Experiment Review in small system

collectivity and thermalization in pp, pA/dA/HeA collisions

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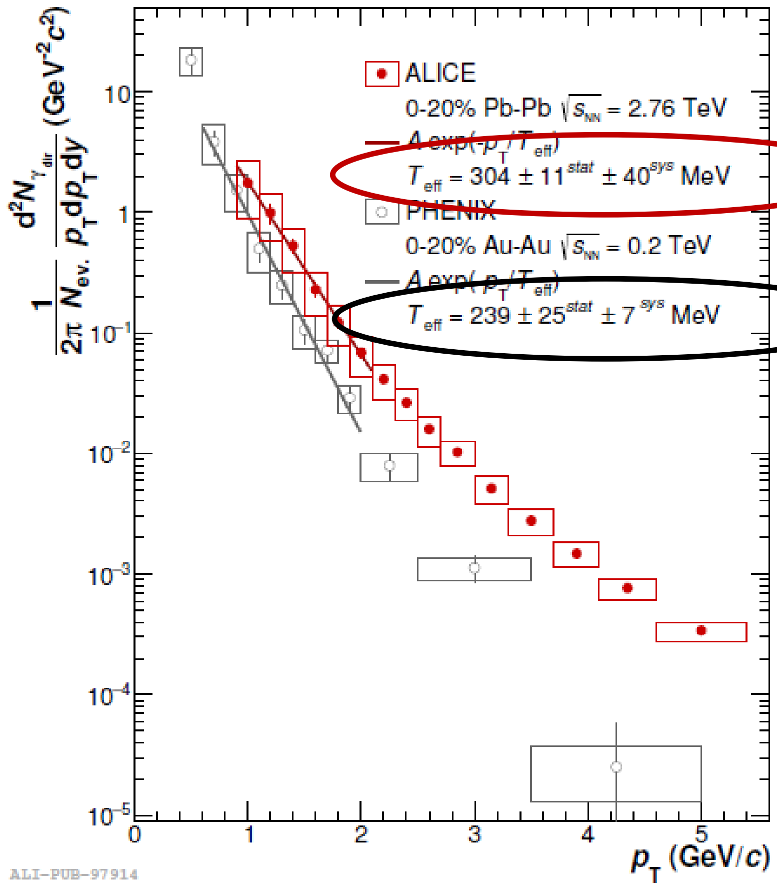
outline

- Introduction
- Ridge and anisotropy in pp collision
- Ridge and anisotropy in p/d/^{3}He+Au collision
- Summary

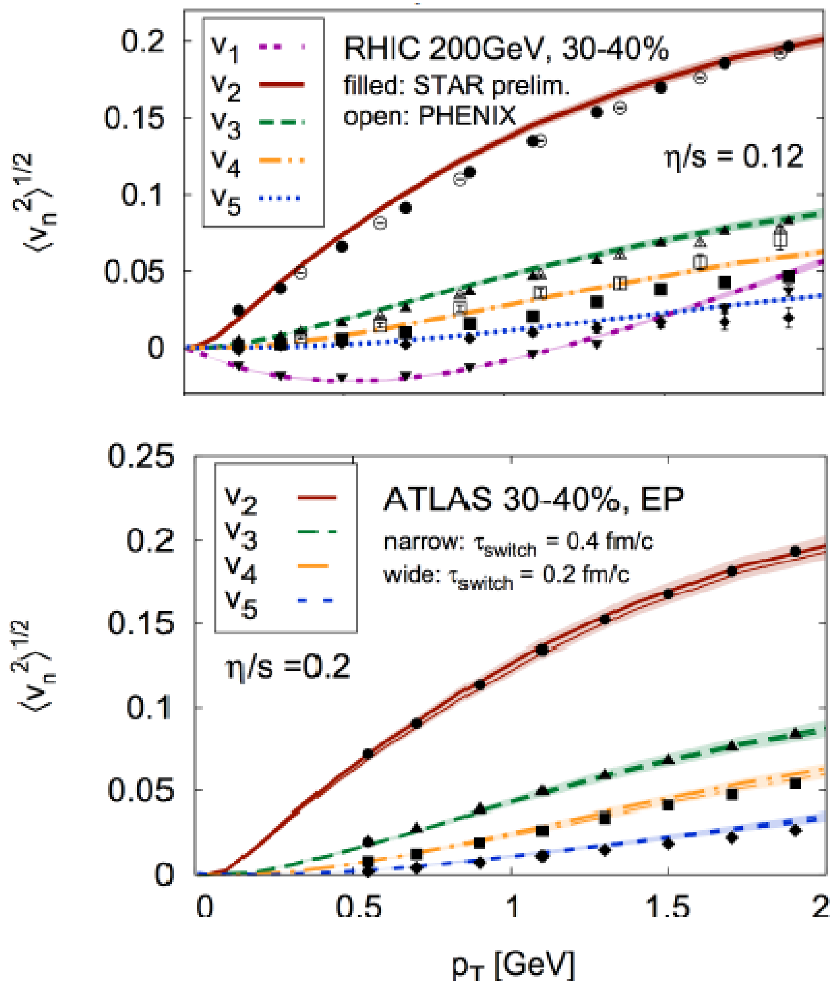
The hot liquid in AA collision

Direct photon yield



ALICE:Phys. Lett. B 754 235-248

PHENIX:*Phys. Rev. Lett.* **104** 132301

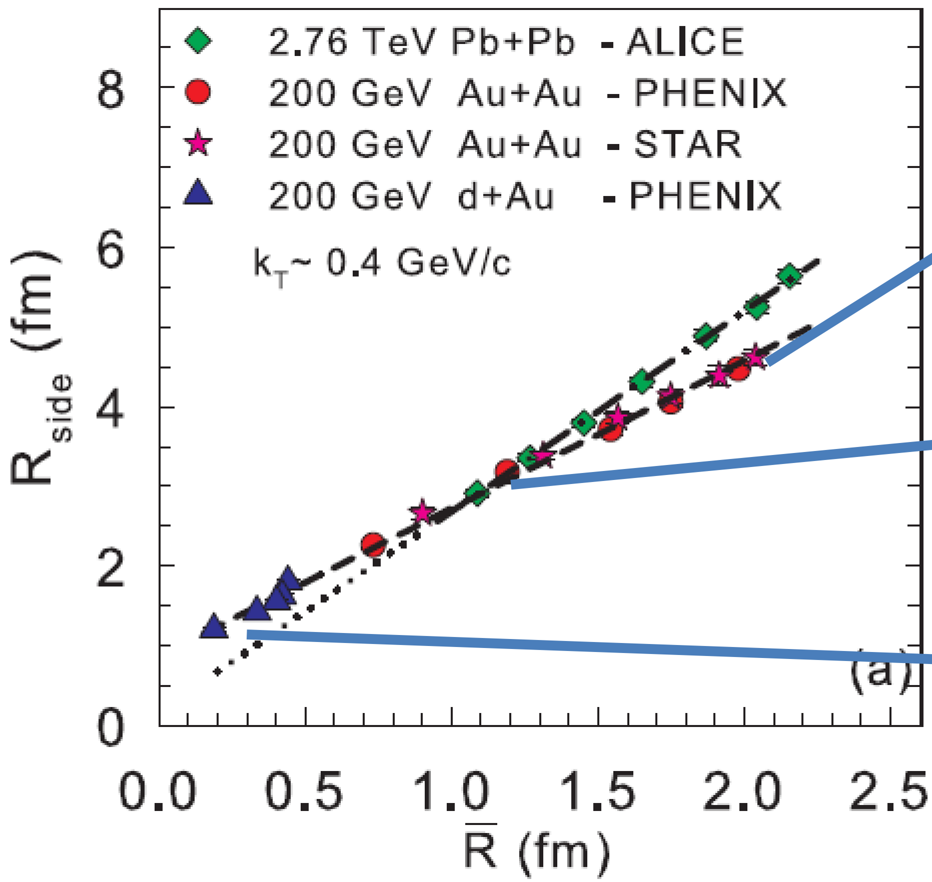


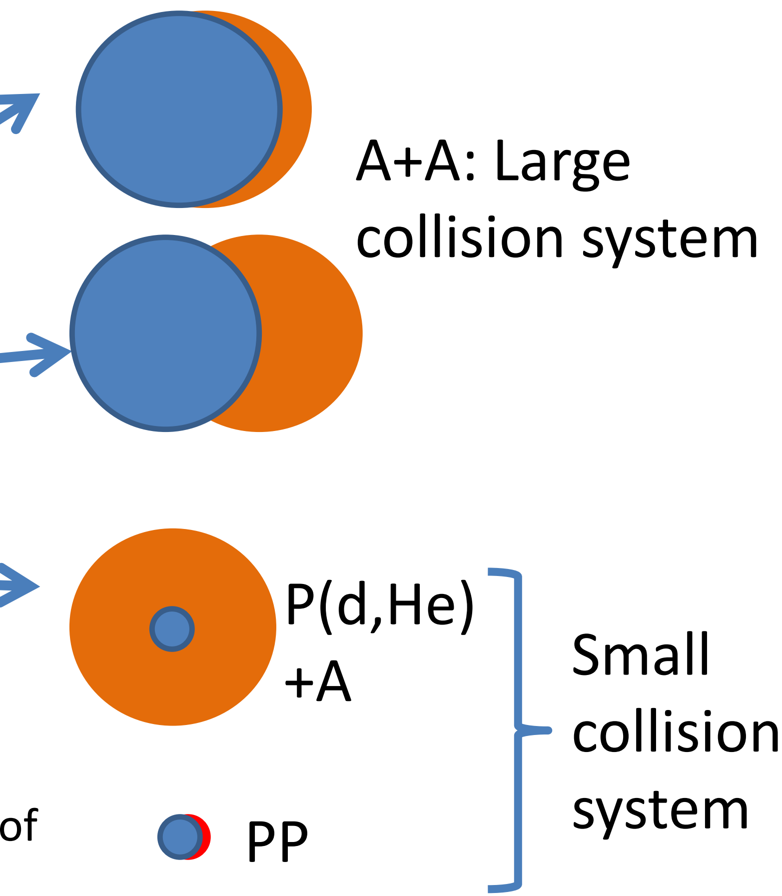
Phys. Rev. Lett. 110 012302

Effective Temperature over 200MeV

Anisotropy well described by hydro.

How small can this QGP liquid be?





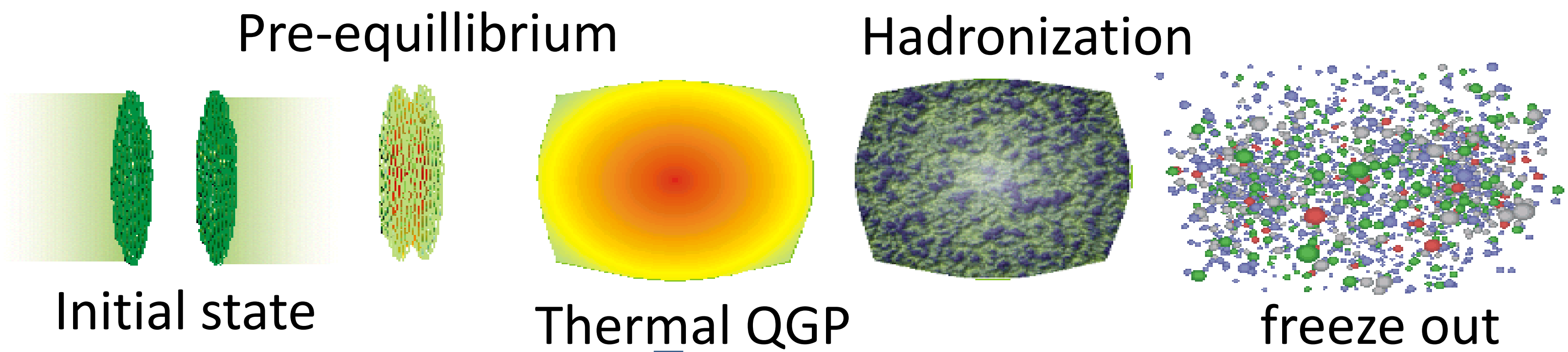
$$1/\bar{R} = \sqrt{(1/\sigma_x^2 + 1/\sigma_y^2)},$$

σ_x, σ_y are RMS widths of density distribution

Rbar: Initial transverse size of collision system

R_{side}: Final transverse size of collision system

Why the small system is interesting?



