Charge Dependence and Scaling Properties of Dynamical K/π, p/π, and K/p Fluctuations from the STAR Experiment

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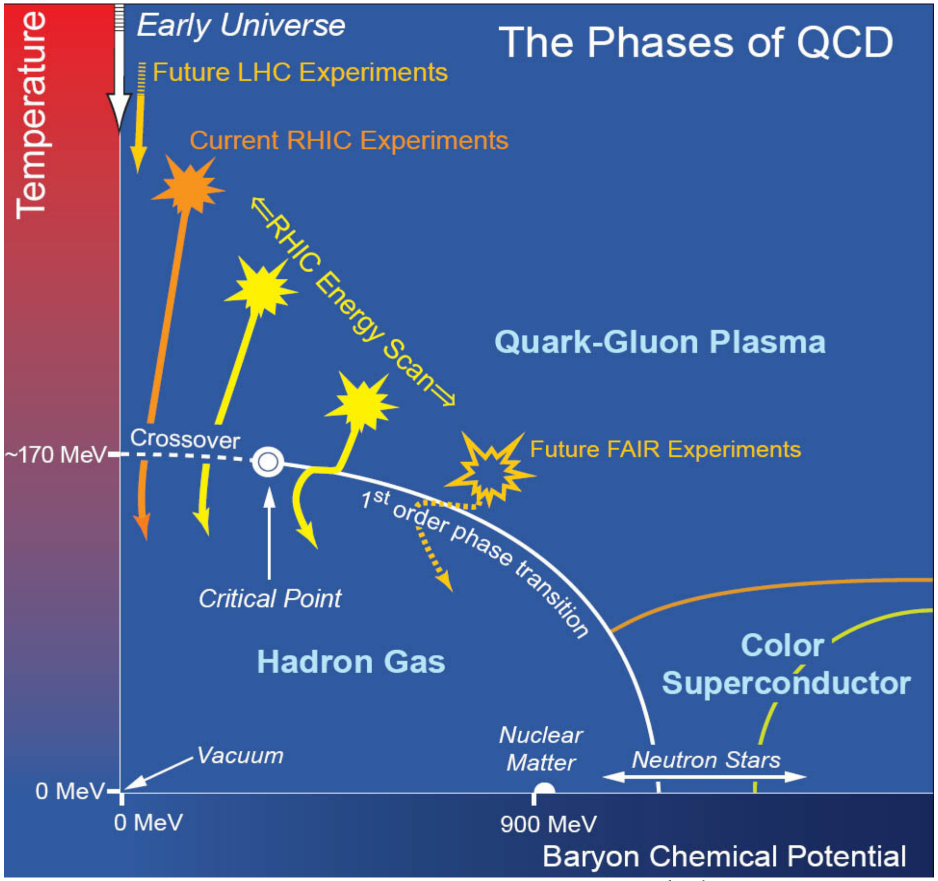
Nuclear Matter

- Finite (charged) nuclear matter occurs at low T and $\mu_B \approx 922$ MeV → energy density (ε) ≈ 0.15 GeV/fm^3.



- Lattice QCD:
  - –Transition between hadronic matter and quark-gluon matter predicted at T ≈ 170 MeV.
  - –Critical point predicted.
    - Transition crossover to left, 1st order to right.

Motivation Behind Correlations and Fluctuations

- Have been many theoretical predictions that the behavior of correlations and fluctuations in a deconfined phase are different than that in hadron gas.

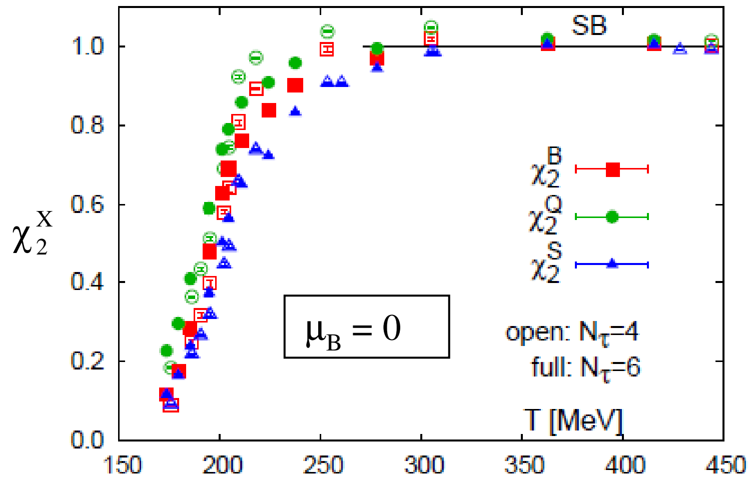
- Experimental justification from studies of the thermodynamics of phase transitions.

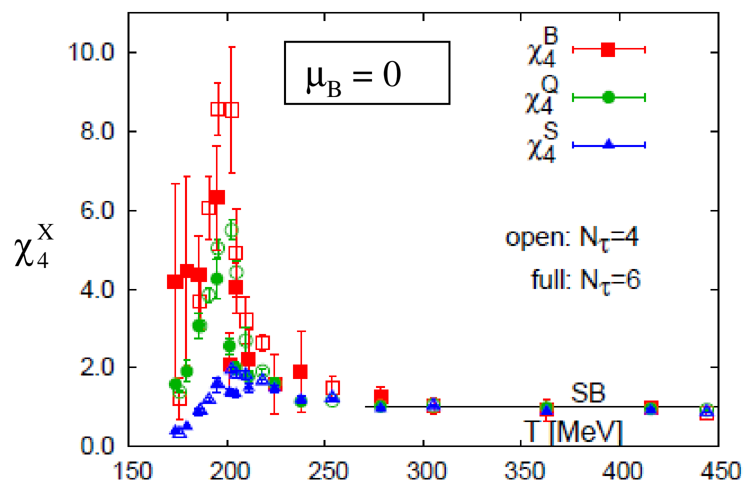
- Even w/o such guidance, can search for discontinuities in fluctuations and correlations as functions of incident energy and centrality (not an inclusive list):
  - Particle ratio fluctuations (K/π, p/π, K/p).
  - Forward-Backward multiplicity correlations.
  - Balance Functions
  - Higher moments of conserved quantities.
  - Etc.

Search for the QCD Critical Point

- In a phase transition near a critical point, an increase in non-statistical fluctuations is expected.
- Finite system-size effects may influence fluctuation measurements.
    - Finite-size scaling of fluctuations may indicate existence of critical point.
    - E.g. Change in behavior of quark susceptibilities.

      Aoki, Endrodi, Fodor, Katz, and Szabó *Nature* **443**, 675-678 (2006)
- These may manifest in final-state measurements.



