Probing hot and dense nuclear matter with particle correlations and jets at RHIC

Hua Pei
University of Illinois at Chicago

The central goal of RHIC/LHC heavy-ion program

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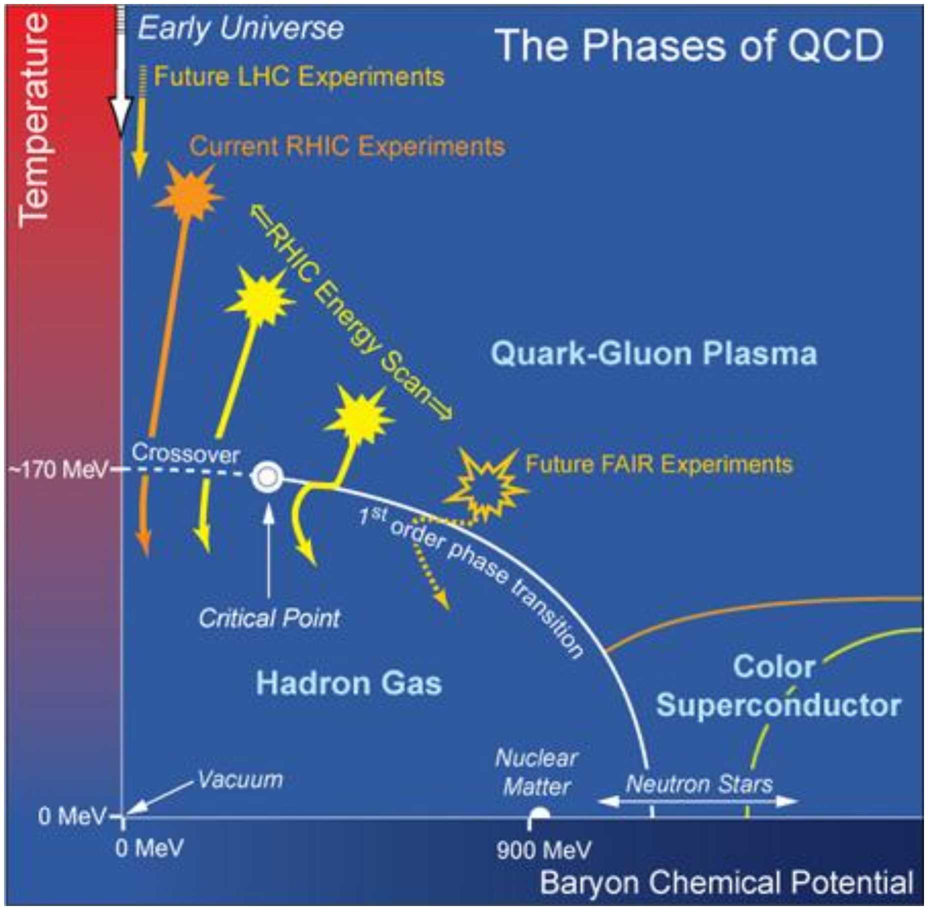
Quantitative study of the phases of QCD

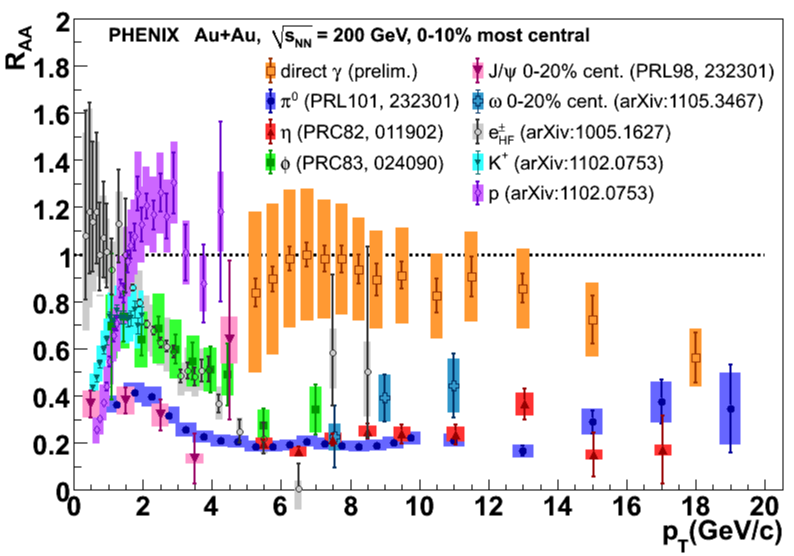


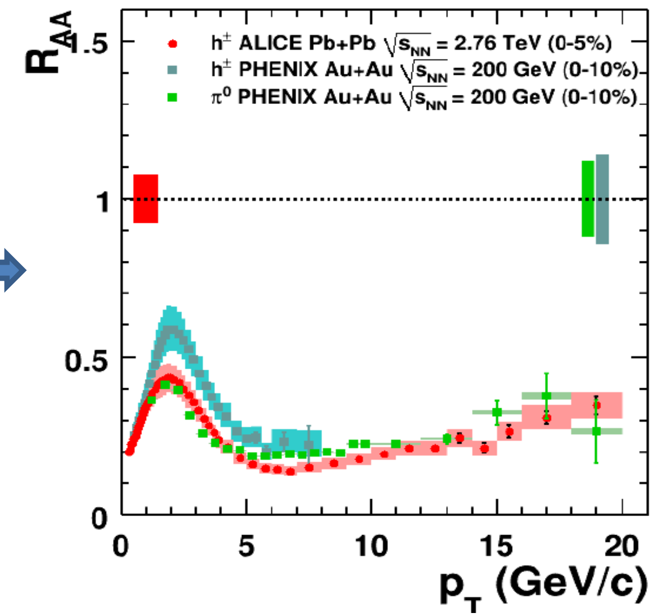
The natural starting point to study the bulk properties:

Begin from single particles observables and extract physics characters:

$$\mathrm{T},\ C_s,\ \hat{q},\ \eta,\ \zeta,\ \mathrm{etc.}$$

Medium in the eyes of R_{AA}, from RHIC to LHC





- Mesons, whether of light quarks or charm/bottoms, showing similar suppression patterns,
- On contrary to “baryon anomaly” and direct-γ.
- A strong indication of medium effects.

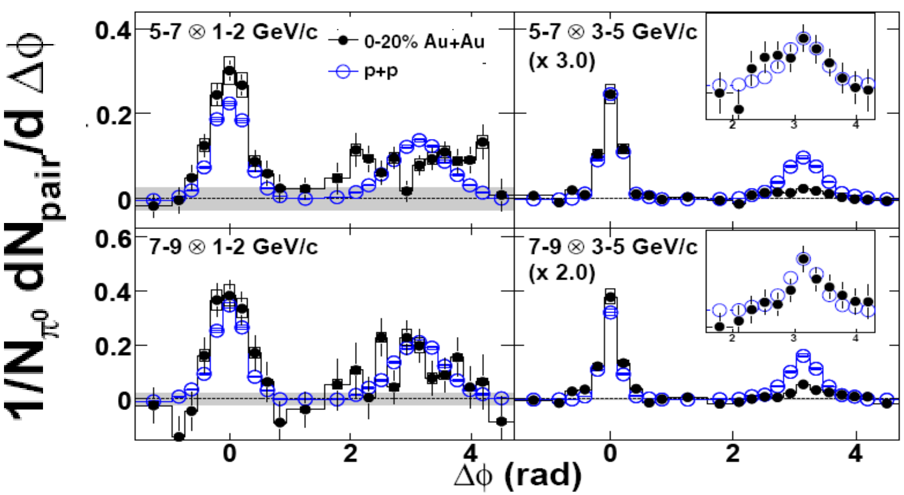
- Despite more than a factor of 20 higher energy, the R_{AA} are very close for RHIC and LHC at 5<pT< 20 GeV/c
- •The same Quark soup cooked at LHC and RHIC?

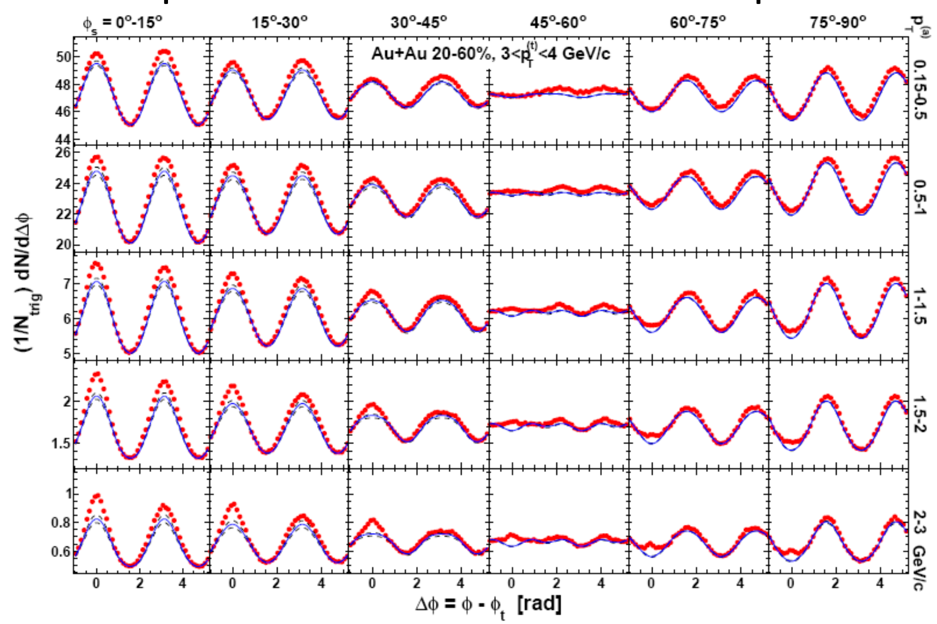
Jets (including the correlation functions as proxies) as the double-edged sword

STAR (arXiv:1010.0690)

Phys. Rev. Lett. 104, 252301 (2010)

In-plane → Out-plane

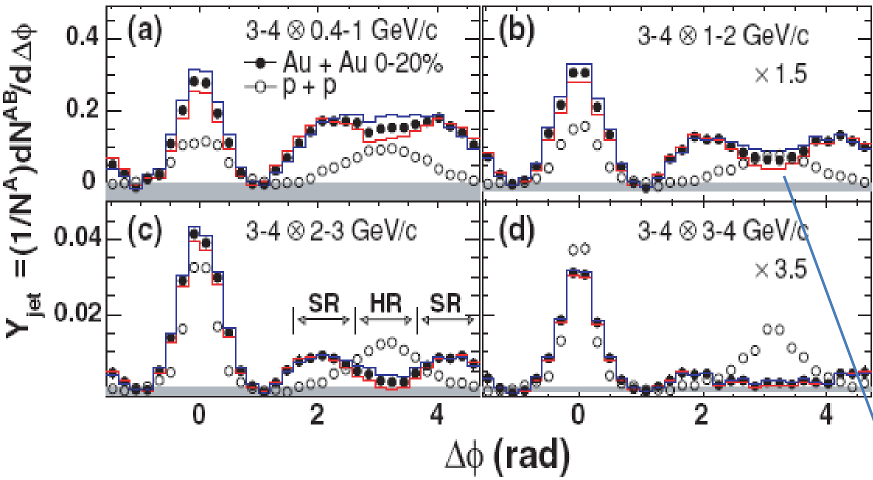




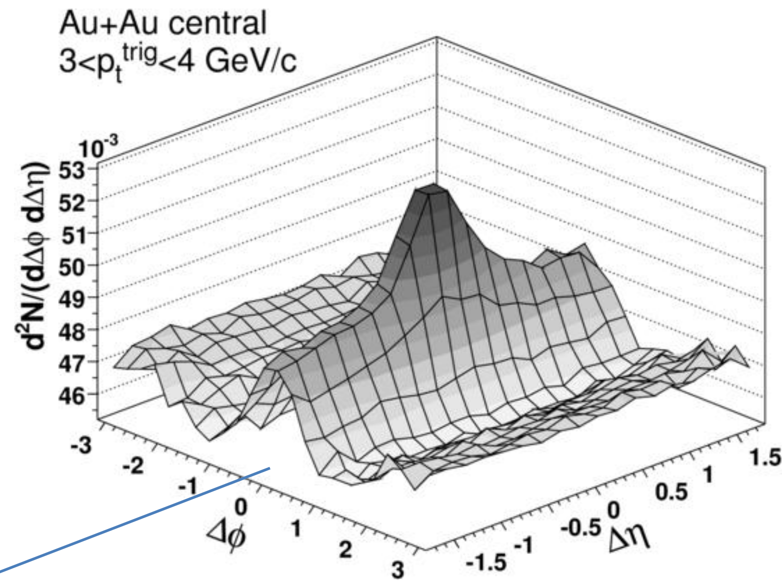
- Jets, originated from the hard-scattering partons, are considered to be a good probe of medium.
- These scatterings happen at the early age of QGP formation, and partons have a chance of carrying the information of medium via the interactions.

- However, RAW correlations contain not only jets, but bulk medium information: event plane, flow v_n.
- They exist in both central A+A (left plot) or mid-central (right plot).

Flow: the primary factor(s) to disentangle



Phys. Rev. C **77**, 011901(R) (2008)



Phys. Rev. C **80** (2009) 64912

Mach-cone?
Ridge?

- All plots here already have v_2 subtracted.
- Are these modified jets production? Or they are medium themselves coincide with trigger particles?
- There are more v_n than that v_2 to modulate the correlation functions?

Azimuthal anisotropy

$$\frac{dN}{d(\phi - \Psi_{RP})} \propto 1$$

Softening of *EOS* ? $+ 2v_1 \cos(\phi - \Psi_{RP})$

$+ 2a_1 \sin(\phi - \Psi_{RP})$ Chiral magnetic effect ?

Partonic d.o.f, thermalization ? $+ 2v_2 \cos(2\phi - 2\Psi_{RP})$

$+ 2v_3 \cos(3\phi - 3\Psi_{RP})$ Initial geometry fluctuations ?

…

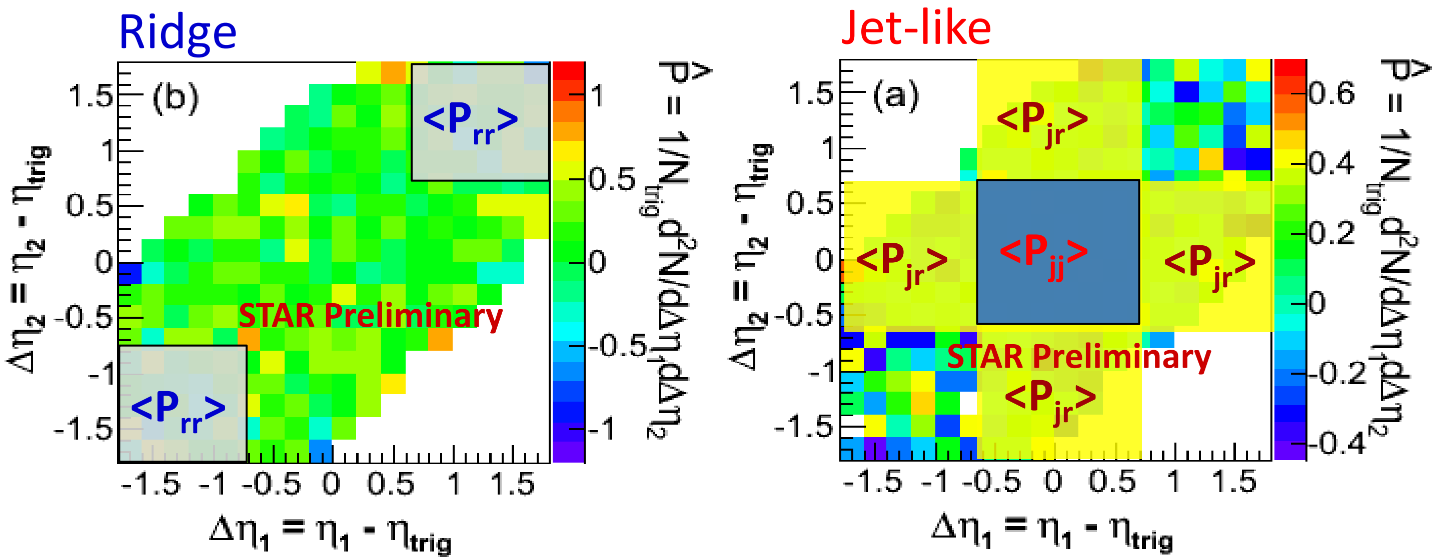
Before v_3 era: $\Delta\eta-\Delta\eta$ pair densities: ridge, jet-like, and their cross-item

Pawan Kumar Netrakanti

CGC workshop, BNL 2010

Au+Au 0-12%

$3<p_T^{trig}<10$ GeV/c
$1<p_T^{assoc}<3$ GeV/c
$|\Delta\phi|<0.7$



$\langle P_{rr}\rangle$: 0.114 ± 0.039

$\langle P_{jj}\rangle$: 0.077 ± 0.026

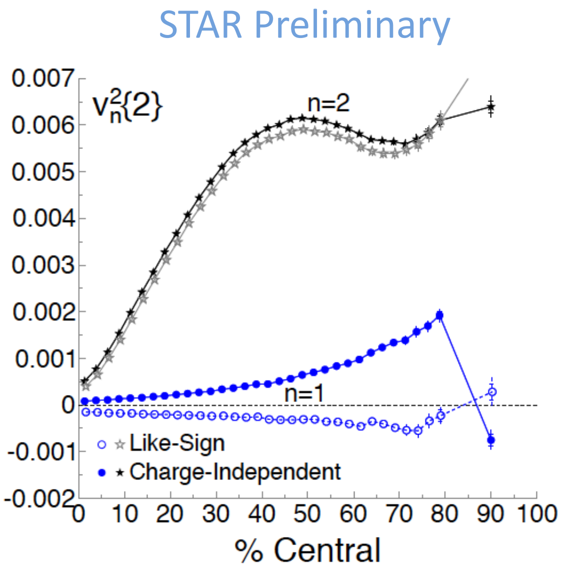
Jet-ridge cross pairs
$\langle P_{jr}\rangle$: -0.004 ± 0.025

