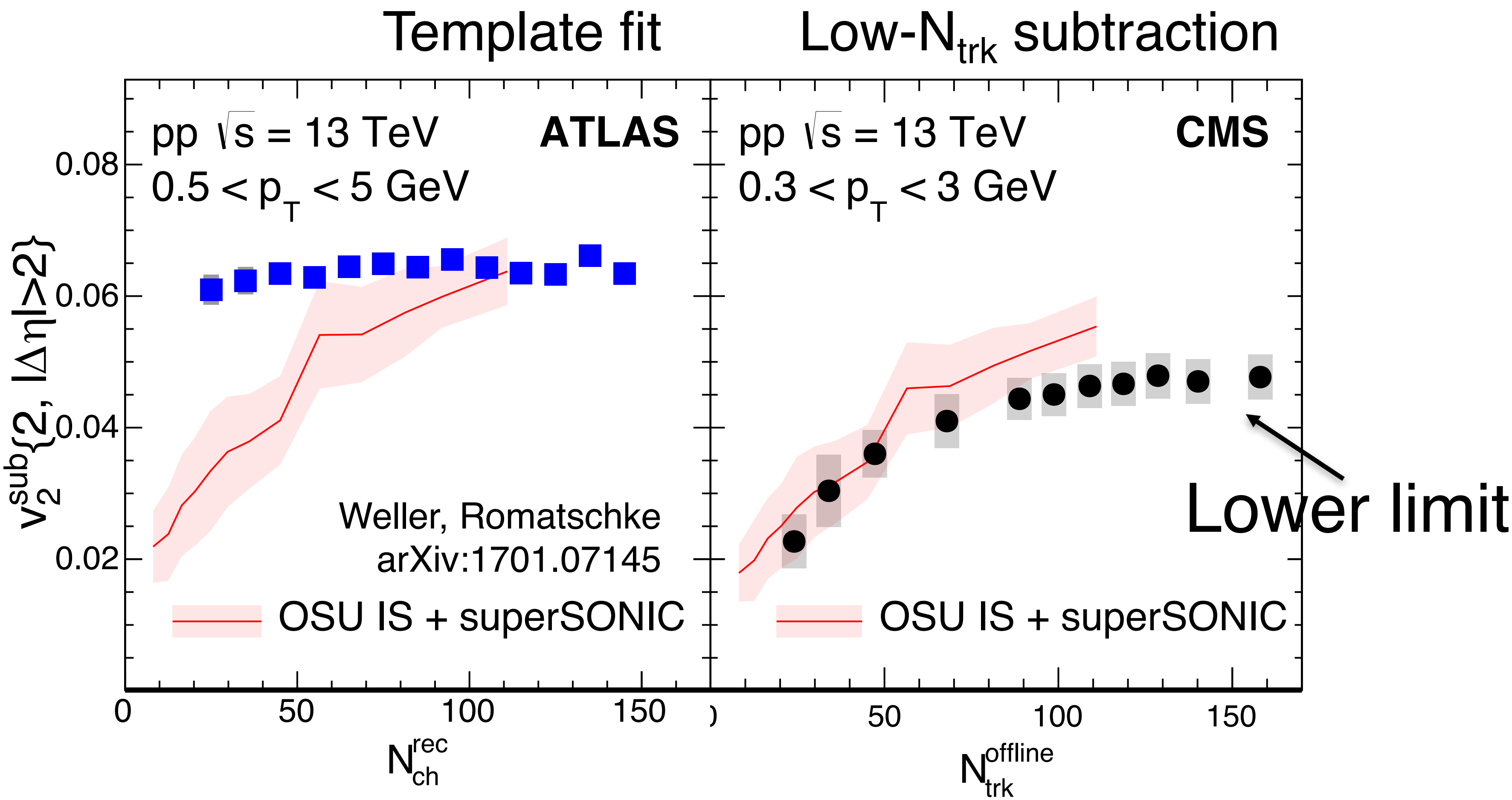


If hydro., v_2 should go down toward low N_{trk}

(shorter lifetime, larger viscous correction, larger λ_{mfp}/L ratio)

Collectivity toward low multiplicity

Hydro. down to dN/dy ~ 2



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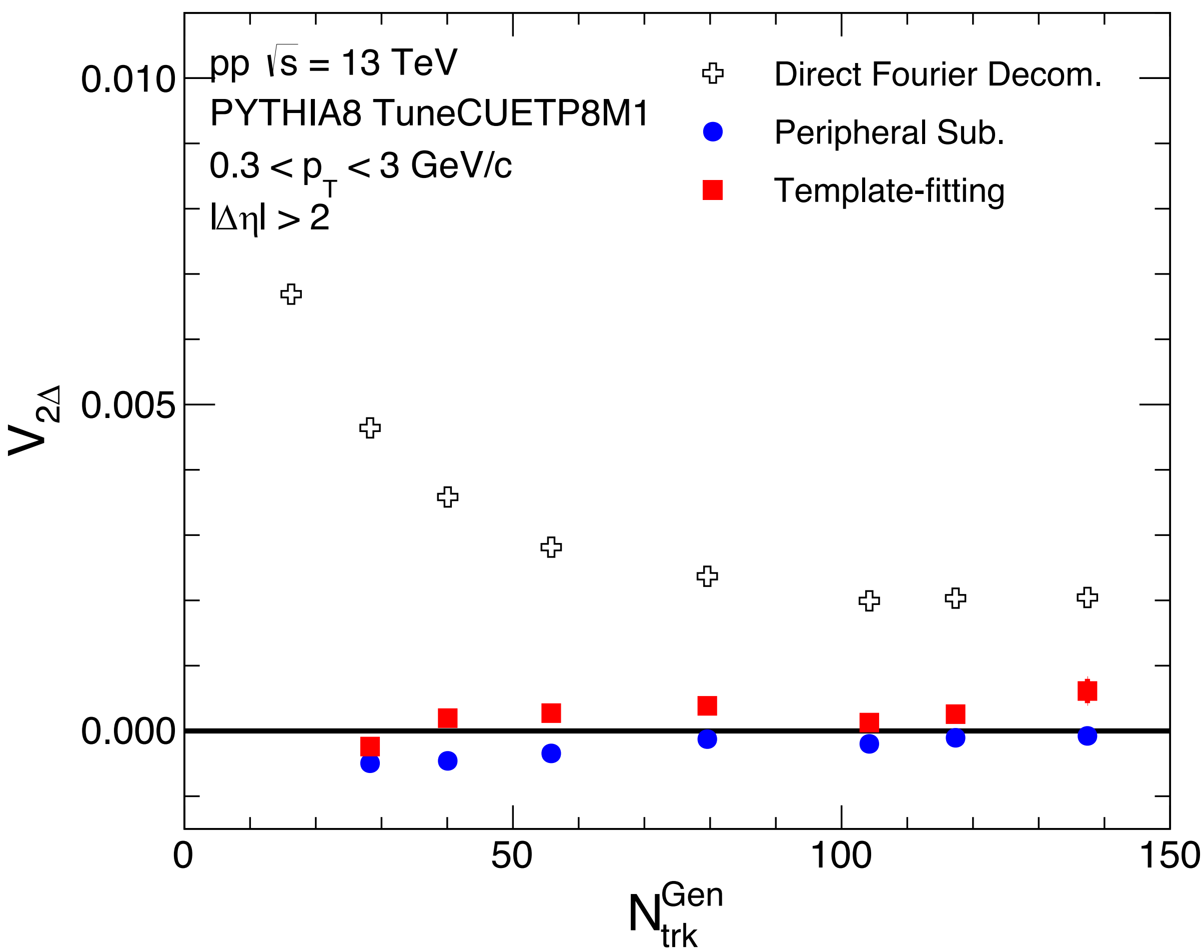
Limitation of subtraction methods

