U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

Workshop Summary

Björn Schenke, Brookhaven National Laboratory

03/16/2019 - Rice University, Houston, TX

Do we make small droplets of QGP?

Let’s start with whether hydrodynamics could be applicable in small systems

Hydrodynamics

Paul Romatschke and Derek Teaney's talk

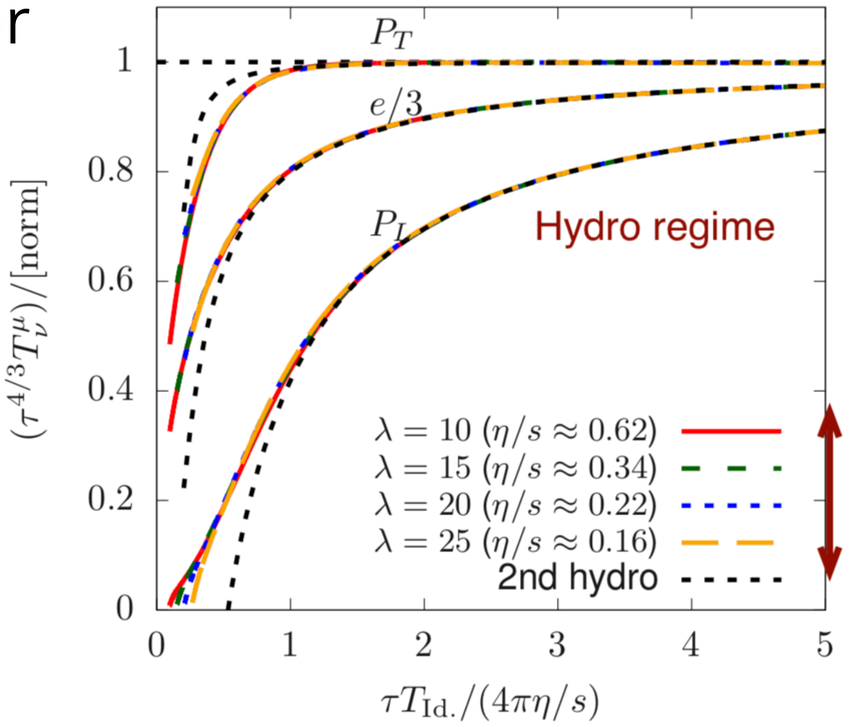
When is it applicable?

Paul: Attractor solution: Hydro breaks down for

- times t_S<0.05 fm (and $T(t_S)$~1.06 GeV)
- momenta k>3.5x1.06 GeV ~3.7 GeV
- for system sizes L<1/k<0.05 fm

Mauricio: Anisotropic hydro seems to be close to the Borel resummed solution

Derek: based on when second order hydro agrees with kinetic theory



$$\tau_{\text{hydro}} \approx 1.1\,\text{fm} \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}} \left(\frac{4.1\,\text{GeV}}{\langle \tau s \rangle}\right)^{-1/2} \left(\frac{\nu_{\text{eff}}}{40}\right)^{1/2}$$

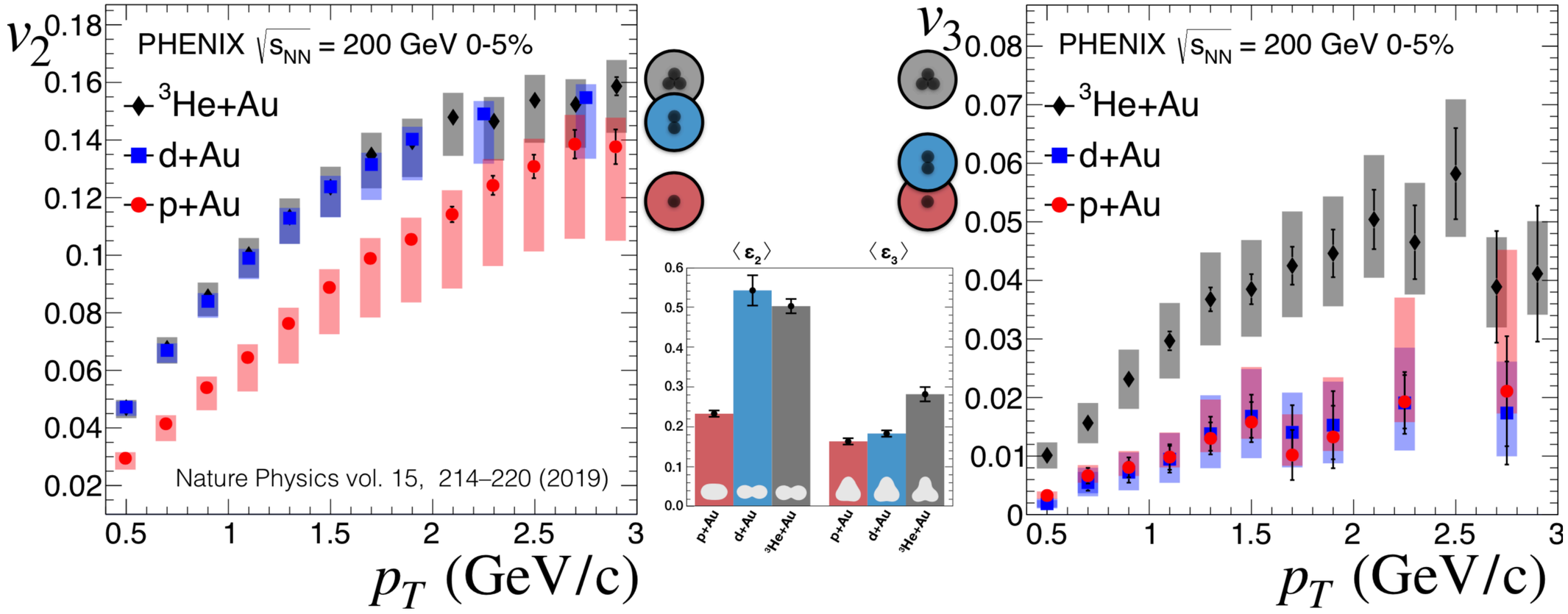
$$\left(\frac{dN}{dy}\right)_{\text{hydro}} = 63 \left(\frac{4\pi(\eta/s)}{2}\right)^{3}$$

Test expectations from hydrodynamics with scan of different geometry systems

RHIC system scan

Julia Velkovska's talk

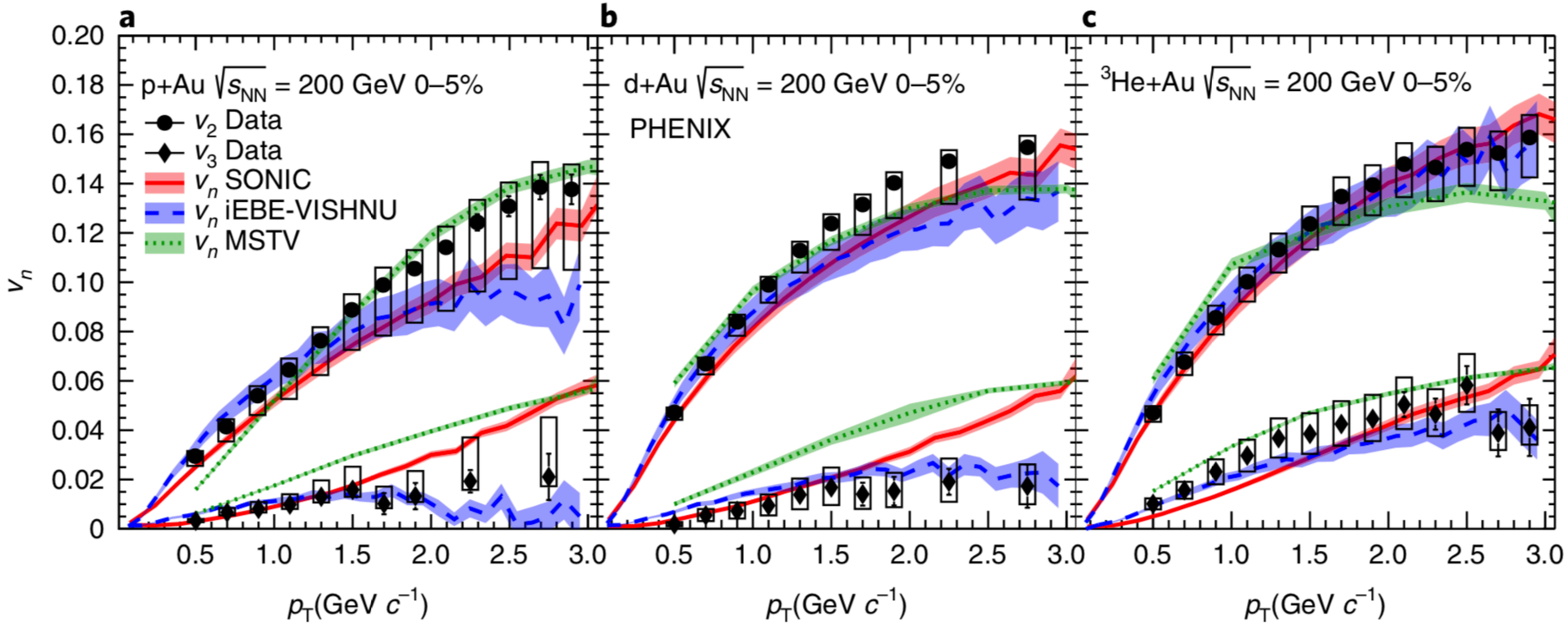
Nucleon MC-Glauber's eccentricities provide expectation for v_n



v_n agree with the expectation - here no non-flow subtracted

RHIC system scan

Julia Velkovska's talk



Hydrodynamic models with simple MC-Glauber initial conditions reproduce the trends

CGC calculation in the dilute dense limit does OK - overestimates

v_3 in pAu and dAu shown are gluon v_n

More arguments for hydrodynamics

Magnitude of v_2 in PbPb and pPb

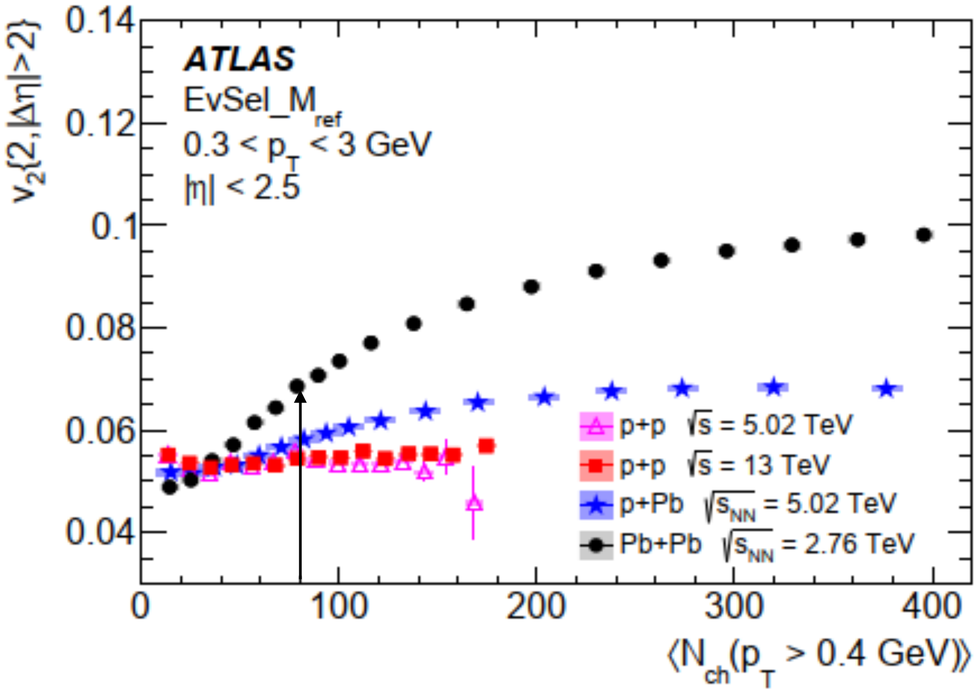
Jürgen Schukraft's talk

v_2(PbPb)/v_2(pPb) ≈ 1.34 @ dN/dη ≈ 80

geometry + FSI expectation: v_2(PbPb) > v_2(pPb)

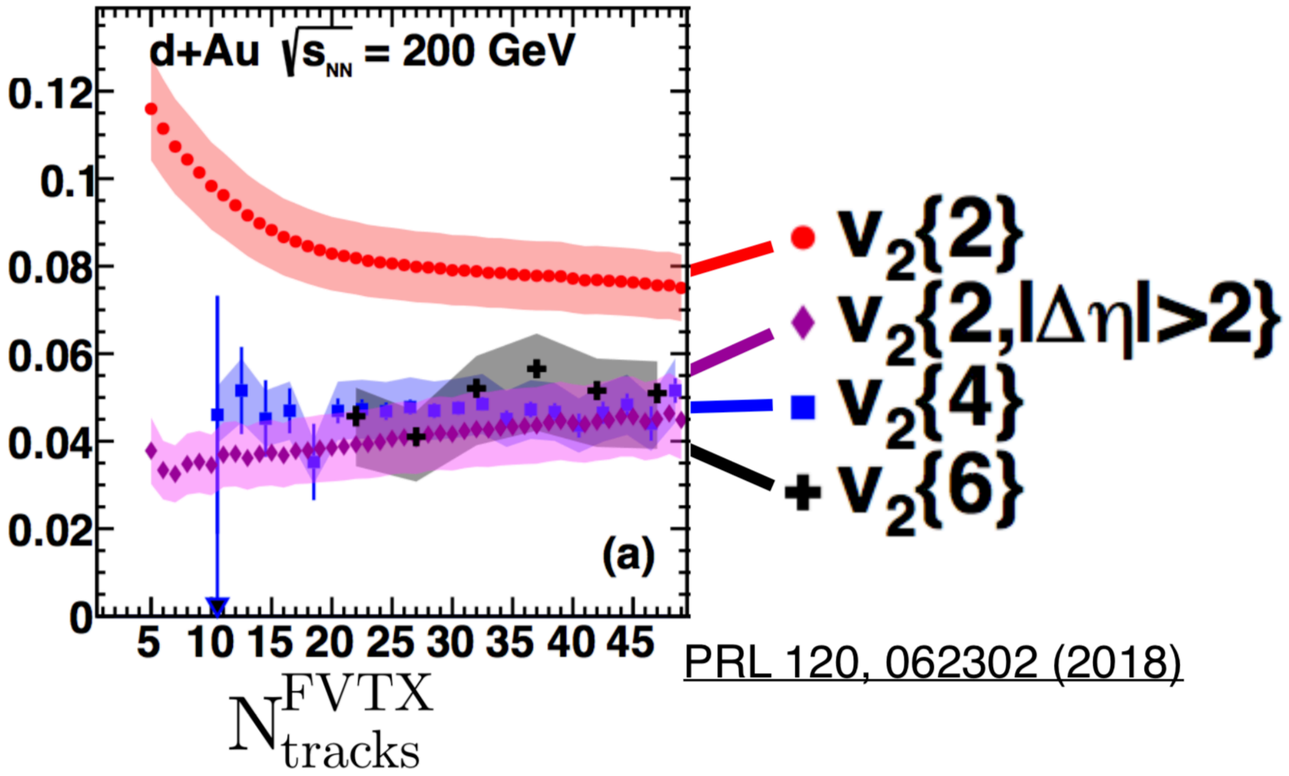
HBT: ε,A(PbPb) > ε,A(pPB) @ FO

εκ(PbPb)/εκ(pPb) ≈ 1.86/1.4 ≈ 1.33 **(1710.07098, 1201.3158)**



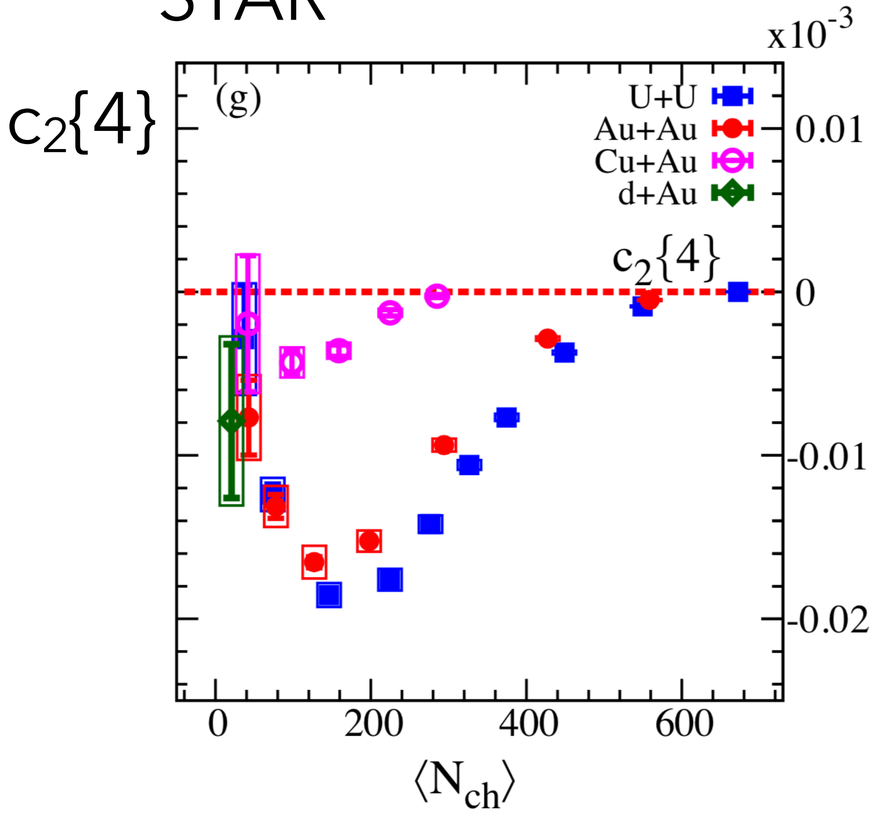
Multi-particle correlations Julia Velkovska's talk

PHENIX



PRL 120, 062302 (2018)

