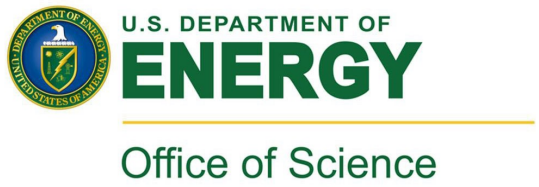
Collectivity from pp collisions at the LHC

Wei Li
Rice University



CPOD 2024
Berkeley, May 20-24

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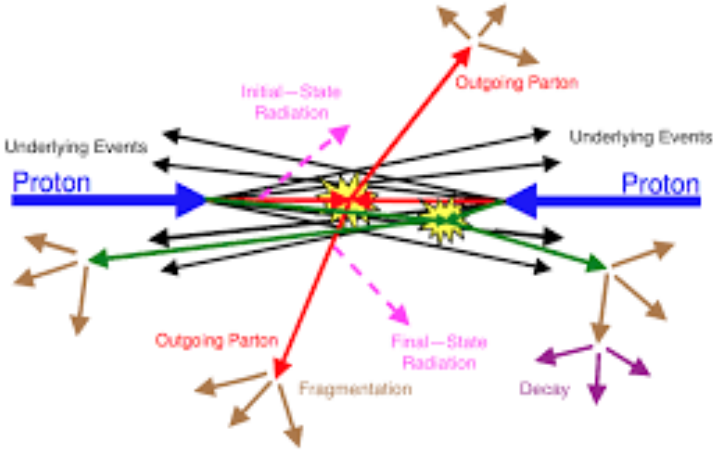
Collectivity ⟷ Emergent phenomena of a many-body **interacting** system

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

QCD matter in high energy collisions

Classical view of a pp collision



- Hard probe (HP): pQCD
- Underlying event (UE): multiple (independent) parton interaction (MPI)

Color (re)connection between HP and UE

No "matter" formed

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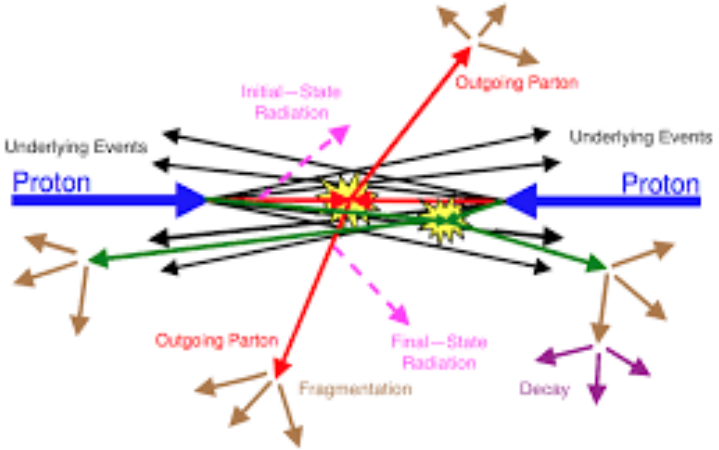

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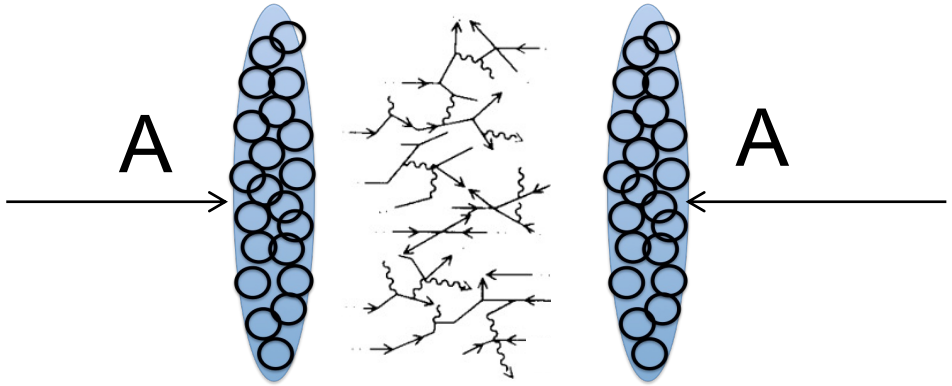
Relativistic Nuclear collisions

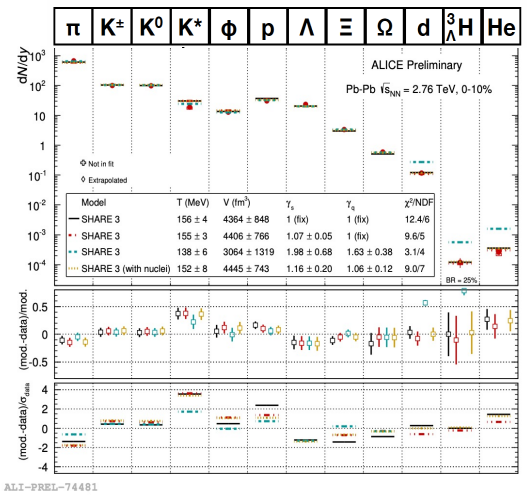


Discovery of **rescatterings** at the partonic degree of freedom

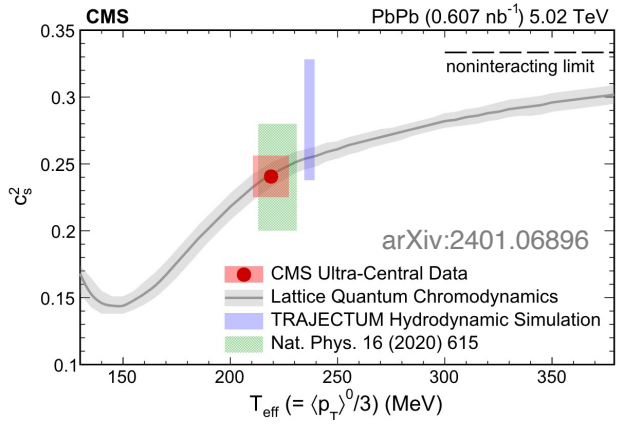
– Collectivity

QCD matter in high energy collisions

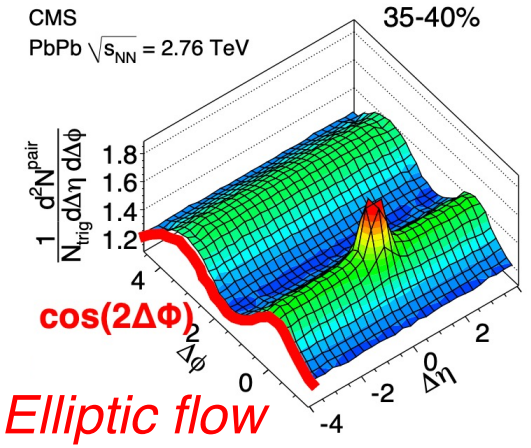
"Thermalization"



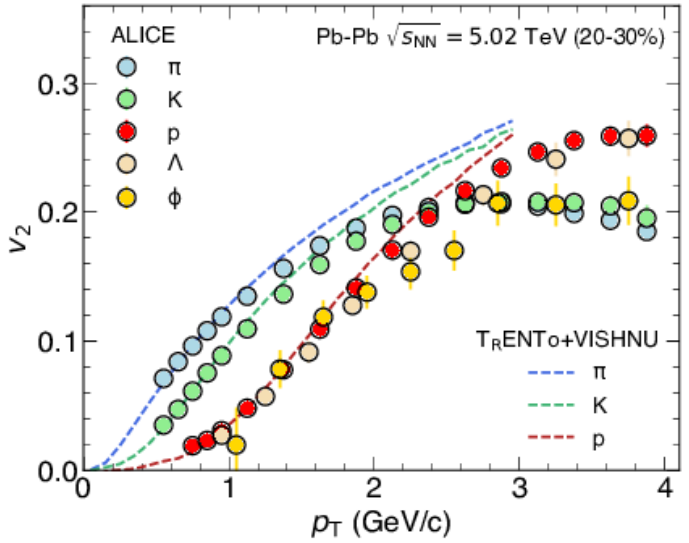
Speed of Sound & EoS

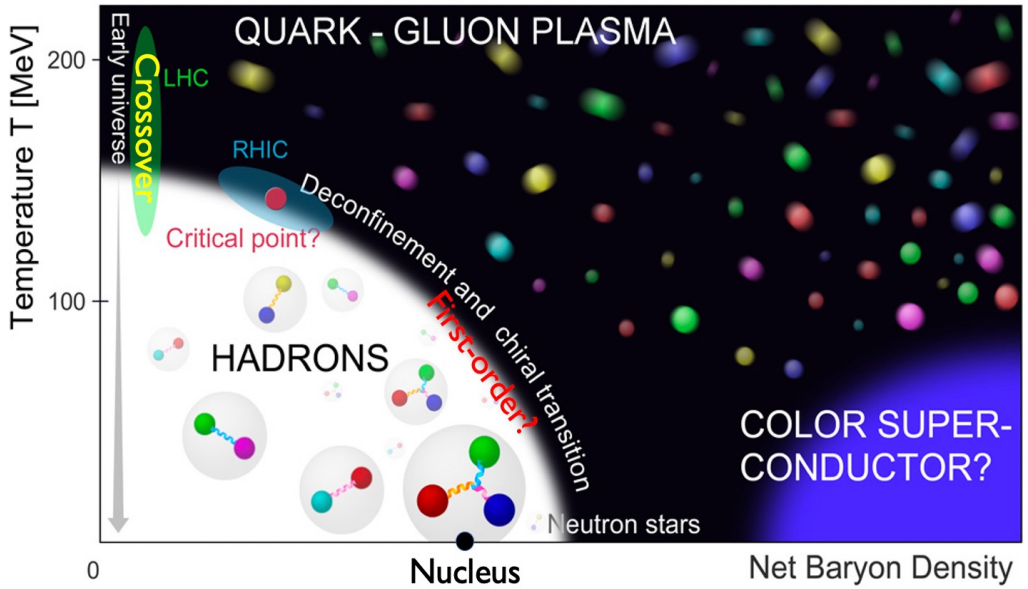


Collective flow



Elliptic flow

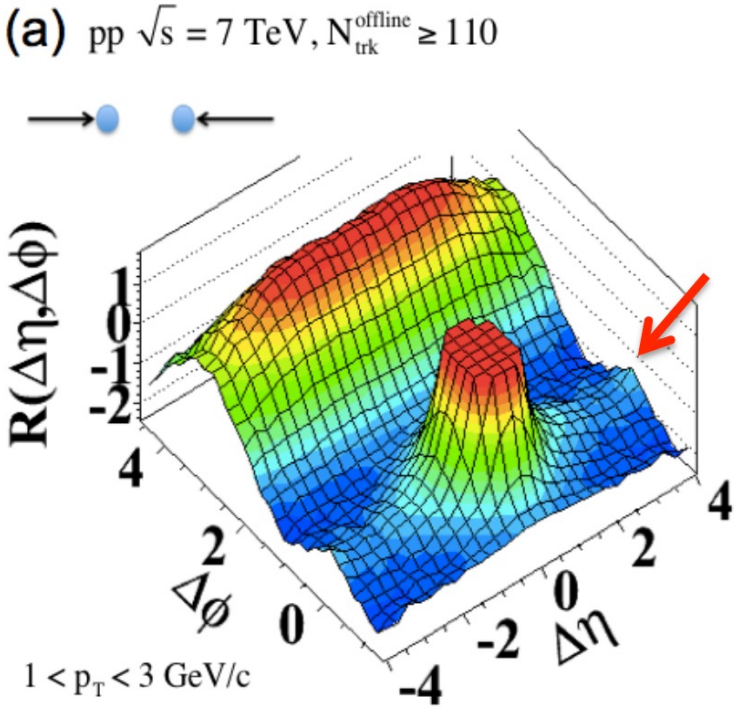




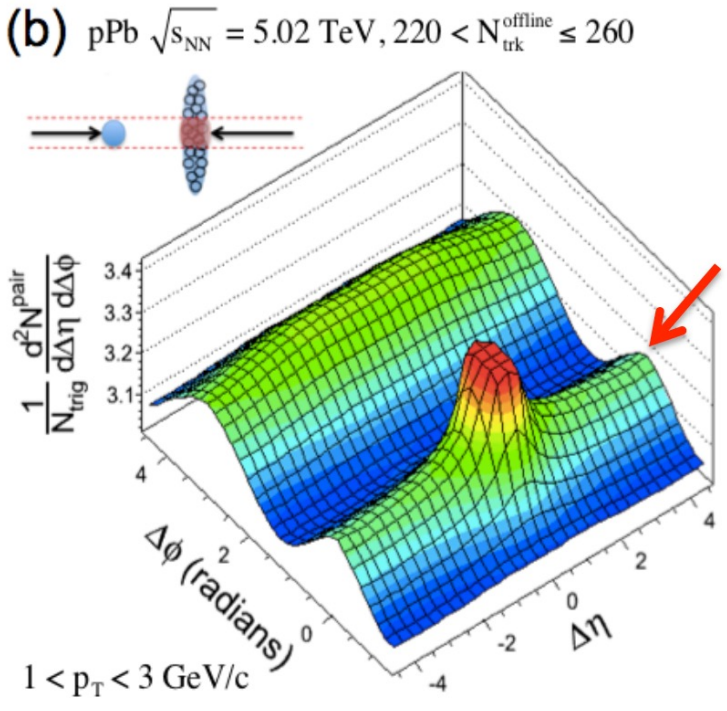
Deconfined matter over large distances, interact and evolve nonperturbatively, approaching ideal hydro. limit (small η/s)

Long-range near-side “ridge” in pp collisions

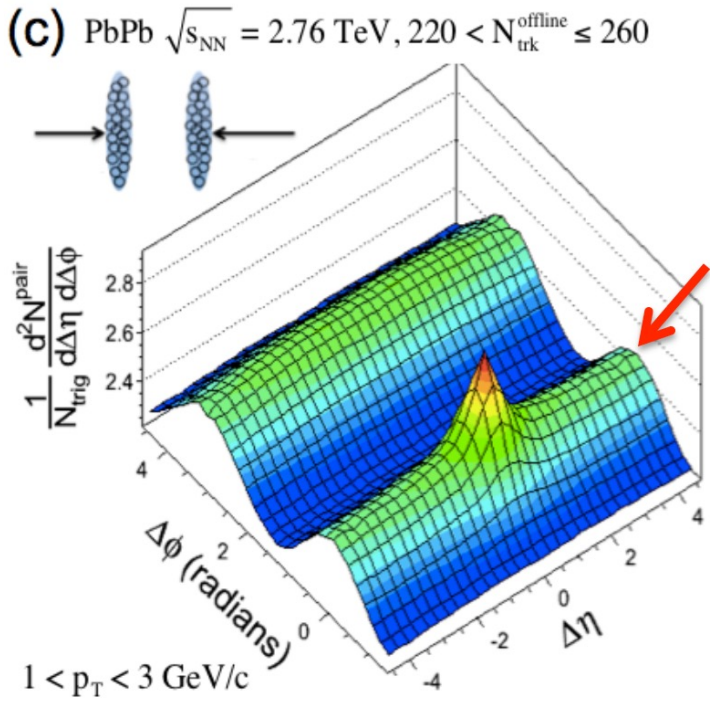
Early surprises at the LHC!



JHEP 09 (2010) 091



PLB 718 (2013) 795



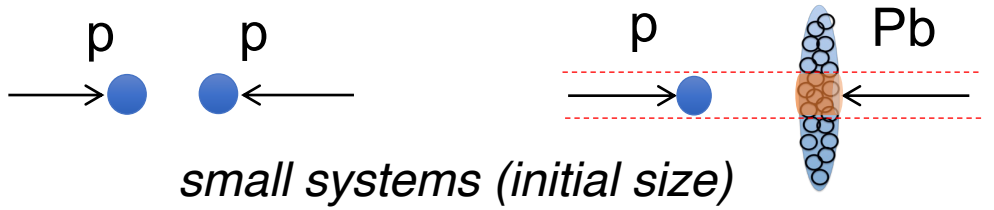
EPJC 72 (2012) 2012

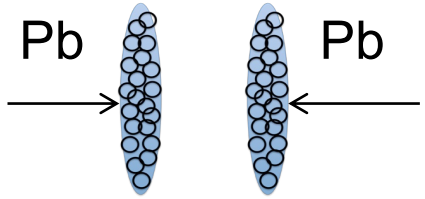
Elliptic flow in pp?

Is there collectivity in pp? Is it partonic (onset of deconfinement) or hadronic?

(How many “fishes” and how they interact to behave collectively?)

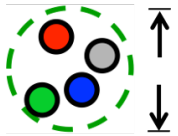
How does the *partonic* collectivity emerge?

