p_T-p_T Correlators at High Baryon Density Region

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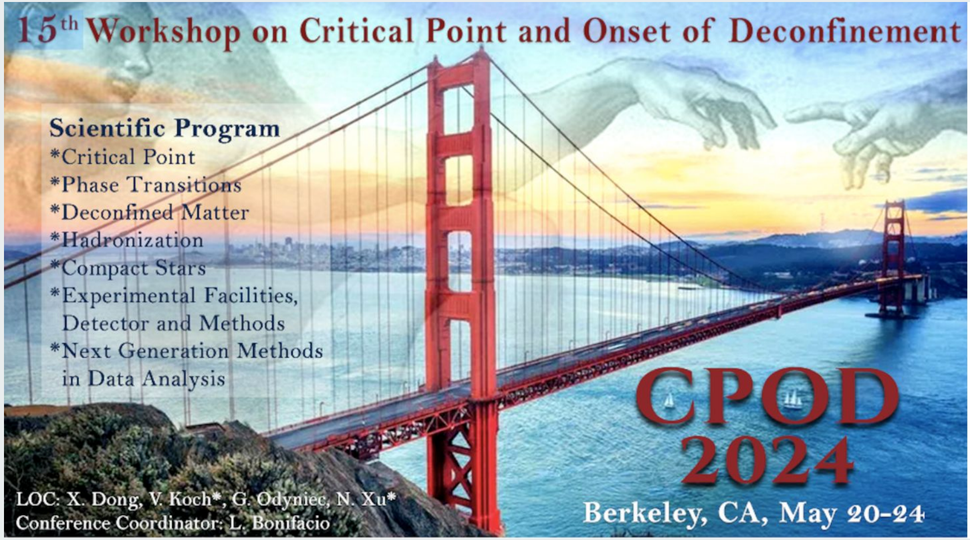
for the STAR Collaboration



15th Workshop on Critical Point and Onset of Deconfinement

Scientific Program
- *Critical Point
- *Phase Transitions
- *Deconfined Matter
- *Hadronization
- *Compact Stars
- *Experimental Facilities, Detector and Methods
- *Next Generation Methods in Data Analysis

CPOD 2024

Berkeley, CA, May 20-24

LOC: X. Dong, V. Koch*, G. Odyniec, N. Xu*
Conference Coordinator: L. Bonifacio

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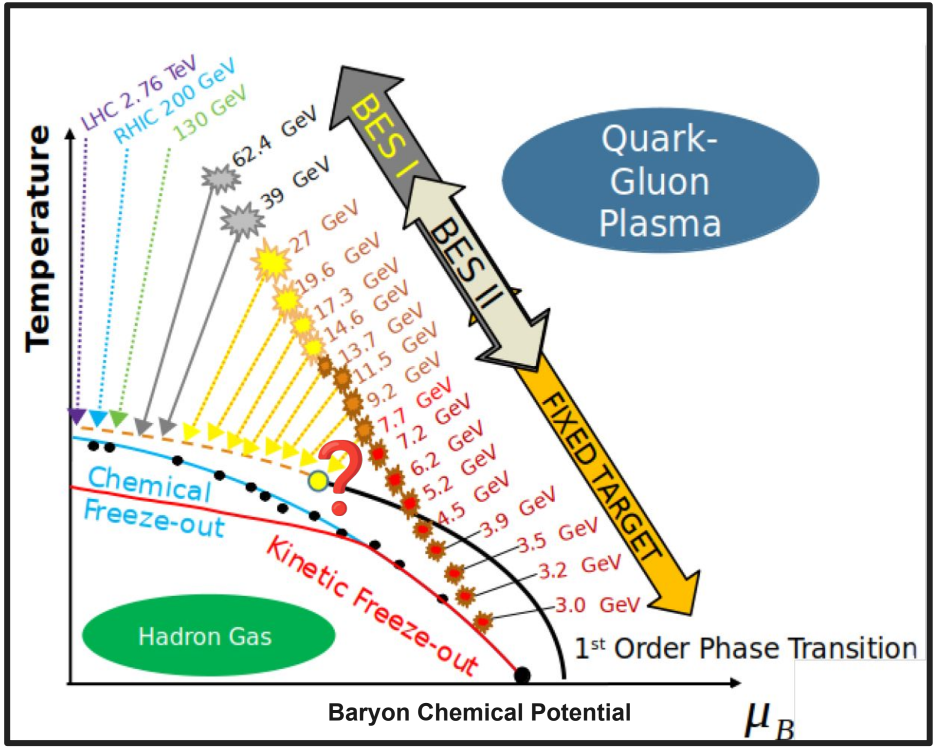
Outline

- Introduction
- STAR-FXT Setup
- Transverse Momentum Correlations
- Results
- Outlook

Phases of QCD Matter

- BES-II collider program at the Relativistic Heavy-Ion Collider scans phase space of QCD matter by colliding gold ions at varying energies.
- Seeking to map onset of deconfinement, and the predicted QCD critical point.
- The BES-II collider program provided the energies $\sqrt{s_{NN}}$ >=7.7 GeV and the BES-II FXT program provided the ones below, down to $\sqrt{s_{NN}}$ = 3 GeV.



