BROOKHAVEN NATIONAL LABORATORY

STAR Results from the RHIC Beam Energy Scan

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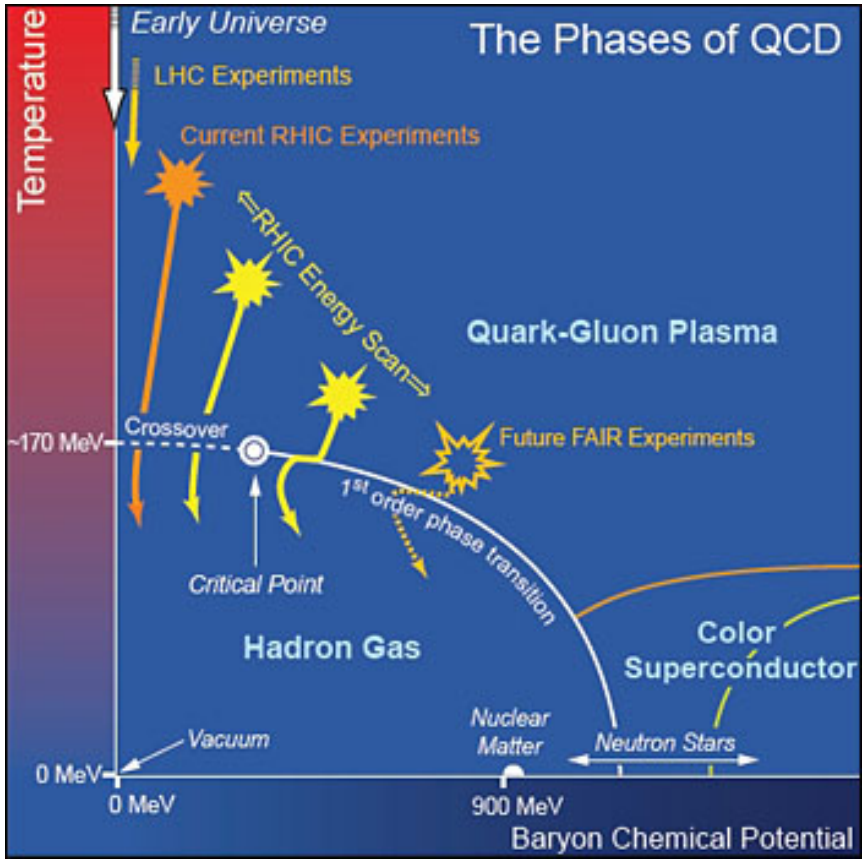
Office of Science
U.S. Department of Energy

RHIC Beam Energy Scan Program



- Search for evidence of
  - Turn-off of QGP signatures
  - Critical point
  - First order phase transition

Proposal: Year 2008

Feasibility: Au+Au 9.2 GeV test run

Year 2010: BES Phase-I

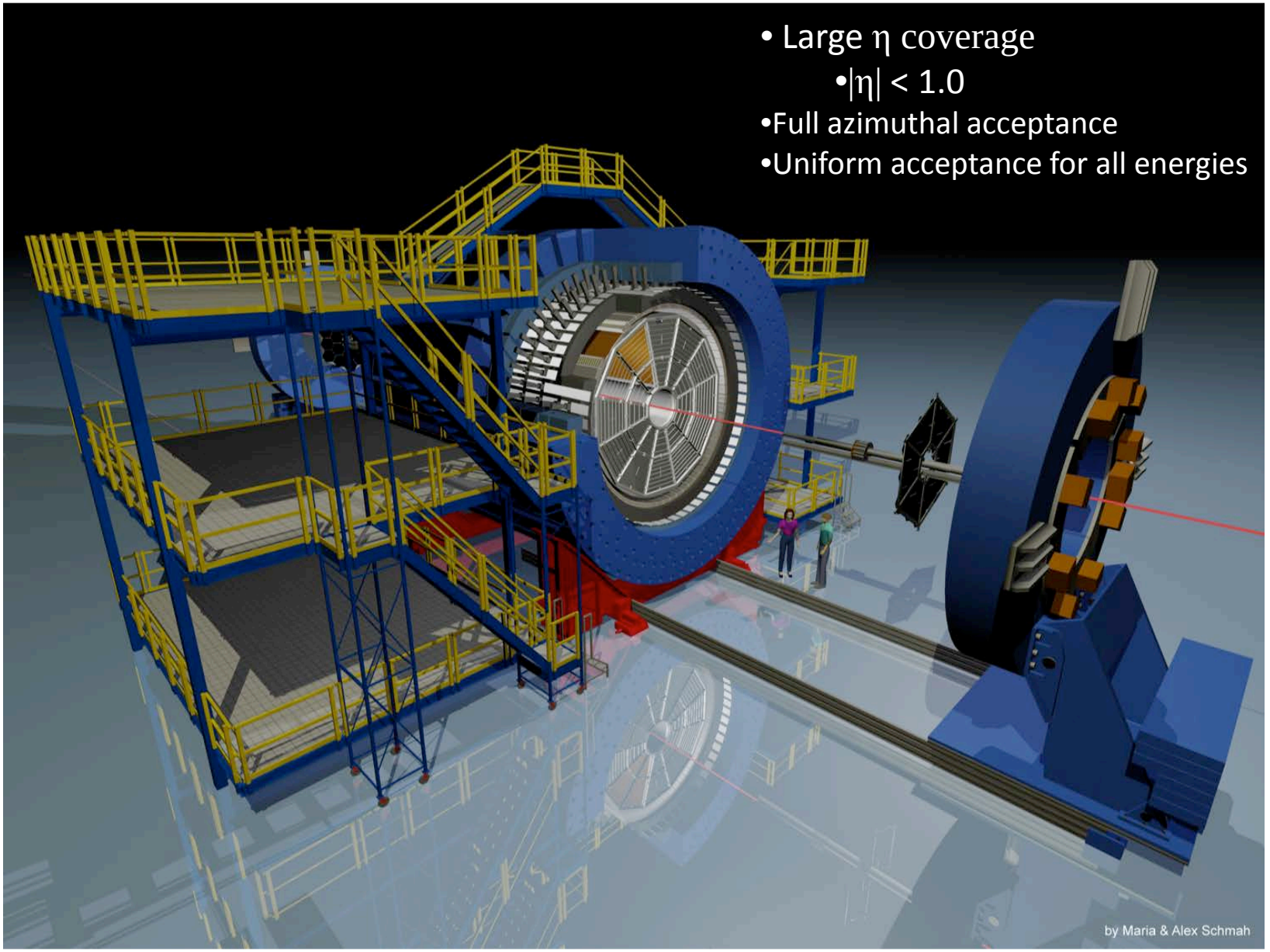
Year 2011: Two more energy points, Phase-I complete

Year 2017: BES Phase-II (planned)

