Jet Quenching at RHIC
vs LHC in Light of Recent dAu vs pPb Controls
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Particle Correlations at RHIC: Present & Future

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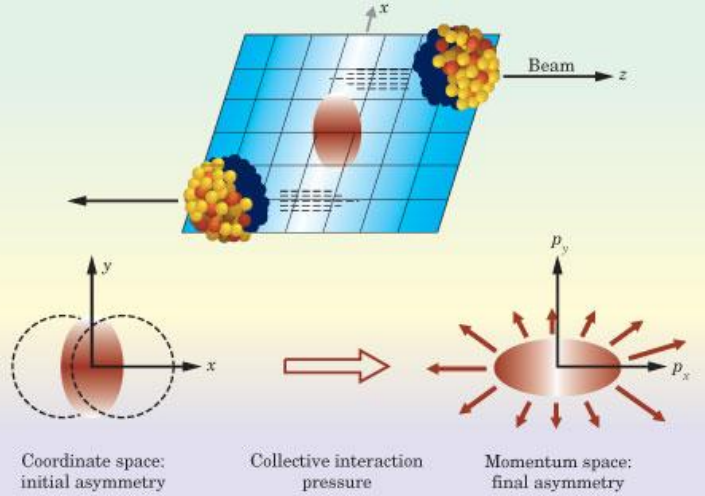
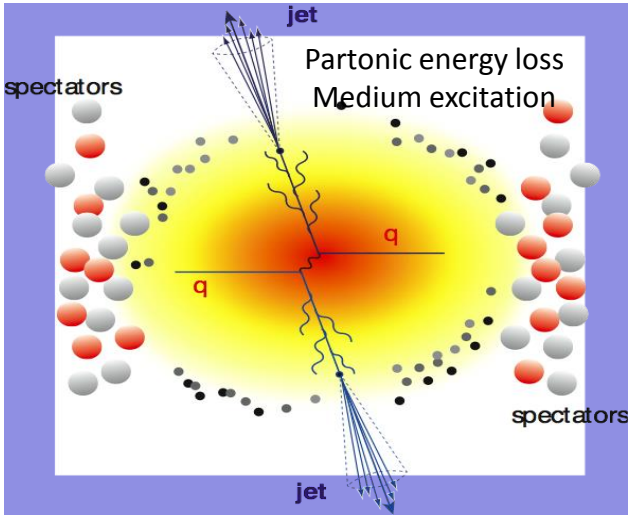
Two types of correlations

FLOW



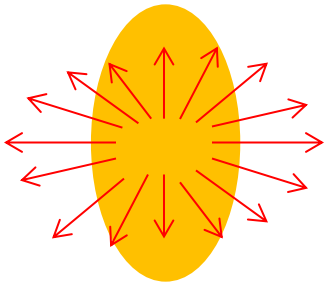
Initial-state anisotropy + fluctuations
Hydrodynamic evolution
Final-state event-wise correlations
Bulk medium properties

JET QUENCHING

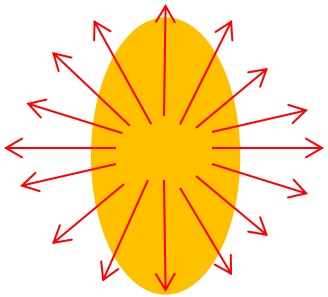


Initial-state hard processes
Jet-medium interactions
Final-state modified particle correlations
Probe ΔE mechanisms, medium properties

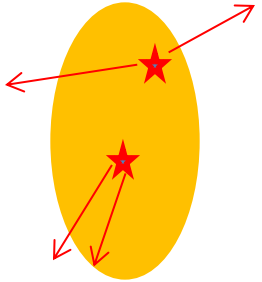
Flow and nonflow



Flow due to hydrodynamic pressure



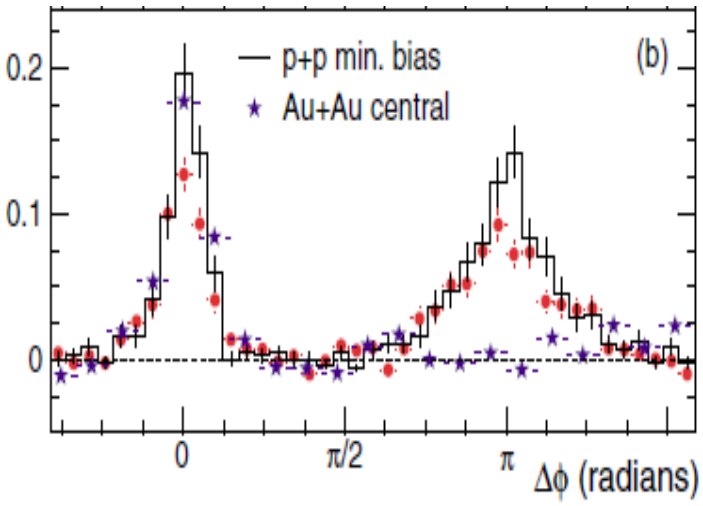
Anisotropy due to pathlength-dep. energy loss



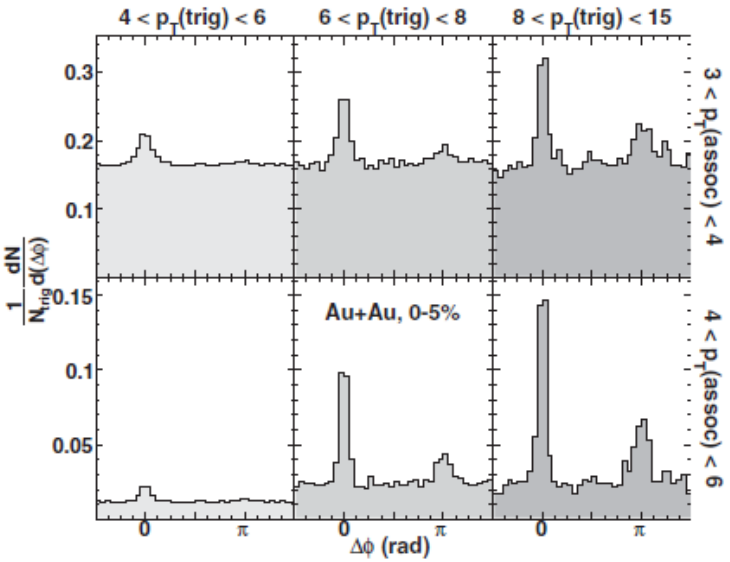
Nonflow correlations

High p_T suppression & re-emergence

STAR, PRL91 (2003)



