Correlations and collectivity from large to small systems

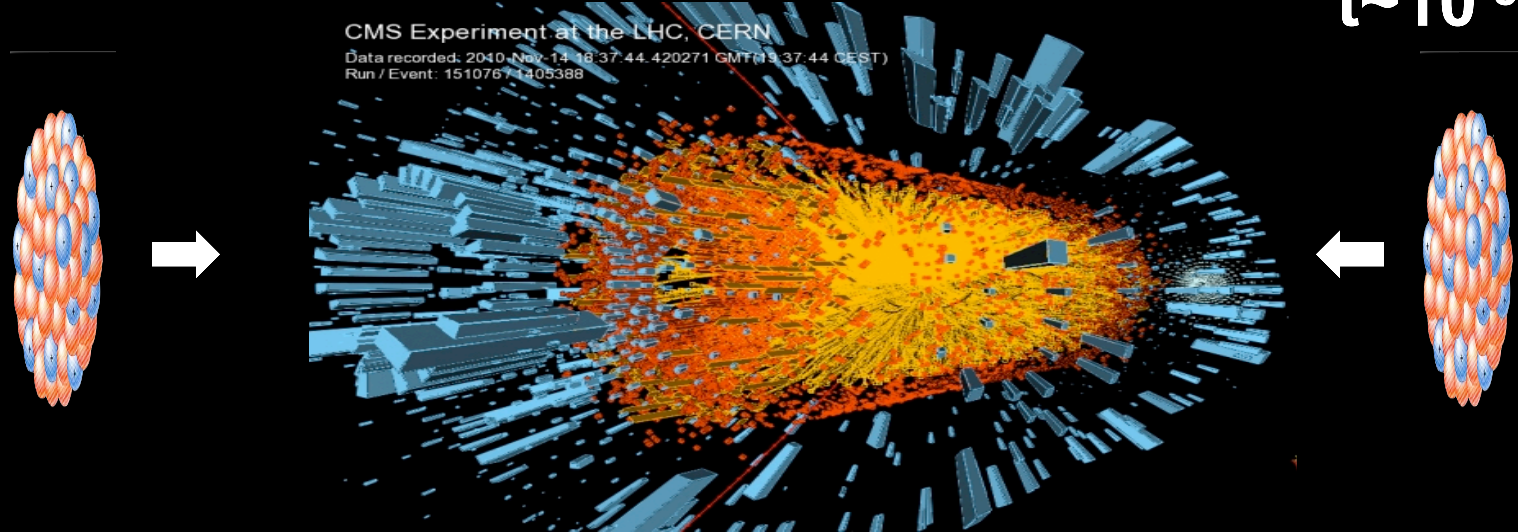
Jiangyong Jia

Stony Brook University and BNL

- Introduce collectivity with A+A
- Collectivity in small systems
- Some future opportunities

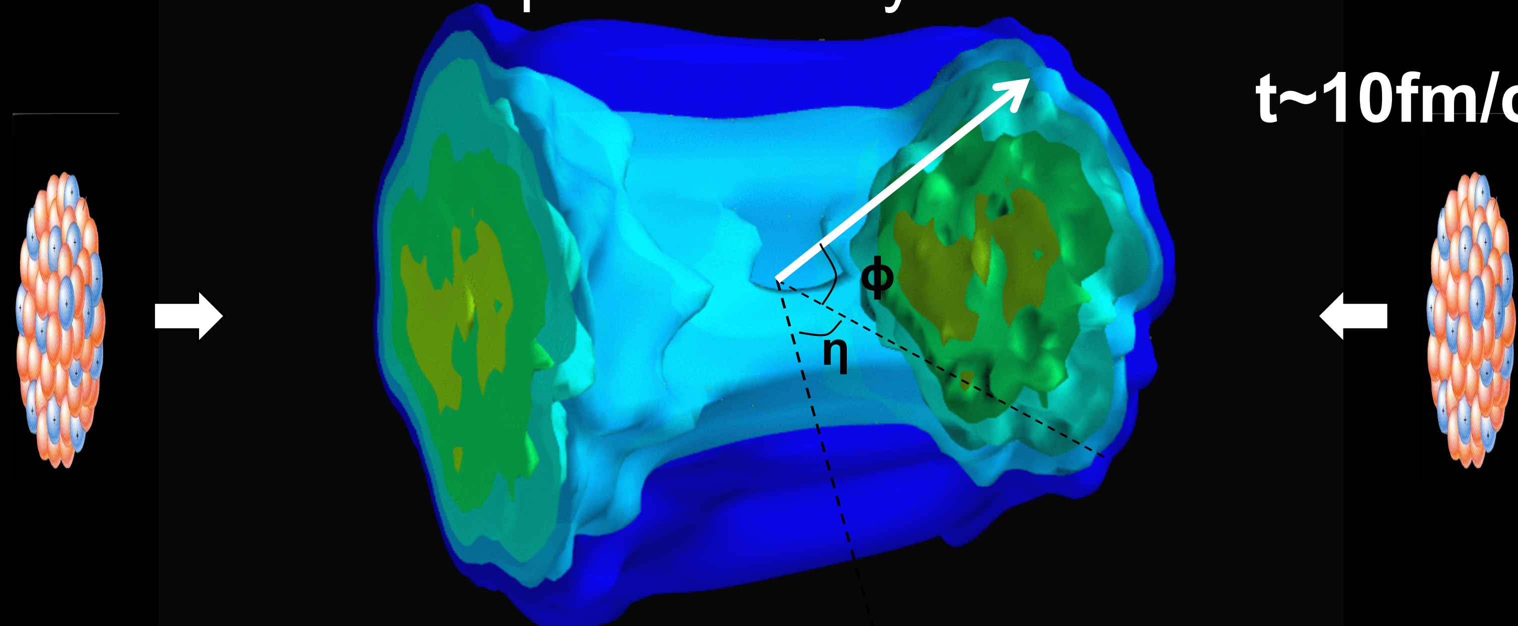
Seen by detector

$t \sim 10^{-8}$ s



Space-time dynamics

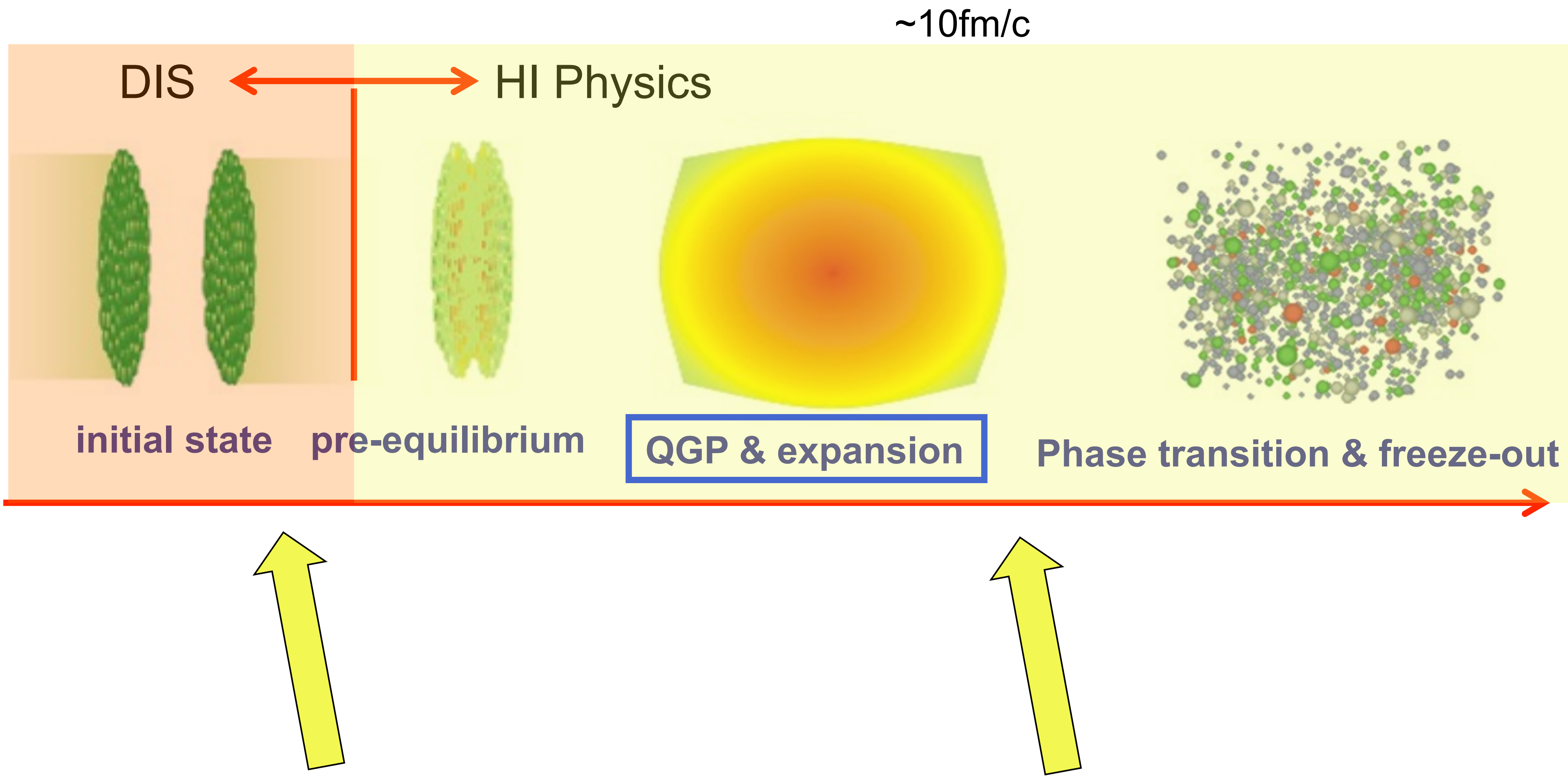
$t \sim 10 fm/c = 10^{-22}$ s



Model by 3D relativistic viscous hydrodynamics

Credit: Bjoern Schenke

Space time history of heavy Ion



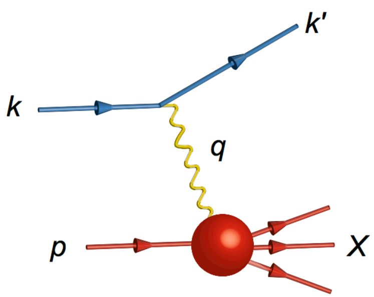
Large uncertainty in the initial state, DIS can help

Space-time dynamics successfully described by hydrodynamics

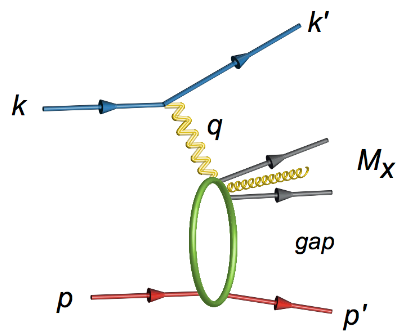
DIS and Heavy Ion

- DIS: initial-state constituent distribution (one-body Wigner func.)
  - Precise control on kinematics

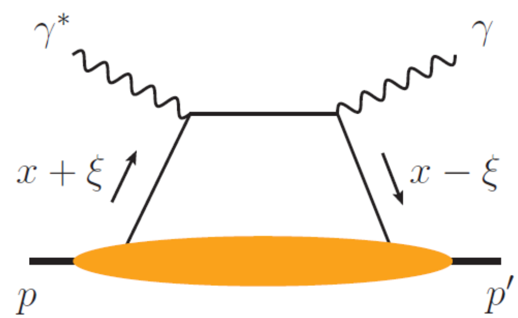
Inclusive

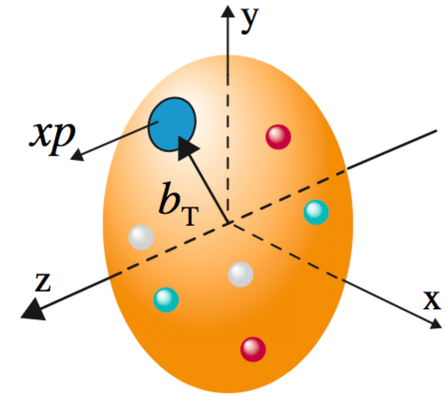


Semi-Inclusive



Exclusive



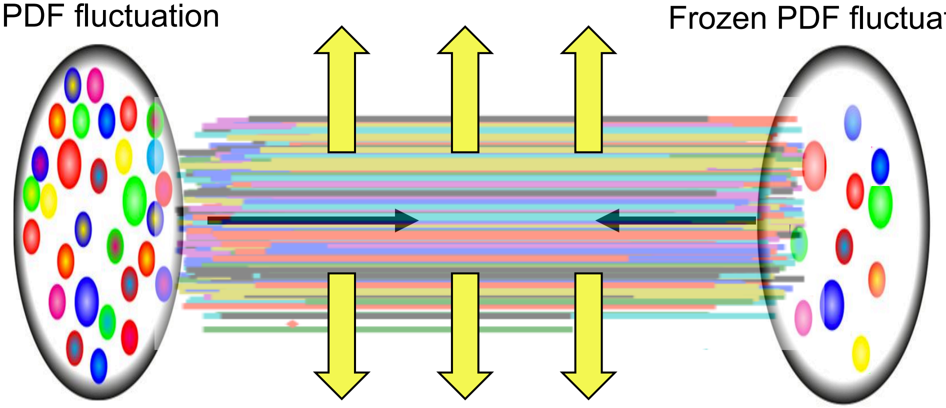


- Heavy-ion: Multi-Parton interactions (many-body Wigner function)

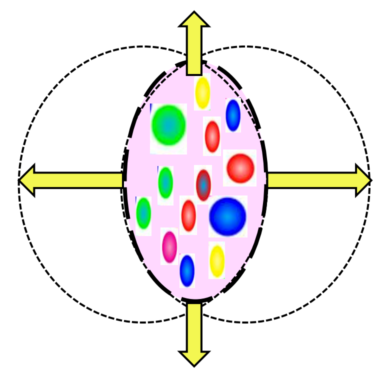
Longitudinal view

Frozen PDF fluctuation

Frozen PDF fluctuation



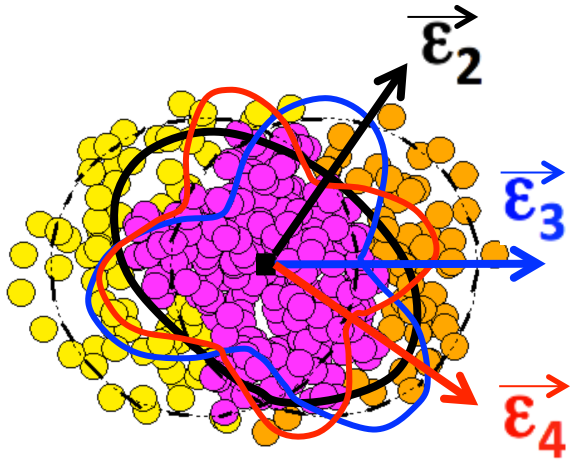
Transverse view



Require: 3D space-momentum distri. of initial-state partonic structure

Collectivity in A+A collisions

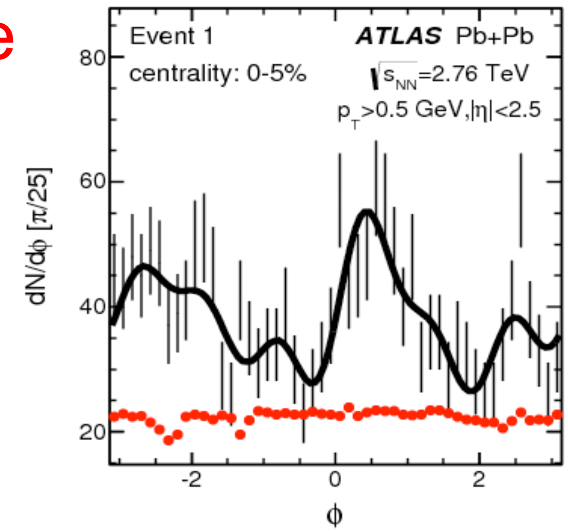
Initial state



Hydrodynamic response

Space-time dynamics

Final particle flow

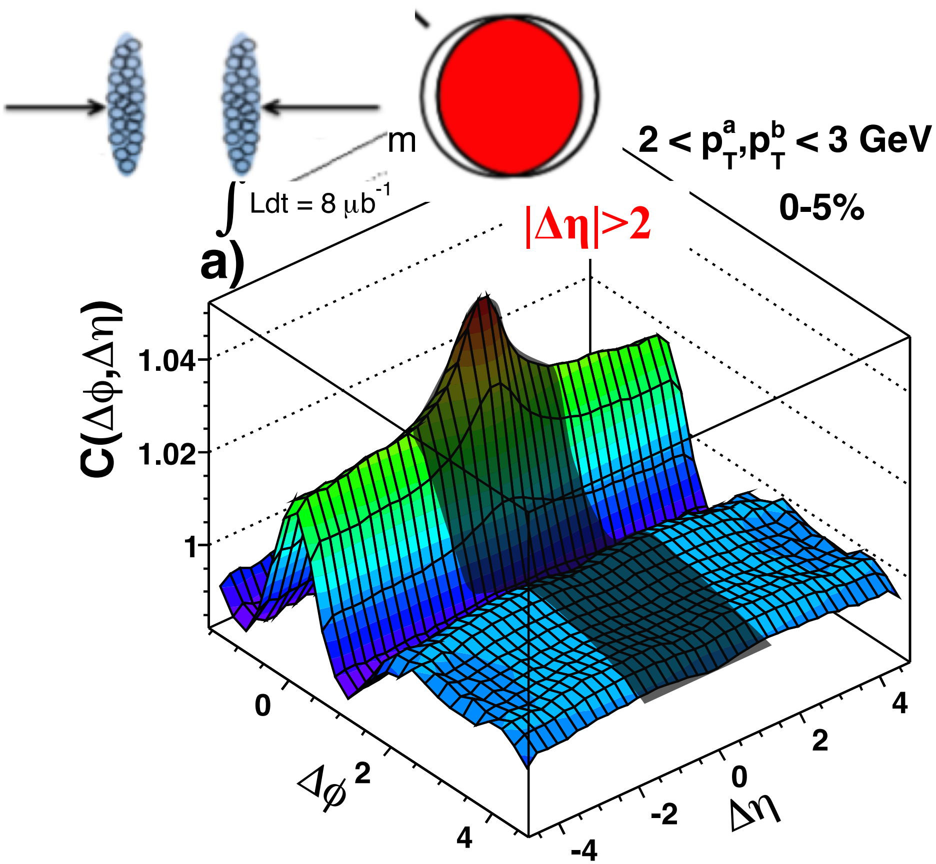


$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle}$$

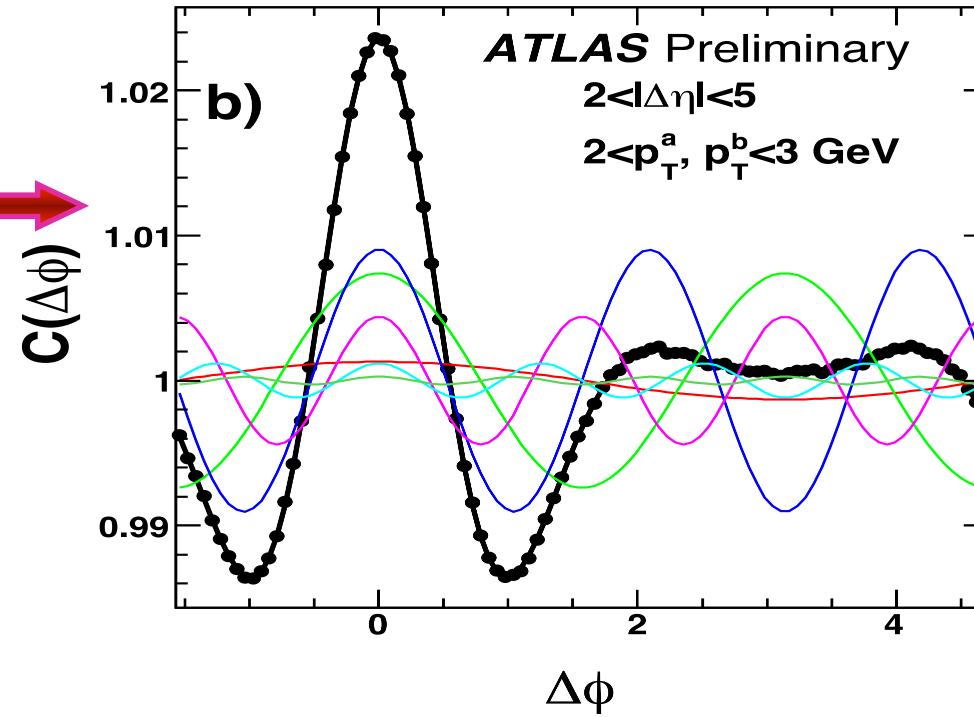
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

