U+U and Cu+Au results from Phenix

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Outline

- Motivation
  - U+U and Cu+Au
- Measuring the bulk properties
  - Mid-rapidity global particle production
  - Mid rapidity identified flow

RHIC Run 12

- RHIC versatility – energy and species scans
- Allows for unique collision environments
  - First U+U collisions at 193 GeV
  - First Cu+Au at 200 GeV
- Recent Improvements
  - EBIS source
  - Horizontal stochastic cooling in both beams

    (small beam size, high luminosity, low beam loss rates)

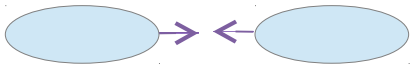
Tests of initial geometry

U+U

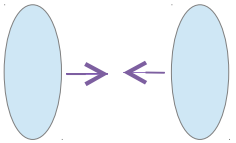
Deformed nuclei

- initial geometry changes event-by-event
  - Expect a higher energy density than Au+Au
    - For tip-tip orientation

Tip-tip



Body-body

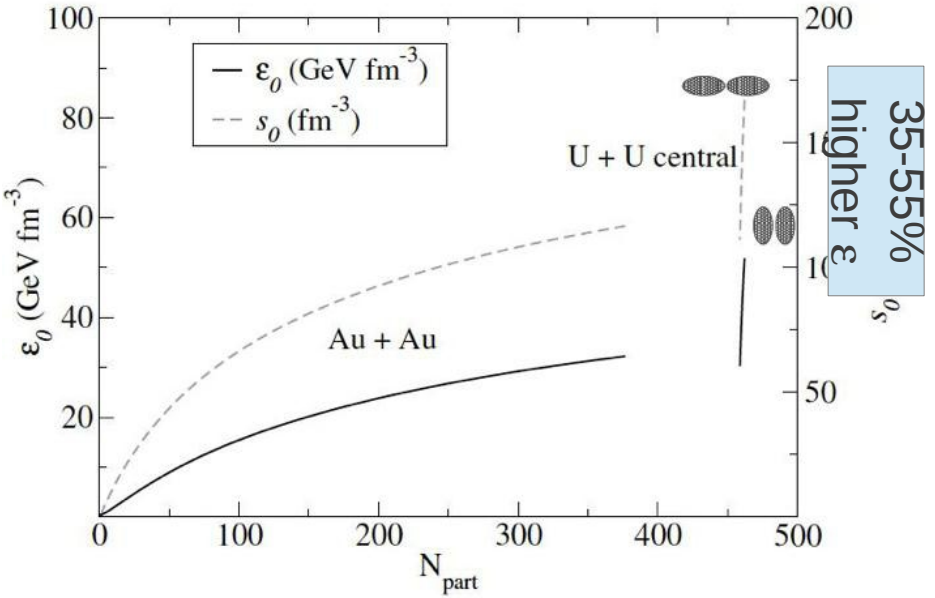


R_{long}/R_{perp} ~ 1.29

Studies

- Initial geometry – flow relation
- Path length – parton energy loss

PRL 94, 132301 (2005)



Key point for this measurement – experimentally separate these configurations

Tests of initial geometry

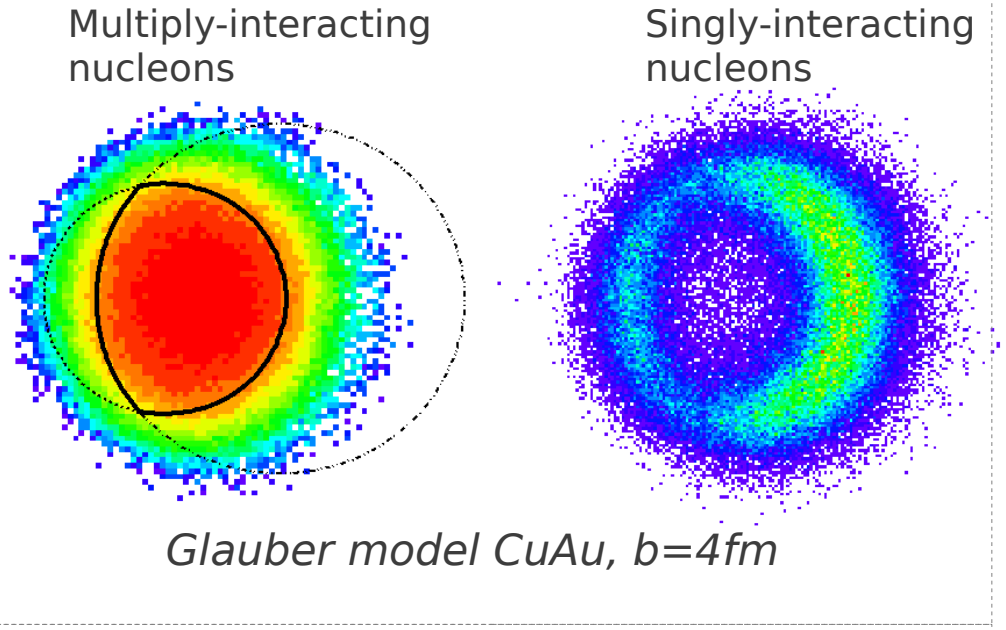
Cu+Au

Asymmetric system

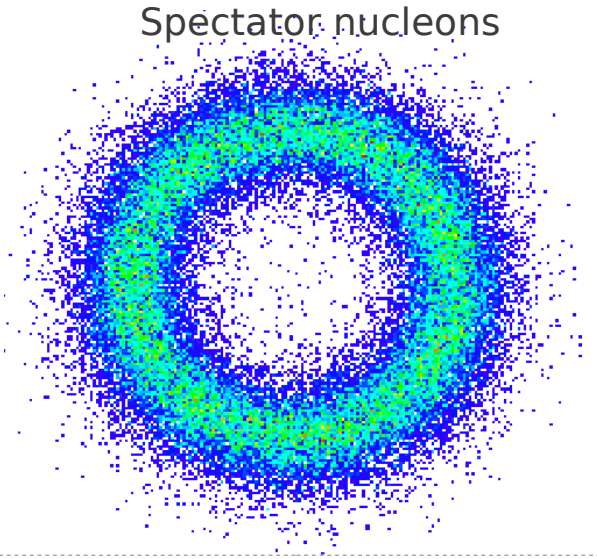
- Core: asymmetric density profile
- Corona: large on Au-side

Study

- Naturally arising odd harmonics
- Central collisions:
  - Cu completely swallowed



Glauber model CuAu, b=4fm



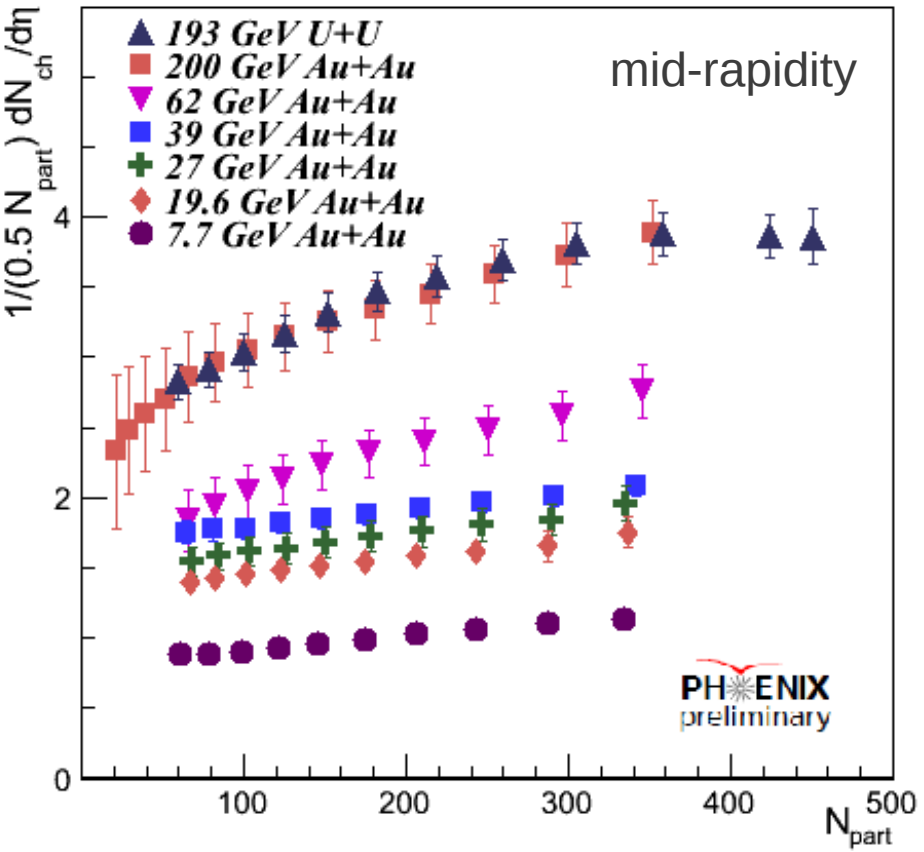
Global particle production

Charged particle multiplicity, $dN_{ch}/d\eta$

U+U

- Charged particle density
  - increases with increasing collision energy.
  - There is an increase for more central collisions at all collision energies.
  - Au+Au and U+U are similar.

- Note: centrality selection uses ZDC+BBC. Cut on central 1% (rightmost point) – no method to separate tip-tip events.



Charged particle multiplicity, $dN_{ch}/d\eta$

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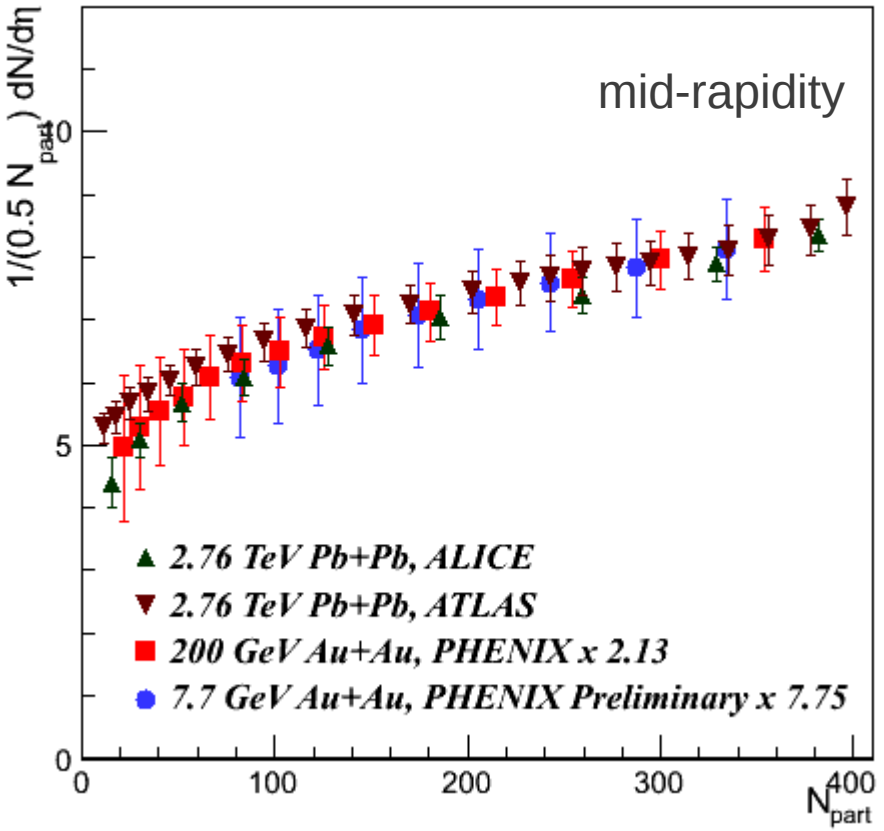
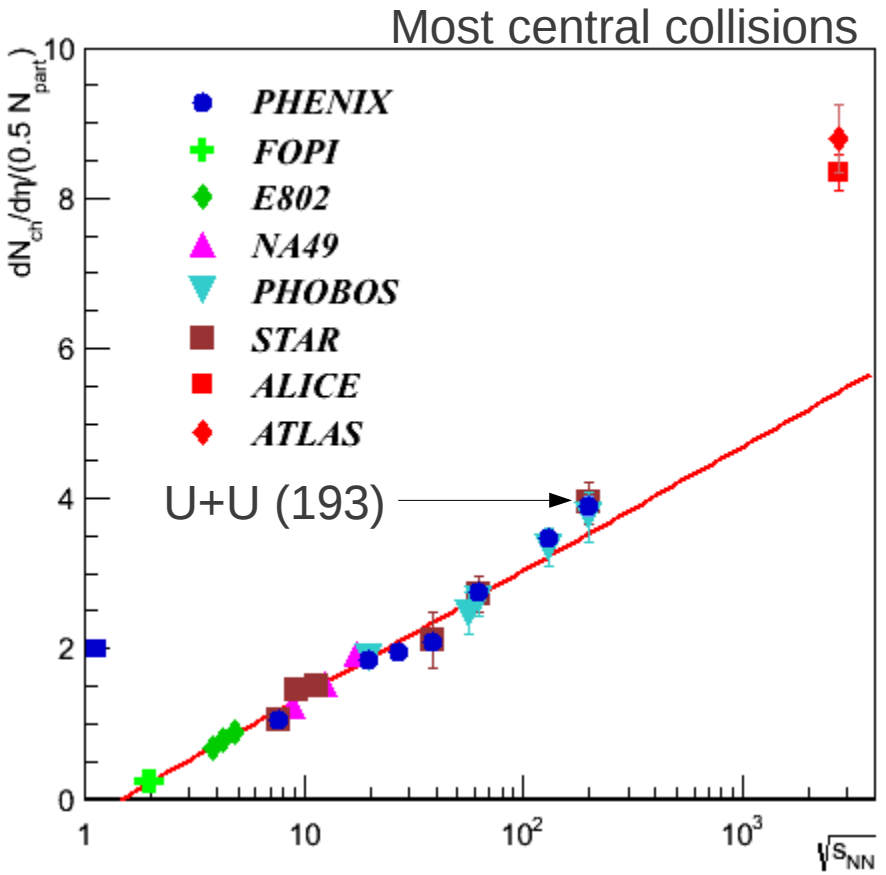


- No significant change in the shape of the centrality-dependence from 7.7 GeV Au+Au collisions up to 2.76 TeV Pb+Pb collisions.

