Search for QCD Phase Transitions and the Critical Point Utilizing Particle Ratio Fluctuations and Transverse Momentum Correlations from the STAR Experiment

Prithwish Tribedy
(for the STAR collaboration)
Variable Energy Cyclotron Centre, Kolkata, India.

Office of Science
U.S. Department of Energy

Outline/Motivation

Multiplicity Ratio fluctuation:

- Dynamical fluctuation of globally conserved quantities like (net baryon, net strange, net charge, isospin) over limited phase space (grand canonical ensemble (GCE) picture)
  - Important probe in the context of phase transition.
- Any non-monotonic behavior of the energy dependence of fluctuation.
  - Important probe in the context of critical phenomenon.

Correlation:

- Correlation of charge-to-neutral pion
  - One of the very few observable that is sensitive to QCD chiral phase transition.
  - Sensitive to possible formation of domains of Disoriented Chiral Condensate (DCC).
- Transverse momentum correlation
  - Sensitive to critical phenomena, temperature fluctuation.

Phys. Rev. Lett. 83, 5435 (1999)
Phys. Rev. D 46, 246 (1992)
Phys. Rep. 351, 161 (2001).

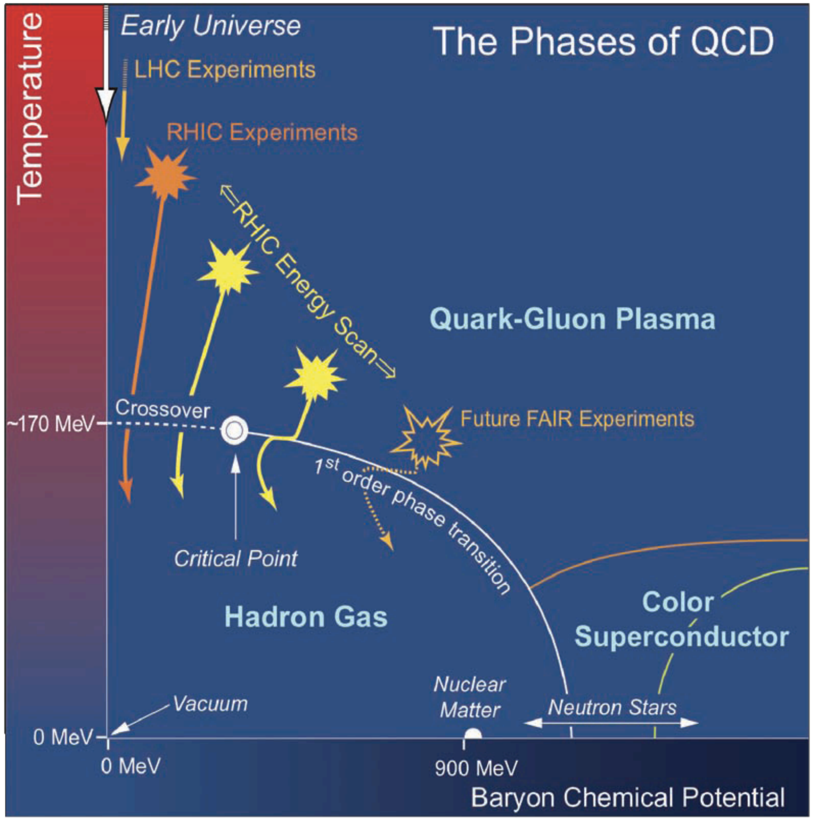
RHIC Beam Energy Scan program

RHIC BES program :

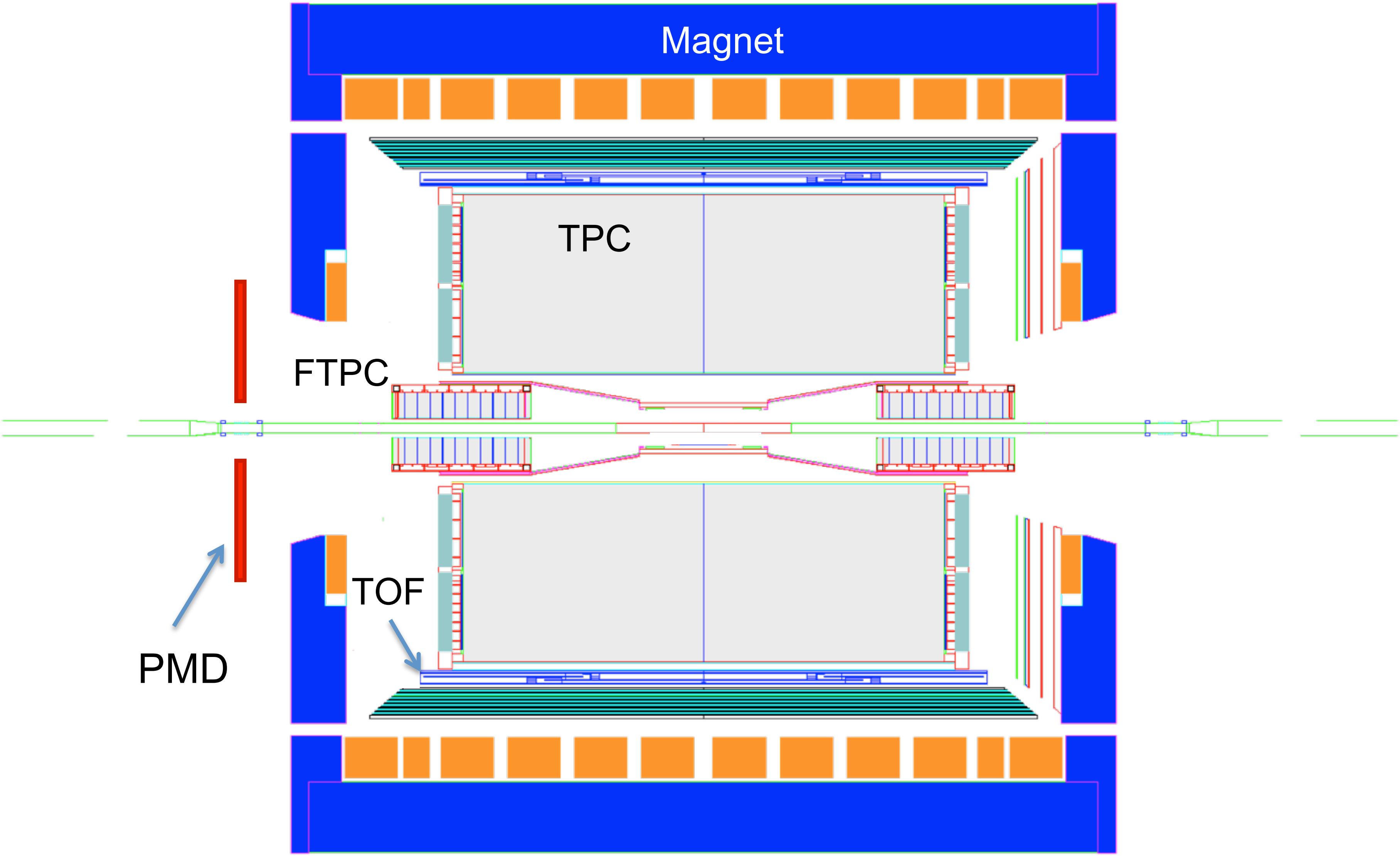
To explore QCD phase diagram
Over a wide range of baryon chemical potential.

In 2010-11 STAR has taken data at 7.7, 11.5, 19.6, 27, 39 (and 62.4, 200) GeV energies.

Energy dependence of various observables have been studied for the search of possible critical phenomena.



STAR experimental setup



Measurement at STAR
(energy range of 7.7-200 GeV)

- STAR measurements at mid-rapidity (-1 < η <1)
  - Measured identified particles from TPC+TOF → kaon, pions, protons multiplicity
  - Measured inclusive particles from TPC → charged particle multiplicity & transverse momentum.