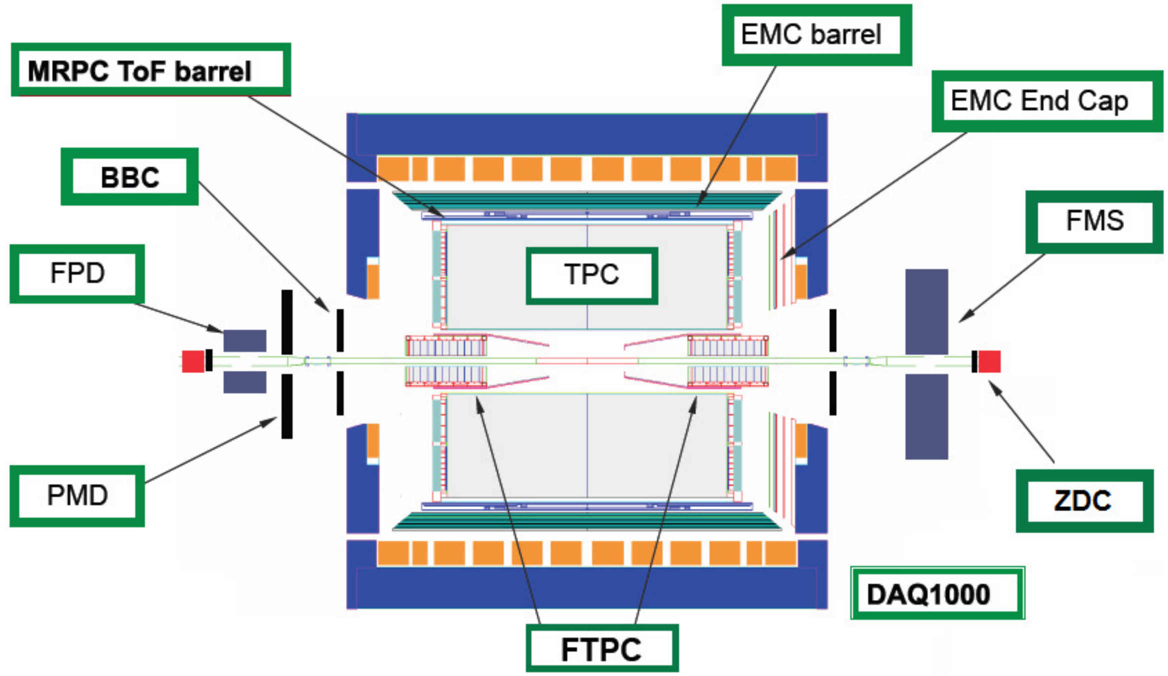


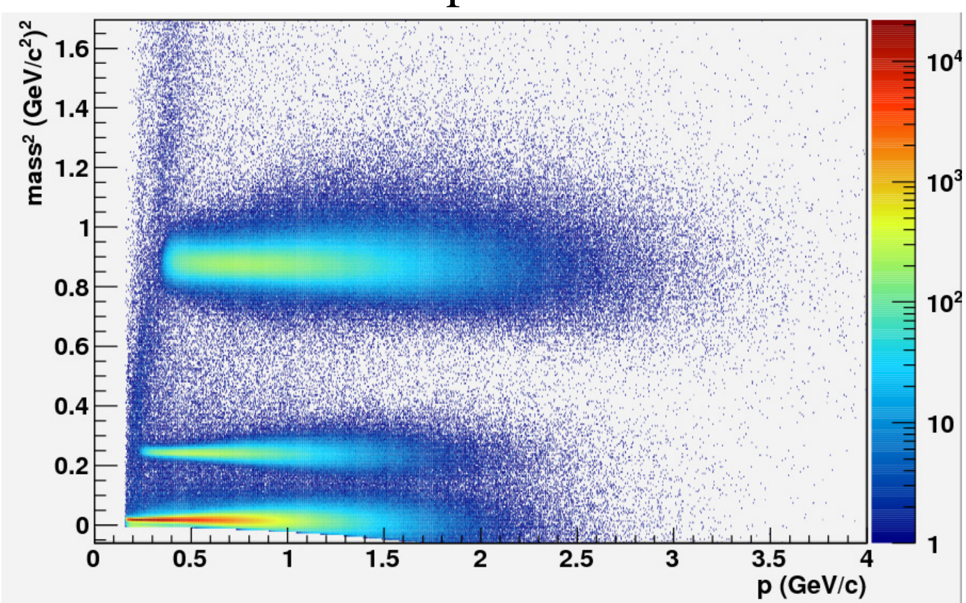
RHIC "Energy Scan"

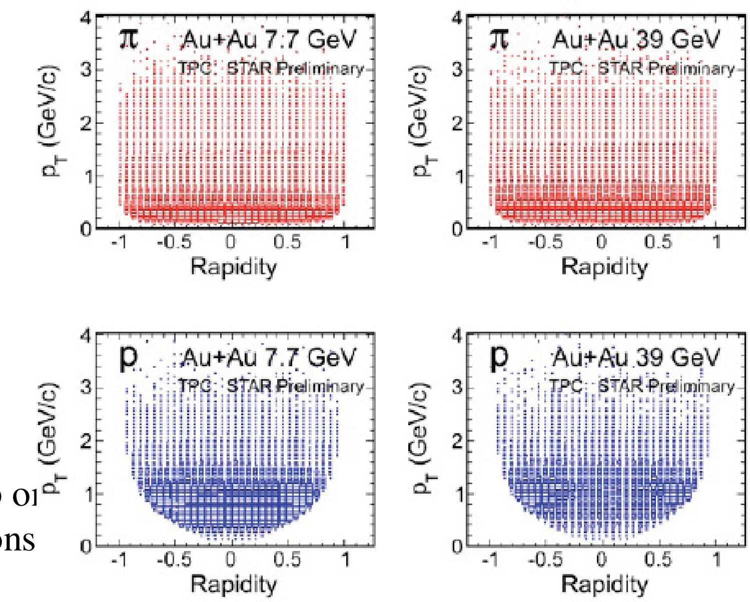
- Using RHIC to run an "energy scan" to search for predicted QCD critical point.
- For 2010, we had Au+Au collisions at $\sqrt{s_{NN}}$ = 200, 62.4, 39, 11.5, and 7.7 GeV.
  - 2011 added Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 and 27 GeV.
- Can examine our observables to look for non-monotonic behavior as a function of collision energy.

STAR Detector

- STAR is a large acceptance detector.
  - Good η and φ coverage for measuring fluctuations.
- TPC: |η| < 1.0, TOF: |η| < 0.9
- TOF upgrade has enhanced STAR's PID capabilities.