$dN_{ch}/d\eta$ versus collision energy

U+U

- The multiplicity per participant pair increases linearly with $\log(\sqrt{s_{NN}})$ to RHIC energies.
- No significant excess particle production in very central U+U
  - Compared to Au+Au at the same energy.

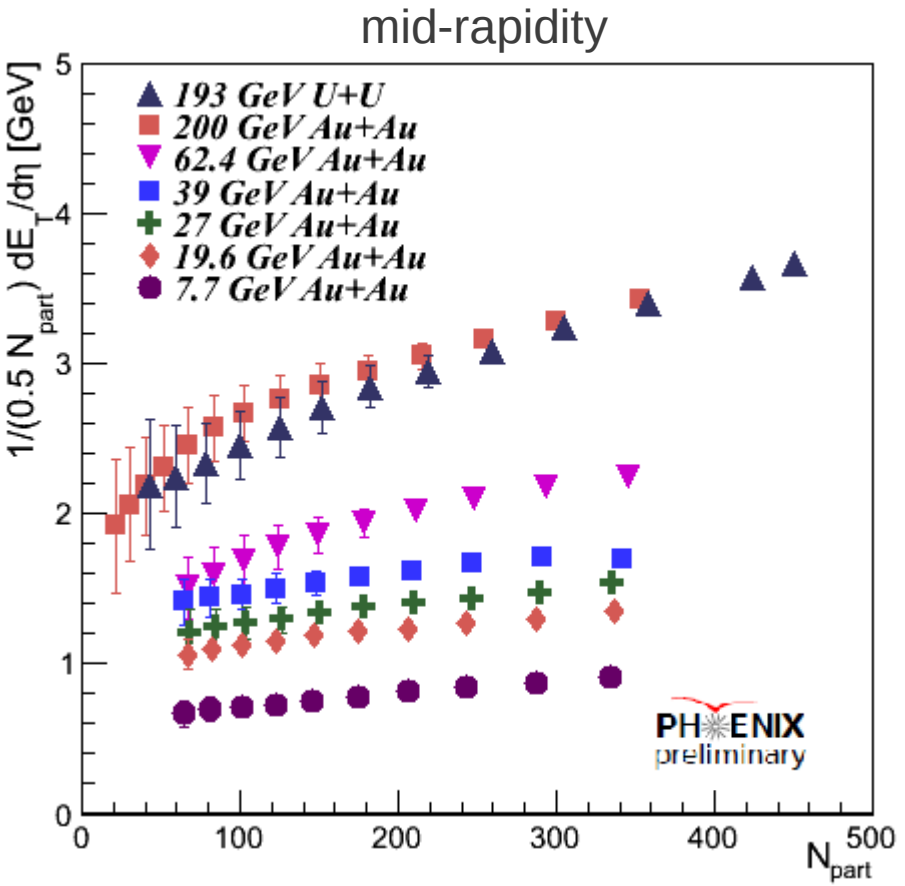


The red line is a logarithmic fit to all data, excluding the LHC points.

Transverse energy density, E_T

U+U

- Transverse energy production
  - Increases with increasing collision energy.
  - Increases for more central collisions at all collision energies.
  - The Au+Au and U+U particle E_T are similar
    - Small increase for most central data.



Upper U+U point 1% most central, all other 5% centrality bins

E_T versus collision energy

U+U

- The transverse energy per participant pair increases linearly with log($\sqrt{s_{NN}}$) to RHIC energies.
- The Au+Au and U+U particle E_T are similar
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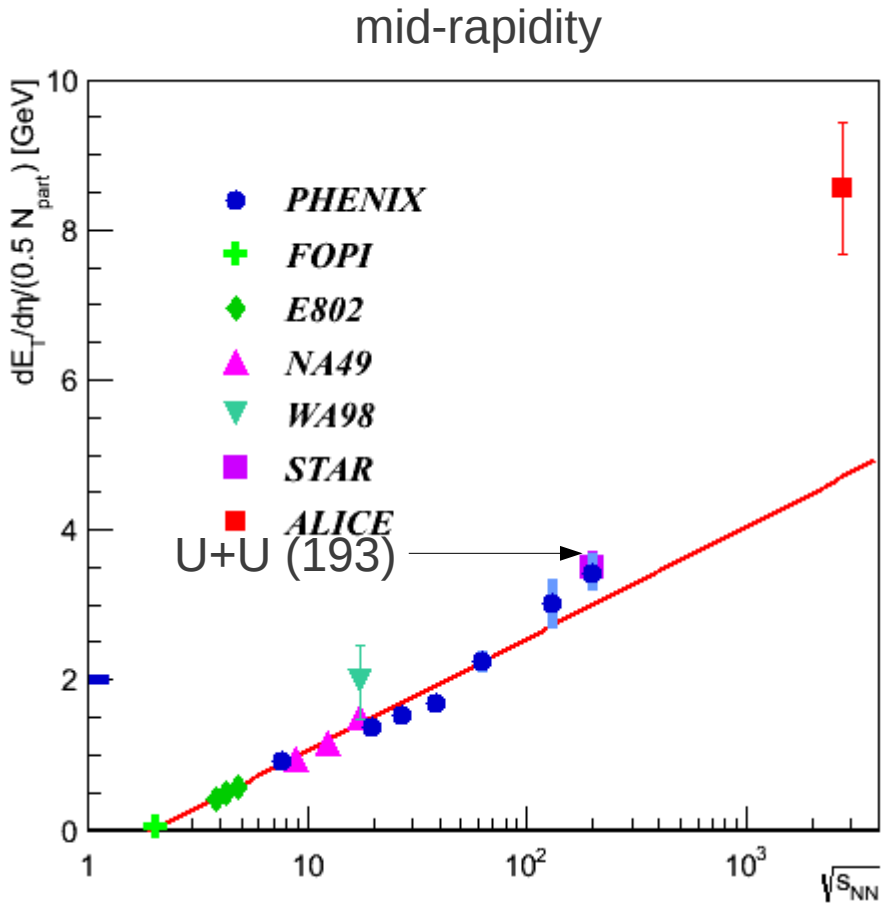
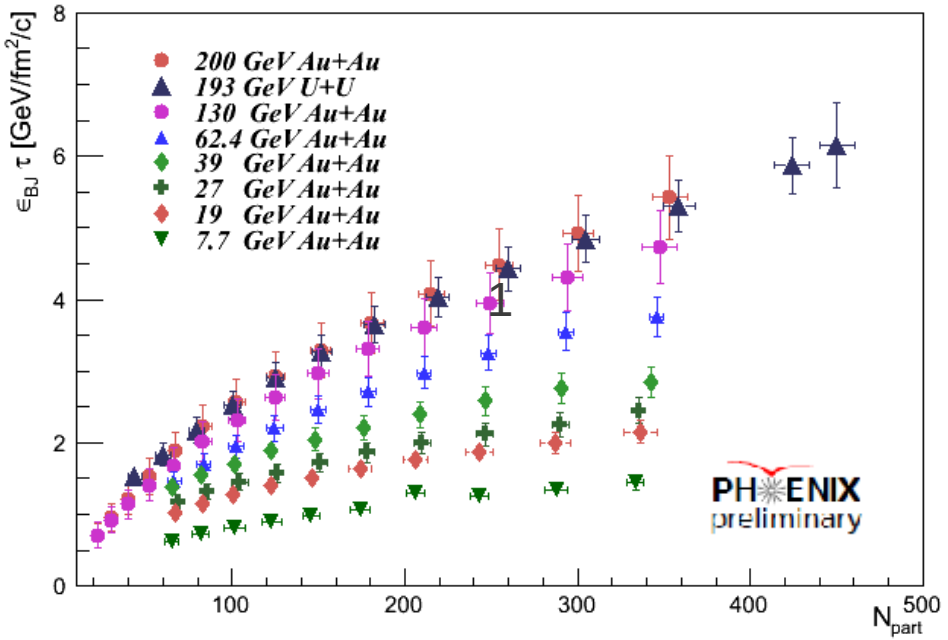


The red line is a logarithmic fit to all points excluding the ALICE point.

Bjorken Energy density, ε_{BJ}

U+U

- New RHIC energy density record in U+U collisions
  - 6.15 GeV/fm^2/c.
- e_{BJ} increases by a factor of 3.8 when going from 7.7 to 200 GeV.
- Moderate increase from central Au+Au to very central U+U (20%).



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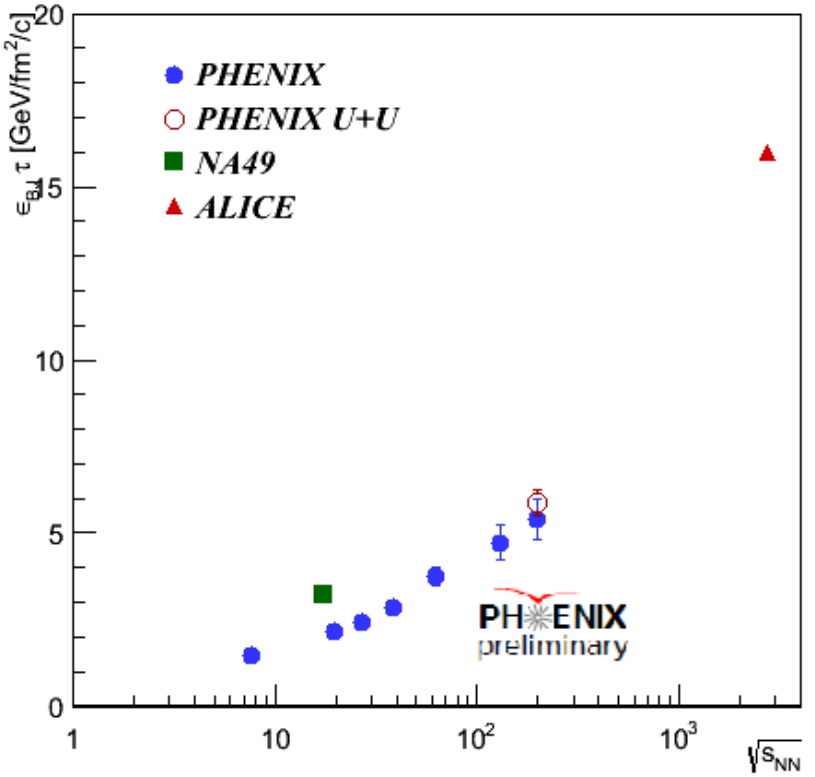
- ε_{BJ} increases by a factor of 3.8 when going from 7.7 to 200 GeV.
- ε_{BJ} increases by a factor of 11 when going from 7.7 GeV to 2.76 TeV.

