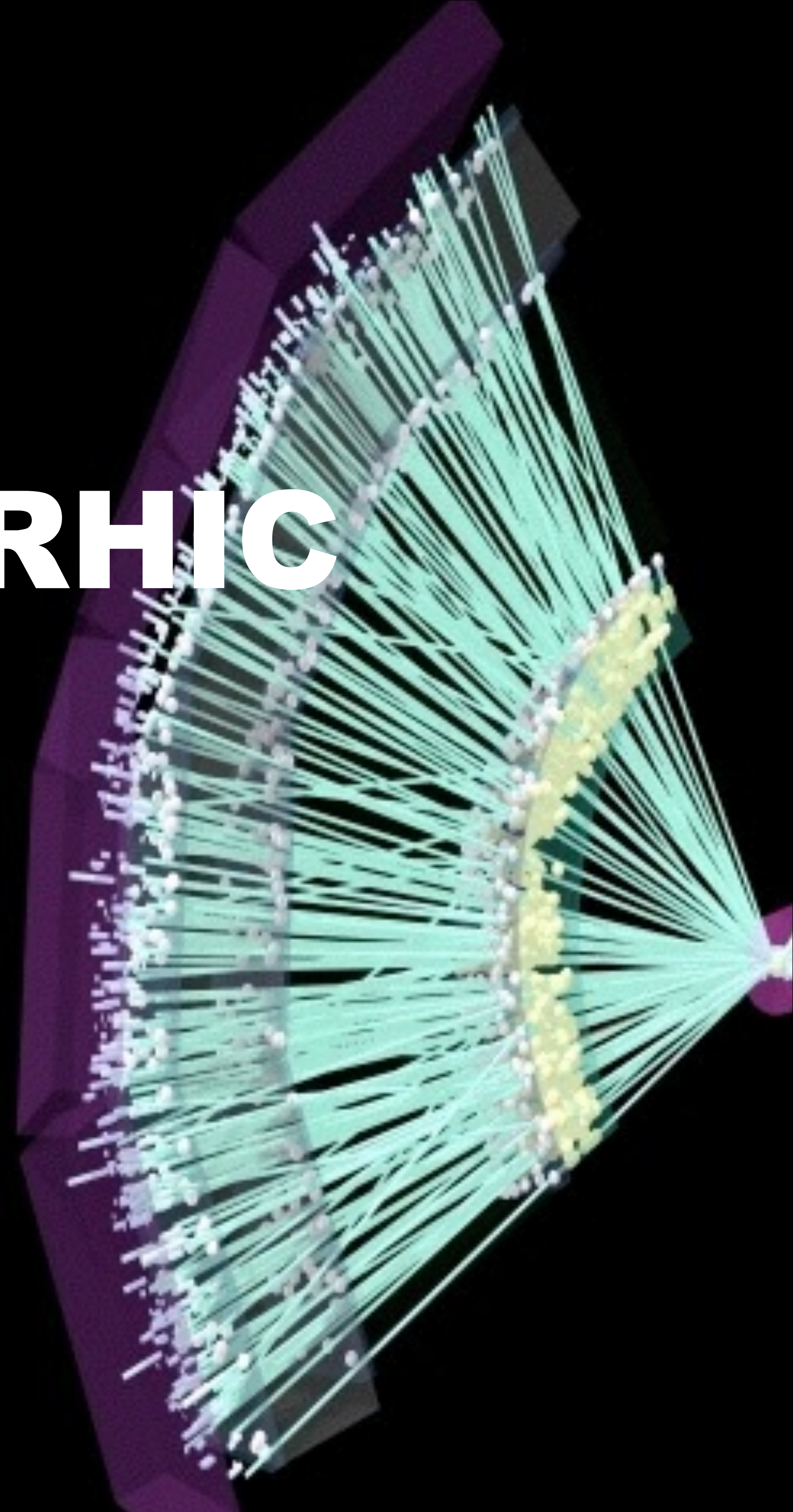
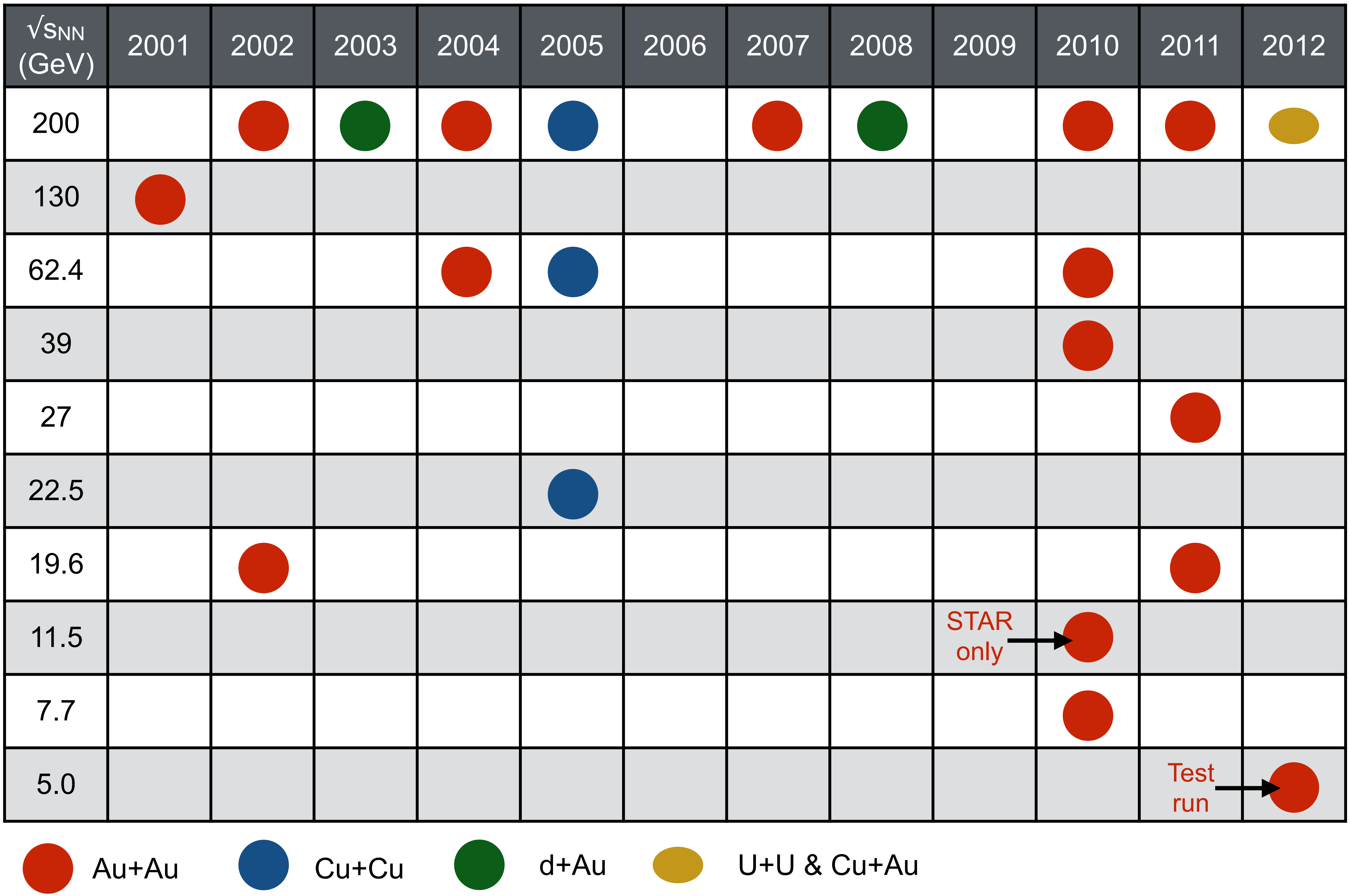