- STAR measurements at forward rapidity (-3.7 < η <-2.8)
  - Measured identified particles from PMD → photon multiplicity (dominantly π^0)
  - Measured inclusive charged particles from FTPC → dominantly for π^+ and π^- multiplicity

Centrality selection is done using uncorrected charged track multiplicity from TPC.

All observables are corrected for centrality bin-width effect. (see X. Luo's talk)

Observable for ratio fluctuation

Observables are constructed out of ratio of factorial moment over mean multiplicity

$$\nu_{dyn}^{M-N} = \underbrace{\frac{\langle M(M-1)\rangle}{\langle M\rangle^2} + \frac{\langle N(N-1)\rangle}{\langle N\rangle^2}}_{\text{Individual fluctuations}} - 2\underbrace{\frac{\langle MN\rangle}{\langle M\rangle\langle N\rangle}}_{\text{correlation}}$$

$$M, N = K, \pi, p, \mathrm{ch}^{\pm}, \gamma$$

Phys. Rev. C 66, 044904 (2002)

→ Sensitive to dynamical fluctuation of ratio of multiplicity.
→ Zero for Poissonian fluctuation.
→ No explicit efficiency dependence.

Sign of ν_{dyn} :

- Negative : dominated by correlation.
- Positive : could either be anti-correlation or dominated by fluctuation.

Observables for particle correlation

Observable for charge-to-neutral multiplicity correlation:

$$r_{m,1}^{\gamma-\mathrm{ch}} = \frac{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m+1)\ N_\gamma\rangle \langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m)\rangle \langle N_\gamma\rangle}$$

Minimax collaboration
Phys. Rev. D 55, 5667 (1997)

→ Originally designed for the search of Disoriented-chiral condensate (DCC).
→ 1 for Poissonian fluctuation and higher order give higher sensitivity.
→ Slope (positive −> correlation, negative −> anti-correlation) of $r_{m,1}$ vs m indicates nature and signals strength (ξ)

$$r_{m,1}^{\gamma-\mathrm{ch}} \approx 1 - \frac{m\xi^2}{(m+1)} F(m,\xi^2)$$

Phys. Rev. C 85, 024902 (2012)

Observable for two-particle transverse momentum correlation:

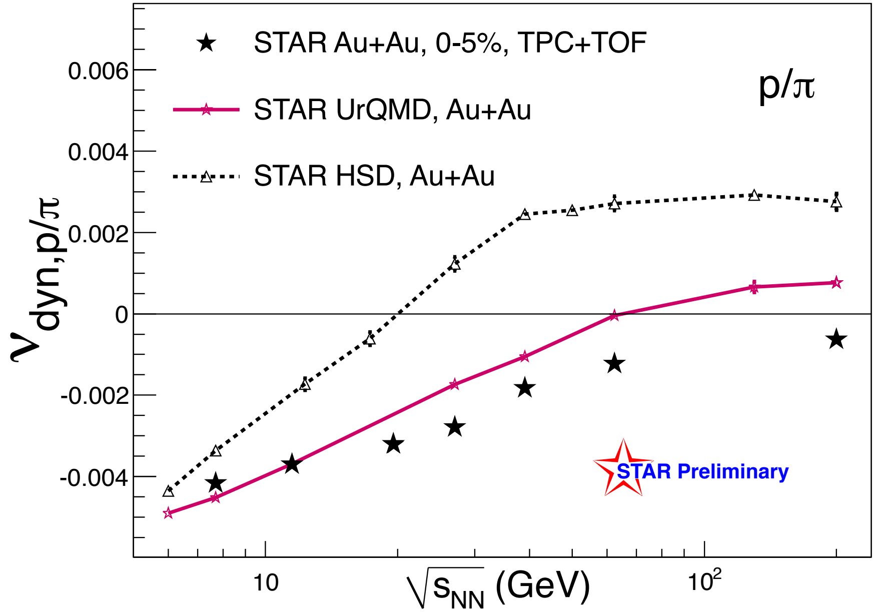
$$\langle \Delta p_{t,i} \Delta p_{t,j} \rangle = \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_K (N_k - 1)}$$

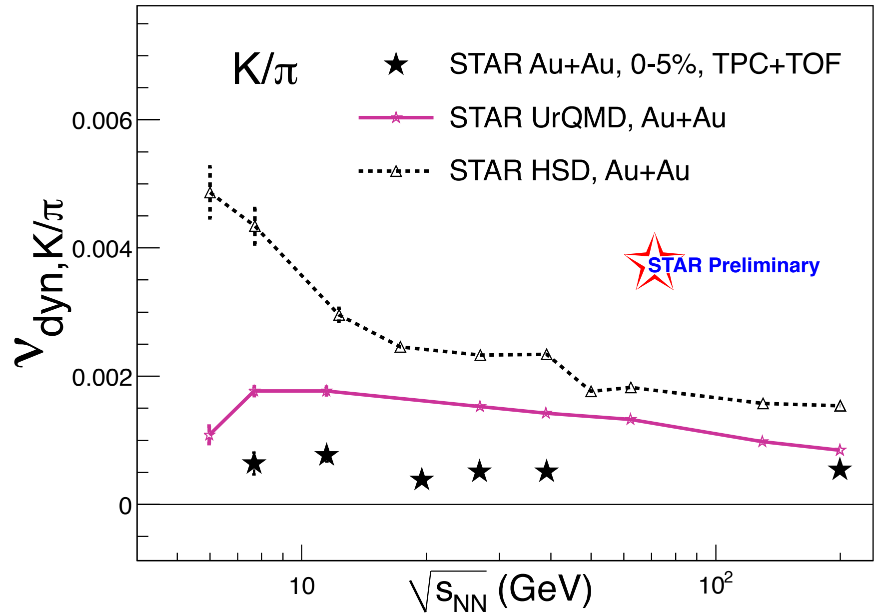
Phys. Rev. C **72**, 044902 (2005)

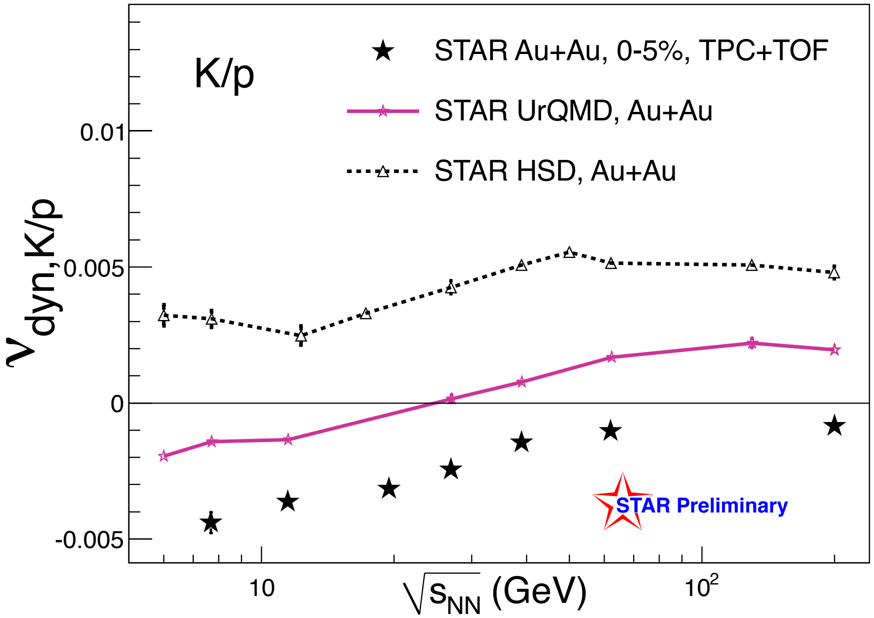
$$C_K = \sum_{i=1}^{N_k} \sum_{j=1, i\neq j}^{N_k} \left(p_{t,i} - \langle\langle p_t \rangle\rangle\right)\left(p_{t,j} - \langle\langle p_t \rangle\rangle\right)$$

$$\langle\langle p_t \rangle\rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t \rangle_k \right) \Big/ N_{event} \qquad \langle p_t \rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i} \right) \Big/ N_k$$

