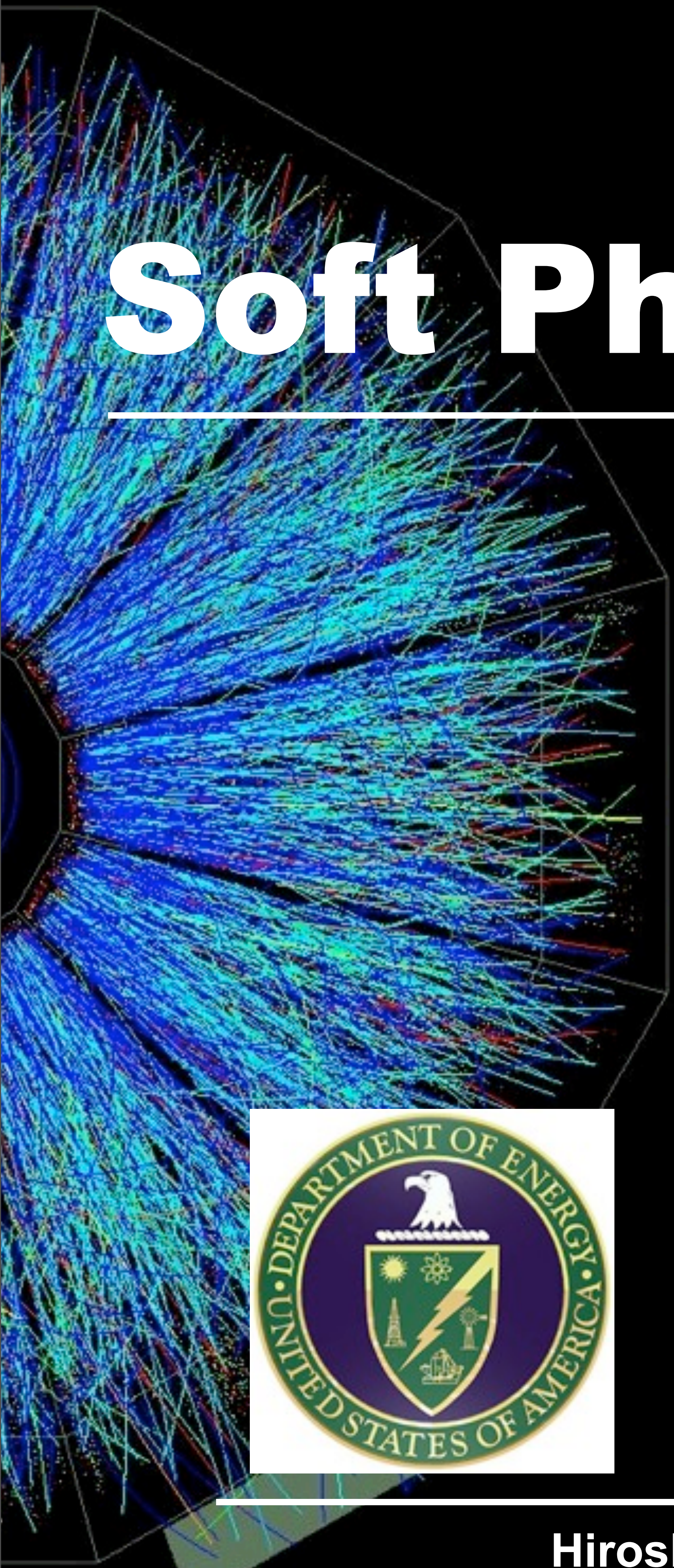
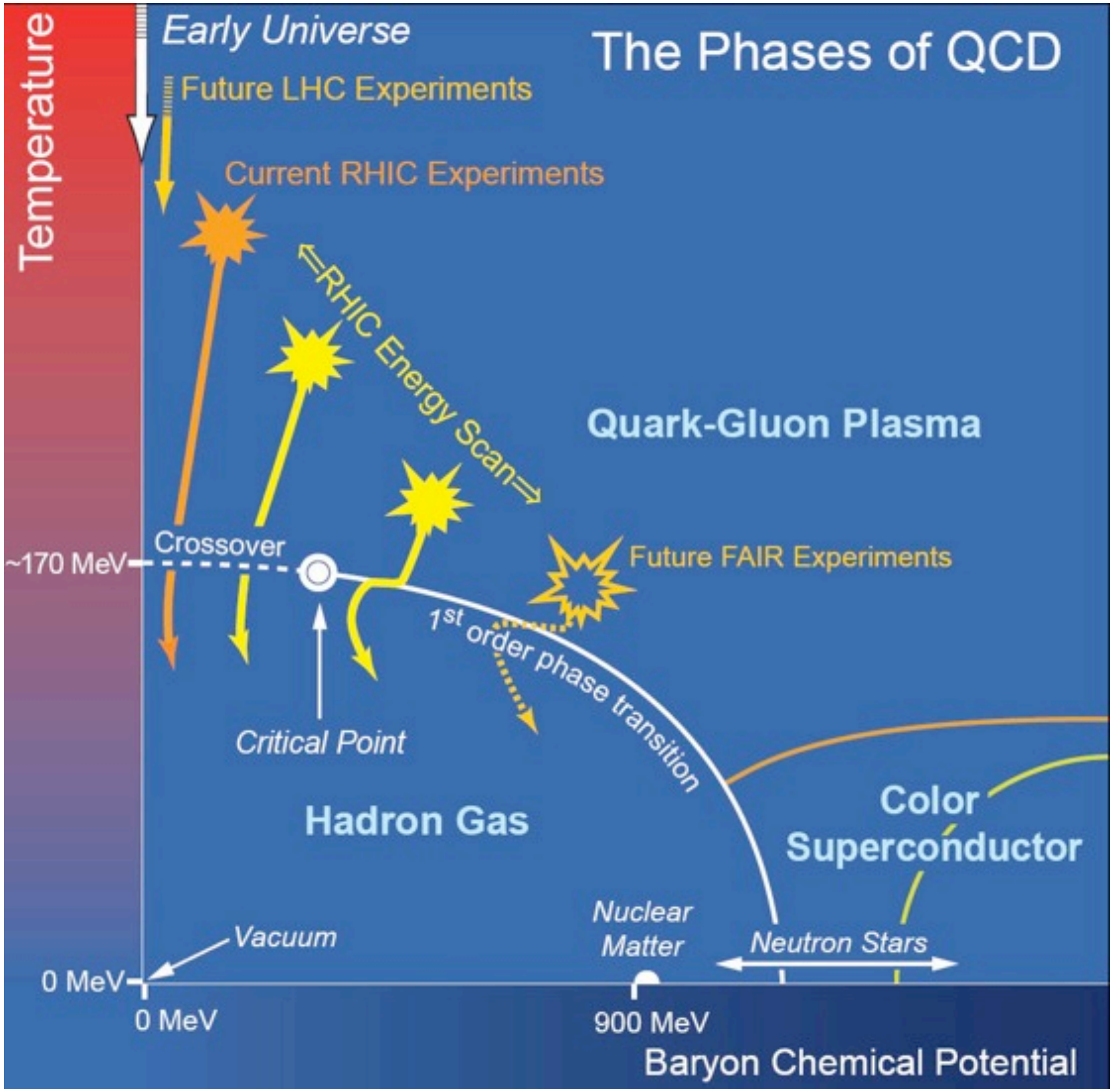


Soft Physics from STAR

Hiroshi Masui
for the STAR collaboration
Lawrence Berkeley National Laboratory

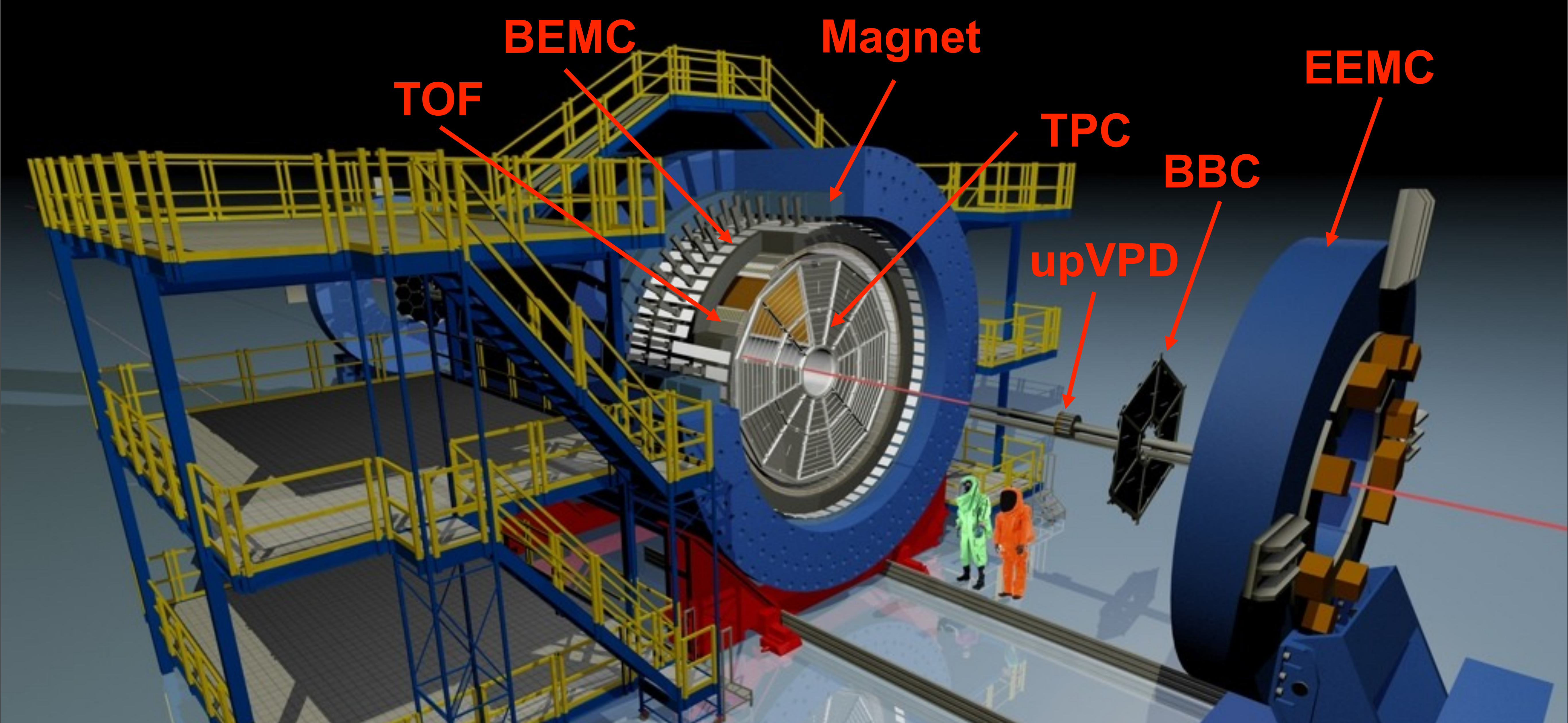
2011 RHIC/AGS users meeting
HI Workshop II, Jun/20/2011