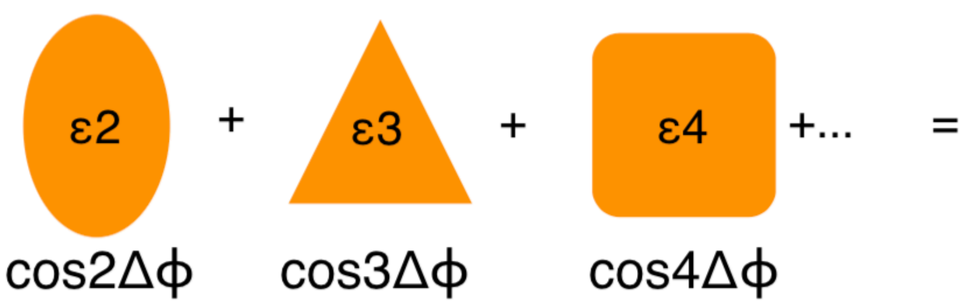
- What we know:
  - Large event-by-event initial state fluctuation
  - Each event follows its own hydrodynamic space-time evolution
  - Small viscosity ensure efficient transfer of $(\varepsilon_n, \Phi_n^*)$ to (v_n, Φ_n)

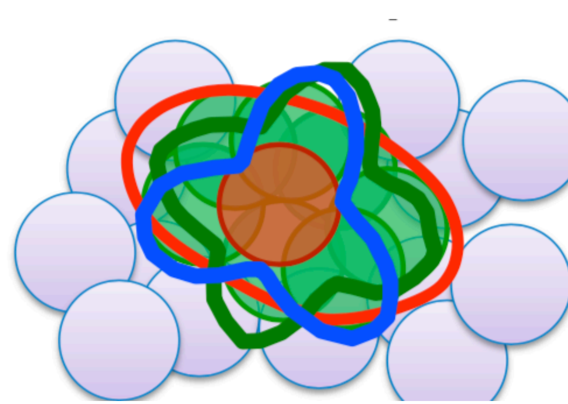
Quantify long-range two-particle correlation



$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + 2\sum_n v_n^2 \cos(n\Delta\phi)$$

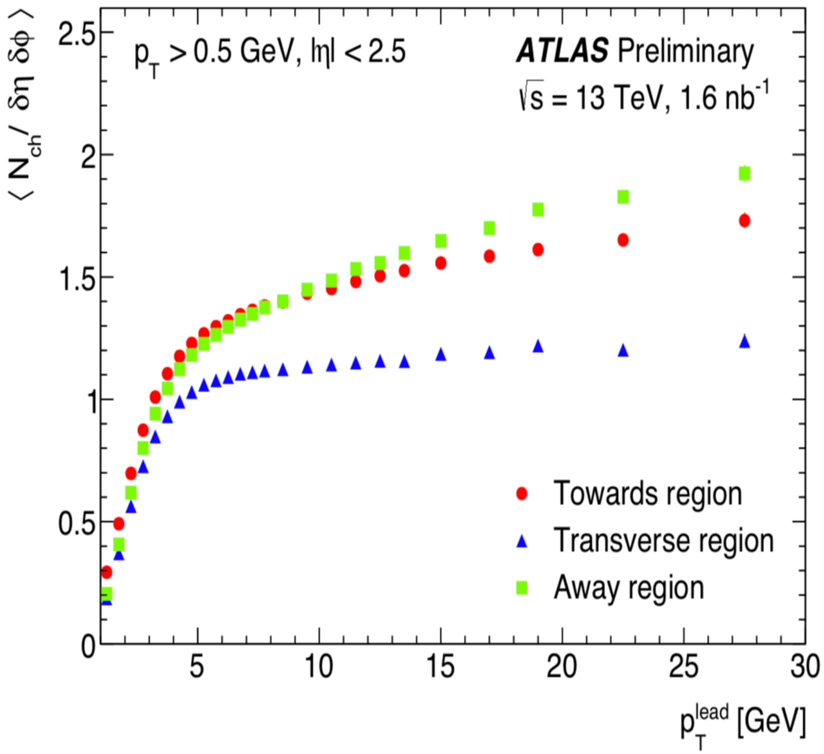


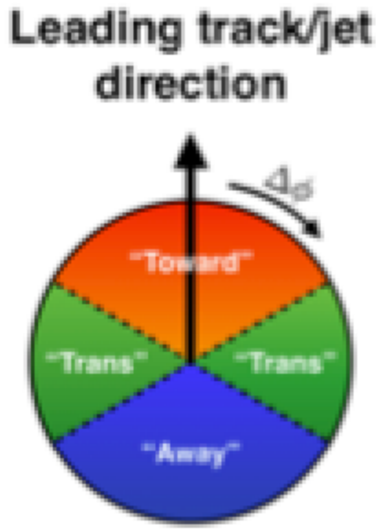


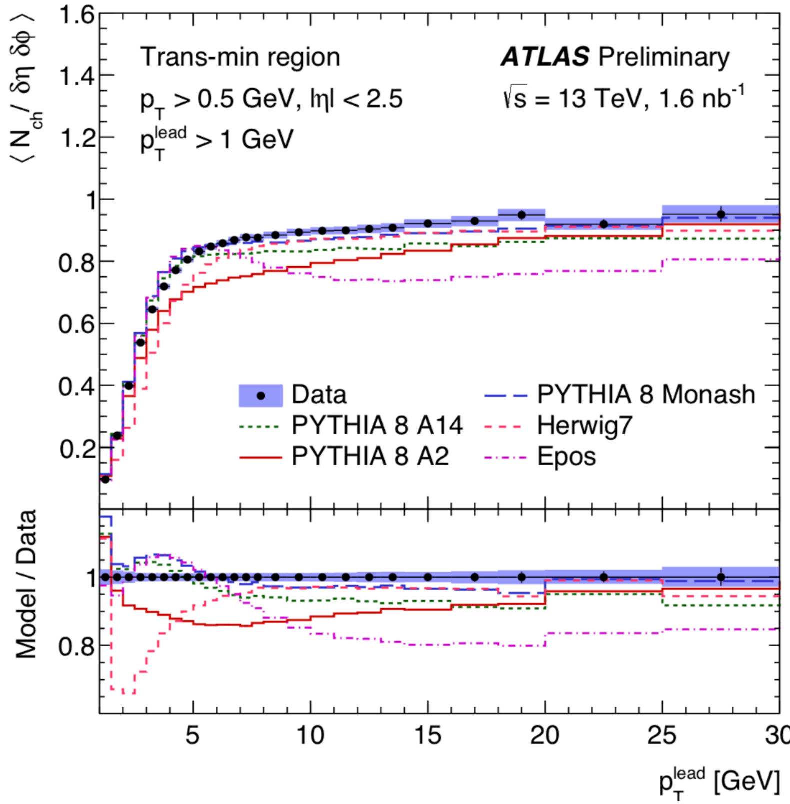


Connection to underlying event analysis

- Traditional UE studies







- Fourier decompose the "long-range" UE (ridge)

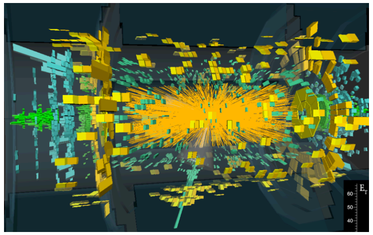
$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

Single-particle distribution

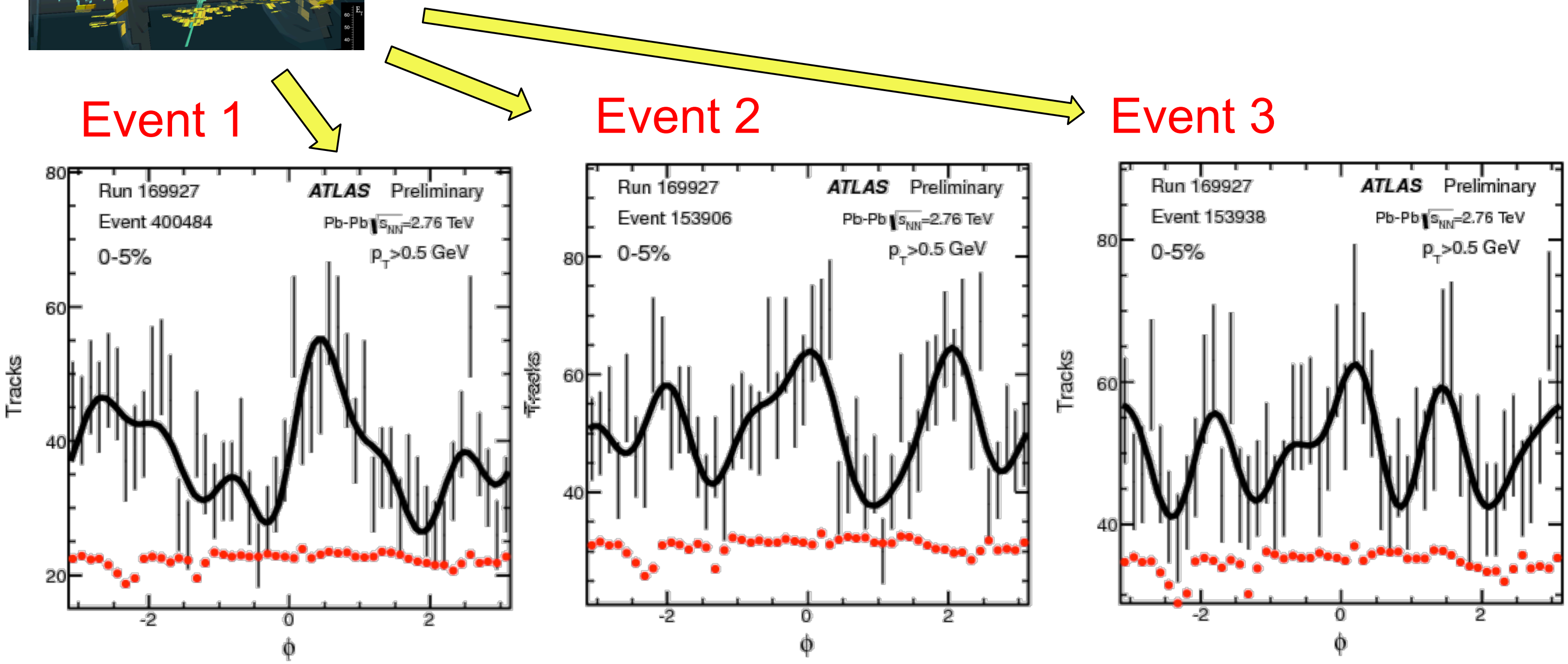
$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + 2\sum_n v_n^2 \cos(n\Delta\phi)$$

Two-particle correlation with Δη gap

Event-by-event fluctuations



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



Object of interest:

$$p(v_n, v_m, ..., \Phi_n, \Phi_m, ...) = \frac{1}{N_{\rm evts}} \frac{dN_{\rm evts}}{dv_n dv_m ... d\Phi_n d\Phi_m ...}$$

Fluctuation observables

- Single particle distribution

$$\frac{dN}{d\phi} = N\left[1+2\sum_n \mathrm{v}_n \cos n(\phi-\Phi_n)\right] = N\left[\sum_{n=-\infty}^{\infty} V_n e^{in\phi}\right]$$

Flow vector: $\boldsymbol{V}_n = v_n e^{in\Phi_n}$

- Tools: Multi-particle correlations

Average over events

$$\left\langle \frac{dN_1}{d\phi}\frac{dN_2}{d\phi}..\frac{dN_m}{d\phi}\right\rangle \Rightarrow \left\langle\left\langle e^{i(n_1\phi_1+n_2\phi_2+...+n_m\phi_m}\right\rangle\right\rangle = \left\langle \boldsymbol{V}_{n_1}\boldsymbol{V}_{n_2}...\boldsymbol{V}_{n_m}\right\rangle \quad n_1+n_2+...+n_m=0$$

$$\left\langle v_{n_1}v_{n_2}..v_{n_m}\cos(n_1\Phi_{n_1}+n_2\Phi_{n_2}+..+n_m\Phi_{n_m})\right\rangle$$

- Examples:

Moments of $p(\mathrm{v}_n, \Phi_n\ldots)$

2PC $\langle\langle\{2\}_n\rangle\rangle = \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle = \langle v_n^2\rangle$

4PC $\langle\langle\{4\}_n\rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle = \langle v_n^4\rangle$

4PC $\langle\langle\{4\}_{n,m}\rangle\rangle = \langle\langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)}\rangle\rangle = \langle v_n^2 v_m^2\rangle$

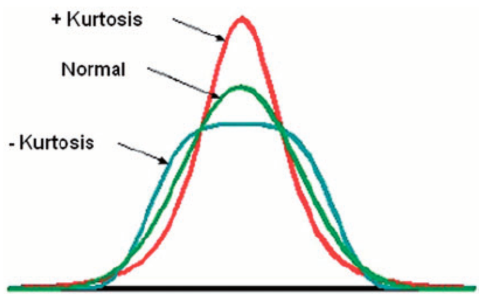
3PC $\langle\langle\{3\}_n\rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-2\phi_3)}\rangle\rangle = \langle v_n^2 v_{2n}\cos 2n(\Phi_n-\Phi_{2n})\rangle$

How to quantify nature of fluctuations?

- The shape of p(X) often quantified by cumulants

$$C_2 = \langle \delta X^2 \rangle \qquad \delta X = X - \langle X \rangle$$
$$C_3 = \langle \delta X^3 \rangle$$
$$C_4 = \langle \delta X^4 \rangle - 3 \langle \delta X^2 \rangle^2$$
$$C_5 = \langle \delta X^5 \rangle - 10 \langle \delta X^3 \rangle \langle \delta X^2 \rangle$$

C_2 variance, C_3 Skewness, C_4 Kurtosis



- Substitute $X=v_n e^{in\Phi_n}$, one derive cumulants for flow, such as:

Four-particle cumulants

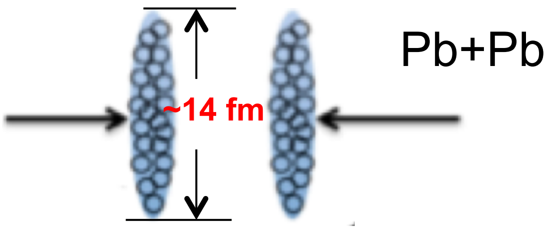
$$c_n\{4\} = \langle v_n^4 \rangle - 2 \langle v_n^2 \rangle^2$$ Probe $p(v_n)$

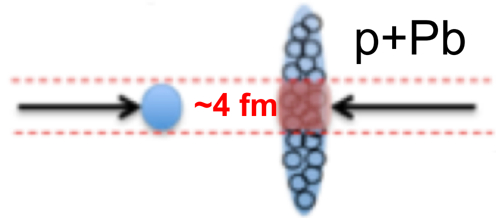
if flow is constant, $c_n\{4\} = -v_n^4 < 0$

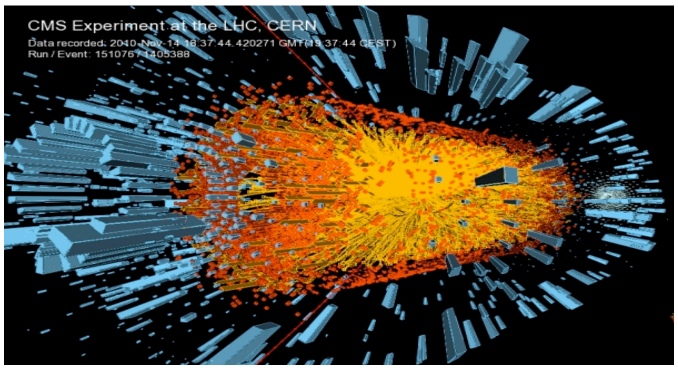
$$sc_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$ Probe $p(v_n, v_m)$

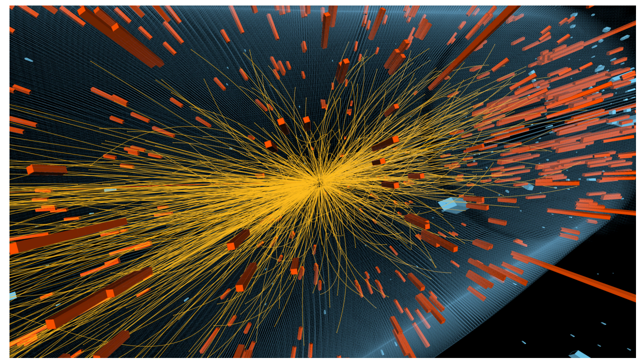
Collectivity in small systems

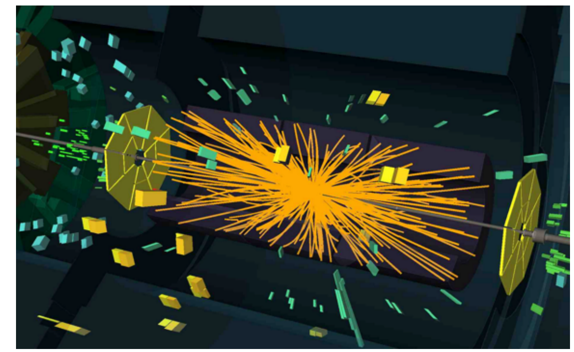
Collectivity in different systems











~30000 particles*

~2000 particles*

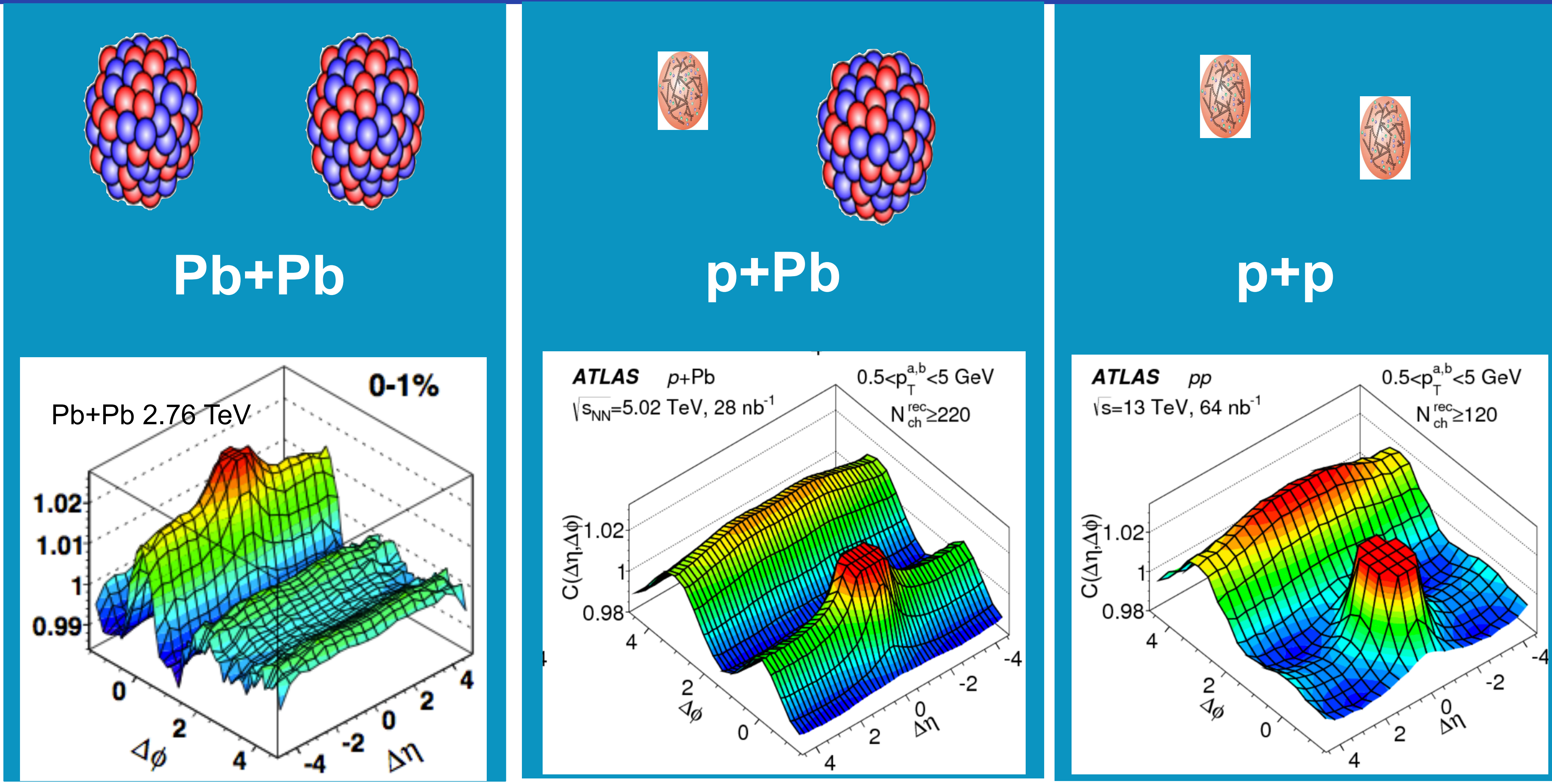
~ 600 particles*

Change system size and shape at RHIC and LHC:

→ Control space-time dynamics!