STAR

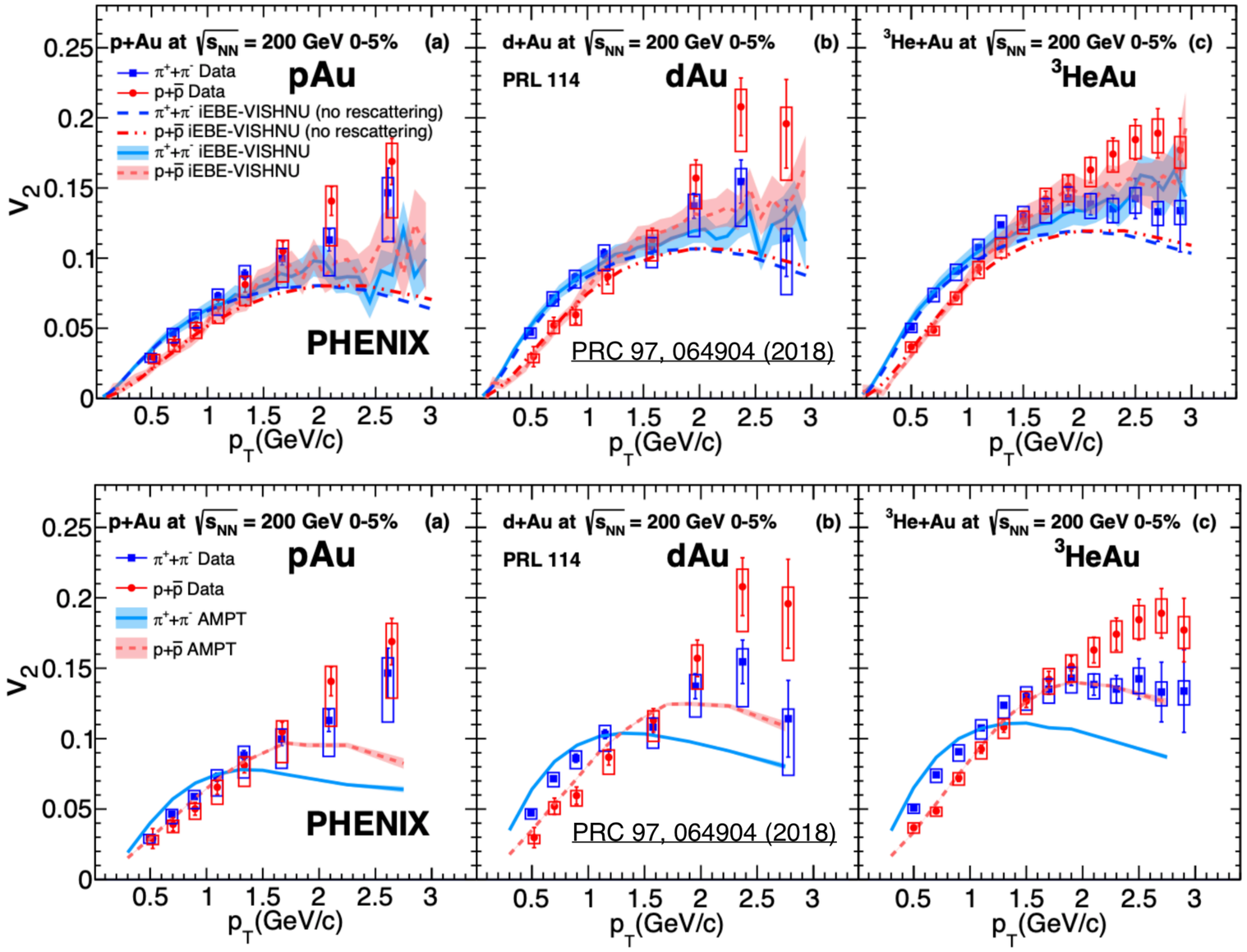


$v_2\{4\}$ is consistent with $v_2\{6\}$

negative $c_2\{4\}$ in d+Au

Mass splitting

Julia Velkovska's talk

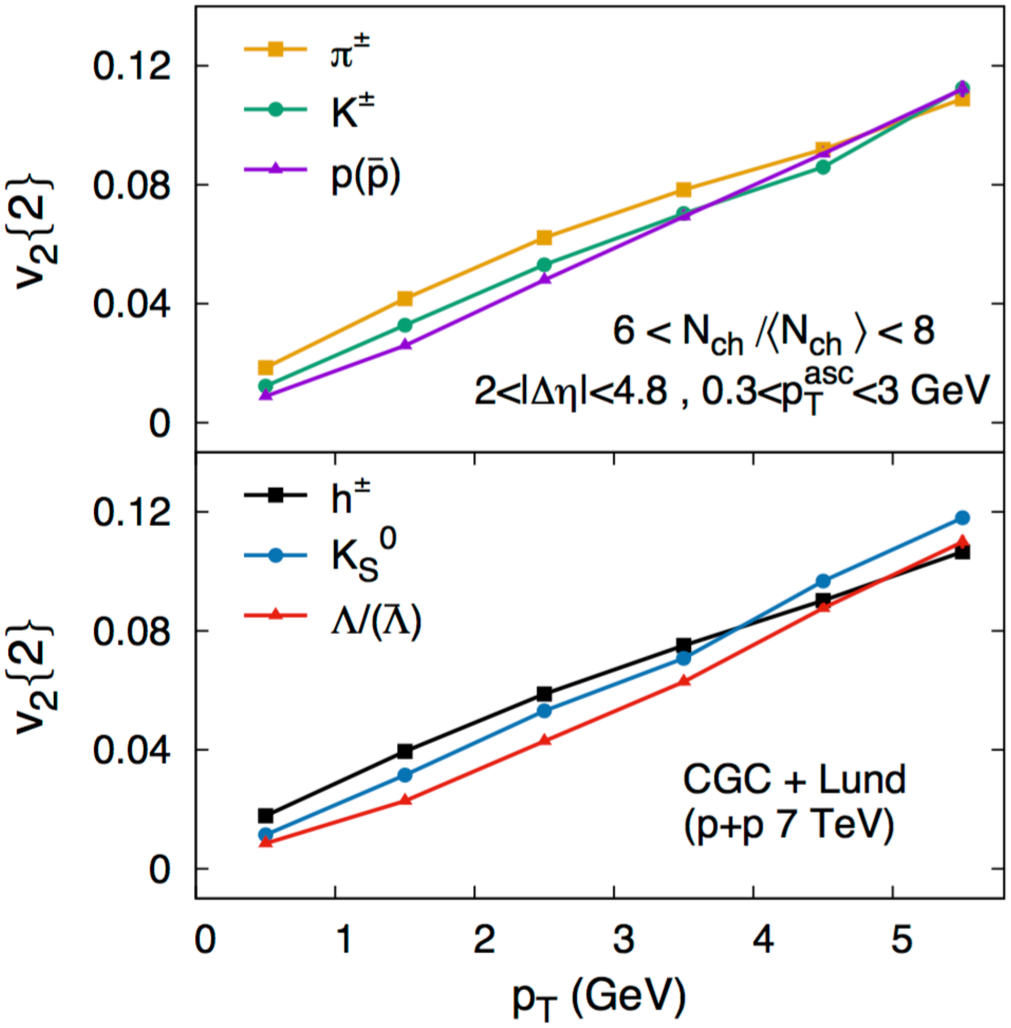


Hydrodynamics reproduces splitting at low p_T

AMPT has splitting at high p_T ; at low p_T only when hadronic rescattering included

Note: Mass splitting without hydro

B. Schenke, S. Schlichting, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 117, 162301 (2016)

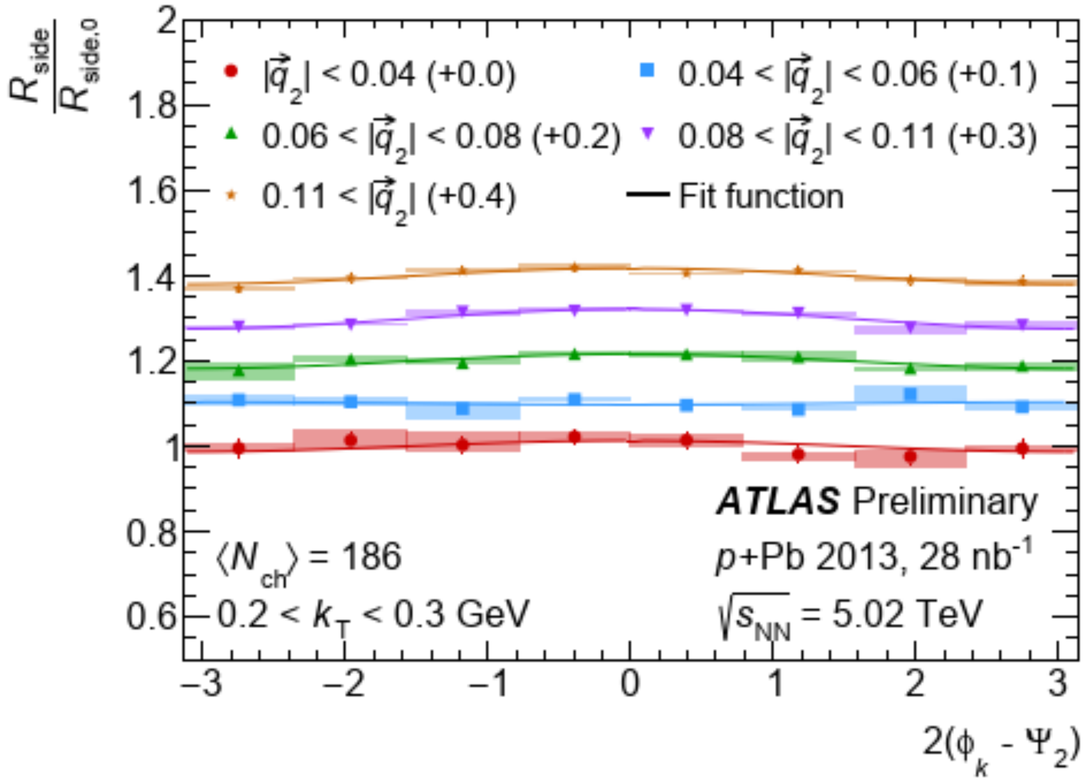


Also seen qualitatively in CGC + Lund string fragmentation where the string gives the common boost

Here shown for p+p
Need to do the calculations for other systems

Angle-dependent HBT

Jürgen Schukraft's talk



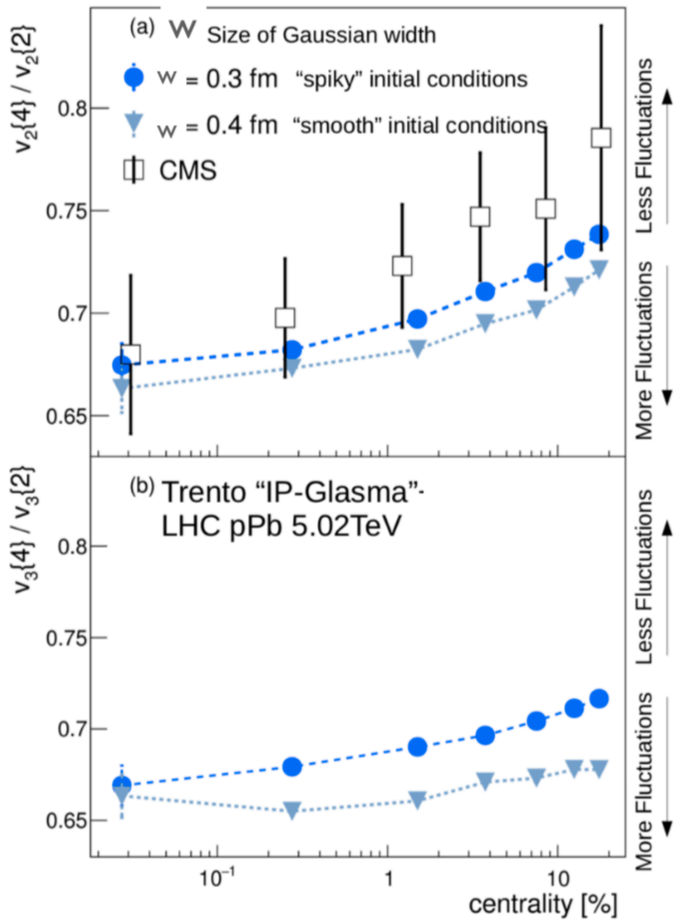
More anisotropy of shape of emitting source for events with larger flow anisotropy

Hints at geometry driven flow

Flow fluctuations

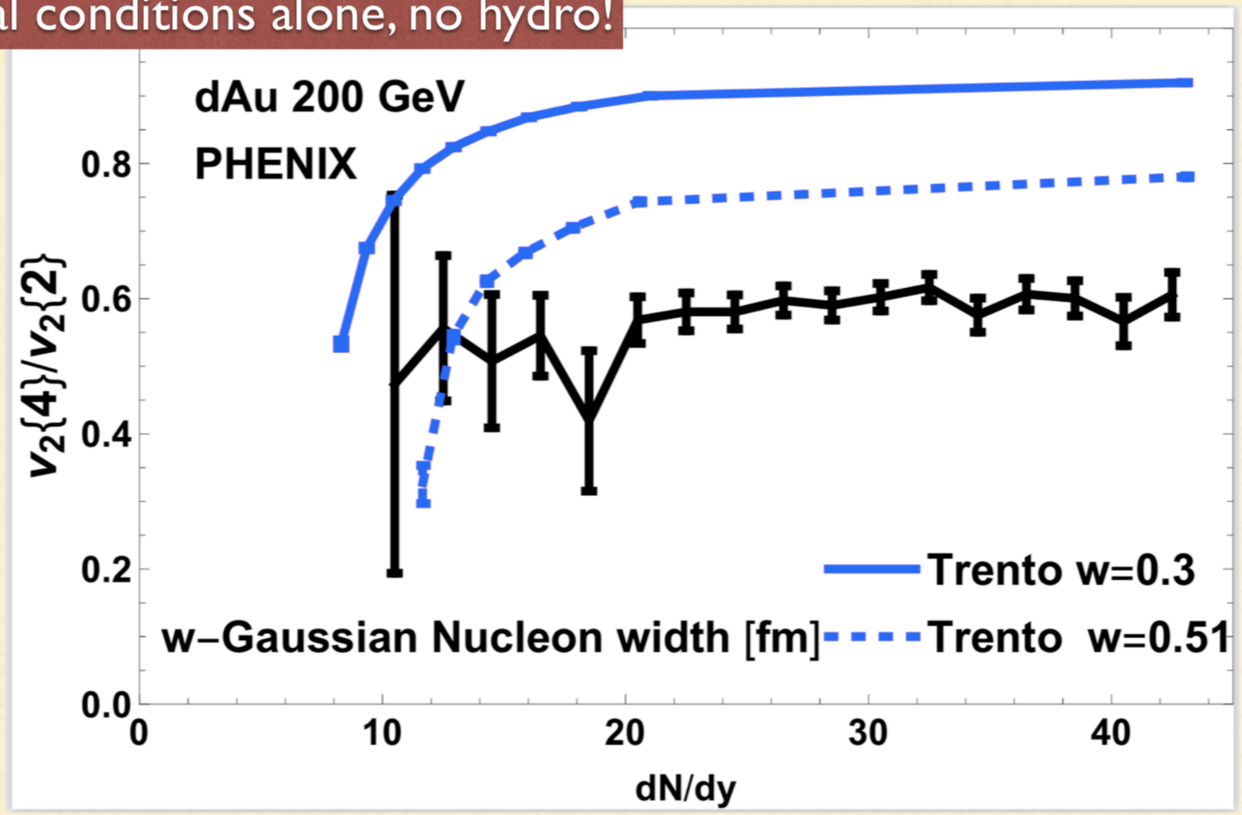
Jaki Noronha-Hostler's talk
also see Maxime Guilbaud's talk

Eccentricity fluctuations alone seem to describe observed flow fluct.



Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.1, 014913

From initial conditions alone, no hydro!

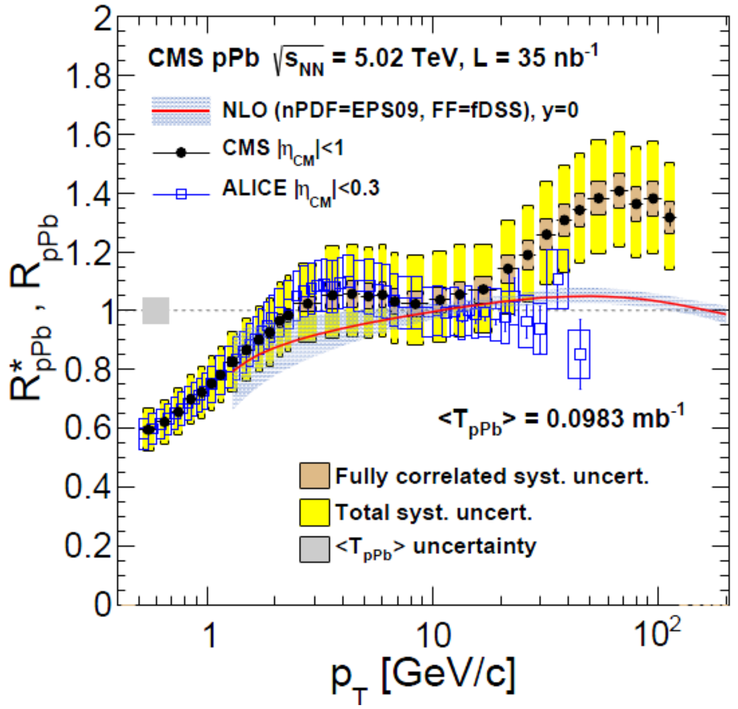


Hydro will move down the theoretical results

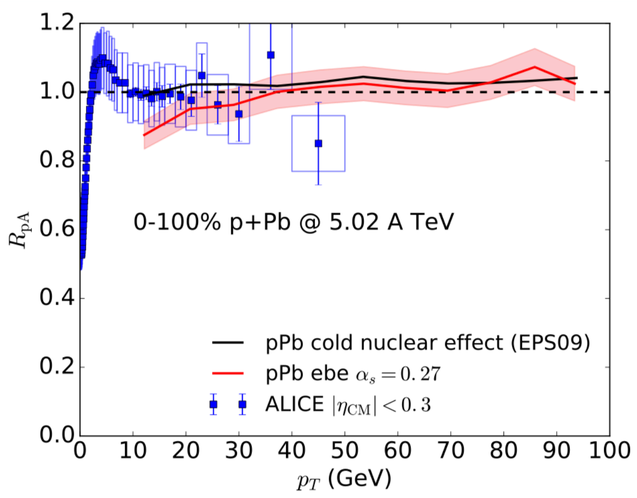
A challenge:Jet quenching

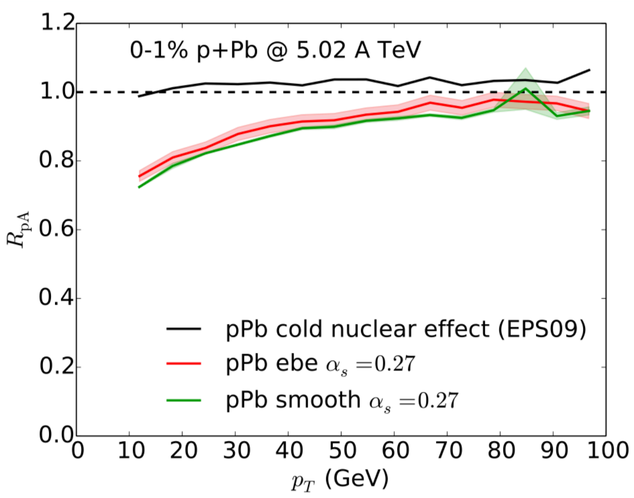
Jürgen Schukraft's talk

- Conventional Wisdom: Not (non-trivially) modified in pA
- Only quantitative comparison between expectation(theory) and data will tell
- How much jet-quenching / melting would actually be expected ?
- Also weakly bound quarkonia are suppressed (strongly bound ones not)



Monte-Carlo event generator MARTINI in hydro background



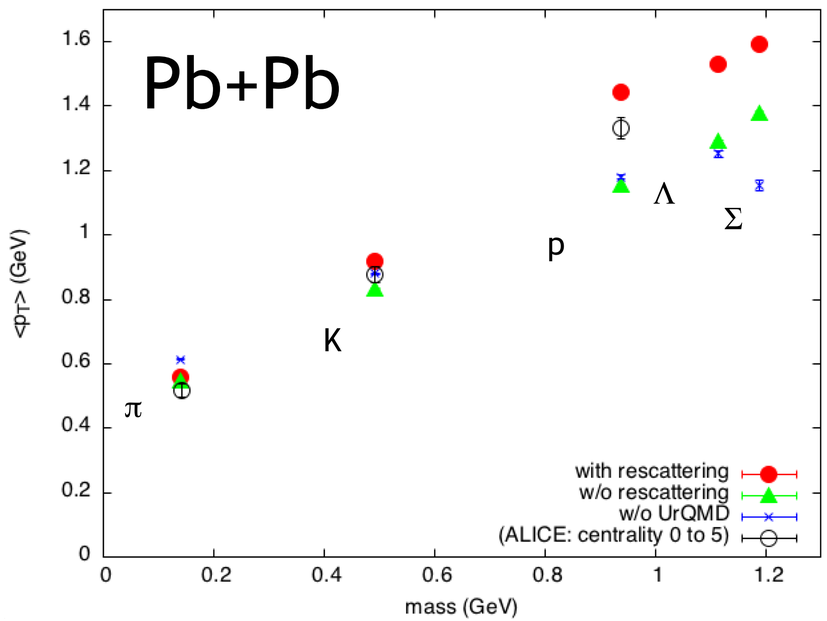


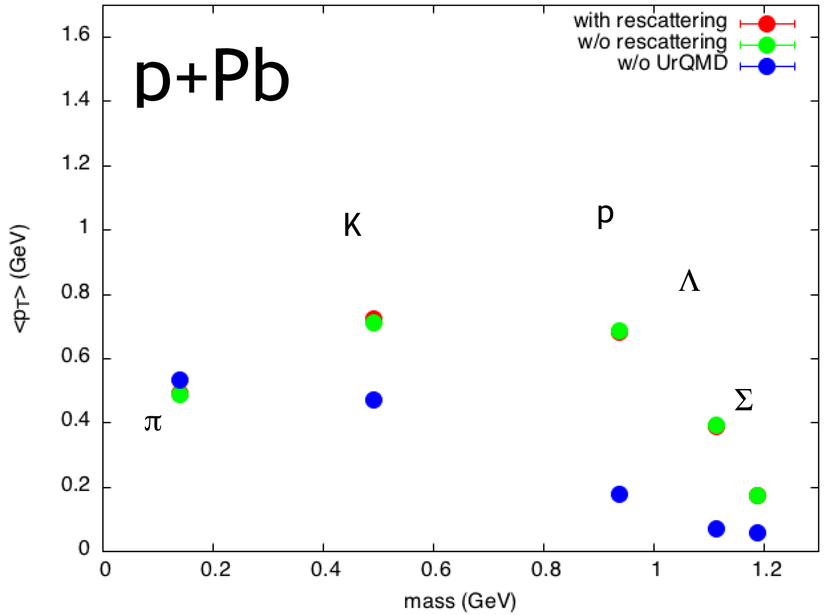
Nucl.Phys. A956 (2016) 741-744

Effects beyond hydrodynamics are important

Chiho Nonaka's talk

0-5 % centrality, |y| < 0.5





$\tau_{\rm fluid} \sim 13$ fm

$\tau_{\rm fluid} \sim 5.3$ fm

p+Pb

- Large effect on mean-p_T of heavier particles from decay processes
- Rescattering effect is small.

