STAR Results from the RHIC Beam Energy Scan

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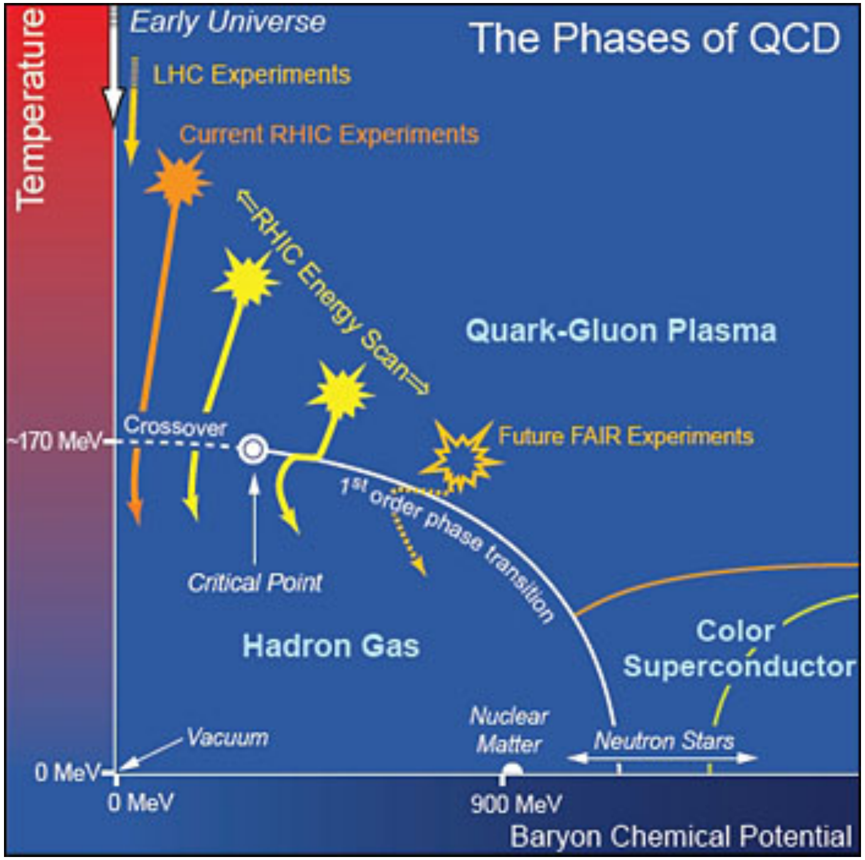
for the STAR Collaboration

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

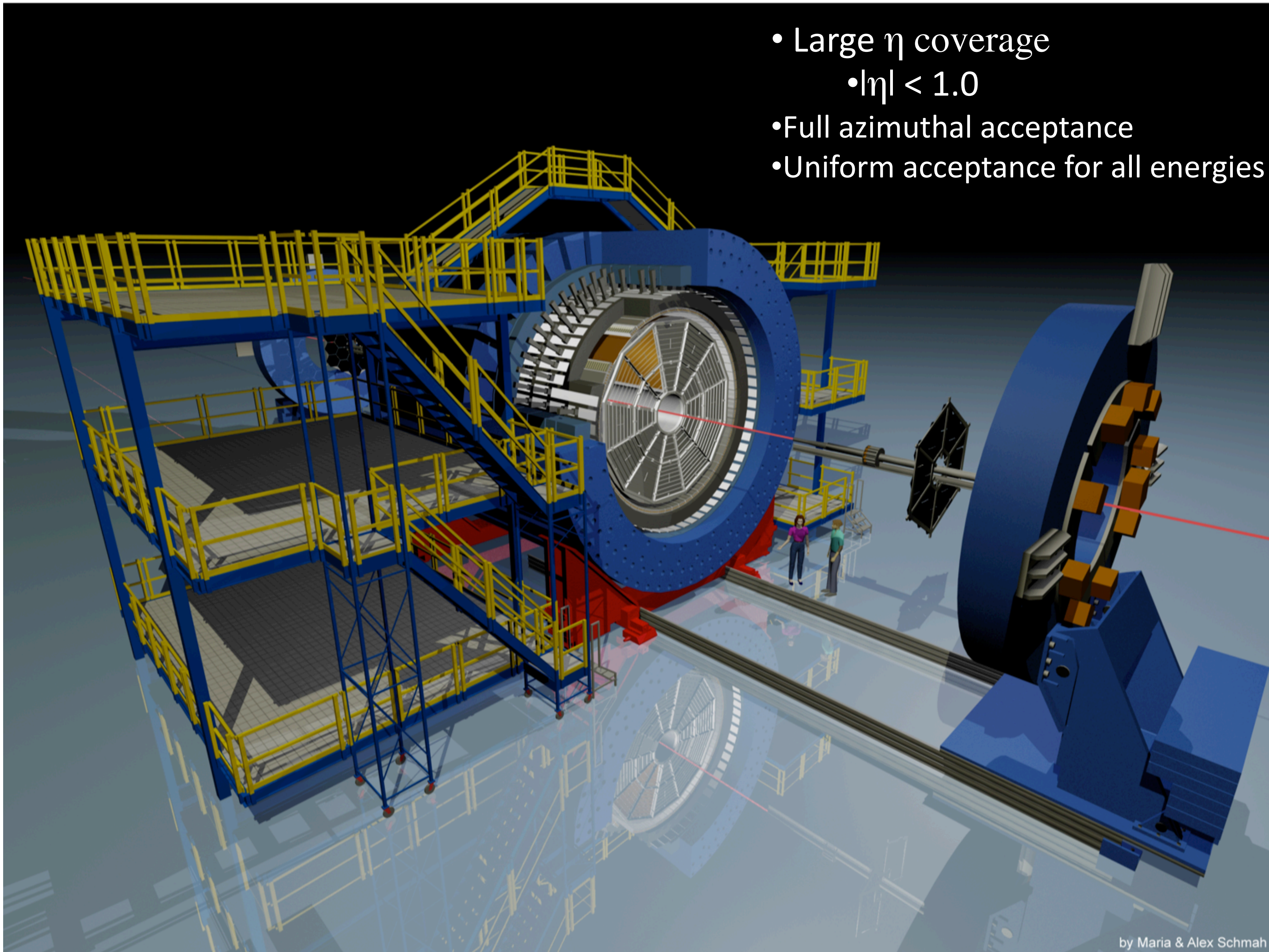
Year 2017: BES Phase-II (planned)

arXiv:1007.2613

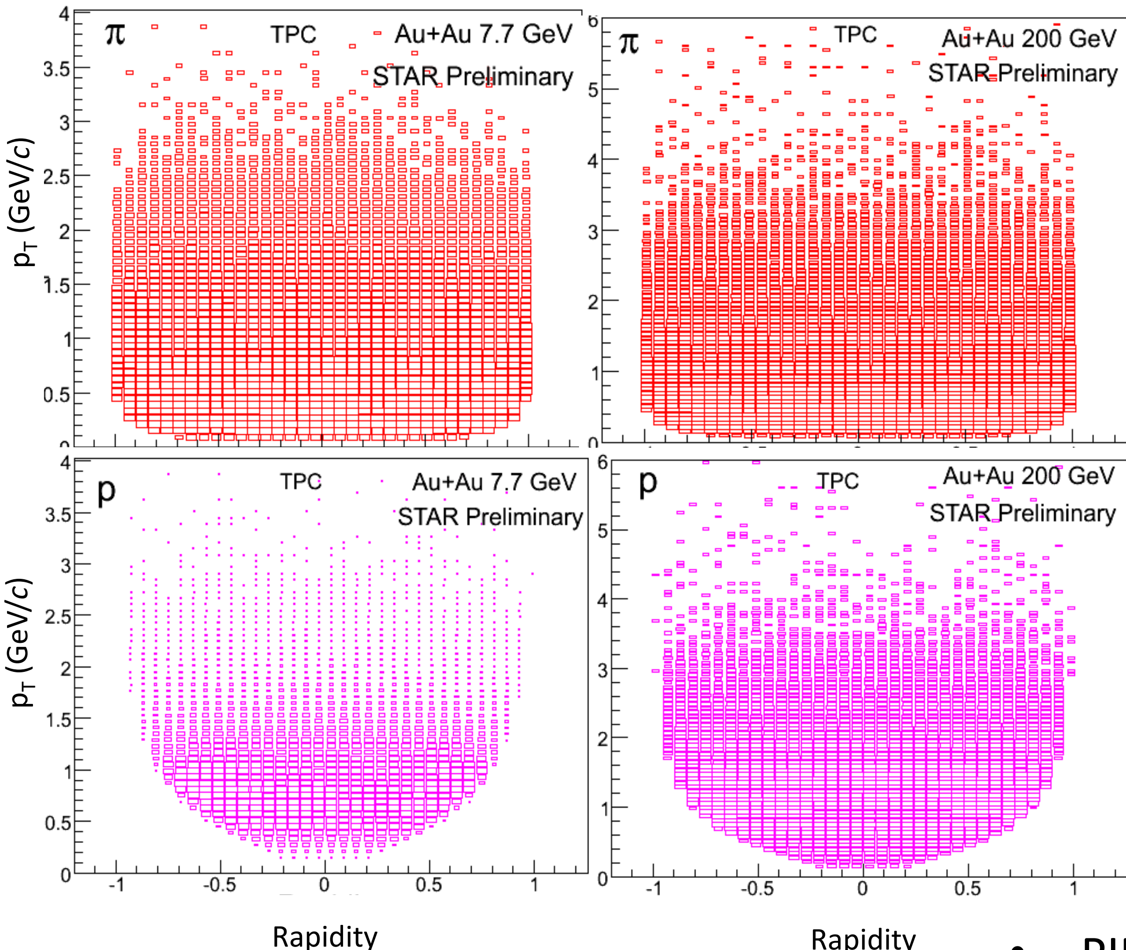
$\sqrt{s_{NN}}$ (GeV)	Min. Bias Events (10^6)	Year
7.7	4.3	2010
11.5	12	2010
19.6	36	2011
27	70	2011
39	130	2010
62.4	67	2010

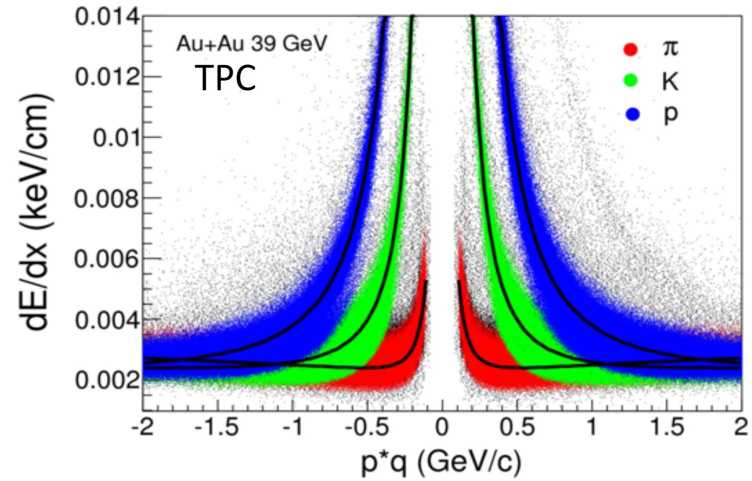
STAR Experiment

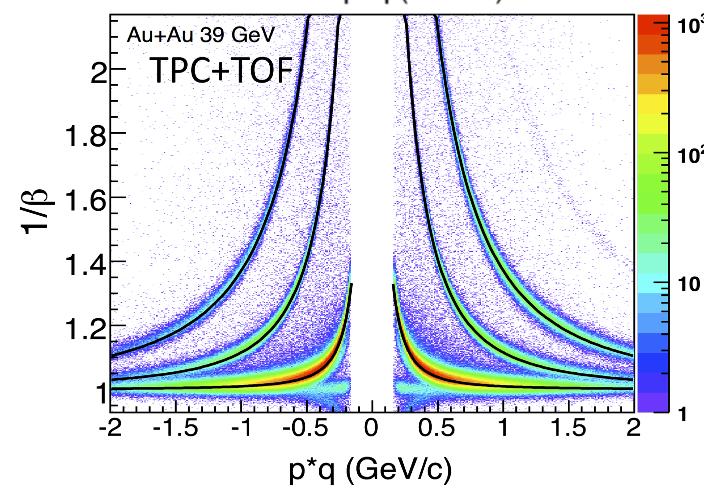
- Large η coverage
  - $|\eta| < 1.0$
- Full azimuthal acceptance
- Uniform acceptance for all energies