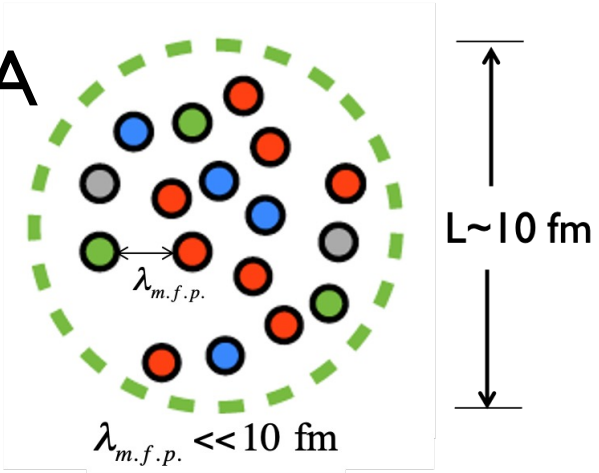




Hydrodynamic limit: $L >> \lambda_{m.f.p.}$ where $\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$

Too small and dilute?

PP  L~1 fm

AA 

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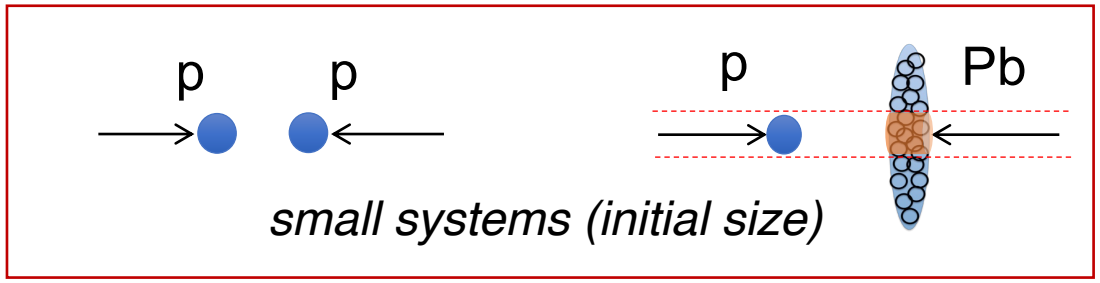

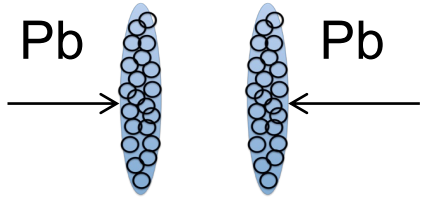

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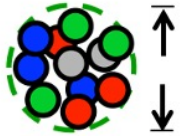
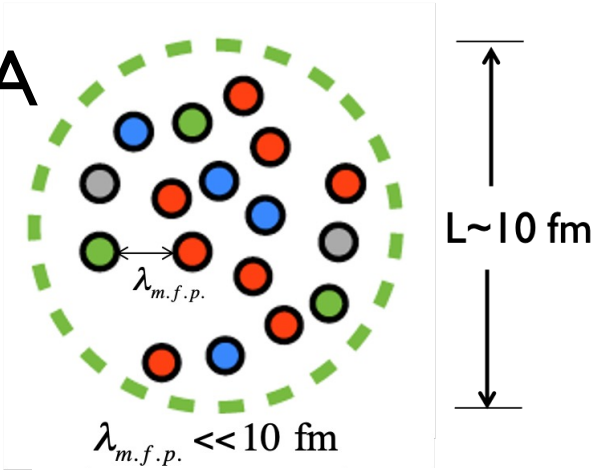
Small but denser? **T↑**

PP  L~1 fm $\left(N_{trk}/L^3 \sim s \sim T^3\right)$

AA



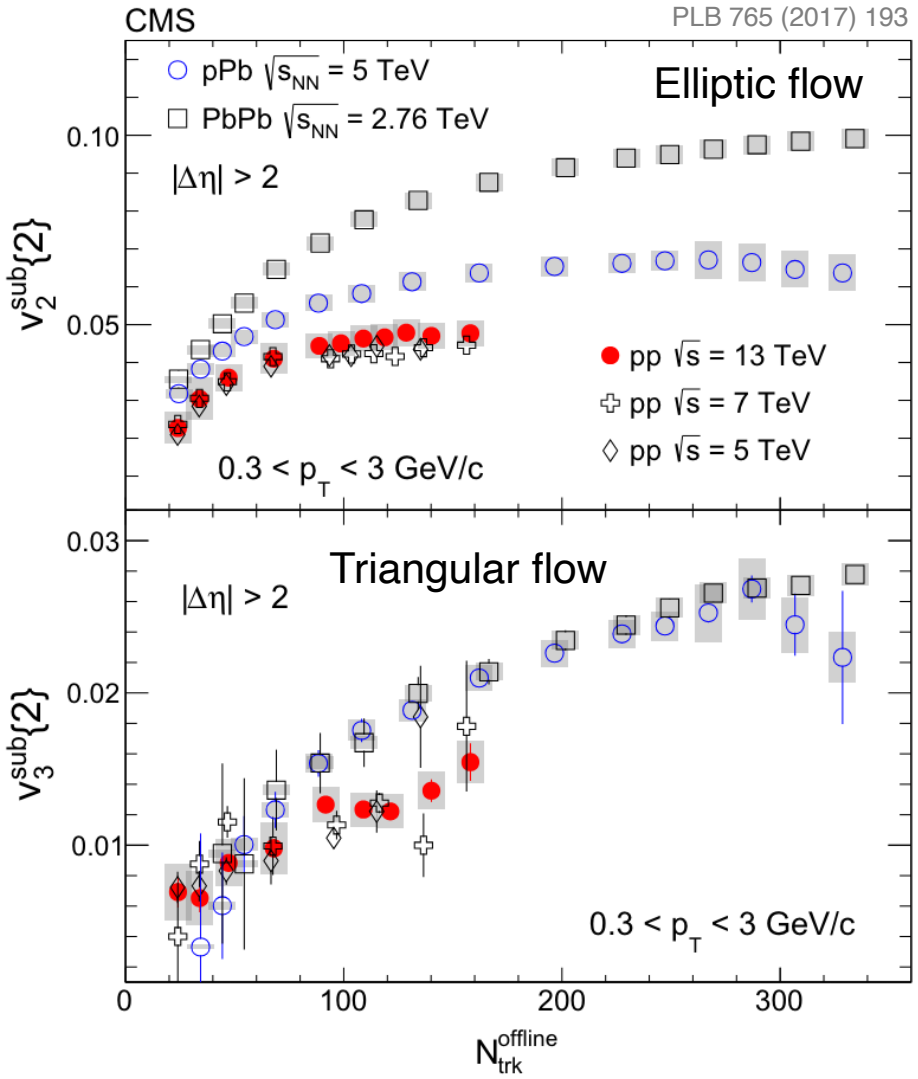
Experimental condition:

$$\left(\frac{L}{\lambda_{m.f.p.}}\right)^3 \sim (LT)^3 \sim N_{ch}$$

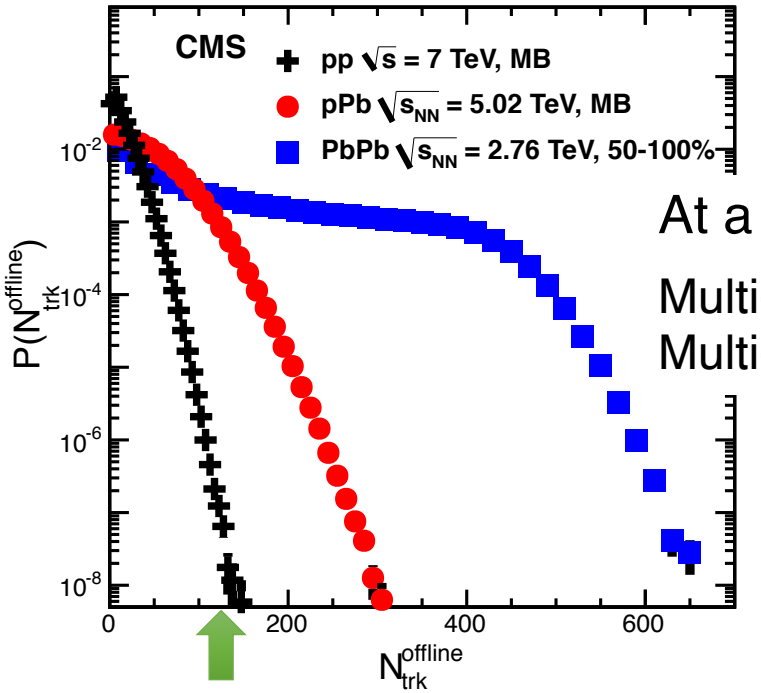
Smaller system starts at higher T and is more explosive

Collectivity in proton-proton collisions

v_2 and v_3 in pp, pPb and PbPb



N_{ch} distribution



At a given N_{ch},

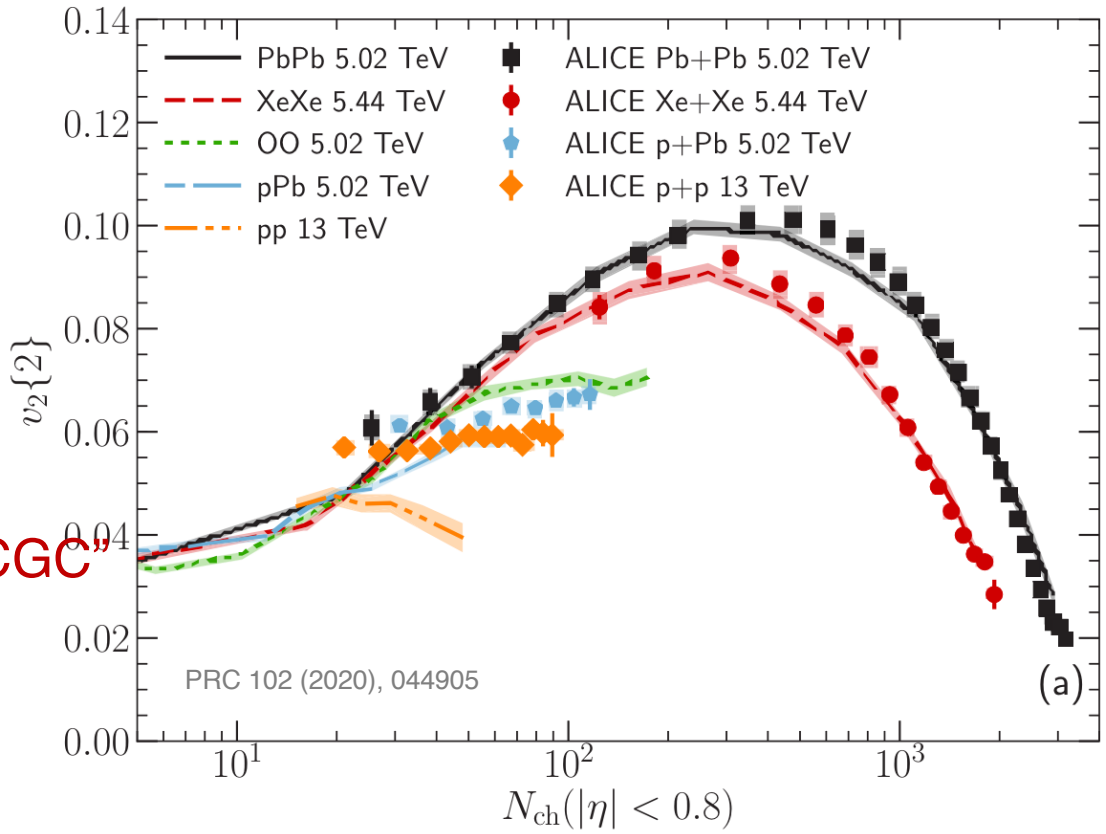
Multi-**parton** interactions in pp

Multi-**nucleon** interactions in AA

Connection between N_{ch} (centrality) and initial geometry well established in AA but NOT in pp

Collectivity in proton-proton collisions

CGC + Hydro. + UrQMD



"CGC"

"Nonflow" subtraction in small systems is a subtle and should always be taken with a grain of salt

State-of-the-art hydro. simulations:

- Excellent descriptions of large AA
- Not yet satisfactory for pp/pA – *how to model the geometry of a proton?*

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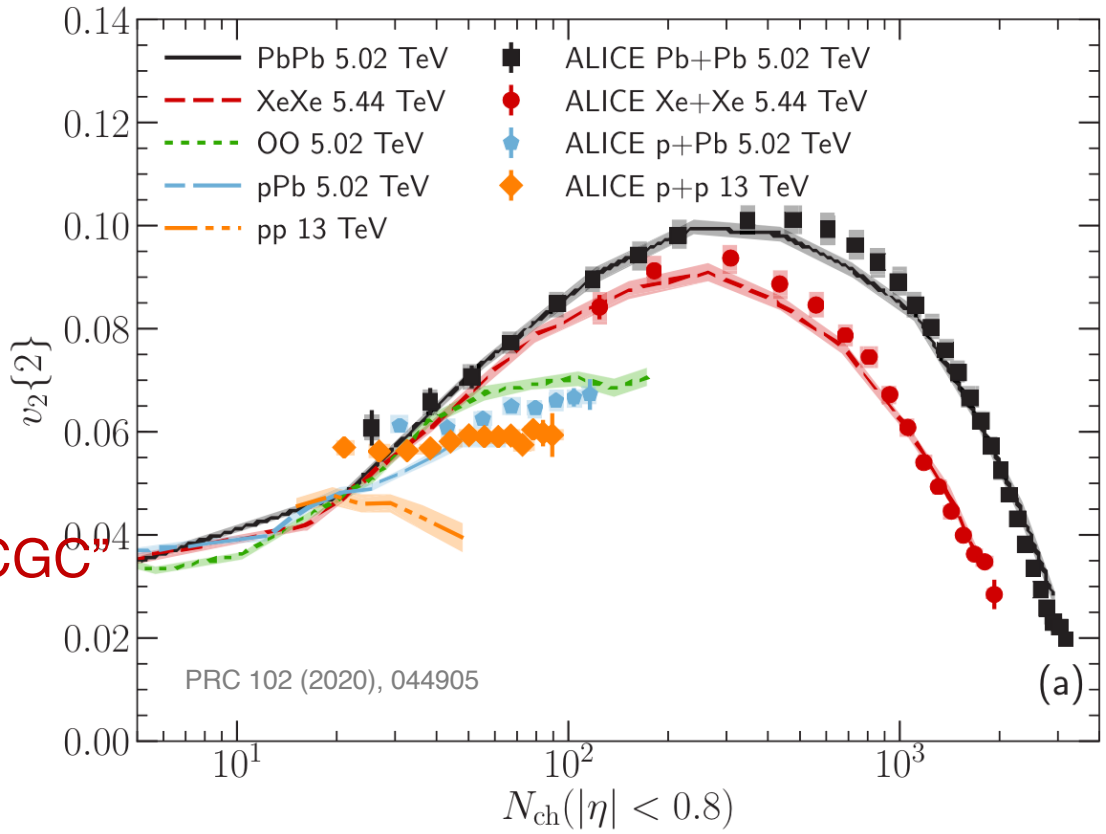

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Alternative origins?