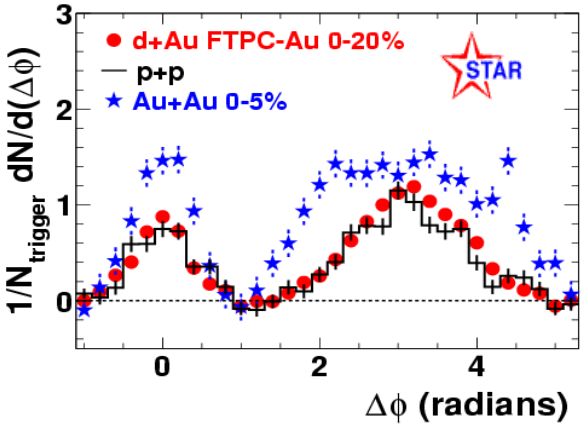
STAR, PRL97 (2006)



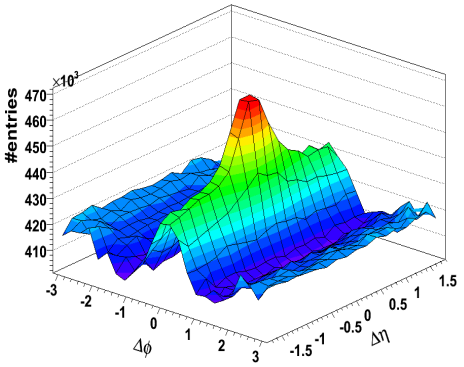
- Clear evidence of jet-quenching, and it's a final-state effect
- Finite probability of non-interacting jets at high p_T.

Low-intermediate p_T broadening

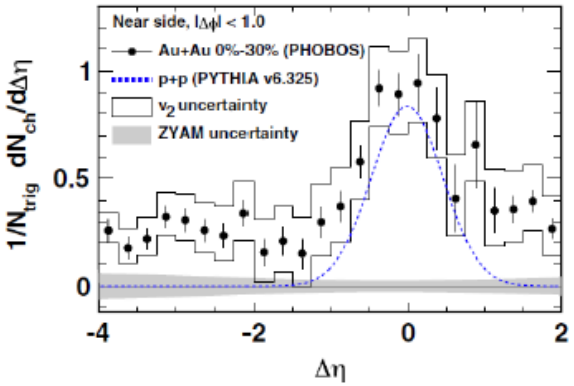
STAR, PRL 95 (2005); PRC82 (2010)



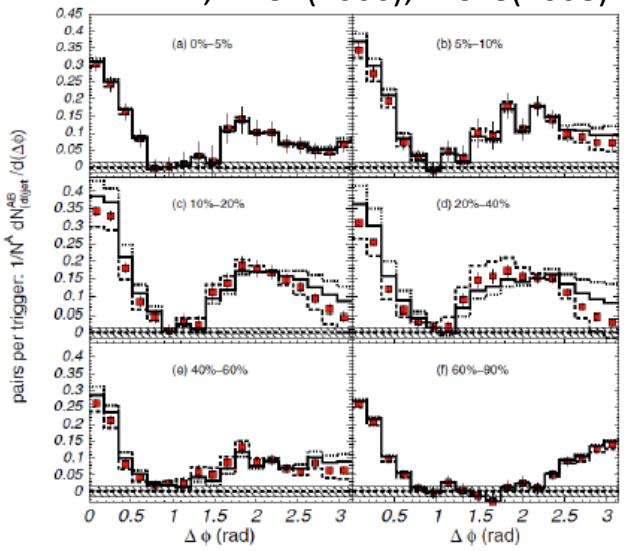
STAR, PRC80 (2009)



PHOBOS, PRL104 (2010)



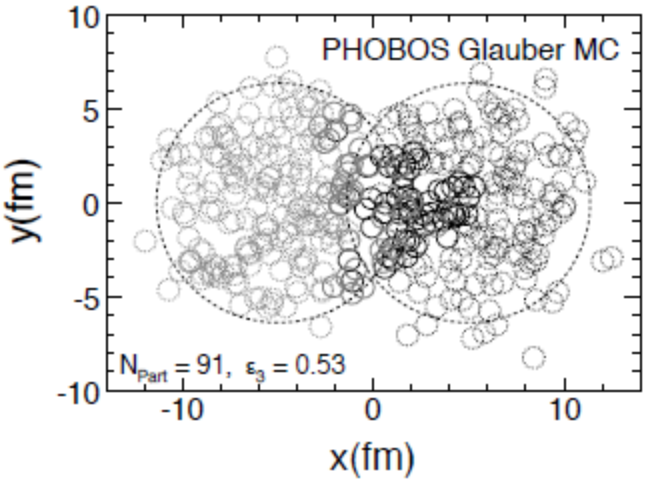
PHENIX,PRL97(2006);PRC78(2008)



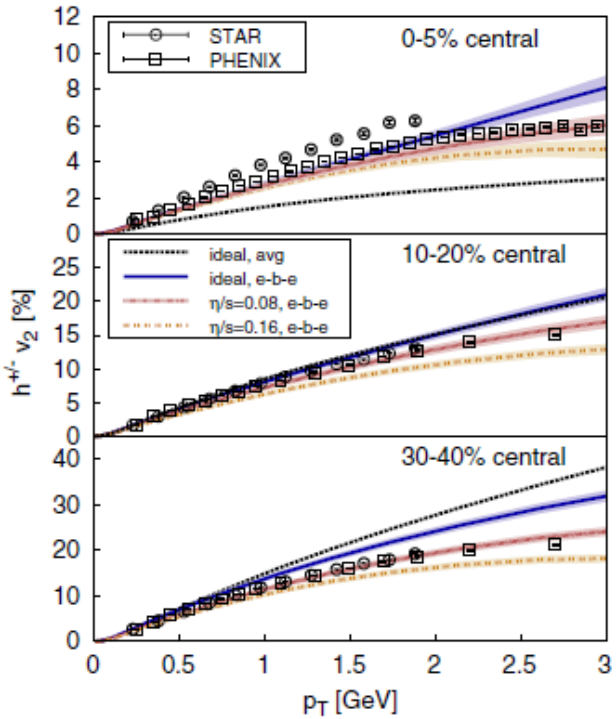
- Low p_T enhancement and broadening
- Large-$\Delta\eta$ small-$\Delta\phi$ ridge correlation
- Away-side double peak
- v_2 subtracted but not higher harmonics