Ratio fluctuation: Identified particles







(measurement at mid-rapidity |η|<1)

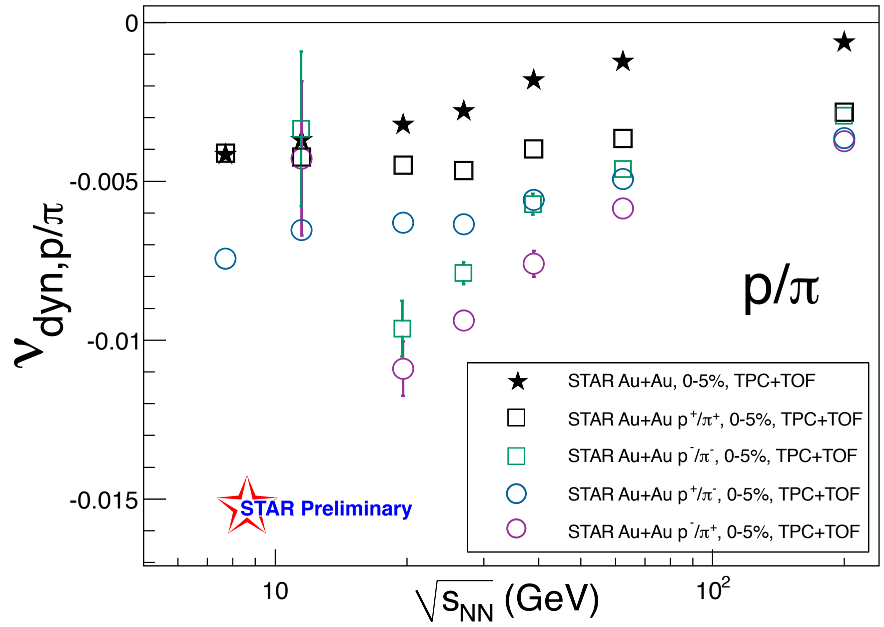
Monotonic trend in the range of 7.7-200 GeV.

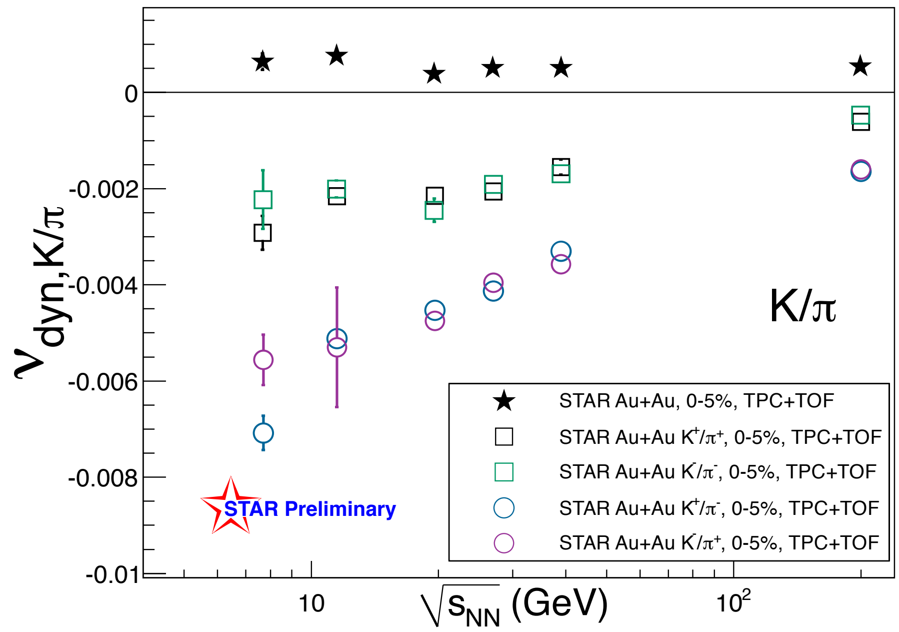
K/p and p/π are dominated by correlation.

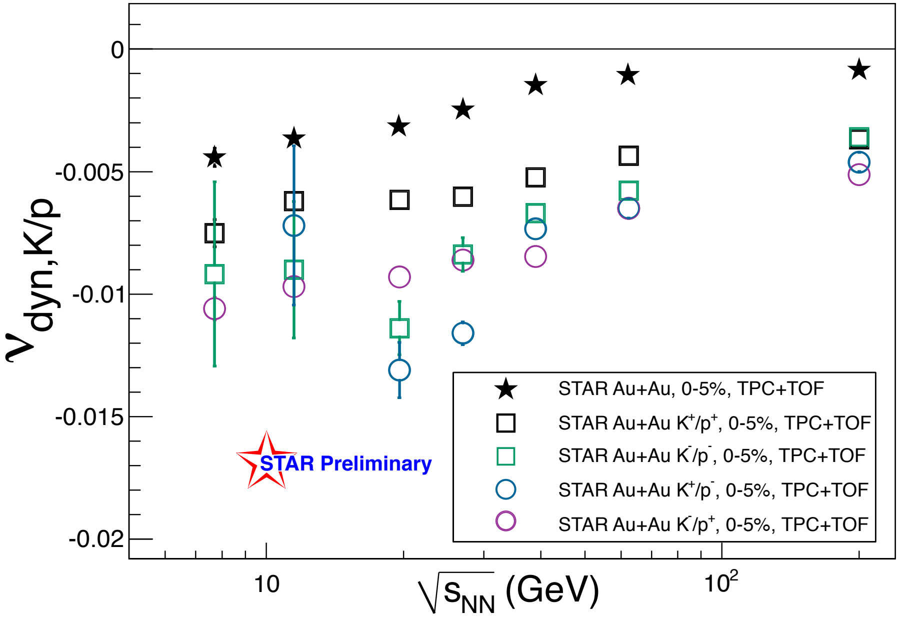
Data are below hadronic model predictions.