- **Can we quantitatively pin down the condition of thermalization?**

Qualitatively: $R/\lambda >> 1$ → **Quantitatively: $R/\lambda > ?$**

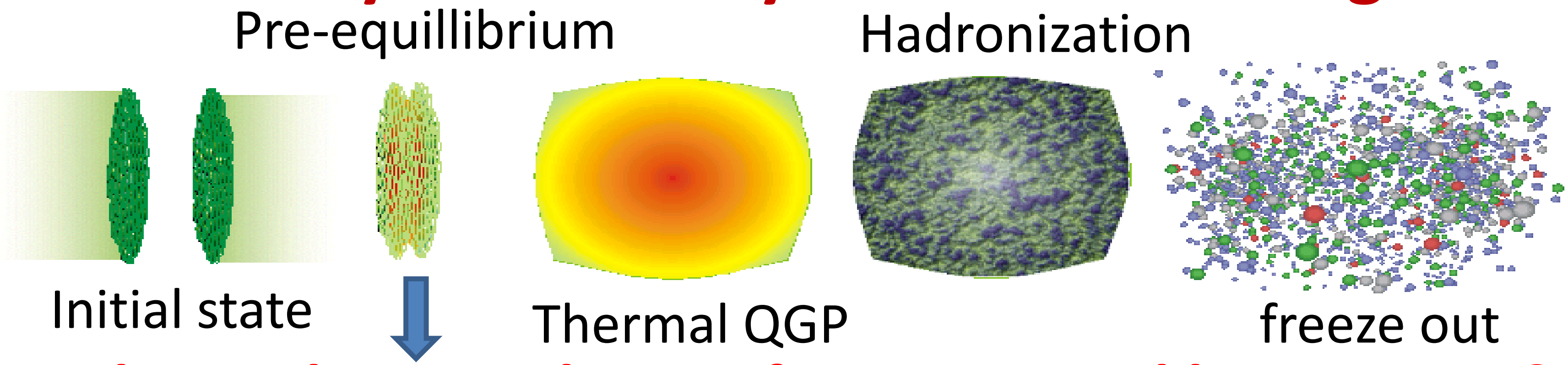
R: system size

λ: mean free path

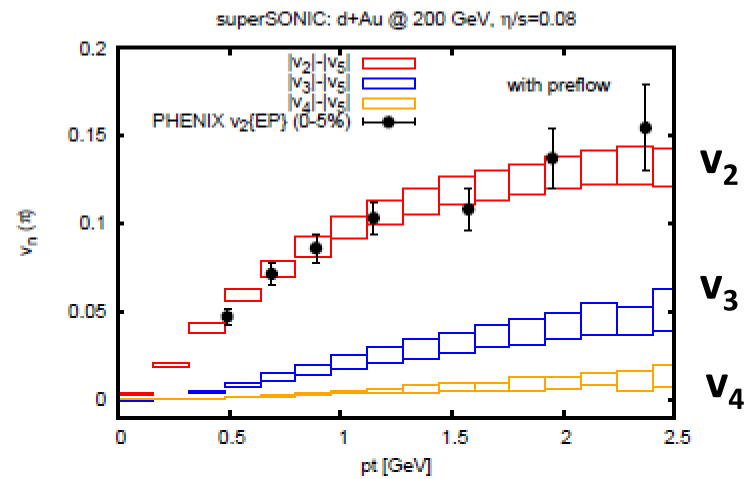
Limit the system size in small collision as pp, then tune the multiplicity to change the mean free path

No way to do in the peripheral AA since system size and multiplicity are correlated there

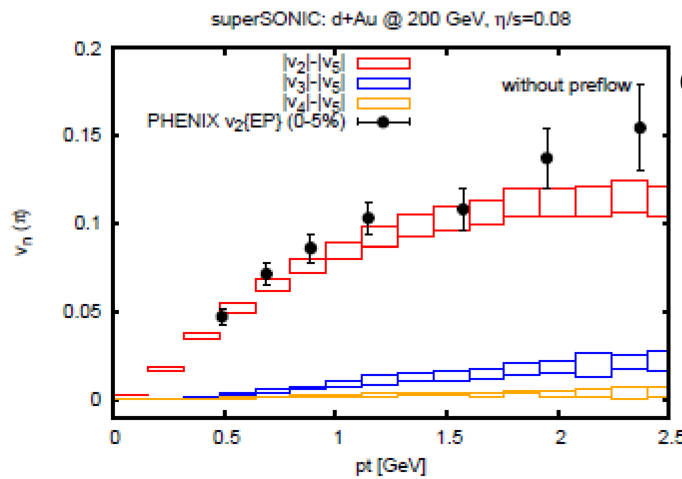
Why the small system is interesting?



- **What is the contribution from pre-equilibrium stage?**



Hydro with pre-equ. flow



Hydro w/o pre-equ. flow

dAu@200GeV

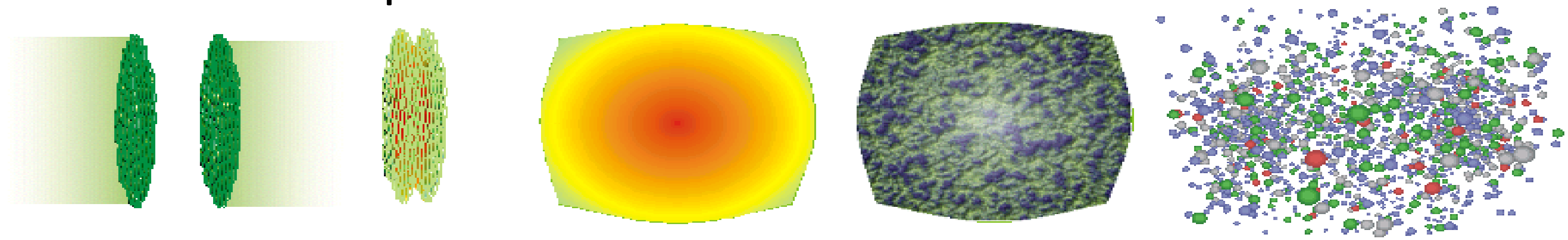
arXiv:1502.04745

The pre-equilibrium flow gives a significant contribution on v_3 in small collisions system .

Hard to see in large system due to the strong final state interactions

Why the small system is interesting?

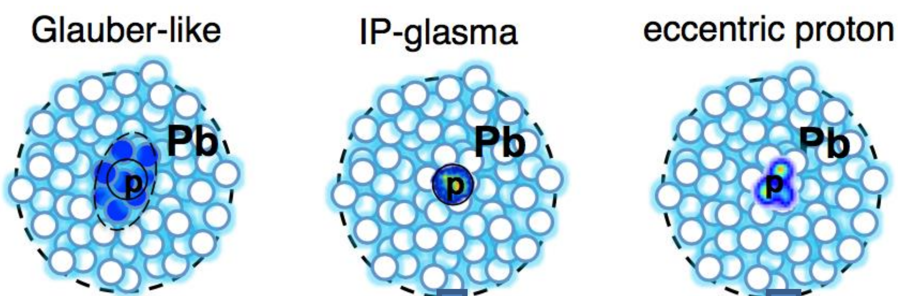
Pre-equillibrium Hadronization

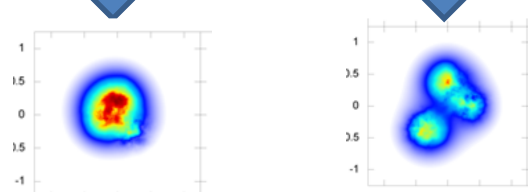


Initial state Thermal QGP freeze out

- **What is the effect initial state and its fluctuation?**

arXiv:1509.07939,arXiv:1603.04349





Round proton **Eccentric proton**

The eccentricity will be around a factor two difference for round and eccentric proton

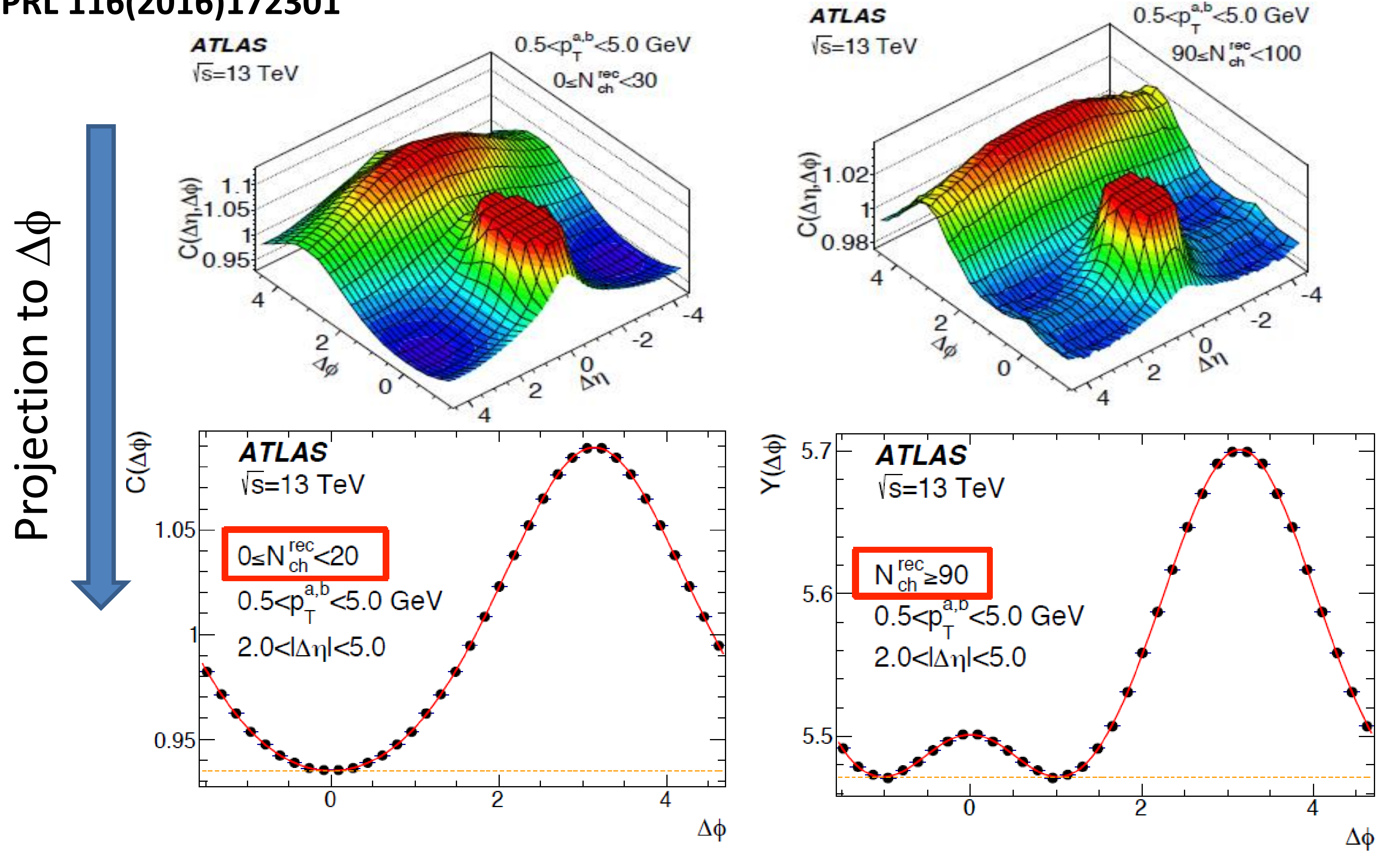
The shape of proton does matter!

- II: The ridge and anisotropy in pp collision

The tiniest QGP drop?

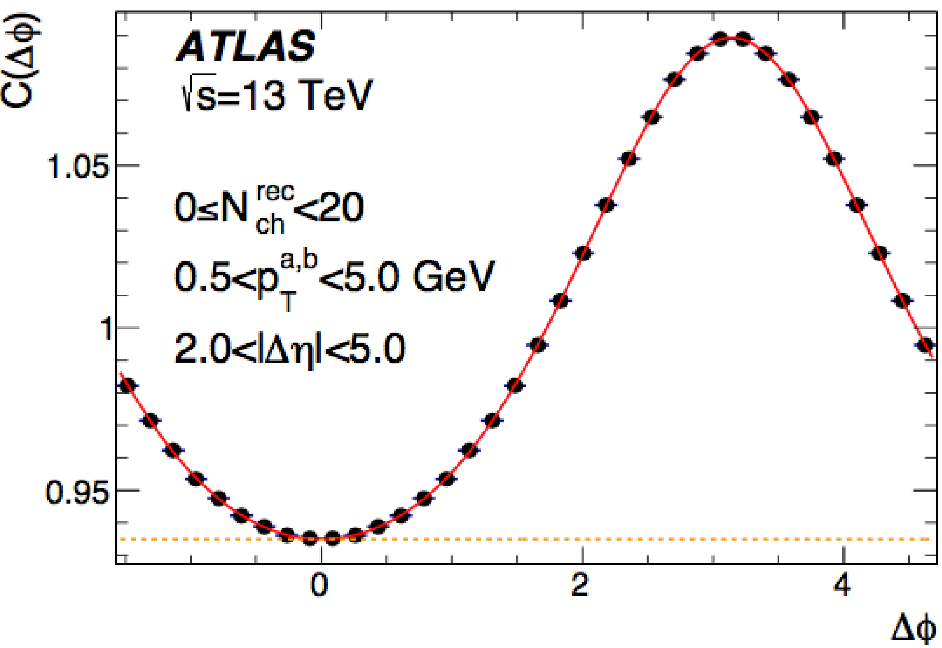
Ridge in pp@LHC at 13 TeV

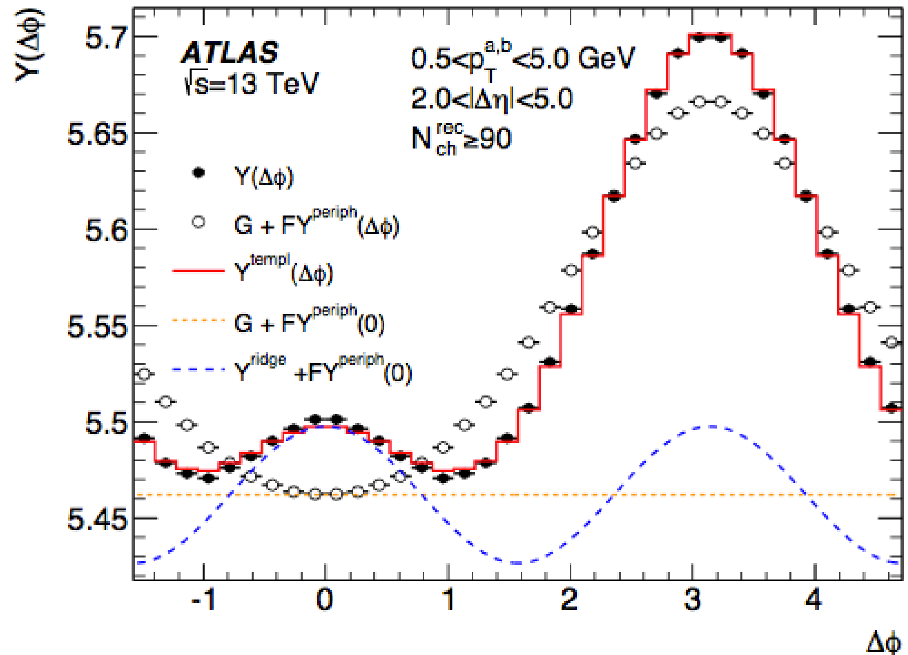
PRL 116(2016)172301



A near side ridge is seen in high multiplicity pp by ATLAS
It confirms the observation from CMS

V_n Extracted from ridge: Template Fitting





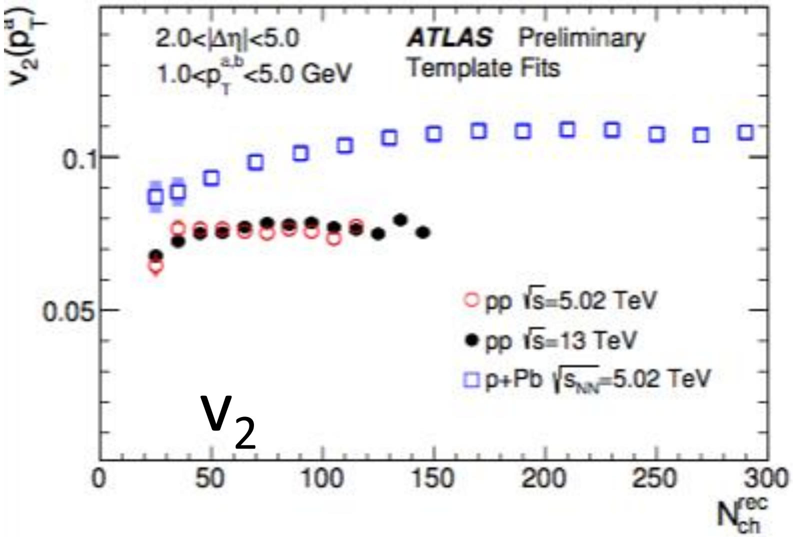
Two components: "Jet"+"Ridge". The correlation shape from jet is assuming to be same as that of low multiplicity pp

