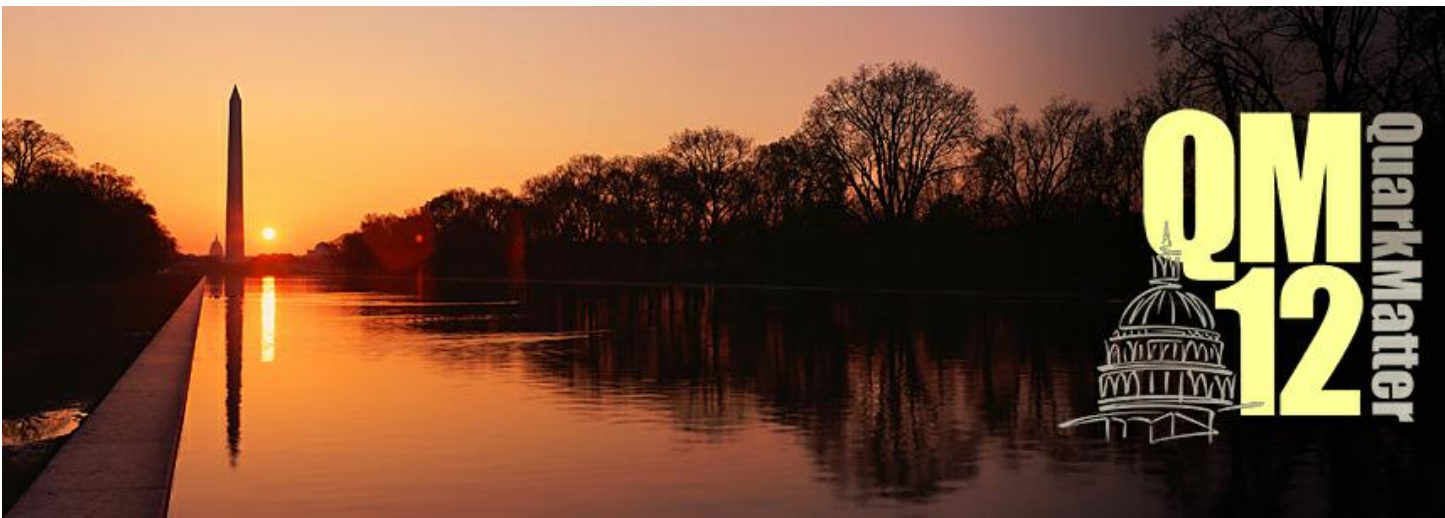


Search for Chiral Magnetic Effects in High-Energy Nuclear Collisions

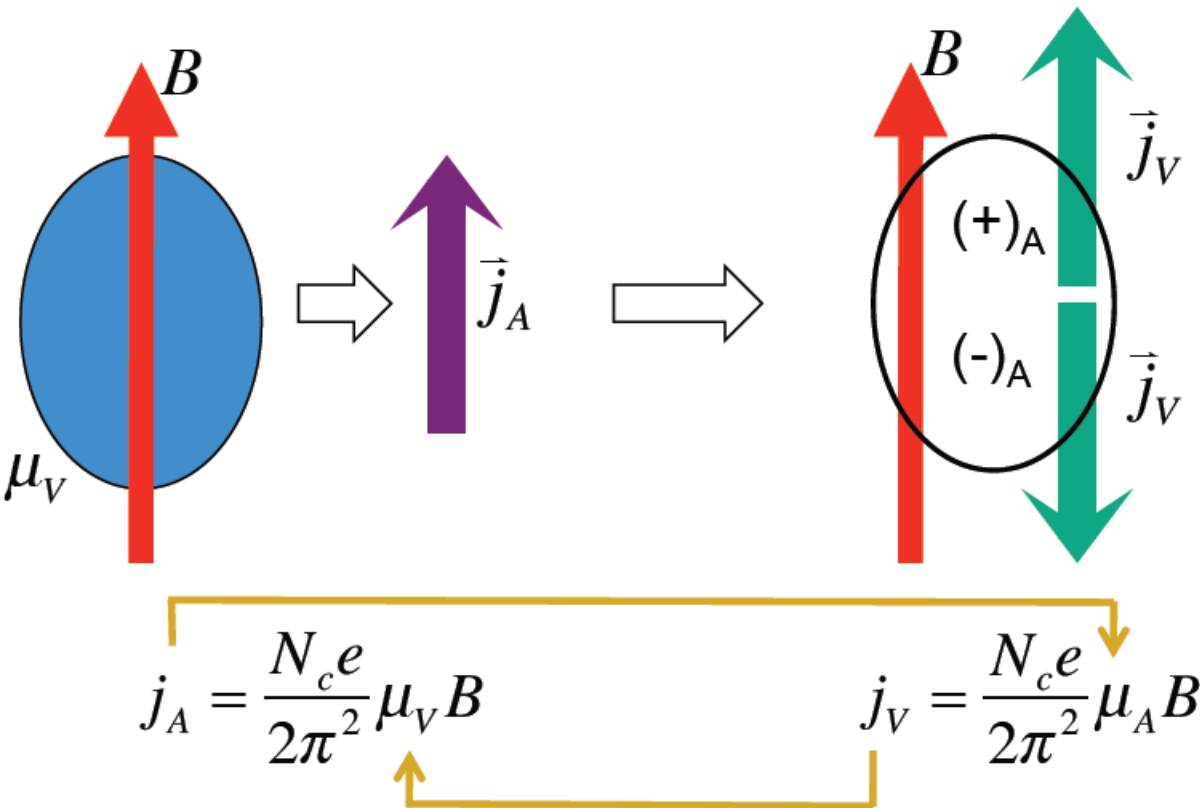
Gang Wang (UCLA)
for STAR Collaboration



Motivation

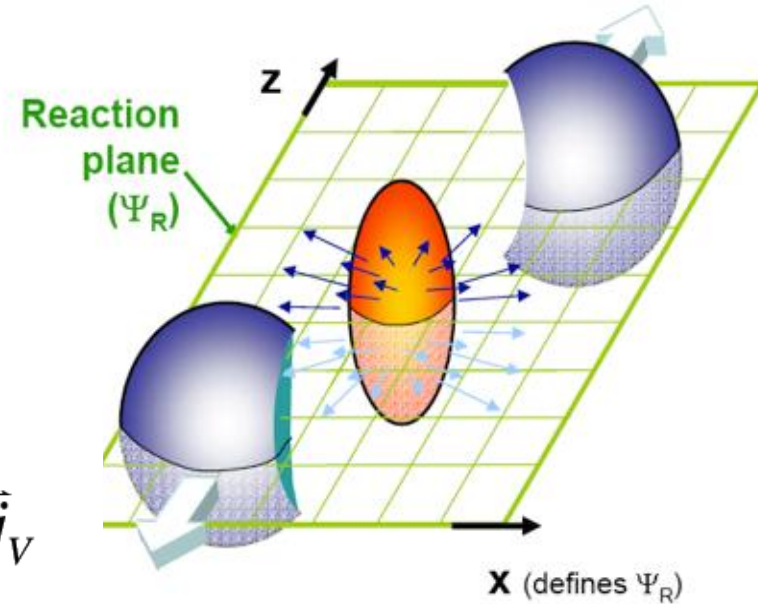
CSE + CME \rightarrow Chiral Magnetic Wave:

- collective excitation
- signature of Chiral Symmetry Restoration



Chiral Separation Effect

Chiral Magnetic Effect

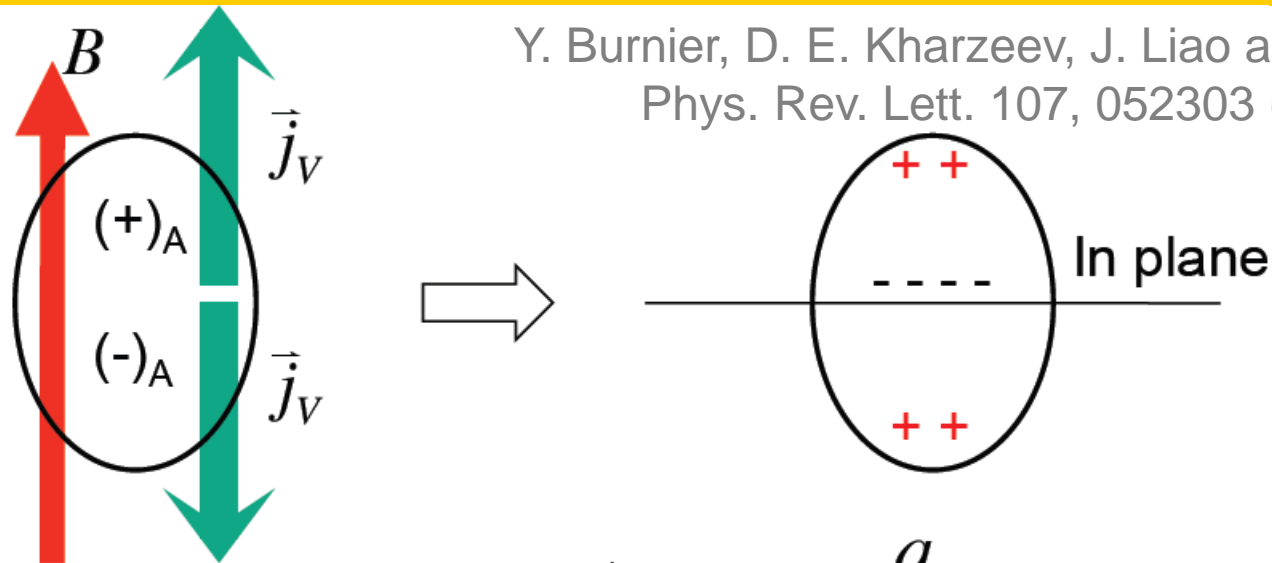


Peak magnetic field \sim
 10^{15} Tesla !

(Kharzeev et al. NPA 803
(2008) 227)

Observable I

Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee,
Phys. Rev. Lett. 107, 052303 (2011)



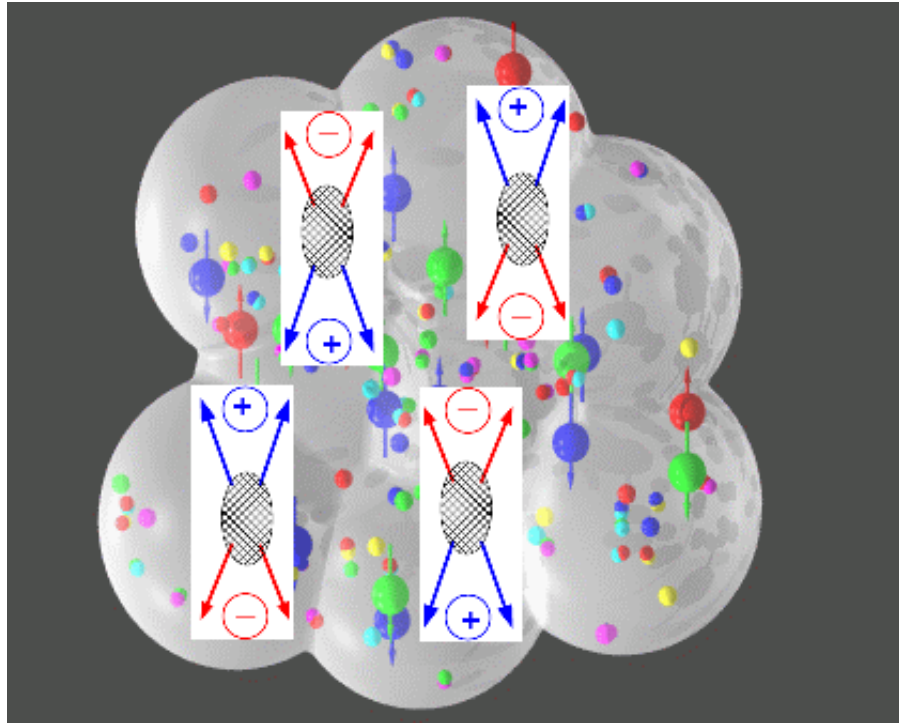
Formation of electric quadrupole: $v_2^\pm = v_2 \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_\pm$,

where charge asymmetry is defined as $A_\pm = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$.

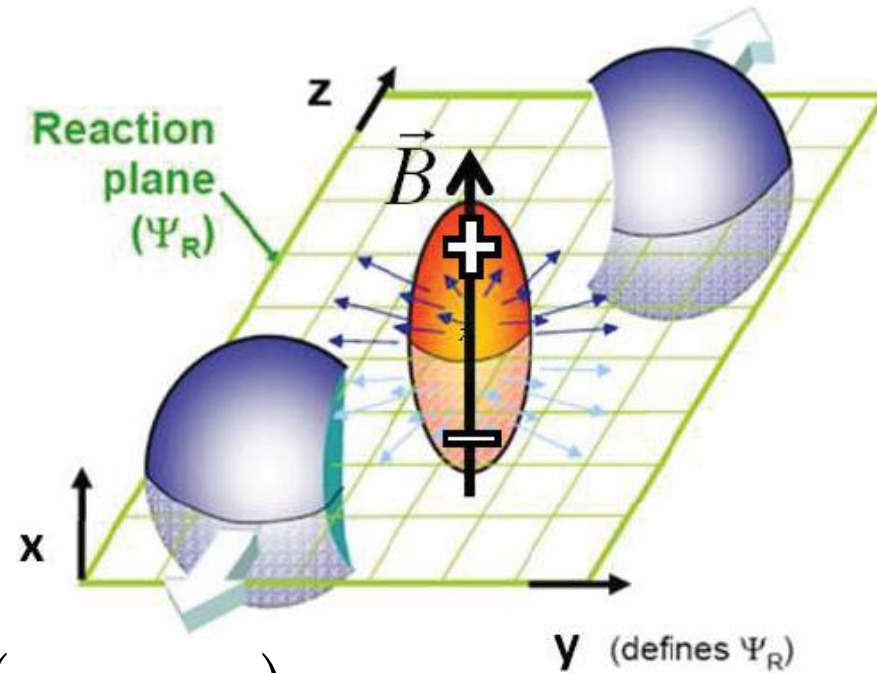
Then $\pi^- v_2$ should have a **positive** slope as a function of A_\pm ,
and $\pi^+ v_2$ should have a **negative** slope with the same magnitude.