see also Z.Ahammed's poster

Ratio fluctuation: Identified particles

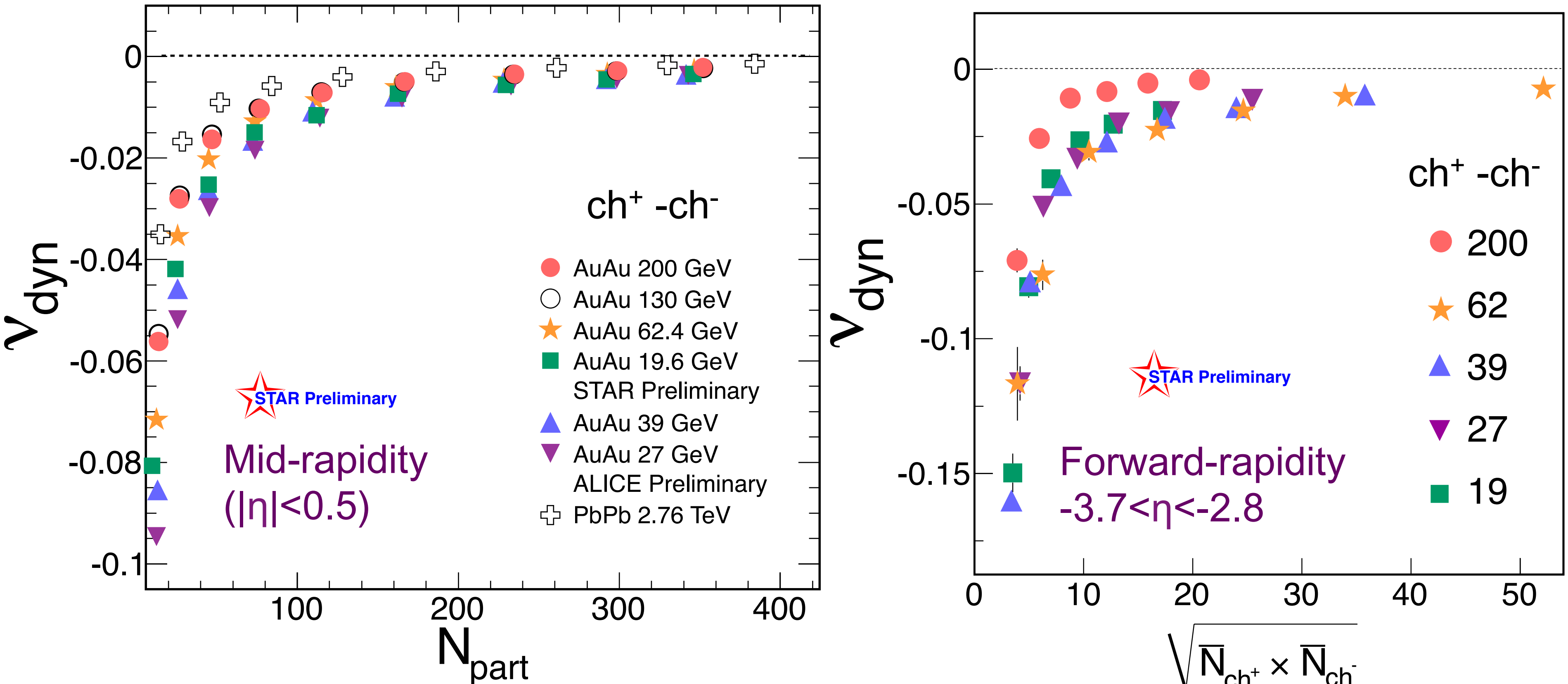






Charge dependence of excitation function appears at lower energy.

Ratio fluctuation: inclusive positive-negative charge

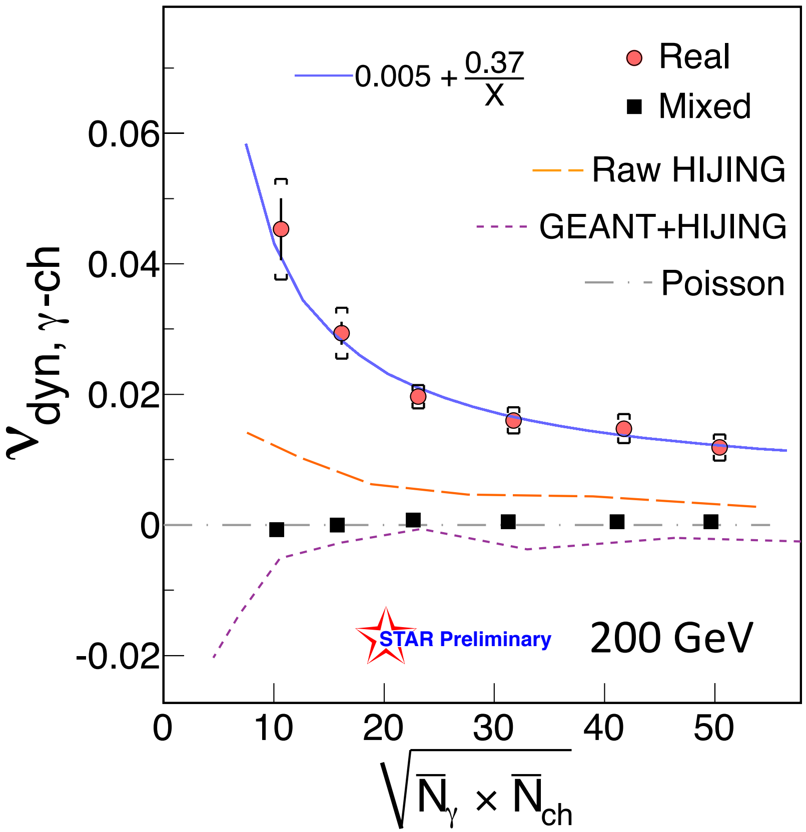


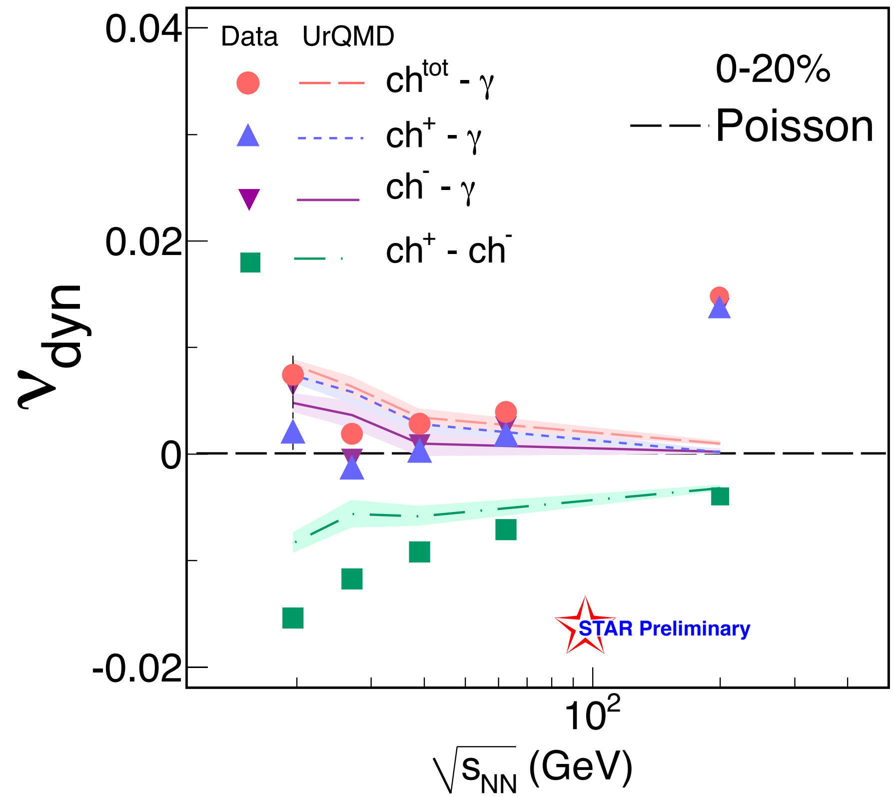
see B. Sharma's poster

Consistent trend with energy at both mid-rapidity and forward rapidity.

Negative value of ν_{dyn} indicates dominance of $ch^+ - ch^-$ correlation at all energies.

Ratio fluctuation: charge-neutral





Measurement at forward rapidity ($-3.7 < \eta < -2.8$) :

ν_{dyn}(γ-ch) positive for data; mixed event and models are close to Poisson.