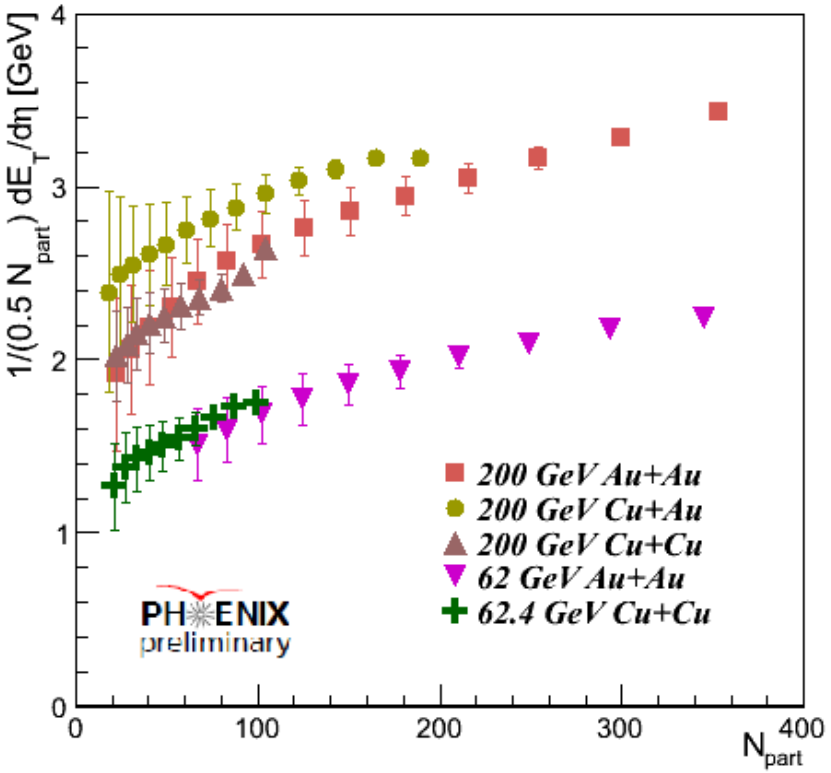


Upper U+U point 1% most central, all other 5% centrality bins.

Cu+Au transverse energy density, E_T

Cu+Au

- E_T production is independent of the collision system
  - Similar E_T in Cu+Cu and Au+Au at the same N_{part}
  - Higher E_T in Cu+Au reflects larger core at the same N_{part}



Mid-rapidity identified flow

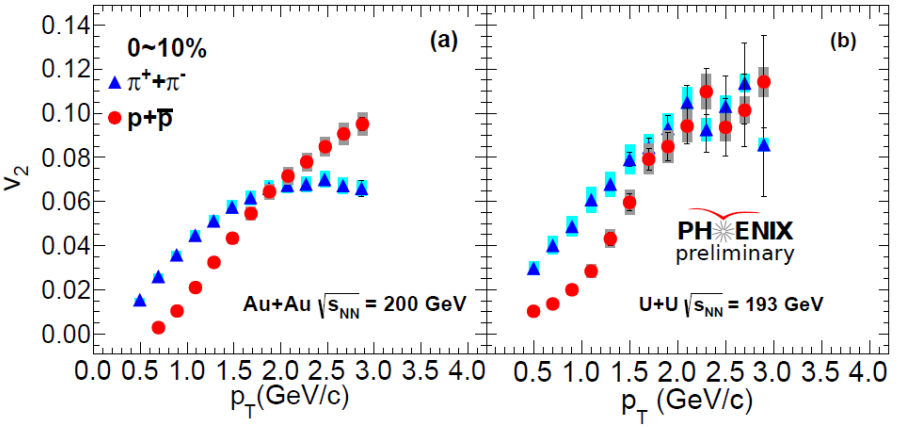
v_2 of identified hadrons

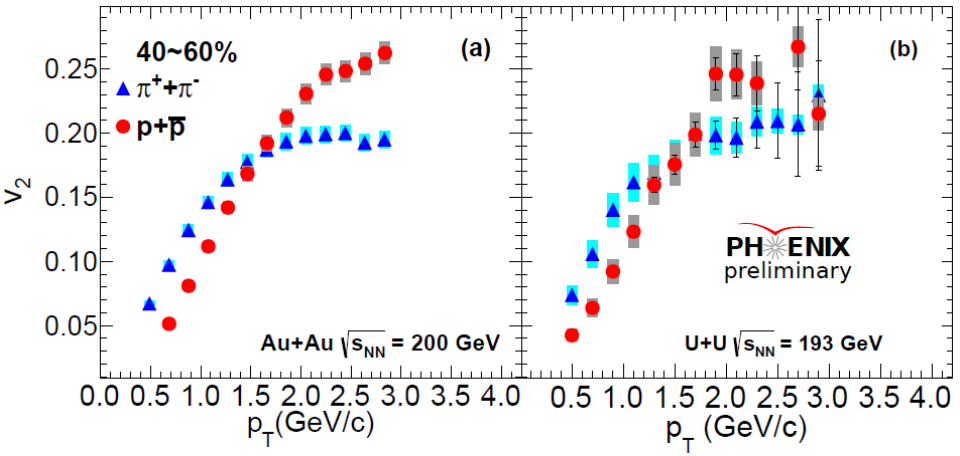
U+U

- v_2 is one of the main tests for U+U collisions.

- Comparison of v_2 of pions and protons in Au+Au and U+U
  - Shows mass ordering at low-p_T.
  - Similar behavior in peripheral collisions.
  - Slight difference in the slope of the proton v_2 in central collisions.

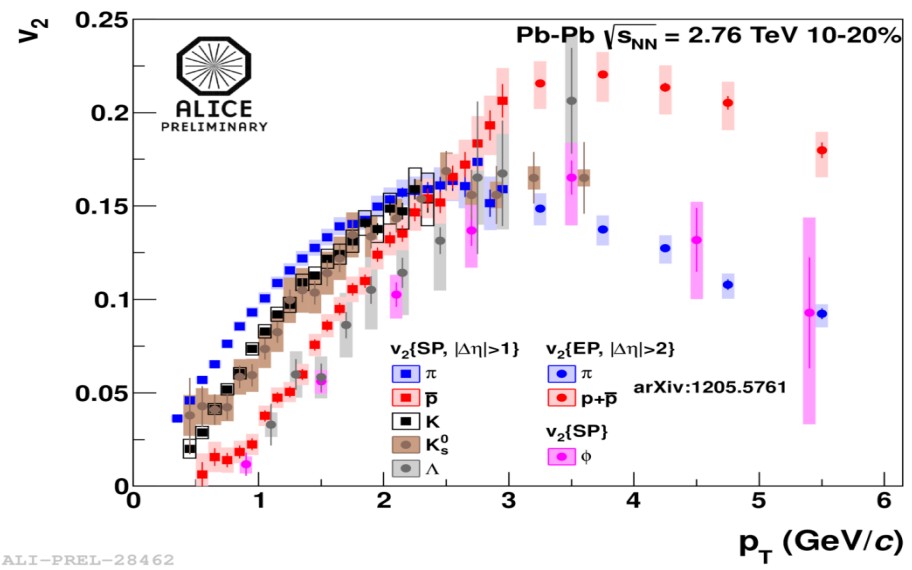
10% of the statistics



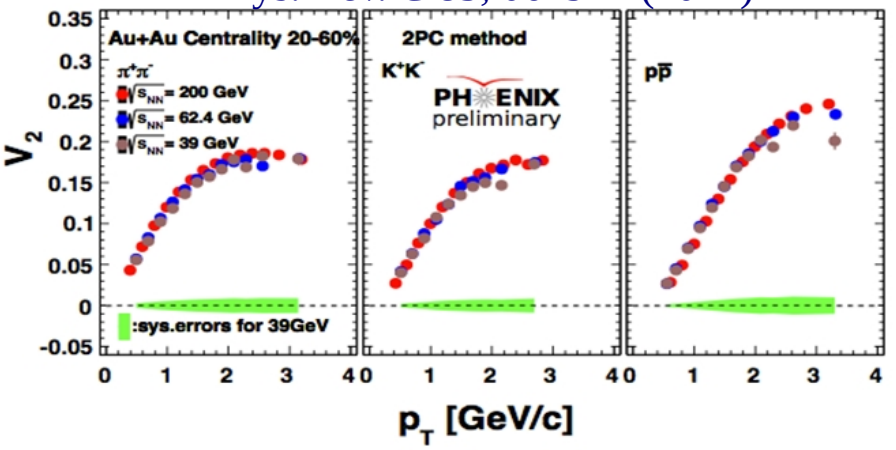


v_2 mass ordering and energy density

- Strong mass ordering is also observed at the LHC (ε increases by 2.5 to RHIC)
  - At low-p_T (p_T<3 GeV/c).
  - Qualitative agreement with Hydro (up to 3 GeV/c).
- RHIC energy scan
  - Increase of ε by factor of 2 from 39 to 200 GeV.
  - Mass ordering holds at low p_T.
  - Proton slope same for all energies (p_T<2 GeV).
- Au+Au → U+U ?



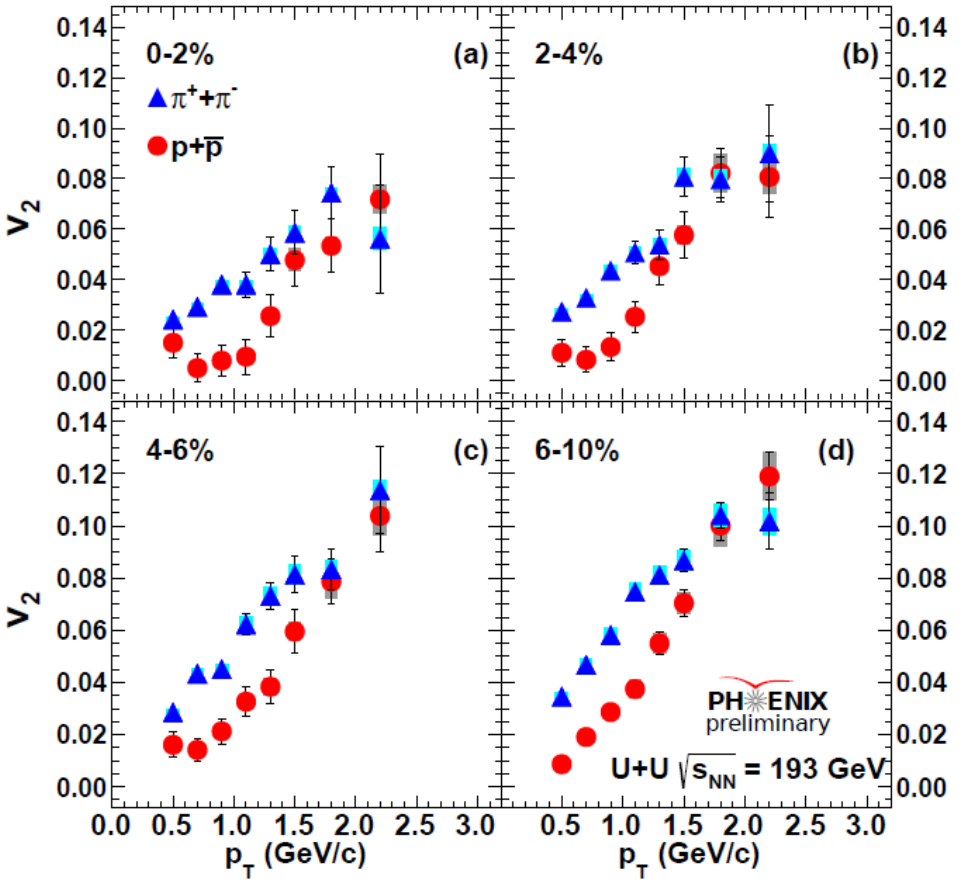
Phys. Rev. C 85, 064914 (2012)



0-2% central U+U

U+U

- Au+Au → very central U+U
  - Moderate increase of ε by 20% form 0-10 Au+Au to 0-1% U+U.
- mass ordering for pions and protons holds.
- Proton slope changes
  - Radial flow or geometry effect?
  - More studies underway.

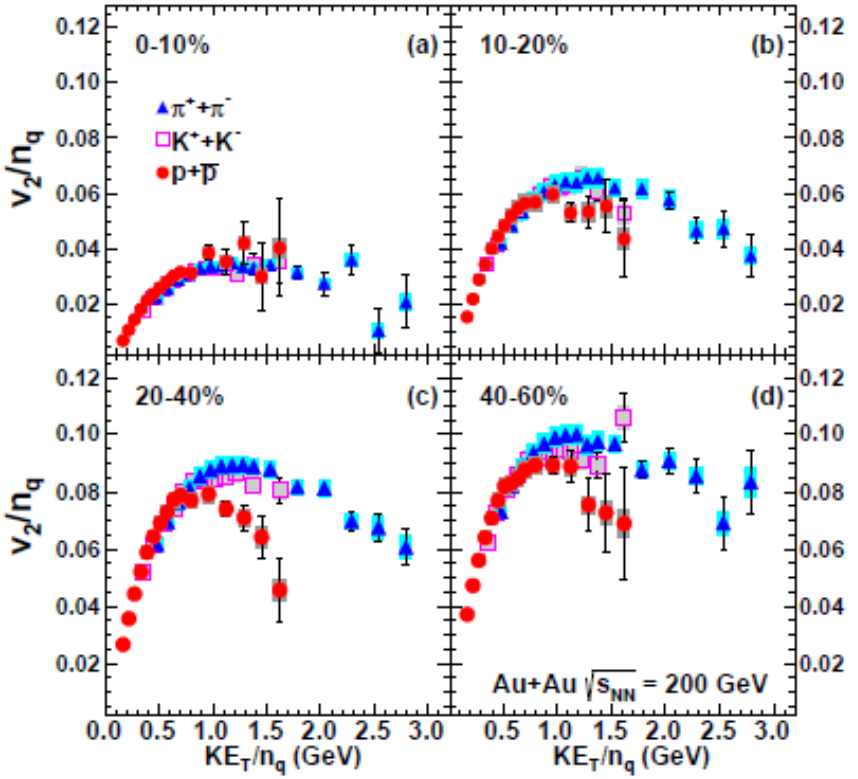


Quark scaling, n_q

Au+Au

- n_q scaling for v_2 of identified hadrons in Au+Au
  - Strong centrality dependence.
  - Holds to KE_T/n_q=1.5 GeV (0-10% central).
  - Breaks at KE_T>0.7 GeV (10-20% central).
- Qualitatively consistent with recombination model calculation.