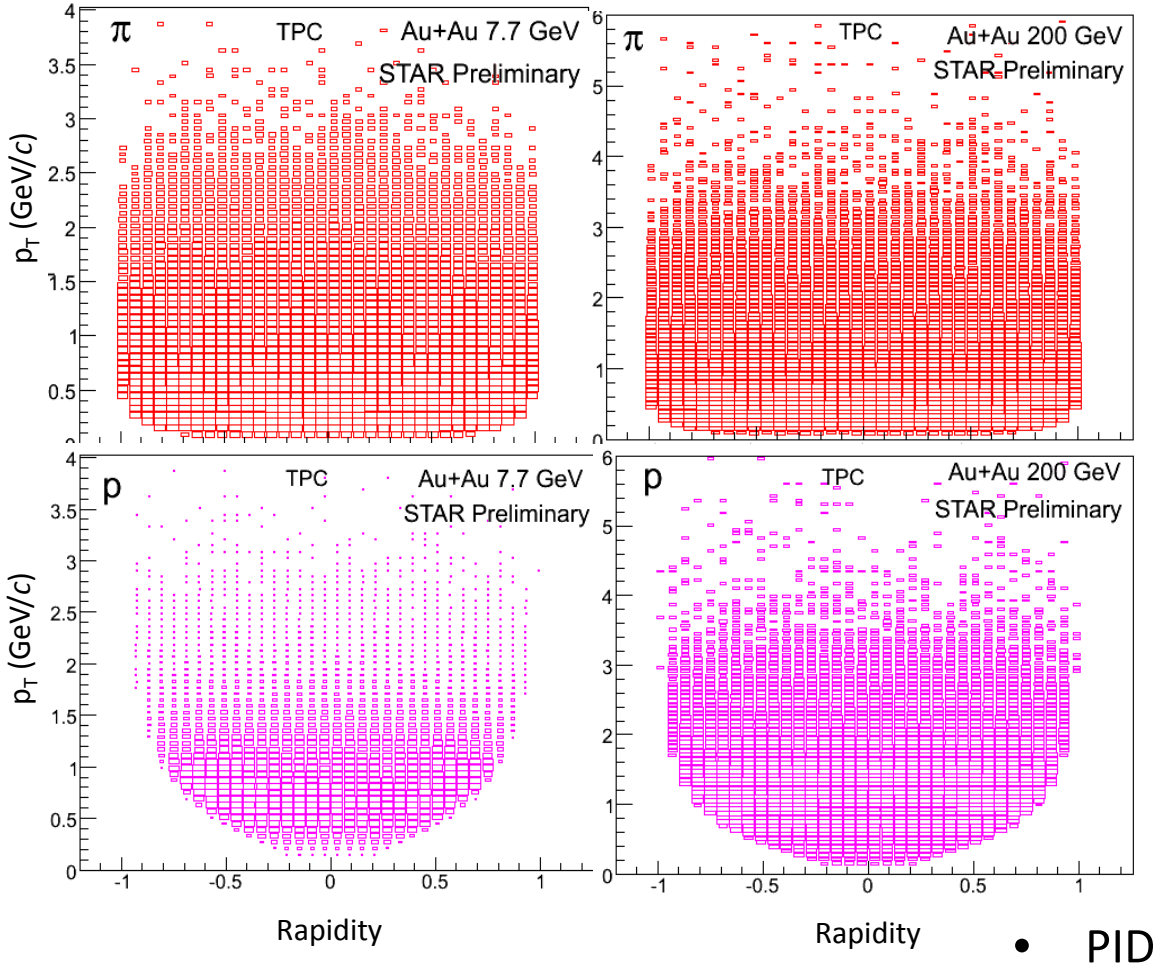
arXiv:1007.2613

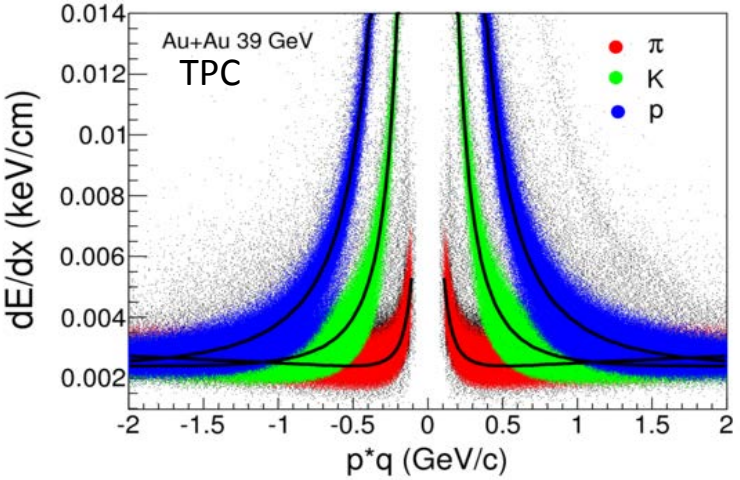
$\sqrt{s_{NN}}$ (GeV)	Min. Bias Events (10^6)	Year
7.7	4.3	2010
11.5	12	2010
19.6	36	2011
27	70	2011
39	130	2010
62.4	67	2010

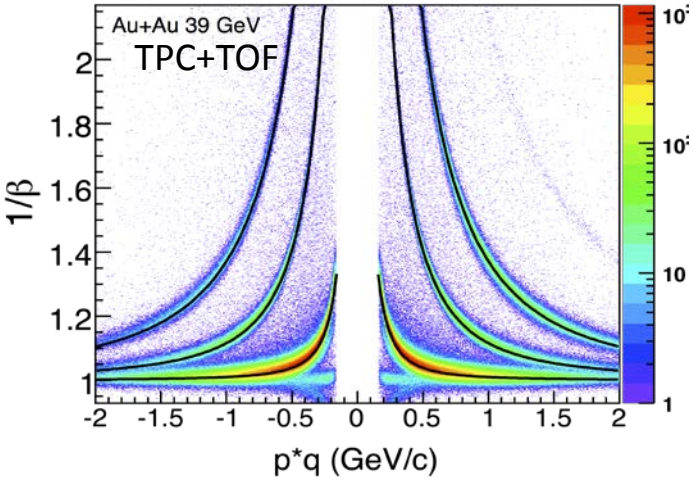
STAR Experiment



STAR Experiment







Similar acceptance over all RHIC energies

- PID (TPC+TOF):
  - pion/kaon: p ~1.6 GeV/c proton: p ~3.0 GeV/c
  - Strange hadrons: decay topology & invariant mass