Particle Ratio Fluctuations

p/π

$(p^+ + p^-)/(\pi^+ + \pi^-)$

K/π

$(K^+ + K^-)/(\pi^+ + \pi^-)$

K/p

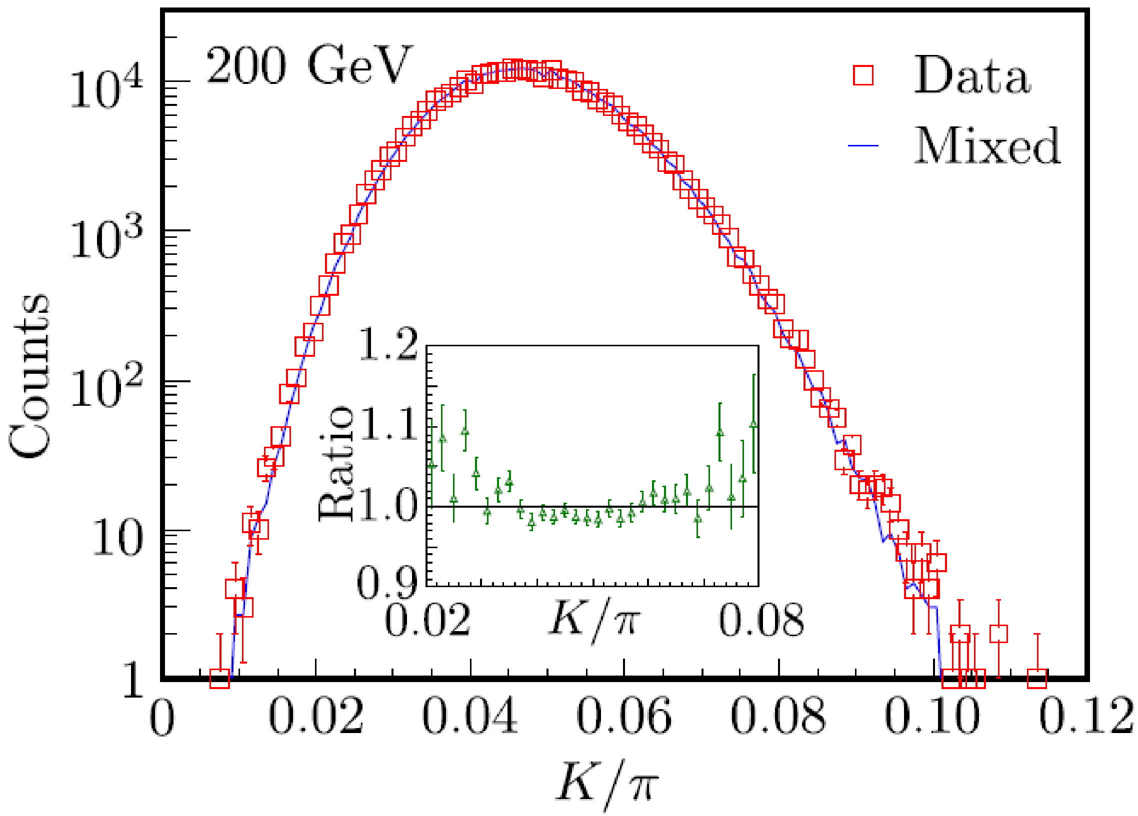
$(K^+ + K^-)/(p^+ + p^-)$

Fluctuation Observables, σ_{dyn}

- NA49 uses the variable σ_{dyn}

$$\sigma_{dyn} = sign\left(\sigma^2_{data} - \sigma^2_{mixed}\right)\sqrt{\left|\sigma^2_{data} - \sigma^2_{mixed}\right|}$$

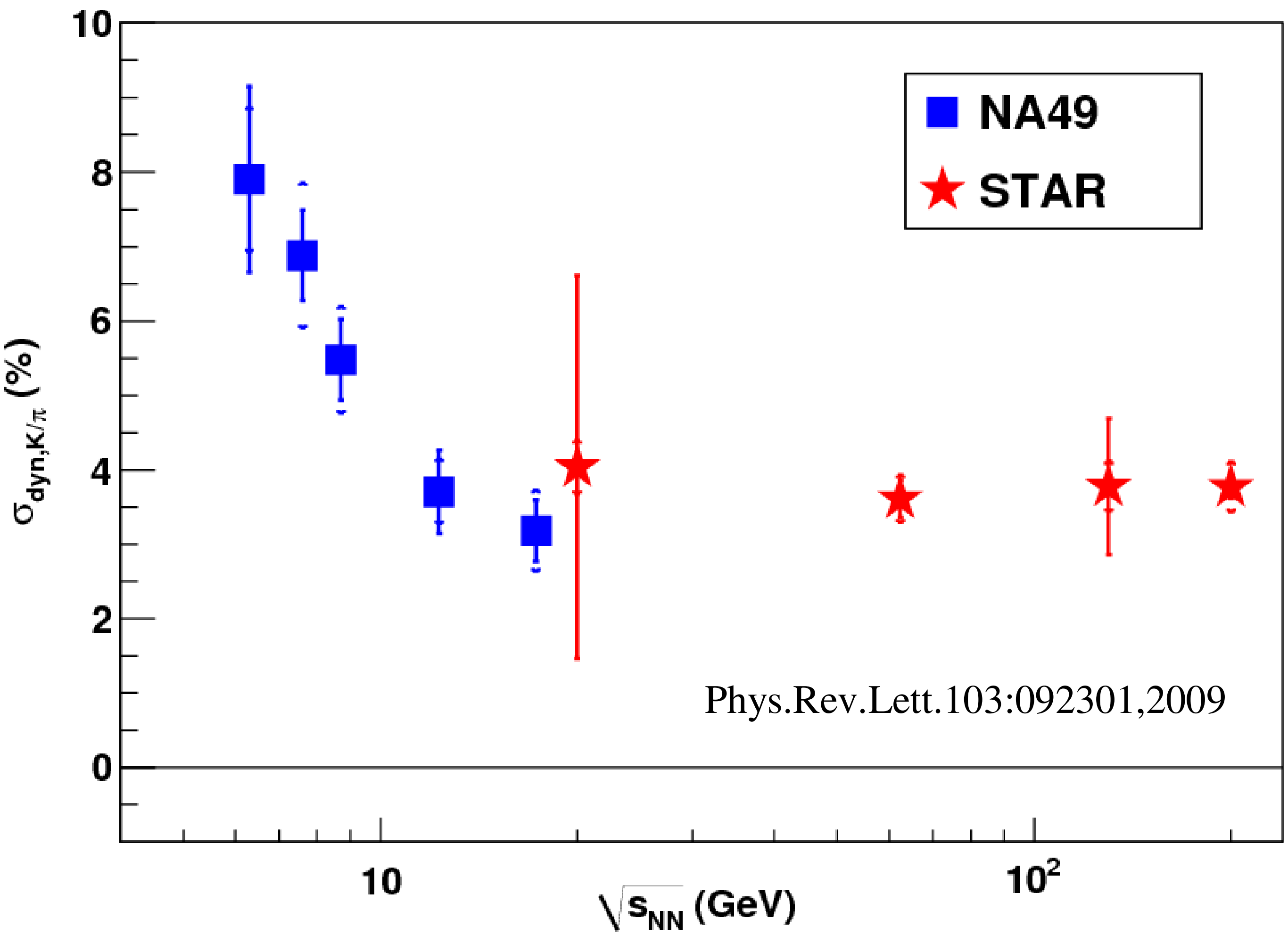
σ is the reduced width of K/π distribution



Excitation Function for $\sigma_{dyn,K/\pi}$

STAR central Au+Au (0-5%) collisions with SPS central Pb+Pb collisions (0-3.5%).

- Large decrease in fluctuations as function of energy from NA49.
- Fluctuations measured by STAR approximately constant as function of energy from 19.6-200 GeV.
- $|\eta| < 1.0$
- π, K: $0.2 < p_T < 0.6$ GeV/c.



Fluctuation Observables, ν_{dyn}

- STAR uses a different fluctuation observable, ν_{dyn}.

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

- Introduced to study net-charge fluctuations.