PHENIX Phys. Rev. C 85, 064914 (2012)

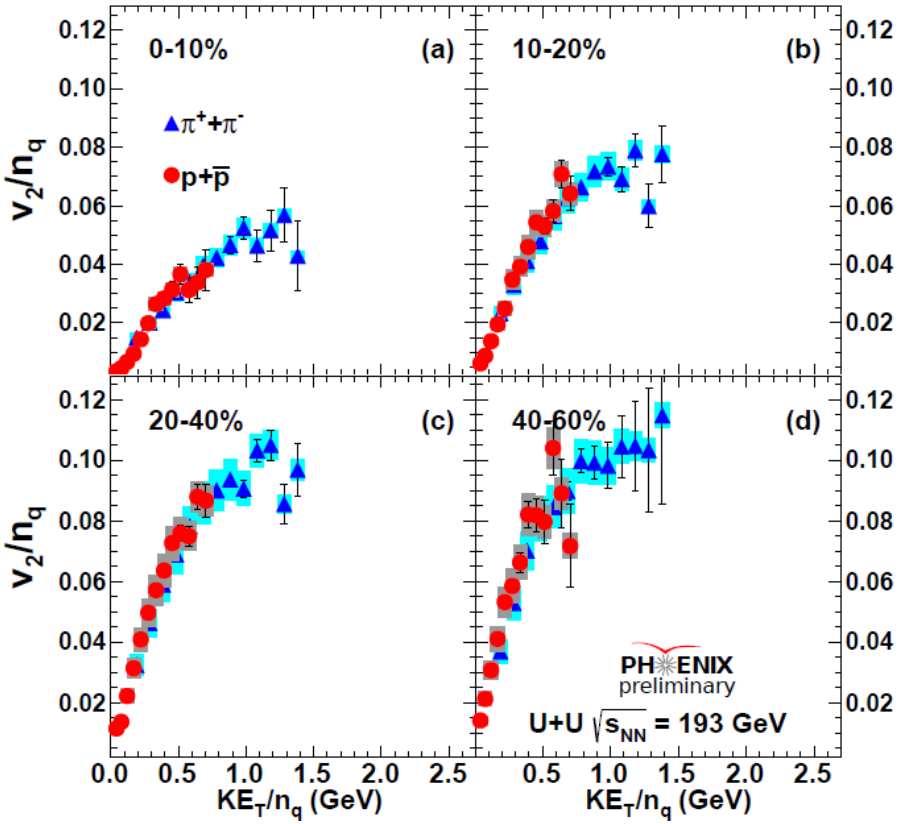


Quark scaling, n_q

U+U

- n_q scaling for v_2 of identified hadrons holds in U+U
  - For all centrality bins.

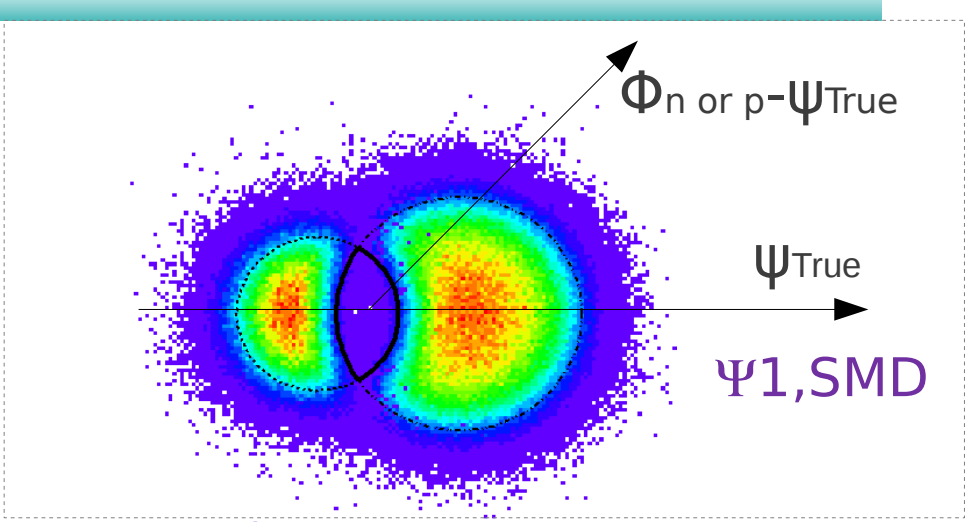
- Future measurement will extend the pion v_2 to lower p_T<0.5 GeV/c.

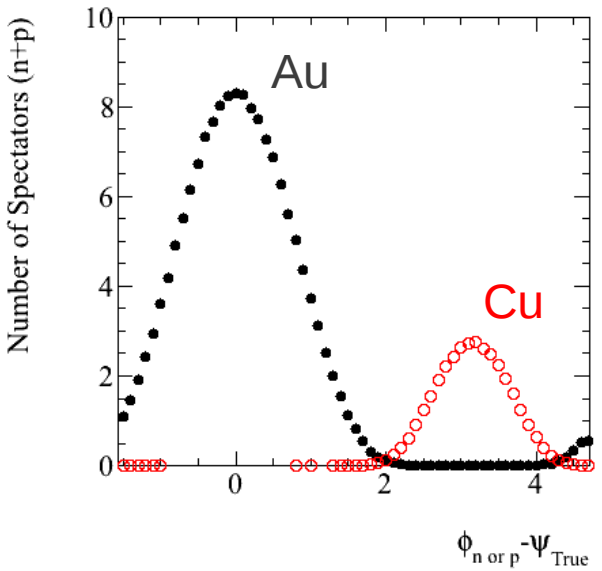


v_n measurements in Cu+Au

Cu+Au

- Asymmetric density profile will lead to asymmetric pressure gradient
  - Measure particle production relative to the Spectator(true) reaction plane.
- In data
  - Use the shower max in the ZDC (neutron).
  - Direction decided by the Au spectators.
  - Ψ1,SMD: combination of **Ψ1,*SMDSouth*** with flipped **Ψ1,*SMDNorth***.





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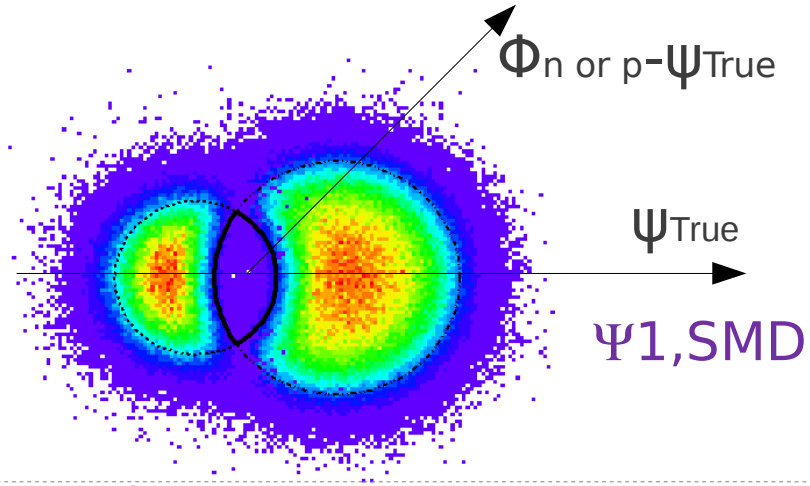
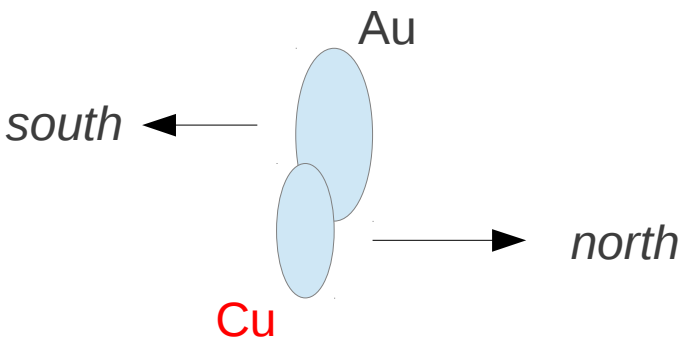
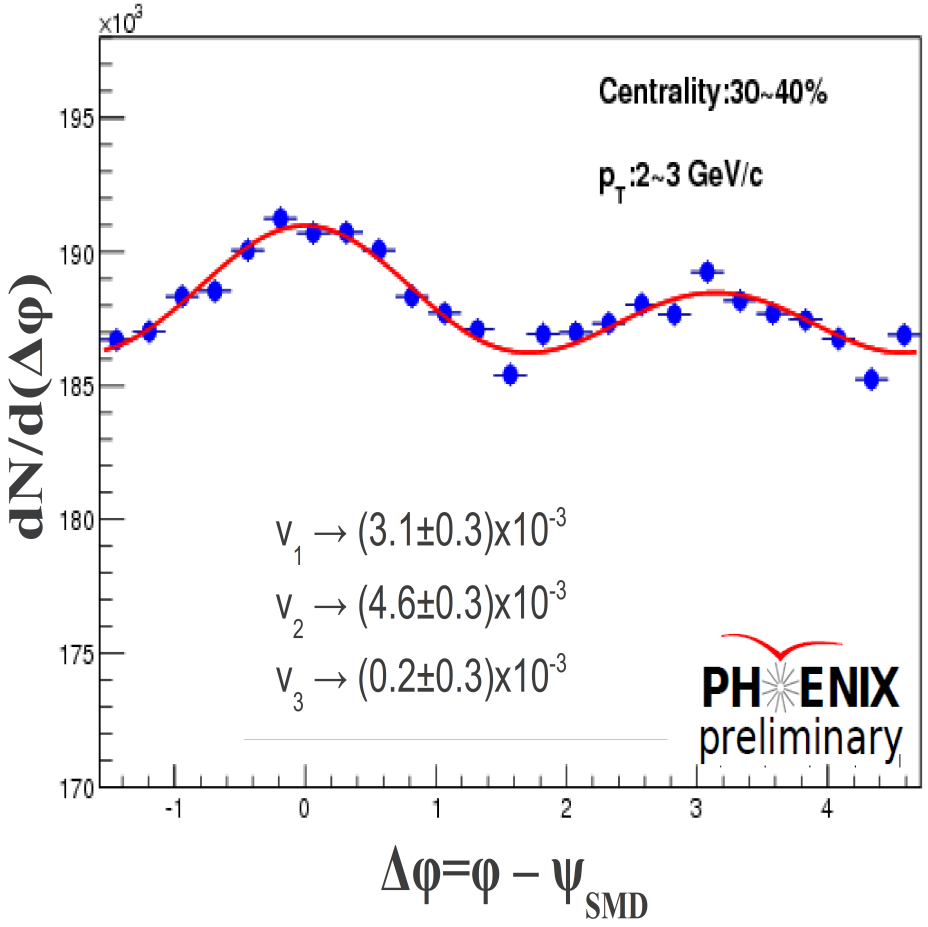




Hadron v_n

Cu+Au

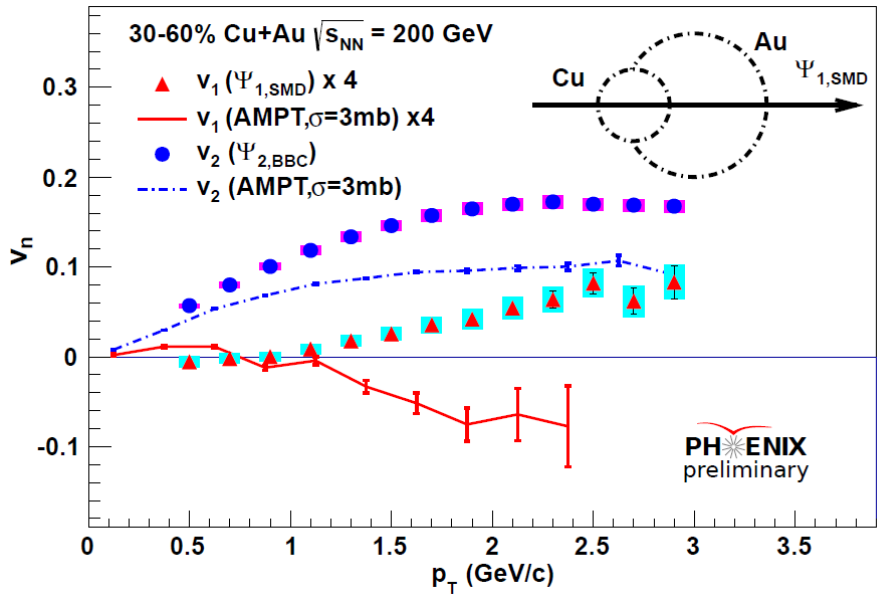
- An asymmetric dN/dΔϕ distribution is observed with Ψ1,SMD
  - more particles emitted from the Au side than from the Cu side.
- Hadrons at mid-rapidity (|η| <0.35) exhibit large v_1 and v_2 (not observed in Au+Au).
- Not consistent with a large v_3.