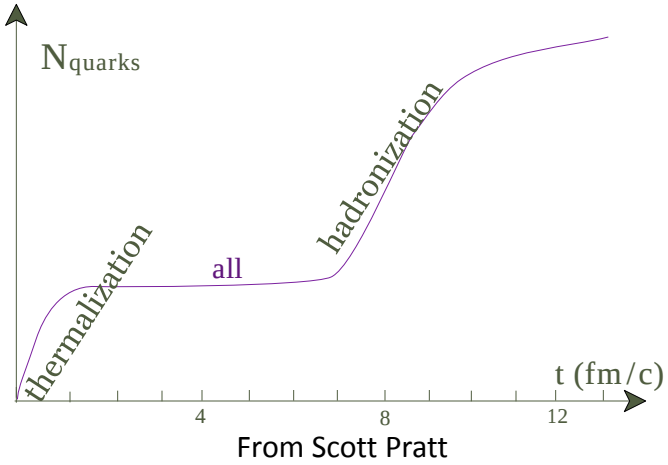
Search for Turn-off of QGP Signatures

- Balance Function
- Dynamical Charge Correlations
- Elliptic Flow
- R_{cp} of Charged Hadrons

Observables

- Balance Function
  - Sensitive to the charge formation time and relative diffusion

$$B(\Delta\eta)=\frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta)-N_{++}(\Delta\eta)}{N_{+}}+\frac{N_{-+}(\Delta\eta)-N_{--}(\Delta\eta)}{N_{-}}\right\}$$



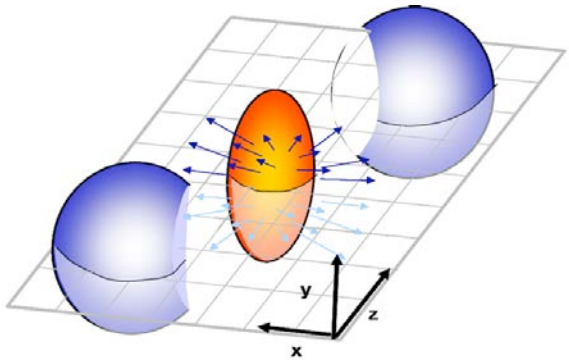
From Scott Pratt

- Dynamical Charge Correlations

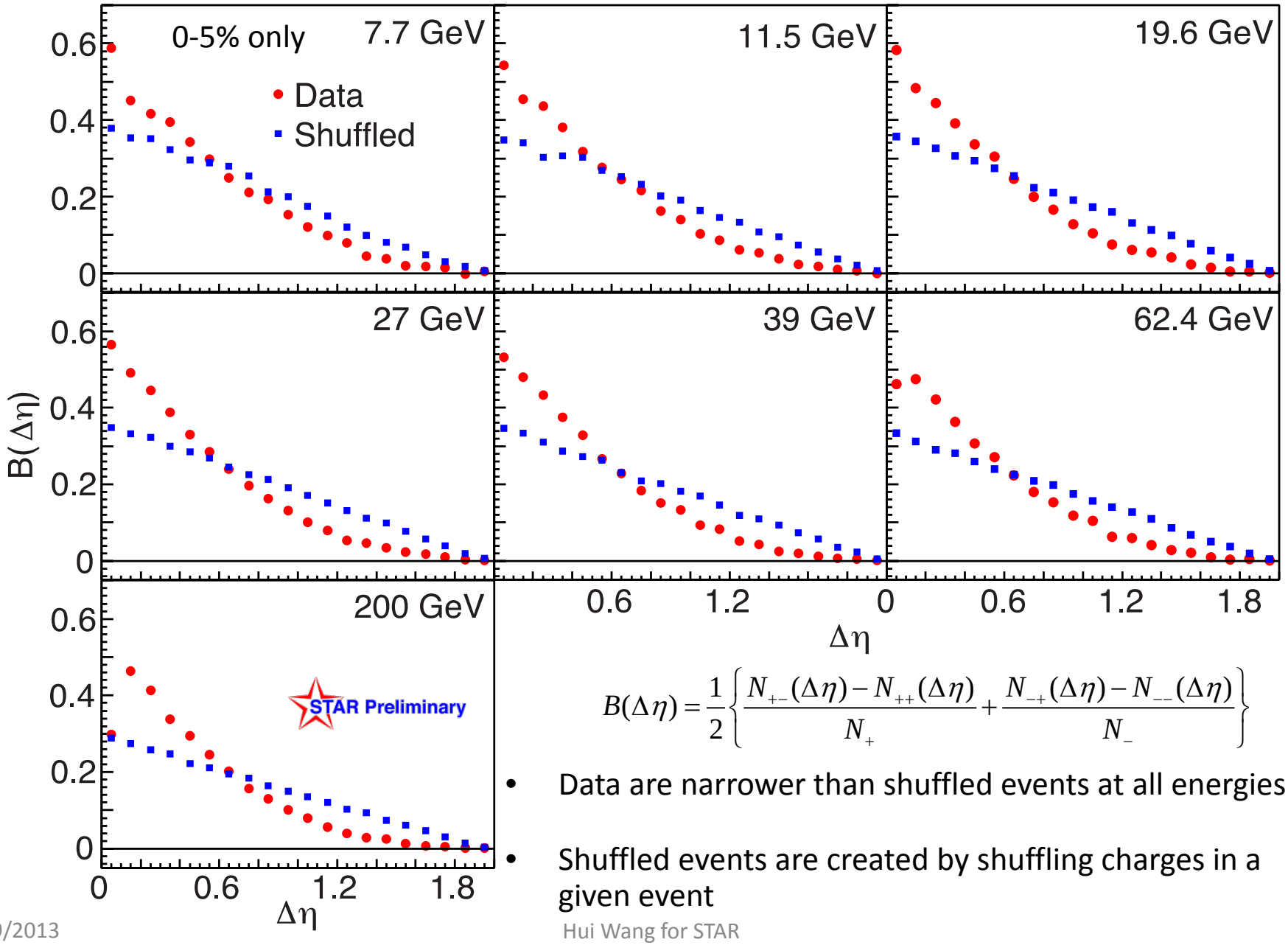
$$\gamma_{\alpha\beta}=<\cos(\phi_{\alpha}+\phi_{\beta}-2\Psi_{RP})>$$

- Elliptic Flow
  - Test of number-of-constituent-quark scaling at lower energies

$$\frac{dN}{d\varphi}\propto\left(1+2\sum_{n=1}^{+\infty}v_{n}\cos\left[n(\varphi-\psi_{n})\right]\right)$$



