A Study of the QCD Critical Point Using Particle Ratio Fluctuations

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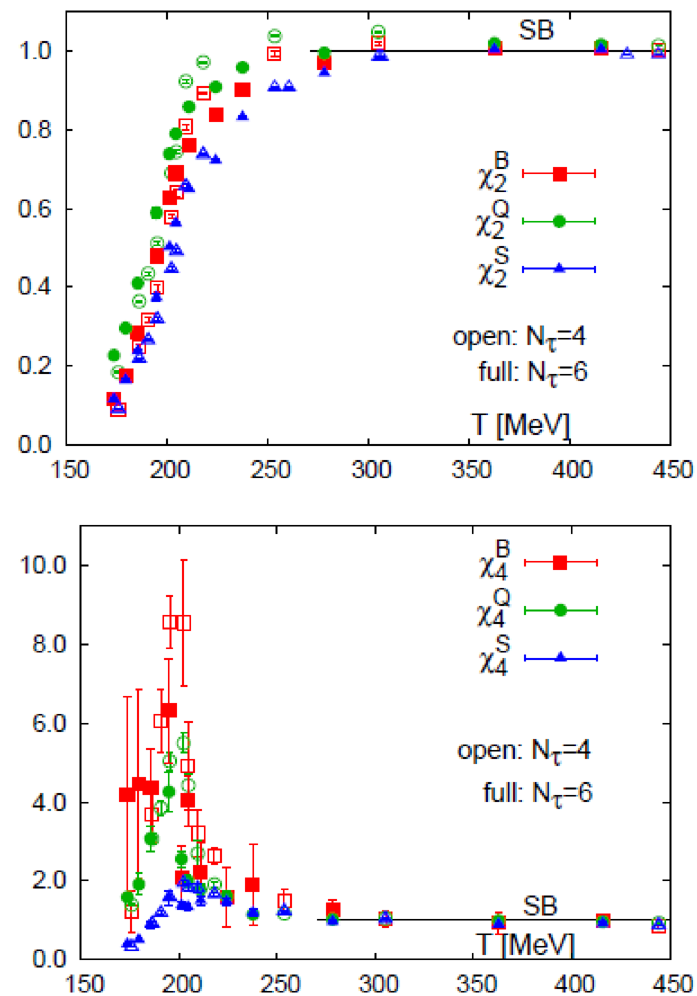
Motivation Behind Correlations and Fluctuations

- 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
  - Net Charge Fluctuations
  - 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.

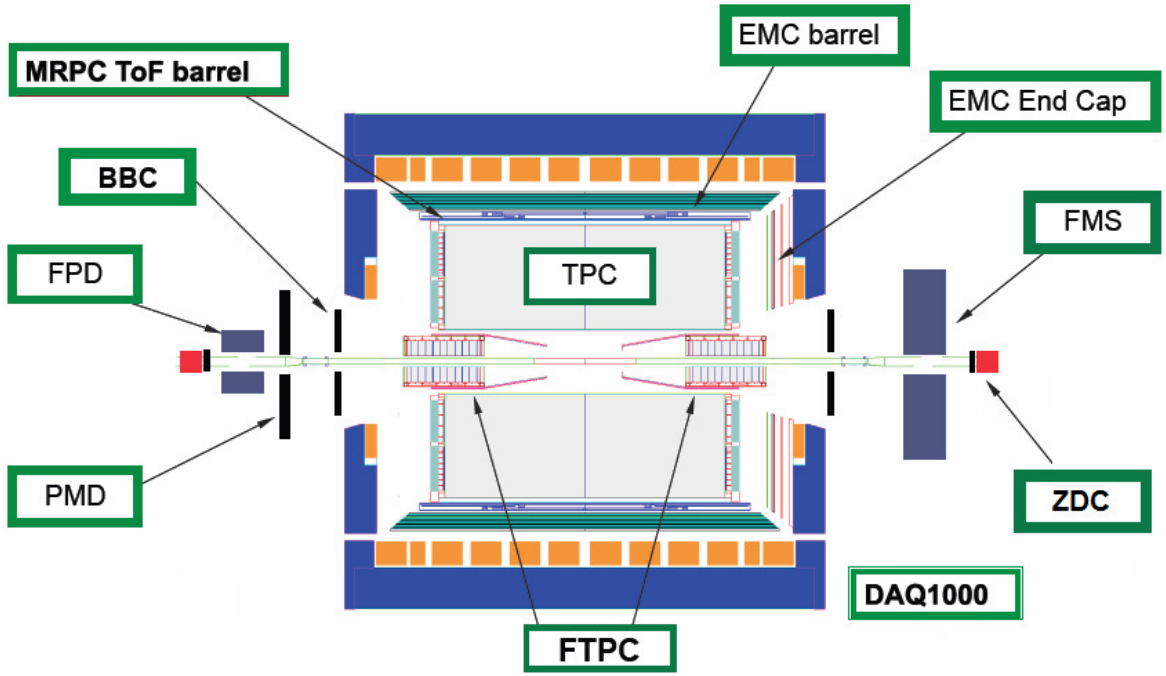


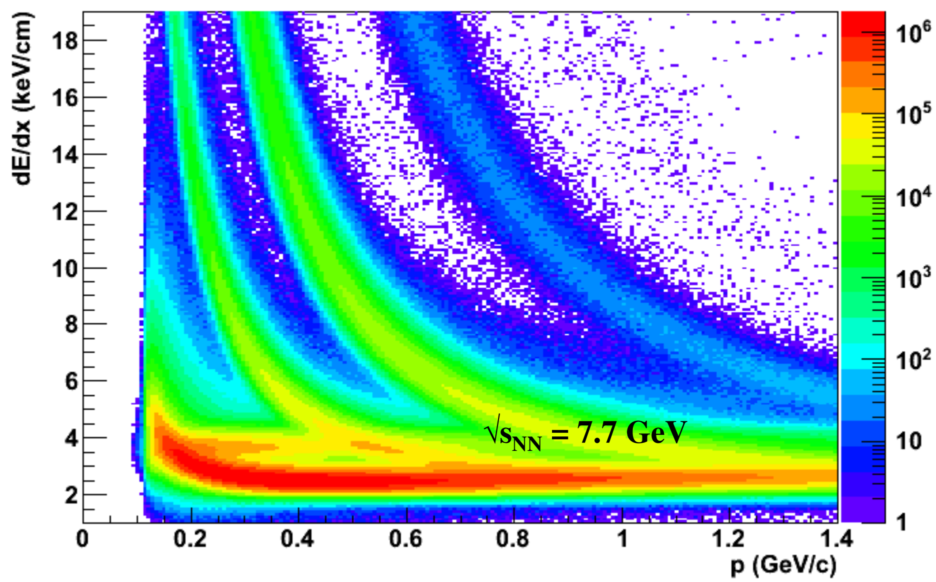
RHIC "Energy Scan"

- 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.
- Can examine our fluctuation observables to look for non-monotonic behavior as a function of collision energy.

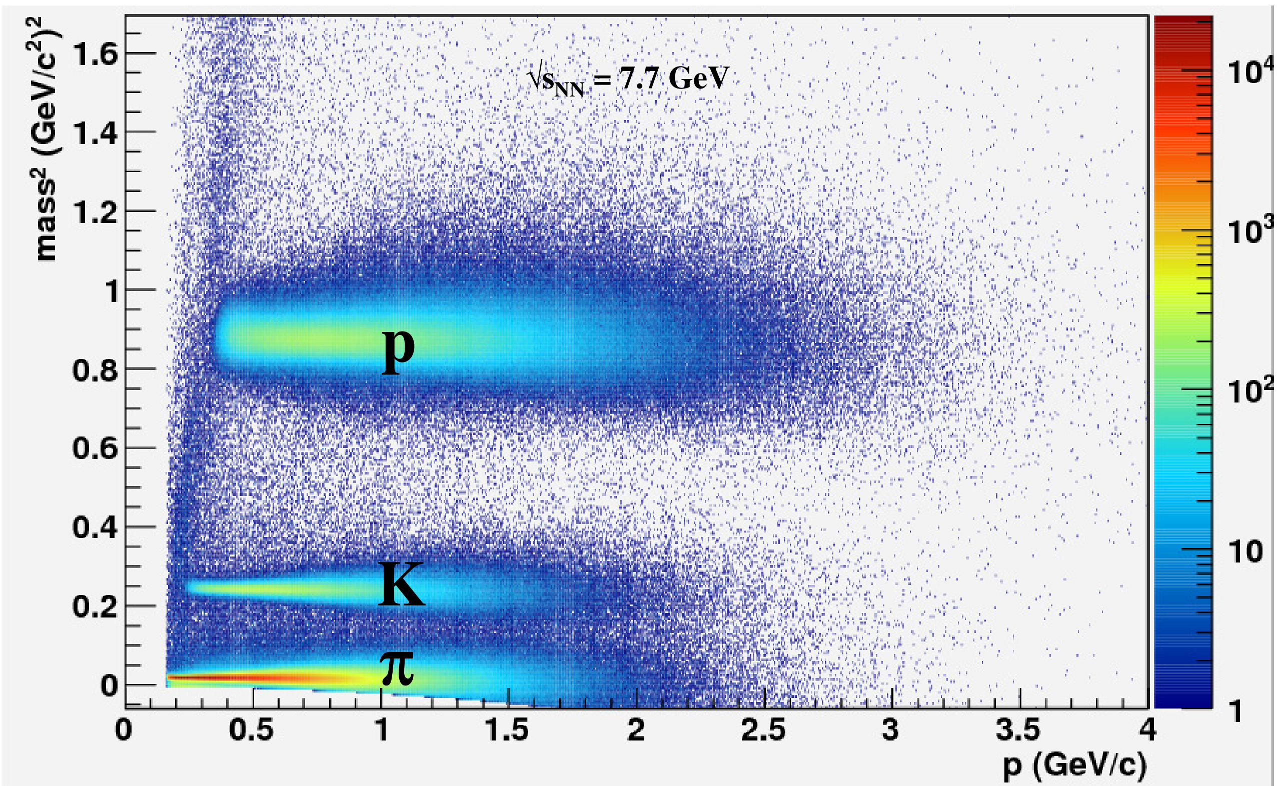
STAR Detector

- STAR is a large acceptance detector.
  - Good η and φ coverage for measuring fluctuations.
- TPC: $|\eta| < 1.0$
- TPC PID (GeV/c):
  - π : $0.2 < p_T < 0.6$
  - K: $0.2 < p_T < 0.6$
  - p: $0.4 < p_T < 1.0$
- TOF PID (GeV/c):
  - π : $0.6 < p_T < 1.4$
  - K: $0.6 < p_T < 1.4$
  - p: $0.4 < p_T < 1.6$
- ToF upgrade has enhanced STAR's PID capabilities.





Particle ID Using STAR Time-of-Flight



- Full TOF installed in 2010. (First stage of energy scan program.)
- Excellent separation in $m^2(p)$ for π, K, p.