Soft physics at RHIC

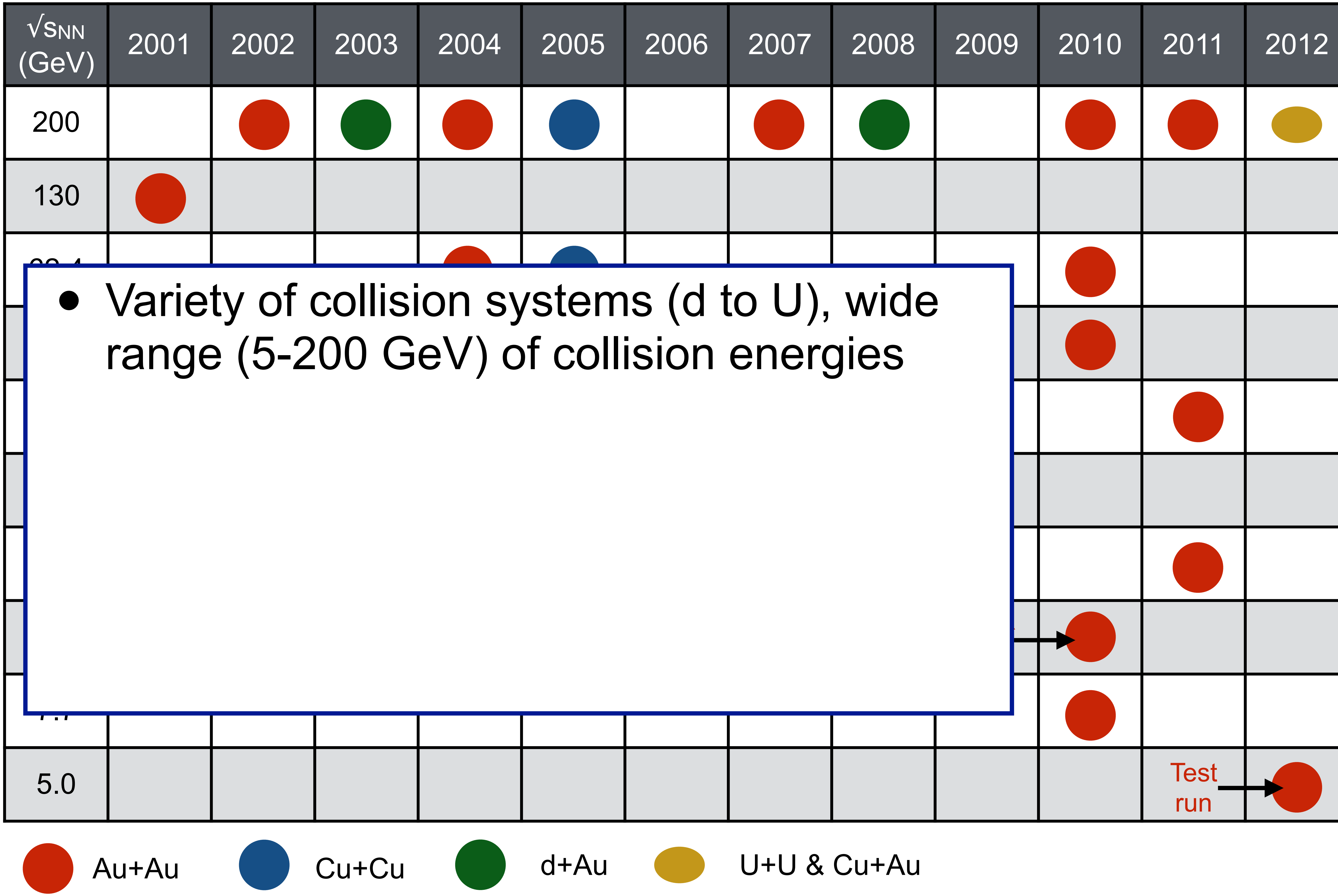
Hiroshi Masui,
University of Tsukuba

Fall KPS meeting, Nov. 2013

RHIC heavy ion collisions

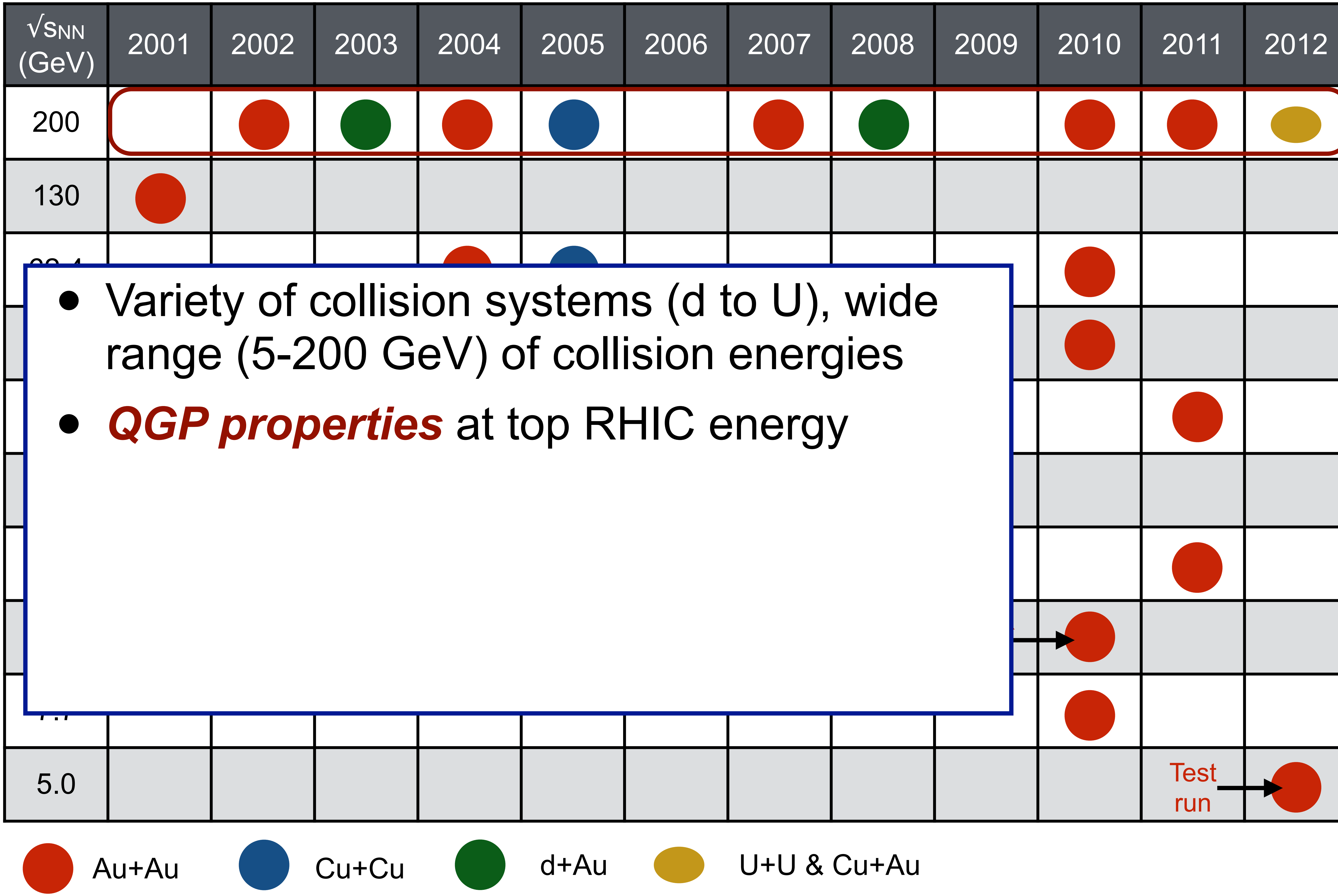


RHIC heavy ion collisions



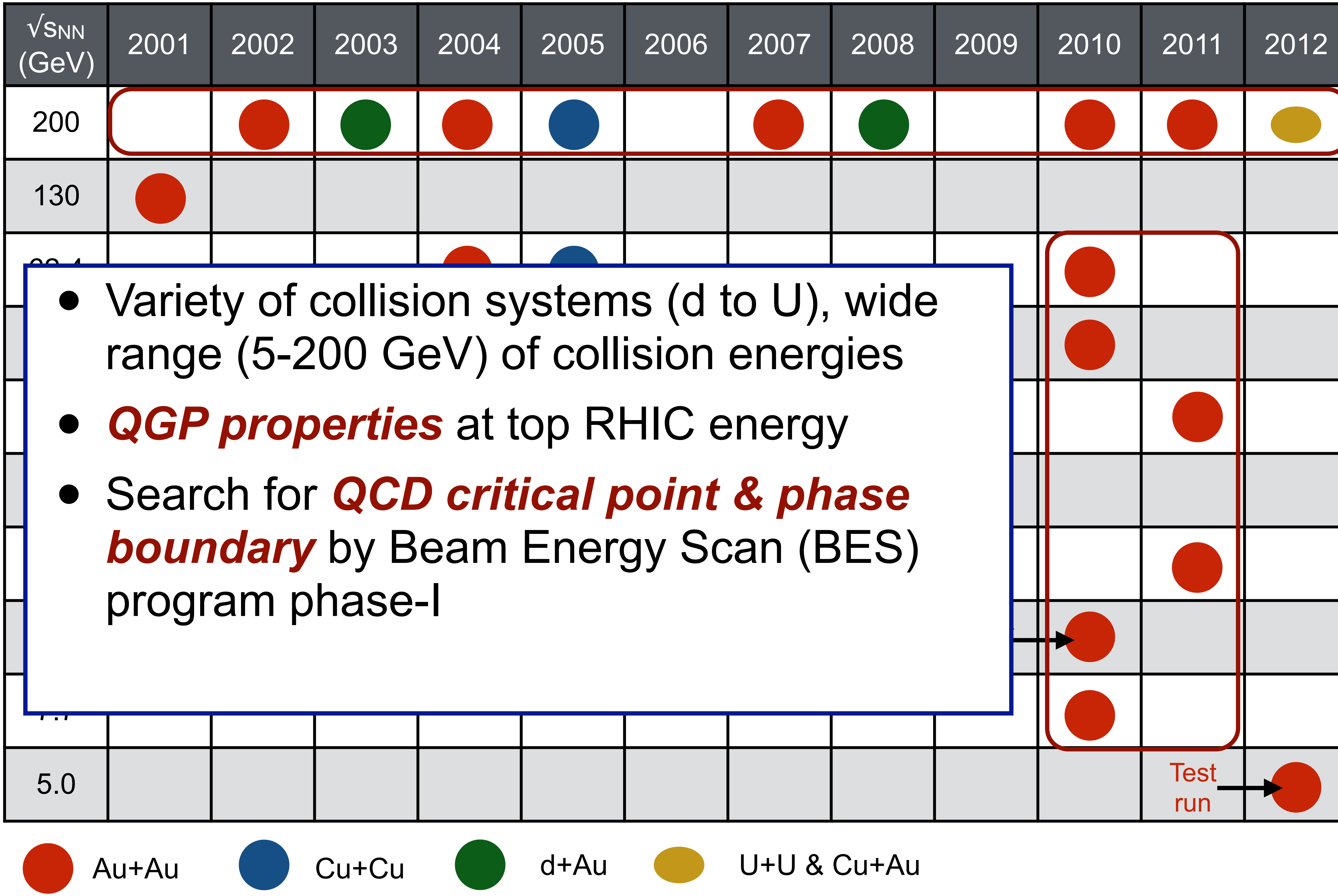
- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies

RHIC heavy ion collisions



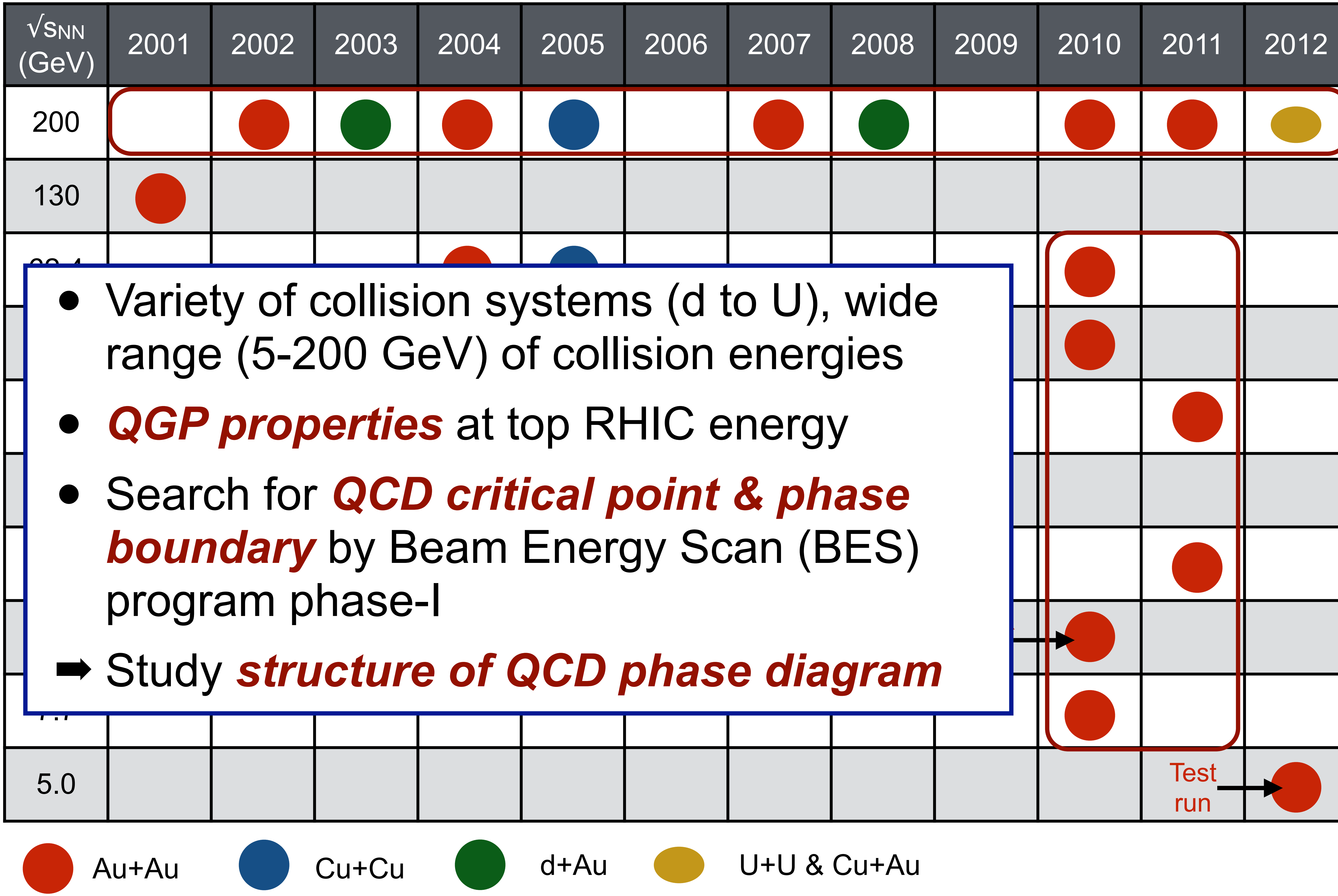
- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
- ***QGP properties*** at top RHIC energy

RHIC heavy ion collisions



- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
- ***QGP properties*** at top RHIC energy
- Search for ***QCD critical point & phase boundary*** by Beam Energy Scan (BES) program phase-I

RHIC heavy ion collisions



- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
- ***QGP properties*** at top RHIC energy
- Search for ***QCD critical point & phase boundary*** by Beam Energy Scan (BES) program phase-I

➡ Study ***structure of QCD phase diagram***

Multi-particle correlations

- Powerful tools to study the bulk properties of the system
  - Azimuthal anisotropy

    $\langle e^{in\phi}e^{-in\psi}\rangle \rightarrow \langle v_n^2\rangle$ Initial geometry (+fluctuations), shear viscosity