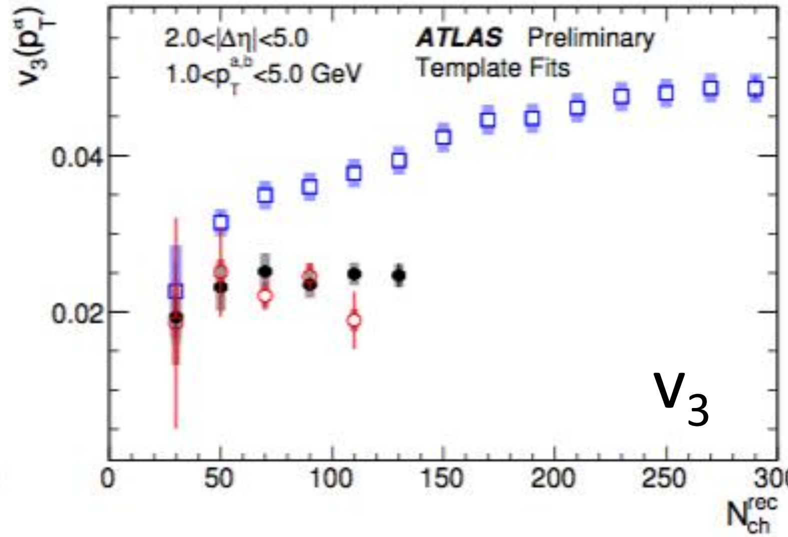
$$Y^{\text{templ}}(\Delta\phi) = F\, Y^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi)$$

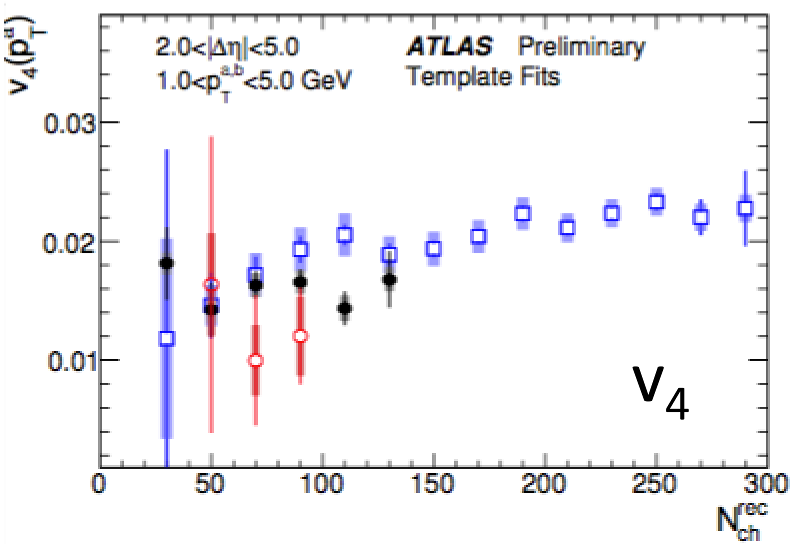
V_2 are from Fourier expansion of the ridge. The v_3 and v_4 are also added in the formula

$$Y^{\text{ridge}}(\Delta\phi) = G\left(1 + 2v_{2,2}\cos(2\Delta\phi)\right)$$

Vn from template fitting





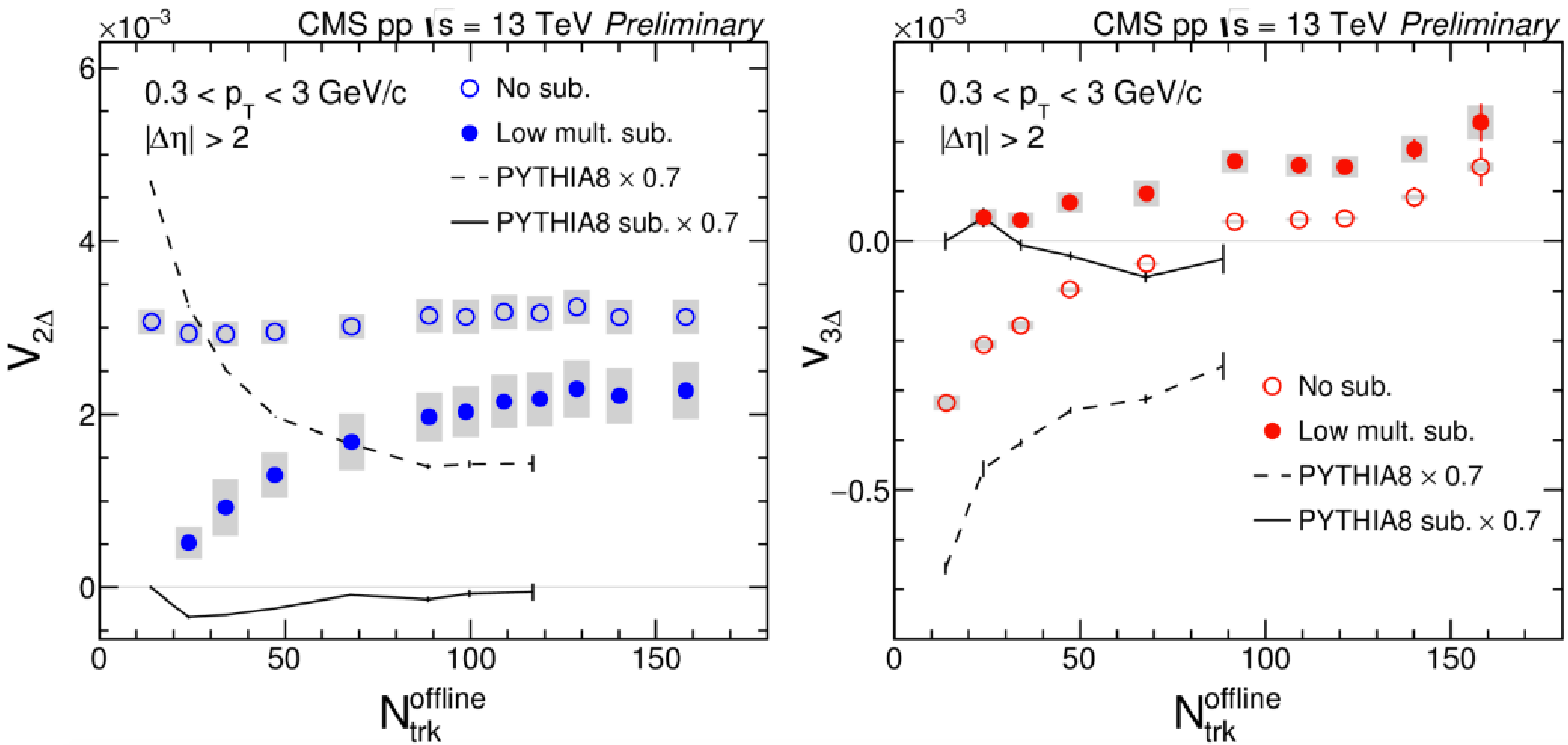


New 5.02 TeV pp from 2015, re-analysis of pPb with template fitting

v_n in pp does not depend on center of mass energy

Smaller than that of pPb

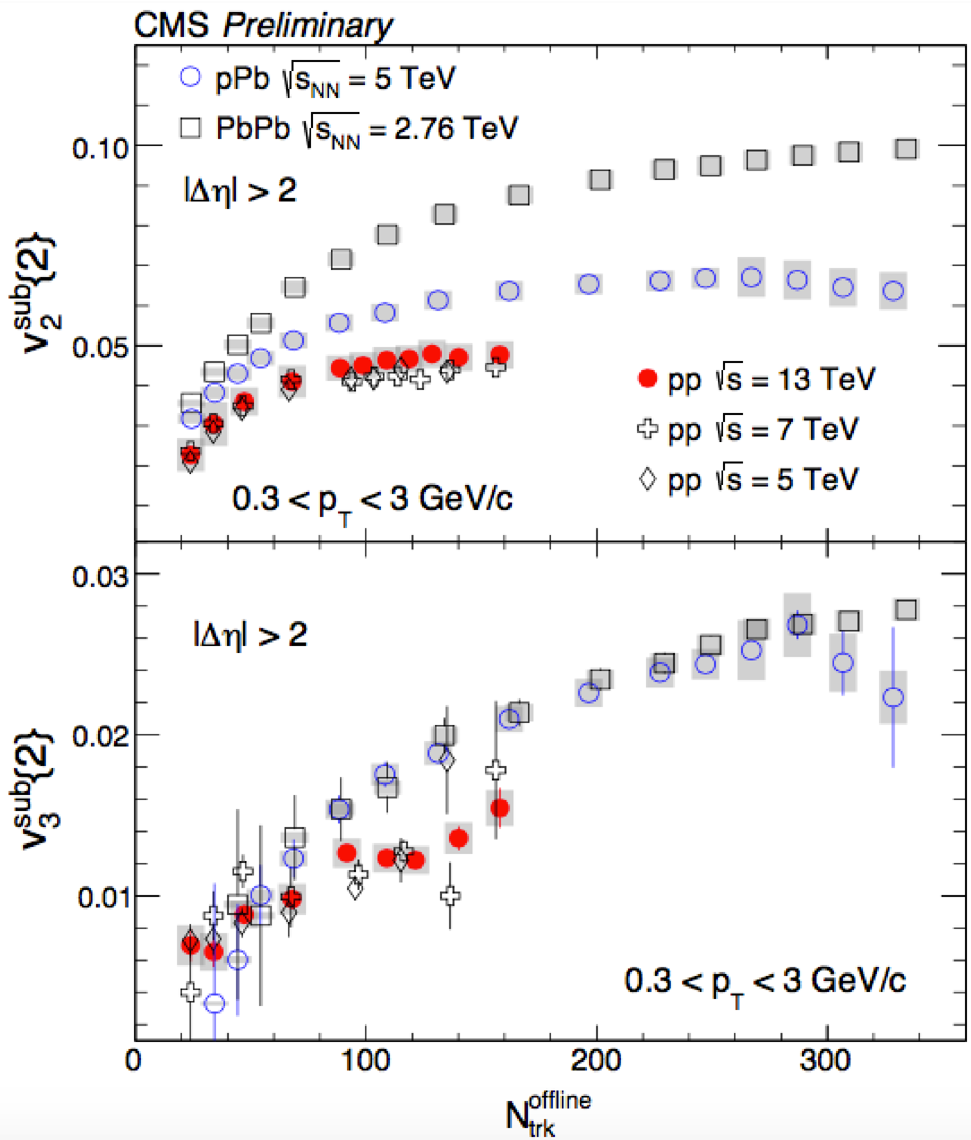
Vn@pp in CMS



$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(10 \le N_{trk}^{offline} < 20) \times \frac{N_{\mathrm{assoc}}(10 \le N_{trk}^{offline} < 20)}{N_{\mathrm{assoc}}} \times \frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(10 \le N_{trk}^{offline} < 20)}$$

CMS also measures the v_n in pp by subtraction method

Vn@pp with subtraction methods

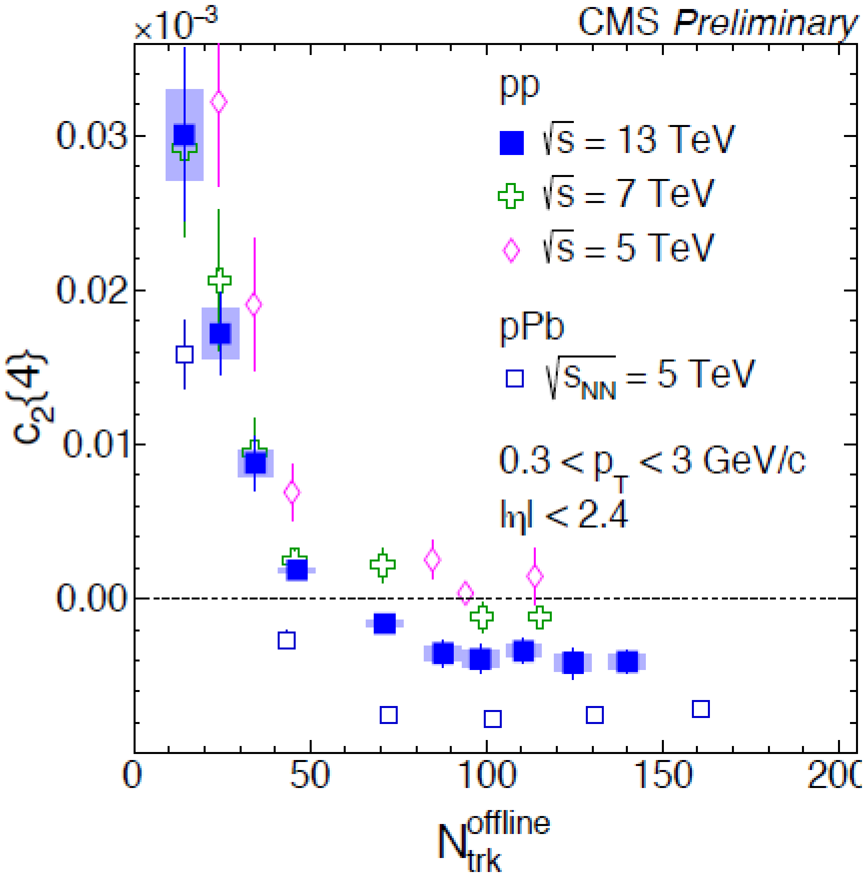


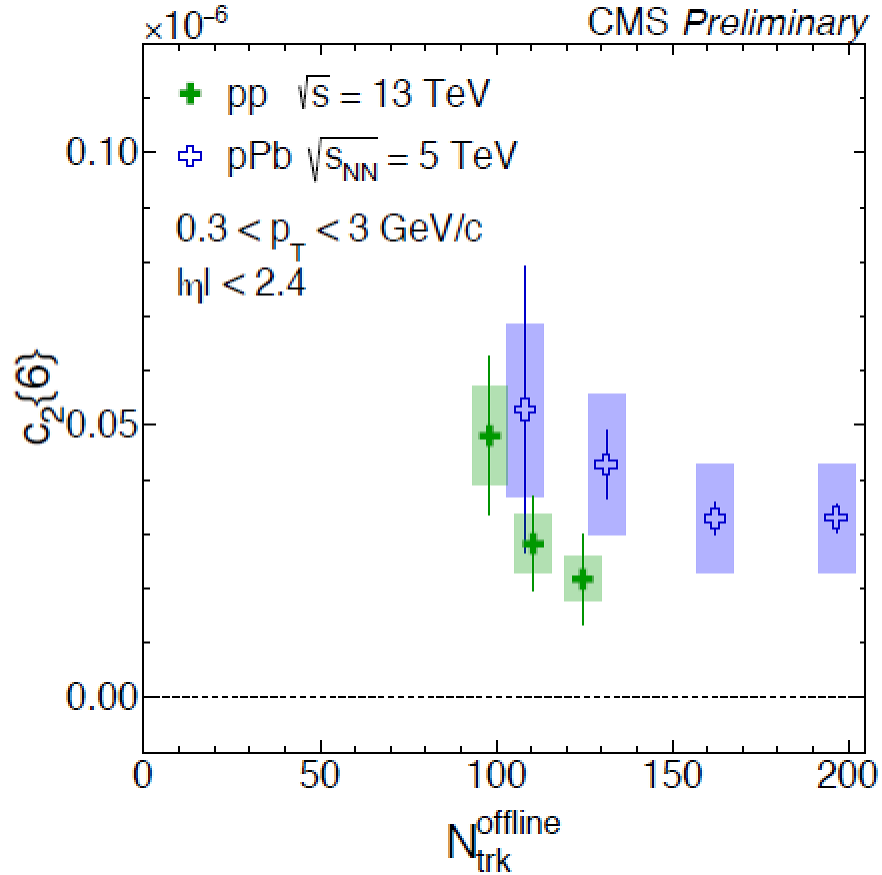
No energy dependence observed for v_2 and v_3 in pp collision from two different methods