Trento + new 3+1D hydro code + UrQMD

Effects beyond hydrodynamics are important

Particlization details can also make a big difference in small systems:

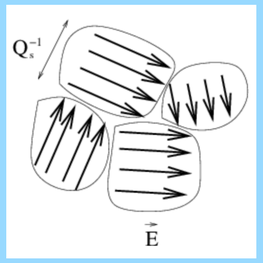
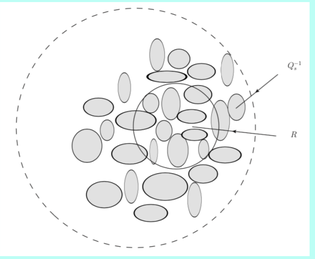
What about local momentum (and charge) conservation
when converting the fluid to particles?

Other sources of momentum anisotropy

Color Glass Condensate

Alex Kovner's talk

Sources of correlations:

	Classical	Quantum
Local anisotropy	 $1/Q_s$	Bose enhancement in incoming wave function
Density gradients	$\frac{dQ_s}{db}/Q_s$	Gluonic HBT 

Incoming gluons need to be close in the transverse plane to feel the same local structure of the target.

Both come with similar contribution for enhancement of anti-aligned momenta of same magnitude (accidental?)

CGC: Challenges

Alex Kovner's talk

Odd harmonics?:
The symmetry in the expression for double inclusive production
(k, p) → (k, –p) is accidental - does not survive corrections to the leading CGC approximation
Real v_3 can come from

a) Corrections to the CGC projectile wave function: $v_3^2 \sim \alpha_s\, v_2^2$
b) Classical final state evolution: $v_3^2 \sim (\alpha_s\, \rho)^2\, v_2^2$

v_4:
For $|k| \approx |p| \gg Q_s$ ~sum of two δ-functions from quantum part.
Leads to $v_4 \approx v_2$ (different from experiment)
But classical contributions different and dominant for large bin width

CGC: Challenges

Alex Kovner's talk

$c_2\{4\}$: How to get a negative $c_2\{4\}$?
Recent paper by Blok and Wiedemann:
Emission of m gluons from N sources with m > N
leads to such negative correlation.

- Hadronization
- Final state evolution
- Projectile wave function (MV model not necessarily good for small projectile)
  - JIMWLK better (but need to regulate rapid growth)

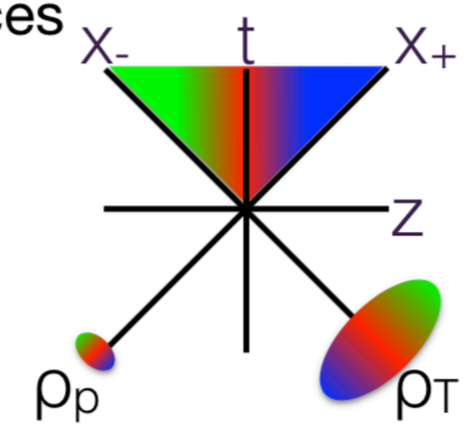
CGC: Dilute dense calculation

Mark Mace's talk

CGC EFT: solve QCD CYM with static color sources

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

$$J^\nu = g\delta^{\nu+}\delta(x^-)\rho_p(\mathbf{x}_\perp) + g\delta^{\nu-}\delta(x^+)\rho_T(\mathbf{x}_\perp)$$



Dilute-dense regime: $\rho_T/k_T^2 \gg \rho_p/k_T^2$

Kovchegov, Mueller NPB 529 (1998), Kovner, Wiedemann PRD 64 (2001), Dumitru, McLerran NPA 700 (2002), Blaizot, Gelis, Venugopalan NPA 743 (2004),…

$$\frac{dN}{d^2k}[\rho_p, \rho_T] \sim g^2\rho_p^2 f_{(1)}(p_\perp) + g^4\rho_p^4 f_{(2)} + \ldots$$

Analytical solution known for ~20 years

Framework has been applied to study numerous final states at RHIC and LHC (heavy quarks, photons,…)

e.g. Ma, Tribedy, Venugopalan, Watanabe PRD 98 (2018), Benic, Fukushima, Garcia Montero, Venugopalan arXiv:1807.03806, Wang, Marquet, Qin, Wei, Xiao arXiv:1901.10320

Dense-dense (all $O(\rho_p^{\#})$) leads to IP-Glasma model

Schenke, Tribedy, Venugopalan PRL 108 (2012), PRC 86 (2012)

Includes quantum correlations (Bose Enhancement, HBT)

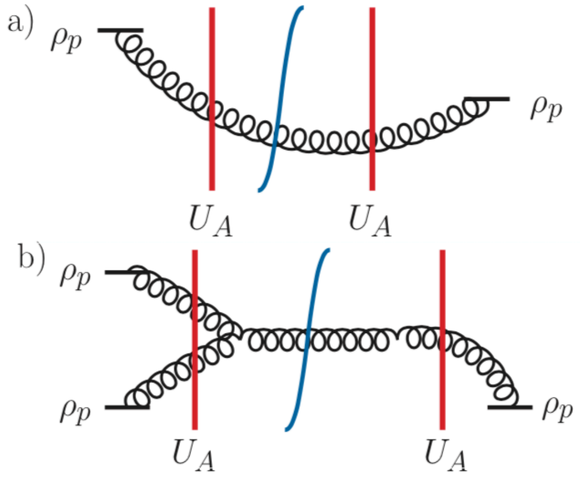
Gelis, Lappi, McLerran NPA 828 (2009), Kovner, Rezaeian, PRD 95, 96 (2017), Altinoluk, Armesto, Beuf, Kovner, Lublinsky, PLB 751 (2015), PRD 95 (2017), Kovner, Skokov PRD 98 (2018), PLB 785 (2018), …

CGC: Dilute dense calculation

Even harmonics appear at LO dilute-dense

Odd harmonics only non-zero at next to leading order in ρ_p —first saturation correction *(full NLO correction not known)*

McLerran, Skokov NPA 959 (2017)



MSTV PLB 788 (2019)

Mark Mace's talk

Then in Fock-Schwinger gauge (A_τ=0)

$$\frac{dN^{\rm even}(\mathbf{k})}{d^2k dy}\Big[\rho_p,\rho_t\Big] = \frac{2}{(2\pi)^3}\frac{\delta_{ij}\delta_{lm}+\epsilon_{ij}\epsilon_{lm}}{k^2}\Omega^a_{ij}(\mathbf{k})\left[\Omega^a_{lm}(\mathbf{k})\right]^\star \sim \rho_p^2$$

$$\frac{dN^{\rm odd}(\mathbf{k})}{d^2k dy}\Big[\rho_p,\rho_T\Big] = \frac{2}{(2\pi)^3}{\rm Im}\left\{\frac{g}{\mathbf{k}^2}\int\frac{d^2l}{(2\pi)^2}\frac{{\rm Sign}(\mathbf{k}\times\mathbf{l})}{l^2|\mathbf{k}-\mathbf{l}|^2}f^{abc}\Omega^a_{ij}(\mathbf{l})\Omega^b_{mn}(\mathbf{k}-\mathbf{l})\left[\Omega^c_{rp}(\mathbf{k})\right]^\star\times\right.$$

$$\left.\left[\left(\mathbf{k}^2\epsilon^{ij}\epsilon^{mn}-\mathbf{l}\cdot(\mathbf{k}-\mathbf{l})(\epsilon^{ij}\epsilon^{mn}+\delta^{ij}\delta^{mn})\right)\epsilon^{rp}+2\mathbf{k}\cdot(\mathbf{k}-\mathbf{l})\epsilon^{ij}\delta^{mn}\delta^{rp}\right]\right\} \sim \rho_p^3$$

Projectile Target

In terms of: $\Omega^a_{ij}(\mathbf{x}) = g\left[\frac{\partial_i}{\partial^2}\rho^b_p(\mathbf{x})\right]\partial_j U^{ab}(\mathbf{x})$

Valence sources rotated by target

Same results in LC gauge (A^+=0)

Kovchegov, Skokov PRD 97 (2018)

MSTV calculation

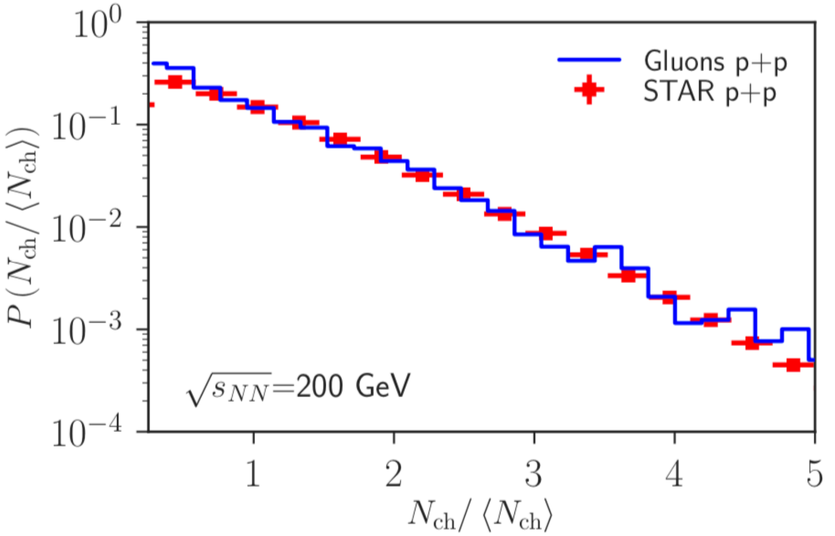
Mark Mace's talk

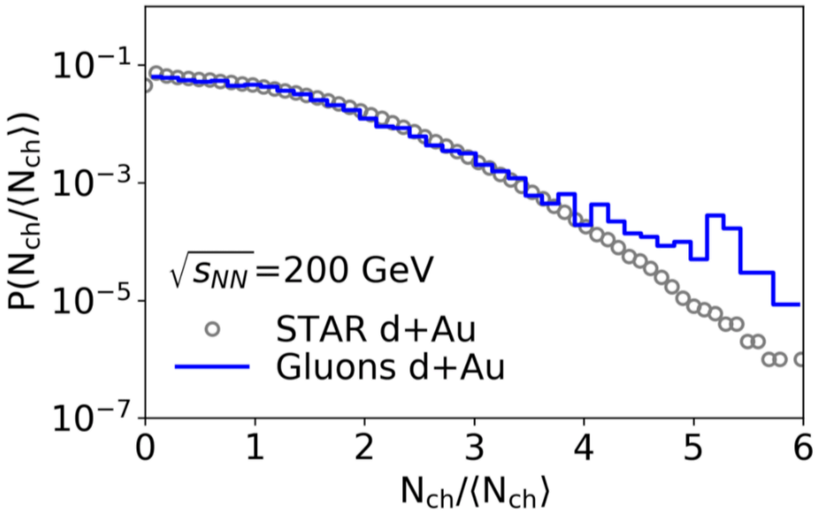
Sample nucleons; Q_s distribution from IP-Sat
Sample color charges using MV model

Compute multiplicities event-by-event

Generates negative binomial fluctuations

Jamie challenged that these fluctuations are actually visible in the multiplicity distributions:





MSTV calculation

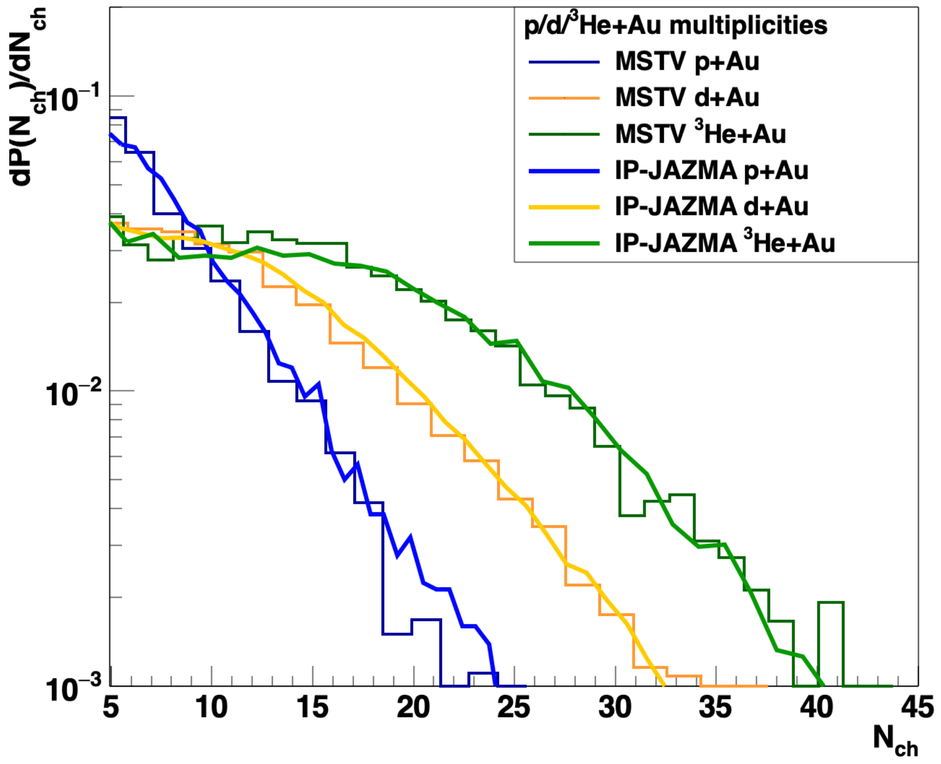
Mark Mace's talk
Jamie Nagle's talk

Sample nucleons; Q_s distribution from IP-Sat
Sample color charges using MV model

Compute multiplicities event-by-event

Generates negative binomial fluctuations

Jamie challenged that these fluctuations are actually visible in the multiplicity distributions: Jazma gets the same without any color charge fluctuations



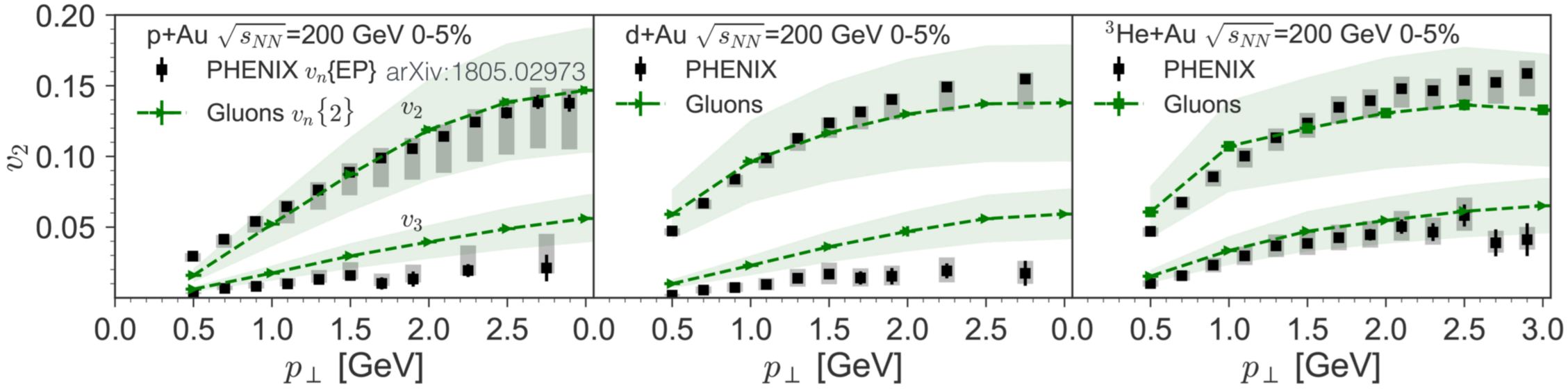
MSTV calculation

Mark Mace's talk

Integrated two-particle anisotropy coefficients expressed as

$$v_n^2\{2\}(N_{ch}) = \int W[\rho_p]W[\rho_t]\ |Q_n[\rho_p,\rho_t]|^2\ \delta(N_{ch} - \frac{dN}{dy}[\rho_p,\rho_t])$$

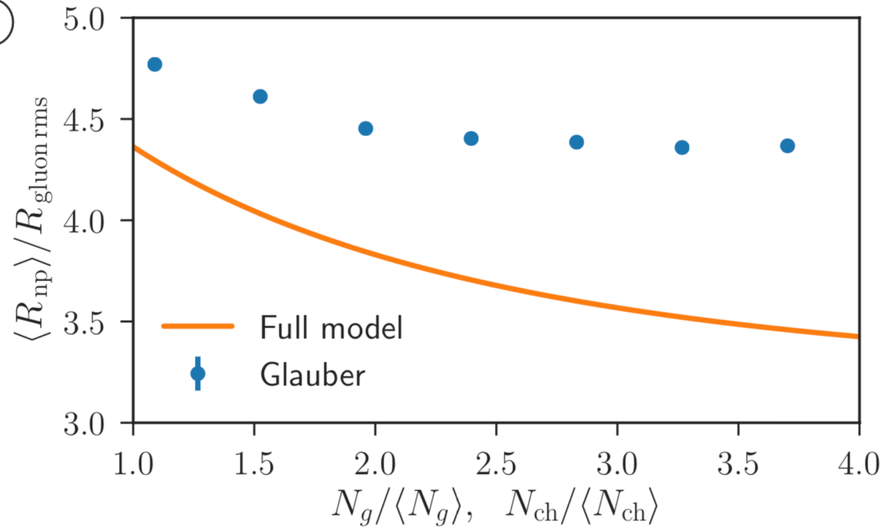
$$Q_{2n}\left[\rho_p,\rho_t\right] = \frac{\int_{p_1}^{p_2}\int_{k_\perp,\phi} e^{i2n\phi}\frac{dN^{\rm even}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]}{\int_{p_1}^{p_2}\int_{k_\perp,\phi}\frac{dN^{\rm even}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]}, \quad Q_{2n+1}\left[\rho_p,\rho_t\right] = \frac{\int_{p_1}^{p_2}\int_{k_\perp,\phi} e^{i(2n+1)\phi}\frac{dN^{\rm odd}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]}{\int_{p_1}^{p_2}\int_{k_\perp,\phi}\frac{dN^{\rm even}(\mathbf{k}_\perp)}{d^2k_\perp dy}\left[\rho_p,\rho_t\right]}$$

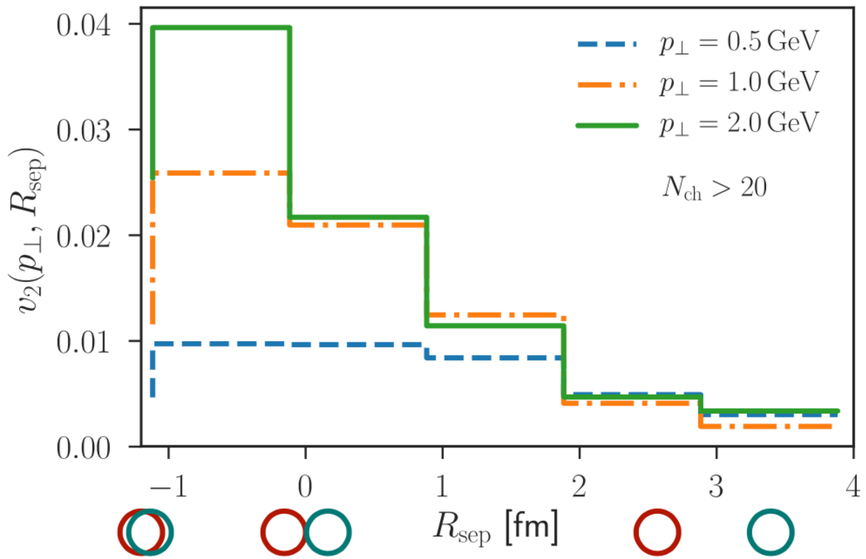


MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018) arXiv:1805.09342, and arXiv:1901.10506