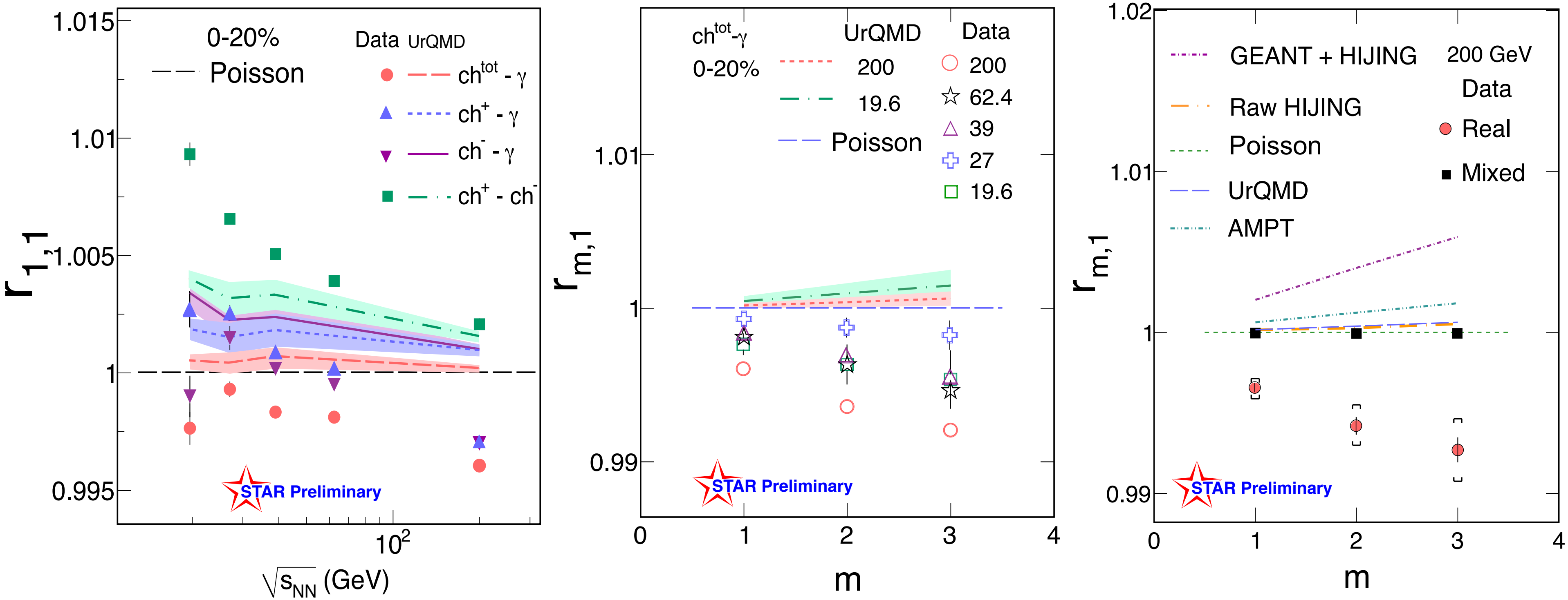
Approximate Central Limit Theorem (CLT) type scaling (χ^2/ndf ≈2) for ν_{dyn} at 200 GeV.

Energy dependence compared to hadronic model UrQMD.

Particle correlation: charge-to-neutral

$$r_{m,1}^{\gamma-\mathrm{ch}} = \frac{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m+1)\ N_{\gamma}\rangle \langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m)\rangle \langle N_{\gamma}\rangle}$$

Minimax DCC observable
<1 (anti-correlation)
>1 (correlation)

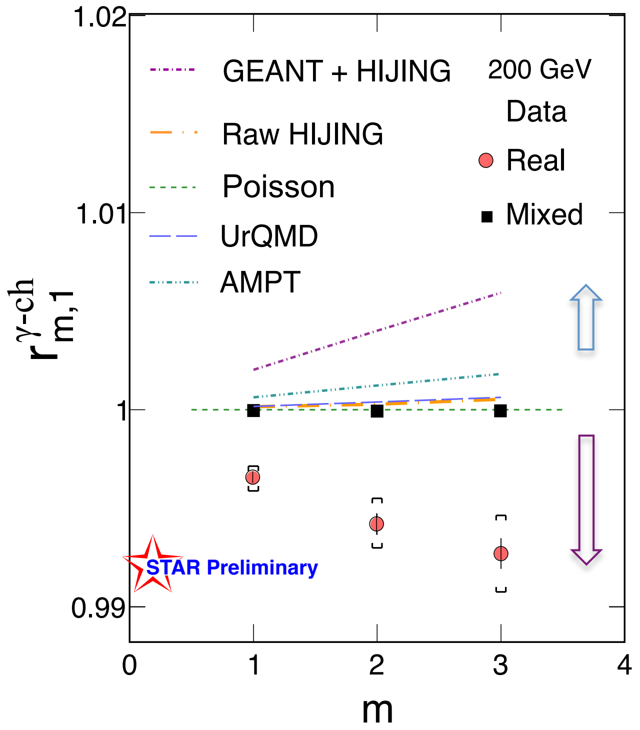


$r_{1,1}$ is below 1 for γ-ch (anti-correlation) and above 1(correlation) for ch^+-ch^- & UrQMD.

$r_{m,1}$ vs m for γ-ch shows presence of anti-correlation at all energies. Data excludes generic pion production (Poisson) scenario and hadronic model predictions (correlated production from resonances).

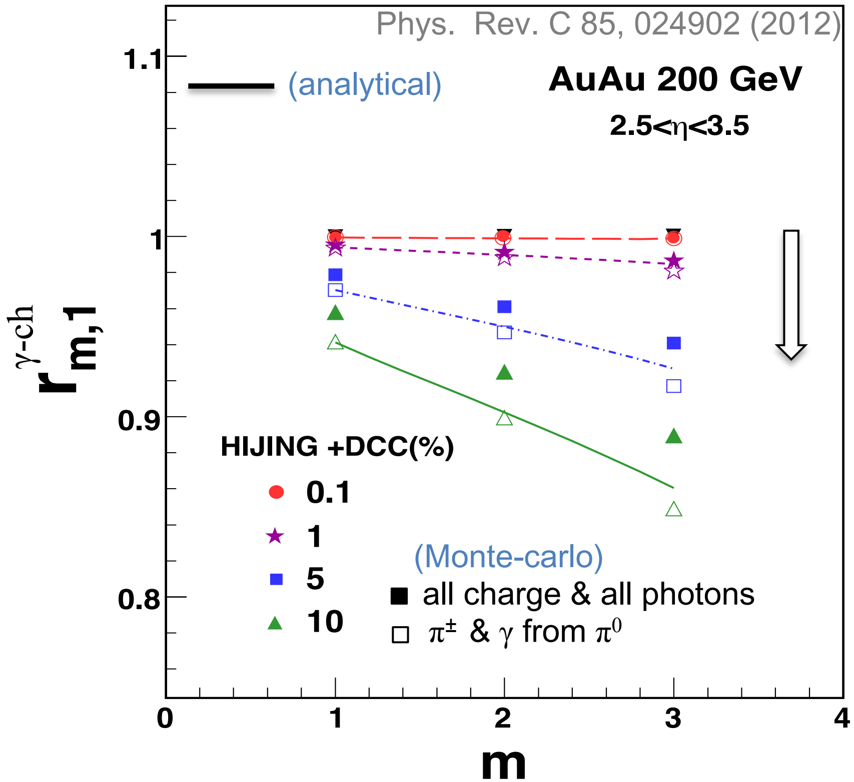
Particle correlation: charge-to-neutral

$$r_{m,1}^{\gamma-\mathrm{ch}} = \frac{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m+1)\ N_\gamma\rangle\,\langle N_{\mathrm{ch}}\rangle}{\langle N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)..(N_{\mathrm{ch}}-m)\rangle\,\langle N_\gamma\rangle}$$



Comparison with DCC like models for $r_{m,1}$ observable:

PRD 55, 5667 (1997), Phys. Rept. 414, 263 (2005), PRC 85, 024902 (2012)