Modeling v_n

Cu+Au

- Comparison with AMPT at midrapidity
  - v_2 observed trends are expected.
  - Stronger v_1 (zero in AuAu)
    - Wrong sign.
    - Naively explained by the corona.

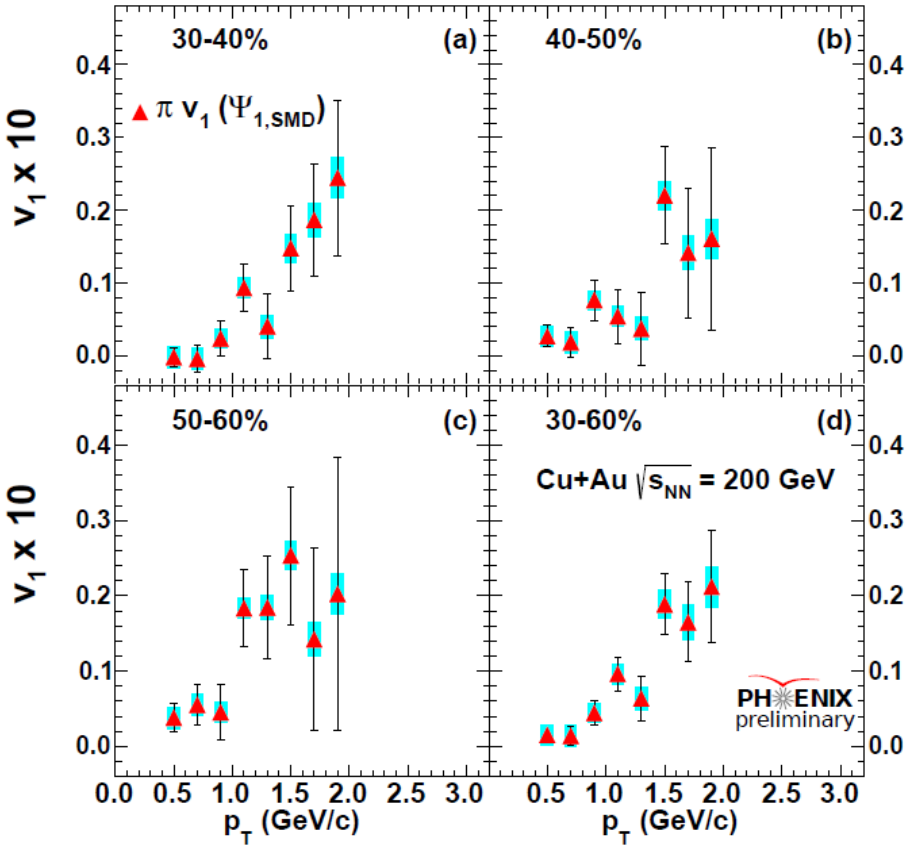


AMPT (v1.21) results calculated by H. Ruiz and J. Nagle with string melting cross section (□) of 3 mb

pion v_1

Cu+Au

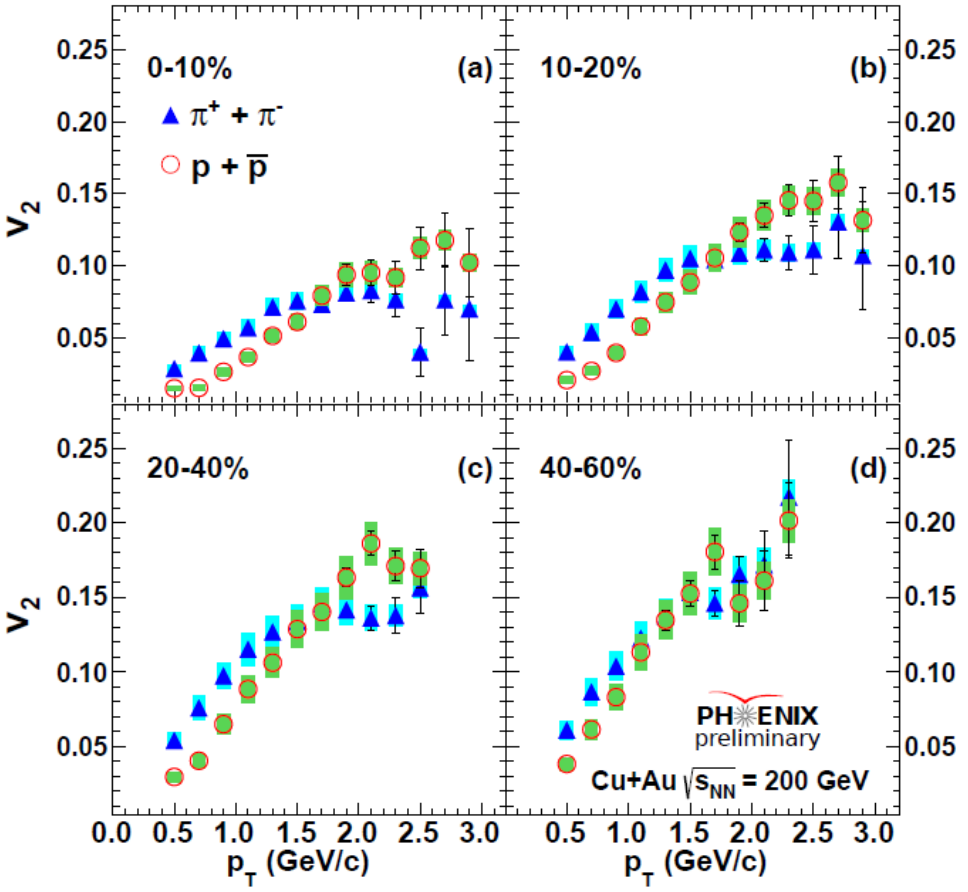
- Sizable positive pion v_1 is observed at $p_T > 1$GeV/c at midrapidity
  - Increases with p_T.
  - Observed in all centrality bins.
  - May be due to asymmetric density profile.
  - Need more statistics for proton.



pion and proton v_2

Cu+Au

- The v_2 of pions and protons are measured as a function of p_T and centrality
  - The v_2 measured from Ψ_1 and Ψ_2 are consistent with each other (Ψ_{BBC}).



pion and proton v_2

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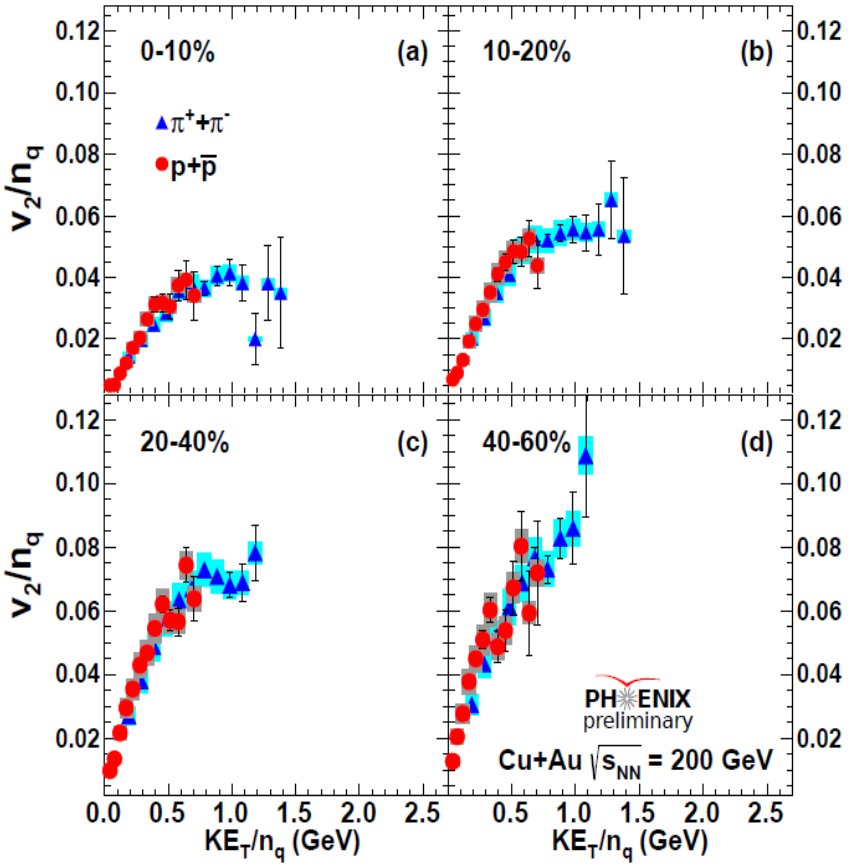
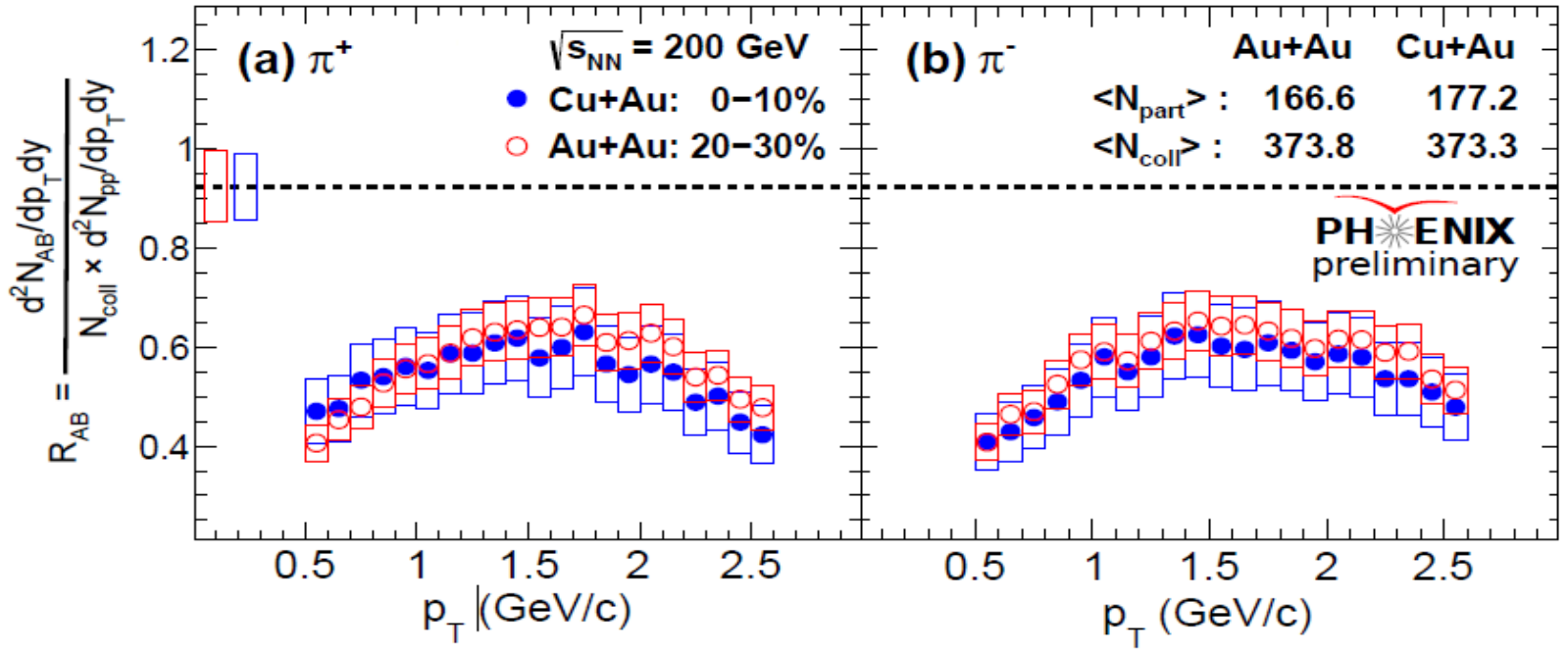
  - The v_2 measured from Ψ_1 and Ψ_2 are consistent with each other (Ψ_{BBC}).
  - The n_q scaling holds in Cu + Au collisions at 200 GeV.