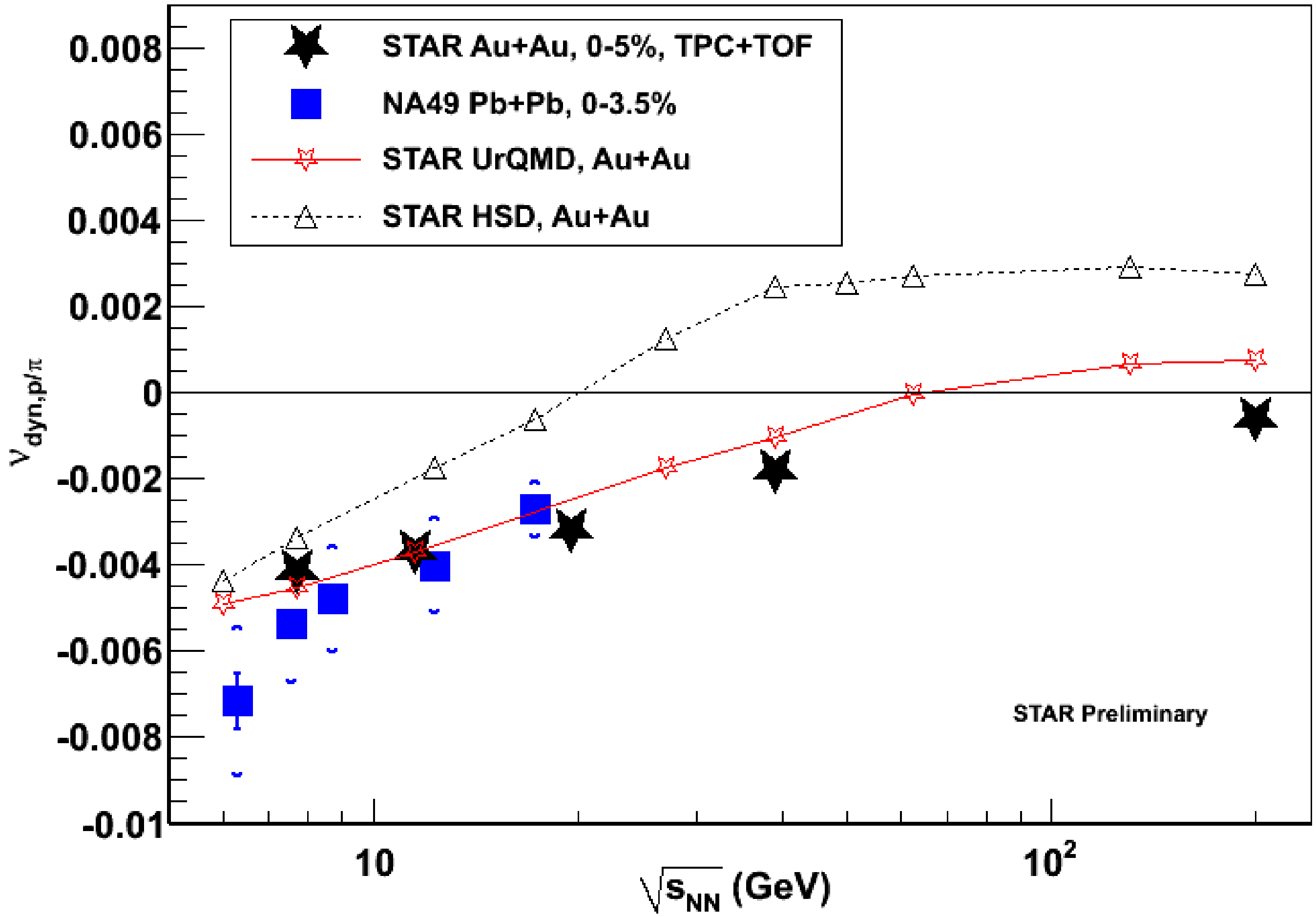
- Measures deviation from Poisson behavior.

- It has been demonstrated that,

$$\sigma_{dyn}^2 \approx \nu_{dyn}$$

Excitation Function for $\nu_{dyn,p/\pi}$

- NA49 $\sigma_{dyn,p/\pi}$ converted to $\nu_{dyn,p/\pi}$ using $\sigma^2_{dyn} = \nu_{dyn}$.

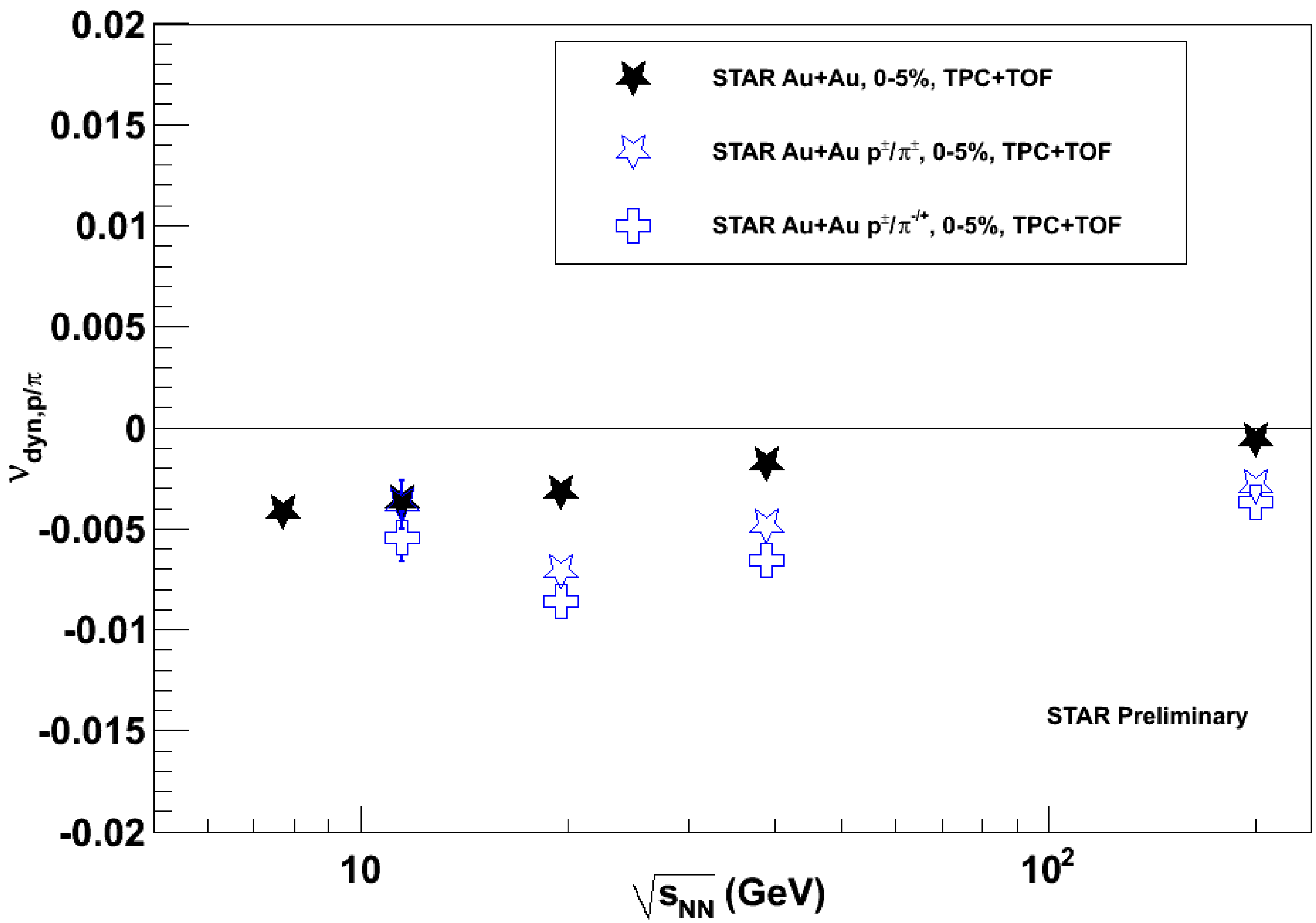


- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- TPC+TOF includes statistical and systematic errors from electron contamination.
- Agreement with measurements from NA49 at low energies.

(NA49 data from: C. Alt et al. [NA49 Collab.], Phys. Rev. C 79, 044910 (2009))

- UrQMD and HSD predictions both change sign at high energies.