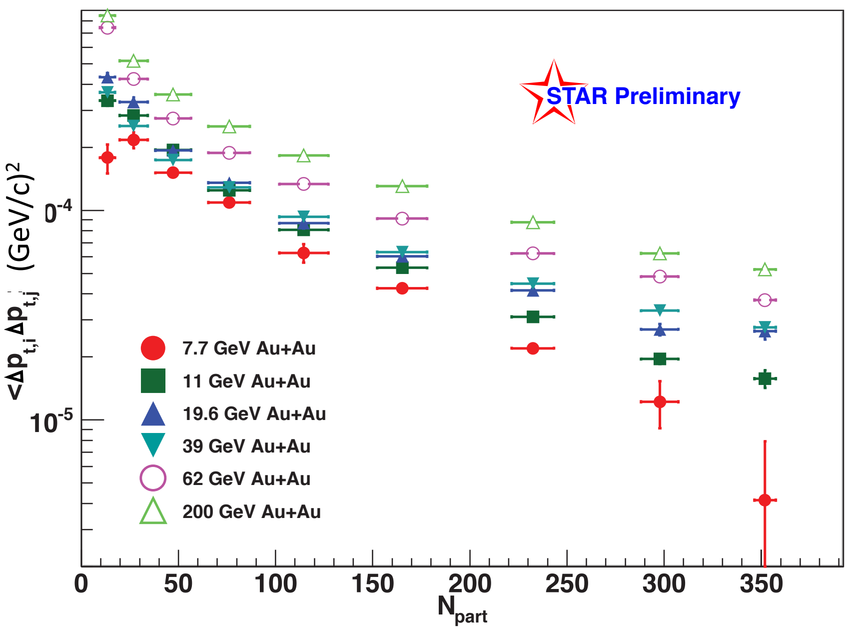


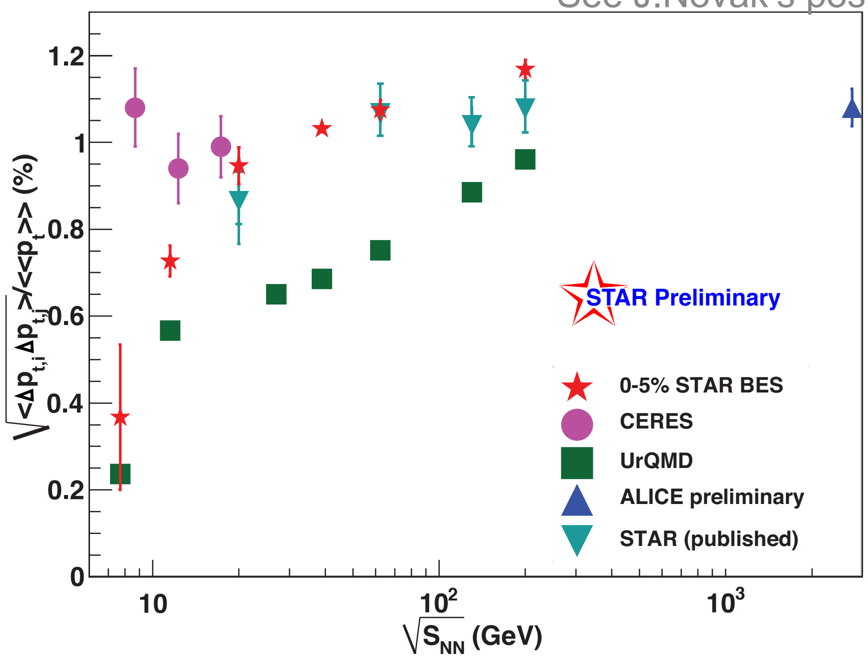
Models are based on assumption that in case of Disoriented Chiral Condensate Formation(DCC) → distribution of neutral pion fraction P(f) gets modified :

P(f) = δ(f-1/3) (generic production) → P(f) = 1/(2√f) (DCC).

Particle correlation: inclusive charge p_T

See J.Novak's poster





Centrality and energy dependence of $<\Delta p_{t,i}\Delta p_{t,j}>$:

- Increases in peripheral collisions.
- Smoothly increases with energy.

Consistent decrease with collision energy.

Correlation scaled with $<<p_T>>$:

- Most central data points show monotonic decrease below 39 GeV.
- UrQMD reproduces trend, lies below data.
- Difference with CERES, e.g. acceptance is under investigation.

CERES point- Nucl. Phys. A727, 97 (2003)
LHC point- J. Phys. G 38 (2011) 124095

Summary

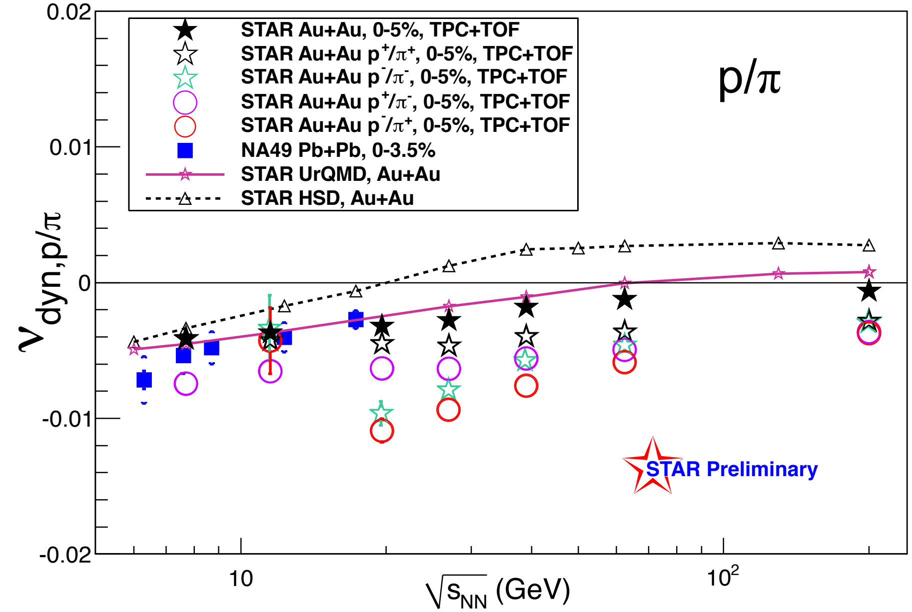
- For p/π
  - Monotonic behavior with collision energy. Charge dependence at low energy.
- For K/p
  - Monotonic decrease with collision, dominated by correlated productions.
- For K/π
  - No strong energy dependence. Charge dependent ratio shows monotonic decrease.
- For ch^{+}/ch^{-}
  - Monotonic decrease with collision energy, consistent at both mid & forward rapidity.

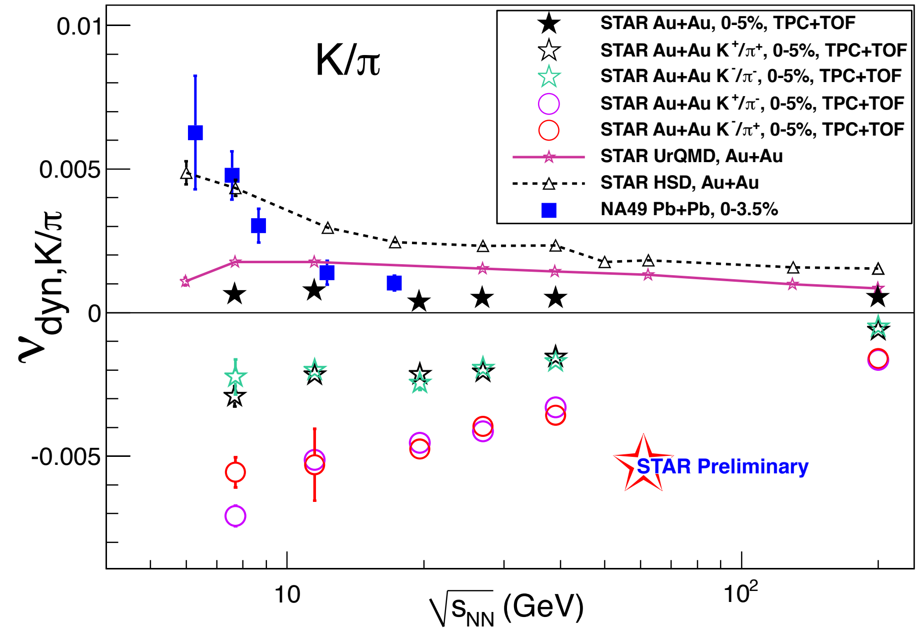
- For γ/ch correlation
  - Anti-correlation signal, decrease in strength within the range 19.6 -200 GeV. Conventional hadronic models can not explain data.
- For p_T correlaion
  - Weak energy dependence above 39 GeV up to 2.76 TeV but decreases with incident energy below 39 GeV.