Characterize Fluctuations

- NA49 uses the variable $\sigma_{\rm dyn}$

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

σ is relative width of K/π distribution

- STAR uses $\nu_{\rm dyn.}$
  - Measures deviation from ideal Poisson behavior,

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

- It has been demonstrated (for K/π and p/π) that,

$$\sigma^2_{dyn} \approx \nu_{dyn}$$

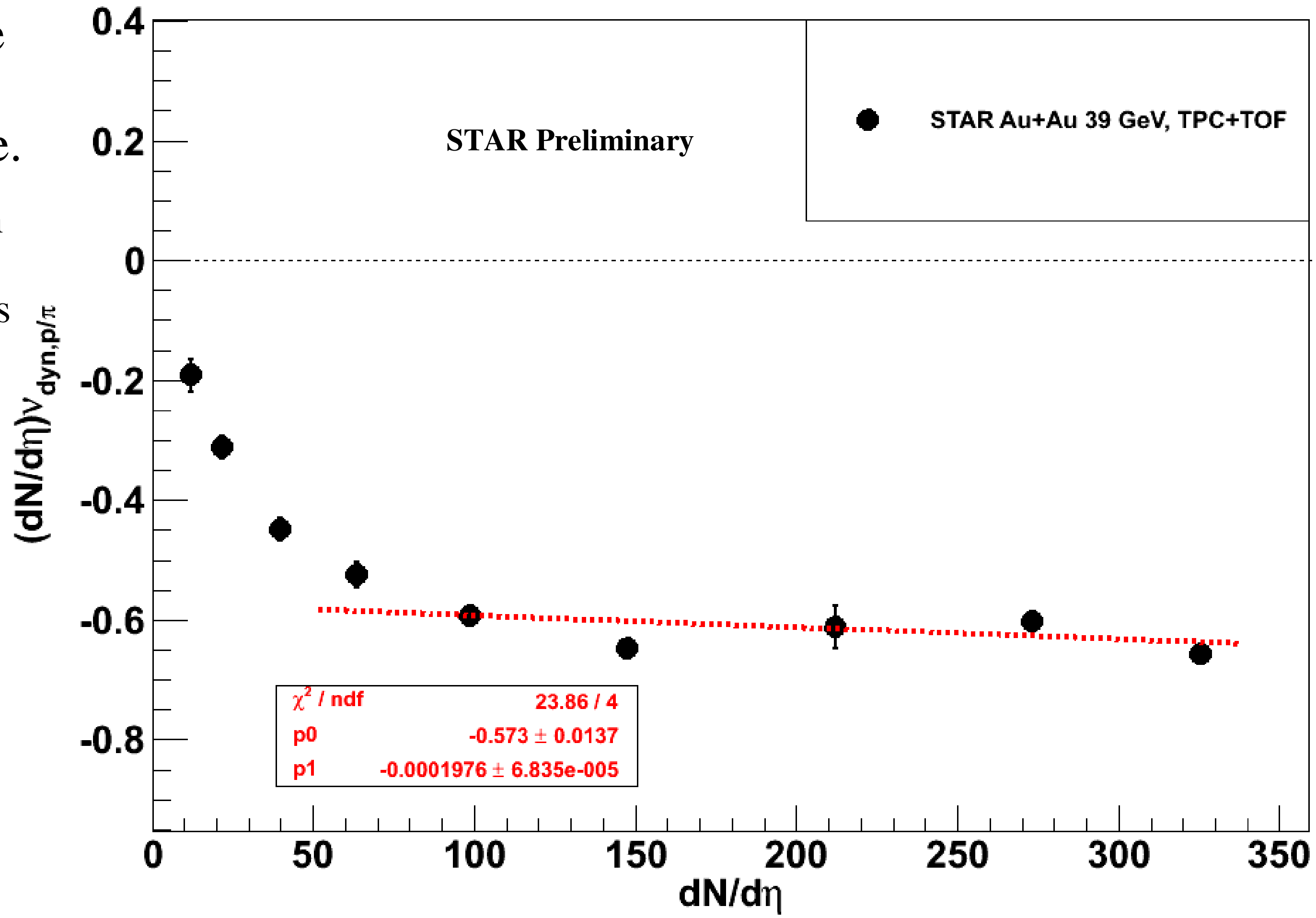
Particle Ratio Fluctuations

p/π

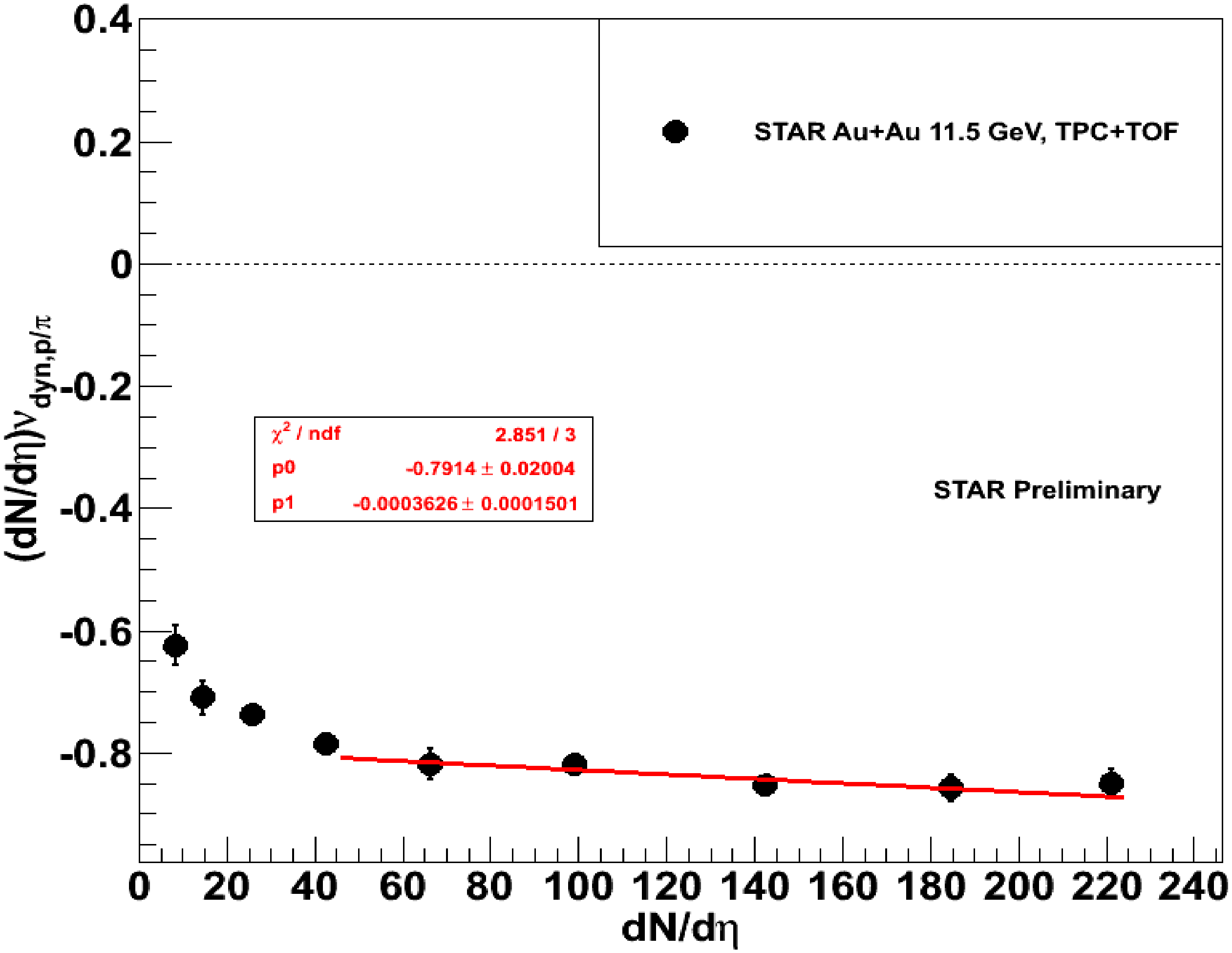
$(p^{+} + p^{-})/(\pi^{+} + \pi^{-})$

Au+Au, 39 GeV $(dN_{ch}/d\eta)\nu_{dyn,p/\pi}$

- Total charged particle $\nu_{dyn,p/\pi}$ for Au+Au 39 GeV is always negative.
  - Correlated production from resonances (e.g Δ's) and particle decays (e.g Λ^0).
  - Seen in higher energy Au+Au (STAR) and lower energy Pb+Pb (NA49) collisions as well.
- Uncorrected $dN_{ch}/d\eta$.
- Large increase in peripheral collisions.



Au+Au, 11.5 GeV $(dN_{ch}/d\eta)\nu_{dyn,p/\pi}$



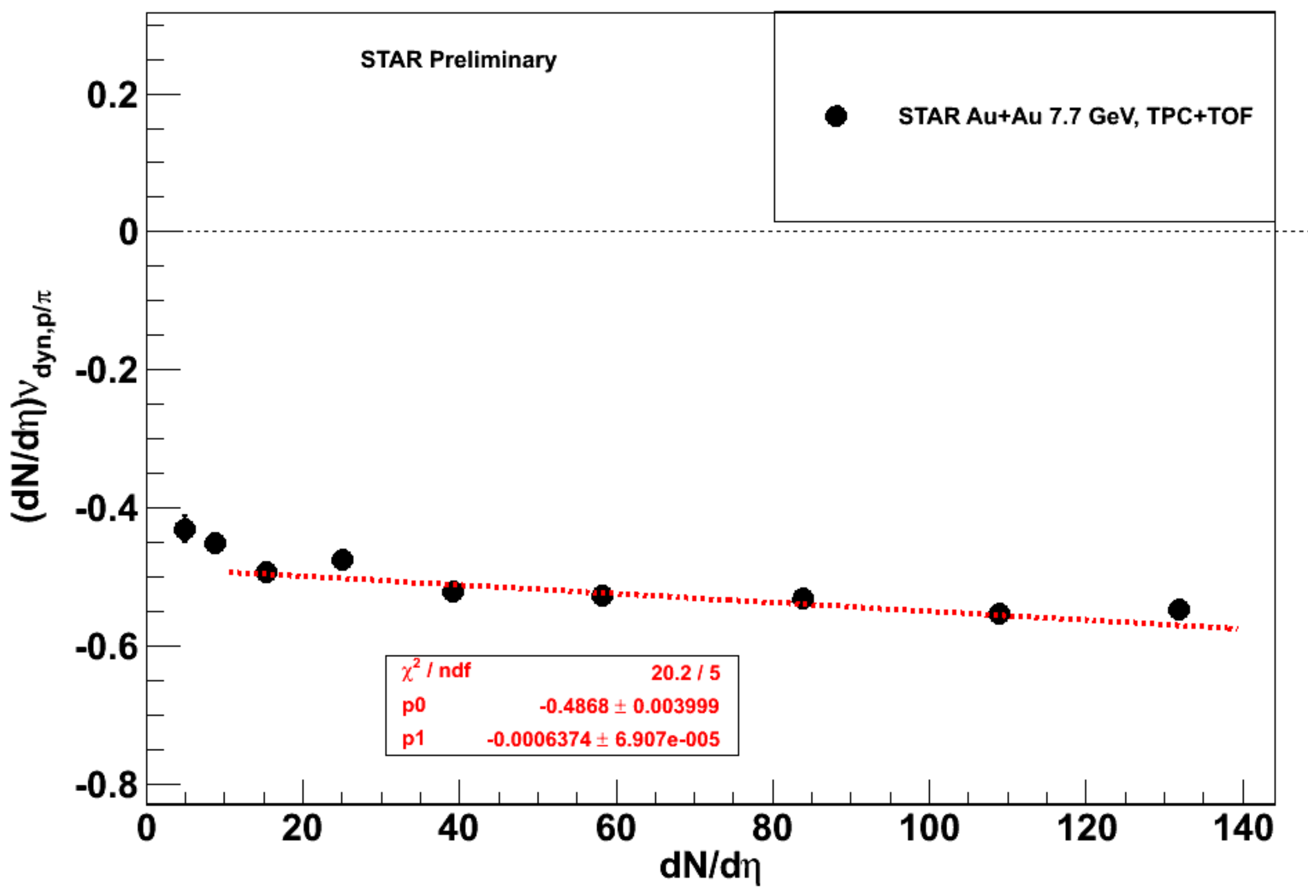
- Uncorrected $dN_{ch}/d\eta$.
- Peripheral $\nu_{dyn,p/\pi}$ scaled by $dN_{ch}/d\eta$ does not show rapid change, as 39 GeV does.
- Lower minimum value than $\nu_{dyn,p/\pi}$ 39 GeV.

Au+Au, 7.7 GeV $(dN_{ch}/d\eta)\nu_{dyn,p/\pi}$

- $\nu_{dyn,p/\pi}$ scaled by $dN_{ch}/d\eta$ almost constant.

- p/p-bar ratio grows with decreasing energy.

- Reaches same minimum value as $\nu_{dyn,p/\pi}$ at 39 GeV.



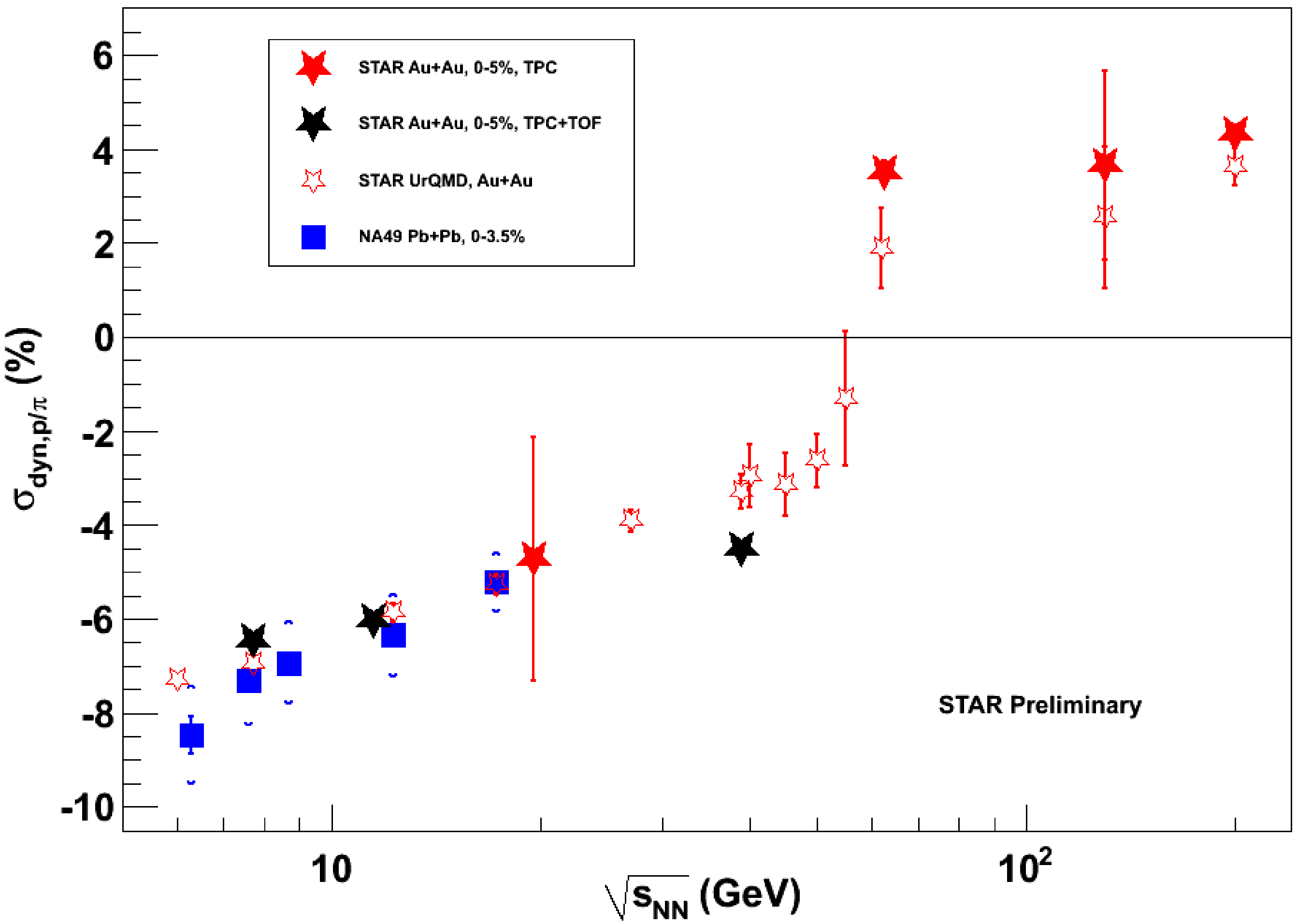
Excitation Function for $\sigma_{\mathrm{dyn},p/\pi}$ from STAR Au+Au data

TPC (GeV/c):

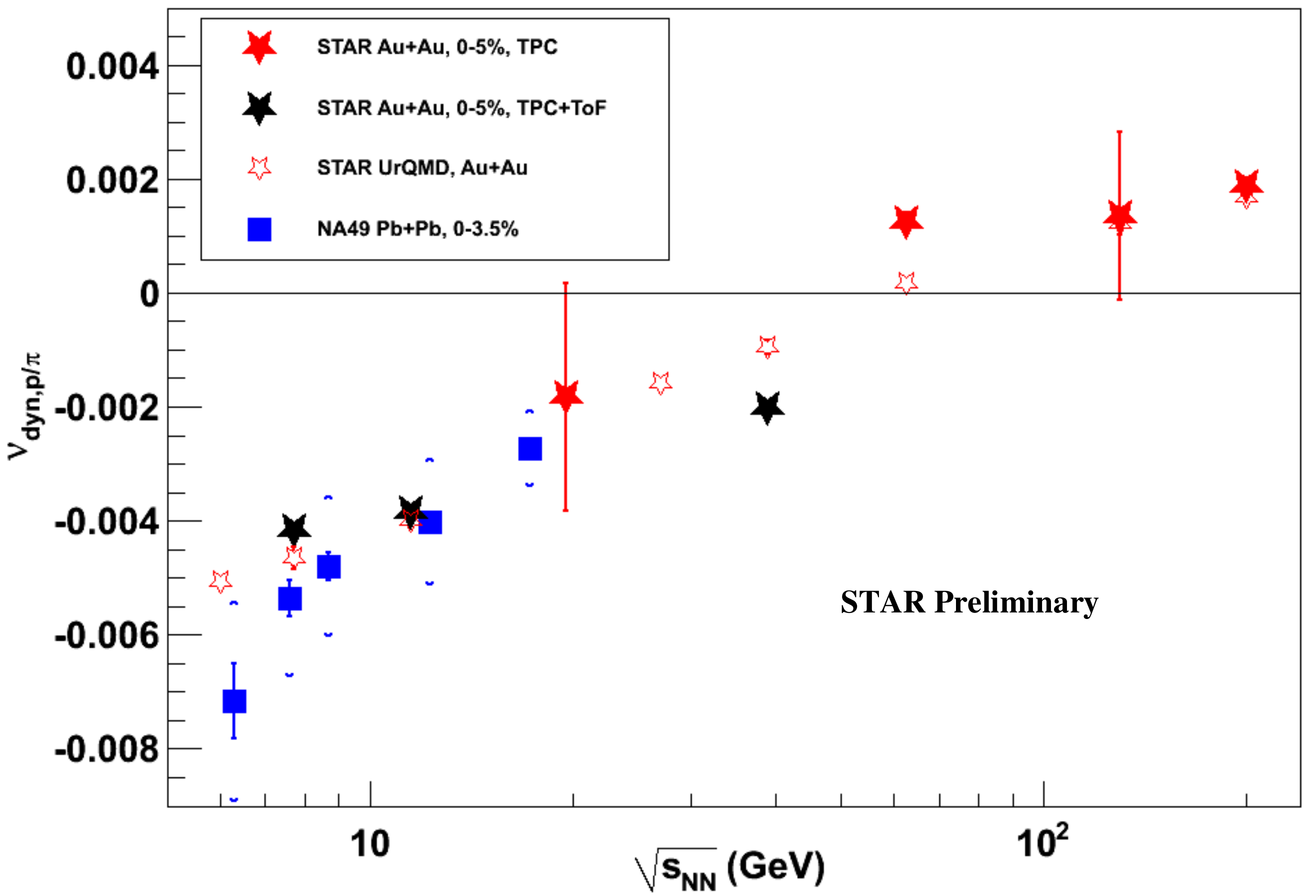
- π : $0.2 < p_T < 0.6$
- p : $0.4 < p_T < 1.0$

TPC+TOF (GeV/c):

- π : $0.2 < p_T < 1.4$
- p : $0.4 < p_T < 1.8$



Excitation Function for $\nu_{dyn,p/\pi}$ from STAR Au+Au data



- NA49 $\sigma_{dyn,p/\pi}$ converted to $\nu_{dyn,p/\pi}$.