STAR physics goals



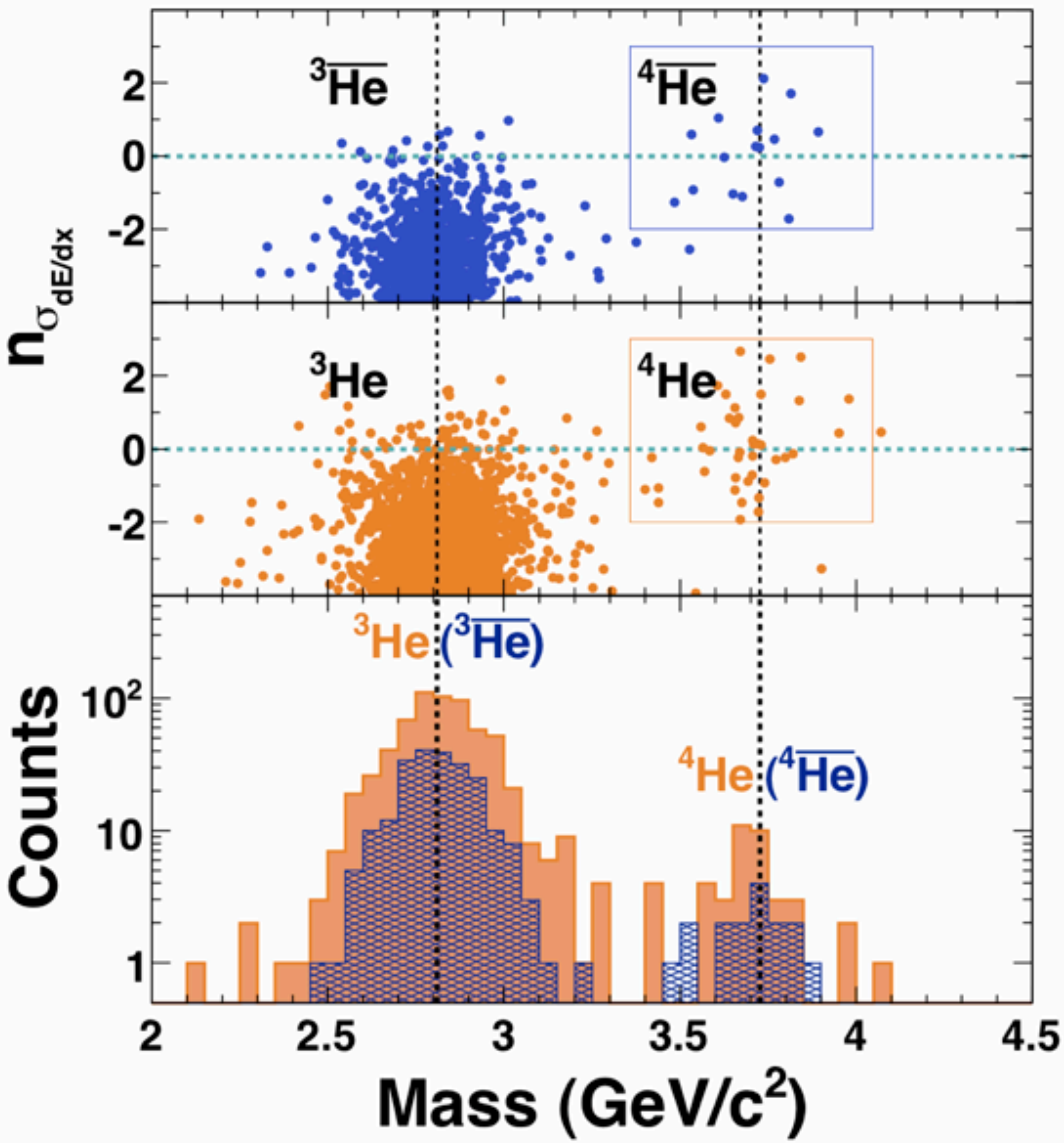
- Study ***structure of QCD phase diagram*** in heavy ion collisions
- At $\sqrt{s_{NN}}$ = 200 GeV
  - pQCD in hot and dense medium
  - ***Medium properties, Equation Of State***
- RHIC Beam Energy Scan
  - Search for the QCD Critical point

STAR experiment



- Large acceptance
  - Full azimuth, good pseudo-rapidity coverage (**TPC** $|\eta|<1$, **TOF** $|\eta|<0.9$)
- **H**igh **L**evel online tracking **T**rigger (HLT)

Discovery of anti-^{4}He

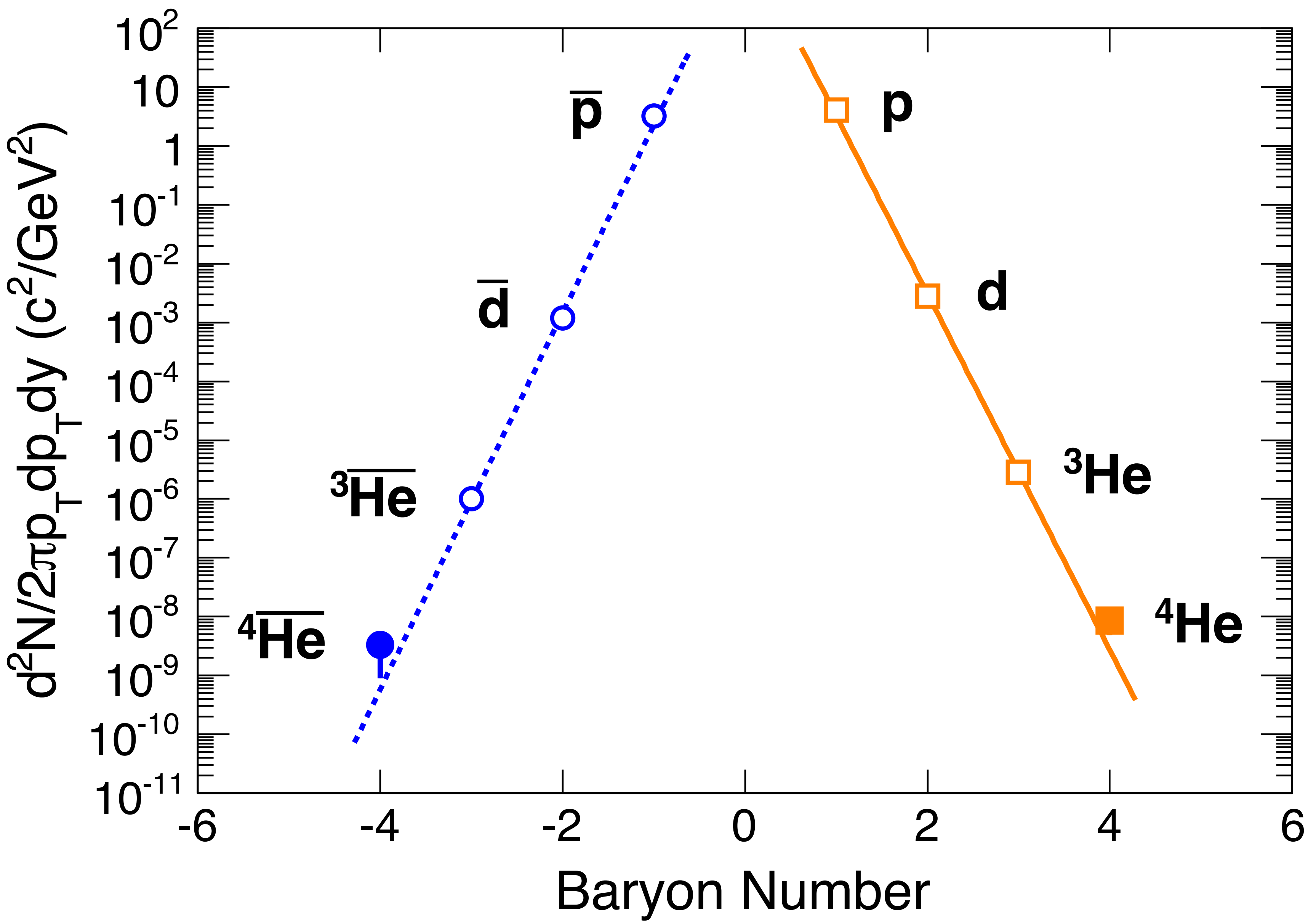


L. Xue, QM2011

Nature 473, 353-356, (19 May 2011)
doi:10.1038/nature10079

- **TPC+TOF+HLT**
- Particle identification by dE/dx (**TPC**) + flight-time (**TOF**)
- A clean separation for anti-^{3}He and anti-^{4}He
- Total 18 counts of anti-^{4}He
  - 2 from 2007
  - 16 from 2010

Invariant yields for anti-^{4}He



L. Xue, QM2011

Nature 473, 353-356, (19 May 2011)
doi:10.1038/nature10079

- Invariant yields for anti-^{4}He
  - consistent with exponential trend expected from both thermal and coalescence models

Azimuthal anisotropy

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

$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

$$\ldots$$

Azimuthal anisotropy

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

$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

Partonic d.o.f,
thermalization ?

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

$$\cdots$$

Azimuthal anisotropy

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

Softening of ***EOS*** ?

$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

Partonic d.o.f, thermalization ?

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

$$\ldots$$

Azimuthal anisotropy

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

Softening of ***EOS*** ?

$$+ \, 2v_1 \cos\left(\phi - \Psi_{\mathrm{RP}}\right)$$

$$+ \, 2a_1 \sin\left(\phi - \Psi_{\mathrm{RP}}\right)$$

Chiral magnetic effect ?

Partonic d.o.f, thermalization ?

$$+ \, 2v_2 \cos\left(2\phi - 2\Psi_{\mathrm{RP}}\right)$$

$$+ \, 2v_3 \cos\left(3\phi - 3\Psi_{\mathrm{RP}}\right)$$

$$\ldots$$

Azimuthal anisotropy

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

Softening of **_EOS_** ?

$$+\ 2v_1 \cos\left(\phi - \Psi_{\mathrm{RP}}\right)$$

$$+\ 2a_1 \sin\left(\phi - \Psi_{\mathrm{RP}}\right)$$

Chiral magnetic effect ?

Partonic d.o.f, thermalization ?

$$+\ 2v_2 \cos\left(2\phi - 2\Psi_{\mathrm{RP}}\right)$$

$$+\ 2v_3 \cos\left(3\phi - 3\Psi_{\mathrm{RP}}\right)$$

Initial geometry fluctuations ?

$$\ldots$$

Azimuthal anisotropy

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

Softening of ***EOS*** ?

$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

Chiral magnetic effect ?

Partonic d.o.f, thermalization ?

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

Initial geometry fluctuations ?

$\ldots$

Dynamical charge separation

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

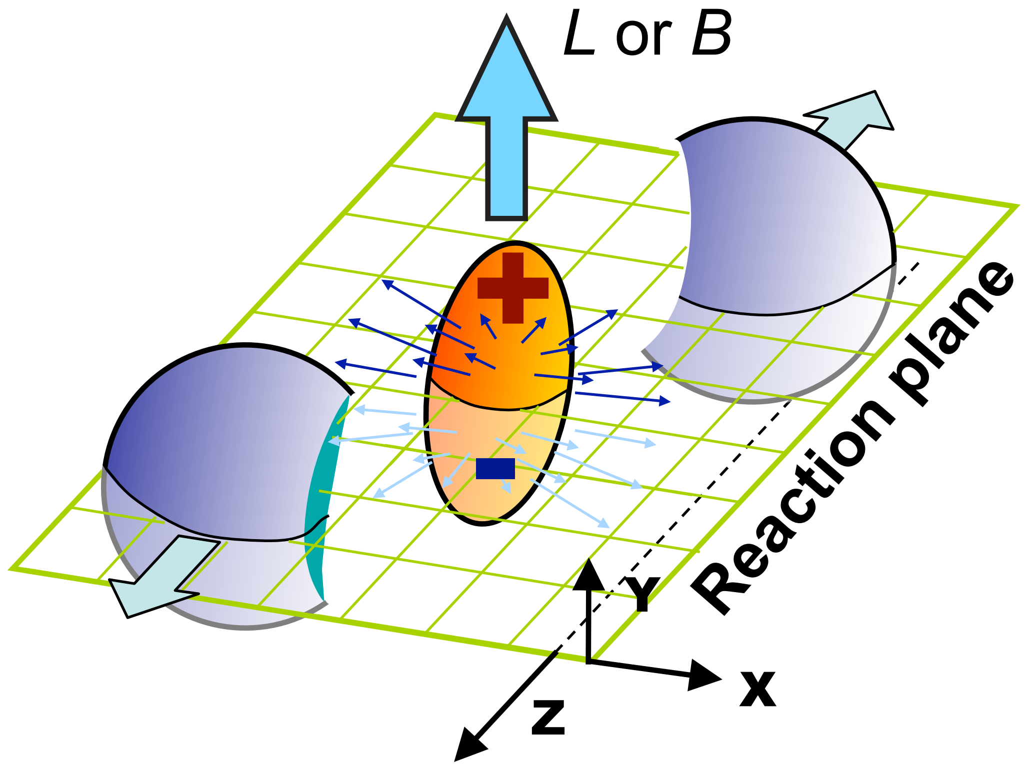
$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

