Correlation and Flow:

Do we understand them as well as we claim?

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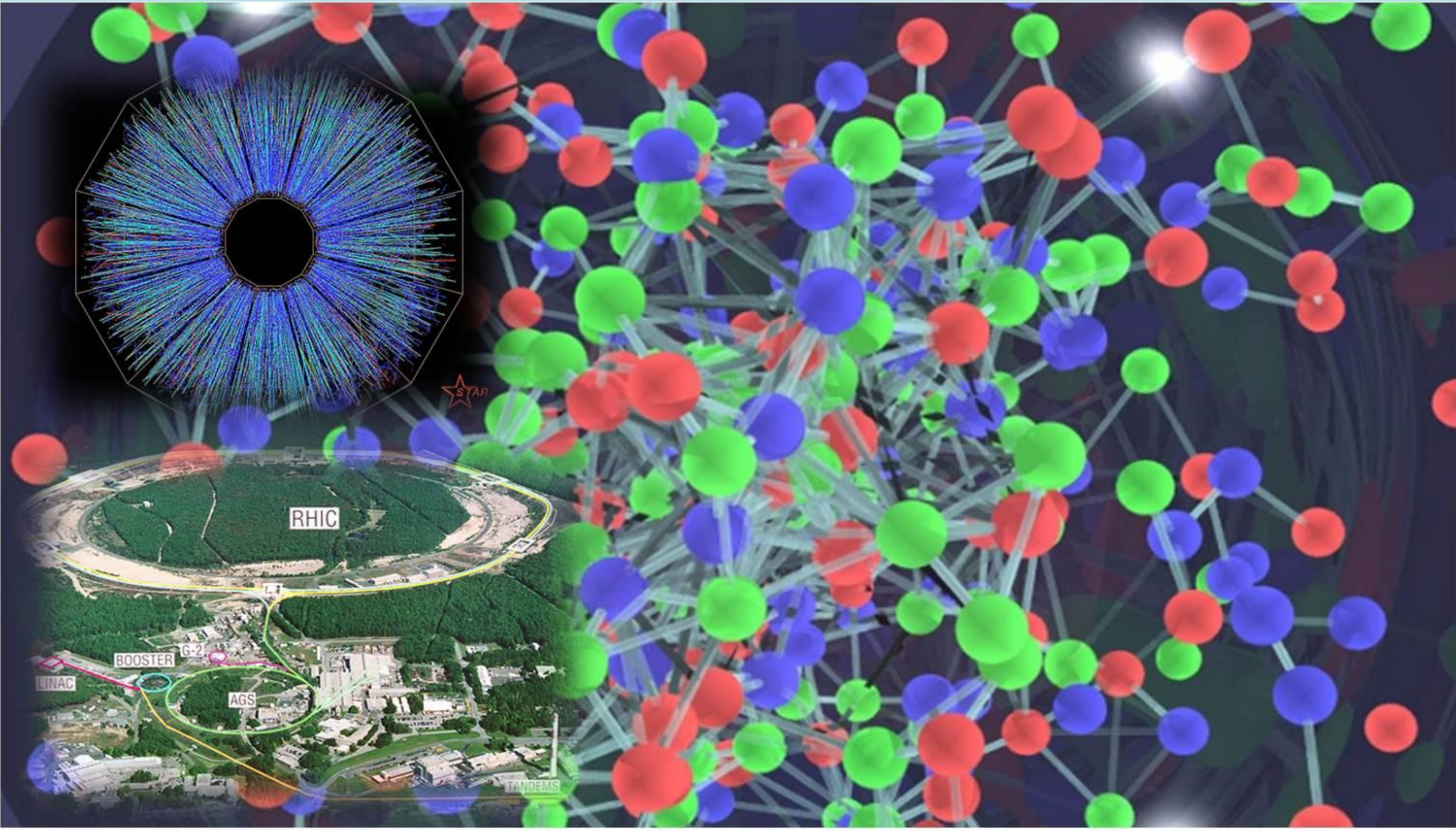
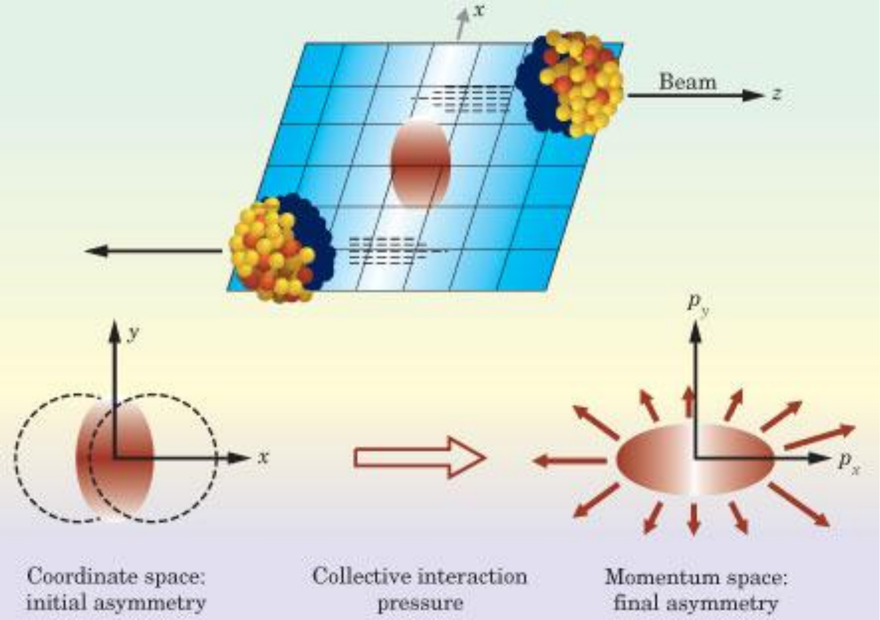
Nearly Perfect Fluid @ RHIC



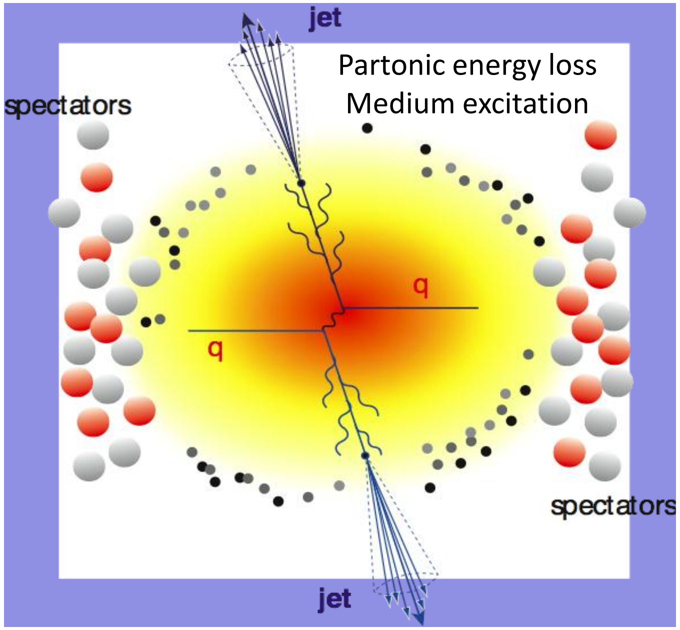
Two main tools

FLOW



Hydrodynamics
Pressure, energy density, Equilibrium
Probe Equation of State
Low p_T

JET QUENCHING

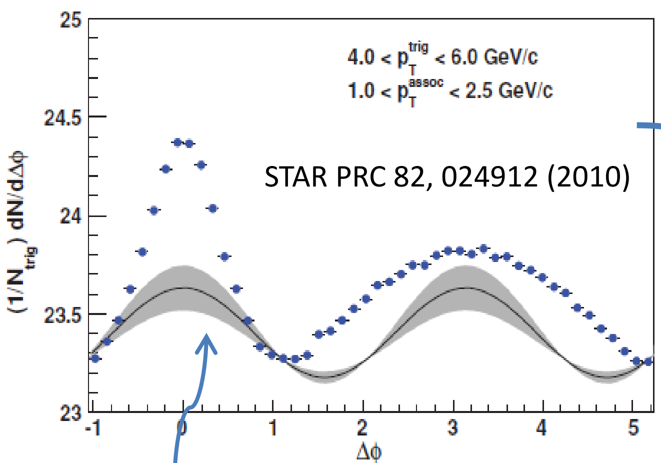


Calibrated probe in pp
Jet-medium interactions, Energy loss
Probe QCD medium properties
High p_T