All v_n's are possible

Mishra et al. PRC77 (2008)
Alver, Roland, PRC81 (2010)



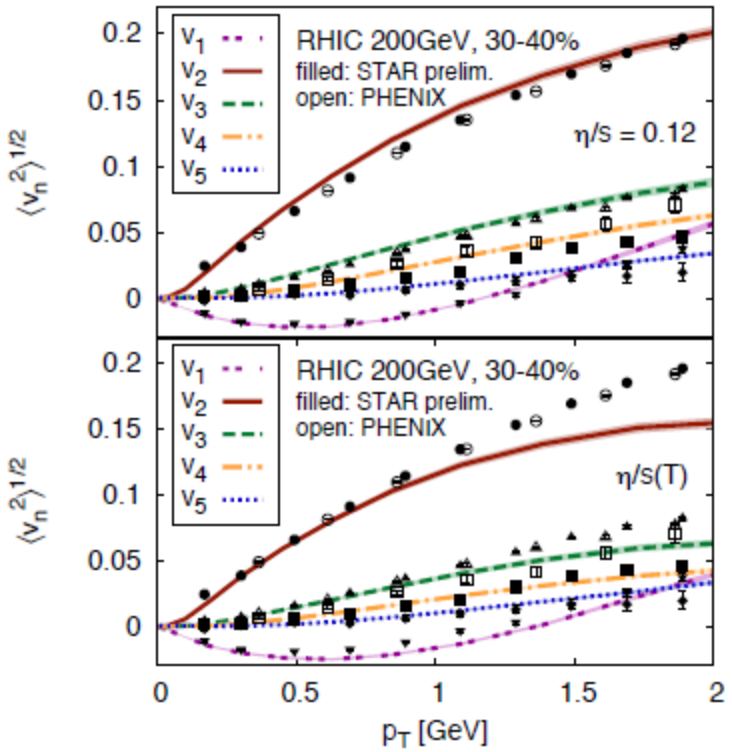
Schenke et al. PRL106 (2011)
Qiu, Heinz, PRC84 (2011)



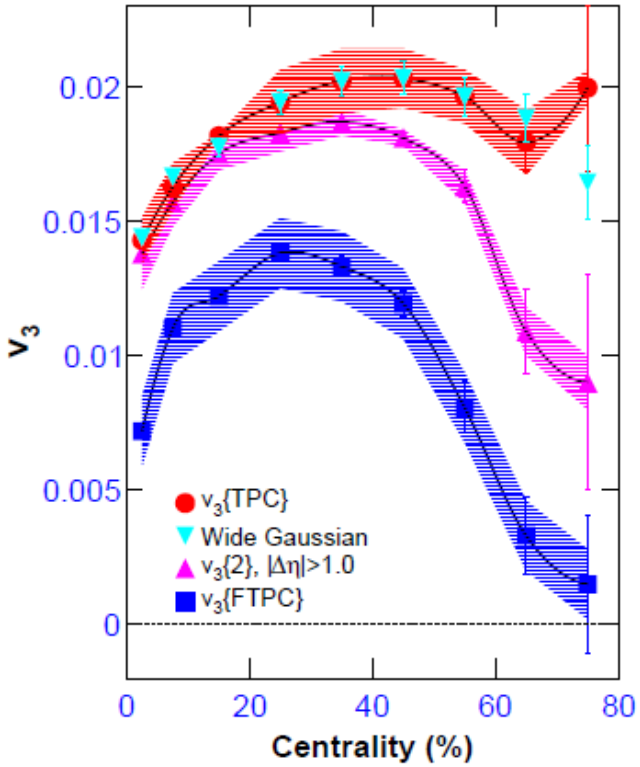
- Event-by-event fluctuations can generate initial-state triangular anisotropy
- Observable consequence in the final-state due to hydro evolution

v_3 measurements at RHIC

PHENIX, PRL107 (2011)