Particle Ratio Fluctuations

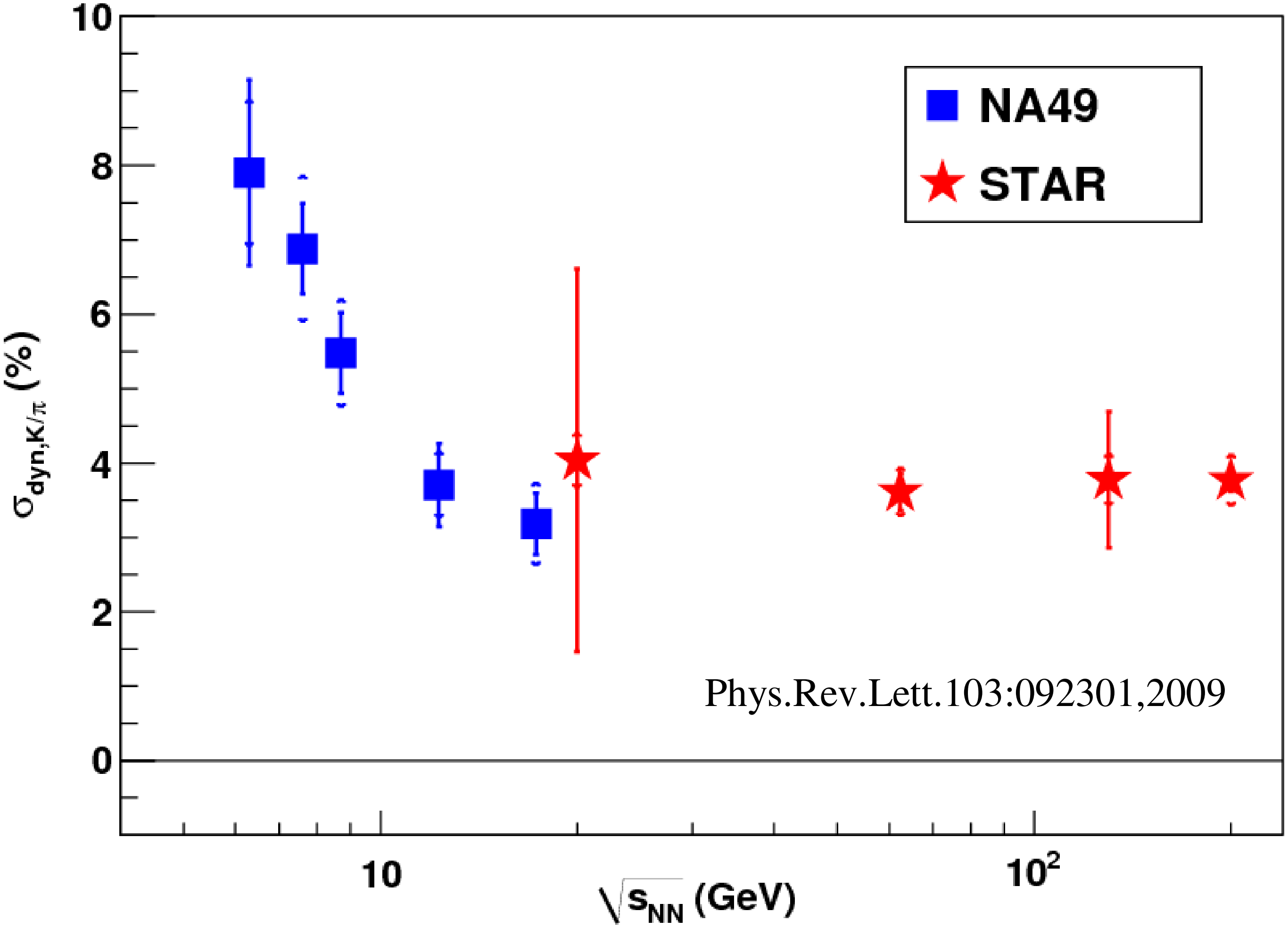
K/π

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

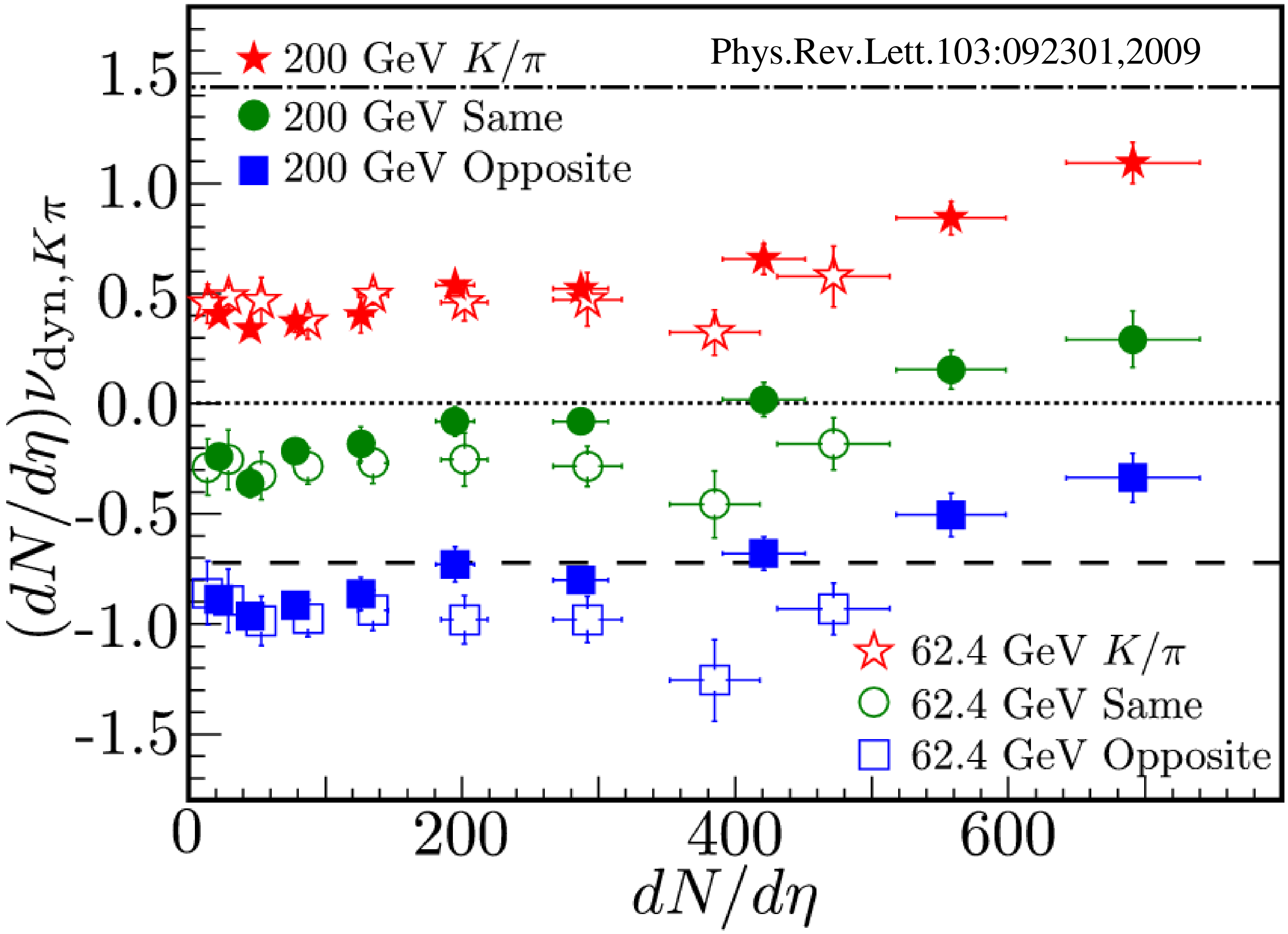
Excitation Function for $\sigma_{dyn,K/\pi}$

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.
- p: $0.4 < p_T < 1.0$ GeV/c.



Scaling w/ $dN_{ch}/d\eta$ in Au+Au



- For independent collisions and no rescattering, ν_{dyn} α 1/M
- Charge dependent and independent $\nu_{dyn,K/\pi}$ was found to scale linearly with $dN_{ch}/d\eta$ (at small $dN_{ch}/d\eta$) in Au+Au at 200 and 62.4 GeV

Au+Au, 39 GeV $(dN_{ch}/d\eta)\nu_{dyn,K/\pi}$

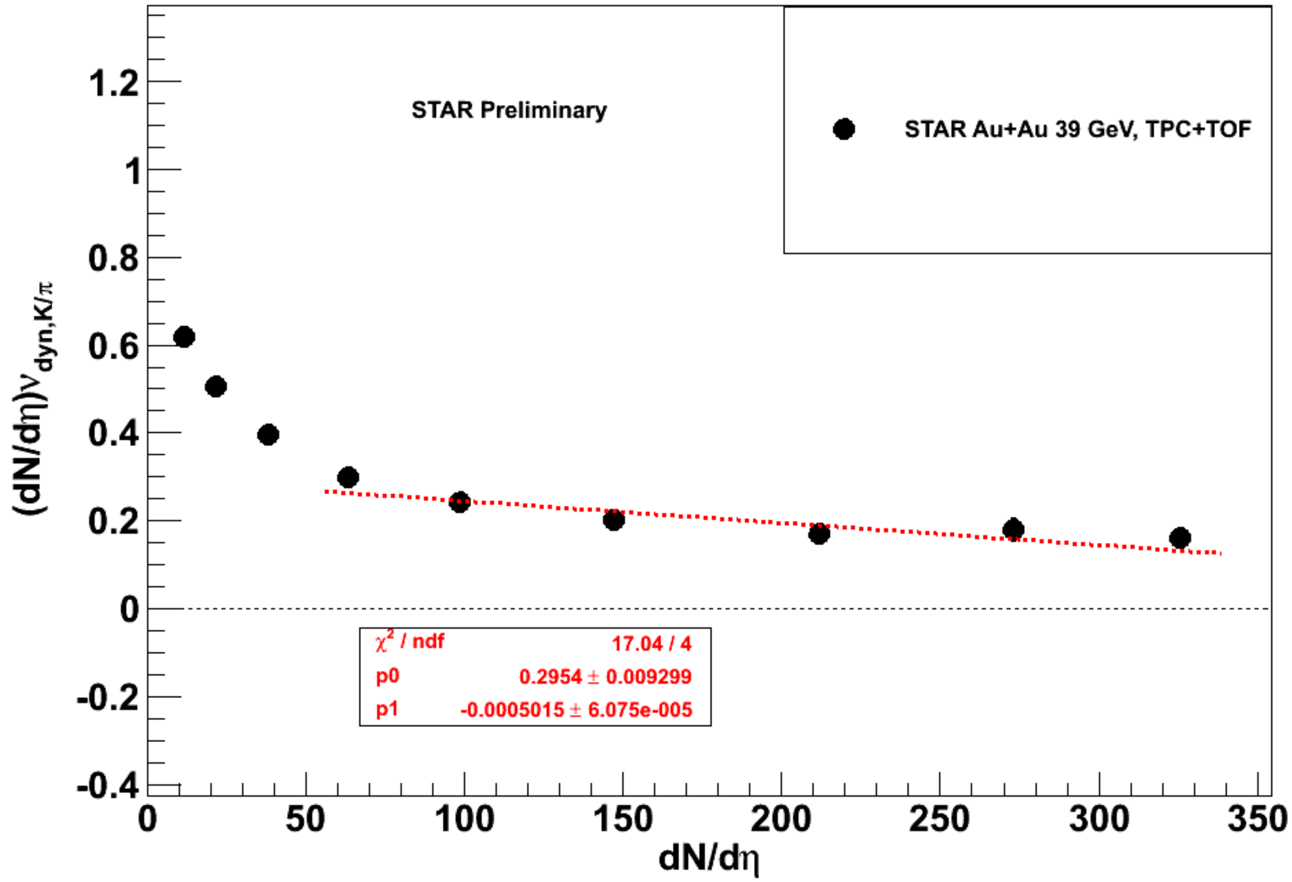
- TPC+TOF includes π and K out to 1.4 GeV/c.

- If similar to higher energies, expect $\nu_{dyn,K/\pi}$ to scale linearly w/ $dN_{ch}/d\eta$ (at least for peripheral bins).