* Rough number in very high-multiplicity events, integrated over full phase space at LHC

Two-particle correlation in different systems

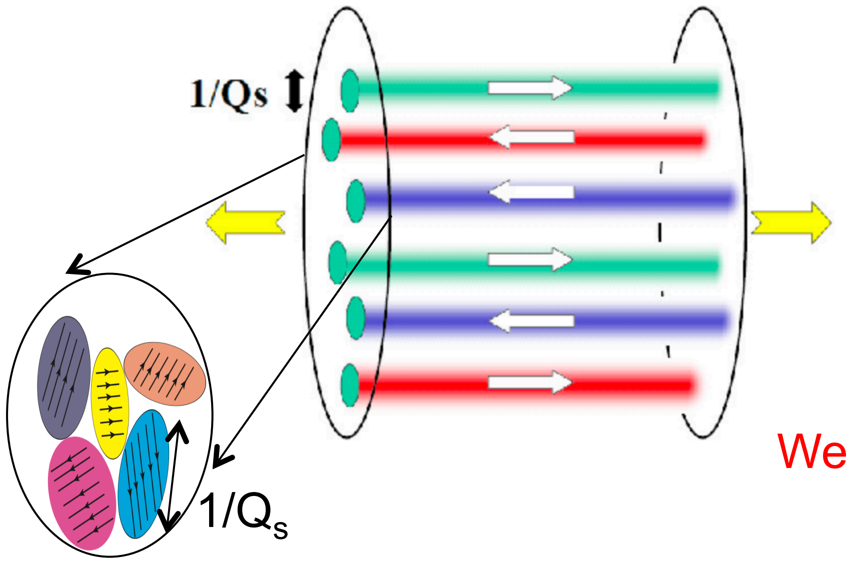


- Long-range correlation comes
  - directly from initial state momentum correlation (structure function, CGC)
  - or it is a final state response to spatial fluctuation at t=0 (hydro/transport).

What is the timescale for emergence of collectivity?

Examples of initial vs final state correlation

Saturation/CGC



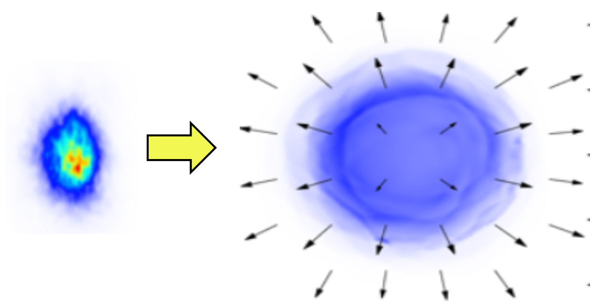
Domain of color fields of size $1/Q_s$, each produce multi-particles correlated across full η.

Uncorr. between domains, strong fluct. in Q_s

More domains, smaller v_n, more Q_s fluct, stronger v_n

Well motivated model framework, need systematic treatment

Hydrodynamics



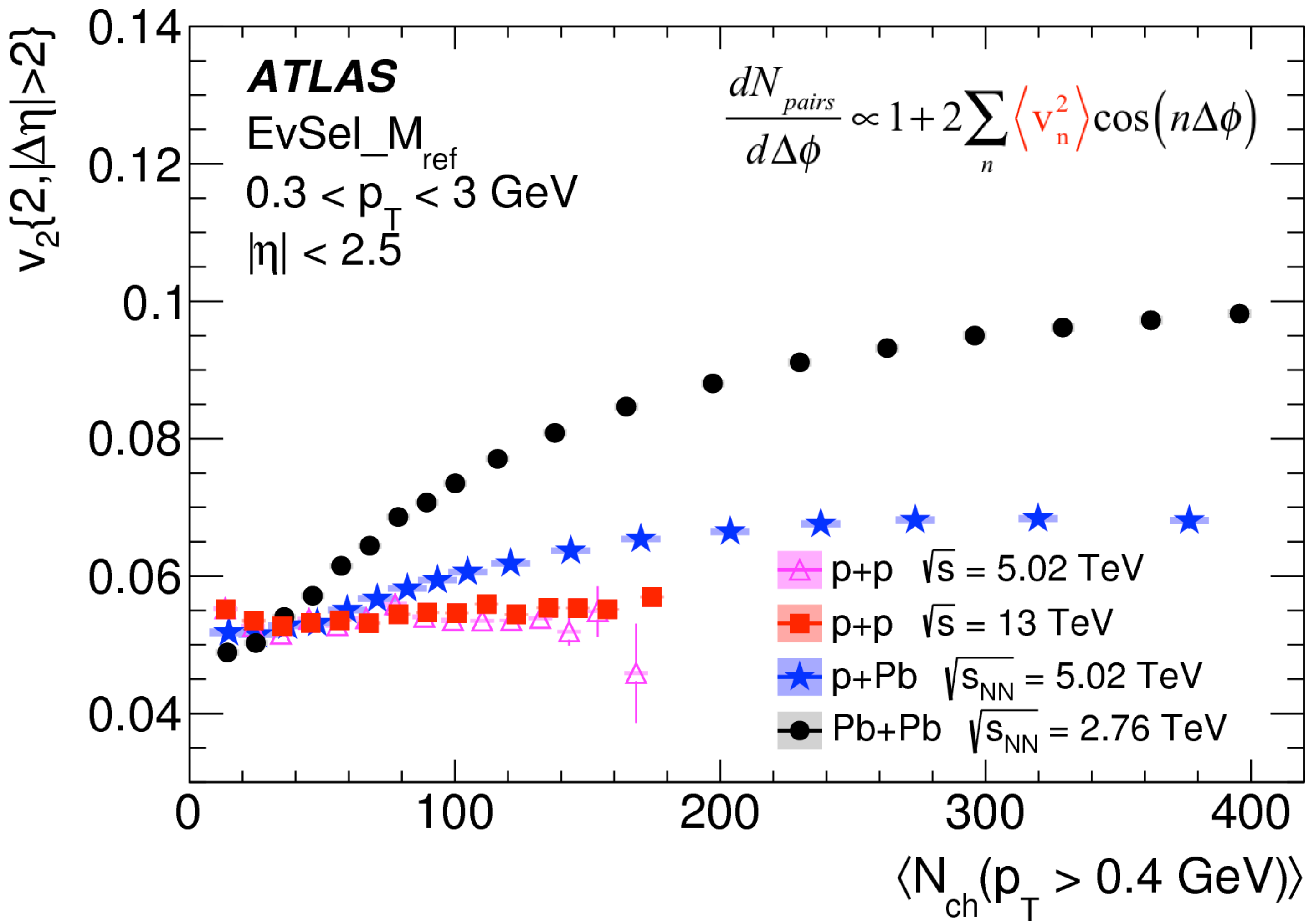
Hot spots in transverse plane e.g IP-plasma, boost-invariant geometry shape

Expansion and interaction of hot spots generate collectivity

v_n depends on distribution of hot spots (ε_n) and transport properties.

Ongoing debate whether hydro is applicable in small systems

v_2 in small systems

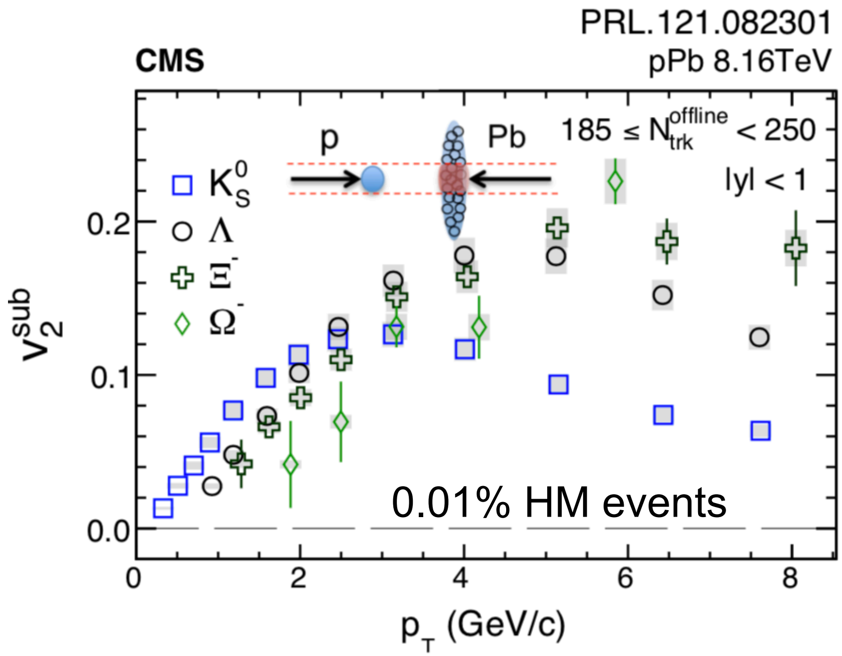


- pp v_2 ~ constant, pPb and PbPb v_2 increase with N_{ch} (due to Geometry)
- v_2 persist to very low N_{ch} (~minbias N_{ch} value in pp and pPb)

Similar origin for the collectivity?

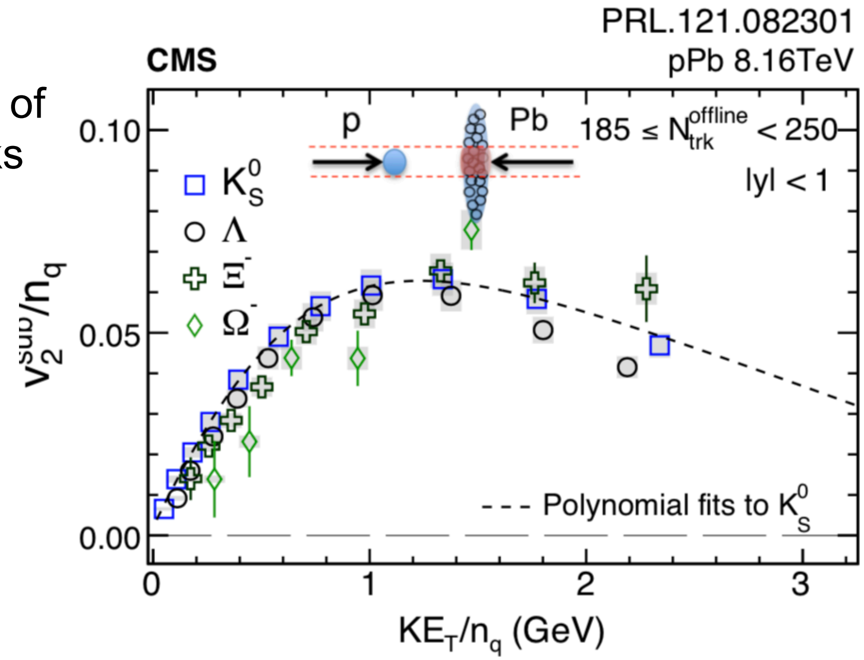
PID v_2 in p+Pb

v_2 show mass ordering



Scale by number of constituent quarks

$$\frac{v_2(\text{meson})}{2} \approx \frac{v_2(\text{baryon})}{3}$$



Similar as observation in A+A

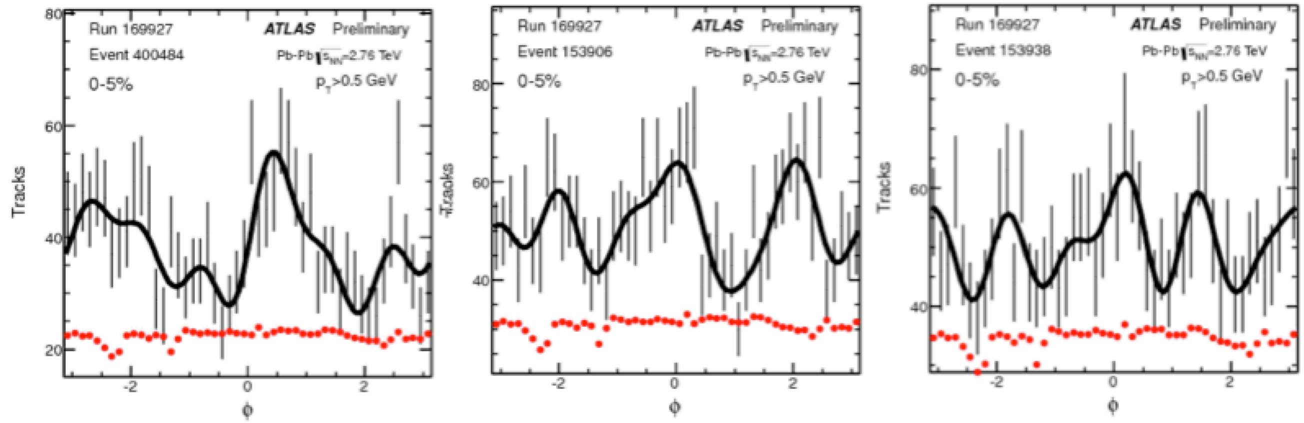
Collectivity occurs at partonic level?

How about event-by-event fluctuations?

$$\frac{dN}{d\phi} = N\left[1 + 2\sum_n v_n \cos n(\phi - \Phi_n)\right]$$

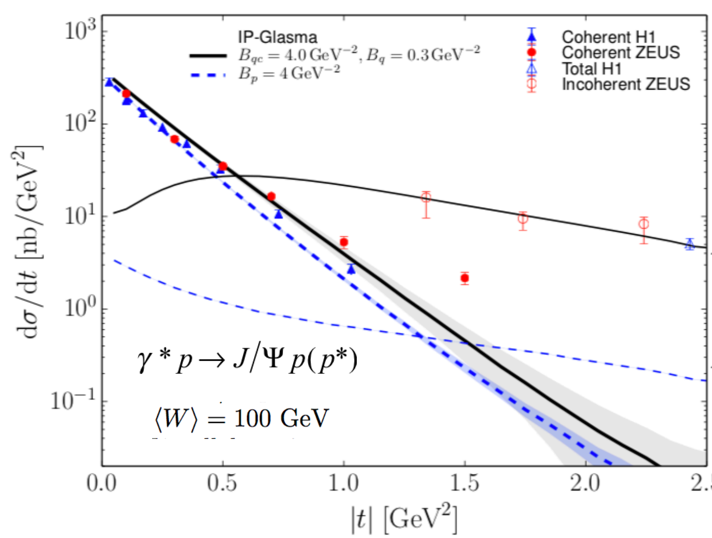
Observed directly in Pb+Pb collisions

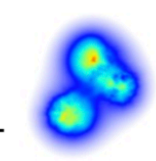
Event 1 Event 2 Event 3



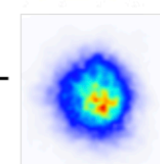
Must also has strong fluctuations in pp and pA

Indirect evidence from diffractive DIS ep J/Ψ cross-section data





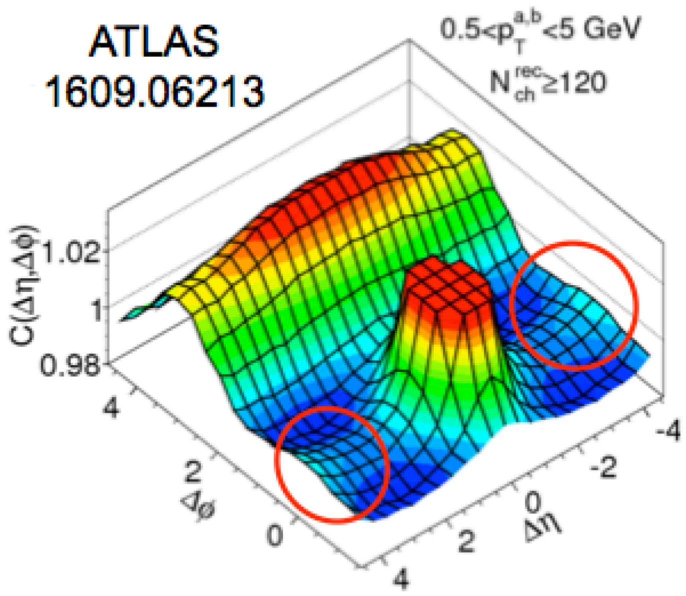
eccentric proton

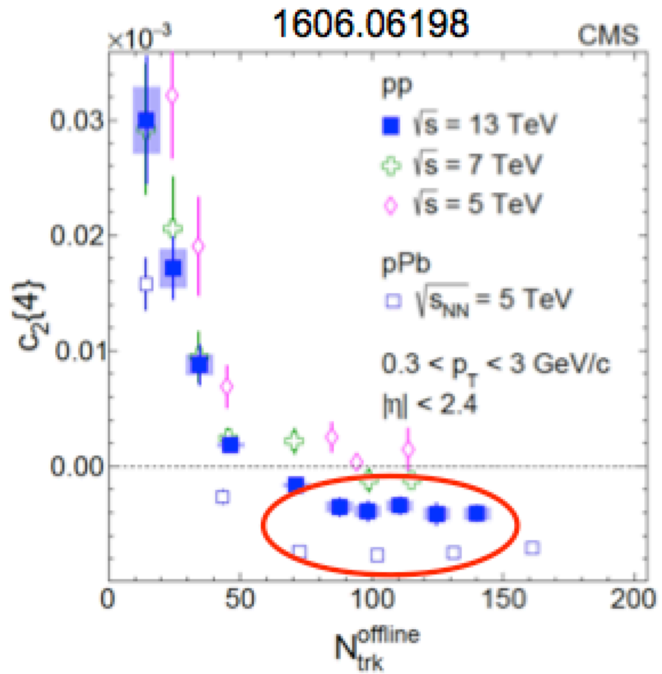


round proton

Mantysaari, Schenke, Phys. Rev. Lett. 117, 052301 (2016), Phys.Rev. D94 (2016) 034042