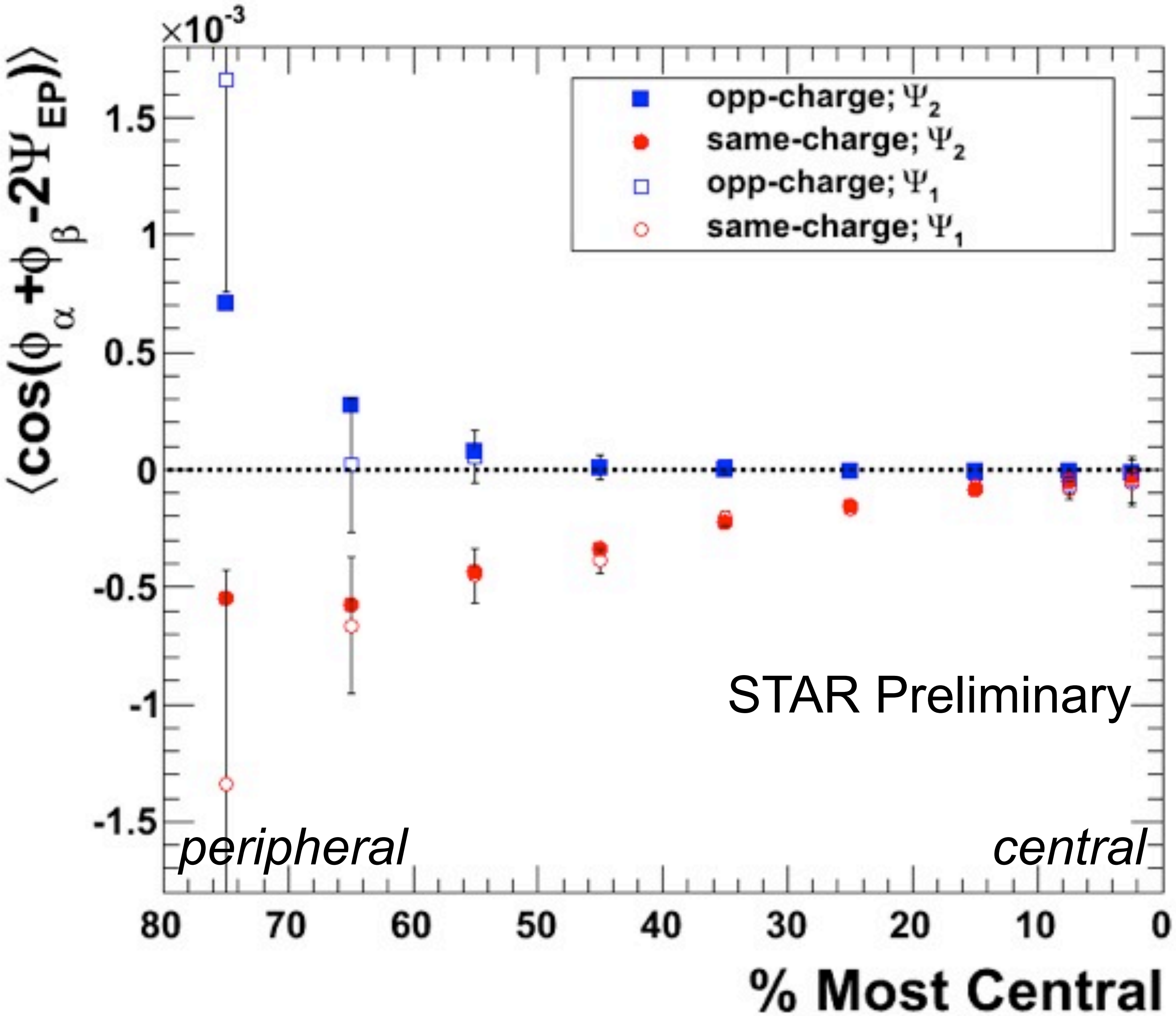
$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

$$\ldots$$



- Charge separation due to ***Chiral magnetic effect***
  - Parity (*P*) odd domain + large magnetic field
- Measured only through 2 or many particle correlation
  - Suffered by *P*-even backgrounds
- Signal is $O(10^{-4})$ in $|a_1|^2$

Three particle correlation



D. Gangadharan, QM2011

$$\langle \cos(\phi_a + \phi_b - 2\Psi_{\mathrm{RP}}) \rangle$$
$$= \langle v_1^a v_1^b \rangle + B_{in} + \langle a_1^a a_1^b \rangle - B_{out}$$

Signal

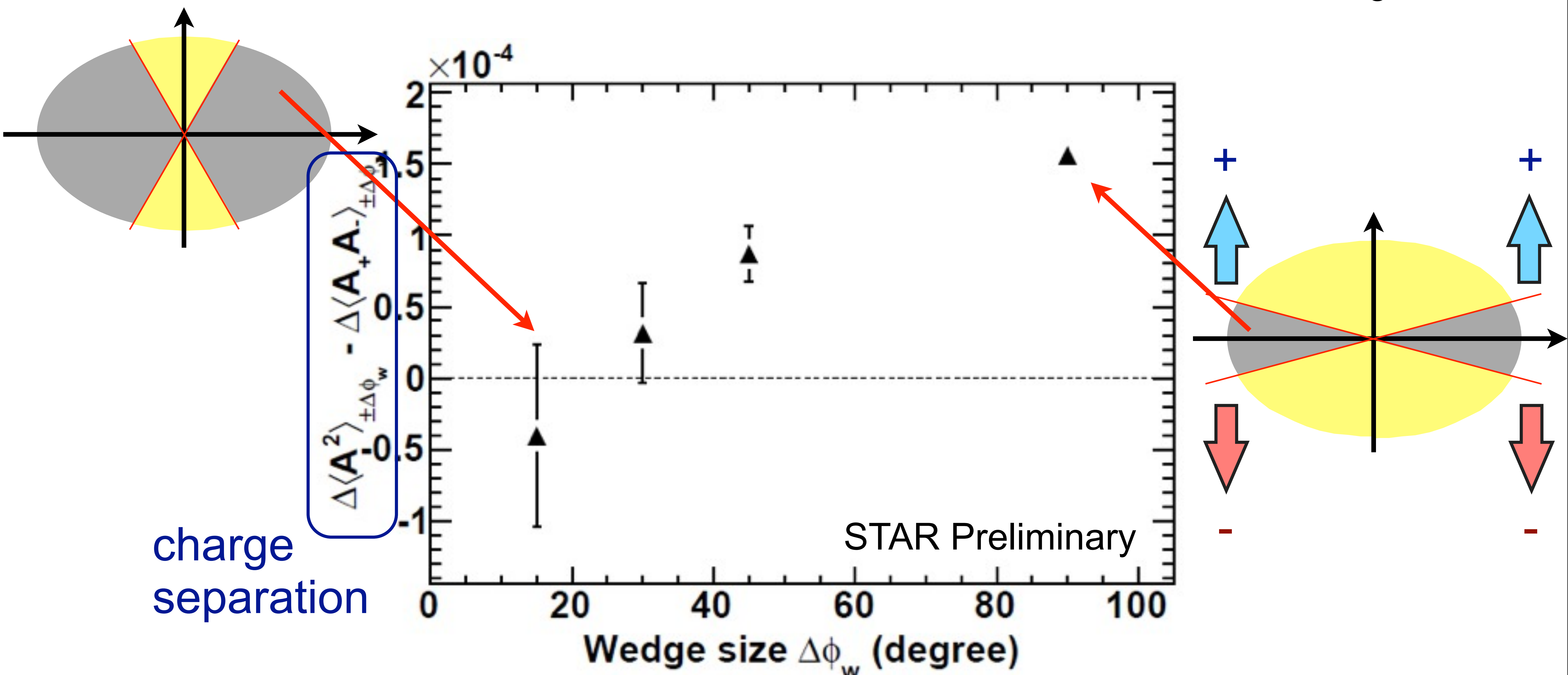
P-even backgrounds may or may not cancel

may cancel in symmetric η may not due to v_1 fluctuations

- Consistent results from ZDC-SMD event plane
  - Signal is likely a genuine correlation with respect to the reaction plane

In-plane or out-of-plane ?

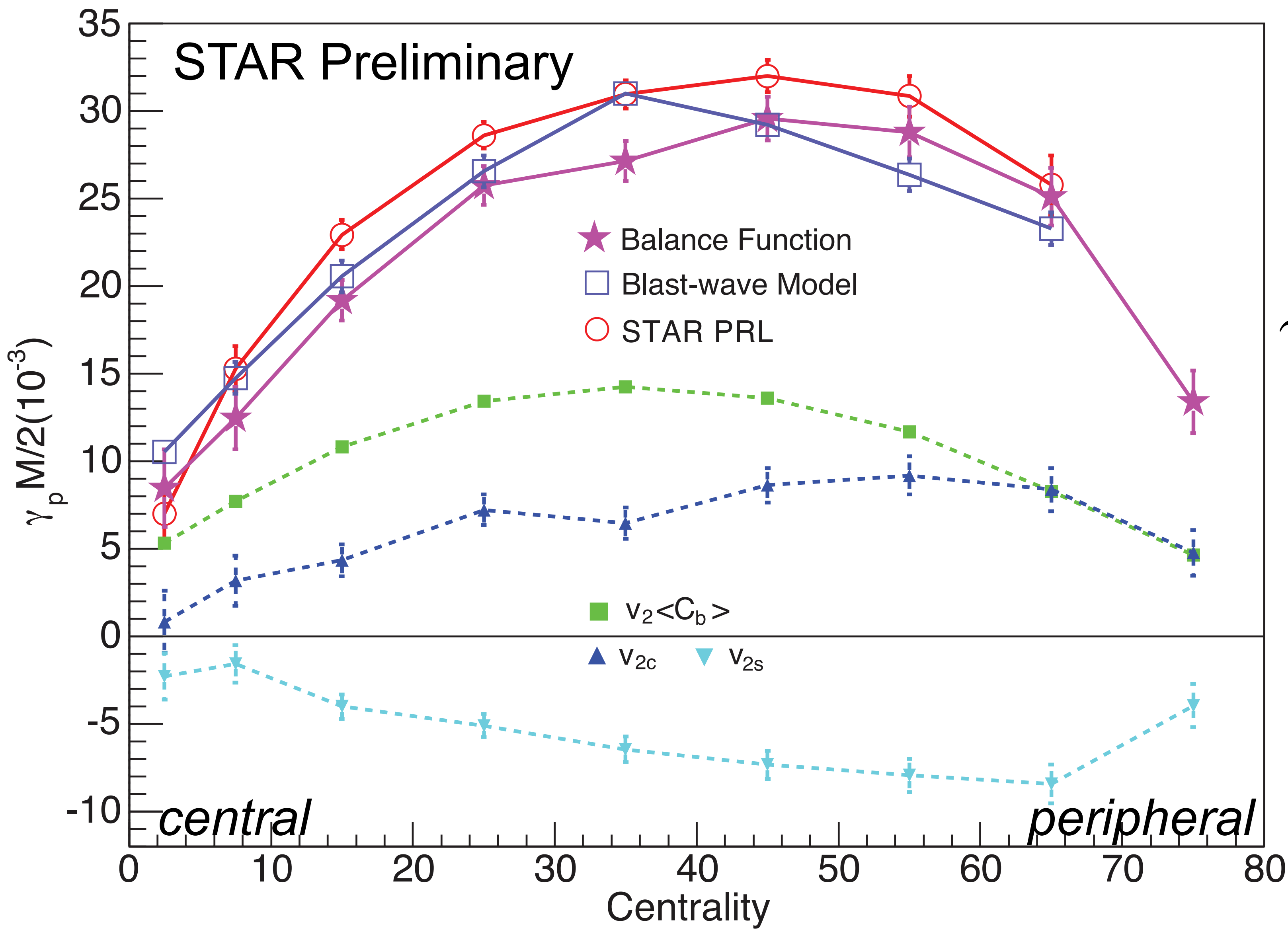
Q. Wang, QM2011



- Charge separation between same and opposite pairs is larger for larger wedge size
  - Larger charge separation in the vicinity of the in-plane direction

Local charge conservation ?