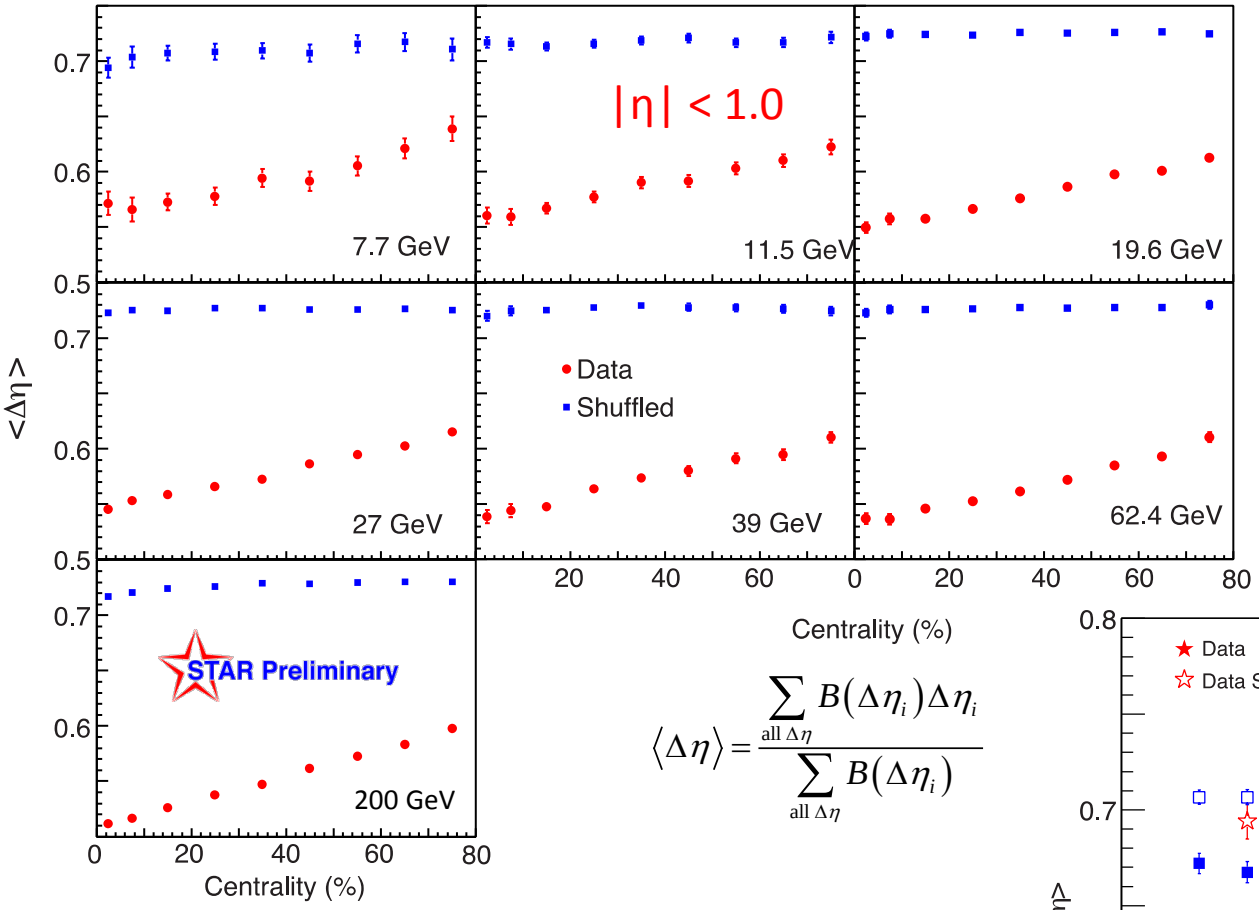
Balance Function



$$B(\Delta\eta) = \frac{1}{2}\left\{\frac{N_{+-}(\Delta\eta) - N_{++}(\Delta\eta)}{N_{+}} + \frac{N_{-+}(\Delta\eta) - N_{--}(\Delta\eta)}{N_{-}}\right\}$$

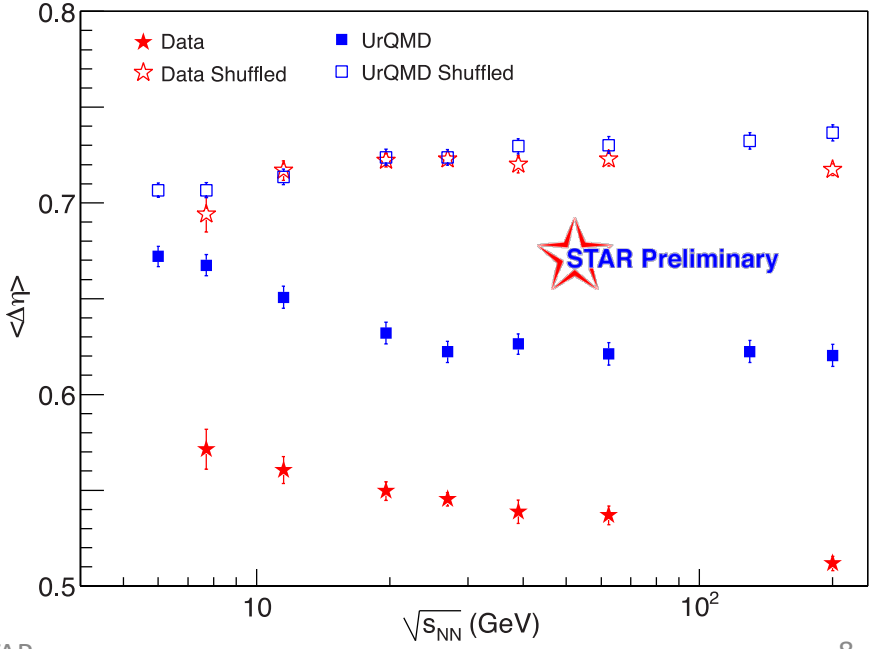
- Data are narrower than shuffled events at all energies
- Shuffled events are created by shuffling charges in a given event

