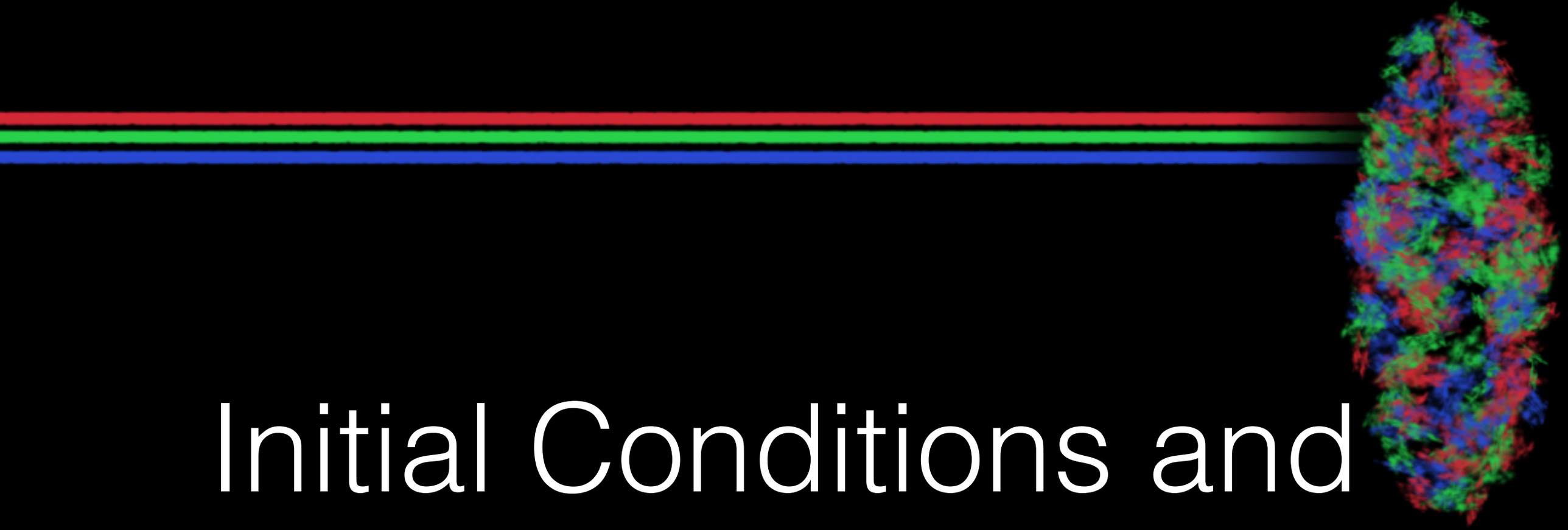


Initial Conditions and Flow in pA Collision

Mark Mace
Stony Brook University and Brookhaven National Lab

RHIC AGS Users Meeting 2017
June 21, 2017

Stony Brook University

BEST COLLABORATION

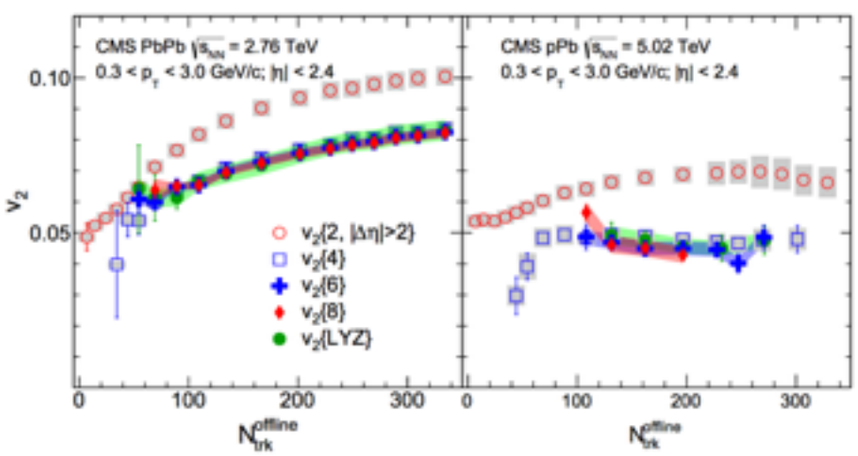
BROOKHAVEN NATIONAL LABORATORY

Introduction

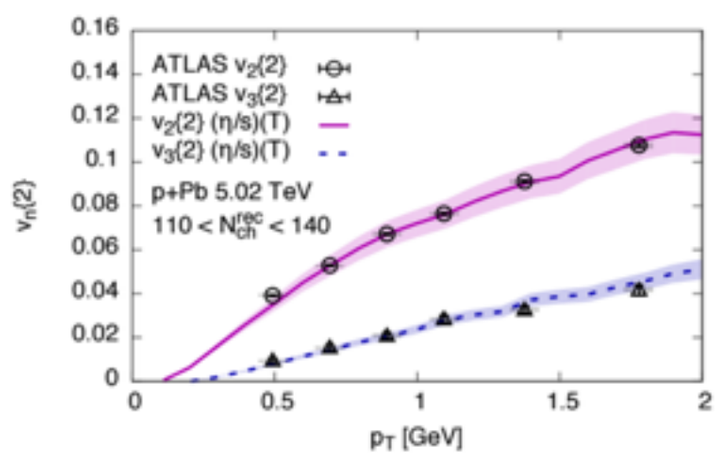
What this talk will be:

a curated look at some of the recent theory developments for small systems

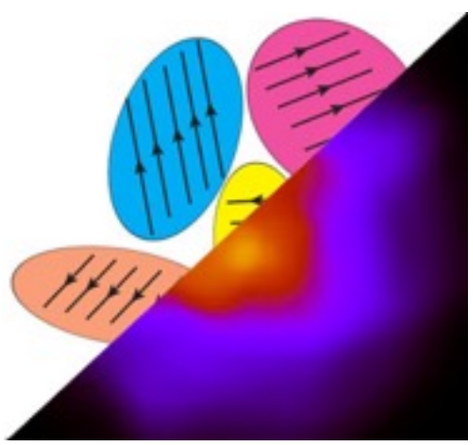
Collectivity



Sub-nucleon fluctuations



Initial/final state



What this talk will not be:

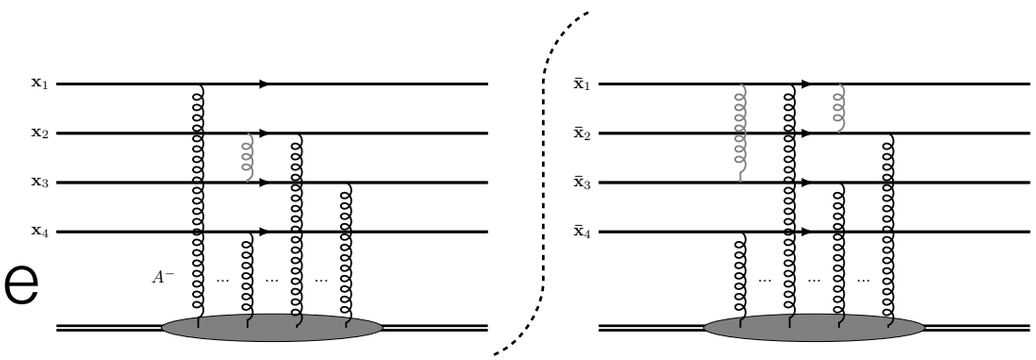
an exhaustive overview of all measurements, systems, and result

Why small systems?

- Smallest droplets of Quark Gluon Plasma?
- An insight into the Color Glass Condensate?
- A mixture of the two??
  - Want to study if this system is collective *and where collectivity comes from*

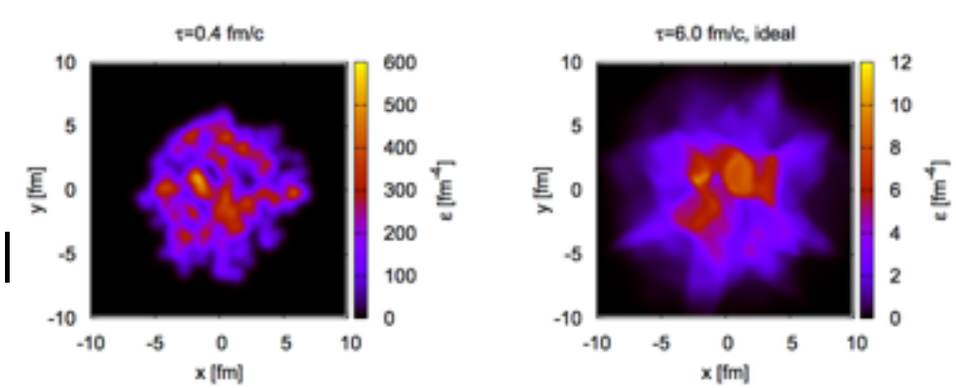
Two theory perspectives

- **Initial state picture:** Correlations come from momentum correlations of initial produced particles



Dusling, MM, Venugopalan, arXiv:1706.06260

- **Final state picture:** Momentum correlations come final state interactions (e.g. in hydro, initial spatial anisotropies becomes final state momentum space anisotropies)



Schenke, Jeon, Gale arXiv:1009.3244

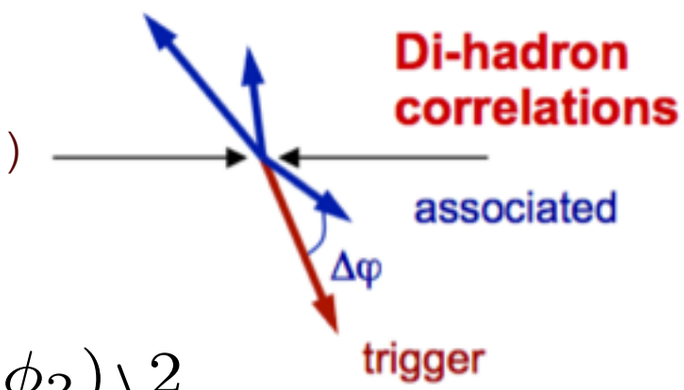
Collectivity?

- Many observables in A+A collisions possess many-body properties from a shared origin
  - v_n, mean p_T,…
  - Is this collectivity?
- “Collectivity in small systems” much more ambiguous

Collectivity?

Collectivity in small systems

Without an absolute definition, we proceed:



Define cumulants Borghini, Dinh, Ollitault PRC 64, 054901 (2001)

$$c_n\{2\} = \langle e^{ni(\phi_1-\phi_2)}\rangle$$
$$c_n\{4\} = \langle e^{ni(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle^2 - 2\langle e^{ni(\phi_1-\phi_2)}\rangle^2$$
$$\cdots$$

Corresponding Fourier harmonics

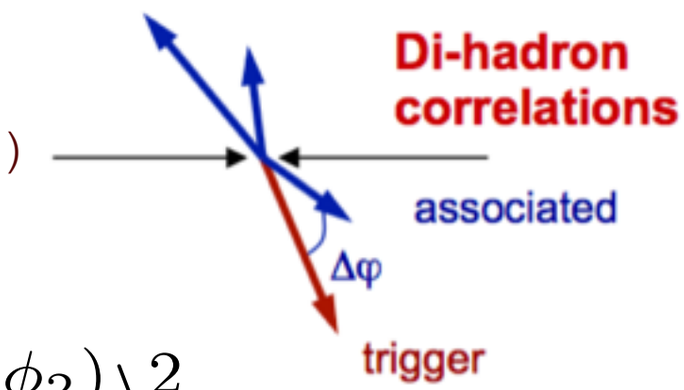
$$v_n\{2\} = (c_n\{2\})^{1/2}$$
$$v_n\{4\} = (-c_n\{4\})^{1/4}$$
$$\cdots$$

$$\epsilon\{2\} \geq \epsilon\{4\} \approx \epsilon\{6\} \approx \cdots \xrightarrow{\text{Hydro linear response}} v_n\{m\} \approx c_n\epsilon_n\{m\}$$

Yan, Ollitrault PRL 112 (2014) 082301, Bzdak, Skokov NPA 943 (2015)

Collectivity in small systems

Without an absolute definition, we proceed:



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$$\cdots$$

Corresponding Fourier harmonics

$$v_n\{2\} = (c_n\{2\})^{1/2}$$
$$v_n\{4\} = (-c_n\{4\})^{1/4}$$
$$\cdots$$

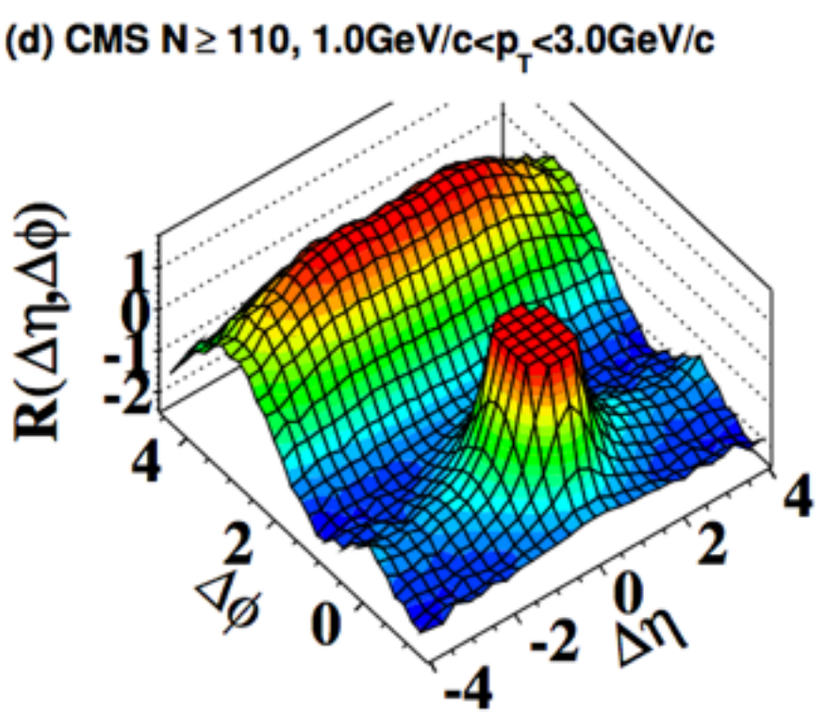
Working necessary condition for collectivity

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

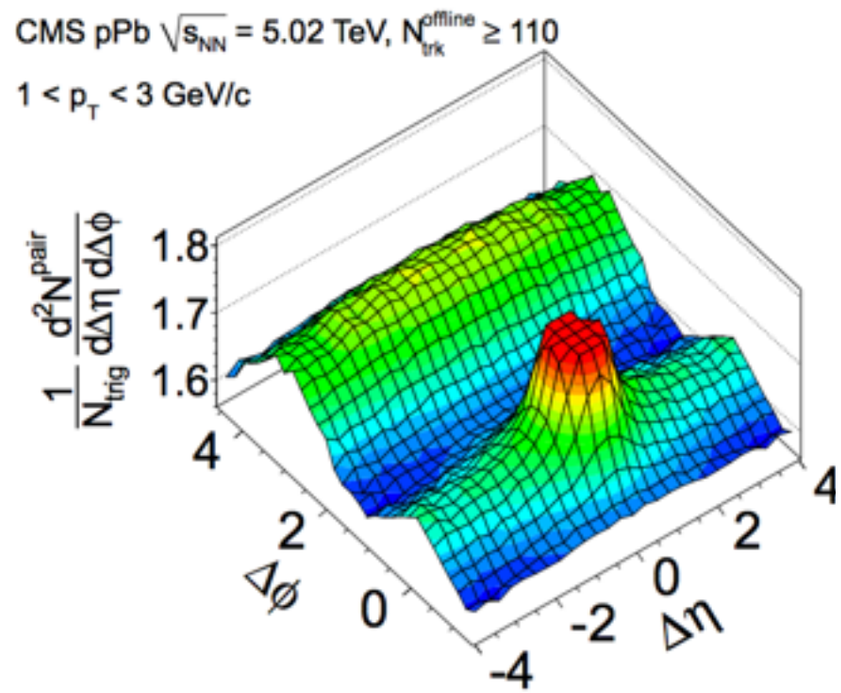
Similarity in all systems

Two particle correlations across all systems look very similar

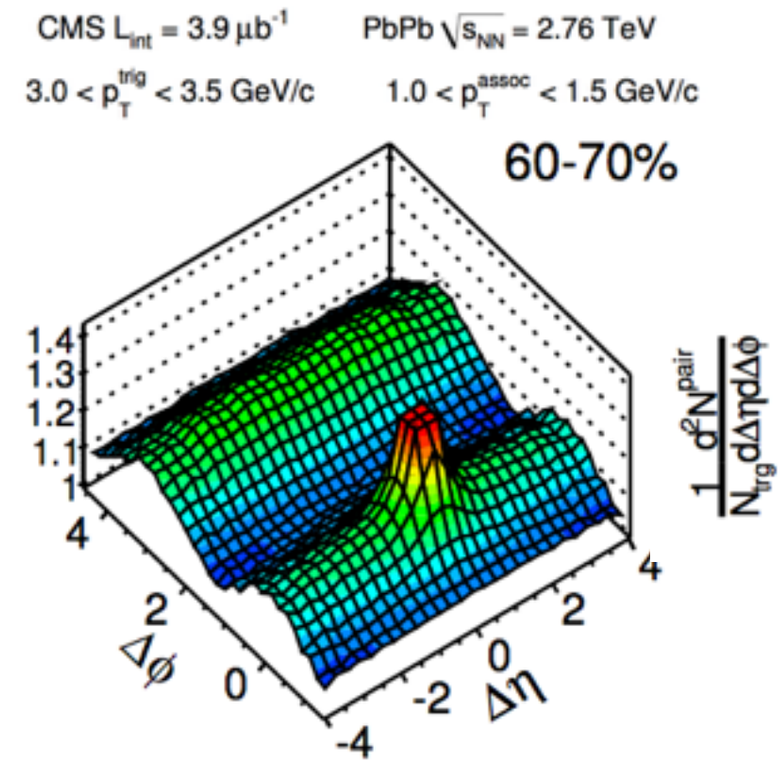
p+A ridge much larger than p+p at same multiplicity, similar to peripheral Pb+Pb collisions