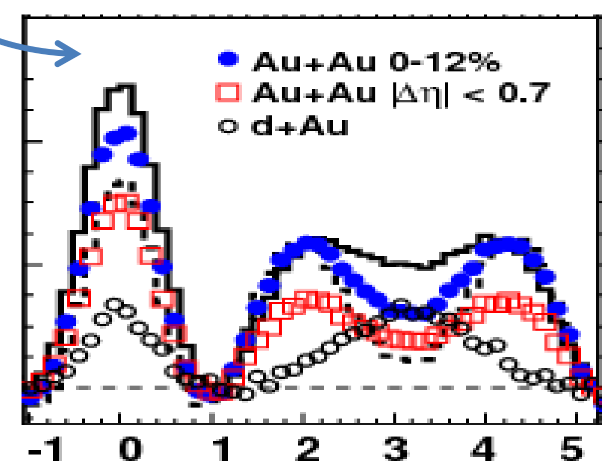
Flows are background to jet-like correlations

Two-particle correlations contain both flow and nonflow

CORREL SIGNAL + CORREL BKGD = NONFLOW + FLOW

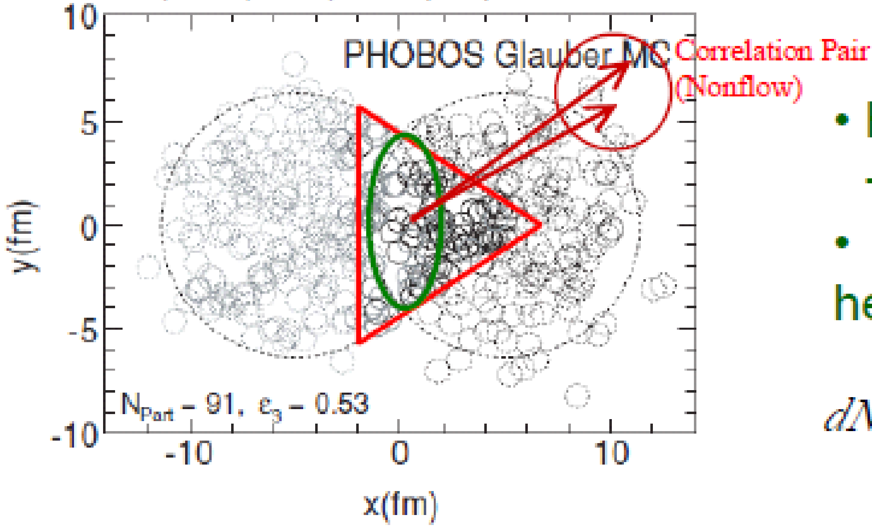


v_2 background subtraction



- Flow = background
- Nonflow = signal

Triangular and higher order harmonics



- Hydrodynamic expansion
  → anisotropic flow;
- Flow is sensitive to early stage of heavy ions collisions

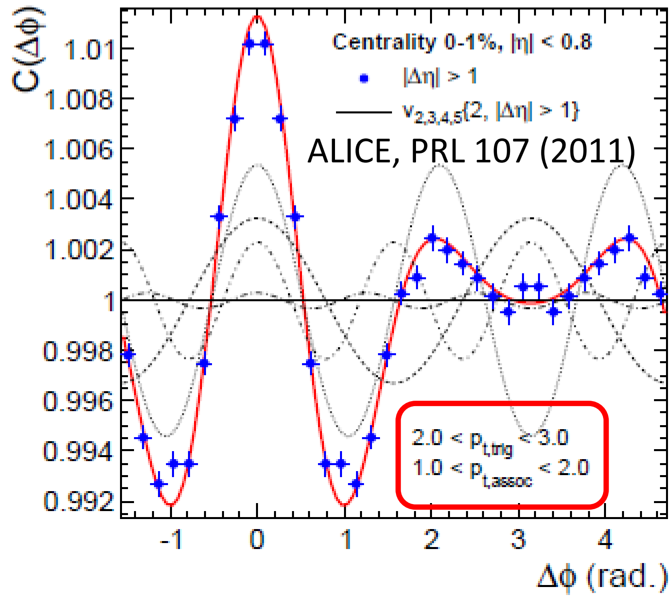
$$dN/d\varphi \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos(n(\varphi - \Psi_{nR}))$$

- Event-by-event initial geometry fluctuation
  → odd harmonics

- The reaction plane azimuthal angle is unknown
  → the measured anisotropies = flow(v) + flow fluctuation (σ) + nonflow (δ)

particle correlation unrelated to the reaction plane

Some say: All are v_n flow



p_T^{ref}=0.2-5 GeV/c

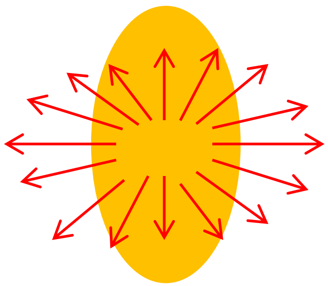
If $p_T^{assoc}=p_T^{ref}$, then

"flow" $v_n(p_T^{trig})v_n(p_T^{assoc})$ = trig-assoc dihadron correlation

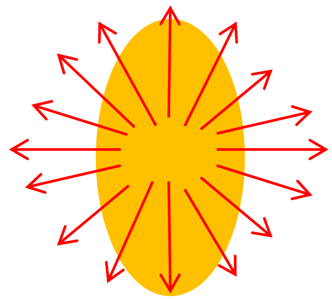
→ signal = data – data = 0.

So, the real question is what's in v_n.

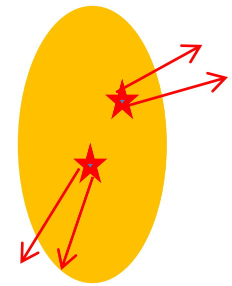
What is in v_n?



Hydrodynamic pressure driven



Pathlength dependent energy loss



Nonflow

Flow: related to the geometry

One support: Flow factorization

$$\langle \cos n(\phi_i - \phi_j) \rangle = \langle \cos n[(\phi_i - \psi_{EP}) - (\phi_j - \psi_{EP})] \rangle = \langle \cos n(\phi_i - \psi_{EP}) \rangle \langle \cos n(\phi_j - \psi_{EP}) \rangle$$

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a) v_n(p_T^b)$$ ← Factorization

$$v_n(p_T) = \sqrt{V_{n\Delta}(p_T, p_T)}$$

$$v_n(p_T) = \frac{V_{n\Delta}(p_T, p_T^{Ref})}{v_n(p_T^{Ref})}$$

Factorization expected due to global correlation with the reaction plane

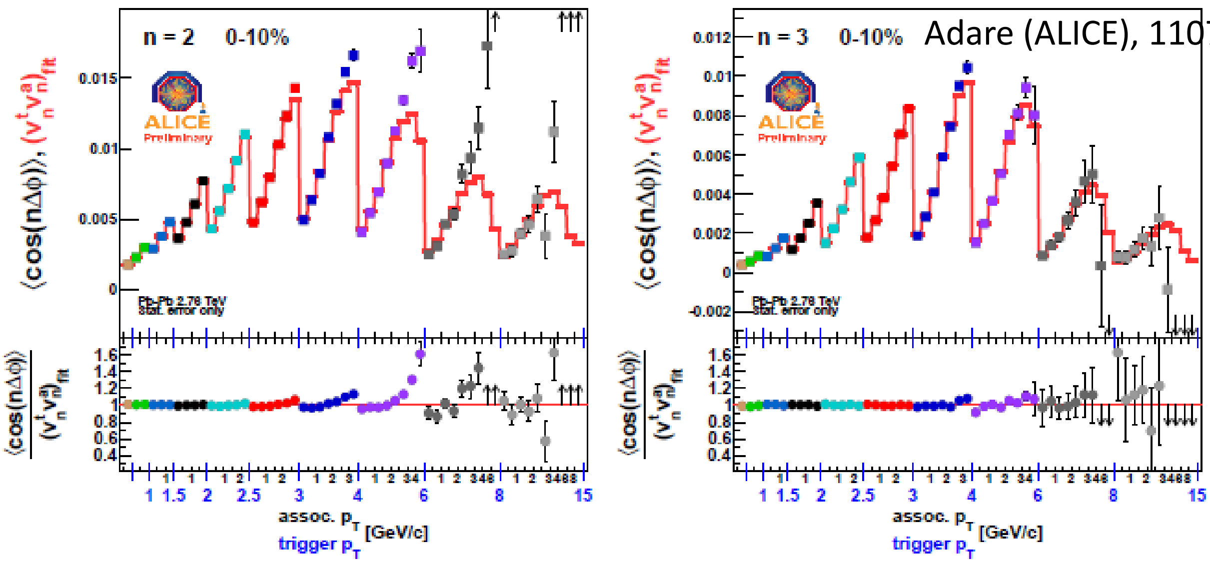
Caveat:

- Due to fluctuations, $V_{n\Delta}$ does not factorize in general
- Precise factorization if $\sigma_n \propto \langle v_n \rangle$

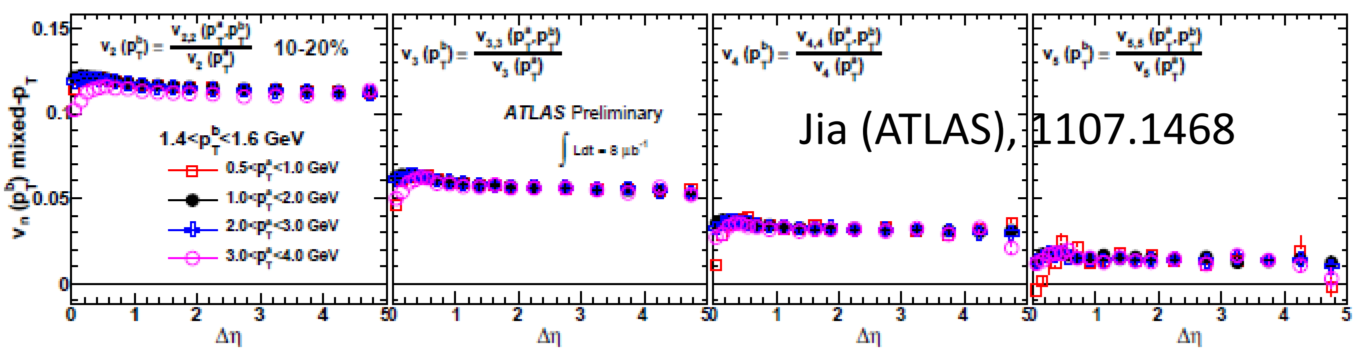
v_n factorization

$$V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a)\, v_n(p_T^b)$$

Adare (ALICE), 1107.0285



Jia (ATLAS), 1107.1468



Nonflow factorization?

Common perception:

Nonflow should not factorize

However:

Independent jet fragmentation (except the common jet thrust axis)

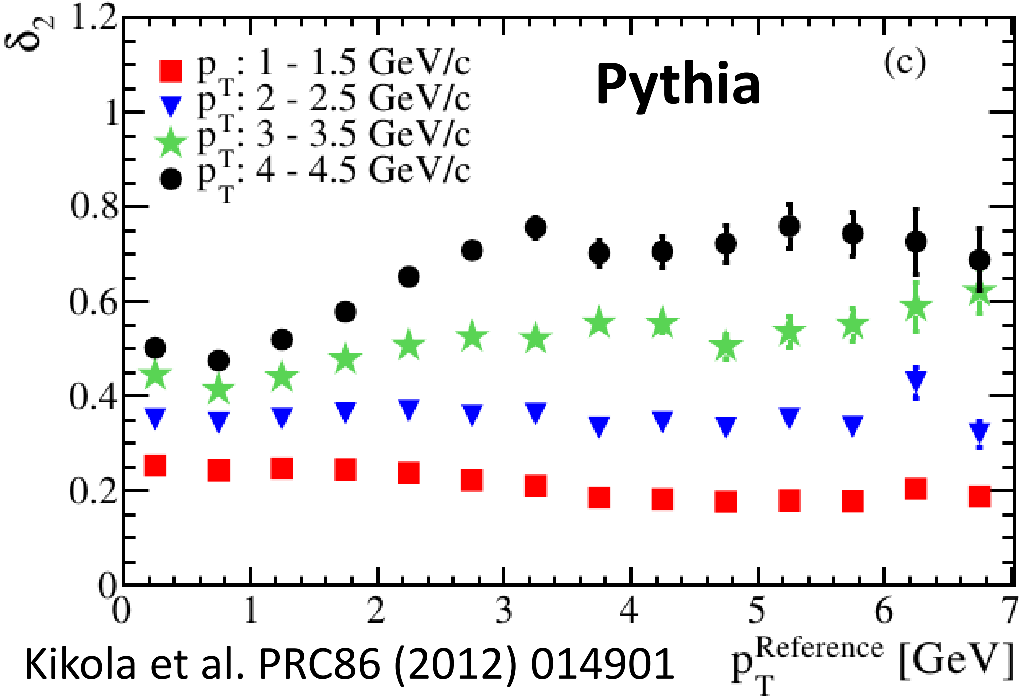
$$\langle \cos n(\phi_i - \phi_j) \rangle = \langle \cos n[(\phi_i - \psi_{jet}) - (\phi_j - \psi_{jet})] \rangle = \langle \cos n(\phi_i - \psi_{jet}) \rangle \langle \cos n(\phi_j - \psi_{jet}) \rangle$$

→ Jet correlation may approximately factorize !

Nonflow approximate factorization

$$\delta_2\left(p_T^{\text{Ref}}\right) = \sqrt{V_{2\Delta}\left(p_T^{\text{Ref}}, p_T^{\text{Ref}}\right)}$$

$$\delta_2\left(p_T\right) = \frac{V_{2\Delta}\left(p_T, p_T^{\text{Ref}}\right)}{\delta_2\left(p_T^{\text{Ref}}\right)}$$



Kikola et al. PRC86 (2012) 014901

$\delta_2(p_T^{\text{Ref}})$ approximately independent on p_T

→ Nonflow approximately factorizes in a limited p_T range

→ factorization <u>is not</u> unique feature of flow

Why is `flow' factorization so good? Because it is bootstrapped!

Anisotropic flow + non-flow: $V_{2\Delta}(p_T^a, p_T^b) = v_2(p_T^a)v_2(p_T^b) + \delta_2(p_T^a)\delta_2(p_T^b)$

$$\frac{V_{n\Delta}(p_T^b, p_T^a)}{v_n'(p_T^a)v_n'(p_T^b)} - 1$$
$$= \frac{v_n(p_T^b)v_n(p_T^c) + \delta_n(p_T^b)\delta_n(p_T^c)}{\frac{v_n(p_T^a)v_n(p_T^c)+\delta_n(p_T^a)\delta_n(p_T^c)}{\sqrt{v_n^2(p_T^c)+\delta_n^2(p_T^c)}}\frac{v_n(p_T^b)v_n(p_T^c)+\delta_n(p_T^b)\delta_n(p_T^c)}{\sqrt{v_n^2(p_T^c)+\delta_n^2(p_T^c)}}} - 1$$
$$\approx \left(\frac{\delta_n(p_T^a)}{v_n(p_T^a)} - \frac{\delta_n(p_T^c)}{v_n(p_T^c)}\right)\left(\frac{\delta_n(p_T^b)}{v_n(p_T^b)} - \frac{\delta_n(p_T^c)}{v_n(p_T^c)}\right) \quad (14)$$

- $\delta_n(p_T)/v_n(p_T)$~10% → deviation ~ 10^{-3}
- $\delta_n(p_T) \propto v_n(p_T)$ → precise factorization even if nonflow is present