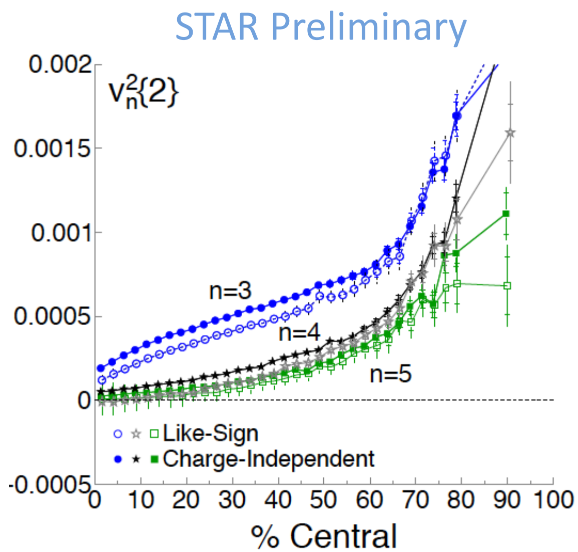
"No correlation is found between production of the ridge and production of the jet-like particles, suggesting the ridge may be formed from the bulk medium itself." from *Phys. Rev. Lett. 105 (2010) 22301*

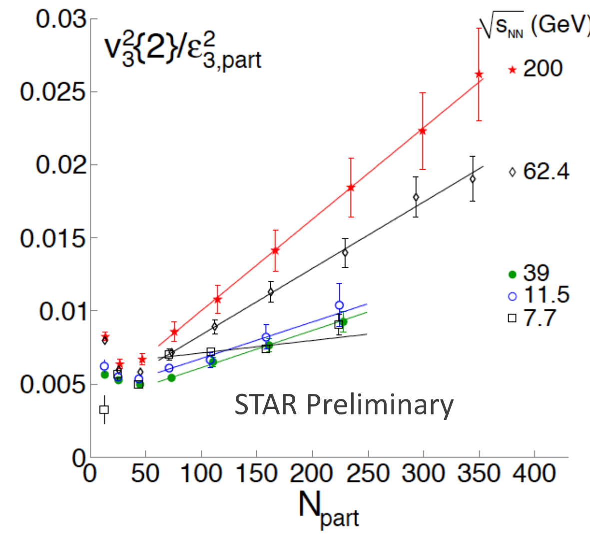
Higher v_n from 2 particle correlations

Q-Cumulants: 200 GeV Au+Au |η|<1.0

P. Sorensen QM11







n=1 shows large difference between LS and CI: charge and momentum conservation?

n=3 exhibits effects of elliptic overlap geometry.

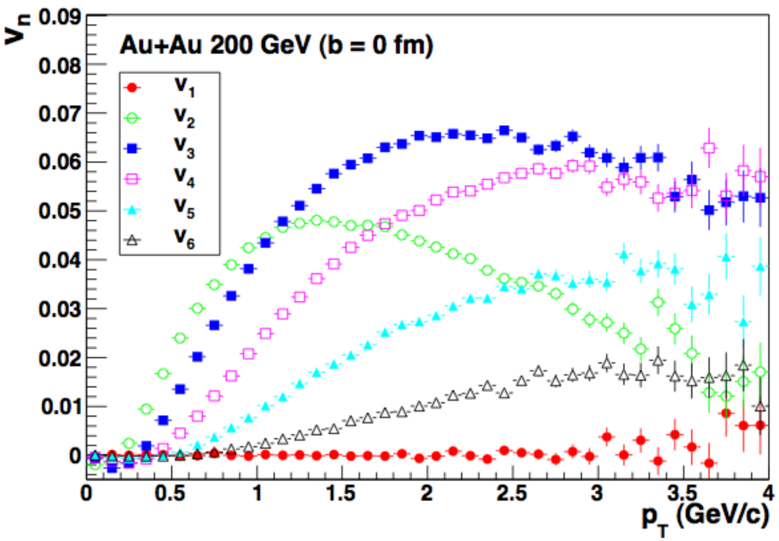
n=4 and larger show 1/N dependence typical of non-flow correlations.

From mid-central to central, $v_3^2\{2\}$ follows an $N_{part}\varepsilon^2_{3,part}$ trend, similar to v_2.

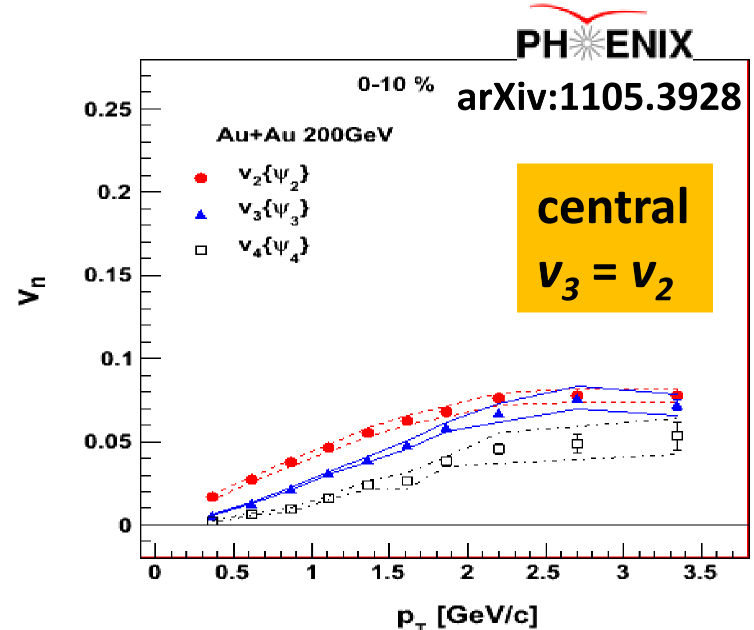
Q-Cumulants: A. Bilandzic, R. Snellings, S. Voloshin, Phys. Rev. C 83, 044913 (2011)

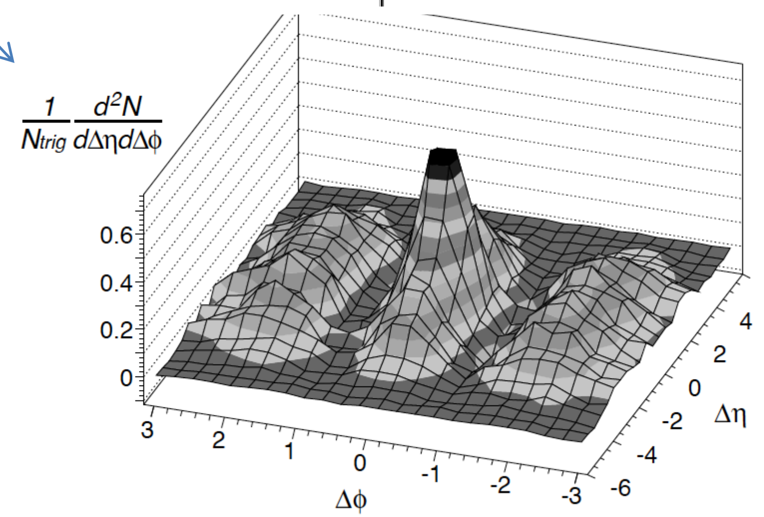
These p_T integrated v_n are already exciting. Can they help us on the intermediate p_T correlations?

Theory expectations of v_n at intermediate p_T



G. L. Ma and X. N. Wang, PRL106, 162301 (2011)





J.Takahashi, B.Tavares, W.Qian, F.Grassi, Y.Hama, T.Kodama & N.Xu and many others

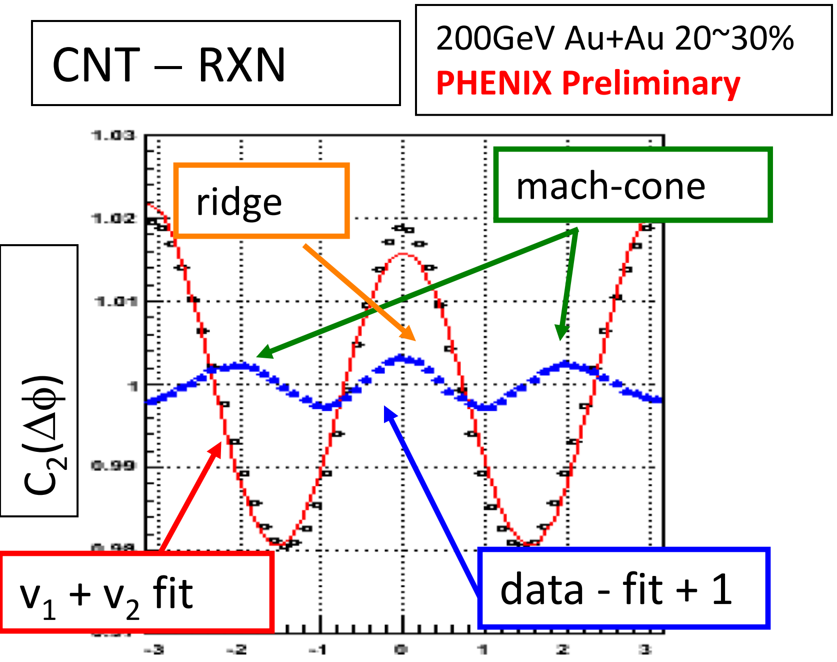
In a system where space-momentum correlations develop, the initial density fluctuations can manifest in momentum space.

For b=0 fm, at low p_T, v_n drops with n, but at intermediate p_T, $v_3 \sim v_2$, agree with RHIC data.

It's possible to reproduce the "ridge" with these v_n, without need of jets.

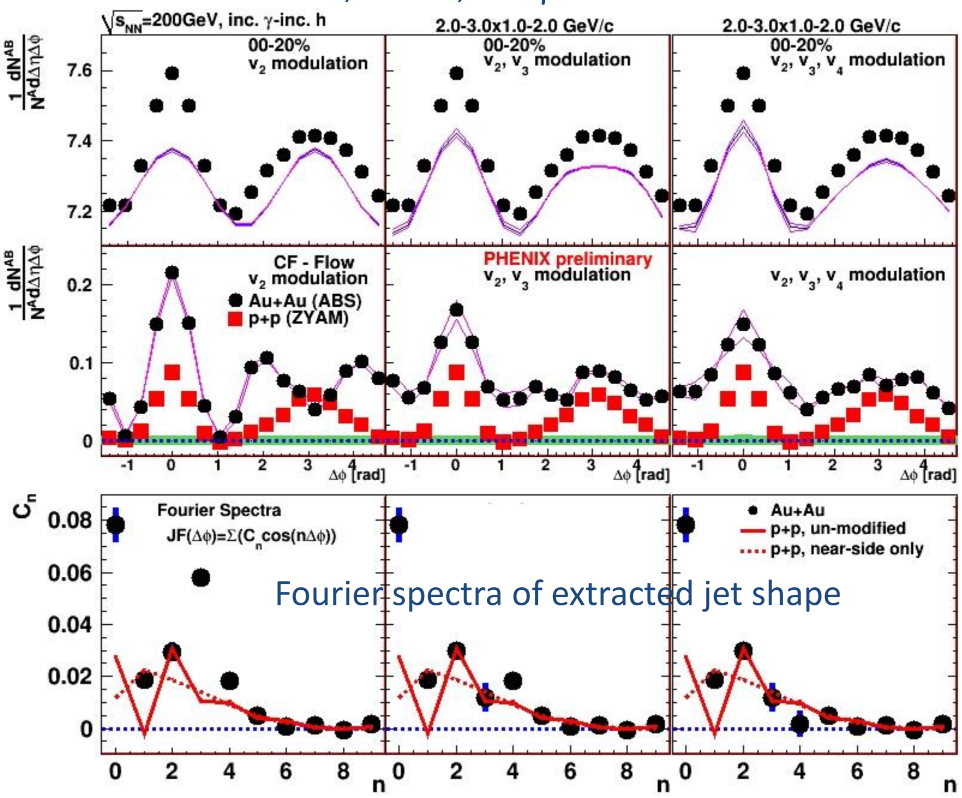
Correlation functions with v_n modulation

ShinIchi Esumi, QM11



$\Delta\phi = \phi$ (CNT) – ϕ (RXN)

200GeV Au+Au, 0-20%, inc. γ-had.

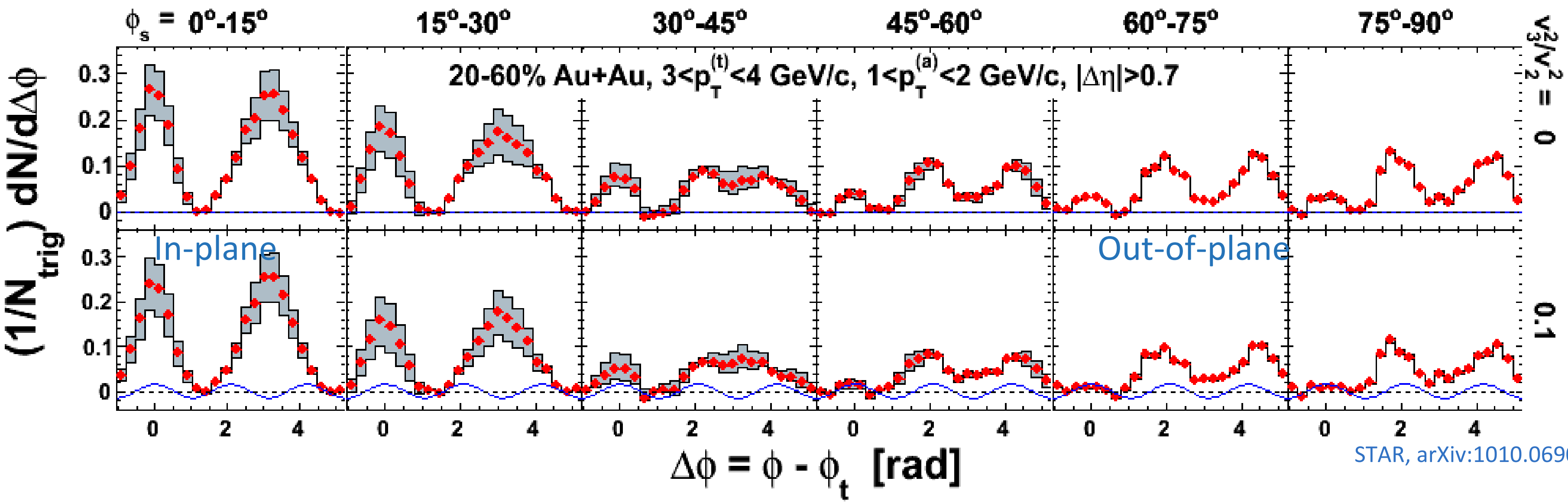


- Great success in central Au+Au.
- The mach-cone is mostly gone.
- Remaining medium effect exists.

The $v_2 + v_3$ isn't the whole world yet

v_2 subtracted di-hadron correlations: v_2 estimated using Ψ_{EP}(high $|\Delta\eta|$ from trigger)

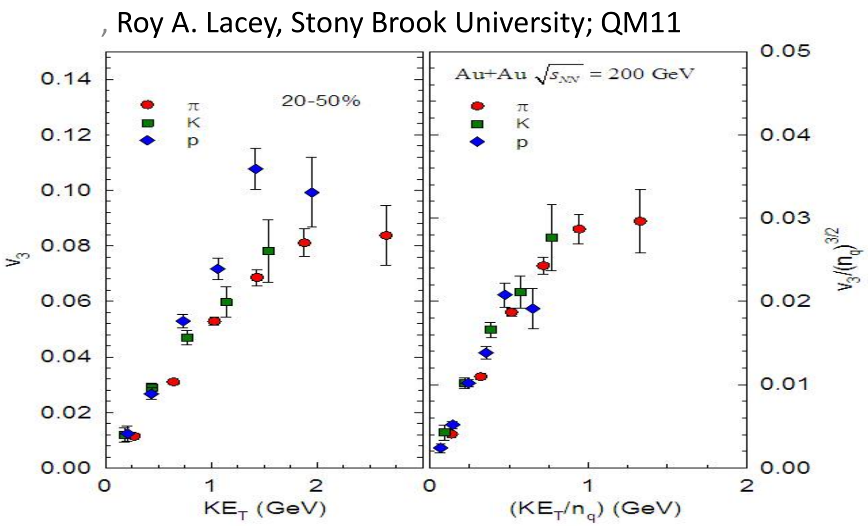
In-plane Out-plane



STAR, arXiv:1010.0690

- It's measured that Ψ_2^{EP} and Ψ_3^{EP} are weakly correlated.
- Thus, the fact that the v_2 modulations subtracted correlation shapes still keep strong 2nd order event plane Ψ_2^{EP} dependence, can't be explained by pure v_3.
- While the measured v_2 and v_3 have weak $|\eta|$ dependence from long $\Delta\eta$ away Ψ_2^{EP} and Ψ_3^{EP} , the factorization of v_2^2 and v_3^2 need further investigation.
- Higher order v_n needed. Or, is it due to those long $\Delta\eta$ non-flow contribution?