CMS JHEP 1009:091 (2010)



CMS PLB 718 (2013) 795

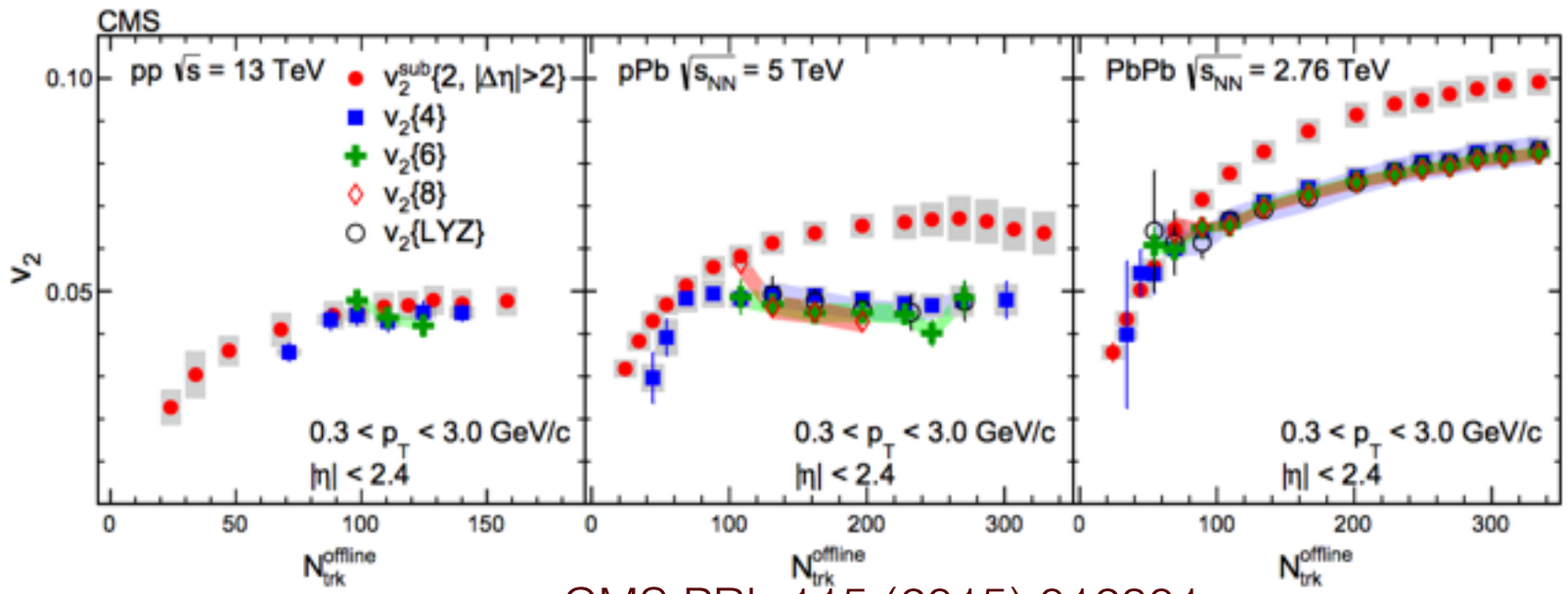


CMS EPC 72 (2012) 10052

Agreement found from ATLAS and ALICE too

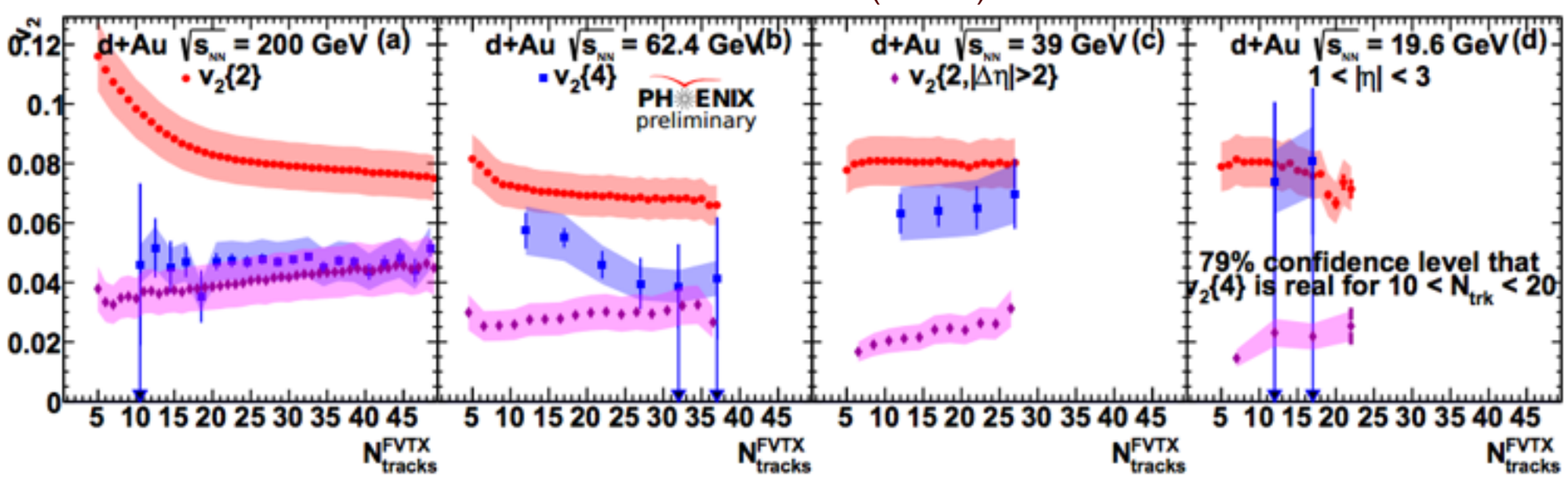
Collectivity in small systems

Looking for collectivity via $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



LHC

CMS PRL 115 (2015) 012301



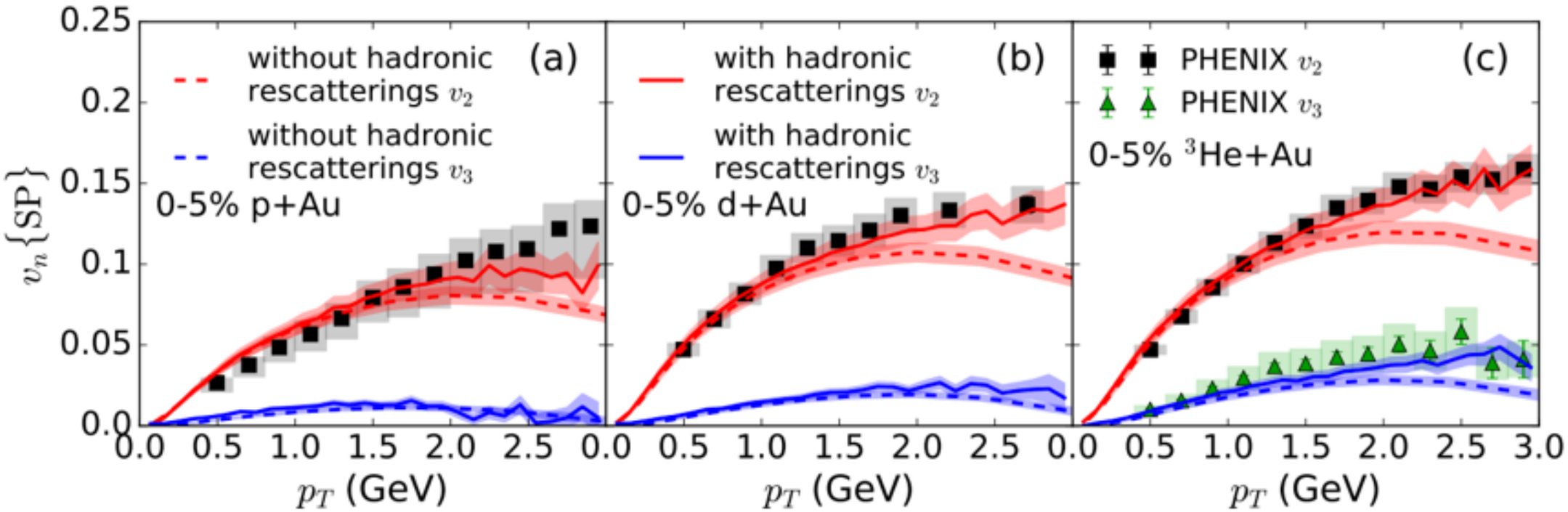
Talk by R. Belmont

RHIC

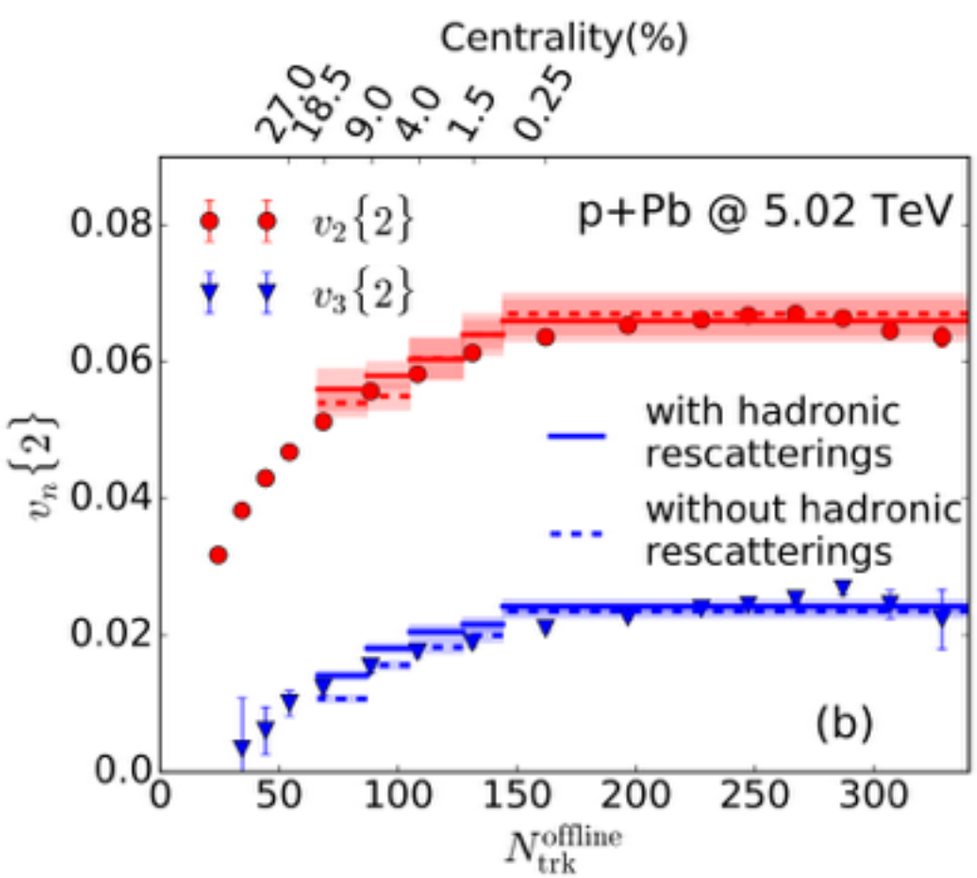
PHENIX (R. Belmont) arXiv:1704.04570

Collectivity is everywhere*

Hydro in small systems



Shen et al Phys.Rev. C95 (2017) no.1, 014906

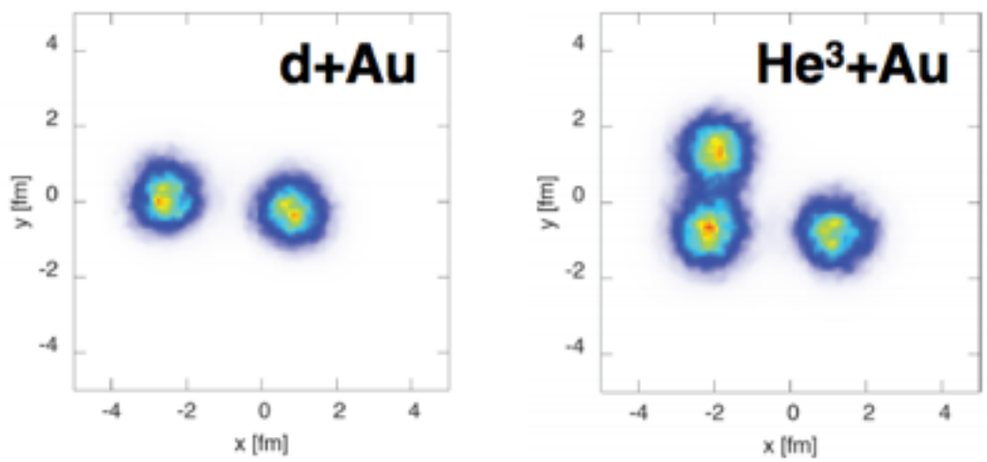


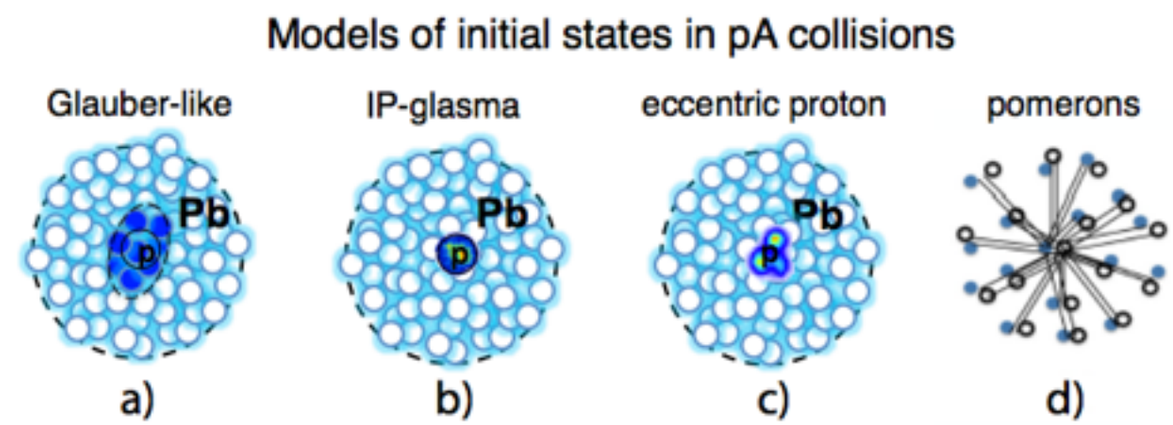
MC-Glauber+Hydro(MUSIC) +Hadron cascade (UrQMD) seems to work well for some observables, systems, energies,…