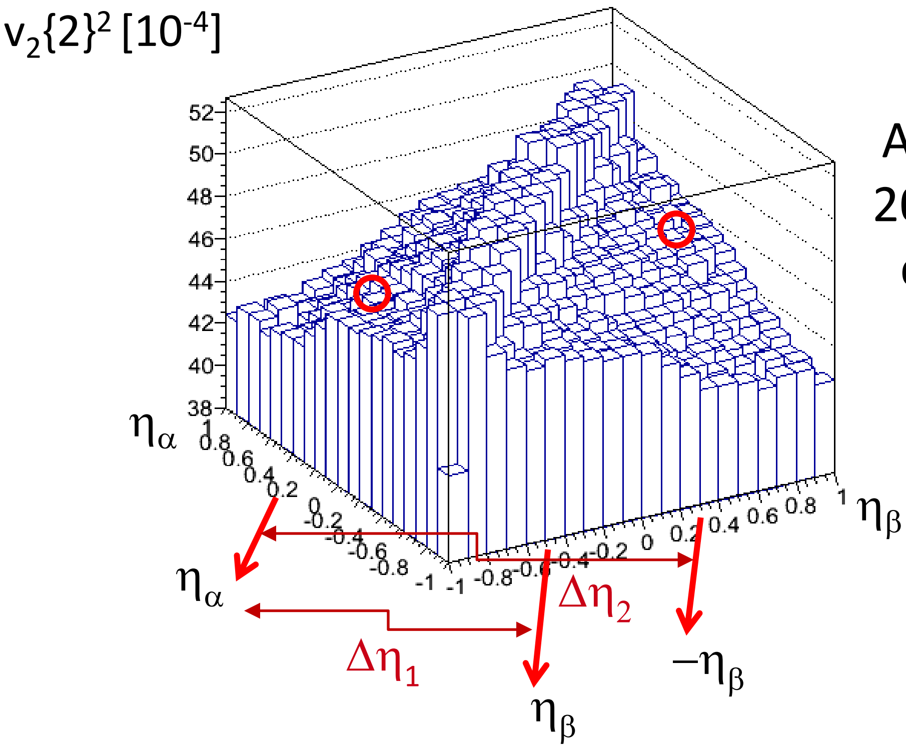
Lessons learned

- Flow $\rightarrow$ factorization; Factorization $\not\rightarrow$ flow
- Fourier components do not give further insights.
- We have to separate flow and nonflow in v_n.

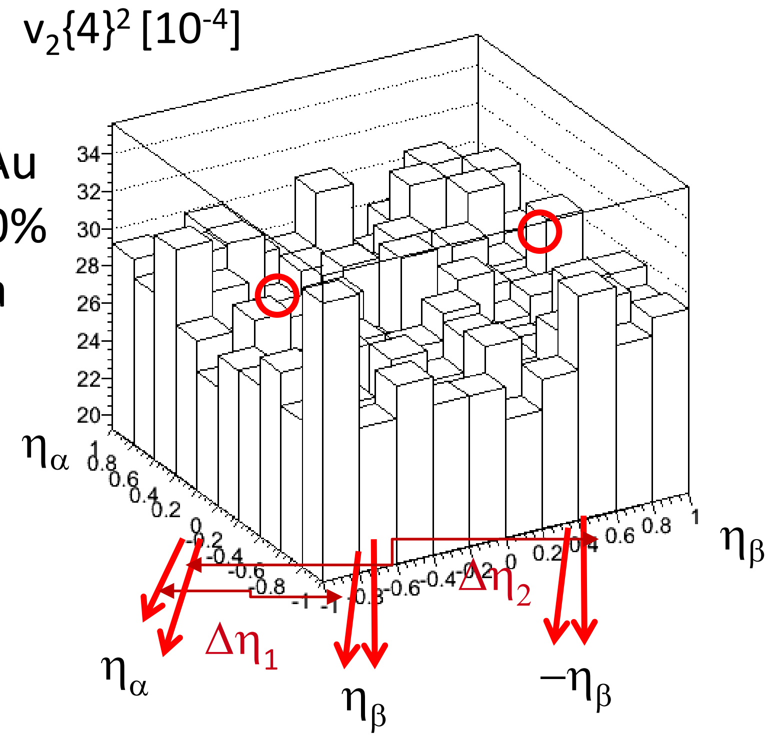
Separate flow and nonflow

Lingshan Xu et al. PHYSICAL REVIEW C **86**, 024910 (2012)

$$v\{2\}^2 = \langle v_\alpha \rangle \langle v_\beta \rangle + \sigma_\alpha \sigma_\beta + \sigma'(\Delta\eta) + \delta(\Delta\eta) \qquad v\{4\}^2 \approx \langle v_\alpha \rangle \langle v_\beta \rangle - \sigma_\alpha \sigma_\beta - \sigma'(\Delta\eta)$$



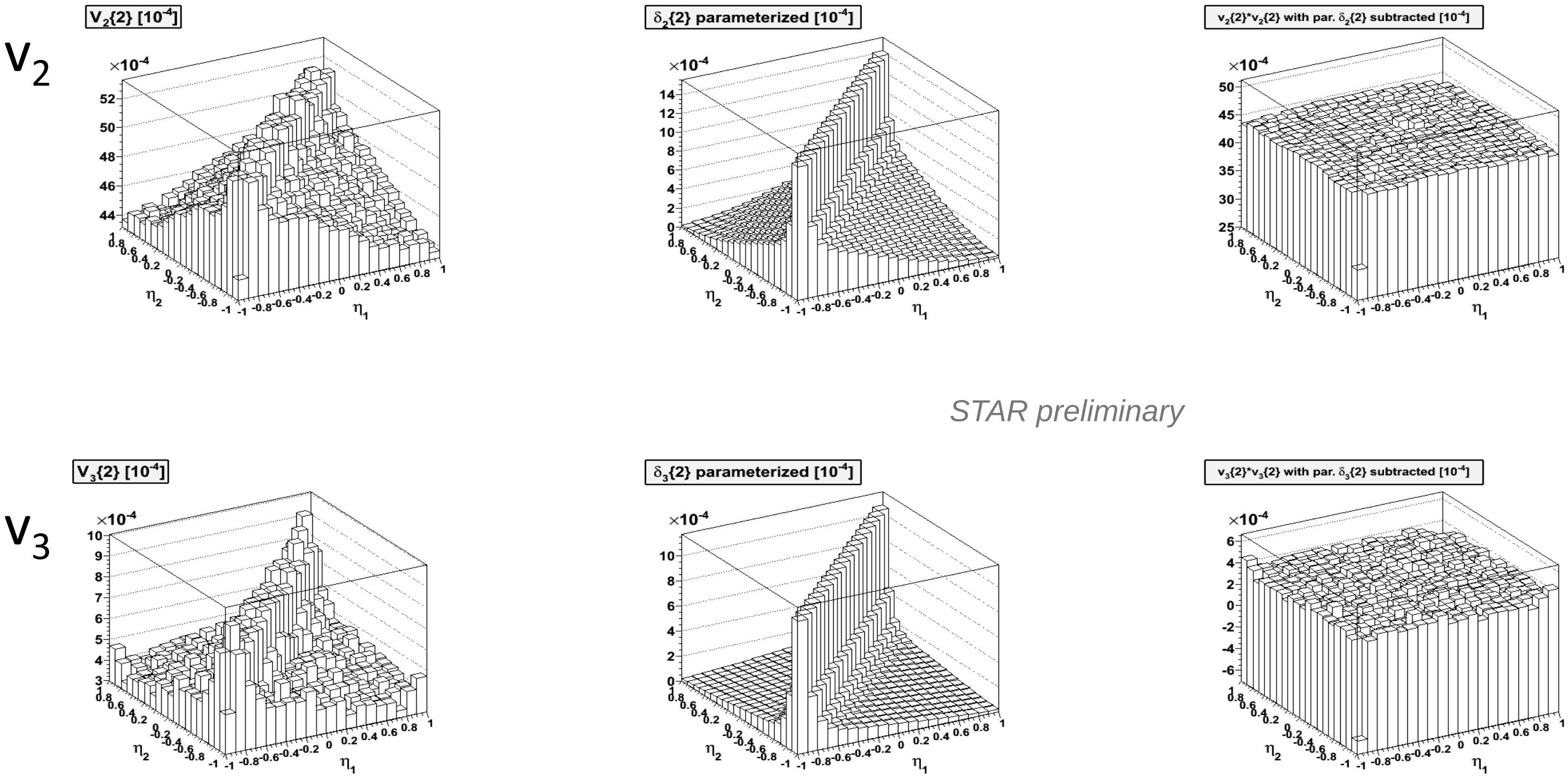
Au+Au
20-30%
data



$\sigma'(\Delta\eta_1) + \delta(\Delta\eta_1)$ vs. $\sigma'(\Delta\eta_2) + \delta(\Delta\eta_2)$