H. Wang, QM2011



$$\gamma_p = \frac{1}{2}(2\gamma_{+-} - [\gamma_{++} + \gamma_{--}])$$

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle$$

Blast-wave model
S. Schlichting and S. Pratt, ***PRC****83, 014913 (2011)*

- Consistent with three particle correlation method
- Data can be also explained by local charge conservation + elliptic flow

Elliptic flow

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

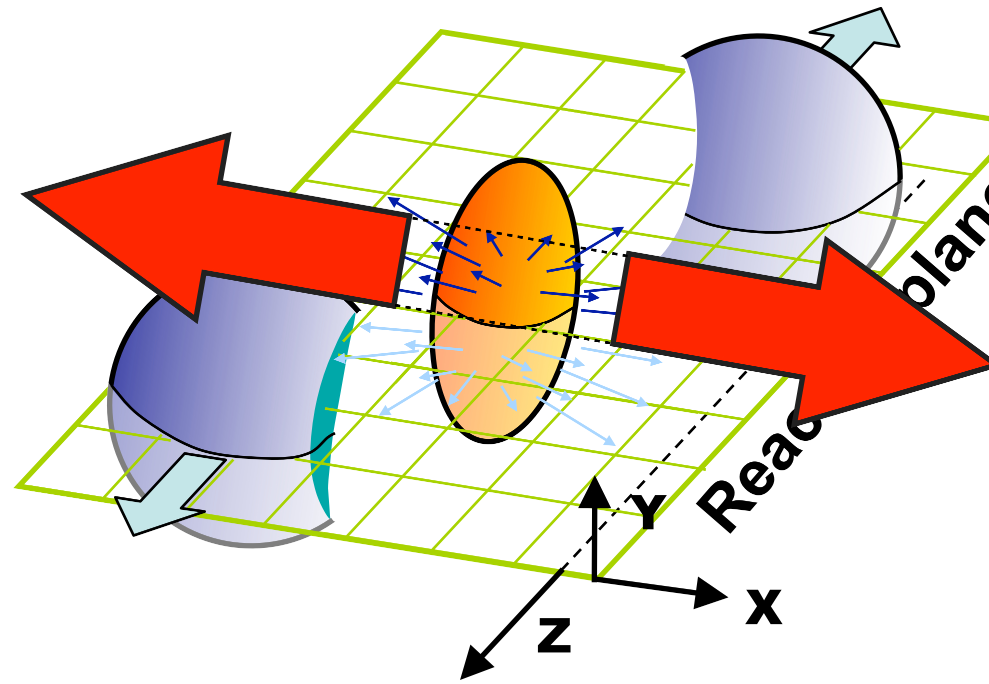
$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

$$\ldots$$

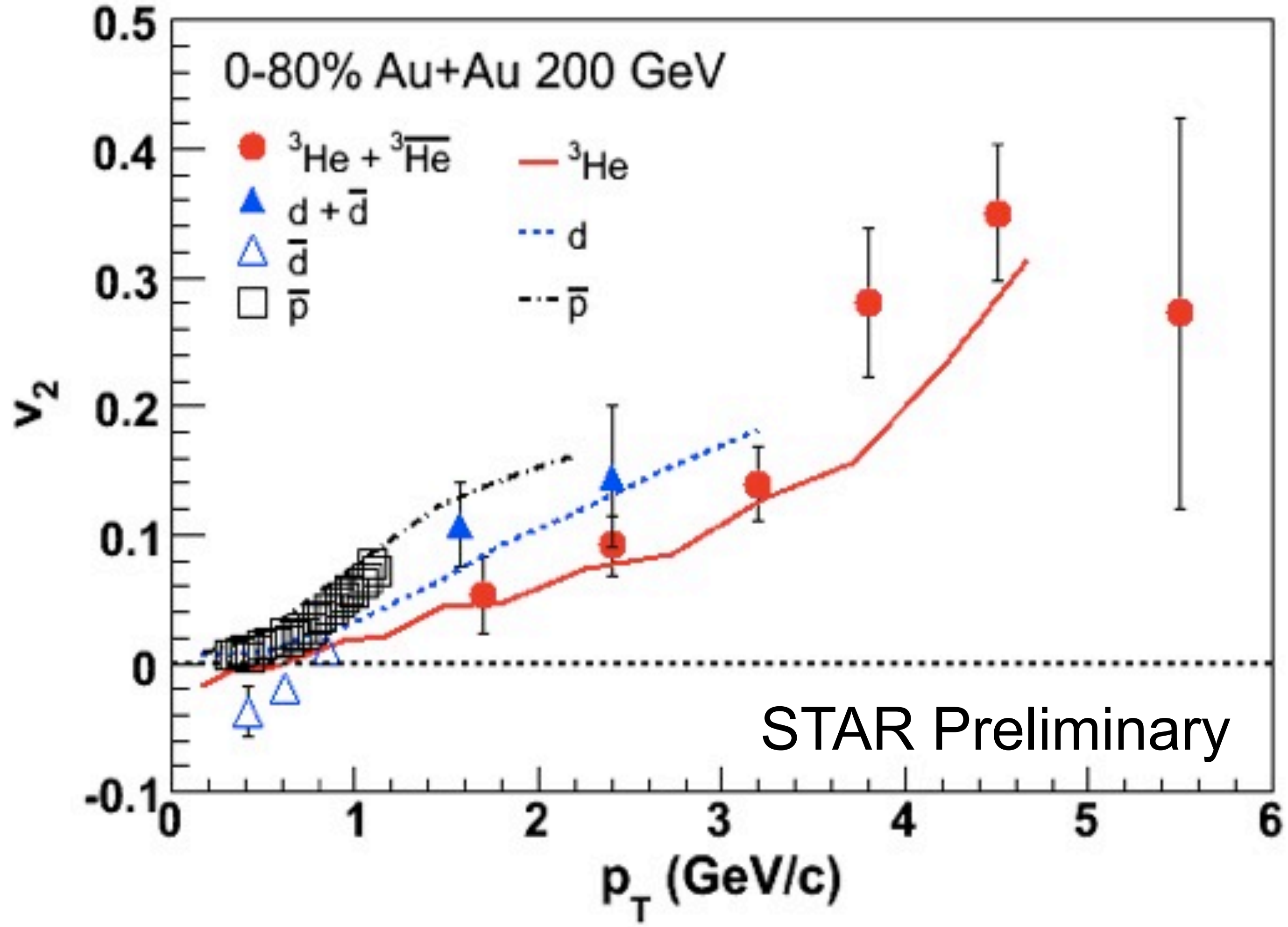


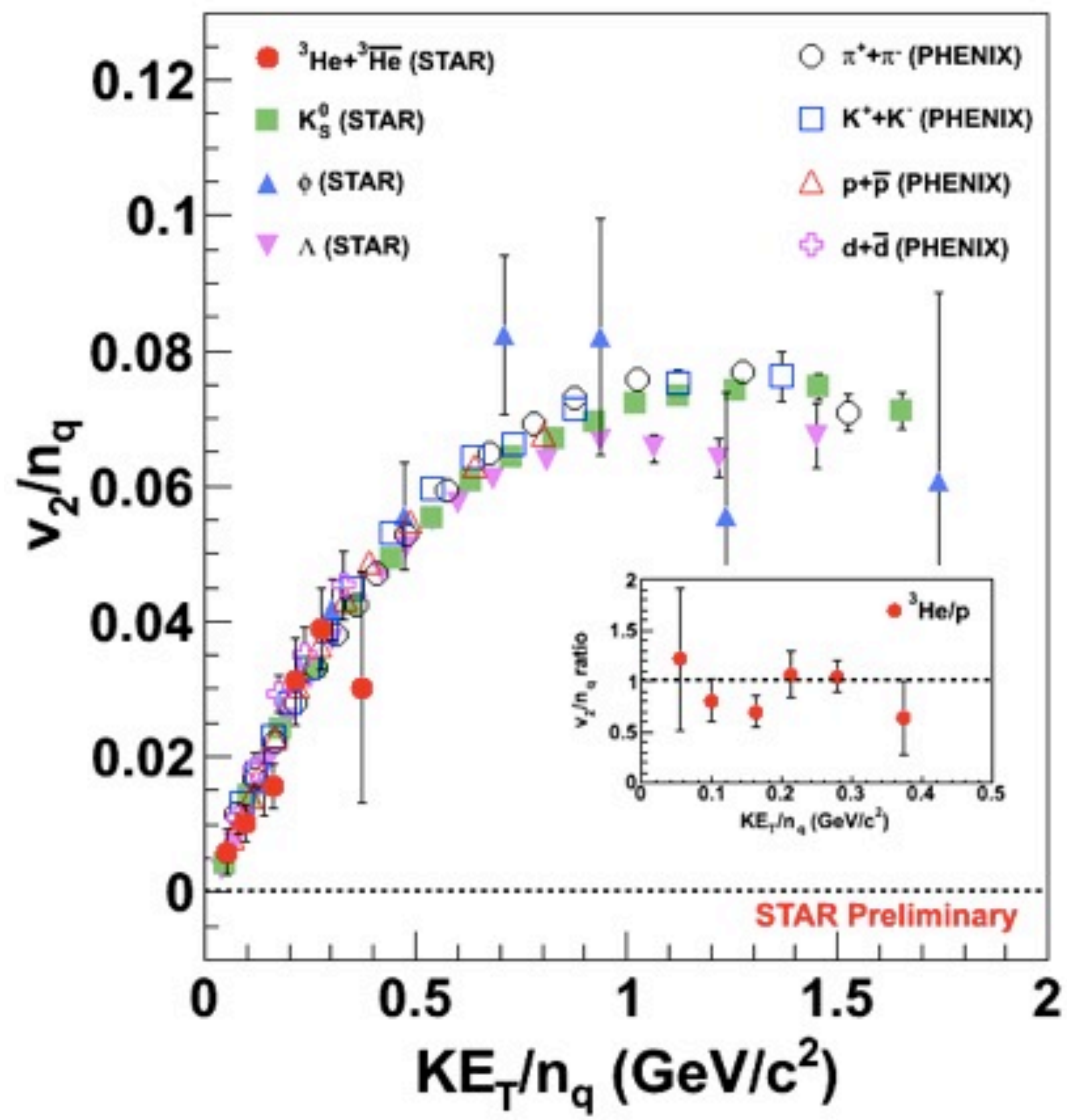
- Initial almond shape → final momentum anisotropy
- Conversion efficiency depends on
  - Density profile, equation of state, ***d.o.f***, transport coefficients, ...