The integrated v_2 of π^- is not necessarily bigger than π^+ : (other physics)
only the A_\pm dependency matters for CMW testing.

Observable II



CME + Parity-odd domain,
 \Rightarrow charge separation across RP



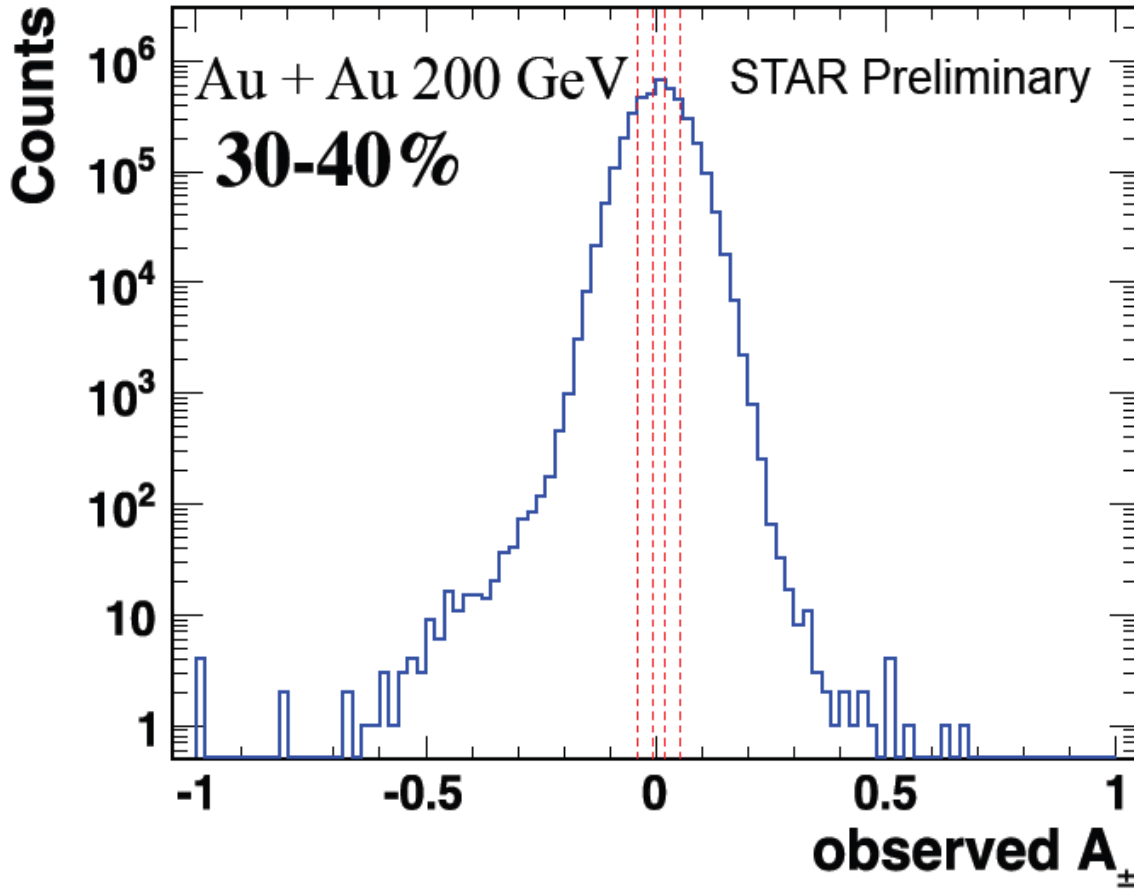
$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin(\phi^{\pm} - \Psi_{RP})$$

This charge separation effect needs to be beyond conventional physics background.

S. Voloshin, PRC 70 (2004) 057901,
 Kharzeev, PLB633:260 (2006)

Kharzeev, McLerran, Warringa, NPA803:227 (2008)

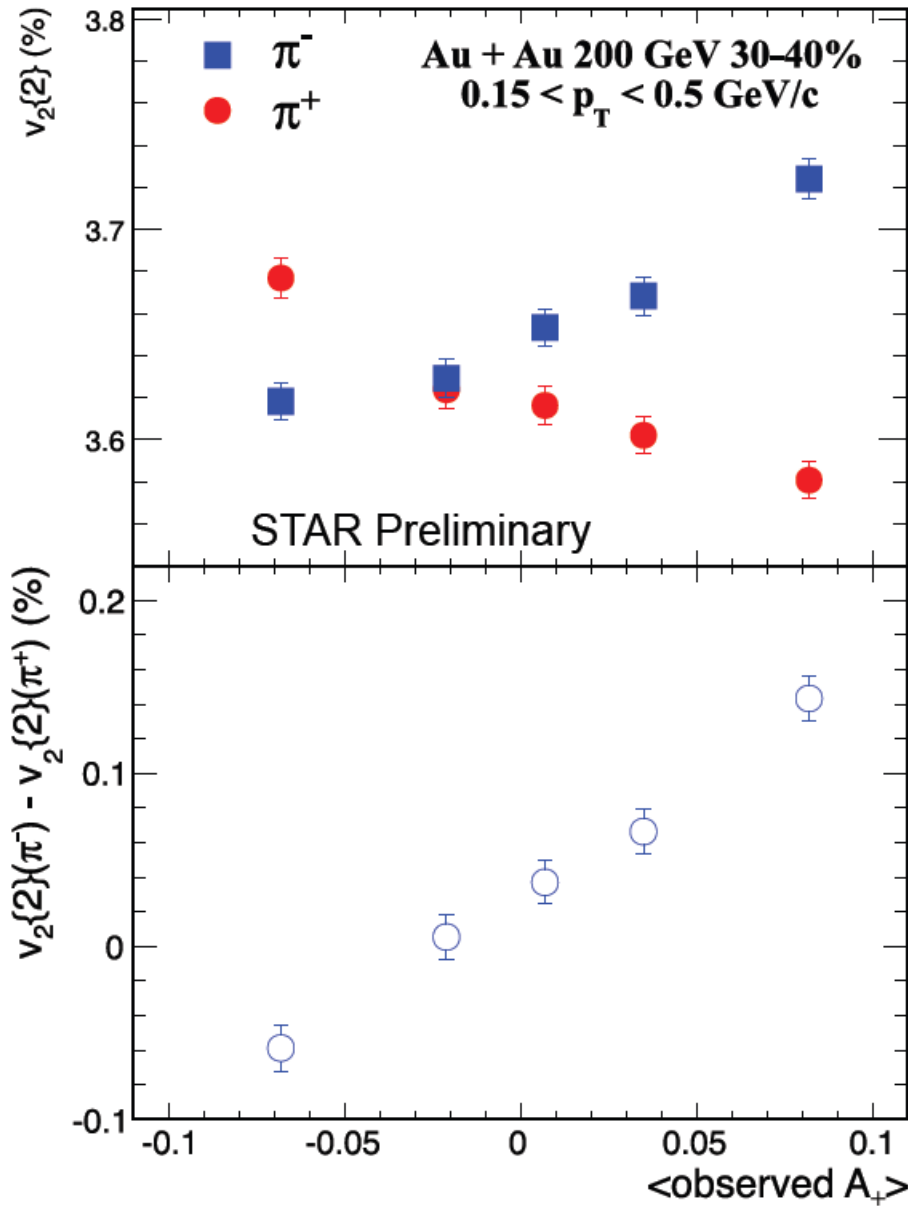
Observed charge asymmetry



$$A_{\pm} = \frac{\bar{N}_{+} - \bar{N}_{-}}{\bar{N}_{+} + \bar{N}_{-}}$$

- N^{+} (N^{-}) is the number of positive (negative) particles within $|\eta| < 1$.
- The distribution was divided into 5 bins, with roughly equal counts.
- Tracking efficiency was corrected later.

Charge asymmetry dependency



- v_2 was measured with the Q-cumulant method.

- Clear A_{\pm} dependency

- $v_2(A_{\pm})$ slopes for π^{\pm} :

- opposite sign

- similar magnitude

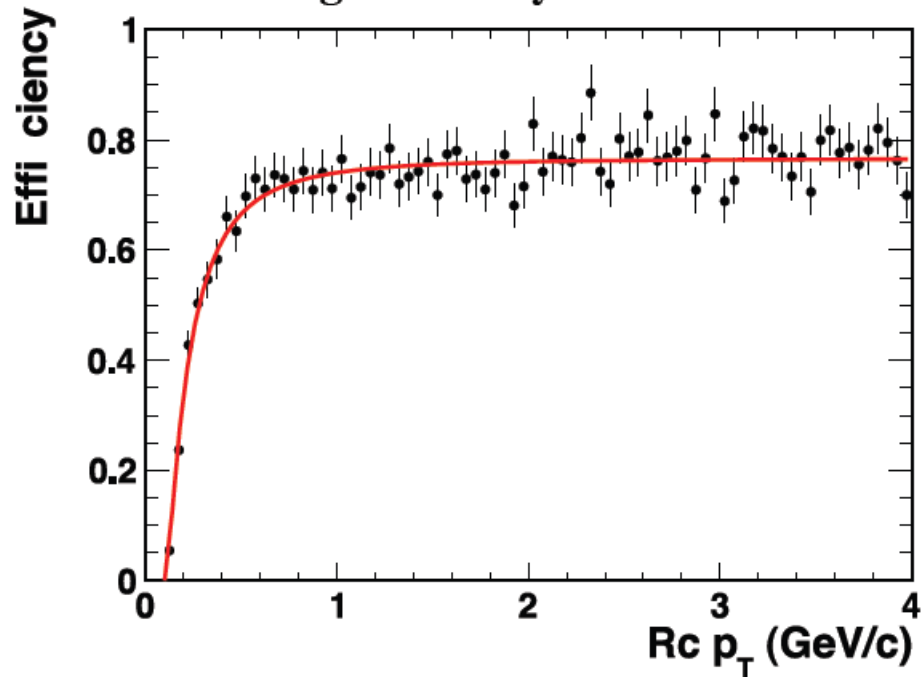
- v_2 difference vs A^{\pm} may have a non-zero intercept: other physics?

$$v_2^{\pm} = v_2^{\mp} \left(\frac{q_e}{\bar{\rho}_e} \right) A_{\pm}$$

The equation shows a linear relationship between v_2^{\pm} and A_{\pm} . A red dotted circle highlights v_2^{\mp} , and a blue dashed circle highlights the term $\left(\frac{q_e}{\bar{\rho}_e} \right)$. Arrows from the text above point to these circled terms.

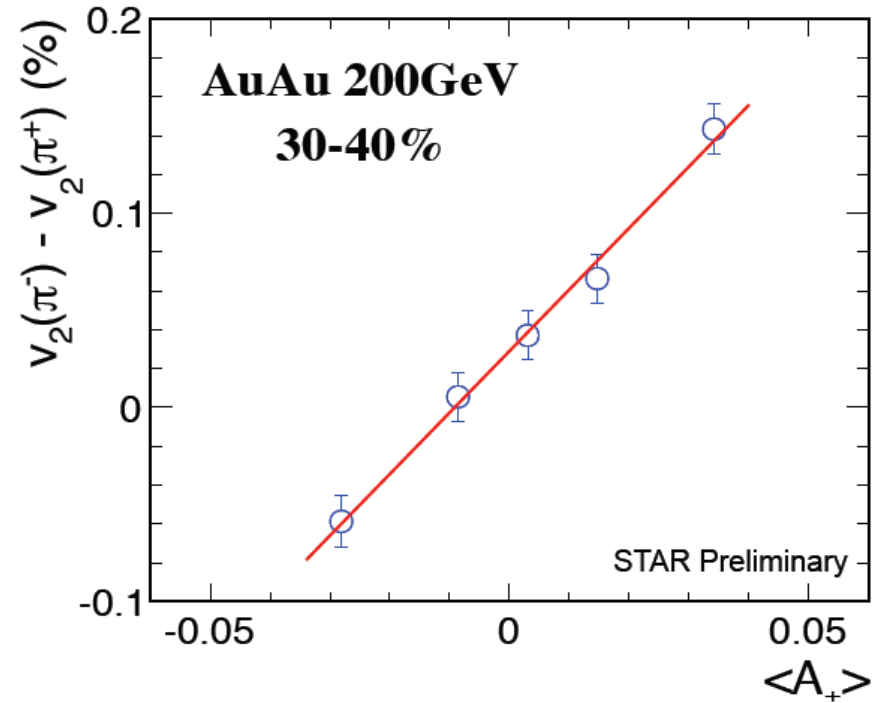
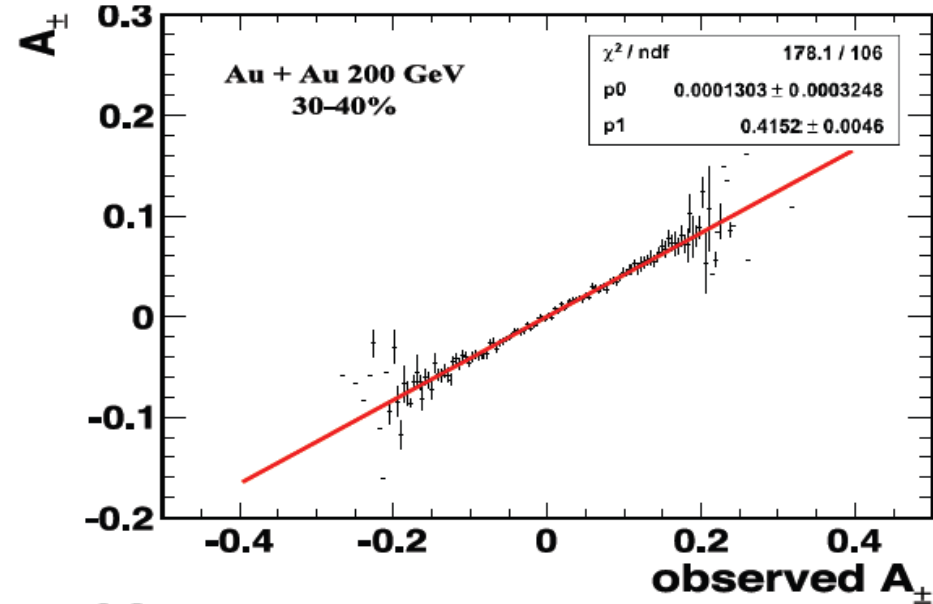
Correction for tracking efficiency