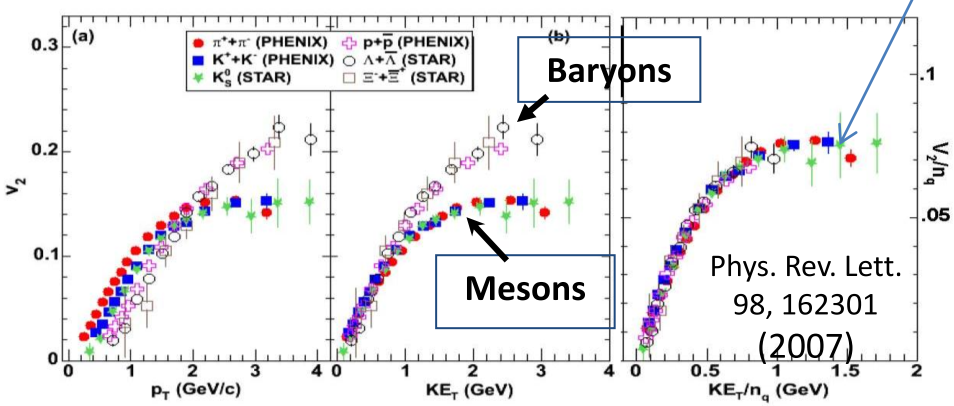
Next task of v_n modulation: PID



As those measurement in R_{AA}, it's necessary to measure and apply PIDed v_n.

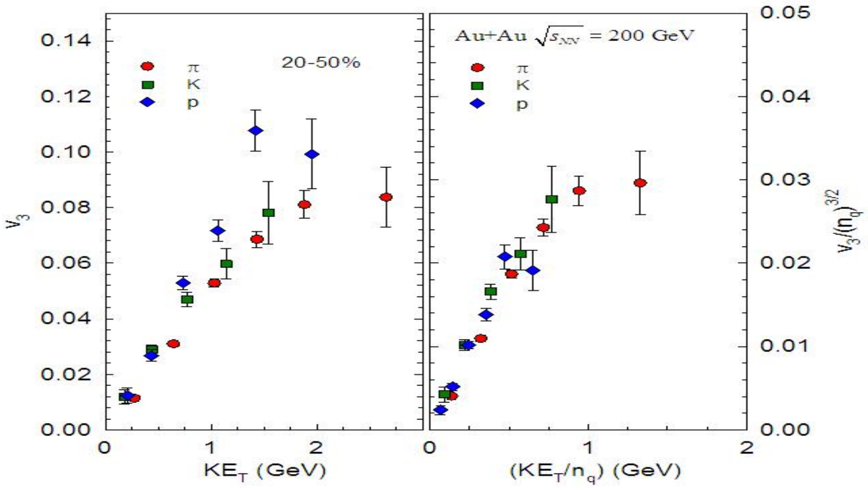
We can already see the kE_T and n_q scaled v_3, up to intermediate p_T region. (Also reported at LHC)

This is consistent with v_2, showing a consistent partonic flow picture.



Next task of v_n modulation: PID

, Roy A. Lacey, Stony Brook University; QM11



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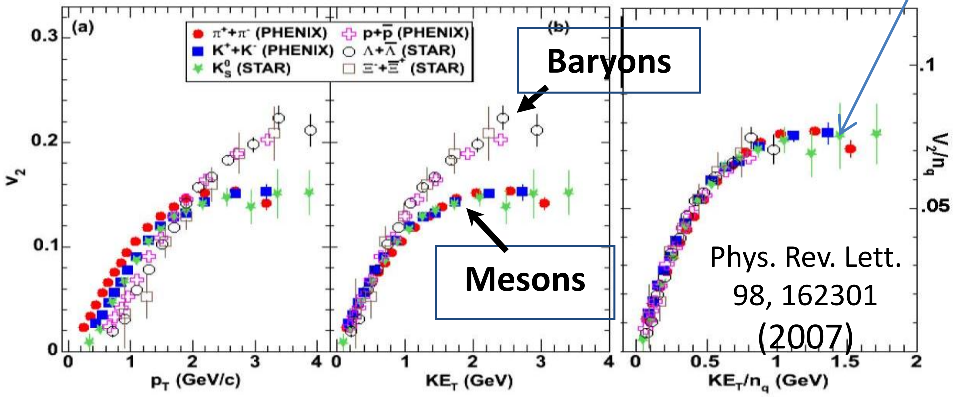


Thus the correlation functions are expected to show **an evident mass splitting effect**, based on higher order v_n modulation pattern:

Ridge? Cone?

The v_n modulation to correlation with PID

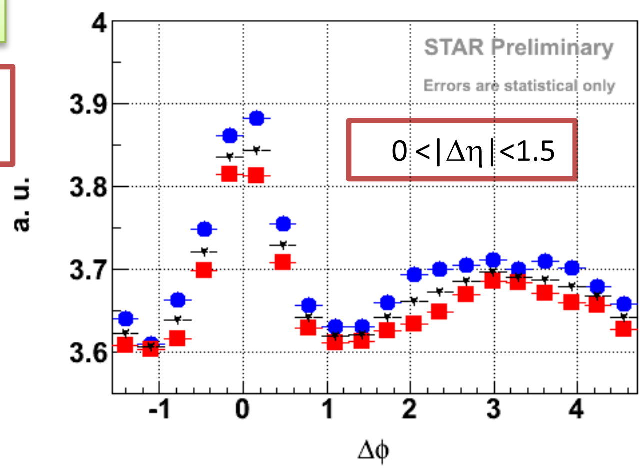
K. Kauder QM11

Au+Au 0-10%

$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

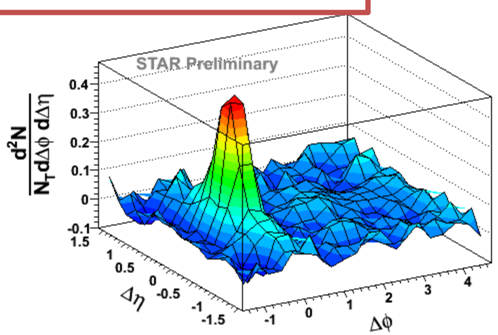
Trigger:
$\pi^{\pm}$
($P^{\pm}+K^{\pm}$)
Charged h

Raw correlations

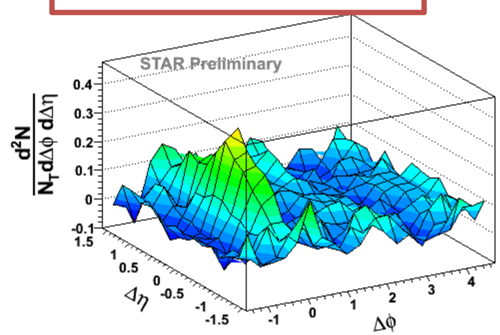


Background subtracted correlations

$\pi^{\pm}$ trigger



($P^{\pm}+K^{\pm}$) trigger



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Thus the correlation functions are expected to show **an evident mass splitting effect**, based on higher order v_n modulation pattern:

Ridge? Cone?

Yes they do!

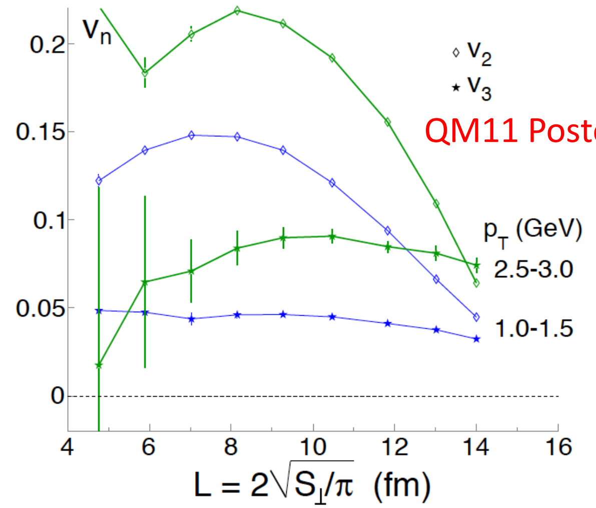
Centrality (in)dependence of v_n

- A much weaker centrality dependent of v_3 is observed at RHIC (LHC), contrary to v_2.

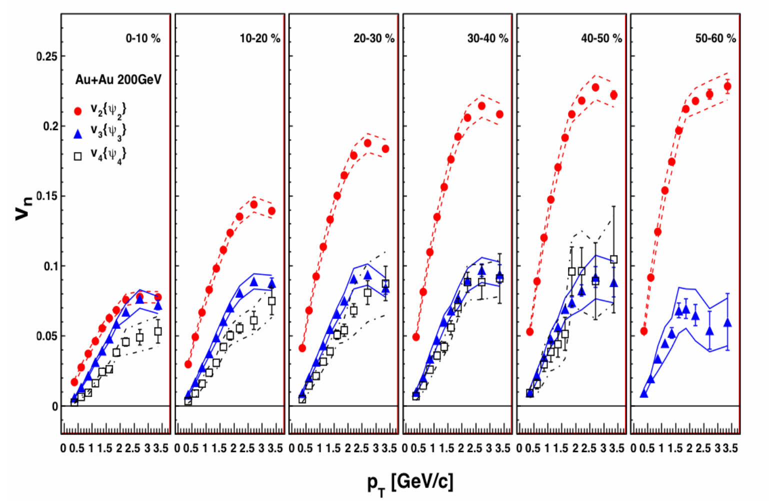
- This is commonly considered an evidence of v_3 is caused by initial state density inhomogeneity, as were predicted by such models.

→ **Current leading explanation.**

$\eta_1>0.5$ & $\eta_2<-0.5$



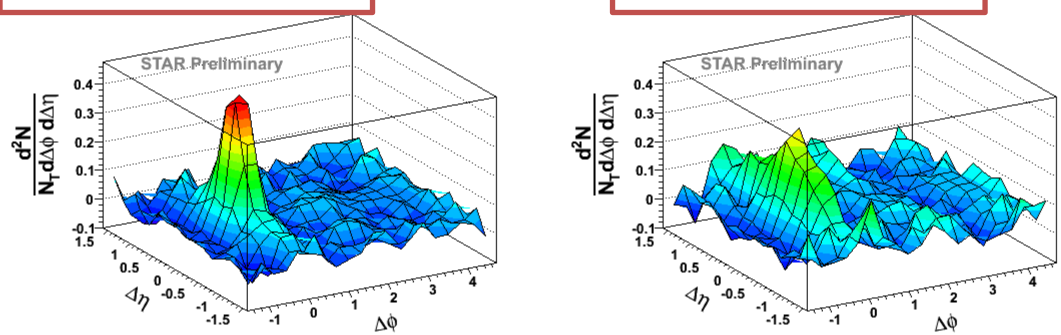
arXiv: 1105.3928



K. Kauder QM11

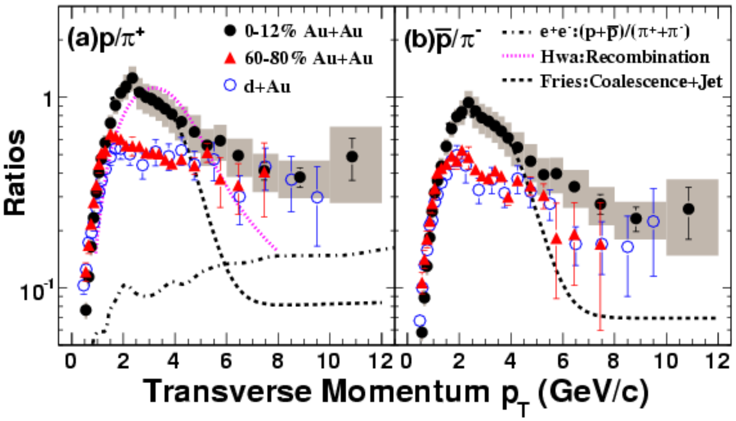
π± trigger

(P±+K±) trigger



More v_n work are needed, when centrality combined with PID

STAR, PRL 97 (2006) 152301

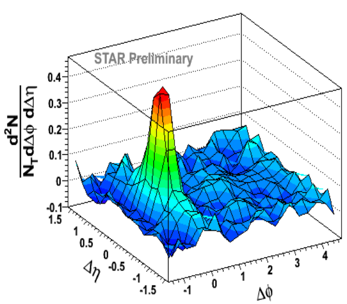


The baryon/meson splitting are centrality dependent.

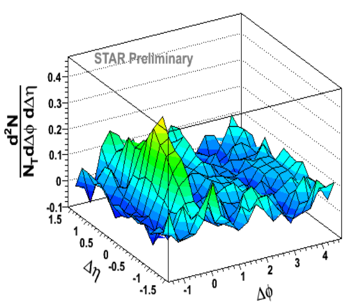
- The baryon/meson splitting, and baryon "anomaly" enhancements are centrality dependent.
- If v_3 is partonic flow as indicated from RHIC (and LHC), then is this weak centrality dependence of v_3 at intermediate p_T due to the convolution of $\varepsilon^2_{3,part}$, PIDed v_3 (proton v_3 > pion v_3) and "baryon anomaly"?
- Will v_3 modulation produce this PID ordering in <u>mid-central</u> Au+Au? *(work in progress)*
- Or is this PID ordering due to non-flow effect coming to work at inter-mediate p_T region? **Jets?**

K. Kauder QM11

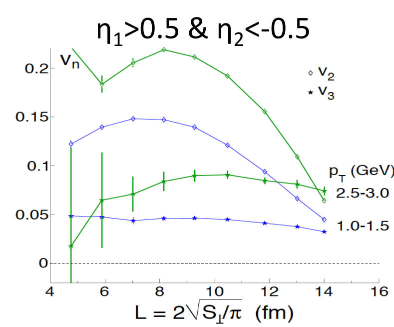
$\pi^\pm$ trigger



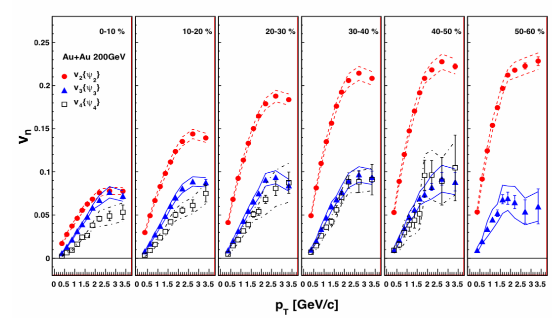
($P^\pm$+$K^\pm$) trigger



QM11 Poster: Li Yi



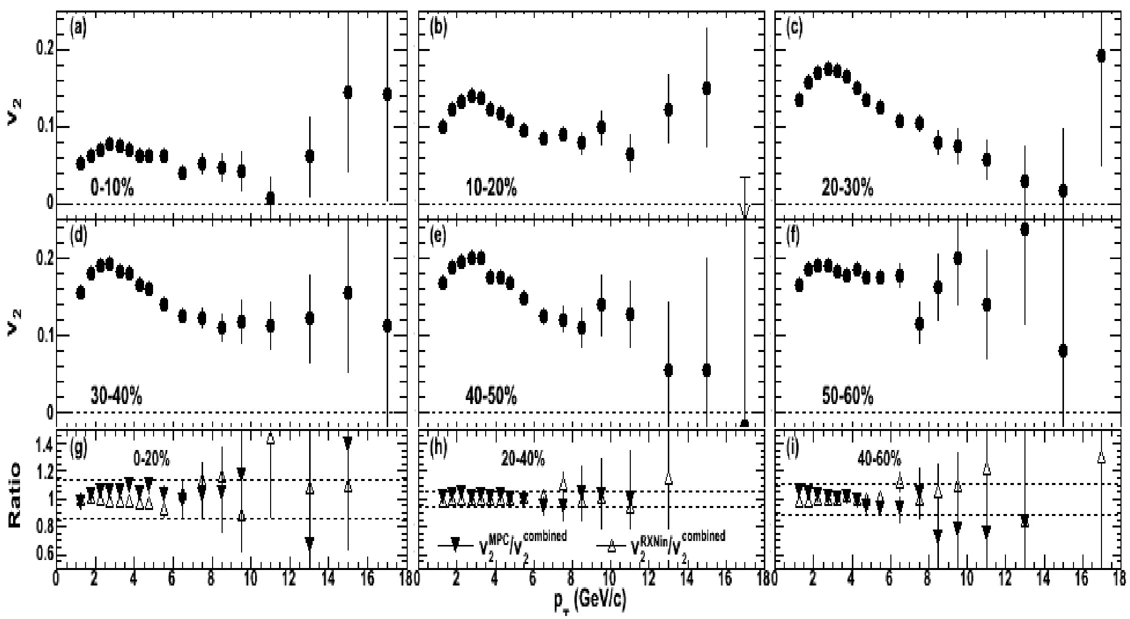
arXiv: 1105.3928



How jets (and proxies: higher p_T, and their correlation) interact with v_n

- The high-p_T v_2 measured at RHIC isn't approaching zero.
- Here the collective effect is small. Instead, the v_2 are dominated by jet source (e.g., jet quenching in medium).
- Do jets also induce v_3?