Hadron coalescence

C. Jena, ICPAQGP2010

AMPT String Melting + nucleon coalescence
*S. Zhang et al., **PLB**684 (2010) 224.*



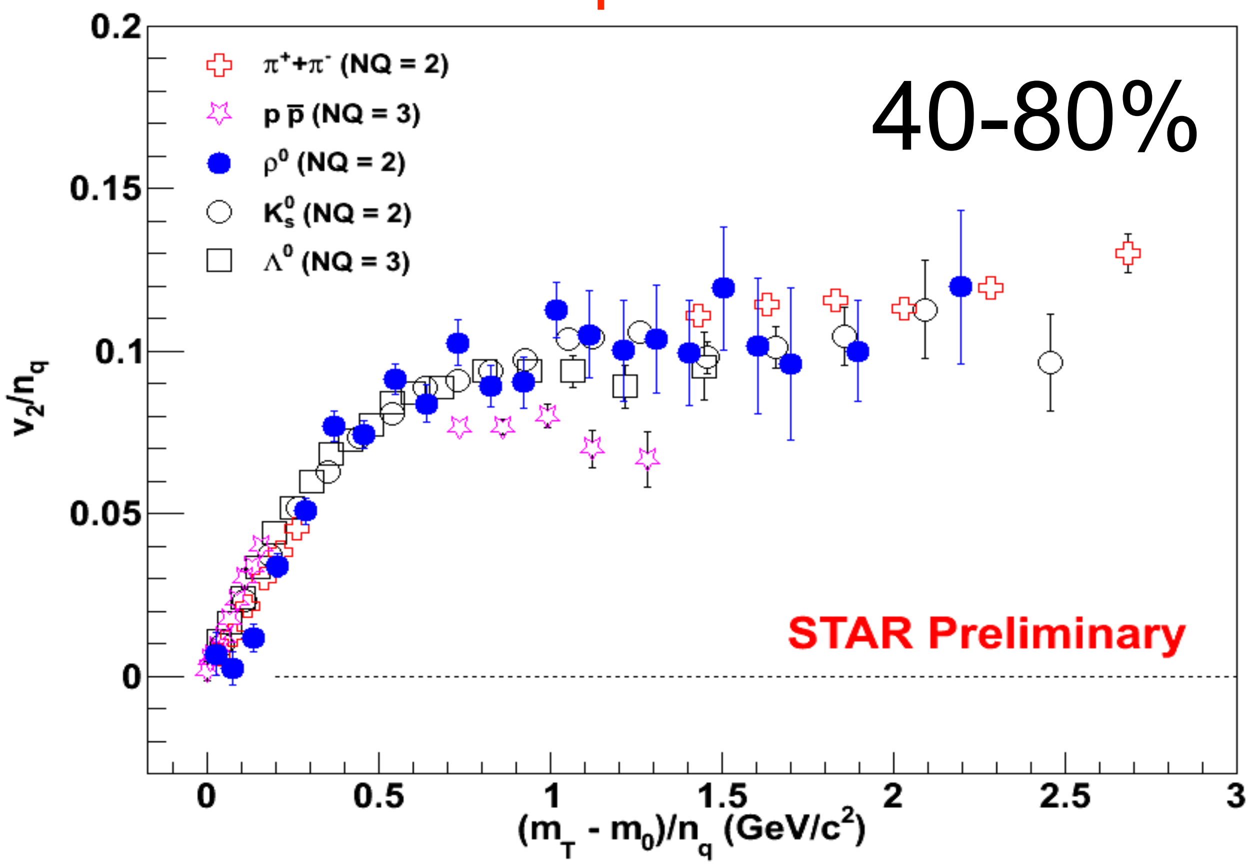


- Deuteron and ^{3}He v_2 consistent with dynamical coalescence model
- Consistent with hadron coalescence (d, ^{3}He vs p)
  - also consistent with quark coalescence (nuclei vs mesons)

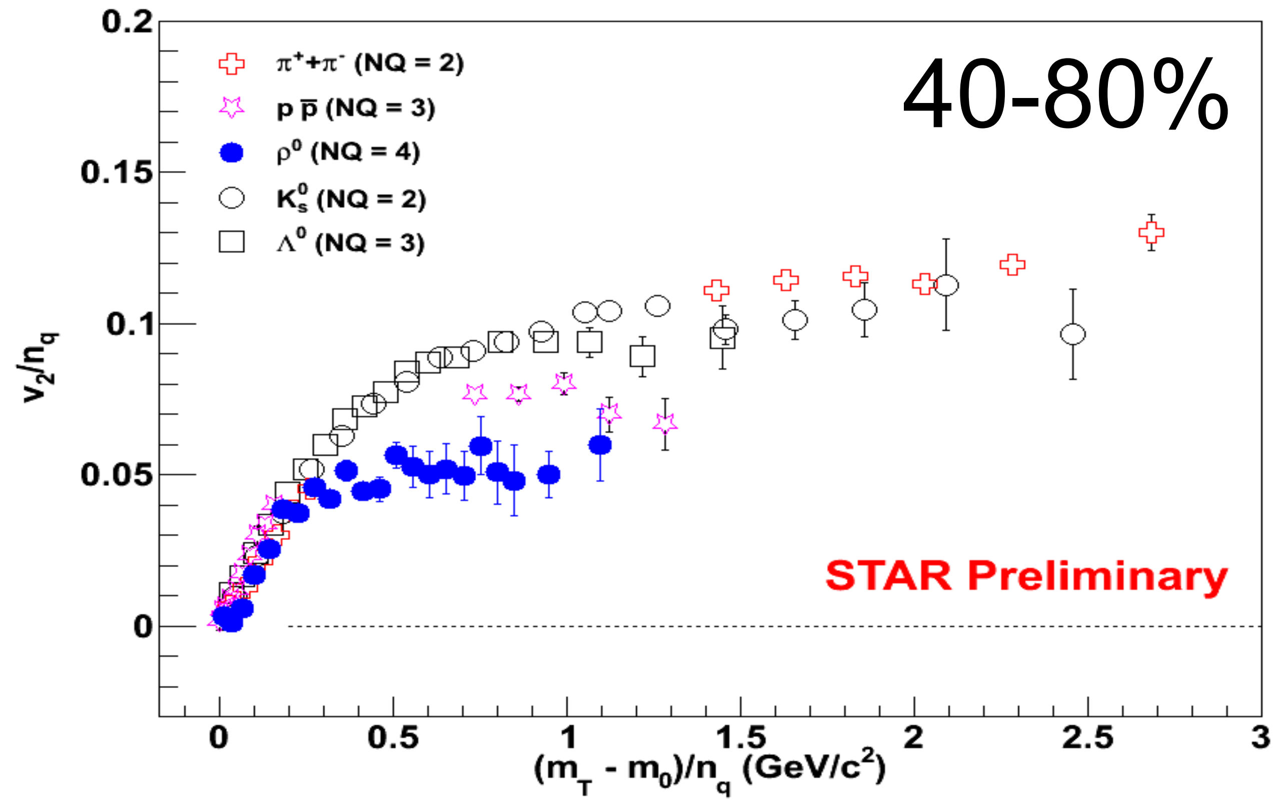
Hadronic or partonic scaling ?

P. Pujahari, QM2011

$n_q = 2$

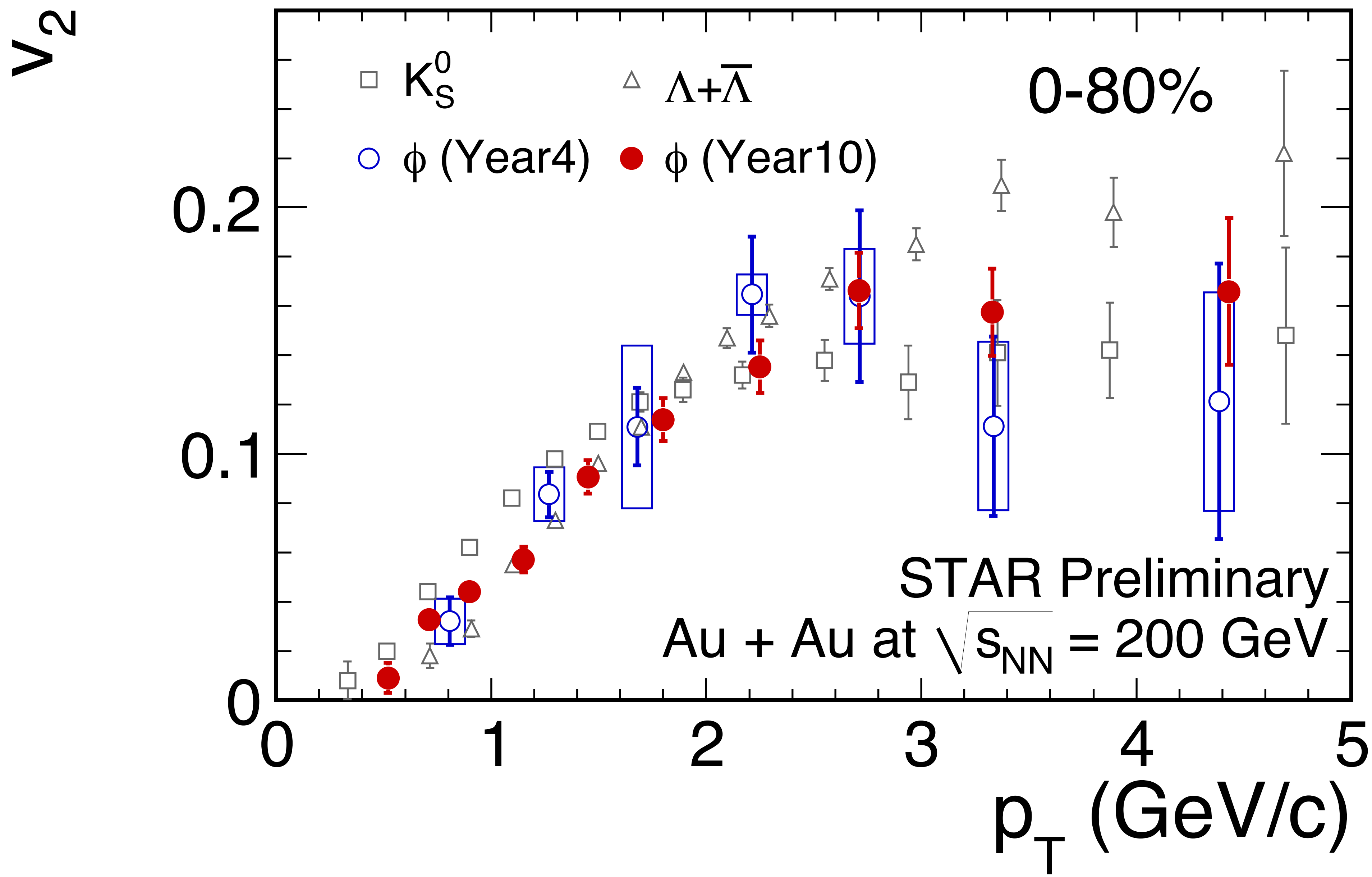


$n_q = 4$



- ρ^0 meson v_2 scales with $n_q = 2$ in $1.5 < p_T < 5$ GeV/c
  - $n_q = 4$ ($2\pi \rightarrow 4$ constituent quarks) doesn't follow the scaling
  - Dominant ρ^0 productions in early partonic stage
- Systematic error study is on-going

ϕ meson v_2



K^0_S, Λ
*STAR; **PRL**92, 052302 (2004)*
ϕ (Year4)
*STAR; **PRL**99, 112301 (2007)*

- High statistics Year10 data
  - Consistent with published results, smaller statistical error bars
  - Centrality dependence, comparison of other strange hadrons are on-going

Higher harmonics

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

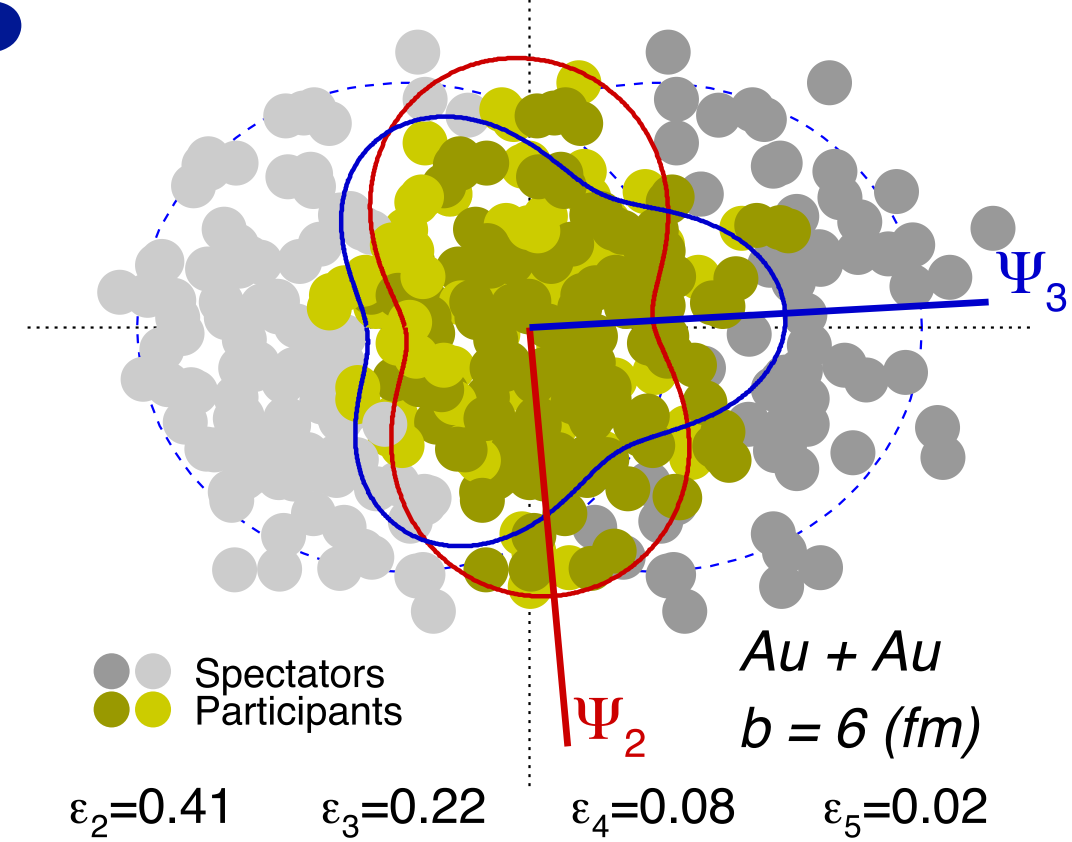
$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