Tracking efficiency for π^+ and π^-



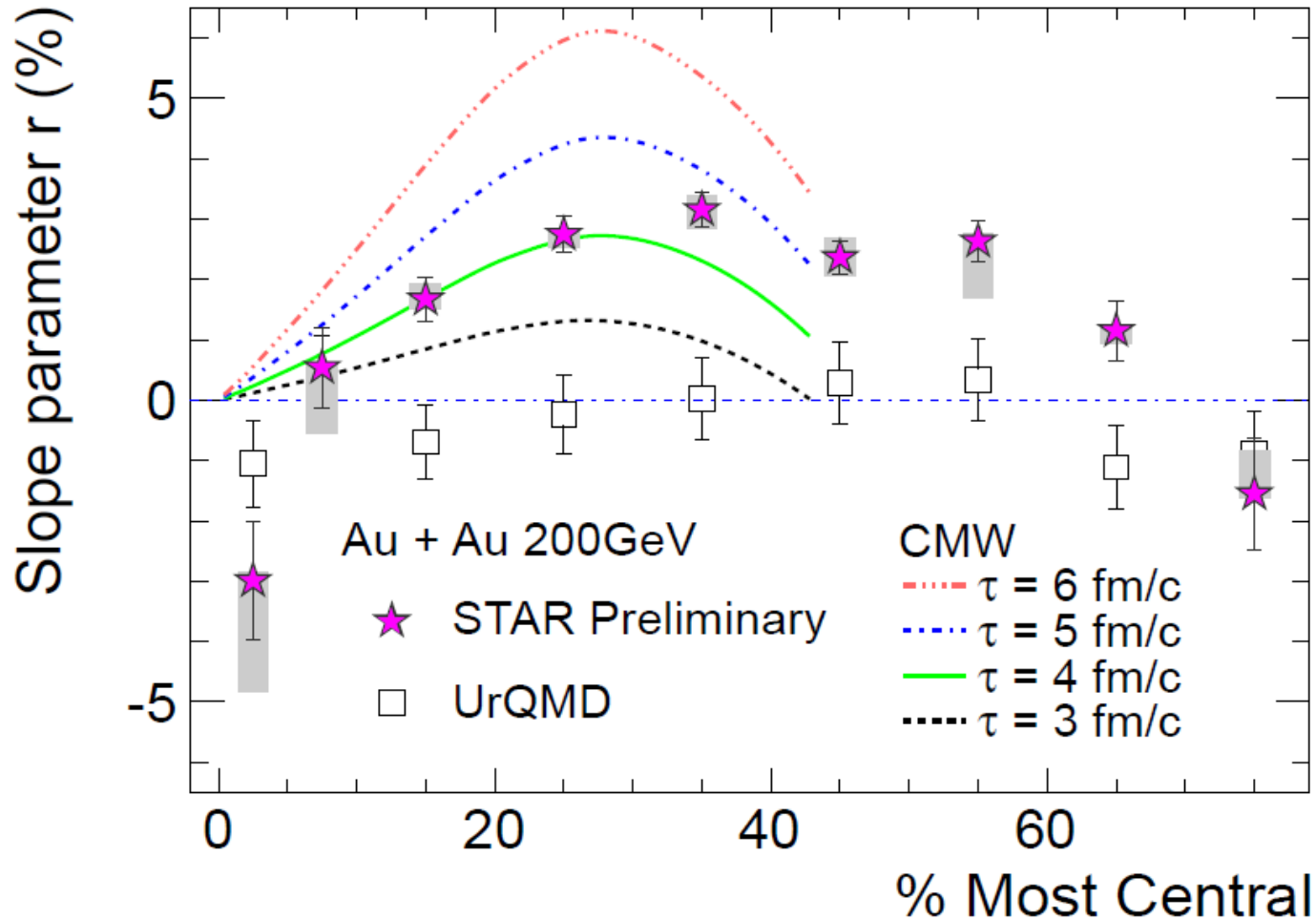
$$v_2^- - v_2^+ = C + 2 \left(\frac{q_e}{\bar{\rho}_e} \right) A_{\pm}$$

- Fit with a straight line to extract the slope $r = 2 \frac{q_e}{\bar{\rho}_e}$.
- Do the same for all centralities



Slope vs centrality

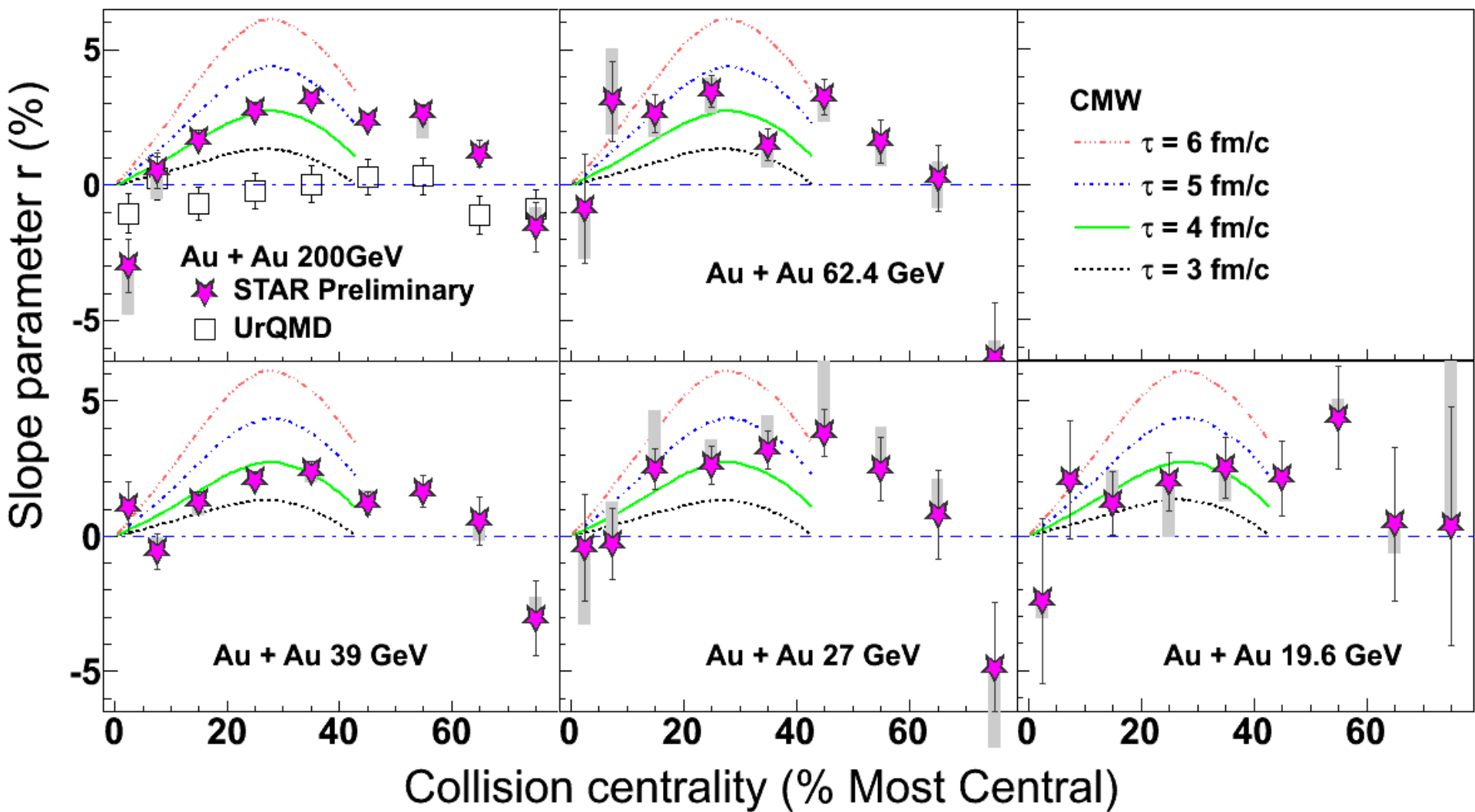
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



Similar trends between data and theoretical calculations with CMW (improved version). There is no specific beam energy input for the calculation.

Slope vs centrality (BES)

Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



Similar trends are observed for different beam energies, where the errors are small.⁹

Summary I

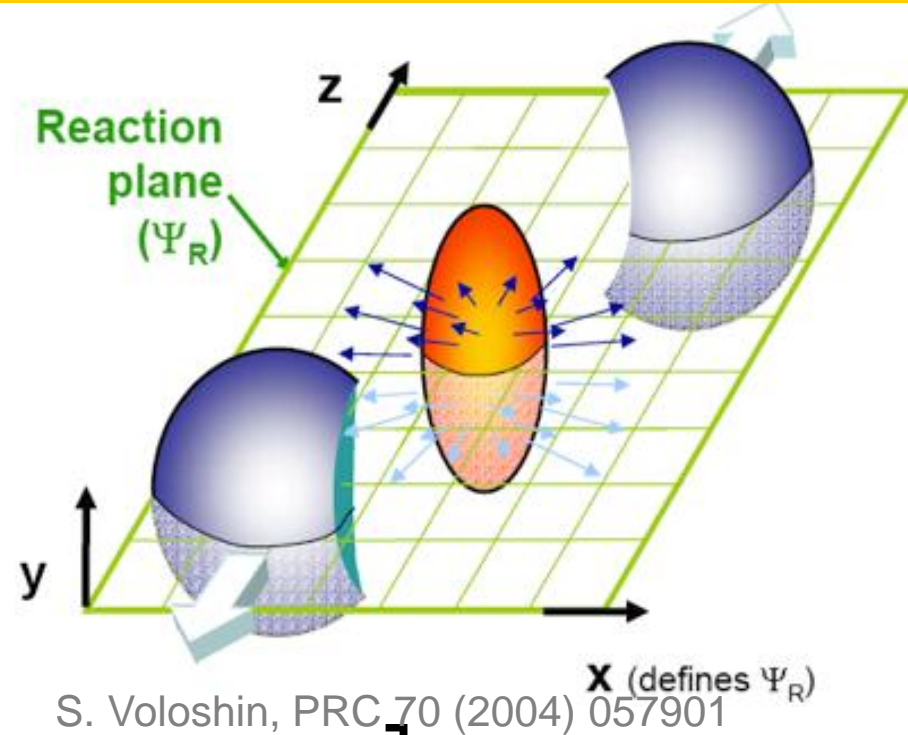
- Charge asymmetry dependency of pion v_2 has been observed.
 - $v_2(A)$ showed opposite slopes for π^+ and π^- .
 - The slopes have similar centrality dependency from 200 GeV to 27 GeV.
- Similarity between real data and calculations with CMW
 - Similar trends of slope vs centrality
 - UrQMD (w/o CMW) showed no such effects.
- Further systematic checks
 - Weak decay contribution
 - Handle on the magnetic field B
- Other physics interpretations
 - Quark transportation?
 - Hadronic potential?

Please also see Hongwei Ke's poster!