Nuclear modification factor, R_{AB}

Cu+Au

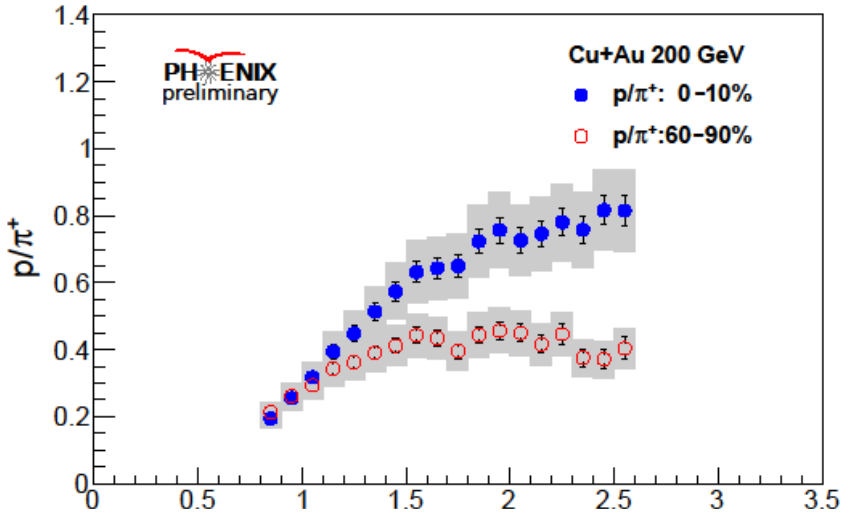
- Cu+Au comparable to Au+Au at the same Ncoll values.

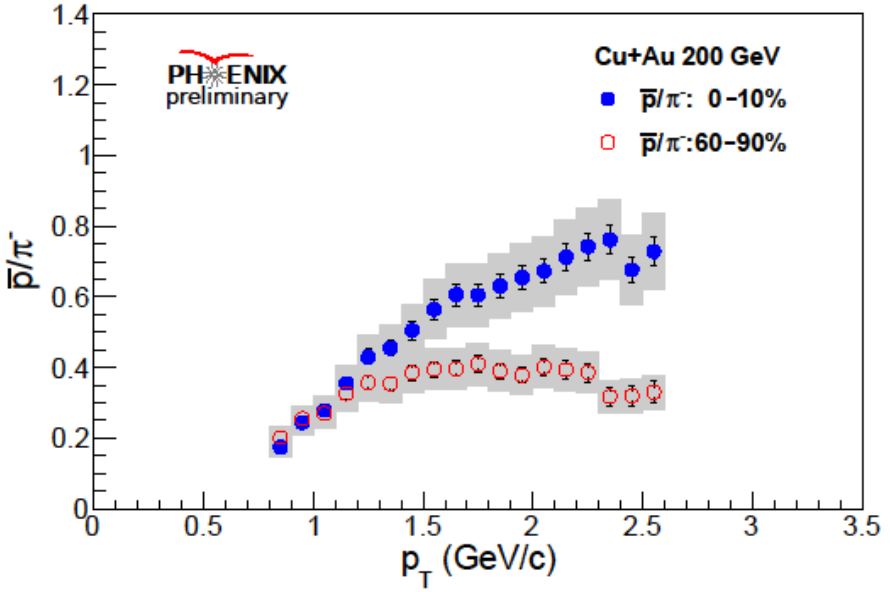


Baryon to meson ratio

Cu+Au

- Significant baryon enhancement in central collisions
  - Magnitude similar for positive and negative ratios.

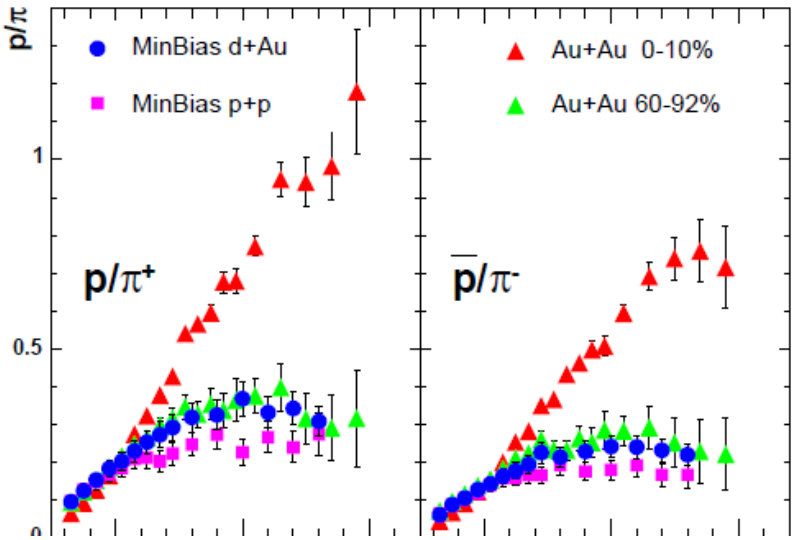


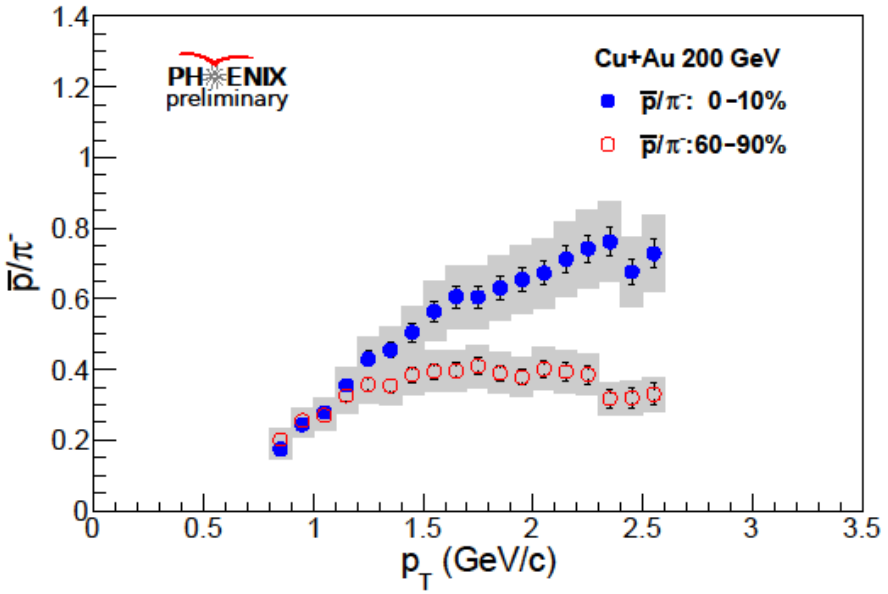


Baryon to meson ratio

Cu+Au

- Significant baryon enhancement in central collisions
  - Magnitude similar for positive and negative ratios.
  - Different from Au+Au and Cu+Cu at the same energy.

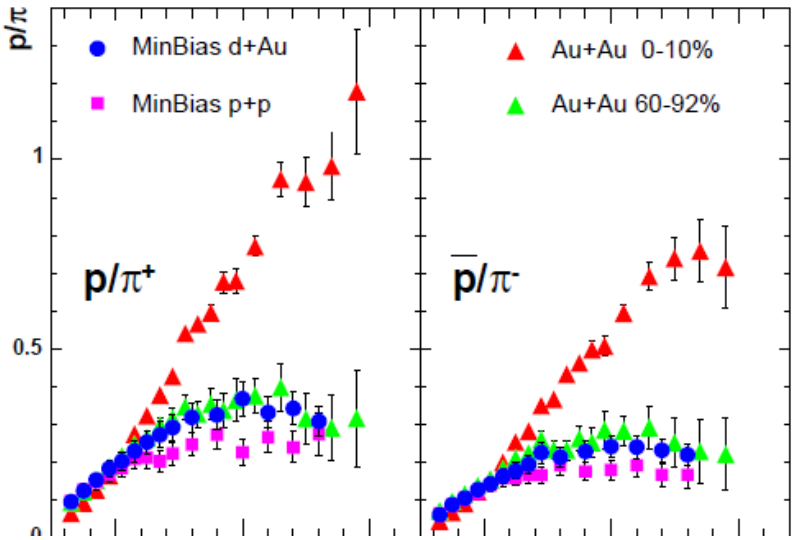


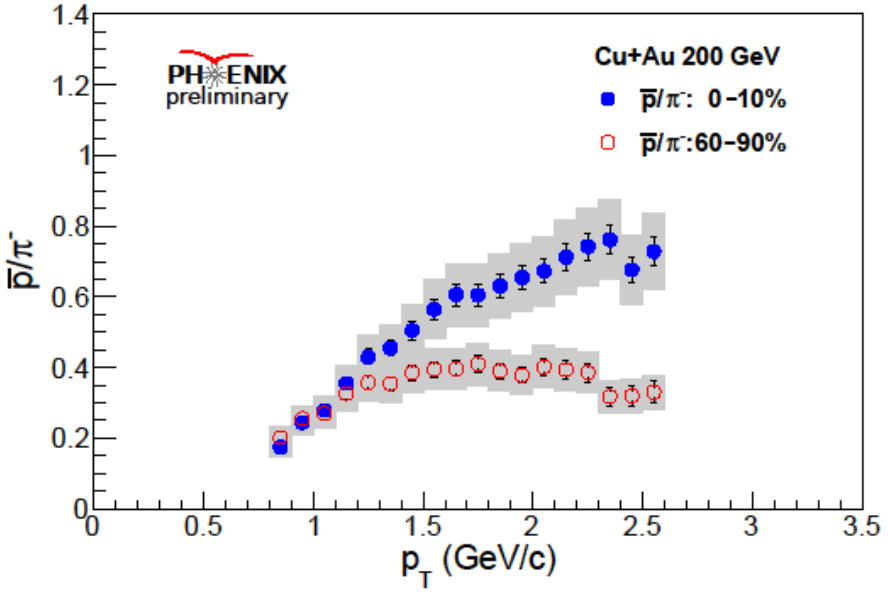


Baryon to meson ratio

Cu+Au

- Pbar/p ratio ***in symmetric systems*** depends on root s only, with small centrality and p_T dependence
  - 200 GeV ~ 0.8
  - 62.4 GeV ~0.5
- Pbar/p ratio in Cu+Au at 200 GeV ~ 0.9
  - Why less protons?
  - Higher ε at the same N_{part} than in a symmetric system.
  - Need further measurements!





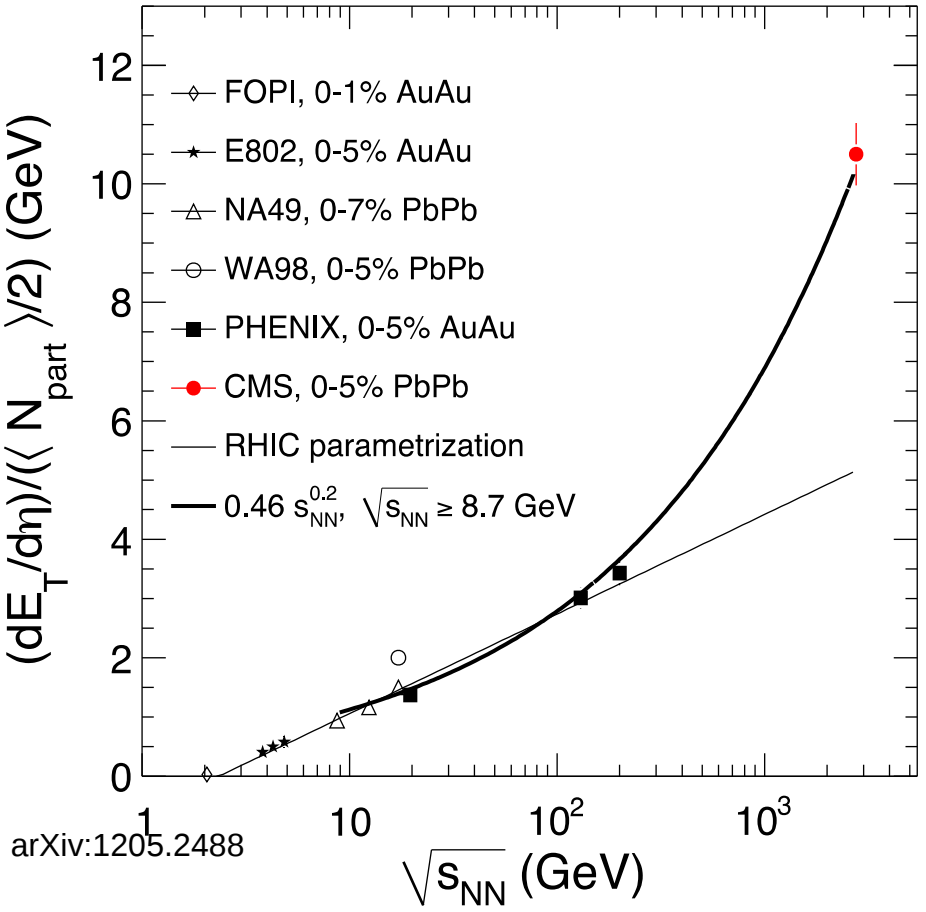
Summary

- First measurements at RHIC from two very unique systems.
- U+U at 193 GeV
  - The highest energy density reached at RHIC.
  - Exploring a way to separate tip-tip collisions.
- Cu+Au at 200 GeV
  - Non zero v_1 observed at mid-rapidity, no v_3.