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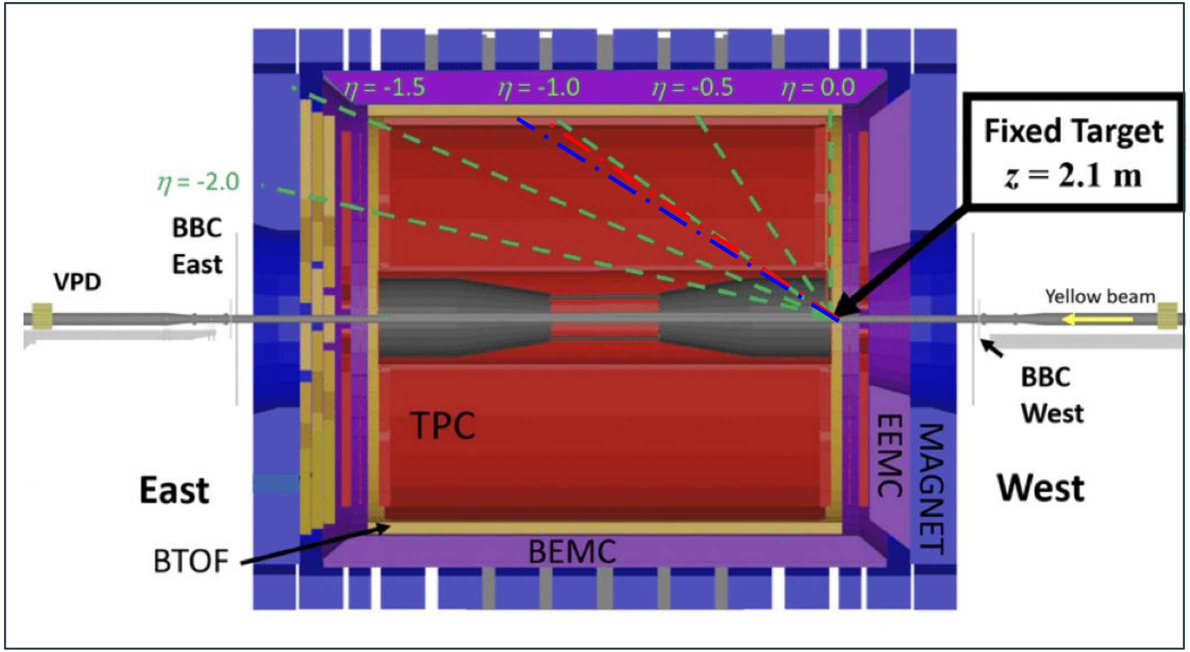
STAR-FXT Setup

- Gold Target fixed at west end of the detector
- TPC Acceptance :
  - η : [-2,0] (lab frame)
- PID Acceptance :
  - η : [-1.5,0] (lab frame)
- Mid rapidity :
  - $\eta \cong -1.05$ (3.0 GeV)
  - $\eta \cong -1.13$ (3.2 GeV)

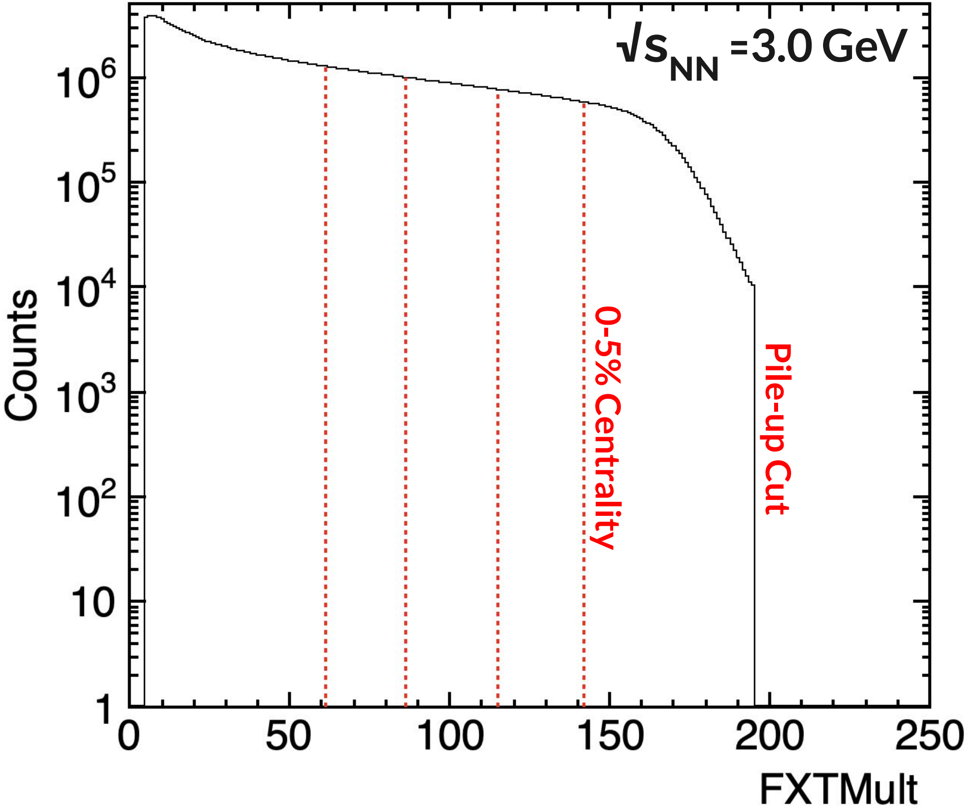


https://www.star.bnl.gov

Centrality Definition

- All primary charged particles within TPC acceptance
- We use the correlation betwee the TPC and ToF to reject the pileup events.