CME + Local Parity Violation

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin(\phi^{\pm} - \Psi_{RP})$$

A direct measurement of the P -odd quantity “ a ” should yield *zero*.



$$\gamma = \langle \cos(\phi_{\alpha} + \phi_{\beta} - \psi_{RP}) \rangle$$

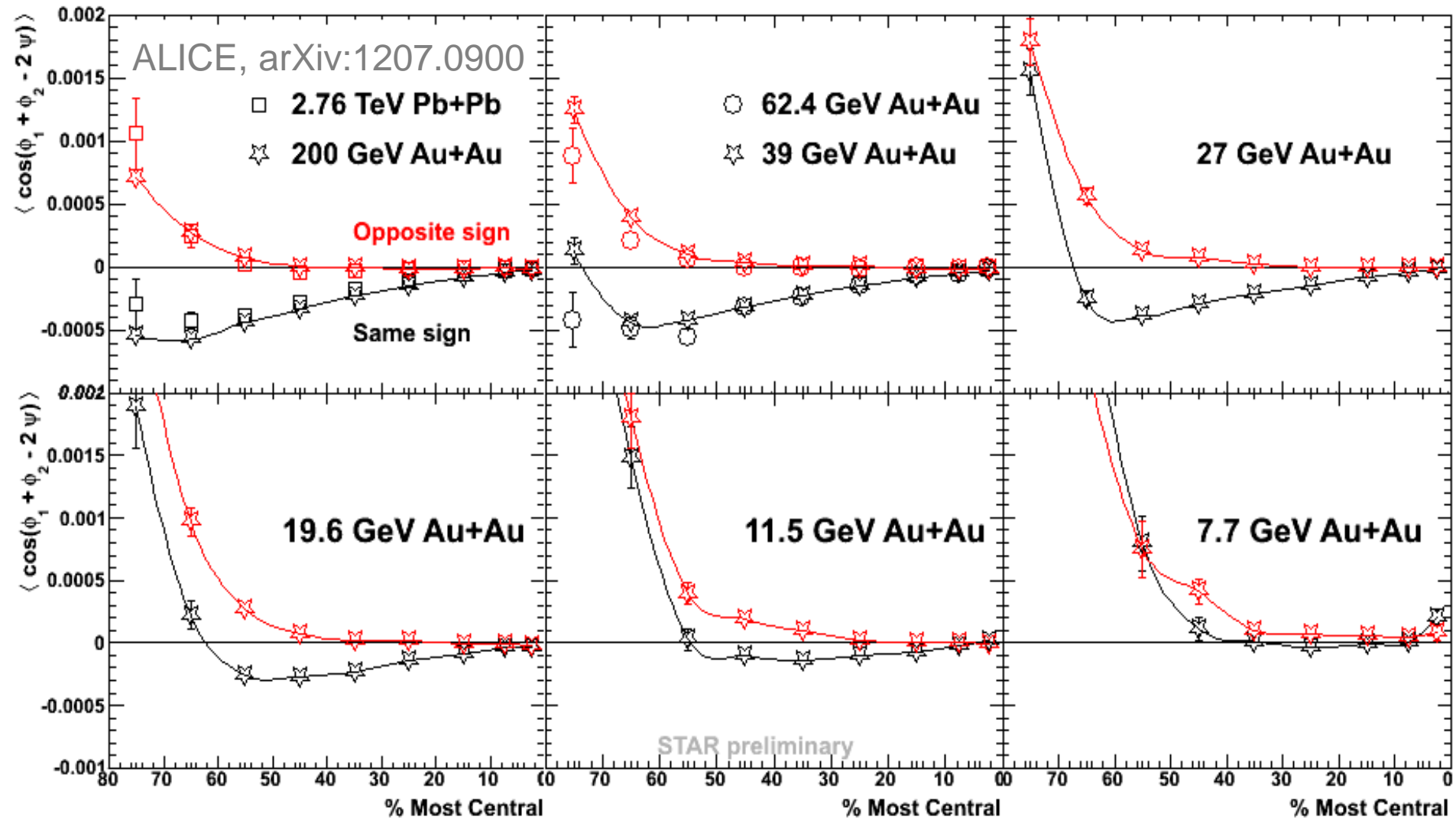
$$= \left[\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in} \right] - \left[\langle a_{\alpha} a_{\beta} \rangle + B_{out} \right]$$

*Non-flow/non-parity effects:
largely cancel out*

*P-even quantity:
still sensitive to
charge separation*

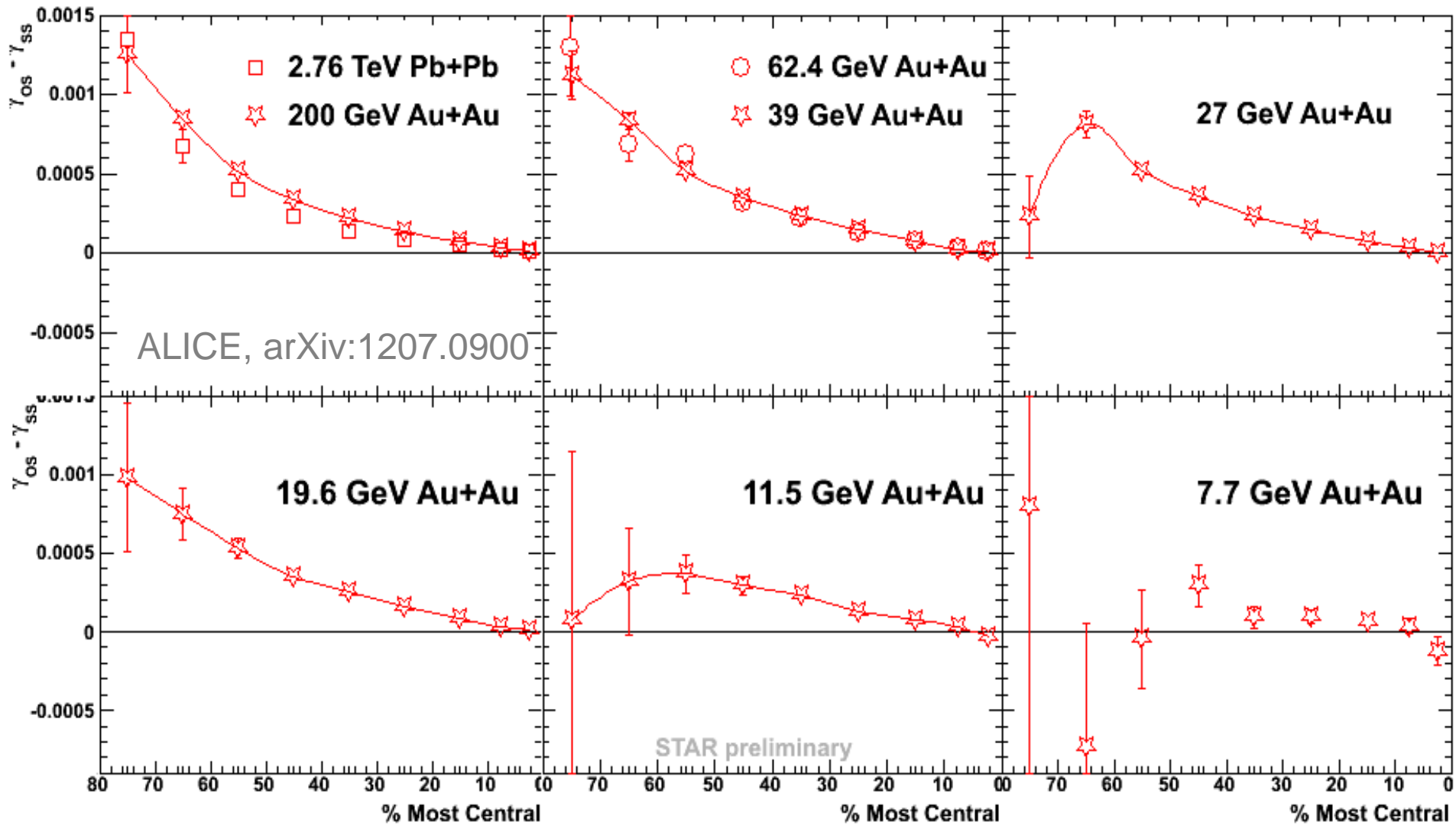
*Directed flow: expected to
be the same for SS and OS*

Beam energy scan



From 2.76 TeV to 7.7 GeV, changes start to show from the peripheral collisions. 12

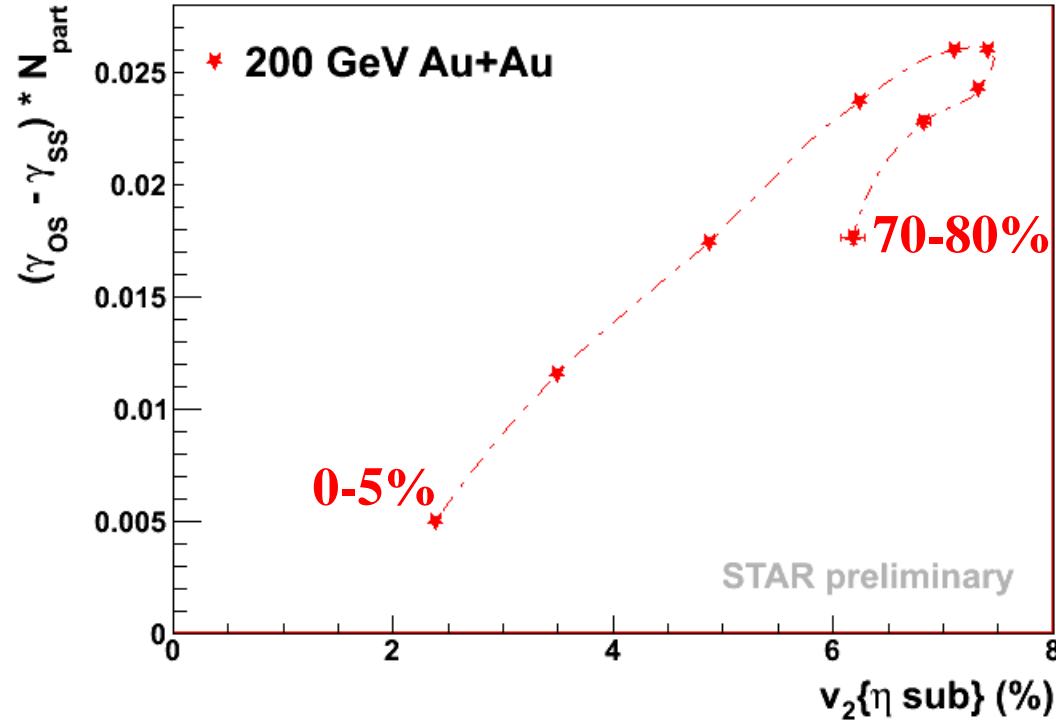
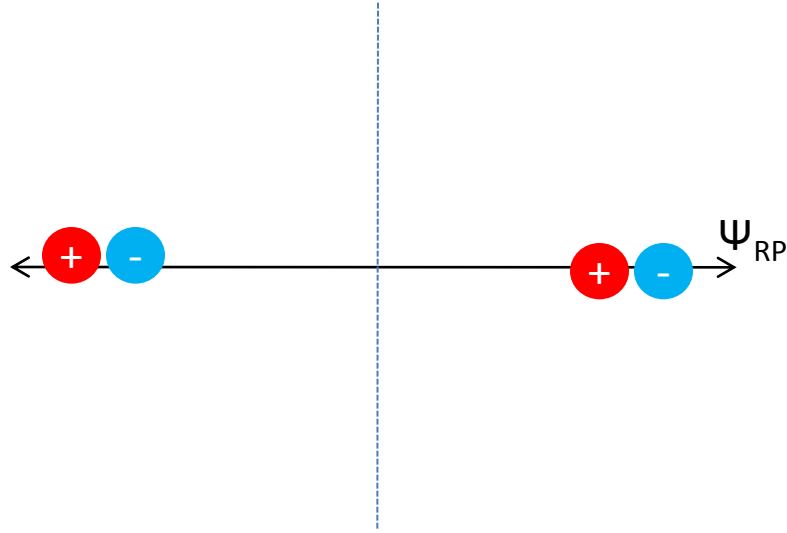
Consider $\gamma_{OS}-\gamma_{SS}$ to be signal...



The signal seems to be disappearing at 7.7 GeV, but the statistical errors are large.

Possible physics background

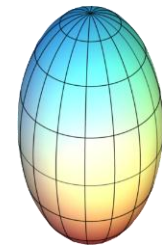
charge conservation/cluster + v_2 Pratt, Phys.Rev.C83:014913,2011



$$\begin{aligned} & \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \\ &= \langle \cos((\phi_\alpha + \phi_\beta - 2\phi_{res}) + 2(\phi_{res} - \Psi_{RP})) \rangle \quad \text{STAR, Phys. Rev. C72 (2005) 014904} \\ &\approx \frac{f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle v_{2,res}}{N_{ch}} \end{aligned}$$