Peripheral subtraction: $V_{n\Delta}^{sub} = V_{n\Delta}^{HM} - \alpha \frac{N^{LM}}{N^{HM}} V_{n\Delta}^{LM}$

Template fit: $Y(\Delta\phi) = F Y_{LM}(\Delta\phi) + G(1 + 2\sum_n V_{n\Delta}^{fit} \cos(n\Delta\phi))$



Apply to PYTHIA8 without v_2

Works equally well

Limitation of subtraction methods

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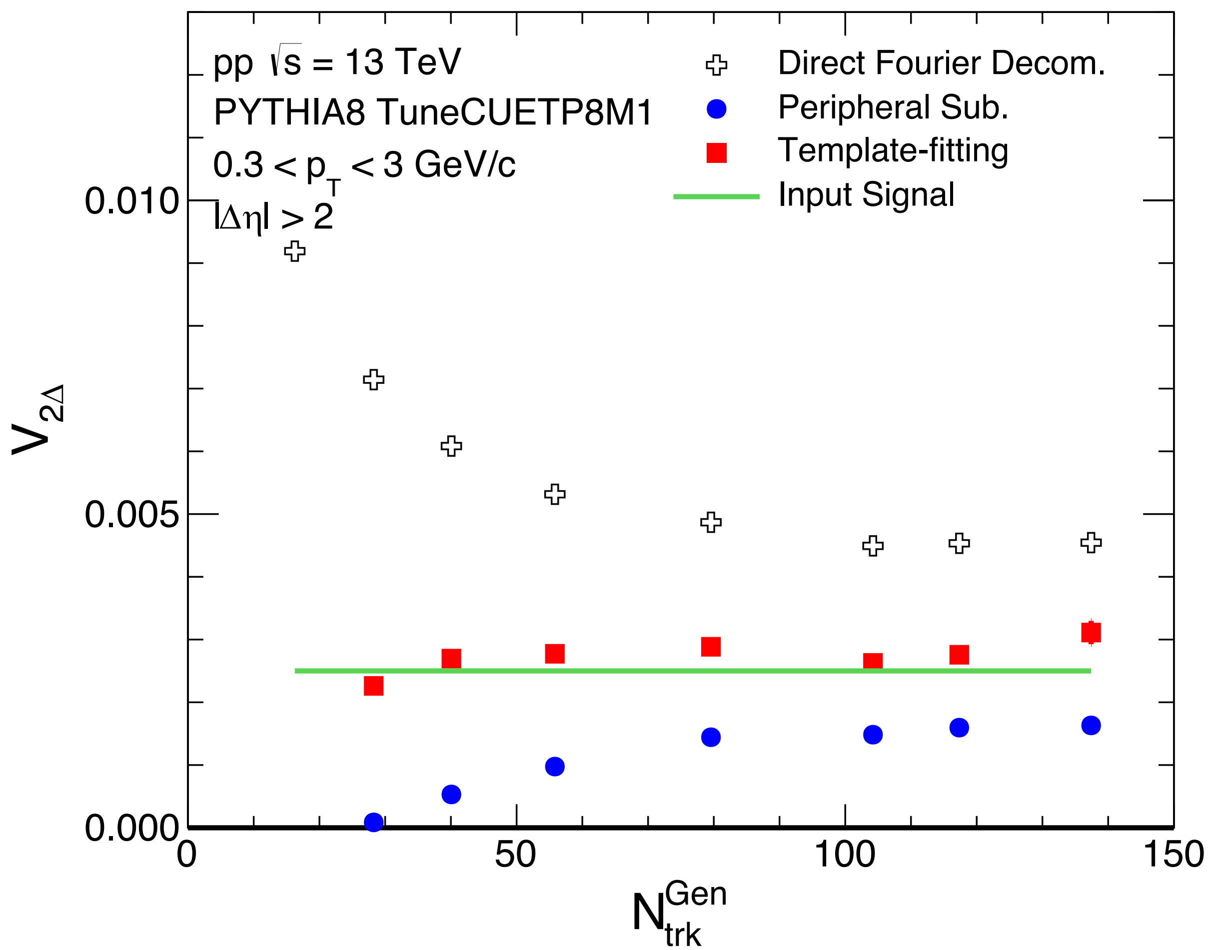