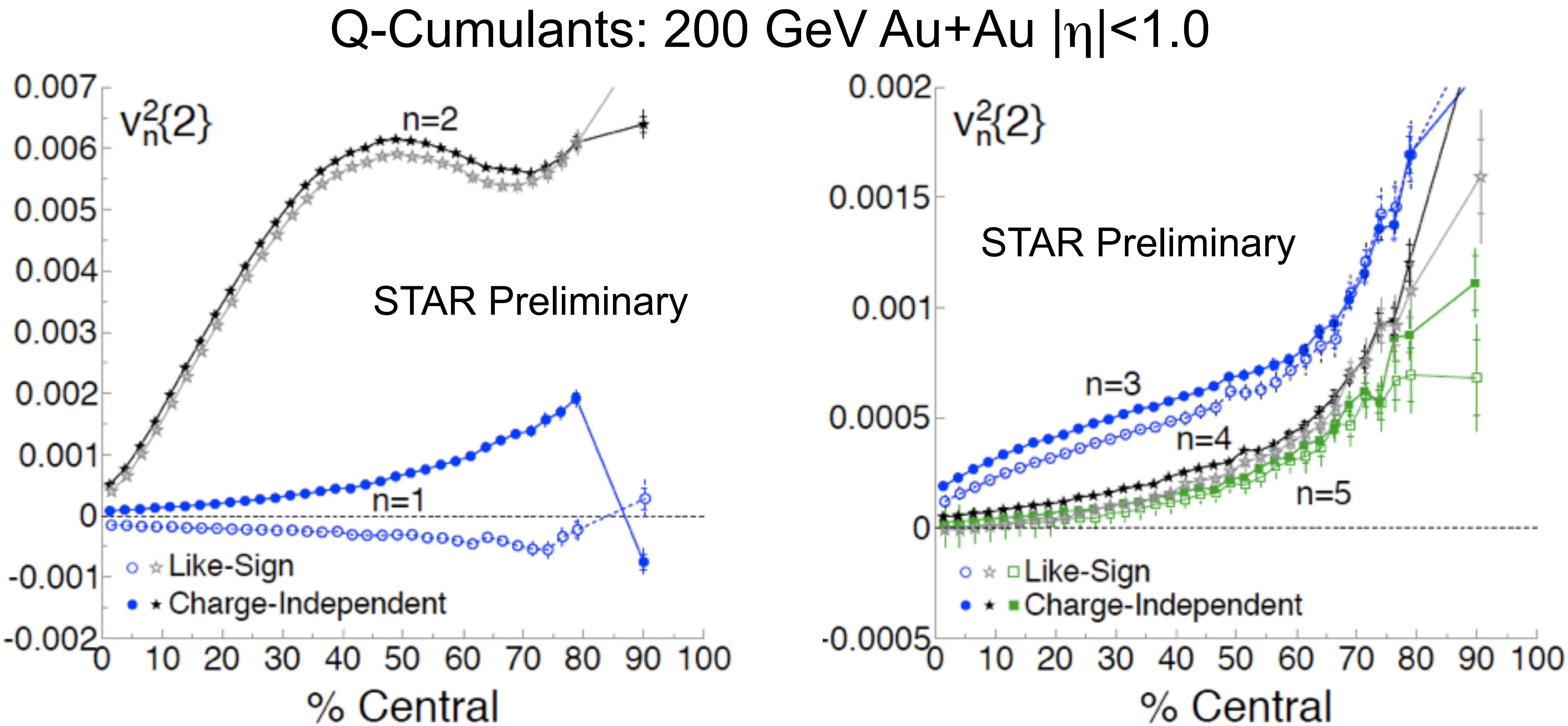
$$\ldots$$



- Higher harmonics (n ≥ 3)
  - might be sensitive to the initial geometry fluctuations
- <u>Mean odd harmonics</u> should be vanished in symmetric rapidity
  - Fluctuations would lead non-zero odd harmonics

2 particle correlation

P. Sorensen, QM2011

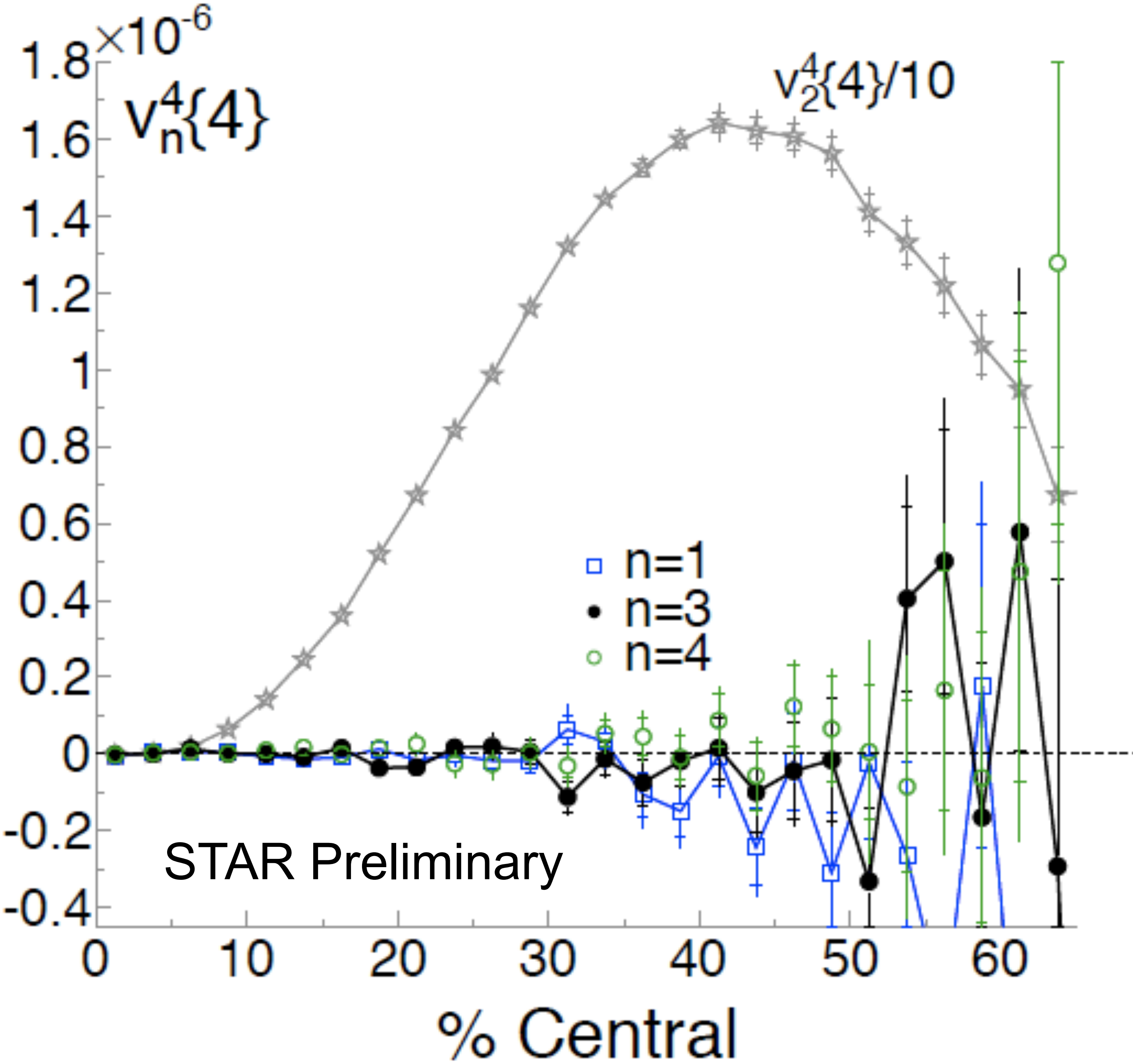


- n=3 exhibits effects of initial overlap geometry
- n≥4 show 1/N dependence - typical two particle non-flow correlation
  - n=3 at peripheral also shows 1/N dependence, dominated by non-flow ?

4 particle correlation

Q-Cumulants: 200 GeV Au+Au |η|<1.0

P. Sorensen, QM2011



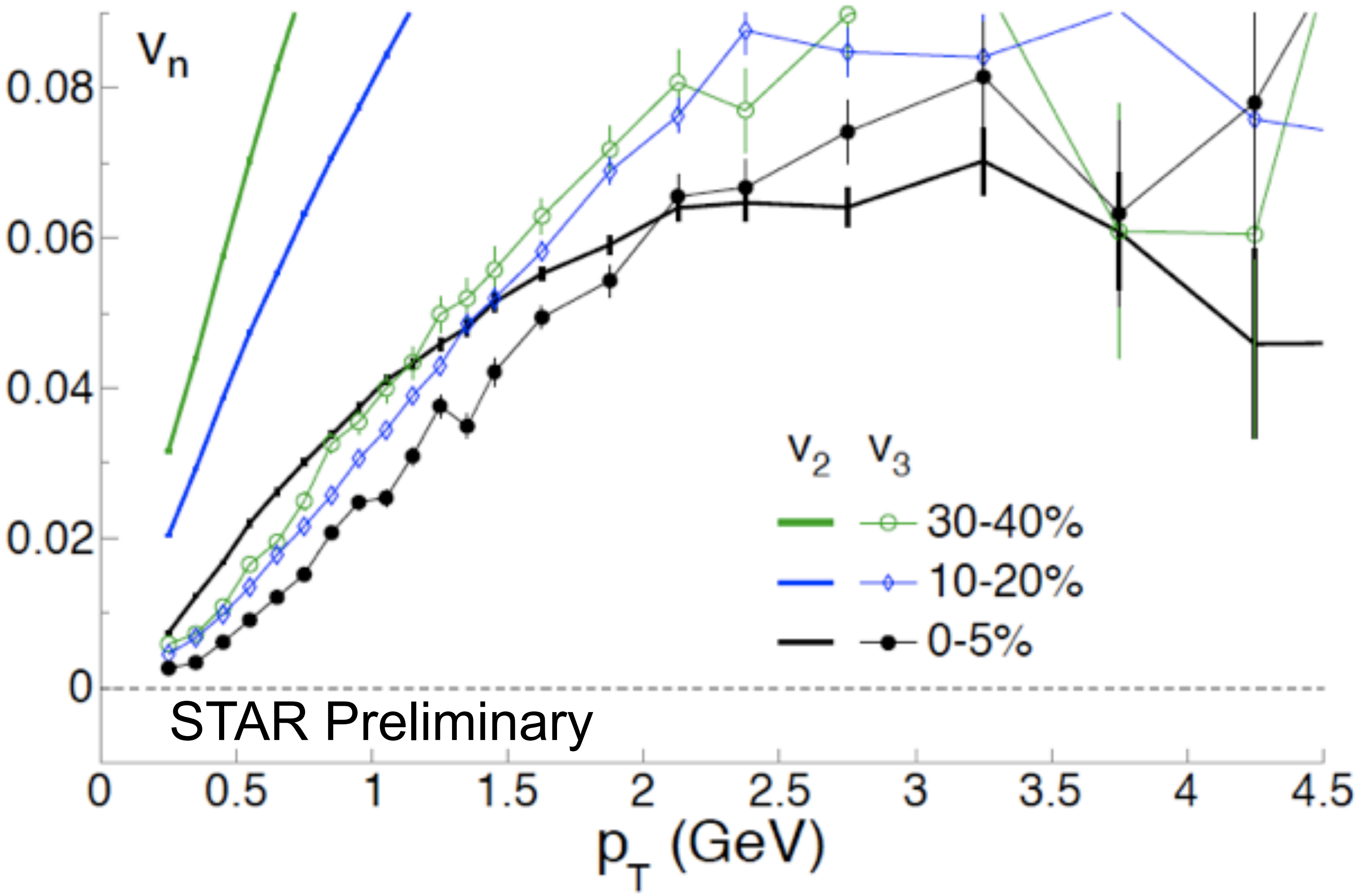
- $v_n\{4\}$ is consistent with 0 → $v_3\{2\}$ due to non-flow and/or $v_n \propto \varepsilon_{n,part}$, $v_n\{4\} \propto \varepsilon_{std}$
  - with gaussian ansatz for fluctuations in reaction plane frame*
- How $v_3(p_T)$ looks like ?