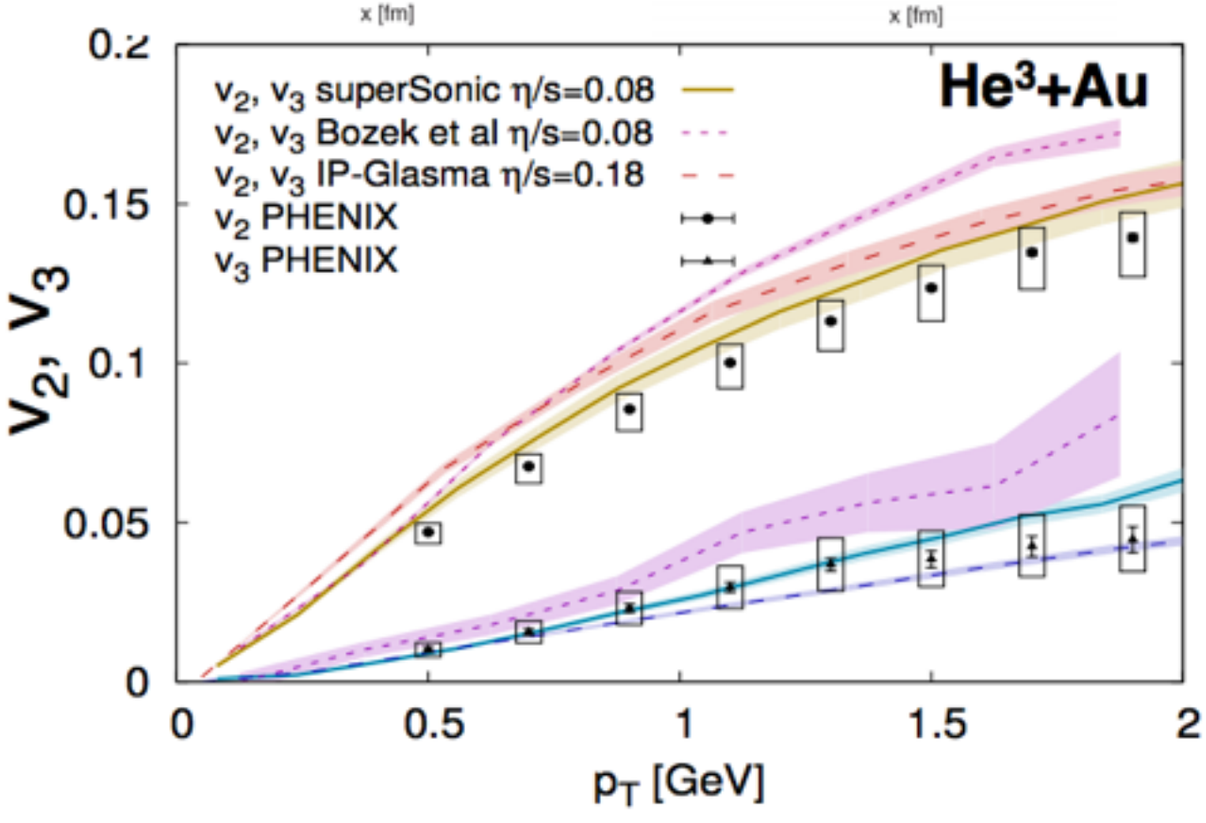
See also talk by R. Weller

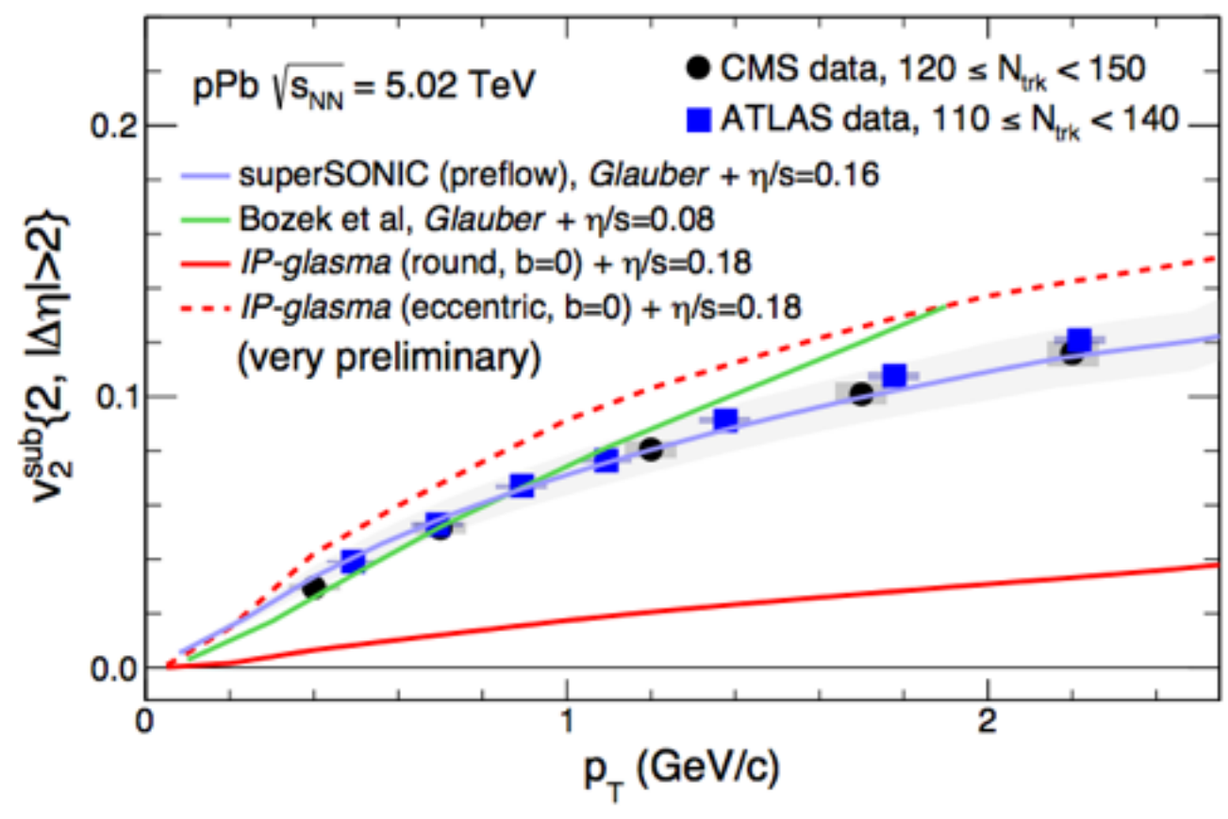
Hydro in small systems

Compare various hydro models and initial states





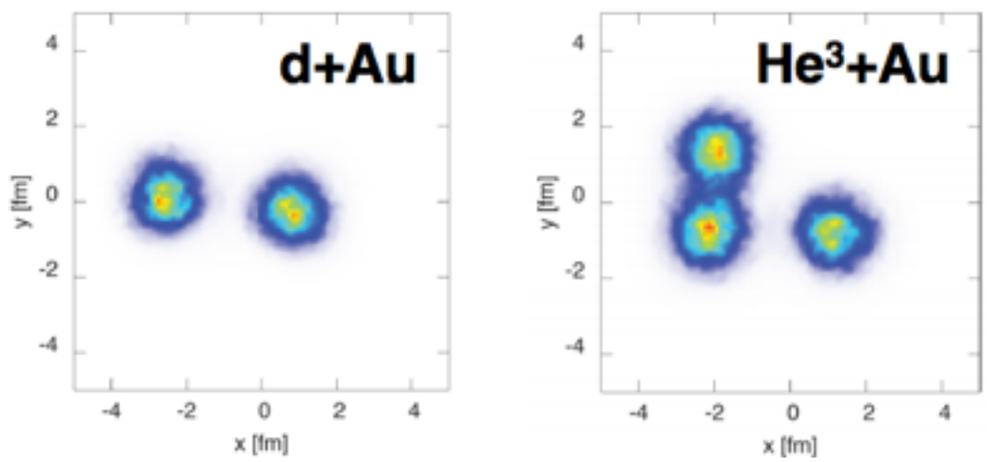


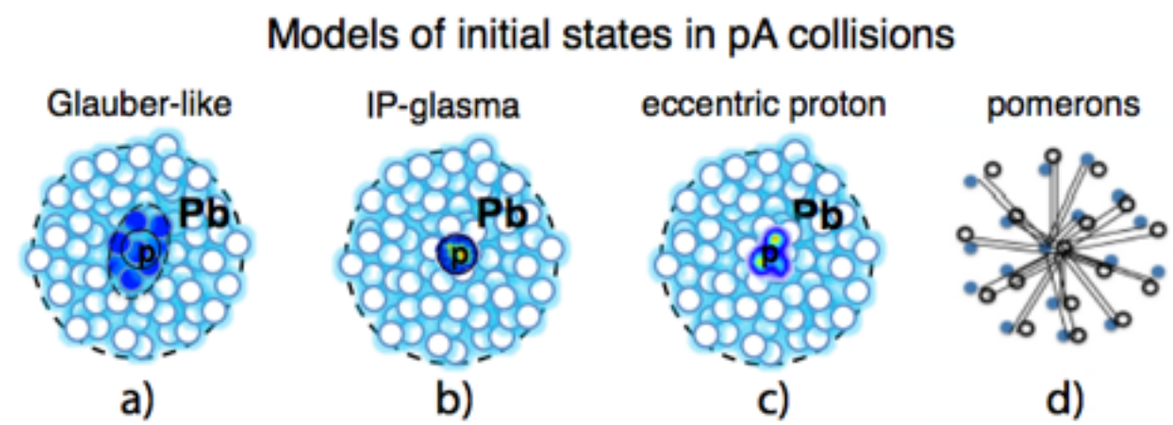


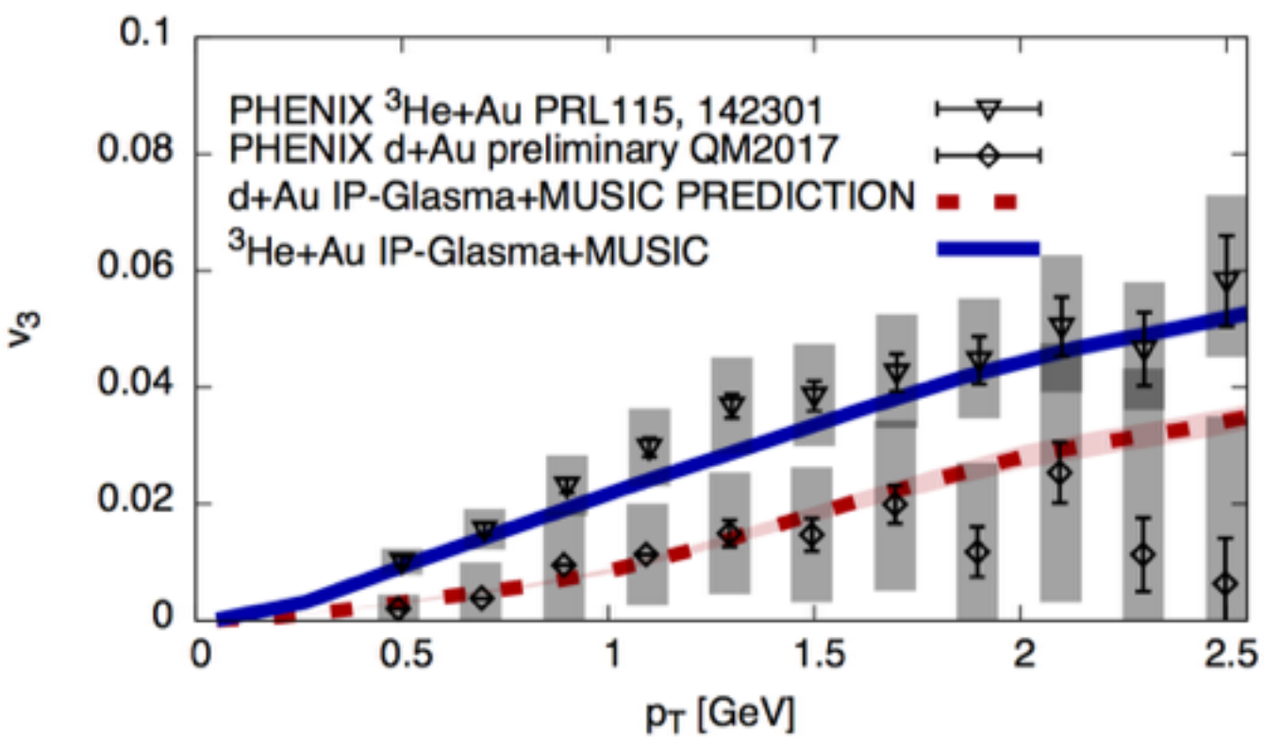
Dusling, Li, Schenke, IJMP E25 (2016) no.01, 1630002