$\sqrt{s_{NN}}$	Events
3.0 GeV	250 M
3.2 GeV	180 M



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Transverse Momentum Correlations

- Transverse momentum correlations have been proposed as a measure of thermalization and as a probe for the critical point of quantum chromodynamics [1].
- Correlation measurements generally have finer ‘resolution’ than fluctuation measurements and can be looked at more differentially [2].
- The correlator is the mean of covariances of all pairs of particles i and j in the same event with respect to the mean.

$$C_m = < \Delta p_{t,i}\,, \Delta p_{t,j} >$$

$$< (p_{t,i} - < p_t >)(p_{t,j} - < p_t >) >$$

$$i \neq j$$

[1]: ALICE, Phys. Part. Nuclei 51,2020
[2]: Pruneau CA. Data Analysis Techniques for Physical Scientists. Cambridge University Press; 2017.

Transverse Momentum Correlations

- Dynamical fluctuations have no contributions from statistical fluctuations.
- Statistical fluctuations are Poissonian.
- Two body correlation function.

$$< \Delta p_{t1}, \Delta p_{t2} >= \int dp_1 \, dp_2 \frac{r(p_1, p_2)}{<N(N-1)>} \Delta p_{t1} \Delta p_{t2}$$

S. Gavin, Phys. Rev. Lett. 92, 162301

$$r(p_1, p_2) = N(p_1, p_2) - N(p_1) N(p_2)$$

Transverse Momentum Correlations

- Locally thermalized systems. (at all energies?)
- F depends on the ratio of the correlation length (ζ_T) to the transverse size.
- R is the scaled variance and depends on N_{part}
- If matter is locally equilibrated in the most central collisions,F(ζ_T) is energy independent.

$$< \Delta p_{t,i} , \Delta p_{t,j} >= F \frac{<p_t^2>R}{1+R}$$

$$R = \frac{<N^2>-<N>^2-<N>}{<N>^2}$$

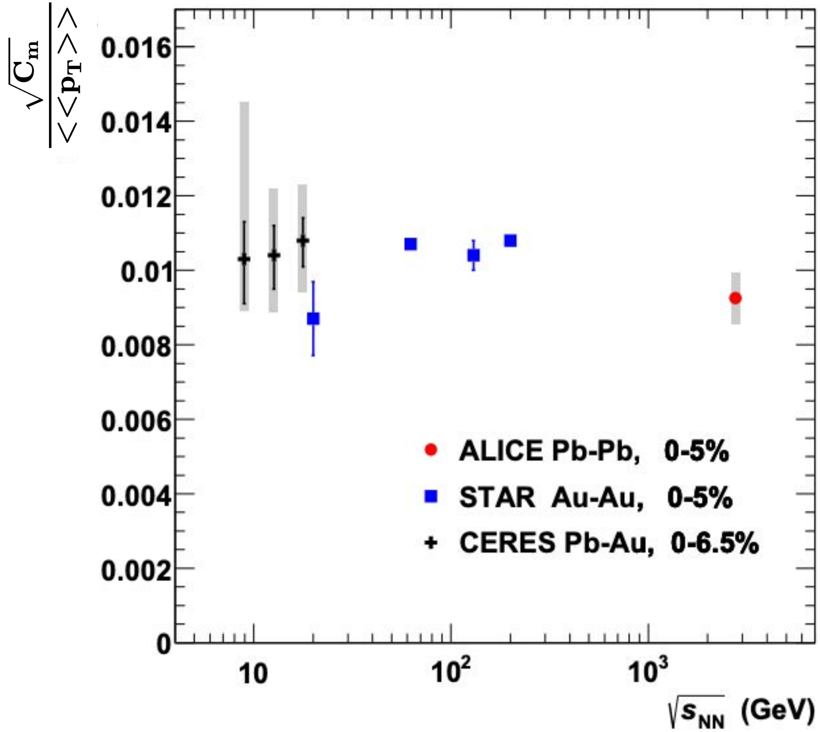
$$\frac{\sqrt{<\Delta p_{t,i},\Delta p_{t,j}>}}{<p_t>} = \left(\frac{F(\zeta_T)R}{1+R}\right)^{1/2}$$

S. Gavin, Phys. Rev. Lett. 92, 162301

CONST!!!