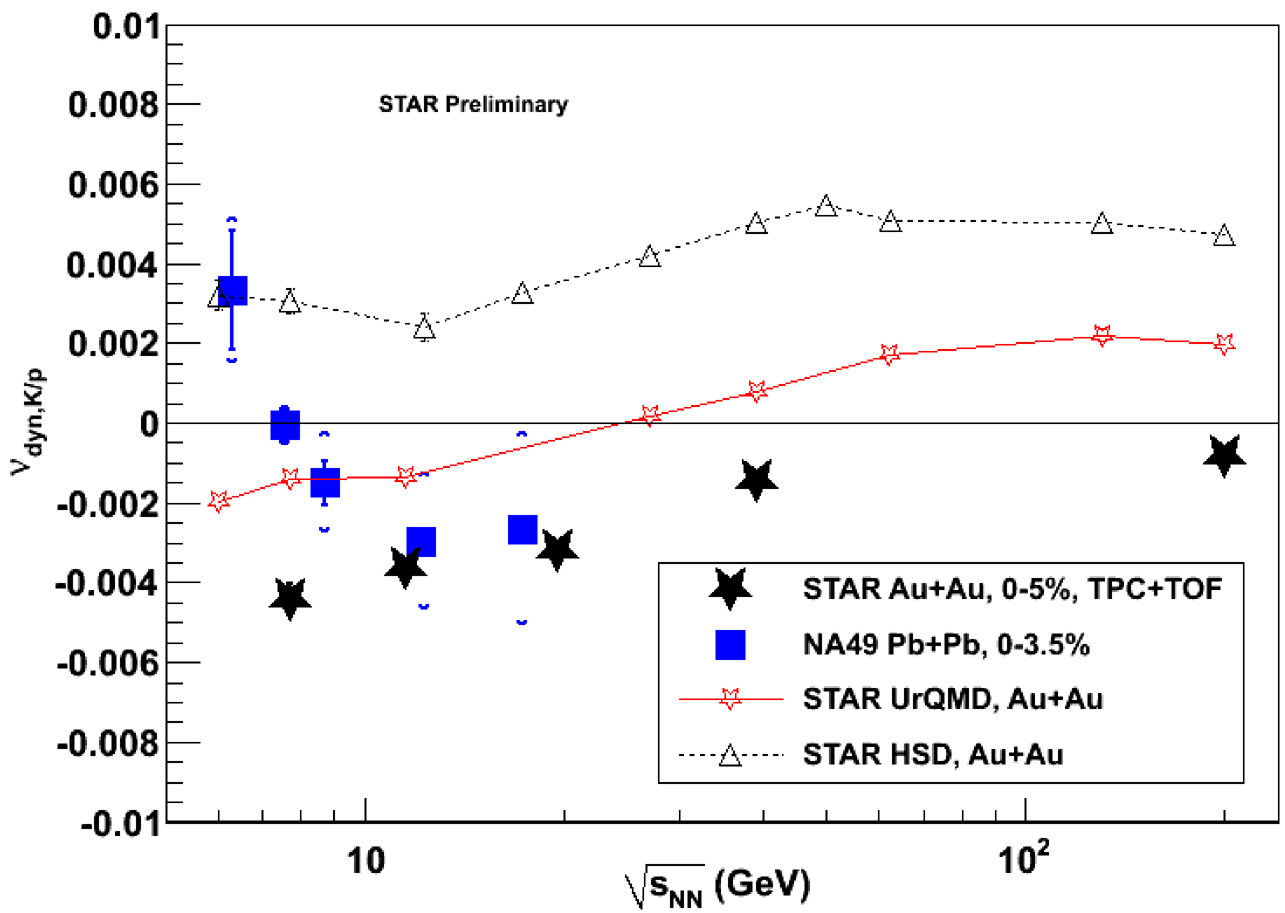
Charge Dependent Excitation Function for $\nu_{dyn,p/\pi}$



- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- Like-sign and opposite-sign charge combinations are similar at 200 GeV.
- Differences arise at lower energies.

Excitation Function for $\nu_{dyn,K/p}$

- NA49 $\sigma_{dyn,K/p}$ converted to $\nu_{dyn,K/p}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



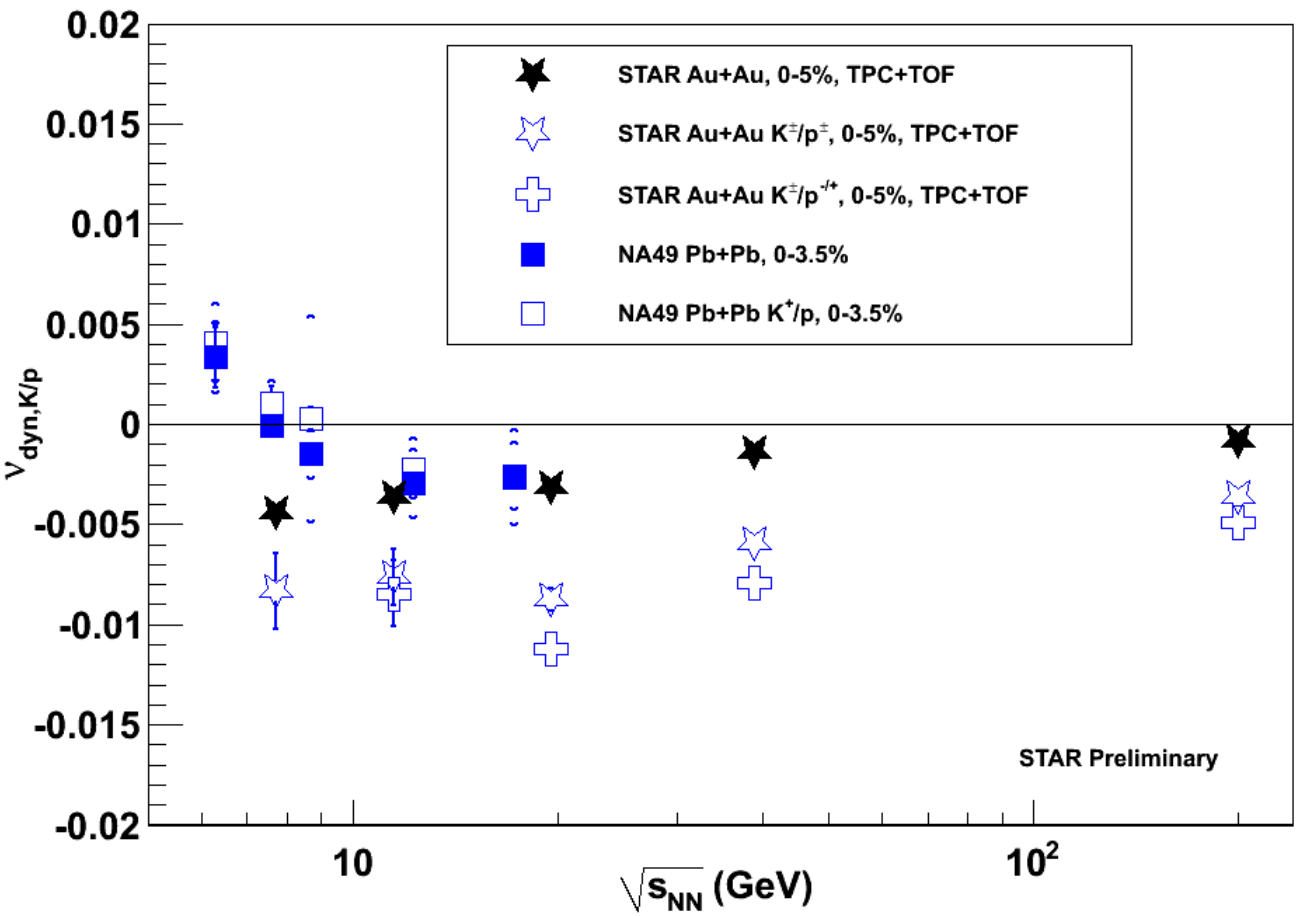
- TPC+TOF (GeV/c):
  - K : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- TPC+TOF includes statistical and systematic errors from electron contamination.
- Large deviation between STAR and NA49 result at $\sqrt{s_{NN}} = 7.7$ GeV.

(NA49 data from: T. Anticic, et al [NA49 Collab.] arXiv:1101.3250v1 [nucl-ex])

- Models predominantly independent of experimental acceptance.