Smaller than that of large systems as pPb and PbPb

CMS results have a stronger multiplicity dependence than that of ATLAS

Multi-particles cumulant

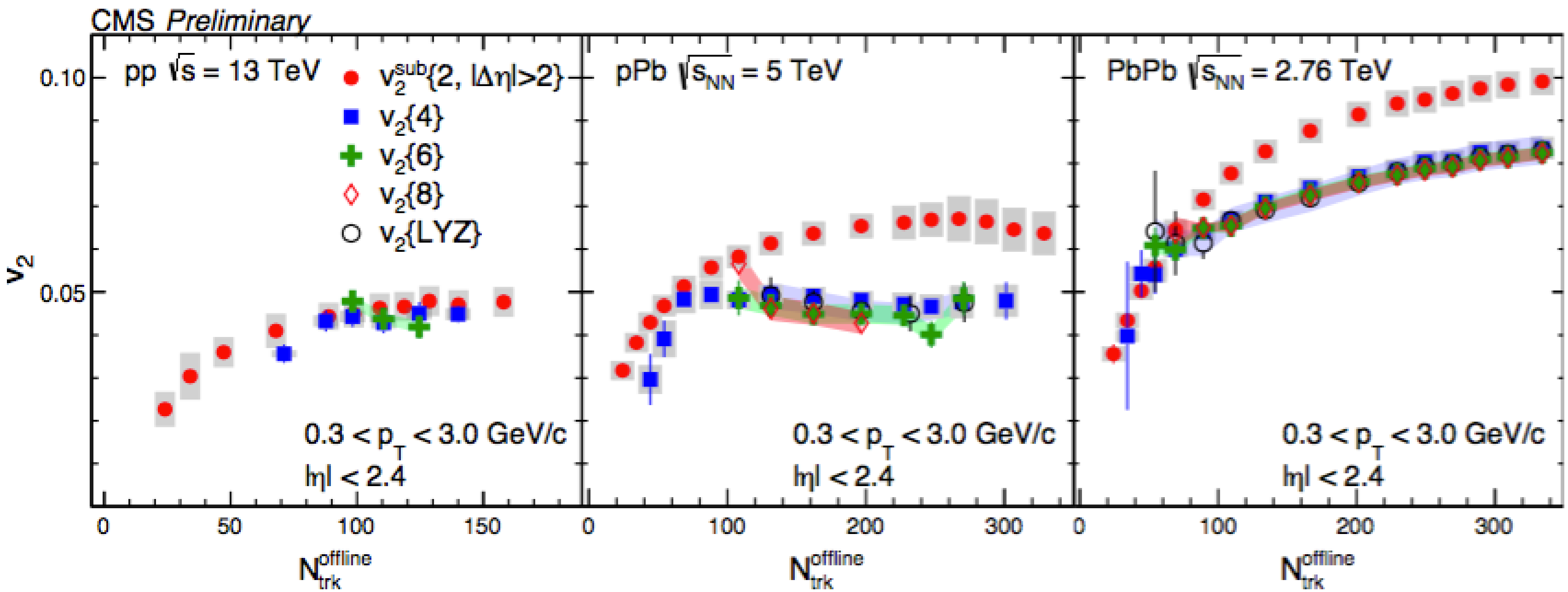




V_2 can also be extracted with four or six particles cumulant method in 13 TeV pp collisions

Shape similar to pPb but with different magnitude

v_2 from Multi-particle Correlations



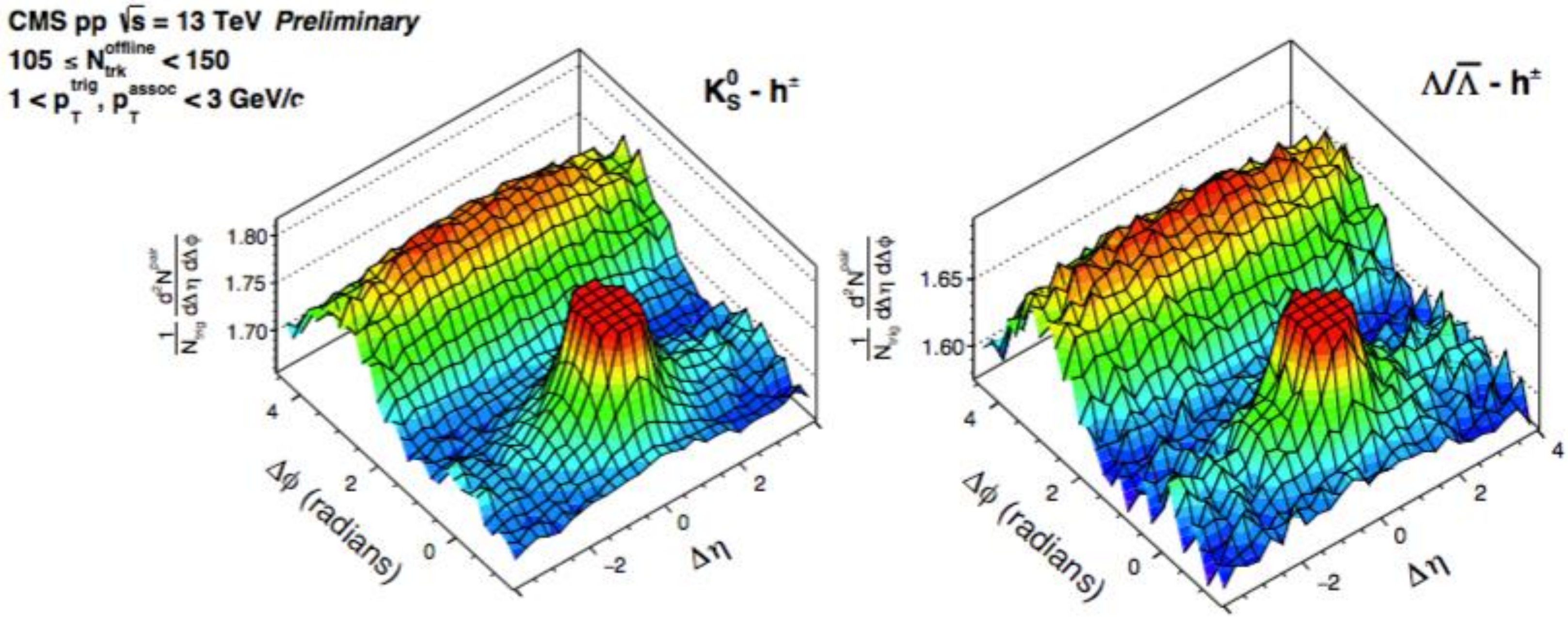
PRL 112 (2014) 082301

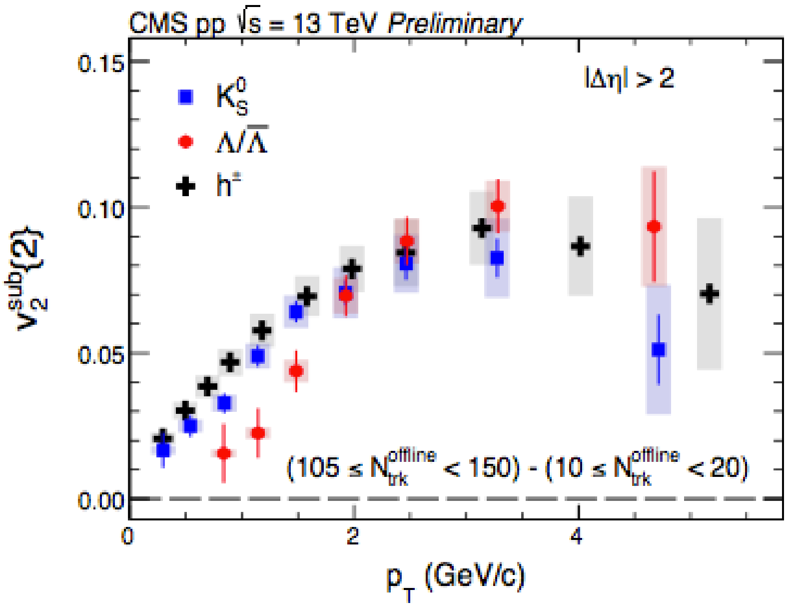
In pPb and PbPb, $v_2\{2\}>v_2\{4\}\approx v_2\{6\}$

In pp at 13 TeV, $v_2\{2\}\approx v_2\{4\}\approx v_2\{6\}$

Less initial state fluctuation in pp at 13 TeV?

Identified particle ridge in pp@13TeV

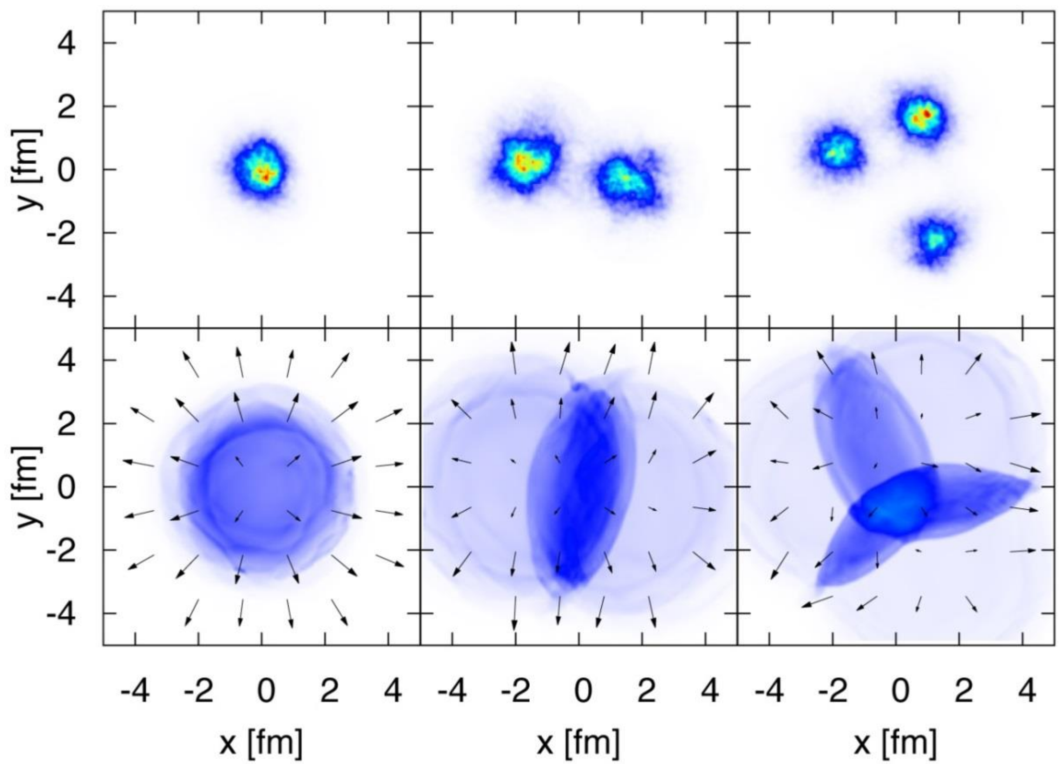




A clear ridge and mass ordering are seen for Ks and lambda in high multiplicity pp at 13 TeV