Correlator Vs Collision energy

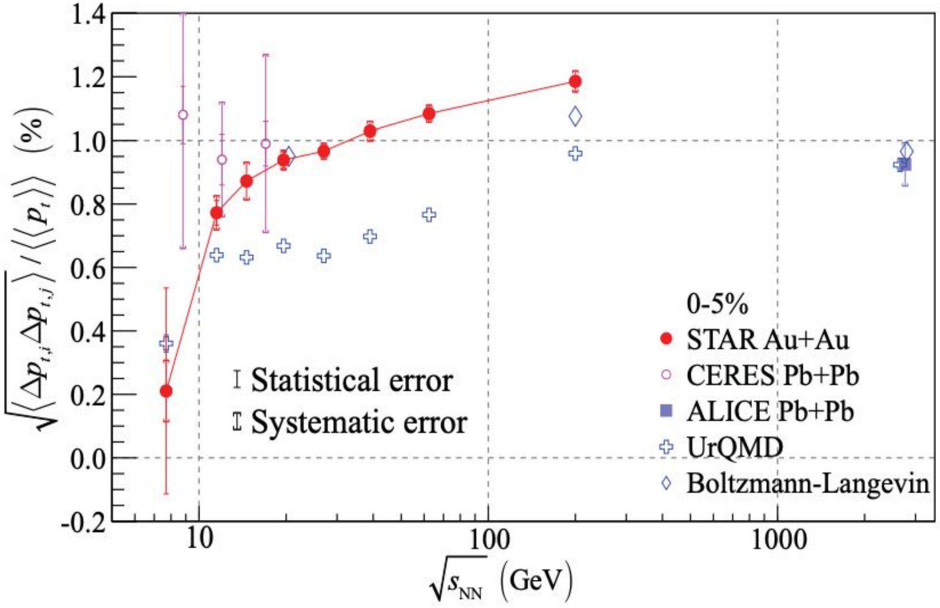
- The correlation observable may have a dependence on energy, so we scale it with $\langle\langle p_T \rangle\rangle$.
- Efficiency independent observable.
- Make a direct comparison with the CERES and ALICE.



ALICE, Eur. Phys. J. C 74, 2014

Correlator Vs Collision energy

- ❖ The correlation observable may have a dependence on energy, so we scale it with $\langle\langle p_T \rangle\rangle$.
- ❖ Efficiency independent observable.
- ❖ Make a direct comparison with the CERES and ALICE.
- ❖ A significant beam energy dependence was found for dynamical correlations.



$\sqrt{s_{NN}}$ (GeV)

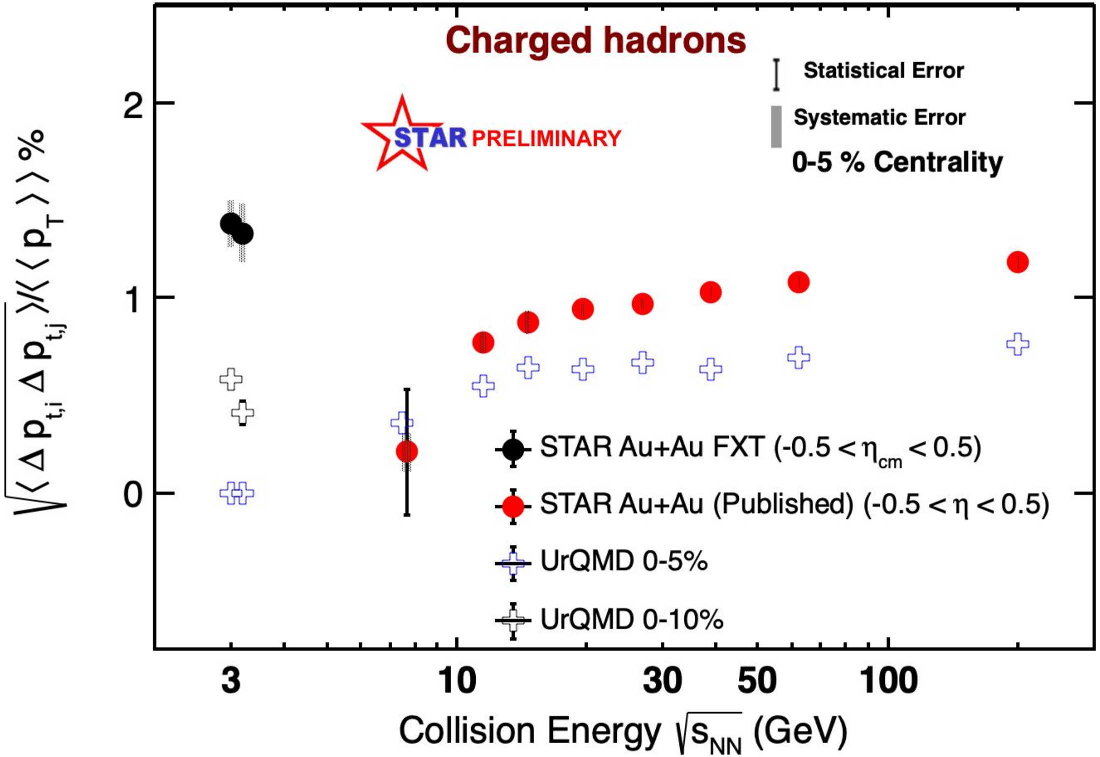
STAR, Phys.Rev.C 99, 2019

Correlator Vs Collision energy

- We see a departure from monotonicity
- Change in correlation length ζ_T ?
- Temperature fluctuations should be reflected in p_T fluctuations.