- Many more results to come!

Backup

Transverse energy parametrization, LHC



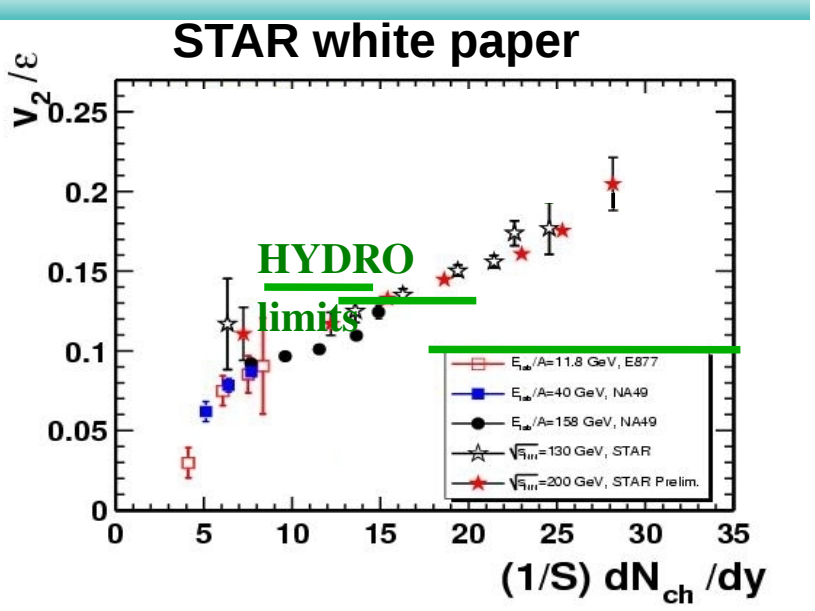
arXiv:1205.2488

U+U → Au+Au advantage

- Theoretical motivation
  - Initial geometry (Eccentricity) – flow studies
    - V2 driven by initial geometry
    - V2/e in central Au as predicted by ideal hydro

    Crusial test: increase the en density, what happens to v2/e

  - Path length – parton energy loss studies



- The medium density in U+U is 35-55% higher than in Au+Au
  - Difference in the overlap area, S

    b=0, S(tip-tip) same as S(Au+Au)

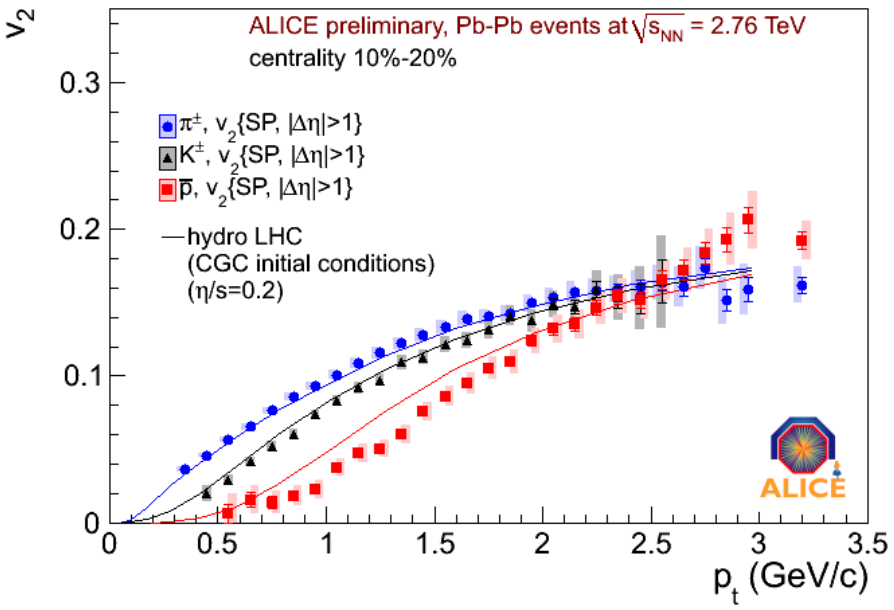
    S(body-body) 24% higher than S(Au+Au)
  - Difference in Nch ~Npart

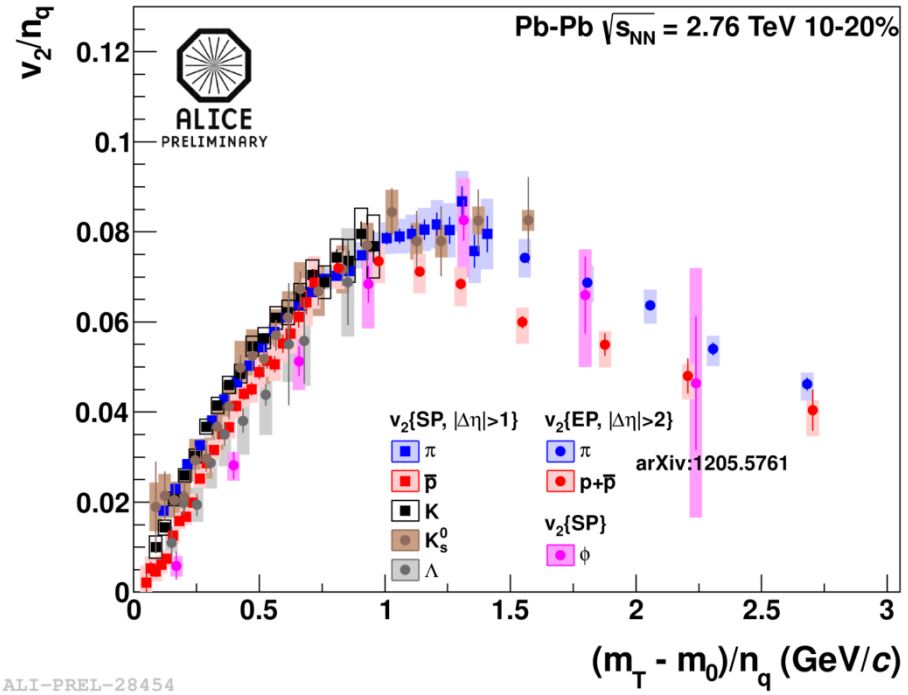
Transverse Nch density

- dNch/dy/S tip-tip 42.6 fm-2, Body-body 31.7 fm-2, Au_Au 31.5 fm-2
- PRC 73, 034911 (2006)