* *R.S. Bhalerao and J-Y.Ollitrault, **PLB**641, 260-264 (2006), S. Voloshin et al, **PLB**659, 537-541 (2008)*

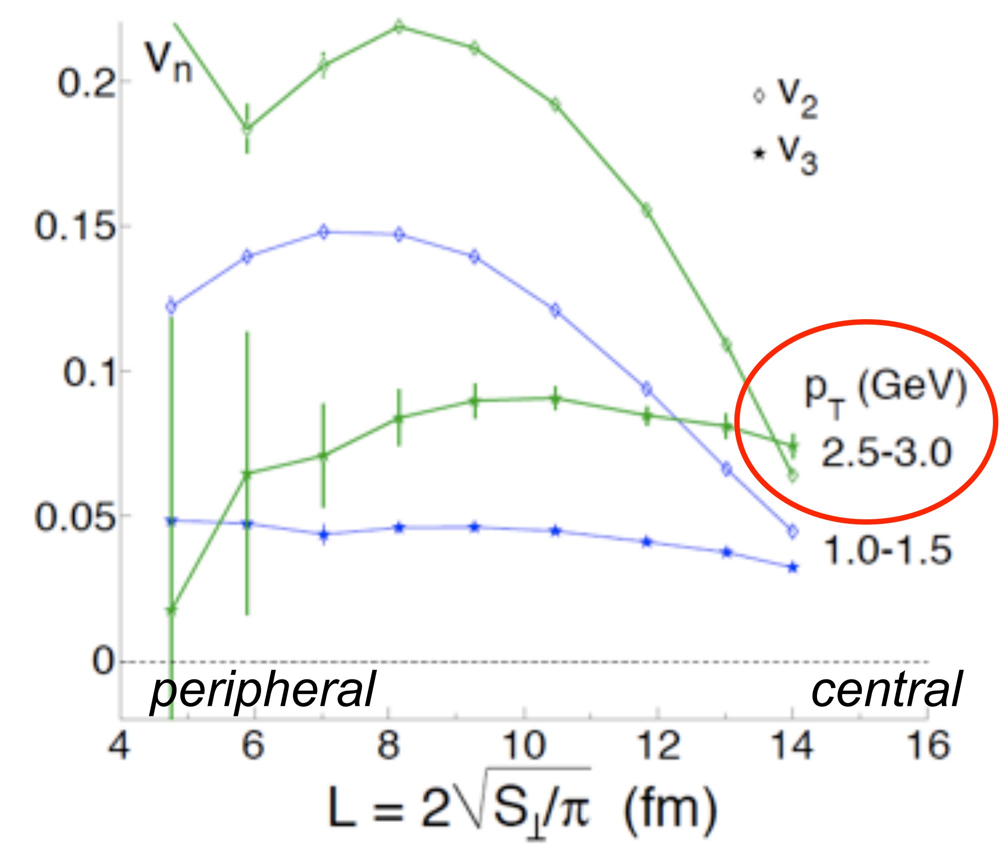
v_3; p_T dependence

L. Yi,
P. Sorensen, QM2011

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



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



- η gap (η>1 at least) to reduce non-flow effects
- $v_3 > v_2$ at central, intermediate p_T, weak centrality dependence of v_3
  - seems to consistent with the scenario of initial geometry fluctuations

Summary

- Discovery of 18 counts of anti-^{4}He with **TPC+TOF+HLT**
  - consistent with expectations from thermal and coalescence models
- Measurements of dynamical charge separation
  - Signal is likely a genuine correlation with respect to the reaction plane
  - Separation seems to occur in the vicinity of the in-plane direction
  - Most of the signal can be also explained by charge conservation + elliptic flow
- Measurements of second harmonic azimuthal anisotropy
  - Light nuclei (d and ^{3}He) v_2 are consistent with dynamical quark coalescence model, seems to scale by hadron & quark coalescence scenario
  - ρ^0 v_2 shows partonic scaling
  - More detailed study for ϕ and other strange hadron v_2 will be coming soon
- Higher harmonics
  - 4-particle correlation suggests v_3 in $|\eta|<1$ is non-flow and/or $v_3 \propto \varepsilon_{3,part}$
  - Centrality dependence of $v_3(p_T)$ seems to favor initial fluctuation scenario

Back up

Directed flow

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

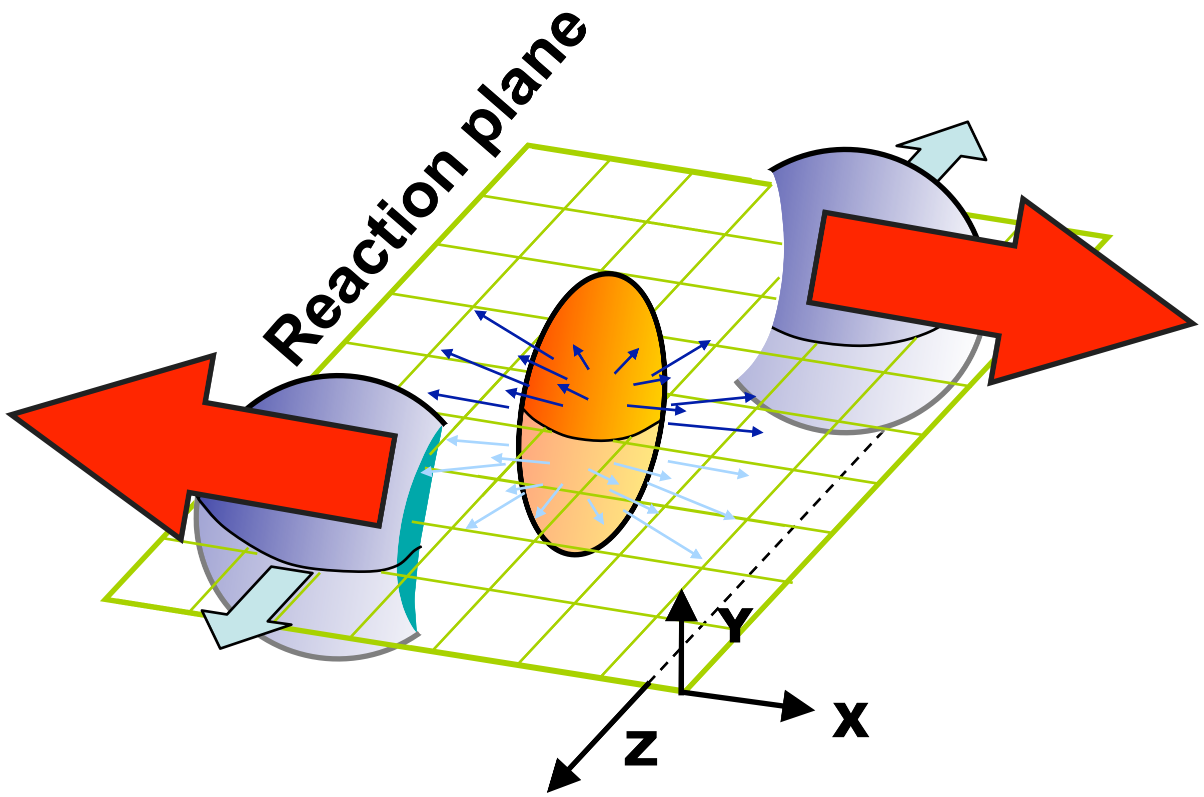
$$+ 2v_1 \cos(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2a_1 \sin(\phi - \Psi_{\mathrm{RP}})$$