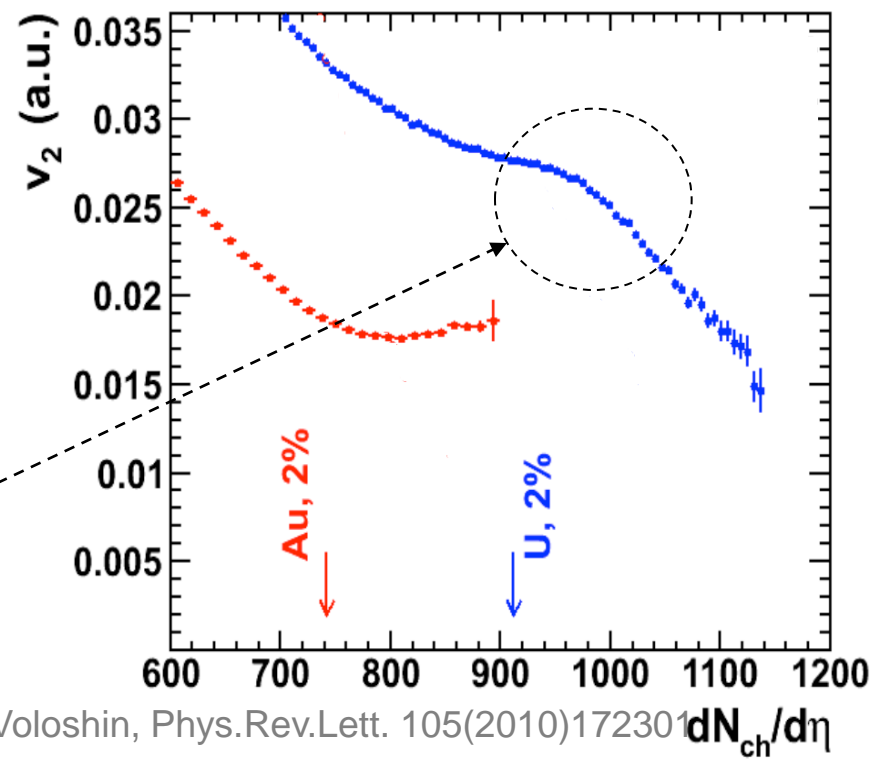
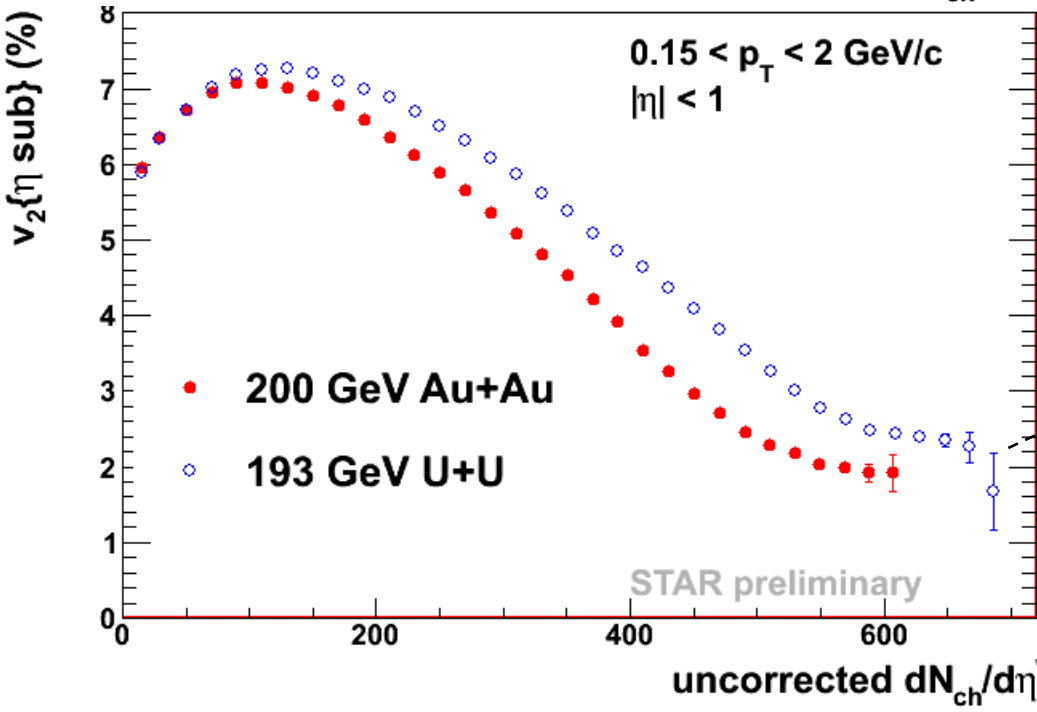
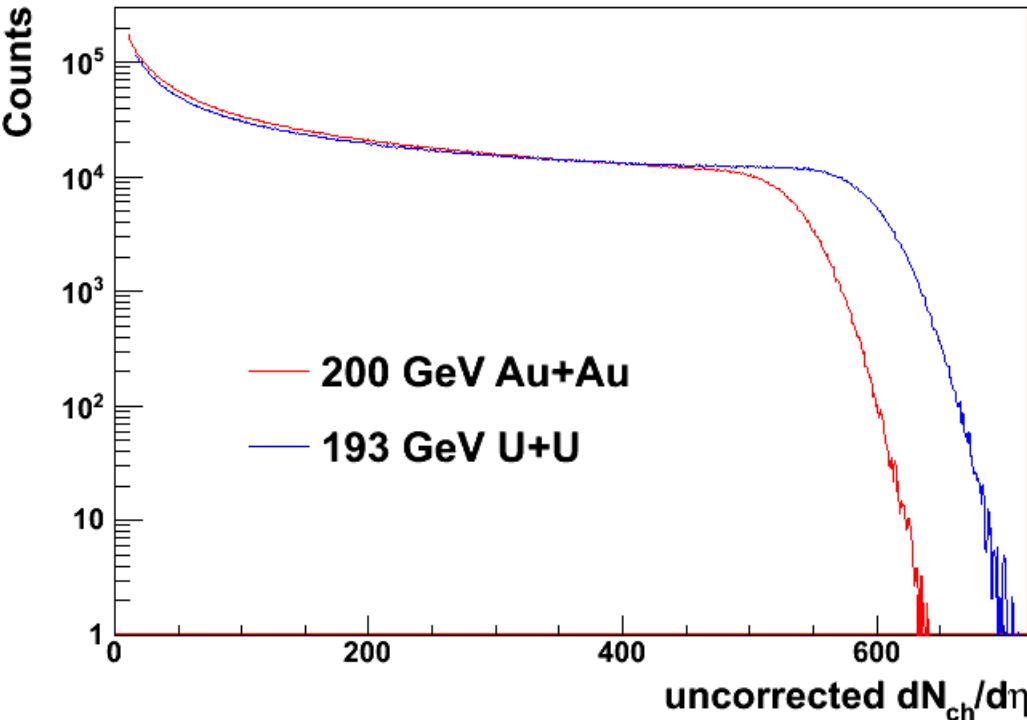
Seemingly correlated!
Can we disentangle the relationship with
U+U?

In RHIC run2012, we took 350M minbias events and 14M central trigger events.

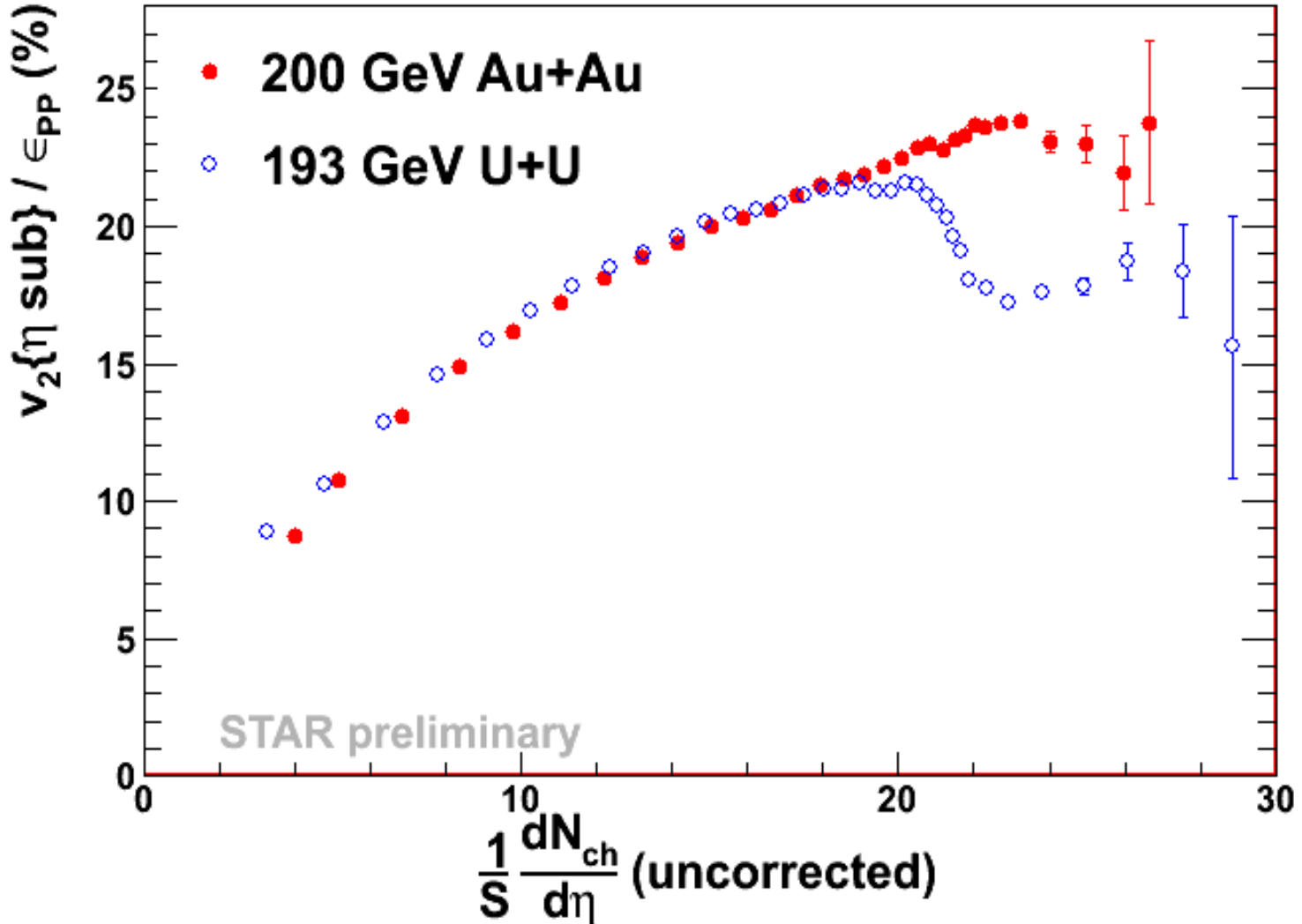


U+U

- A larger and deformed system
- $v_2(M)$ in U+U is higher than that in Au+Au. Not as high as expected in central collisions. (4% expected)
Masui, Phys.Lett.B679:440-444,2009
- The cusp in the simulation **not seen**.
If any, maybe in very central events.

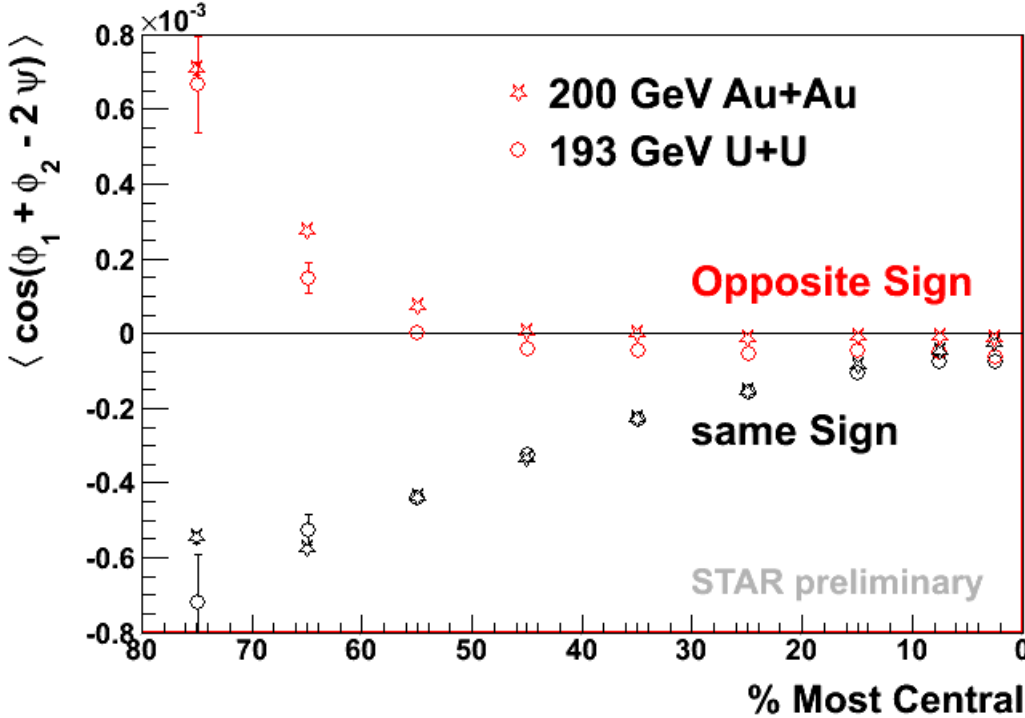


v_2 in U+U



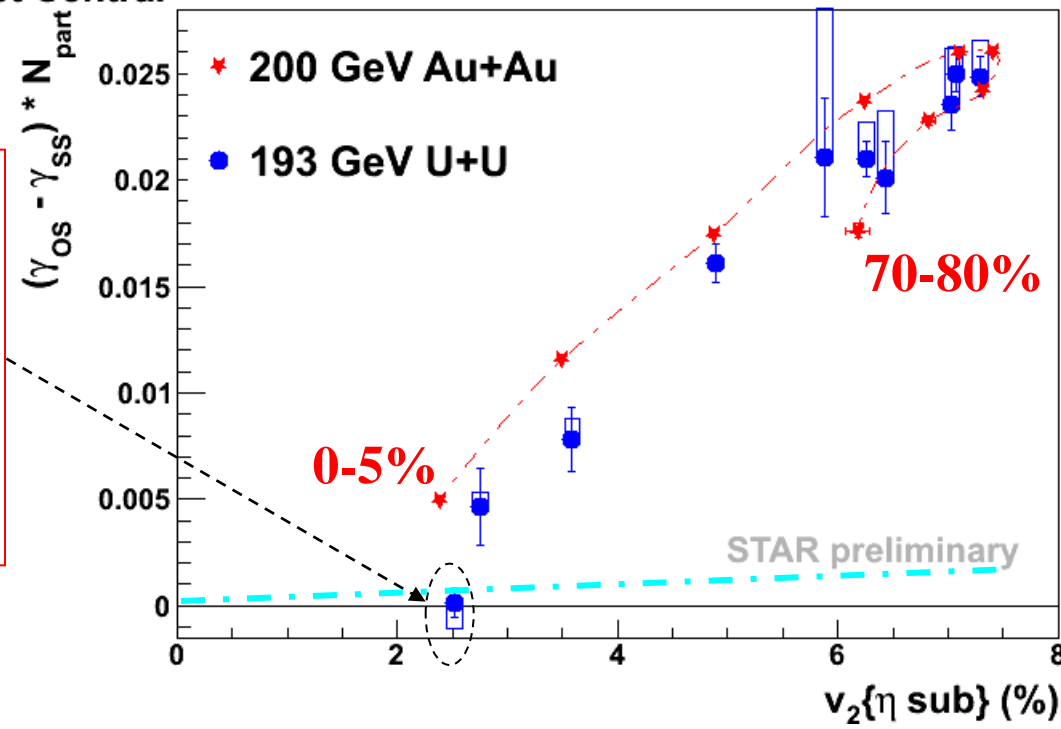
- If $dN/d\eta$ is divided by the overlap area (S) and v_2 is divided by eccentricity, there is a **split** in central and mid-central collisions.
- The area and eccentricity are calculated with Glauber Monte Carlo.