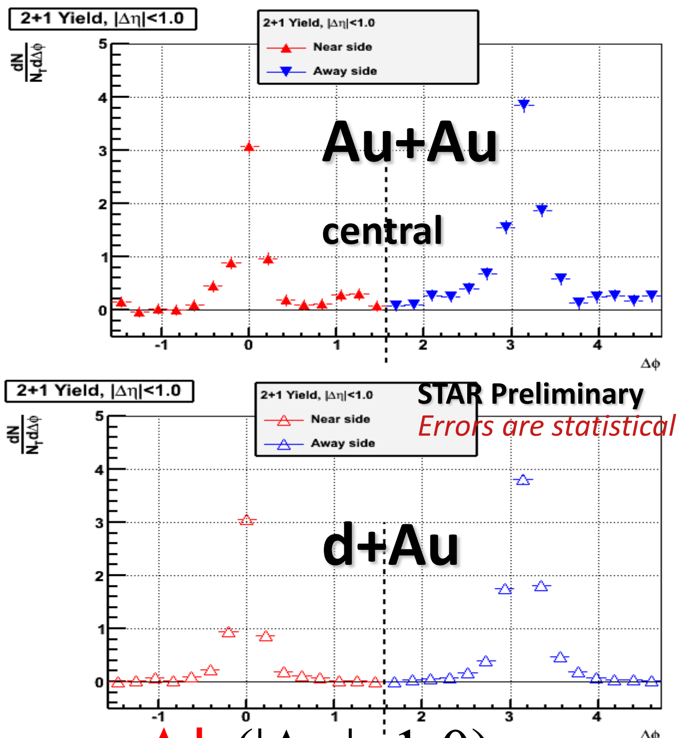
Phys. Rev. Lett. 105, 142301 (2010)



How jets (and proxies: higher p_T, and their correlation) interact with v_n

H. Pei DIS2011

Red: Same-side, Blue: Away-side



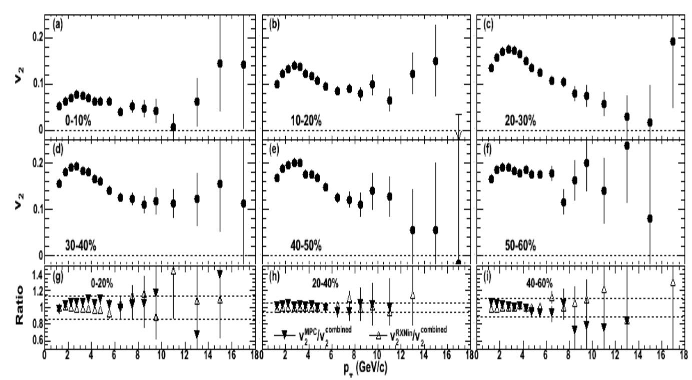
Δϕ (|Δη|<1.0)

$Trig_1 E_T \in [10, 15] GeV$
$Trig_2 p_T \in [4, 10] GeV$
$assoc p_T \in [1.5, 10] GeV$

- Back-to-back high-p_T trigger are selected to tag "jet-like" events.
- v2 modulation subtracted.

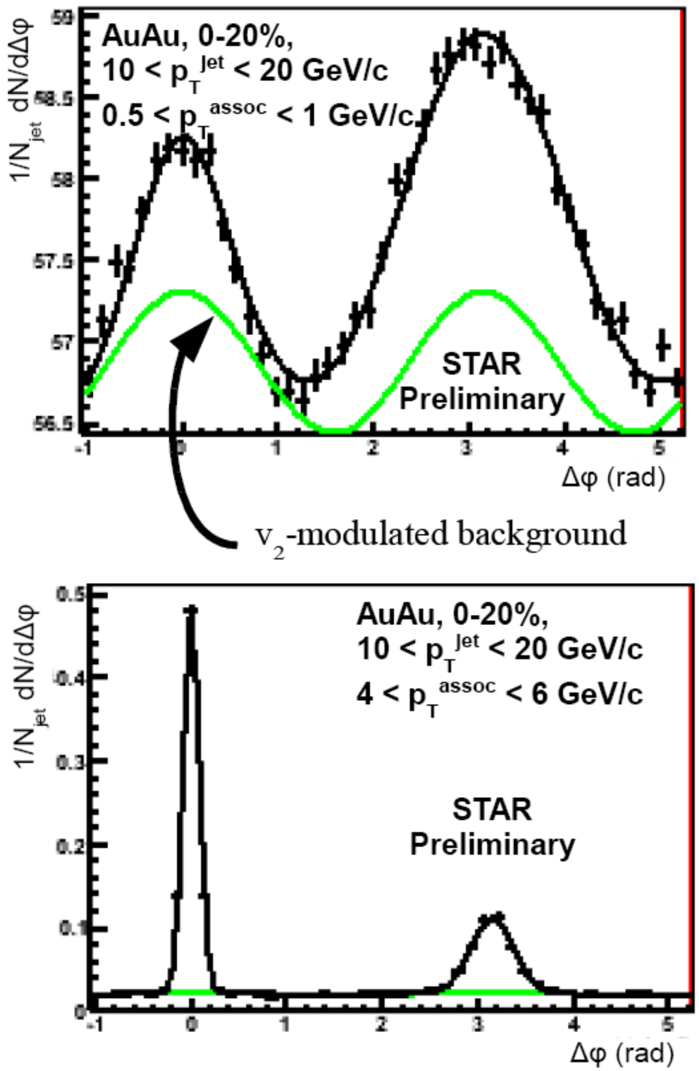
- The high-p_T v_2 measured at RHIC isn't approaching zero.
- Here the collective effect is small. Instead, the v_2 are dominated by jet source (jet quenching in medium?).
- Do jets also induce v_3?
- No v_3 observed in the "jet-like" correlation (v_2 subtracted) yet.

Phys. Rev. Lett. 105, 142301 (2010)



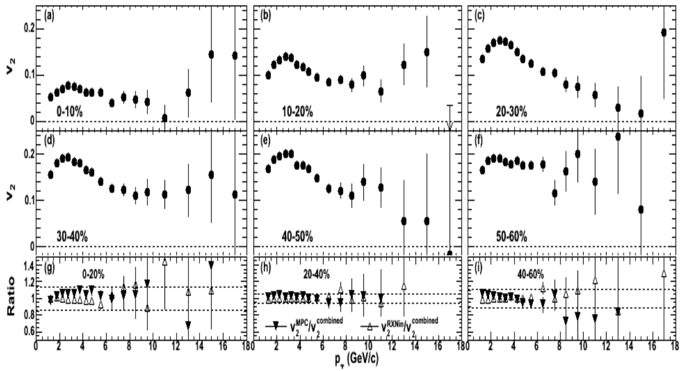
How jets (and proxies: higher p_T, and their correlation) interact with v_n

A. Ohlson QM11



- The high-p_T v_2 measured at RHIC isn't approaching zero.
- Here the collective effect is small. Instead, the v_2 are dominated by jet source (jet quenching in medium?).
- Do jets also induce v_3?
- No v_3 observed in the "jet-like" correlation (v_2 subtracted) yet.
- No v_3 observed in the "jet-hadron" correlation.

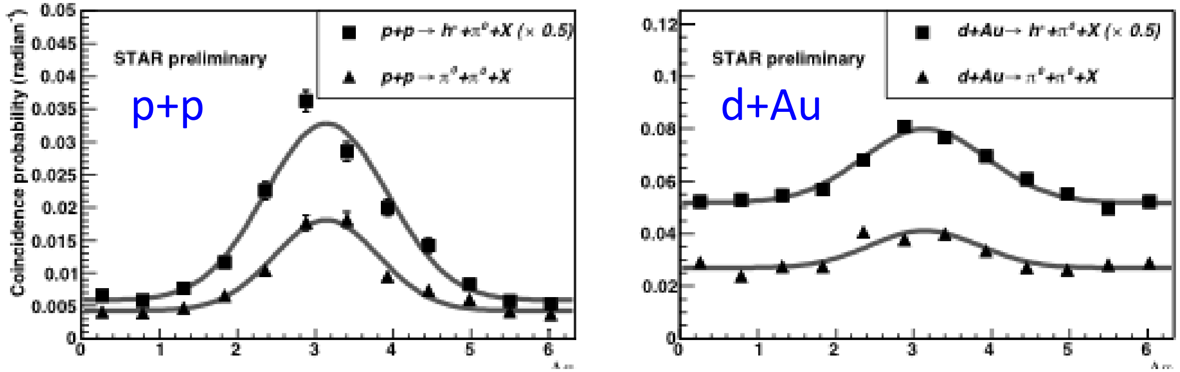
Phys. Rev. Lett. 105, 142301 (2010)



Cold nuclear matter effect

- Forward (FMS) π^0 trigger particle
- Mid-rapidity (BEMC/TPC) $\pi^0/h^{\pm}$ associated particle
- Includes efficiency and background corrections
- Similar $\Delta\eta$ between trigger/associated as those v_3 measured in broad $|\eta|$.

P_T(FMS) > 2.5 GeV/c ; 1.5 GeV/c < P_T(BEMC/TPC) < P_T(FMS)



Shown by Chris Perkins on DIS2011, ref. Ermes Braidot (arXiv:1102.0931)

- No significant broadening from p+p to d+Au
- No hints of away-side peak disappearance

- As for now, the observed long $\Delta\eta$ higher-order v_n are still heavy-ion specific.

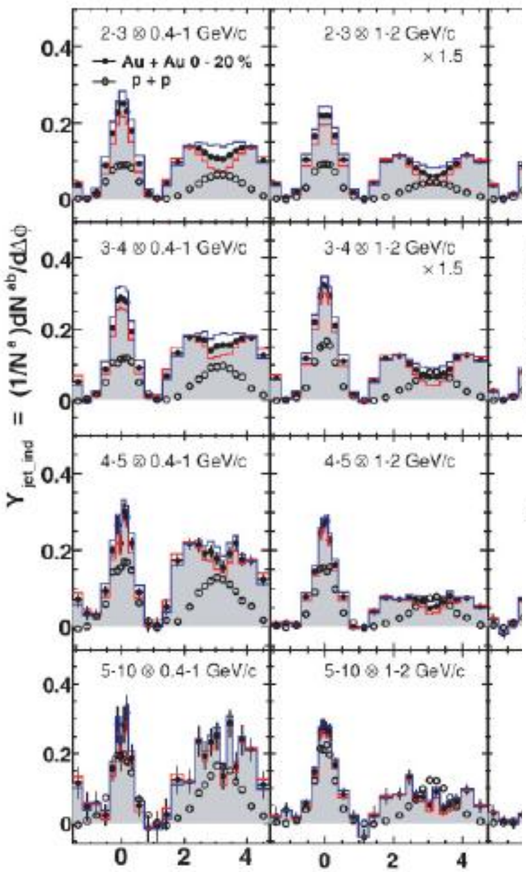
Summary and outlook

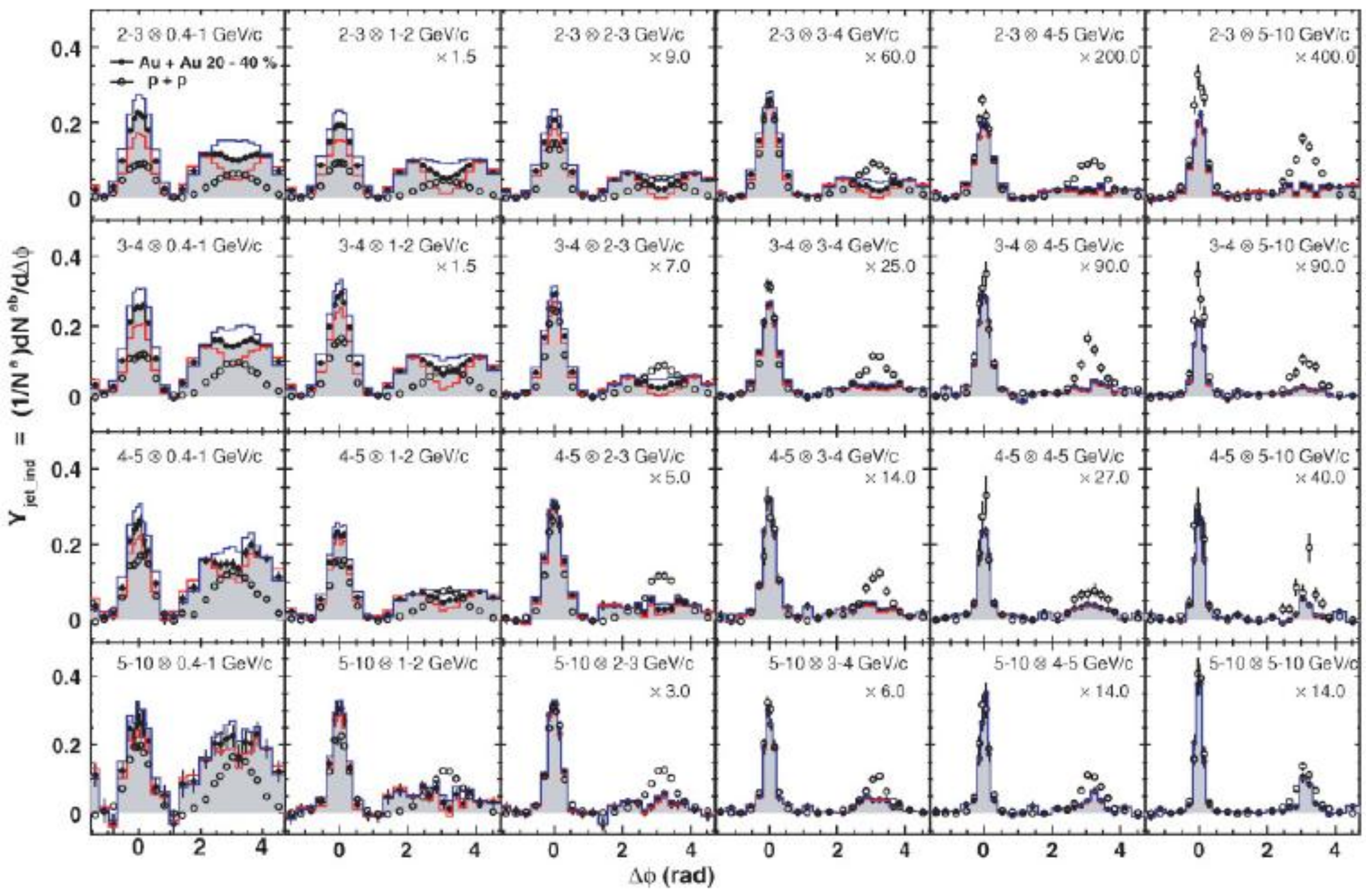
- Recent results from RHIC on the "ridge" and the away-side correlation structure are presented in central A+A collisions.
- Higher order Fourier harmonics v_n based on initial geometry fluctuation, in addition to the common v_2, make an important role in disentangle different sources of physics. These v_n successfully reproduce the correlation structures (ridge/cone) with little help from jets-medium interaction.
- More quantitative analysis/prediction on these higher order v_n are necessary, including their dependence on pT, $\Delta\eta$, centrality, and PID, etc.
- The hadron correlations with multiple high-energy triggers (as proxies of jets) and/or fully reconstructed jets show no signal of higher order v_n, on contrary to the high-p_T v_2, also supporting assumption of v_2 and higher order v_n from different sources.
- No evident cold-nuclear-matter effect observed for high order v_n at current stage.

Back up

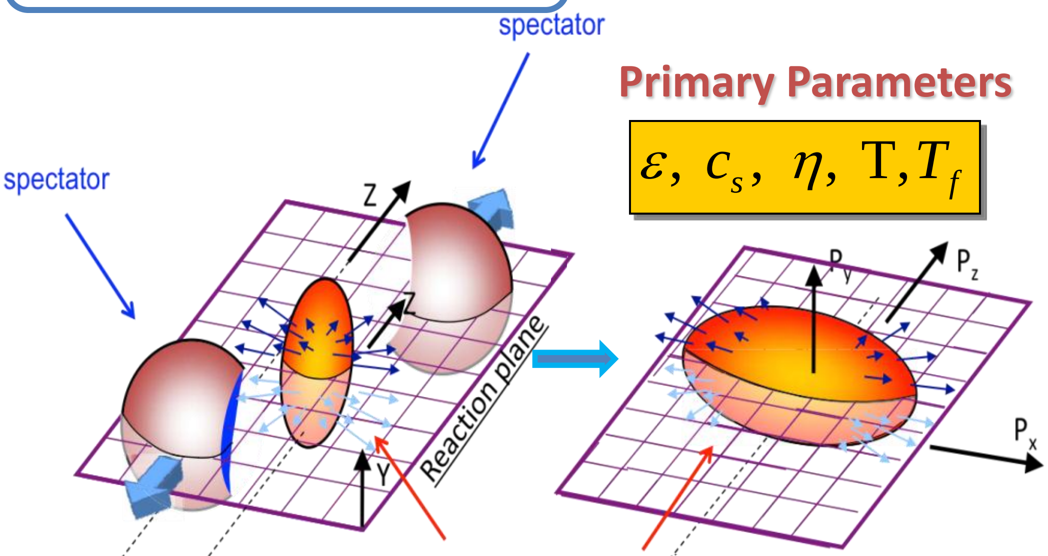
Phys. Rev. C 78, 014901 (2008)

0-20% Au+Au (left) and 20-40% Au+Au (right). The “cone” appear at the same positions, showing very weak trigger/associate pT and centralities.