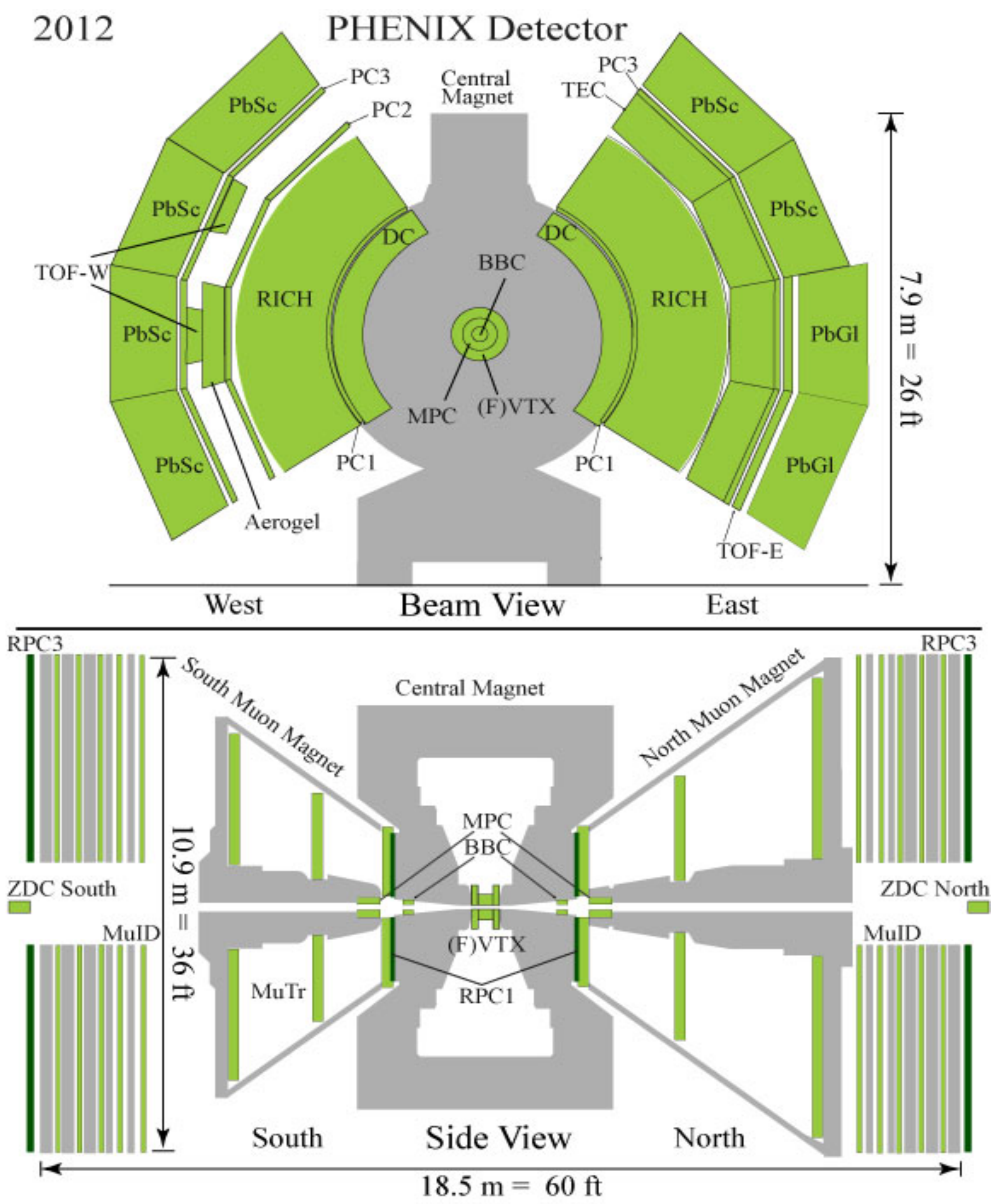
    $\langle e^{i\phi_1}e^{i\phi_2}e^{-i2\psi}\rangle \rightarrow \langle a_1^2\rangle$ Local parity violation, chiral magnetic effect
  - Femtoscopy (identical bosons)

    $\langle \rho_1(x)\rho_2(x)\rangle \rightarrow 1 + e^{-R^2q^2}$ Source size, geometrical anisotropy at freeze-out
  - Conserved charge fluctuations

    $\langle (N-\overline{N})^2\rangle \rightarrow \chi_2$ Susceptibility, QCD critical point

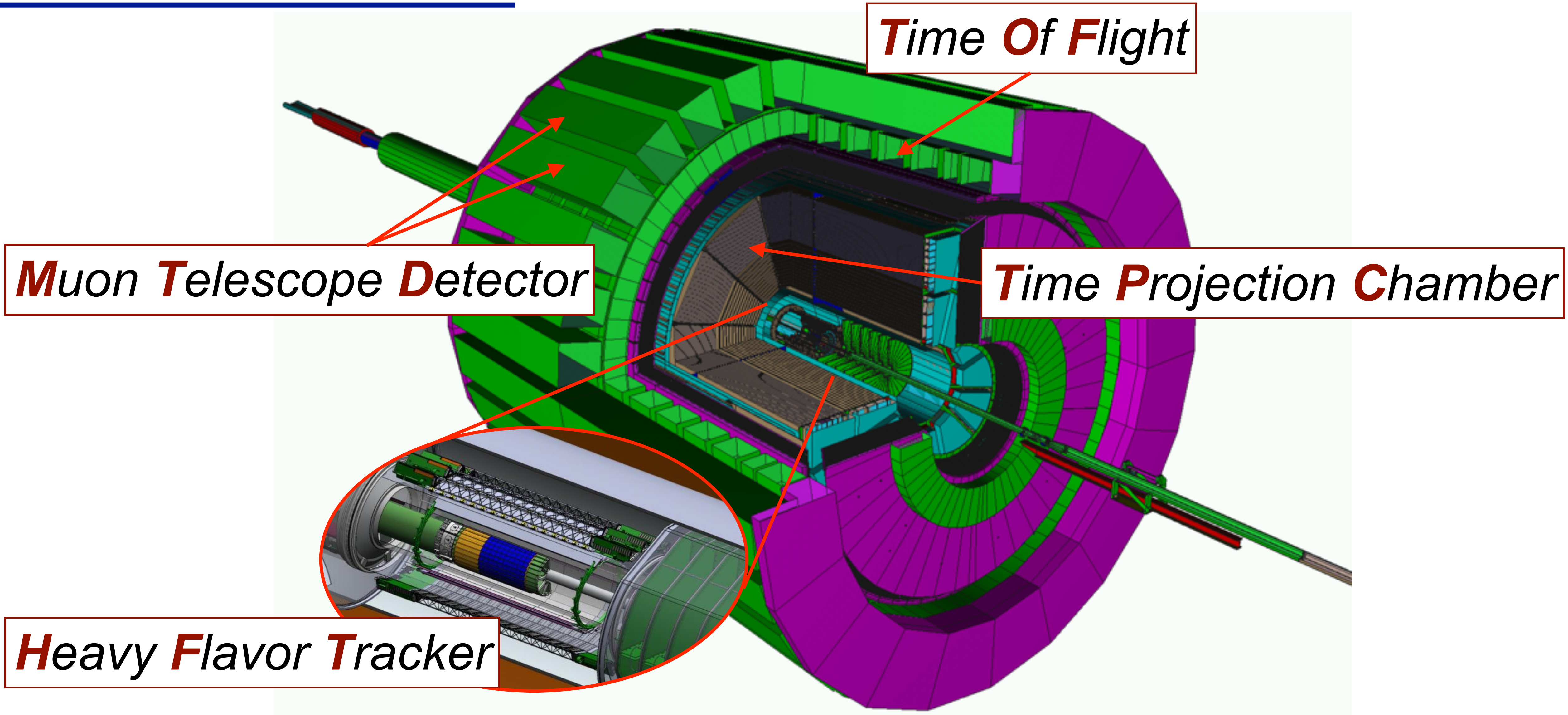
- I'm going to review the recent correlation measurements from RHIC

PHENIX

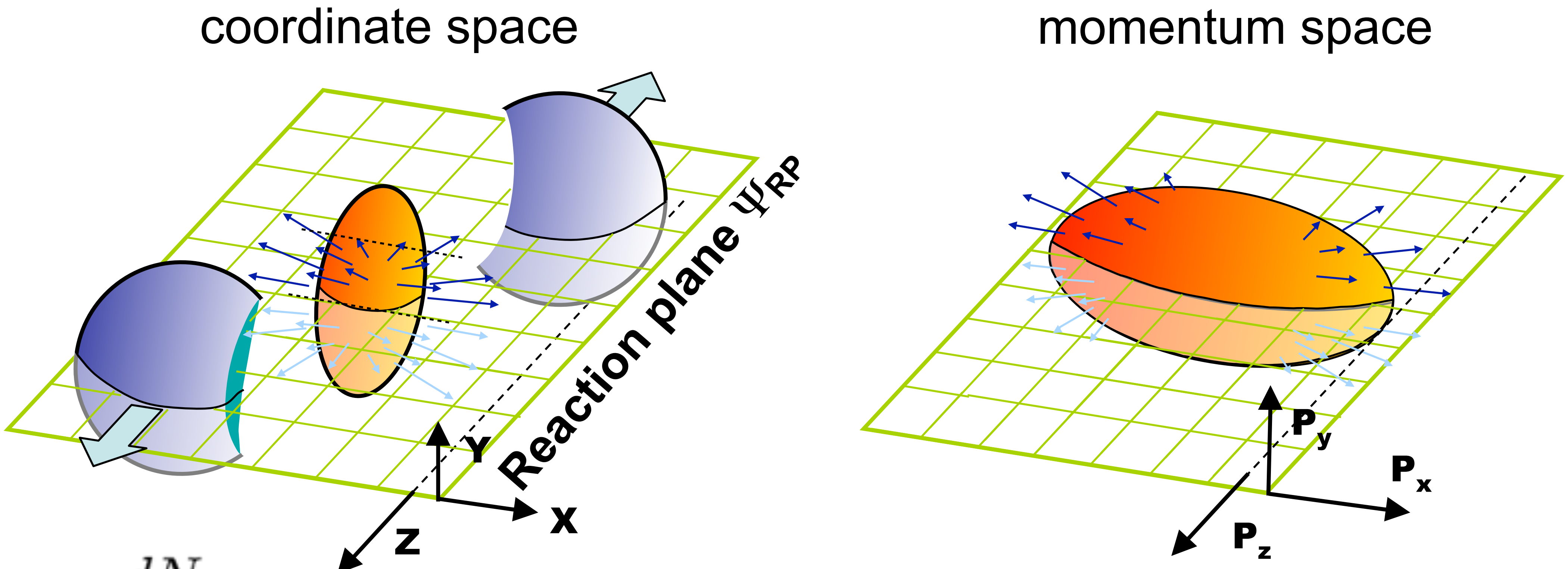


- Fast triggers
  - Hard probes by electrons & photons
- TOF + EMC + Aerogel
  - hadrons
- Forward beam counters (BBC, MPC, RXN)
  - support measurements of azimuthal anisotropy
  - large pseudorapidity gap reduces 'non-flow' effects
- VTX, FVTX
  - heavy flavors

STAR



- Large acceptance - Time Projection Chamber (TPC)
- PID capabilities have been (will be) significantly improved
  - TOF (2009-) - charged hadrons
  - MTD (2013-) - muons
  - HFT (from 2014) - heavy flavors



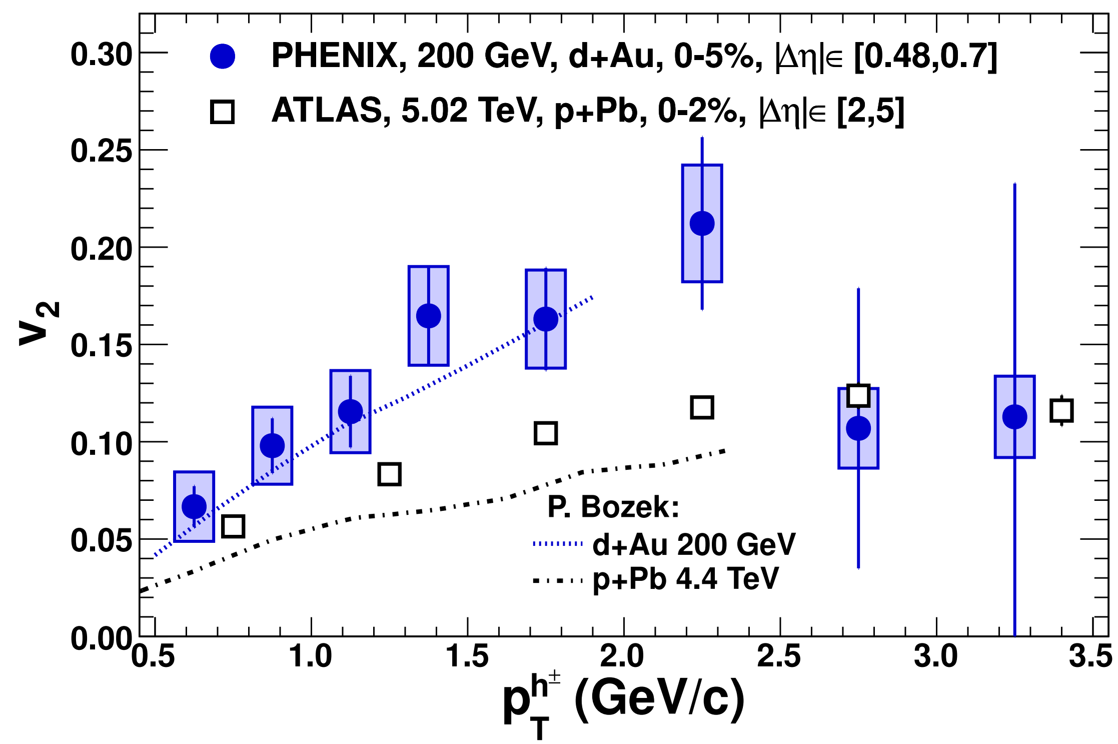
$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots$$

Azimuthal anisotropy

Flow in d+Au ?