LPV in U+U



- The difference between OS and SS is still there in **U+U**, with **similar** magnitudes.
- Consider OS-SS to be the signal
- N_{part} accounts for dilution effects

- A dedicated trigger selected events with 0-1% spectator neutrons.
- With the magnetic field suppressed, the charge separation signal **disappears** (while v_2 is still $\sim 2.5\%$).

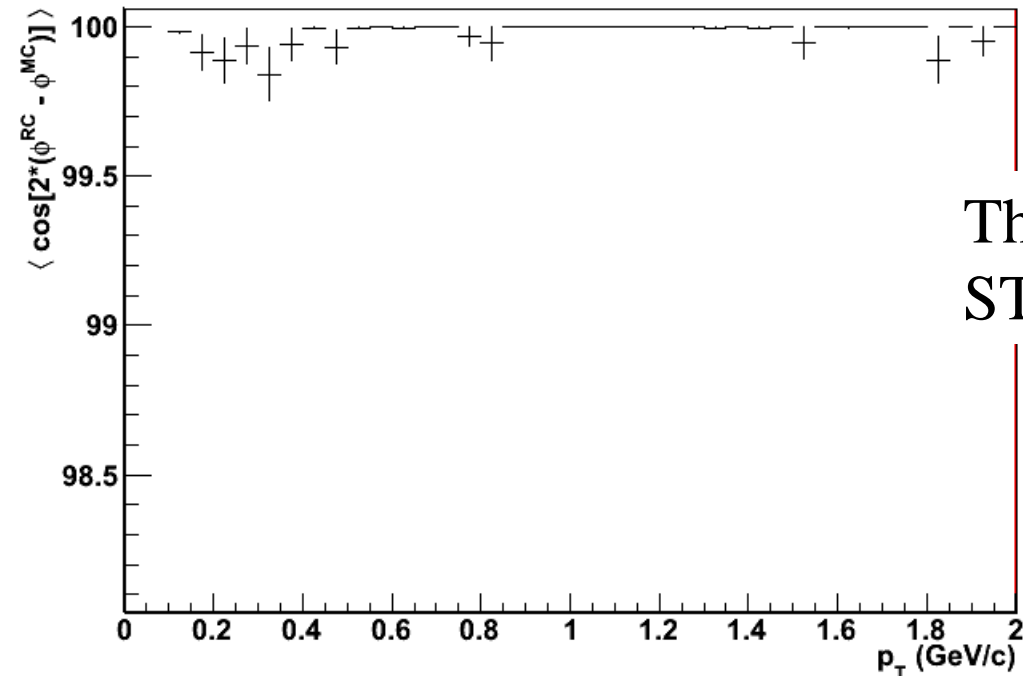
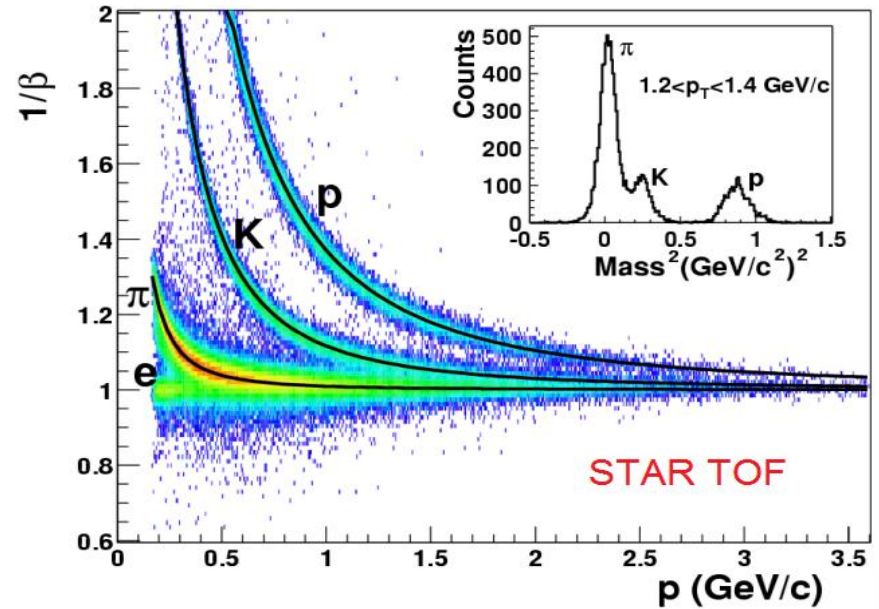
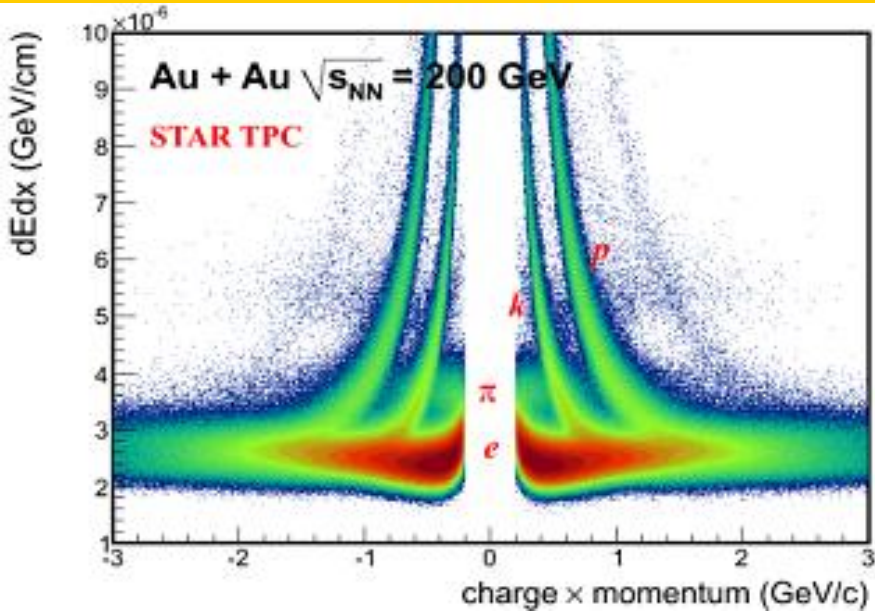


Summary II

- The three-point correlation showed charge separation w.r.t RP
 - $(Y_{OS} - Y_{SS})$ has similar magnitudes from 2.76 TeV to 11.5 GeV
 - Similar in Au+Au, Pb+Pb and U+U (also in Cu+Cu, not shown)
 - The signal of charge separation seems to disappear when
 - the beam energy is down to ~ 7.7 GeV
 - the magnetic field from spectators is suppressed (v_2 is still sizable)
 - Further studies
 - Correlations between identified particles
 - pion, kaon, proton and Lambda
 - Collisions of isobars?
- See also Kent Riley's poster!
- U+U collisions show interesting features of v_2 , which needs further investigation and calls for interpretation...

Backup slides

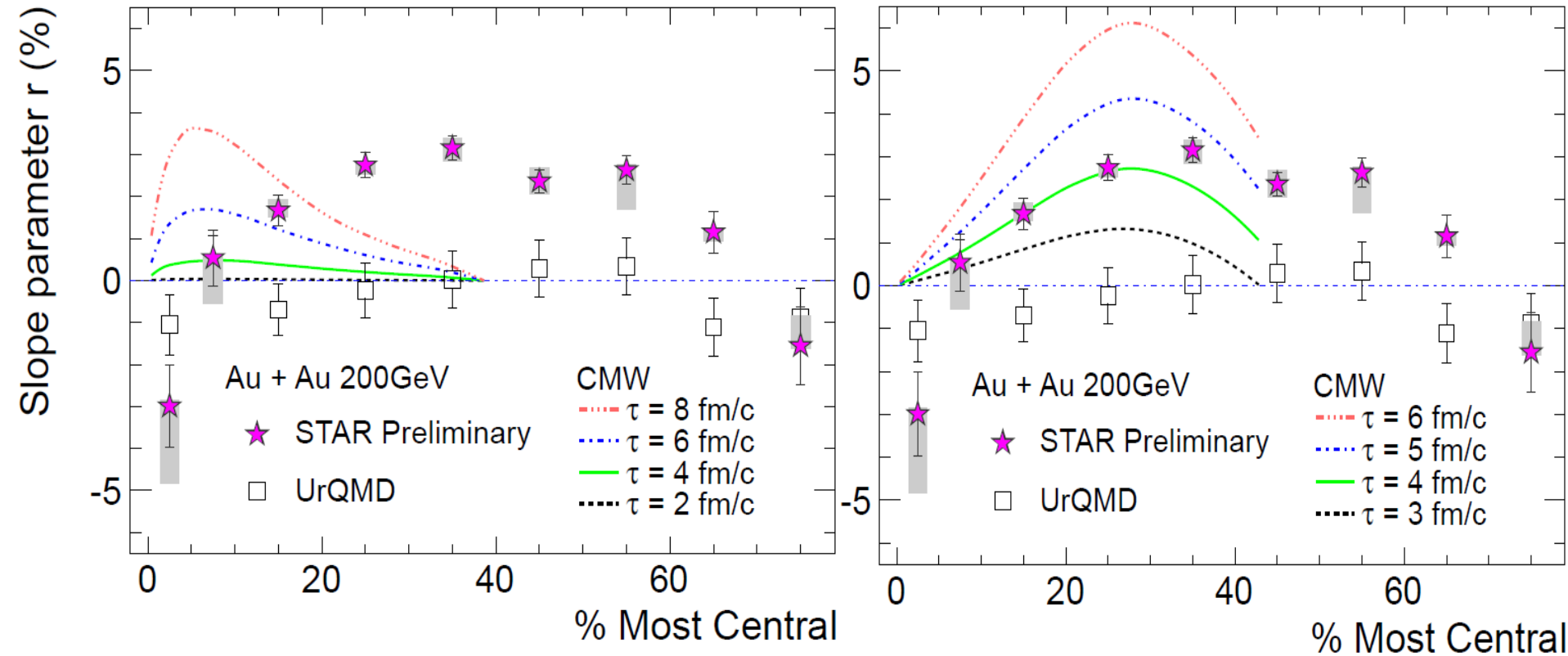
STAR: excellent PID and tracking



The correlation measurements at STAR are accurate to relative 0.1%.

Slope vs centrality

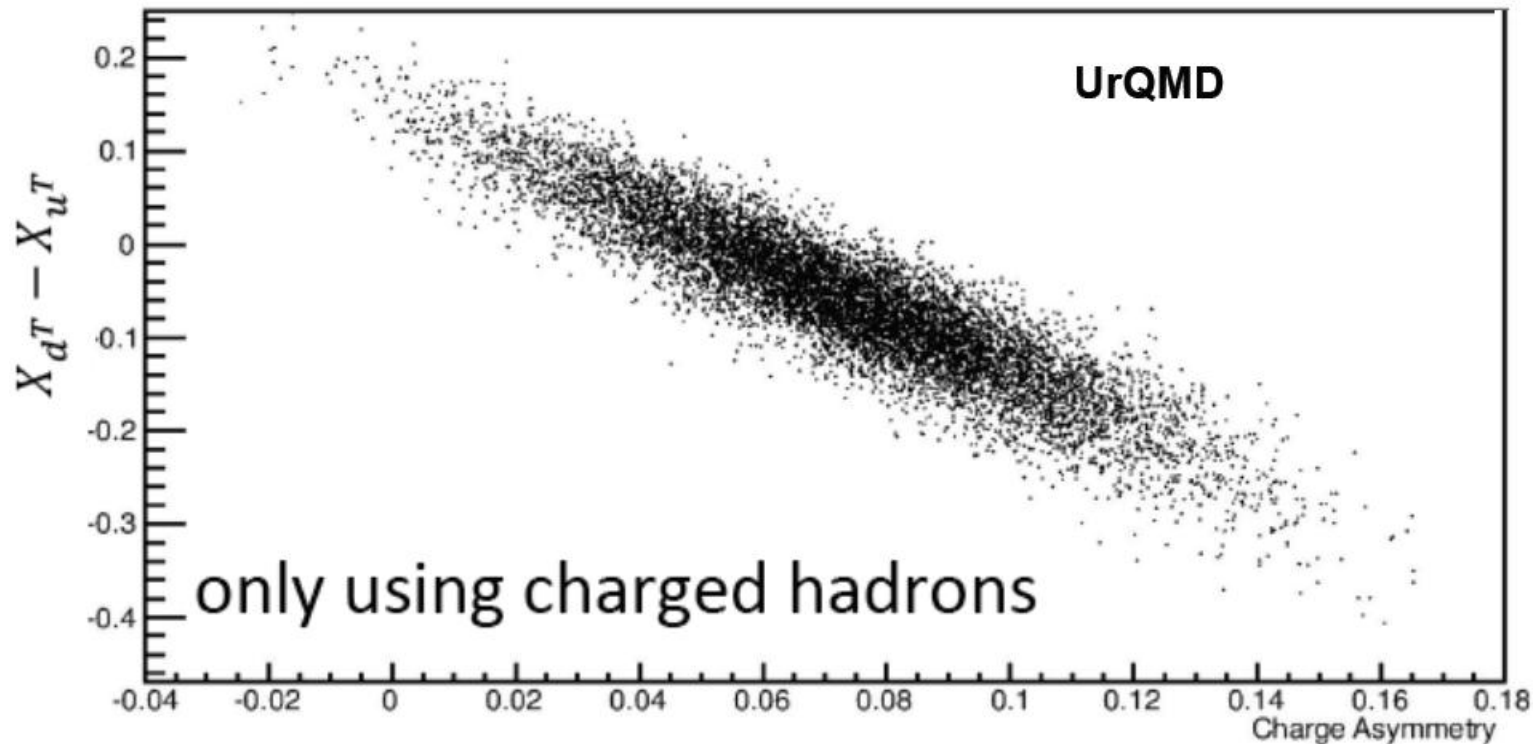
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. 107, 052303 (2011)
and arXiv:1208.2537v1 [hep-ph].