STAR Experiment





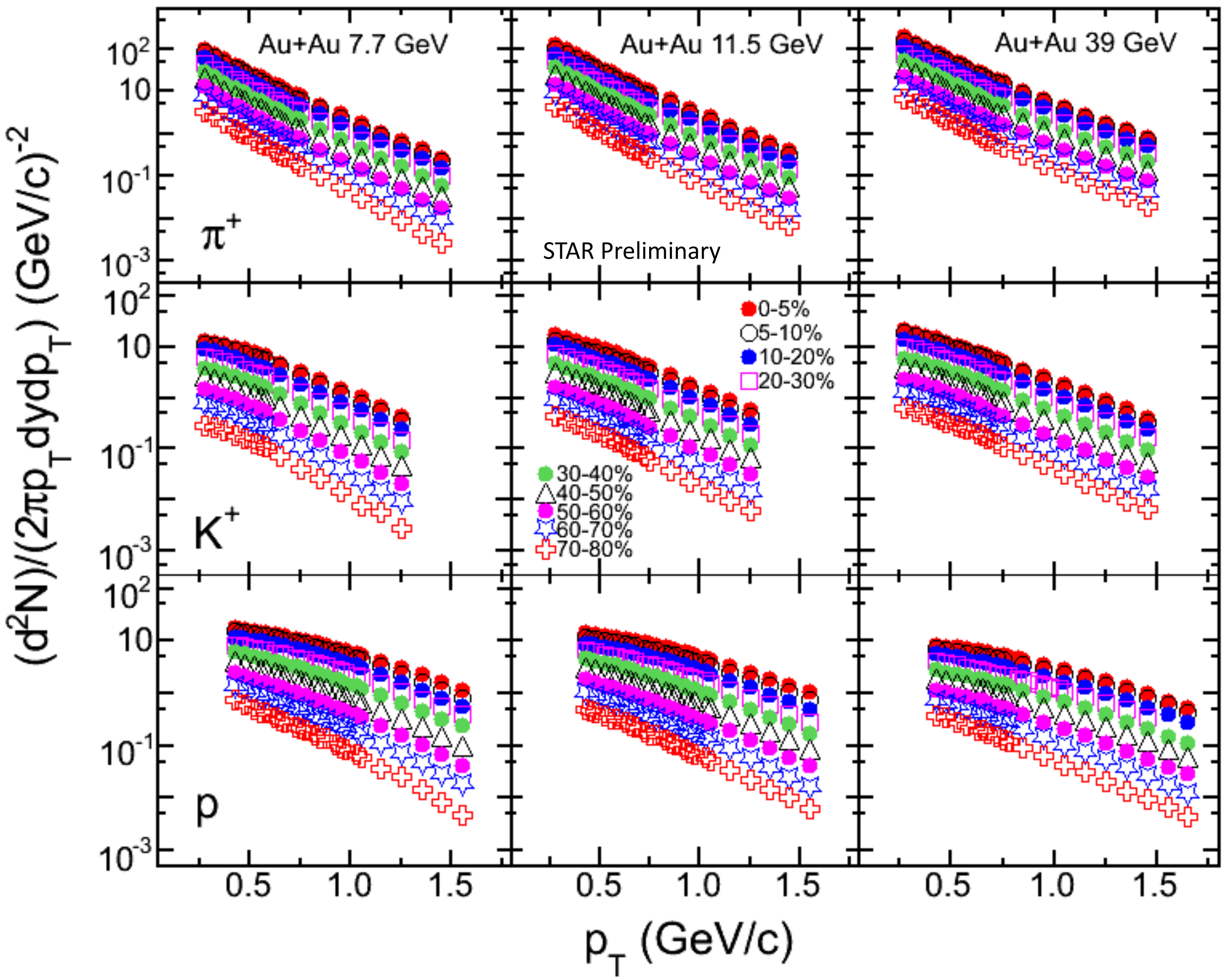


Uniform acceptance over all RHIC energies

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

Accessing Phase Diagram

π, K, p Spectra

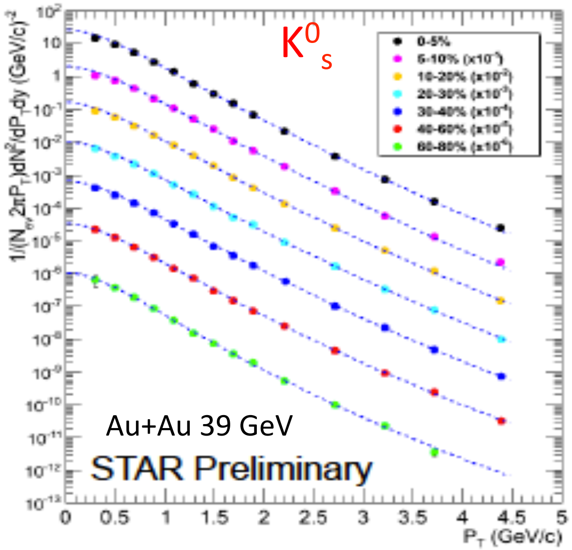


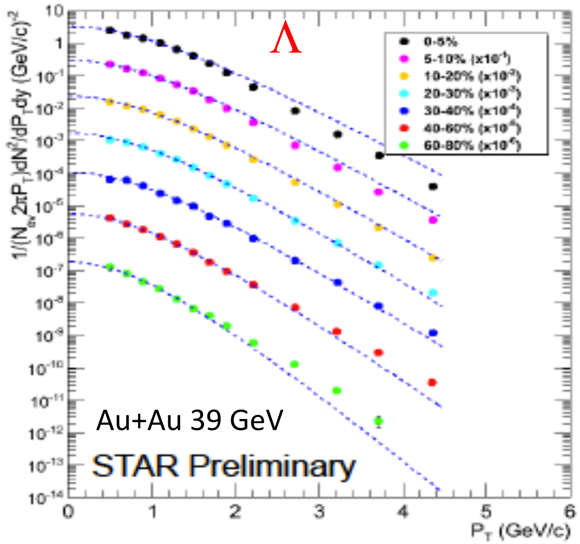
Slopes: π > K > p

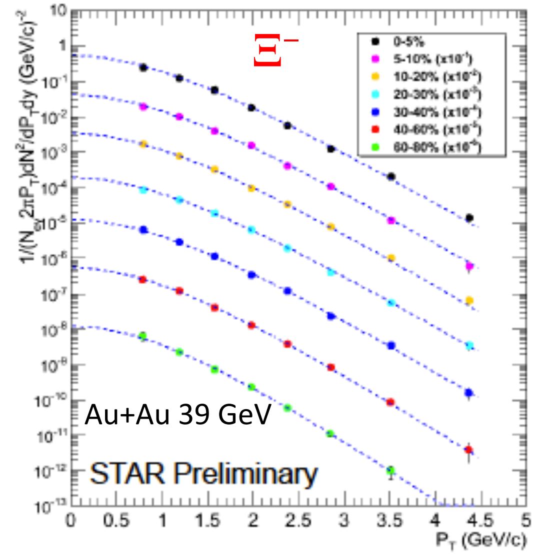
Inclusive Proton spectra:
- less model dependence

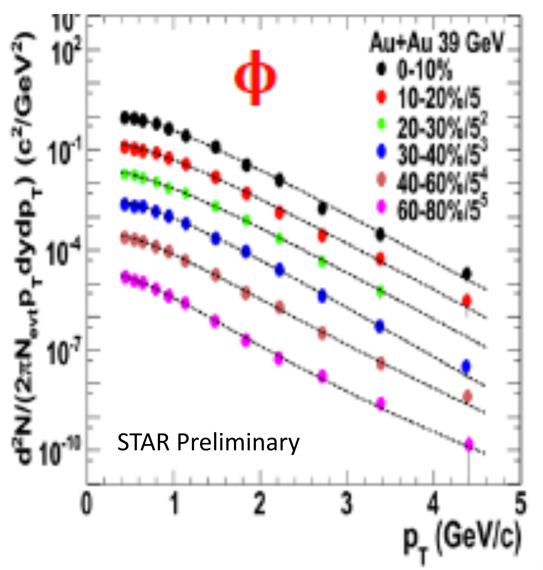
π,K,p yields within measured p_T ranges: 70-80% of total yields

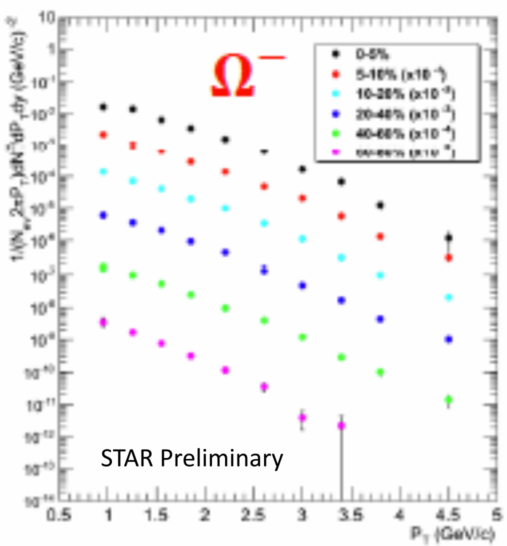
Strange Hadron Spectra









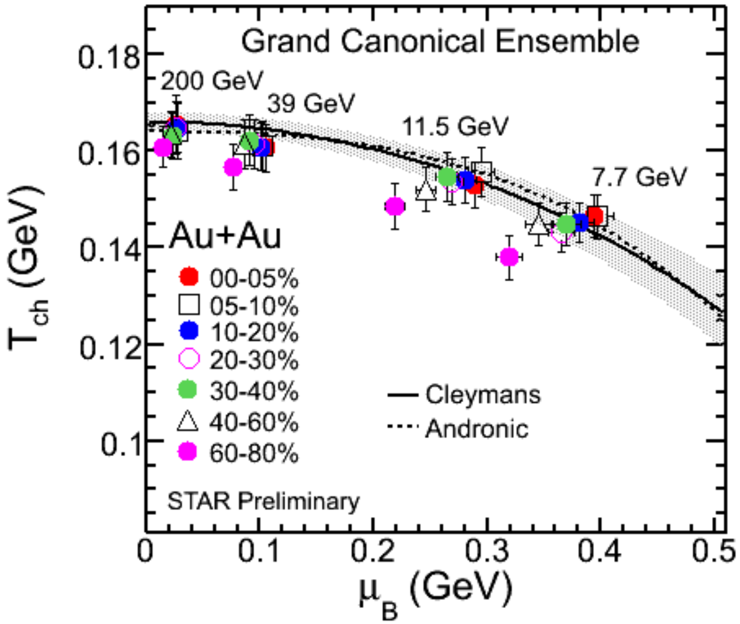


Λ, K^0_s: Levy function fit

Λ, Ξ : Boltzmann fit

Λ: feed-down corrected

Freeze-out Parameters



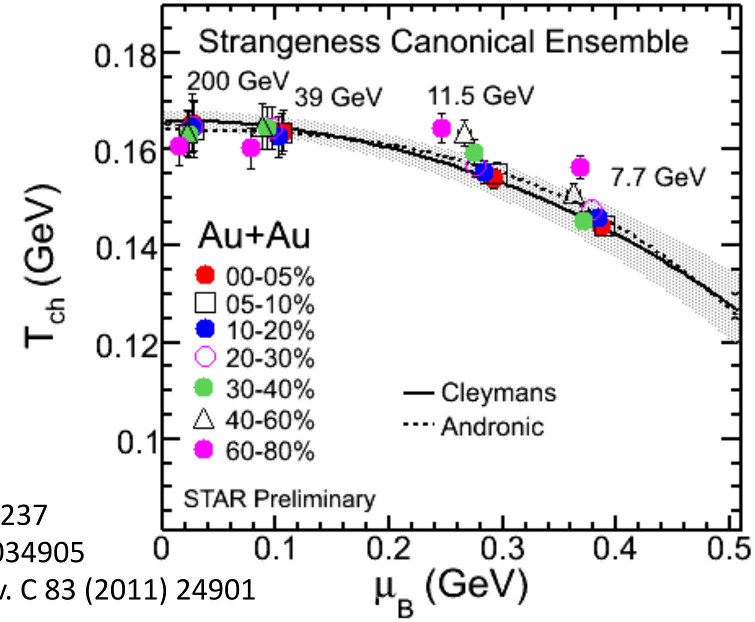
Particles used:

π, K, p, Λ, K^0_s, Ξ

THERMUS Model:

T_{ch} and μ_B

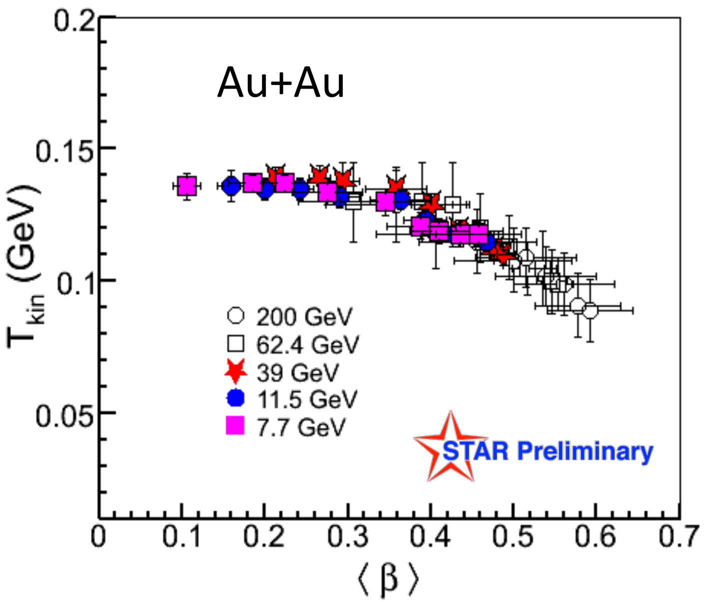
Chemical



Andronic: NPA 834 (2010) 237

Cleymans: PRC 73 (2006) 034905

Au+Au 200 GeV : Phys. Rev. C 83 (2011) 24901



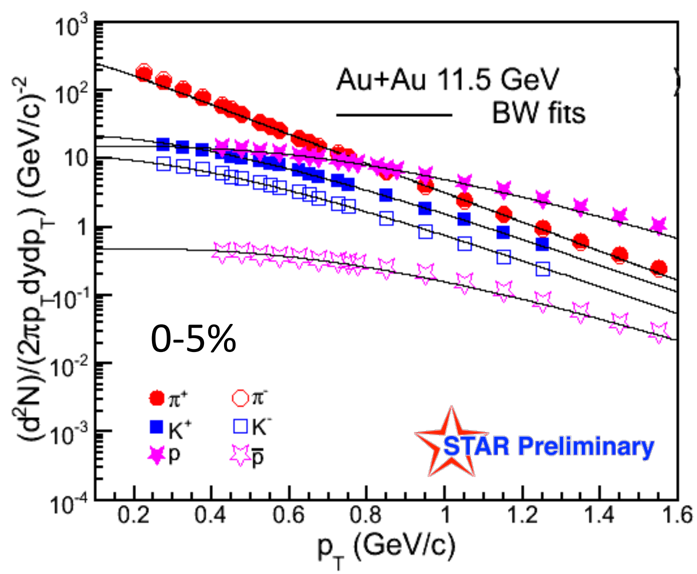
Blast Wave:

T_{kin} and <β>

Particles used:

π ,K,p

kinetic

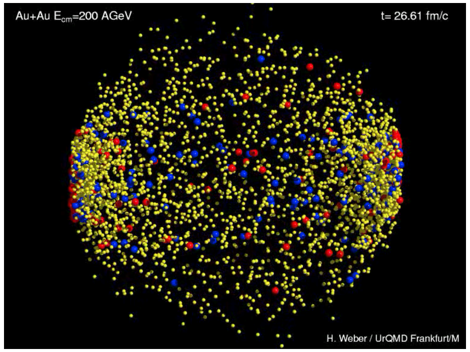


Search for Turn-off of QGP Signatures

Observables

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

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

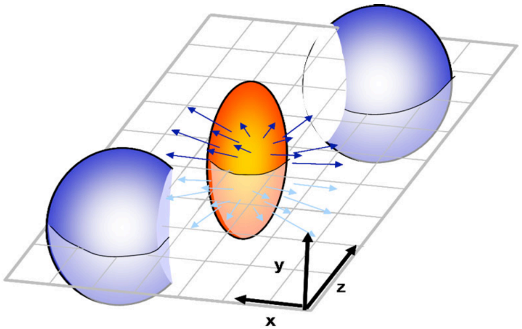


- Dynamical Charge Correlations

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

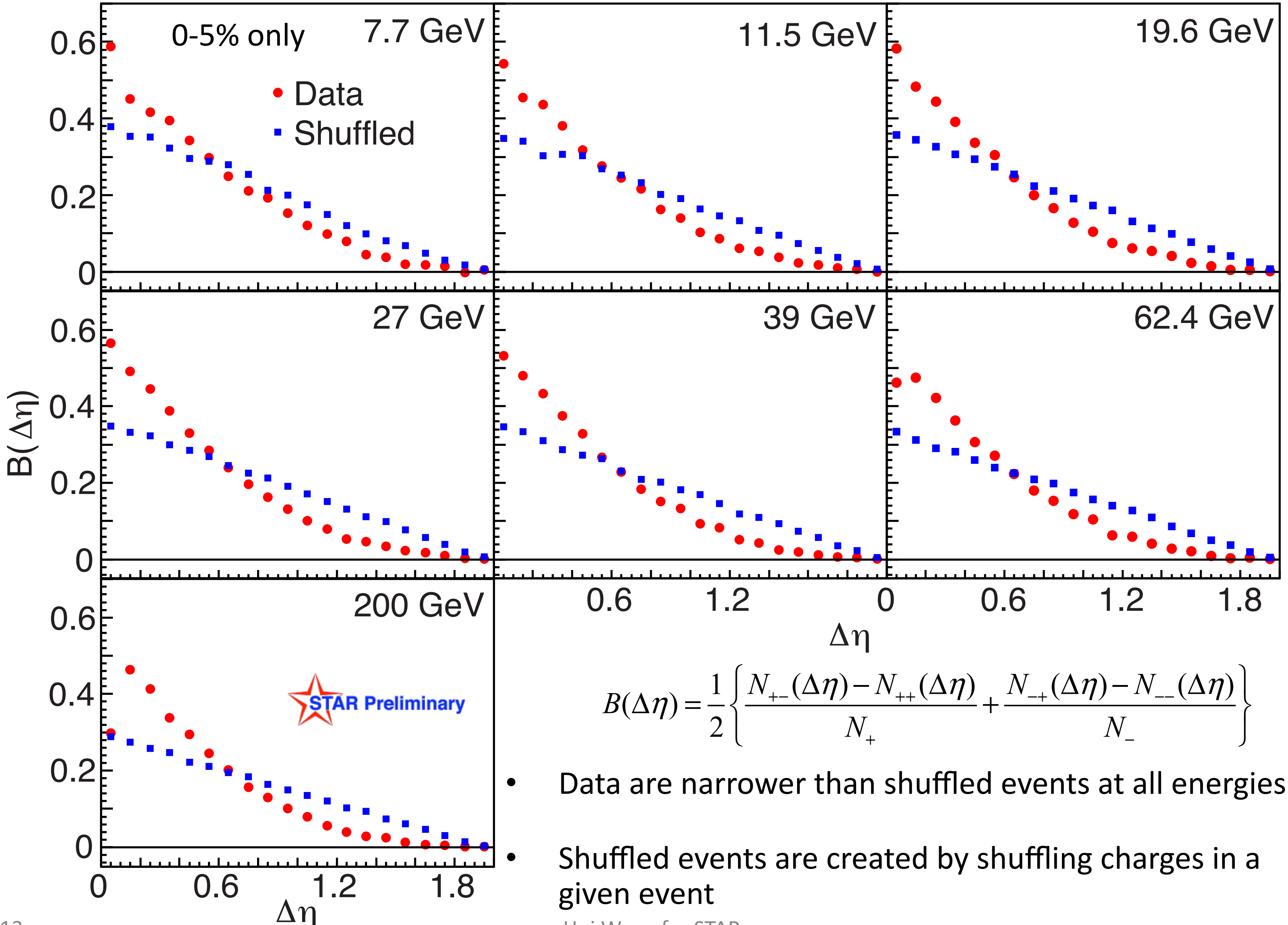
- Elliptic Flow
  - Test of number-of-constituent-quark scaling at lower energies

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



- R_{CP}
  - High pT suppression as a clear evidence of energy loss by color objects (quarks) in a color medium (QGP)