$$<p_T> \rightarrow T_{eff}$$

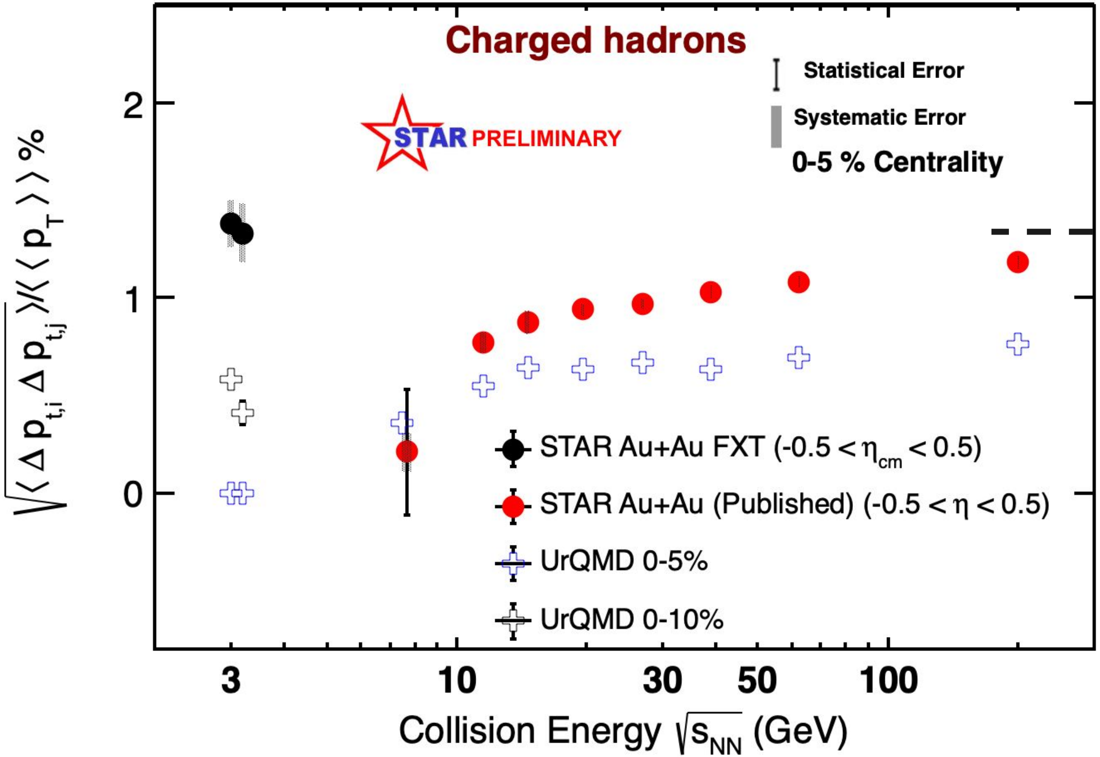
$$T_{eff} = T_{kin} + m_0 < \beta_T >^2$$



Sumit Basu et. al., Phys.Rev.C 94, 2016

Correlator Vs Collision energy

- $F(\zeta_T)$ and R to be constant as a function of collision energy.
- $F(\zeta_T) = 0.046$
- R = 0.0037 (Central Au+Au at 200 GeV)