Improvement of theoretical calculations with CMW:
Simplified hard-disk (pancake) type of model \rightarrow Monte Carlo Glauber

Multi-component Coalescence (MCC) + Quark Transport

$X_{d^T} - X_{u^T}$ vs Charge Asymmetry

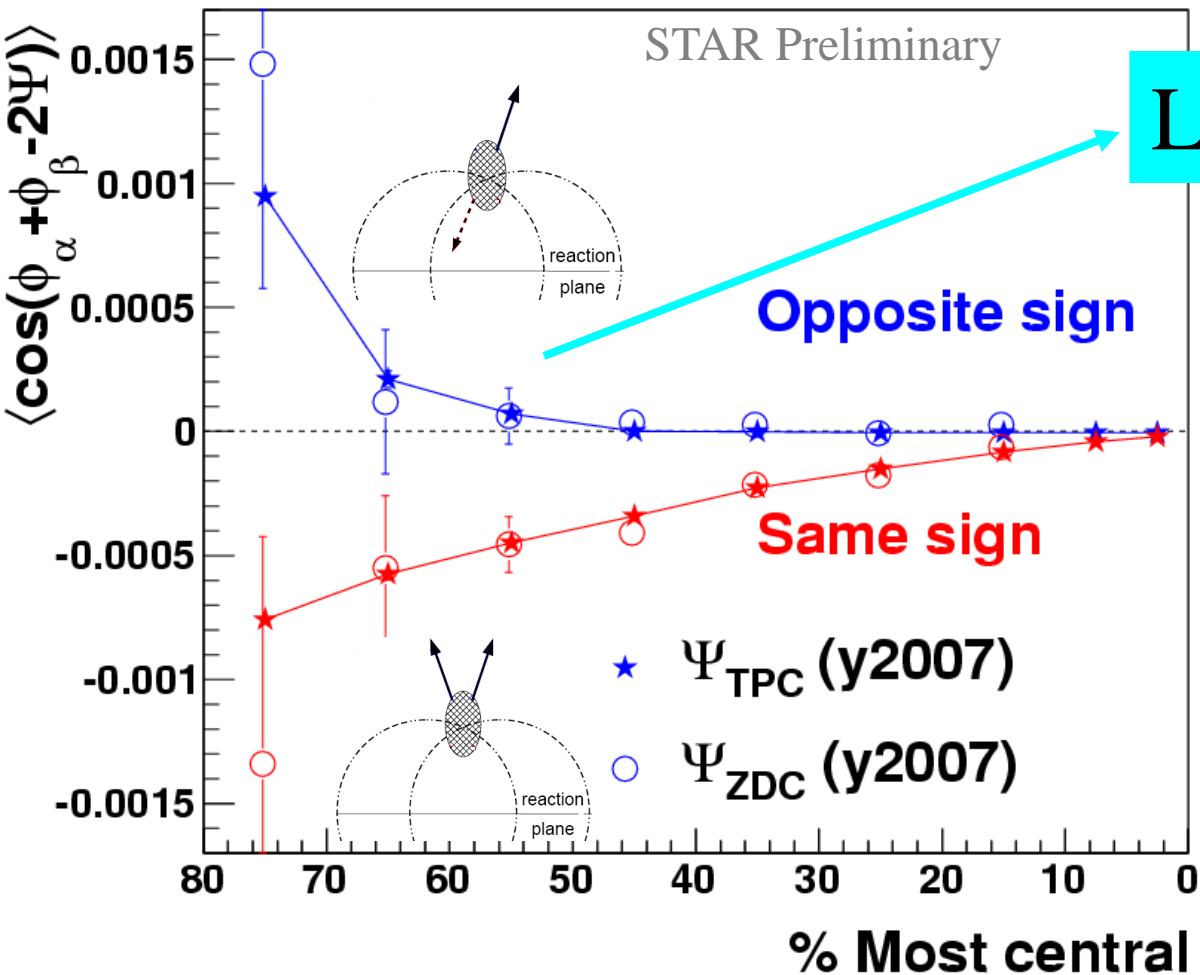


Pearson coefficient : -0.92 → Strong negative correlation

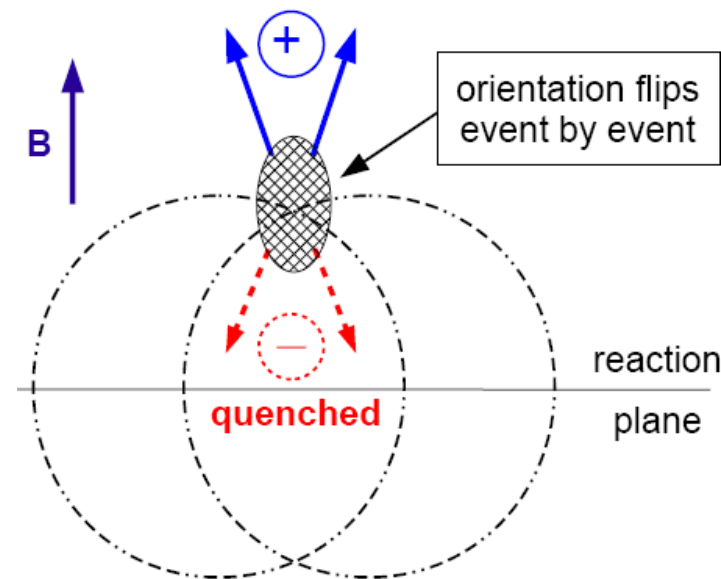
$$\Delta v_2^\pi \equiv v_2^{\pi^-} - v_2^{\pi^+} = (X_{d^T} - X_{u^T}) (v_2^T - v_2^P)$$

John Campbell's poster.

Results with different EPs

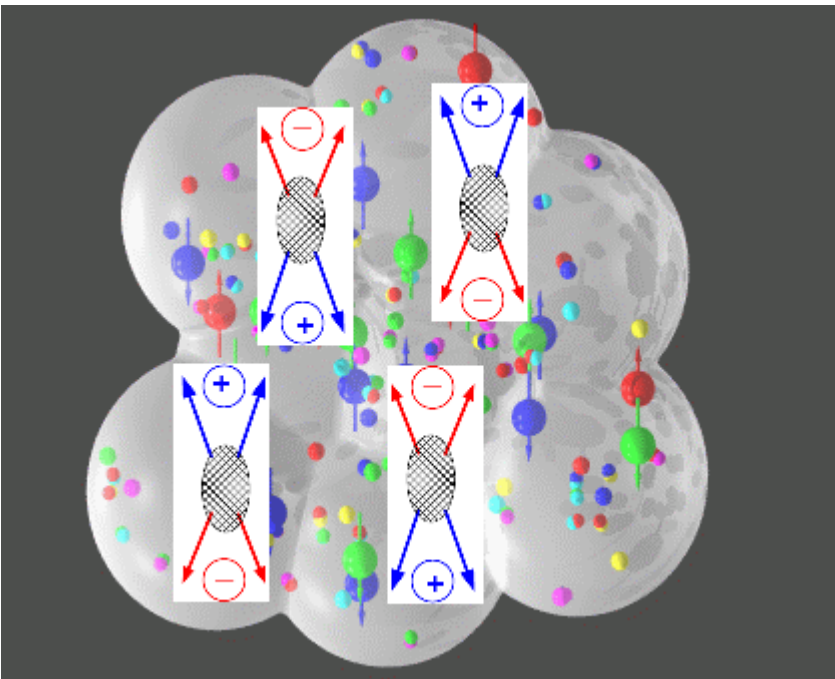


Lost in the medium?



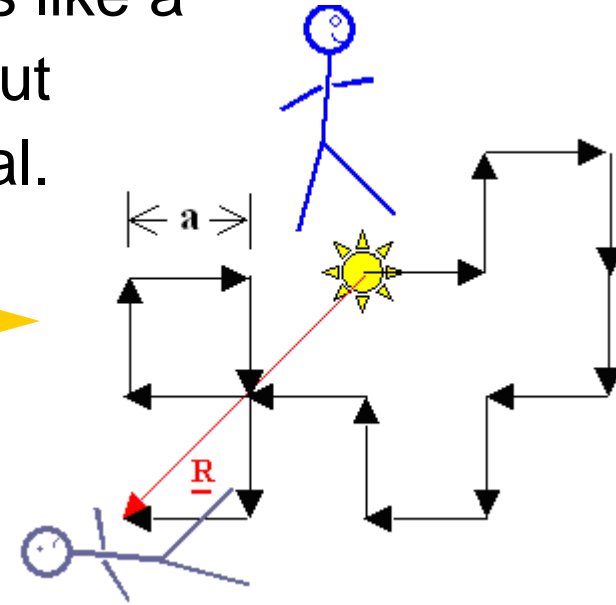
The correlators using TPC/ZDC event planes are consistent with each other.

Dilution effect



In the quark-gluon medium, there could be multiple P -odd domains.

The **net effect** is like a *random walk*, but one-dimensional.



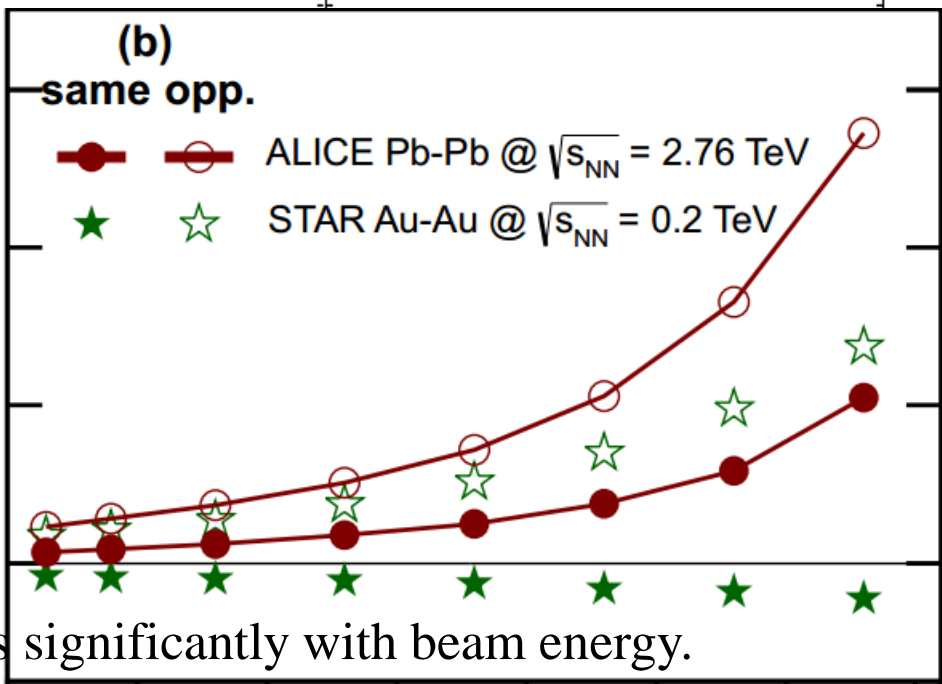
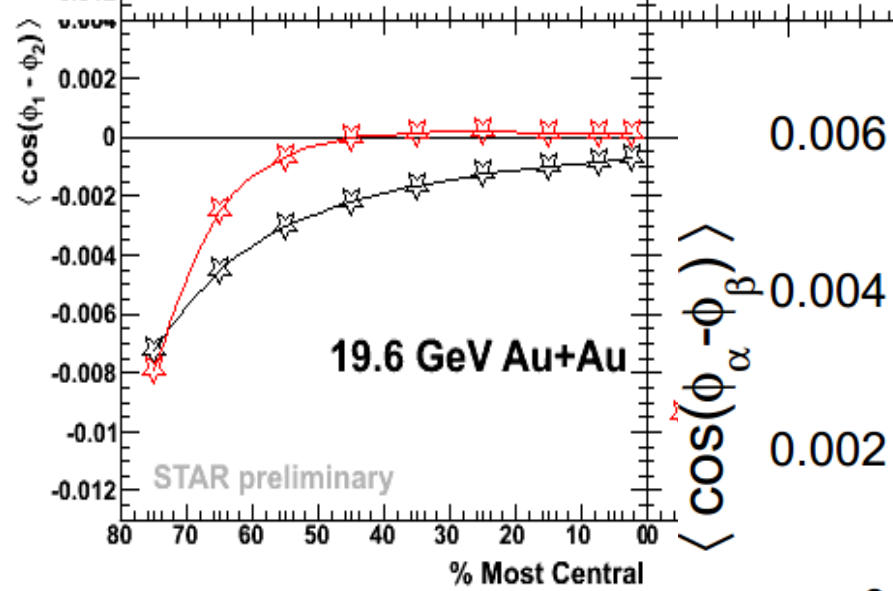
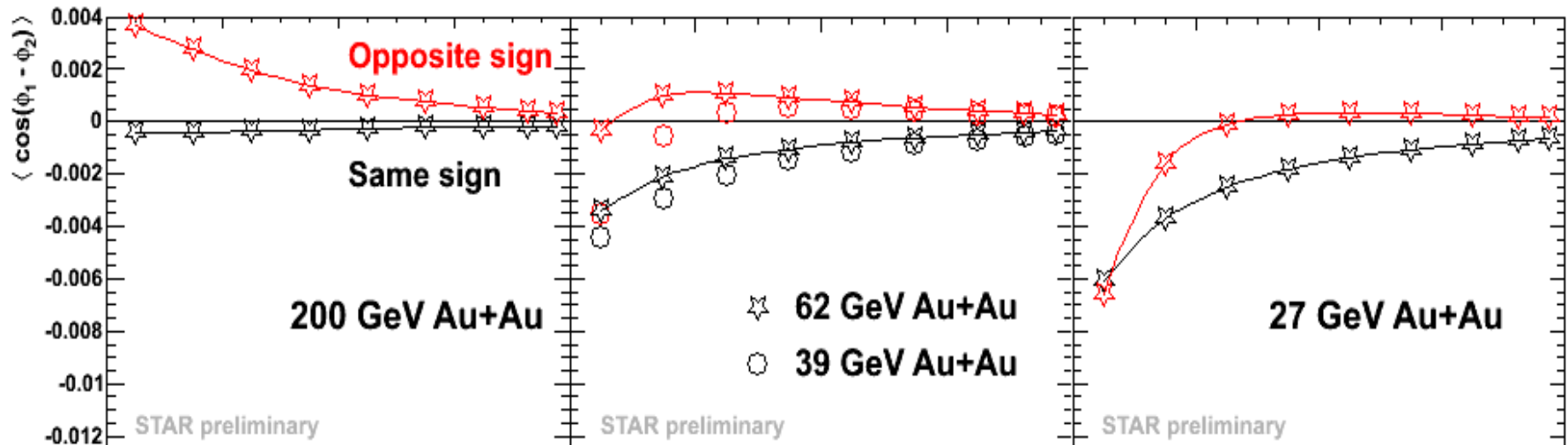
What do we know about the position R_n after n steps?