$\sigma'(\Delta\eta_1)$ vs. $\sigma'(\Delta\eta_2)$

2-particle cumulant, nonflow δ, flow v_n^2

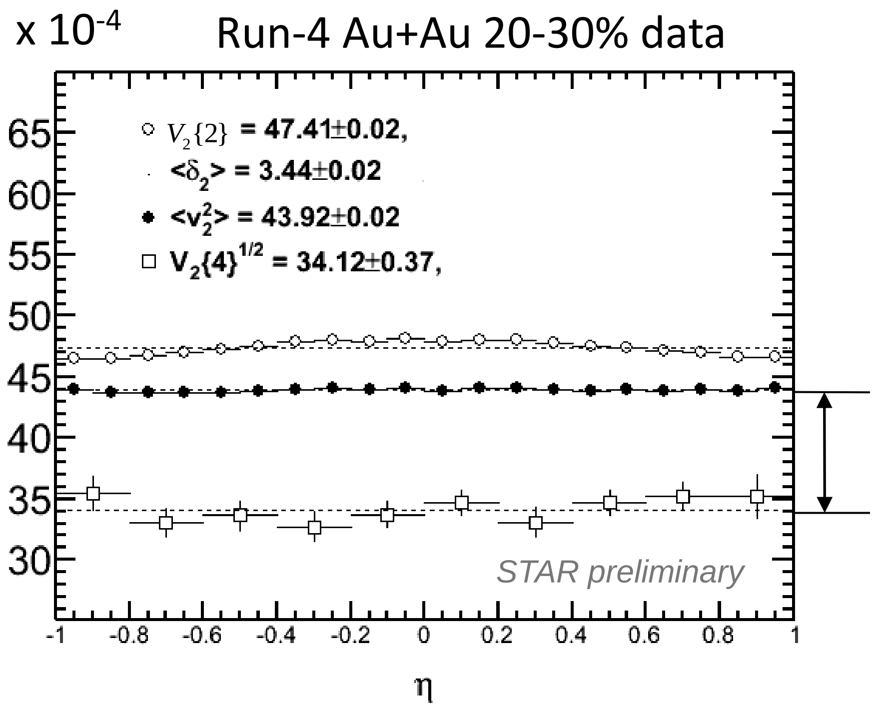


Run-4 Au+Au 20-30% data

No Assumption about flow η dependence on our analysis!

The decomposed 'flow' appears to be independent of η .

Flow vs η



$$\frac{\sigma_2^{\ 2}}{\langle v_2\rangle^2} \sim \frac{\langle v_2^2\rangle - V_2\{4\}^{1/2}}{\langle v_2^2\rangle - V_2\{4\}^{1/2}} \sim 13\%$$

- Flow seems independent of η. Note no assumption of η dependence in our approach.
- Fluctuation / flow ~ 36%

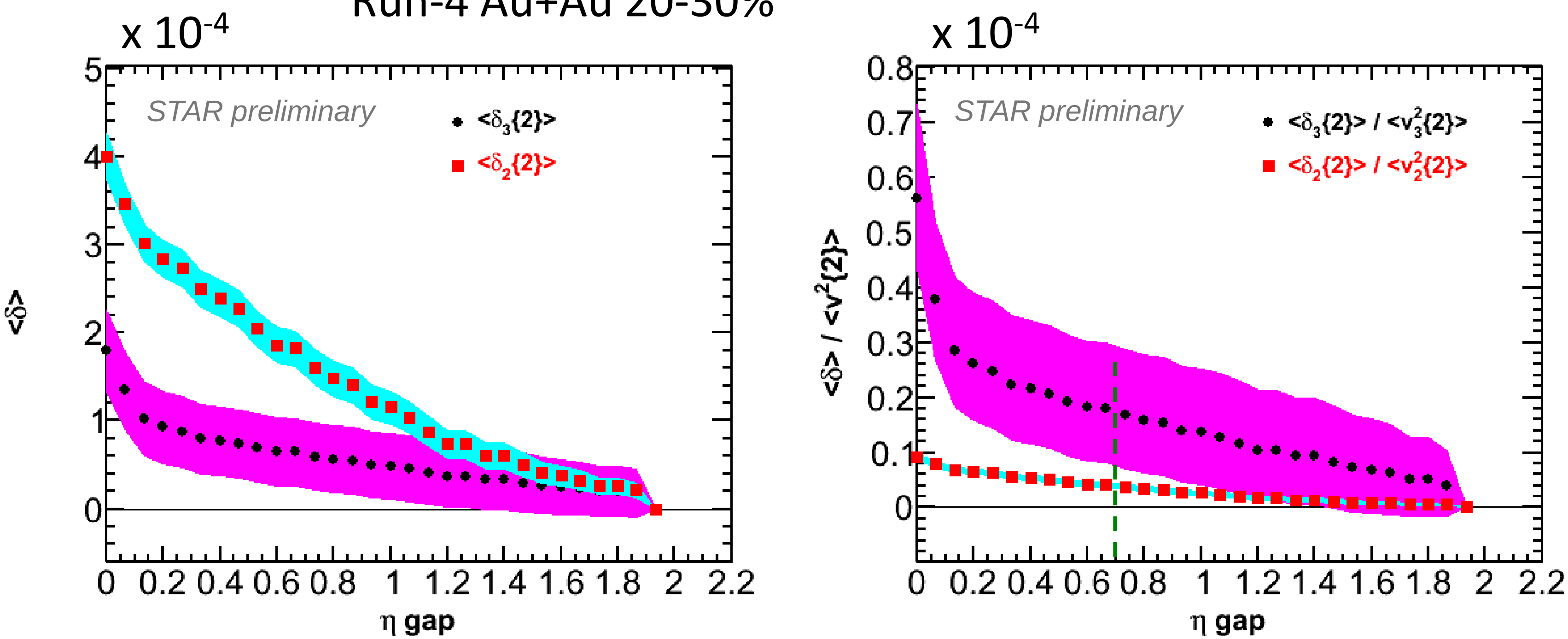
Near-side nonflow

- Calculate <nonflow> of all (η_1,η_2) bins with x < η-gap < 2. (x = horizontal axis)