- Initial momentum correlations from gluon saturation relevant at low multiplicity?
  – *inconclusive and no clear evidence*

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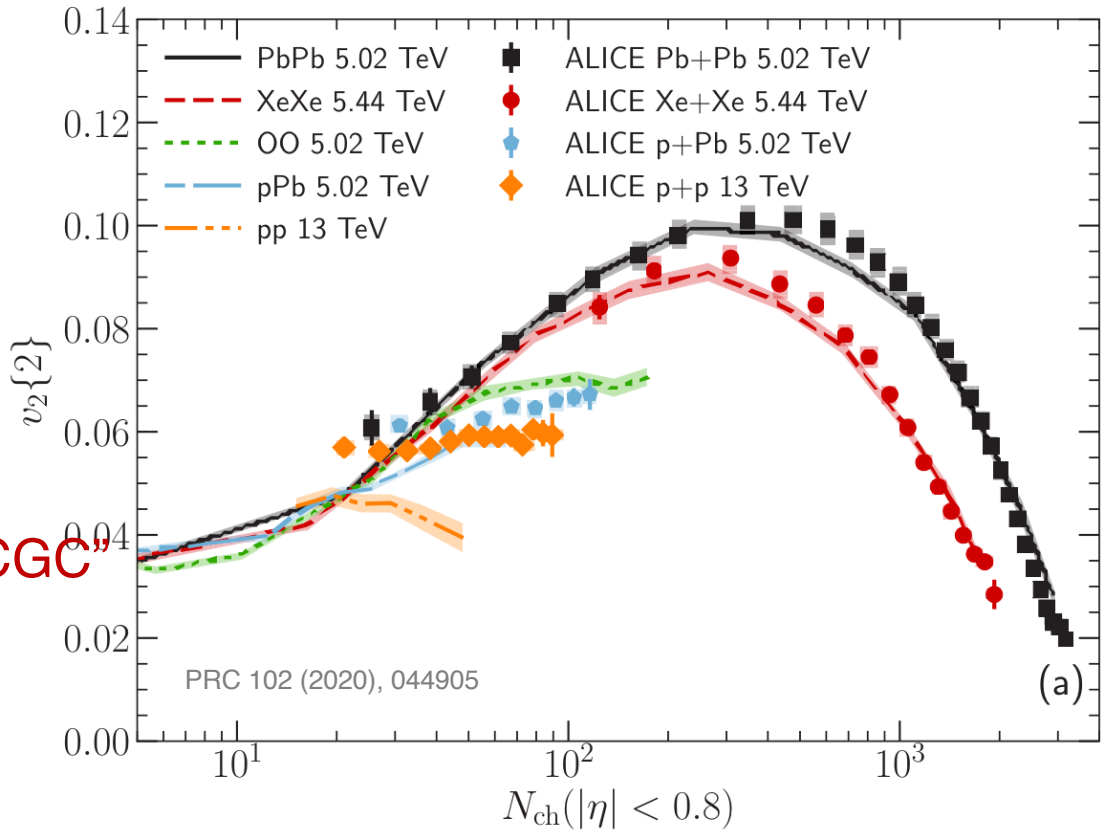

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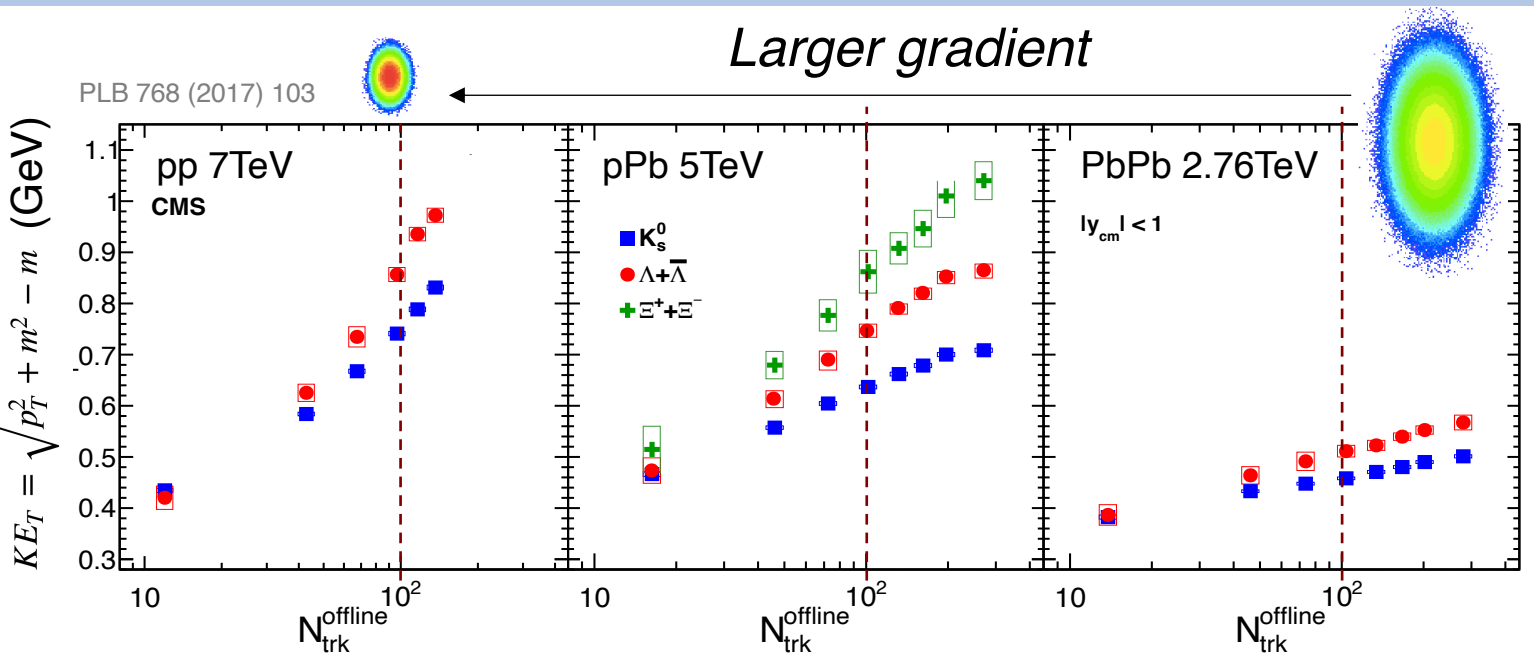
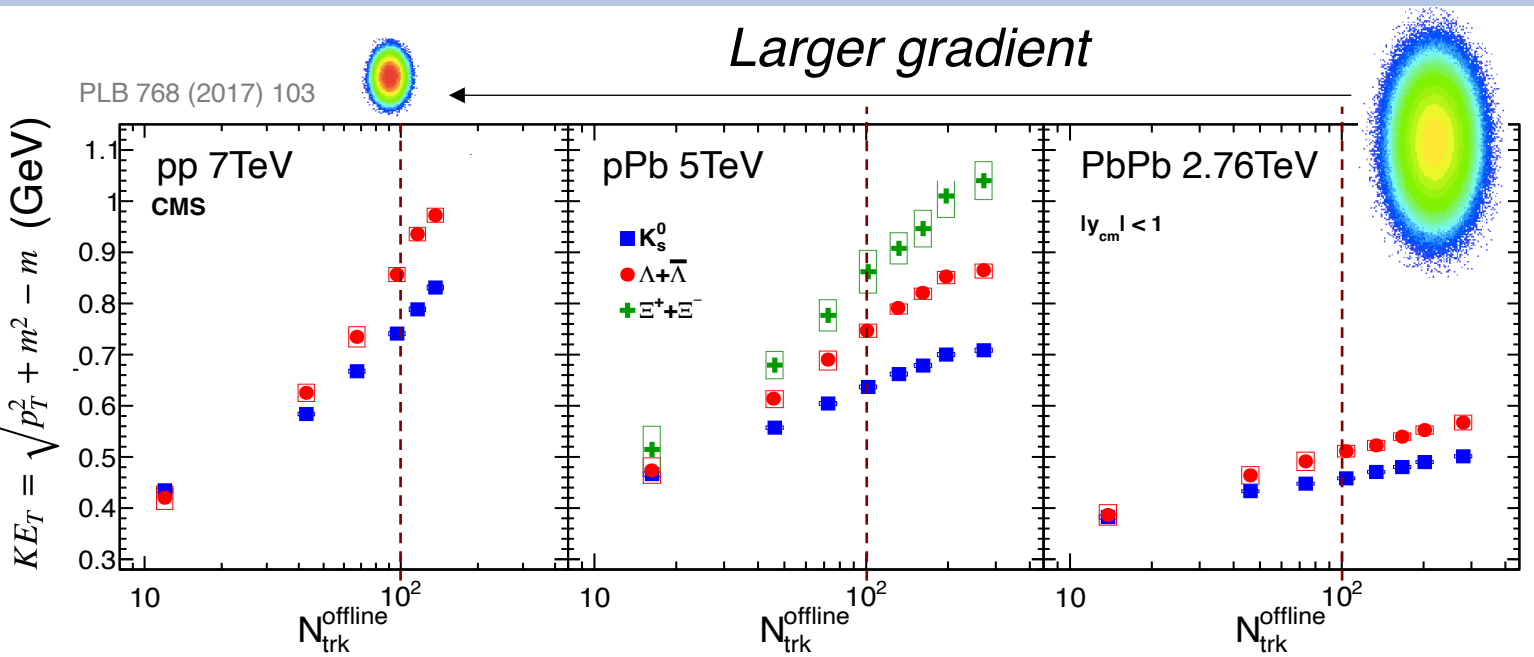
Is there an onset of collectivity from low- to high multiplicity? – *possibly but inconclusive*

Radial flow and mass ordering



At a given N_{ch}, larger splitting in **<KE$_T$>** for pp/pPb

Radial flow and mass ordering



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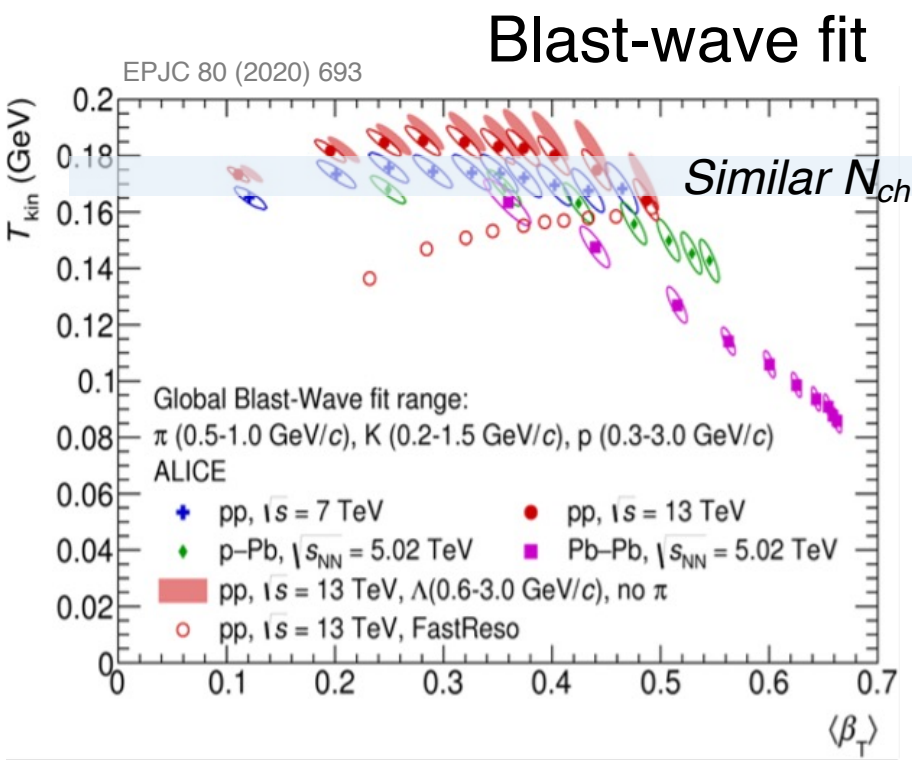
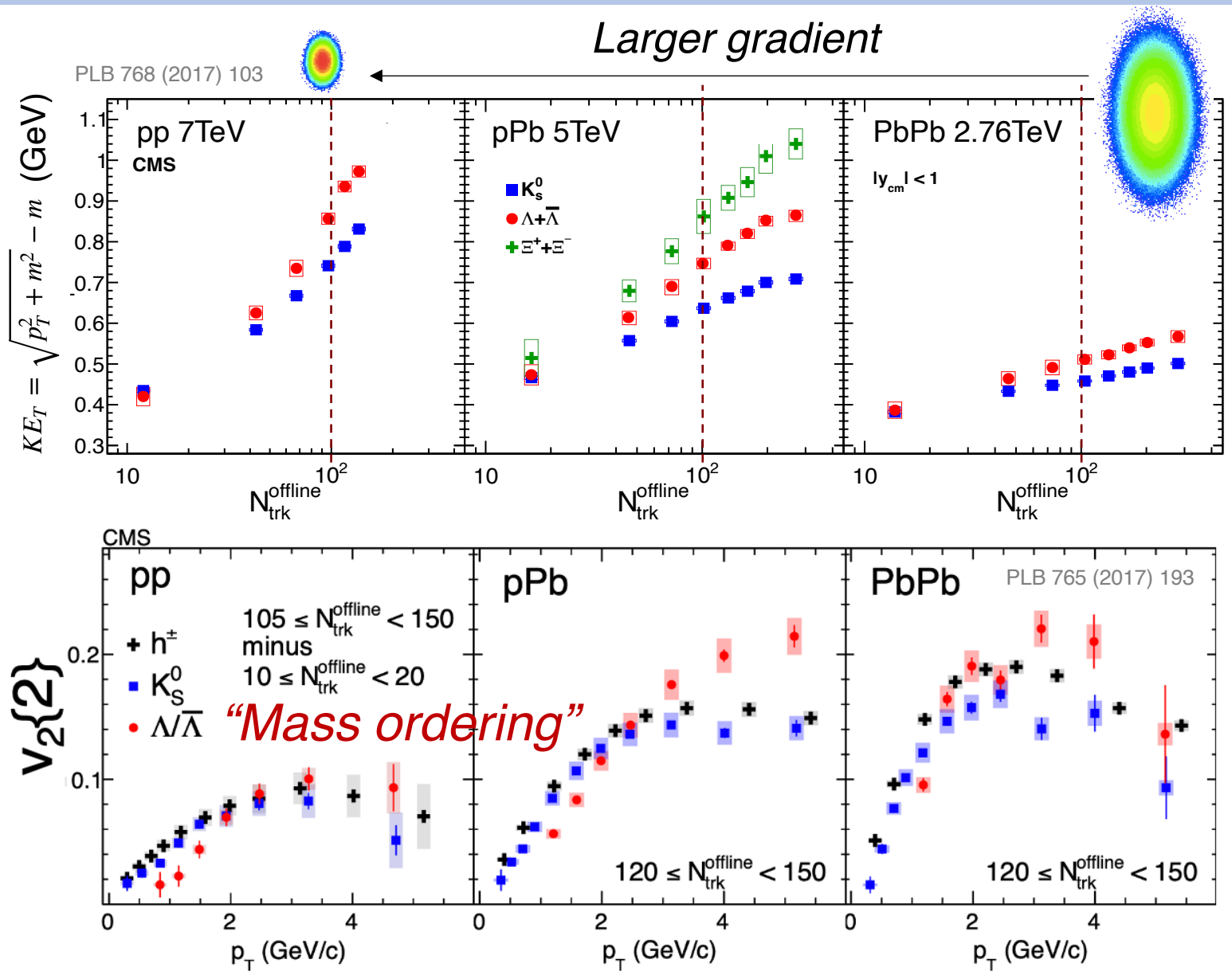


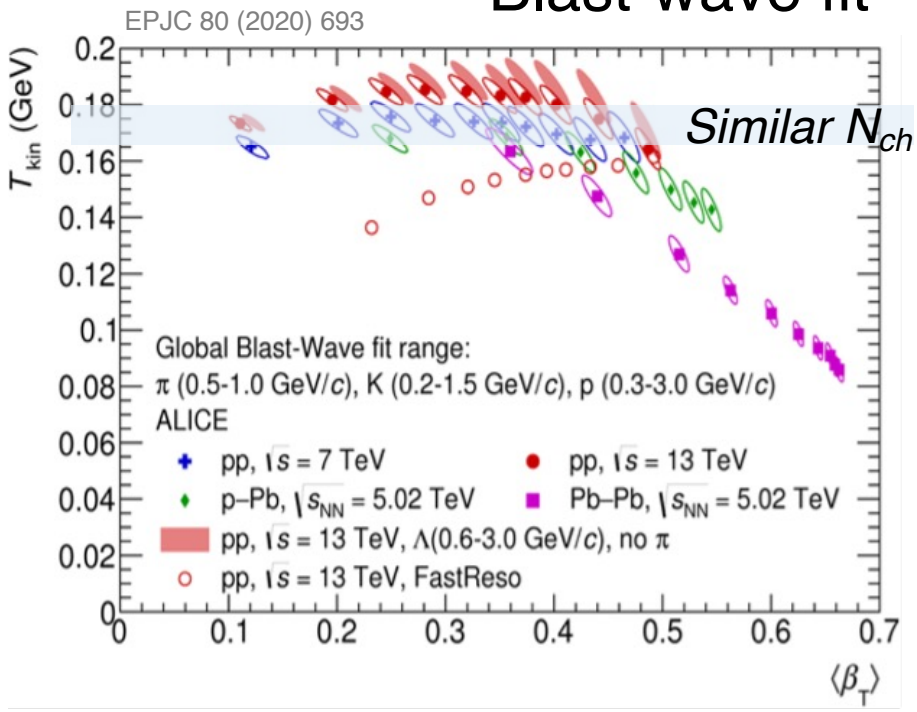
pp has higher T_0, and more explosive

Shorter duration of hadronic rescatterings

Radial flow and mass ordering



Blast-wave fit



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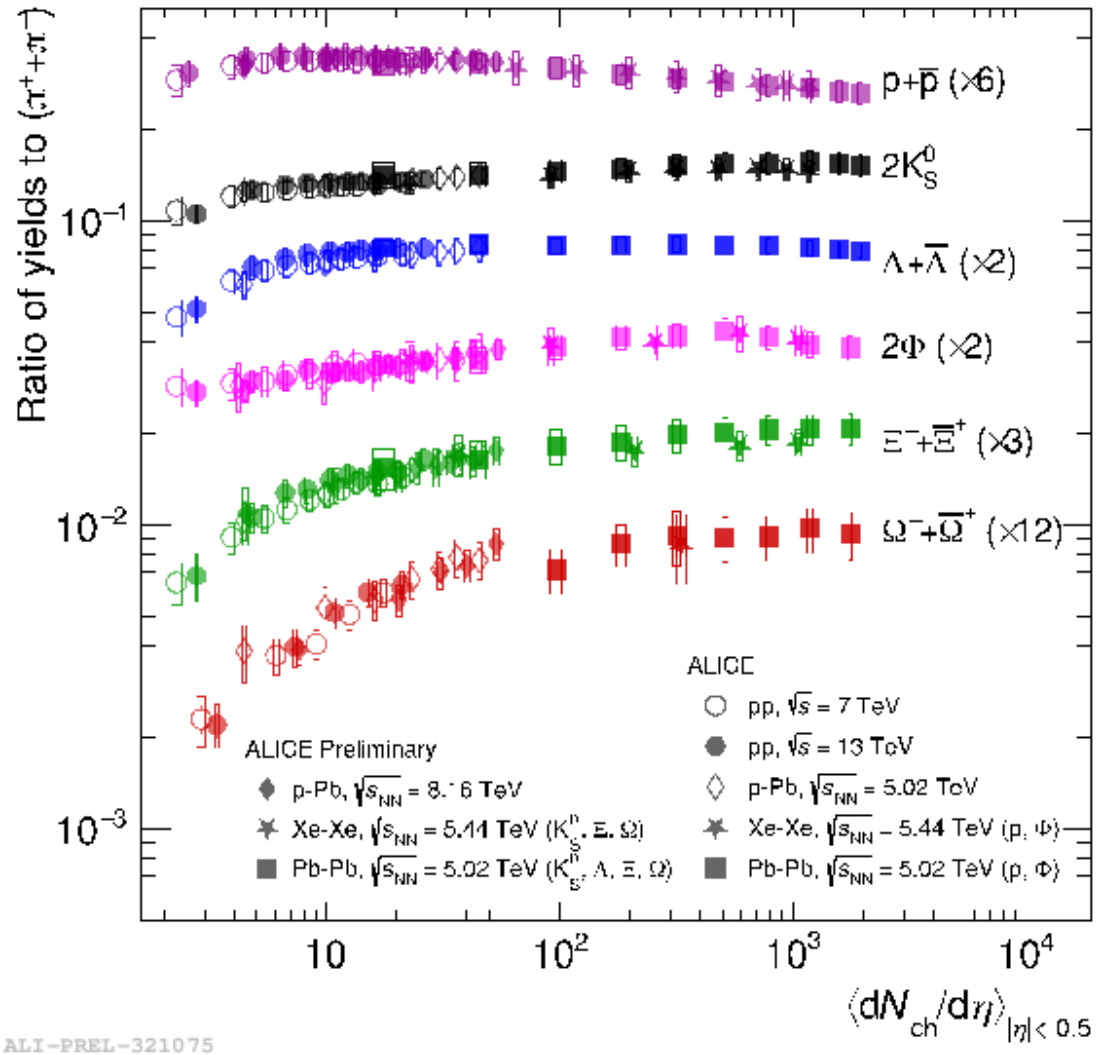
Strangeness enhancement