Balance Function Width



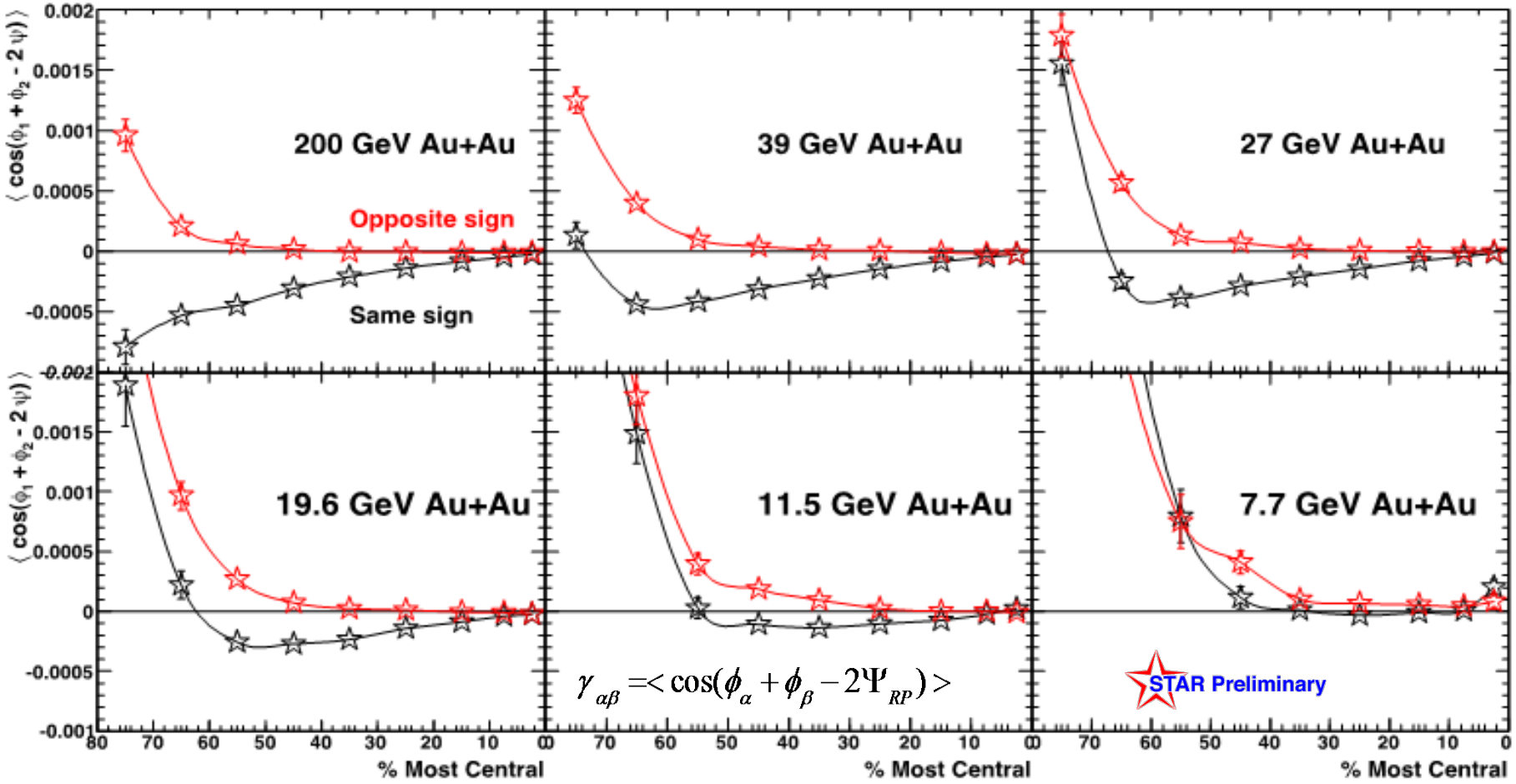
$$\langle \Delta\eta \rangle = \frac{\sum_{\text{all }\Delta\eta} B(\Delta\eta_i)\Delta\eta_i}{\sum_{\text{all }\Delta\eta} B(\Delta\eta_i)}$$

- Balance function width is sensitive to hadronization time
- Balance functions narrow smoothly with increasing collision energy and as the collisions become more central



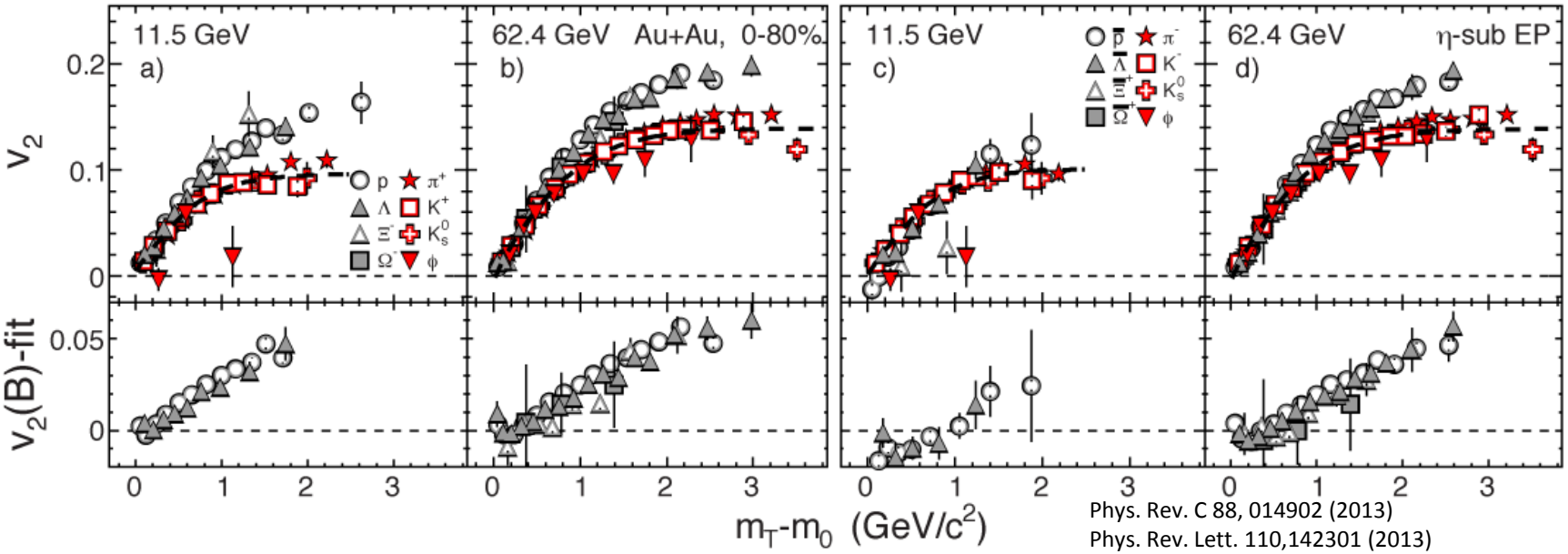
- Most central (0-5%) events only
- Remove lowest bin when calculating <Δη> to reduce HBT/Coulomb effects

Dynamical Charge Correlations



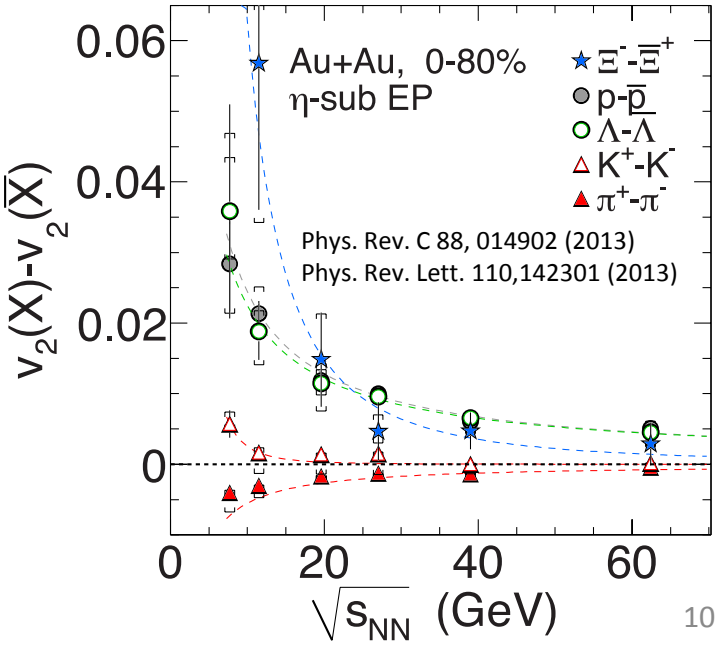
Splitting between same and opposite-sign charges decreases with decreasing $\sqrt{s_{NN}}$