- III. The ridge and anisotropy in p/d/He+Au

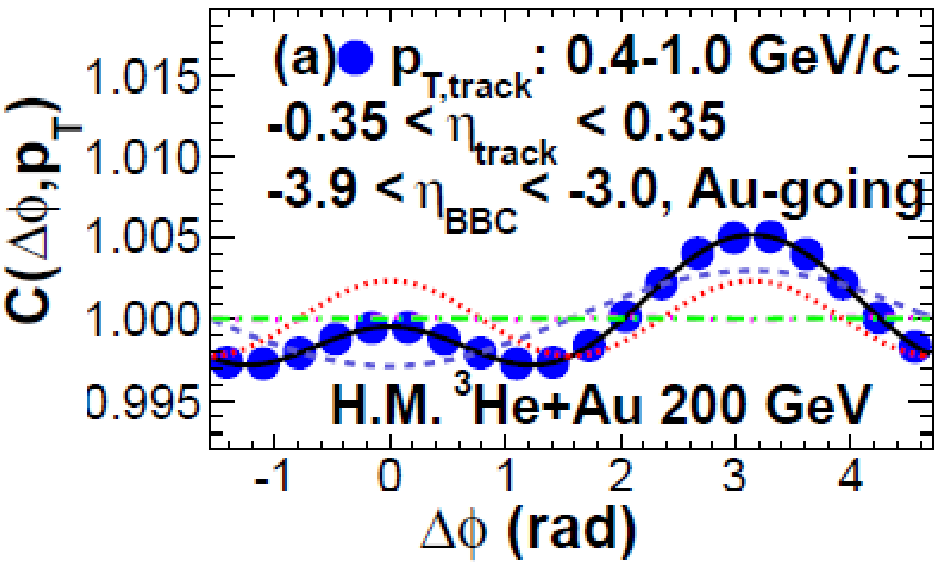
The Geometry Engineering

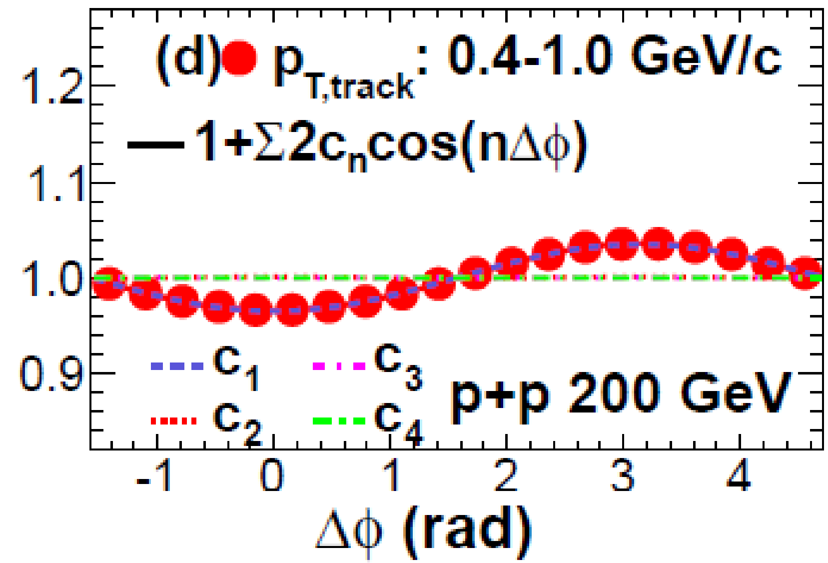


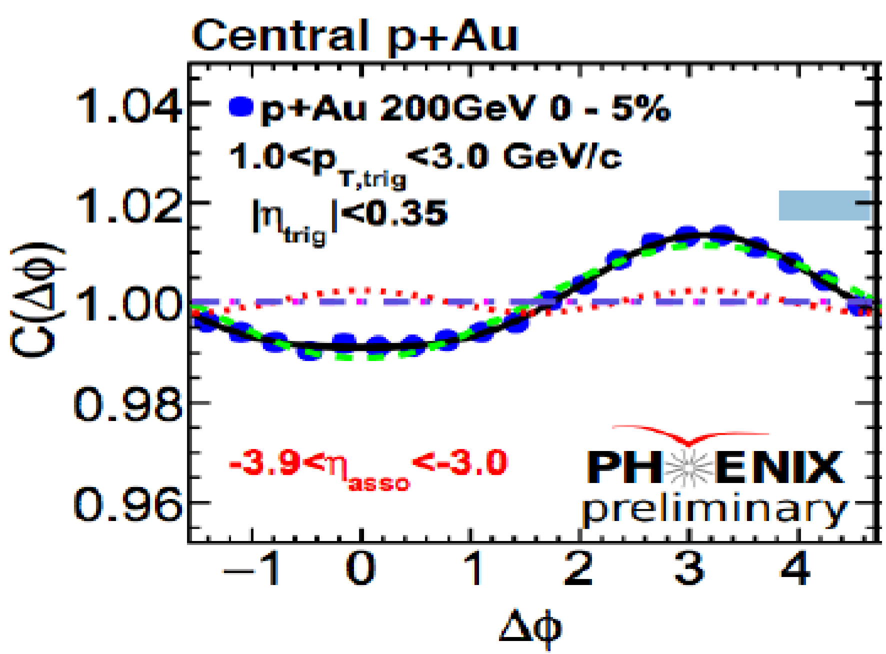
Initial State

Final State

The ridge in p/HeAu







- ✓ A ridge is observed in high multiplicity(0-5%) ^{3}He+Au collisions
- ✓ In cental pAu, there is a near side enhancement comparing with pp even though there is no peak

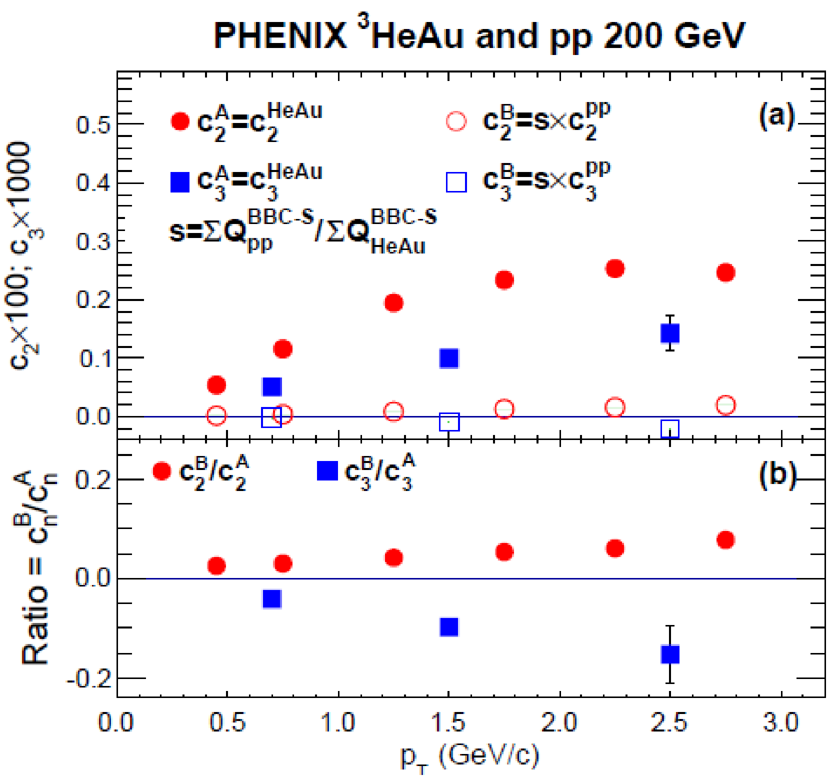
non-flow estimation in PHENIX

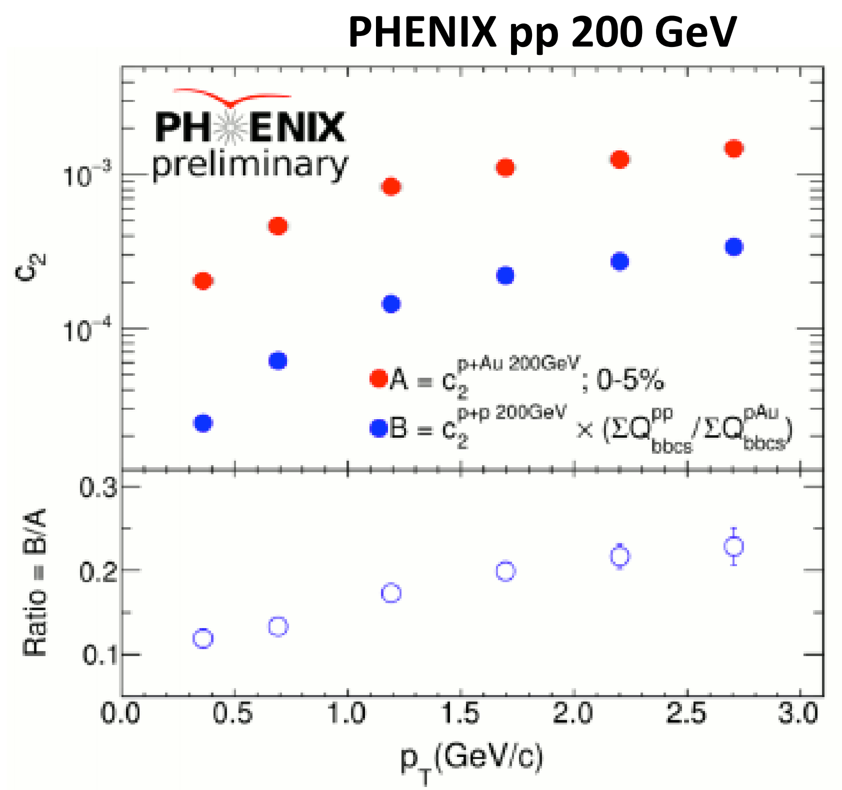
$$c_2(p_T) = c_2^{\text{Non-Elementary}} + c_2^{\text{Elementary}}$$

$$c_2(p_T) = c_2^{\text{Non-Elementary}} + c_2^{p+p} \times \frac{\text{Charge at Forward } \eta \text{ in p+p}}{\text{Charge at Forward } \eta \text{ in p+Au}}$$