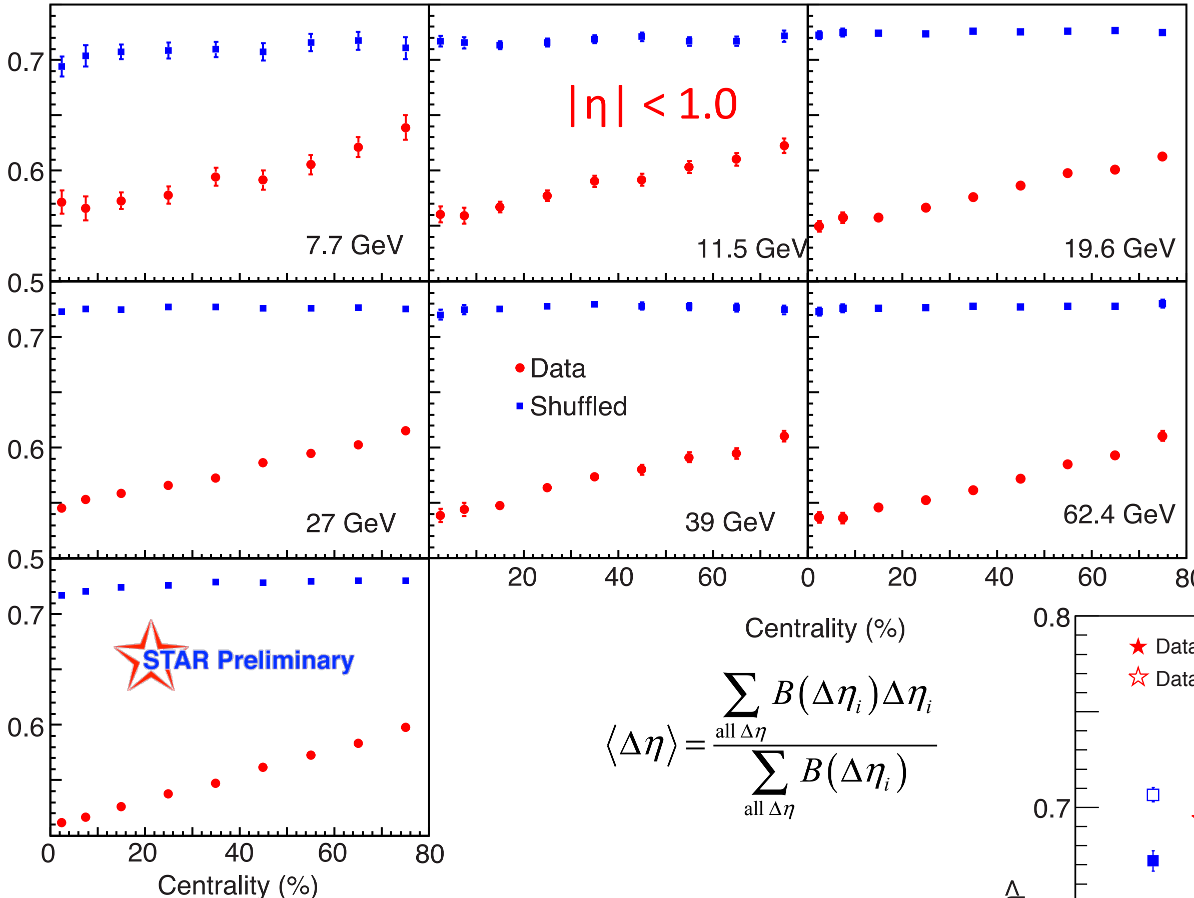
Balance Function



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

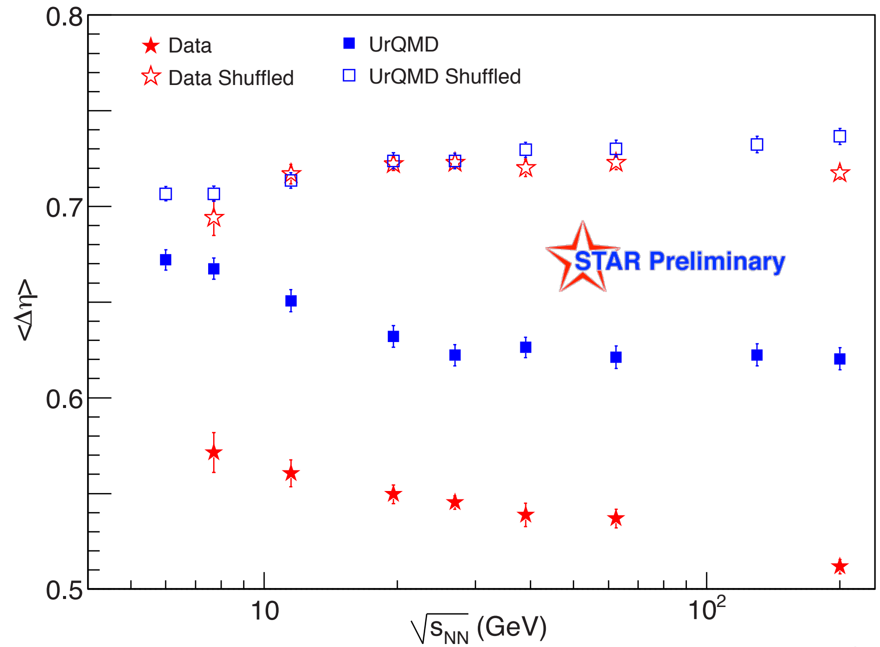
- Data are narrower than shuffled events at all energies
- Shuffled events are created by shuffling charges in a given event

Balance Function Width



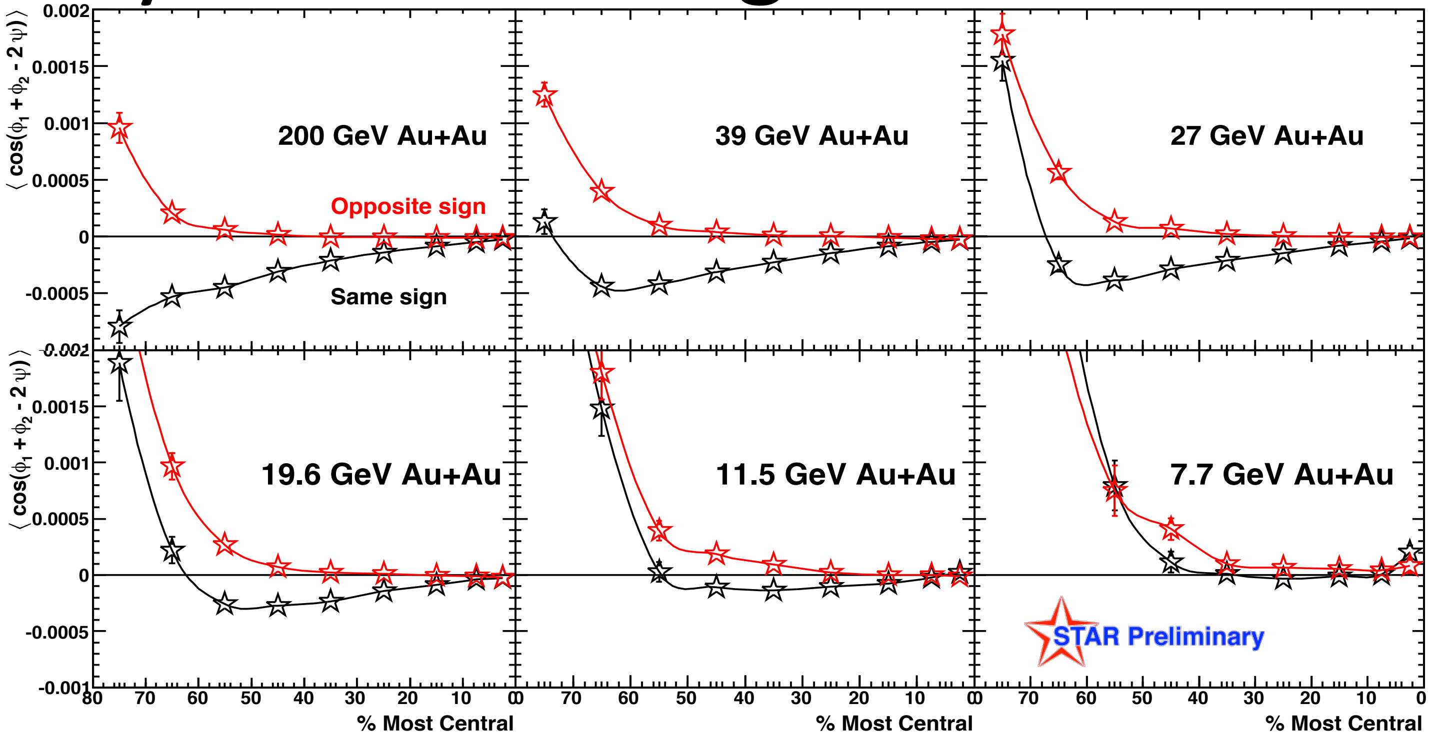
$$\langle \Delta\eta \rangle = \frac{\sum_{\text{all } \Delta\eta} B(\Delta\eta_i)\Delta\eta_i}{\sum_{\text{all } \Delta\eta} B(\Delta\eta_i)}$$

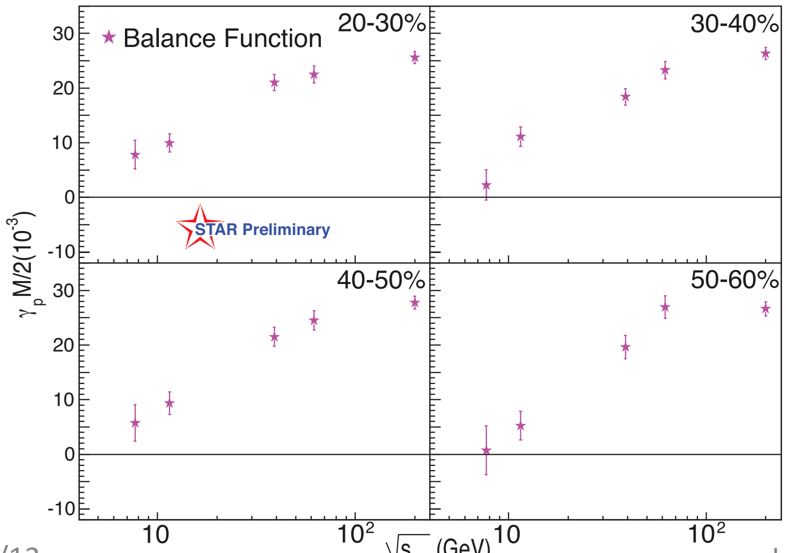
- Balance function width is sensitive to hadronization time
- Balance functions narrow smoothly with increasing collision energy and as the collisions become more central



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

Dynamical Charge Correlations



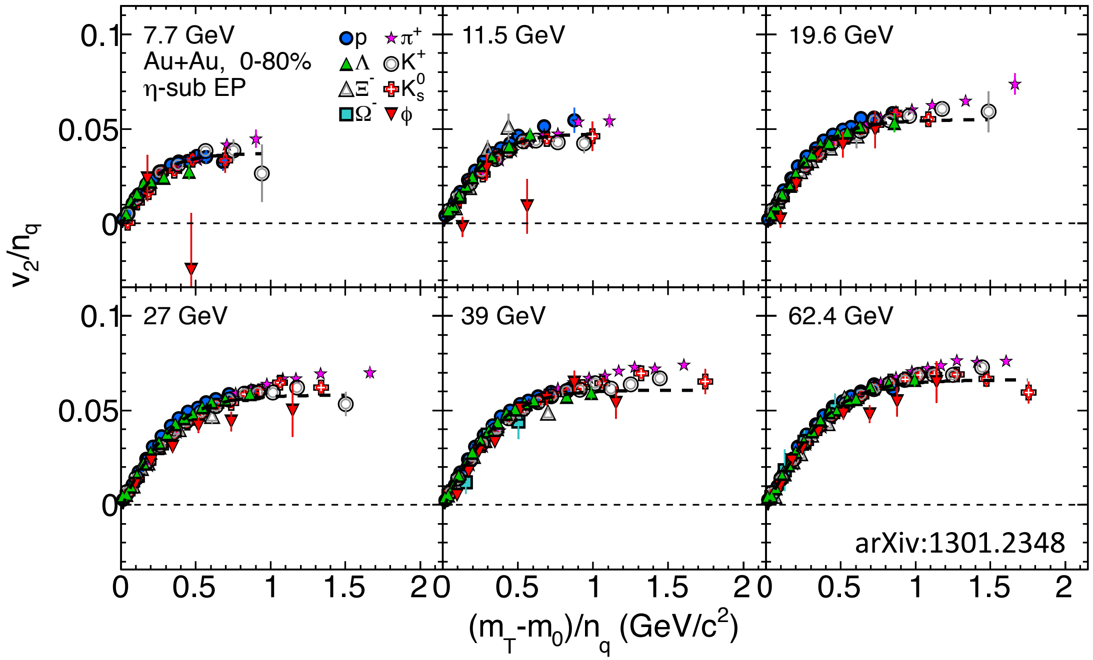


Splitting between same and opposite-sign charges decreases with decreasing $\sqrt{s_{NN}}$