Understanding v_2 in dAu (vs pAu)

Mark Mace's talk



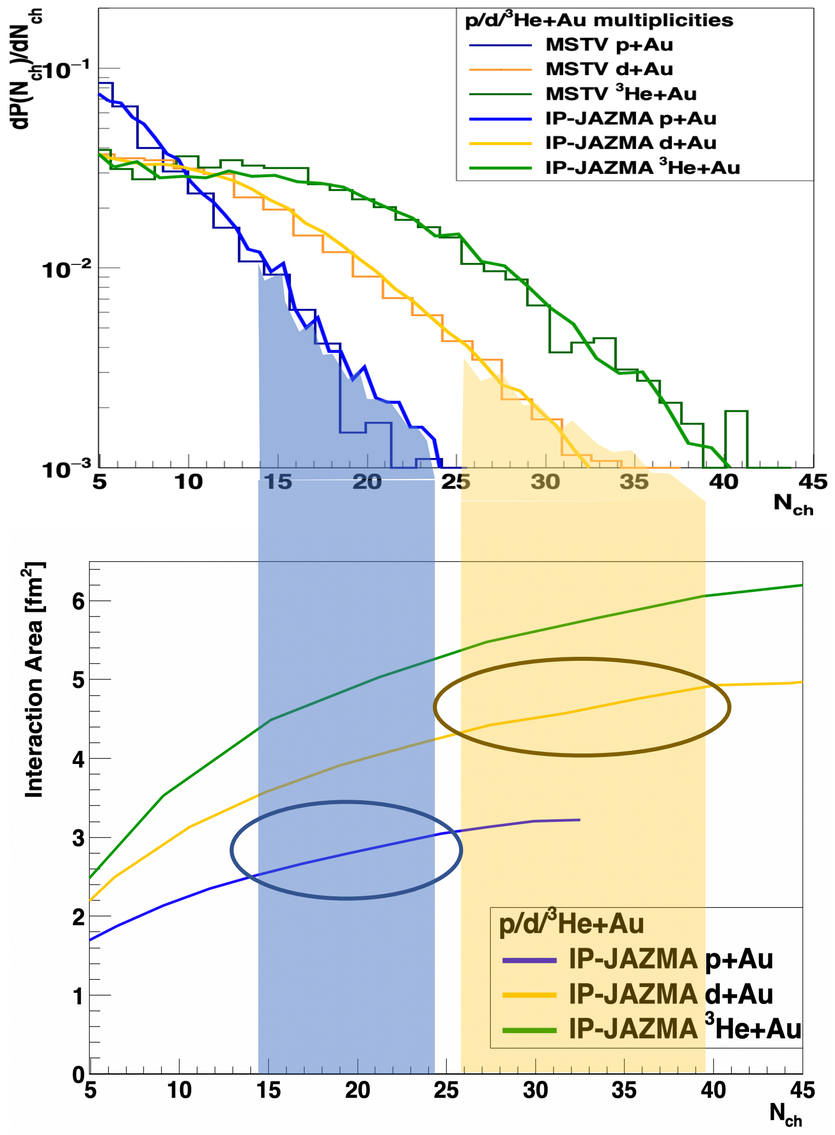


Deuteron configurations with nucleons on top of one another produce

a) higher multiplicity

b) larger v_2 (qualitatively different from geometry driven scenario)

Understanding v_2 in dAu (vs pAu)



Jamie Nagle's talk

Jazma model seems to find something different: Larger multiplicity in dAu for larger area, not larger Q_s

Measure v_2 in p+d collisions vs. multiplicity :)

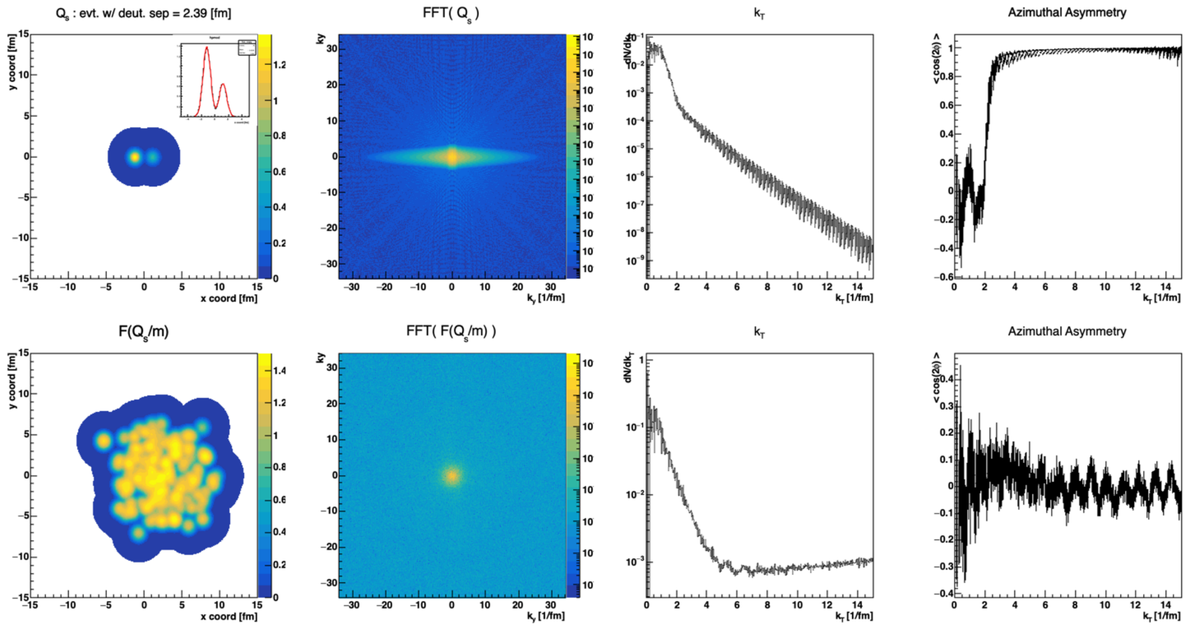
Interpretations

Mark Mace and Jamie Nagle's talks

Problem is more with the interpretation of the results in the dilute-dense calculation - not with the results themselves

Complicated calculation - possible some interpretations are not quite right or incomplete

Jamie suggested that geometry may play a more important role in the MSTV results than given credit Fourier transforms involved in the momentum space calculation will know about geometry



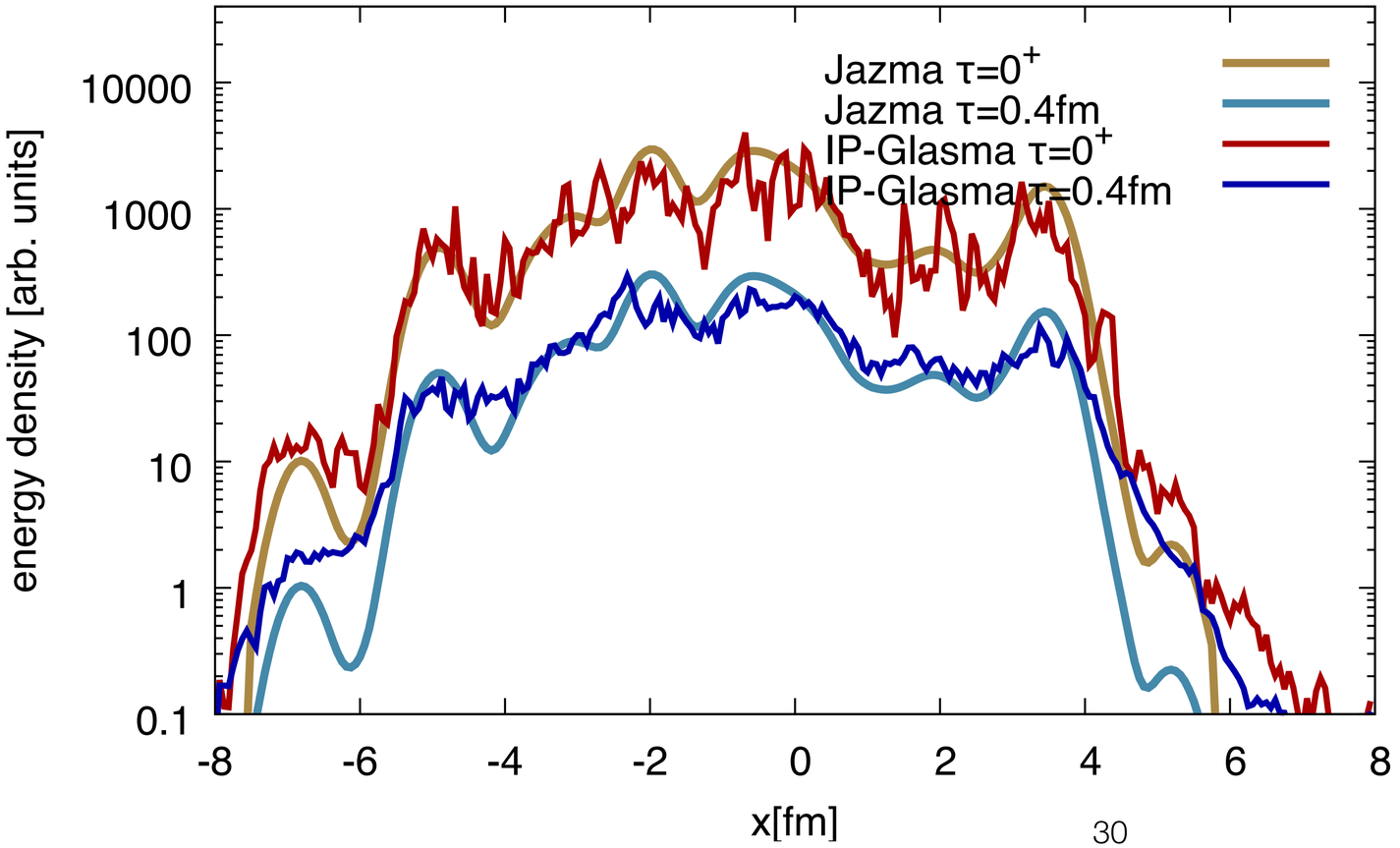
Room for improvement

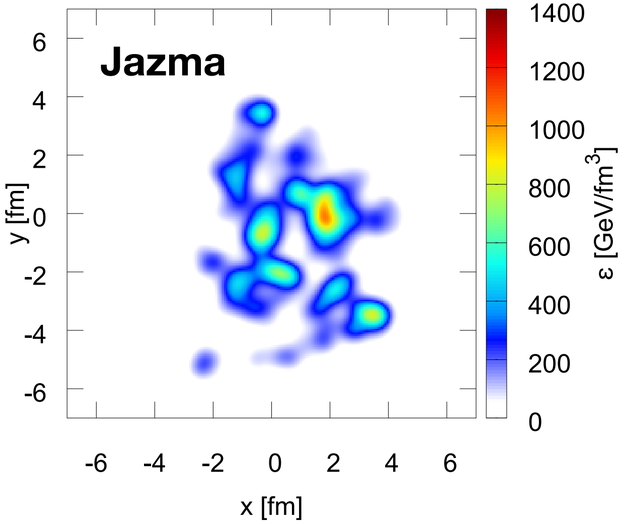
- Hadronization is an issue in all calculations
- In the CGC calculation one needs to convert gluon distributions to hadron distributions (different options - worth exploring)
- Hydrodynamics also has uncertainties in the hadronization, especially in small systems
- v_n coefficients need to be computed with the same method the experiment uses (or as close as possible)
- Experiments: Please try to measure p_T spectra or mean-p_T for charged hadrons in p+Au and ^{3}He+Au (and d+Au, for which older data exists) Are corrected multiplicity distributions possible? - models need to describe them together with the momentum anisotropies

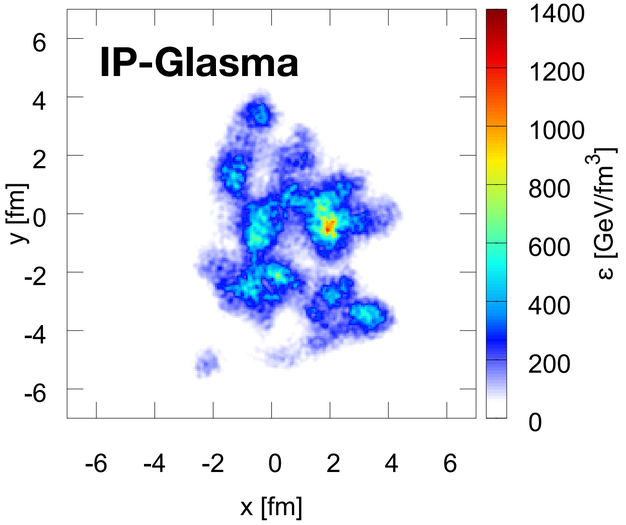
Jazma vs. IP-Glasma

https://github.com/jamienagle/IPJazma
https://github.com/schenke/ipglasma

- Jazma assumes that energy density is proportional to $\sim Q_{sA}^2 Q_{sB}^2$
- IP-Glasma solves Yang-Mills equations and provides $T^{\mu\nu}$





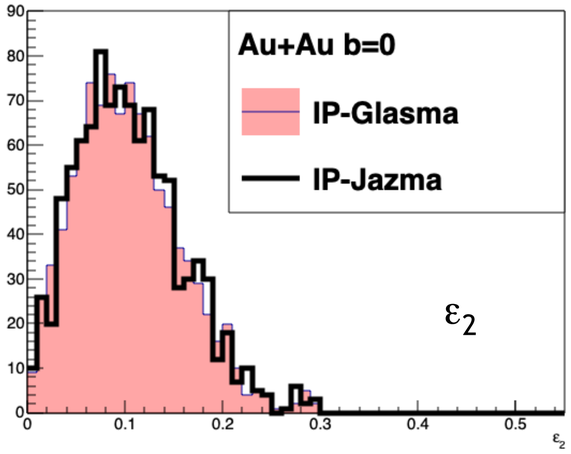


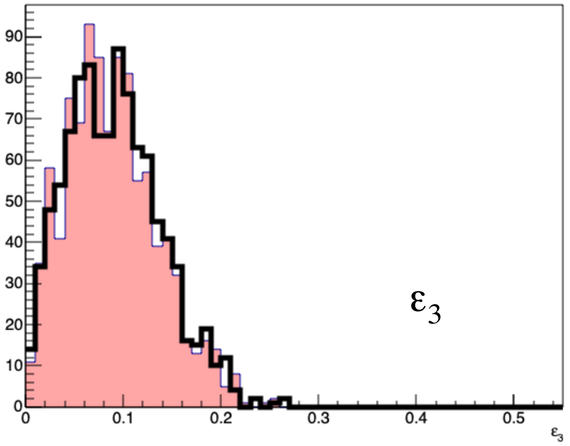
Jazma vs. IP-Glasma

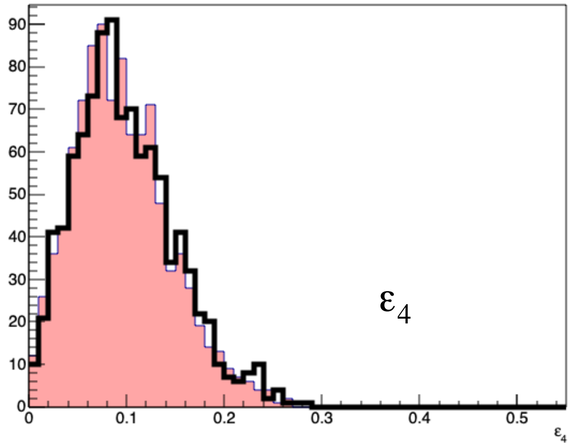
https://github.com/jamienagle/IPJazma
https://github.com/schenke/ipglasma

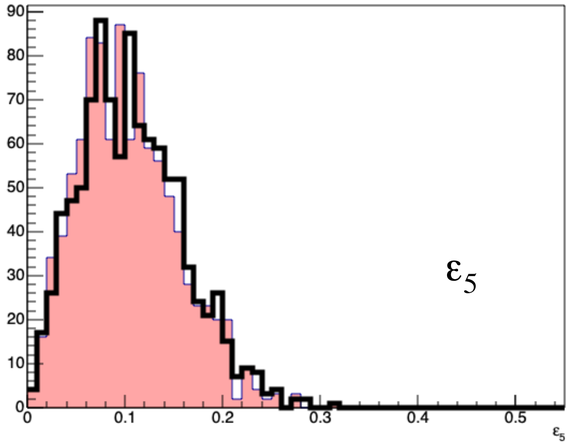
Jamie Nagle's talk

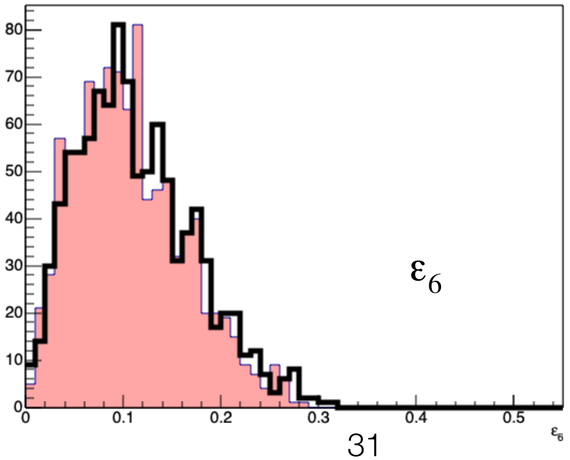
- Eccentricities are essentially the same in the two approaches