Relative strangeness yields are enhanced as a function of N_{ch}

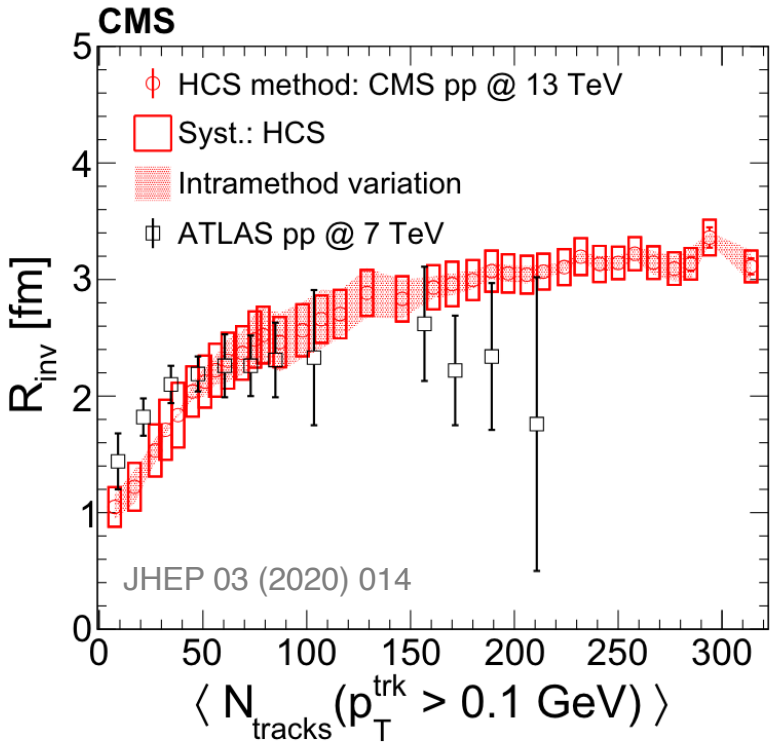
- AA is not simply a superposition of pp
- HM pp is not a superposition of more MPIs

– Collectivity

Ratios across all systems scales with N_{ch}, regardless of system size, initial T, etc.!

“Geometric size” from HBT correlations

1-D HBT radii vs N_{ch} in pp



Increases as $(N_{ch})^{1/3}$ but saturate at very HM? (CGC?)

NPA 916 (2013) 210

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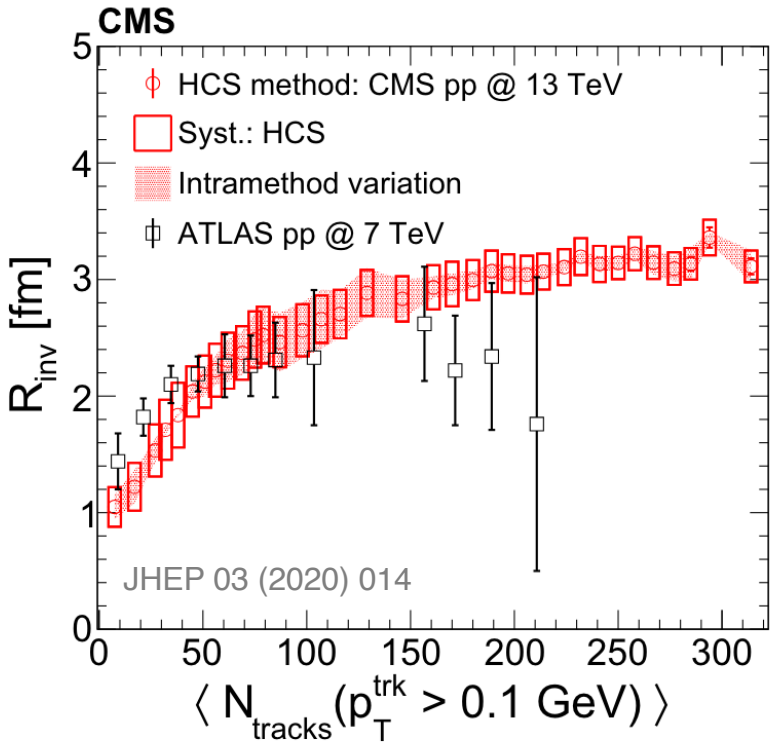

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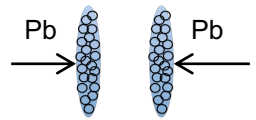
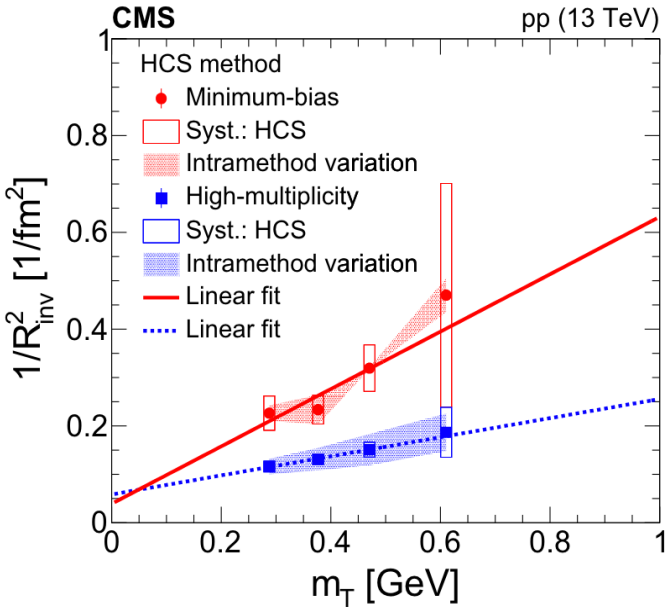
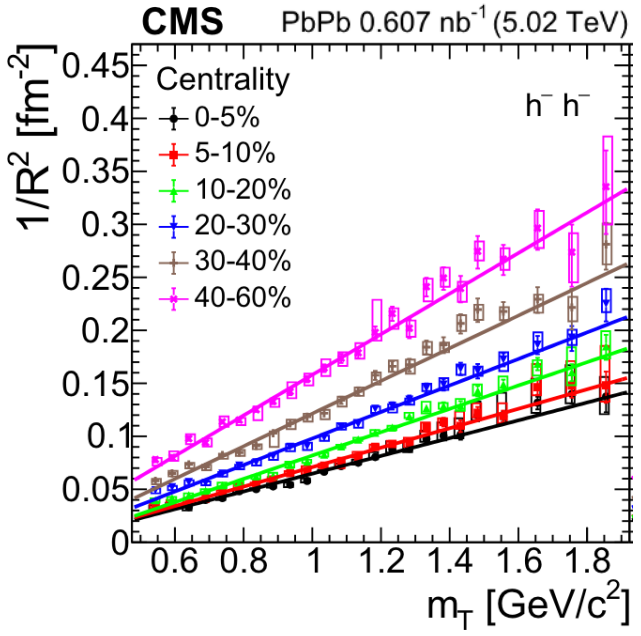
NPA 916 (2013) 210

1-D HBT radii vs m_T (motivated by hydro.)







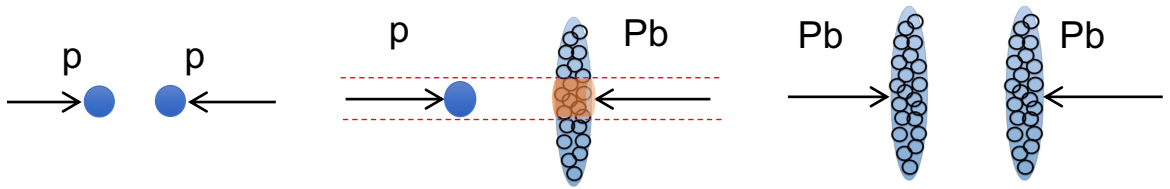
$$R_{\mathrm{inv}}^{-2} \propto a + b m_{\mathrm{T}}$$

“Geometric size”
- 4-5 fm in pp

“Hubble constant”
- Smaller for HM events

Striking similarity between pp and PbPb

How small is too small?



Overwhelming evidence for partonic collectivity and QGP signatures in HM events across all system!

- *Excitation of QCD vacuum → collectivity*

Is collectivity or “QGP” an intrinsic feature of any non-pert. many-body QCD system?

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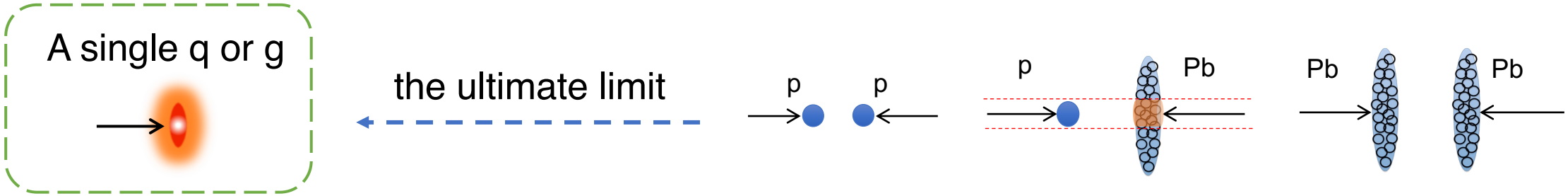
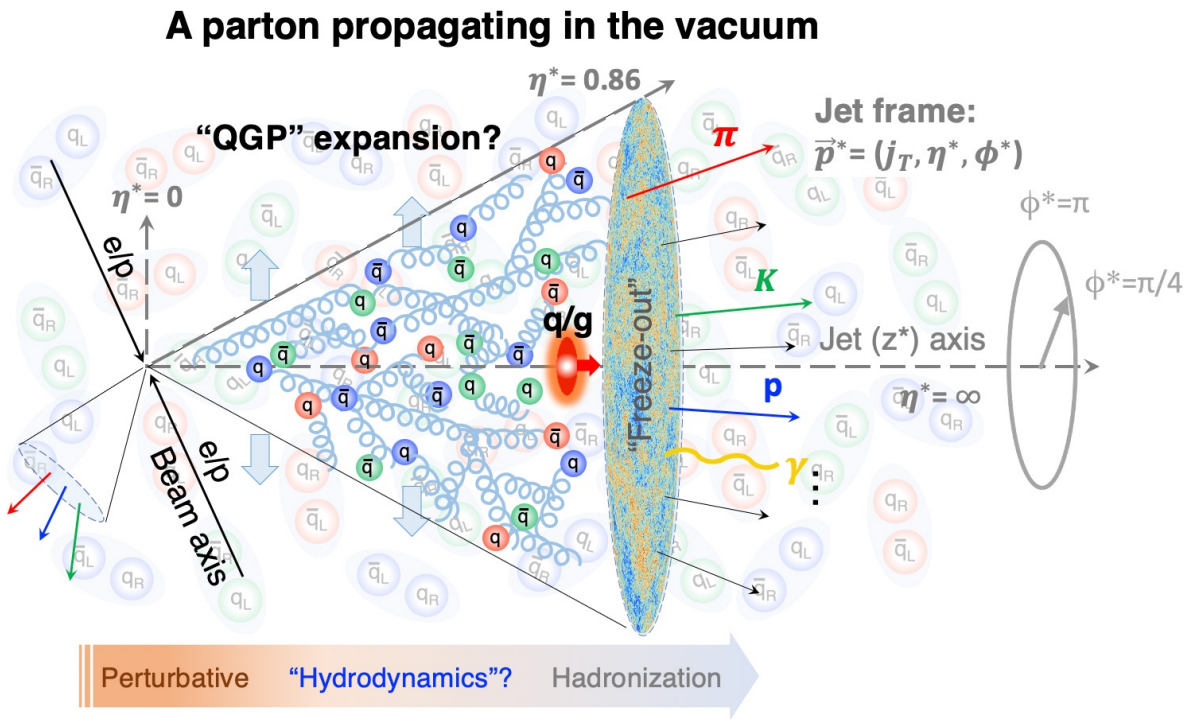