Multi-particle nature of the ridge

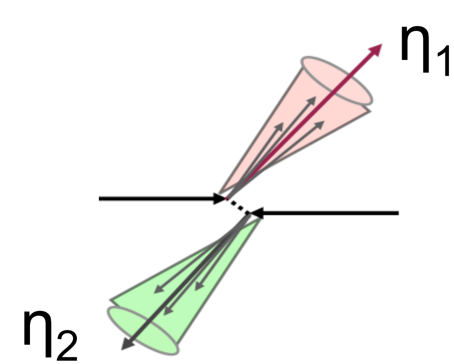




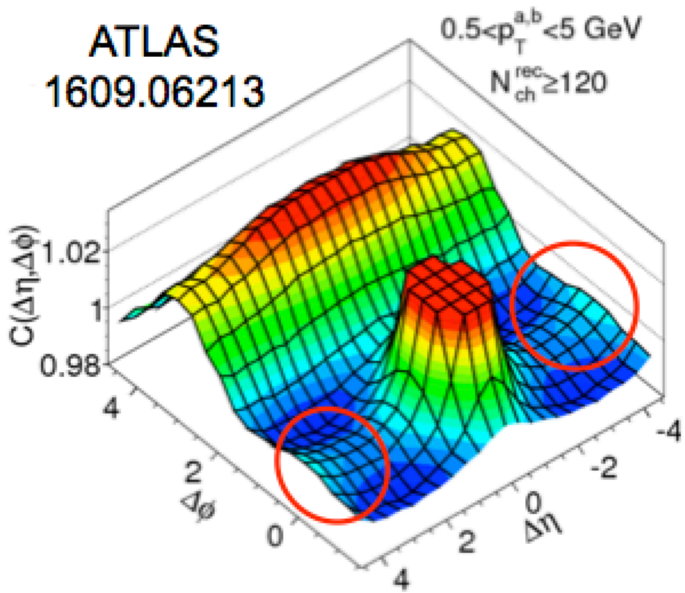
Long-range in η

Multi-particle (3,4,5..) signal

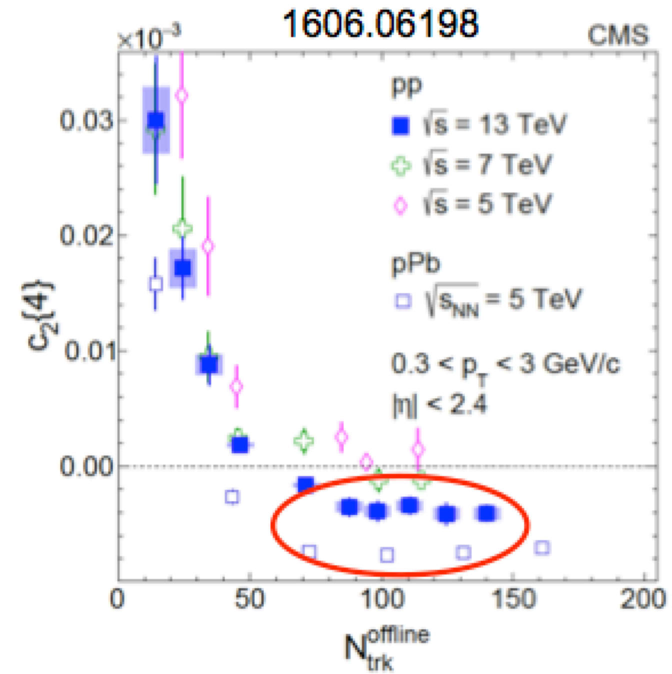
Very different from jets and dijet correlations, which are confined in **one or two η regions**



Multi-particle nature of the ridge



Long-range in η



Multi-particle (3,4,5..) signal

Suppress by requiring correlations between more than two η ranges

Example: WW TMD in DIS dijet production

$$E_1 E_2 \frac{d\sigma^{\gamma_L^* A \to q\bar{q} X}}{d^3k_1 d^3k_2 d^2b} = \alpha_{em} e_q^2 \alpha_s \delta\left(x_{\gamma^*} - 1\right) z^2 (1-z)^2 \frac{8\epsilon_f^2 P_\perp^2}{(P_\perp^2 + \epsilon_f^2)^4} \times \left[x G^{(1)}(x, q_\perp) + \cos(2\phi)\, x h_\perp^{(1)}(x, q_\perp) \right]$$

$$e\, A \to e'\, Q \bar{Q} X$$

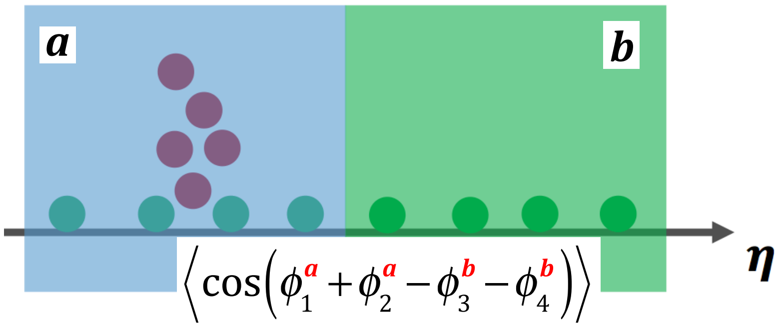
gluon distribution ($G^{(1)}$) + linearly polarized partner ($h^{(1)}$)

Dumitru et al Phys. Rev. D 94, 014030 (2016),
Dumitru et al Phys. Rev. Lett. 115 (2015) 25, 252301

Long-range collectivity via subevent correlations

arXiv:1701.03830

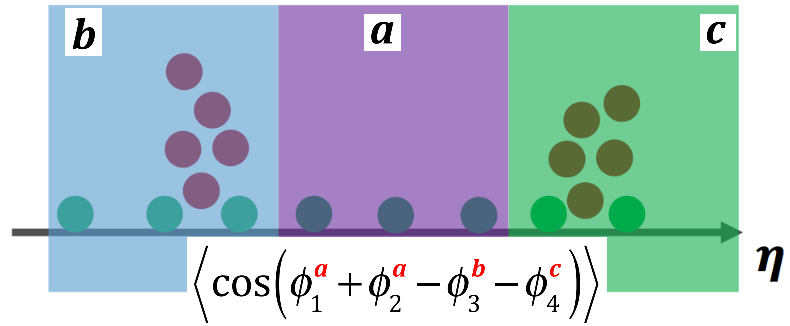
Event with jet



2 sub-event

suppress intra-jet correlations

Event with dijet



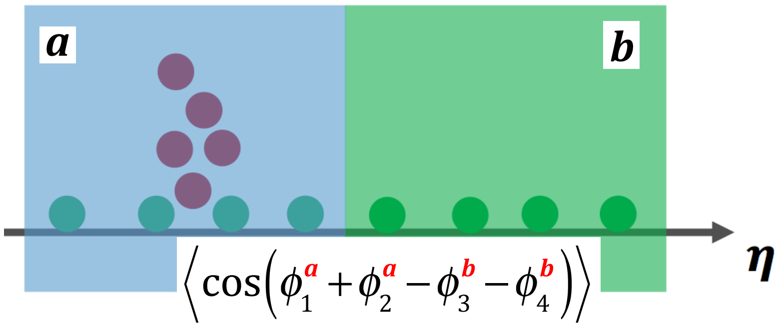
3 sub-event

suppress inter-jet correlations

Long-range collectivity via subevent correlations

arXiv:1701.03830

Event with jet

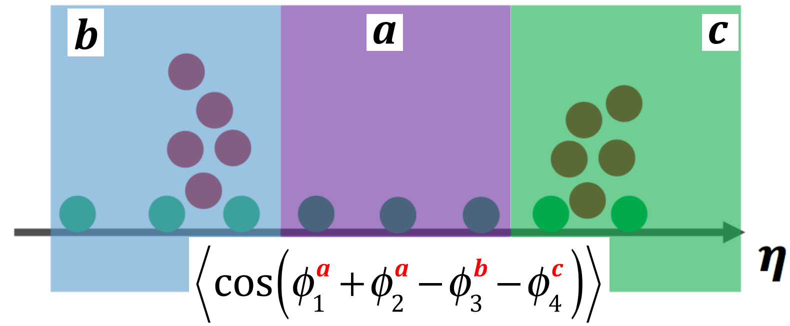


$$\left\langle \cos\left(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^b\right)\right\rangle$$

2 sub-event

suppress intra-jet correlations

Event with dijet

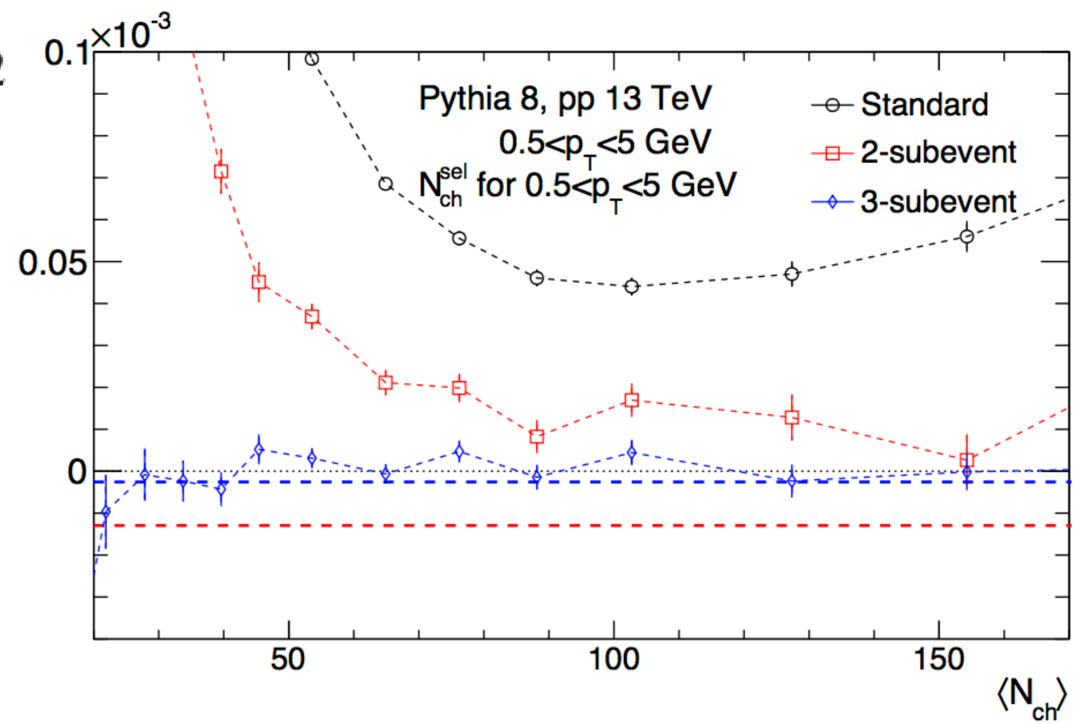


$$\left\langle \cos\left(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c\right)\right\rangle$$

3 sub-event

suppress inter-jet correlations

$$c_2\{4\}=\left\langle v_2^4\right\rangle-2\left\langle v_2^2\right\rangle^2$$

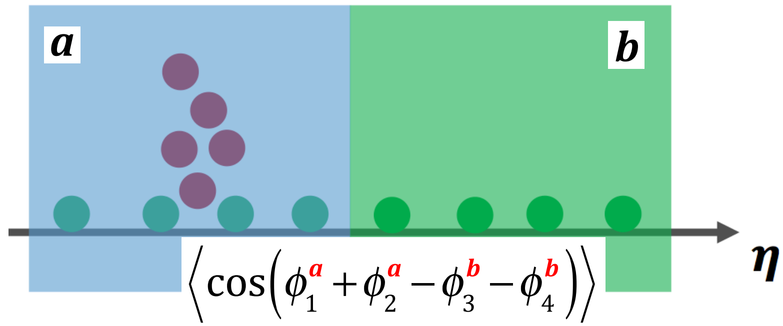


Mini-jet correlations
suppressed by the method!

Long-range collectivity via subevent correlations

arXiv:1701.03830

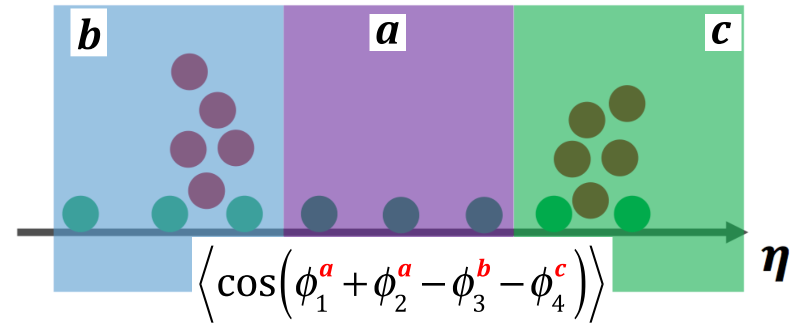
Event with jet



2 sub-event

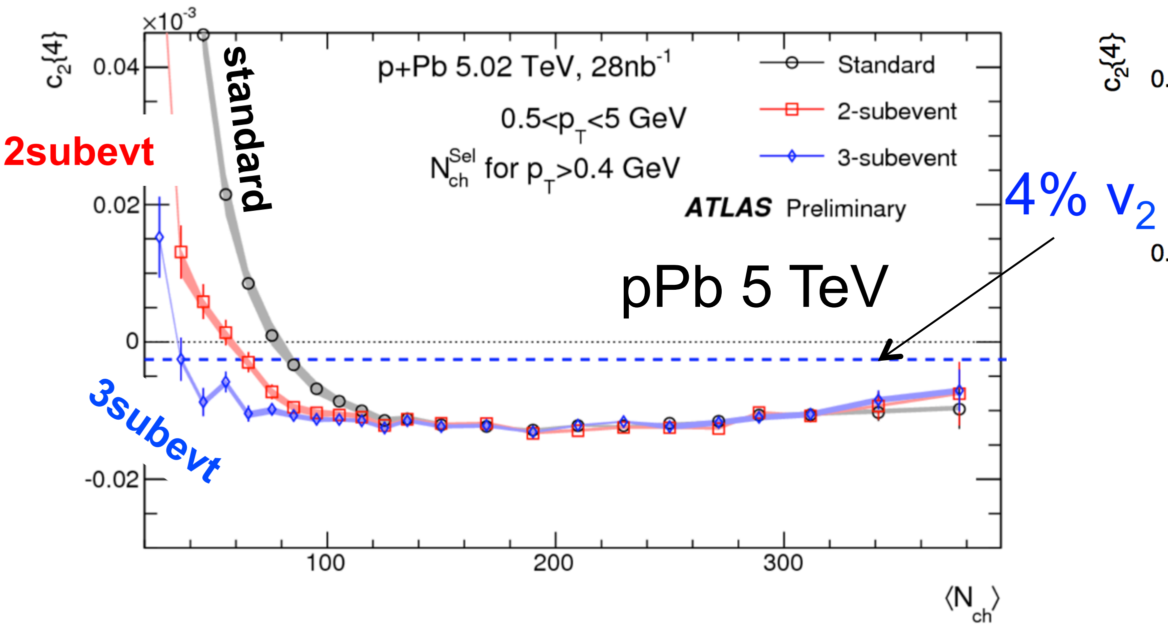
suppress intra-jet correlations

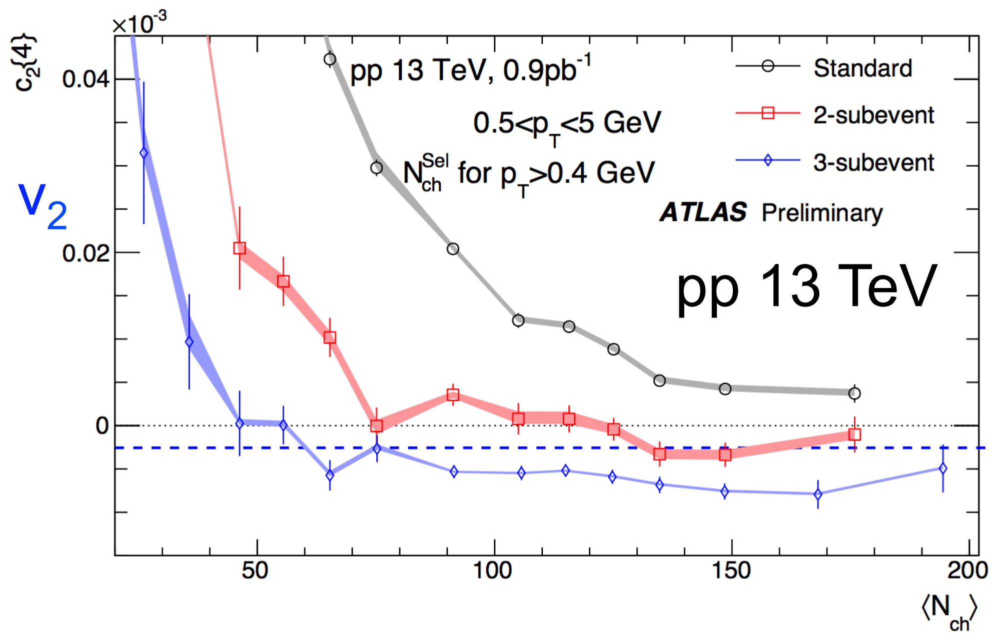
Event with dijet



3 sub-event

suppress inter-jet correlations





Jet correlation important at low N_{ch} for pPb, and over all N_{ch} in pp

Subevent method required to suppress the jet correlations in small system

Sign-change of $c_2\{4\}$

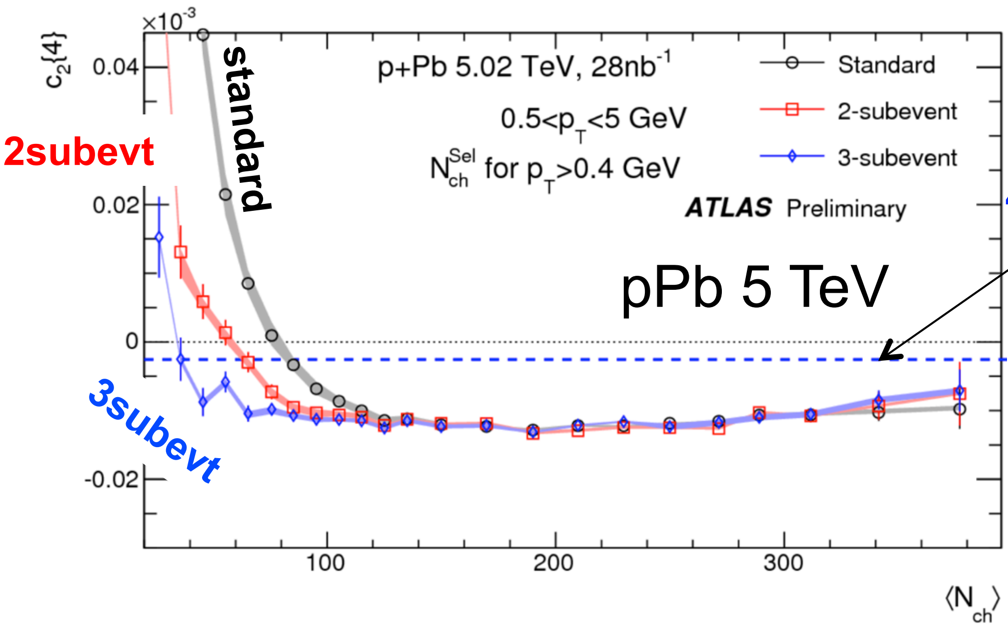
- Most positive $c_2\{4\}$ in standard cumulants are jets and dijets.
  - Remaining positive $c_2\{4\}$ in 3-subevent due to residual dijets.