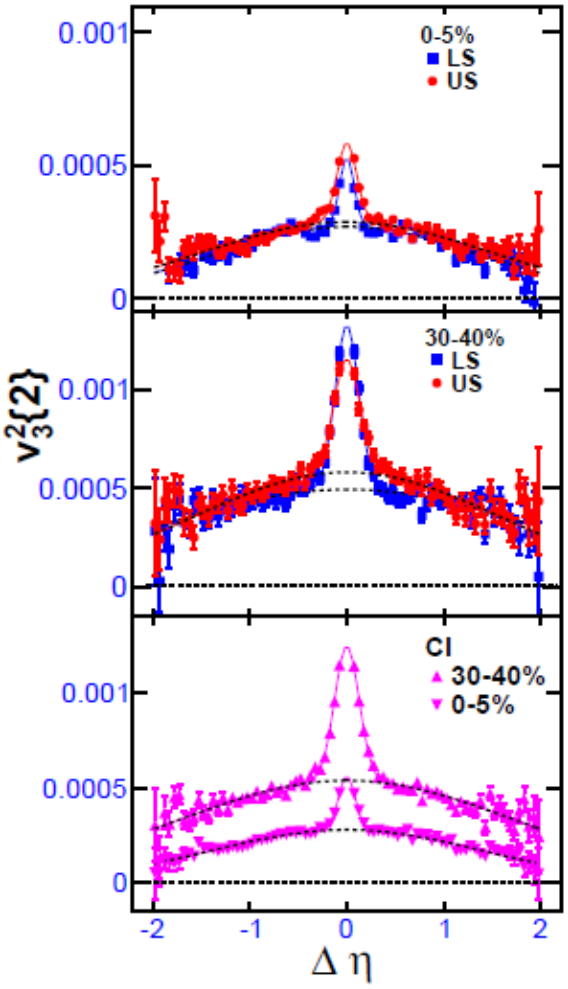
STAR, arXiv:1301.2187



- There might be tension between STAR/PHENIX

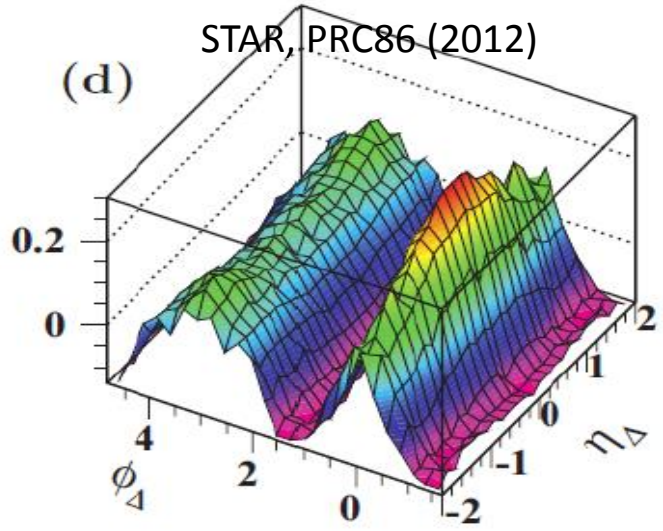
v_3 decreases with $\Delta\eta$

STAR, arXiv:1301.2187



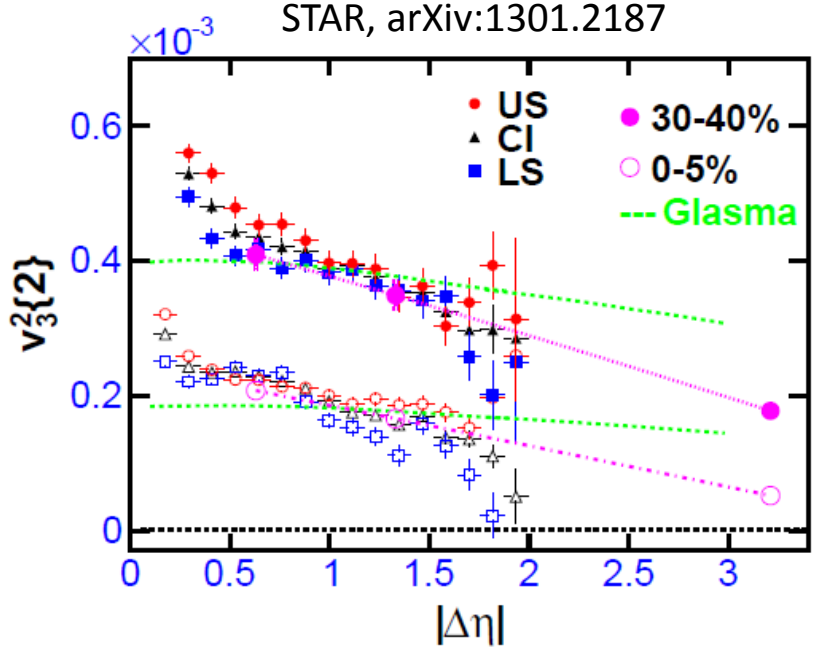
- v_3 decreases with $\Delta\eta$
- Consistent with untriggered correlations

STAR, PRC86 (2012)



v_3 depends $\Delta\eta$

STAR, arXiv:1301.2187

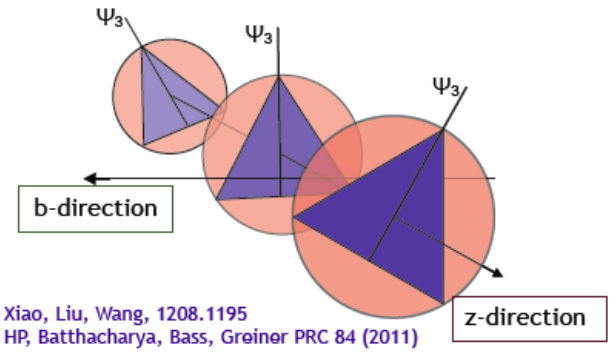


- Nonflow?

- $\Delta\eta$-dependent flow fluctuations? Harmonic planes may decorrelate over $\Delta\eta$

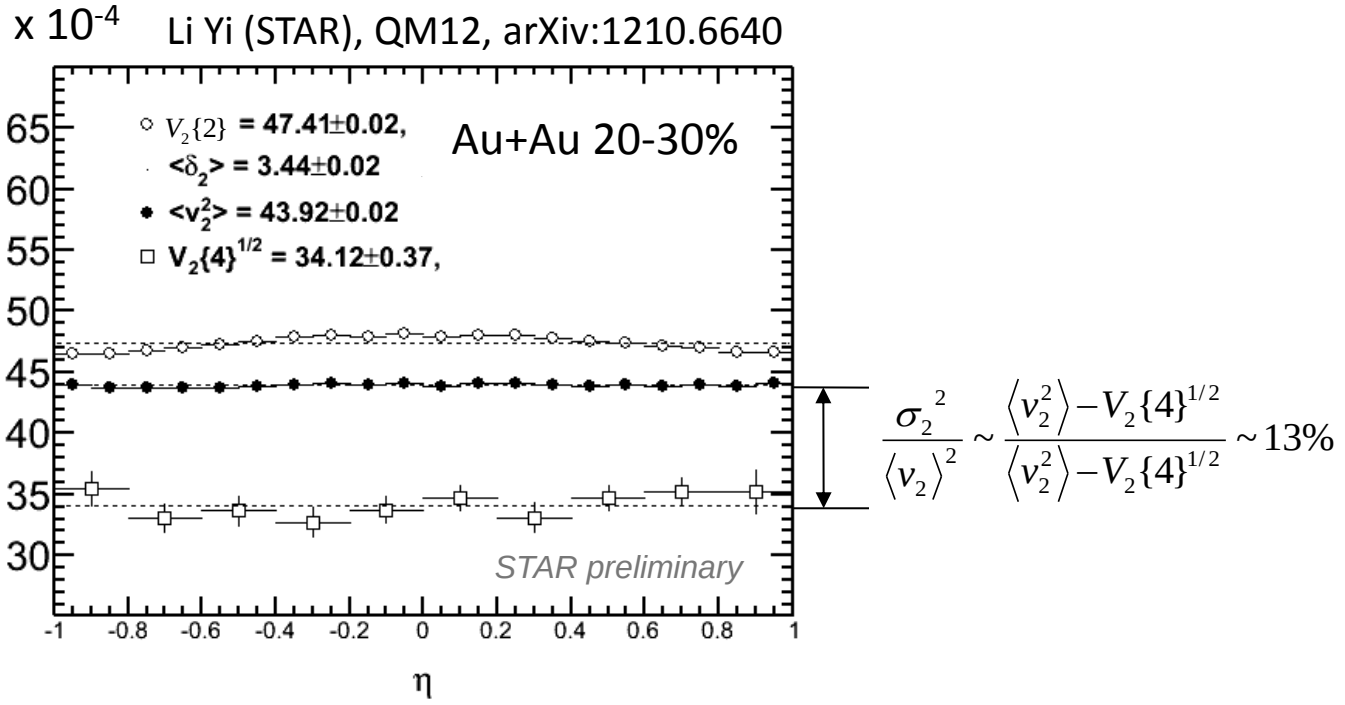
  Bozek et al. PRC83 (2011)
  Petersen et al. PRC84 (2011)
  Xiao et al. PRC87 (2013)