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

$$\gamma_P = \gamma_{Opp} - \gamma_{Same}$$

Elliptic Flow

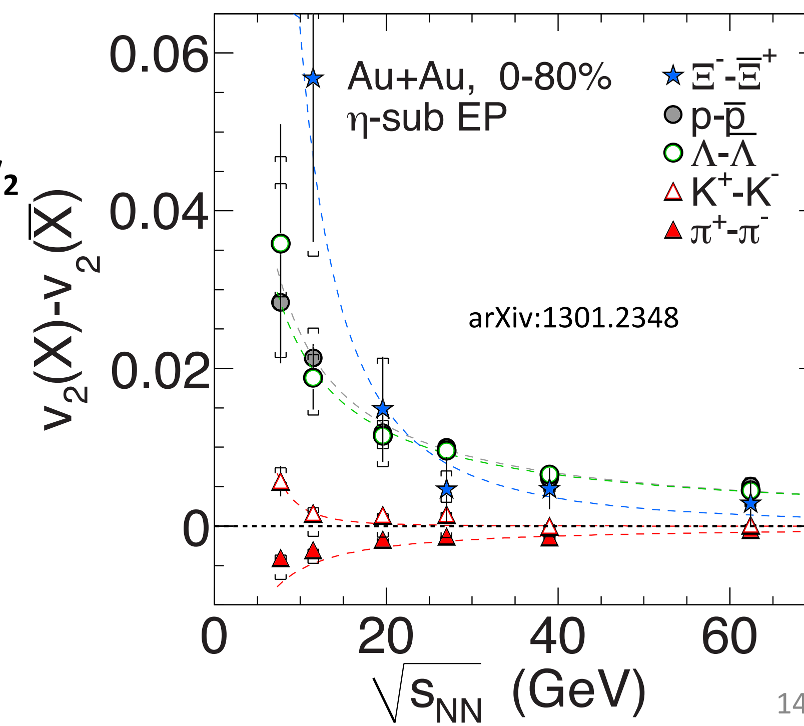


- Universal trend for most of particles
- ϕ meson v_2 deviates from other particles at low energies. More data for 7.7 and 11.5 GeV are needed for clear conclusion

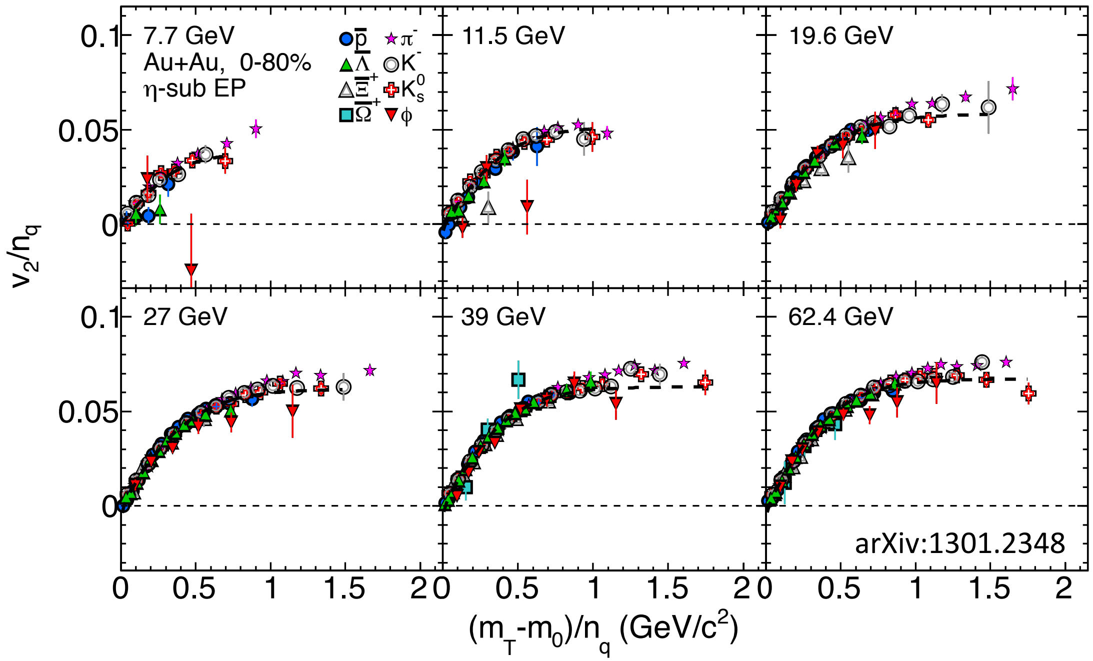
- **Difference in positive/negative charged particle v_2**
  - Increasing with decrease of beam energy
  - $v_2(K^+)>v_2(K^-)$ at 7.7-19.6 GeV
  - $v_2(\pi^-)>v_2(\pi^+)$ at 7.7-19.6 GeV
- **Possible explanation**
  - Baryon transport to mid-rapidity?

    ref: J. Dunlop et al., PRC 84, 044914 (2011)
  - Hadronic potential?

    ref: J. Xu et al., PRC 85, 041901 (2012)



Elliptic Flow



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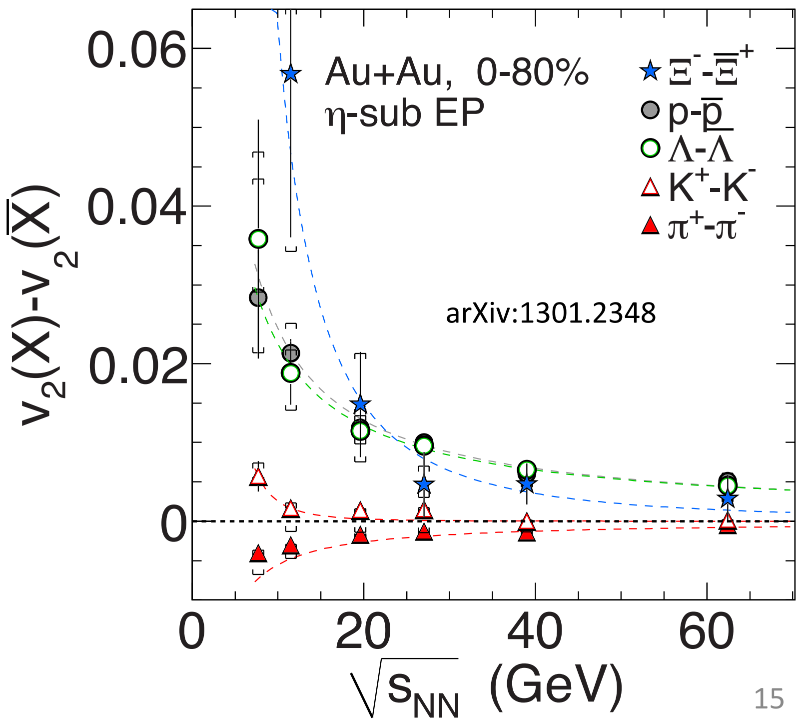
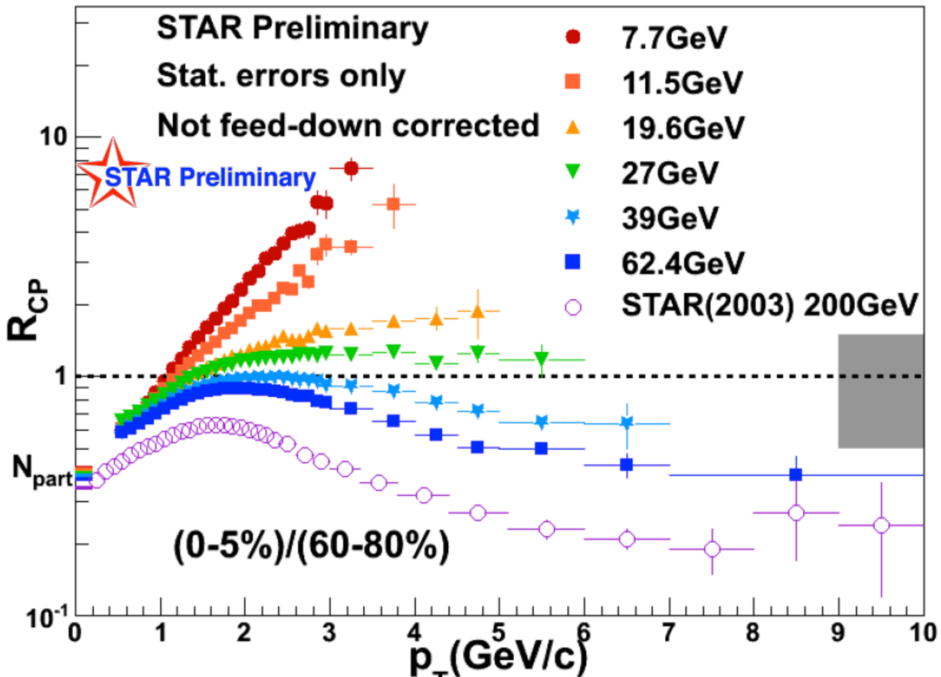
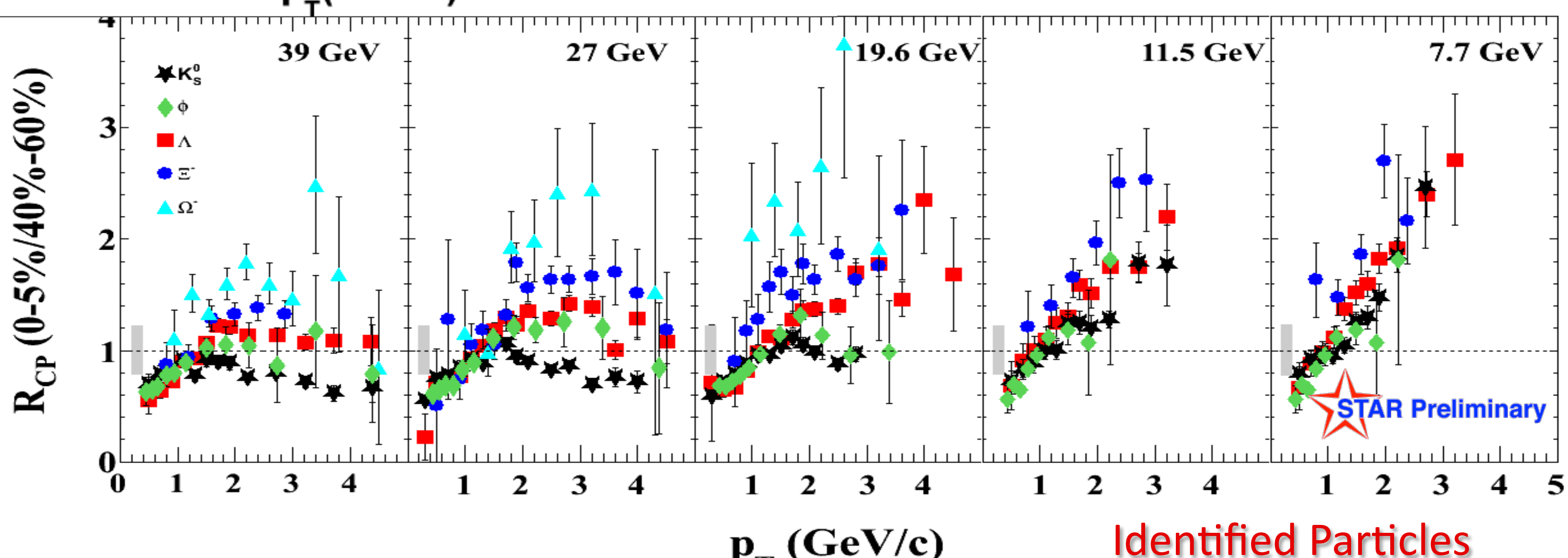


R_{CP}



- R_{cp} suppression NOT seen at lower energies
  - Possible disappearance of QGP?
  - Relative contributions of soft physics and hard scattering