S. Gavin, Phys. Rev. Lett. 92, 162301

$$\left(\frac{F(\zeta_T)R}{1+R}\right)^{1/2} = \text{constant } (- - -)$$

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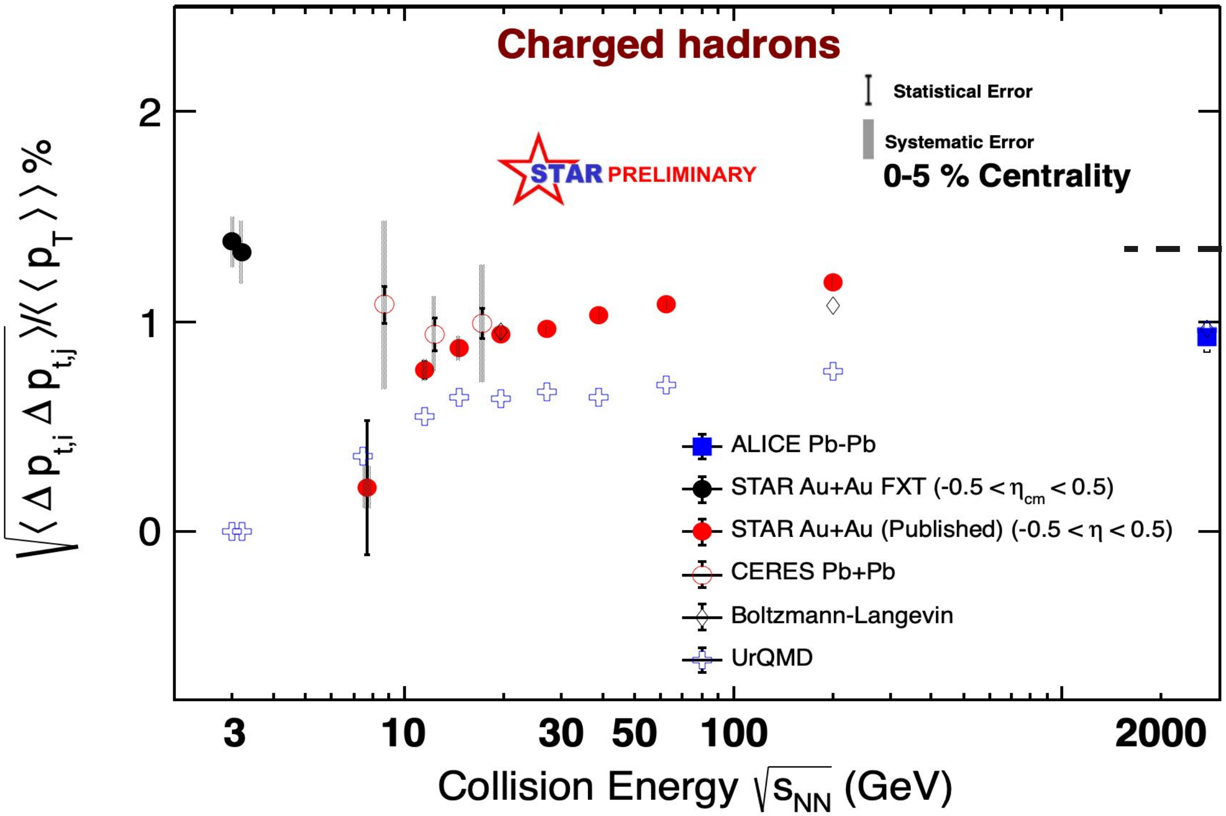
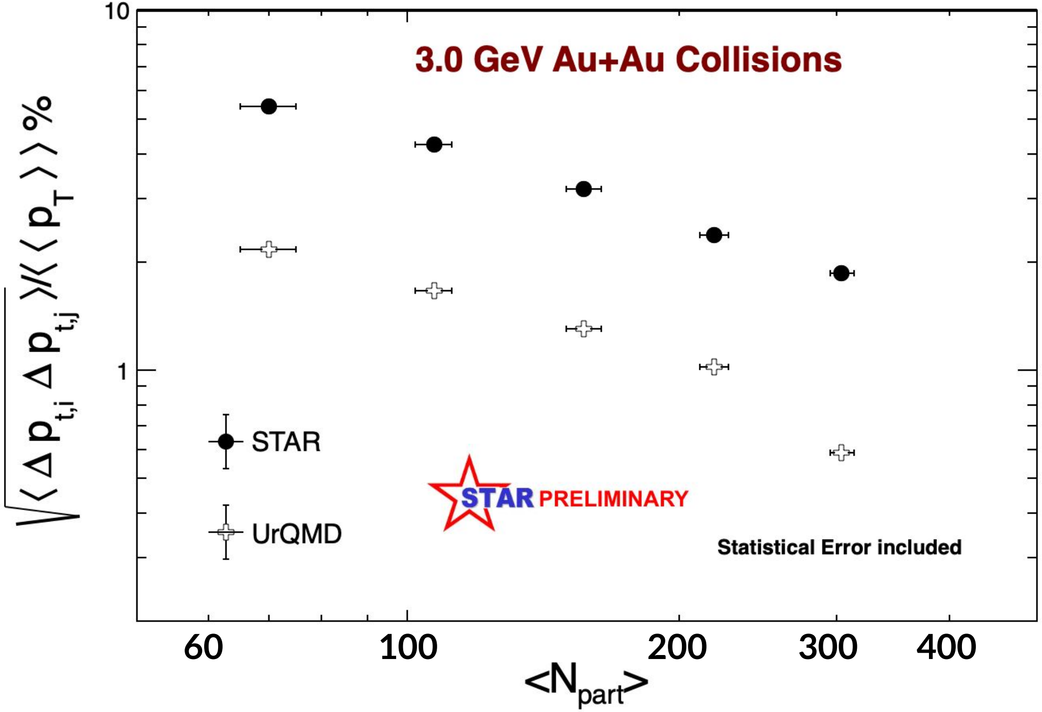
Correlator Vs Collision energy

- CERES in agreement with STAR.
- Boltzmann-Langevin implies thermalization.
- ALICE lower than STAR, due to different N_{part}