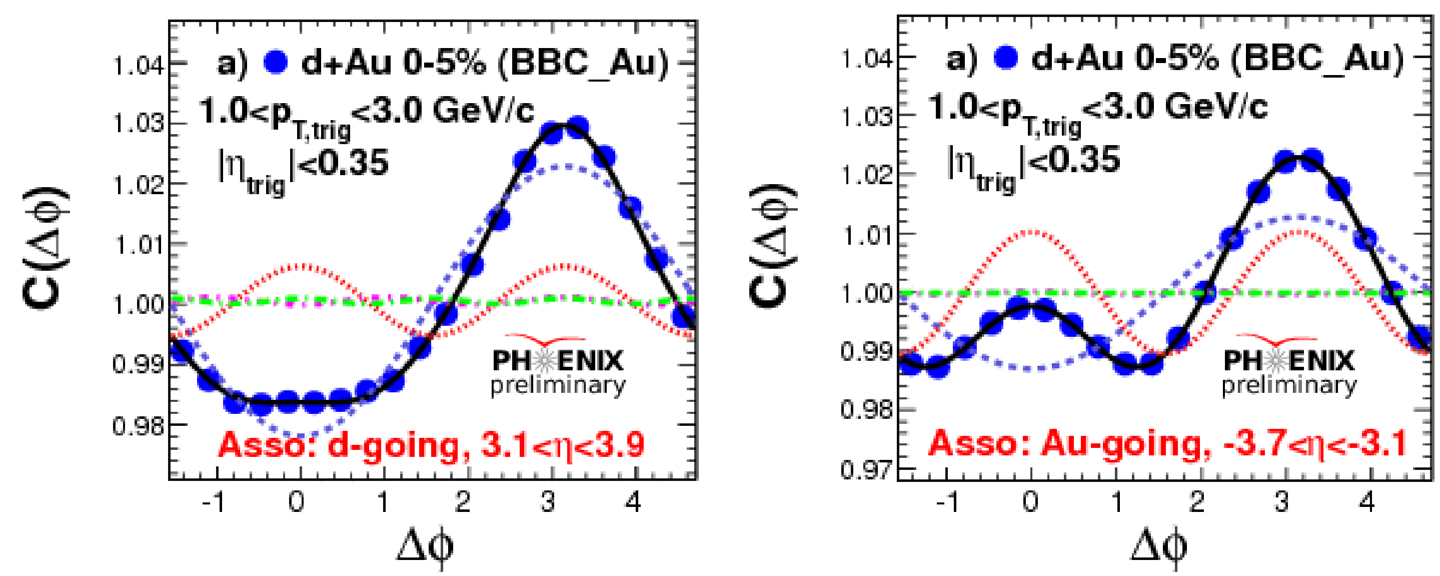
PHENIX, arXiv:1303.1794v1 [nucl-ex]

$|\Delta\eta|$=0.48-0.7



PHENIX, IS2013

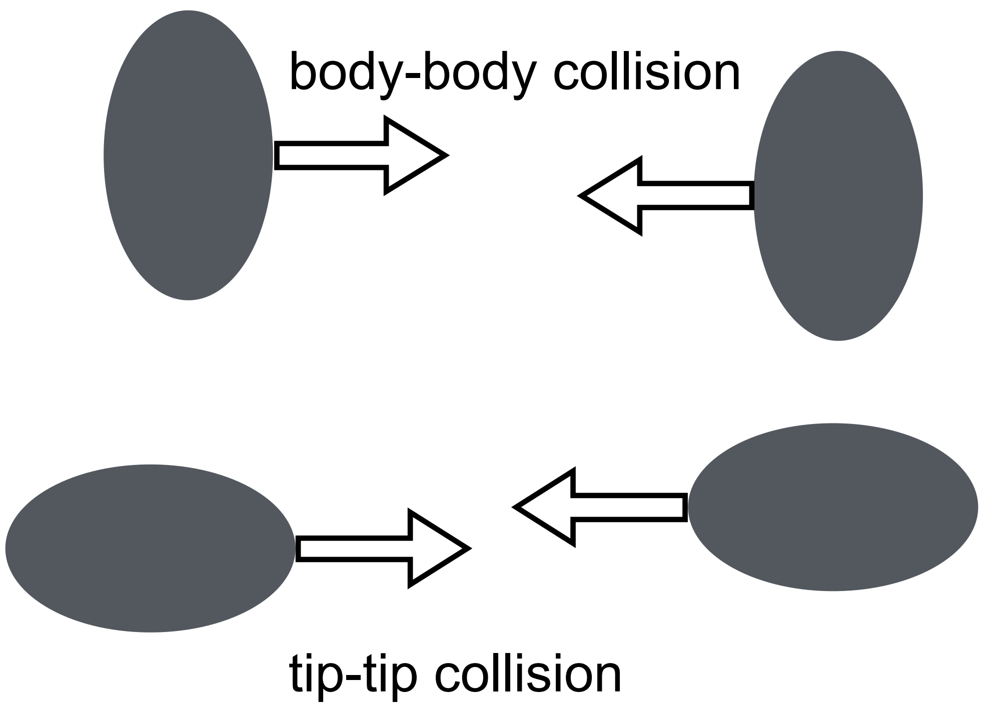
$\Delta\eta$>3



- Large v_2 in 0-5% d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
- Near side correlation in 0-5% on Au-going side
  - No near side peak on d-going side
  - Need to understand away side jet contributions to extract v_n
- Interesting to see the centrality dependence
  - (Two-particle) non-flow scales like 1/N

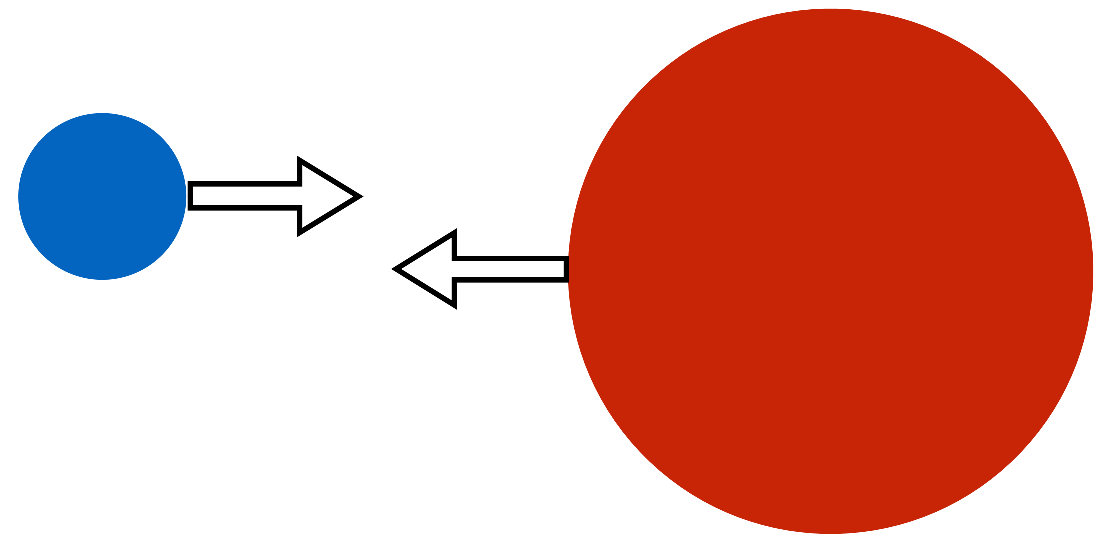
Geometry control

Collisions with deformed nuclei; U+ U



* Average deformation of Uranium ~ 28%
Cu ~ 16%, Au ~ -13%

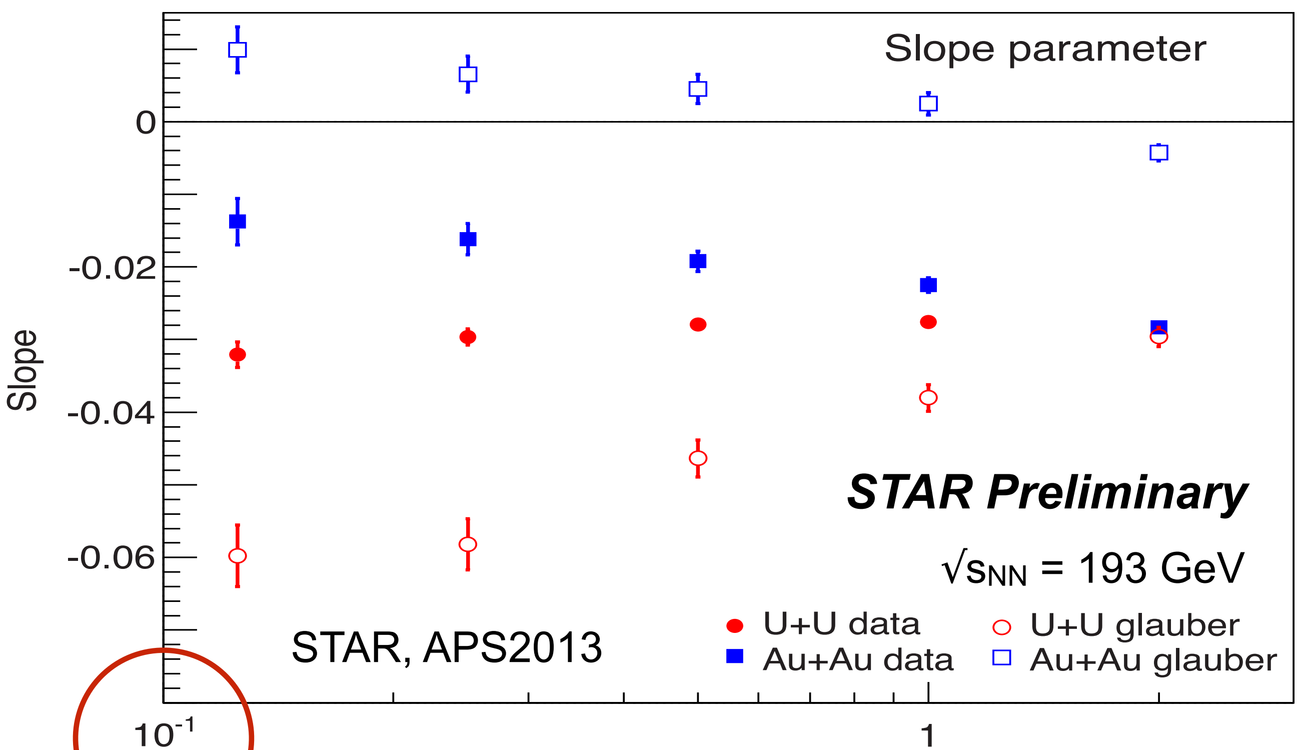
Asymmetric collisions; Cu + Au



- Test the relation between initial geometry and final momentum anisotropy
  - Achieve higher density in deformed collisions with the same energy
  - Path length dependence
  - Finite odd harmonics from geometry overlap
  - Control magnetic field (test chiral magnetic effect)