Elliptic Flow



Phys. Rev. C 88, 014902 (2013)
Phys. Rev. Lett. 110,142301 (2013)

- Baryon–meson splitting is observed when collisions energy ≥ 19.6 GeV for both particles and the corresponding anti-particles
- For anti-particles the splitting is almost gone within errors at 11.5 GeV



- **Difference in positive/negative charged particle v_2**
  - Increasing with decrease of beam energy
  - Larger for baryons than mesons
- **Possible explanation**
  - Baryon transport to mid-rapidity?
  - Hadronic potential?

Search for Critical Point

- Particle Ratio Fluctuations
- p_t Correlations
- High Moments of Net-protons and Net-charge Distribution

Observables

- Particle Ratio Fluctuations
  - Related to strangeness and baryon number fluctuations
  - Look for non-monotonic behavior of the fluctuations near critical point

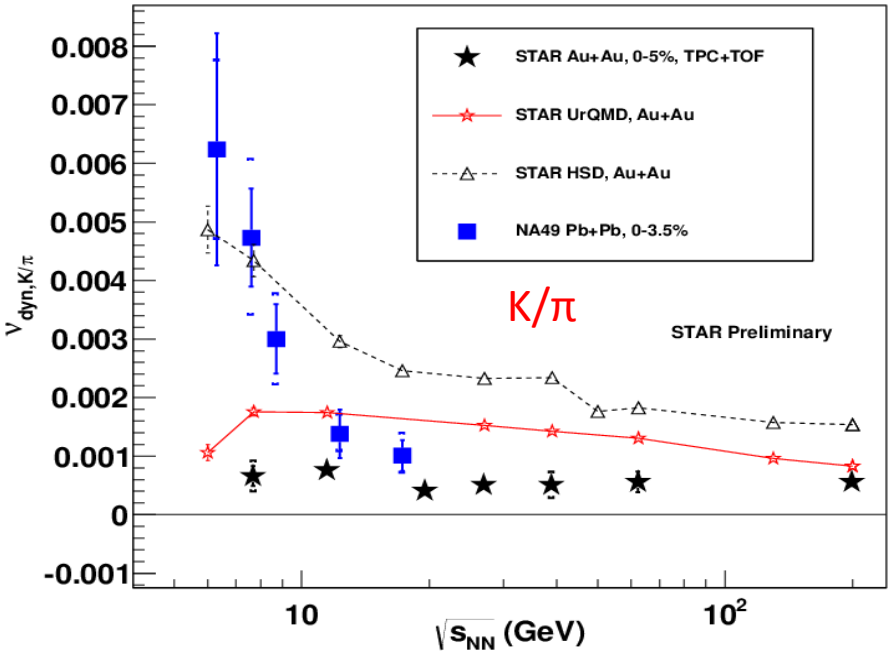
$$\nu_{\mathrm{dyn},K\pi} = \frac{\left\langle N_K\left(N_K-1\right)\right\rangle}{\left\langle N_K\right\rangle^2} + \frac{\left\langle N_\pi\left(N_\pi-1\right)\right\rangle}{\left\langle N_\pi\right\rangle^2} - 2\frac{\left\langle N_K N_\pi\right\rangle}{\left\langle N_K\right\rangle\left\langle N_\pi\right\rangle}$$

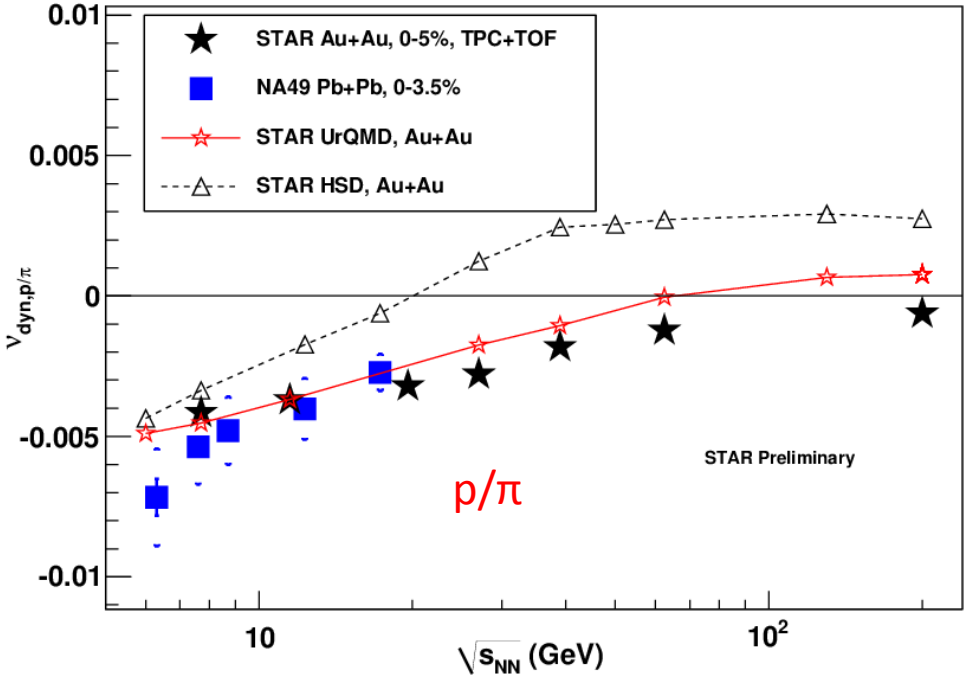
- p_t Correlations
  - Looking for non-monotonic change as a function of incident energy