Adding a v_2 to $Y(\Delta\phi)$:

$$2N^{HM} V_{2\Delta}^{input} \cos(n\Delta\phi)$$

Flat v_2 vs N_{trk}

➡ Temp. fit works better

Limitation of subtraction methods

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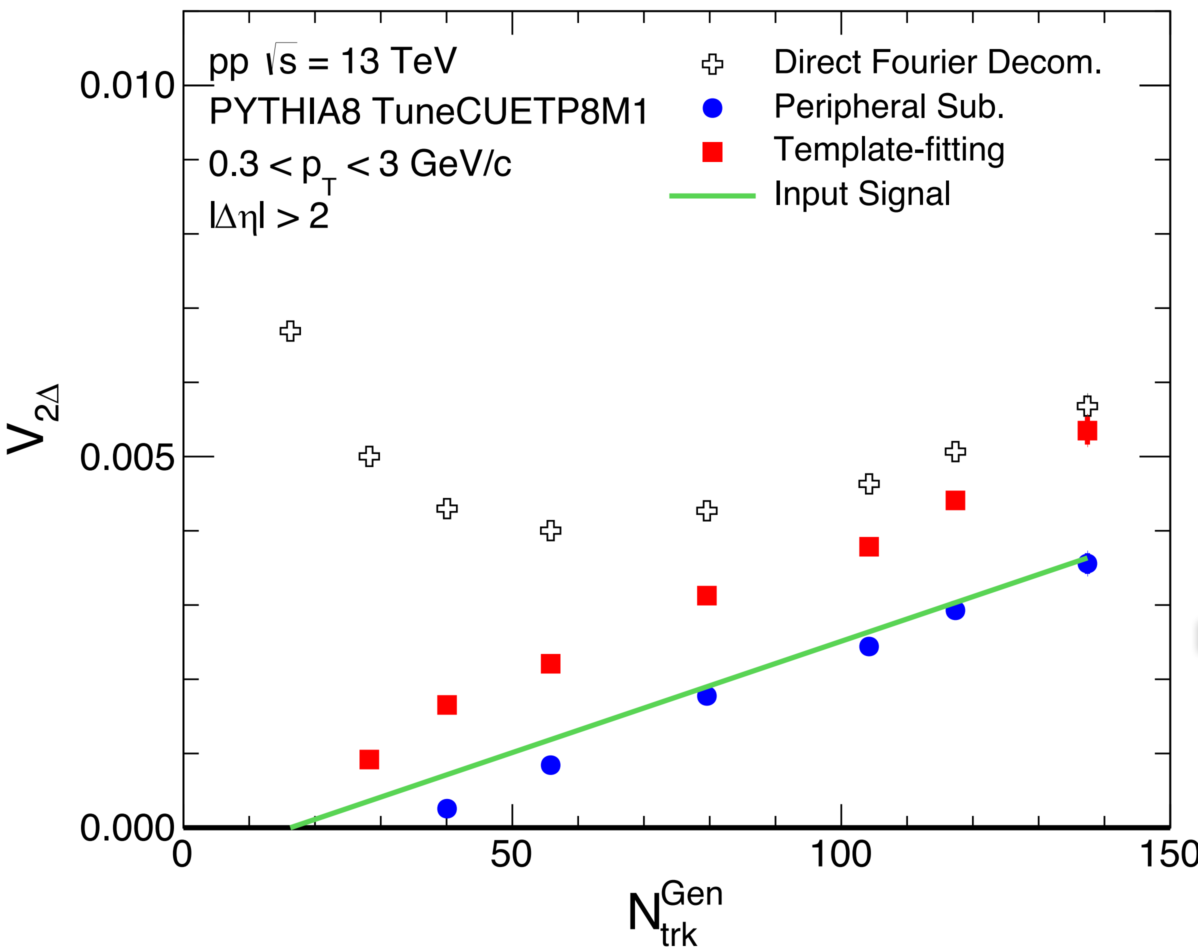
Template fit: $Y(\Delta\phi) = F Y_{LM}(\Delta\phi) + G(1 + 2\sum_n V_{n\Delta}^{fit} \cos(n\Delta\phi))$



Adding a v_2 to $Y(\Delta\phi)$:

$2N^{HM} V_{2\Delta}^{input} \cos(n\Delta\phi)$

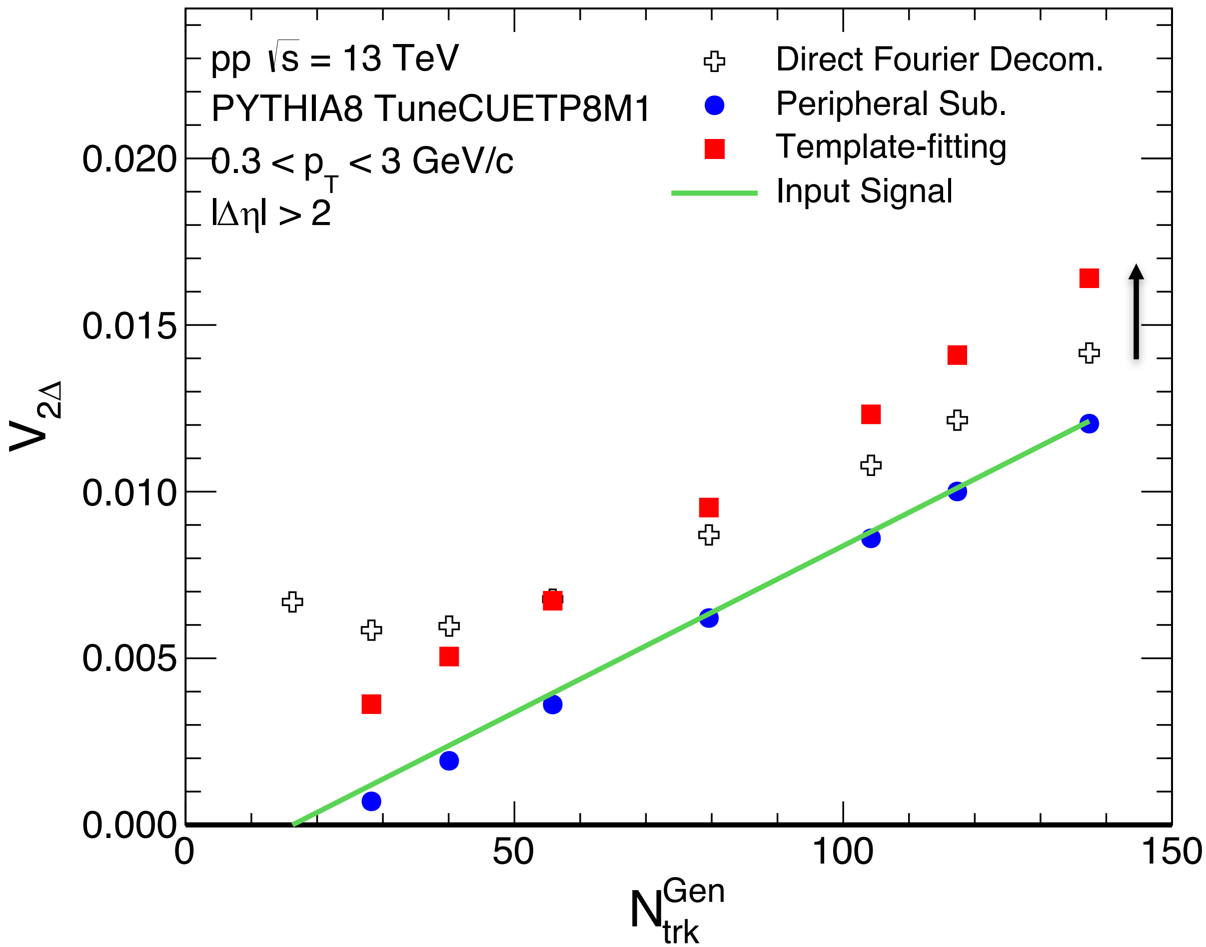
Rising v_2 vs N_{trk}

➡ **Peri. sub.** works better

Limitation of subtraction methods

Peripheral subtraction: $V_{n\Delta}^{sub} = V_{n\Delta}^{HM} - \alpha \frac{N^{LM}}{N^{HM}} V_{n\Delta}^{LM}$

Template fit: $Y(\Delta\phi) = FY_{LM}(\Delta\phi) + G(1 + 2\sum_n V_{n\Delta}^{fit} \cos(n\Delta\phi))$



Adding a v_2 to $Y(\Delta\phi)$:

$2N^{HM} V_{2\Delta}^{input} \cos(n\Delta\phi)$

Making input v_2 larger

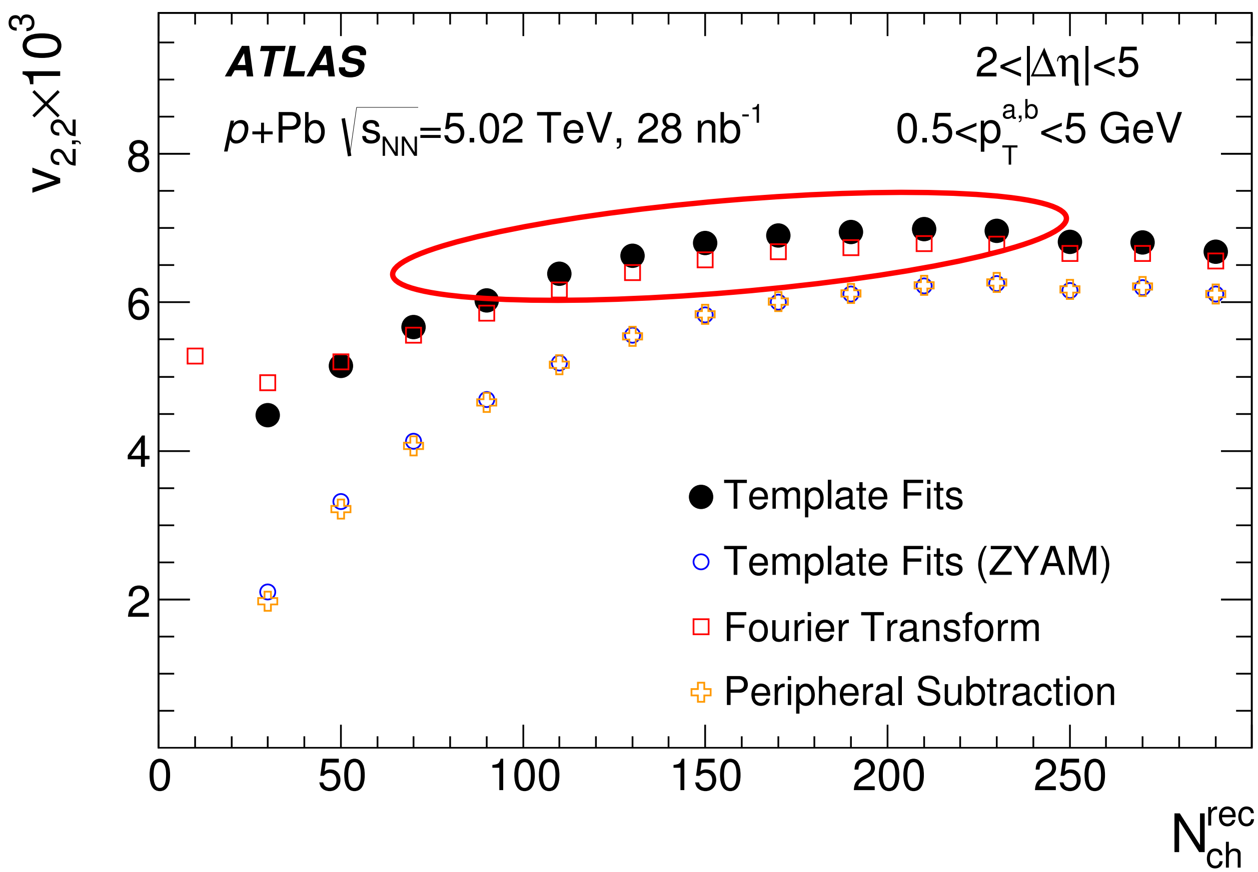
Temp. fit can be even **LARGER** than unsub.!