Results

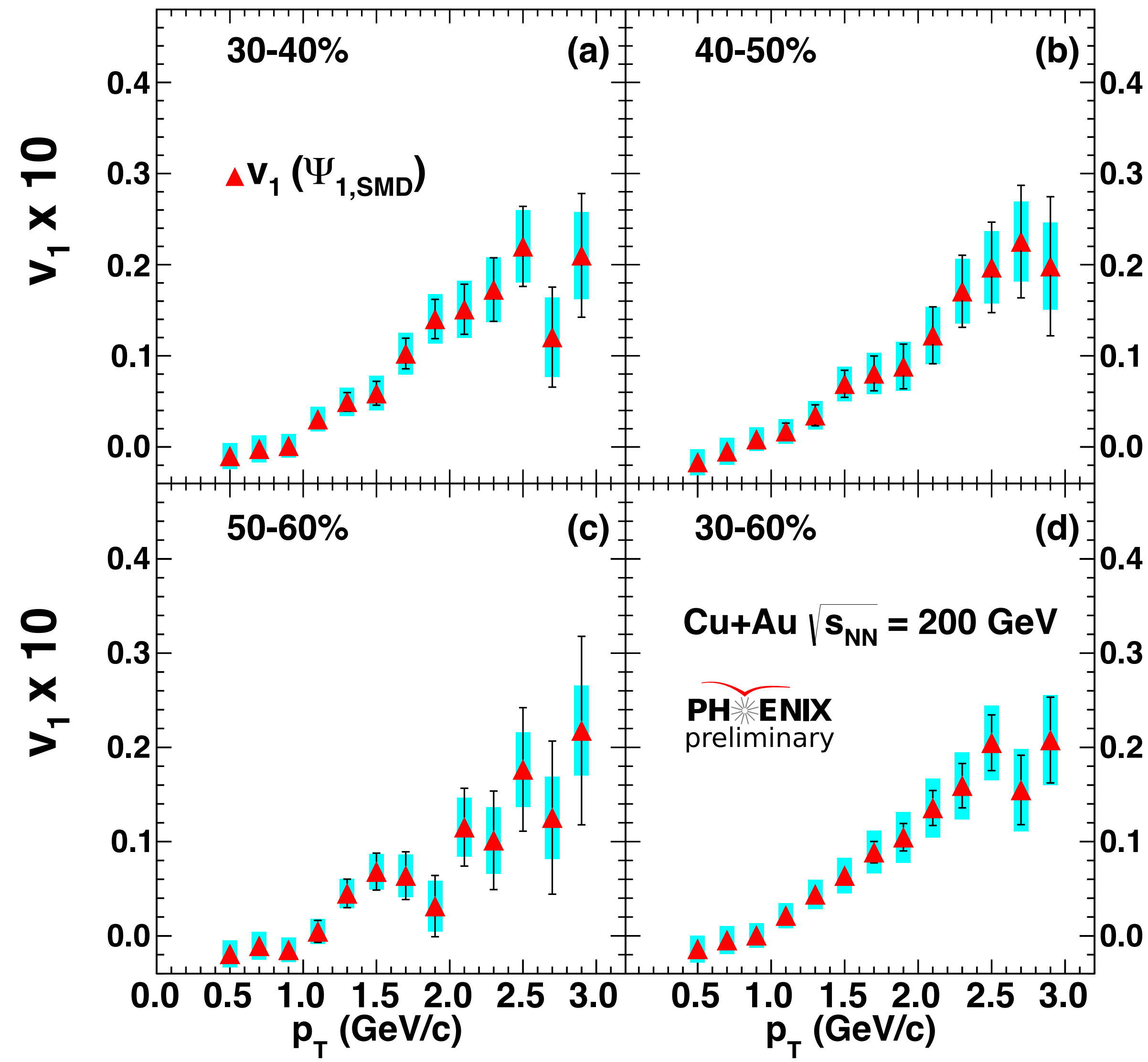
Slope of v_2 for multiplicity dependence



Centrality percentile by ZDC

0.1% most central

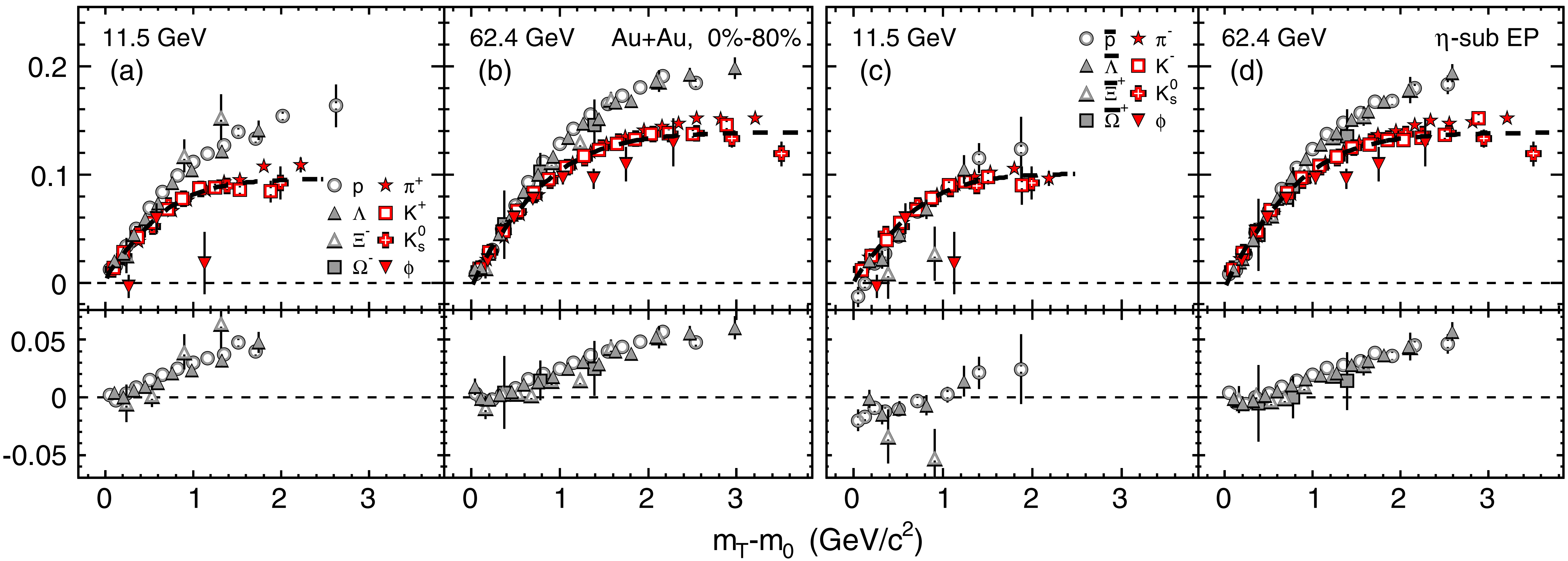
PHENIX, RHIC&AGS users meeting



- v_2 slope shows clear difference between Au+Au and U+U
  - super central U+U could enhance tip-tip collisions
- Large v_1 @ mid-rapidity in Cu+Au (not observed in Au+Au)
  - also for pions. Need more statistics for protons

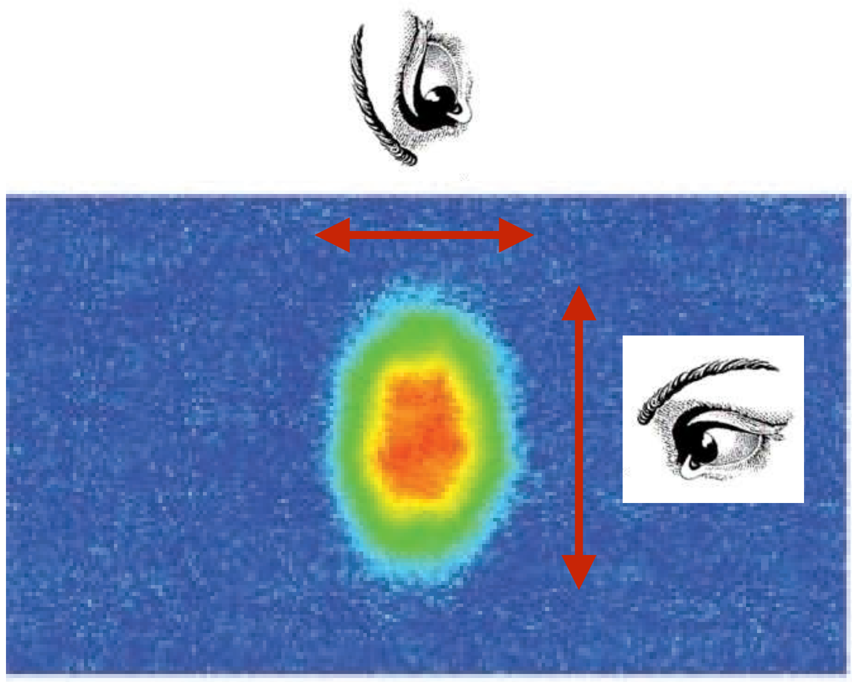
Break down of NCQ scaling

STAR ***PRL110***, *143201 (2013)*, ***PRC88***, *014902 (2013)*

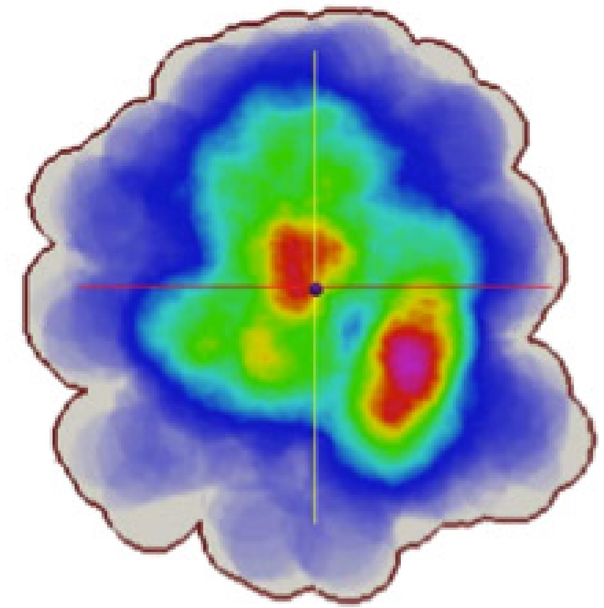


- Number of Constituent Quark scaling of v_2
  - Indication of deconfinement at early stage of heavy ion collisions
- Meson-baryon splitting at 62.4 GeV - NCQ scaling of v_2
  - No difference between particles and anti-particles
- Meson-baryon splitting is gone at 11.5 GeV
- NCQ scaling is broken between particles and anti-particles