☐ $\Delta\eta$ > 0, nonflow / flow ~ 40% for v_3, 10% for v_2

☐ $\Delta\eta$ > 0.7, nonflow / flow ~ 20% for v_3, 5% for v_2

Run-4 Au+Au 20-30%



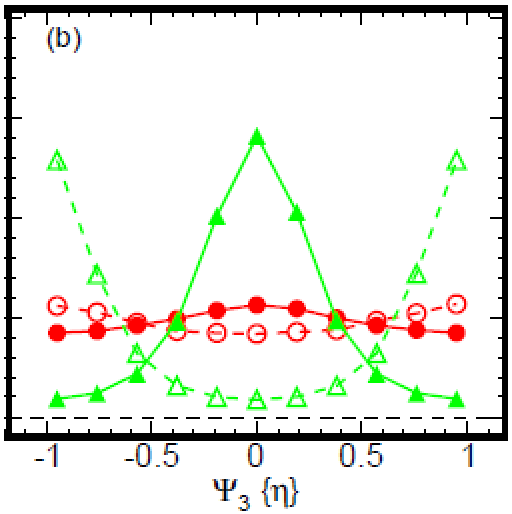
$\Delta\eta$-indep. away-side nonflow

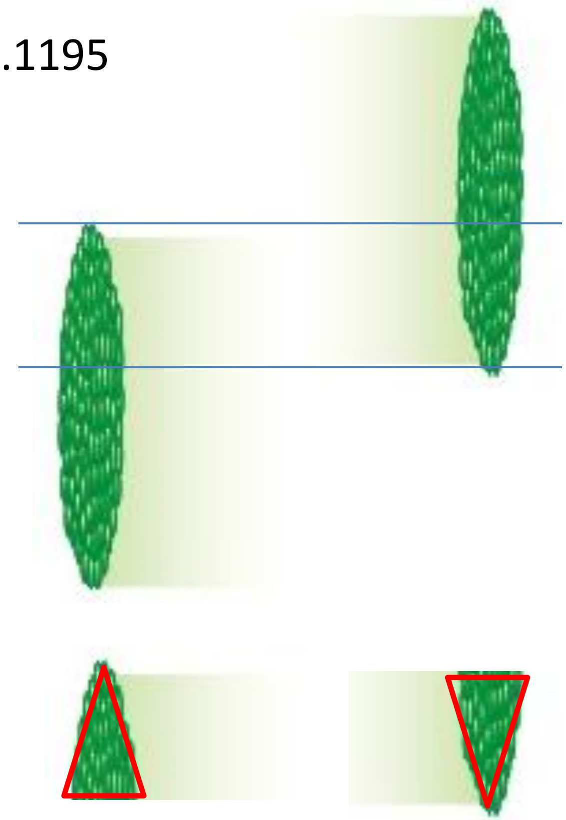
- Hijing: away-side/ near-side = 1 at $\Delta\eta > 0$
- Assuming the same ratio in data:
  - $\Delta\eta > 0$: $\delta_2^{\text{Near Side}} / v_2^2 = 10\%$ $\delta_2^{\text{Away Side}} / v_2^2 = 10\%$
  - $\Delta\eta > 0.7$: $\delta_2^{\text{Near Side}} / v_2^2 = 5\%$ $\delta_2^{\text{Away Side}} / v_2^2 = 10\%$

Large enough $\Delta\eta$ gap, near-side nonflow dies off and the away-side nonflow eventually also dies off. However…

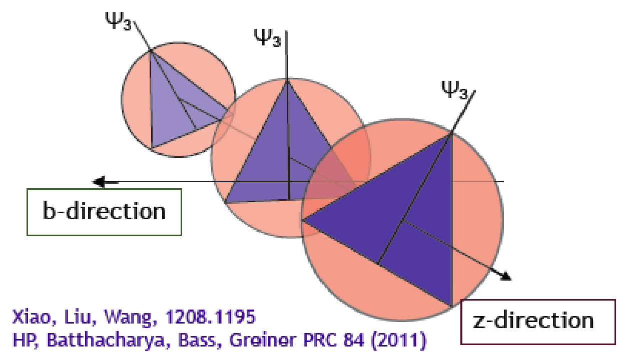
Large Δη to reduce nonflow?

Xiao et al. arXiv:1208.1195





Petersen, QM 2012



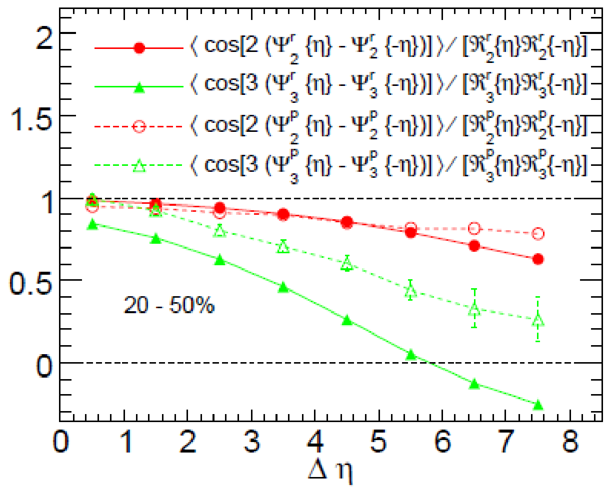
Backward rapidity

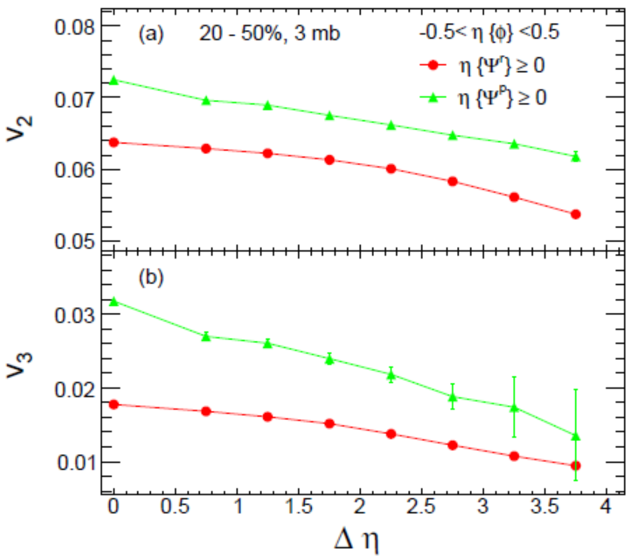
Forward rapidity

Harmonic planes may decorrelate over Δη

EP decorrelation over η

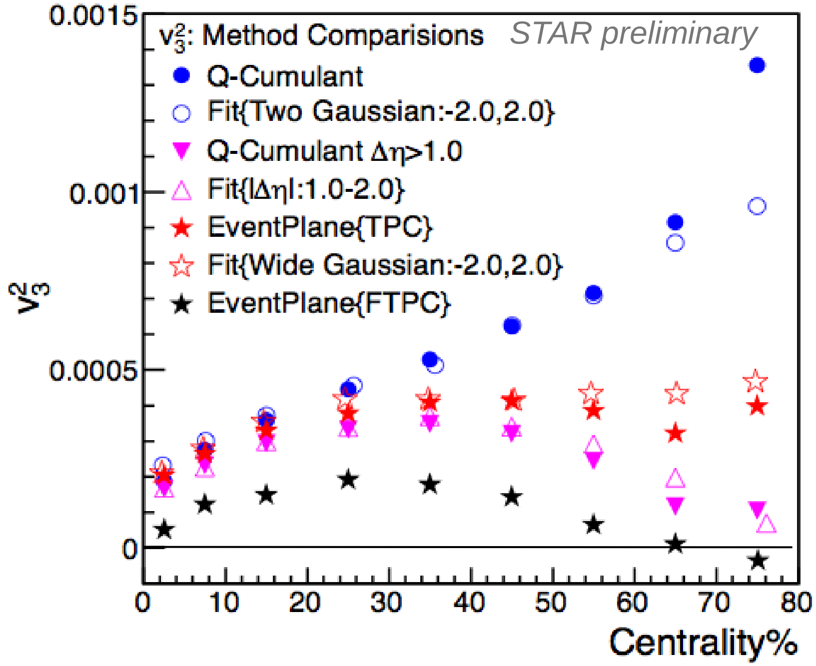
Xiao et al. arXiv:1208.1195

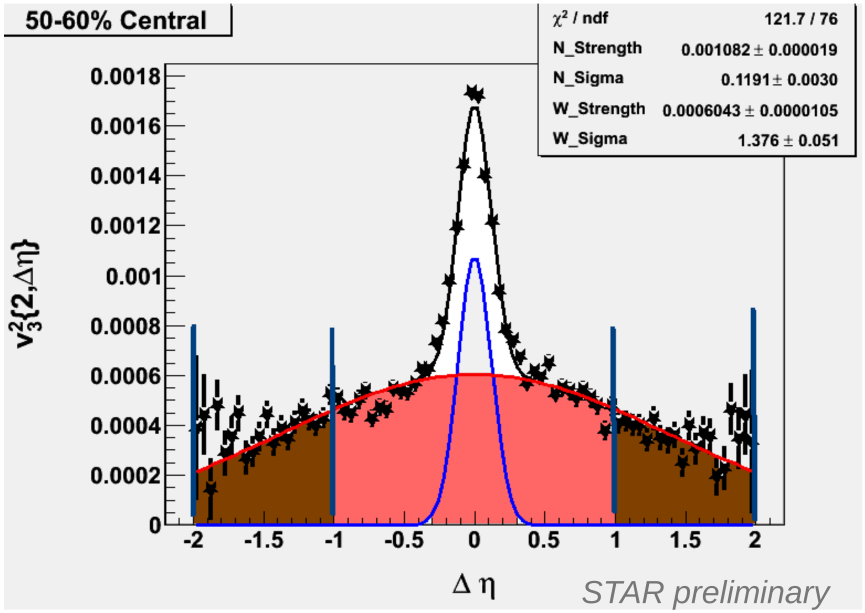




- EP's decorrelate with Δη.
- η-gap reduces nonflow, but also under-measures flow.