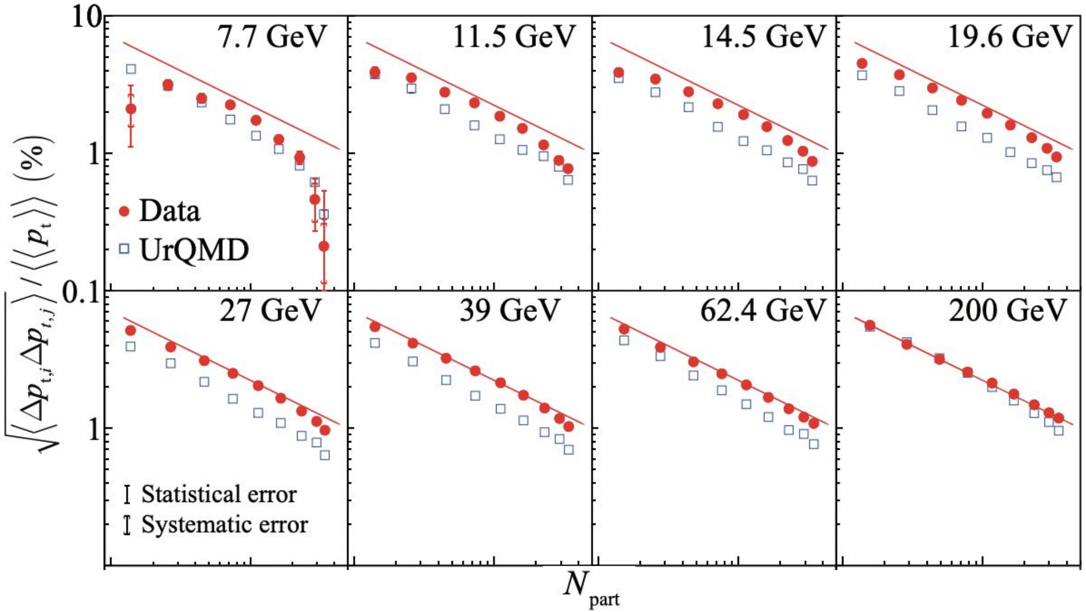
Correlator Vs Centrality

- ❖ Monotonic increase in decreasing centrality.
- ❖ UrQMD underpredicts the data.
- ❖ UrQMD Acceptance:
  - ➢ η:[-0.5,0.5] (Collider mode)
  - ➢ p_T:[0.2,2.0] GeV/c
  - ➢ All charged particles



Correlator Vs Centrality

- Power law seems to describe the data at 200 GeV , implying an independent sources scenario.
- We see significant departure from this power law dependence at the lower energies.
- UrQMD tends to underpredict the data at all energies.

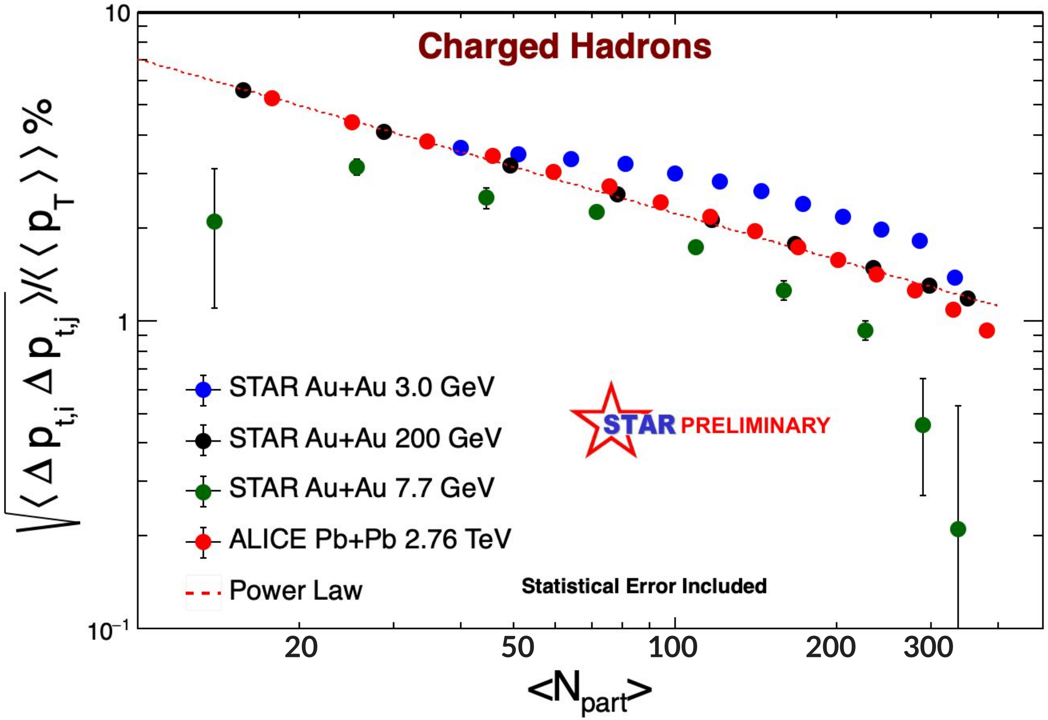


STAR, Phys.Rev.C 99, 2019

Power Law: $\frac{\sqrt{C_m}}{<<p_T>>} \propto < N_{part} >^b$

Correlator Vs Centrality

- Power law implies uncorrelated sources (b=-0.5).
- STAR data from 200 GeV Au+Au collision shows minimal deviation.
- Deviation increases as we go down the collision energy
- Deviation holds at STAR 3.0 GeV Au+Au collisions as well.