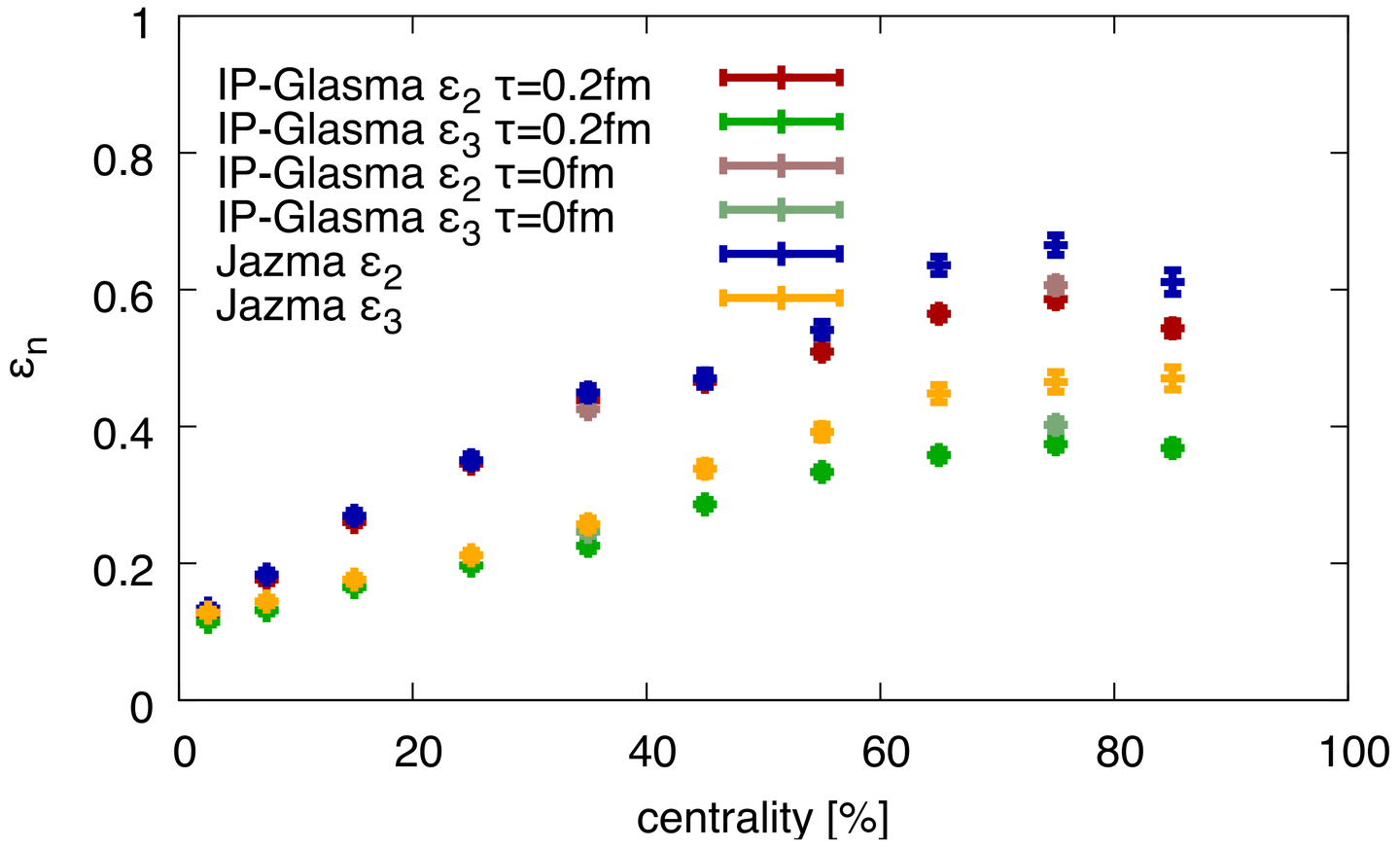




Jazma vs. IP-Glasma

https://github.com/jamienagle/IPJazma
https://github.com/schenke/ipglasma

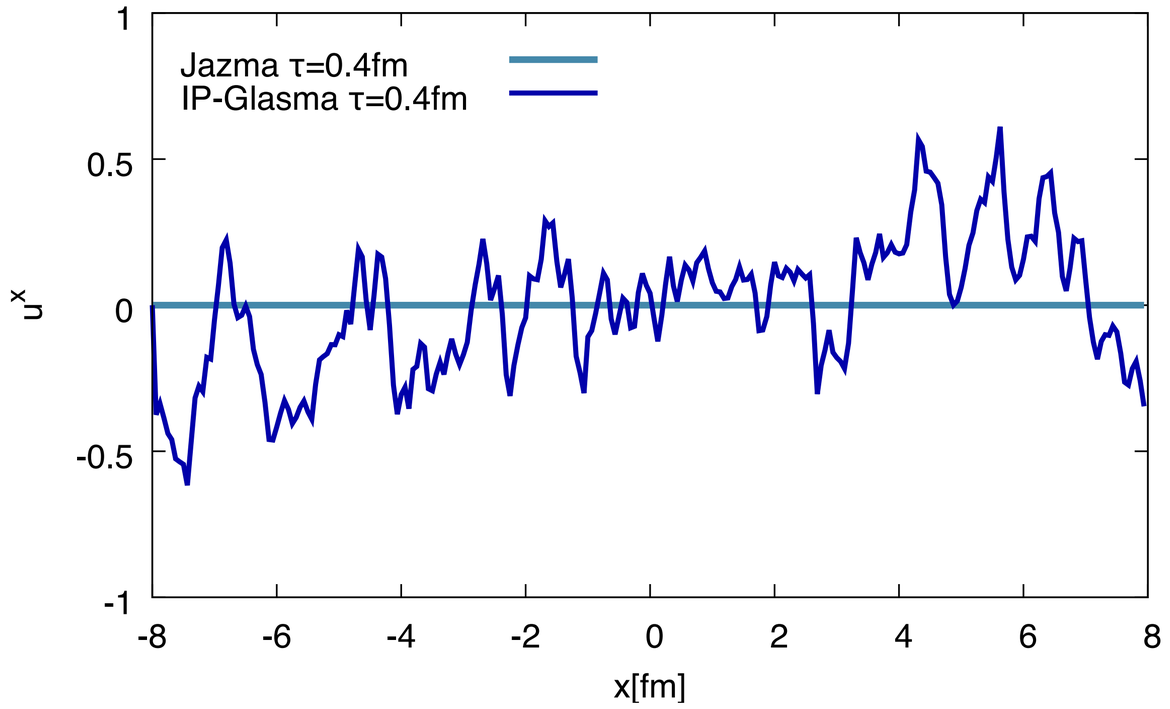
- With my Jazma model (slight difference) eccentricities deviate at larger b.

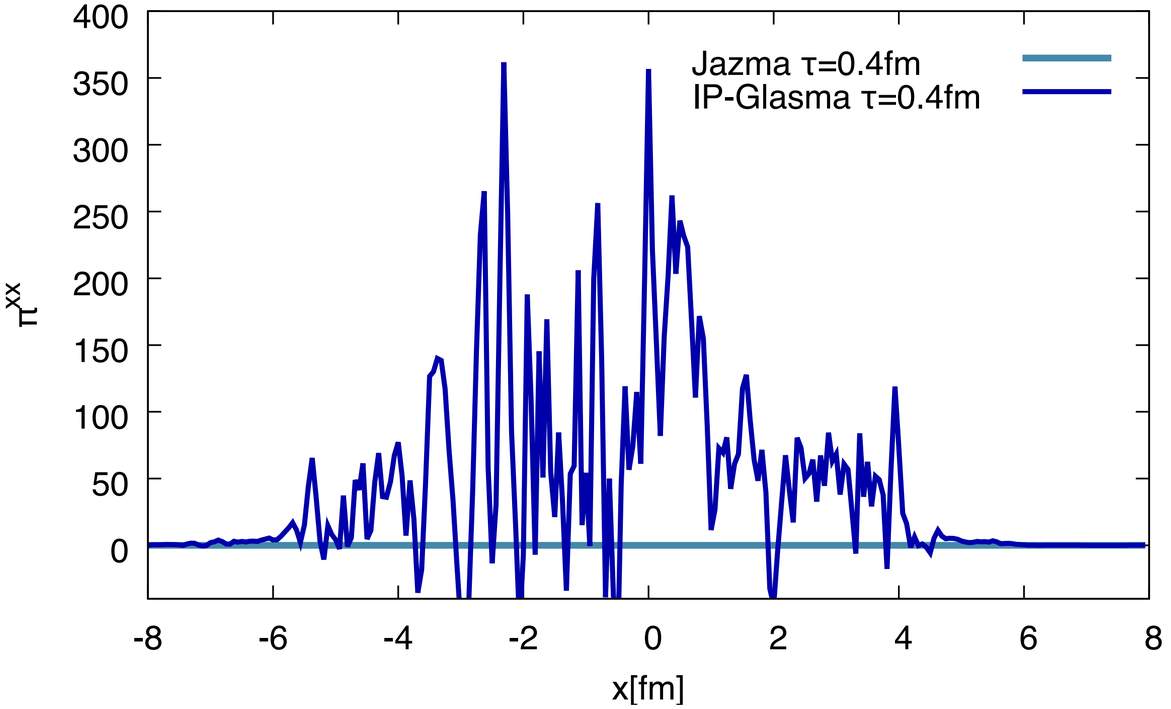


Jazma vs. IP-Glasma

https://github.com/jamienagle/IPJazma
https://github.com/schenke/ipglasma

- IP-Glasma provides $T^{\mu\nu}$
- Jazma does not have initial flow or off-equilibrium contributions



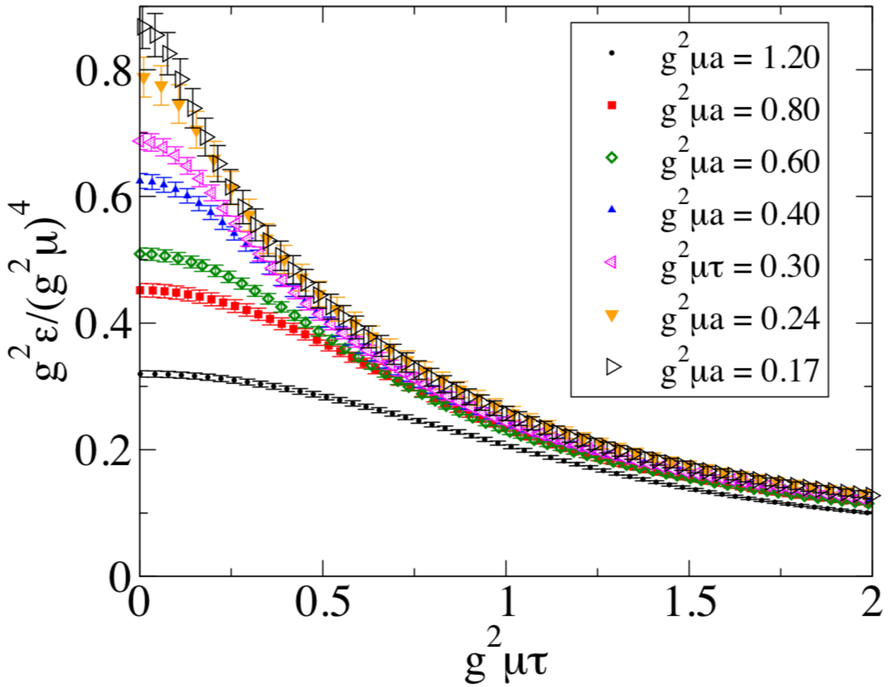


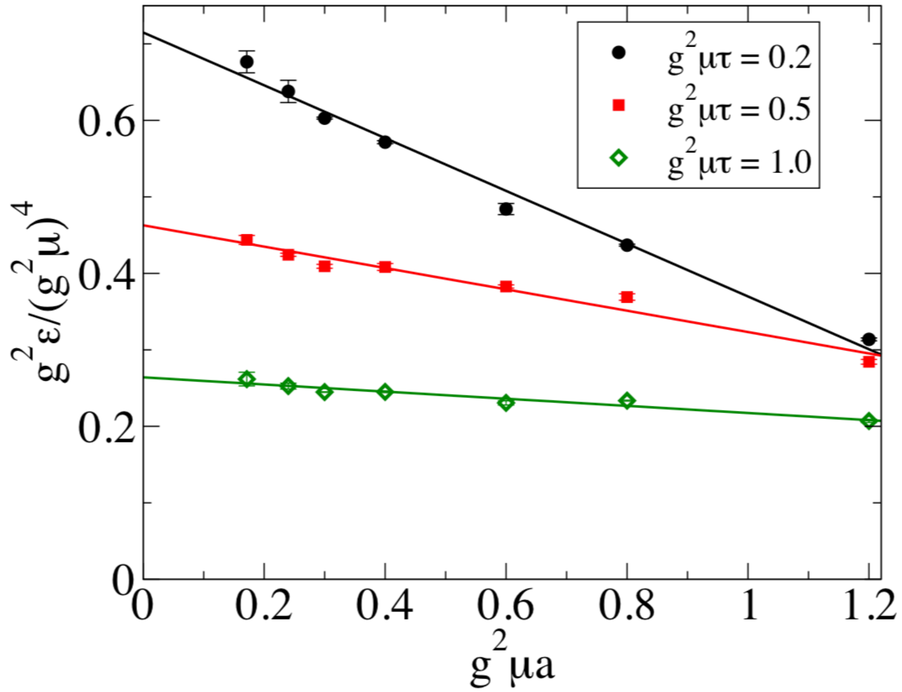
- This matters, especially in small systems

Lattice artifacts?

A. Krasnitz, R. Venugopalan, Phys.Rev.Lett. 84 (2000) 4309-4312, hep-ph/9909203
T. Lappi, Phys.Lett. B643 (2006) 11-16, hep-ph/0606207

- IP-Glasma at the initial time is affected by finite lattice spacing
- But they are gone by the time we match to hydrodynamics





Energy density diverges logarithmically at τ=0, but is finite for all τ>0
Solution of the field equations is well defined as an initial value problem only in the presence of an ultraviolet cutoff (inverse lattice spacing) in the transverse momenta, but for later times the system loses memory of this cutoff

Initial + final state

Model components

Hydro models

- Initial Geometry
- Pre-Hydrodynamic Flow
- Hydrodynamic Evolution
- Hadronization/Hadron Gas Dynamics
- Analysis

Initial State Models

- Initial Geometry
- Pre-Hydrodynamic Flow
- Analysis

Paul Romatschke's talk

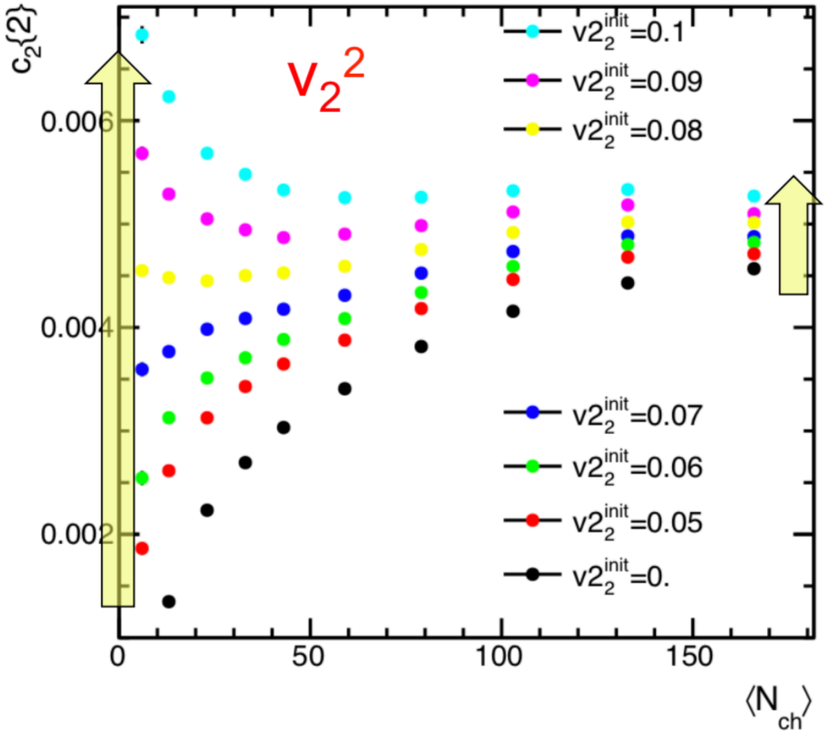
IMHO it is time to fully embrace the IS+fluid paradigm

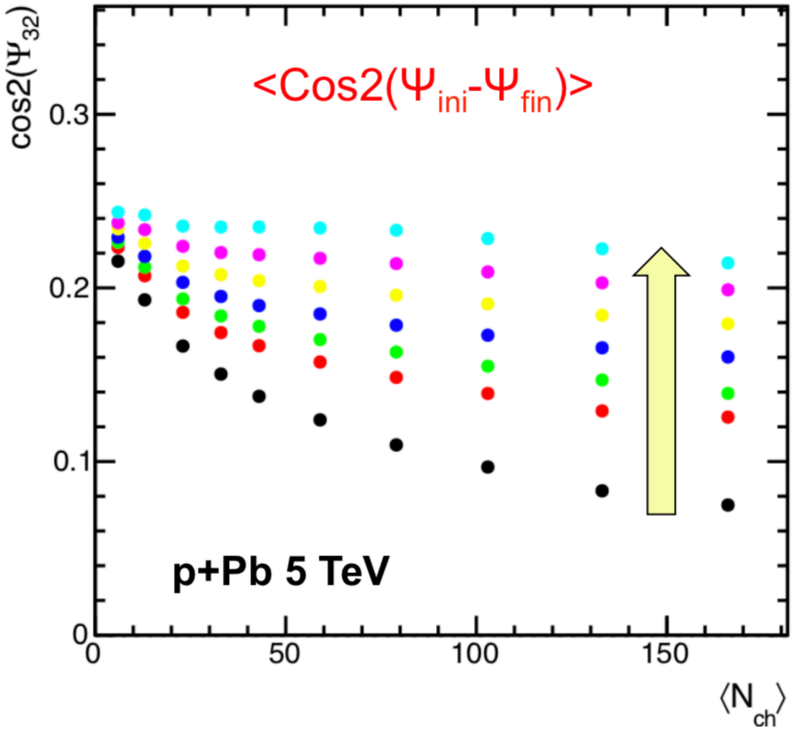
- All components should be there. Together.
  - Pre-flow should not be neglected (different models)
    We have IP-Glasma, AdS/CFT, free streaming, AMPT,…
  - Final state evolution should not be neglected
- Are there long range rapidity correlations and Bjorken expansion in AdS/CFT?

Initial and final state anisotropies

Jiangyong Jia's talk

- Low N_{ch} : Final flow <≈ Initial flow expected for free streaming
- High N_{ch}: Final flow increases slowly with initial flow.
- The final flow is biased toward the direction of the initial flow.



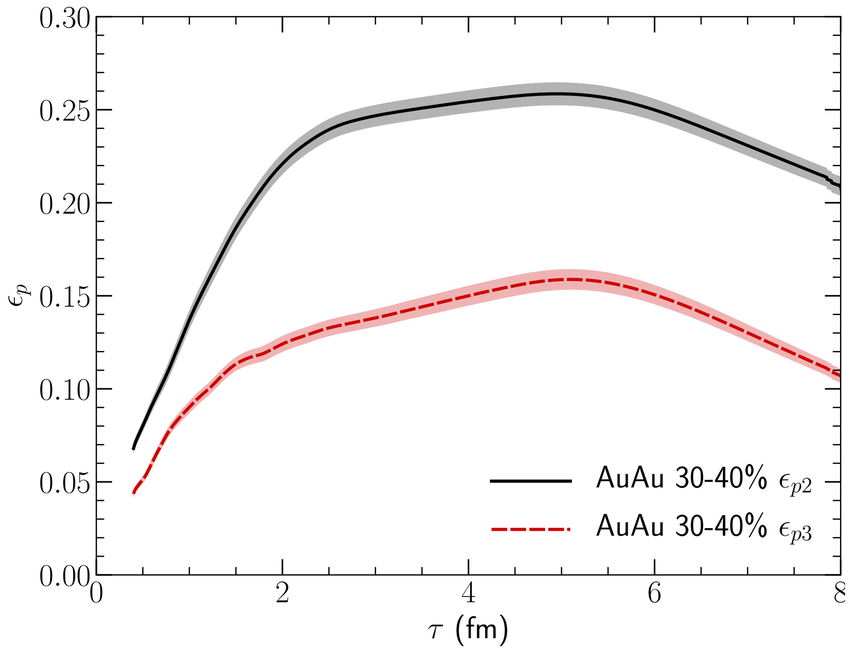


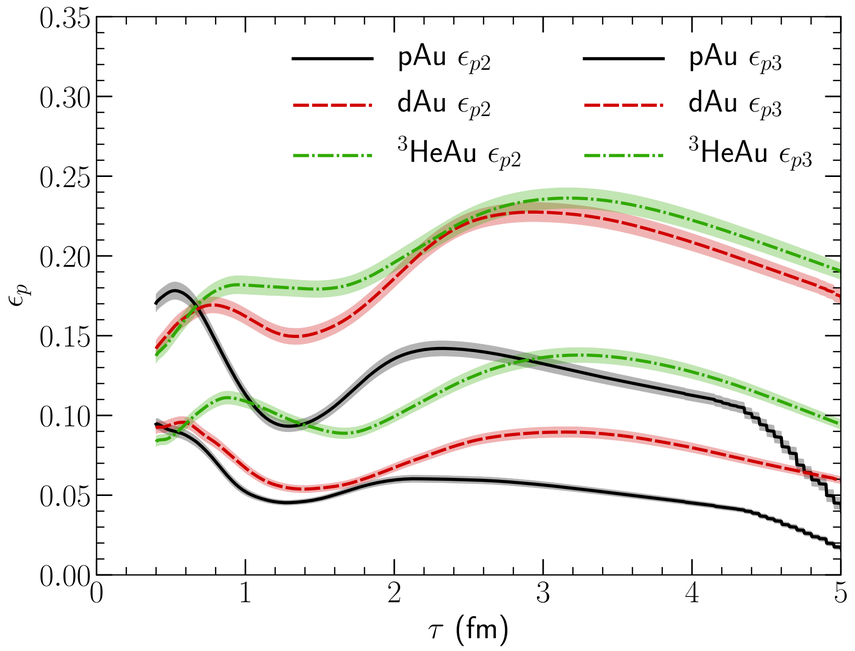
Initial flow could survive and bias the geometry-driven flow (in AMPT)

Initial and final state anisotropies

Chun Shen's talk

- IP-Glasma + Hydrodynamics has CGC initial anisotropy which is uncorrelated with the geometry
- Strong contribution from initial state to momentum anisotropy measure
- In the IP-Glasma phase ε_{pn}: pAu > dAu >≈ ^{3}HeAu > AuAu