Charge Dependent Excitation Function for $\nu_{dyn,K/p}$

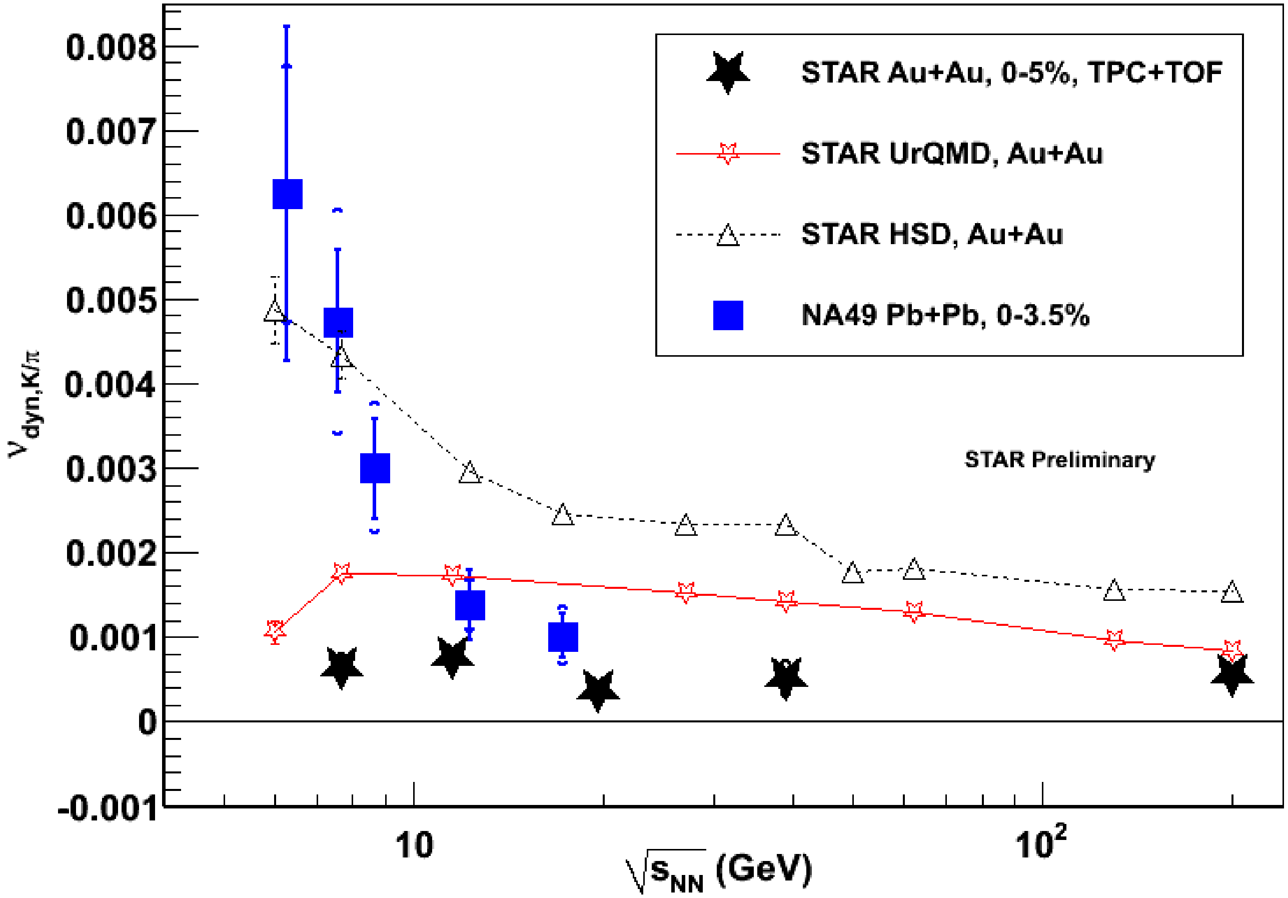
- NA49 $\sigma_{dyn,K/p}$ converted to $\nu_{dyn,K/p}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



- TPC+TOF (GeV/c):
  - K : $0.2 < p_T < 1.4$
  - p : $0.4 < p_T < 1.8$
- Like-sign and opposite-sign charge combinations are similar at 200 GeV.
- Like for $\nu_{dyn,p/\pi}$, also see that differences arise at lower energies.

Excitation Function for $\nu_{dyn,K/\pi}$

- NA49 $\sigma_{dyn,K/\pi}$ converted to $\nu_{dyn,K/\pi}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



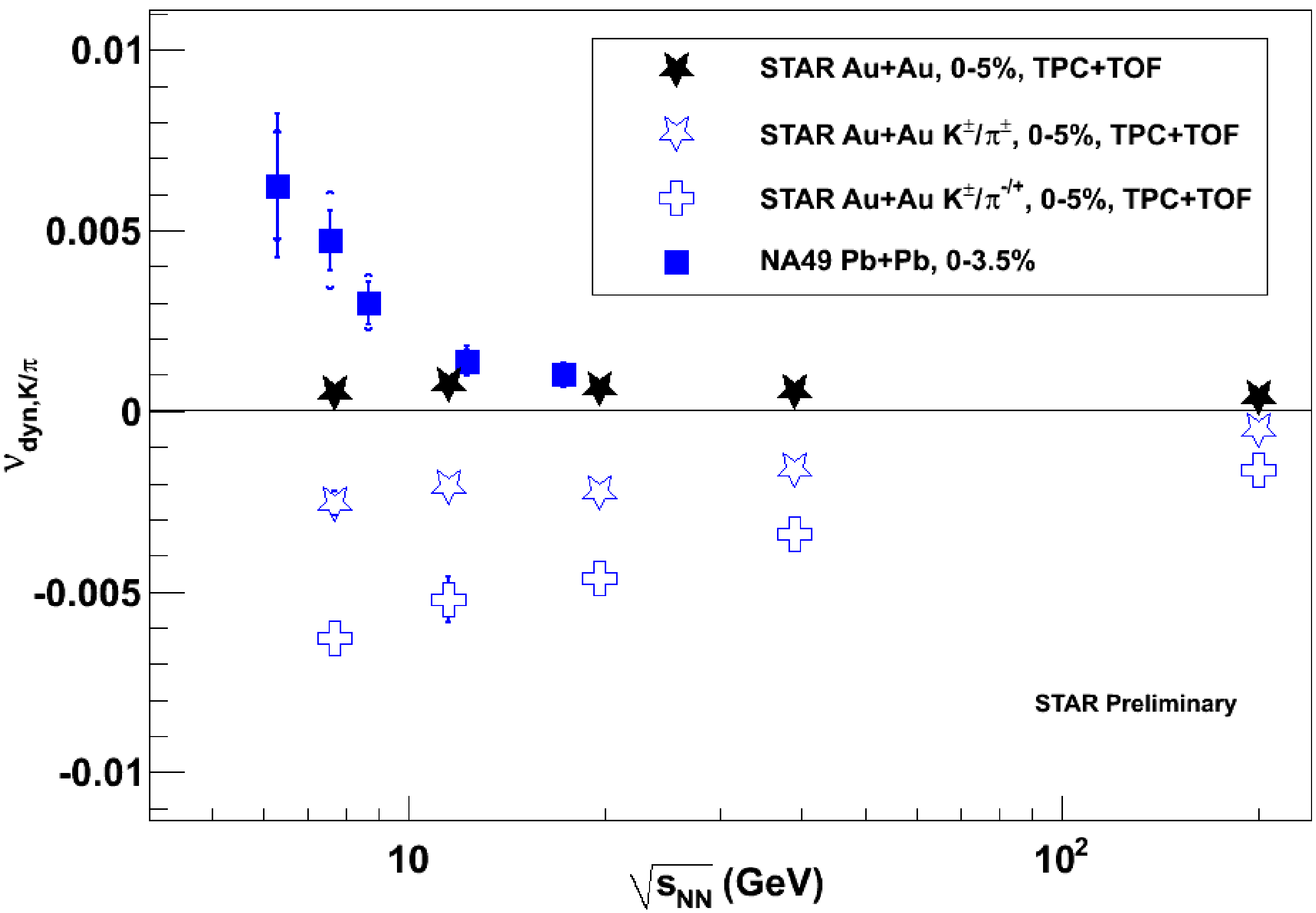
- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - K : $0.2 < p_T < 1.4$
- TPC+TOF includes statistical and systematic errors from electron contamination.
  - Pion contamination of kaons < 3% using TPC and TOF.
- Difference between STAR and NA49 result below $\sqrt{s_{NN}}$ = 11.5 GeV.