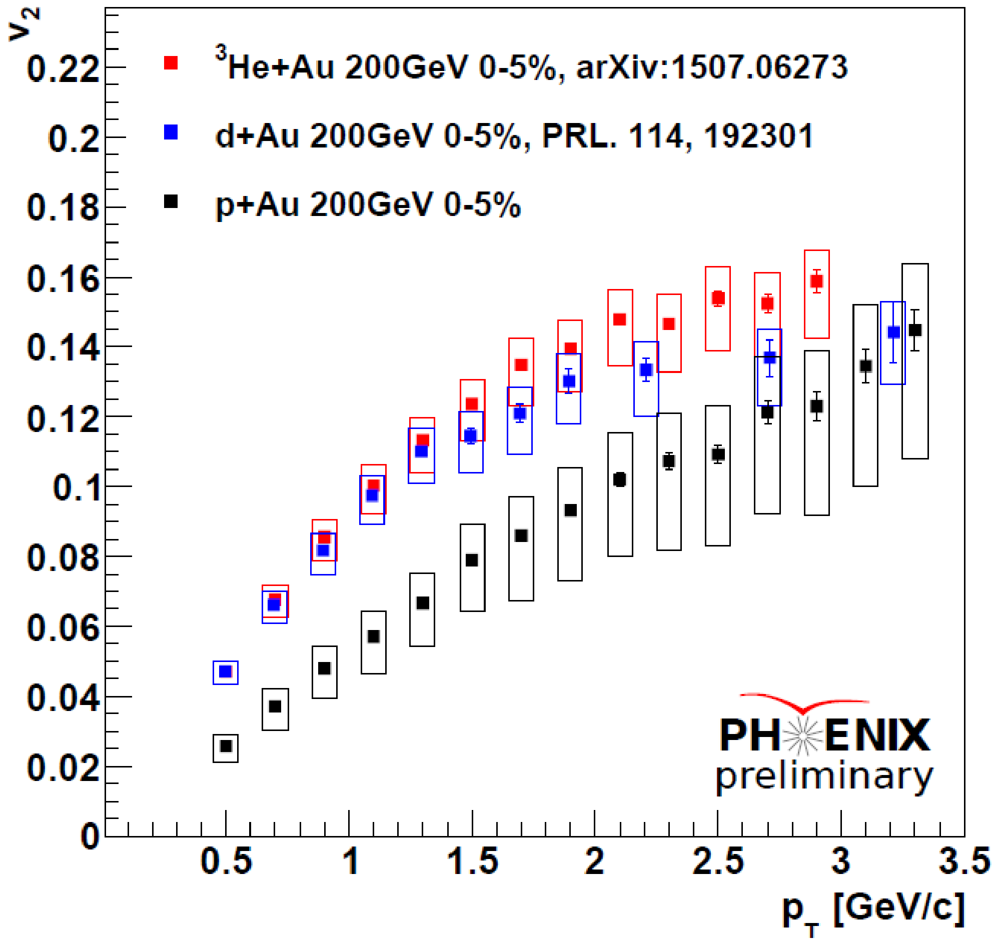
Use pp as reference

Scaled up by relative multiplicity





V_2 in p/d/He+Au 200 GeV

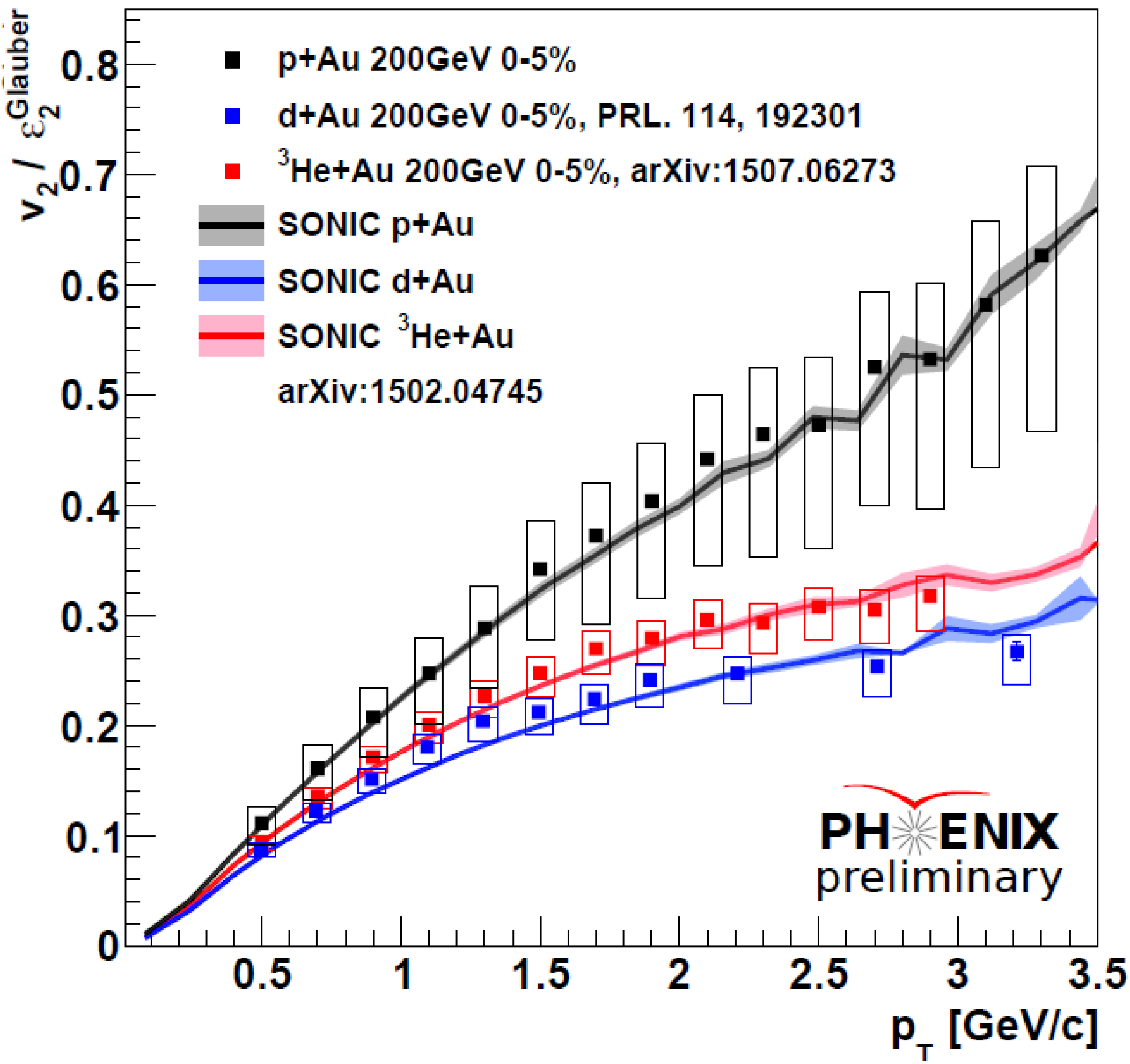


$\varepsilon_2^{d+Au} \sim \varepsilon_2^{3He+Au} > \varepsilon_2^{p+Au}$

$V_2^{d+Au} \sim V_2^{3He+Au} > V_2^{p+Au}$

Smaller initial geometry eccentricity → smaller v_2

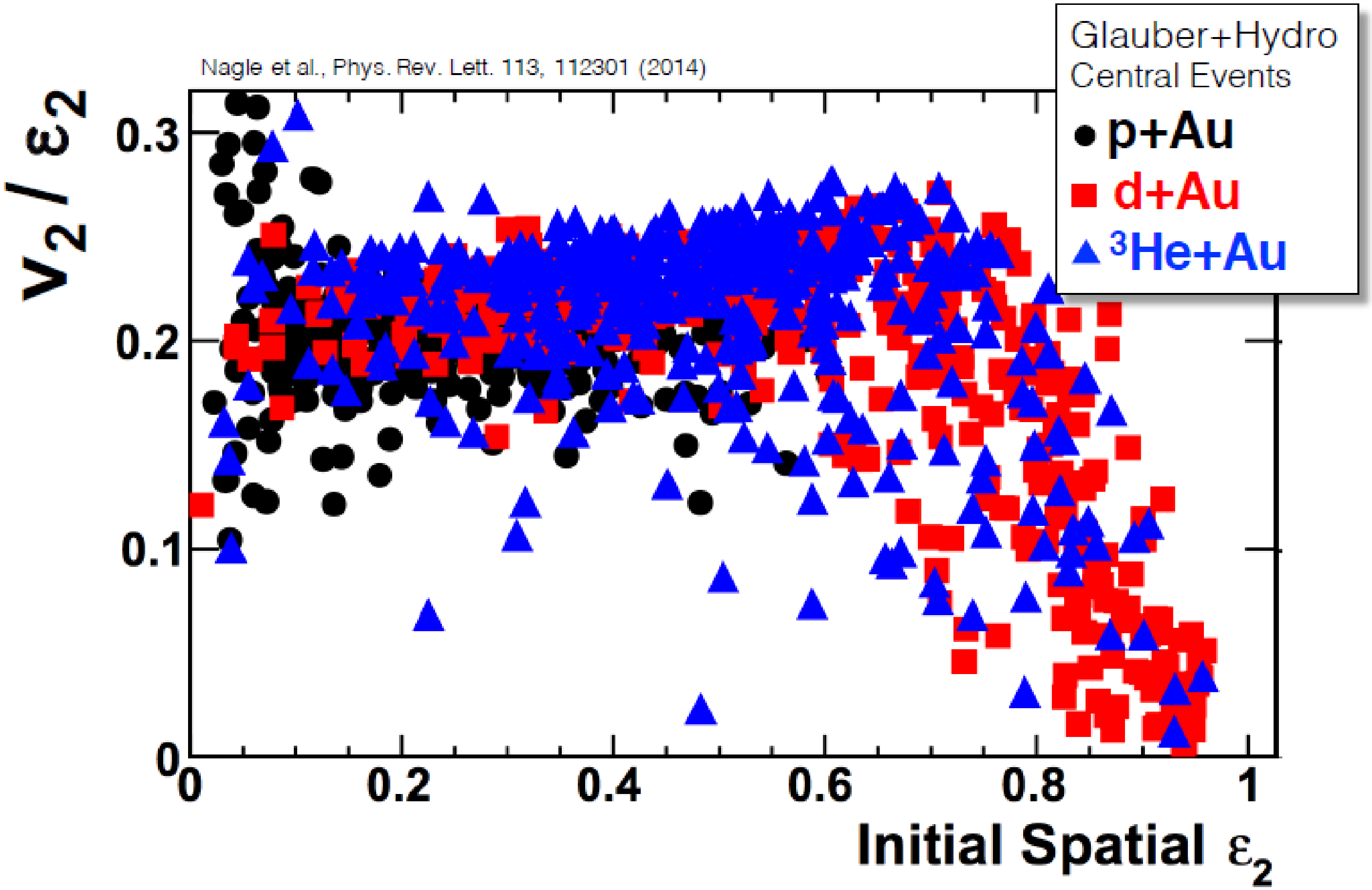
v_2/ε_2 in small collision systems



The v_2/ε_2 in p+Au is higher than that of d+Au and ^{3}He+Au collisions

This behavior is within the expectation of SONIC model, which includes Glauber initial geometry and viscous hydro evolution.

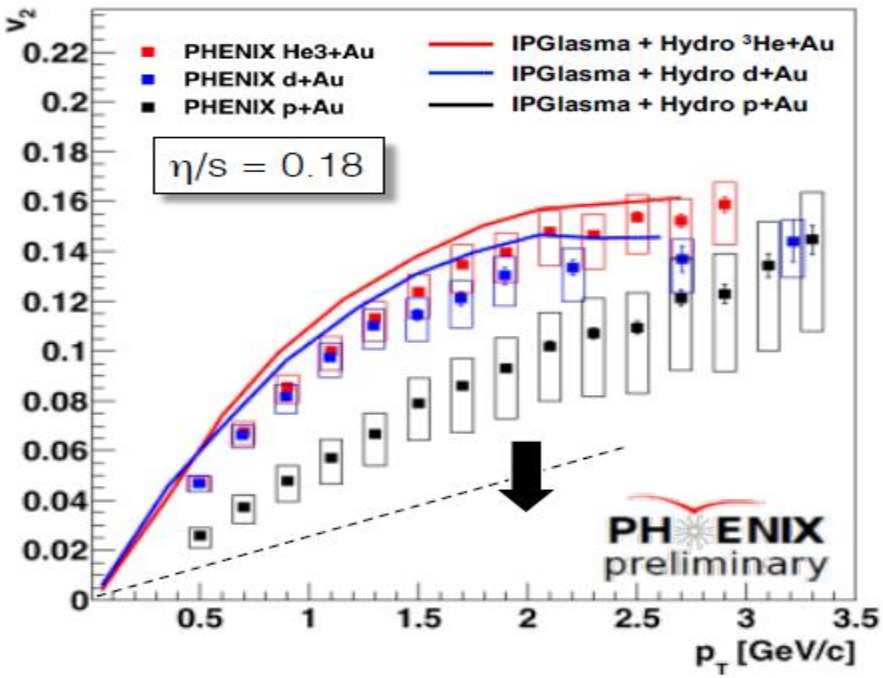
Initial eccentricity=> final momentum flow

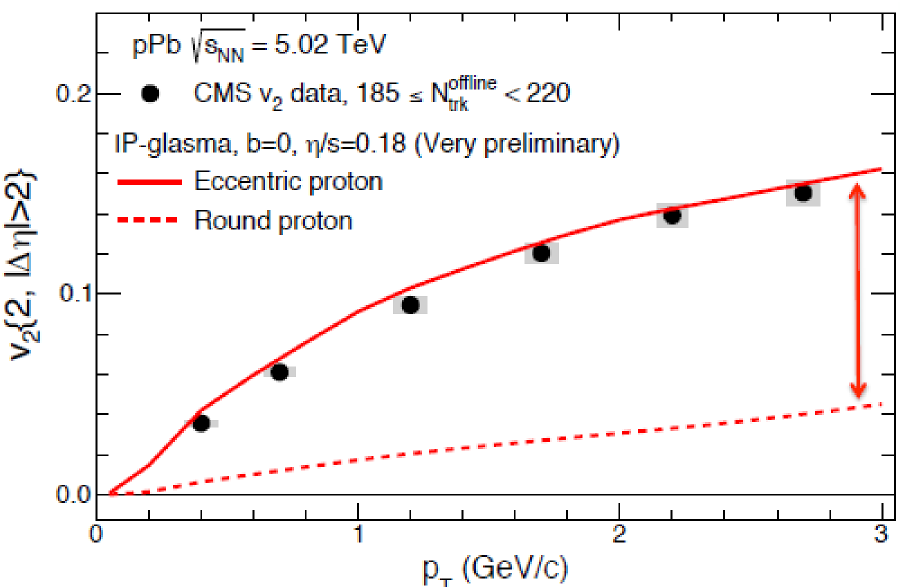


For d/He+Au, the eccentricities are largest at beginning while the systems do not fully flow together

In d/He+Au, systems are harder to pick up the initial geometry information comparing with that of pAu