Dumitru,McLerran,Skokov

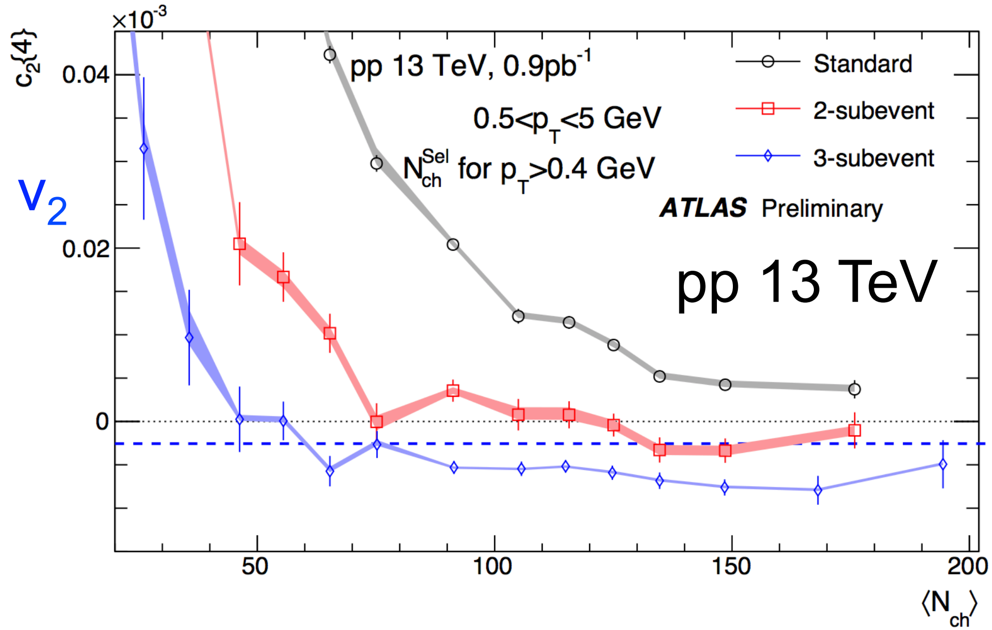
- CGC expect sign change at low N_{ch}

$$c_2\{4\} = \frac{1}{N_D^3}\left(\frac{1}{4(N_c^2-1)^3} - A^4\right)$$

Glasma diagram — non-linear/non-Gaussian effects



4% v_2



Glasma diagram contribution is small?

$p(v_2)$ in pp and pPb

- Constrain $p(v_2)$ from two- and four-particle correlations

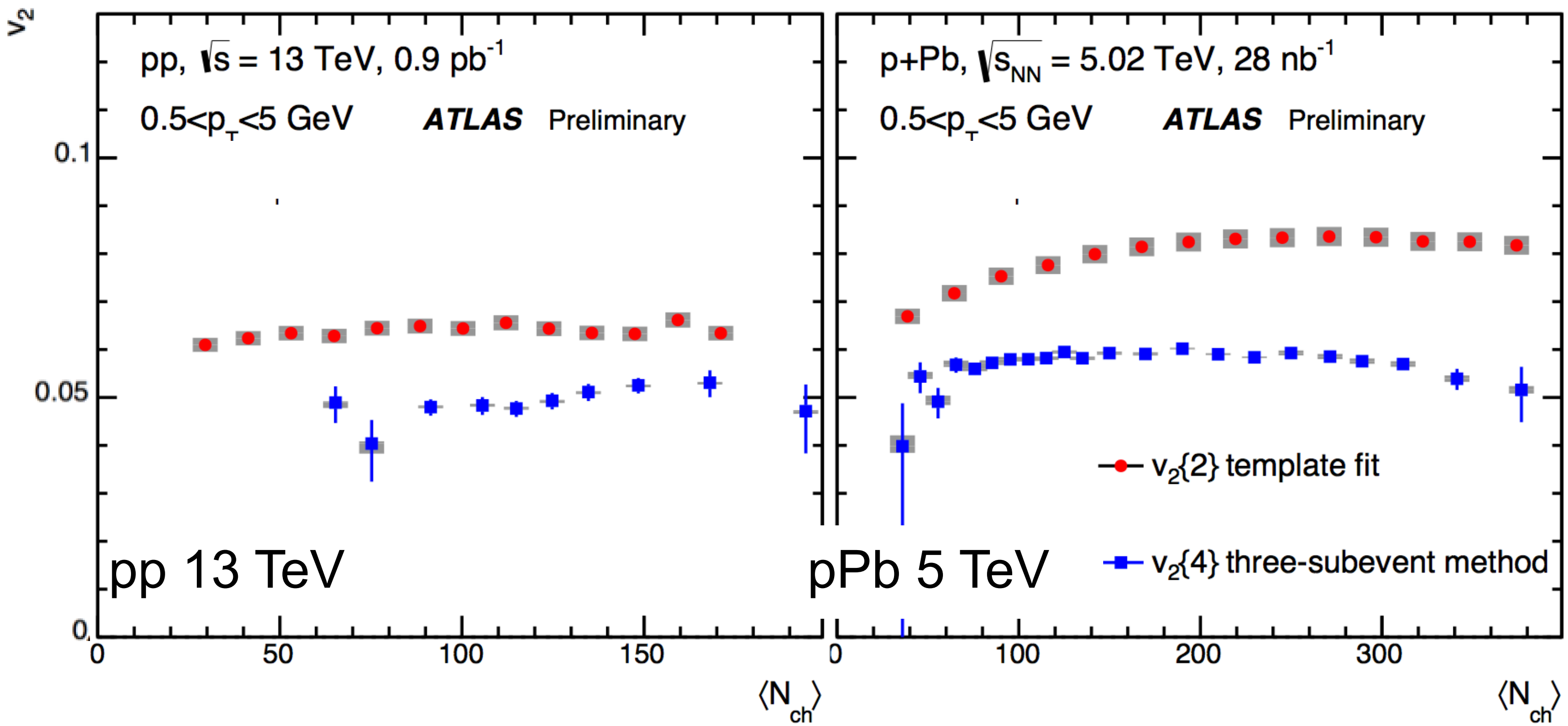
$$c_2\{2\} = \left\langle v_2^2 \right\rangle \equiv v_2\{2\}^2$$

Two-particle correlation

$$c_2\{4\} = \left\langle v_2^4 \right\rangle - 2\left\langle v_2^2 \right\rangle^2 \equiv -v_2\{4\}^4$$

Four-particle correlation

- Results suggest significant non-Gaussian EbyE fluctuations



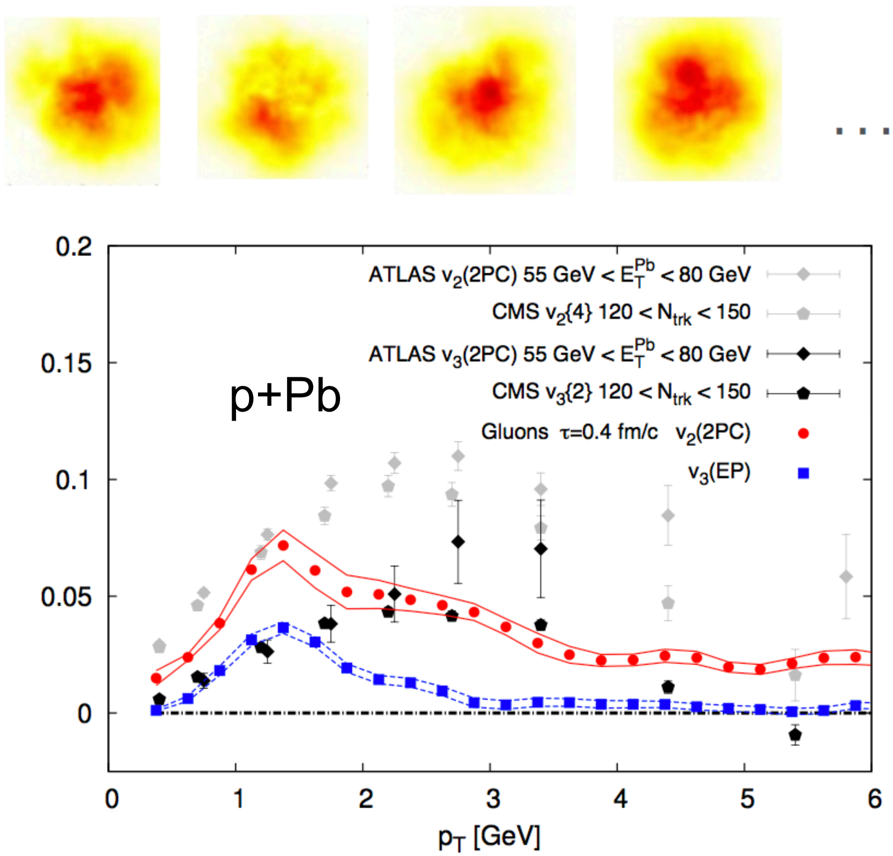
Both $v_2\{2\}$ and $v_2\{4\}$ show No hint of collectivity turning-off at low N_{ch}!

Challenge both initial and final state models?

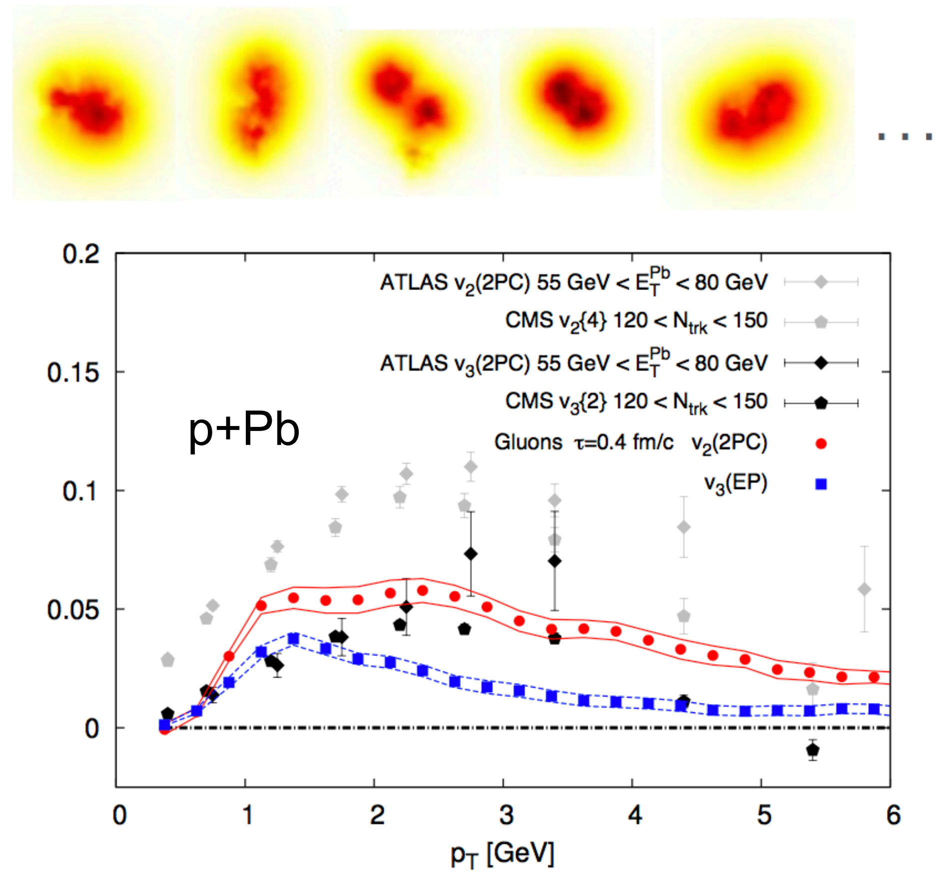
Role of initial geometry in CGC

Schenke, Schlichting, Venugopalan

'Spherical' proton



'Eccentric' proton

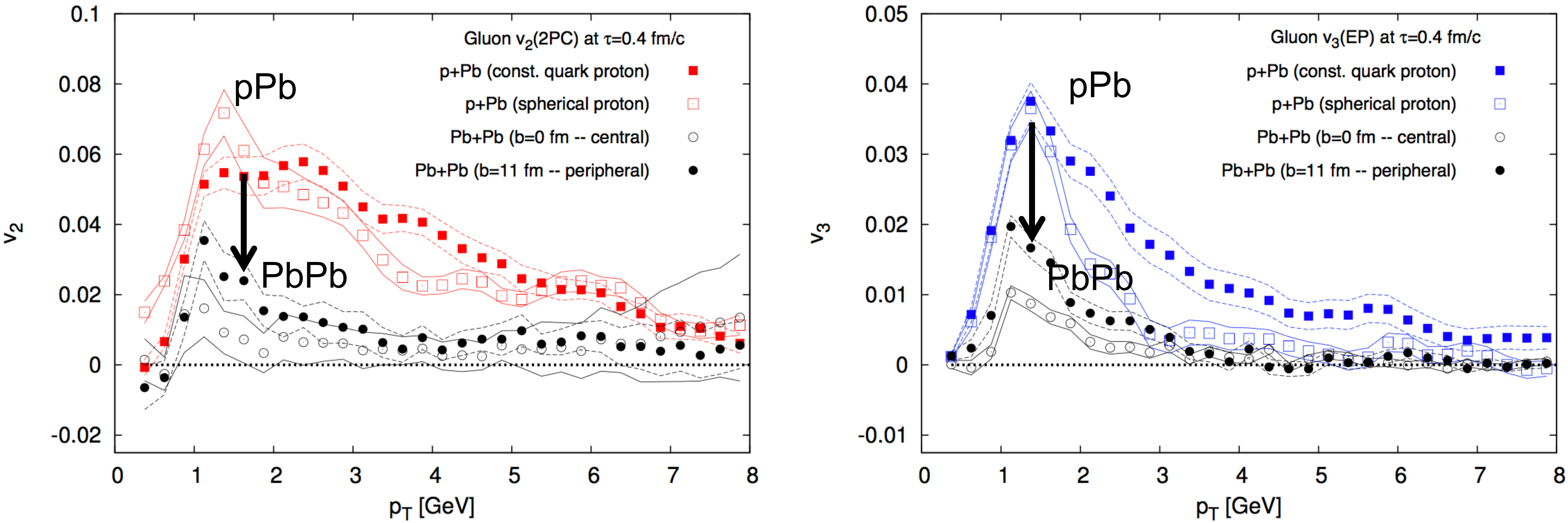


The orientation of collectivity is unrelated to initial eccentricity

→Very different from hydrodynamics

Role of initial geometry in CGC

Schenke, Schlichting, Venugopalan

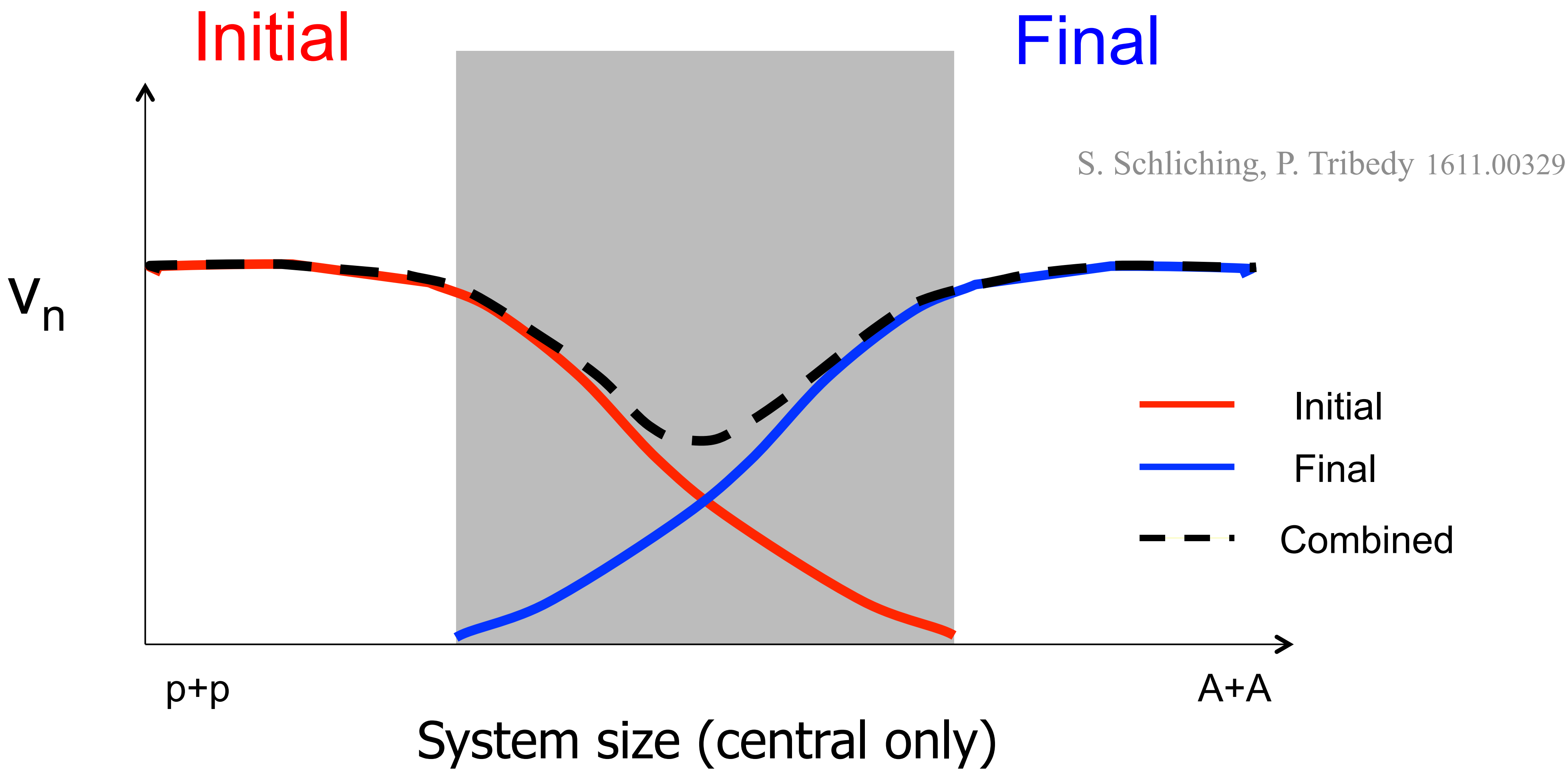


The orientation of collectivity is unrelated to initial eccentricity

→Very different from hydrodynamics

Expect contribution diminish as system size is increased

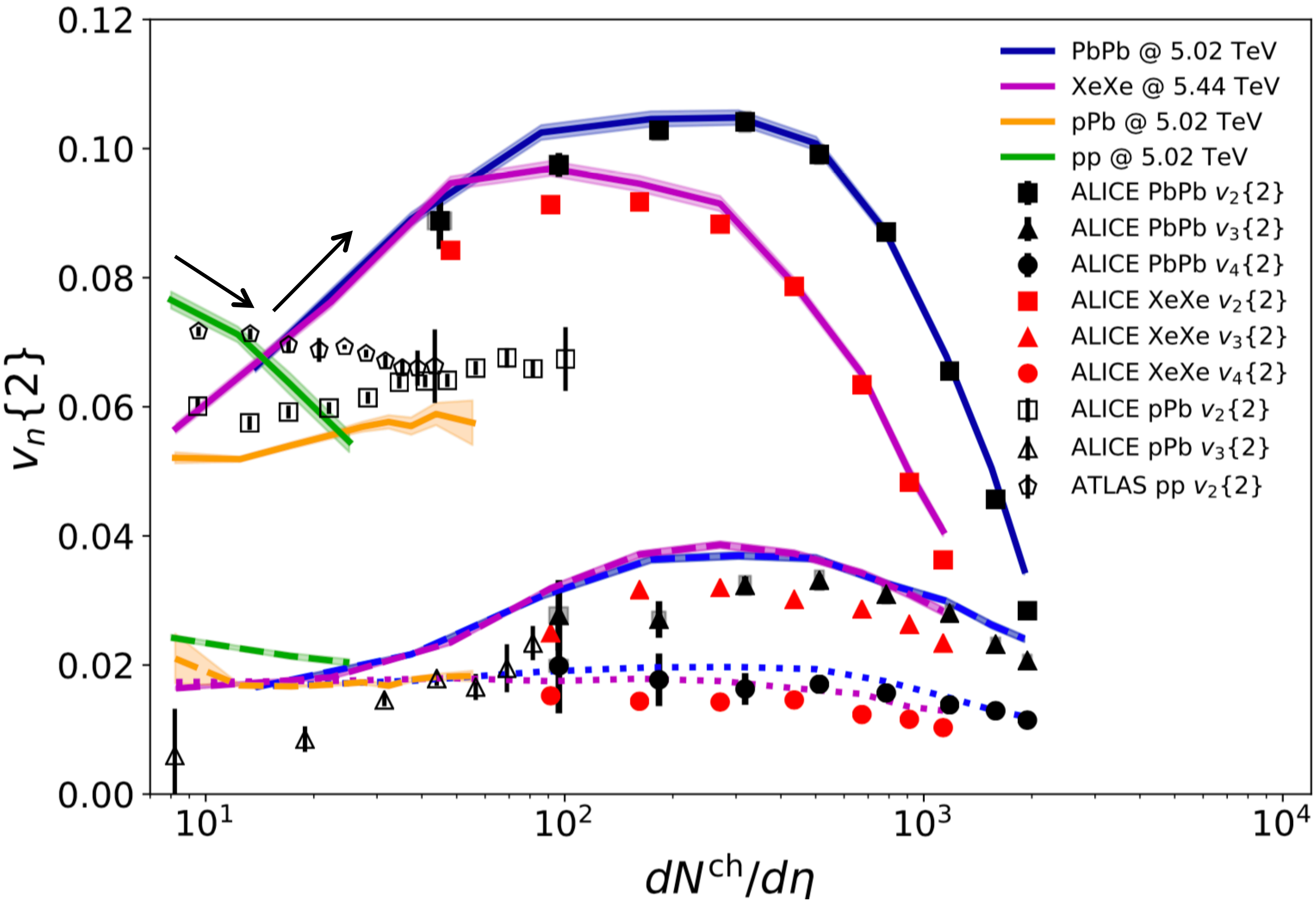
Presence of both initial and final state scenarios?