All Charged Particles



Identified Particles

Search for Critical Point

Observables

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

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

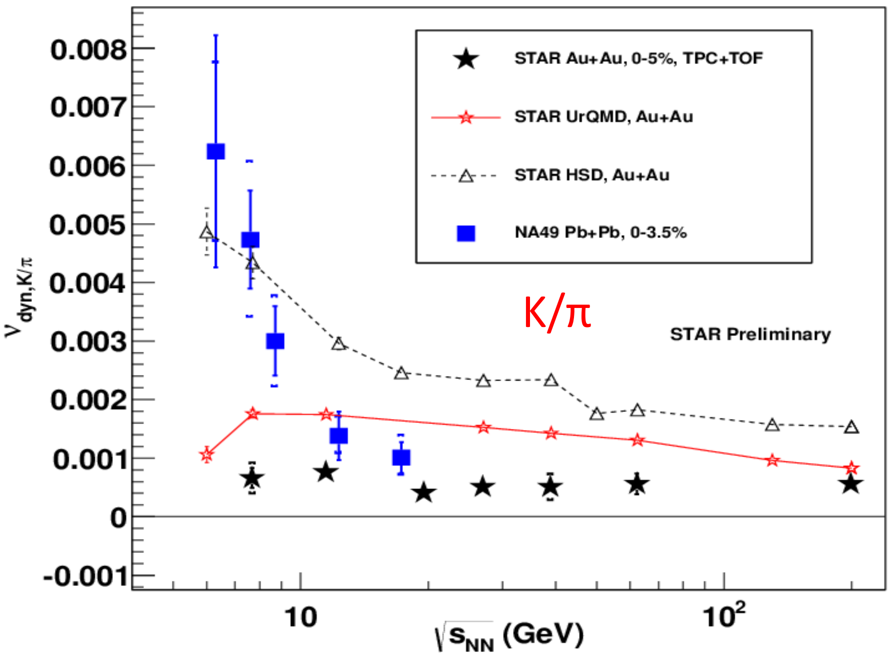
- Net Particle Moments
  - Higher moments of the net particle distributions are predicted to be sensitive to high powers of the susceptibility

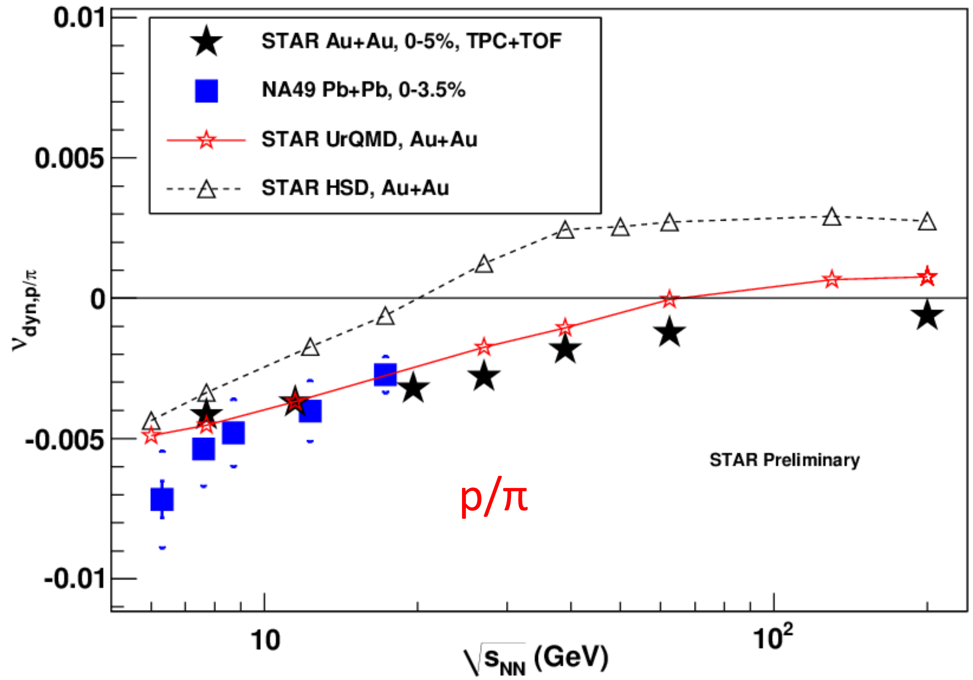
$$\sigma = \sqrt{<(N-<N>)^2>} \qquad S = \frac{<(N-<N>)^3>}{\sigma^3} \qquad \kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$

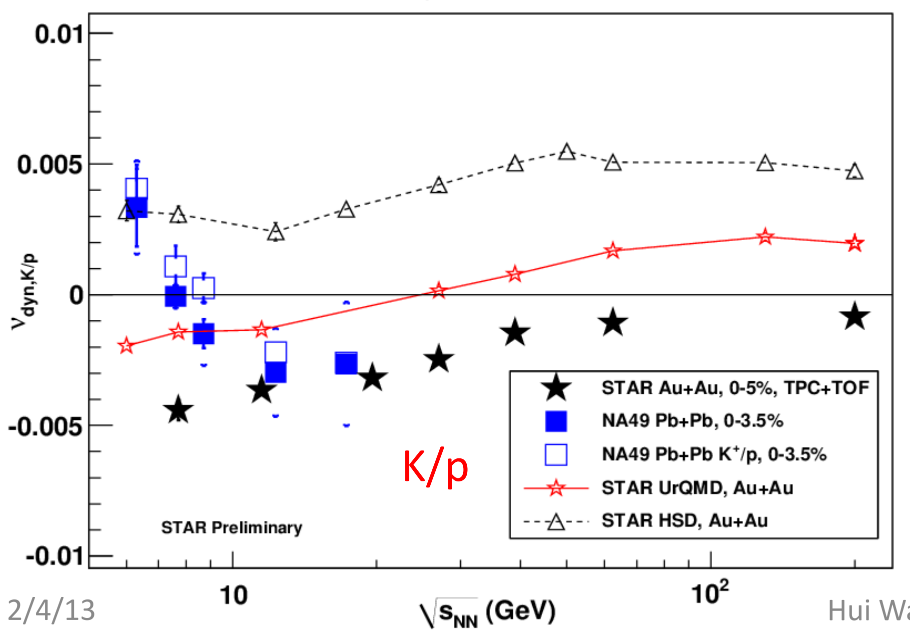
- p_t Correlations
  - Looking for non-monotonic change as a function of incident energy

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

Particle Ratio Fluctuations

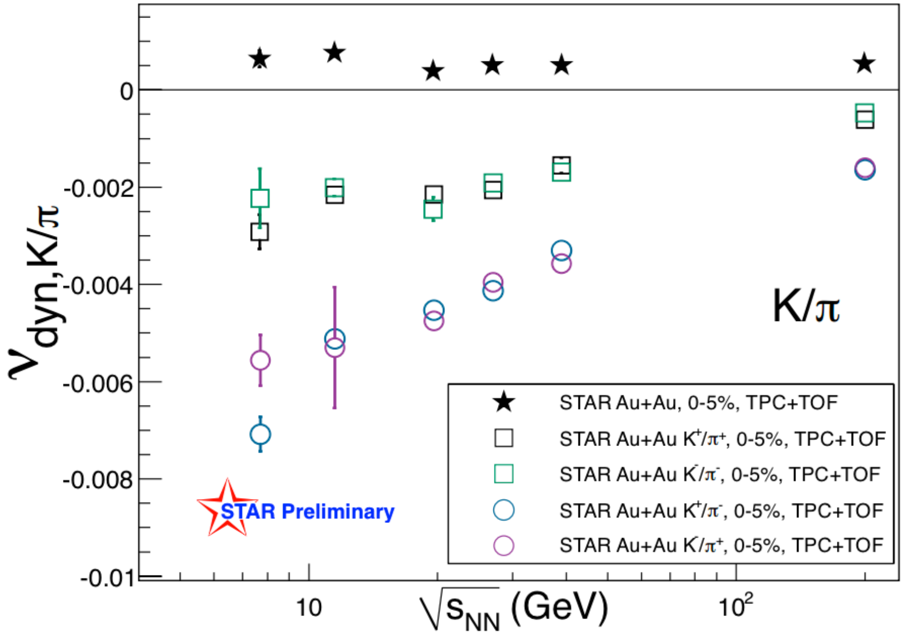


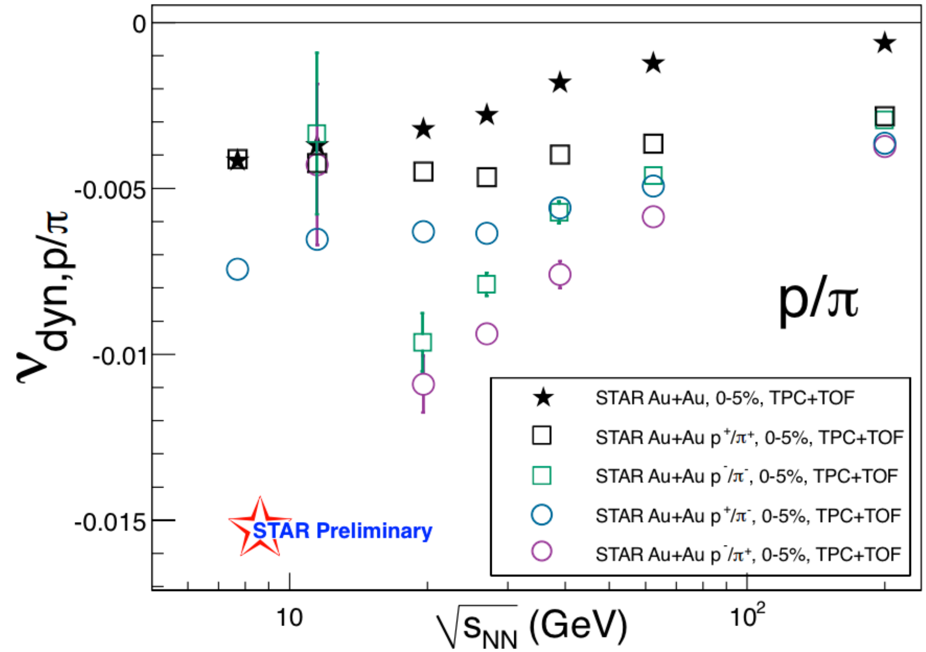


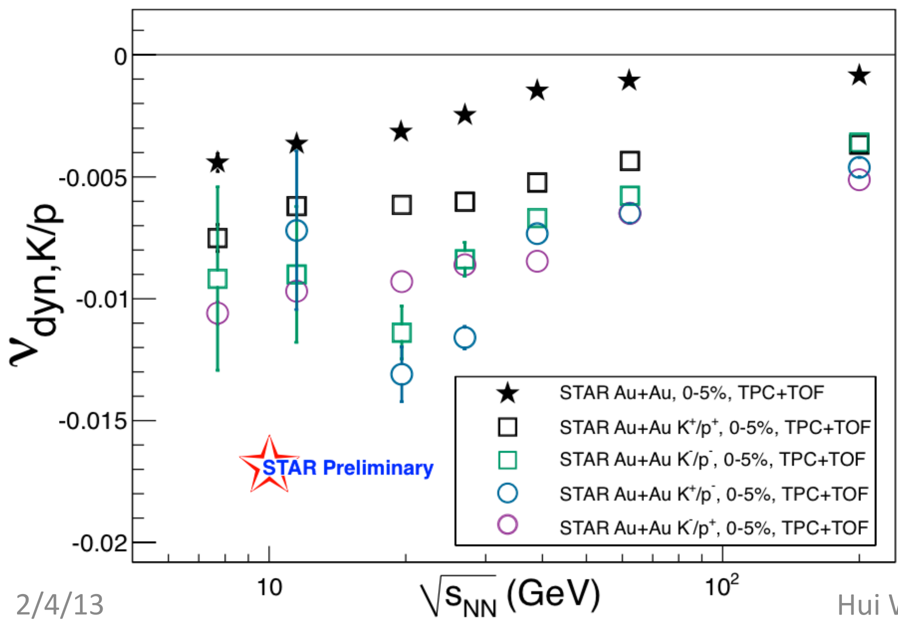


- STAR data show no significant energy dependence for K/π fluctuations
- STAR data decrease smoothly with decreasing incident energy for p/π and K/p fluctuations
- Disagreement between STAR and NA49 results for K/π and K/p fluctuations
- No non-monotonic behavior is observed