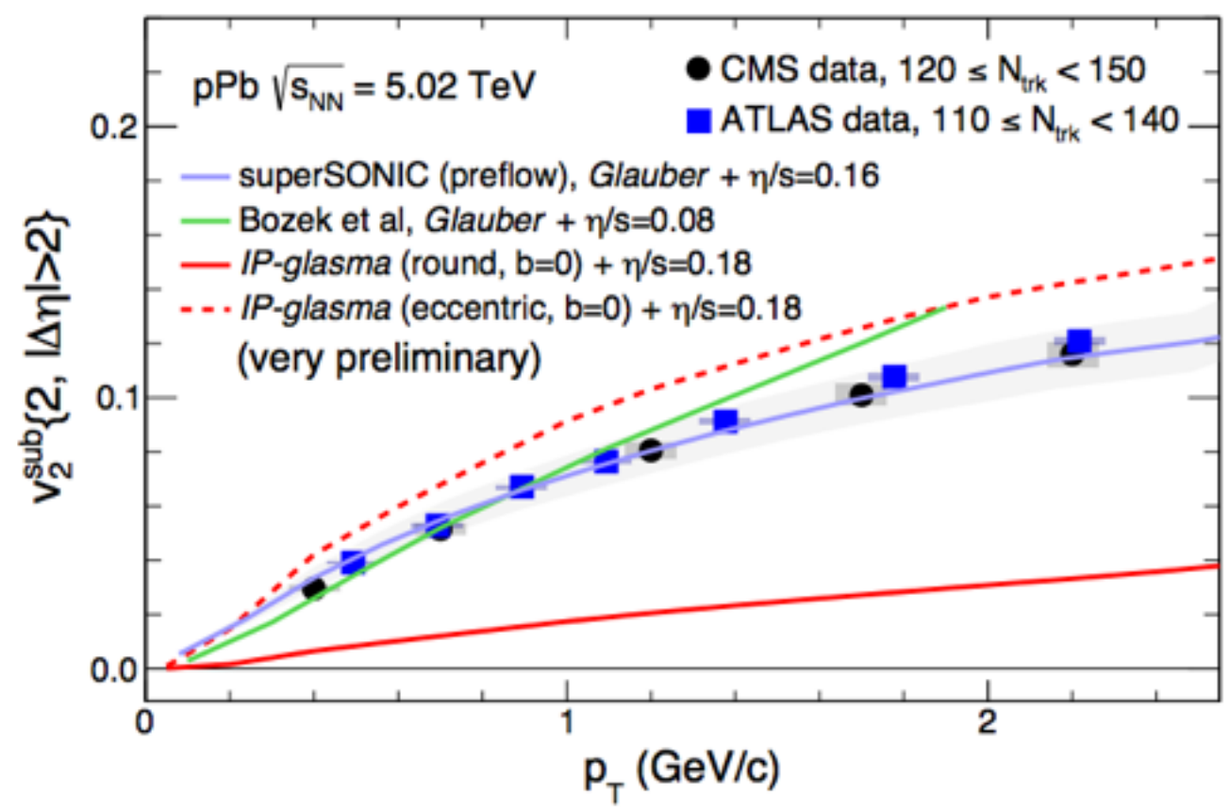
Hydro in small systems

Compare various hydro models and initial states





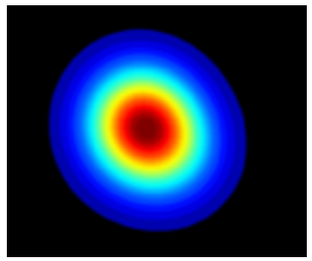




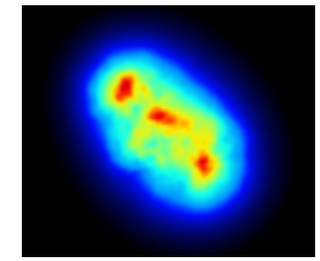
Schenke, QM2017 Proceedings

Hydro in small systems

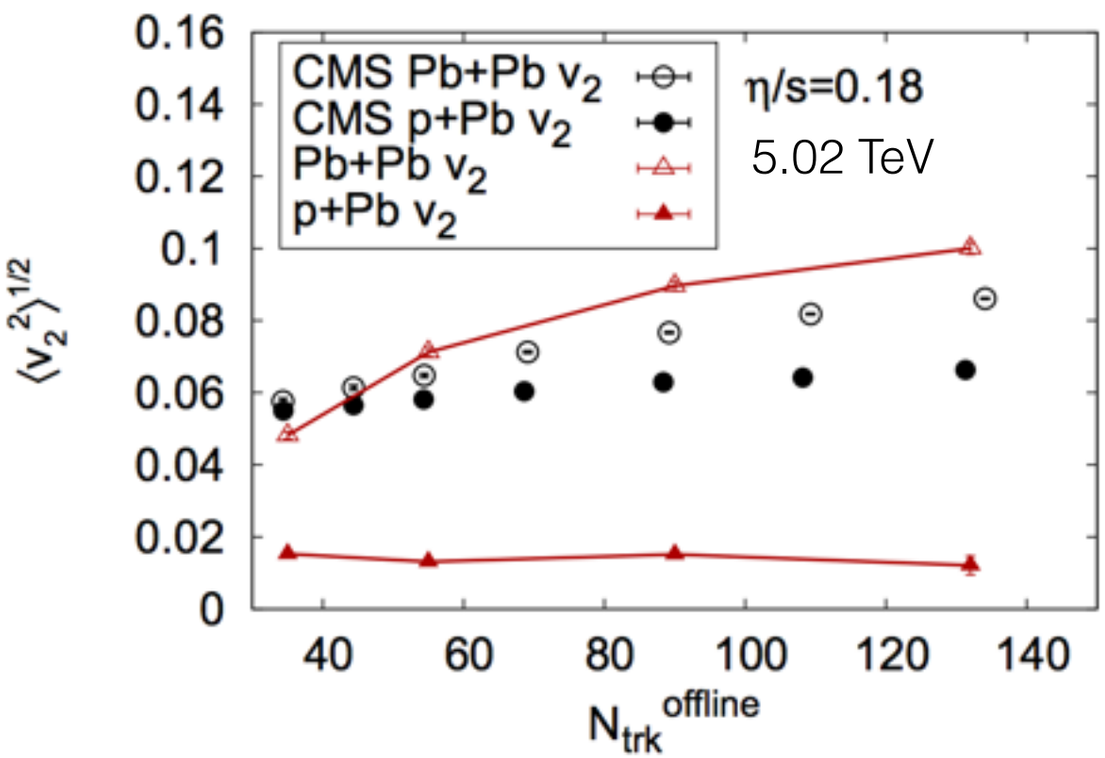
Round proton



Fluctuating proton

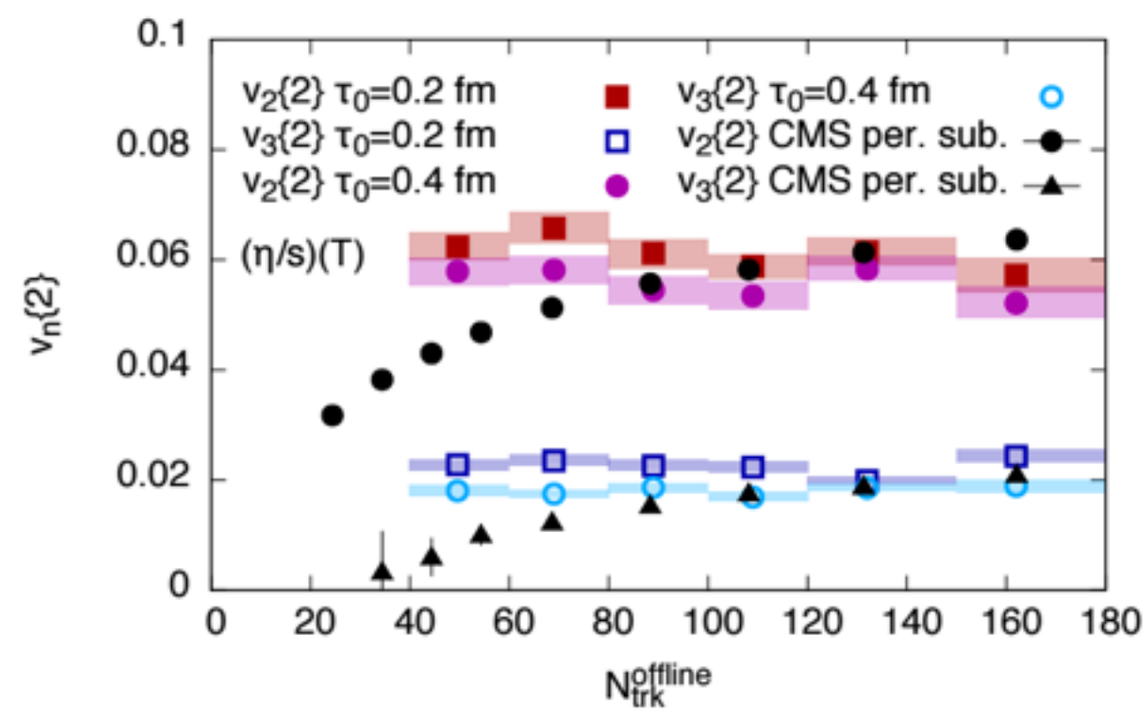


Constrain proton shape fluctuations using exclusive J/Ψ production (HERA)



Schenke, Venugopalan PRL 113 (2014) 102301

IP-Glasma+Hydro



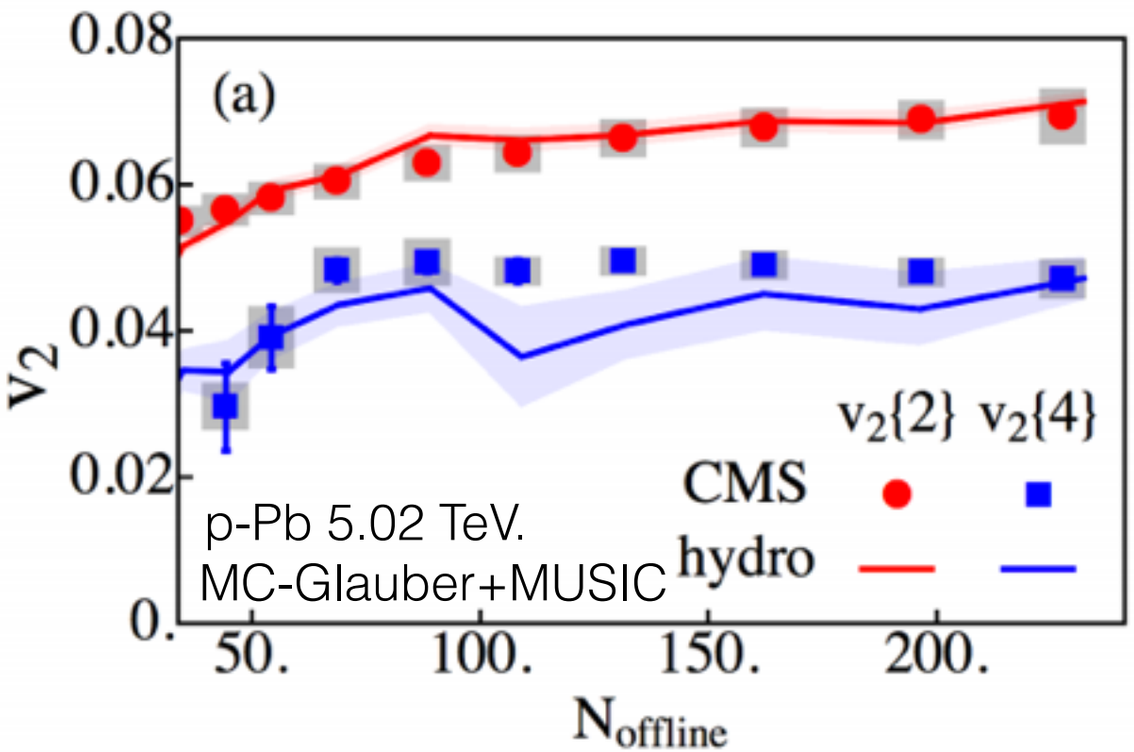
Mäntysaari, Schenke, Shen, Tribedy arXiv:1705.03177

IP-Glasma+Fluct. proton +Hydro+UrQMD

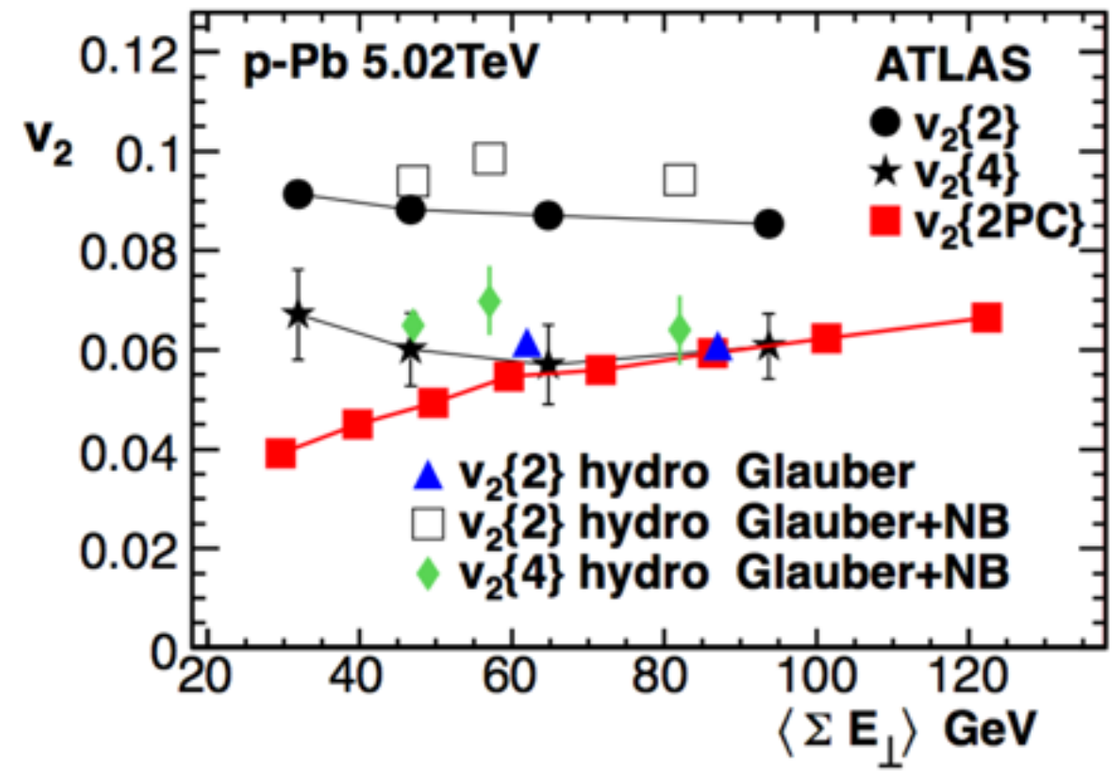
Talk by Heikki Mäntysaari 2:30 pm

Collectivity from hydro

Two and four particle correlations in p+A in hydro



Kozlov, Denicol, Luzum, Jeon, Gale
NPA 931 (2014) 1045-1050



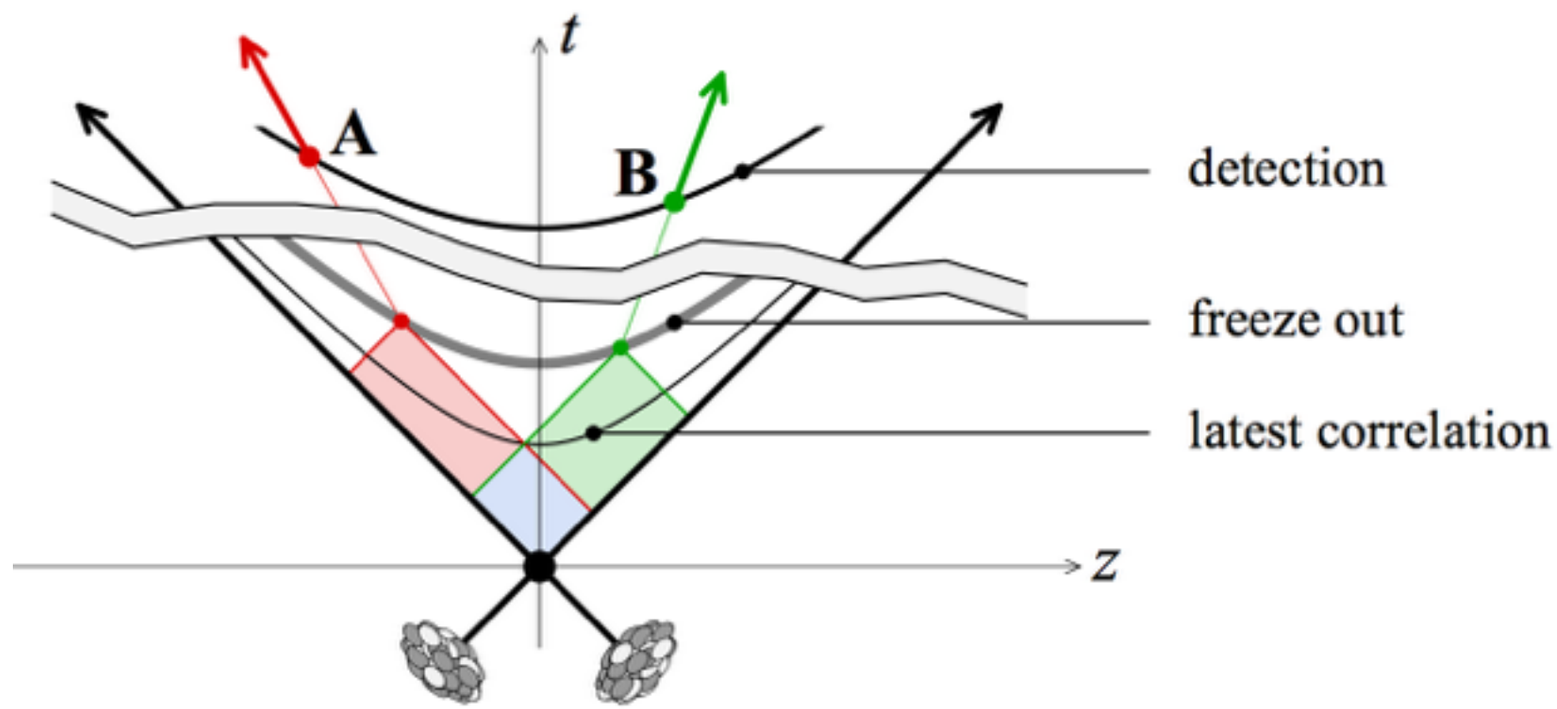
Bozek, Broniowski
Phys. Rev. C 88, 014903 (2013)

From eccentricities, expect similar for higher particles

Many positive results from hydro; issues linger about applicability, size of gradients,…

Can there be an alternative explanation to the observed phenomena?