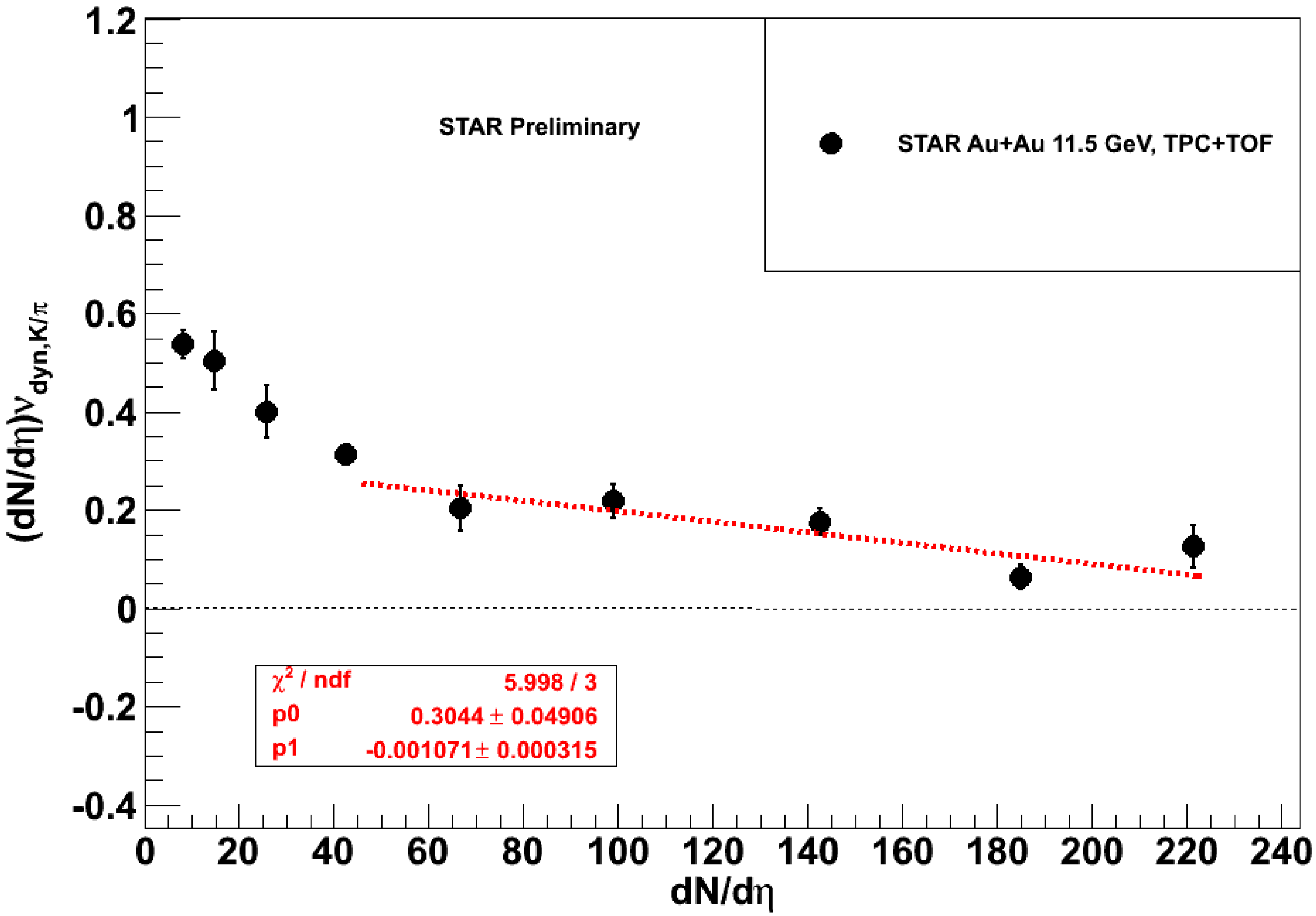
- Extrapolated value is near to mid-periperhal Au+Au 200 GeV (0.30).

- No scaling w/ $dN_{ch}/d\eta$ for peripheral collisions.
  - Rapid increase below $dN_{ch}/d\eta$ = 50.

- More study is needed to determine if linear scaling w/ $dN_{ch}/d\eta$ is broken for $dN_{ch}/d\eta$ > 50.
  - Uncorrected $dN_{ch}/d\eta$.



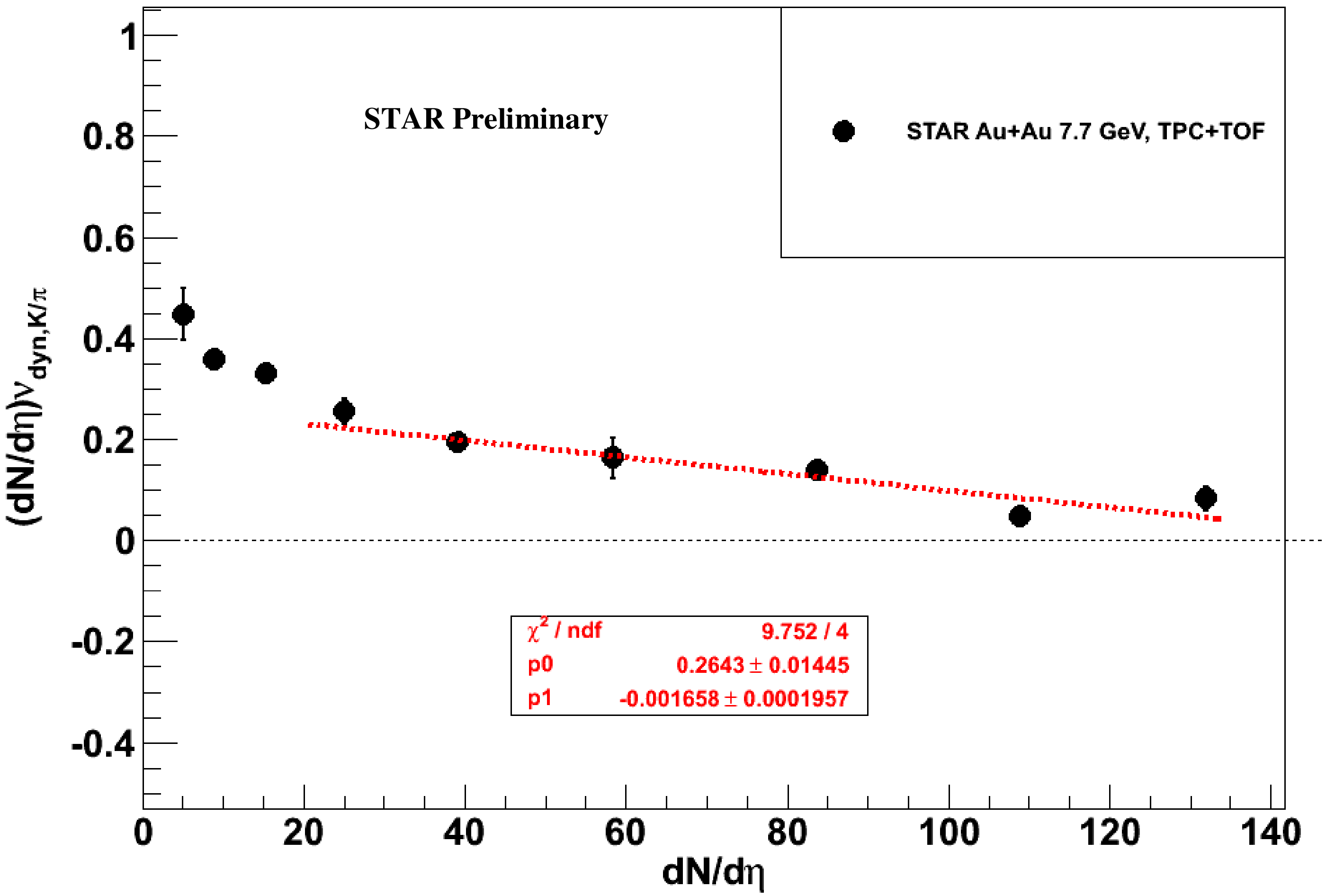
Au+Au, 11.5 GeV $(dN_{ch}/d\eta)\nu_{dyn,K/\pi}$



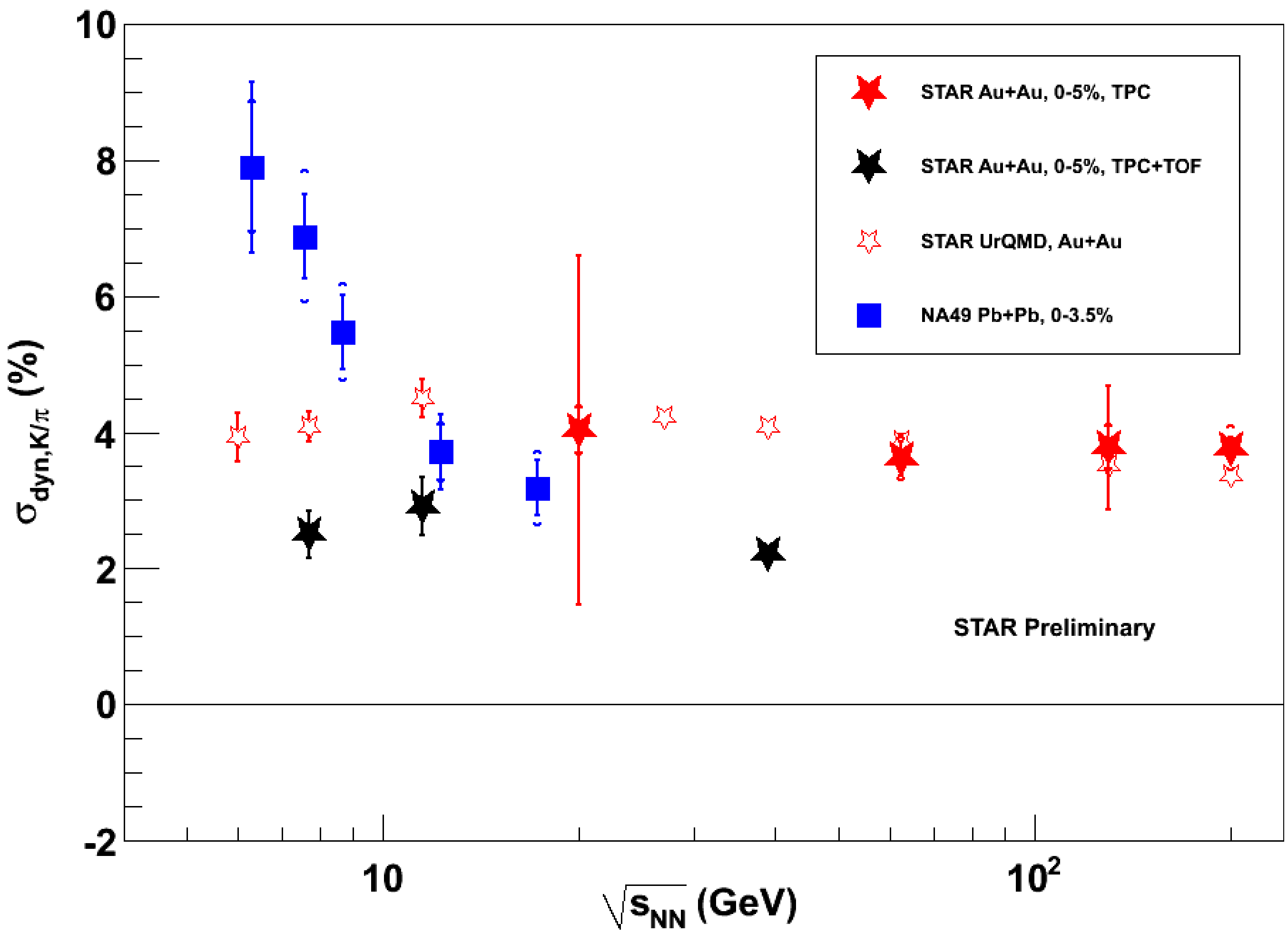
- Uncorrected $dN_{ch}/d\eta$.
- No scaling w/ uncorrected $dN_{ch}/d\eta$ for any centralities.
- Similar magnitude as 39 GeV.

Au+Au, 7.7 GeV $(dN_{ch}/d\eta)\nu_{dyn,K/\pi}$

- Uncorrected $dN_{ch}/d\eta$.
- Similar trend as 39 and 11.5 GeV.
- Decreases with increasing charged particle multiplicity.
- Examine energy dependence of 0-5% bin.



Excitation Function for $\sigma_{dyn,K/\pi}$ from STAR Au+Au data



TPC (GeV/c):

- π : $0.2 < p_T < 0.6$
- K : $0.2 < p_T < 0.6$

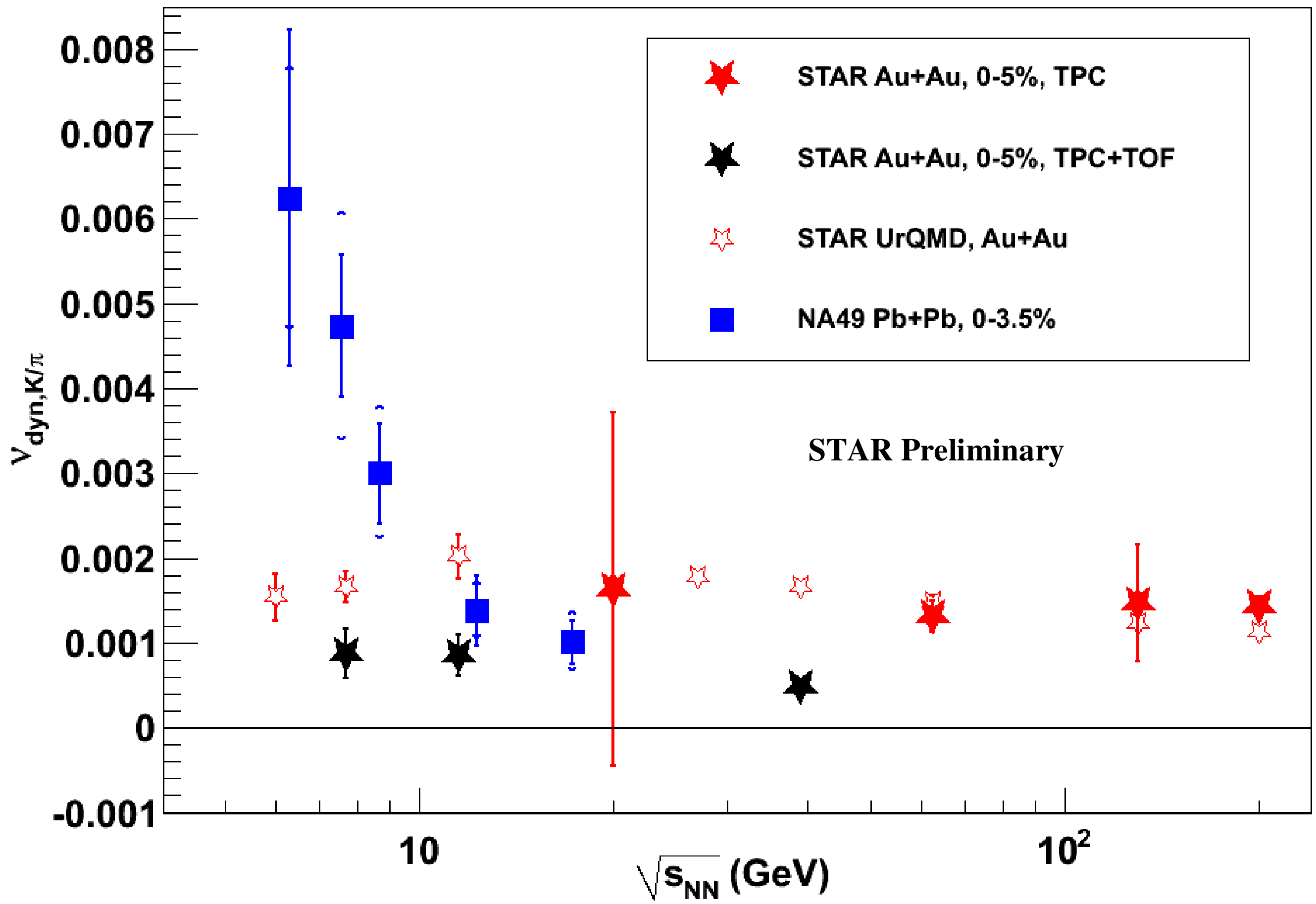
TPC+TOF (GeV/c):

- π : $0.2 < p_T < 1.4$
- K : $0.2 < p_T < 1.4$

- TPC+TOF includes statistical errors. Systematics under study.