The Flow probe



Primary Parameters

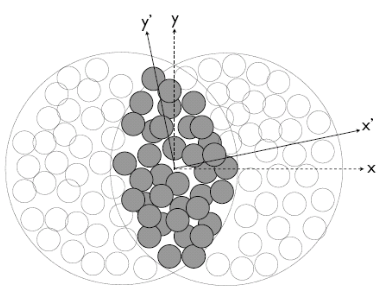
$\varepsilon,\ c_s,\ \eta,\ \mathrm{T}, T_f$

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$\left(\mathrm{P} = \rho^2 \cdot \left(\partial \varepsilon_{Bj} / \partial \rho \right) \Big|_{s/\rho} \right)$$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

$$\sim 5 - 15 \ \frac{GeV}{fm^3}$$



Azimuthal Distribution

$$f(\varphi) \propto \left(1 + 2 \sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n) \right] \right)$$

$$\langle e^{in\varphi} \rangle \equiv \int_0^{2\pi} e^{in\varphi} f(\varphi) d\phi = v_n e^{in\psi_n}$$

$$v_\mathrm{n} = \left\langle e^{in(\varphi_p - \Psi_n)} \right\rangle, \quad n = 1, 2, 3..,$$

$$\frac{dN^{\text{pairs}}}{d\Delta\varphi} \propto \left(1 + \sum_{n=1} 2 v_n^a v_n^b \cos(n\Delta\varphi) \right)$$

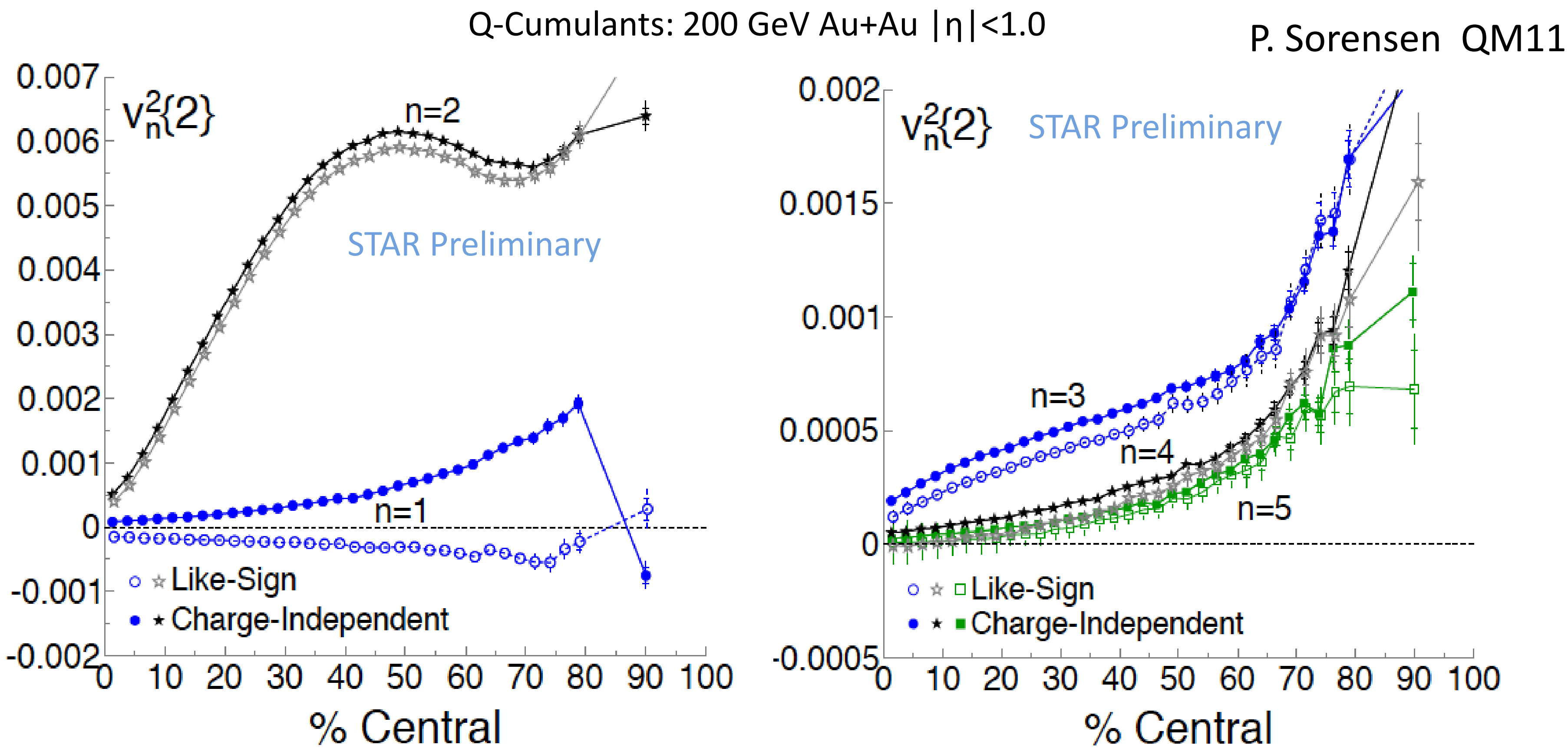
For *smooth profile* $\varphi \to \varphi + \pi$

Odd harmonics = 0

For "lumpy" *profile* $\varphi \neq \varphi + \pi$

Odd harmonics ≠ 0

Higher v_n from 2 Particle Correlations



n=1 shows large difference between LS and CI: charge and momentum conserv?

n=3 exhibits effects of elliptic overlap geometry

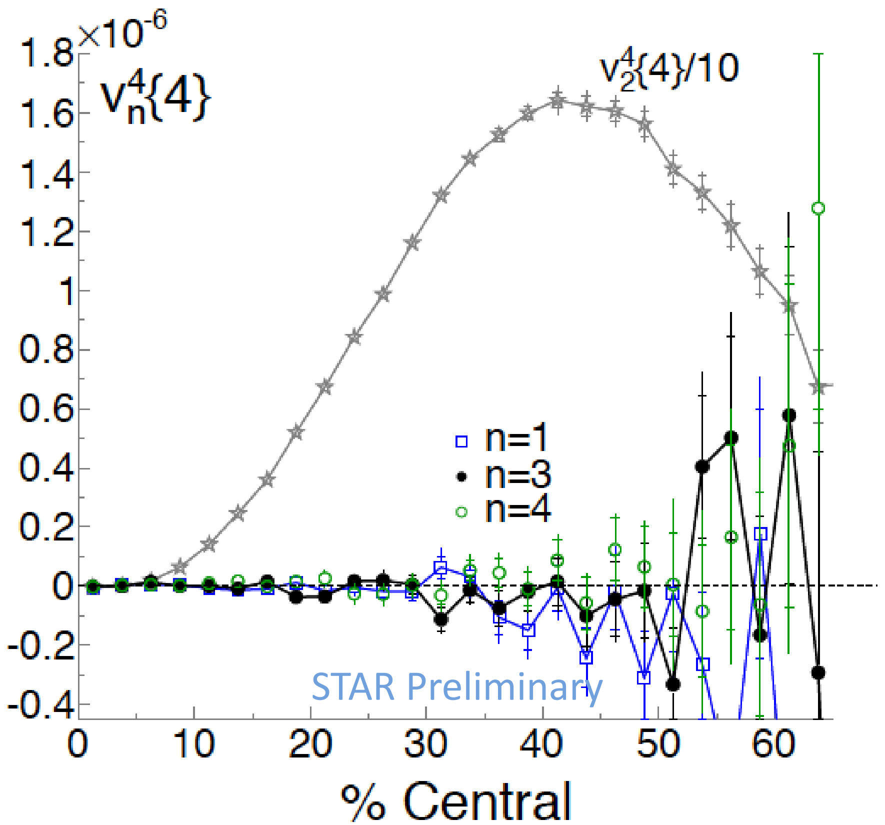
n=4 and larger show 1/N dependence typical of non-flow correlations

Q-Cumulants: A. Bilandzic, R. Snellings, S. Voloshin, Phys. Rev. C 83, 044913 (2011)

Higher v_n from 4 Particle Correlations

Q-Cumulants: 200 GeV Au+Au |η|<1.0

P. Sorensen QM11



v_4 from mixed harmonics is within errors of $v_4^4\{4\}$:

$v_4 \sim v_2^2 \sim 0.1^2$

$v_4^4 \sim 10^{-8}$

$v_n\{4\}$ consistent with zero for odd terms. Consistent with $v_3^2\{2\}$ being due to non-flow **and/or** with $v_n \propto \varepsilon_{n,part}$: for $v_n \propto \varepsilon_{n,part}$, $v_n\{4\} \propto \varepsilon_{n,std}$

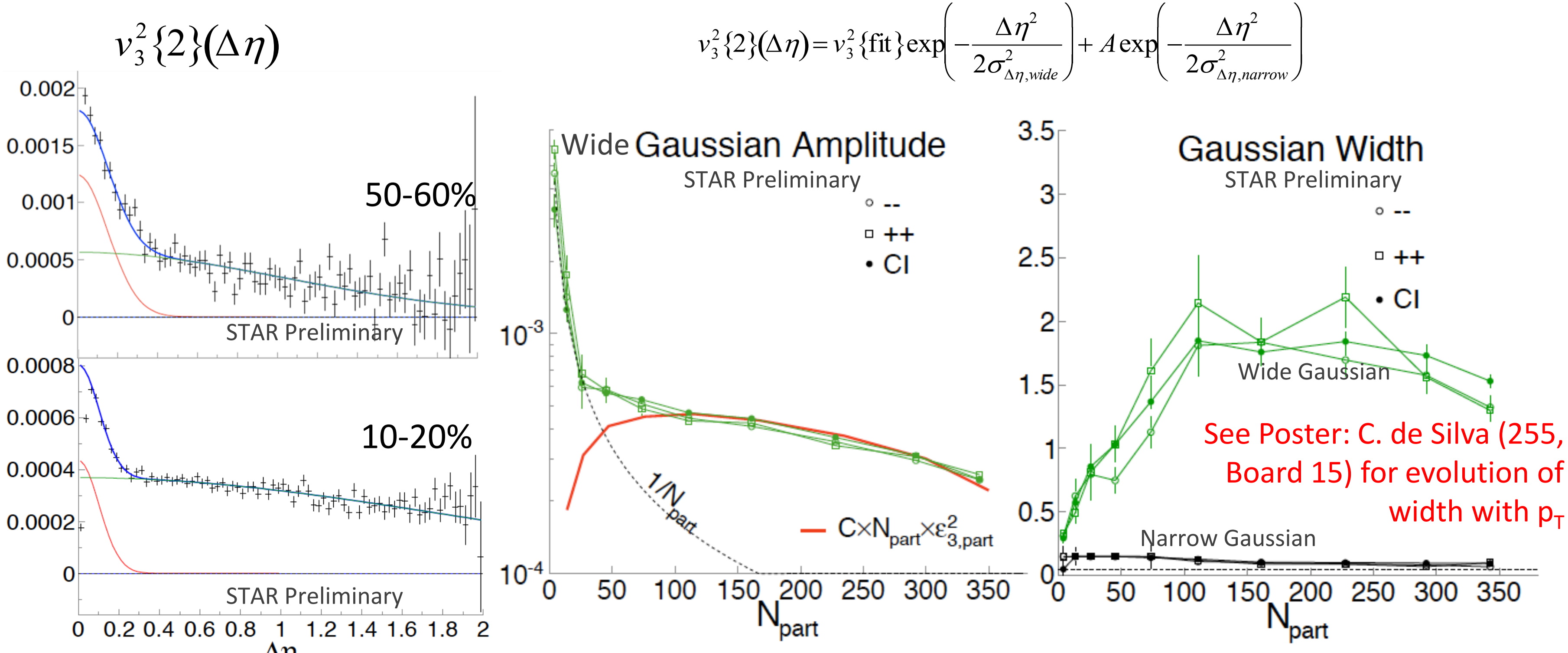
R.S. Bhalerao and J-Y.Ollitrault, Phys.Lett.B641:260-264 (2006)

S. Voloshin, A. Poskanzer, A. Tang, G. Wang, Phys.Lett.B659:537-541 (2008)

For 0-2.5% central $v_2\{4\} \approx 0$ indicates elliptic shape is nearly gone. We'll look at the shape of $v_n^2\{2\}$ vs. n for nearly symmetric collisions

$v_3^2\{2\}$ vs Δη and Non-flow

$$v_3^2\{2\}(\Delta\eta) = v_3^2\{\text{fit}\}\exp\left(-\frac{\Delta\eta^2}{2\sigma^2_{\Delta\eta,wide}}\right) + A\exp\left(-\frac{\Delta\eta^2}{2\sigma^2_{\Delta\eta,narrow}}\right)$$



See Poster: C. de Silva (255, Board 15) for evolution of width with p_T

σ≈2 is indistinguishable from linear within acceptance

Initial state density correlations may drop with Δy: interesting physics $\sigma_{\Delta y}$~$1/\alpha_s$?

Dusling, Gelis, Lappi & Venugopalan, Nucl. Phys. A 836, 159 (2010)

Petersen, Greiner, Bhattacharya & Bass, arXiv:1105.0340

Fit with a wide and a narrow peak. Wide peak amplitude first drops with 1/N but then deviates from trend near N_{part}=50. Above that it follows an $N_{part}\varepsilon^2_{3,part}$ trend

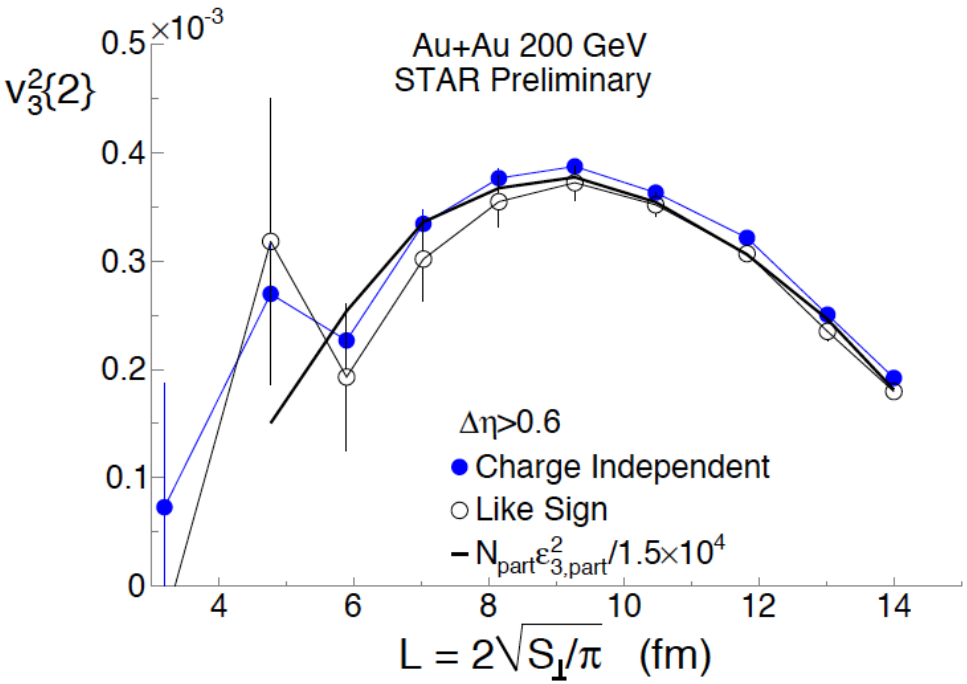
Is the wide Gaussian non-flow as in previous interpretations* and/or Δη dependence of initial density fluctuations?