Compare with Hydro + IPGlasma



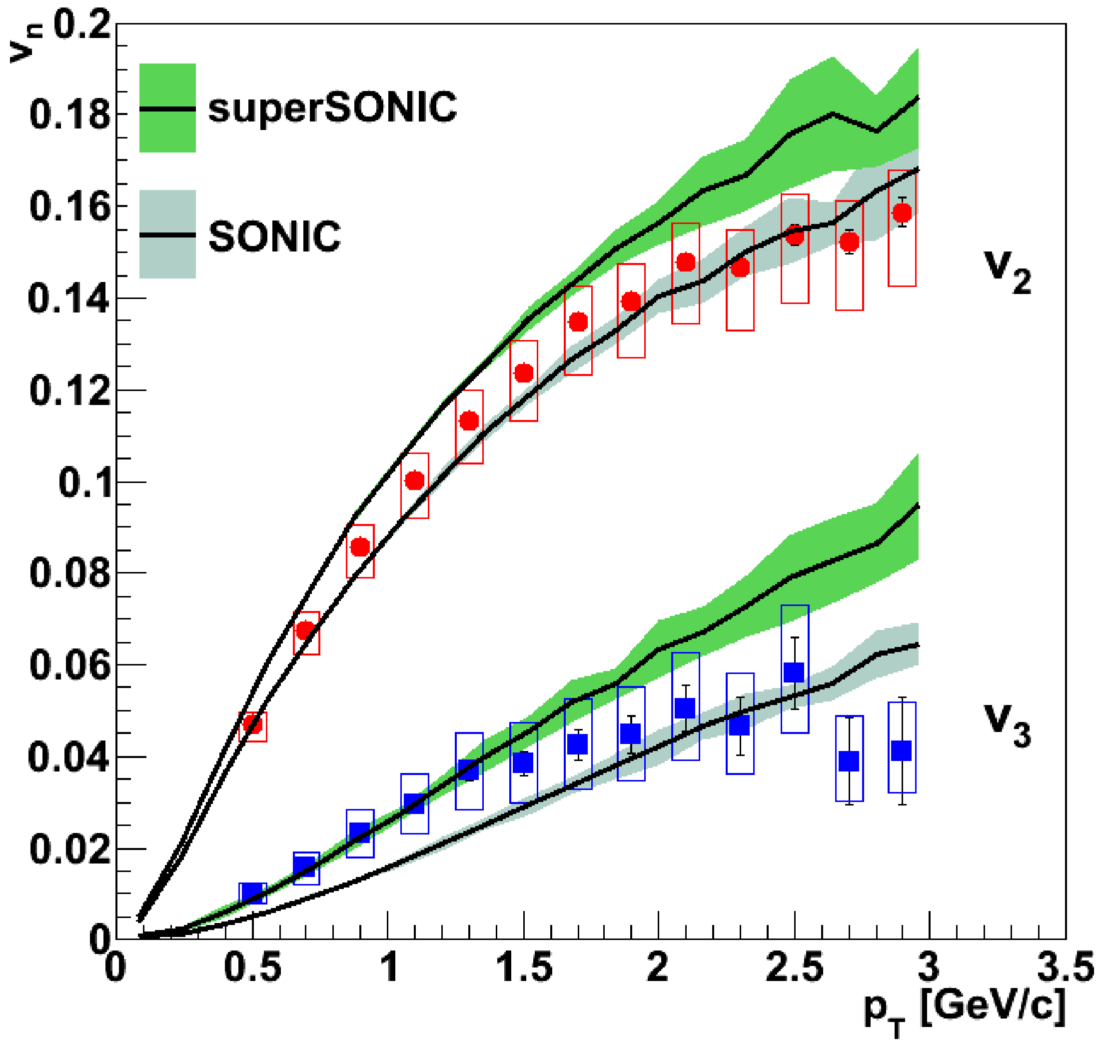


Hydro+IPGlamas with round proton under-estimates the v_2 in pAu and pPb

Shape of proton plays a huge role in the calculation of hydro+IPGlasma

The role of pre-equilibrium flow

0-5% 3He+Au collisions



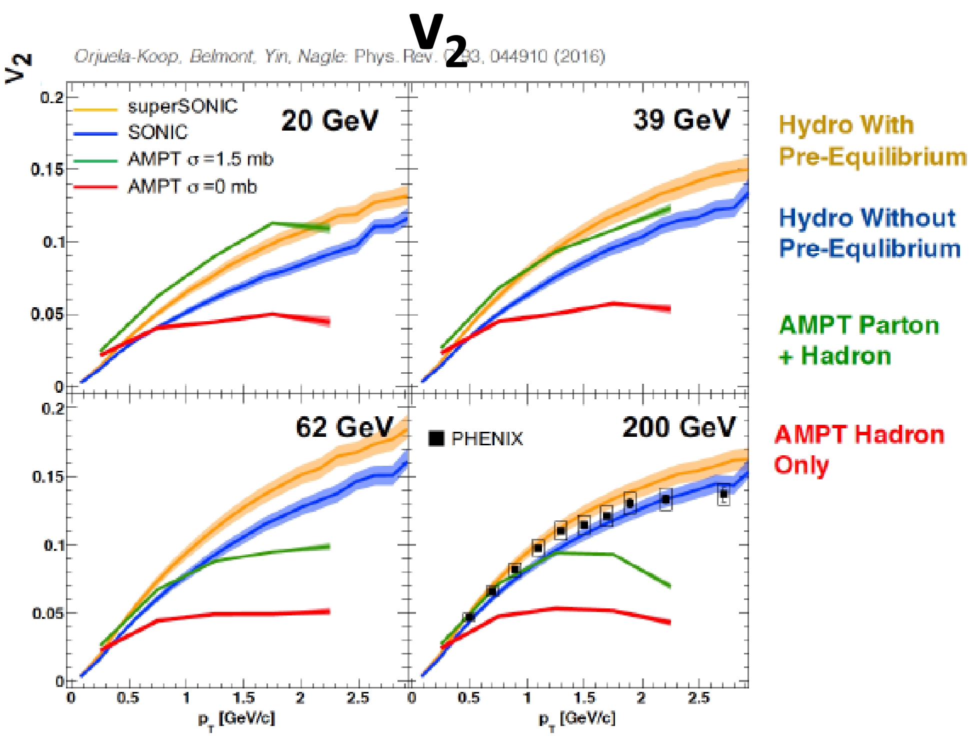
(Super)SONIC: arXiv:1502.04745

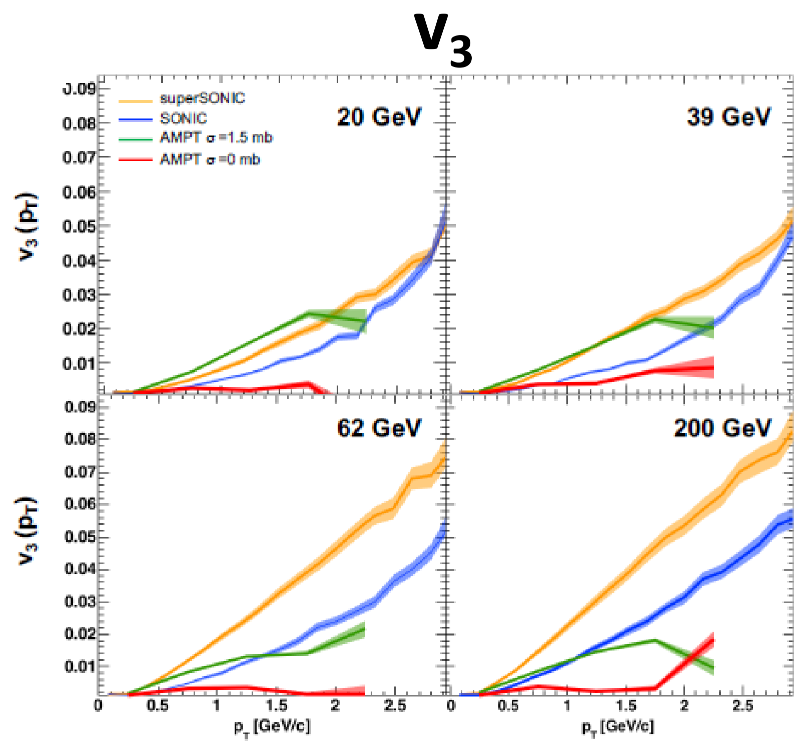
At low p_T, v_3 in ^{3}He+Au collisions prefer to the calculation from super SONIC which has the pre-equilibrium flow

Require more accurate measurement!

New d+Au run in 2016 from sqrt(s)=19.6 GeV to 200 GeV

Model predictions for energy scan in dAu

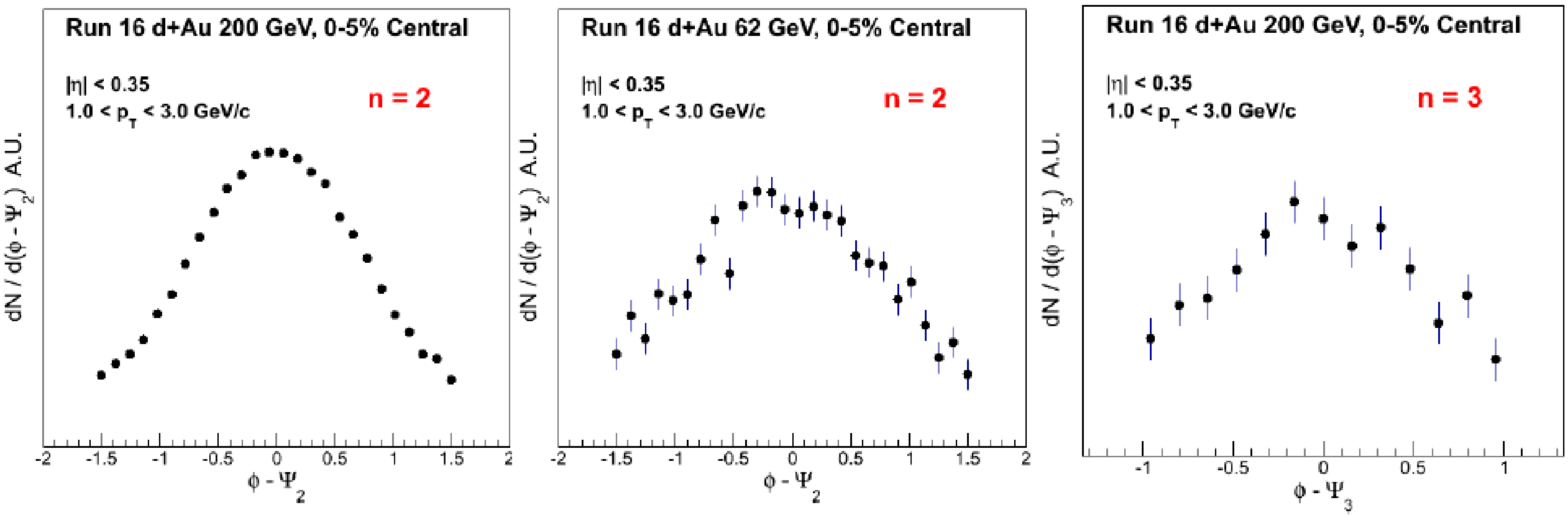




Elliptic flow : Weak energy dependence. Sensitive to the pre-equilibrium flow at low energy

Triangle flow: Takes long time to develop and more sensitive to the short QGP life time. Collapses if the system is hadronic. More sensitive to pre-equilibrium flow at higher energy

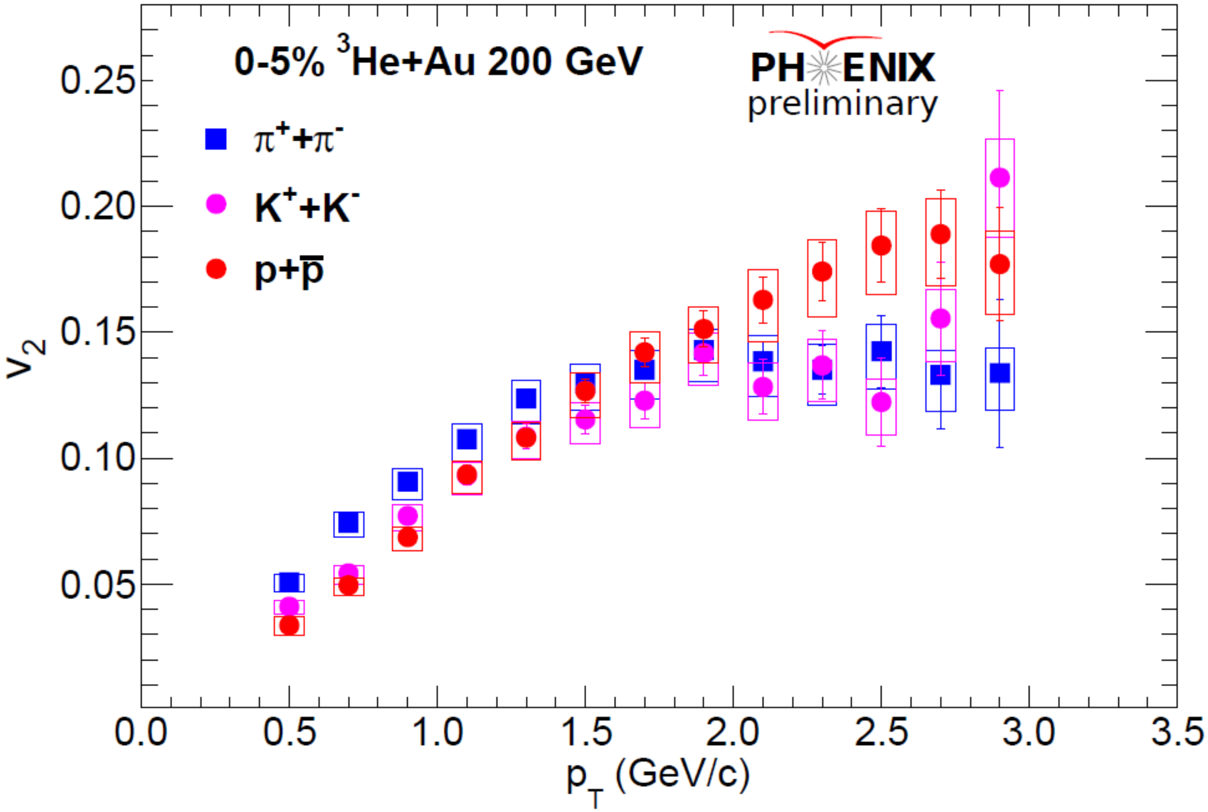
A quick look from dAu low energy scan data by PHENIX



$\phi - \Psi_n$

- First signs of v_2 at 200 GeV and 62 GeV
- First indication of non-zero v3 in d+Au at 200 GeV!

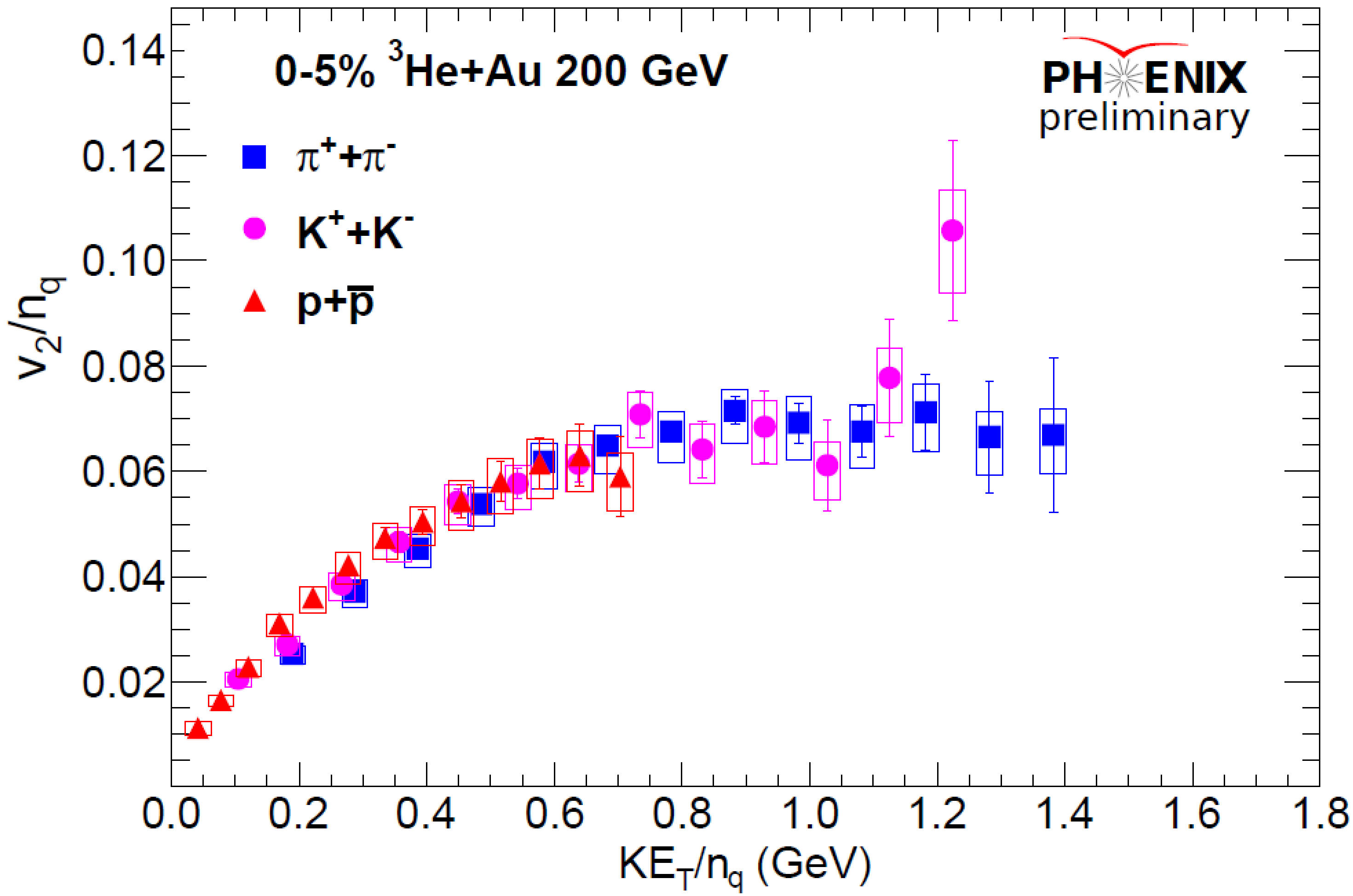
Identified particle v_2 in ^{3}He+Au



- ❑ At p_T < 1.5 GeV/c: mass order -- v2(proton)< v2(kaon)< v2(pion)
- ❑ At p_T> 2.0 GeV/c: difference for meson and baryon