Excitation Function for $\nu_{dyn,K/\pi}$ from STAR Au+Au data

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

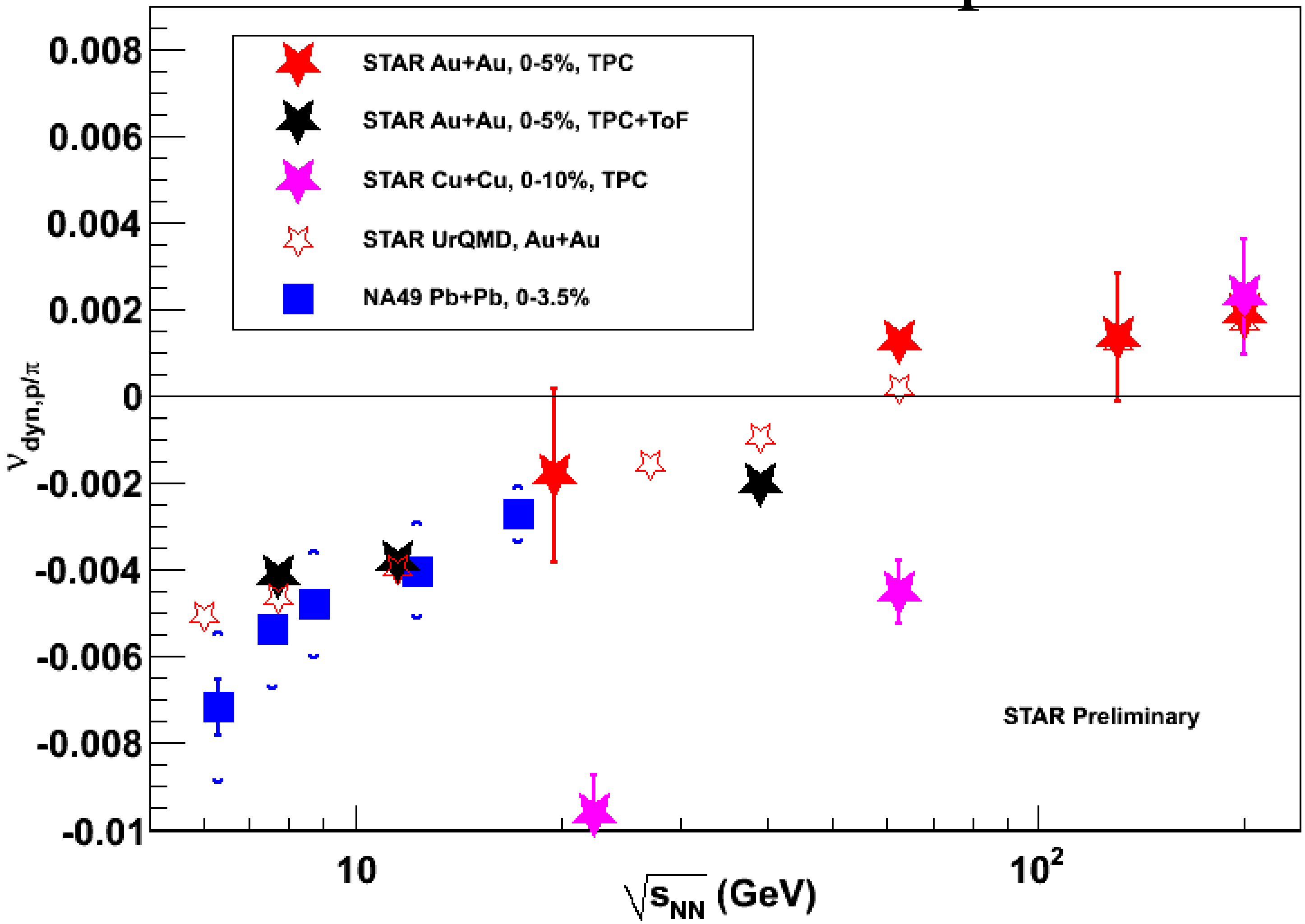


System Size Dependence

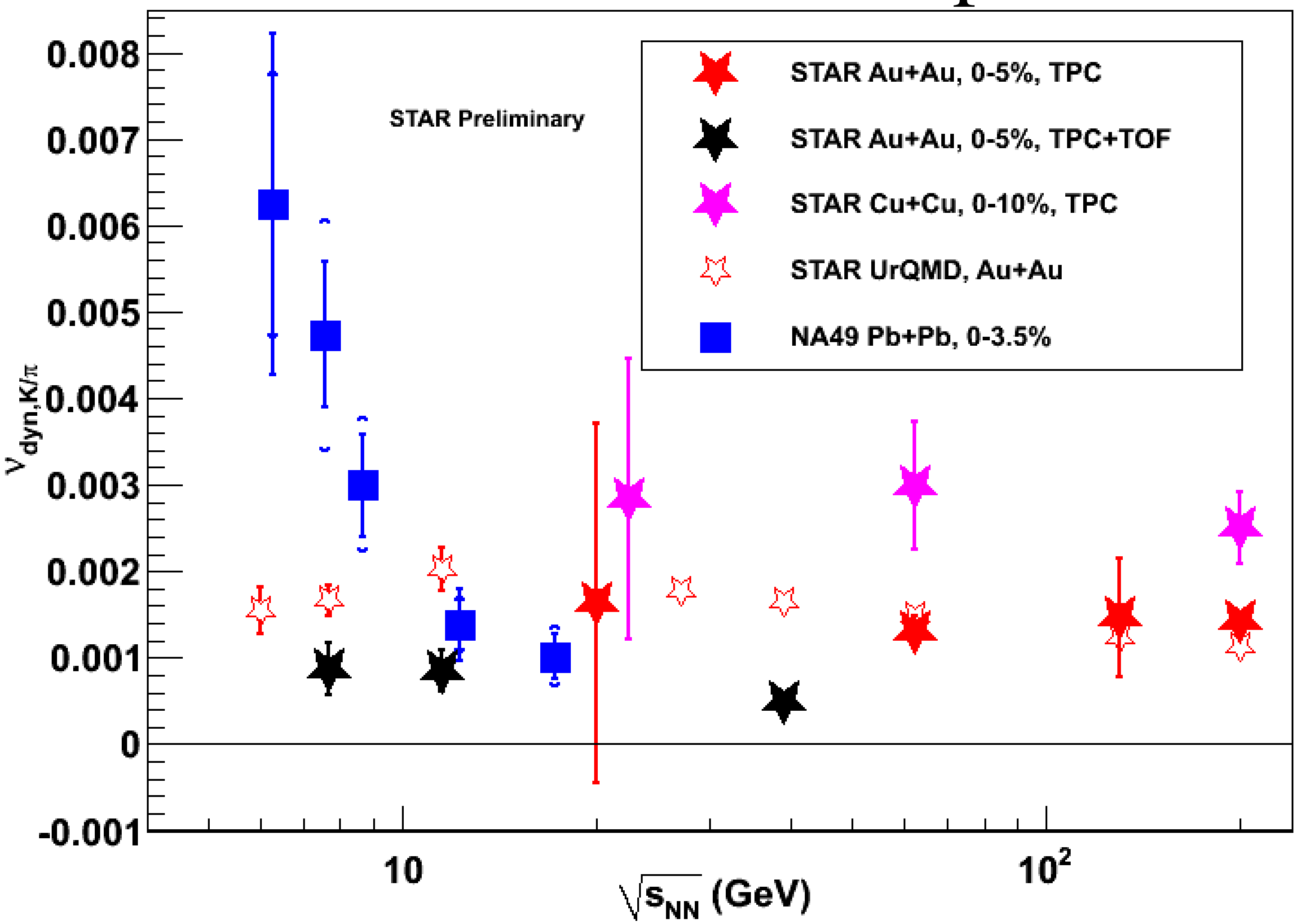
Why Cu+Cu?

- Provides different energy density at same μ_B as Au+Au.
  - Look for deviations from behavior in Au+Au.
- Some observables (e.g. v_1, F-B correlations, …) do not scale with N_{part} in Cu+Cu → Au+Au.
- Complete systematic checks.

Excitation Function for $\sigma_{dyn,p/\pi}$ Current Landscape



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



Summary

- The STAR experiment has results on fluctuations and correlations for several colliding systems and energies that provide new insights into particle production.

- New results from data collected during first part of the RHIC energy scan to search for QCD critical point.
  - For p/π fluctuations:
    - Some differences in the evolution as a function of centrality between the three new energies.
    - Find that $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV results from STAR are consistent with previous measurement from NA49.
  - For K/π fluctuations:
    - STAR does not observe any strong energy dependence of K/π fluctuations in central Au+Au collisions.
    - Fluctuation result from $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au is not consistent within statistical errors with previous measurements.

- Future: Au+Au 200 GeV with TPC+TOF, K/p fluctuations, and charge separated results coming soon.

BACKUP

Critical Fluctuations

- An example of critical fluctuations:

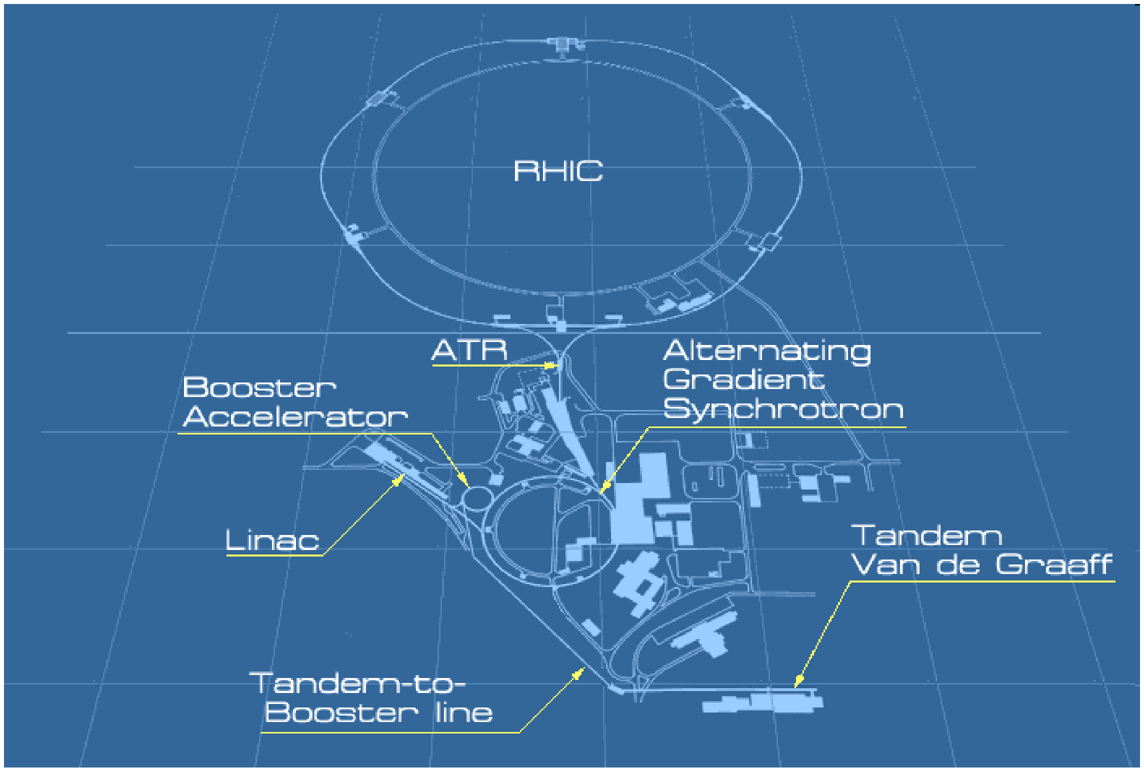
- Mixture of cyclohexane (C_6H_{12}) and aniline (C_6H_7N).

Summary II

- K/π and p/π fluctuations Cu+Cu are constant from $\sqrt{s_{NN}}$ = 200-22.4 GeV.
  - Cu+Cu 0-10% larger fluctuations than Au+Au 0-5%, consistent with N_{ch} scaling. Better agreement w/ Au+Au 0-5% if comparing Cu+Cu 0-5%.
  - UrQMD (not shown) predicts larger values for Cu+Cu 0-10% than the data shows.

- The RHIC Beam Energy Scan (BES) program is ongoing and is probing new regions of the QCD phase diagram, while revisiting energies studied at fixed target experiments using a mature collider and well understood detector setup.
  - Provide a comprehensive picture of the T-μ_B phase space at the same facility.

RHIC



RHIC is an extremely versatile machine!

- Intersecting storage ring (ISR) hadron collider.
- 6 intersection points, currently 2 major experiments:
  - PHENIX
  - STAR
- Center-of-mass collision energies
  - $\sqrt{s_{NN}}$ = 20-200 GeV for heavy ions (e.g. Au, Cu).
  - $\sqrt{s_{NN}}$ = 22-500 GeV for polarized protons.
- Two independent, superconducting rings, allow for asymmetric collisions (e.g. d+Au).
- New ion source (EBIS) will allow for U+U collisions.
- New possibilities for heavy ion collisions at CM energies as low as $\sqrt{s_{NN}}$ = 5 GeV.

Summary II

- ν_{dyn} will be an important variable to characterize fluctuations at all energies for the proposed QCD critical point search. This study provides a baseline for future measurements.