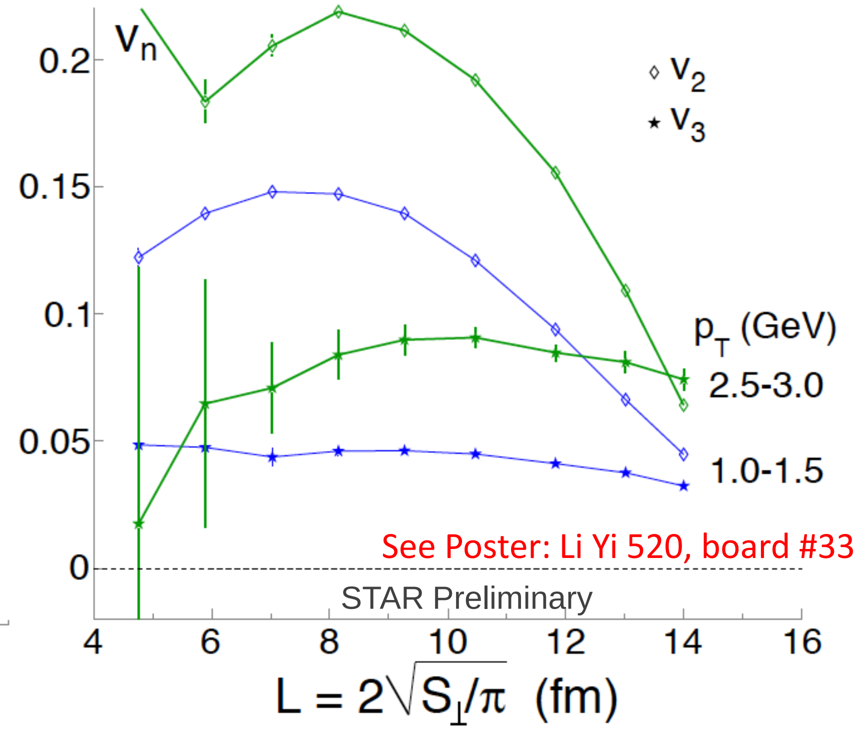
* Trainor, Kettler RefInt.J.Mod.Phys.E17:1219,2008

v_3^2 at Large Δη

$\langle\cos 3(\phi_1-\phi_2)\rangle$ for $|\eta_1-\eta_2|>0.6$

$\eta_1>0.5$ & $\eta_2<-0.5$





Centrality variable L estimates the transverse size of the system

v_3^2 for Δη>0.6 rises then falls with centrality as the overlap shape becomes symmetric. Similar to v_2

See Poster: J. Thomas (576, Board #43)

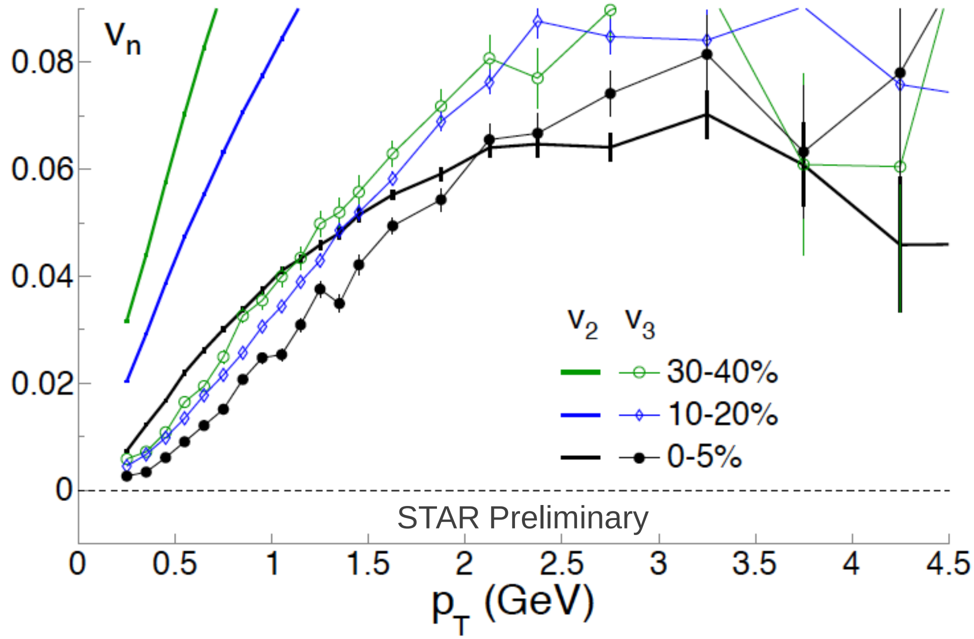
Almond shape of the overlap area appears to couple to n=3

D. Teaney, L. Yan, arXiv:1010.1876 [nucl-th]
P. S., A. Mocsy, B. Bolliet, Y. Pandit, arXiv:1102.1403

v_3 and $(v_3/v_2)^2$ vs centrality and p_T

$v_3\{2\}$ using separate η ranges: $\eta_1<-0.5$ and $\eta_2>0.5$

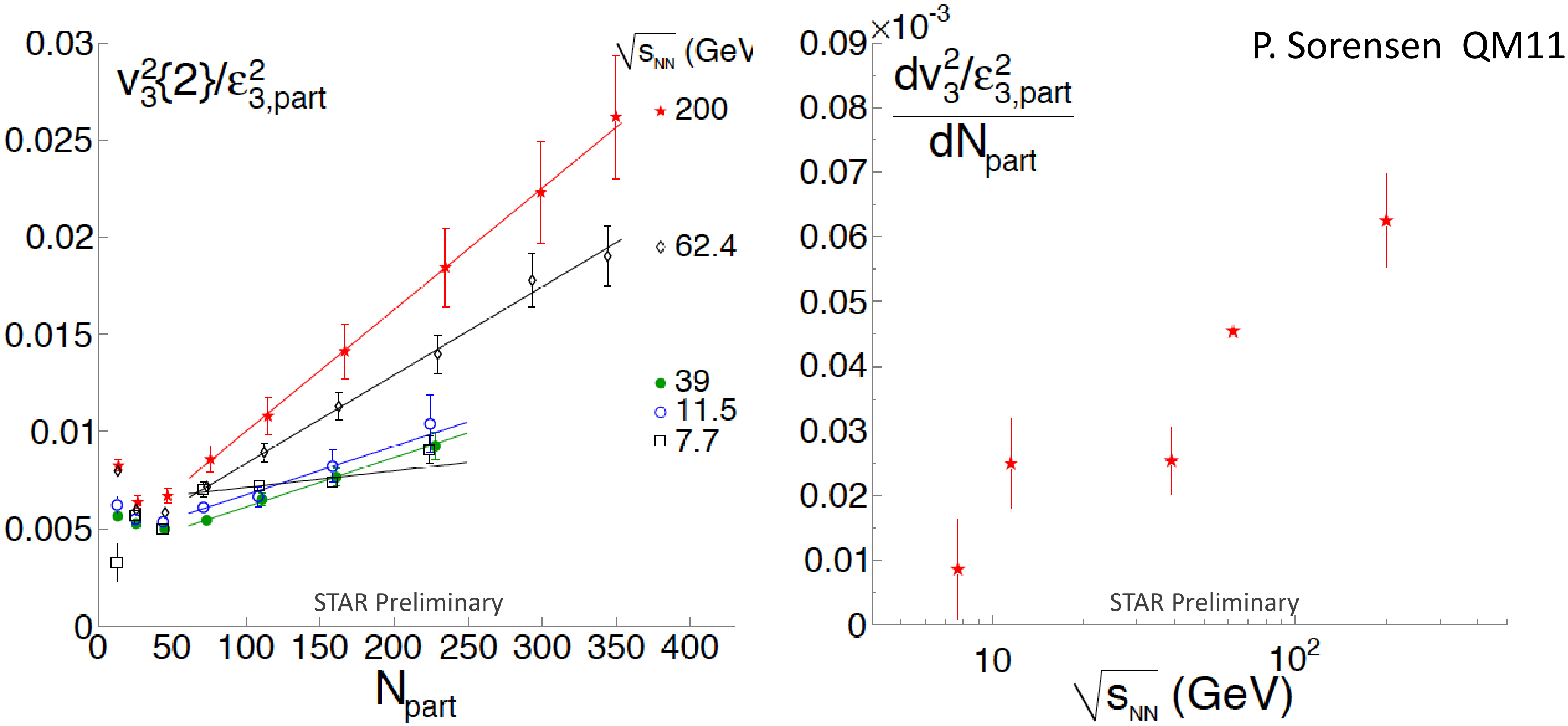
See Poster: Li Yi 520, board #33



For central collisions at intermediate p_T, $v_3\{2\} \geq v_2\{2\}$: what non-flow source would give such a behavior?

Weak $v_3\{2\}$ centrality dependence & $v_3 \geq v_2$ in central were predicted by models based on initial state density inhomogeneity ➪ leading explanation

$v_3^2/\varepsilon^2_{3,part}$ vs Beam Energy



Analysis based on Q-Cumulants for all charges and $-1<\eta<1$

$v_3^2/\varepsilon^2_{3,part}$ follows a simple trend with N_{part}: consistent with fits to $v_3^2\{2\}$ vs $\Delta\eta$

Slope of $v_3^2/\varepsilon^2_{3,part}$ is increasing with beam energy: what about the difference between $v_2^2\{2\}-v_2^2\{4\}$

Method of event plane determination

(1) Detector calibration / cell-by-cell calibration
(2) Q-vector, re-centering, normalization of width

$Q_{\{n\}x} = \Sigma_i \{ w_i \cos (n \phi_i) \}$ $Q'_{\{n\}x} = (Q_{\{n\}x} - <Q_{\{n\}x}>) / \sigma_{Q\{n\}x}$

$Q_{\{n\}y} = \Sigma_i \{ w_i \sin (n \phi_i) \}$ $Q'_{\{n\}y} = (Q_{\{n\}y} - <Q_{\{n\}y}>) / \sigma_{Q\{n\}y}$

$Q_{\{1\}x}^{ZDC} = \Sigma_i \{ w_i x_i \} / \Sigma_i \{ w_i \}$

$Q_{\{1\}y}^{ZDC} = \Sigma_i \{ w_i y_i \} / \Sigma_i \{ w_i \}$

(3) n-th harmonics reaction plane

$\Phi_{\{n\}} = \mathrm{atan2}\,(Q'_{\{n\}y} , Q'_{\{n\}x}) / n$

(4) Fourier flattening (Sergei's+Art's method paper)

$n \Phi'_{\{n\}} = n \Phi_{\{n\}} + \Sigma_i (2/i) \{ - <\sin(i\, n\, \Phi_{\{n\}})> \cos(i\, n\, \Phi_{\{n\}}) + <\cos(i\, n\, \Phi_{\{n\}})> \sin(i\, n\, \Phi_{\{n\}}) \}$

(5) measure v_n w.r.t. Φ_n and correct for E.P. resolution

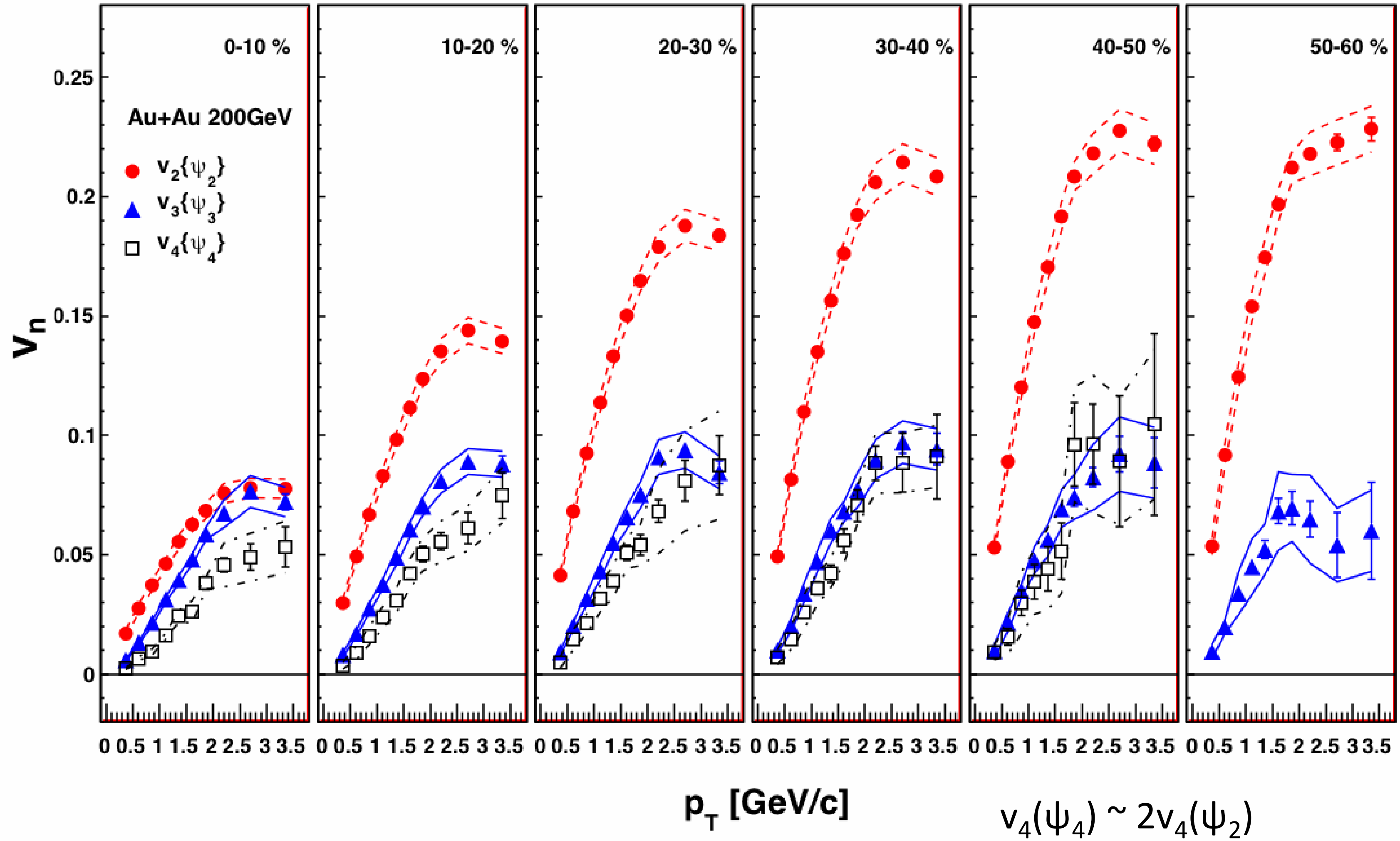
2-particle correlation among 3-sub detectors

Forward^{Hit} (F), Backward^{Hit} (B), Central^{Track} (C)

(1) measure $d\phi$ distribution between 2 detectors weighting by the hit amplitude
(2) normalize by the event mixing to make correlation functions for 3 combinations
(3) fit the correlation with Fourier function to extract $v_n^F v_n^B$, $v_n^F v_n^C$ and $v_n^B v_n^C$
(4) v_n^F(Hit) and v_n^B(Hit) can be determined as a function of centrality
(5) v_n^C(Track) can be determined as a function of centrality and p_T

Results: $v_n(\psi_n)$

http://arxiv.org/abs/1105.3928

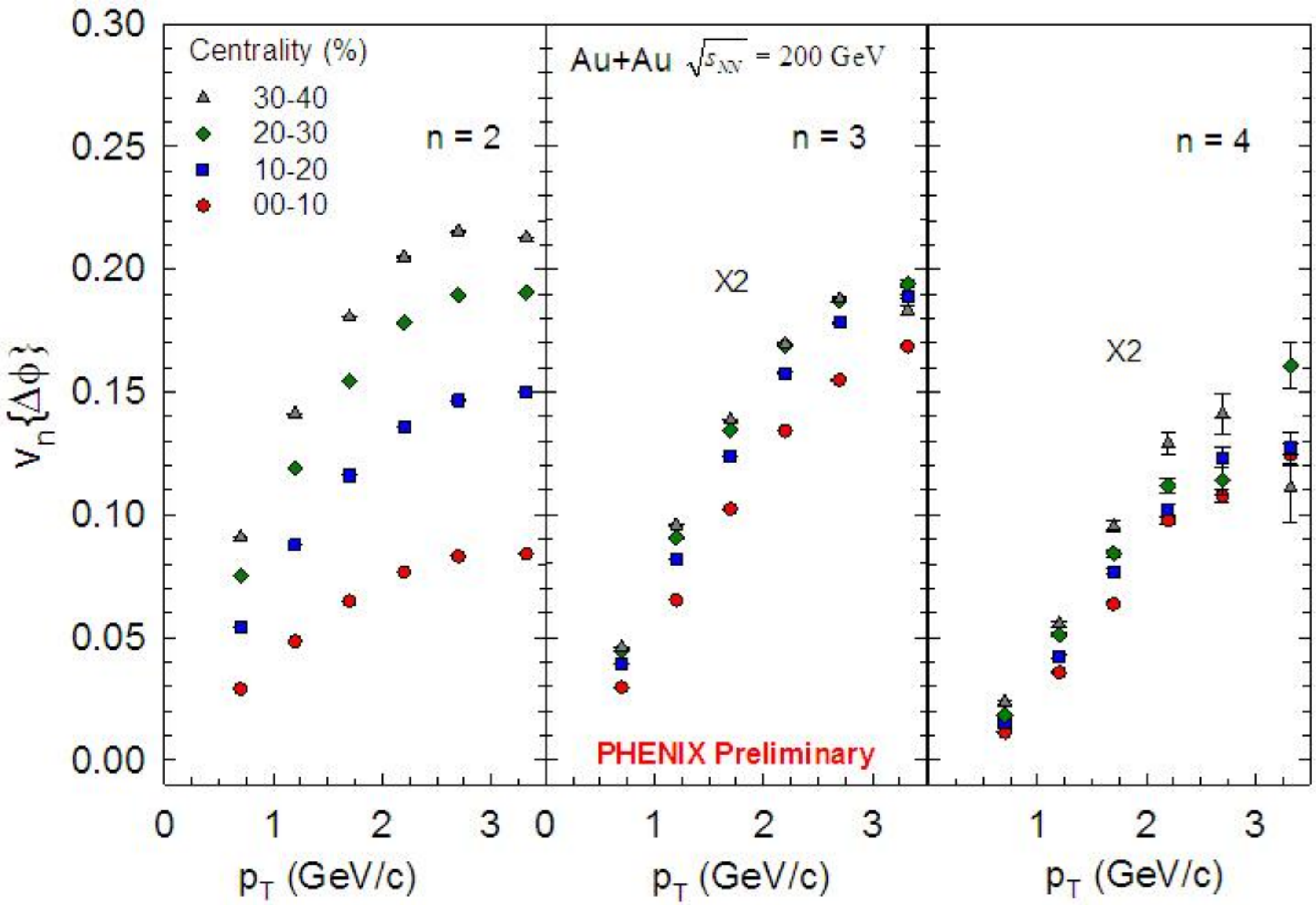


$v_4(\psi_4) \sim 2v_4(\psi_2)$

Robust PHENIX measurements performed at 200 GeV
(Crosschecked with correlation method)