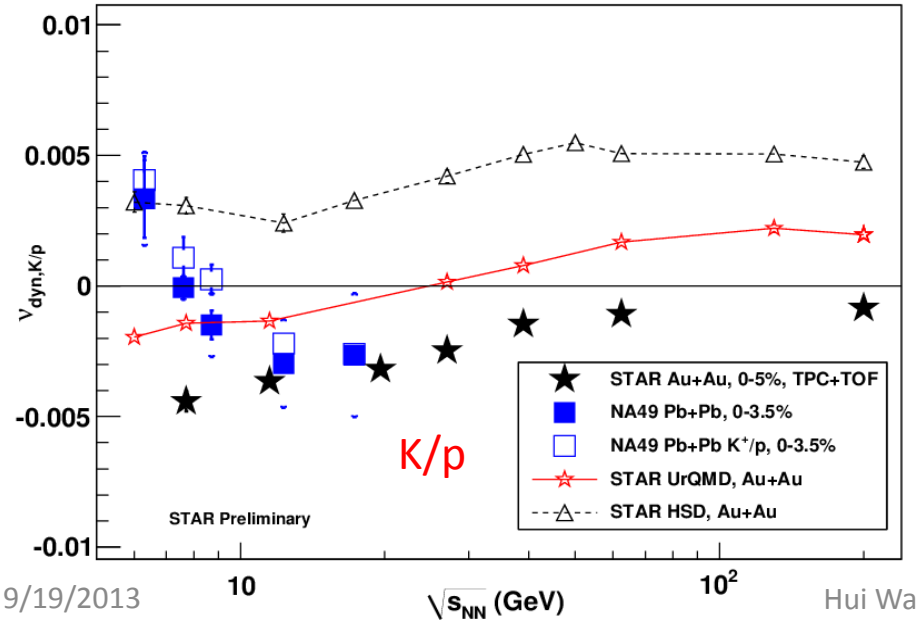
$$< \Delta p_{t,i} \Delta p_{t,j} >= \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_k(N_k-1)}$$

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i\neq j}^{N_k} (p_{t,i} - << p_t >>)(p_{t,j} - << p_t >>)$$

Particle Ratio Fluctuations

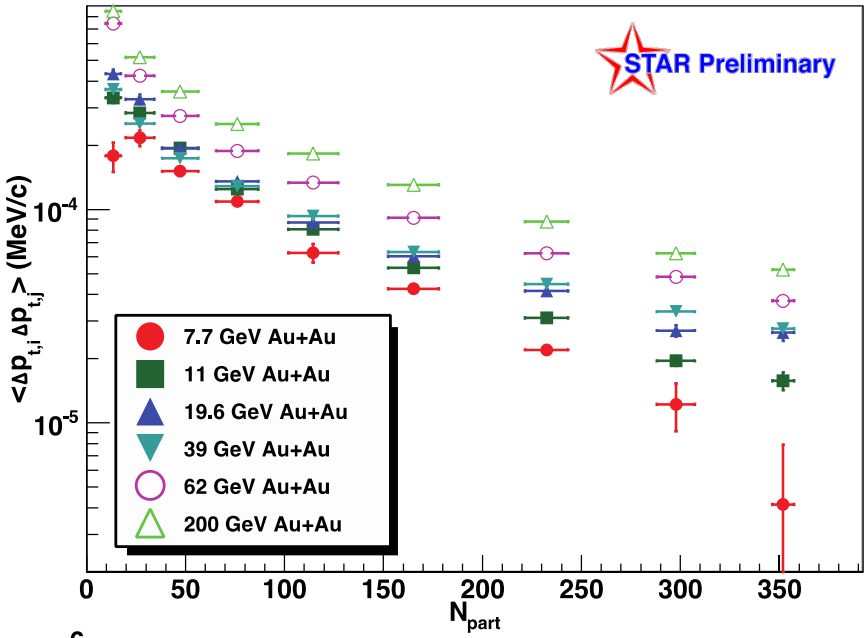




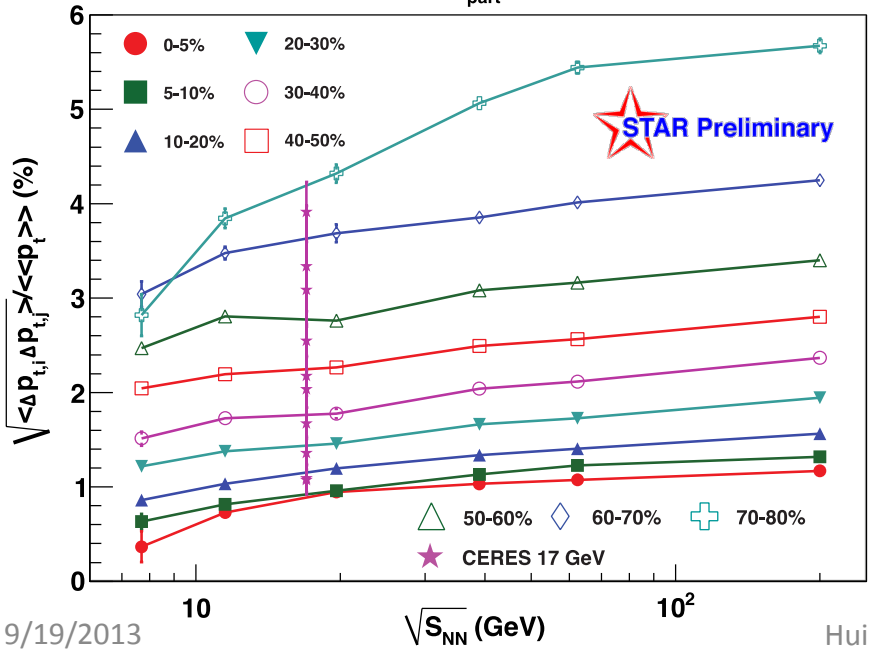


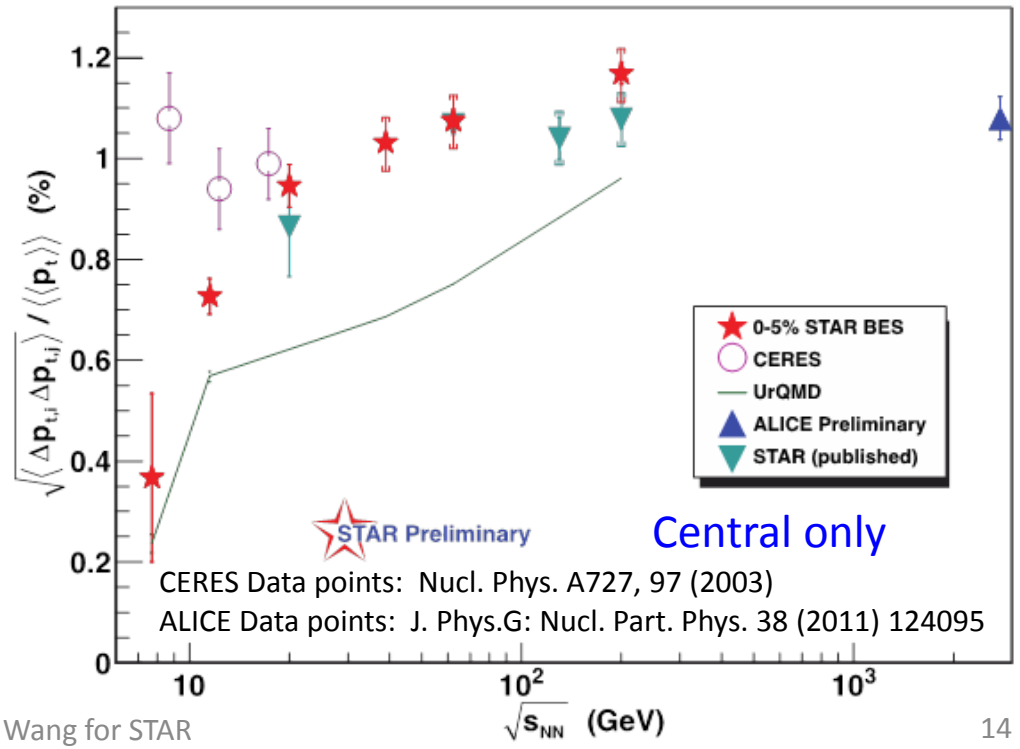
- STAR data show no significant energy dependence for K/π fluctuations
- STAR data decrease smoothly with decreasing incident energy for p/π and K/p fluctuations
- Disagreement between STAR and NA49 results for K/π and K/p fluctuations
- No non-monotonic behavior is observed