At the beginning of the RHIC



Now

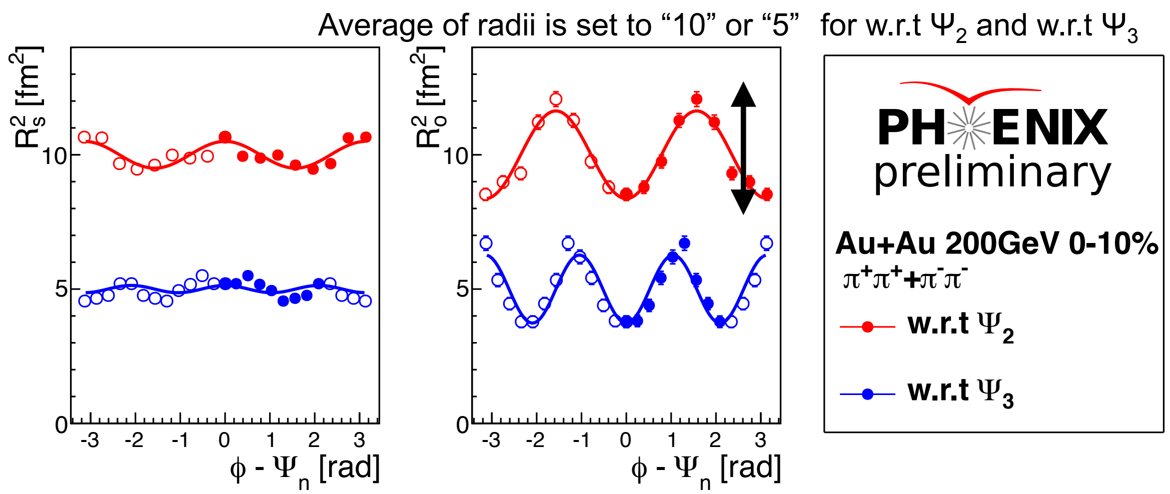


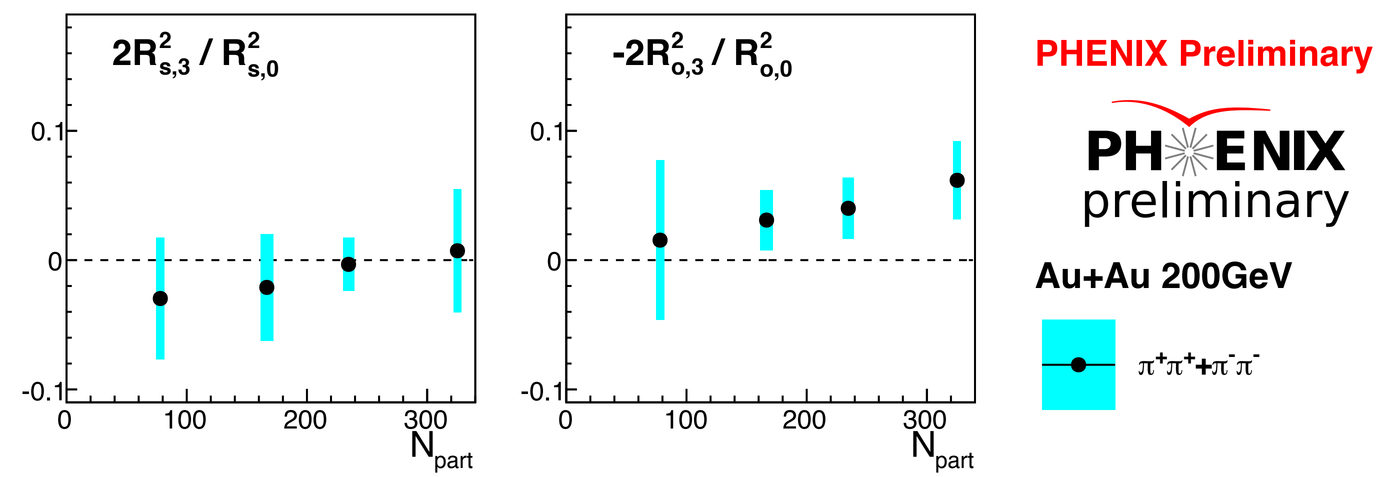
?

Femtoscopy

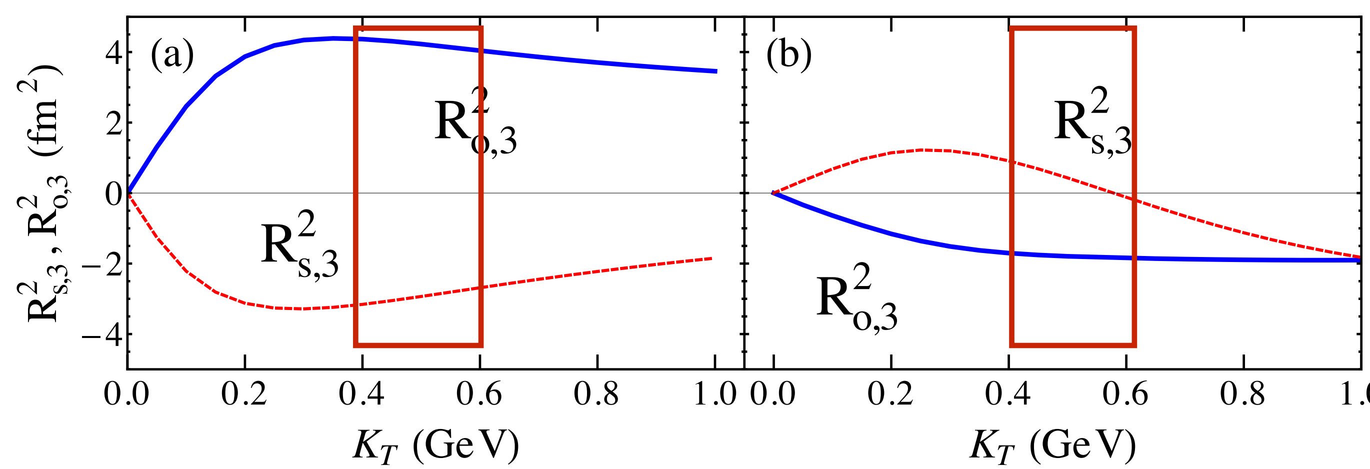
Triangular oscillation

PHENIX, QM2012



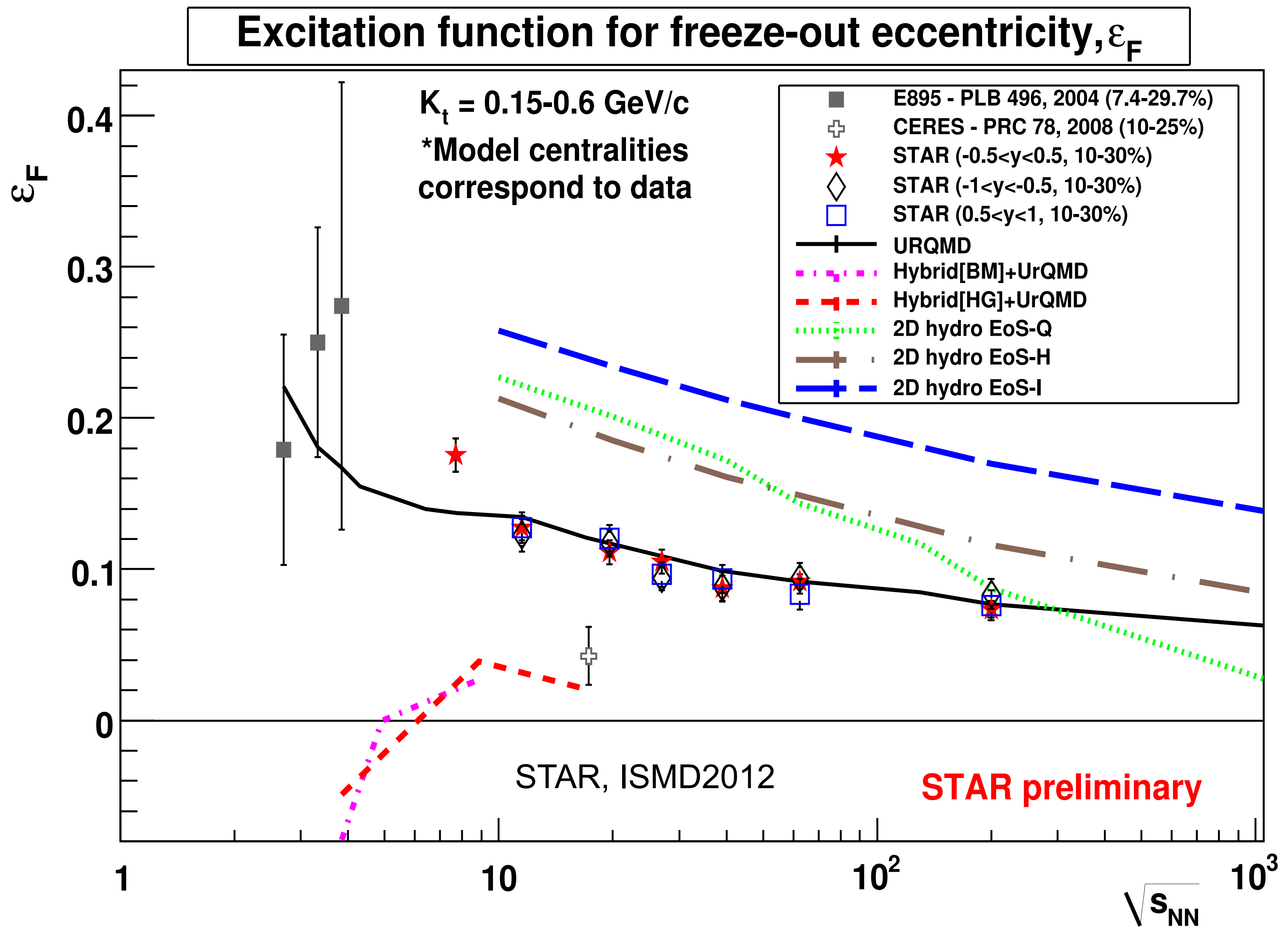


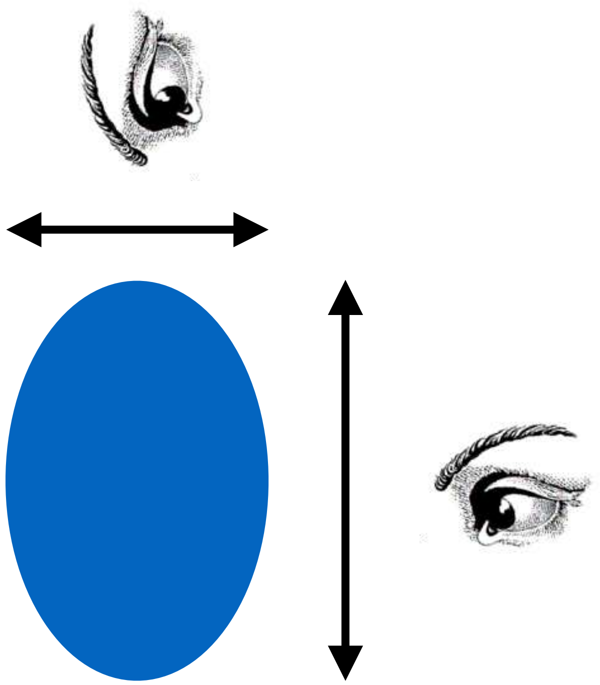
C. J. Plumberg, C. Shen, U. Heinz, arXiv:1306.1485 [nucl-th]



- R_{out} shows clear oscillation with respect to Ψ_3
- Finite R_{out}, zero R_{side}
  - could suggest triangular flow is dominated at freeze-out
    - whereas triangular source shape is very small at freeze-out
  - Important to study k_T dependence of asHBT

Freeze-out eccentricity @ BES





- Spatial anisotropy is sensitive to equation of state
  - might be signal for 1st order phase transition
- Pion freeze-out eccentricity smoothly decreases as a function of beam energy
  - STAR data don't show non-monotonic energy dependence

Fluctuations

Higher (n>2) order moments

- At critical point (with infinite system)
  - susceptibilities and correlation length diverge
    - both quantities cannot be directly measured
- Experimental observables
  - Moment (or cumulant) of conserved quantities: net-baryons, net-charge, net-strangeness, ...
  - Moment product (cumulant ratio) ↔ ratio of susceptibility

$$\kappa_2 = \left\langle (\delta N)^2 \right\rangle \sim \xi^2, \kappa_3 = \left\langle (\delta N)^3 \right\rangle \sim \xi^{4.5}, \kappa_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N) \right\rangle^2 \sim \xi^7$$

$$S\sigma = \frac{\kappa_3}{\kappa_2} \sim \frac{\chi_3}{\chi_2}, \; K\sigma^2 = \frac{\kappa_4}{\kappa_2} \sim \frac{\chi_4}{\chi_2}$$

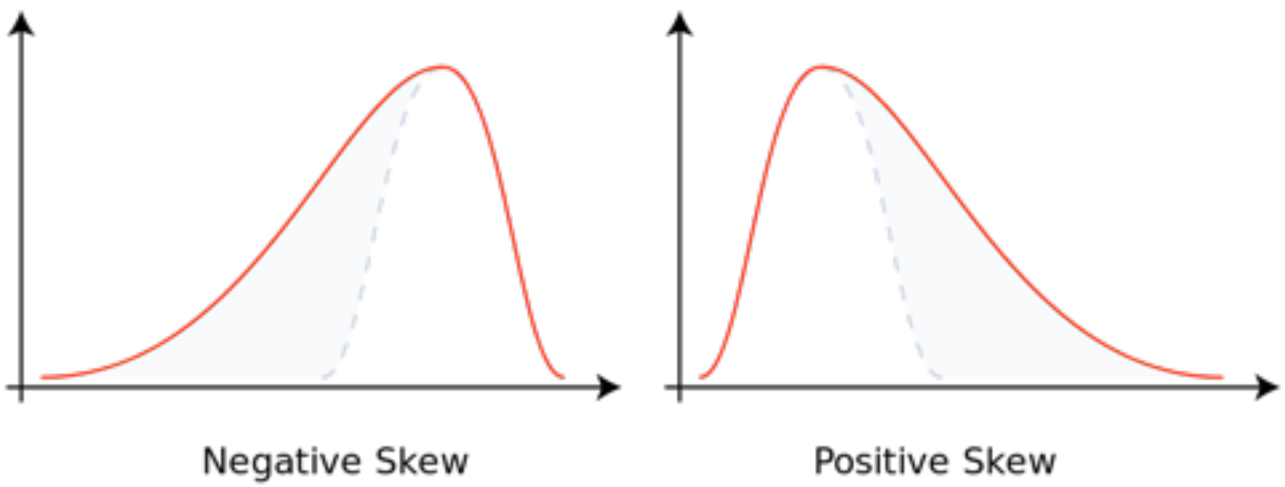
- directly related to the susceptibility ratios (Lattice QCD)
- higher moments (cumulants) have higher sensitivity to correlation length