A. Baty, P. Gardner, WL,
PRC 107 (2023) 064908



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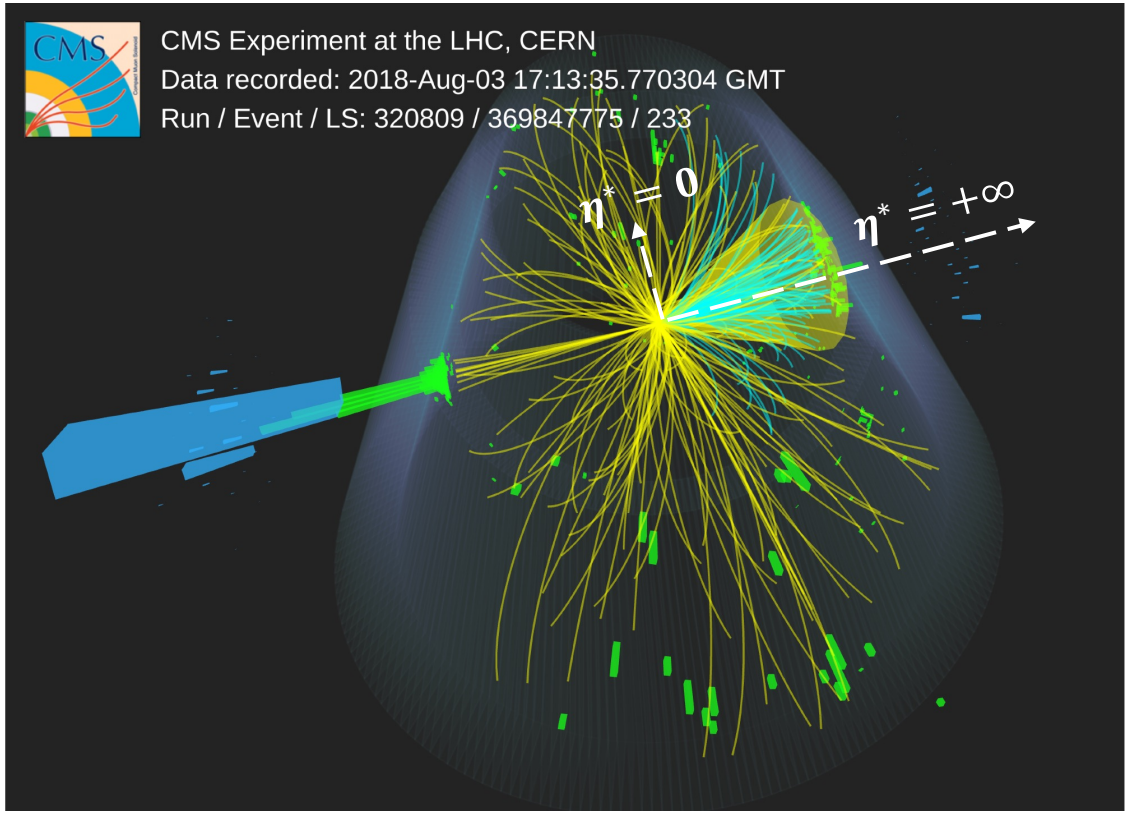
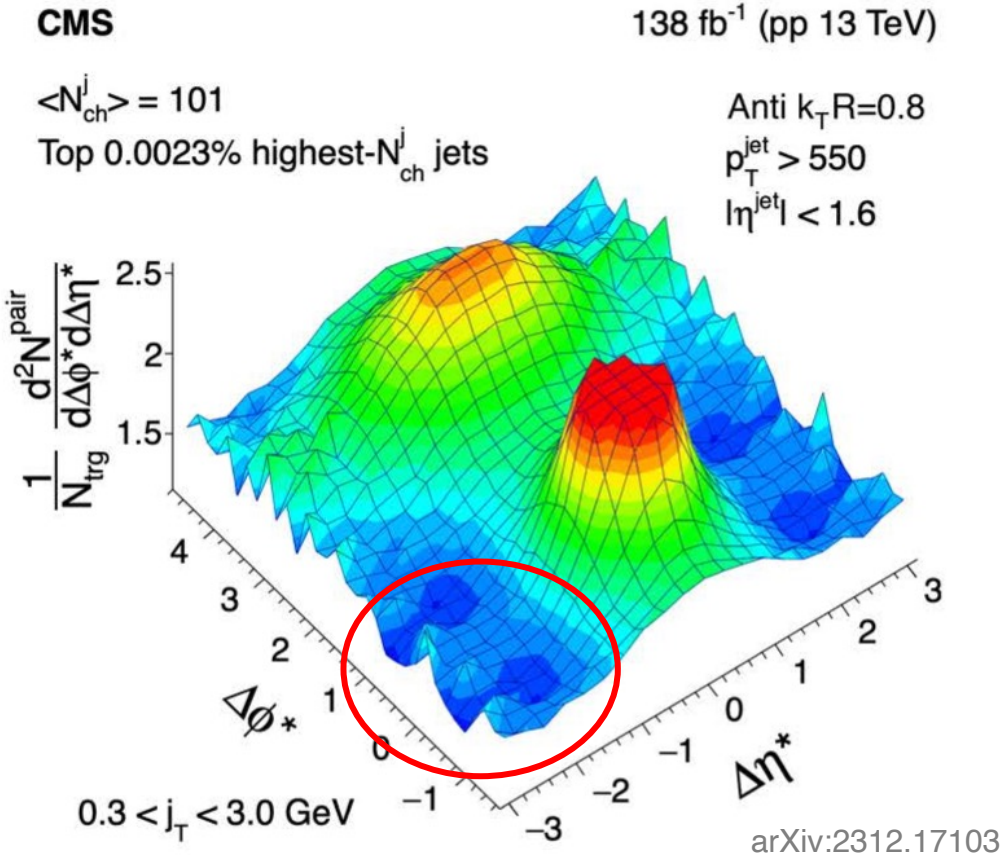
Can hydro. be generalized as an effective tool to describe the dynamics of any many-body QCD system (e.g., jet fragmentation)

Collectivity initiated by a single parton!?

A HM jet with N_{ch}>100 inside the cone

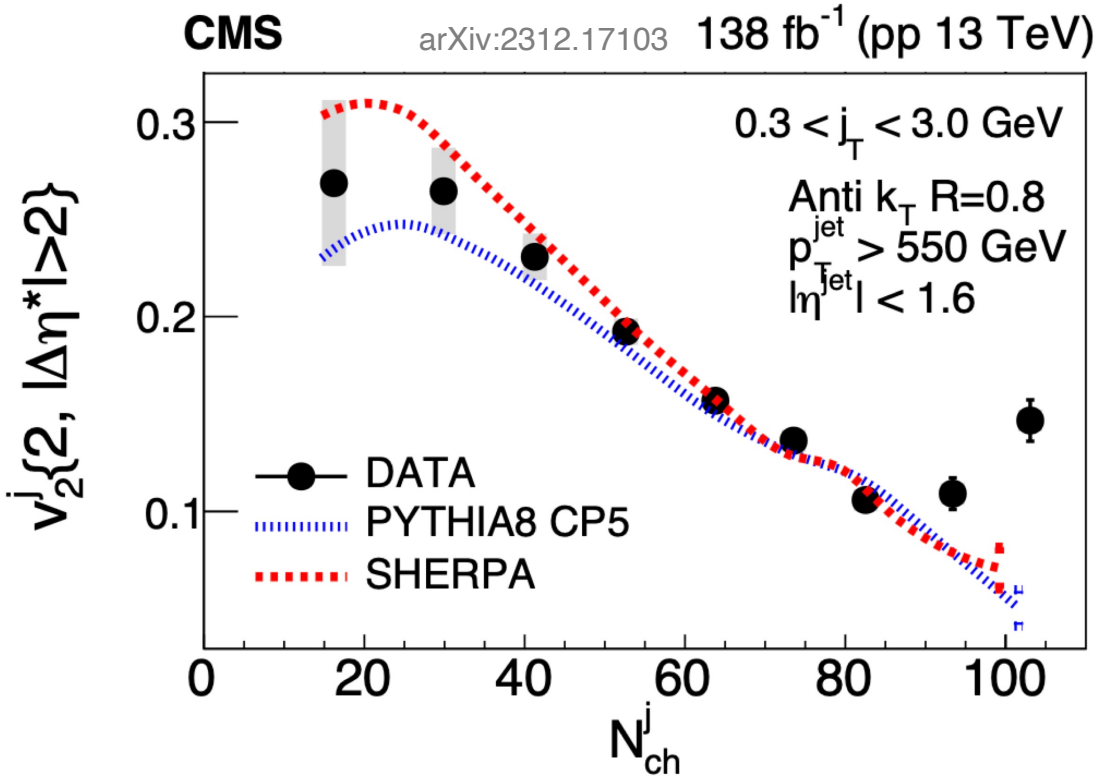


Two-particle correlations **in the jet frame**



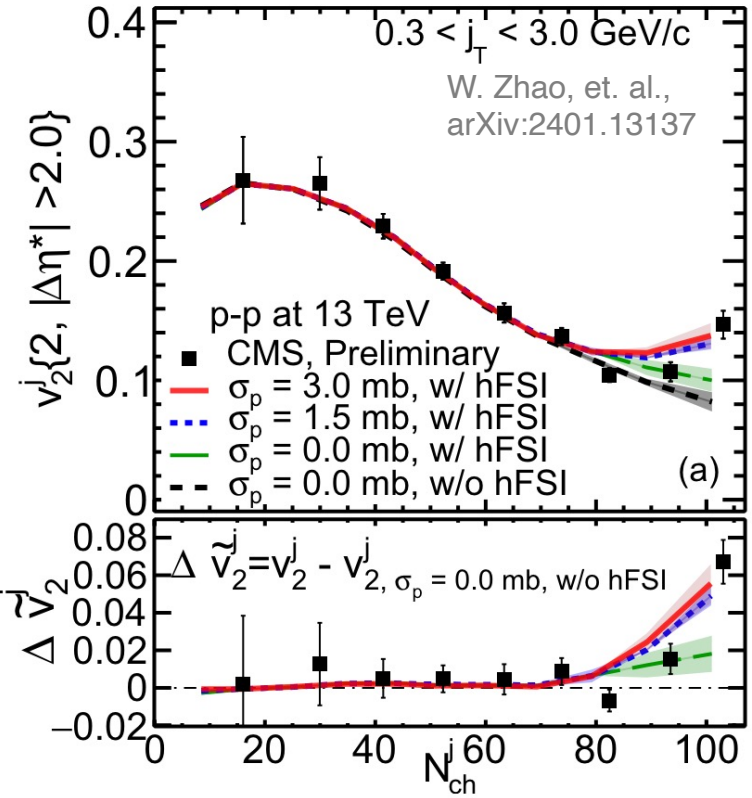
A near-side ridge in HM jets?

“Elliptic flow” and collectivity in HM jets!?



Rising trend for high multiplicity jets!

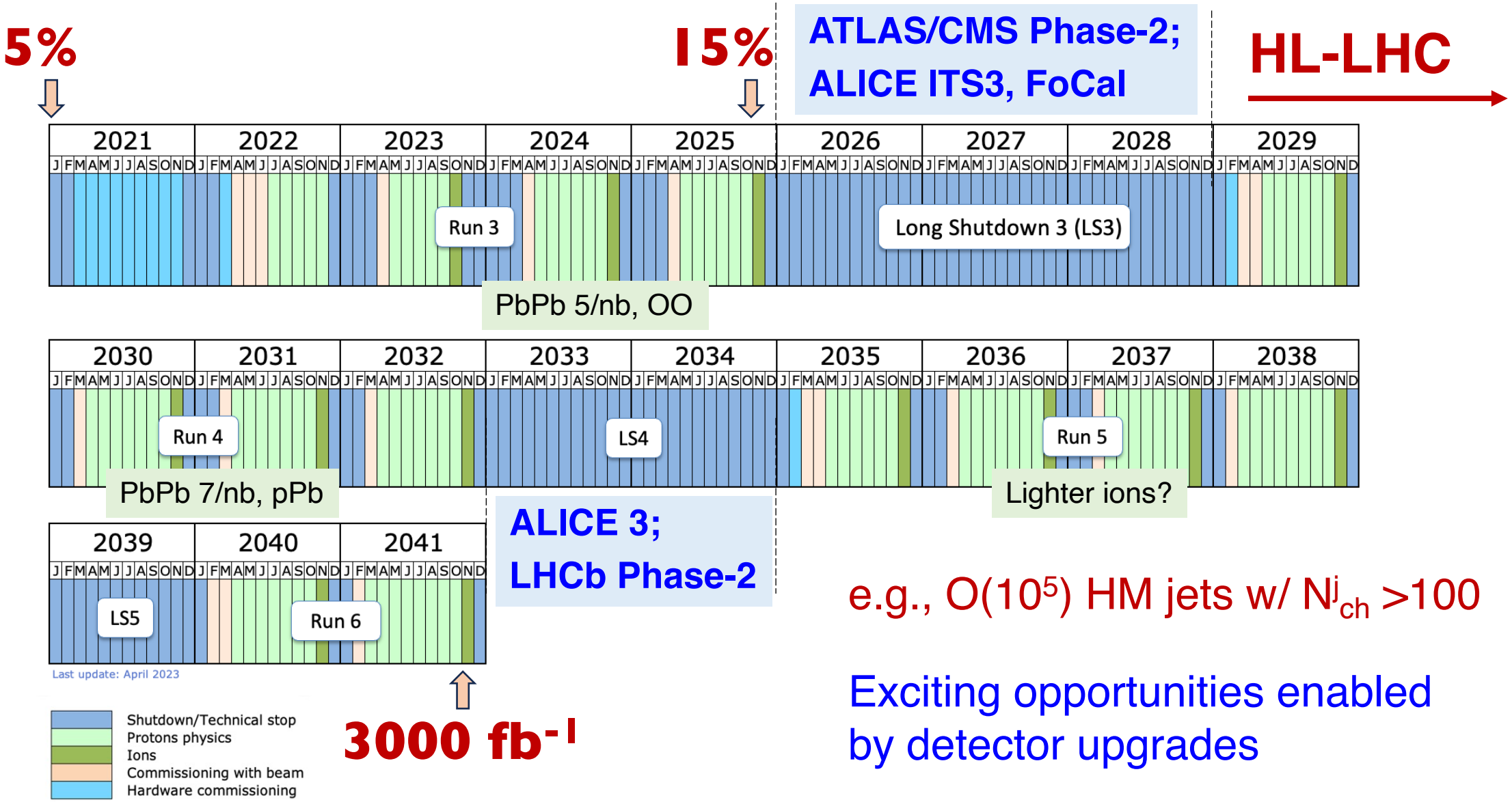
Jet frag. model incorporating rescatterings among showers



Observation of enhanced elliptic anisotropies – onset of collectivity?

Other “QGP” signatures in a jet: radial flow, HBT, strangeness, …?

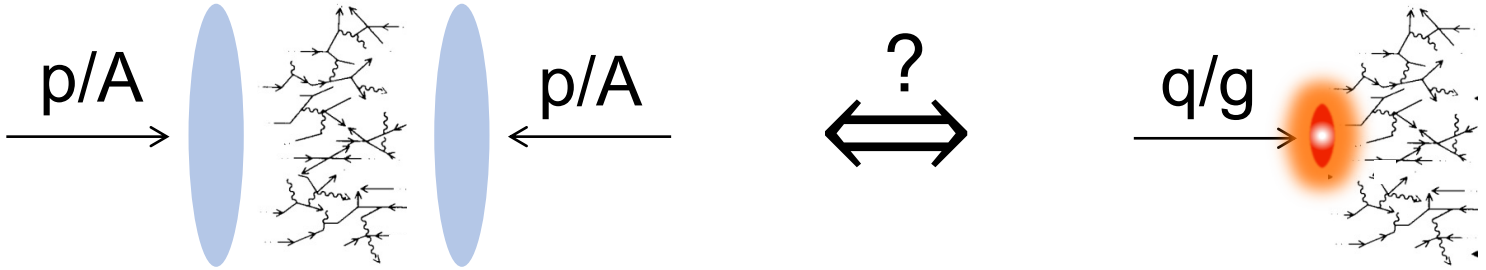
Future LHC program



e.g., O(10^5) HM jets w/ N^j_{ch} >100

Exciting opportunities enabled by detector upgrades

Summary



Small systems (pp/pA) exhibit strong collectivity and “QGP” signatures as AA

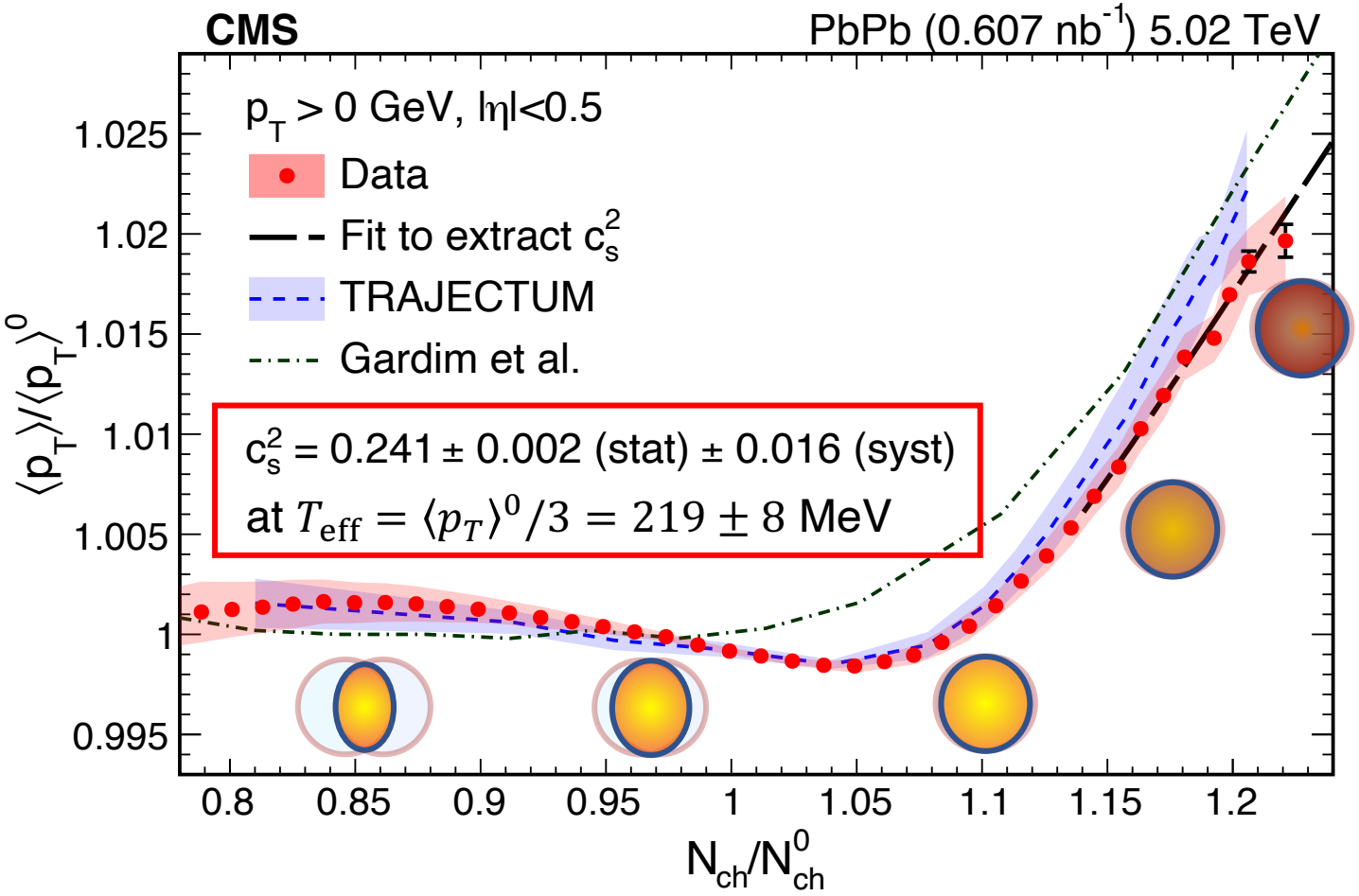
- Dominated by final-state partonic rescatterings for HM events
- Gradual onset as a function of multiplicity

AA vs. a vacuum jet fragmentation not that fundamentally different?:
is collectivity a “built-in” feature in any excited, dense state of QCD vacuum?