Limitation of subtraction methods

Peripheral subtraction: $V_{n\Delta}^{sub} = V_{n\Delta}^{HM} - \alpha \frac{N^{LM}}{N^{HM}} V_{n\Delta}^{LM}$

Template fit: $Y(\Delta\phi) = \mathrm{F}Y_{LM}(\Delta\phi) + \mathrm{G}(1 + 2\sum_n V_{n\Delta}^{fit} \cos(n\Delta\phi))$

Subtracted $V_{n\Delta}^{fit}$ > Unsubtracted $V_{n\Delta}$



Limitation of subtraction methods

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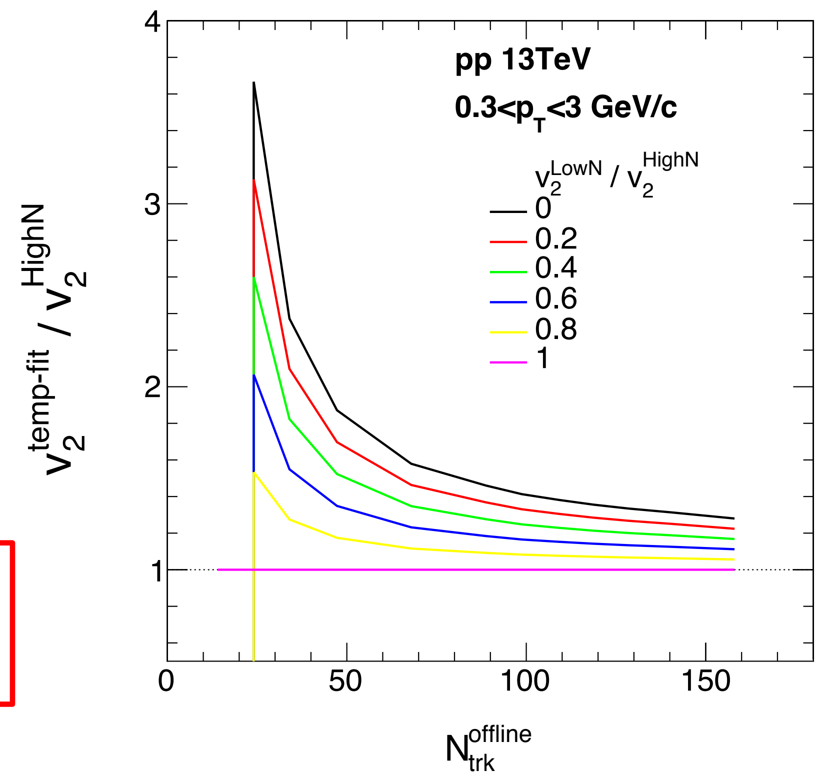
Template fit: $Y(\Delta\phi) = FY_{LM}(\Delta\phi) + G(1 + 2\sum_n V_{n\Delta}^{fit}\cos(n\Delta\phi))$

What's going on?

$$V_{n\Delta}^{fit} = \frac{N^{HM}}{G} V_{n\Delta}^{HM} - F\frac{N^{LM}}{G} V_{n\Delta}^{LM}$$

where $G = N^{HM} - FN^{LM}$

If $V_{n\Delta}^{HM} > V_{n\Delta}^{LM}$ ⇨ $V_{n\Delta}^{fit} > V_{n\Delta}^{LM}$!