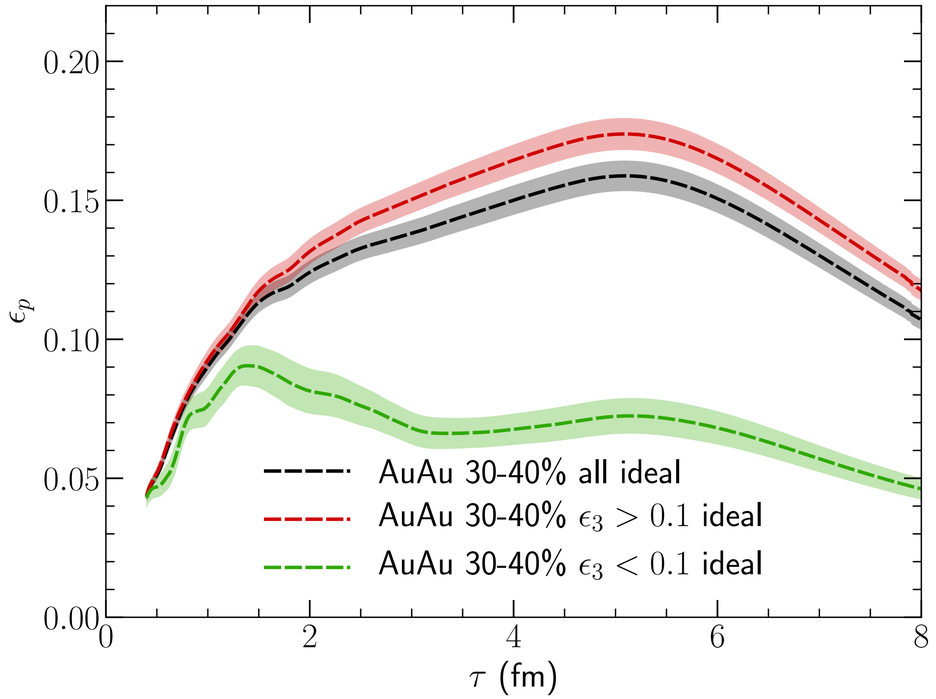
$$\epsilon'_{pn} = \sqrt{\frac{\langle T^{0r} cos(n\phi_u)\rangle^2 + \langle T^{0r} sin(n\phi_u)\rangle^2}{\langle T^{0r}\rangle^2}}$$

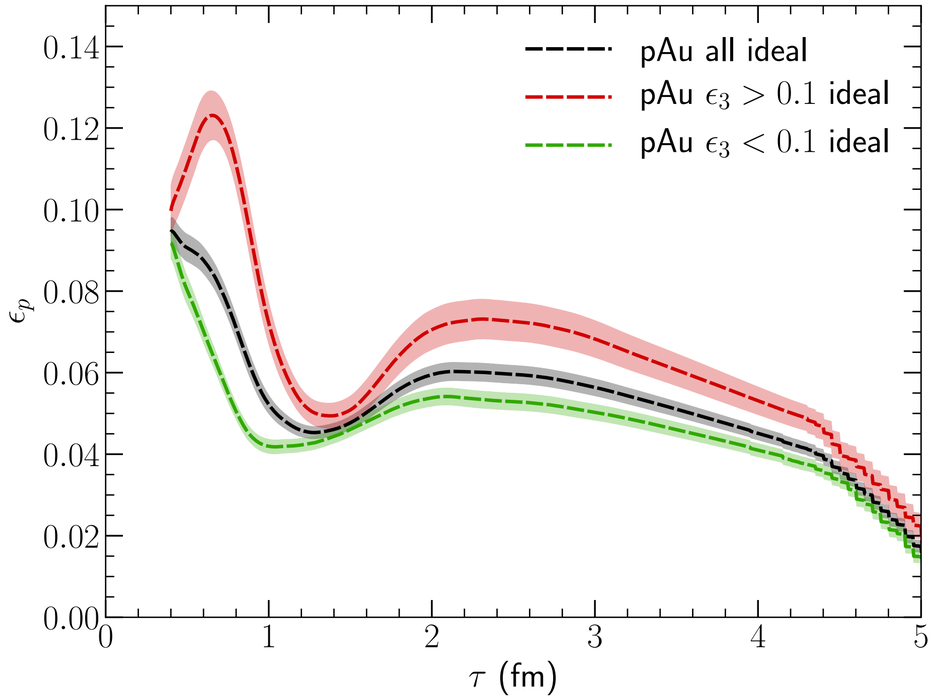
standing strong

Initial and final state anisotropies

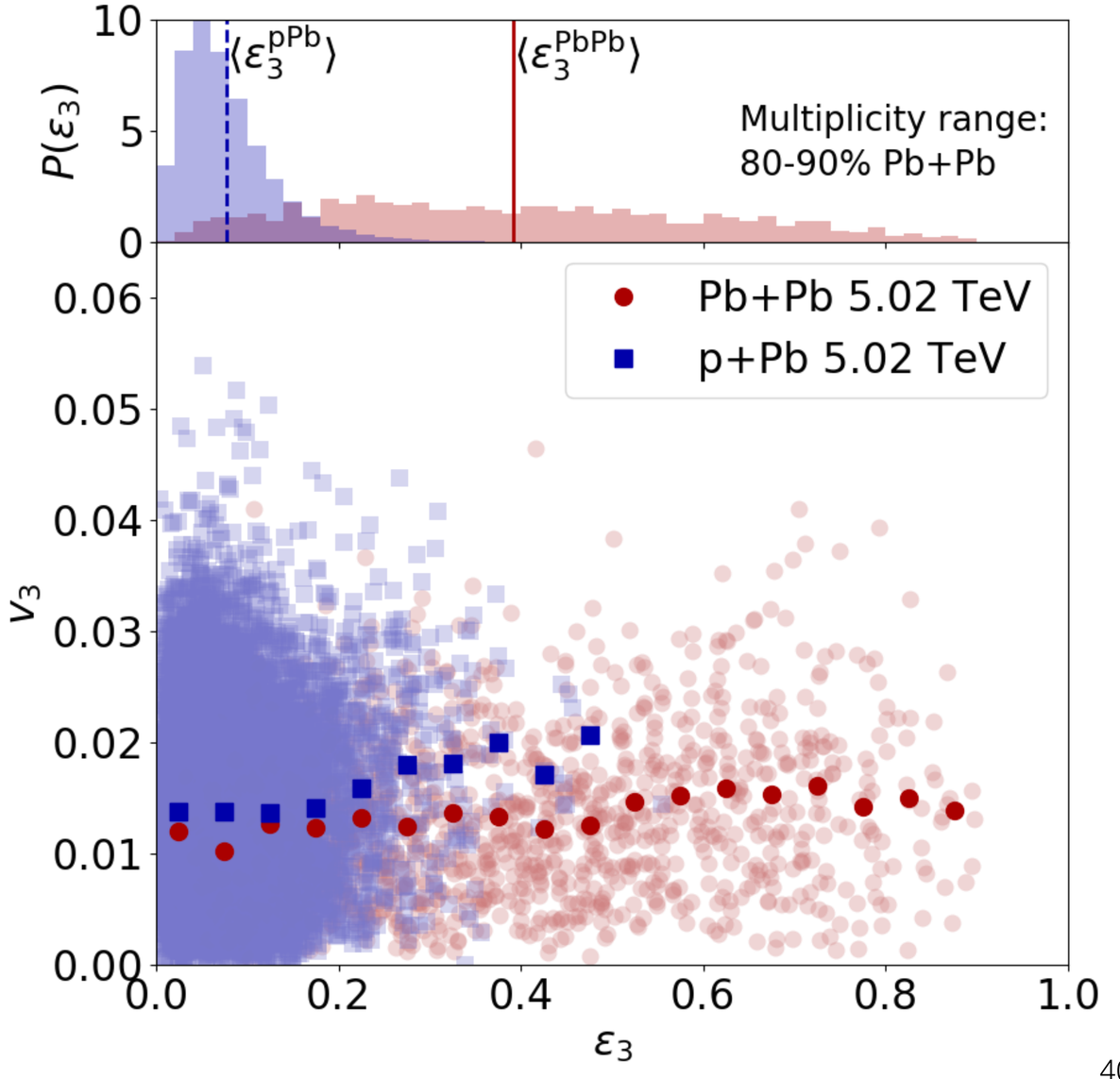
Chun Shen's talk

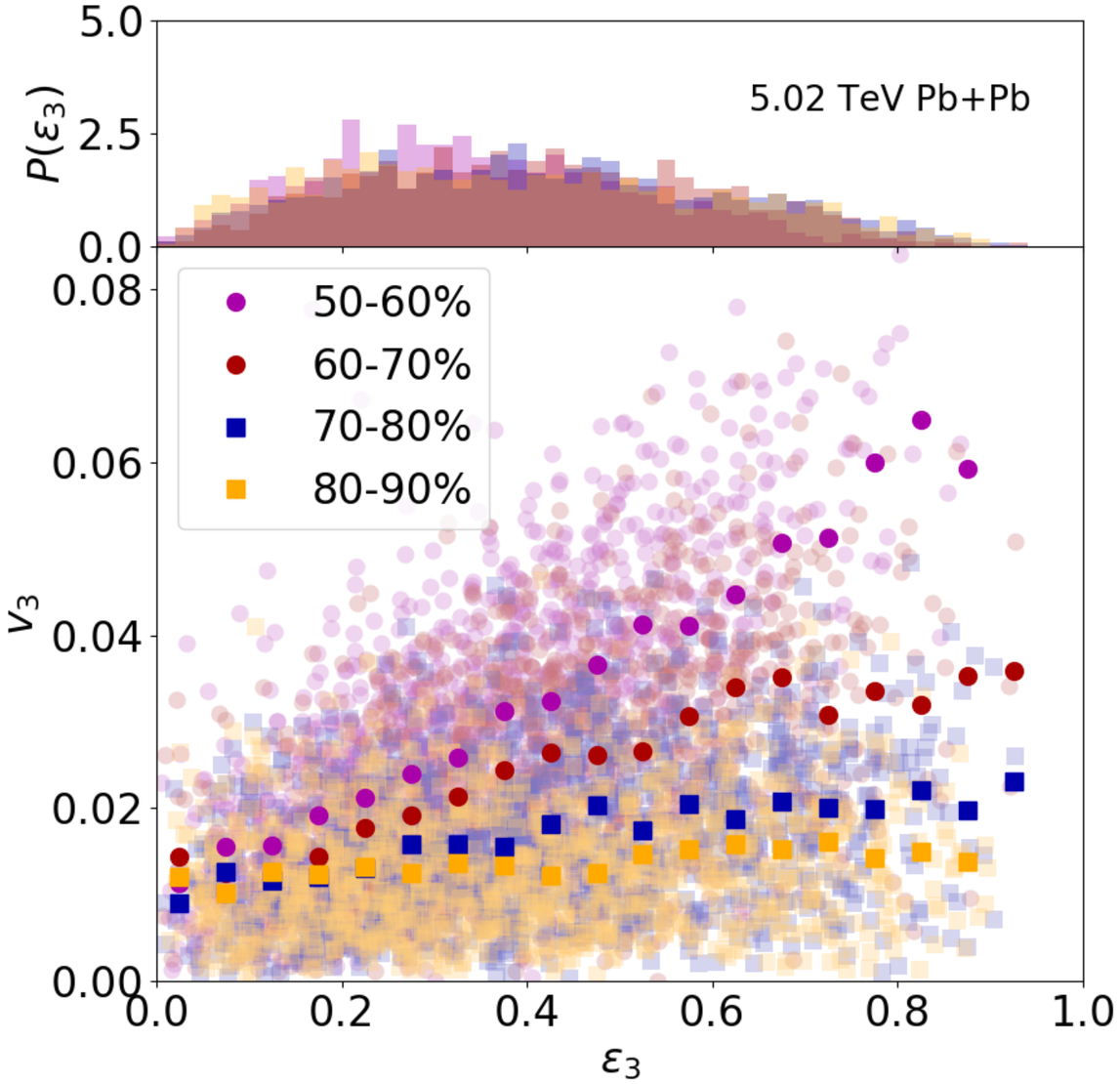
- IP-Glasma + Hydrodynamics has CGC initial anisotropy which is uncorrelated with the geometry
- Strong contribution from initial state to momentum anisotropy measure
- Hydrodynamic response to geometry develops around τ~2 fm/c in AuAu





Weak correlation between geometry and v_3

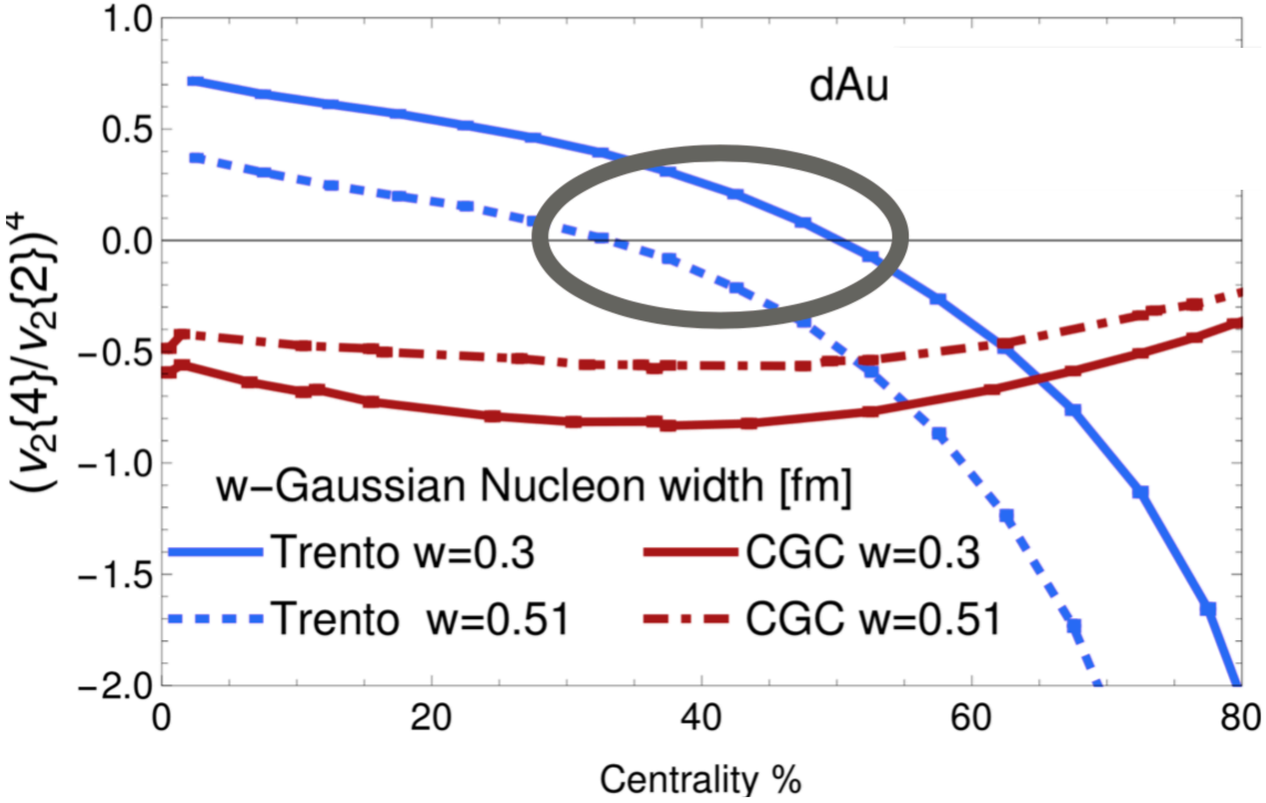




Sign of $c_2\{4\}$

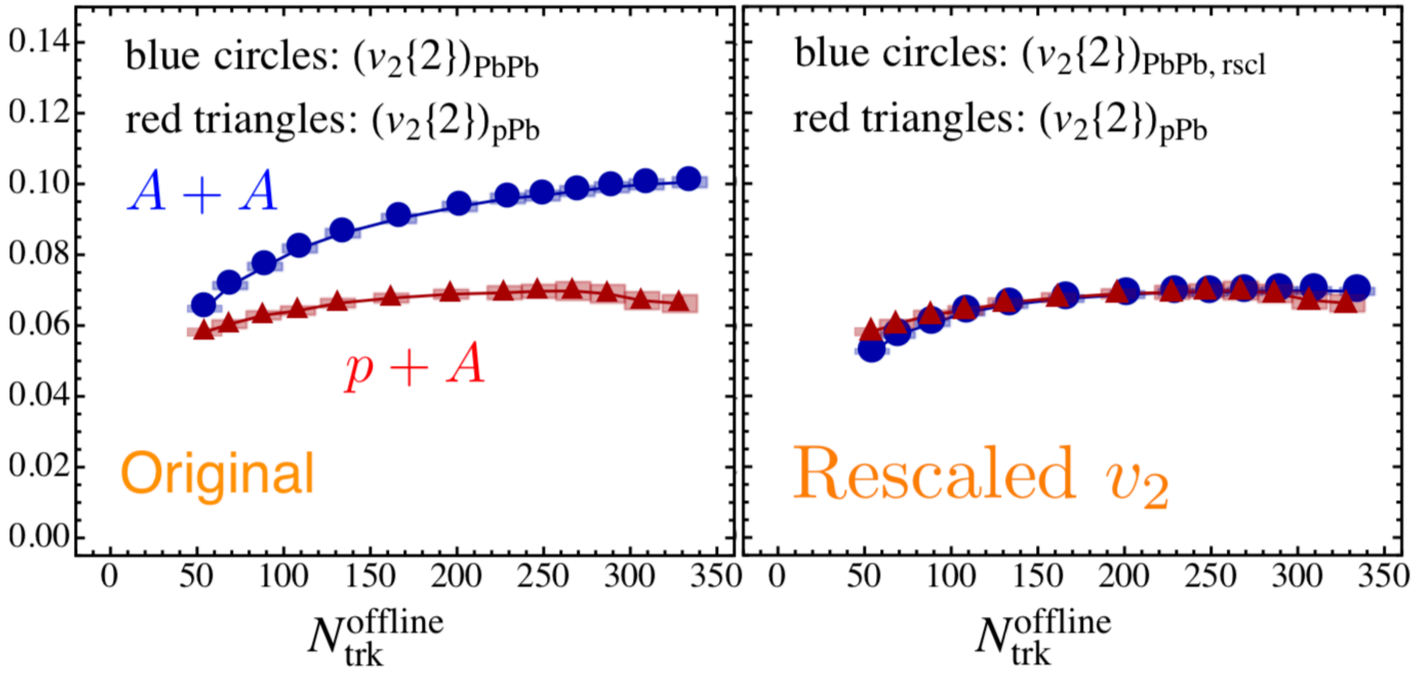
Jaki Noronha-Hostler's talk

- CGC picture: need anisotropy in single particle distribution to get negative c2{4}
- Geometry picture can get either sign depending on initial state model



- Data changes sign: Room for dominance of a source different from geometry at small multiplicity

Room for two contributions? Derek Teaney's talk



Fluctuation driven v_2's are equal to 5% accuracy!
Strong indication that v_2 is a response to geometry in $p + A$

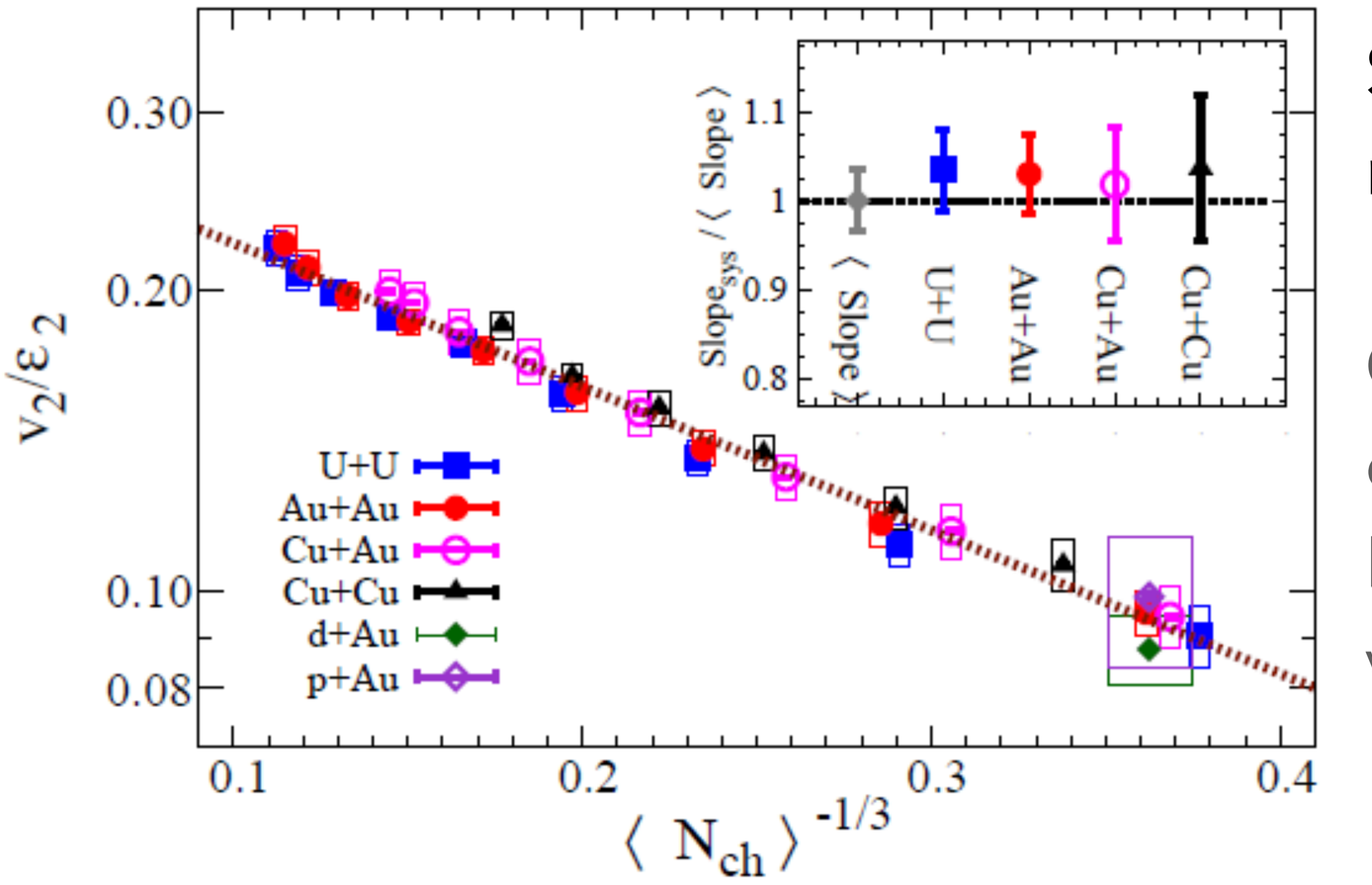
Argues response coefficients and geometries are the same