Roy A. Lacey, Stony Brook University; QM11, Annecy, France 2011

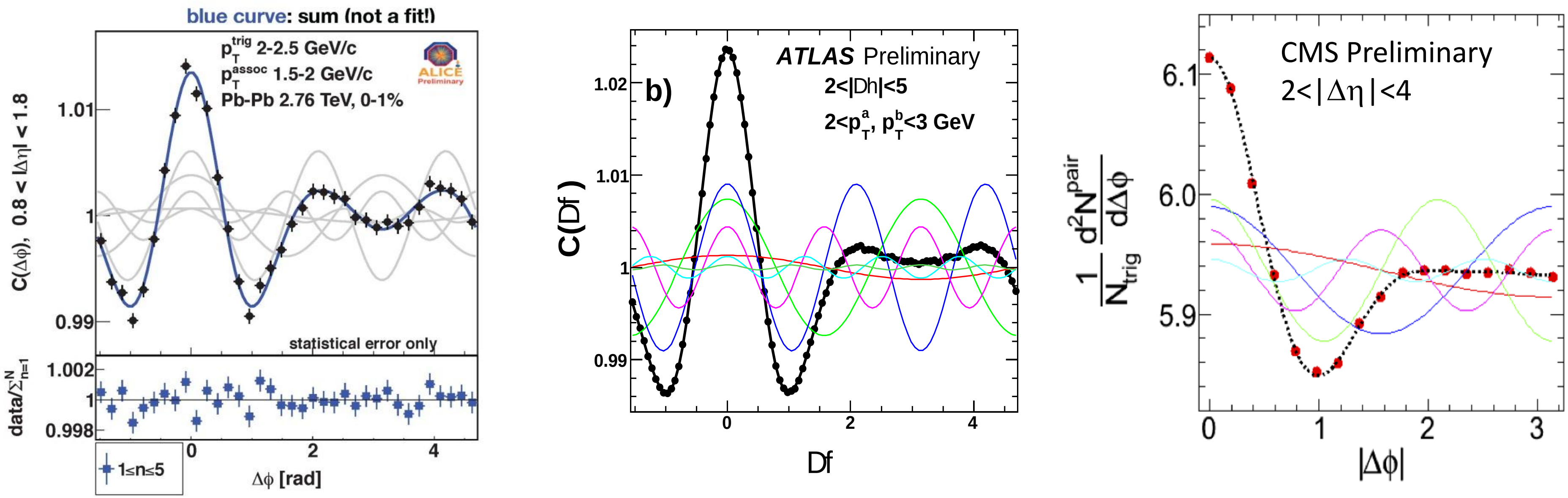
Results: $v_n(\Delta\phi)$



Robust measurements performed at 200 GeV

(Crosschecked with event-plane method)

Dihadron Correlations and v_n Harmonics at LHC



- ALICE, ATLAS, CMS:
- Correlation function can be obtained from sum (not fit) of Fourier Components
  - including v_2, v_3, v_4, v_5…

Test of v_n factorization at Alice

ALICE correlation paper:
arXiv: 1107.0556

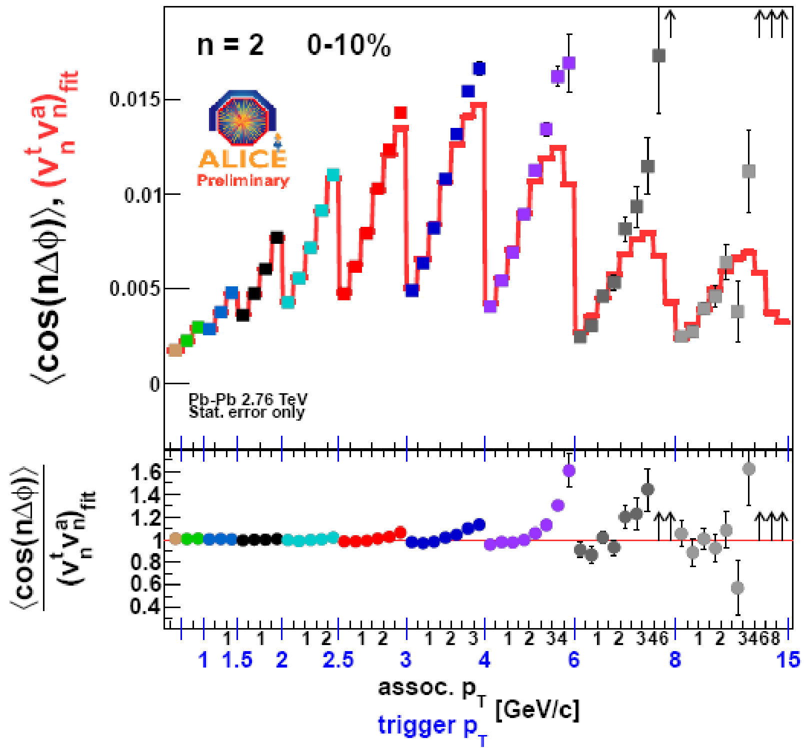
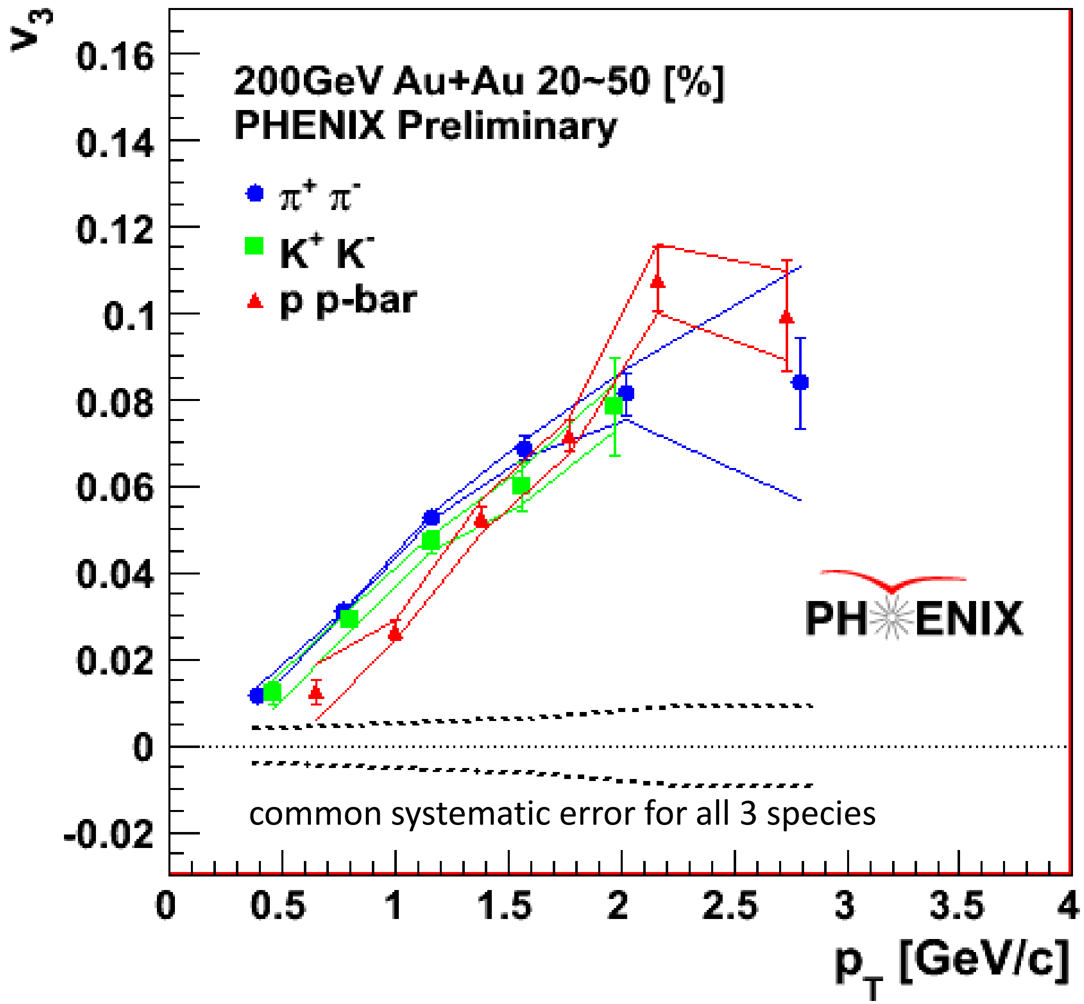


Figure 6. Test of the factorization relation for: $V_{2\Delta}(p_{T,\mathrm{assoc}}, p_{T,\mathrm{trig}})$ (points); $v_2(p_{T,\mathrm{assoc}}) \cdot v_2(p_{T,\mathrm{trig}})$ (line). The bottom panel shows their ratio.

Identified π/K/p $v_3\{\Phi_3\}$ at 200GeV Au+Au



- lower p_T

  particle mass dependence

radial flow

- intermediate p_T

  baryon / meson splitting

quark coalescence at hadronization with partonic v_3

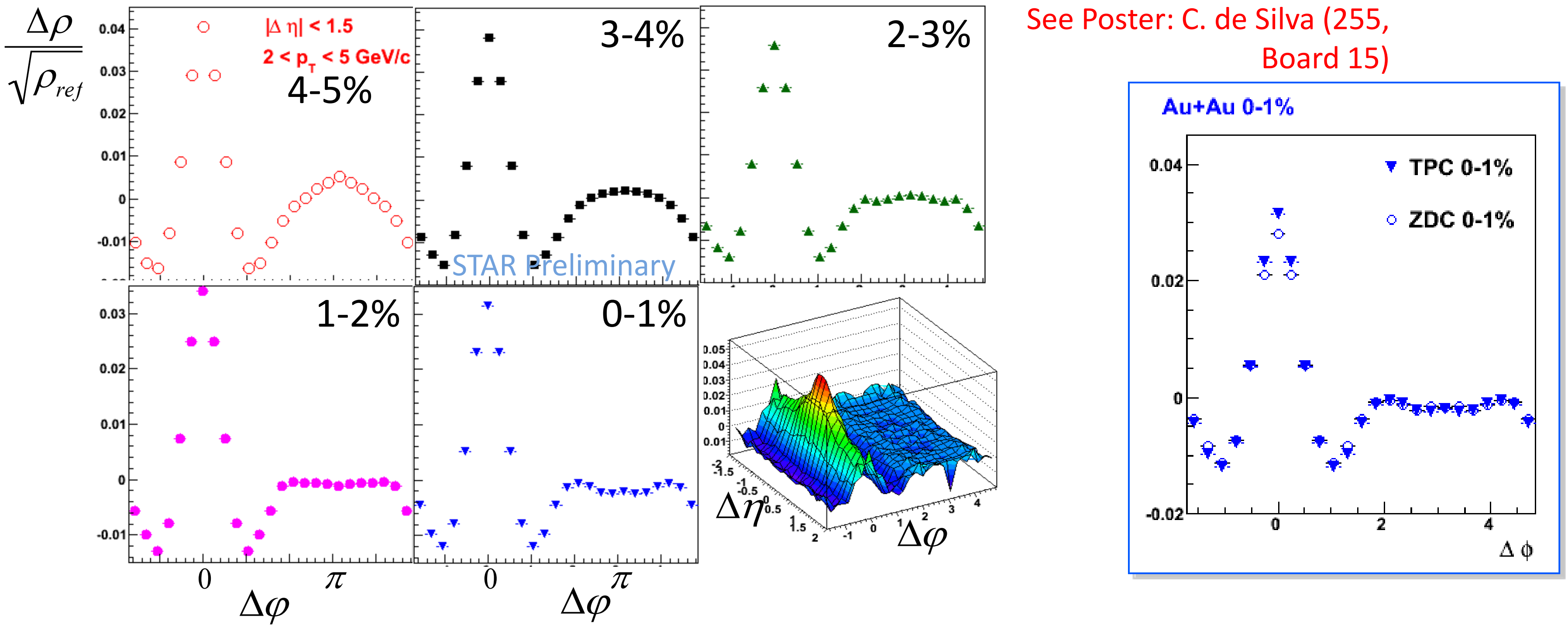
Radial & Partonic collective flow seen in v_3

Correlations at Intermediate p_T

v_3 should be most evident at intermediate p_T and for central collisions where the overlap geometry is most symmetric

P. Sorensen QM11

See Poster: C. de Silva (255, Board 15)

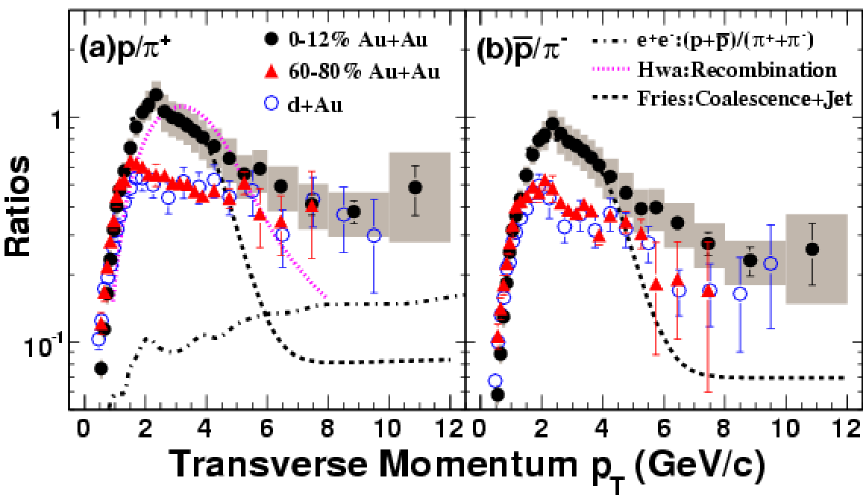


For 0-1% central, n=3 double hump is present on the away-side without v_2 subtraction

We see effects consistent with expectations, we'll investigate further by looking at various measurements related to v_n

A remind of the baryon / meson splitting

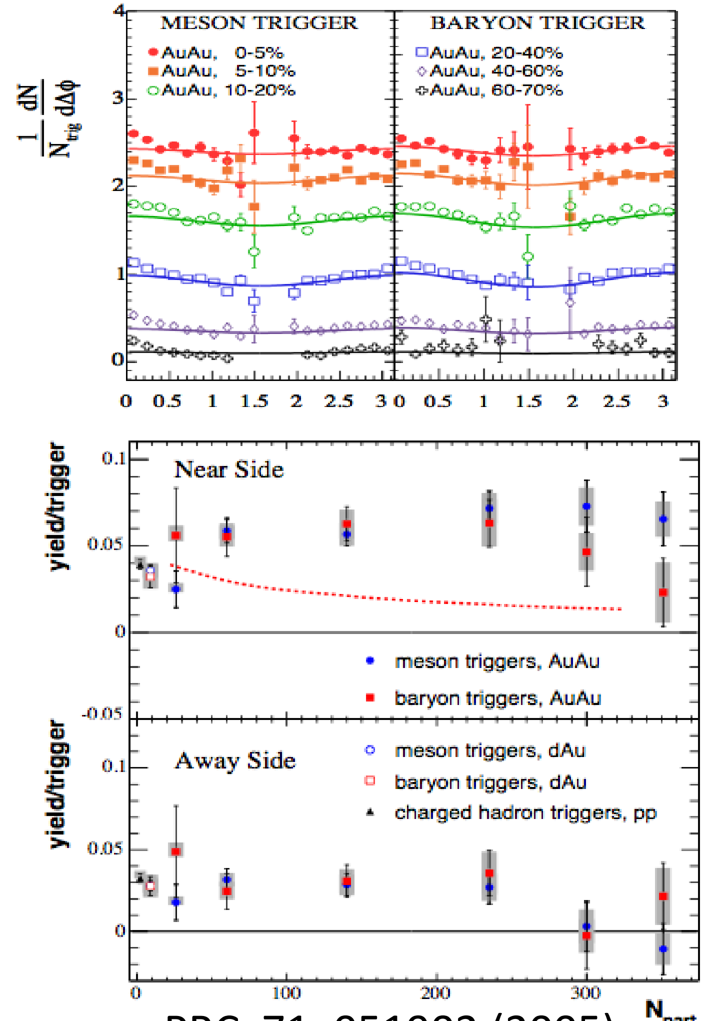
STAR, PRL 97 (2006) 152301



From simplistic recombination:

Stronger trigger dilution for enhanced baryons

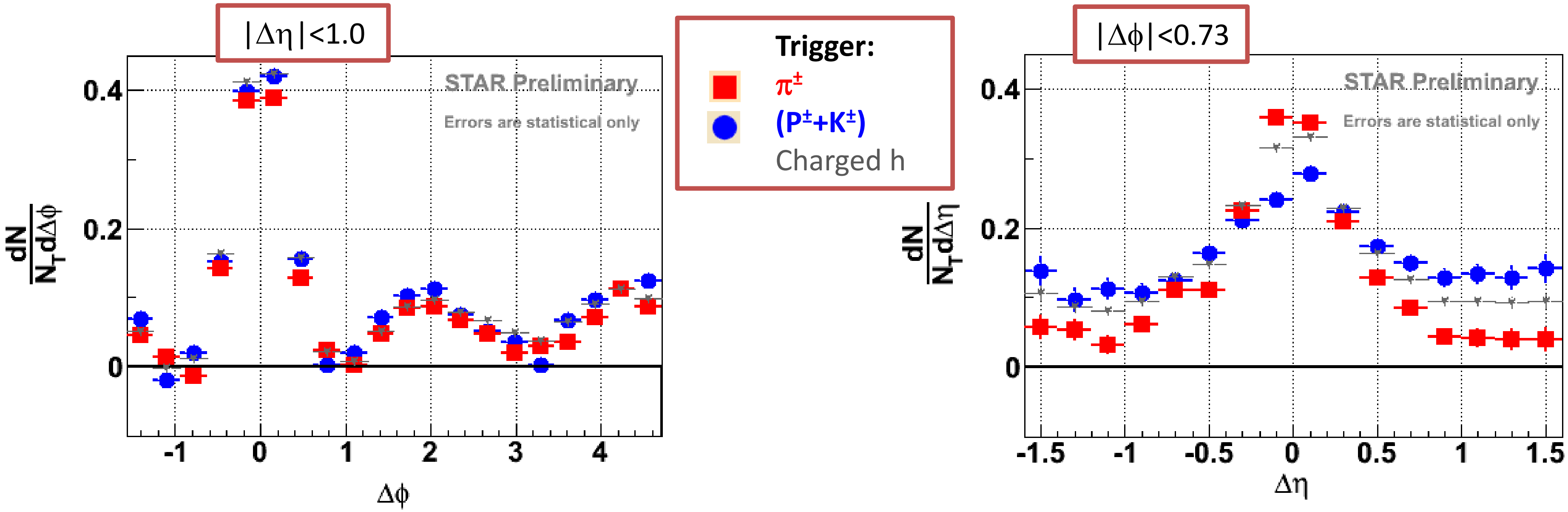
→ **Lower associated yield** per hadron trigger