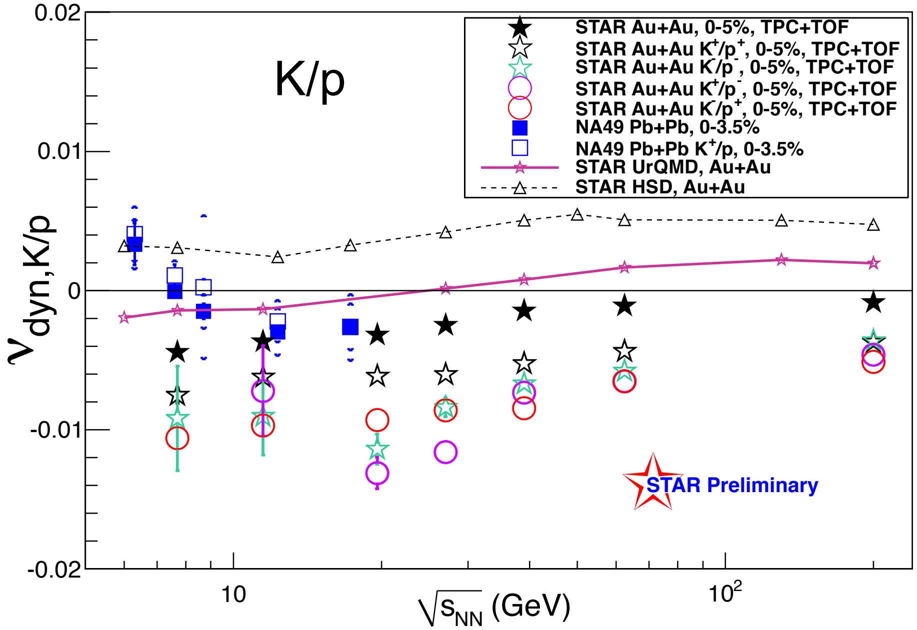
Ratio fluctuations and correlation results studied in the energy range (7.7 - 200 GeV) do not show any non-monotonic trend, hadronic models can not fully explain data.

BACK-UP slides

Ratio fluctuation: Identified particles







(measurement at mid-rapidity |η|<1)

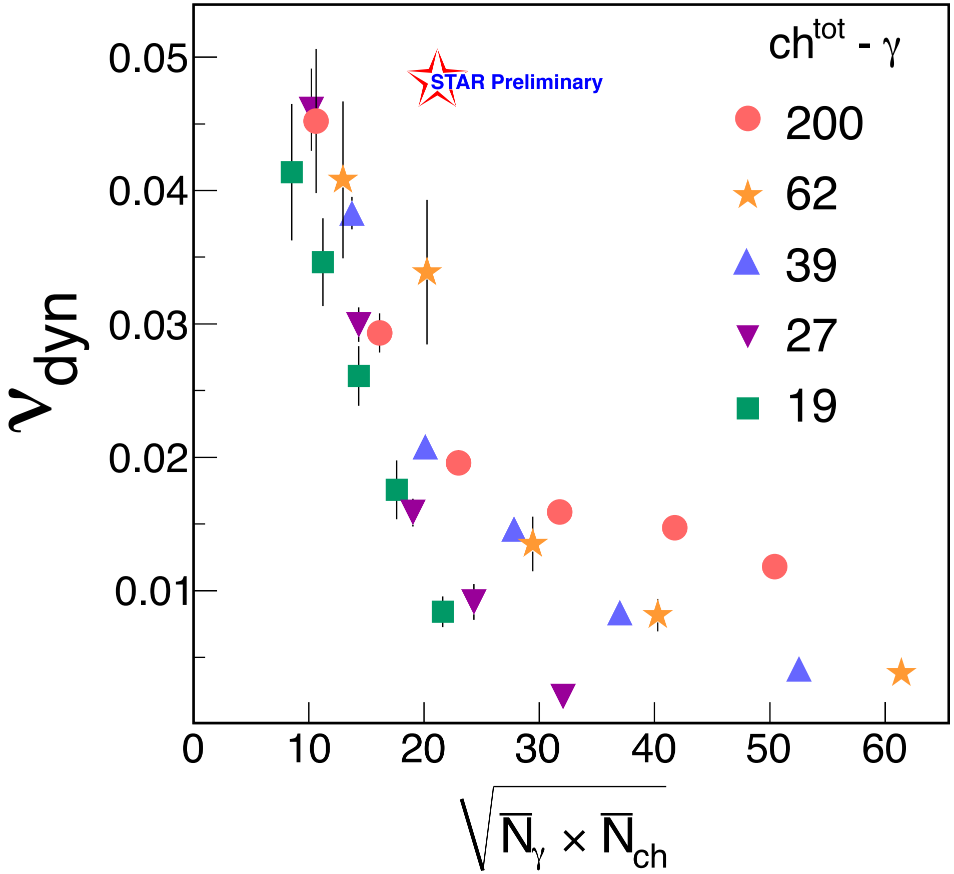
Monotonic trend in the range of 7.7-200 GeV.

Charge dependence of excitation function appears at lower energy.

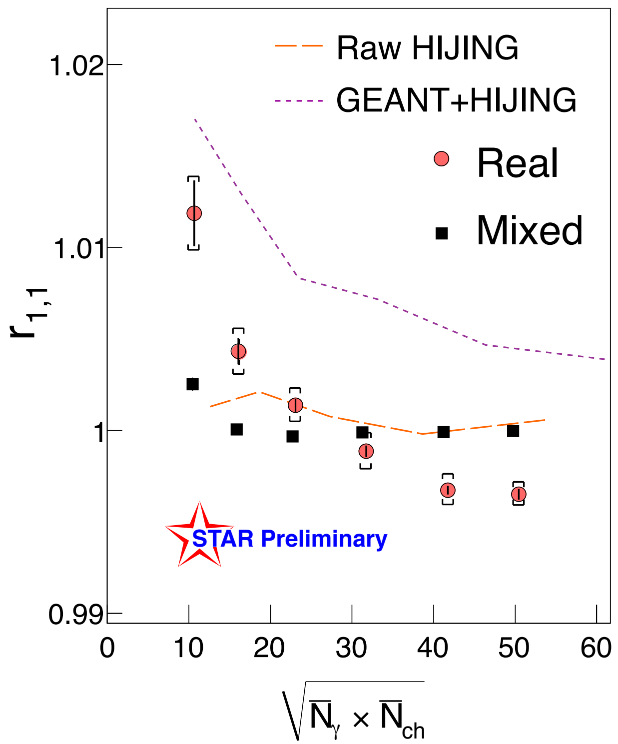
K/p and K/π have different trend than NA49 data at lower energies. Hadronic models cannot explain data.