So if there is pre-flow it has to be also geometry driven

Scaling of all systems

Roy Lacey's talk

arXiv:1901.08155



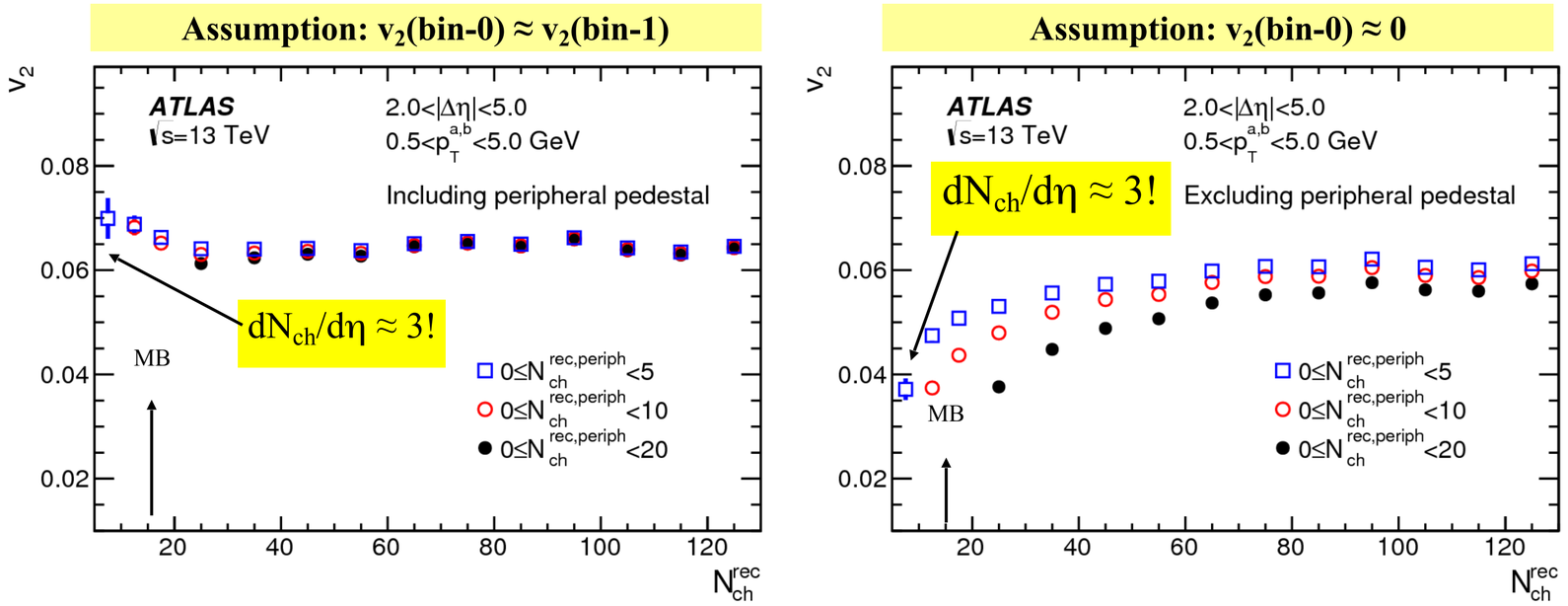
Same N_{ch} means same response coefficient

Characteristic 1/(RT) viscous damping validated
Both eccentricities and viscous damping matter

Can we turn hydrodynamics off?

No obvious onset of flow

Jürgen Schukraft's talk



- Significant v_2 down to dN/dη~3
- Also smooth behavior of p/π ratio vs. N_{ch} (radial flow)
- Smooth behavior of strangeness enhancement vs. multiplicity through all systems

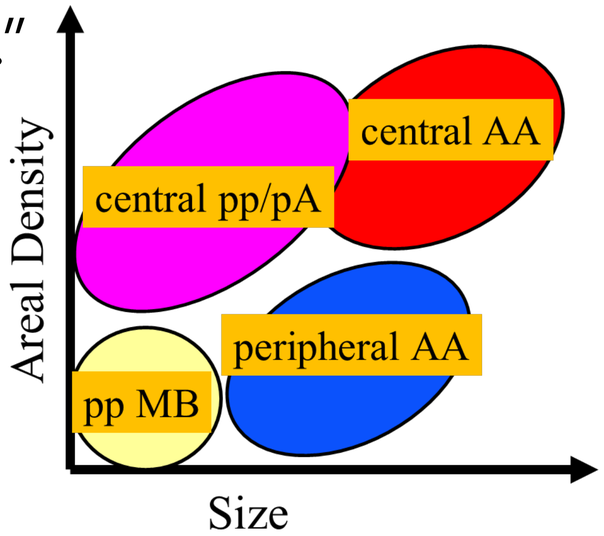
Can we turn hydrodynamics off?

- Maybe an Electron Ion Collider can help
- e+p or e+A collisions at low Q^2 are like a vector meson colliding with the target - similar to p+A - low momentum modes can act hydrodynamically (need quite large W)
- Varying Q^2 could be the extra handle we need to turn hydro off

Better observables and methods

Jiangyong Jia and Maxime Guilbaud's talk
Roy Lacey and Jürgen Schukraft's talk

- Explore all the observables and methods developed in A+A system
- "The azimuthal anisotropy in systems spanning the broadest range of collision-system sizes, shapes and asymmetries should be employed for any meaningful distinction between Flow and CGC-EFT models."
- Two-particle correlations
  - Understand non-flow subtraction systematics.
  - Quantify behavior of collectivity at low N_{ch}
- Three- and four-particle correlations
  - Nature of the EbyE fluctuations $c_n\{4\}$ **(see Jaki's talk)**
  - Correlation between different harmonics: symmetric & asymmetric cumulants
  - Subevent method to suppress non-flow
- Find observables and event classification that are usable for all

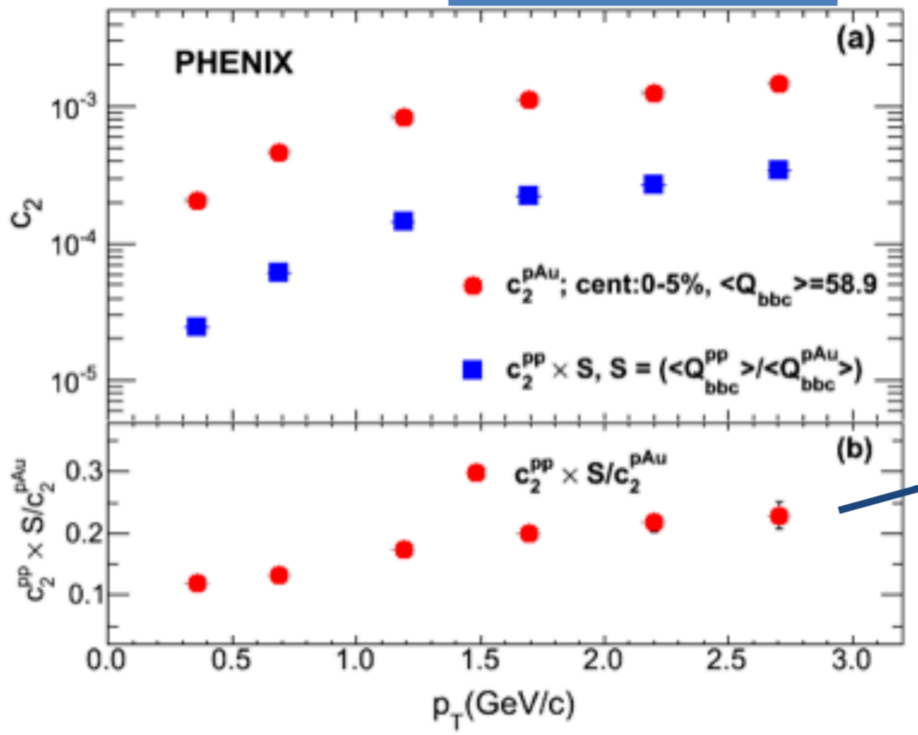


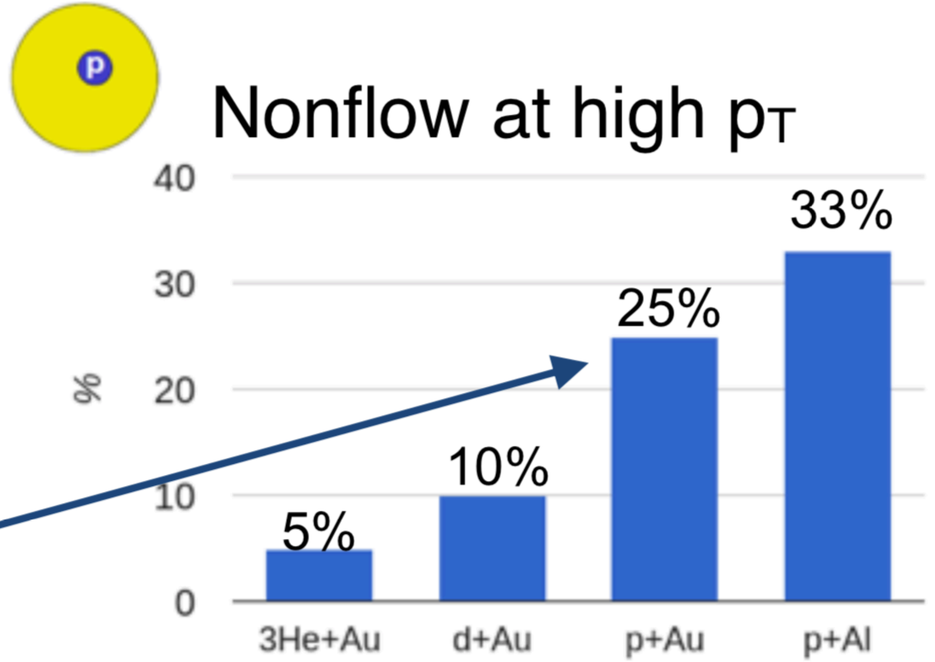
“Non-flow”

Julia Velkovska’s talk

arXiv:1609.02894

Central p+Au

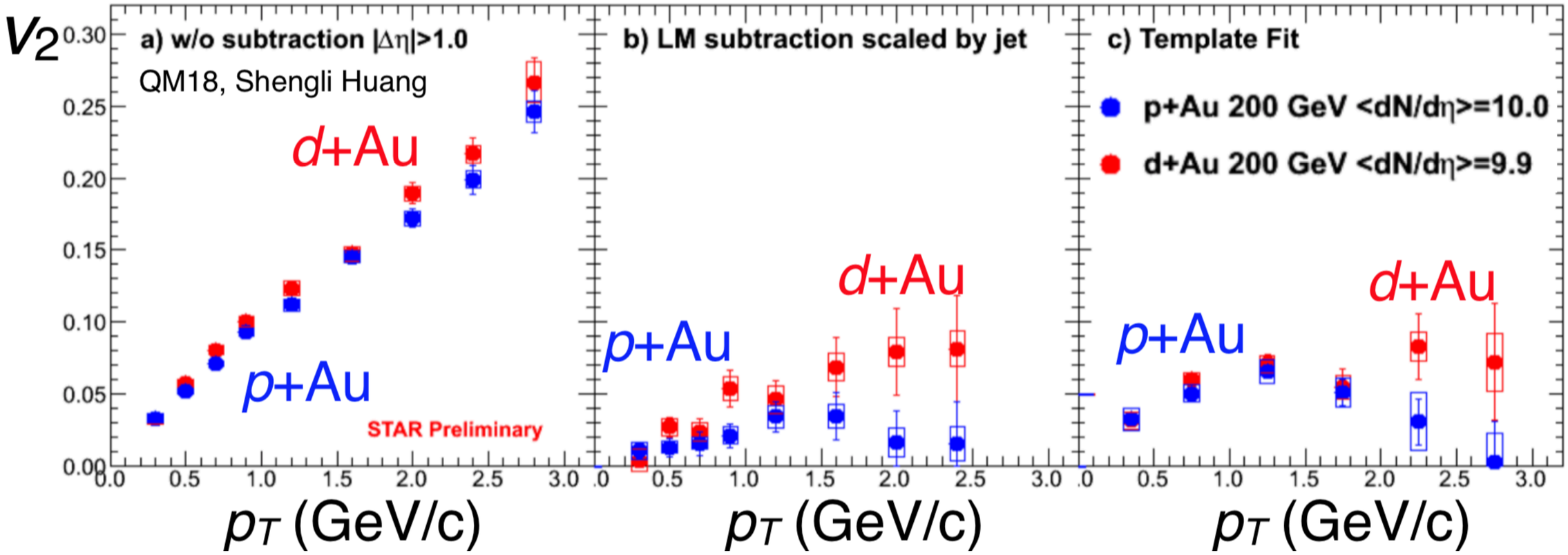




- Estimated by multiplicity scaled min-bias pp c_2
- At low p_T <1.5GeV all subtraction methods yield the same result
- Avoid short-range correlations with large $\Delta\eta$ separation

"Non-flow"

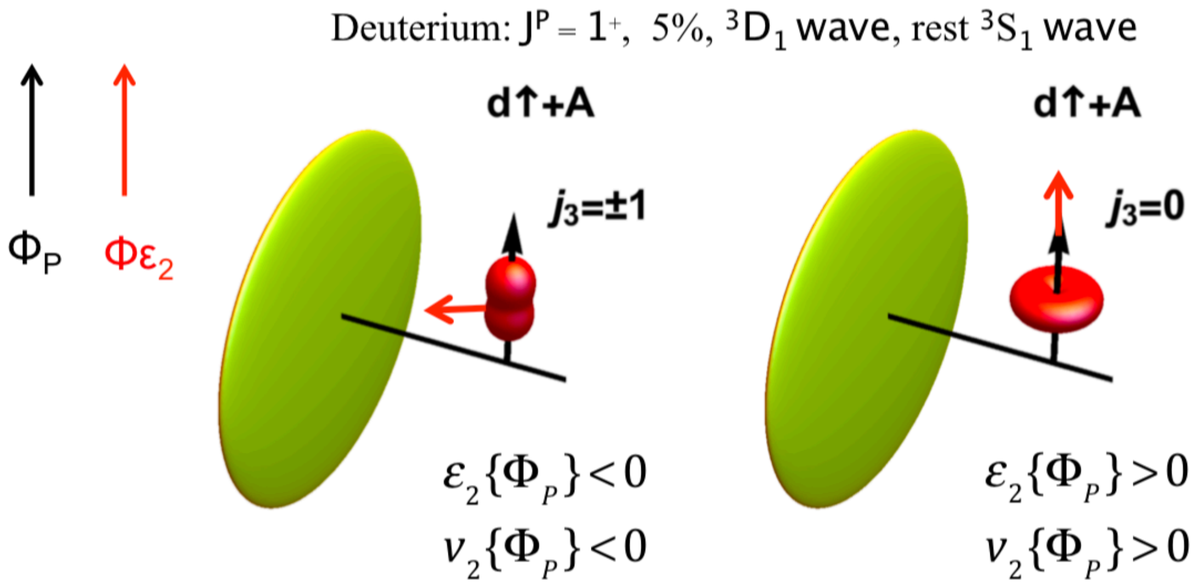
Julia Velkovska's talk



- In p+Au STAR sees large differences between different subtraction methods
- Template fit method has p+Au v_2 ≈ d+Au v_2

Flow with polarized light-ion+A collisions

Jiangyong Jia's talk



- Polarization direction serves as an absolute reference
  - uncorrelated with jets
  - Eccentricity projected to Φ_P has opposite sign
- The estimated signal is very small.

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Phi_P)\right] \quad v_2 \simeq k\epsilon_2, \quad k \sim 0.2$$

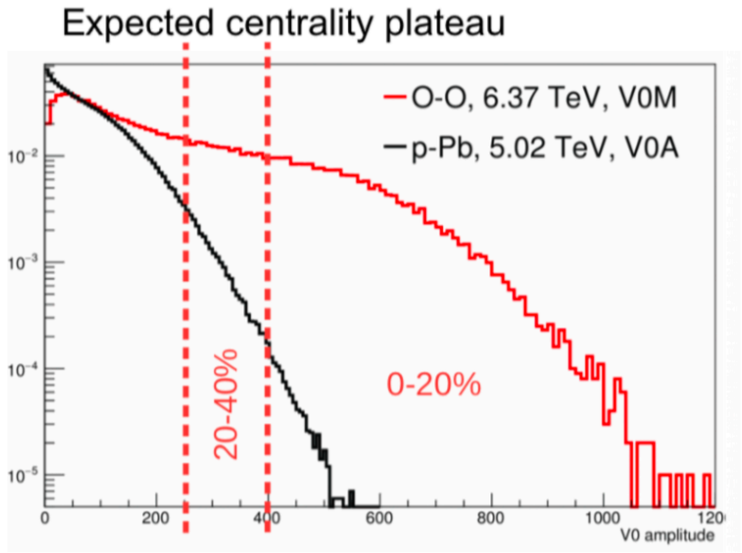
With 50% polarization: $-0.5\% \lesssim v_2\{\Phi_P\} \lesssim 1\%$

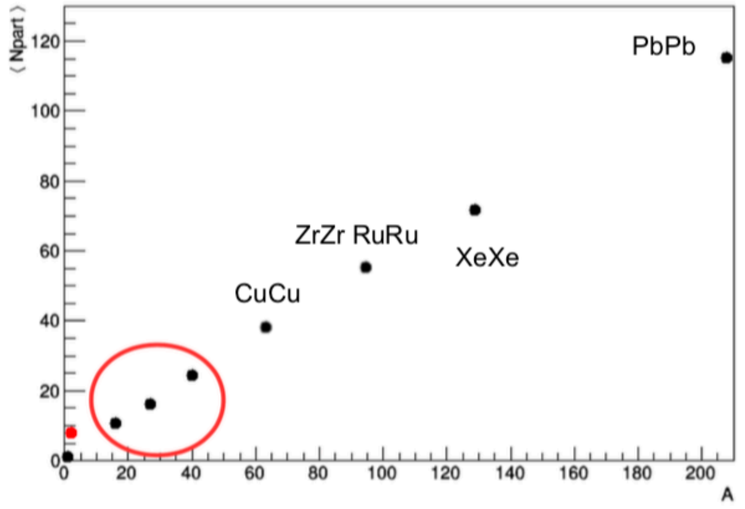
A case for small symmetric systems

Jiangyong Jia's talk

- Cleaner selection of geometry (centrality plateau helps)
- System may be large enough for jet quenching
- Can do a system scan

  $(^{12}C+^{12}C, ^{16}O+^{16}O, ^{32}S+^{32}S, ^{40}Ar+^{40}Ar)$
- Reduce decorrelation effect along the longitudinal direction
- Compare RHIC and LHC energies (different role of fluctuations expected)