Petersen, QM 2012



- $\Delta\eta$-gap method may not be suitable

Flow/nonflow vs. η



- Method does not assume flow shape vs. η
- Flow seems independent of η.
- (Nonflow/flow)^2 ~ 4%, (Nonflow/flow) ~ 20%,
- (Fluctuation/flow)^2 ~ 13%, Fluctuation/flow ~ 36%

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

$$V_n(p_T^a, p_T^b) \times V_n(p_T^{ref}, p_T^{ref}) \approx V_n(p_T^a, p_T^{ref}) \times V_n(p_T^b, p_T^{ref})$$

Kikola et al. PRC86 (2012) 014901

Independent jet fragmentation → Jet correlation may approximately factorize!

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

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

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

- $\delta_n(p_T) / v_n(p_T) \sim 20\%$ → deviation ~ 10^{-2} - 10^{-3}
- $\delta_n(p_T) \propto v_n(p_T)$ → precise factorization

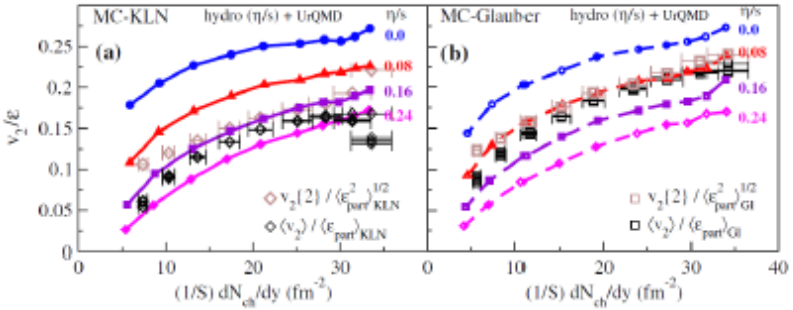
Is it important to remove nonflow?

Important because it affects extracted QGP medium property, such as η/s.

Hydro-data comparison (e.g. Uli Heinz): $v/\varepsilon \rightarrow \eta/s \sim (1\text{-}2) * 1/4\pi$
20% error on ε (Glauber vs CGC) → 100% uncertainty on η/s.

The question is how to reduce uncertainty in v_2/ε :
1. ε from theoretical part
2. v_2 from experimental part

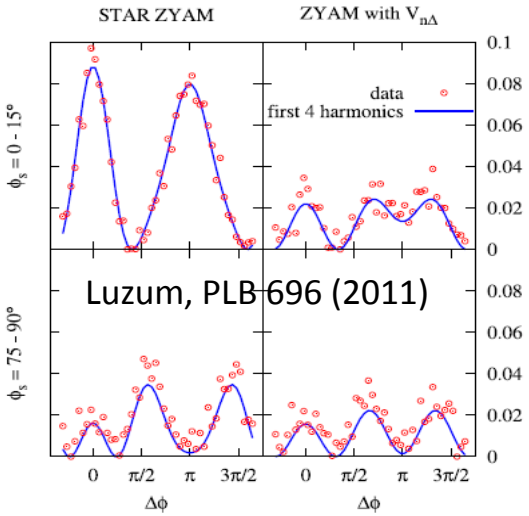
Song, Bass, Heinz, etal. PRL 106, 192301 (2011)

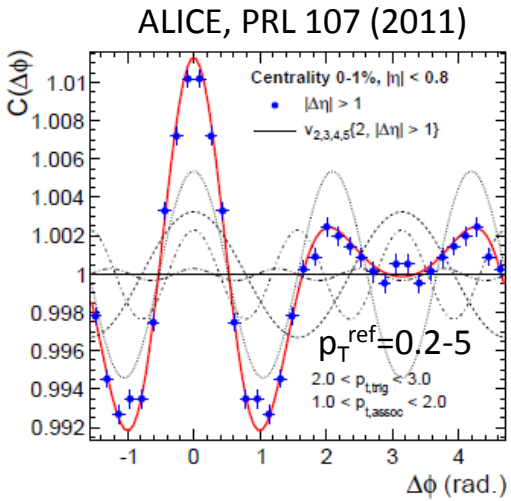


"The extraction of η/s from a comparison with hydrodynamics thus requires careful treatment of both fluctuation and nonflow effects"

v_n background subtraction

- It's absolutely important to remove all sizeable v_n's in jet-correlations
- What v_n to subtract? v_n with minimal jet (nonflow) contributions
- But v_n have to be measured by final-state particle correlations