see also Z.Ahammed's poster

Ratio fluctuation: charge and photon



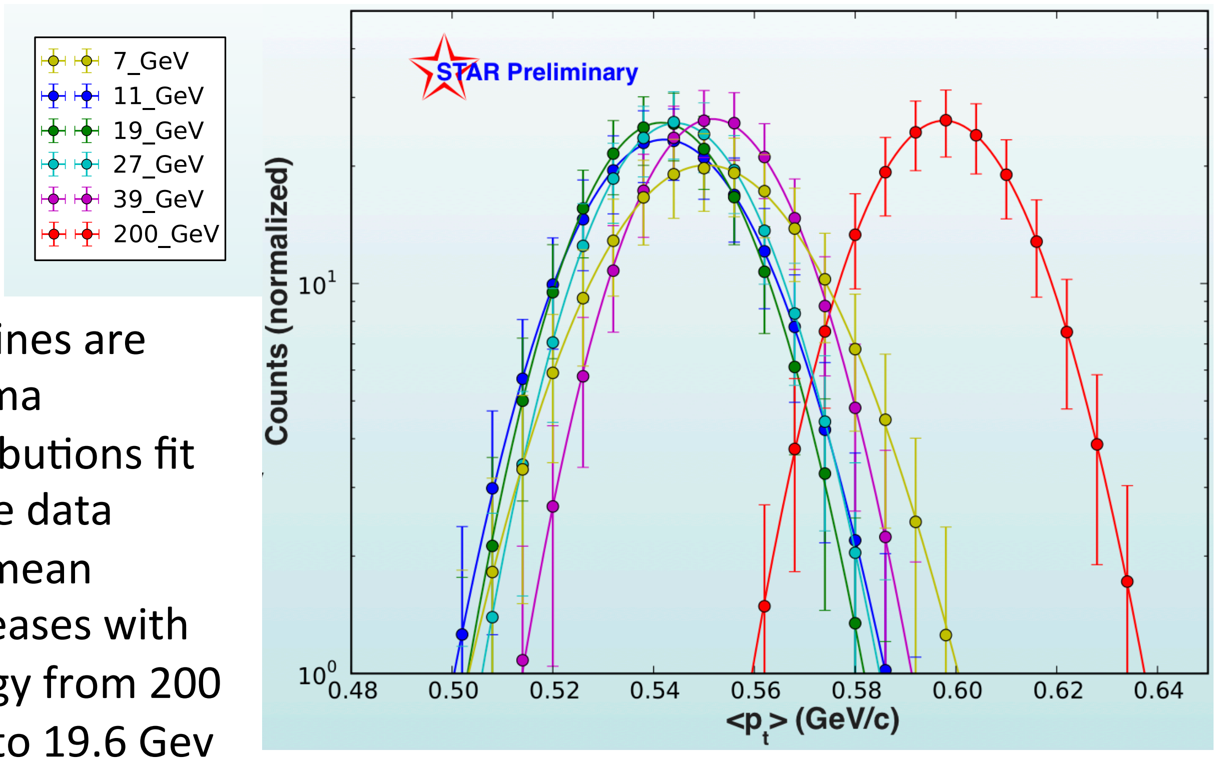
Measurement at forward rapidity
For a given multiplicity ν_{dyn} (γ-ch) is lower for lower energy



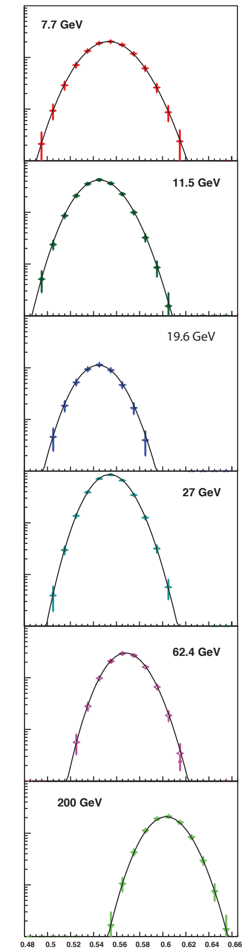
– Non-zero dynamical signal which has anti-correlation at top centrality
(Anti-correlation : consistent with the picture of QCD Chiral Phase transition?
More theoretical inputs needed)

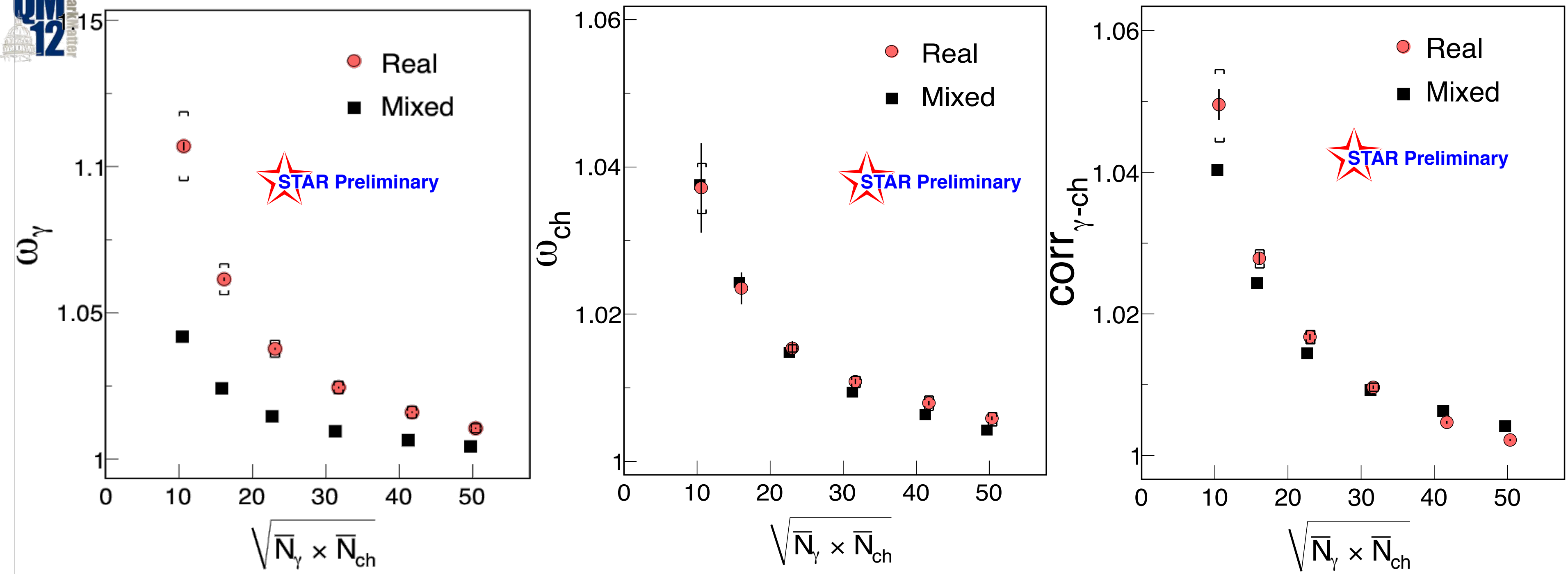
See J.Novak's poster

<p_T> Spectra – Central Bin



- The lines are gamma distributions fit to the data
- The mean decreases with energy from 200 GeV to 19.6 Gev then increases to 7.7 GeV





$$G(z) = \sum_{N=0}^{\infty} z^N P(N)$$

Moment generating function

Generalized Factorial moment

$$f_{m,n} = \frac{\partial^{m,n} G_{\rm obs}(z_{\rm ch}, z_\gamma)}{\partial z_{\rm ch}^m \, \partial z_\gamma^n}\bigg|_{z_{\rm ch}=z_\gamma=1} = \left\langle \frac{N_{\rm ch}!\; N_\gamma!}{(N_{\rm ch}-m)!\,(N_\gamma-n)!} \right\rangle$$

$$\nu_{dyn}^{\gamma-ch} = \frac{f_{20}}{f_{10}^2} + \frac{f_{02}}{f_{01}^2} - 2\frac{f_{11}}{f_{10}\, f_{01}} \qquad r_{m,1}^{\gamma-ch} = \frac{f_{m1}\, f_{10}}{f_{(m+1)0}\, f_{01}}$$

$$\langle n \rangle = \varepsilon \langle N \rangle$$

$$\langle n(n-1) \rangle = \varepsilon^2 \langle N(N-1) \rangle$$