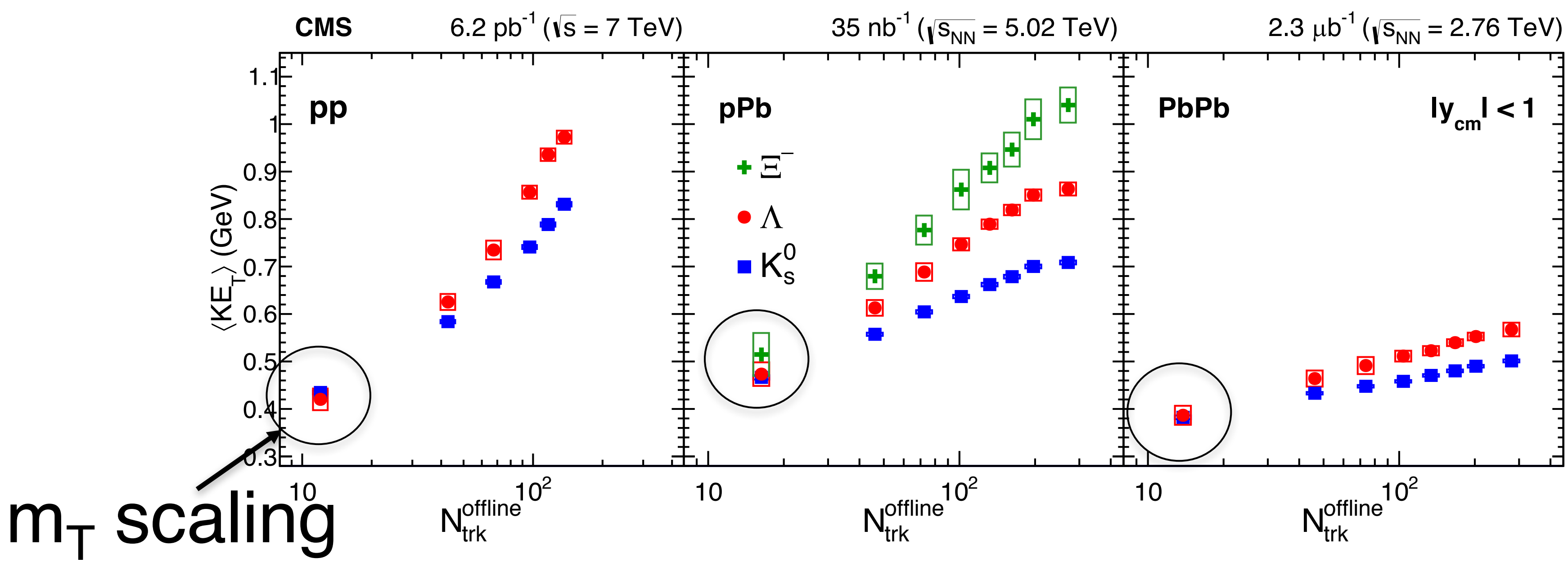


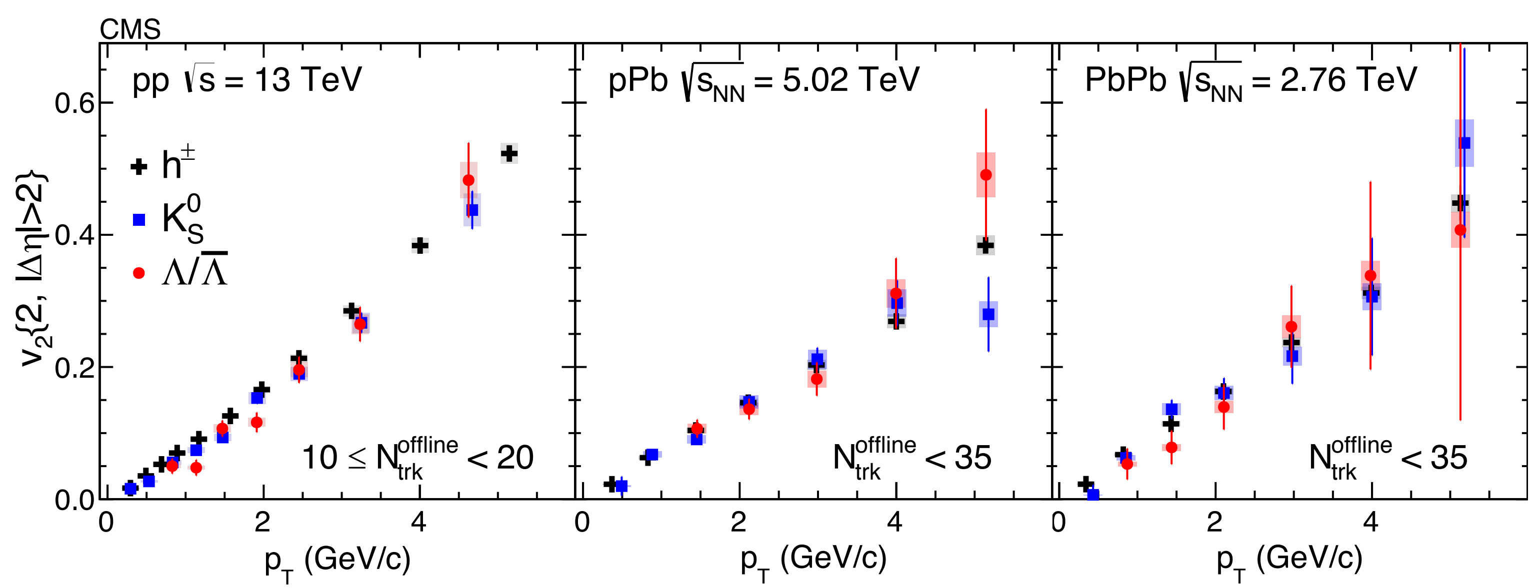
Conclusions:

- Template fit changes the baseline and defines a new v_n
- **Peri. sub.: a lower limit** and **unsub.: an upper limit**

“Radial flow” diminishing at low N_{trk}

Examine other signatures of collectivity at low N_{trk}





Summary

Strong evidence of novel collectivity in pp/pA/AA

A QGP fluid in pp/pA? Two aspects still to be established:

- Connection to initial-state geometry
- Direct evidence of final-state interactions (jets, heavy flavor)

Why important? impacts of a QGP fluid in small systems:

- Proton shape fluctuations
- Fundamental coupling strength of the system

Summary

Strong evidence of novel collectivity in pp/pA/AA

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Why important? impacts of a QGP fluid in small systems:

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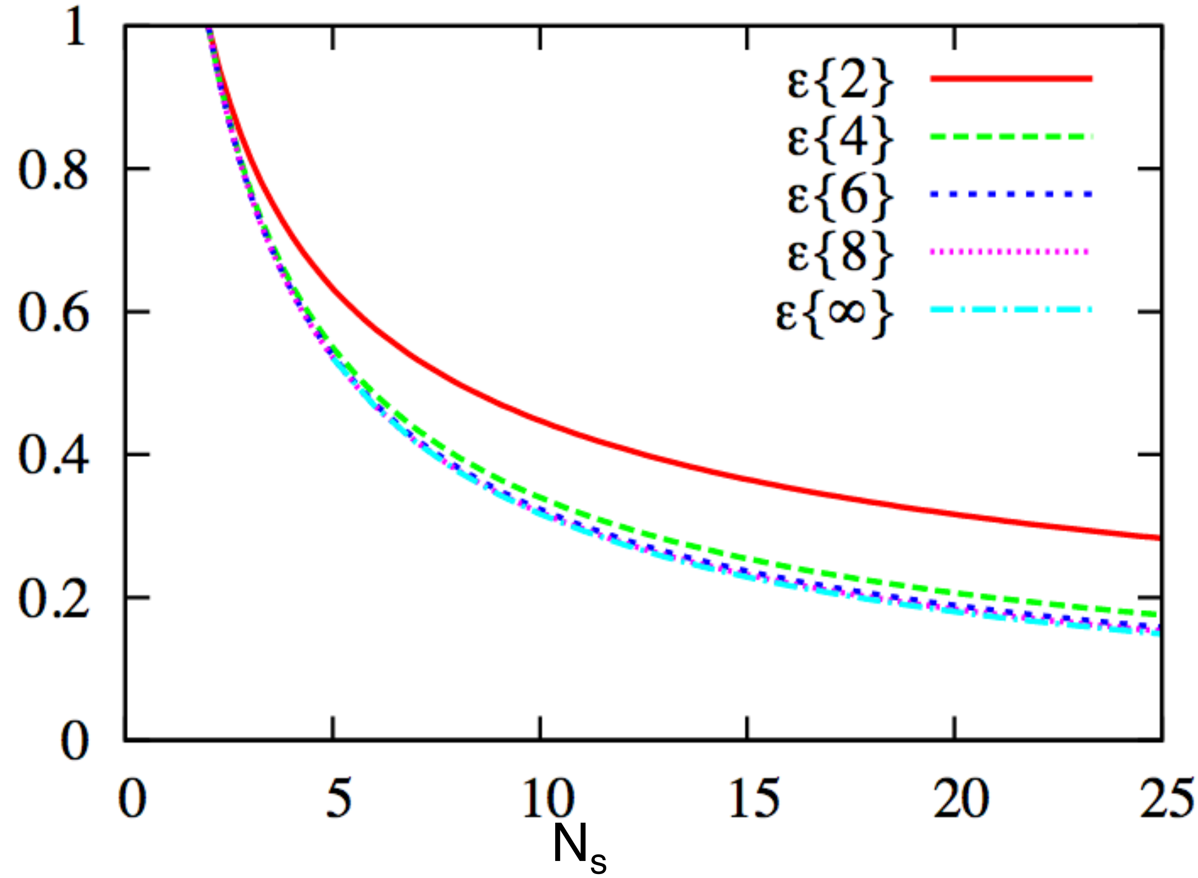
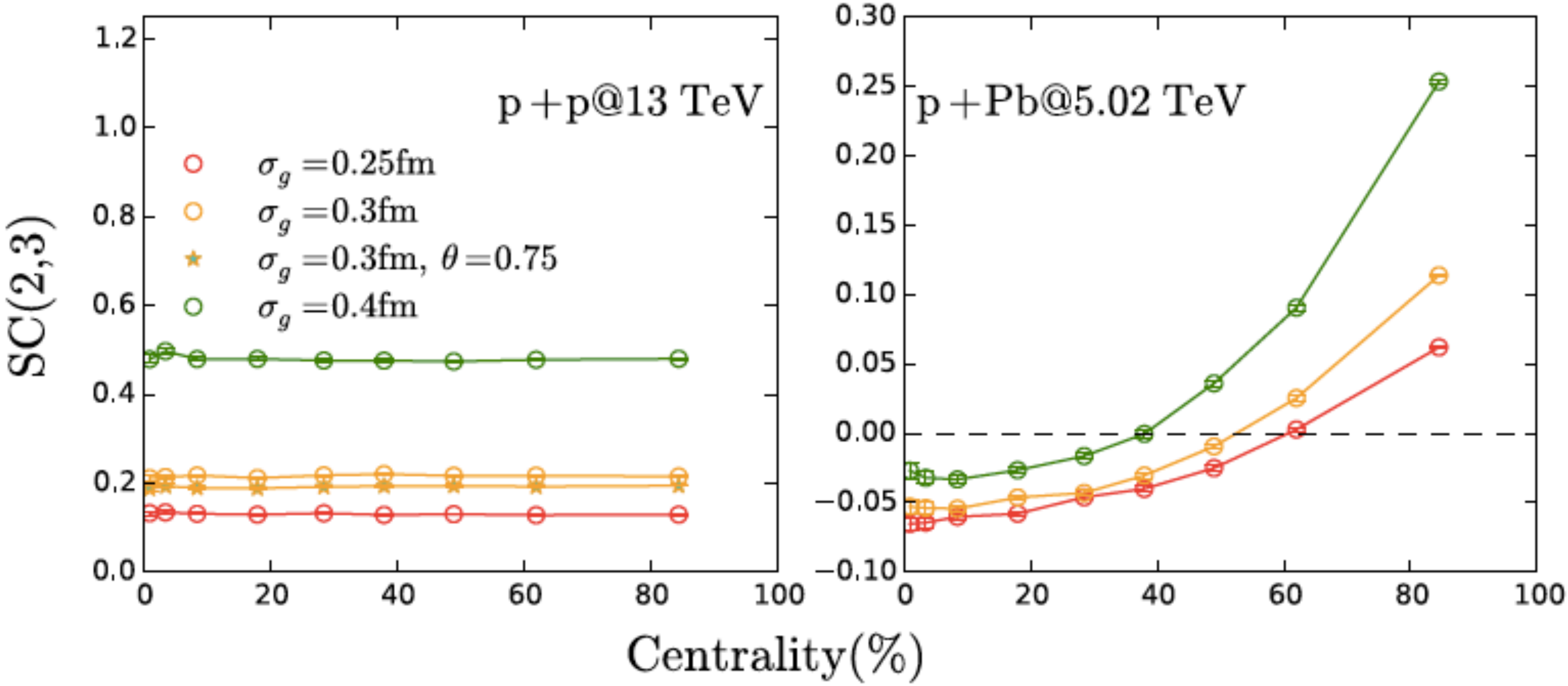
- Fundamental coupling strength of the system

To continue the exciting program at the LHC requires strong supports from the community as a whole