Charge Dependent Ratio Fluctuations



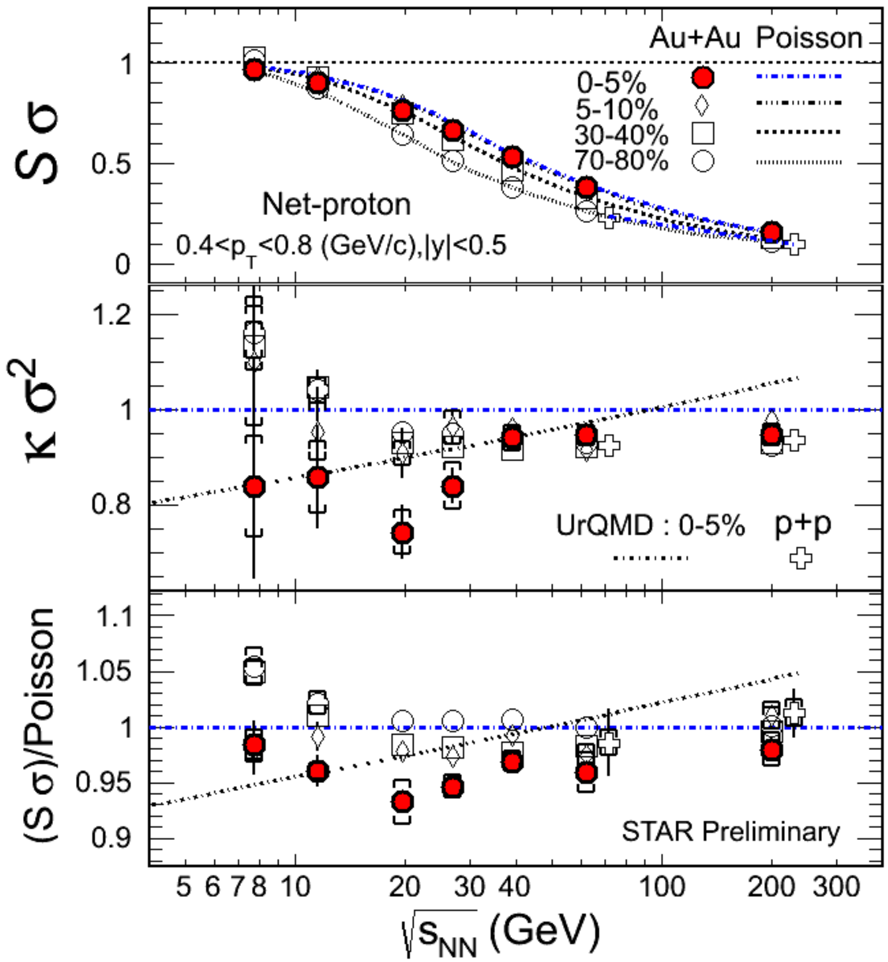


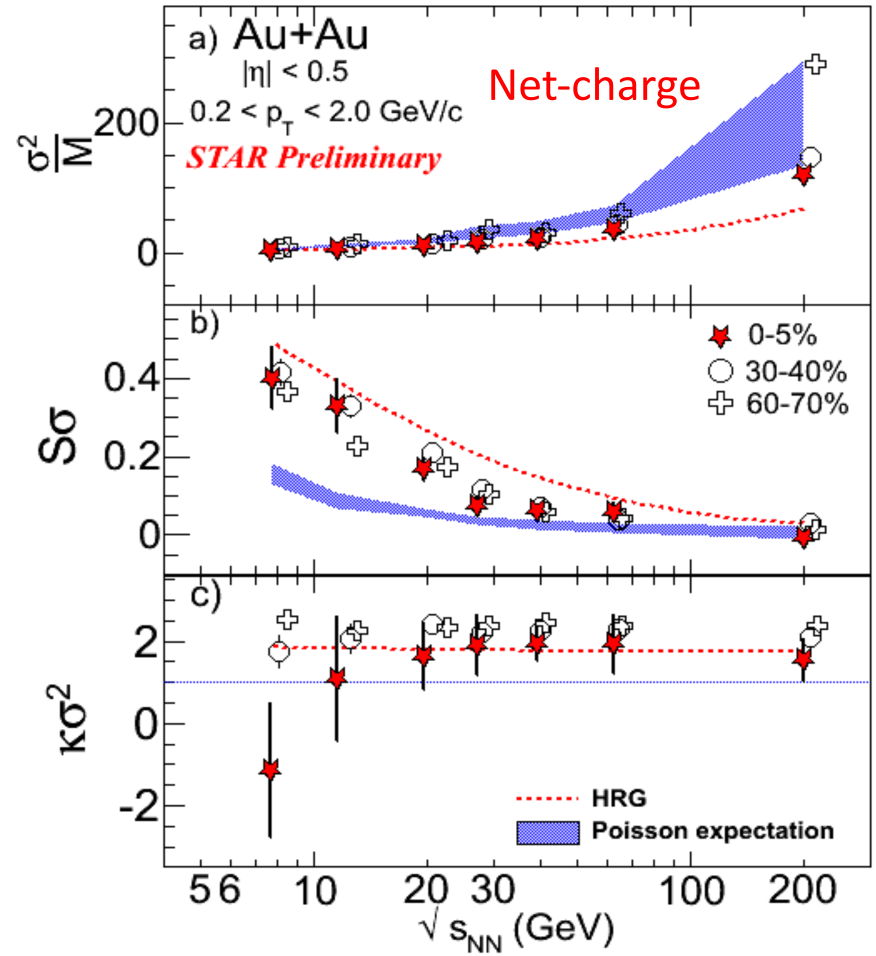


$$\nu_{\mathrm{dyn},K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

- Unstable particle decays might introduce more correlations for opposite signs
- Same sign fluctuations are also negative, needs further study to investigate the origin
- Antiproton results at the lowest energies are higher due to vanishing antiproton yields

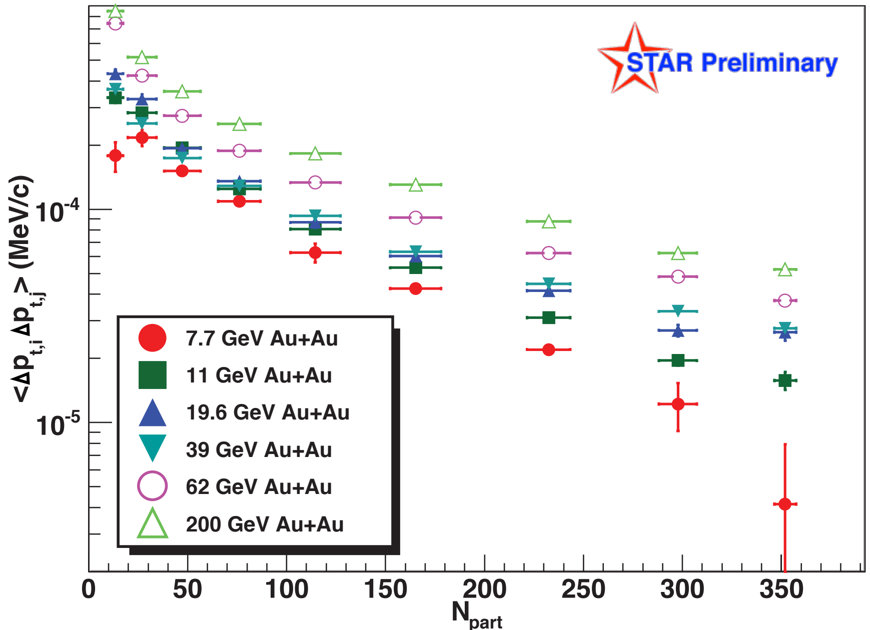
Higher Moments



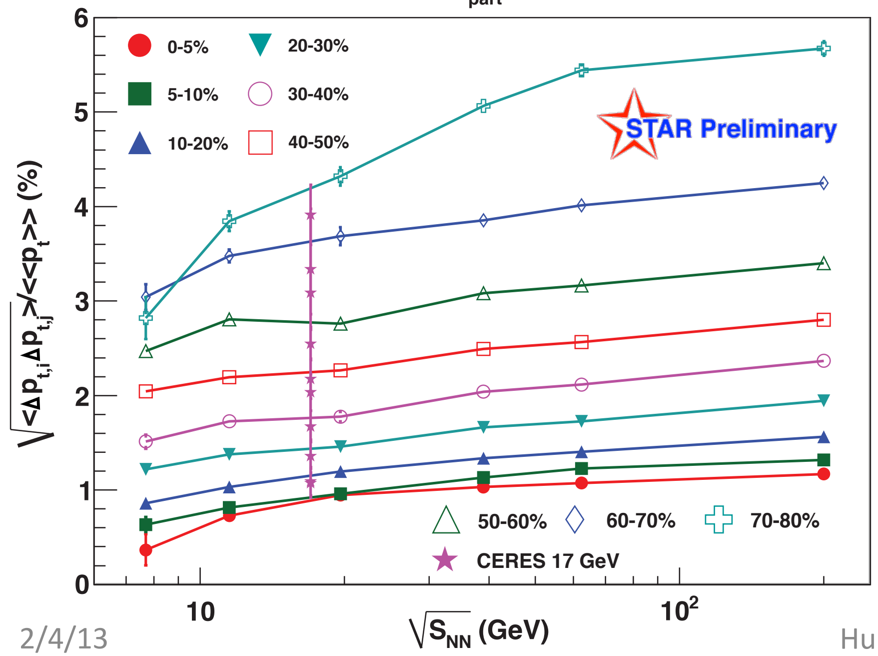


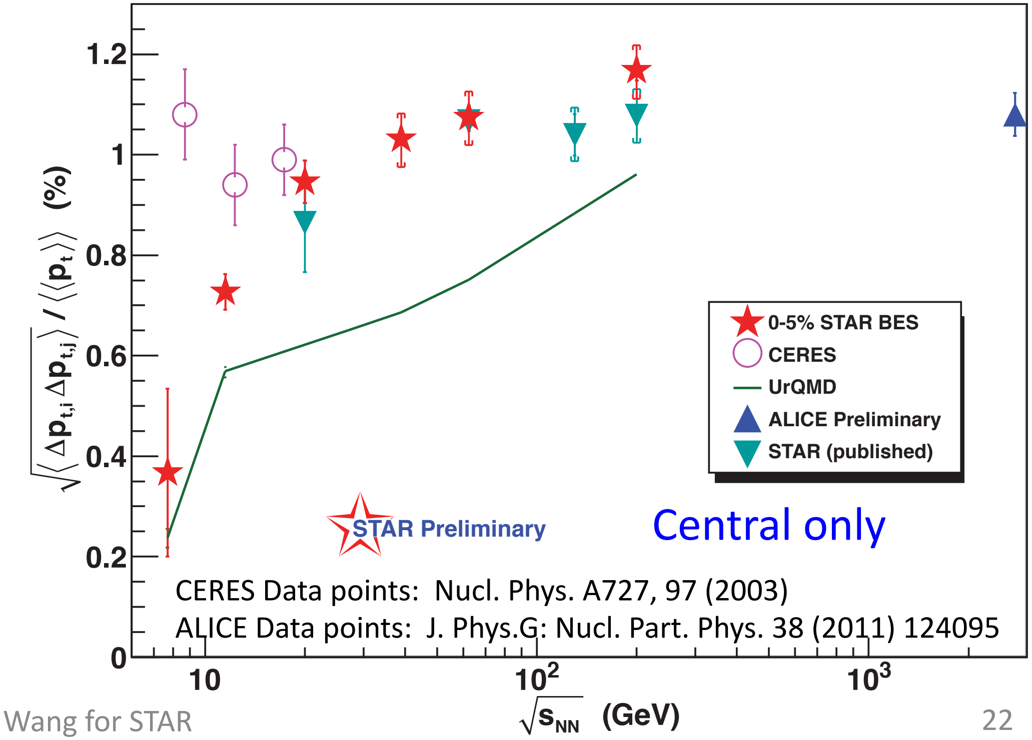
- Possible non-monotonic behavior limited to 0-5% only
  - Large statistical and systematical errors make conclusions difficult
- New Negative Binomial baseline study
  - See Gary Westfall's talk on Thursday