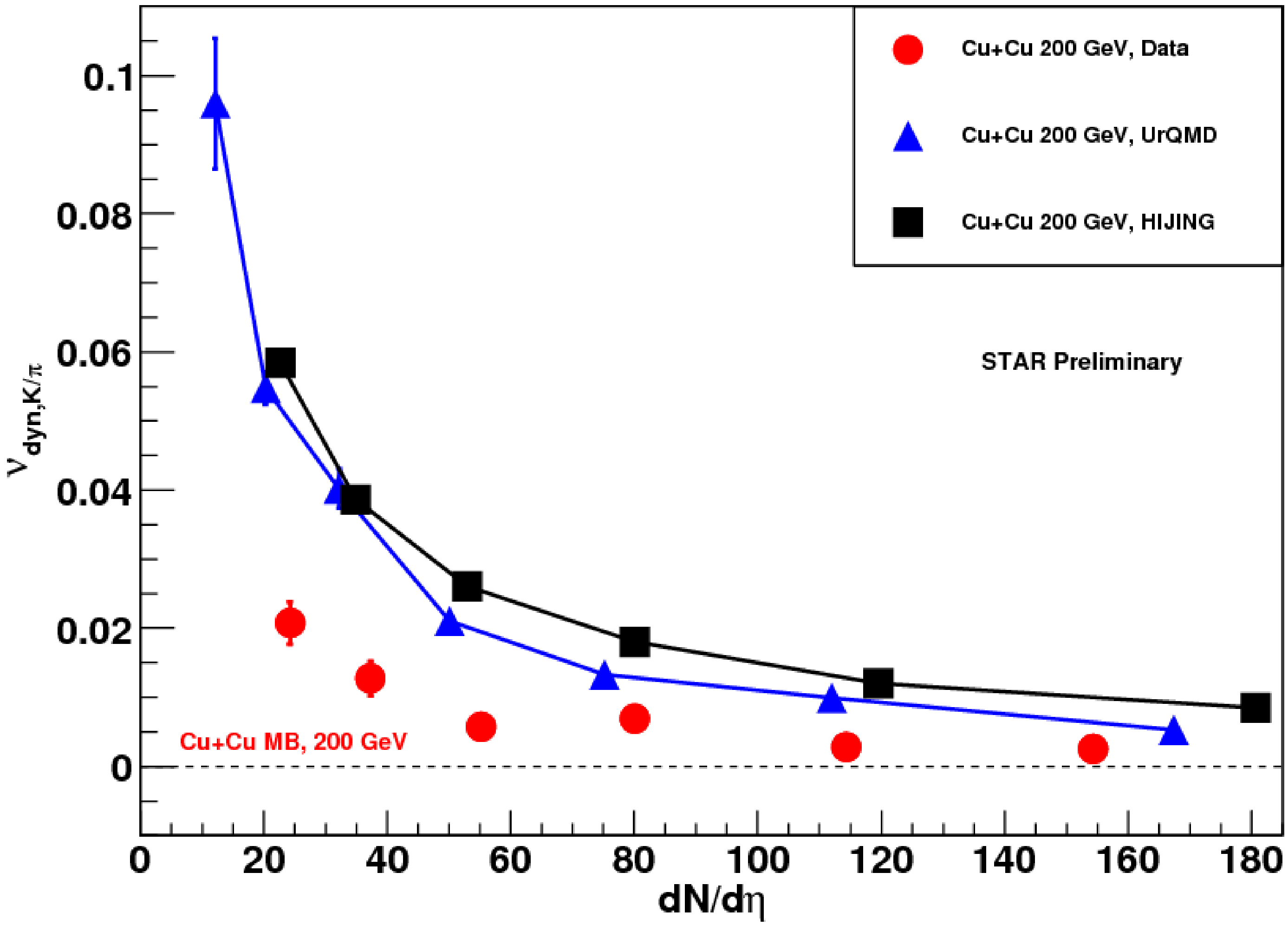
Basic Analysis Cuts

- $|v_z| < 30$ cm, $r = \sqrt{(v_x^2 + v_y^2)} < 1.0$ cm
- Minimum bias trigger.
- Mean event dip angle w/in 2σ of event sample mean dip angle.
- NFitpts > 15, NFitpts/NMaxPts > 0.52
- gDca < 1.0 cm
- $|\eta| < 1.0$
- PID: TPC
  - π : $n_{\sigma\pi} < 2.0$, $n_{\sigma K} > 2.0$, $0.2 < p_T < 0.6$
    K: $n_{\sigma\pi} > 2.0$, $n_{\sigma K} < 2.0$, $0.2 < p_T < 0.6$
    p: $n_{\sigma p} > 2.0$, $n_{\sigma\pi} > 2.0$, $n_{\sigma K} > 2.0$, $0.4 < p_T < 1.0$

  Electrons suppressed, $n_{\sigma e} > 1.0$ for all particles.

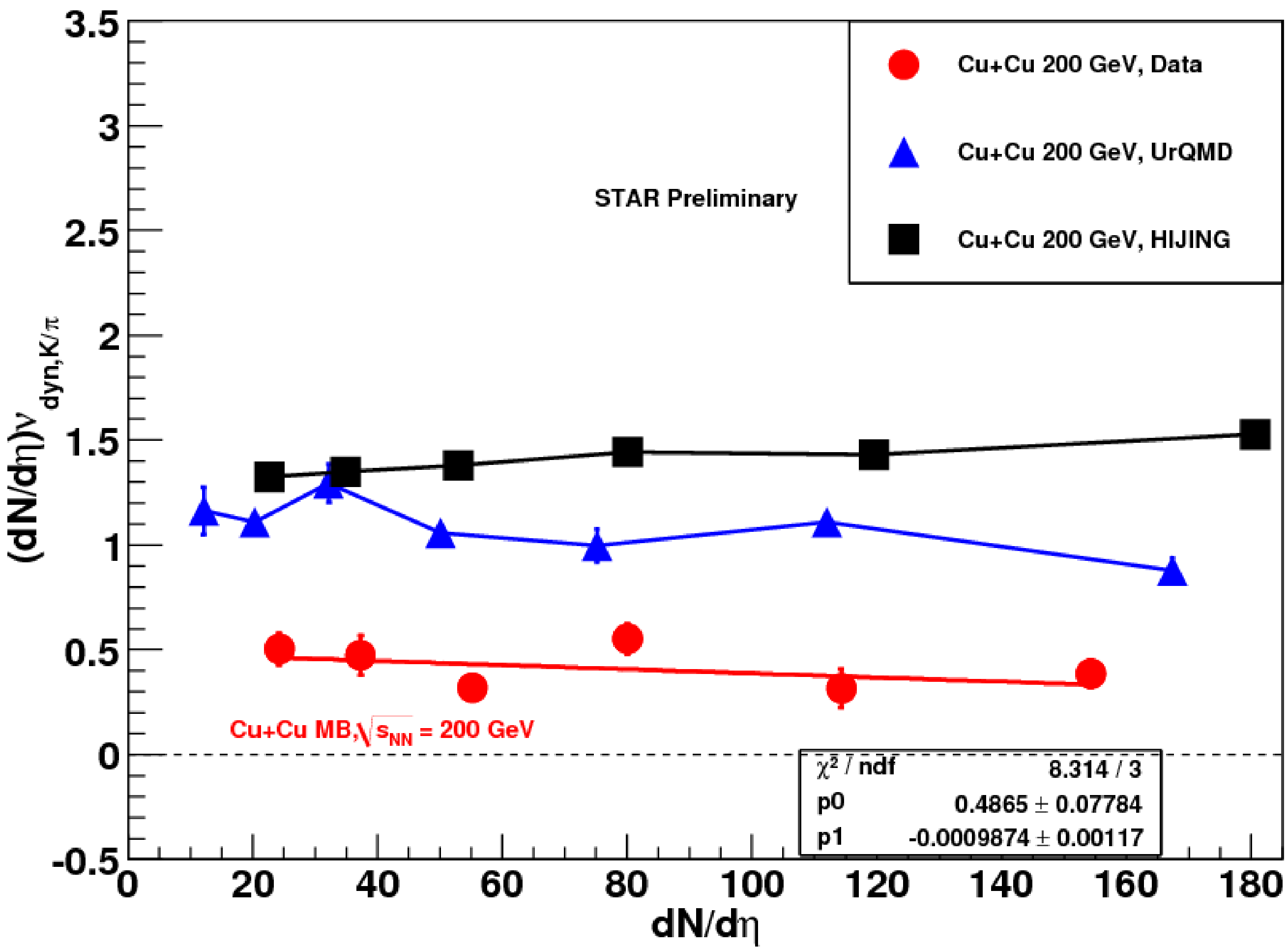
  Similar cuts for ToF PID, though we know nSigmaToF is not properly calibrated (1/β resolution same for all particle species).

Cu+Cu 200 GeV, $\nu_{dyn,K/\pi}$

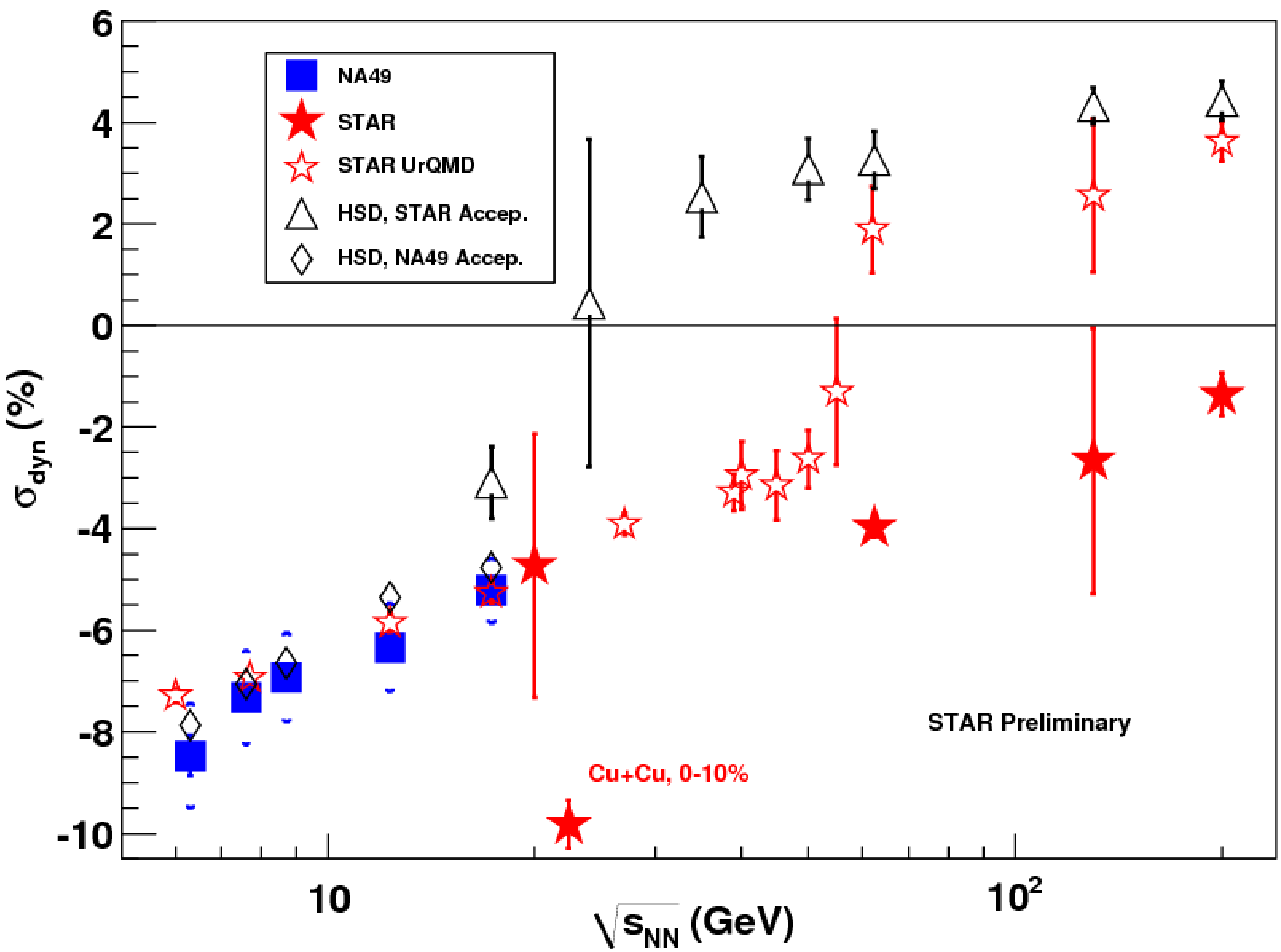


Cu+Cu 200 GeV, $(dN/d\eta)\nu_{dyn,K/\pi}$

- $\nu_{dyn,K/\pi}$ Cu+Cu 200 GeV linearly scales with $dN/d\eta$.
  - -Intercept = 0.40
  - -Consistent with Cu+Cu 22.4 GeV and peripheral Au+Au 200 and 62 GeV.
- Errors are statistical.



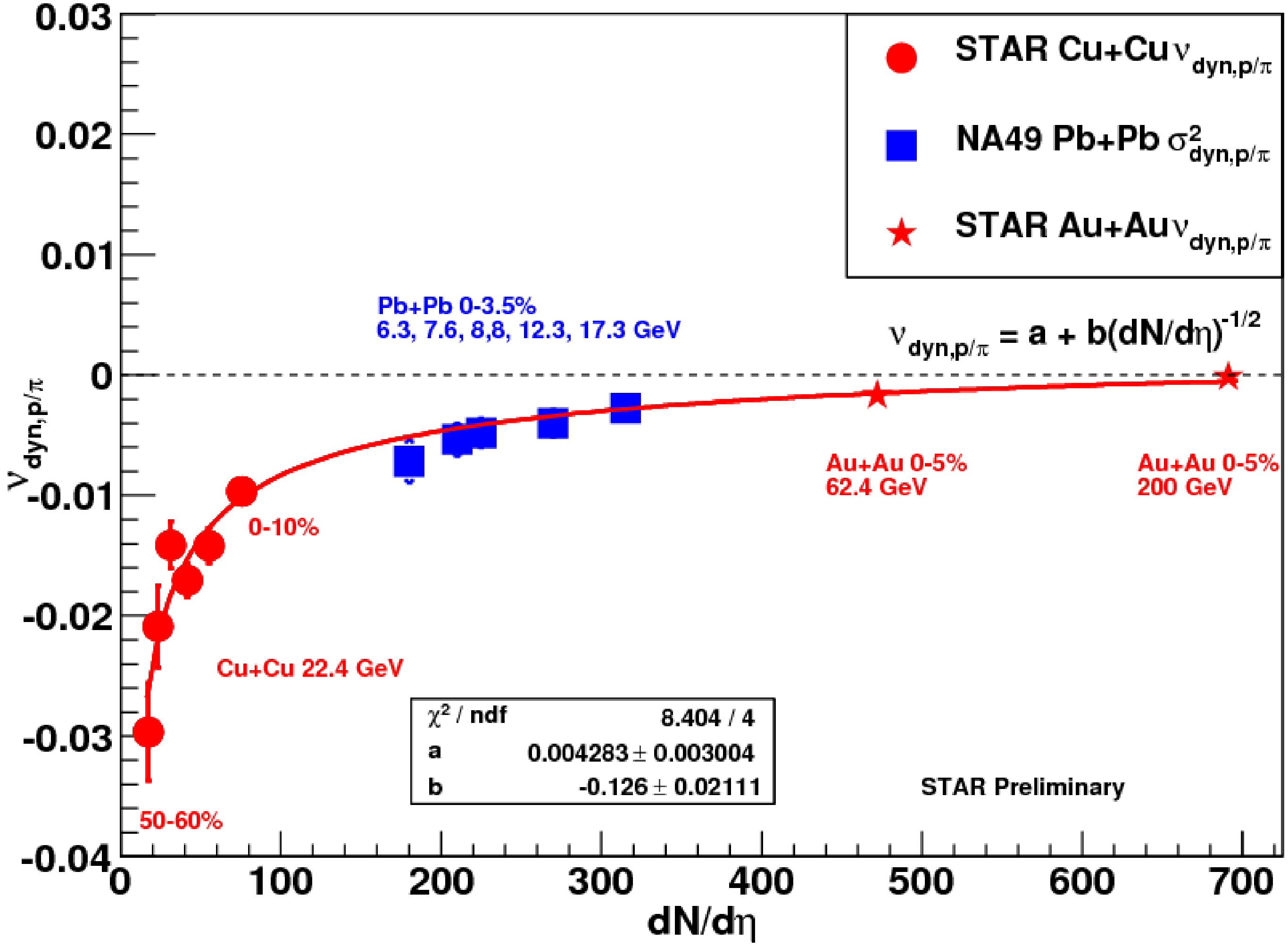
Excitation Function for $\sigma_{dyn,p\pi}$