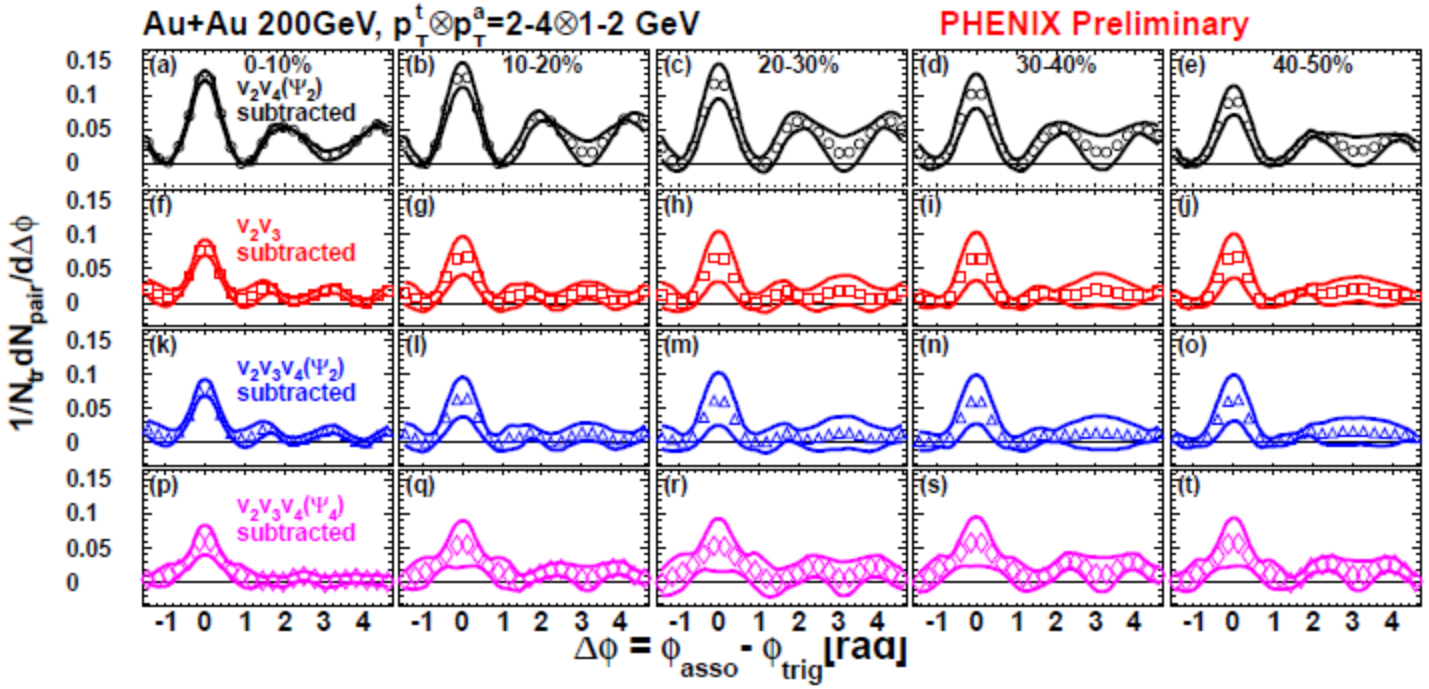


Word of caution: With non-vanishing odd harmonics, nothing really prevents people from fitting everything to v_n. Fine in itself, but dangerous if people subsequently take it as entirely hydro flow.
The real question is what's in v_n?

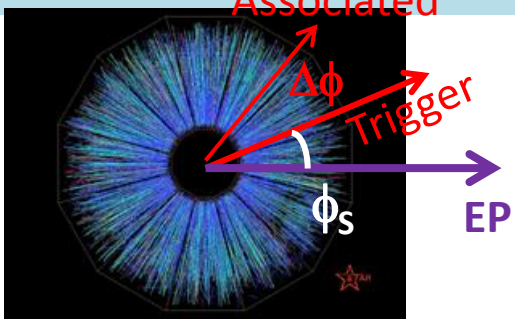
- Apply $\Delta\eta$-gap: may not work because of potential $\Delta\eta$-dep. flow fluctuations
- Viable way is to use as low p_T reference particles as possible. Disadvantage is flow is small at low p_T.