Long range rapidity correlations as a chronometer



Dumitru, Gelis, McLerran, Venugopalan
NPA 810 (2008) 91-108

$$\tau_0 \leq \tau_{\mathrm{f.o.}} \exp\left(-\frac{1}{2}|y_a - y_b|\right)$$

Long range rapidity correlations sensitive to very early time dynamics (0.1 fm/c) in collision

Initial state for small systems

Correlations should be developed at very early times

The initial nuclear wave function in high energy collisions dominated by gluons, can have correlations

Formulated in terms of effective theory of high energy QCD - Color Glass Condensate

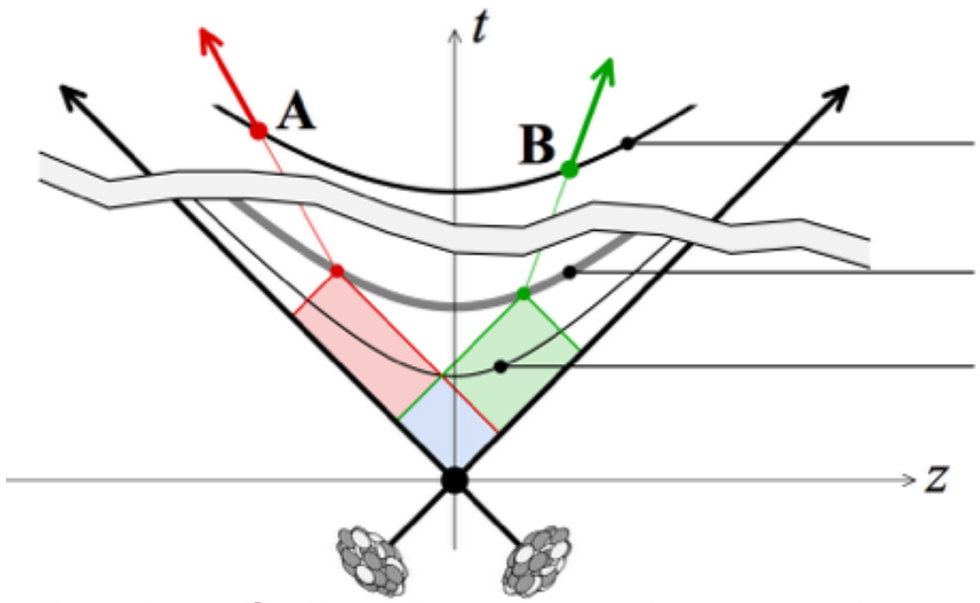
Iancu and Venugopalan,Quark gluon plasma 249-3363; Iancu, Jalilian-Marian Venugopalan, Ann. Rev. Nucl. Part. Sci. 60, 463 (2010)

Solve classical Yang Mills eqns with color current sources

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

$$J_a^\mu(x) = \delta^{+\mu}\delta(x^-)\rho_a(\mathbf{x})$$

Various levels of approximation



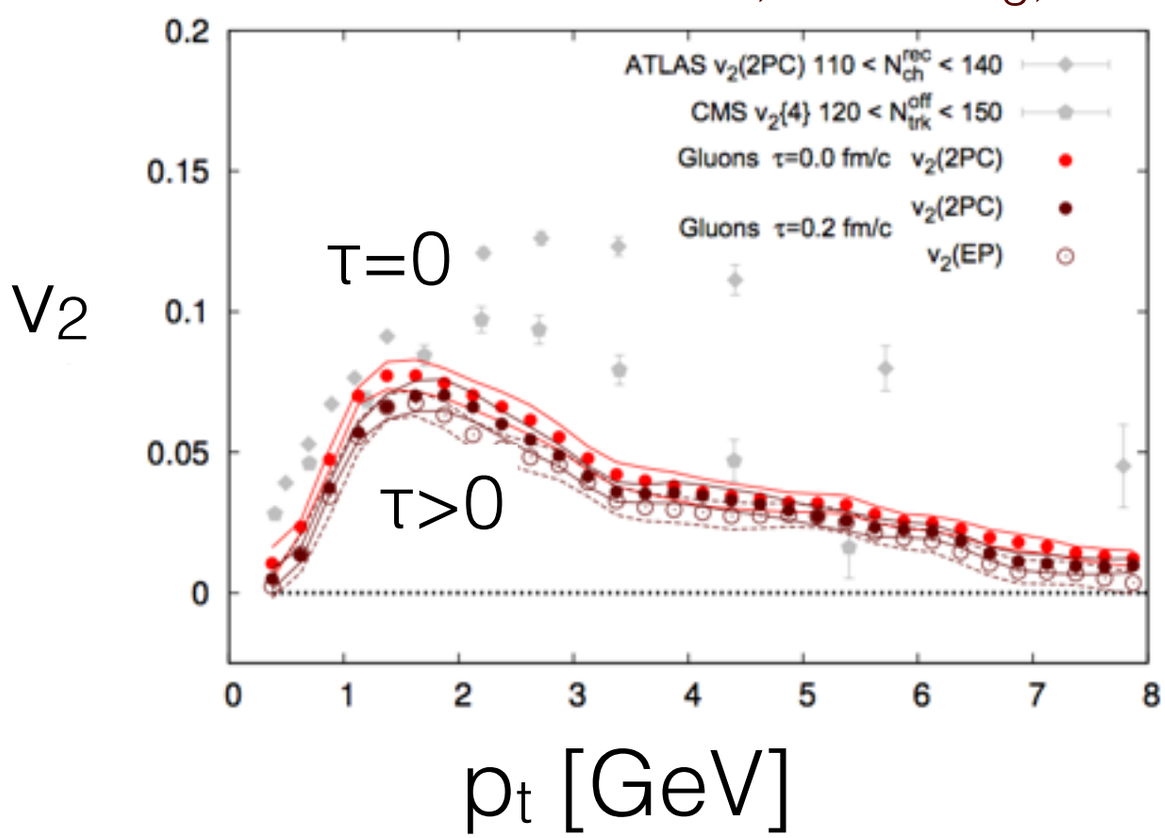
Dumitru, Gelis, McLerran, Venugopalan NPA 810 (2008) 91-108

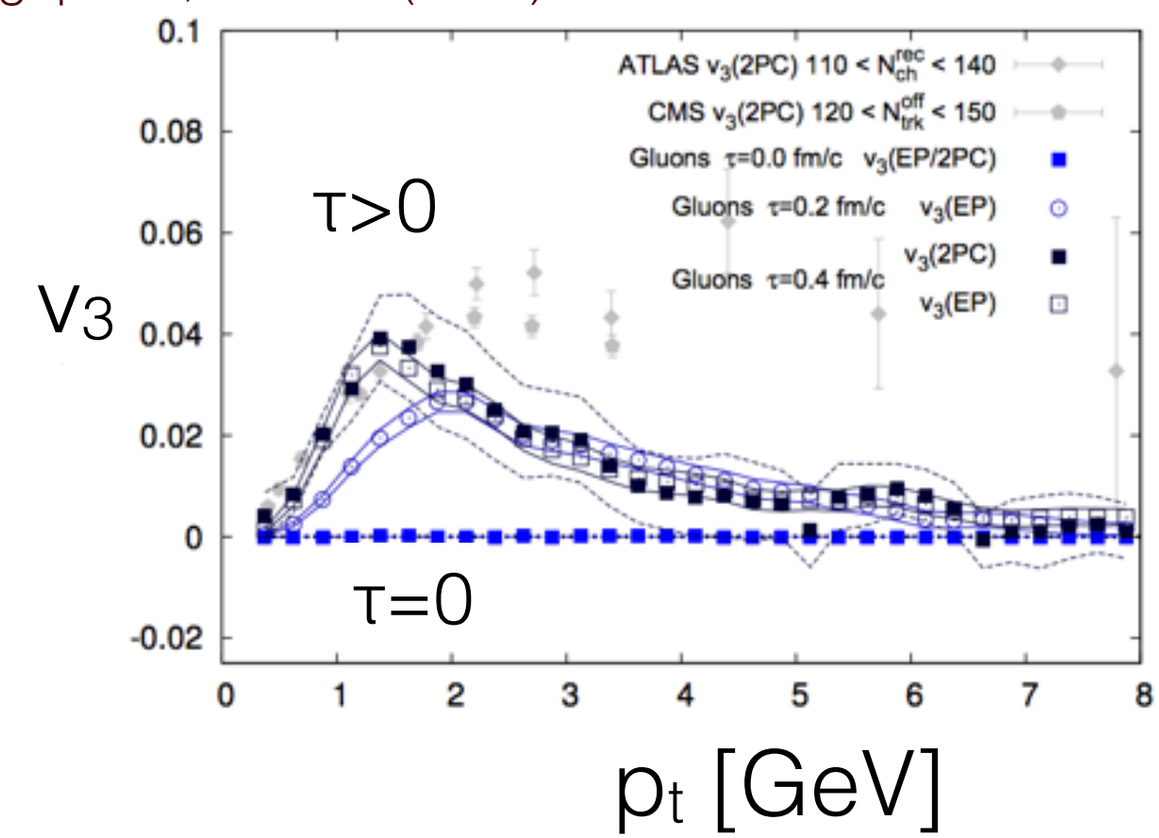
Initial state for small systems

Simulate numerically with classical Yang-Mills without approximation

Two particle v_2,v_3 from gluons from initial momentum correlations

Schenke, Schlichting, Venugopalan, PLB747 (2015) 76-82





Very different origin than hydro; not related to initial geometry

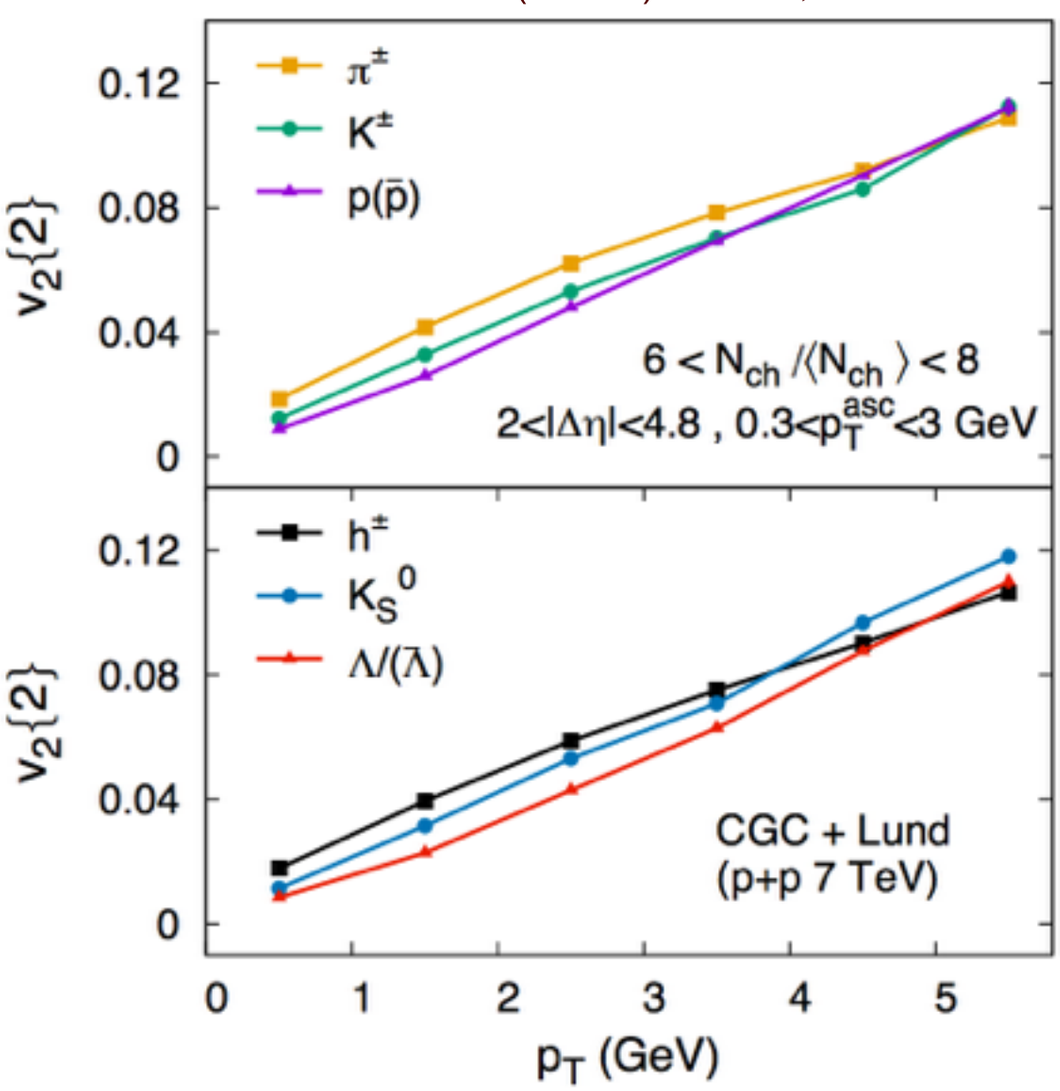
Talk by V. Skokov on odd azimuthal harmonics

Skokov, McLerran arXiv:1611.09870, Kovner, Lublinsky, Skokov, arXiv:1612.07790

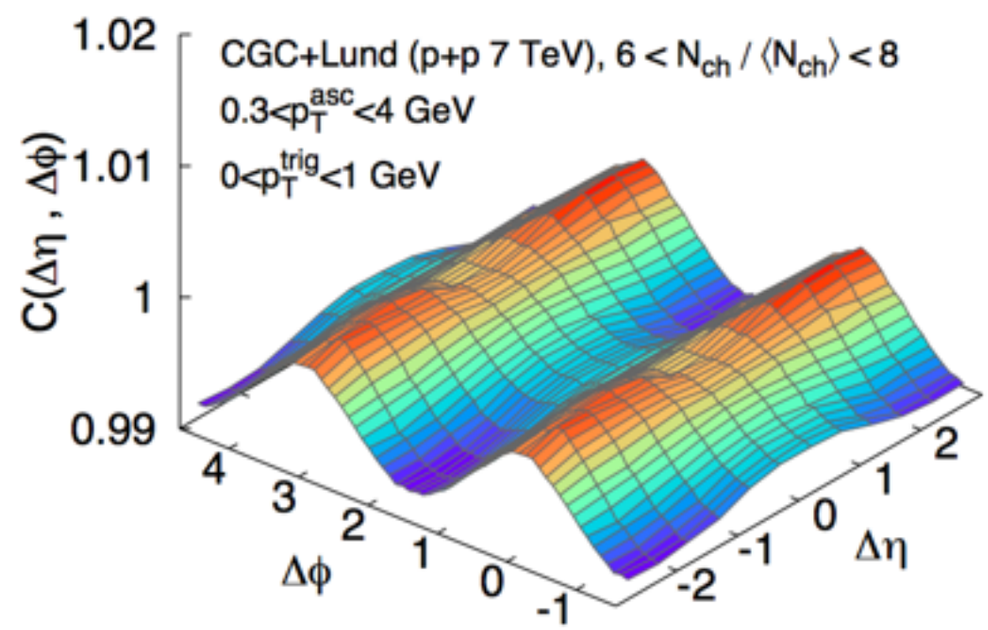
Classical Yang Mills + Hadrons

Numerically solve classical Yang-Mills + Lund string fragmentation (Pythia) to get hadrons

Schenke, Schlichting, Tribedy, Venugopalan, PRL 117 (2016) no.16, 162301



Reproduce mass ordering, ridge in p+p



No four particle yet; numerically very intense

What about multi-particle correlations?