p_t Correlations

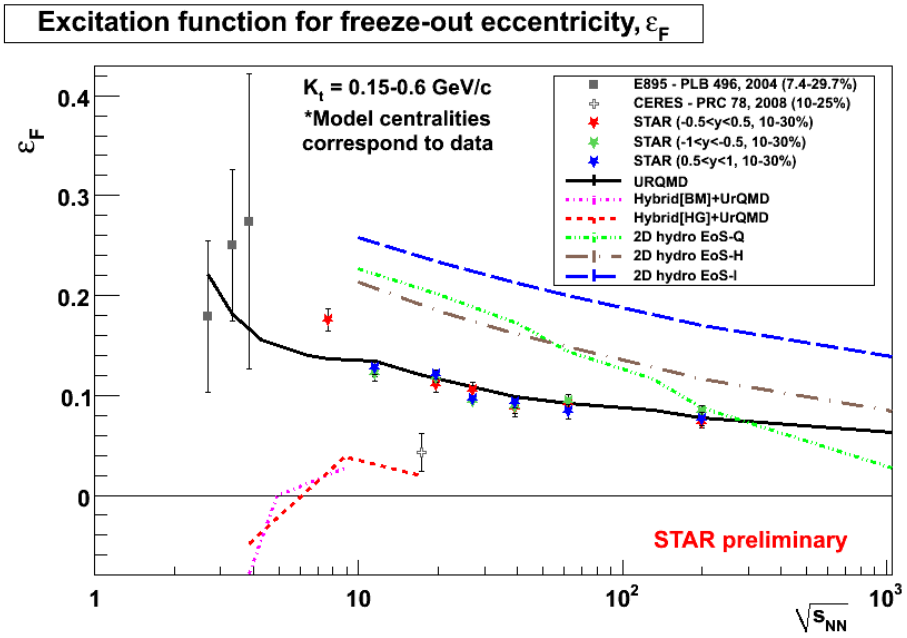


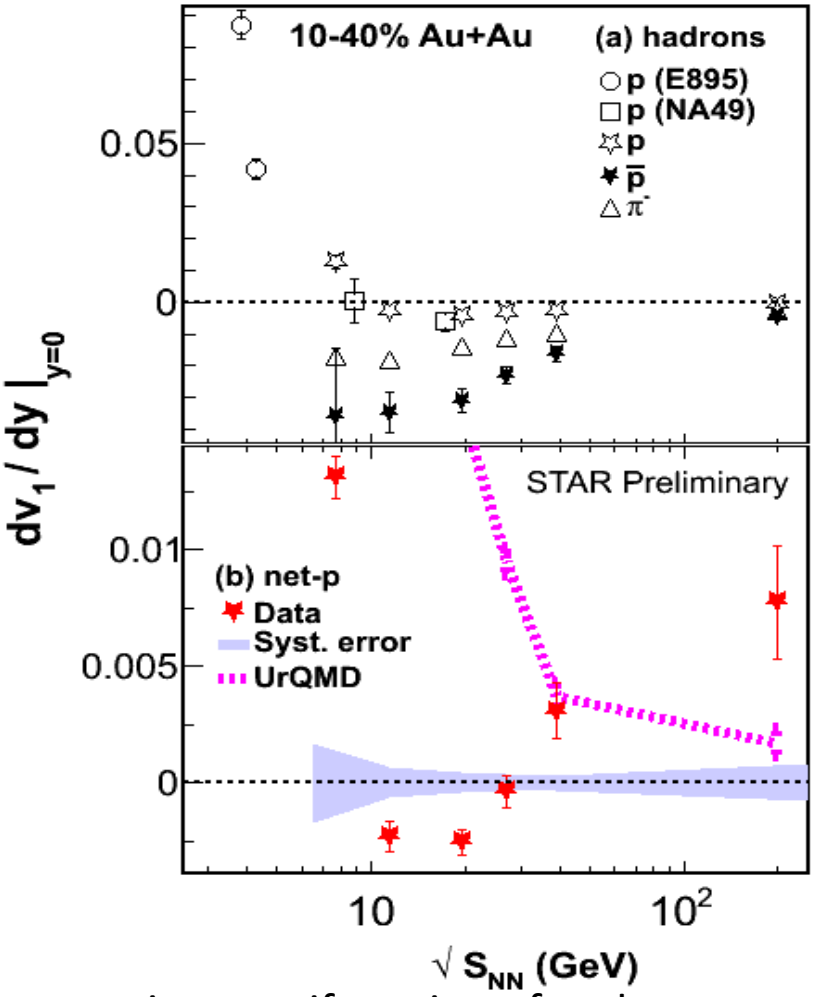
- Scaled correlations strongly decrease with decreasing energy below 39 GeV
- No non-monotonic behavior is observed
- Acceptance difference effect under investigation





Search for First Order Phase Transition





- Freeze-out eccentricity sensitive to the 1st order phase transition[1]
- STAR data shows smooth decrease with increasing energy. No conclusive deviations from UrQMD model observed

- v_1 is a manifestation of early pressure in the system[2]
- The v_1 slope for net-proton changes sign between 7.7 and 11.5 GeV

[1] Kolb and Heinz, 2003, nucl-th/0305084
[2] H. Stocker, Nucl. Phys. A **750** (2005) 121

Summary

- sQGP Signatures:
  - Several key sQGP signatures are either decreasing or not seen at low energies
  - Hadronic interactions become more important at low energies
- Critical Point Signatures :
  - No direct evidence from Particle Ratio and p_t fluctuations
- Softening of Equation Of State:
  - Double sign change in directed flow of net-protons
- Beam Energy Scan-II:
  - Propose higher statistics data below 20 GeV
  - Fixed target proposal to extend μ_B coverage up to 800 MeV

Thank You