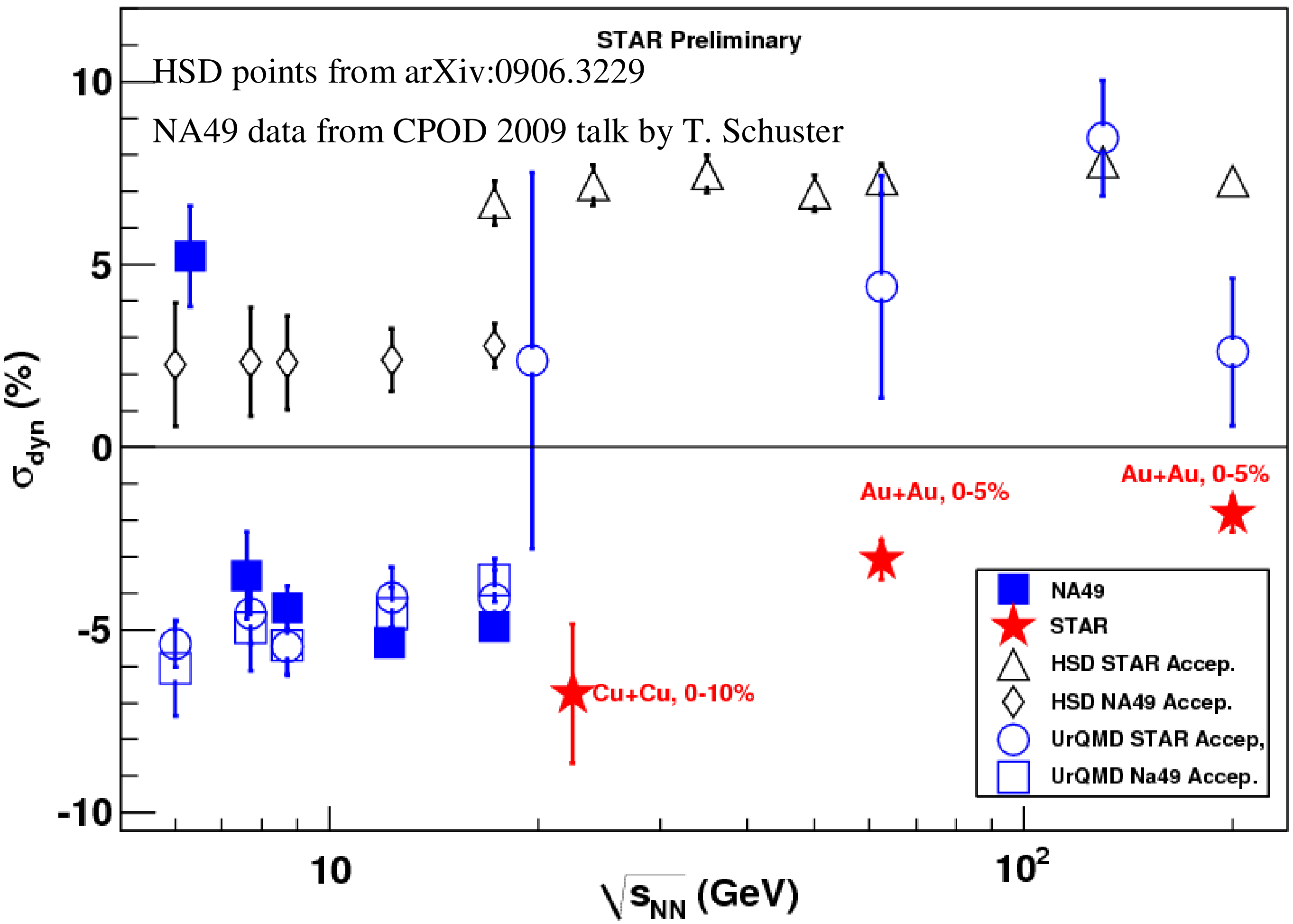
- Solid points are data from STAR or NA49.
- Open black points are HSD prediction from Konchakovski, et. al. arXiv:0906.3229.
- Open red points are UrQMD run locally with STAR acceptance.

$\nu_{dyn,p/\pi}$, STAR and NA49

- $\nu_{dyn,p/\pi}$ displays strong system size dependence for small dN/dη.
- Fit is to STAR Cu+Cu 22.4 GeV data only.
- Interpretation still under study.

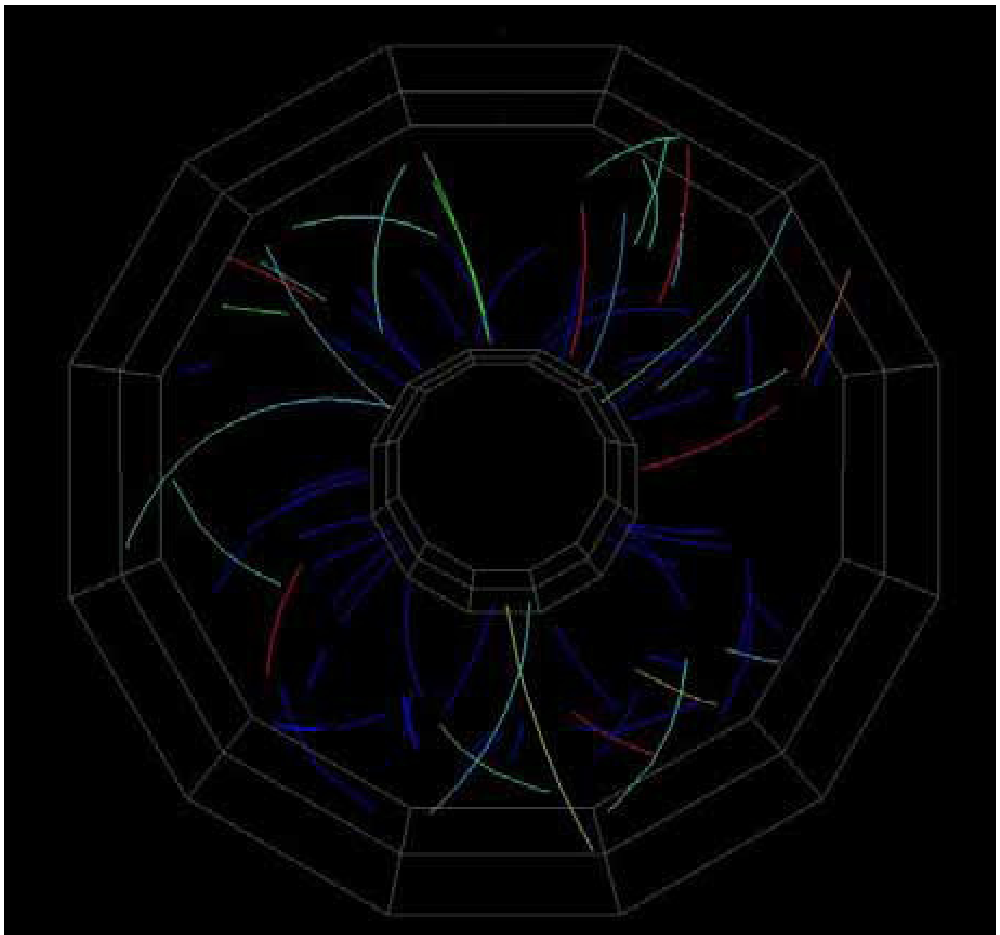


Excitation Function for $\sigma_{dyn,Kp}$



- $\sigma_{dyn,K/p}$ for central Cu+Cu 22.4 GeV is strongly negative.
  - -General agreement w/ NA49 at 17.3 GeV.
  - -Does not show large increase seen in model predictions.
- $\sigma_{dyn,K/p}$ for central Au+Au 200 and 62.4 GeV are also negative.

2008 Test at $\sqrt{s_{NN}} = 9.2$ GeV



STAR

- The STAR detector is in a prime configuration for measuring fluctuations and correlations:
  - Full ToF is installed. Will provide enhanced PID capabilities.
  - Low material budget between beam pipe and TPC.
  - DAQ 1000 installed as of Run 9. Not rate limited by DAQ at higher energies of BES.

Search for the QCD Critical Point

- Proposal for future running at RHIC to consist of an "energy scan" to search for predicted QCD critical point.
- Fluctuations and correlations (particle ratios, multiplicity, p_T, etc.) and behavior of flow (directed and elliptic) in vicinity of the critical point are expected to be primary signatures.
- STAR has the capability to measure correlations and fluctuations at all energies.

Particle Ratio Fluctuations

- In a phase transition near a critical point, an increase in non-statistical fluctuations is expected.
- Cu+Cu at $\sqrt{s_{NN}}$ = 22.4 GeV provide lowest energy density A+A collisions (and second largest $\mu_B \approx 184$ MeV) for measuring fluctuations currently available at RHIC.

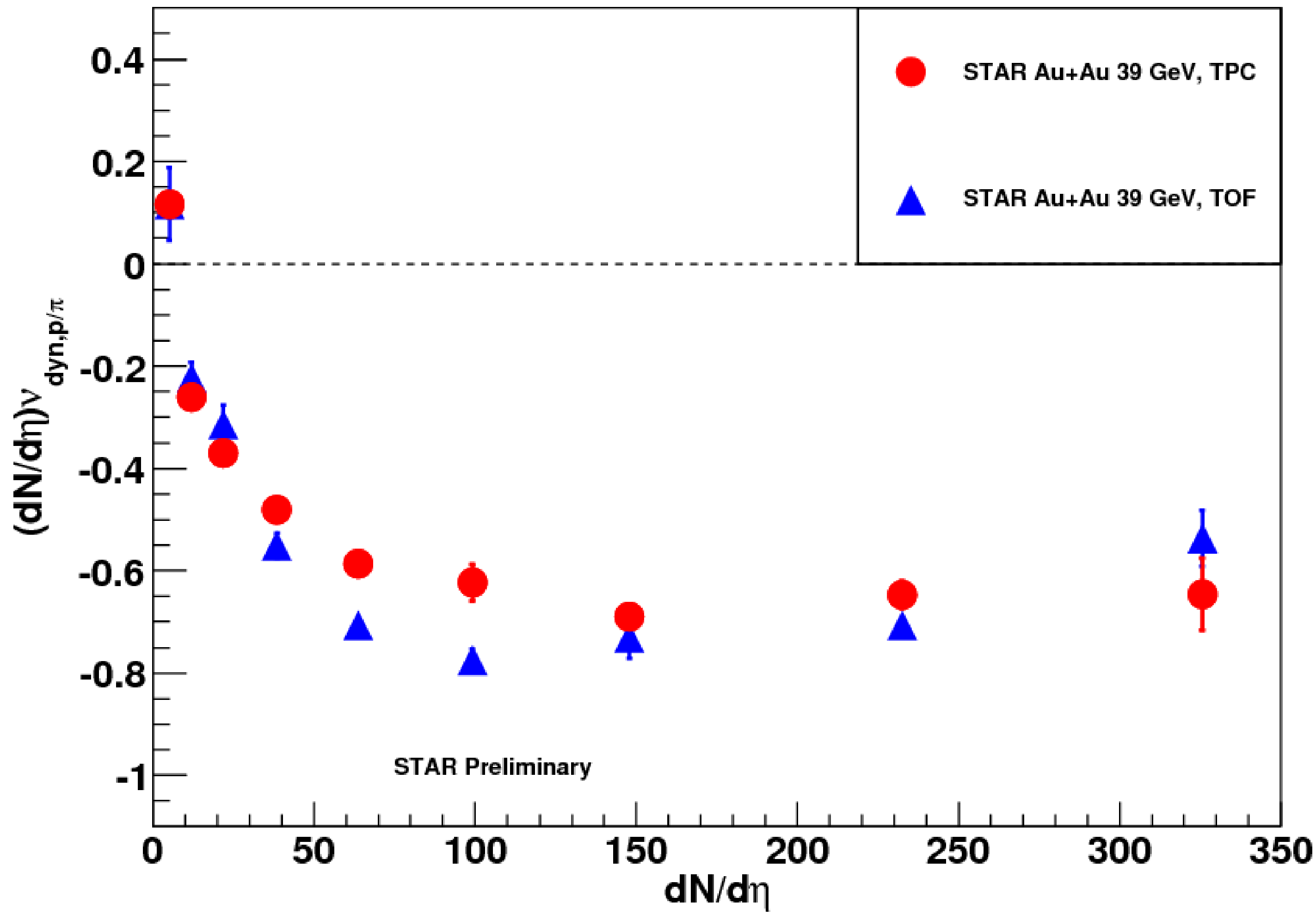
$$\mu_B(\sqrt{s}) = \frac{1.308\ GeV}{1 + 0.273\ GeV^{-1}\sqrt{s}}$$

J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton J.Phys.G32:S165-S170, 2006

- Smaller system size than $\sqrt{s_{NN}}$ = 19.6 GeV Au+Au collisions at RHIC and central Pb+Pb collsions at SPS.
- A range that will be covered by future energy scan at RHIC.
- 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.