Multiparticle correlations from the initial state

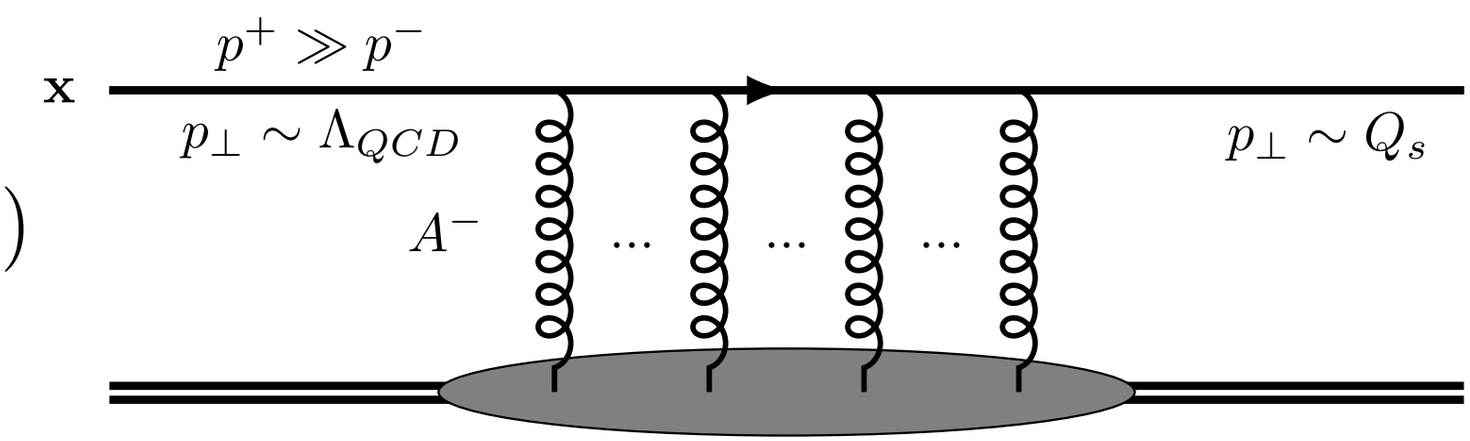
Non-linear Gaussian model: Consider parton based model of eikonal quarks scattering off dense nuclear target with color domains of size $\sim 1/Q_s$

Lappi, PLB 744, 315 (2015); Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061; Dusling, MM, Venugopalan arXiv:1705.00745, arXiv:1706.06260

Multiple scattering of gluons from target on quarks through Wilson line $U(\mathbf{x}) = \mathcal{P}\exp\Big(- ig \int dz^+ A^{a-}(\mathbf{x}, z^+)\, t^a \Big)$

Dipole operator:

$$D(\mathbf{x}, \bar{\mathbf{x}}) = \frac{1}{N_c} \mathrm{Tr}\left(U(\mathbf{x}) U(\bar{\mathbf{x}})^\dagger \right)$$



$$\frac{dN_q}{d^2\mathbf{p}} \simeq \int_{\mathbf{b},\mathbf{r}} e^{-|\mathbf{b}|^2/B_p} e^{-|\mathbf{r}|^2/4B_p}\, e^{i\mathbf{p}\cdot\mathbf{r}} \left\langle D\left(\mathbf{b} + \frac{\mathbf{r}}{2}, \mathbf{b} - \frac{\mathbf{r}}{2}\right) \right\rangle$$

Bjorken, Kogut, Soper, PRD 3 1382 (1971), Dumitru, Jalilian-Marian, PRL 89:022301 (2002)

Multiparticle correlations from the initial state

Generalizing for multiple particle correlations

Lappi, PLB 744, 315 (2015); Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061;
Dusling, MM, Venugopalan arXiv:1705.00745, arXiv:1706.06260

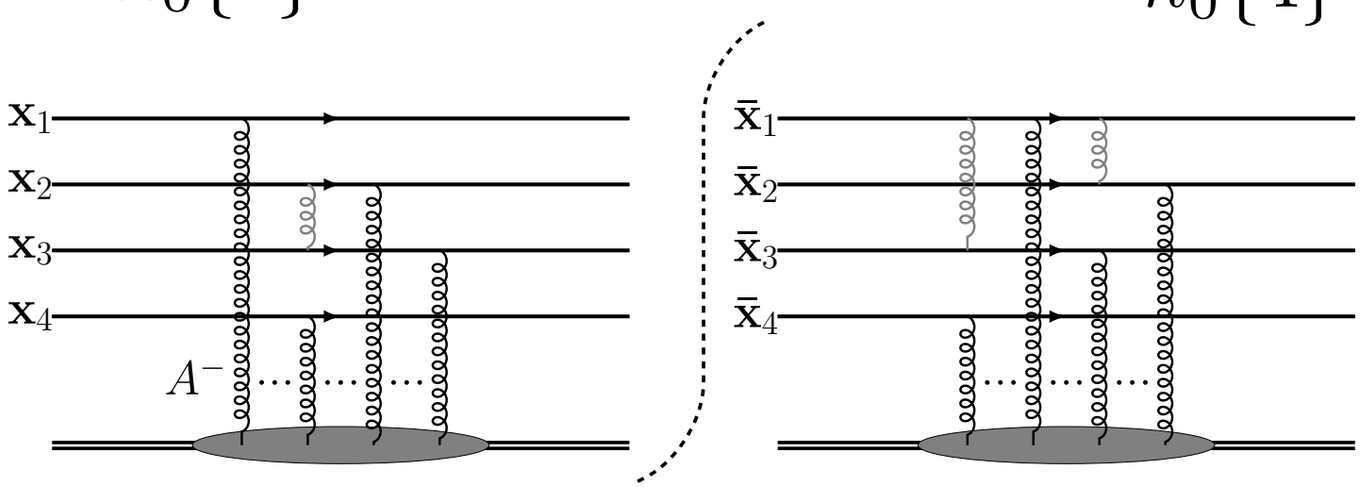
$$\frac{d^2N}{d^2\mathbf{p}_2 d^2\mathbf{p}_2} = \left\langle \frac{dN}{d\mathbf{p}_1}\frac{dN}{d\mathbf{p}_2} \right\rangle \simeq \int \langle DD \rangle \quad , \quad \frac{d^4N}{d^2\mathbf{p}_1 \cdots d^2\mathbf{p}_4} \simeq \int \langle DDDD \rangle$$

Expectation values from MV model, Gaussian color correlations

McLerran, Venugopalan, PRD 49, 3352, 2233 (1994)

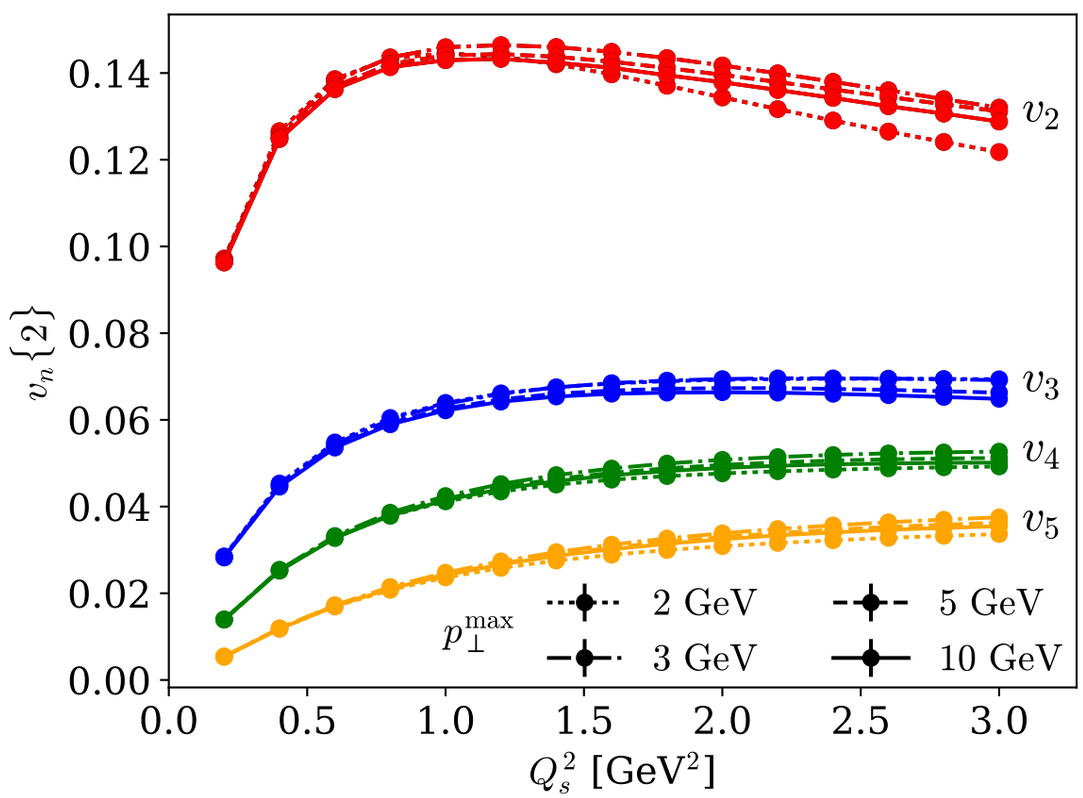
$$\kappa_n\{m\} = \int_{\mathbf{p}_1 \cdots \mathbf{p}_m} \cos\left(n(\phi_1^p + .. - \phi_m^p)\right) \frac{d^m N}{d^2\mathbf{p}_1 \cdots d^2\mathbf{p}_m}$$

$$c_2\{2\} = \frac{\kappa_2\{2\}}{\kappa_0\{2\}} \qquad c_2\{4\} = \frac{\kappa_2\{4\}}{\kappa_0\{4\}} - 2\left(\frac{\kappa_2\{2\}}{\kappa_0\{2\}}\right)^2$$