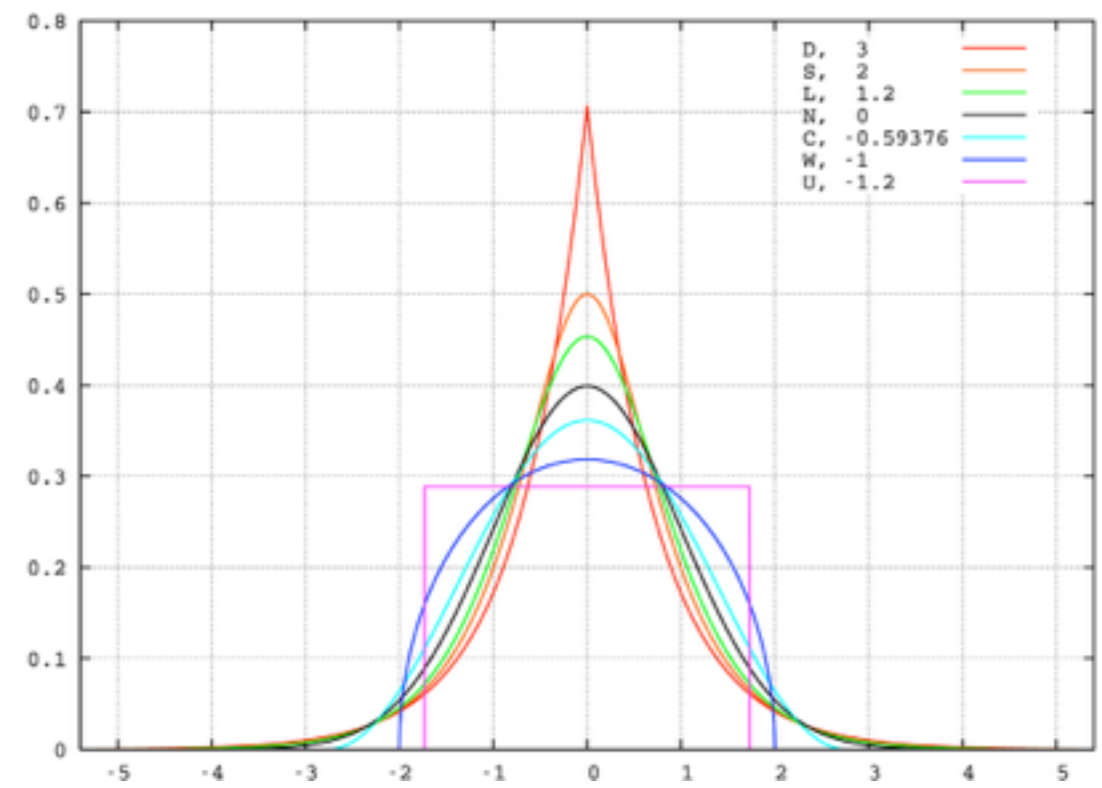
M. A. Stephanov, PRL ***102****, 032301 (2009)*

- Signal = Non-monotonic behavior of moment products (cumulant ratios) vs beam energy

Non-gaussian fluctuations

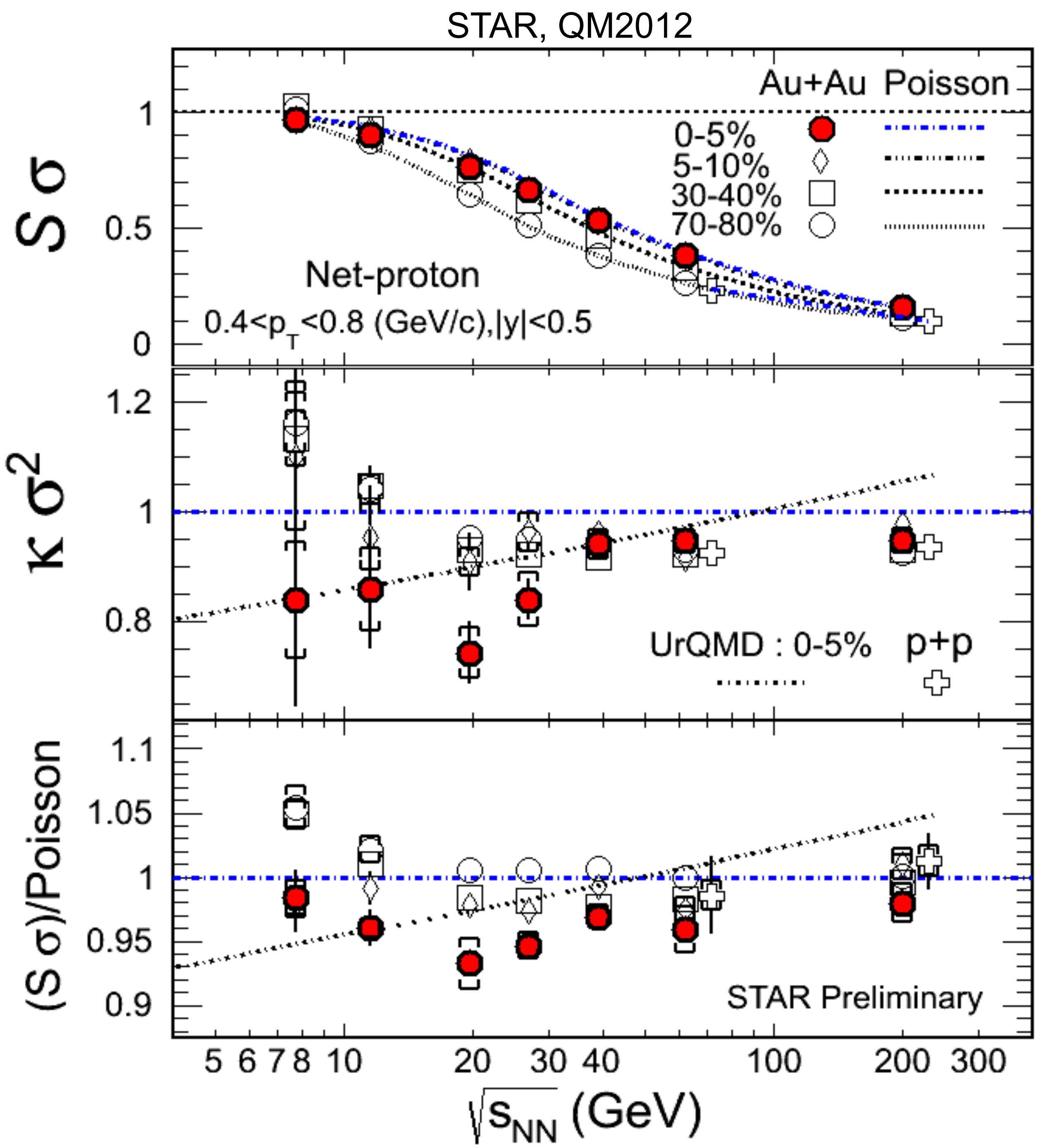
From Wikipedia





- 3rd moment = Skewness *S*
  - Asymmetry
- 4th moment = Kurtosis *K*
  - Peakedness
- Both moments = 0 for gaussian distribution
- Critical point induces non-gaussian fluctuations