Phases of collectivity from CGC and hydro are unrelated
→ a minimum of total v_n at certain system size?

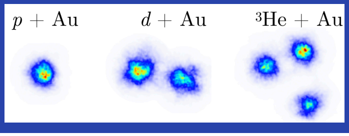
Presence of both initial and final state scenarios?

B. Schenke, QM2018



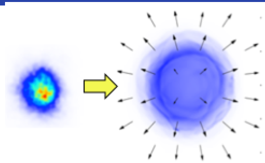
IP-Glasma + hydrodynamic calculation

RHIC small system scan



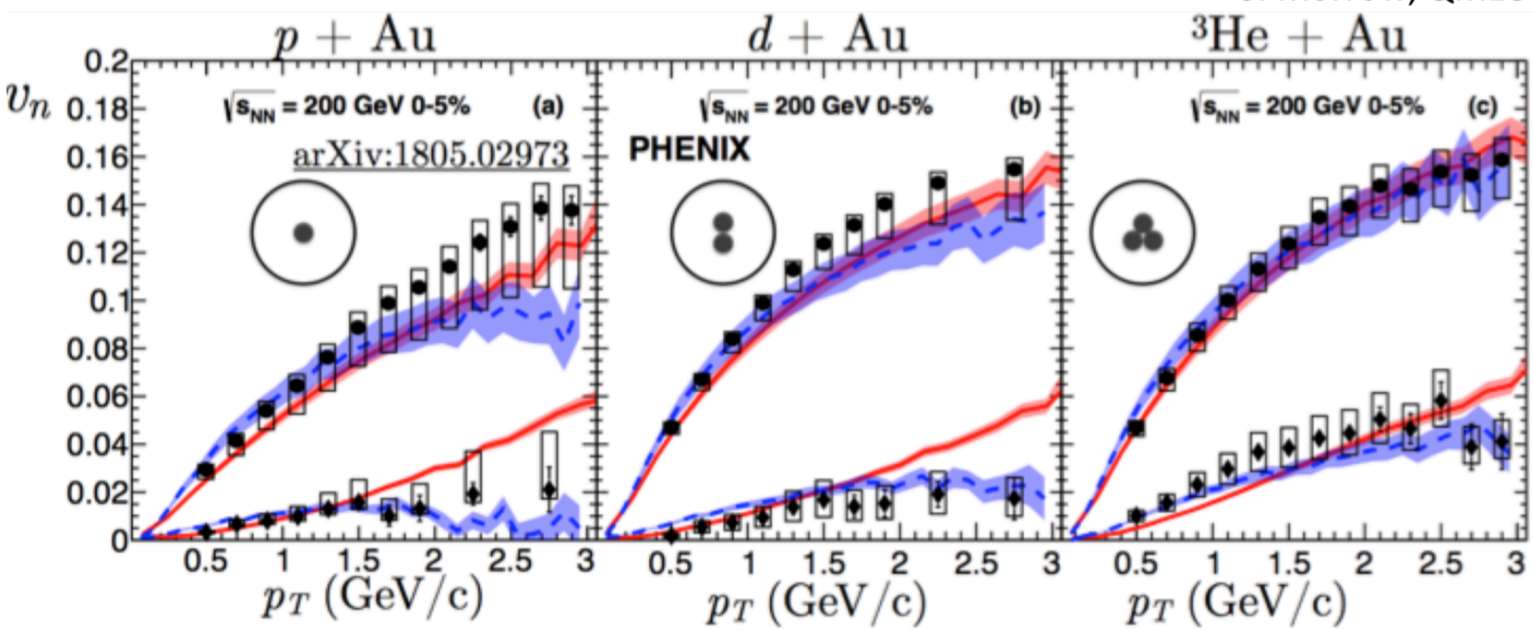
S. Morrow, QM18

Hydro

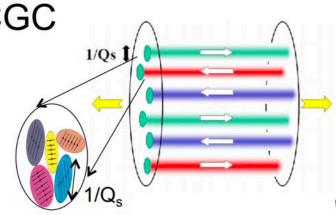


$$\varepsilon_2^{p+\mathrm{Au}} < \varepsilon_2^{d+\mathrm{Au}} \approx \varepsilon_2^{^3\mathrm{He+Au}}$$

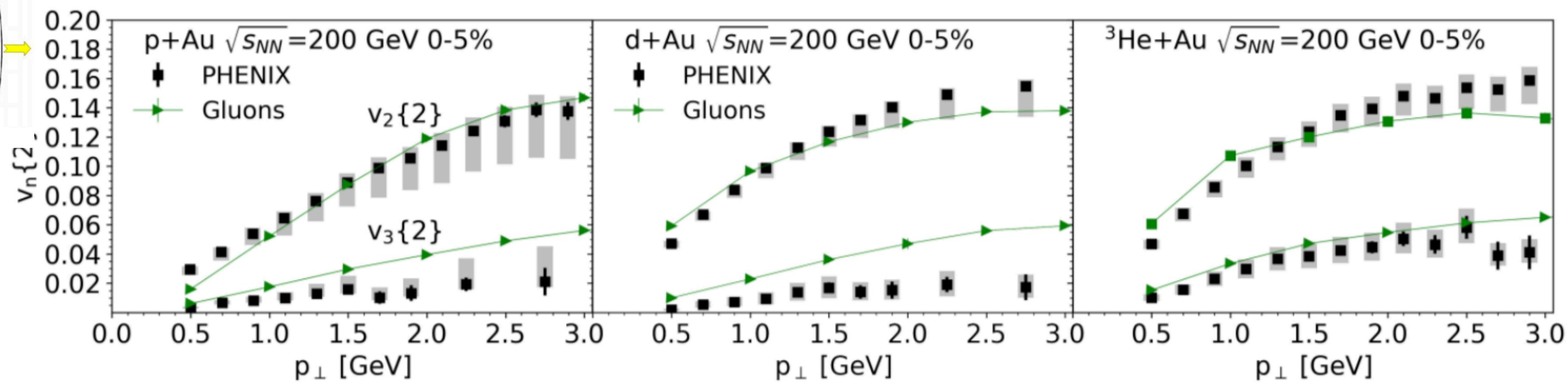
$$\varepsilon_3^{p+\mathrm{Au}} \approx \varepsilon_3^{d+\mathrm{Au}} < \varepsilon_3^{^3\mathrm{He+Au}}$$



CGC

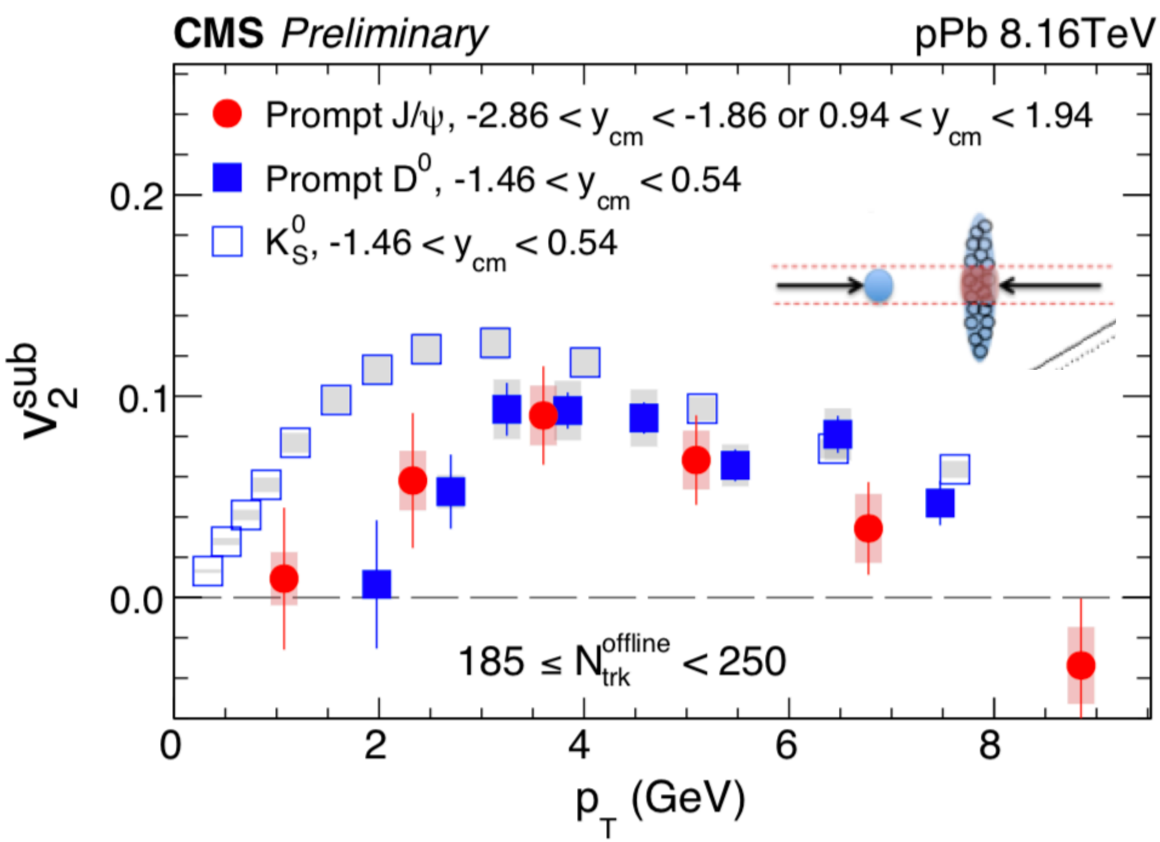


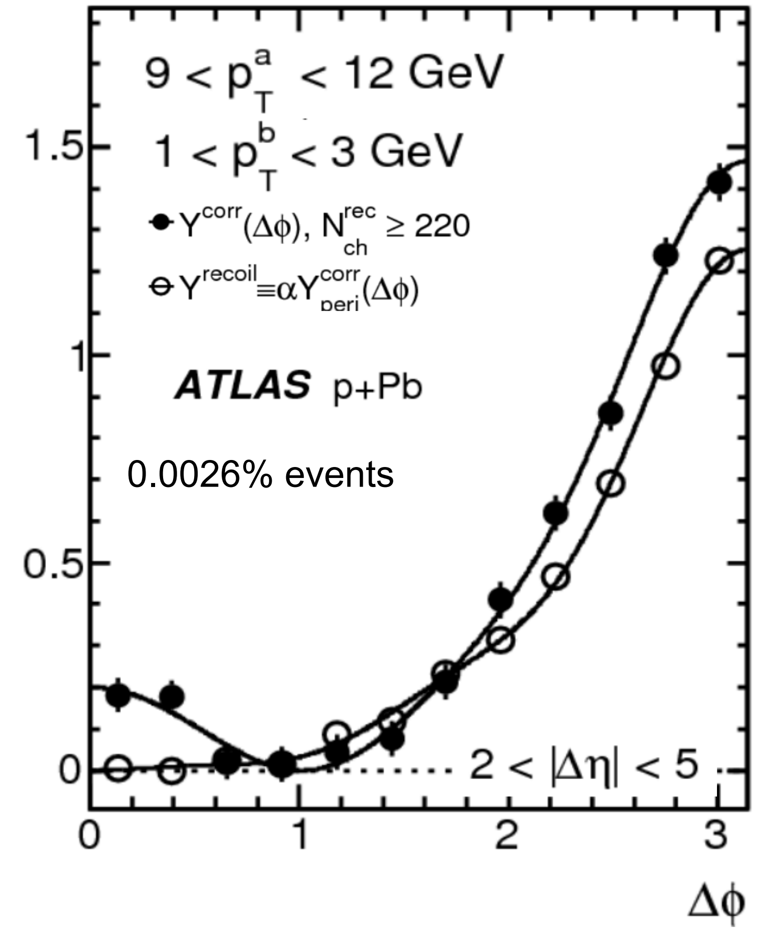
M.Mace, V.Skokov, P.Tribedy, R.Venugopalan 1805.09342



Can initial state correlation knows the shape of initial geometry?

Flow of heavy quark and high-p_T hadron





Significant but smaller v_2 for D^0 and J/Psi.

Charm **less** thermalized than light quarks?

Significant ridge for high p_T hadron

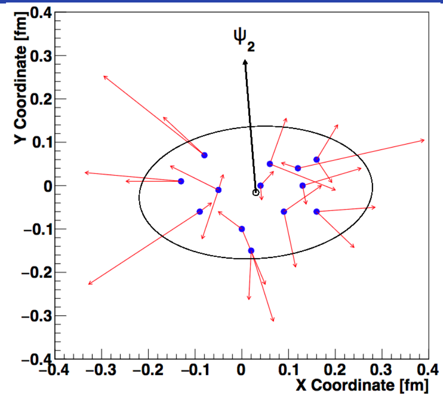
Hint of jet-medium interaction?

Implication for initial-state correlation models?

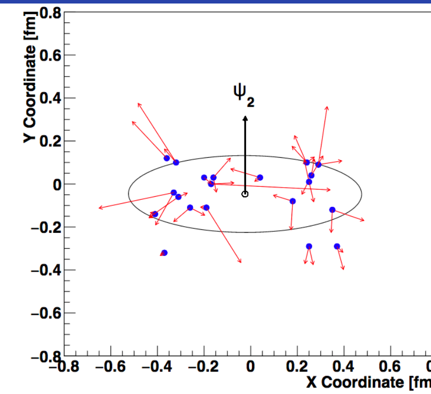
Minimal requirement for long-range ridge