p_t Correlations

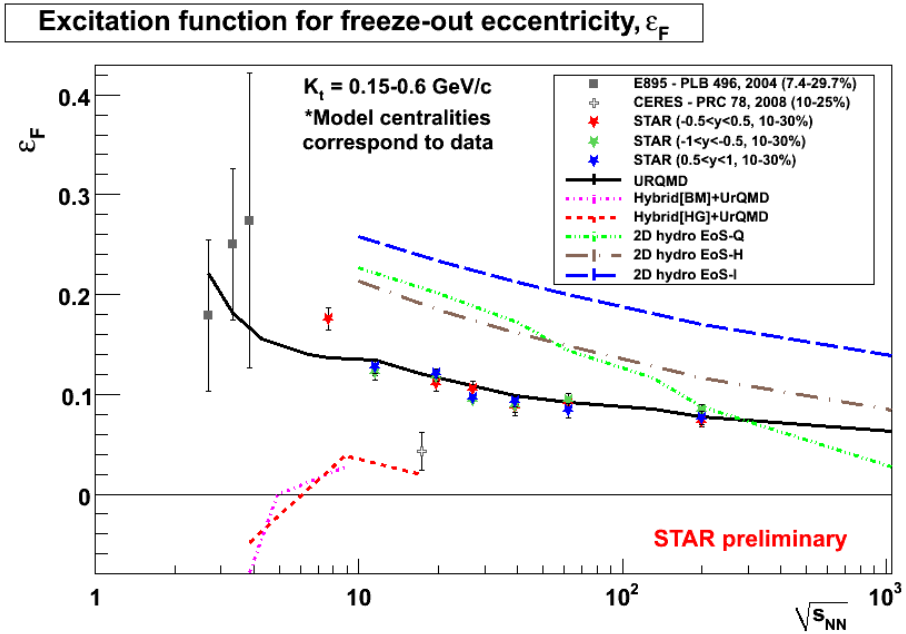


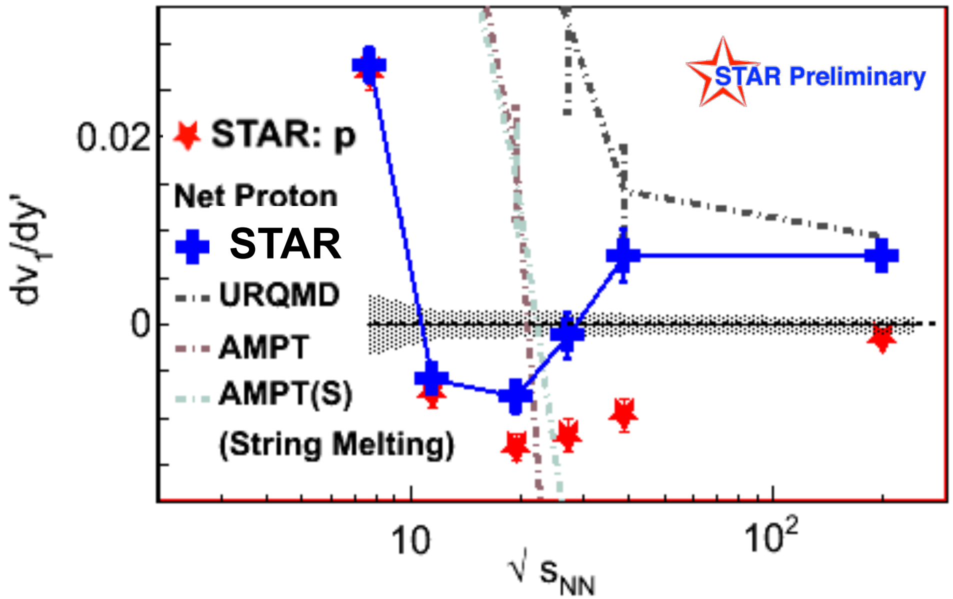
- Scaled correlations strongly decrease with decreasing energy below 39 GeV
- No non-monotonic behavior is observed
- Acceptance difference effect under investigation





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

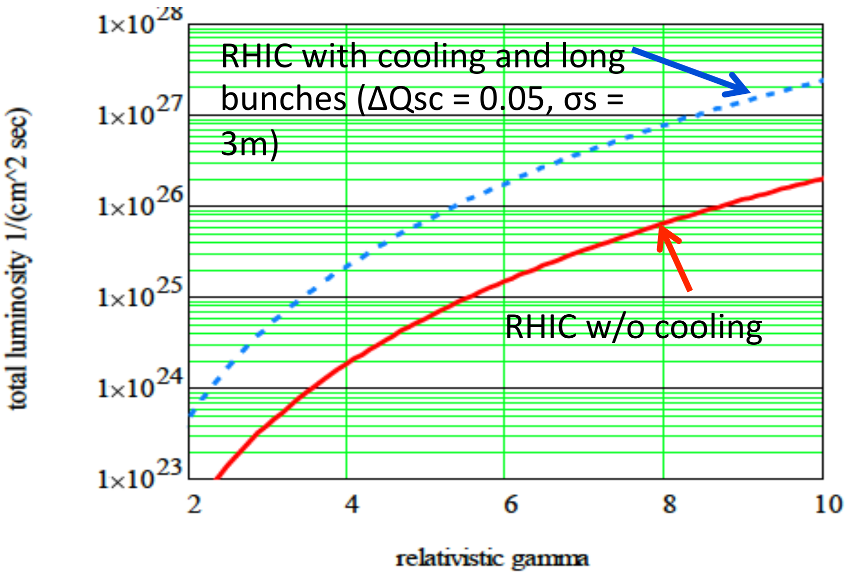
[1] Kolb and Heinz, 2003, nucl-th/0305084
[2] H. Stocker, Nucl. Phys. A **750** (2005) 121

BES Phase-II proposal

BES Phase-II proposal

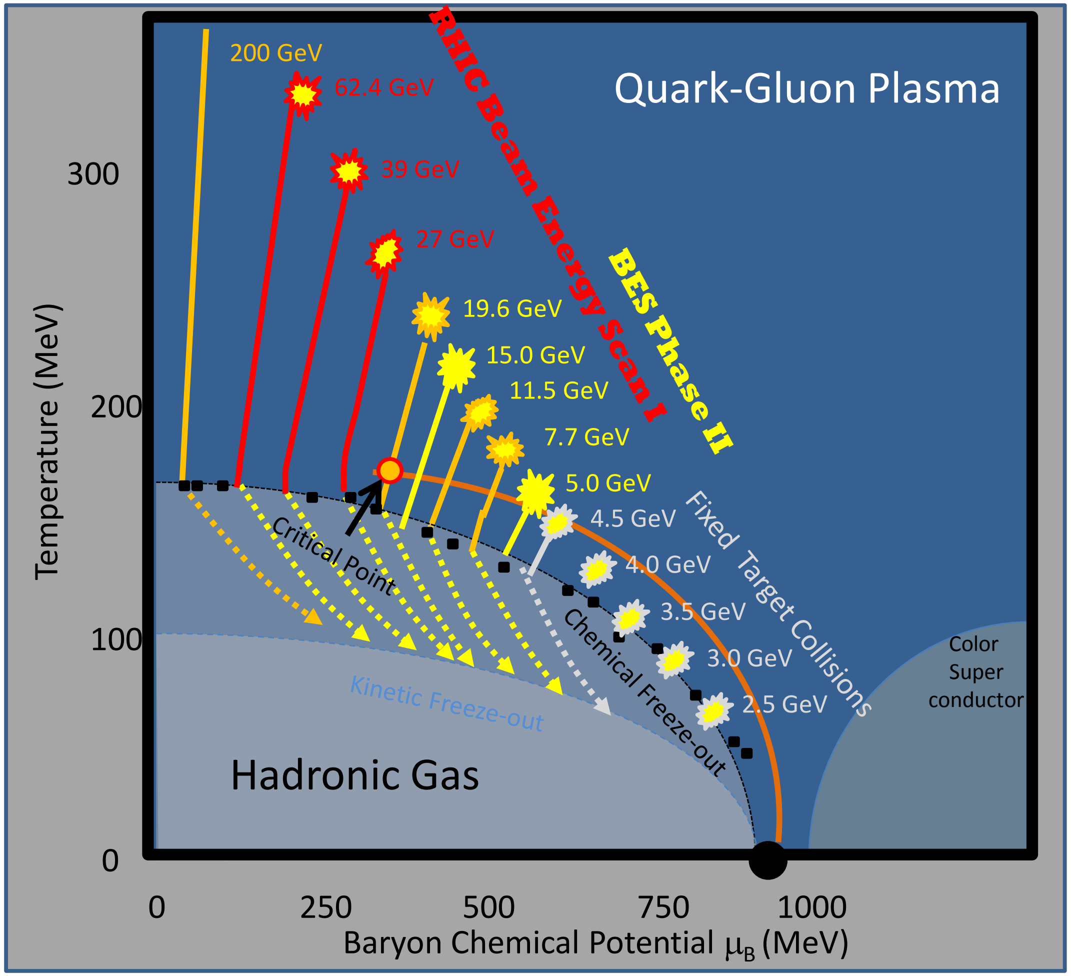
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	BES-I	BES-II	Weeks*
39	112	130 (M)		
27	156	70 (M)		
19.6	206	36 (M)	**400** (M)	**2**
15	250		**100** (M)	**2**
11.5	316	12 (M)	**120** (M)	**3.5**
7.7	420	5 (M)	**80** (M)	**10**

* Estimates are based on electron cooling upgrade currently under development and are approximate without electron cooling, the program would require ~150 weeks

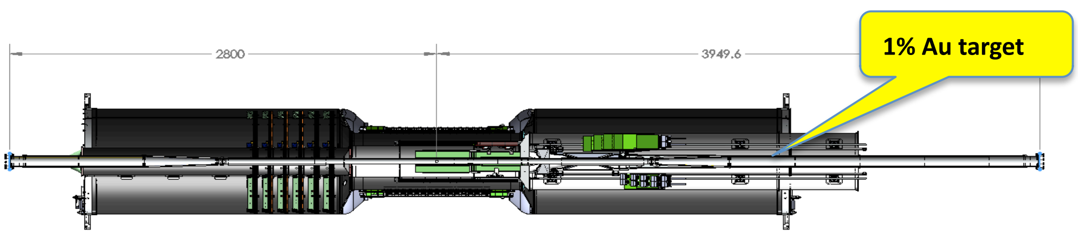


- Physics Motivation
  - Net-proton, Ω yield, φ-meson v_2, etc
- Electron Cooling
  - Raise the luminosity by a factor a 3-10 in the range from 3 – 10 GeV
  - Long Bunches increase luminosity by factor of 2-5

Fixed Target Proposal



$\sqrt{s_{NN}}$ [GeV] (Collider)	$\sqrt{s_{NN}}$ [GeV] (Fixed Target)
19.6	4.5
15	4.0
11.5	3.5
7.7	3.0



- Annular 1% gold target inside the STAR beam pipe
- 2m away from the center of STAR
- Data taking concurrently with collider mode at beginning of each fill

Summary

- Accessing Phase Diagram:
  - Large μ_B range covered in the phase diagram
- Different features show up at low energies:
  - Turn-off of QGP signatures:
    - Several key sQGP signatures not seen at low energies
  - Critical Point Signatures :
    - Need more statistics
  - First order phase transition:
    - Some hints
- 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