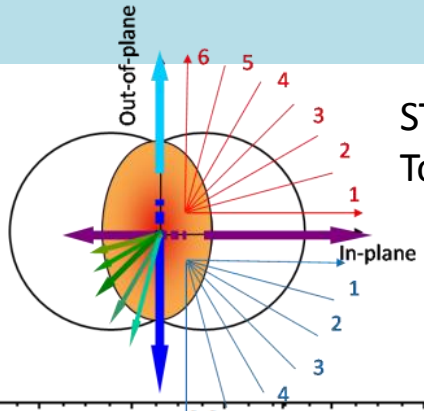
Dihadron correl. with vn subtractions

Todoroki (PHENIX), QM12, arXiv:1304.2852

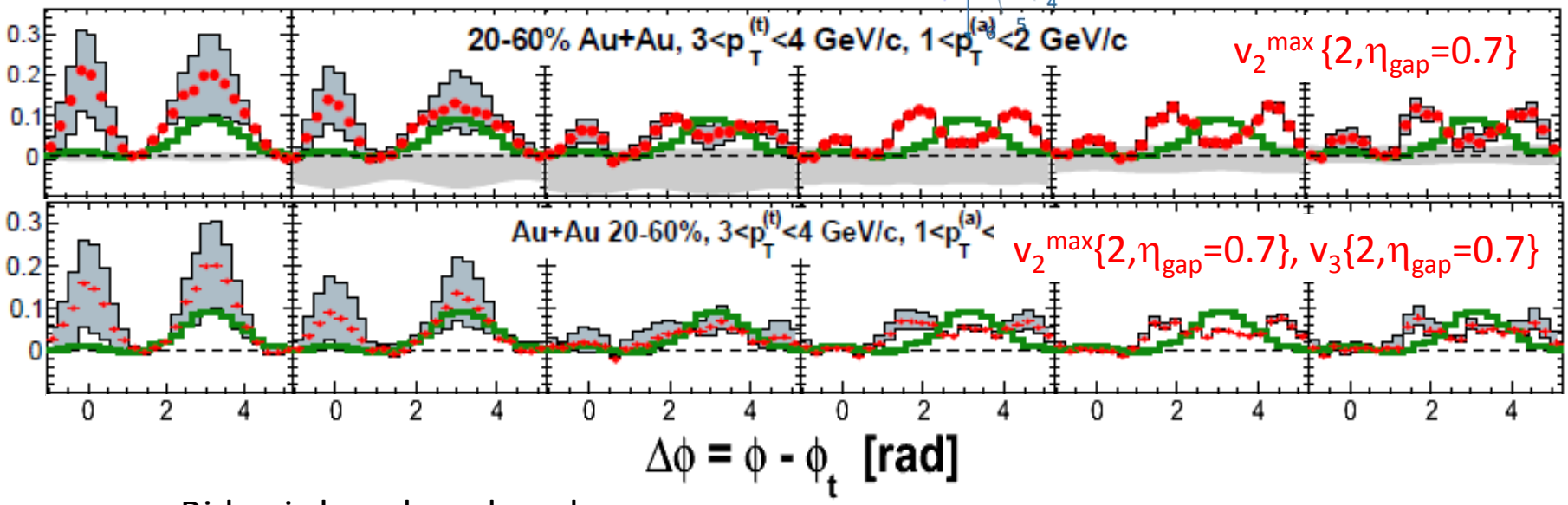


Relative to the Event Plane



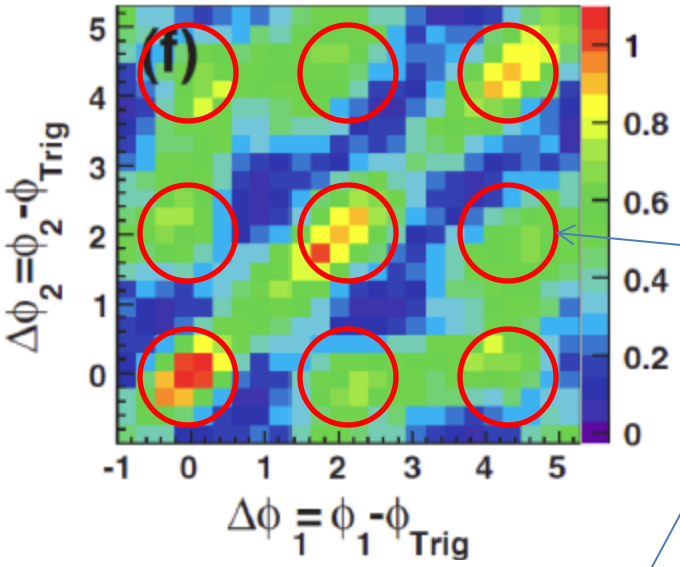


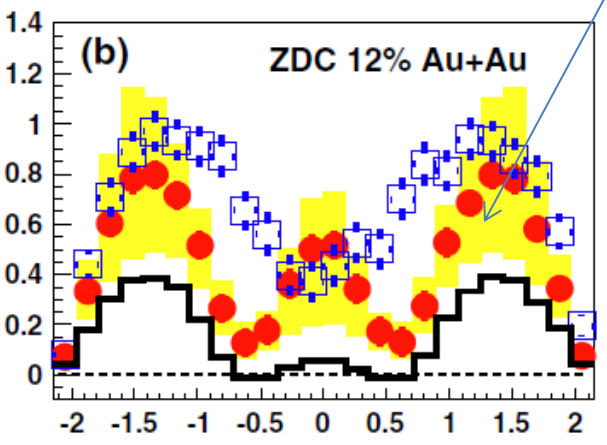
STAR, arXiv:1010.0690v1
Todoroki (PHENIX) 1304.2852



- Ridge is largely reduced.
- Evolution of structure seems to remain from in-plan to out-of-plane.
- Possible biases in EP reconstruction due to jet-correlations?

v_3 effect on 3-particle correl.

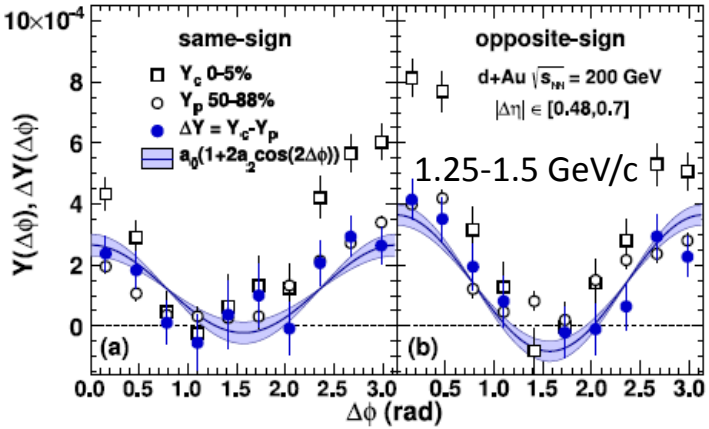


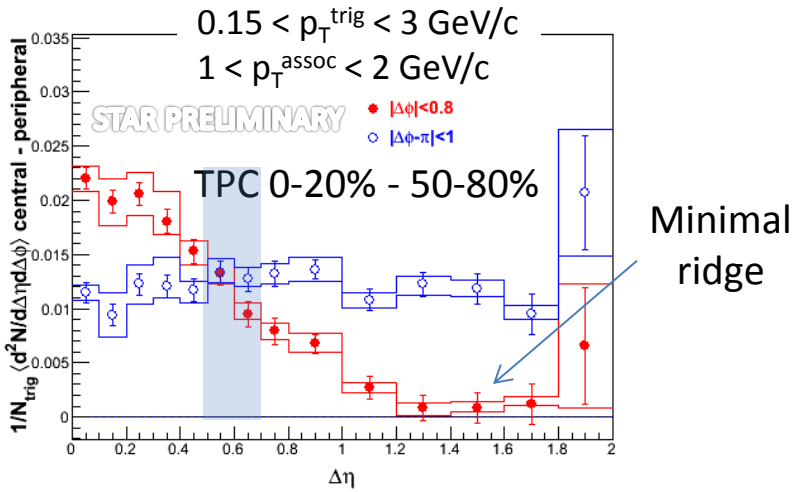


- v2 and v4 subtracted.
- Does v3 remove all of the off-diag. peak strength? Need further study.
- Deflected jets contributions (to diag. peaks) must be present.
- Need to be followed up.