PRC 71, 051902 (2005)

Lower baryon-triggered yield in central collisions

Projections – Au+Au



- Consistent with previous results – but that is a function of projection range!
- Does not reveal entire structure

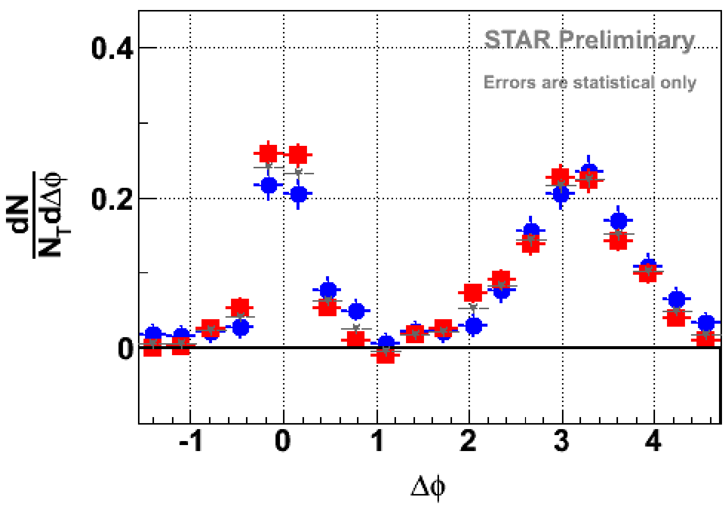
- Δη reveals rich trigger PID dependent structure:
  - Higher jet-like amplitude for pions
  - Ridge predominantly contributed by non-pion-triggered events

Au+Au

$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

Projections – d+Au

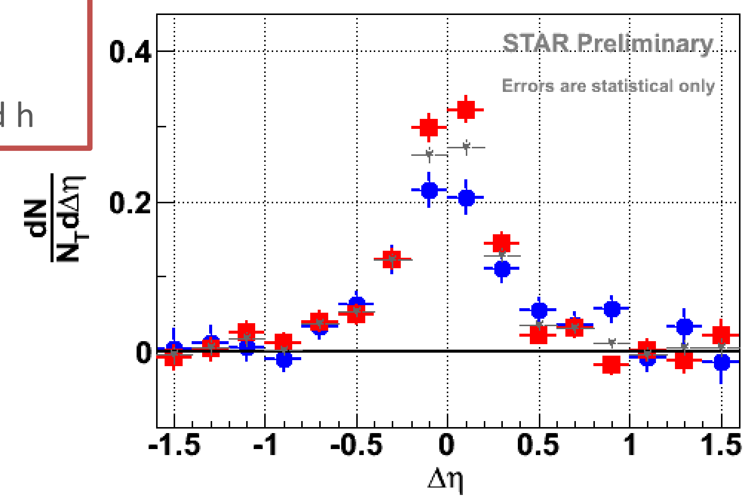
|Δη|<1.0



Trigger:

- $\pi^{\pm}$
- **$(P^{\pm}+K^{\pm})$**
- Charged h

|Δϕ|<0.73



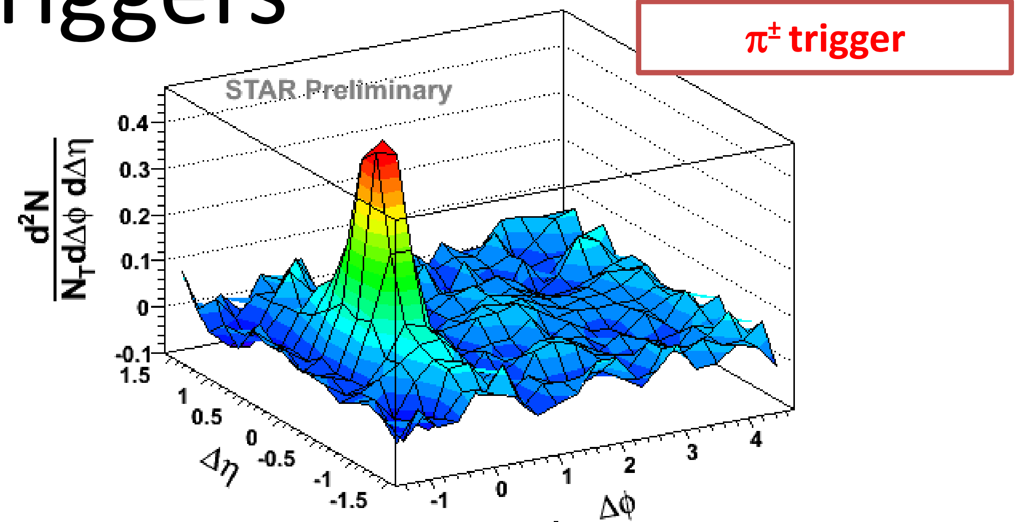
- Difference in Jet-like amplitude persists

d+Au MB

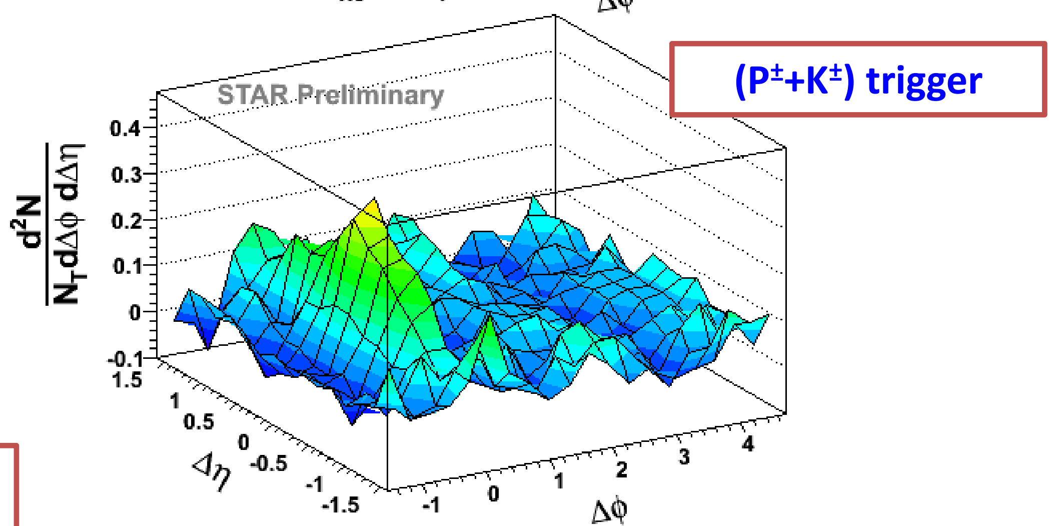
$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

Di-Hadron Correlation with PID triggers

- Large jet-like cone, small ridge from pion triggers



- Smaller cone, large ridge from P+K triggers

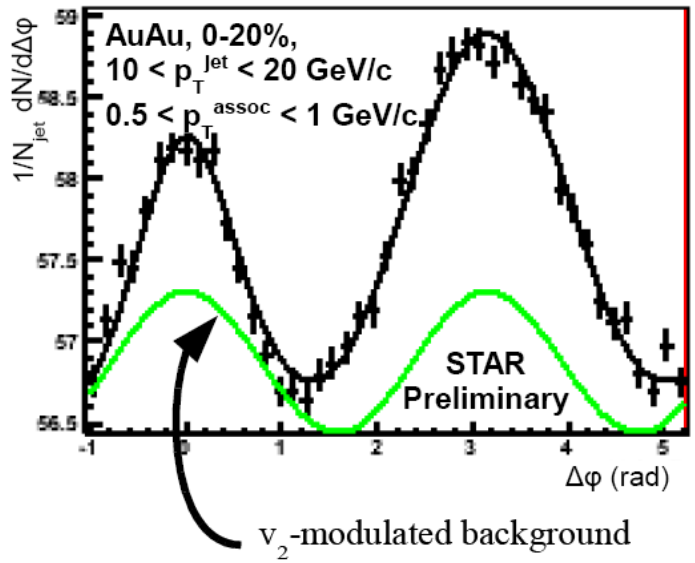


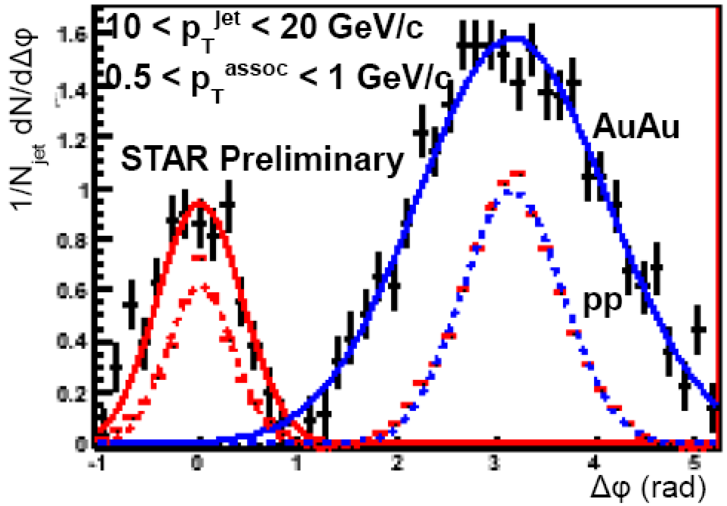
Au+Au

$4 < p_{T,trigger} < 6$ GeV/c
$p_{t,assoc.} > 1.5$ GeV/c

How jets (and proxies: higher p_T, and their correlation) interact with v_n

A. Ohlson QM11





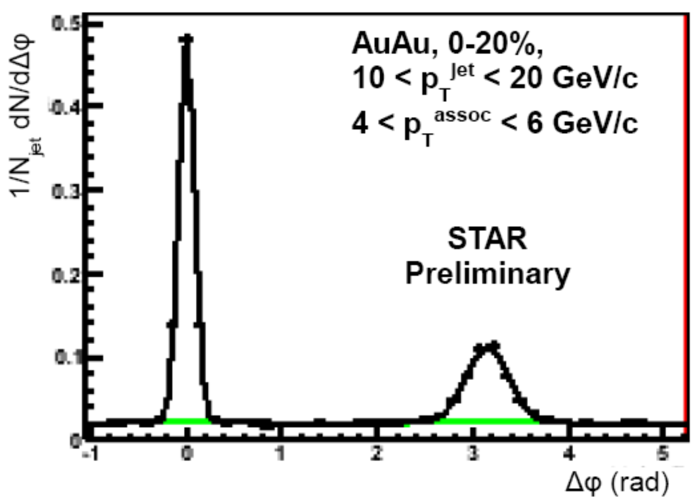
t RHIC isn't

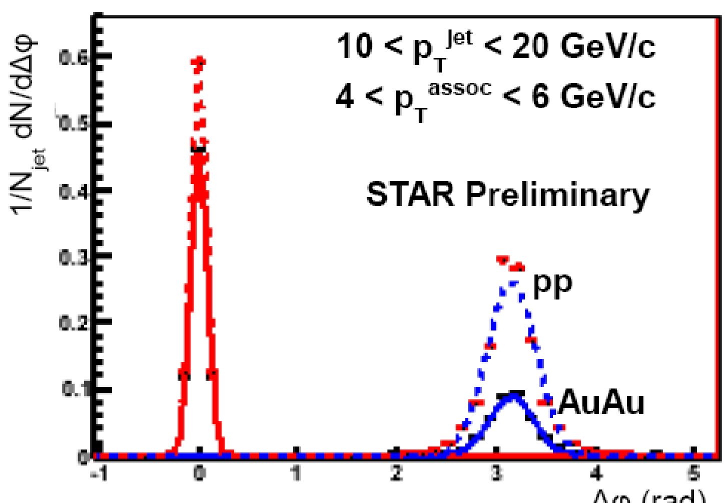
s small. Instead, the

ce (jet quenching in

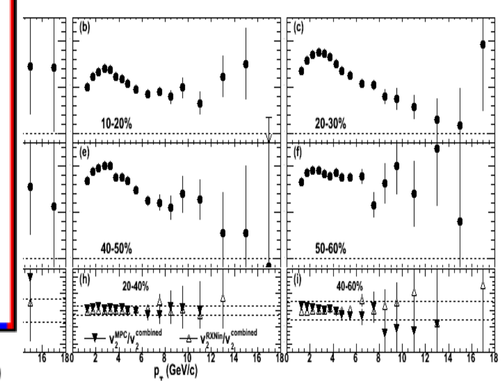
like" correlation yet.

hadron" correlation.

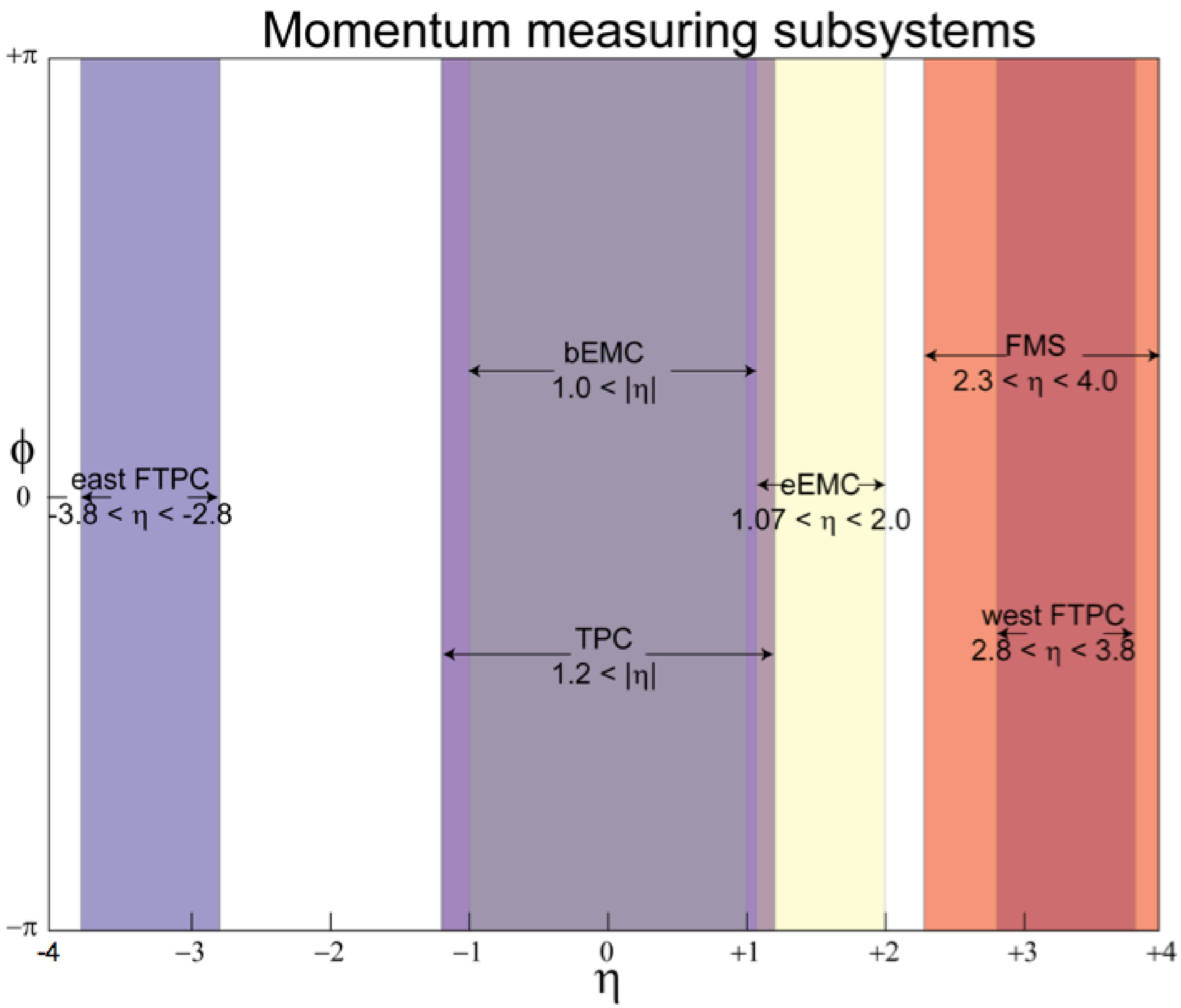




ys. Rev. Lett. 105, 142301 (2010)



STAR η-ϕ Coverage



STAR has nearly hermetic coverage over full azimuthal range and wide pseudorapidity range