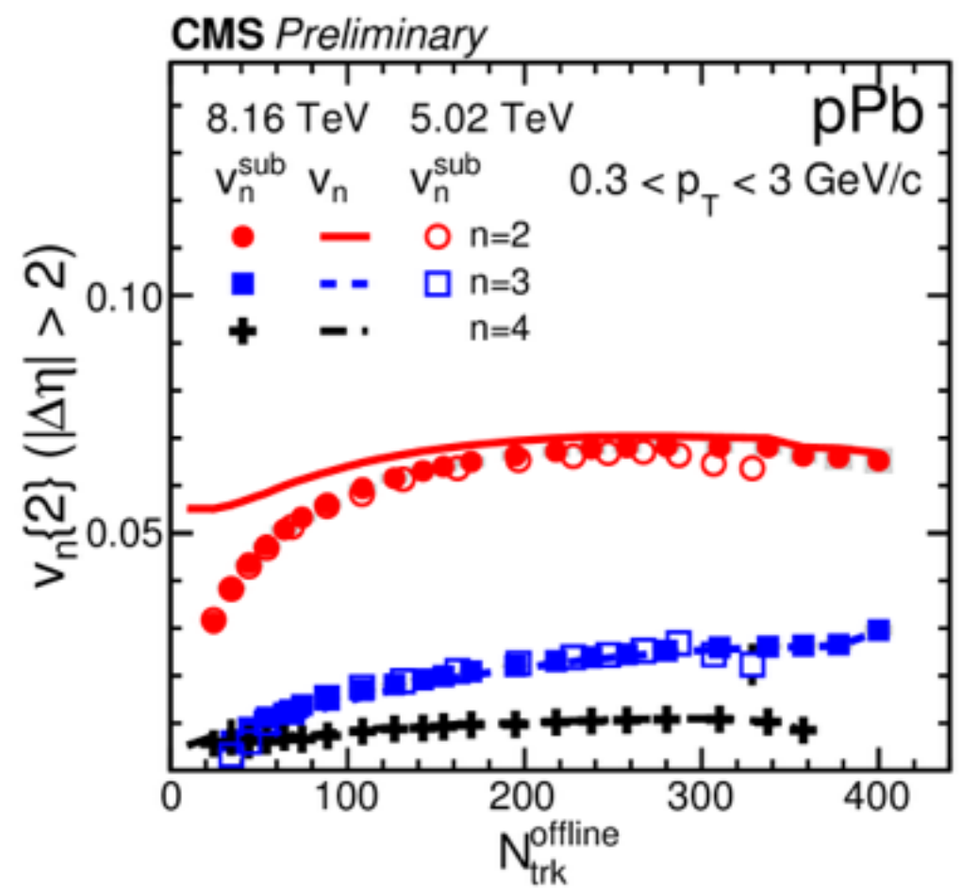


Multiparticle correlations from the initial state

Ordering in two particle Fourier harmonics similar to data



Dusling, MM, Venugopalan arXiv:1705.00745



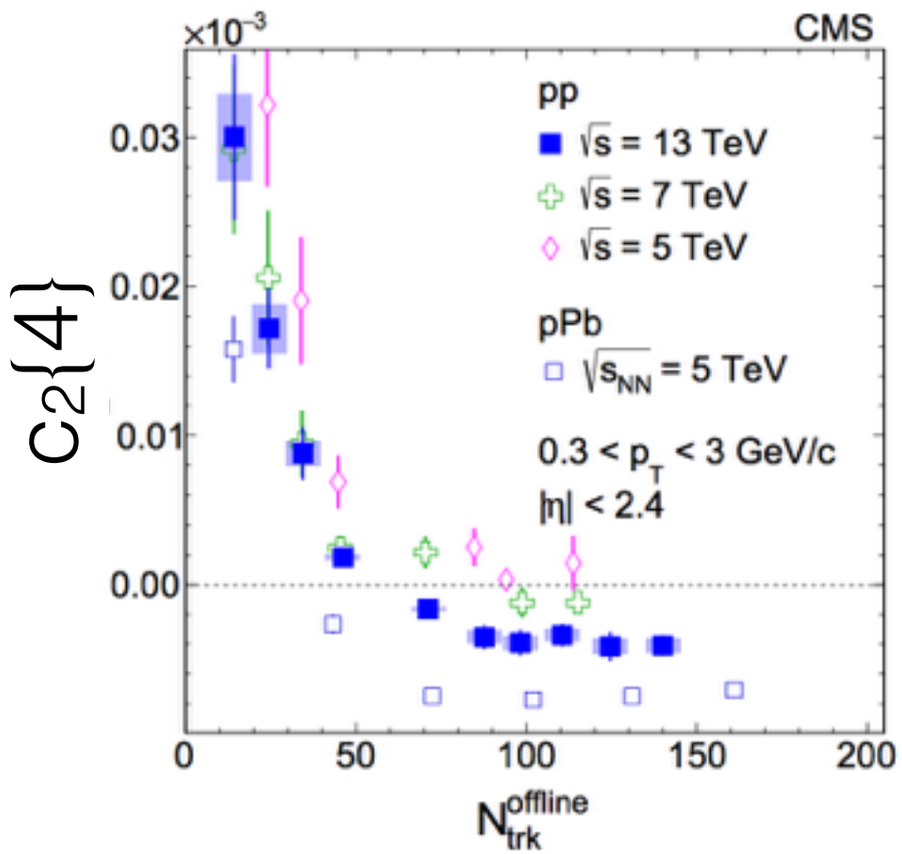
CMS-PAS-HIN-16-022

Warning: Q_s not direct map to energy or multiplicity

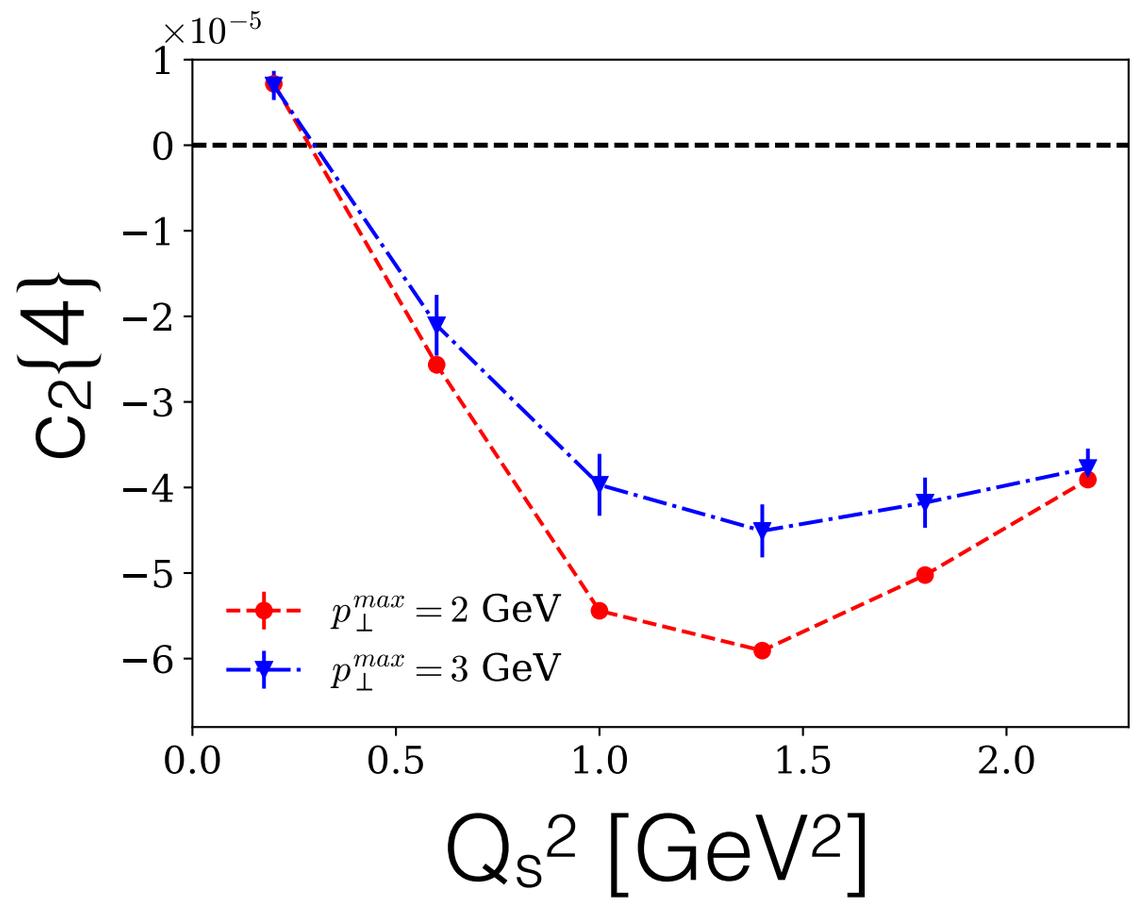
Final state is quarks, not hadrons

Collectivity from initial state

Becomes negative $c_2\{4\}$ for increasing Q_s



CMS PLB 765 (2017) 193

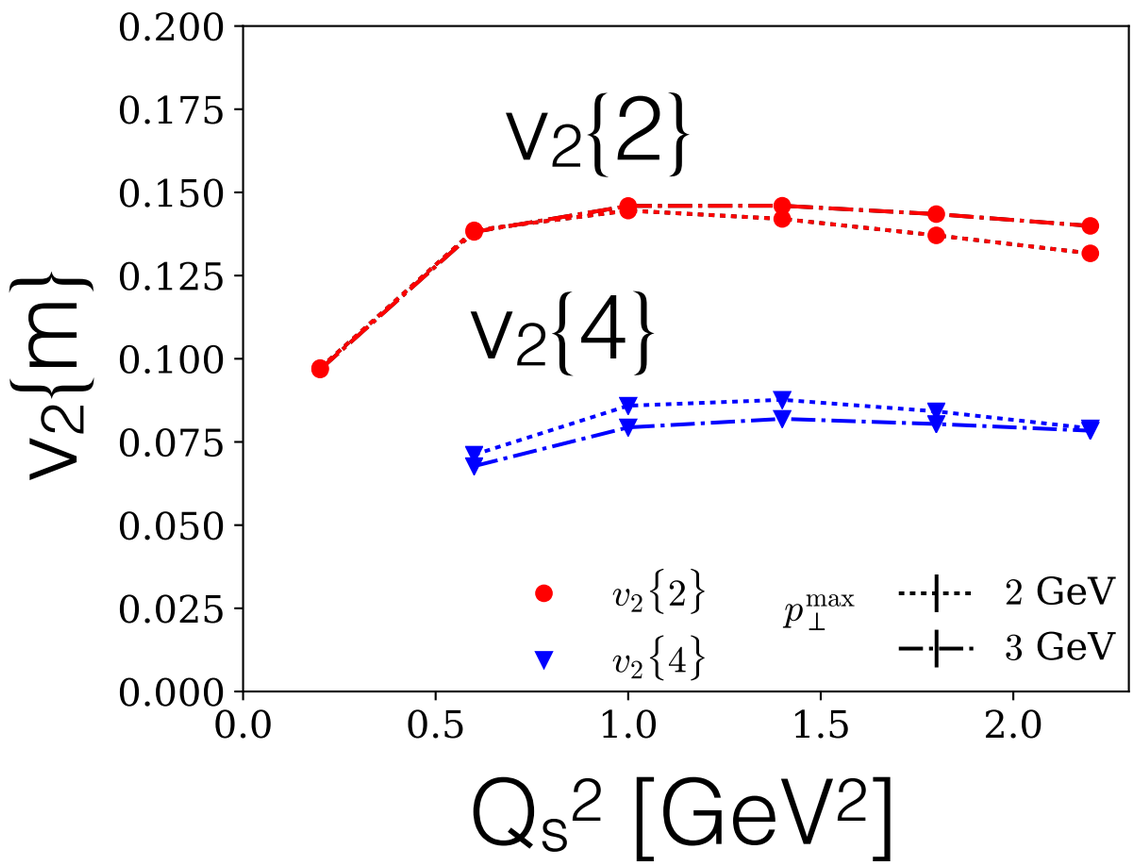


Dusling, MM, Venugopalan, arXiv:1706.06260

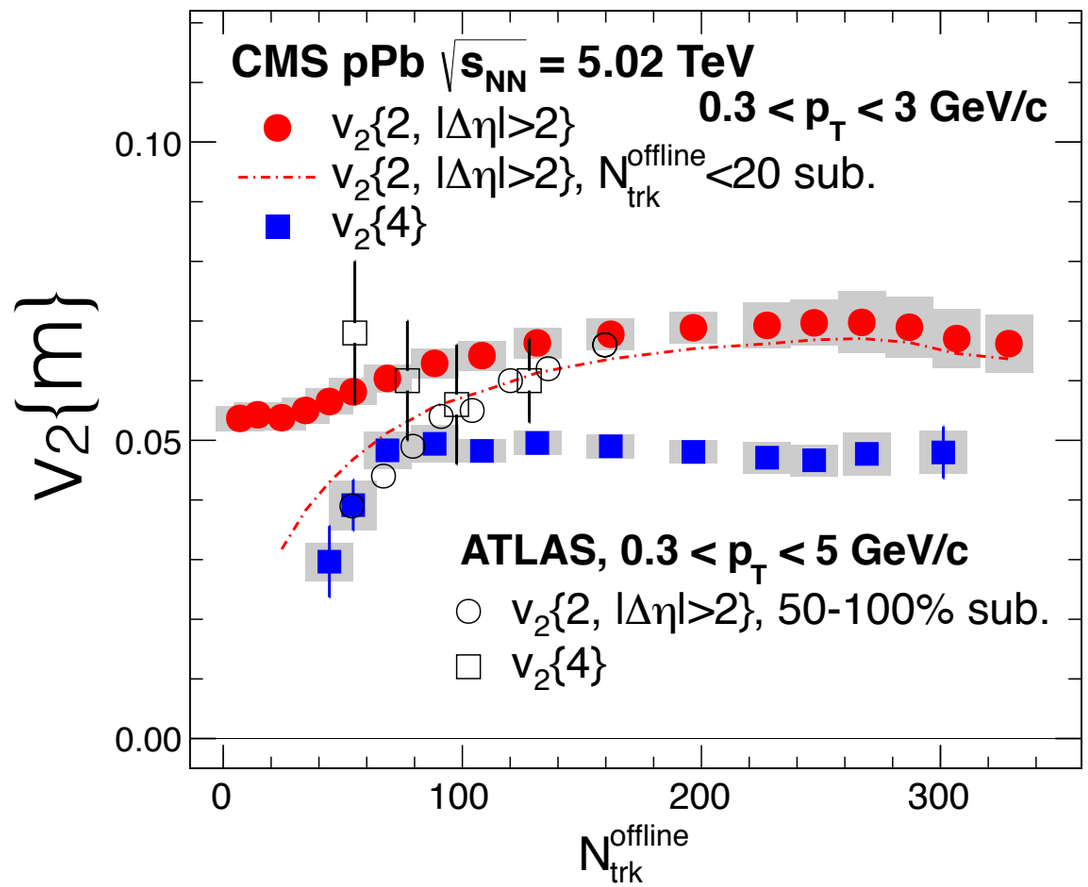
Collectivity from initial state

Real $v_2\{4\}$, fairly independent of 'energy'

Dusling, MM, Venugopalan, arXiv:1705.00745



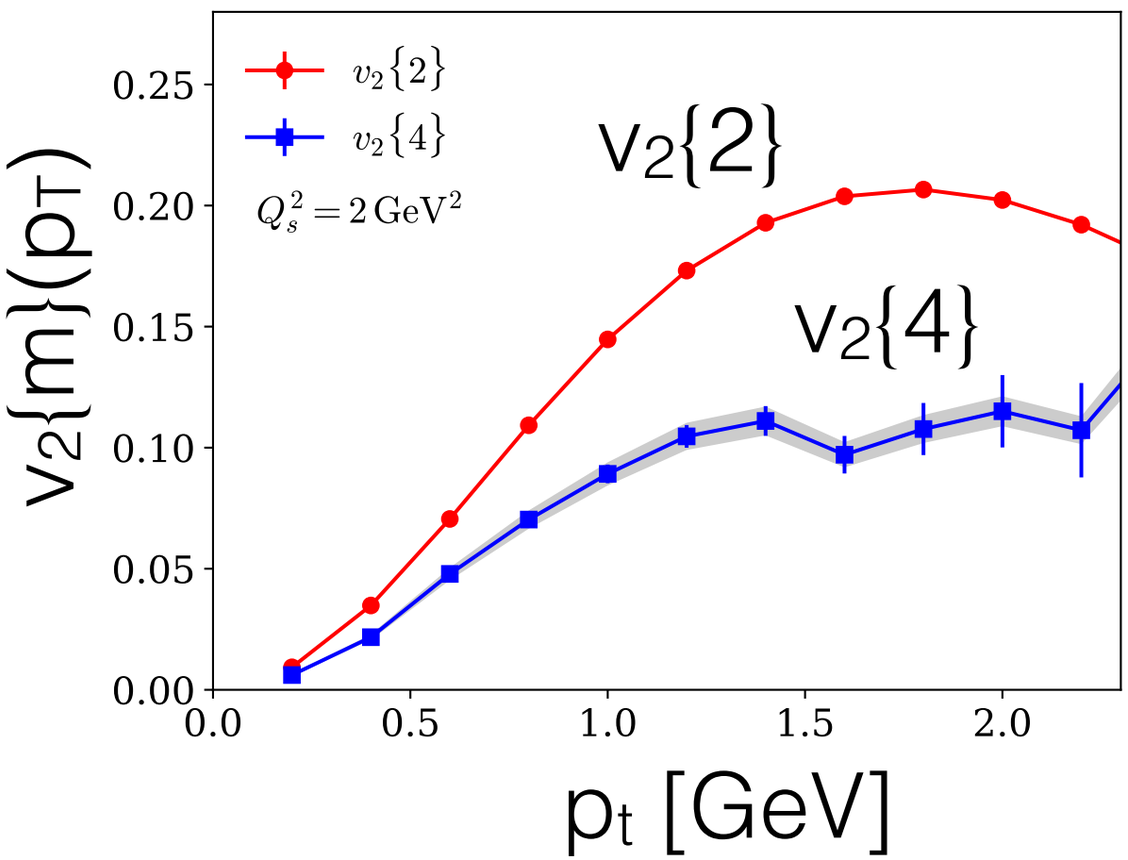
Dusling, MM, Venugopalan, arXiv:1705.00745



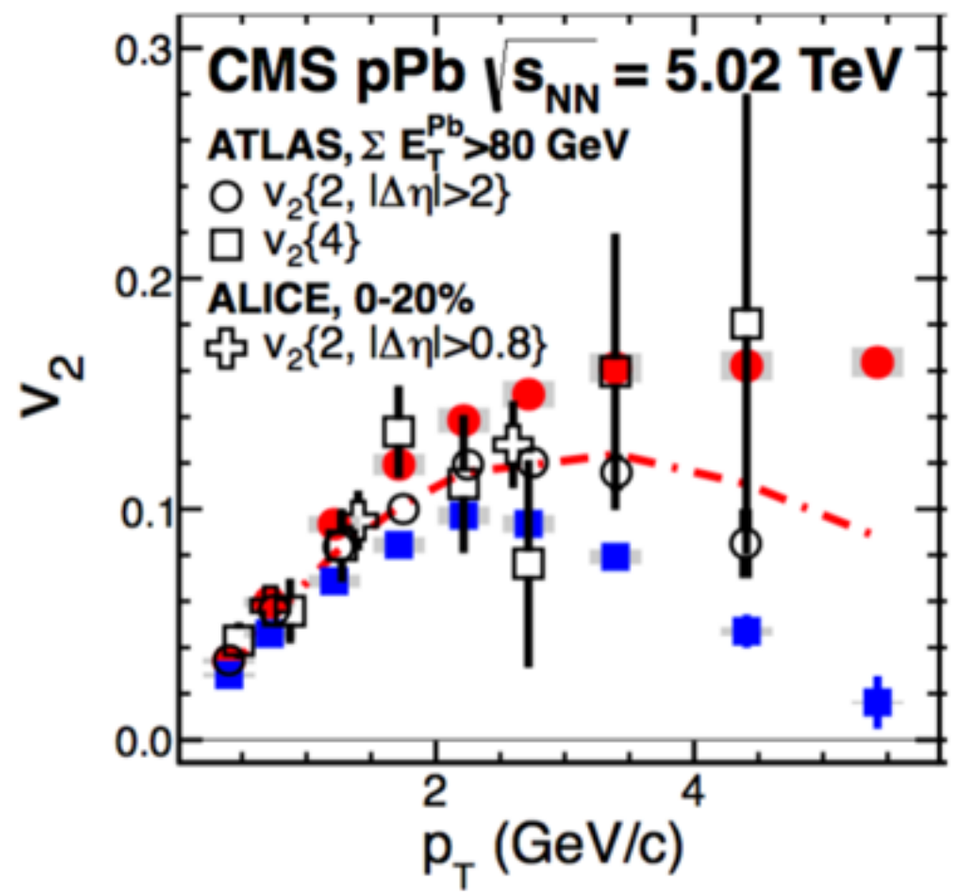
PLB 724 (2013) 213

Collectivity from initial state

Study p_T dependence by integrating over momentum of m-1 particles



Dusling, MM, Venugopalan, arXiv:1706.06260



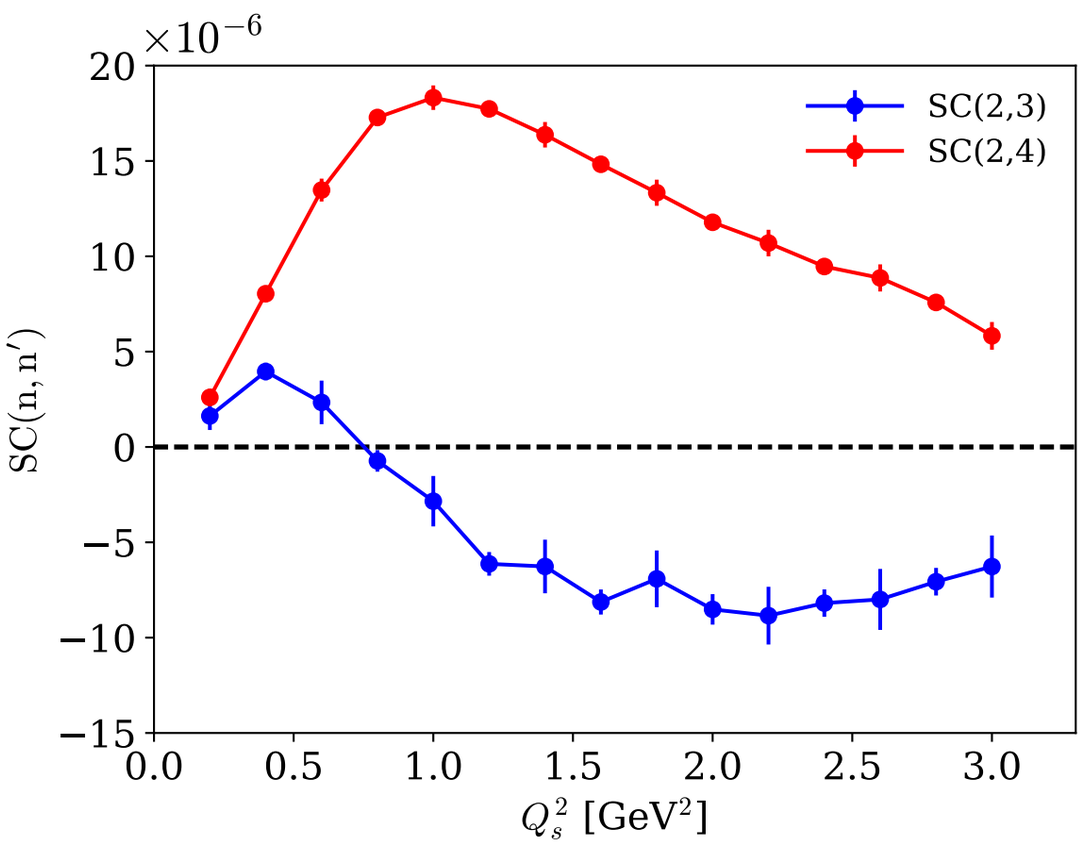
CMS PLB 724 (2013) 213

Collectivity from initial state

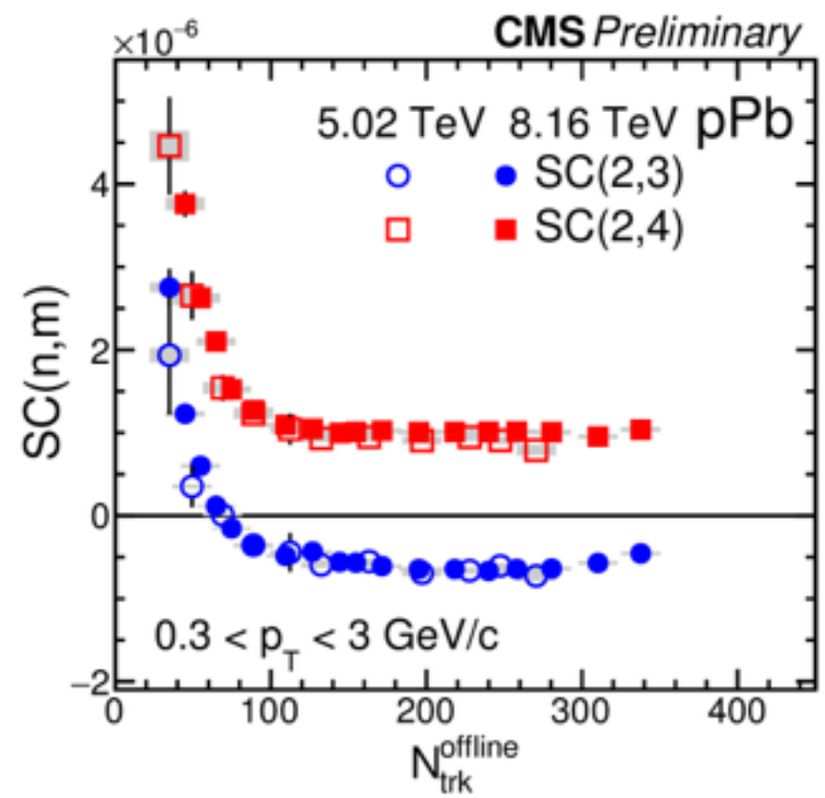
Symmetric cumulants: mixed cumulants of Fourier harmonics