ALICE v_2

M. Krzewicki@ALICE QM2011

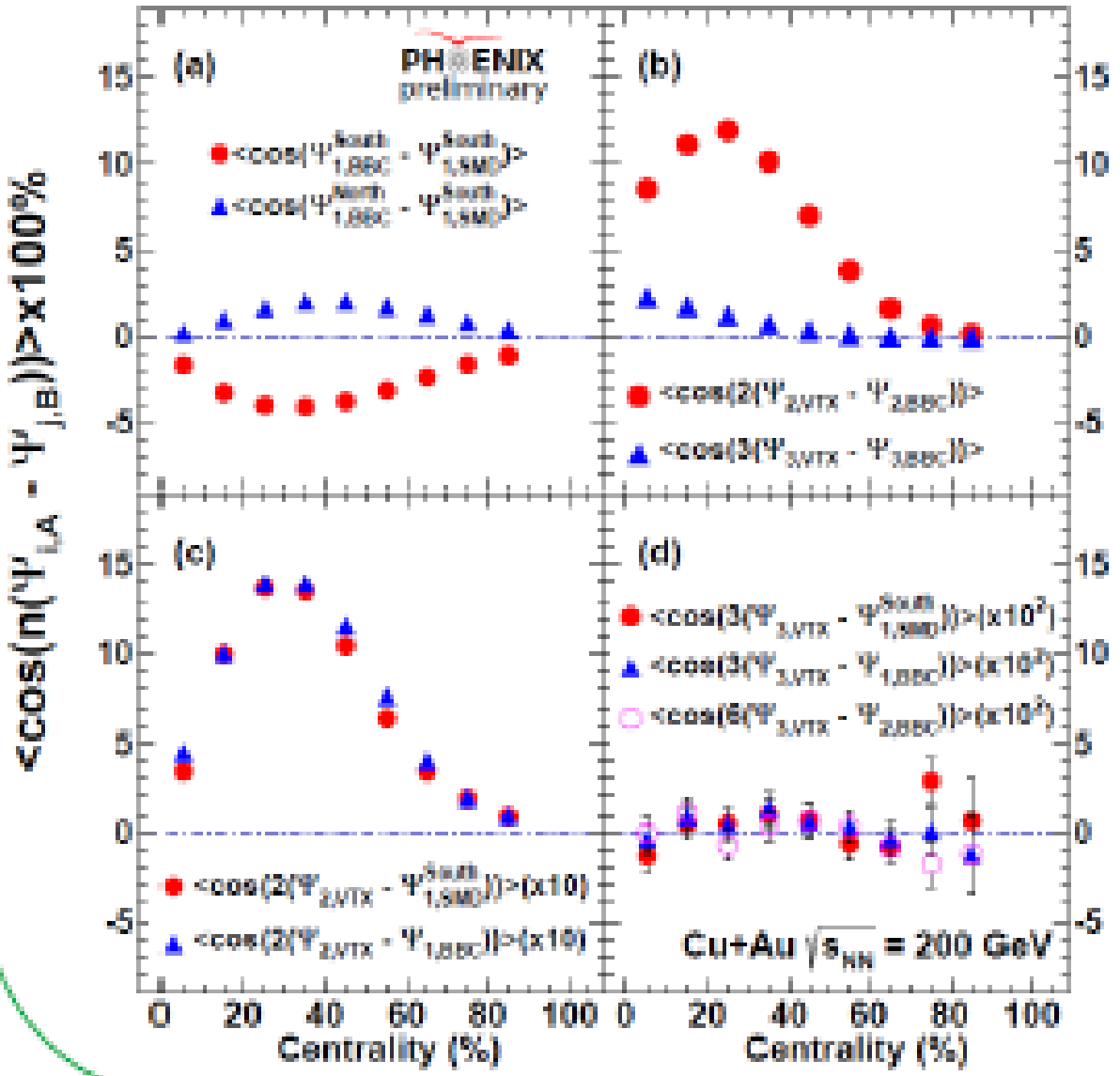




*n*q(*m*T)-scaling worse than at RHIC

*n*q(*p*T)-scaling at *p*T > 1.2 GeV/*c* violation 10–20%

3. Event plane correlation



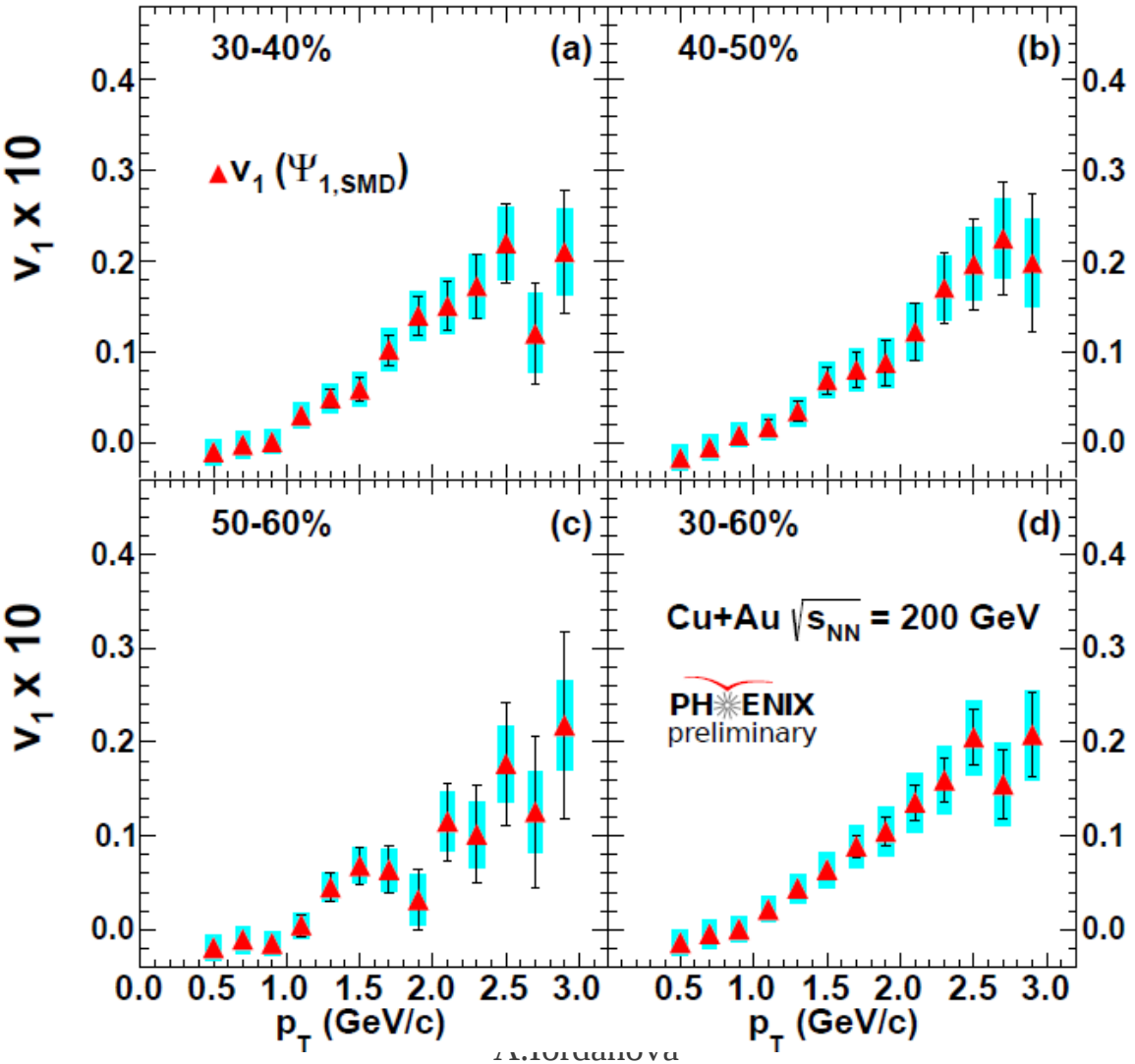
1. The correlation between $\Psi_{1,\mathrm{BBC}}^{South}$, measured by the south BBC in the Au-going direction, and $\Psi_{1,\mathrm{SMD}}^{South}$ is stronger than the correlation between $\Psi_{1,\mathrm{BBC}}^{North}$ in the Cu-going direction and $\Psi_{1,\mathrm{SMD}}^{South}$. It indicates that v_1 is larger in the Au-going direction than that of Cu-going direction

2. The raw correlation of Ψ_3 with Ψ_1 and Ψ_2 are pretty weak

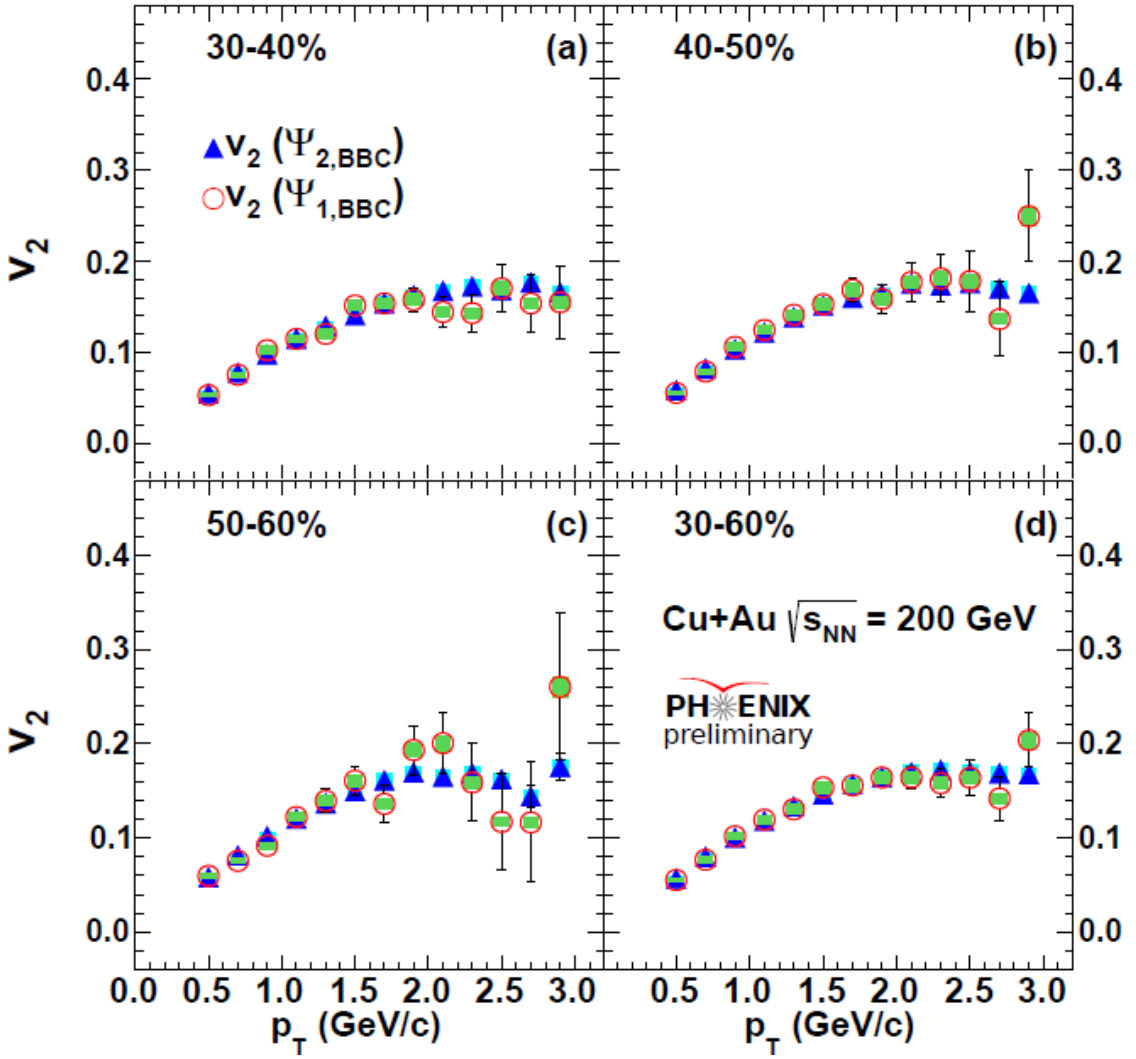
South : Au-going
North: Cu-going

Find a better plot

Hadron v_1


30-40%
(a)
v_1 ($\Psi_{1,SMD}$)
40-50%
(b)
50-60%
(c)
30-60%
(d)
Cu+Au $\sqrt{s_{NN}}$ = 200 GeV
PHENIX
preliminary
v_1 x 10
p_T (GeV/c)

Hadron v_2

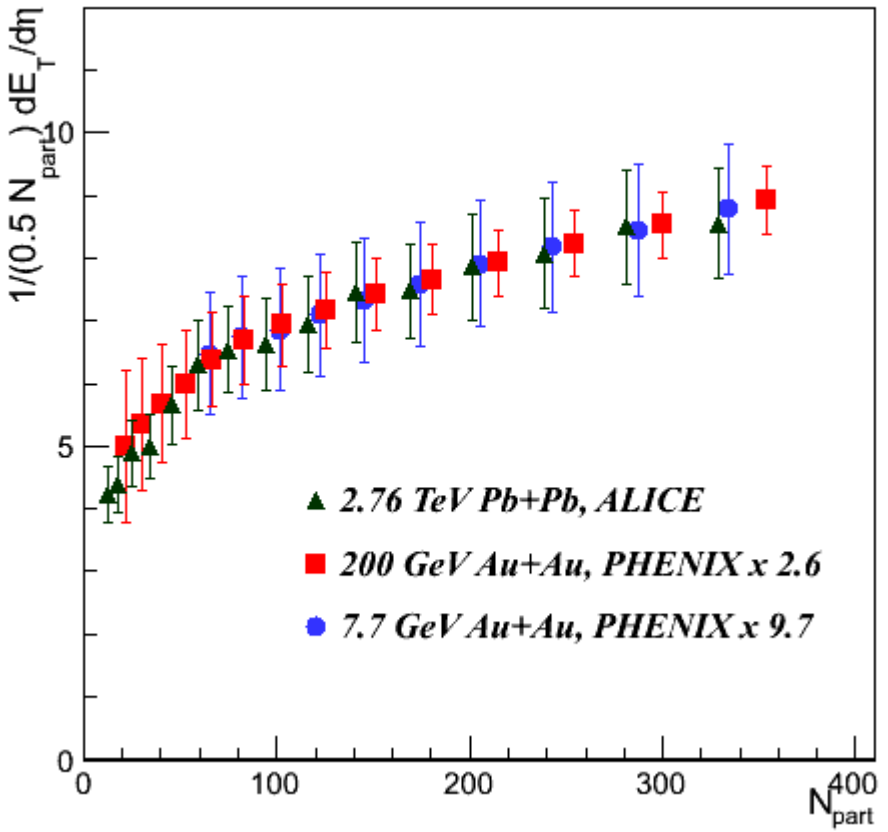

30-40%
(a)
v_2 ($\Psi_{2,BBC}$)
v_2 ($\Psi_{1,BBC}$)
40-50%
(b)
50-60%
(c)
30-60%
(d)
Cu+Au $\sqrt{s_{NN}}$ = 200 GeV
PHENIX
preliminary
v_2
p_T (GeV/c)
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0
2.5
3.0

Transverse energy density, E_T

- Transverse energy production
  - increases with increasing collision energy.
  - There is an increase in for more central collisions at all collision energies.
  - The Au+Au and U+U particle E_T are similar.

- No significant change in the shape of the centrality-dependence from 7.7 GeV Au+Au collisions up to 2.76 TeV Pb+Pb collisions
  - collision geometry is driving the centrality dependence

mid-rapidity



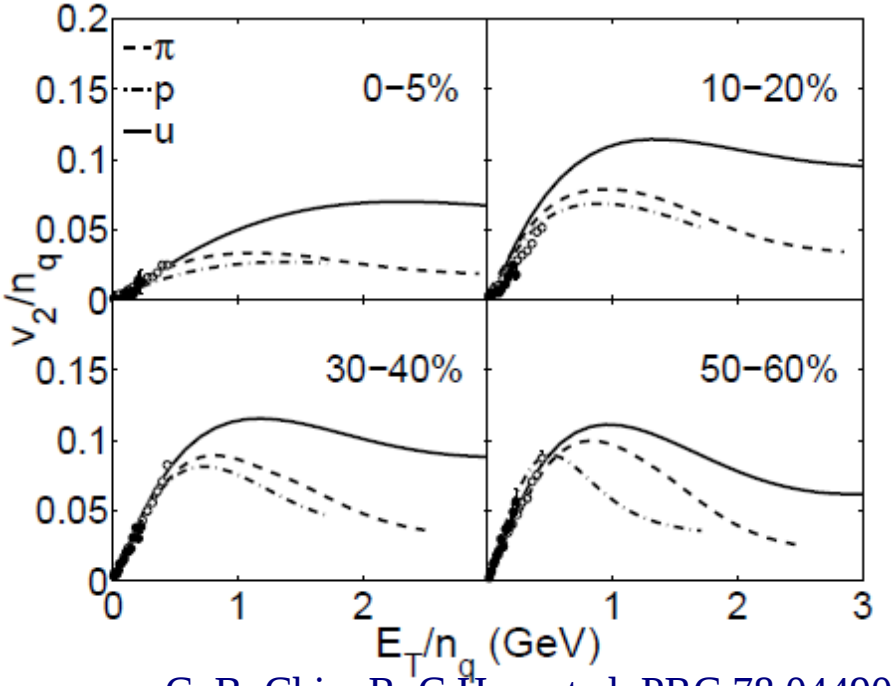
Upper U+U point 1% most central, all other 5% centrality bins

Run 12 parameters

species	s	wks	+_30cm	+-10	motivation
U+U	193	2.9	171.2 μb-1	89.9 μb-1	explore geometry
Cu+Au	200	5.5	4.96 nb-1	2.47 nb-1	control geometry

Quark scaling, n_q

- n_q scaling for v_2 of identified hadrons in Au+Au
  - Strong centrality dependence
  - Holds to kE_T/n_q=1.5 GeV (0-10% central)
  - Breaks at kE_T>0.7 GeV (10-20% central)
- Qualitatively consistent with recombination model calculation



C. B. Chiu, R. C Hwa et al. PRC.78.044903