(NA49 data from C. Alt et al. [NA49 Collab.], Phys. Rev. C 79, 044910 (2009))

- Both models show little acceptance effects.
  - UrQMD predicts little energy dependence.
  - HSD predicts an energy dependence.

Charge Dependent Excitation Function for $\nu_{dyn,K/\pi}$

- NA49 $\sigma_{dyn,K/\pi}$ converted to $\nu_{dyn,K/\pi}$ using $\sigma^2_{dyn} = \nu_{dyn}$.



- TPC+TOF (GeV/c):
  - π : $0.2 < p_T < 1.4$
  - K : $0.2 < p_T < 1.4$
- Growing difference between same- and opposite-sign combinations with decreasing energy.
- Opposite-sign charge fluctuations tend to be lower for all ratios due to decays of neutral resonances.

B.I. Abelev et al. [STAR Collab.], Phys. Rev. Lett. 103, 92301 (2009)

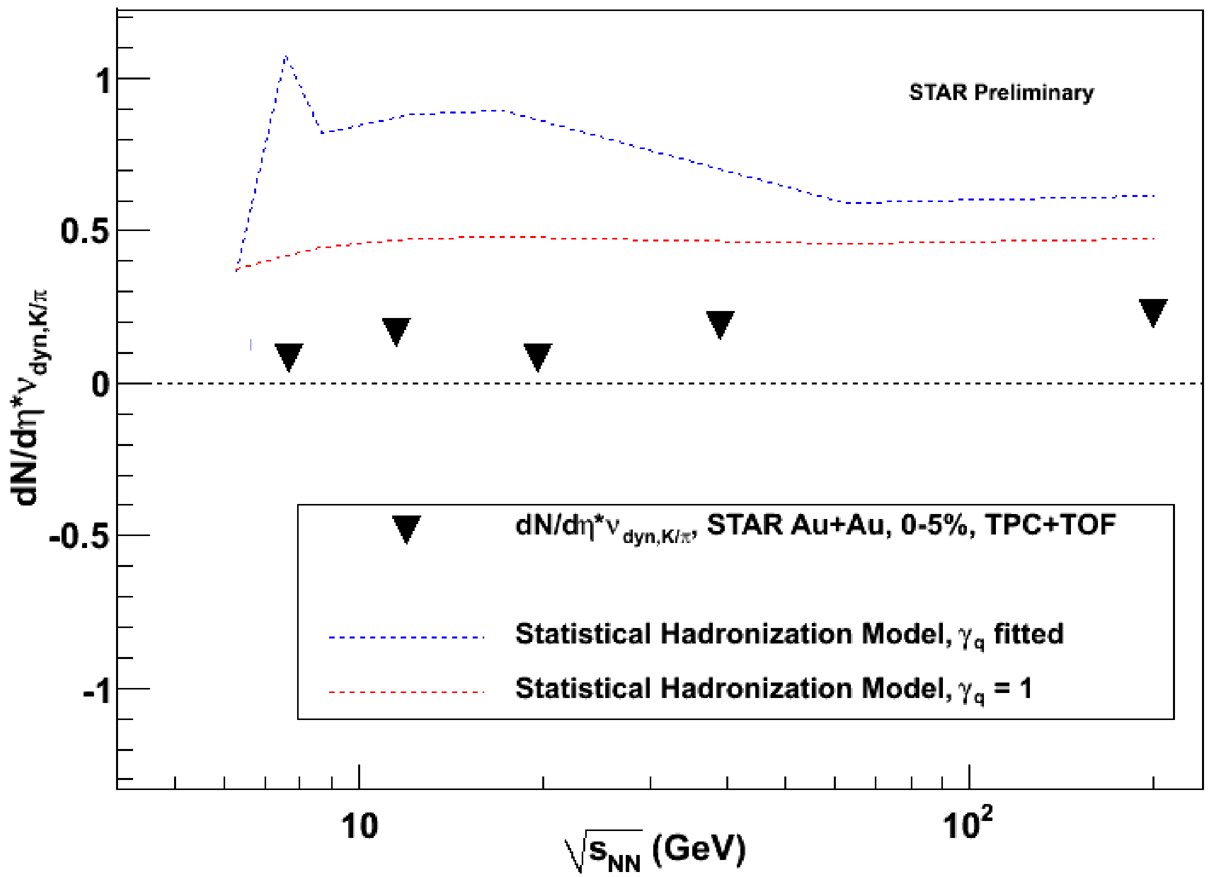
Scaled Particle Ratio Fluctuations

Scaling of Particle Ratio Fluctuations

- ν_{dyn} alone is not an intensive quantity (multiplicity/system volume dependence).
- Scaling ν_{dyn} by number of particles used in measurement can produce an intensive quantity.
  - STAR has results for $\nu_{dyn,K/\pi}$ scaled by corrected $dN/d\eta$.
    - Scaled $\nu_{dyn,K/\pi}$ independent of centrality except in central collisions.
- Allows direct comparisons to thermodynamic models.

M. Stephanov, MIT Workshop on Fluctuations and Correlations, 2005

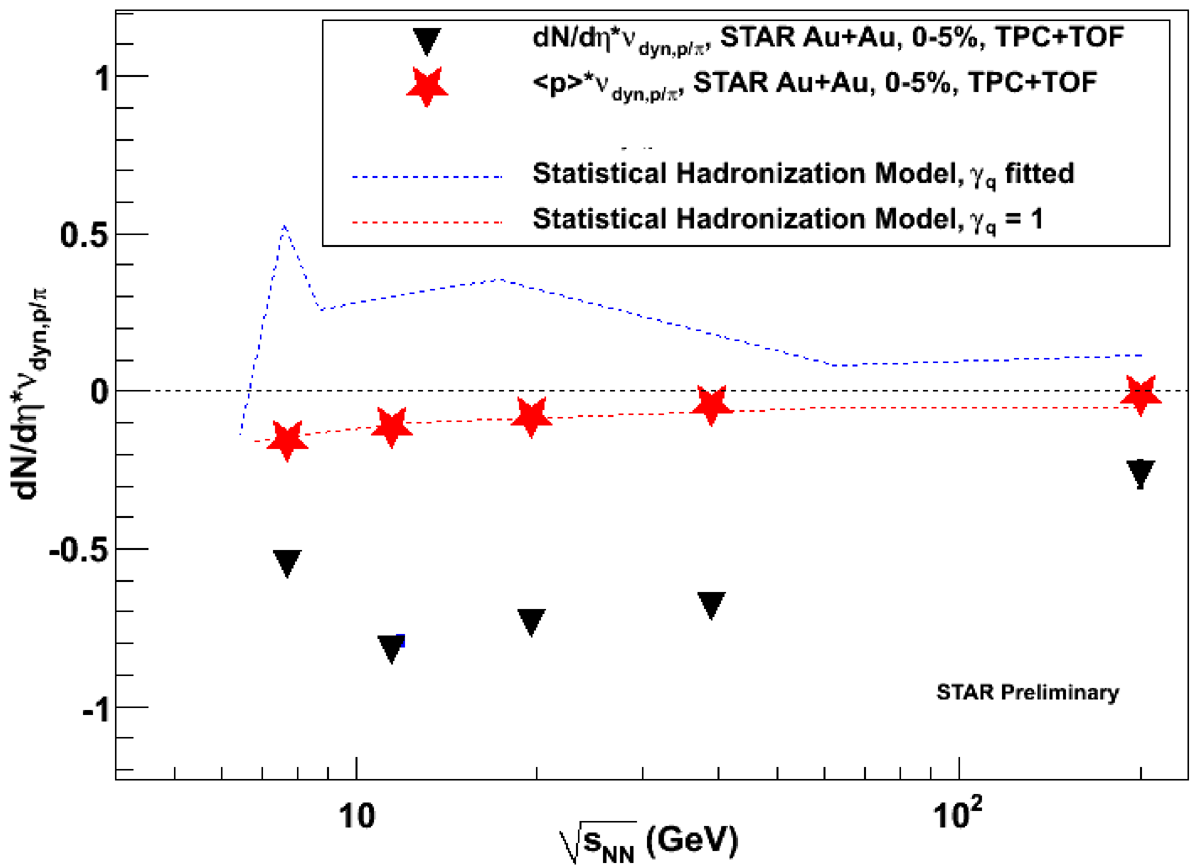
Multiplicity Scaling of $\nu_{dyn,K/\pi}$