$$\mathrm{SC}(n,n') = \langle e^{i(n(\phi_1-\phi_3)-n'(\phi_2-\phi_4))}\rangle - \langle e^{in(\phi_1-\phi_3)}\rangle\langle e^{in'(\phi_2-\phi_4)}\rangle$$

Bilandzic et al, PRC 89, no. 6, 064904 (2014)



Dusling, MM, Venugopalan arXiv:1705.00745



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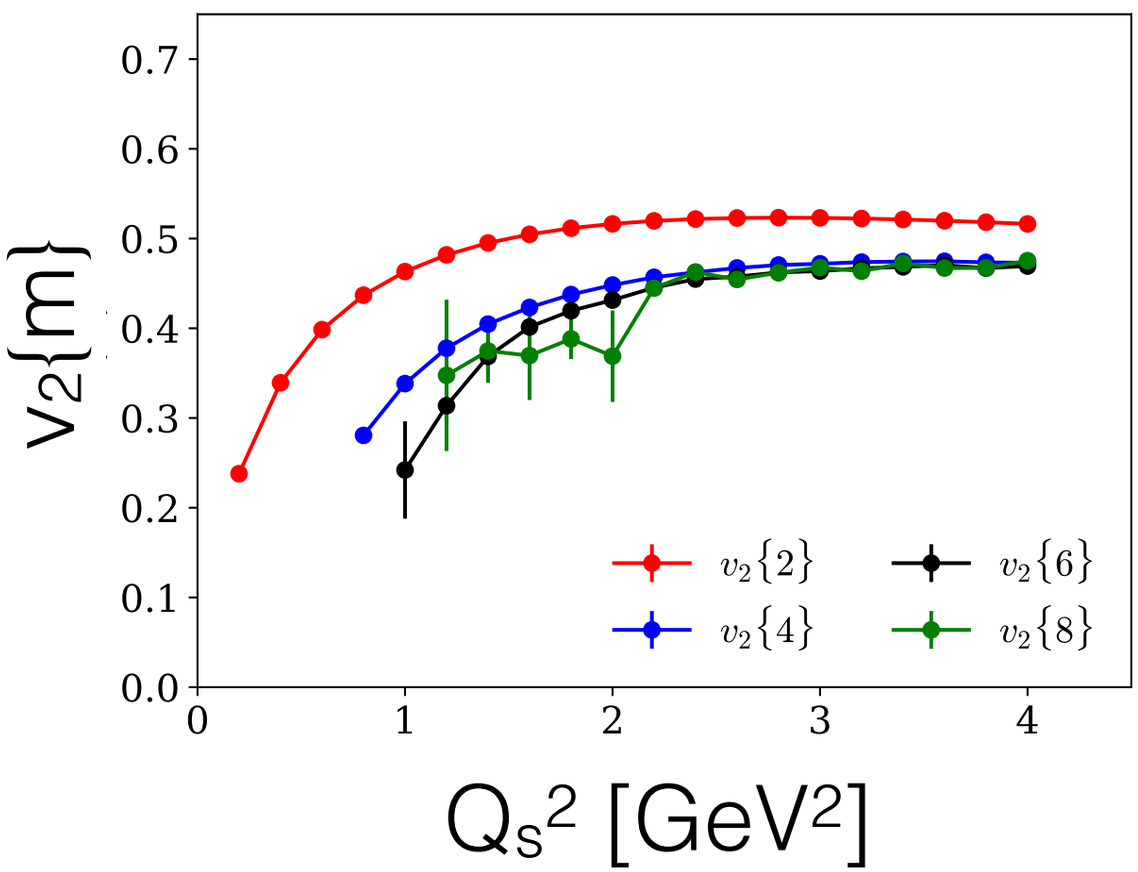
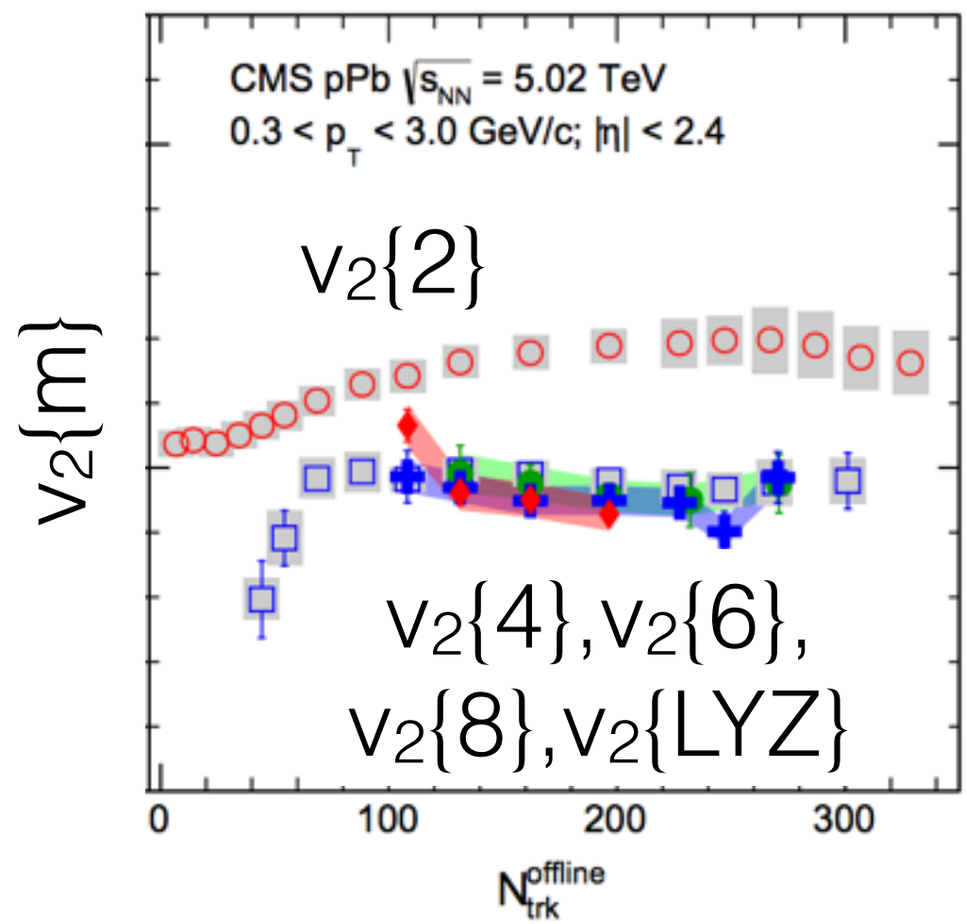
Collectivity from initial state

Can also study Abelian version, computationally much easier (N_c x N_c trace -> scalar)



Dusling, MM, Venugopalan, arXiv:1705.00745



CMS PRL 115 (2015) 012301

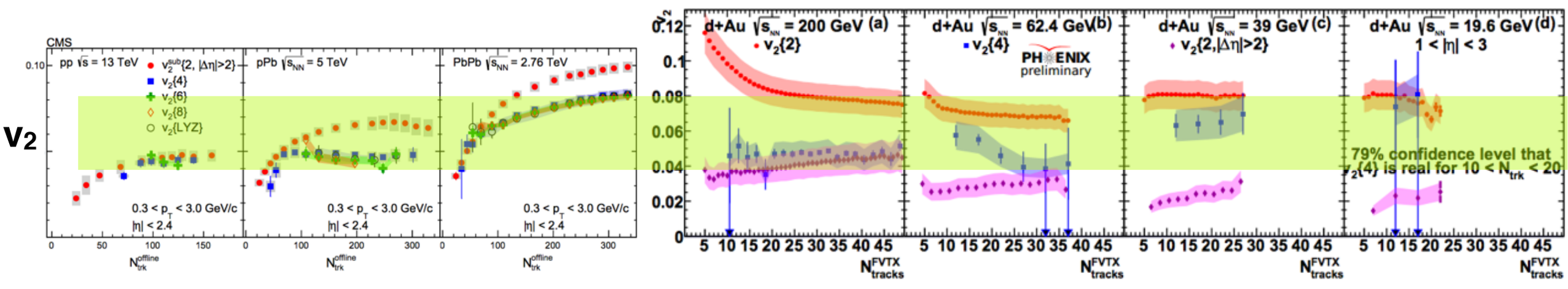
However, need for more quantitative calculations perhaps from classical Yang-Mills

Conclusions

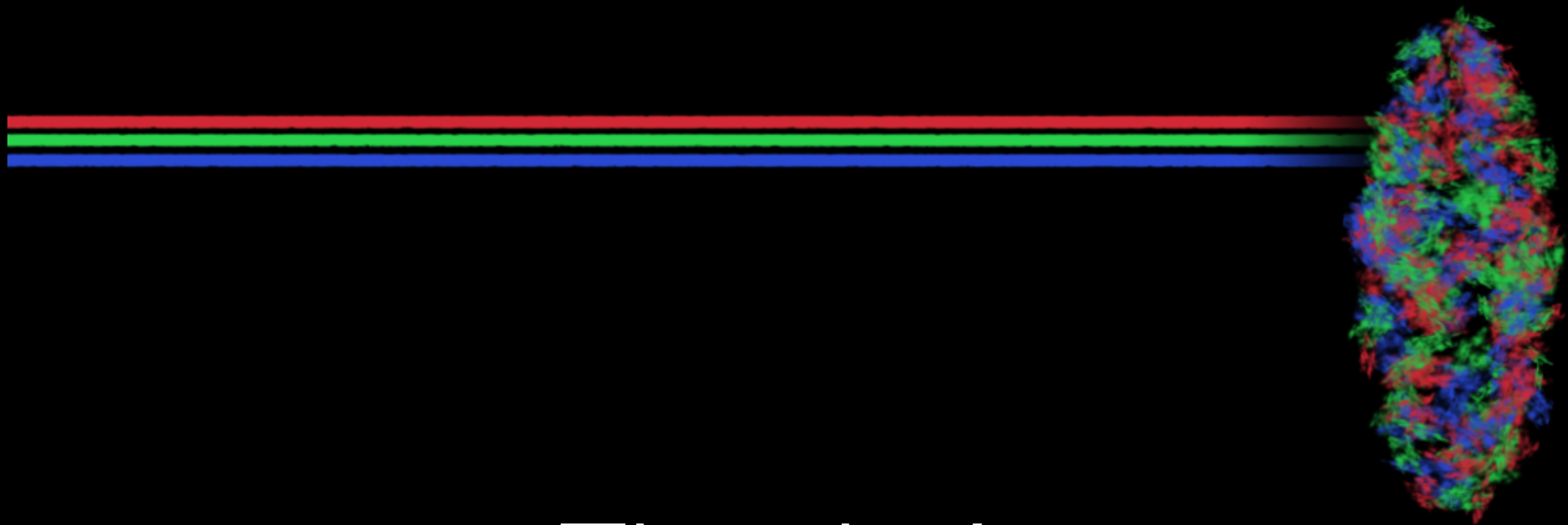
- Much progress has been made within both initial state and final state approaches to describe much of the two particle results
- Multi-particle correlations are less clear
  - Can be captured in hydrodynamics
  - But not unique to hydro, can be captured qualitatively in an initial state model
  - Current definition of collectivity not differential enough

Open questions

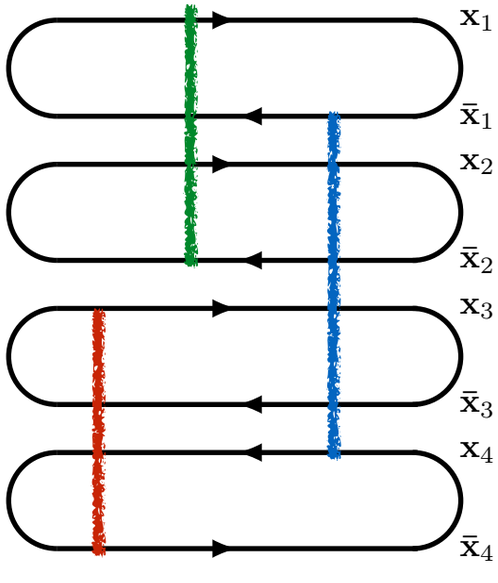
- How to reconcile or ***combine*** initial and final state interpretations?
- How to make initial state models more phenomenological?
- How far can we push hydrodynamics? Why no jet quenching?
- Can one theory describe all of the (rather similar looking) data at all of the energy ranges and systems?



Energy →



Thanks!


$\mathbf{x}_1$
$\bar{\mathbf{x}}_1$
$\mathbf{x}_2$
$\bar{\mathbf{x}}_2$
$\mathbf{x}_3$
$\bar{\mathbf{x}}_3$
$\mathbf{x}_4$
$\bar{\mathbf{x}}_4$

BACKUP

Initial state references

Numerical Classical Yang-Mills solved exactly without approximation, includes multiple gluon exchange

Krasnitz, Venugopalan, NPB 557 (1999) 237; Krasnitz, Nara, Venugopalan, NPA 717 (2003) 268; Lappi, PRC 67 (2003) 054903; Schenke, Tribedy, Venugopalan, PRL 108 (2012) 252301; Schenke, Schlichting, Venugopalan, PLB 747, 76-82 (2015), Schenke, Schlichting, Tribedy, Venugopalan PRL 117 (2016) no.16, 162301

Glasma graph approximation: Only consider two gluon exchange and Gaussian statistics of color charges (MV model)

Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009), Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan, PLB697 (2011) 21-25, Dusling, Venugopalan PRD 87 (2013) 5, 051502; PRD 87 (2013) 5, 054014; PRD 87 (2013) 9, 094034

Non-linear Gaussian approximation: Resums multiple gluon exchanges - assumes Gaussian statistics

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Other

V. Skokov, Phys.Rev. D91 (2015) 054014,A. Kovner, M. Lublinsky, V. Skokov, arXiv:1612.07790
E. Gotsman, E. Levin, and U. Maor, Eur. Phys. J. C76, 607 (2016) arXiv:1607.00594, E. Gotsman and E. Levin (2016) arXiv:1611.01653, Iancu, Rezaeian, Phys. Rev. D 95, no. 9, 094003 (2017), Gotsman, Levin PRD 95 (2017) no.1, 014034, arXiv:1705.07406