$$+ 2v_2 \cos(2\phi - 2\Psi_{\mathrm{RP}})$$

$$+ 2v_3 \cos(3\phi - 3\Psi_{\mathrm{RP}})$$

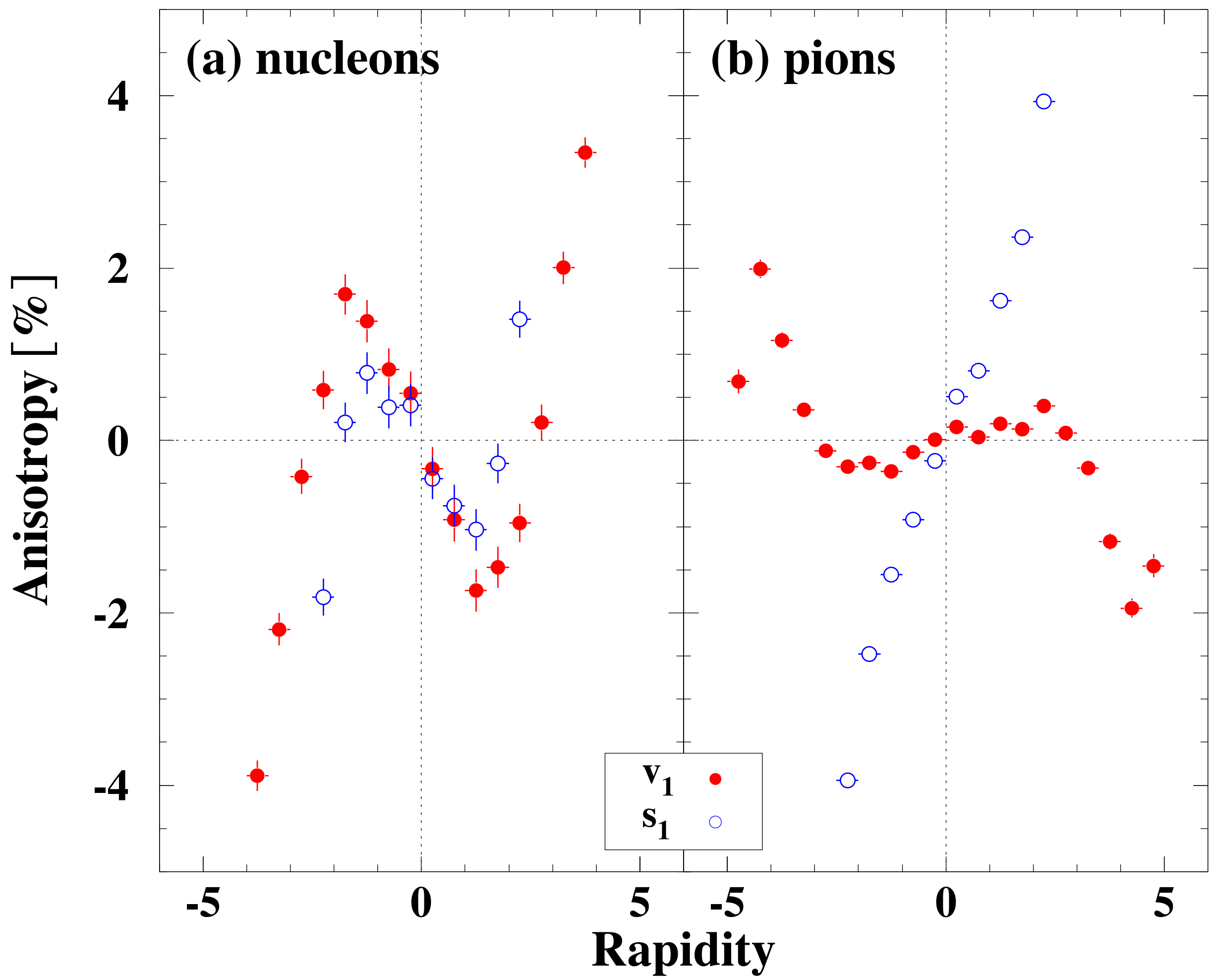
$\ldots$



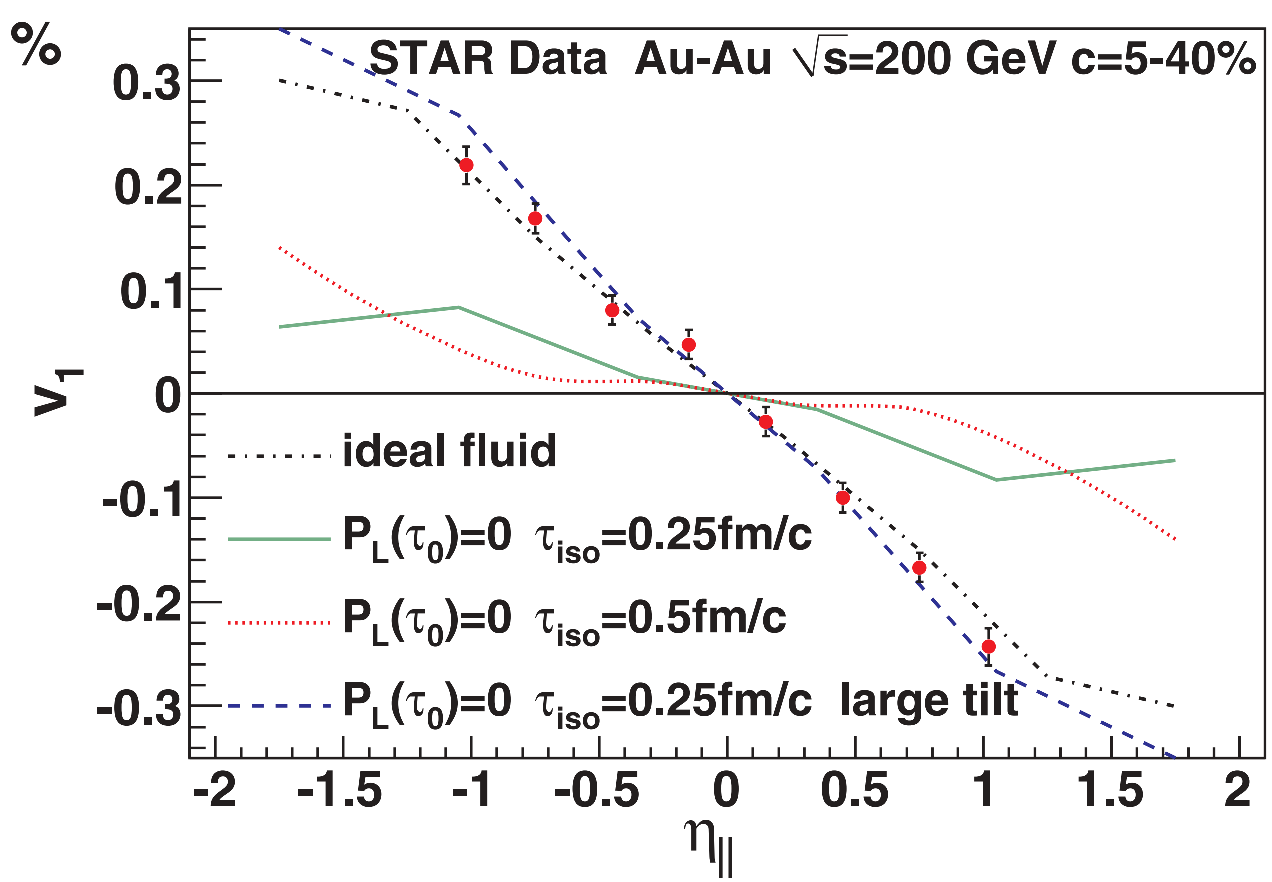
- Sideward motion of particles
- Sign of v_1 is arbitrary
  - Conventionally, define positive v_1 at forward spectators

Rapidity dependence of v_1

*R. J. M. Snellings et al., **PRL**84, 2803 (2000)*

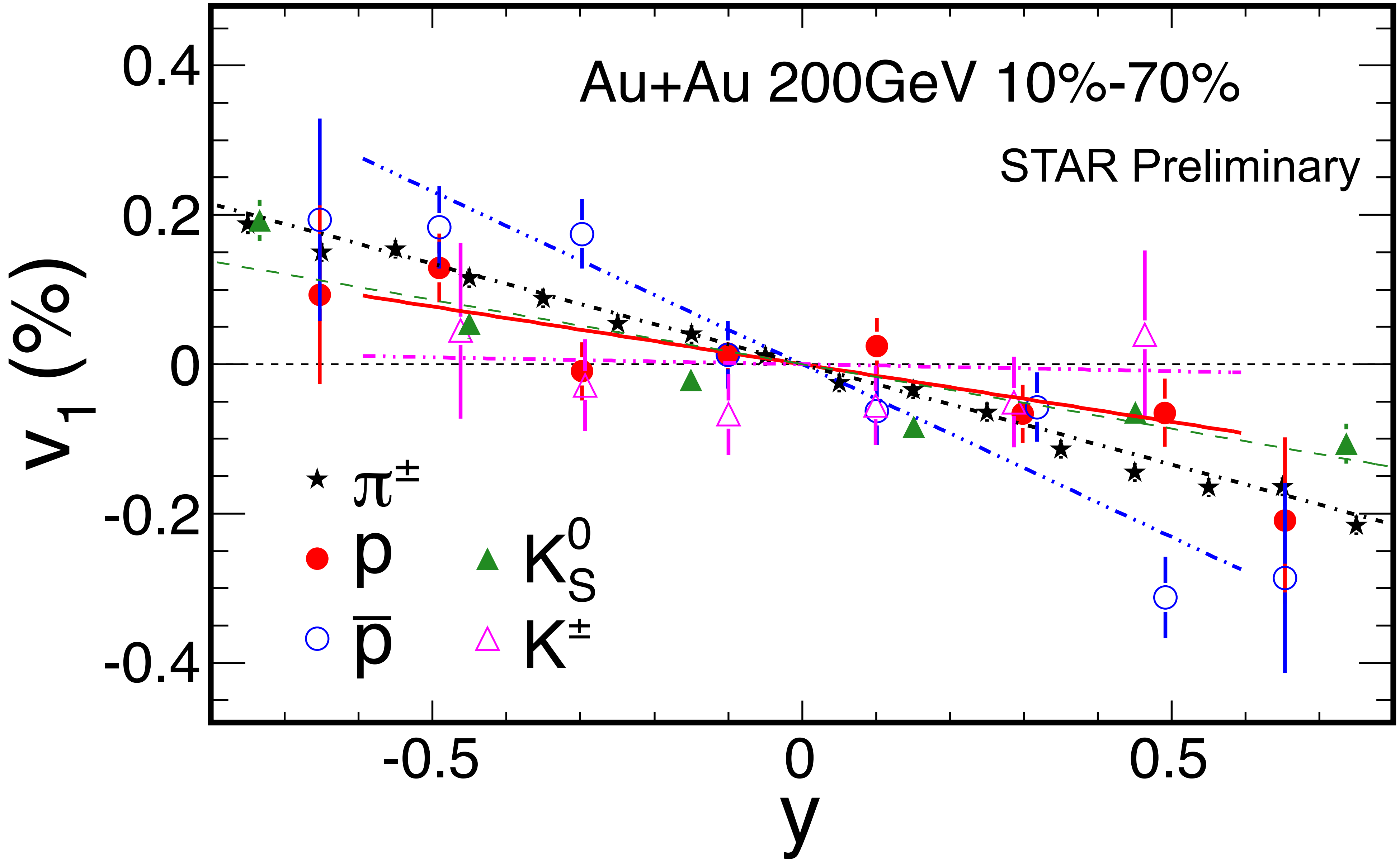


*P. Bozek and I. W.-Piekarska, **PRC**83, 024910 (2011)*



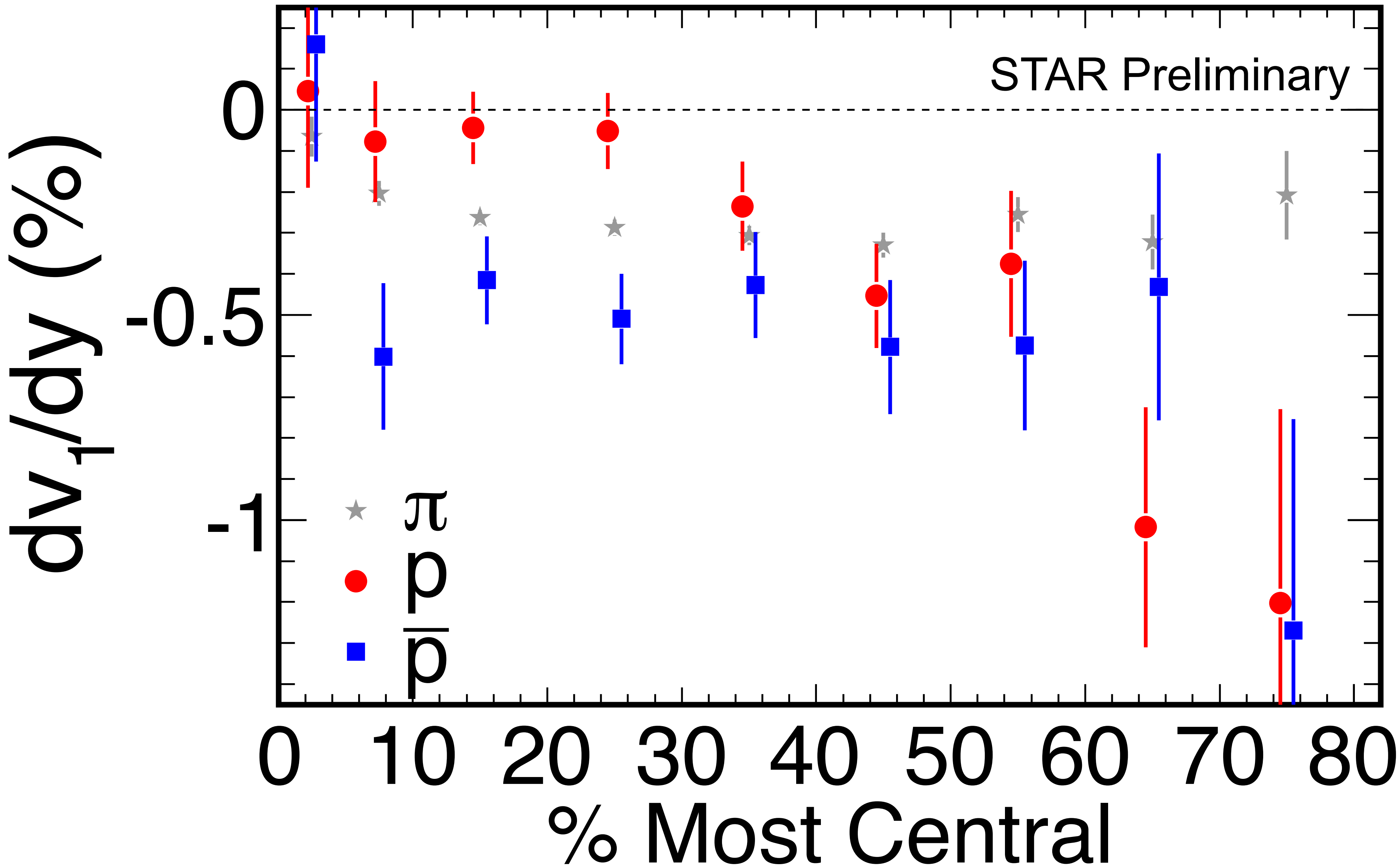
- Sensitive to the ***EOS*** and ***thermalization time***
  - Flat or wiggle shape $v_1 \rightarrow$ softening of EOS ? Baryon stopping ?
  - Reduction of longitudinal pressure and/or large tilt of initial geometry ?
  - ➡ v_1 for identified hadrons (protons vs mesons)

Identified hadron v_1 vs rapidity



- Measured hadrons show flat or negative slope of v_1
  - Similar slope between π and anti-protons

Proton v_1 slope



- Negative v_1 slope in 30-80% - consistent with π
- Difference of v_1 slope between protons and anti-protons in 5-30%
  - No difference in hydro + tilted source