v_n depends on $\Delta\eta$

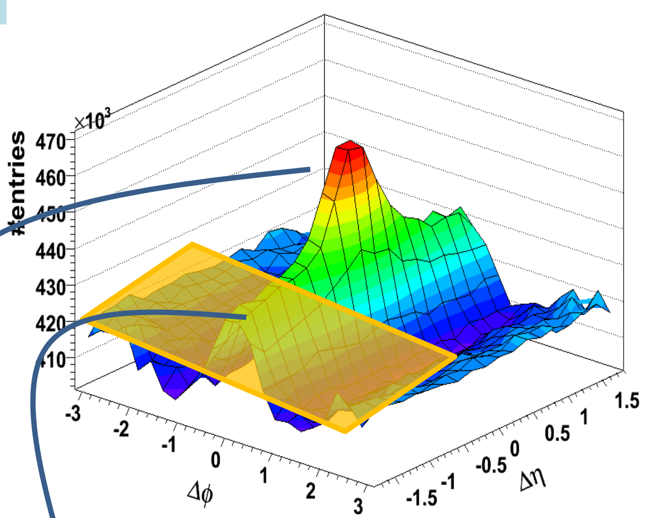


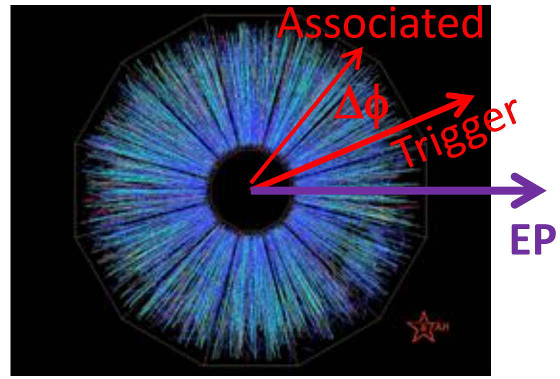


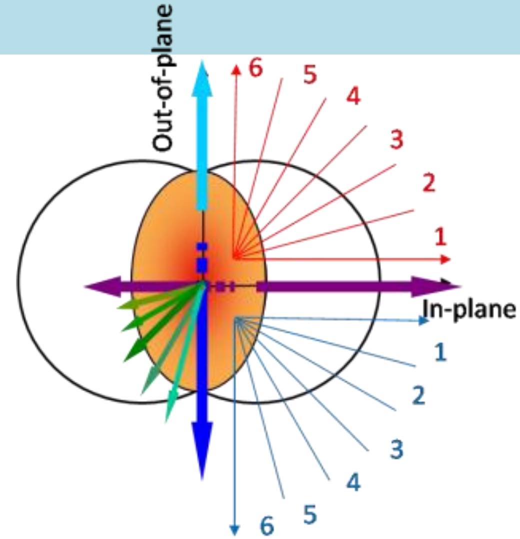
Li Yi (STAR) QM 2012.

The difference in different methods are due to different $\Delta\eta$ window used to measure v_3.