Backups

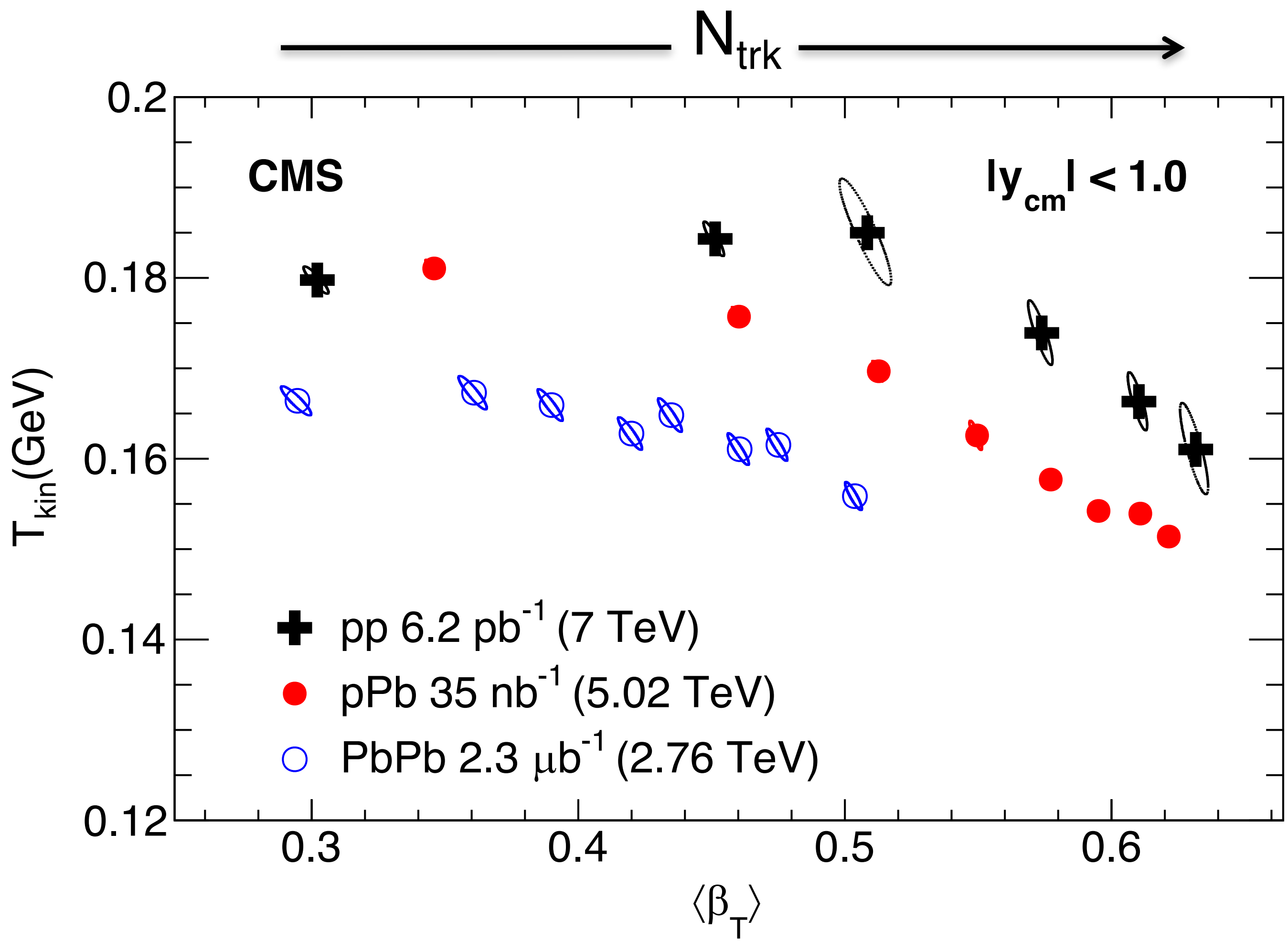


$$\frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} = \left(\frac{2}{1+N_s/2}\right)^{1/4}$$



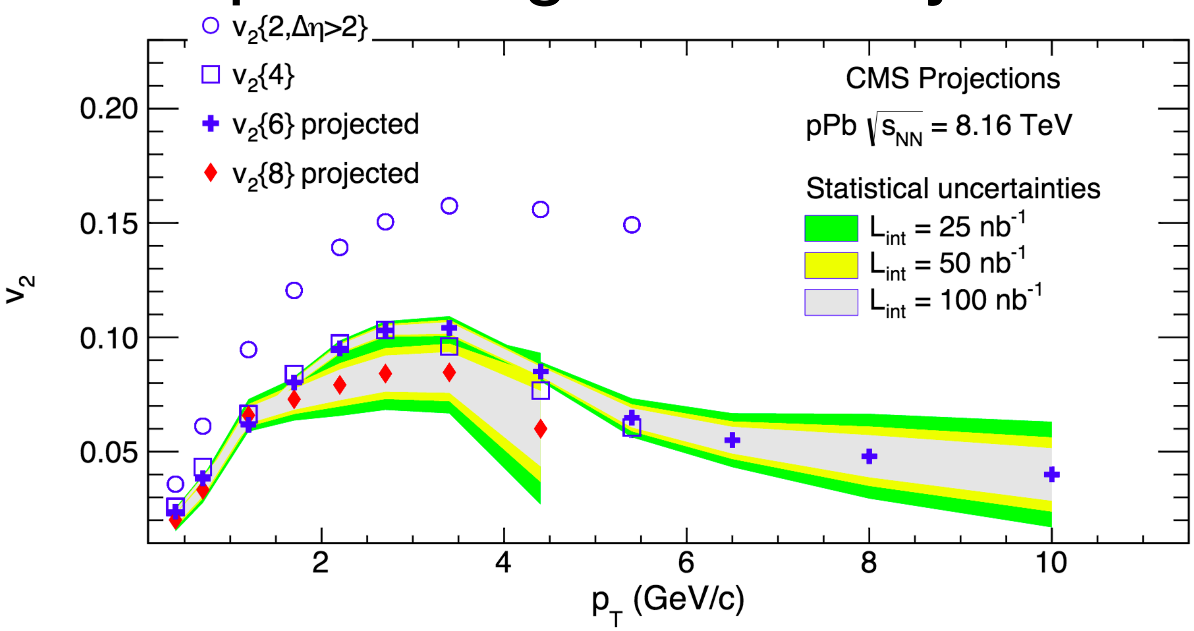
p+p@13 TeV
p+Pb@5.02 TeV
σ_g =0.25fm
σ_g =0.3fm
σ_g =0.3fm, θ=0.75
σ_g =0.4fm
SC(2,3)
Centrality(%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
20
40
60
80
100
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30

Blast-Wave fits to K_0^s, Λ and Ξ^-



$<\beta_T>$ larger as N_{trk} increases

Jet quenching in small system?



multiparticle v_2
at high p_T

***L_{int}* ~ 186 nb^{-1}**
collected in 2016