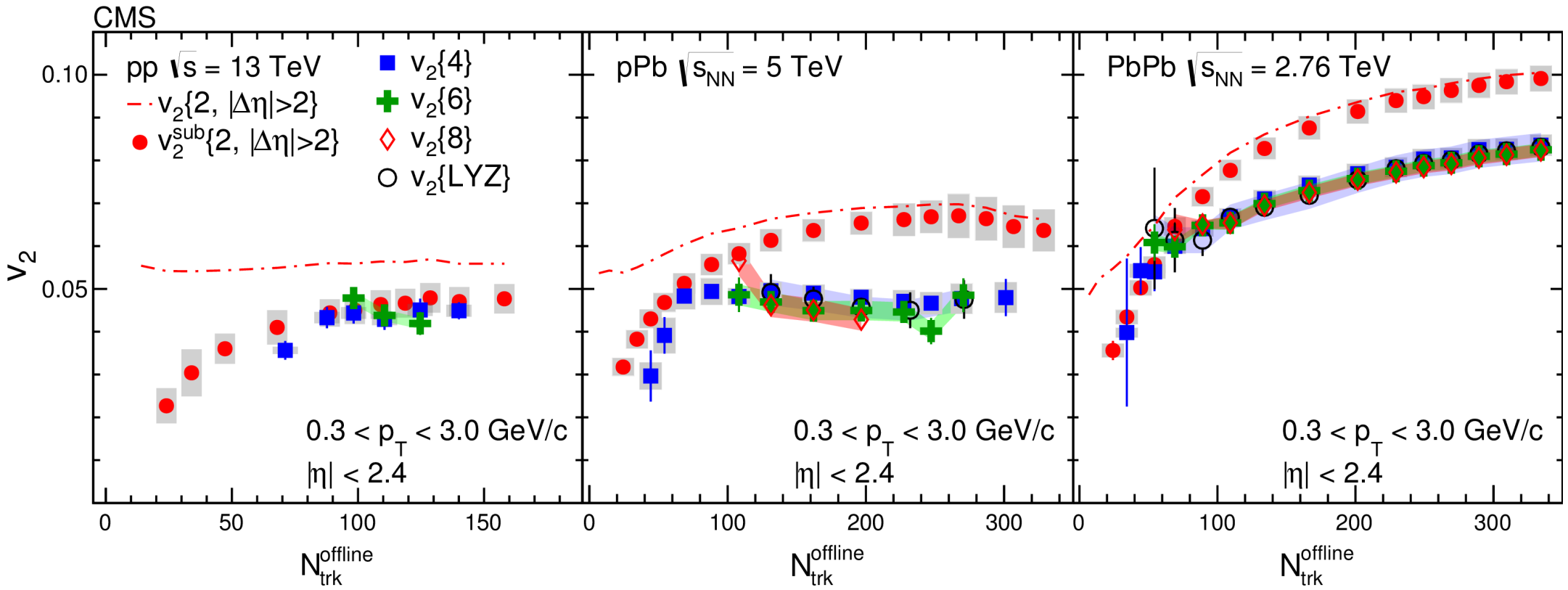
A very rich program ahead at the LHC of high-density QCD physics

Backup

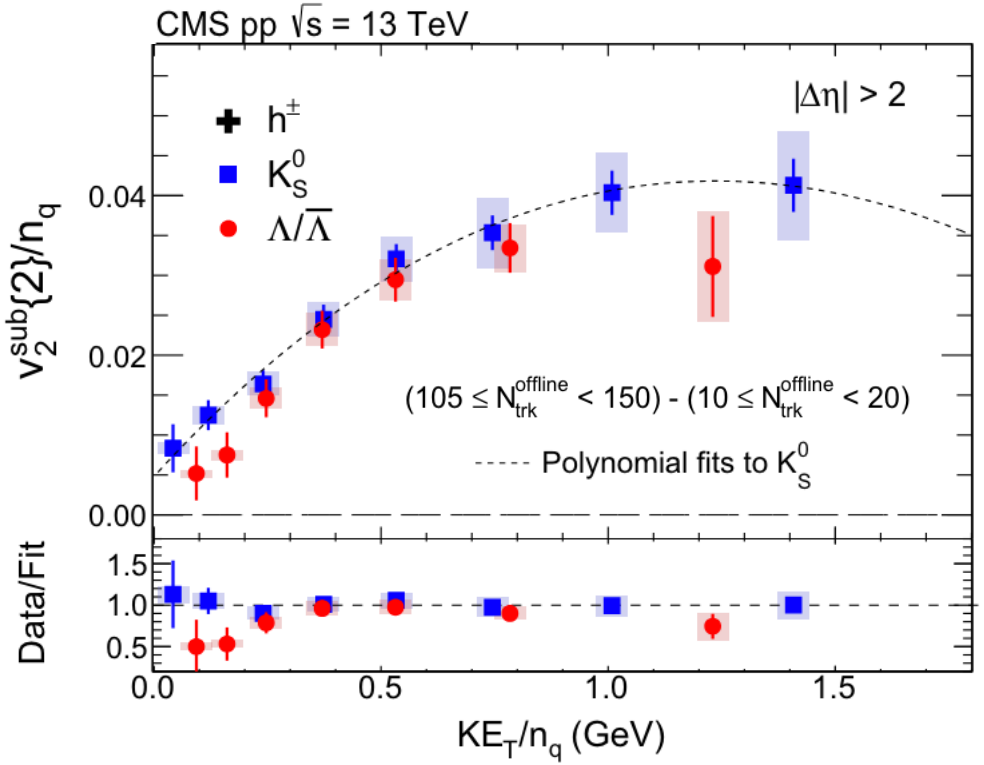
Extracting the speed of sound

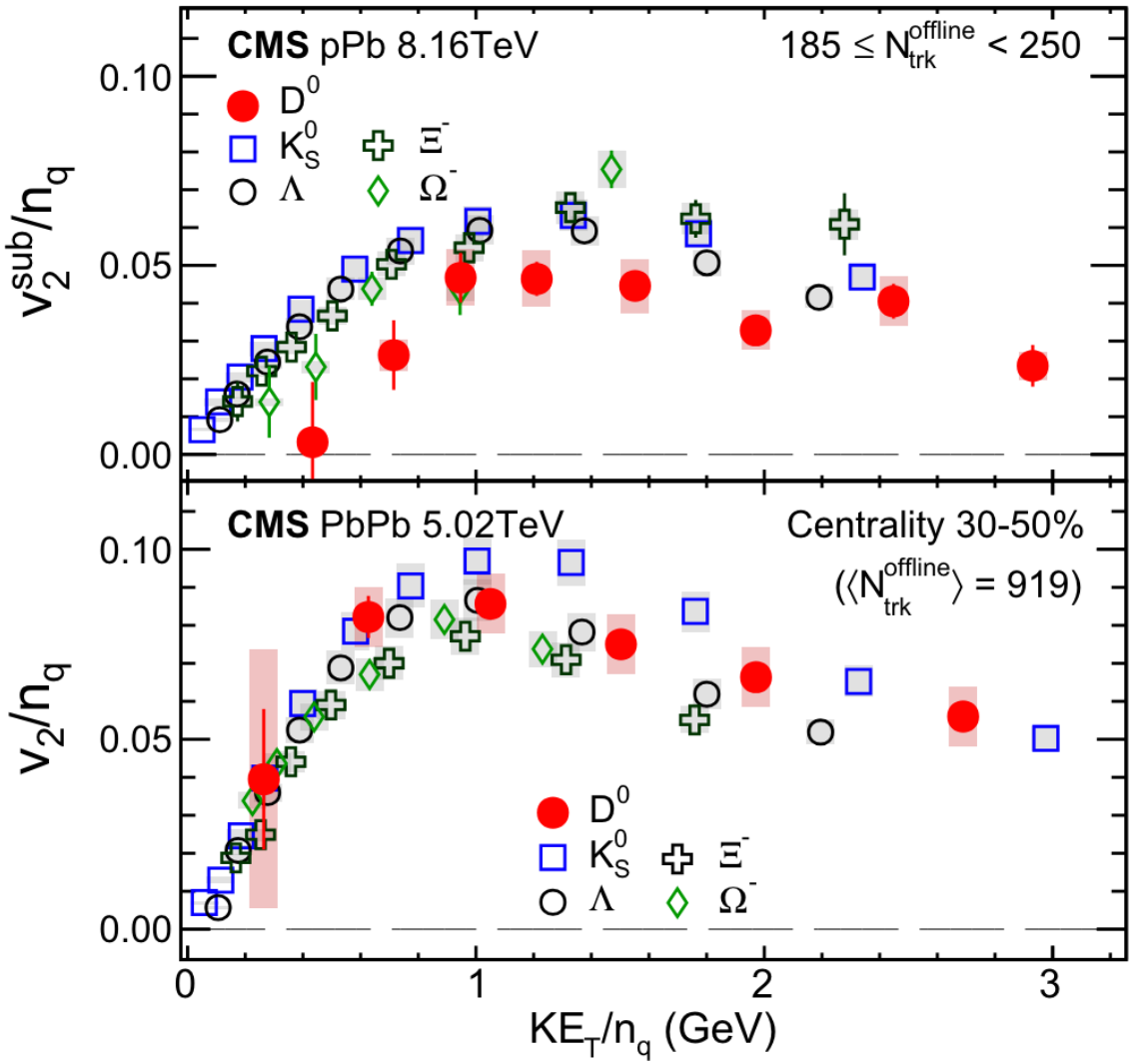


Collectivity in nuclear collisions

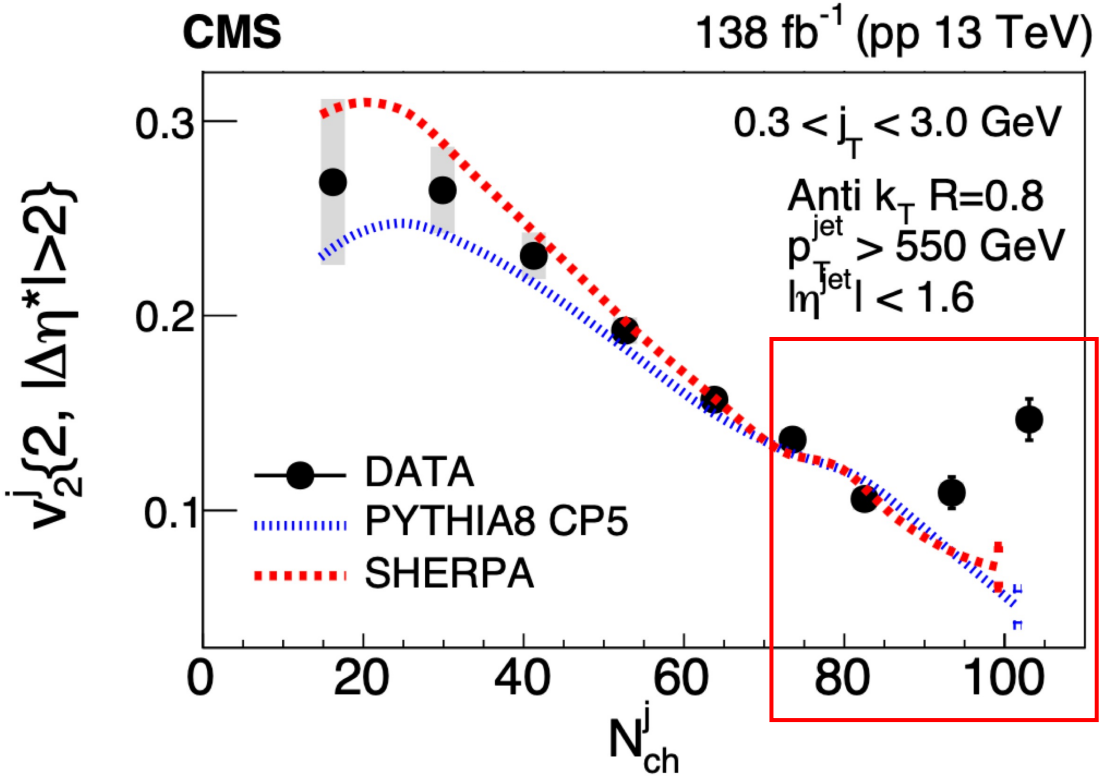


NCQ scaling in small systems

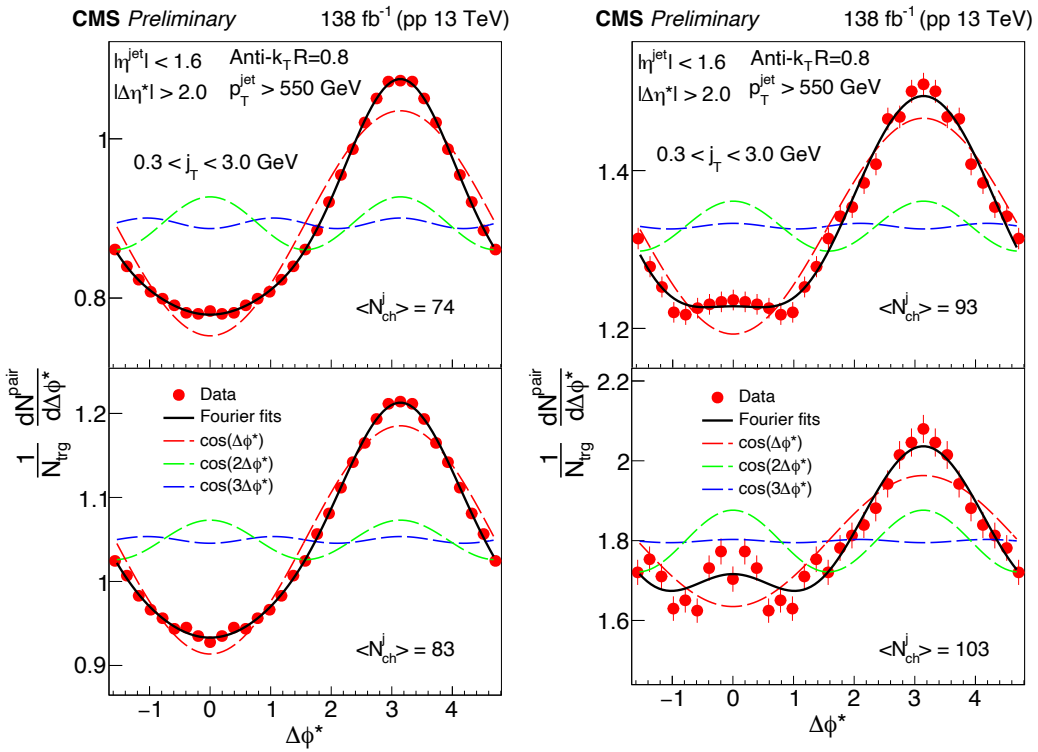




“Elliptic flow” and collectivity in HM jets!?