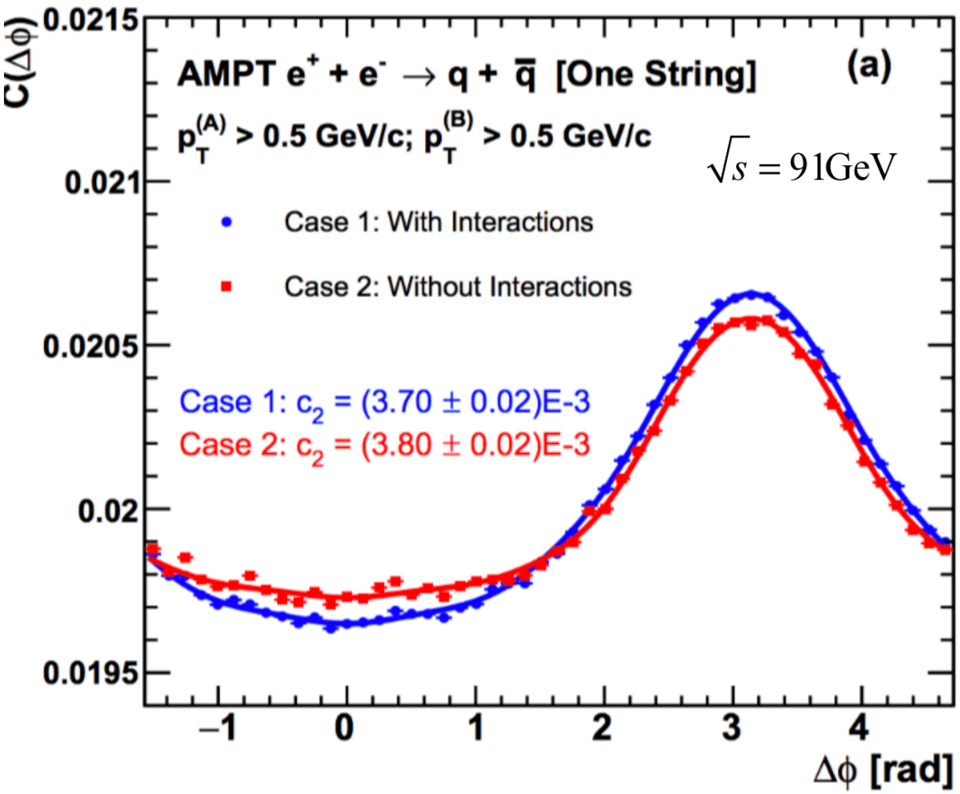
J. L Nagle et.al. 1707.02307

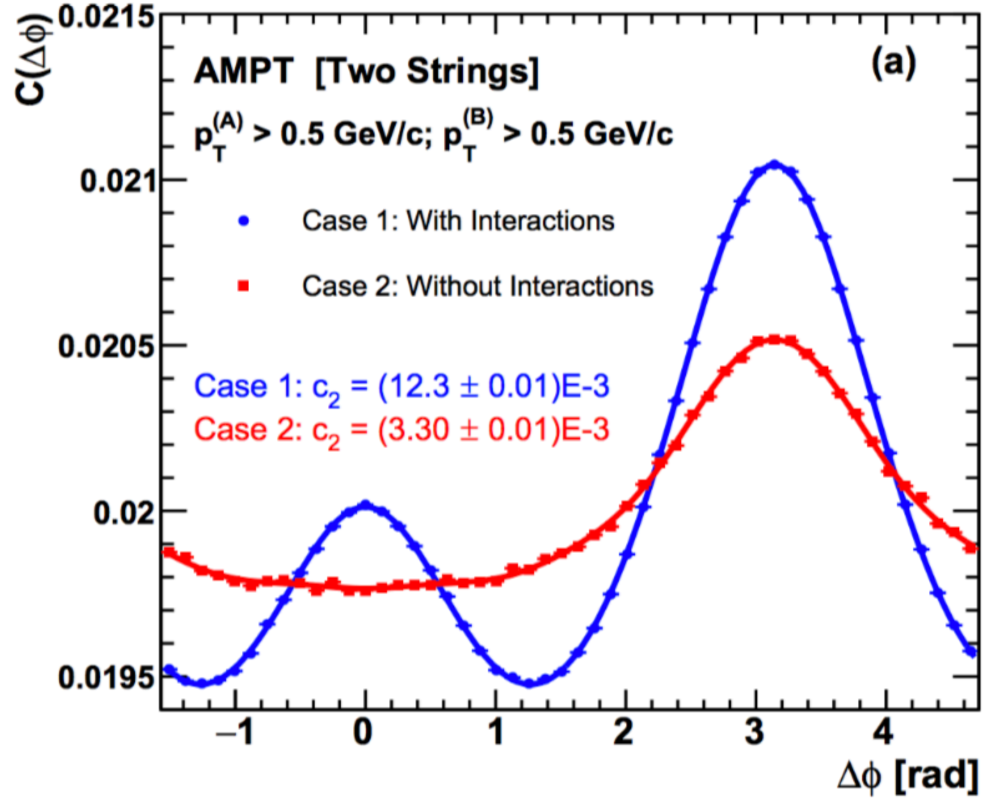
One String



Two Strings

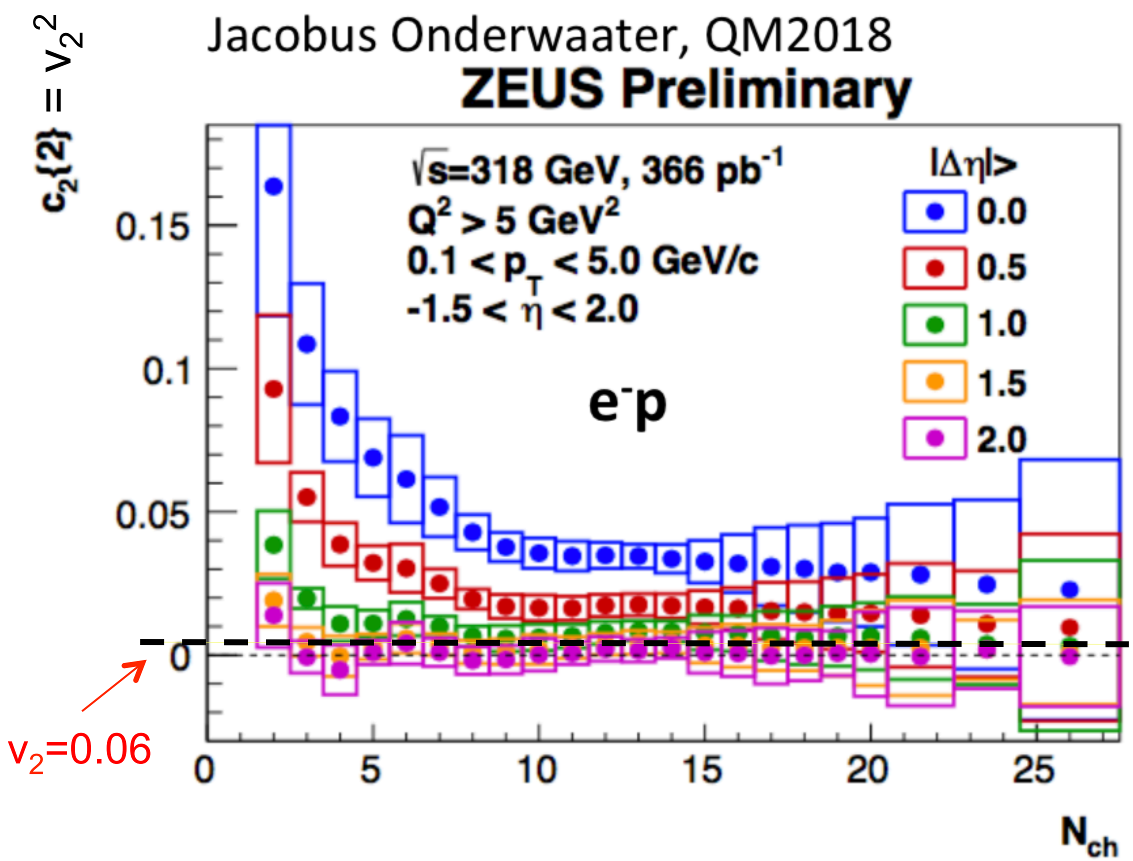


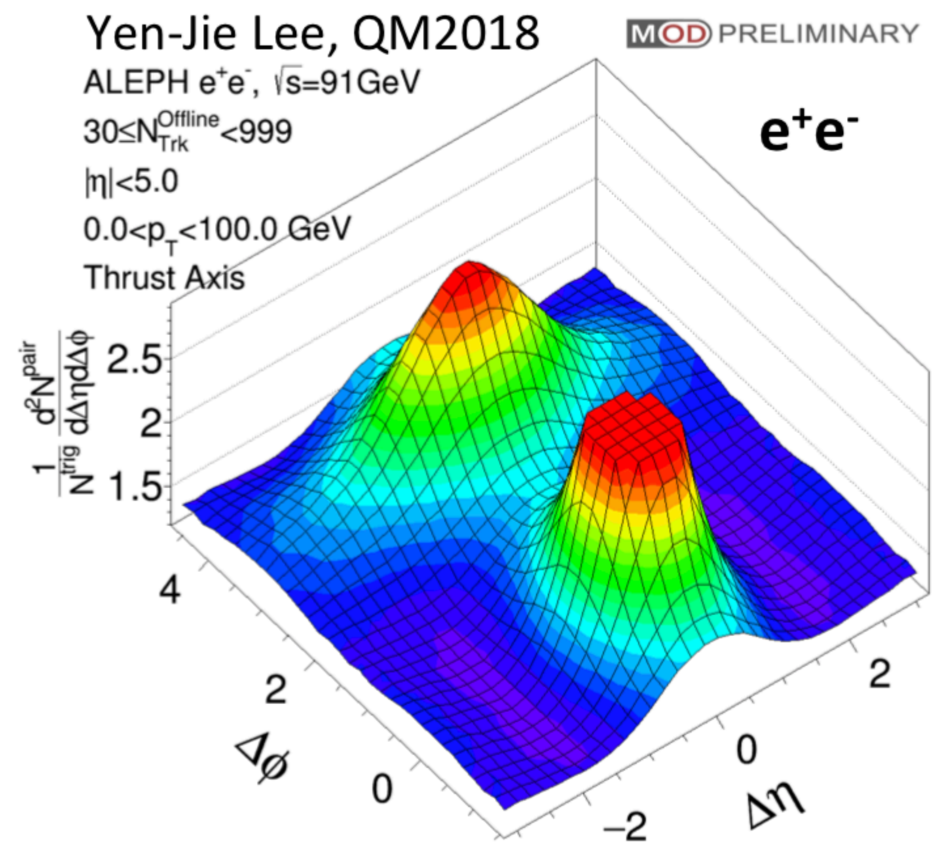




Two interacting strings are enough to create long-range correlation!

Towards even smaller systems: ep, e+e-

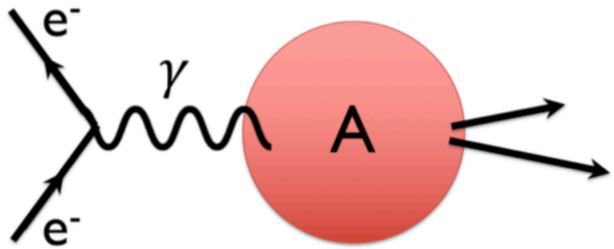




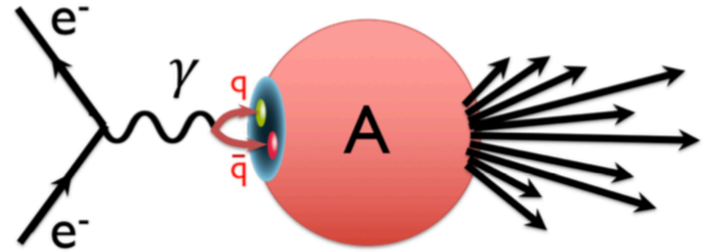
Ridge observation in ep or ee is currently limited by statistics

High-multiplicity e+A at EIC?

Typical e+A

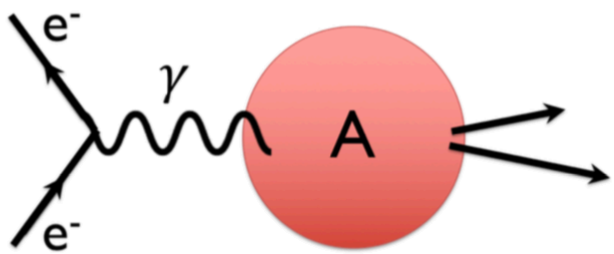


High-multiplicity e+A = $(q\bar{q})$+A?

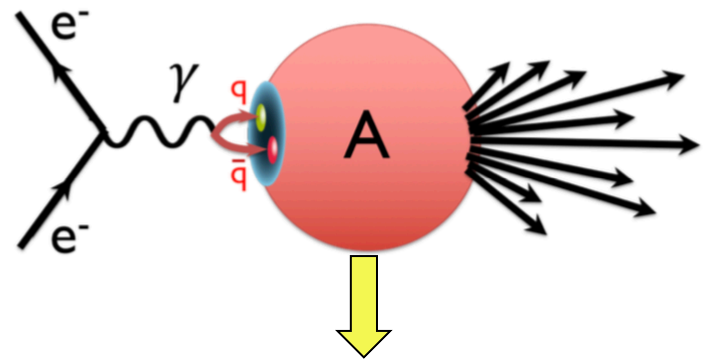


High-multiplicity e+A at EIC?

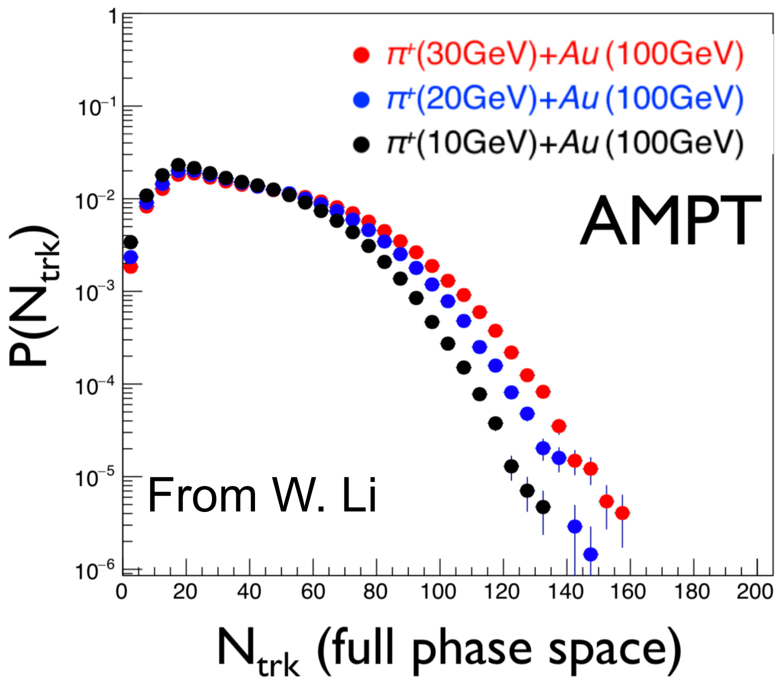
Typical e+A



High-multiplicity e+A = $(q\bar{q})$+A?

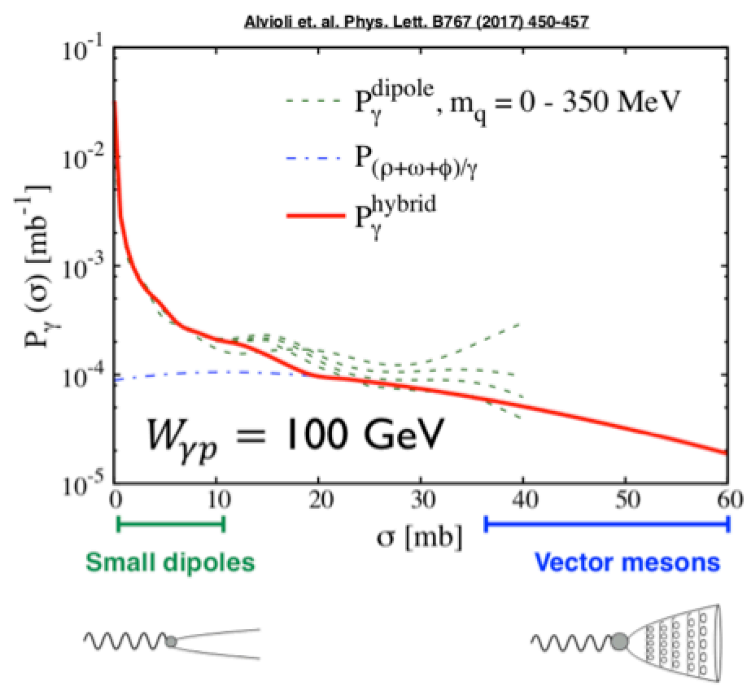


Multiplicity fluct.



$\sigma \sim N_{trk}$

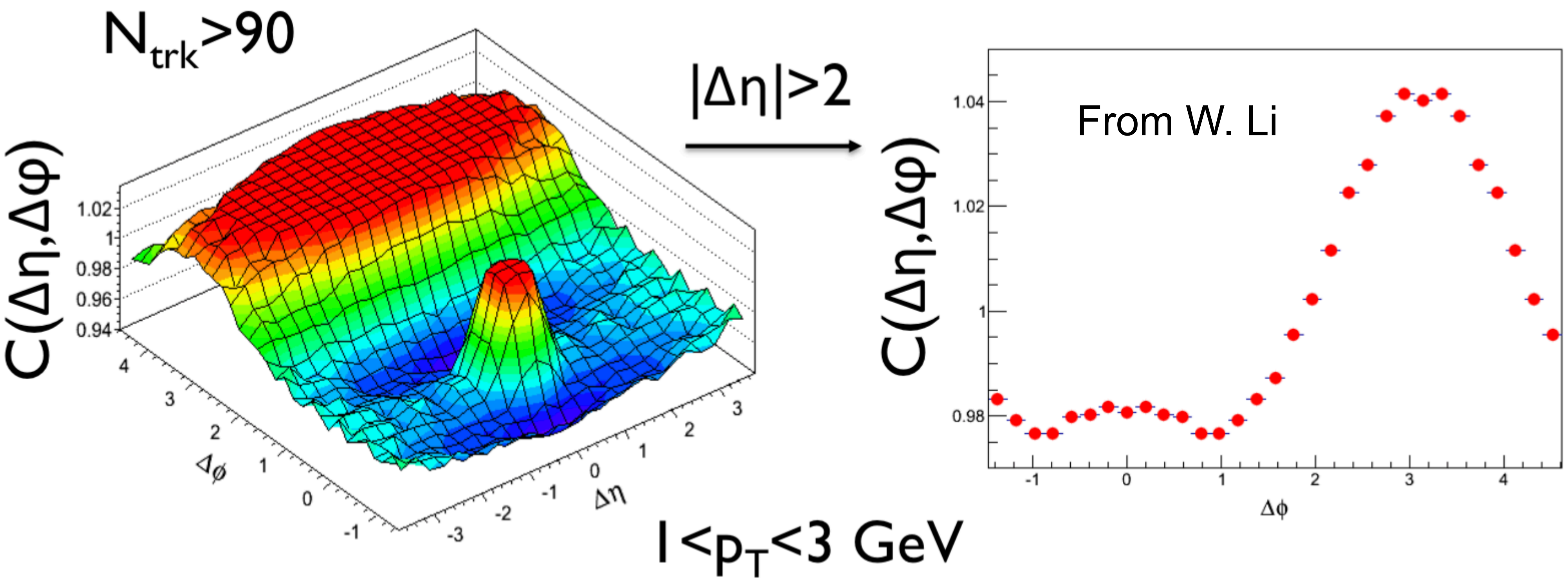
Size/cross section fluct.



Control the size and energy of the probe via x and Q^2

High-multiplicity e+A at EIC?

π^+(30GeV)+*Au*(100GeV) from AMPT

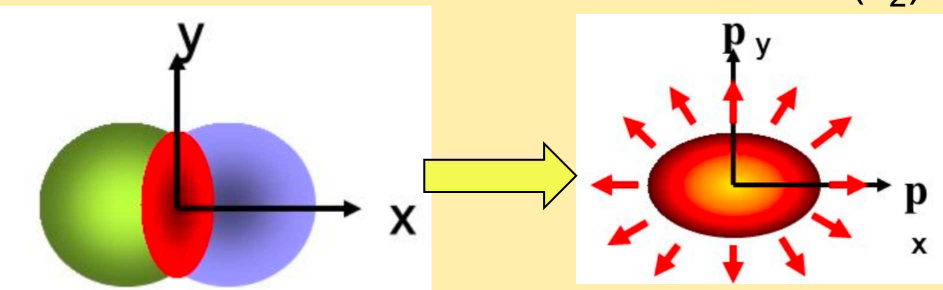


A long-range ridge can be observed at EIC in high-multiplicity e+Au events!

Can already check and confirm this idea in high-multiplicity UPC events

Flow with polarized light-ion+A collisions

Initial shape (ε_2) Final flow (v_2)



Flow angle Φ unknown.