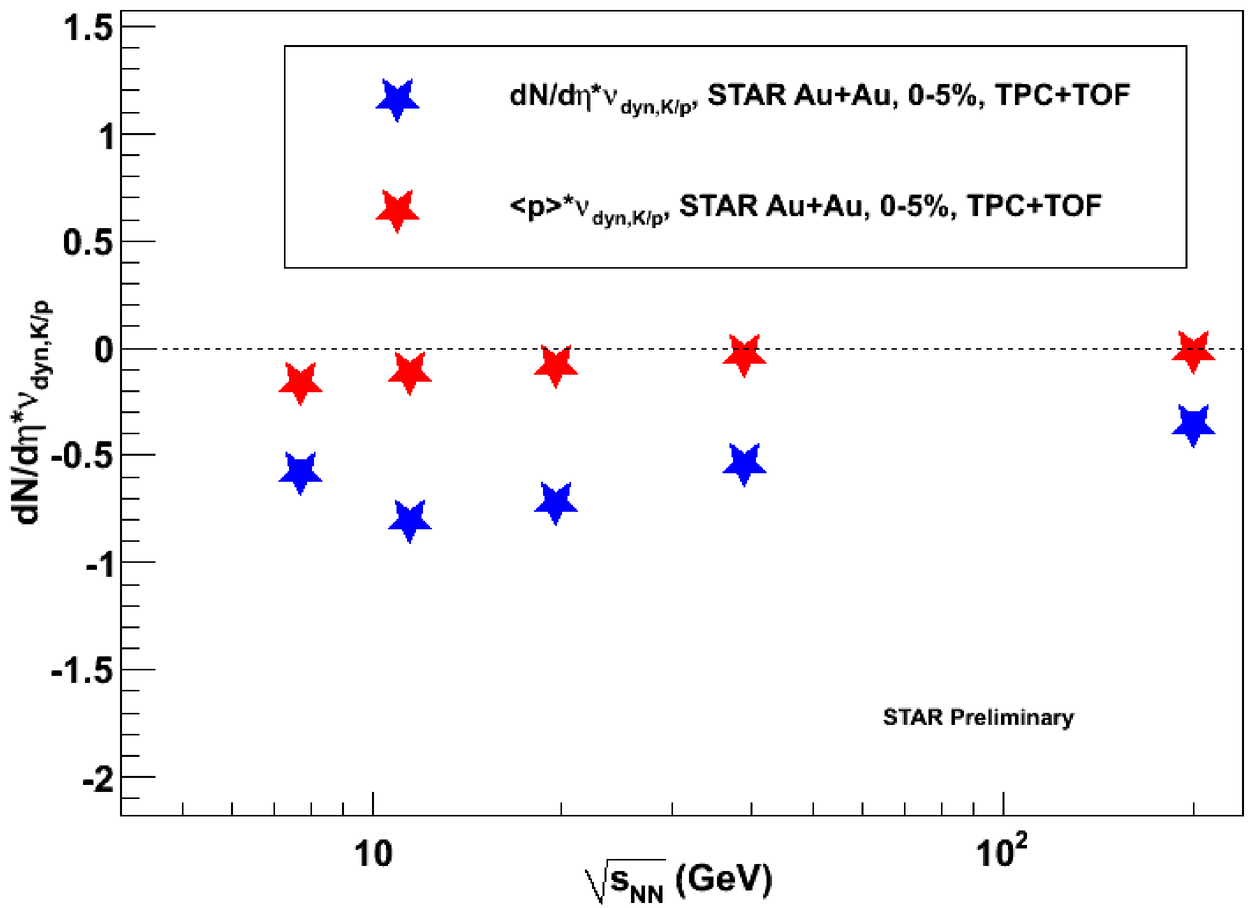
- 0-5% Au+Au $\nu_{dyn,K/\pi}$ scaled by measured $dN/d\eta$.
- Approximate increase with energy.
- Compared to Statistical Hadronization model prediction:
  - γ_q = light quark phase space occupancy.
    - = 1, equilibrium.
    - Fitted: fit to ratio yields, etc.
  - Scaled by $dN/d\eta$ from the model
- Uncorrected experimental multiplicities.

Multiplicity Scaling of $\nu_{dyn,p/\pi}$

- 0-5% Au+Au $\nu_{dyn,p/\pi}$ scaled by measured dN/dη.
- More negative from 7.7-11.5 GeV, then decreases toward zero.
- Compared to Statistical Hadronization model prediction:
  - γ_q = light quark phase space occupancy.
    - = 1, equilibrium.
    - Fitted: fit to ratio yields, etc.
  - Scaled by dN/dη from the model
- Scaling by <p> (p+pbar) approaches zero smoothly with increasing energy.
- Uncorrected experimetal multiplicities.



Multiplicity Scaling of $\nu_{dyn,K/p}$



- 0-5% Au+Au $\nu_{dyn,K/p}$ scaled by measured dN/dη.
- Qualitatively similar to scaled $\nu_{dyn,p/\pi}$ for both total dN/dη and <p> (p+pbar) scaling.
- Uncorrected multiplicities.

Summary

- Results for dynamical particle ratio fluctuations from data collected during first part of the RHIC energy scan to search for QCD critical point.
  - For p/π fluctuations:
    - From $\sqrt{s_{NN}}$ = 7.7-200 GeV, all measured fluctuations are negative.
  - For K/p fluctuations:
    - Similar to p/π, fluctuations measured from $\sqrt{s_{NN}}$ = 7.7-200 GeV are negative.
  - For K/π fluctuations:
    - STAR does not observe any strong energy dependence of K/π fluctuations in central Au+Au collisions.

- First results on charge separated particle ratio fluctuations have been shown.
  - Disentangle different contributions to charge independent ν_{dyn}.

- Energy dependence of central (0-5%) K/π, p/π, and K/p fluctuations scaled by uncorrected dN/dη have been calculated from STAR data.
  - $dN/d\eta * \nu_{dyn}$ has been calculated to allow direct comparisons to thermodynamic models.
    - Form an intensive variable.

- Interesting energy dependence for scaled p/π, and K/p fluctuations.

- Compare to Statistical Hadronization (SH) model prediction for two different γ_q.
  - SH overpredicts magnitude of scaled K/π fluctuations for both fitted and equilibrium assumption.
  - Equilibrium assumption works better for scaled p/π fluctuations, but does not exhibit minimum seen in data.