1-D $\Delta\phi^*$ projection at $|\Delta\eta^*|$

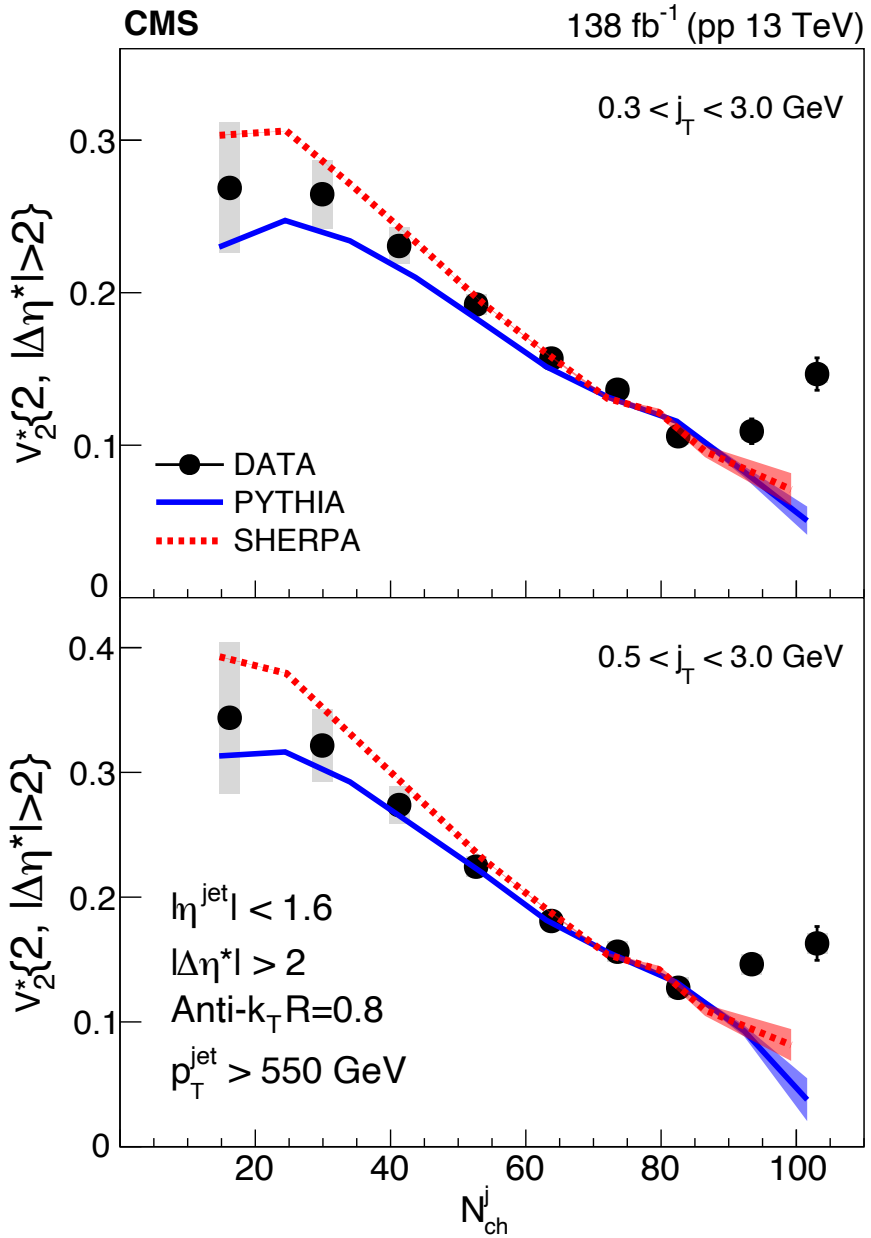


- N_{ch}<80 trend captured by models
- **Rising trend for high multiplicity jets!**

Observation of enhanced elliptic anisotropies – onset of collectivity?

Other “QGP” signatures in a jet: radial flow, HBT, strangeness, …?

Elliptic anisotropy or “flow” in jets



Enhancement of v_2 observed at multiple j_T ranges

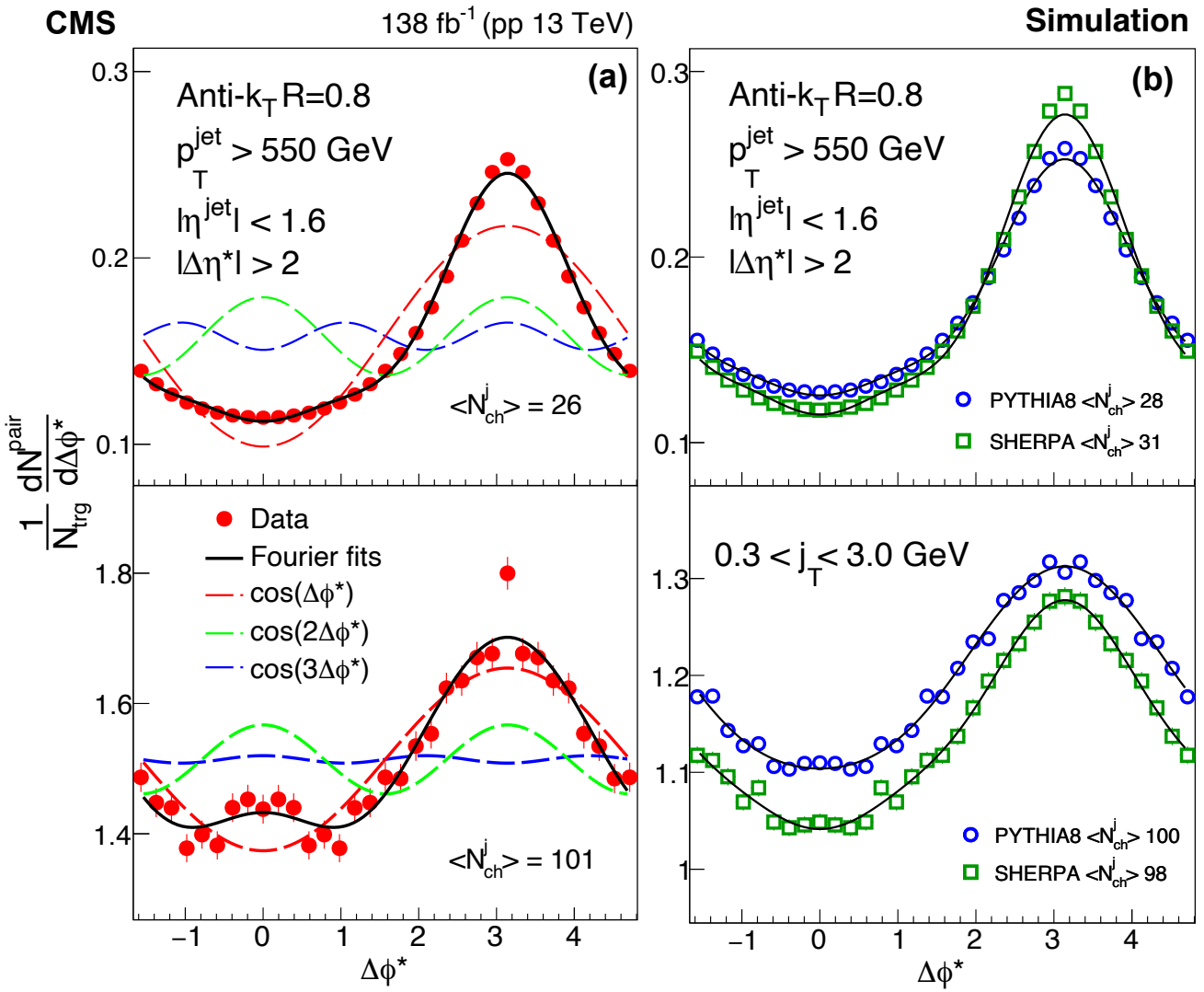
- Slightly stronger at higher j_T, similar to pp/pA/AA
- Signals NOT from the potentially flowing underlying event

QGP droplet initiated by **a “single parton”** in the vacuum?!

Two-particle correlations in the jet frame

$N^{j}_{ch} \sim 26$

$N^{j}_{ch} \sim 100$



No near-side ridge in low N^{j}_{ch} data and any MC model

Anisotropy flow coefficients in the jet frame

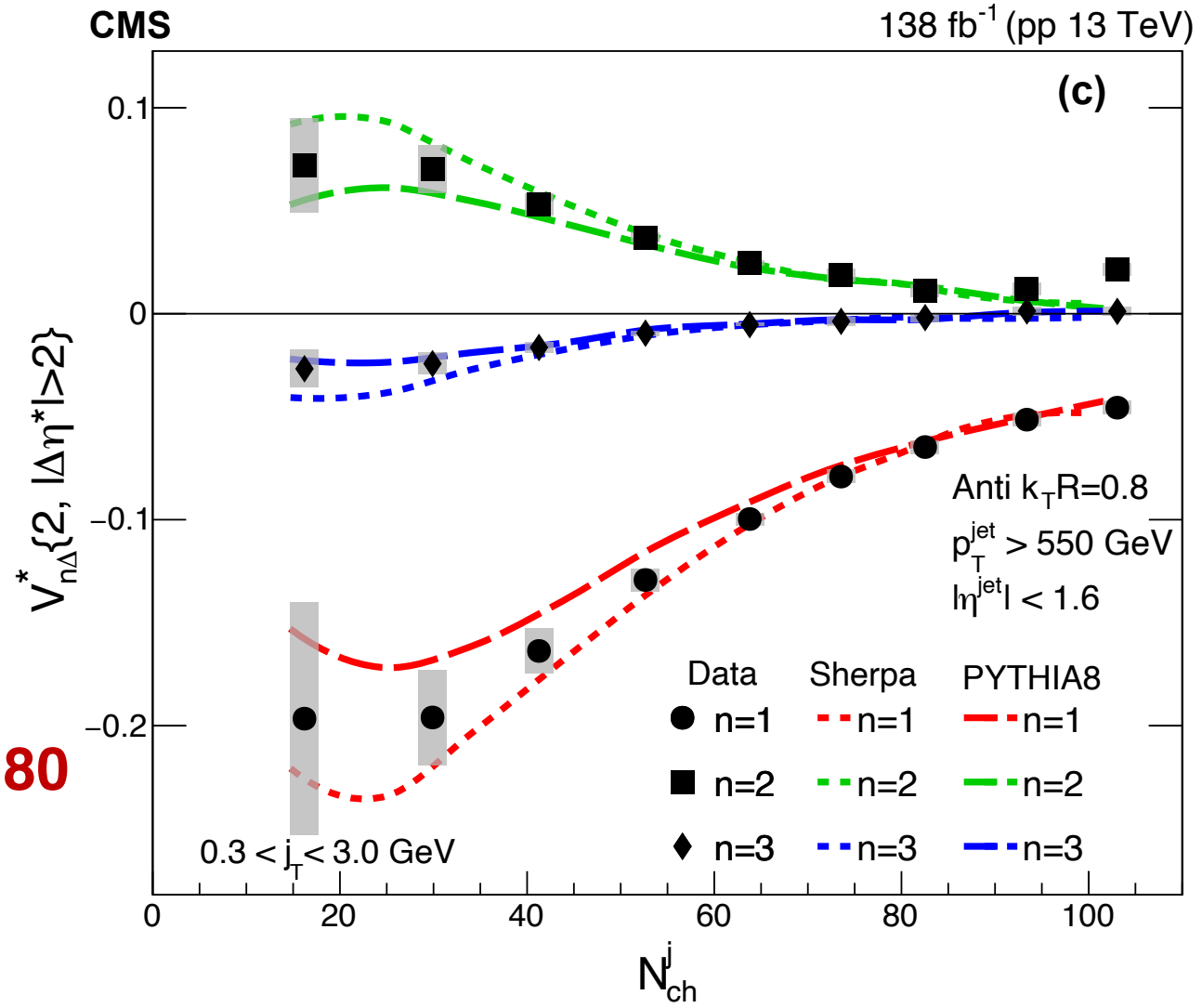
$$\frac{1}{N_{\mathrm{ch}}^{j}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi^{*}} \propto \sum_{n=1}^{\infty} V_{\mathrm{n}\Delta}\cos(\mathrm{n}\Delta\phi^{*})$$

Fourier fit coefficients vs. N_{ch}

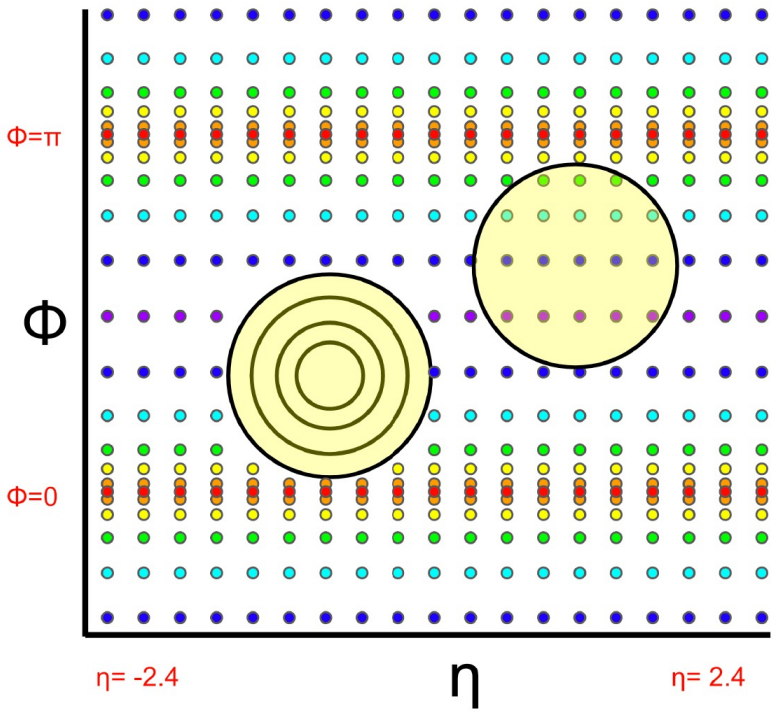
- Positive even & negative odd harmonics
- Magnitudes decrease with $N_{ch} < 80$
  - Agrees well with PYTHIA 8 prediction

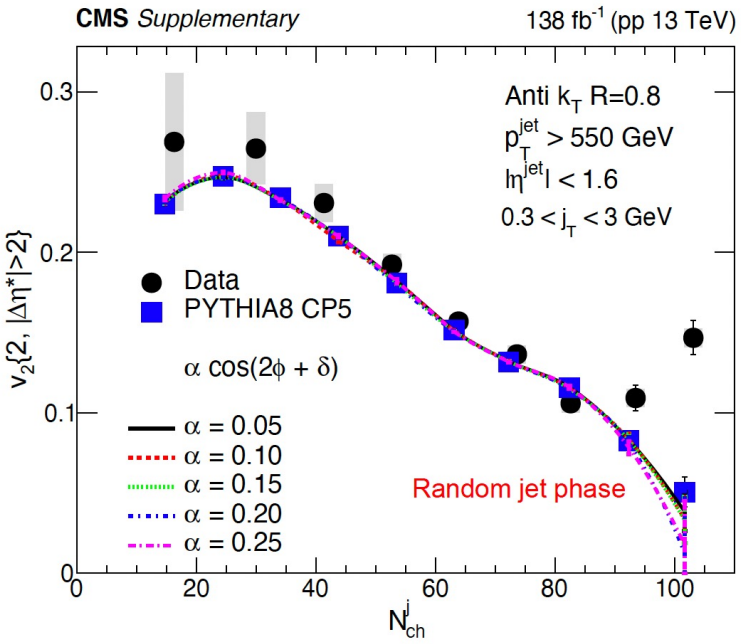
Deviation of $V_{2\Delta}$ (and $V_{3\Delta}$?) for $N_{ch} > 80$

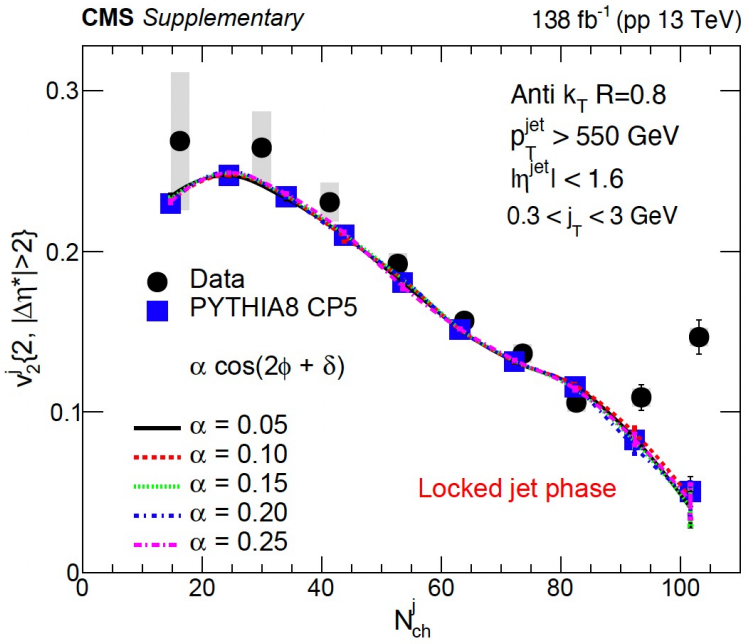
- Onset of new physics phenomena?