pA and dA ridge

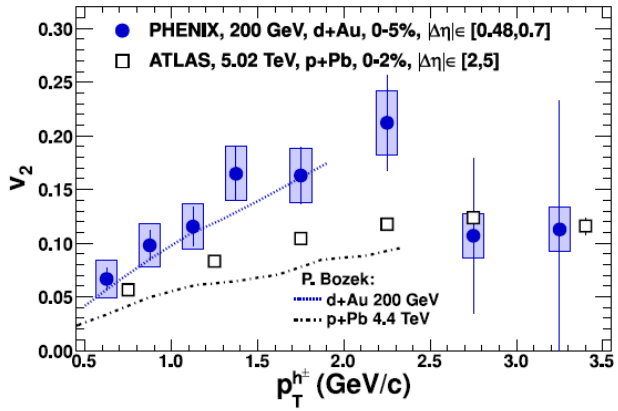
PHENIX, arXiv:1303.1794



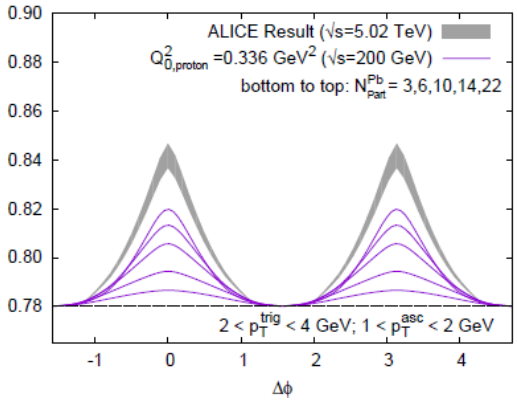


Minimal ridge

Bozek, PRC85 (2012)



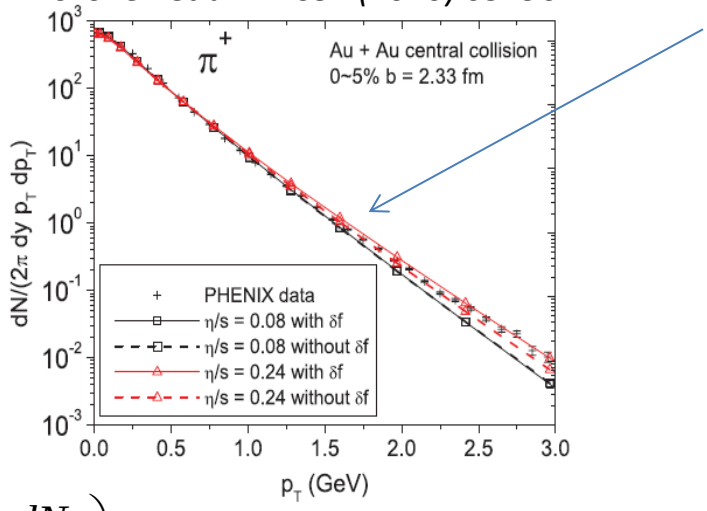
Dusling and Venugopalan, arXiv:1302.7018



- LHC+RHIC more stringent test on theoretical models.

Where is hydro bkgd to triggers?

C. Shen et al. PRC82 (2010) 054904

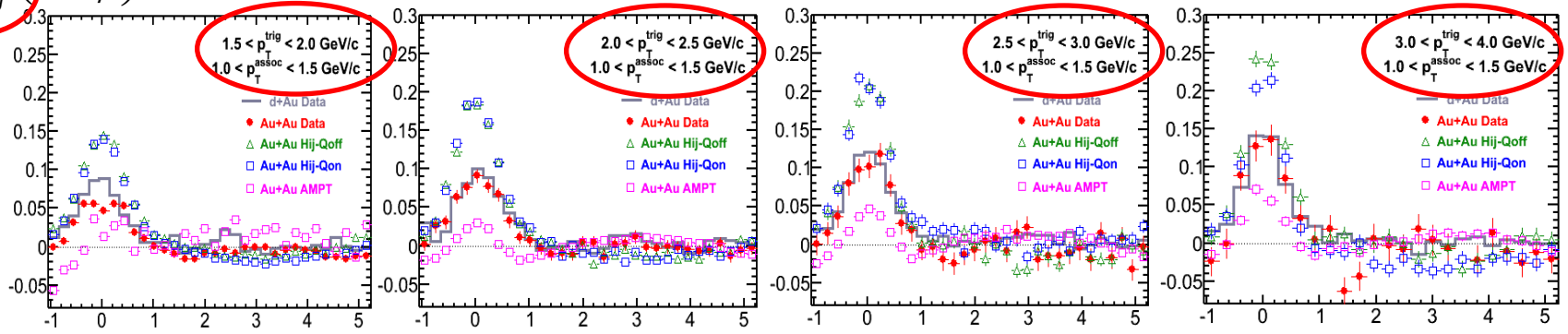


- Going to lower trigger p_T, expect large hydro contribution to particle production → Jet-like correlations should be reduced.

- Surprisingly similar Au+Au and d+Au near-side jet-like signal strength
- No evidence of trigger dilution from hydro background triggers

$$\frac{1}{N_{trig}}\left(\frac{dN}{d\Delta\phi}\right)$$

Konzer (STAR) QM 2012, STAR preliminary



Prospective future measurements

- Hydro v_n explains majority of ridge and double-peak correlations in heavy-ions. Does hydro v_n explain all of the correlation signals?
- v_n measurements with minimal nonflow: go to low p_T reference particles, $\Delta\eta$-gap?
- Precision measurements of jet-correlations with v_n subtraction
- Dihadron correlations w.r.t. EP with EP far removed in η.
- More clever way to separate flow/nonflow?

- γ-jet with no flow background
- Heavy flavor induced correlations

- Can we learn something fundamental from small systems?
- How high dA multiplicity can we reach at RHIC?