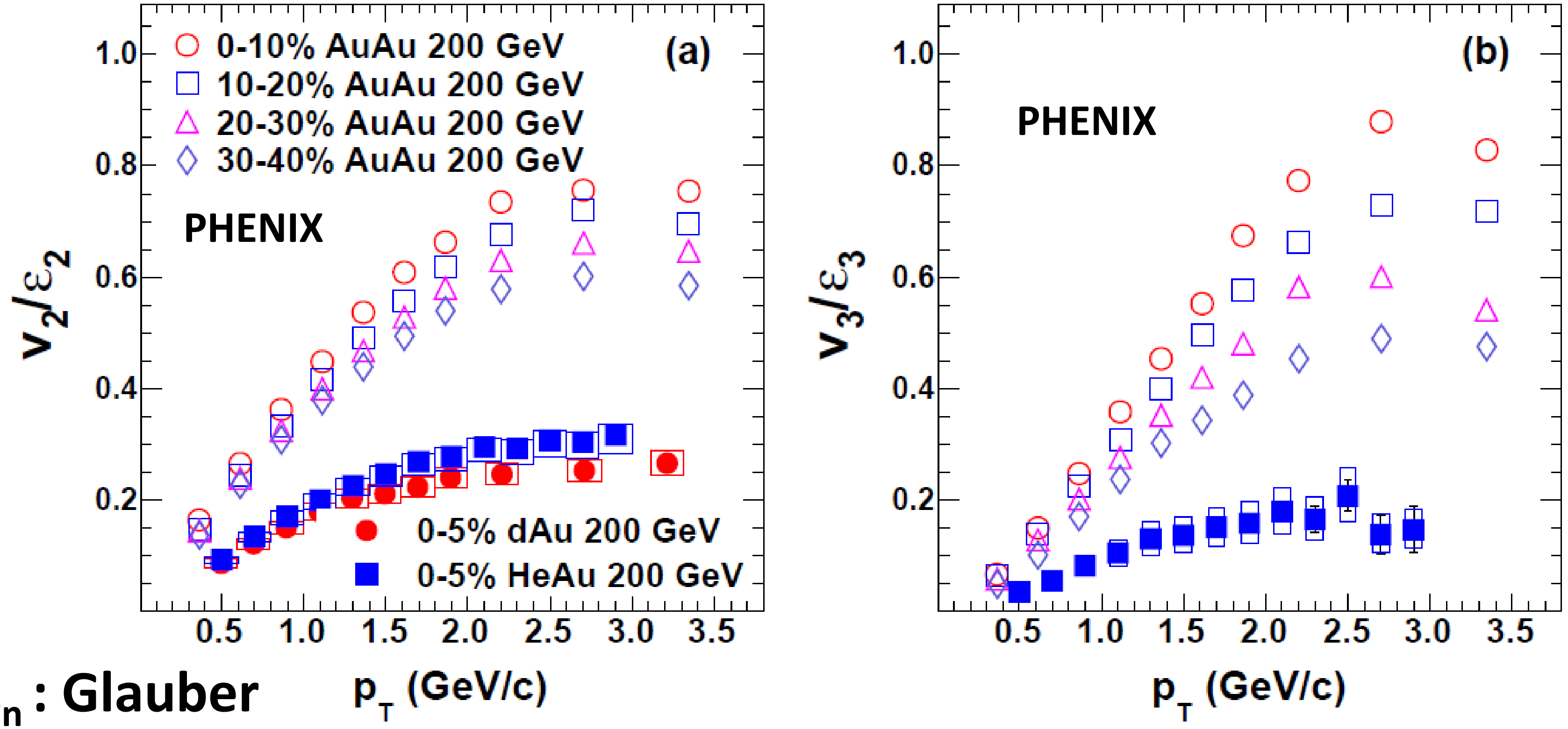
These behaviors are very similar to that in Au+Au collisions and calculations of viscous hydro.

Number of Quark Scaling in ^{3}He+Au



The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small ^{3}He+Au system

From small to big system

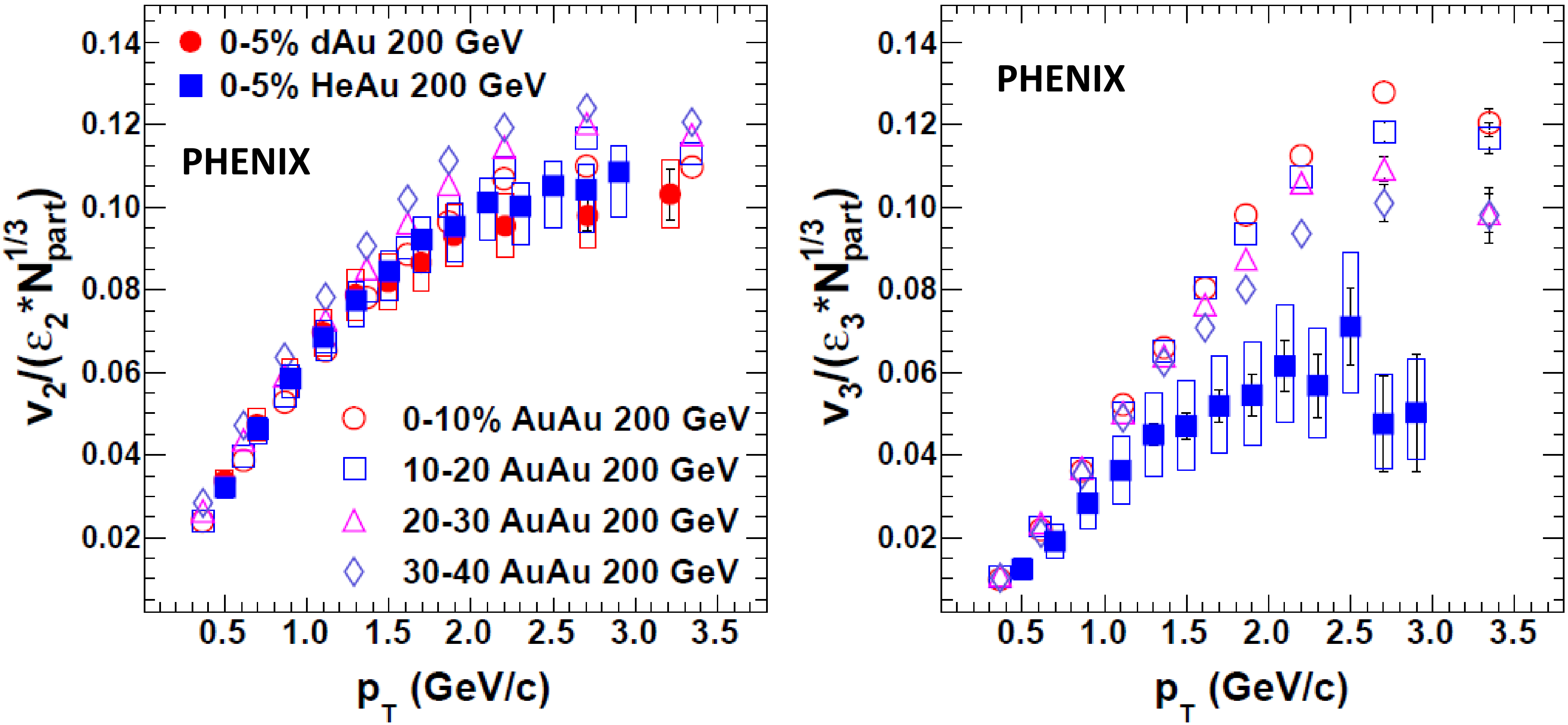


ε_n **: Glauber**

Au+Au $v_{2,3}$ Phys. Rev. Lett. 107, 252301

- ❑ v_n/ε_n decreases from large collision system such as Au+Au to small collision system as d+Au and ^{3}He+Au
- ❑ Small system with shorter lifetime would not fully reflect initial geometry information

$V_n/(\varepsilon_n * N_{part}^{1/3})$ scaling



An empirical scaling of $v_n/(\varepsilon_n * N_{part}^{1/3})$, seen for A+A in PHENIX arXix:1412.1043(accepted by PRC), works for v_2 but *not* v_3 in the small system

Summary

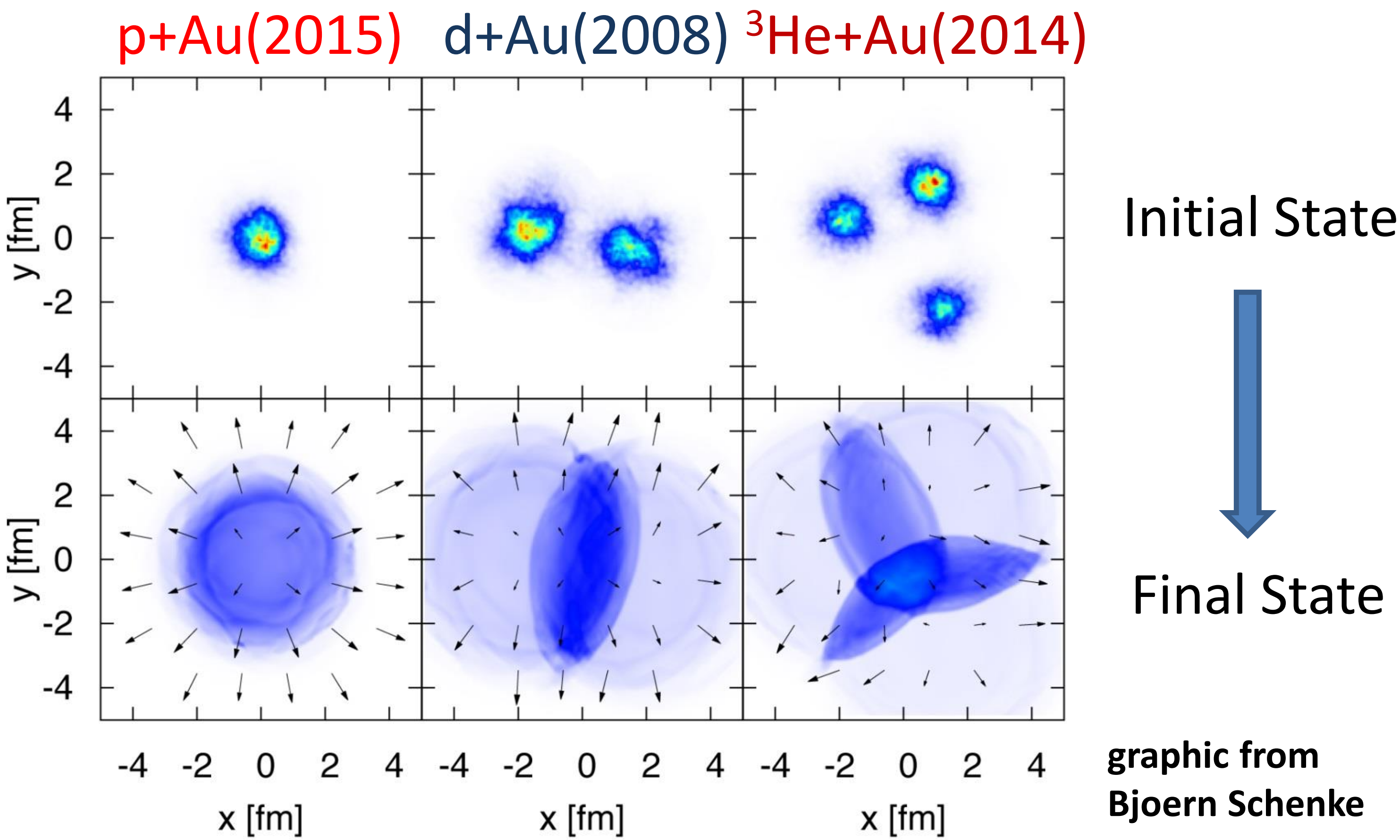
1. The ridge and anisotropy have been observed in high multiplicity pp

2. The anisotropy measured in p/d/He Au collision suggests that the initial geometry plays an important role

3. Lots of signatures of QGP in AA can also be found in small systems and consistent with hydro calculations→ mini-QGP?

backup

Geometry engineering



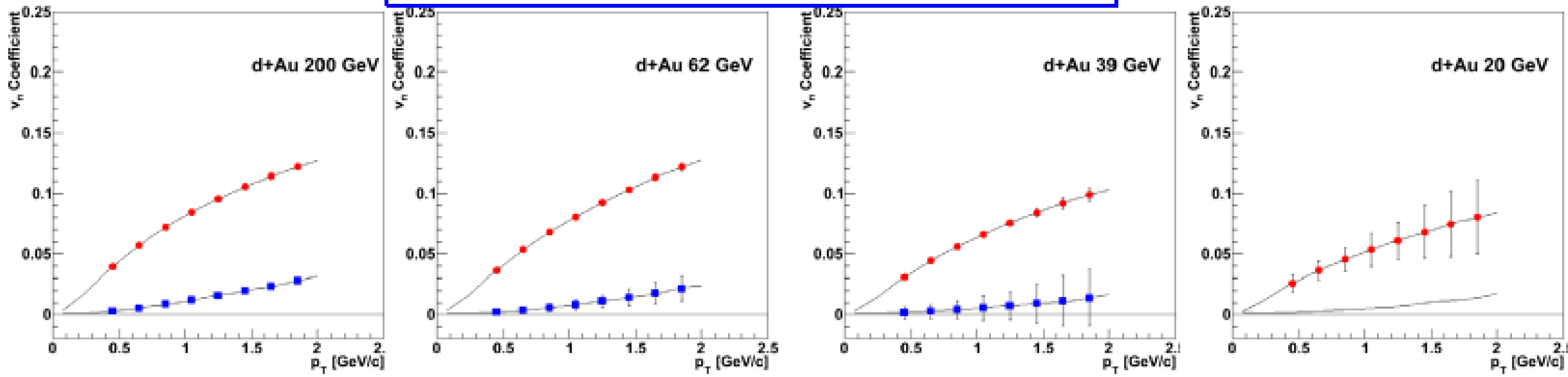
graphic from Bjoern Schenke

- Different initial geometry → different final state particle emission for p+Au, d+Au and ^{3}He+Au collisions
- The dedicated heavy ion machine RHIC can provide this kind of test with its unmatched versatility

d+Au low energy scan in RHIC

Projections (based on SONIC) for 5 weeks BES

0-5% central events within $|z_{vtx}| < 10$ cm



1 week, 1.6 B evts	1 week, 160 M evts	1.5 weeks, 110M	1.5 weeks, 9M
robust baseline v_2 and v_3 measurements	All 3 lower energies for robust v_2 measurements to establish • role of pre-equilibrium stage • role of hadronic stage		
Factor of ~20 stat increase from Run8 FVTX improved EP	v_3 at lower energy: more sensitive to time spent in QGP	Does v_3 collapse at lower energy ? upper limits of v_3 can be established	
same detector conditions=> systematics control in the BES	Statistically significant measurements for both v_2 and v_3	Transition region for v_3 collapse	Largest lever arm for v_2 measurements