R_n follows a Gaussian distribution: *mean* = 0, and *rms* = \sqrt{n}

Our measurement of PV is like R_n^2 , expected to be n .

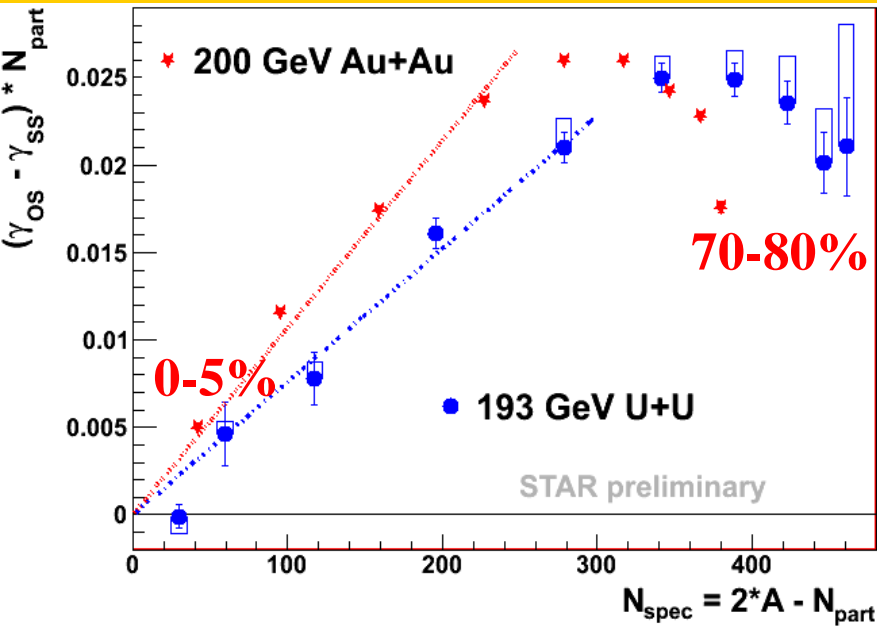
Compared with going in one fixed direction, where $R_n^2 = n^2$, the "random-walk" measurement is diluted by a factor $\sim n \sim N_{part}$.

Two particle correlation

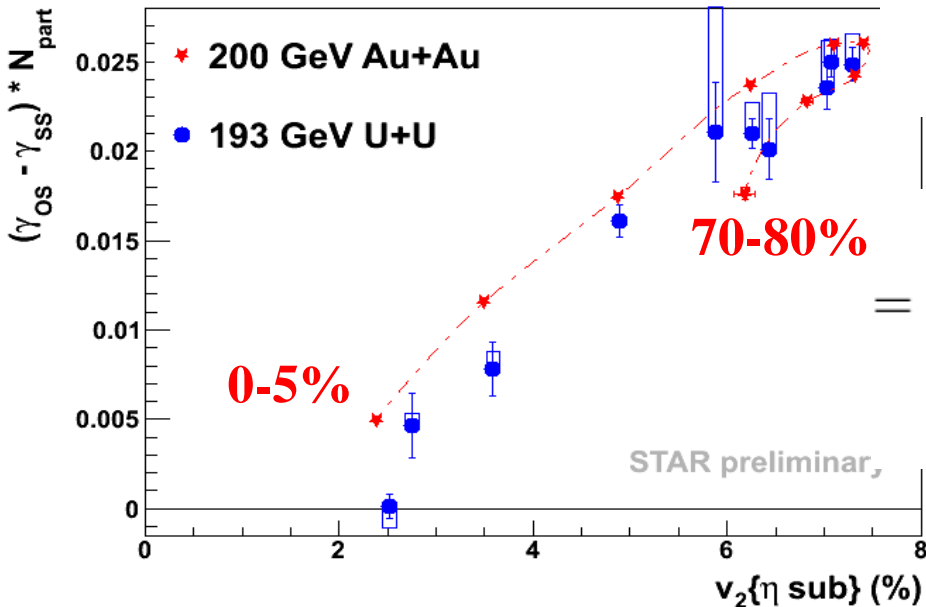
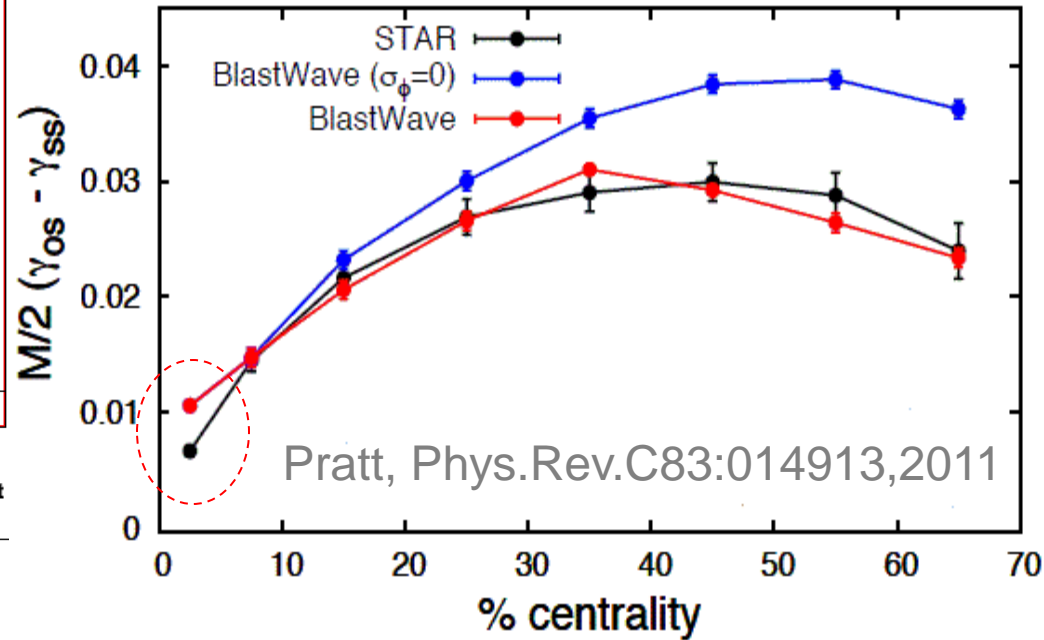


Two-particle correlation changes significantly with beam energy.

Possible physics background



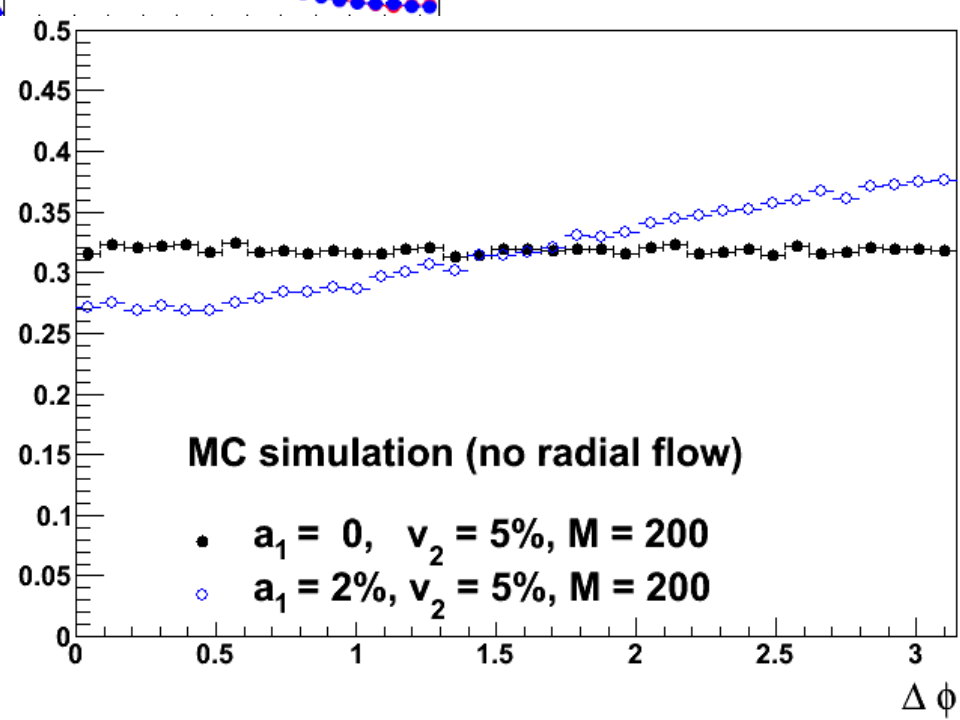
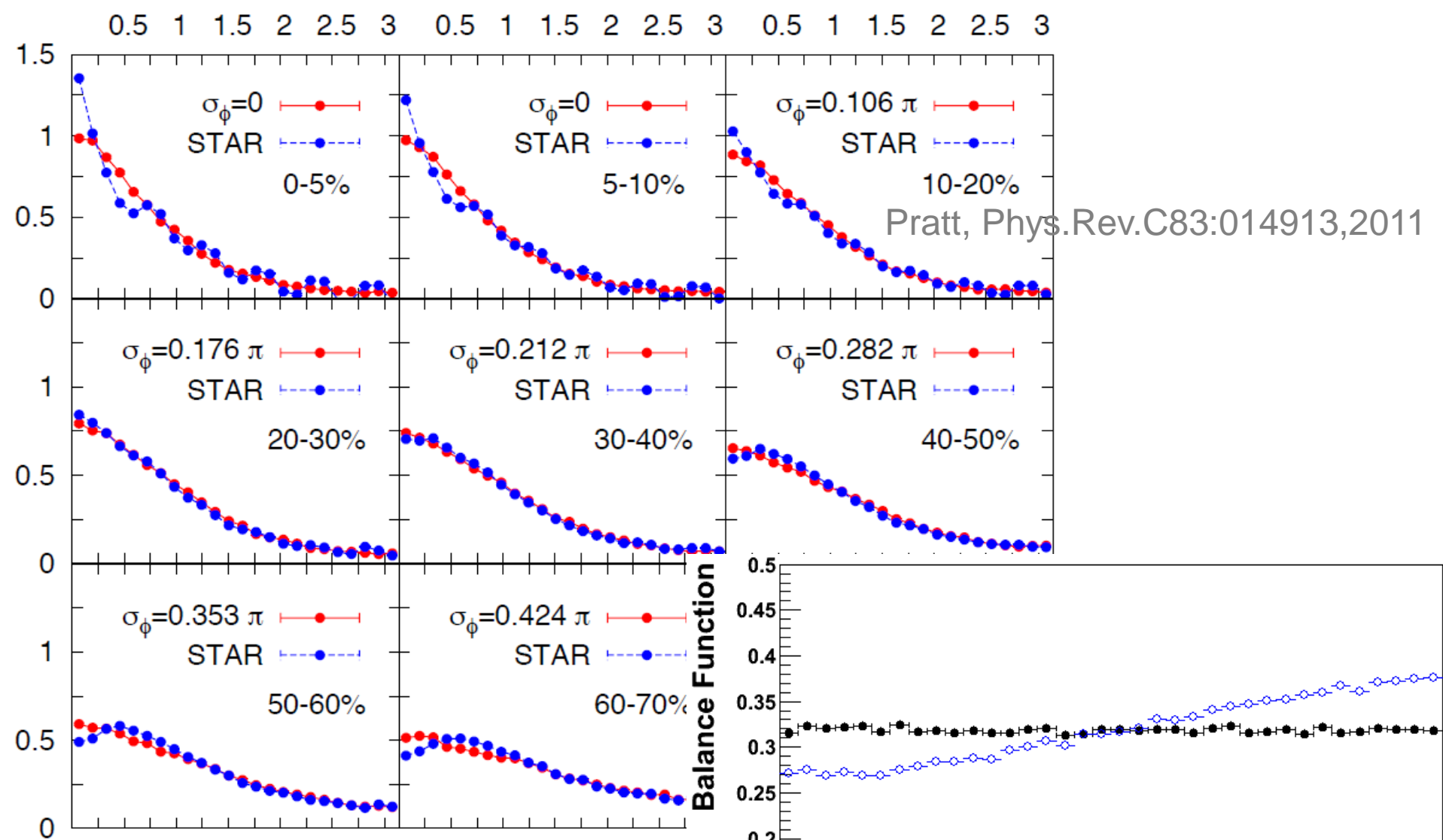
charge conservation/cluster + v_2



$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

$$= \langle \cos((\phi_\alpha + \phi_\beta - 2\phi_{res}) + 2(\phi_{res} - \Psi_{RP})) \rangle$$

$$\approx \frac{f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle v_{2,res}}{N_{ch}}$$



Balance function