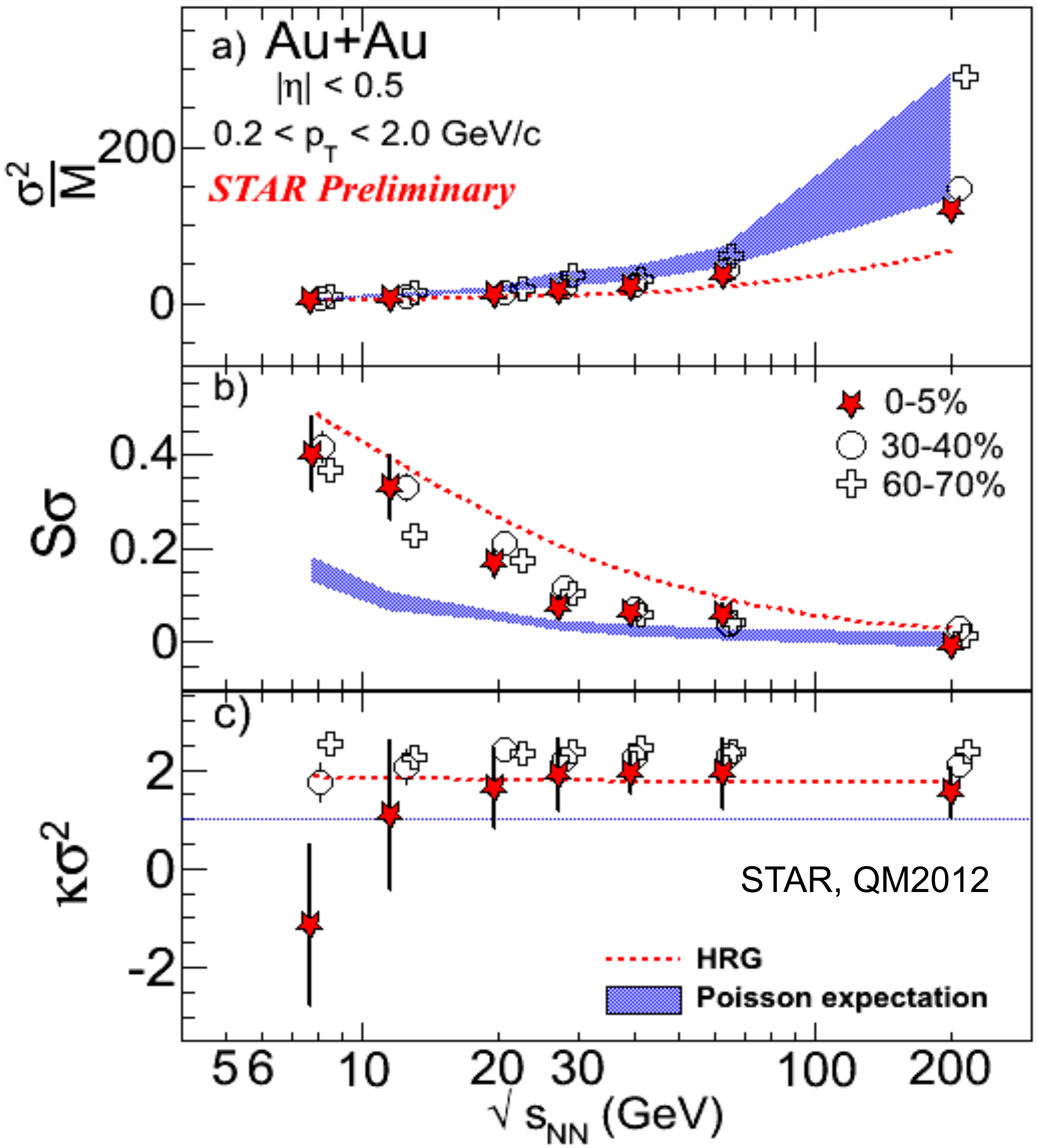
Net-proton fluctuations

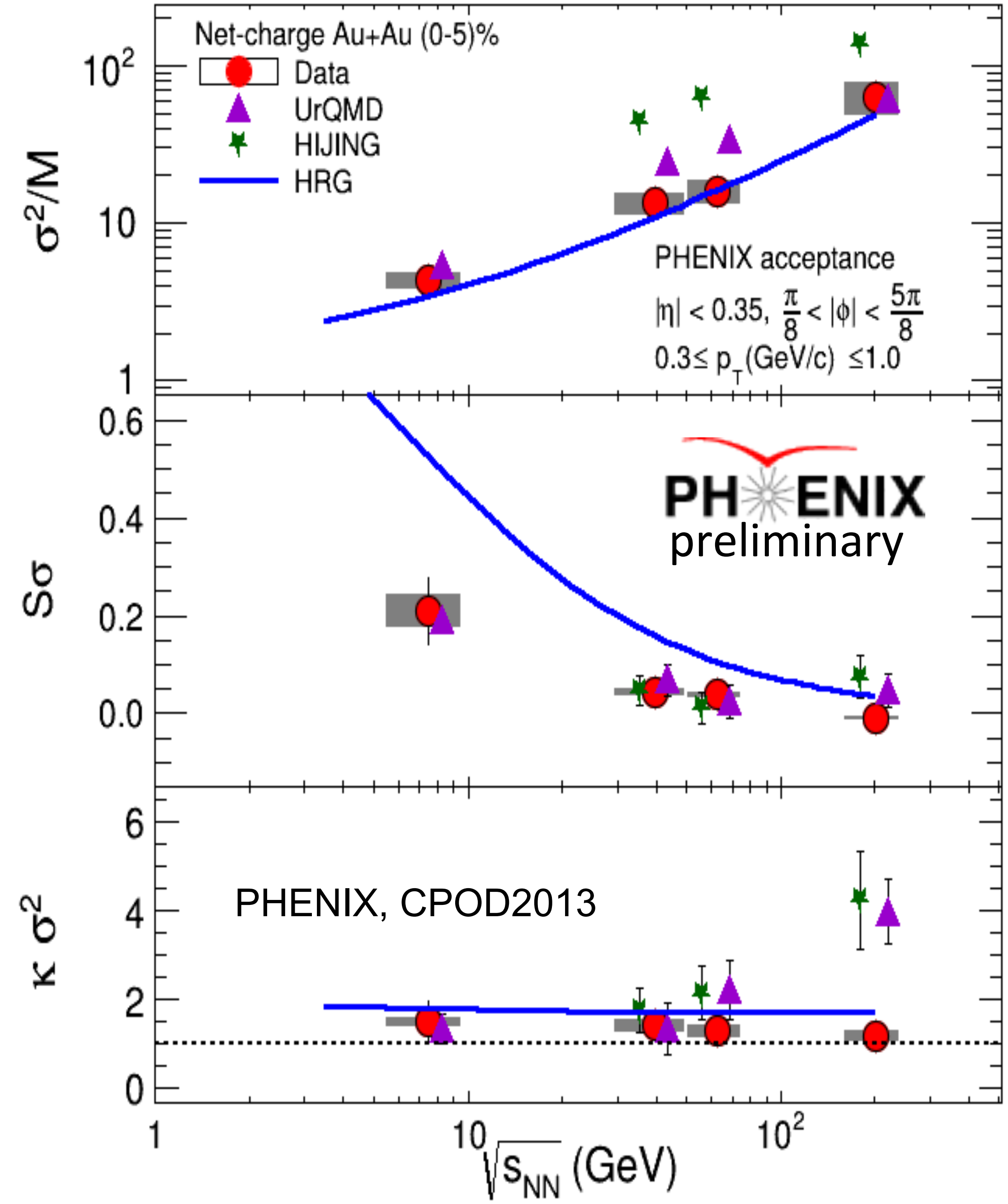


- Data
  - efficiency uncorrected*
- Data compared to various expectations
  - Poisson
  - (Negative-) binomial*
- No significant excess compared to Poisson & UrQMD
  - Need precision measurements at low energies

* under investigation (not shown here)

Net-charge fluctuations





- No significant excess compared to Poisson, models
  - STAR ≠ PHENIX → acceptance ? efficiency correction ?

Summary

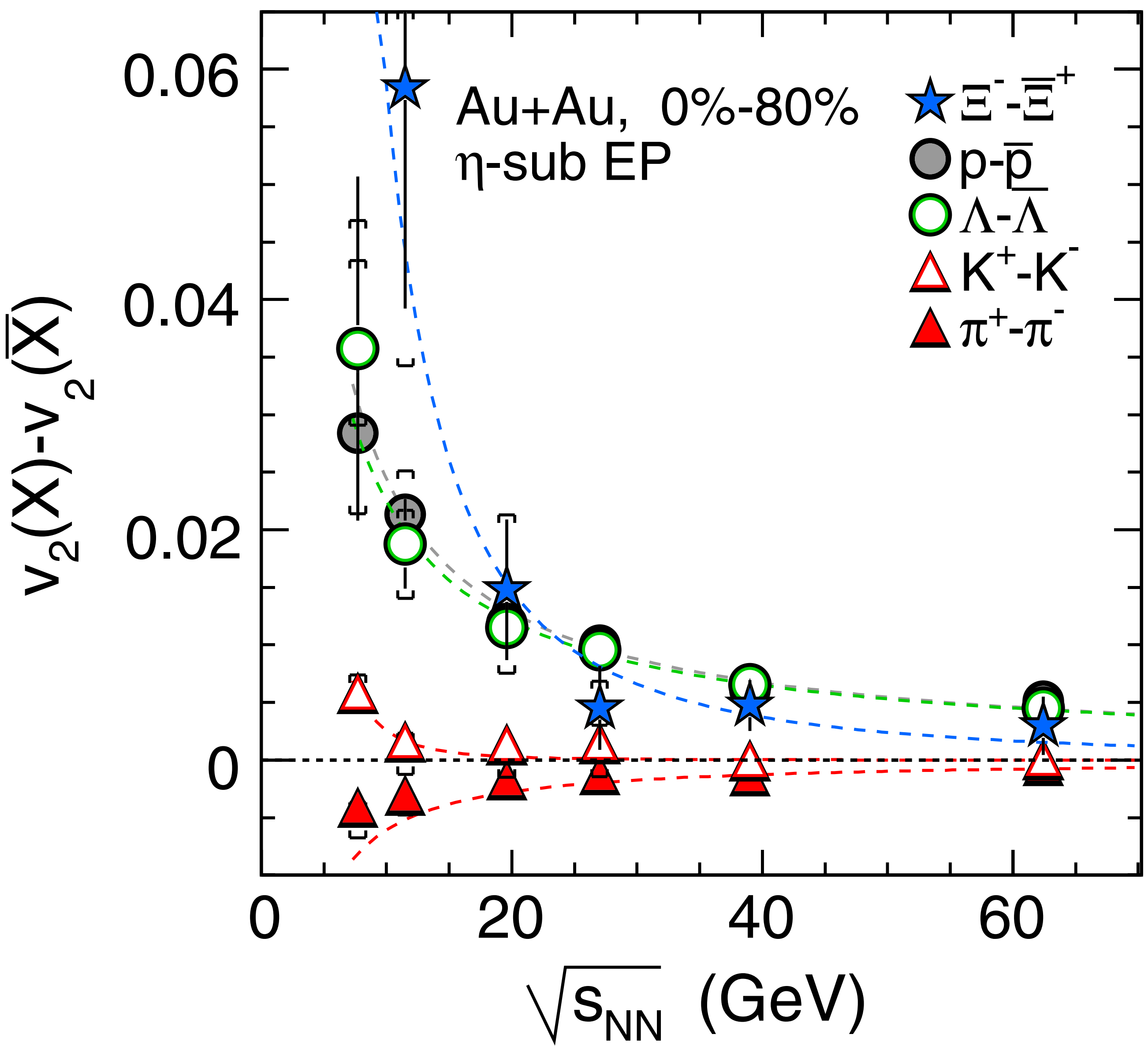
- Multi-particle correlations are powerful tool to understand the underlying collision dynamics in heavy ion collisions

- Azimuthal anisotropy
  - Flow in d+Au ? Need centrality dependence
  - Possibility to enhance tip-tip collisions by using v_2
  - Hint of turn-off signal by breakdown of NCQ scaling between particles and anti-particles
- Femtoscopy
  - Triangular flow is dominated at freeze-out ?
  - Smooth energy dependence of final freeze-out eccentricity
- Fluctuations
  - Need precision measurements for QCD critical point search

Back up

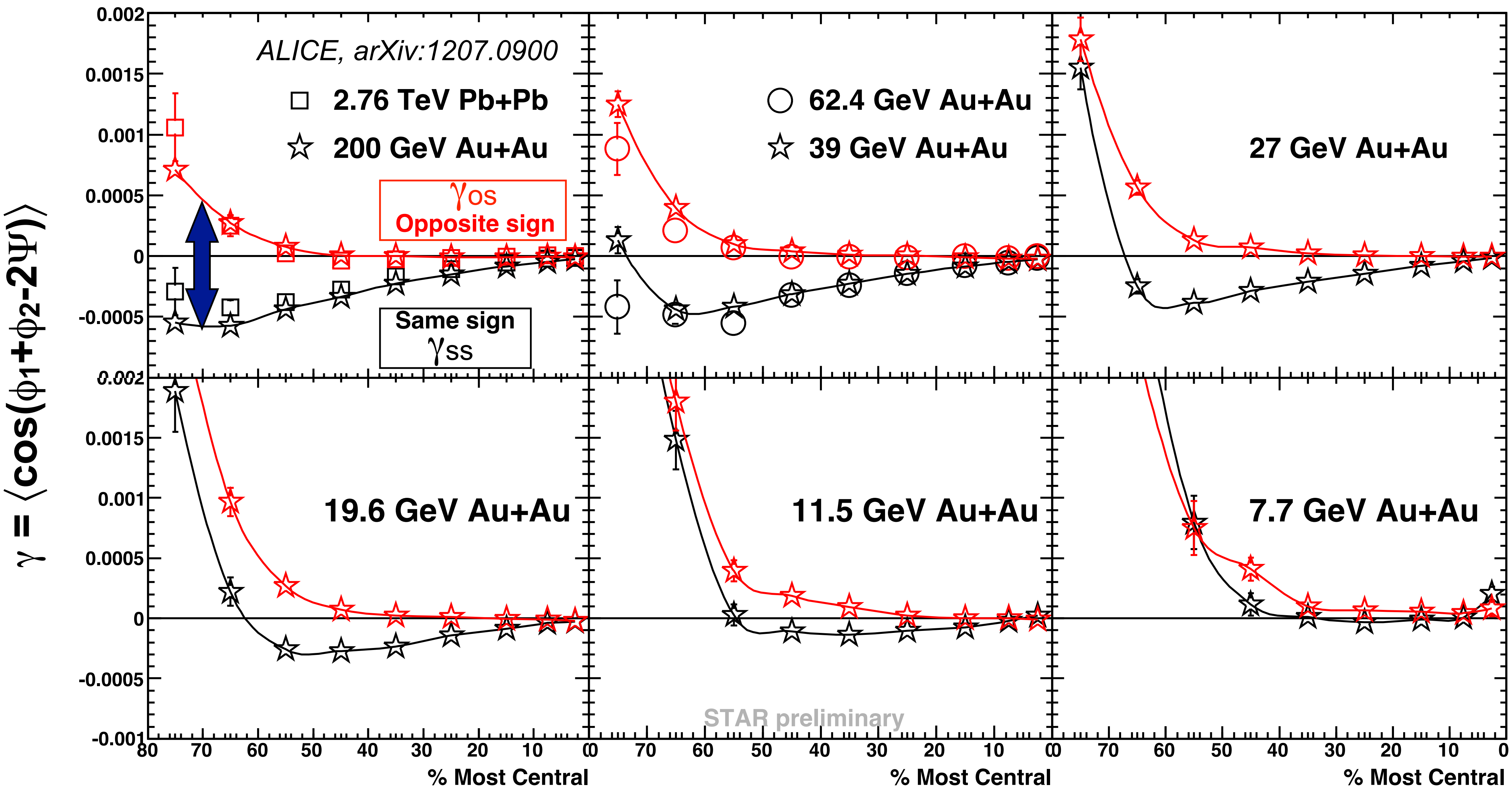
Large v2 difference for baryons

STAR ***PRL110***, *143201 (2013),*
PRC88, *014902 (2013)*



- Difference of v_2 between particles and anti-particles increase in low energies
- Baryons show larger difference than mesons

Disappearance of charge separation



- Charge separation (γ_{OS}-γ_{SS}) at 200 GeV
  - chiral magnetic effect ?
- Separation decreases with decreasing beam energies, disappears at $\sqrt{s_{NN}}$ = 11.5 GeV or less