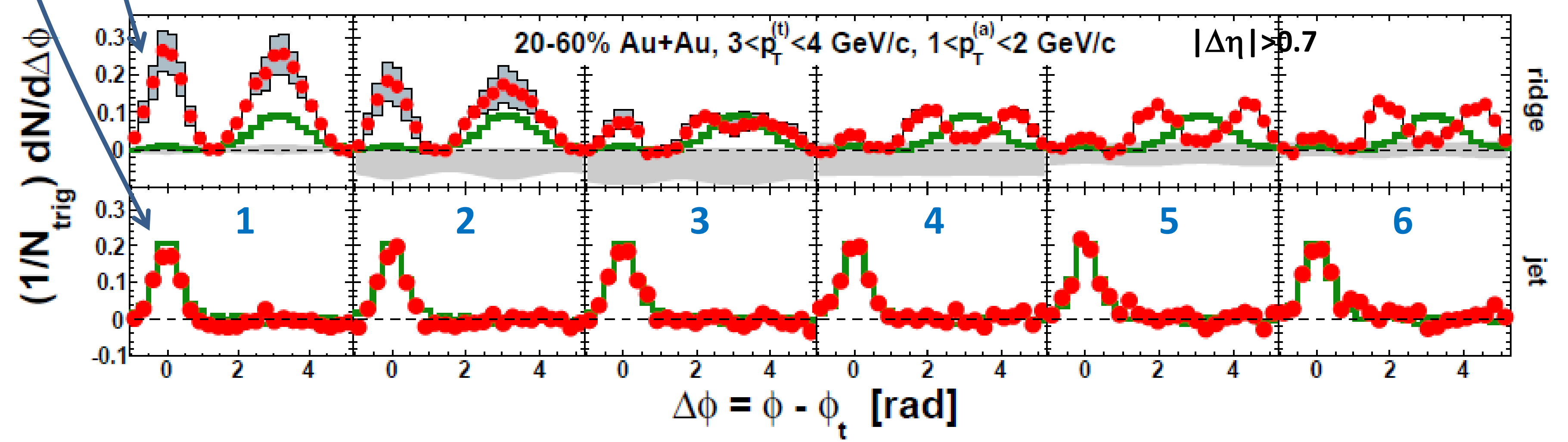
RP-dependent dihadron correlations



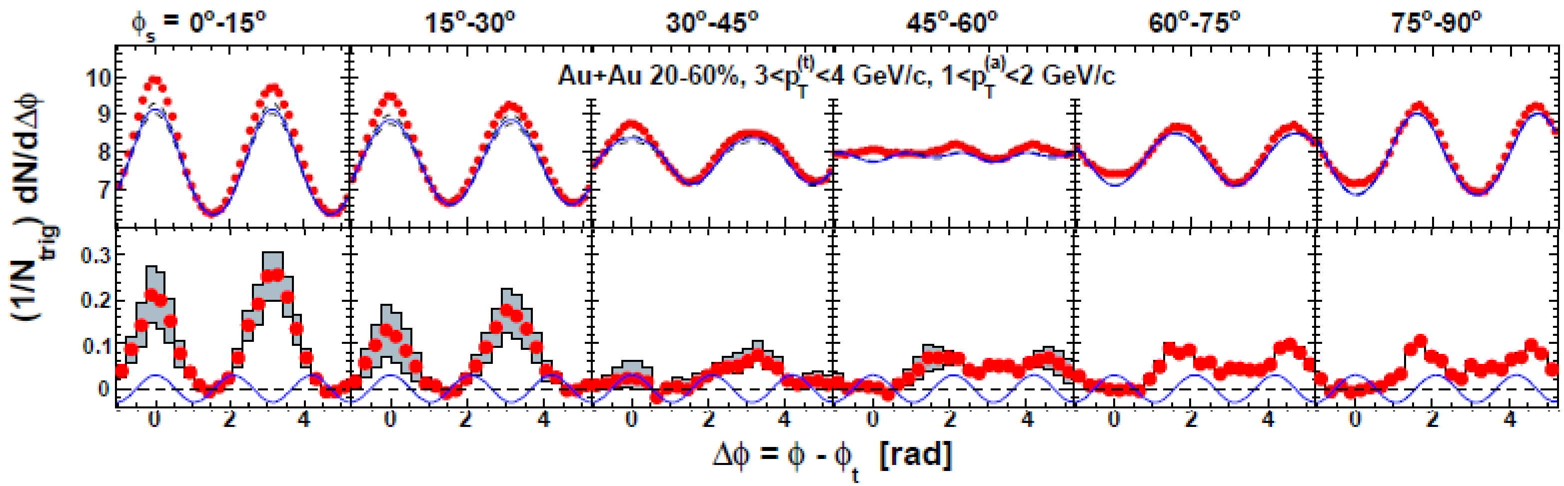




STAR, arXiv:1010.0690



v_3 does not change conclusion

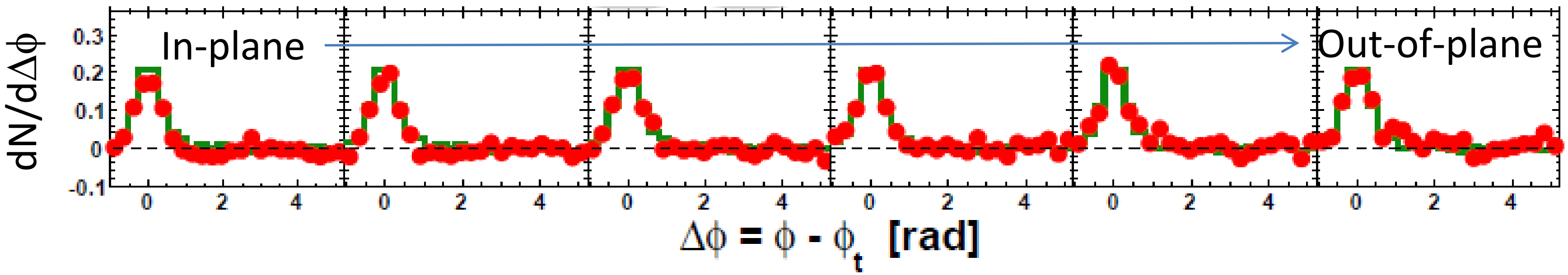


v_3/v_2 =0.45

- Flow may depend on trigger particle direction ϕ_S wrt RP, e.g. v_2 may decrease with ϕ_S.
- The in-plane ridge may not be as prominent. The in-plane away-side may be broad.
- We've taken $<v_2^{trig}\{2\}>*<v_2^{asso}\{2\}>$. This is OK even flow fluctuation is large, because $v_2\{2\}$ already include fluctuation. However, if v_2^{asso} is correlated with ϕ_S, then $<v_2^{trig}\{2\}*v_2^{asso}\{2\}> \neq <v_2^{trig}\{2\}>*<v_2^{asso}\{2\}>$.
- Actually, the inclusive correction $<v_2^{trig}\{2\}*v_2^{asso}\{2\}>$ should be larger than $<v_2^{trig}\{2\}>*<v_2^{asso}\{2\}>_{max}$! The flow subtraction to inclusive dihadron correlation would be too small.

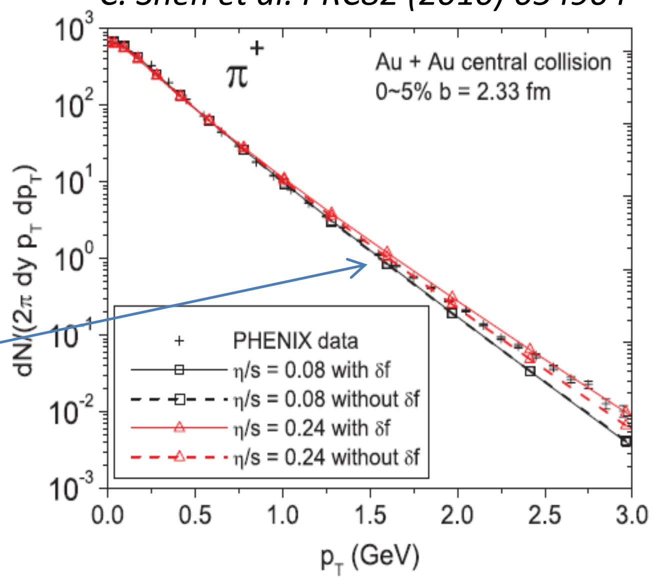
Jet-like correlations

Trigger p_T=3-4 GeV/c, Assoc p_T=1-2 GeV/c



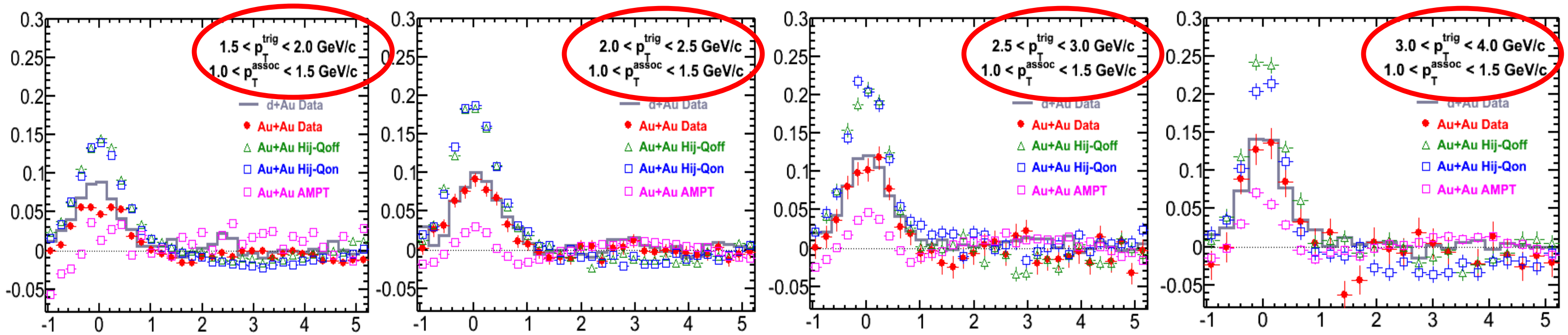
- Jet-like correlations with p_T>3 GeV/c trigger particles are invariant in-plane to out-of-plane, and from pp to central AA → these high p_T particles are mainly from jets.
- Going to lower trigger p_T, expect hydro contribution to particle production → Jet-like correlations will be reduced.
- Look at low p_T triggered dihadron correlations

C. Shen et al. PRC82 (2010) 054904

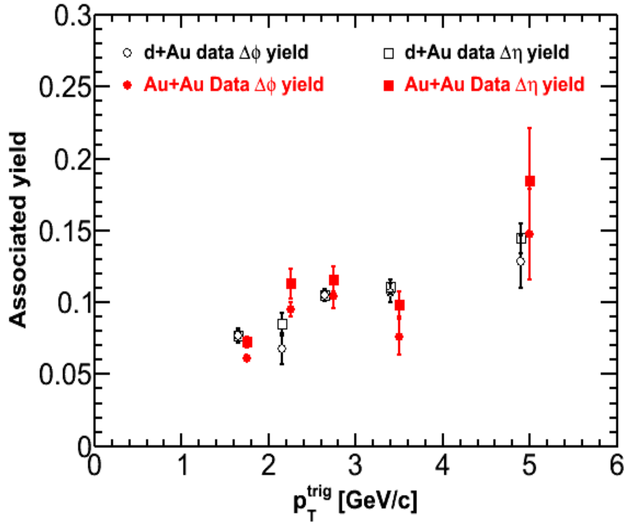


Low-p_T trigger jet-like correlations

Konzer (STAR) QM 2012



STAR Preliminary



- Surprisingly similar Au+Au and d+Au near-side jet-like signal strength
- No evidence of trigger dilution from background triggers
- Models do not reproduce data
- Challenges current understanding of particle production mechanisms

Correlation and Flow: Do we understand them as well as we claim?

NO.

Issues and open questions:

- Need to refrain a bit from simple Fourier components.
- η gap to reduce nonflow may have undesired side effect.
- Is it possible to remove all nonflow?
- $\langle v_2^{trig} * v_2^{asso} \rangle \neq \langle v_2^{trig} \rangle * \langle v_2^{asso} \rangle$
- Can hydro particles have same jet-like correlations as in d-Au?
- Do we understand p-p and d-Au?