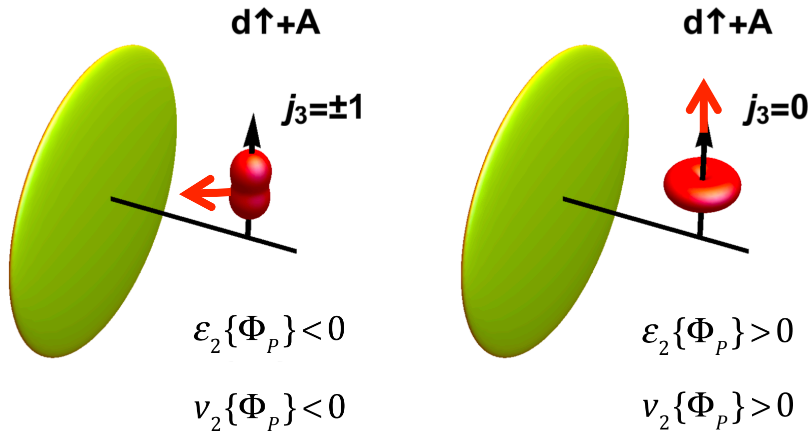
Has to determined via momentum flow

Can't distinguish initial state flow or final state flow

Problem for small system

W. Broniowski and P. Bozek 1808.09840

Deuterium: $J^P = 1^+$, 5%, $^3D_1$ wave, rest $^3S_1$ wave

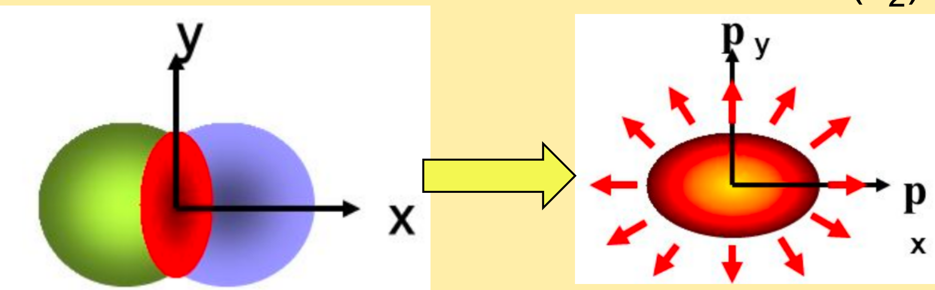


Polarization direction as absolution reference
→uncorrelated with jets

Eccentricity w.r.t. Φ_P has opposite sign

Flow with polarized light-ion+A collisions

Initial shape (ε_2) Final flow (v_2)



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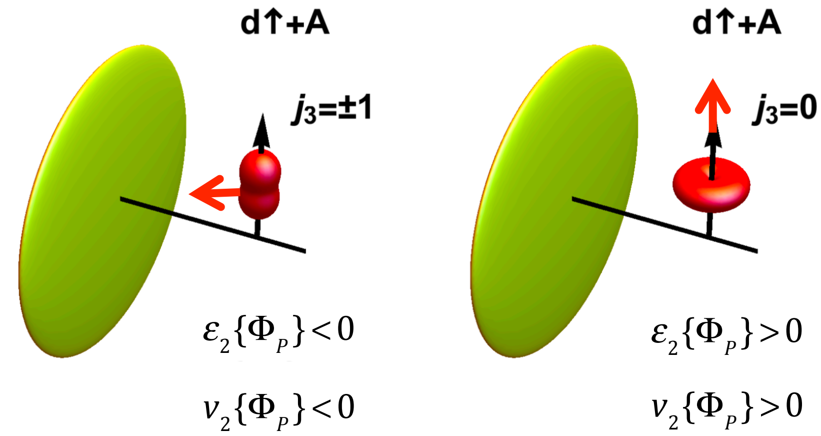


Polarization direction as absolution reference

→uncorrelated with jets

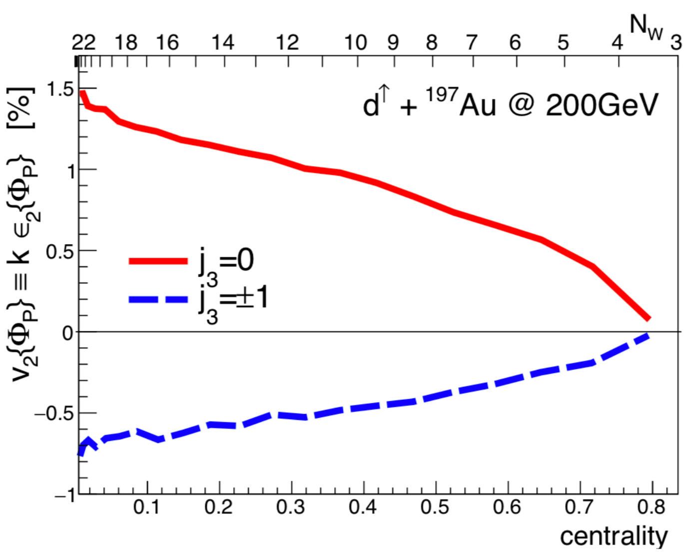
Eccentricity w.r.t. Φ_P has opposite sign

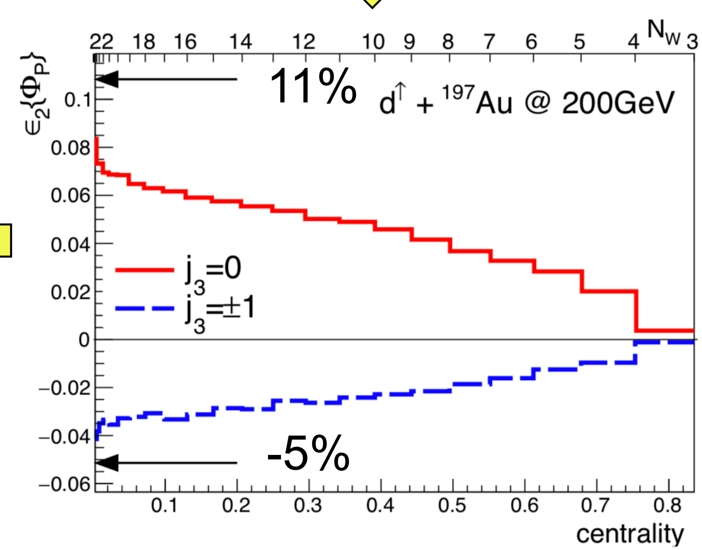
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Phi_P)\right]$$

$$v_2 \simeq k\epsilon_2, \quad k \sim 0.2$$

With 50% polarization:

$$-0.5\% \lesssim v_2\{\Phi_P\} \lesssim 1\%$$





Summary

- Ridge observed in small collision systems at RHIC/LHC experiments
  - Implies a long-range and multi-particle collectivity qualitatively similar to those in AA collisions
  - Results of strong multi-parton dynamics in hadronic collisions

- From AA to pA to pp allow push the boundary between initial state correlations and final state interactions.
  - Both models are successful to some extents.
  - Would be useful to check the existing eP and e+e- data, but statistically limited

- A few unique opportunities to further test nature of collectivity.
  - Particle correlations in high-multiplicity e+P and e+A collisions.
  - Polarized light-ion + heavy-nucleus collisions offers a new way to disentangle initial vs final state effects.

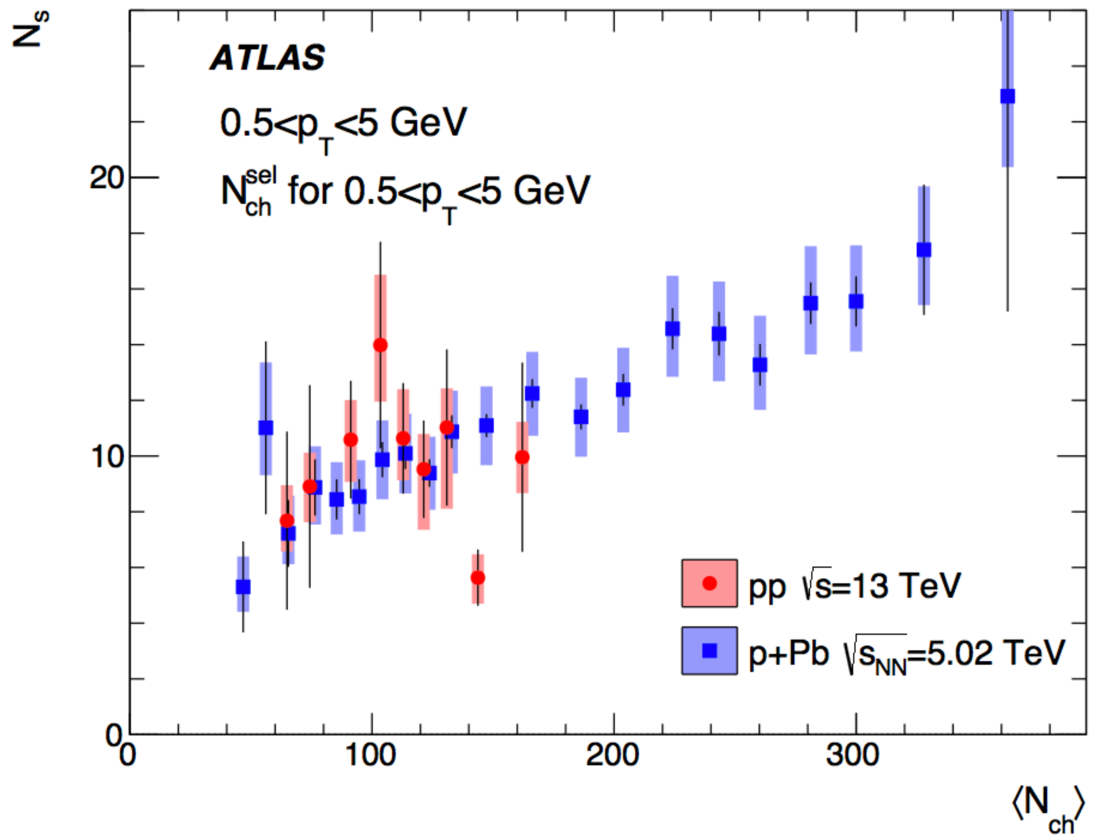
- Can final-state physics shed some insight on initial-state physics i.e. EIC

What do we learn from this?

PRL112,082301(2014)

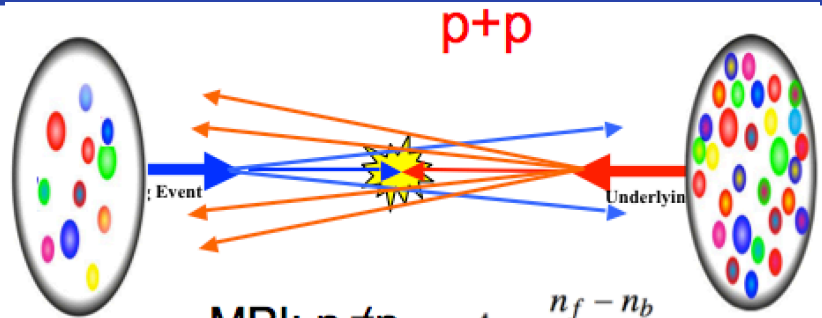
- $p(v_2)$ driven by fluc. of independent sources: multi-parton interactions (MPI)
- Number of sources N_s can be estimate from $v_2\{4\}/v_2\{2\}$

$$\frac{v_2\{4\}}{v_2\{2\}} = \left[\frac{4}{(3+N_s)}\right]^{1/4}$$



N_s similar for pp and pPb at similar multiplicity.

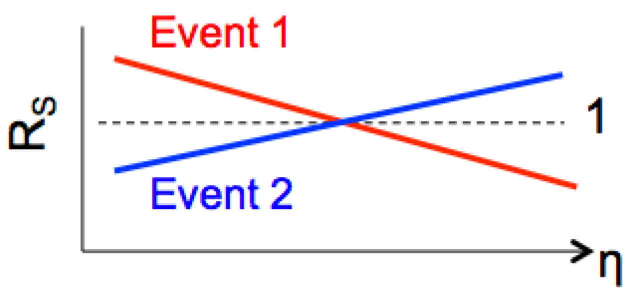
N_s from forward-backward multiplicity fluc.



MPI: $n_f \neq n_b$ $\quad A_n = \frac{n_f - n_b}{n_f + n_b}$

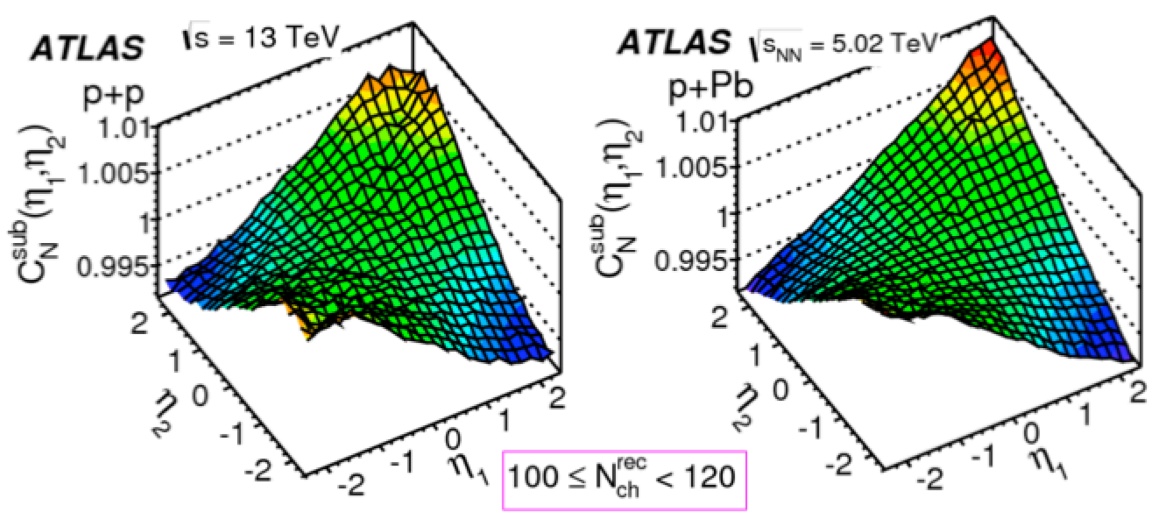
- Rapidity correlation:

$$R_S(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle} \qquad C = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} = \langle R_S(\eta_1) R_S(\eta_2) \rangle_{events}$$



$$R_S(\eta) \approx 1 + a_1 \eta \qquad C = \langle R_S(\eta_1) R_S(\eta_2) \rangle \approx 1 + \langle a_1^2 \rangle \eta_1 \eta_2$$

- Confirmed by data:



PRC 95, 064914 (2017)

Relate to the initial geometry

arXiv:1708.03559

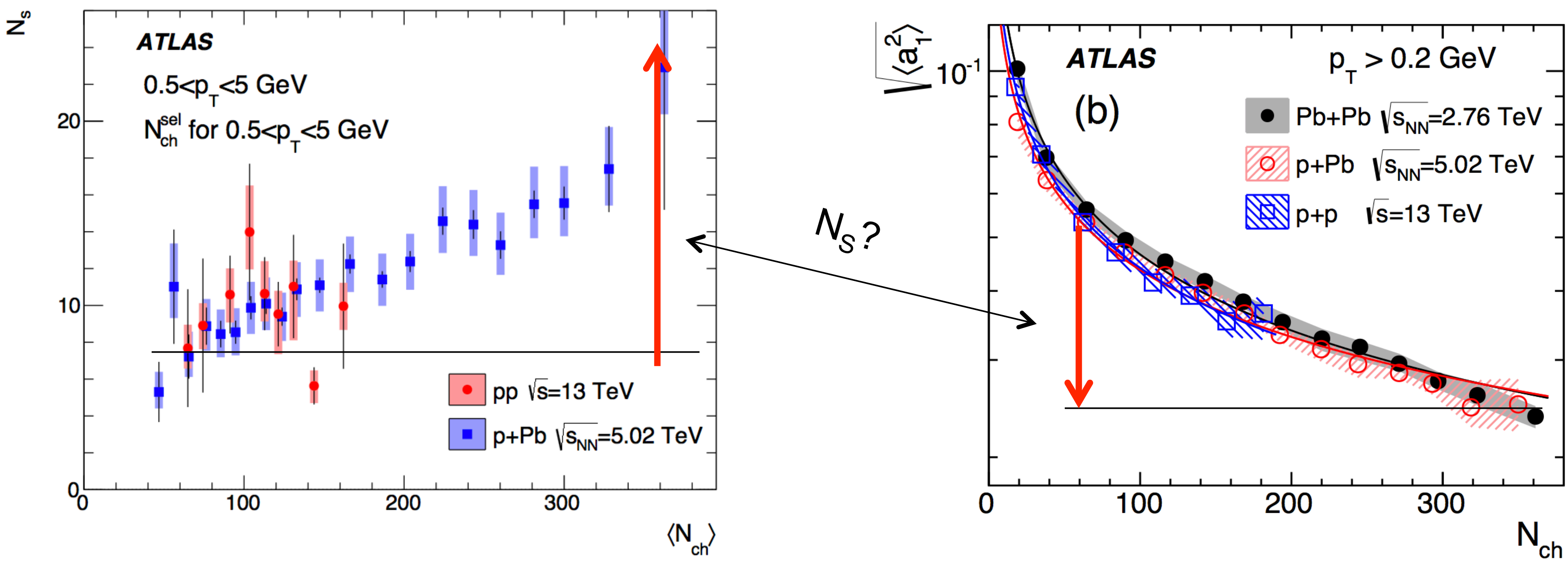
PRC 95, 064914 (2017)

Sources driving the transverse flow

$$\frac{v_2\{4\}}{v_2\{2\}} = \left[\frac{4}{(3+N_s)}\right]^{1/4}$$

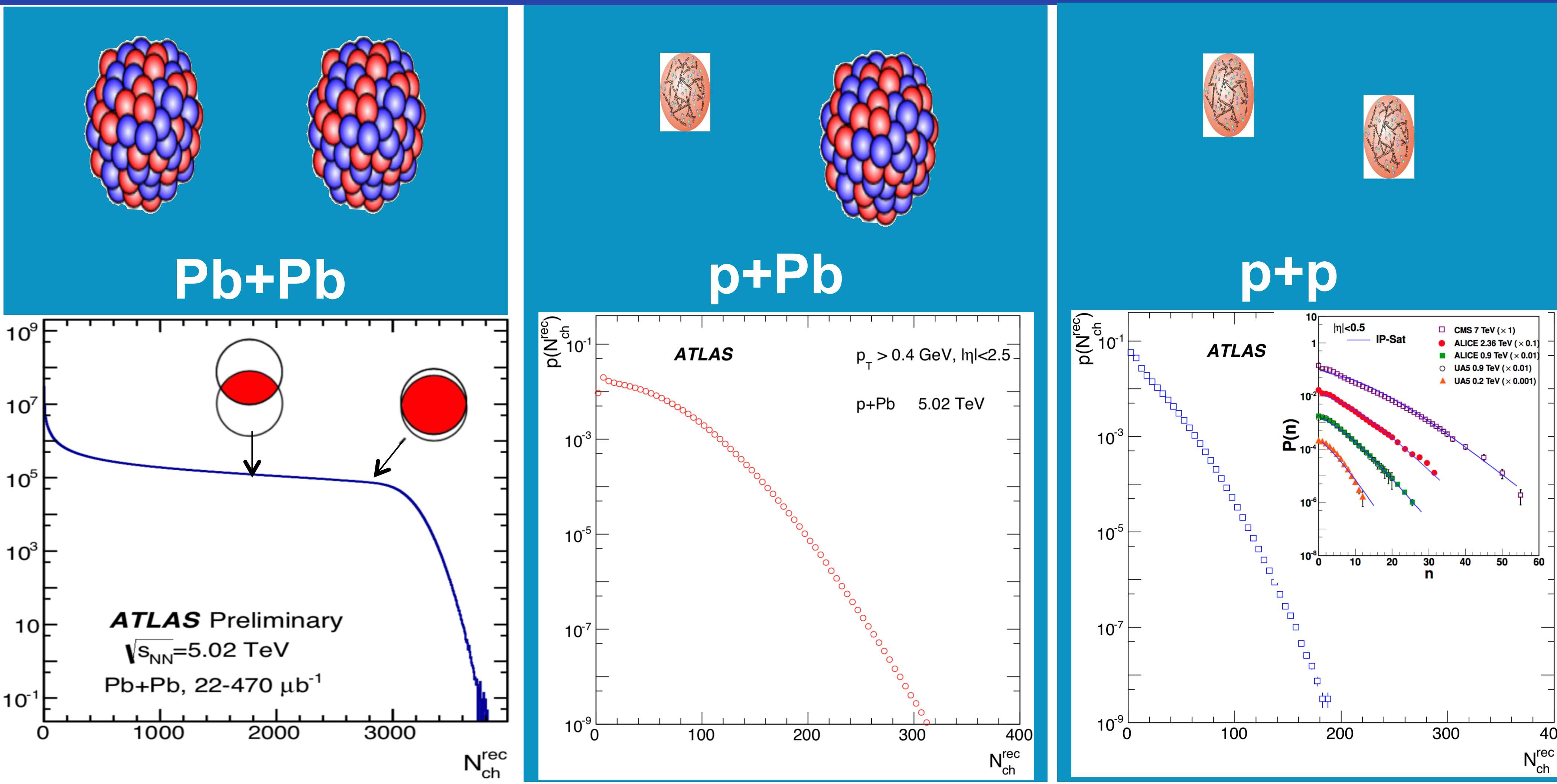
Source for particle production which drives FB multiplicity fluc.

$$\frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1+a_1\eta \qquad a_1 \propto 1\Big/\sqrt{N_s}$$



Same sources responsible for particle production and flow?

Large event-by-event multiplicity fluctuations



shoulder & knee

~absent in pp, pPb

signature of multiple sources for particle production