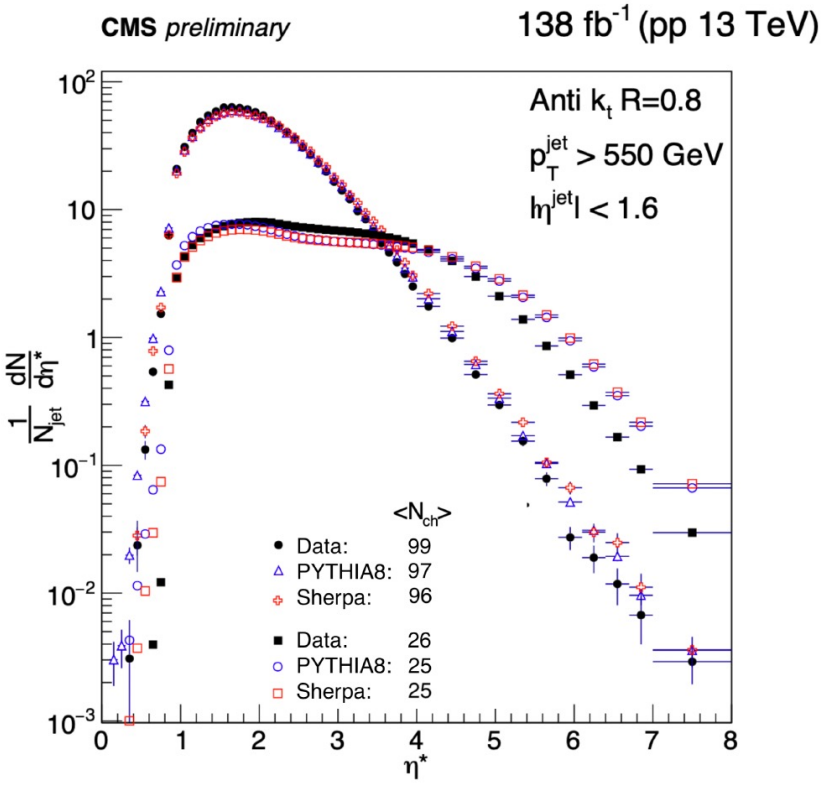
Underlying event

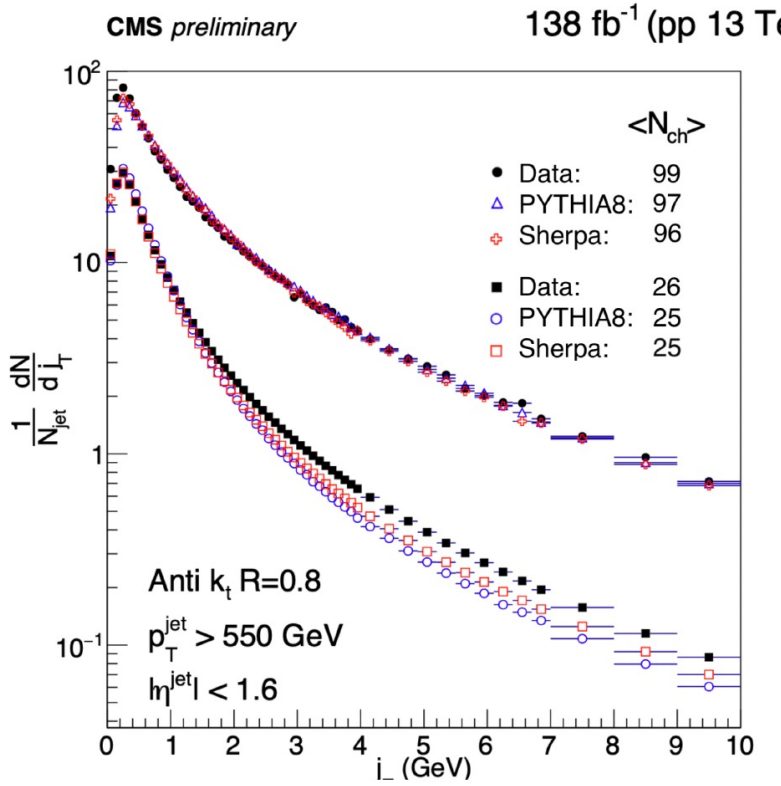


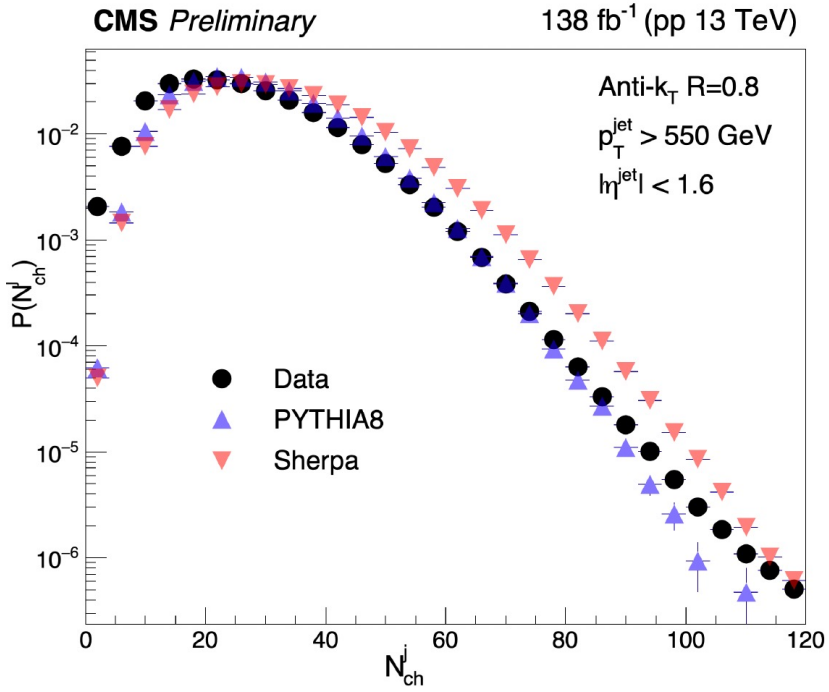




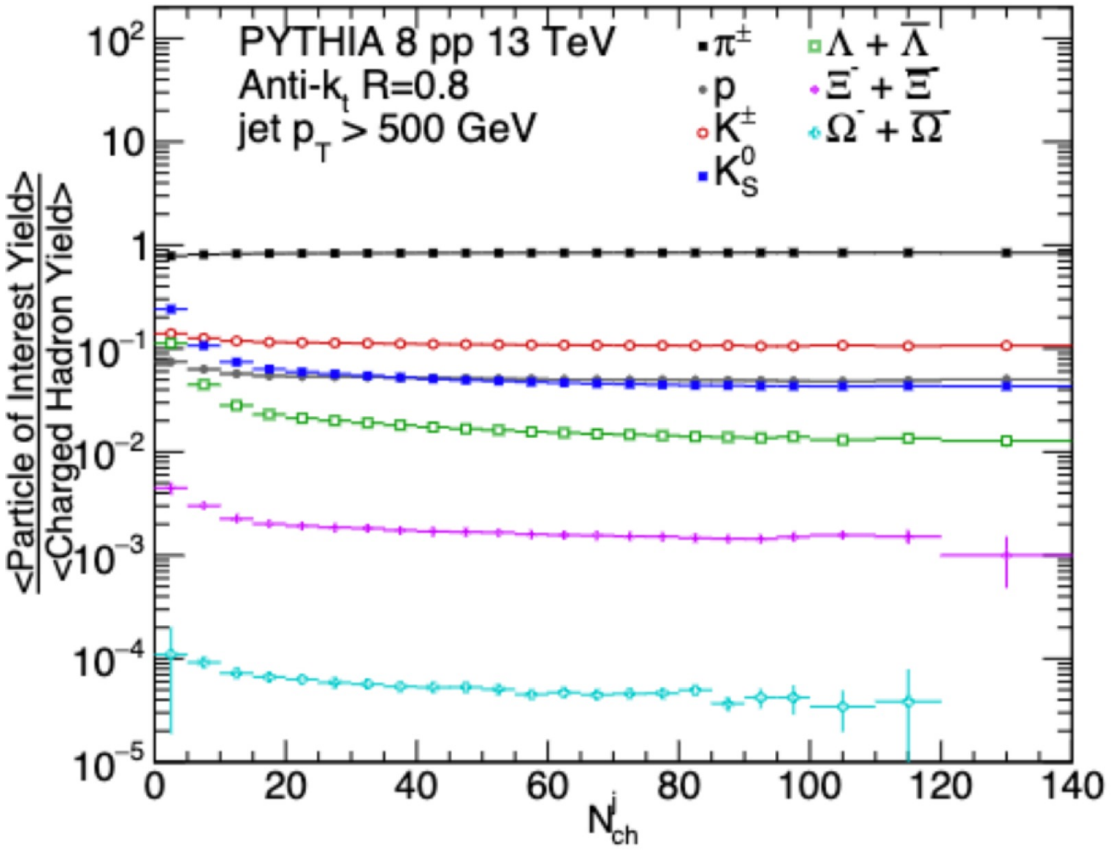
Basic distributions





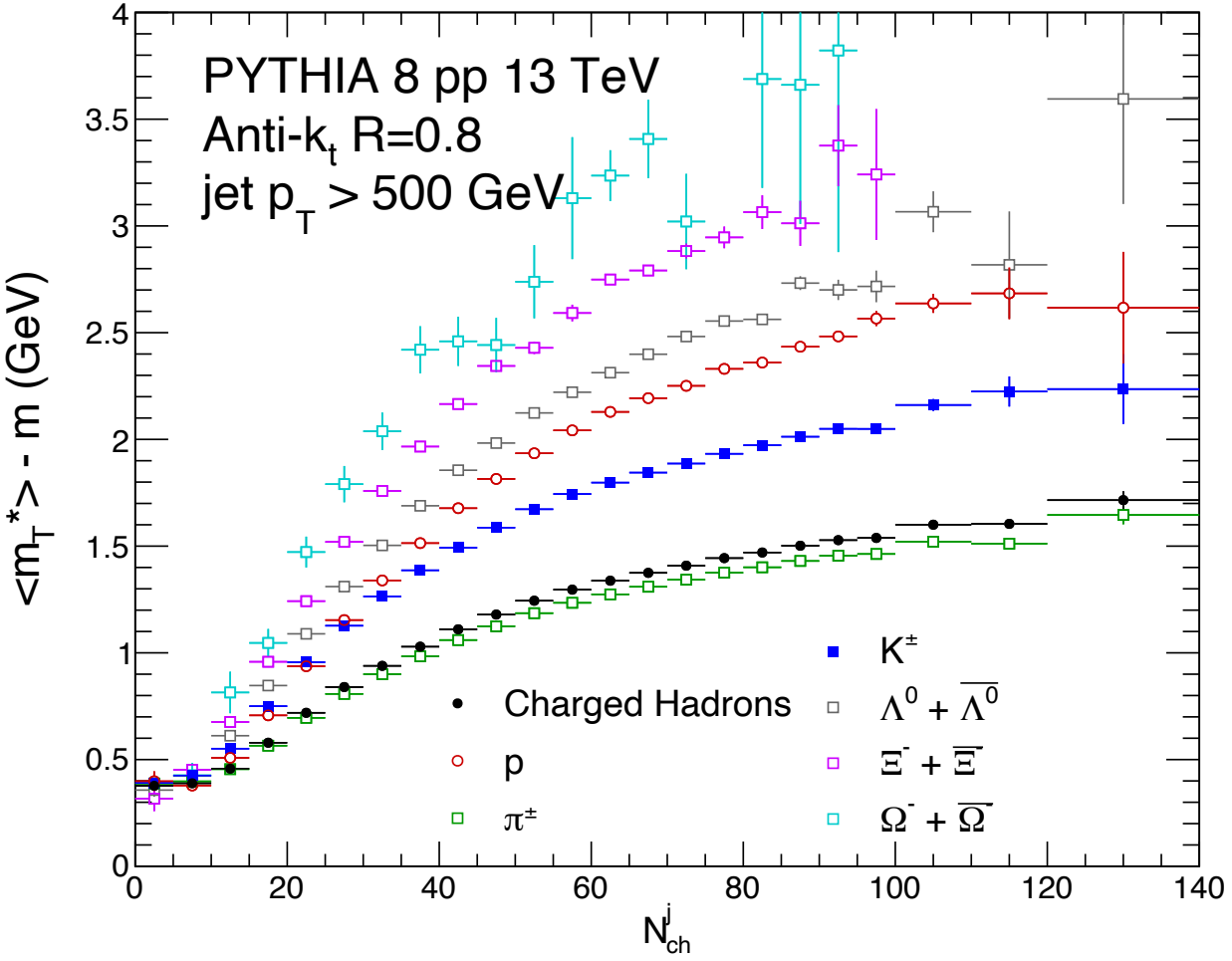


Strangeness enhancement



Radial flow in jets

Average kinetic energy vs N_{ch}^{j} in jets

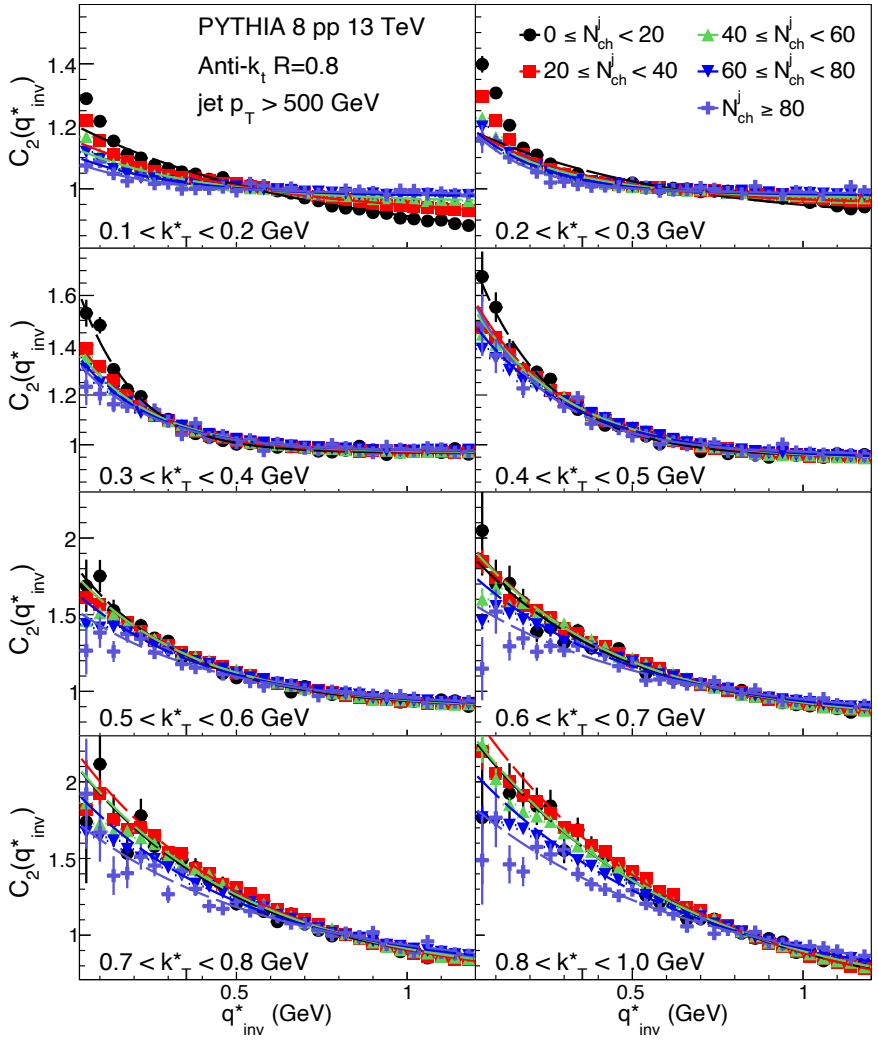


"Radial flow" effect is qualitatively in PYTHIA jets

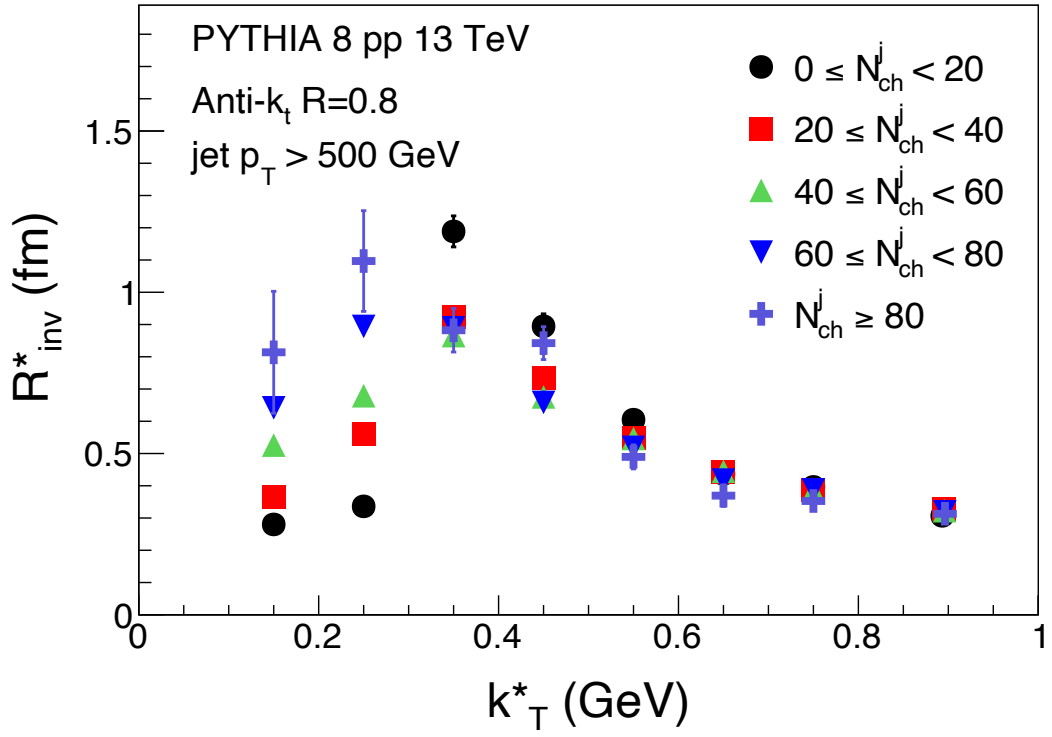
Color reconnection as for in the lab frame?

HBT correlations in jets

1-D HBT correlation functions



HBT radii of a jet:



Non-zero but dropping toward low k_T^*, opposite to AA collisions