Summary^2

- Geometry driven effects likely dominant at lowest p_T and highest multiplicities
- If weak coupling limit is good, CGC predicts momentum anisotropies:
  - they are of similar size as the anisotropies from the final state and we can probably agree that they are extremely interesting
- Both should be there, but we are only beginning to study models that contain both initial and final state correlations
- Big issues: hadronization, comparing apples-to-apples (centrality selection/multiplicity experiment vs. theory), applicability of limits where we can do calculations (both weak and strong coupling)
- Working together has proven very useful for understanding each others work - so has this workshop

BACKUP

Color Glass Condensate

Alex Kovner's talk

Which dominates? Quantum or classical?
Quantum correlations are leading in $1/(SQ_s^2)$, S=projectile area

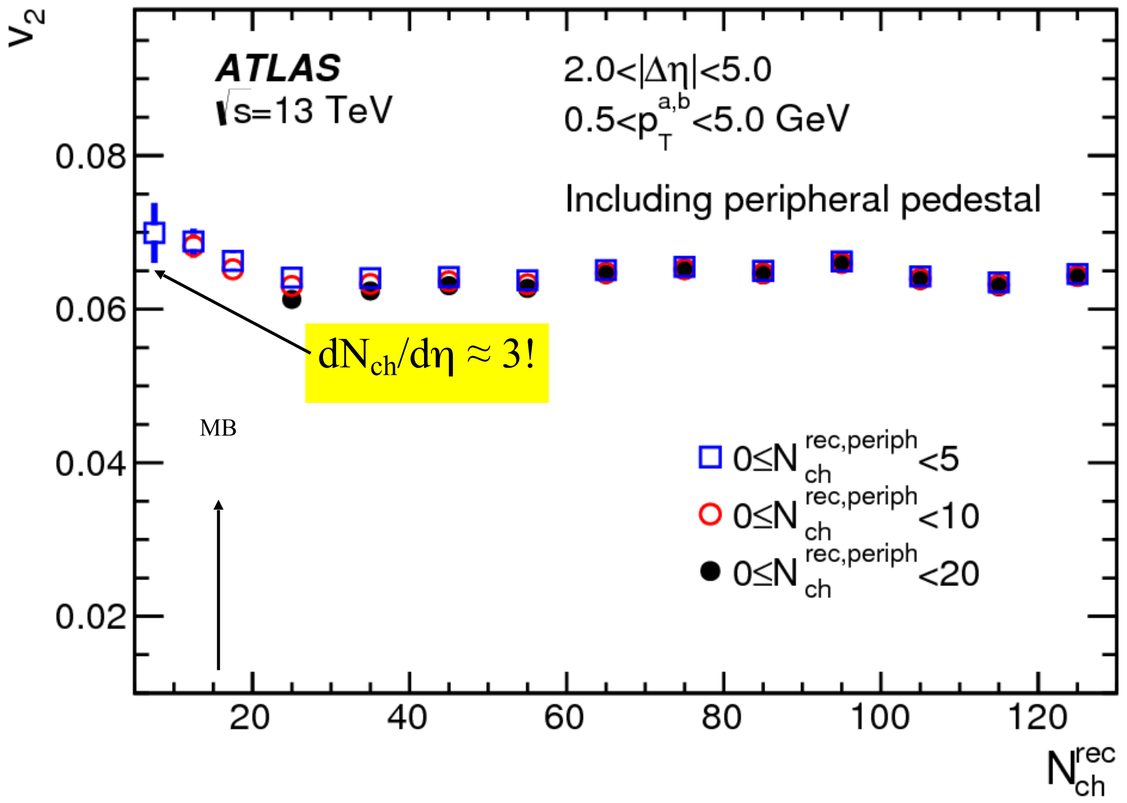
But quantum correlations are narrow in momentum:
Width of BE correlation: $\Delta k \sim Q_s$
Width of the HBT correlation $\Delta k \sim \Lambda_{QCD}$
Both sharply peaked around |k| = |p|.
For a wide momentum bin quantum correlations are suppressed

Classical are present also if $|k| \ll |p|$.
Local anisotropy correlation scales inverse proportionally to the number of domains, and thus $1/Q_s^2$. Decreases with increasing energy

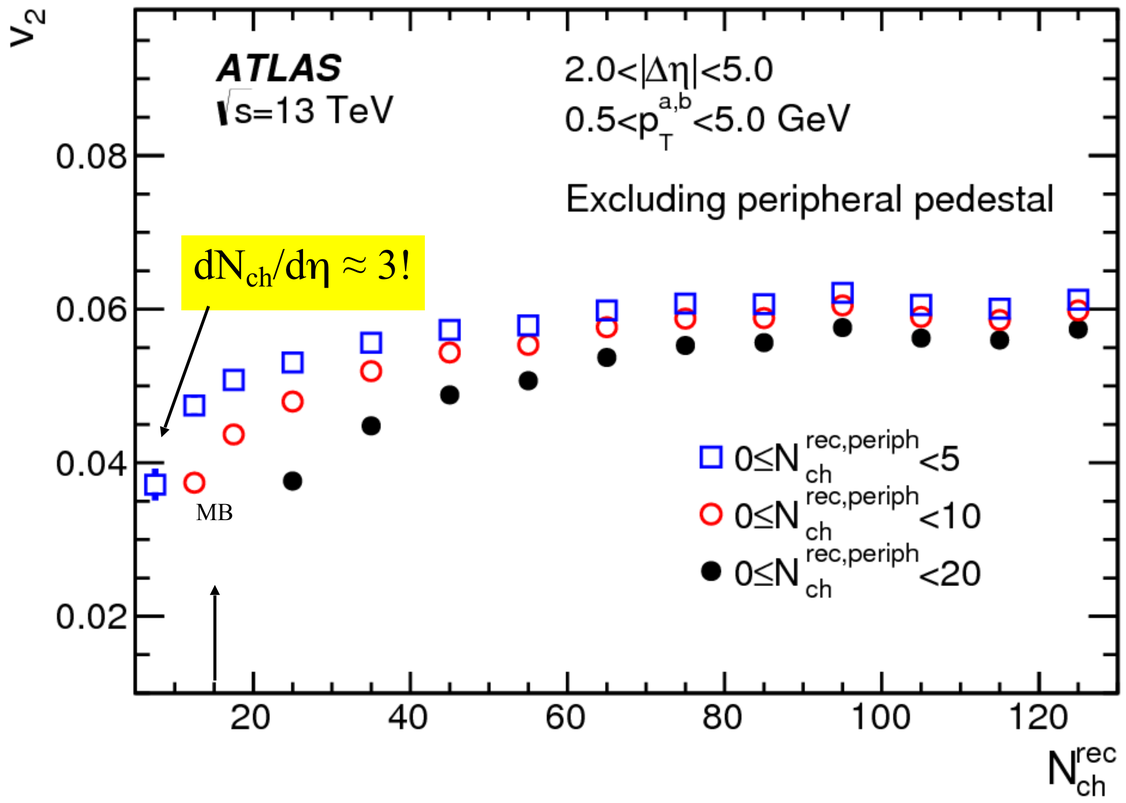
“Non-flow” subtraction

Jürgen Schukraft’s talk

Assumption: v_2(bin-0) ≈ v_2(bin-1)



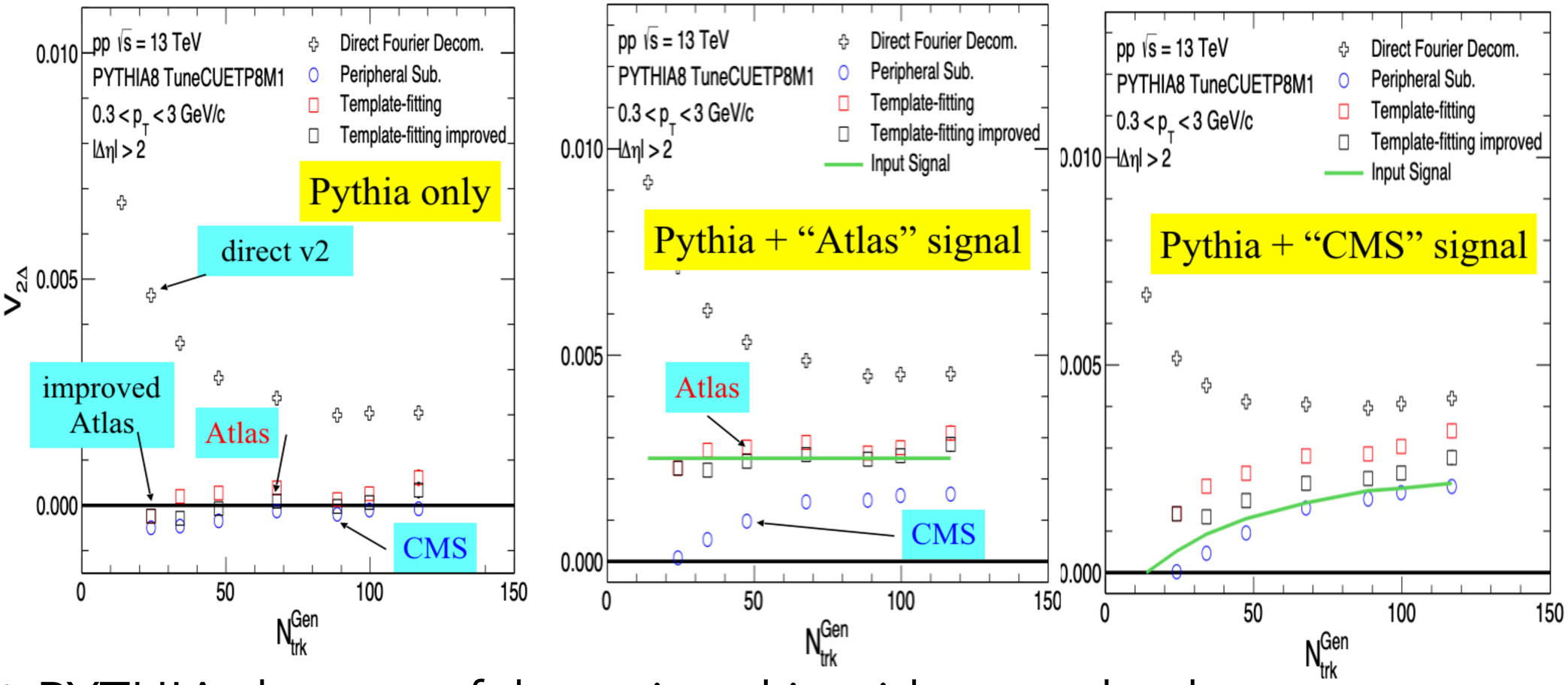
Assumption: v_2(bin-0) ≈ 0



Significant v_2 down to dN/dη~3

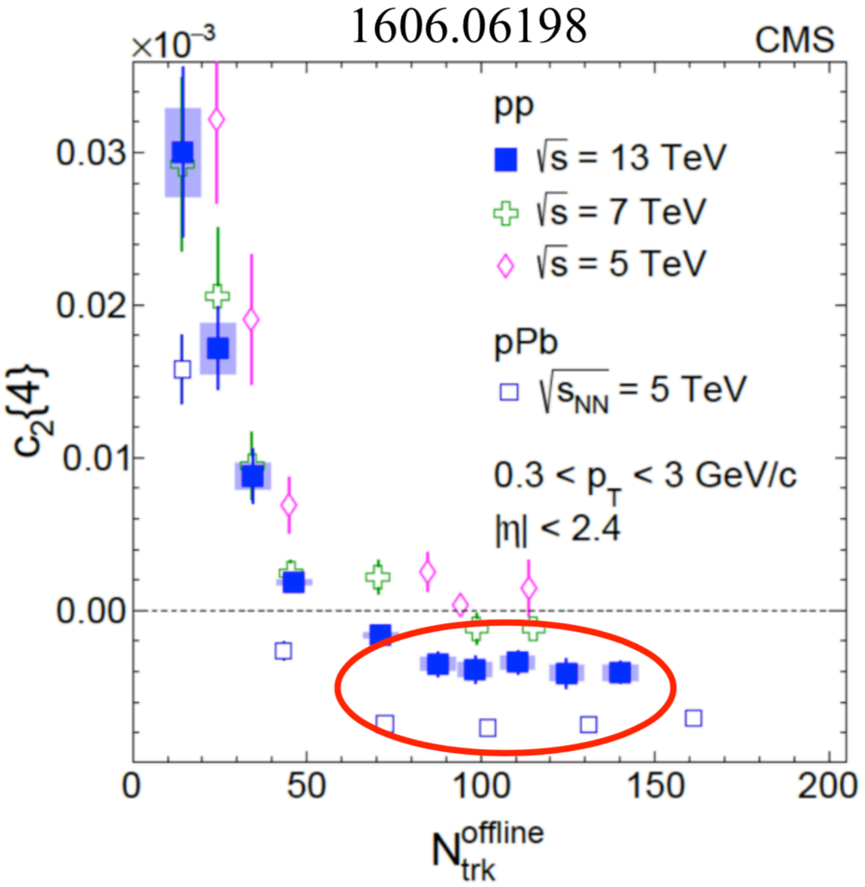
"Non-flow"

Jürgen Schukraft's talk



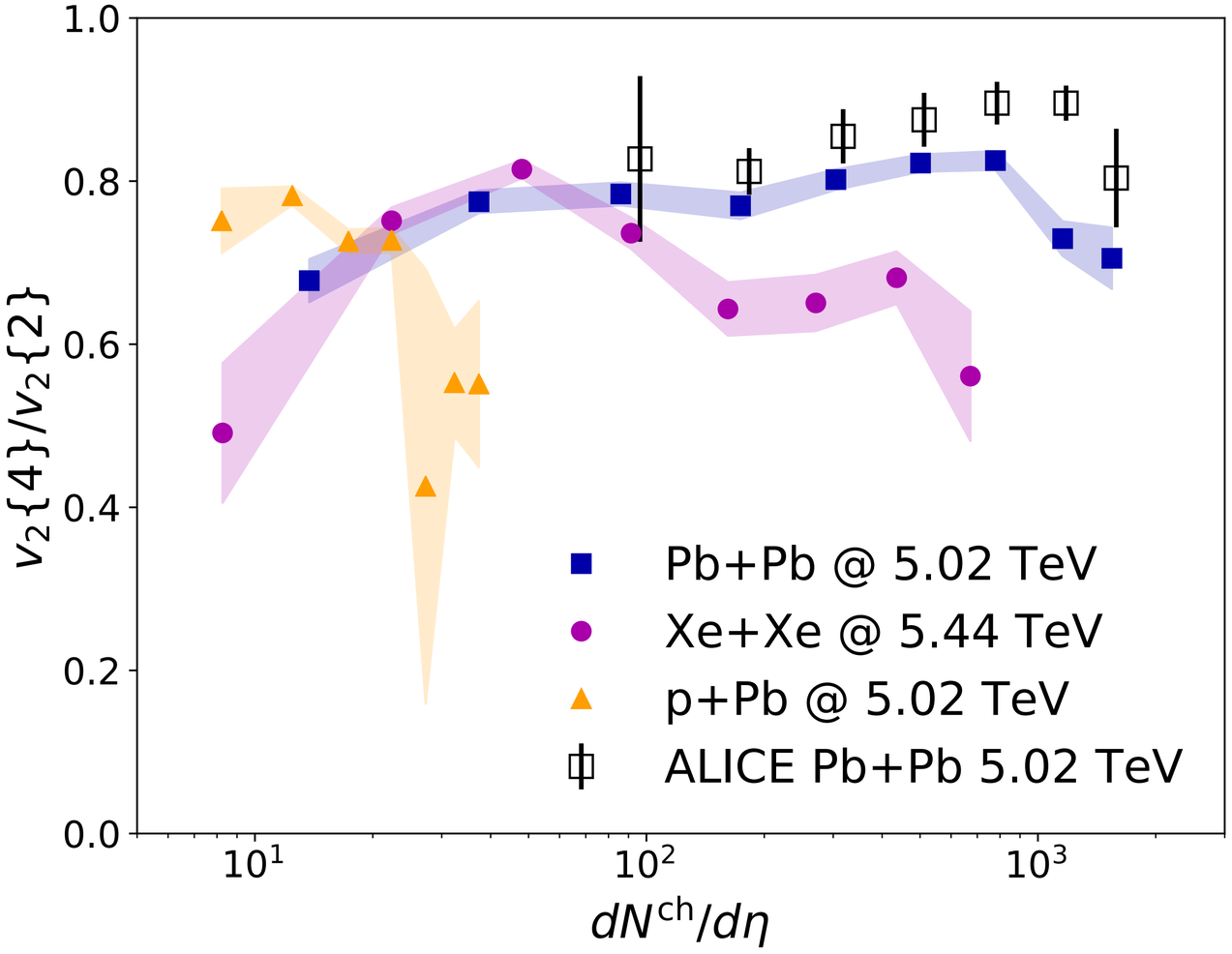
- PYTHIA does not fake a signal in either method

Multi-particle correlations Jiangyong Jia's talk



Cumulant ratios

B. Schenke, C. Shen, P. Tribedy, in preparation



Experimental data: J. Adam et al. (ALICE), Phys. Rev. Lett. 116, 132302 (2016)

"Non-flow"

Jiangyong Jia's talk

- In small systems we cannot see flow in a single event

N_{ch}	20	100	1000
5% flow in/out plane diff v_2N	±1	±5	±50
Random noise in/out plane diff	±3	±7	±22

- Assume N particles from N/2 resonances. It gives real two-particle correlation with a strength of $v_2 \sim \sqrt{\frac{1}{2N}}$

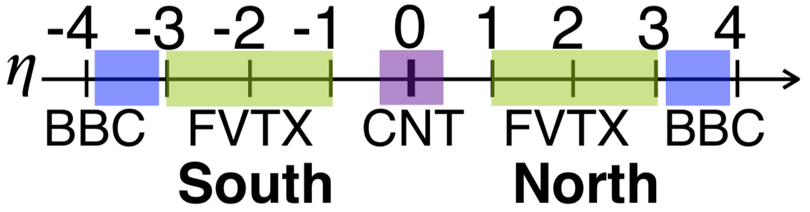
N_{ch}	20	100	1000
Correlated pairs	10	50	500
v_2^B	22%	10%	3%

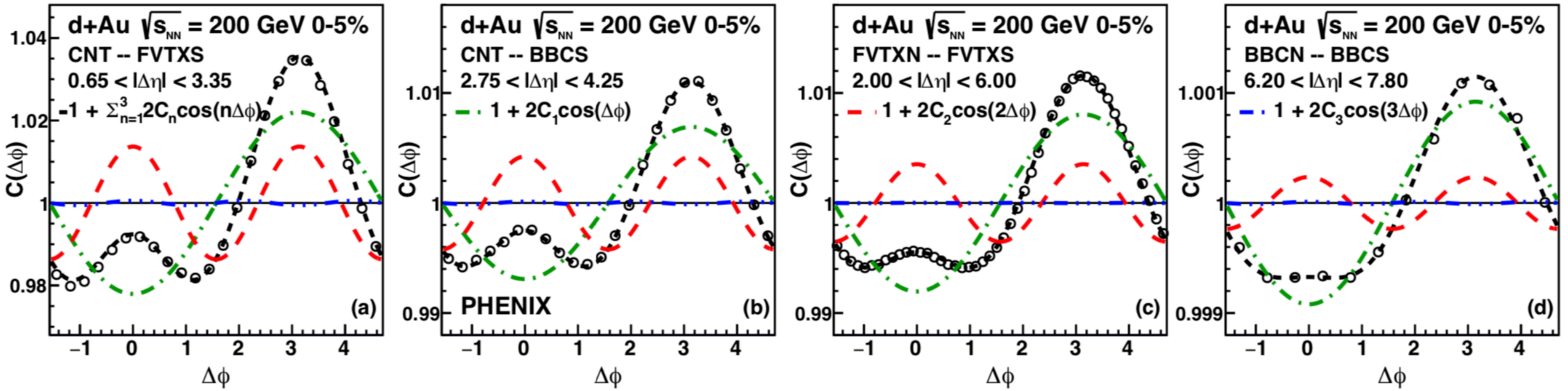
- Large raw 2PC v_2^{obs} in small systems does not necessary imply event-wise collectivity since real $v_2 < v_2^B$ Multi-particle correlation a must in small systems!

Experimental results

Julia Velkovska's talk

PHENIX 2016 data has high statistics and covers large Δη range





A sizable c_2 component is seen even for $6.2 < |\Delta\eta| < 7.8$