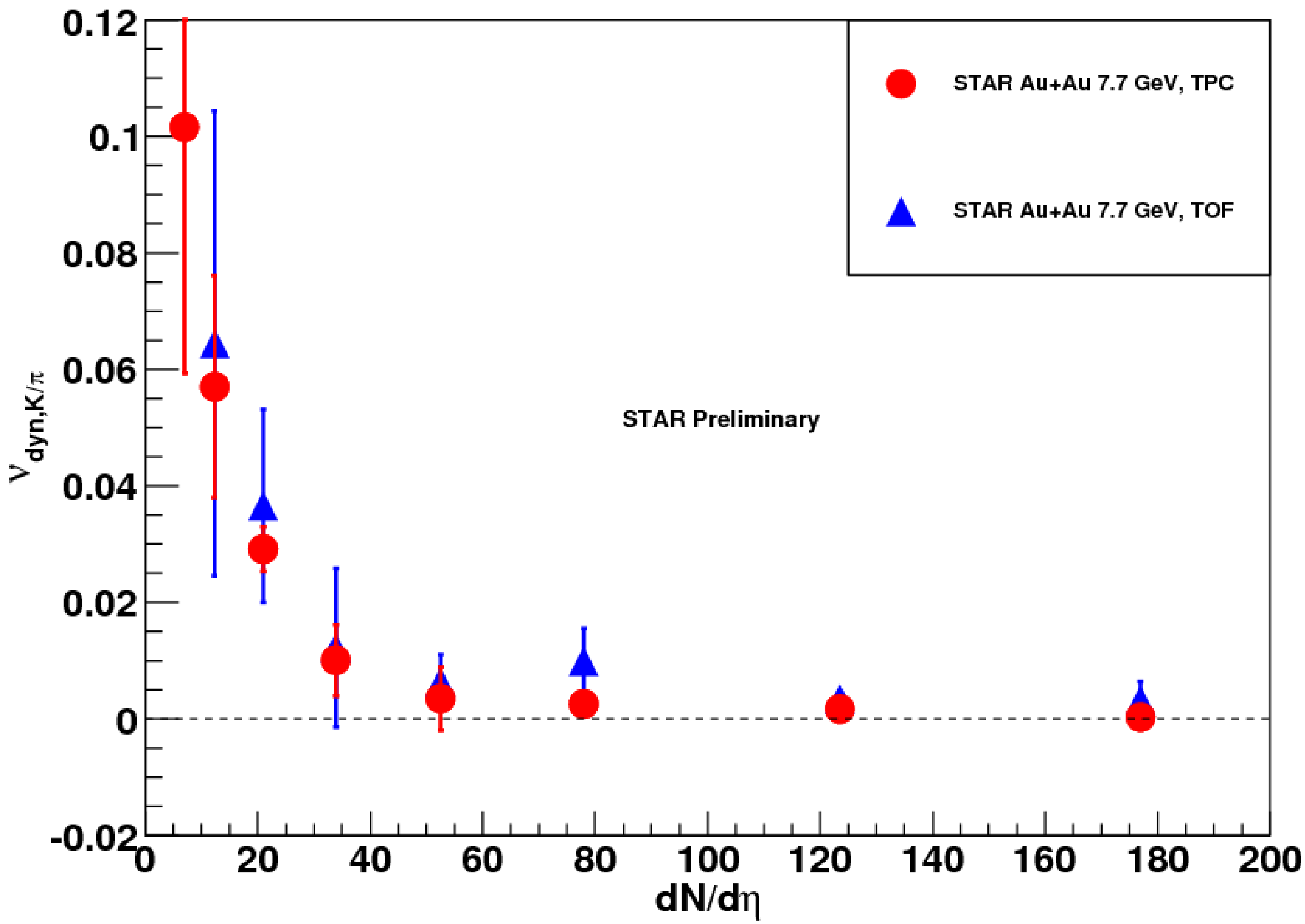
Aoki, Endrodi, Fodor, Katz, and Szabó *Nature* **443**, 675-678 (2006)

Au+Au 39 GeV, $(dN/d\eta)\nu_{dyn,p/\pi}$



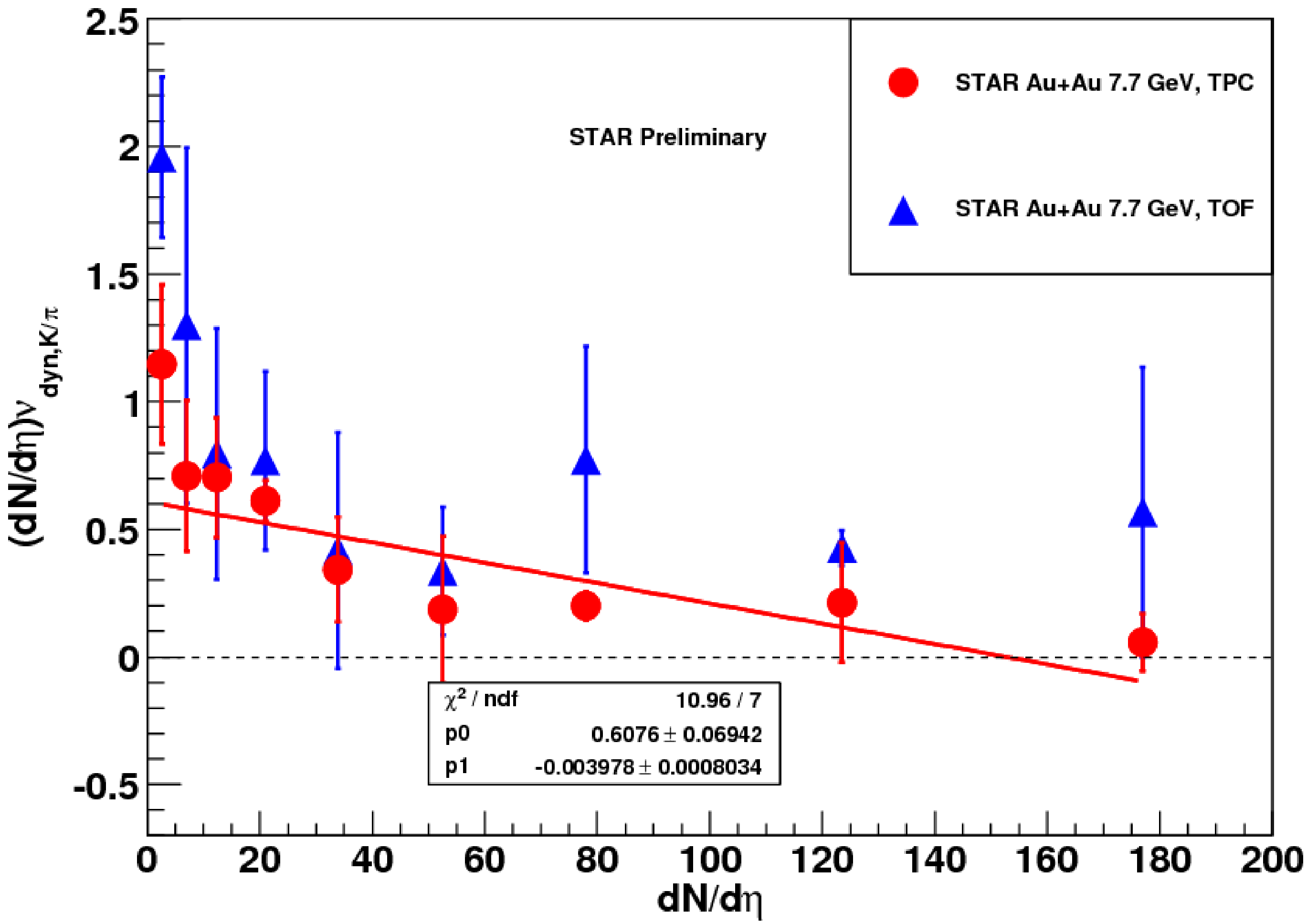
Au+Au 7.7 GeV, $\nu_{dyn,K/\pi}$

- As w/ Au+Au 39 GeV, can see general $1/N_{ch}$ dependence.
- Data from TPC and TOF is in good agreement.
- Statistical errors (only half the data was available).

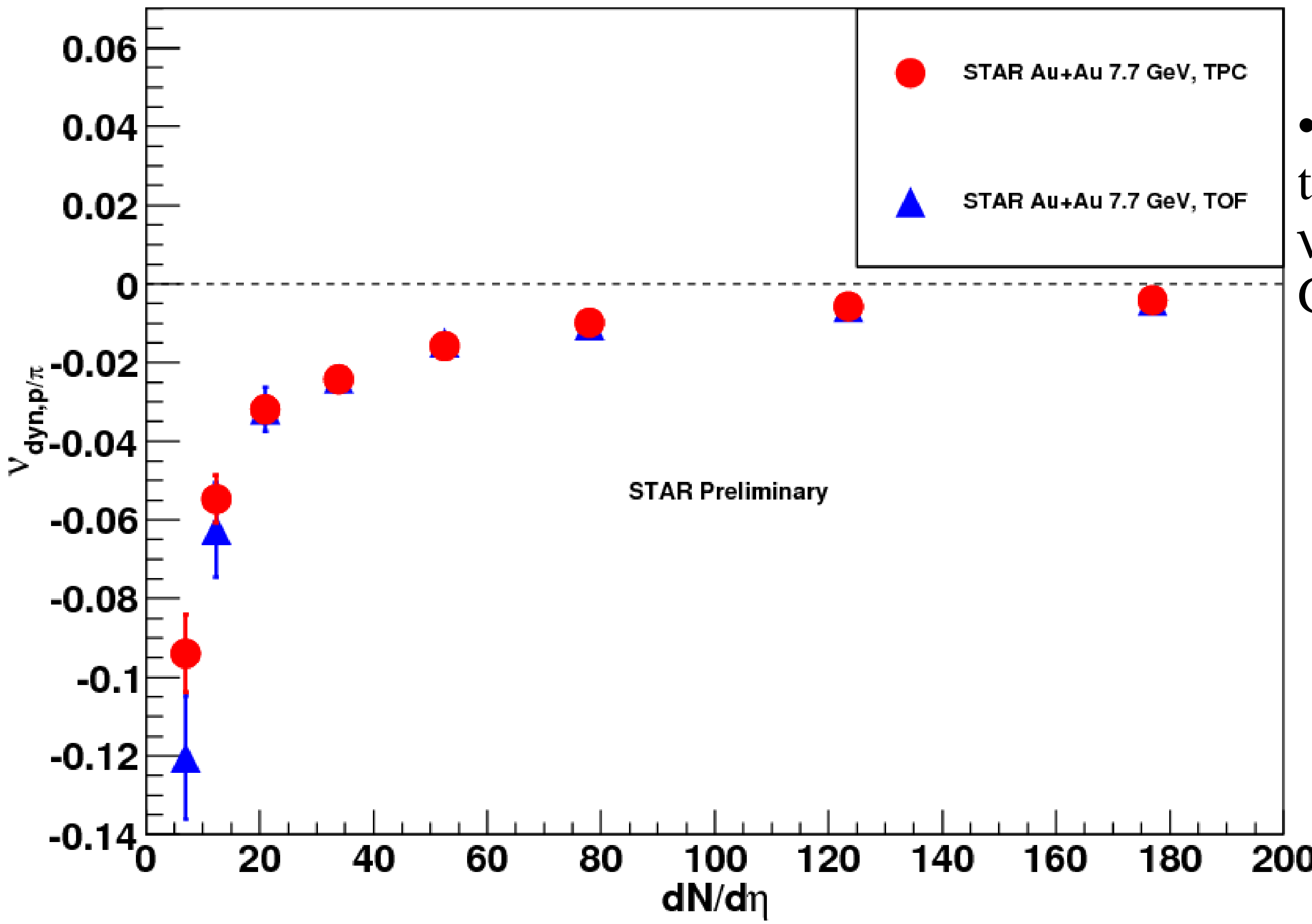


Au+Au 7.7 GeV, $(dN/d\eta)\nu_{dyn,K/\pi}$

- If similar to other energies, expect $\nu_{dyn,K/\pi}$ to scale w/ $dN/d\eta$.
- If fit with a line, intercept = 0.61, but poor statistics.
- Have to wait for remaining data to draw conclusions.

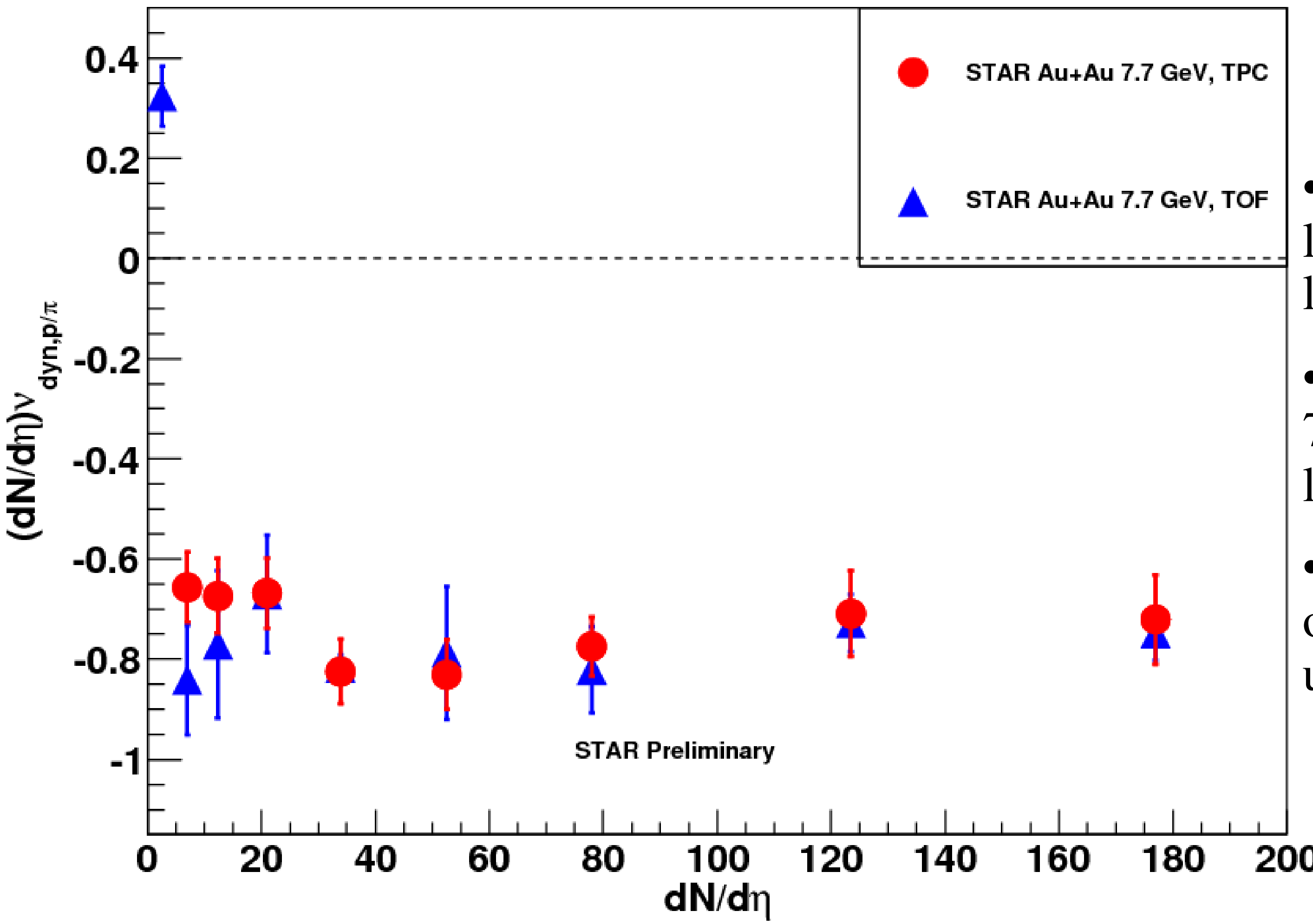


Au+Au 7.7 GeV, $\nu_{dyn,p/\pi}$



- Similar behavior for total charge particle $\nu_{dyn,p/\pi}$ for Au+Au 7.7 GeV.

Au+Au 7.7 GeV, $(dN/d\eta)\nu_{dyn,p/\pi}$



- Does $\nu_{dyn,p/\pi}$ scale lineearly w/ dN/dη at lower energies?
- $\nu_{dyn,p/\pi}$ for Au+Au 7.7 GeV might scale linearly w/ dN/dη.
- Need remaining half of data to help understand.