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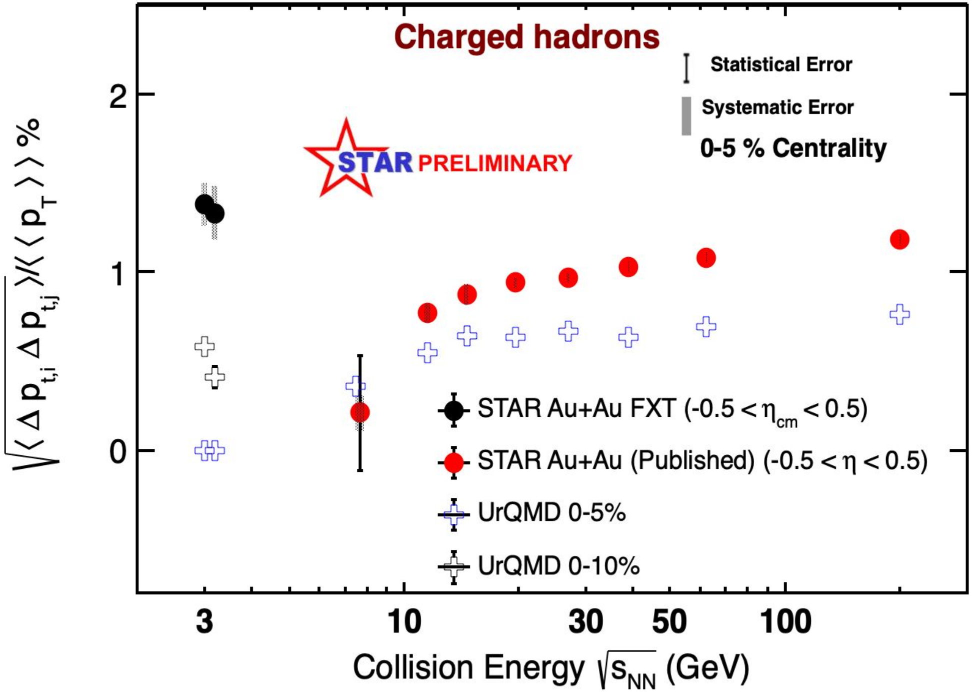
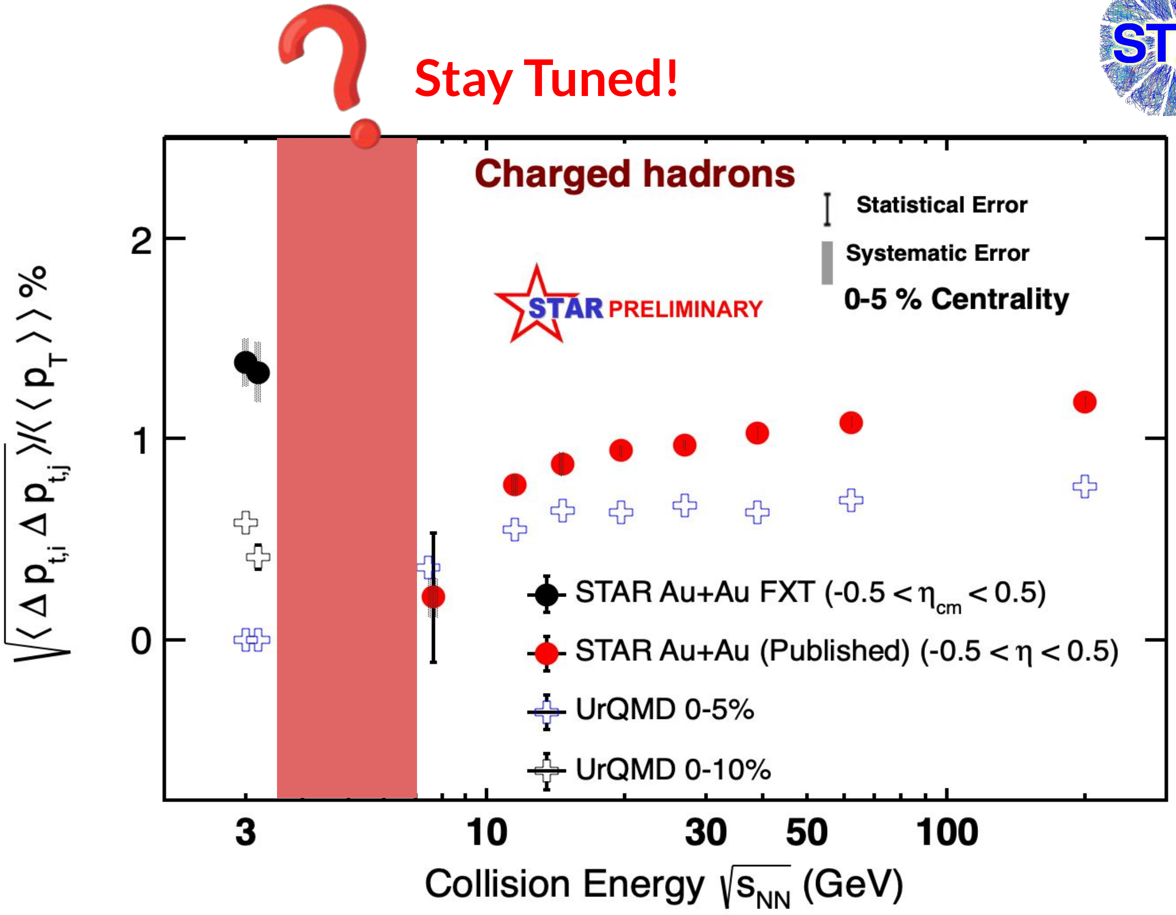
Conclusions

- First measurement of Δp_T-Δp_T correlators at high baryon density region
    - Δp_T-Δp_T show a non-monotonic behaviour.
    - Possibility of correlation length changing in between ?
- We need to delve deeper into the disparity observed between UrQMD and experimental data at Fixed-Target (FXT) energies.



Outlook

- BES-II FXT energies are crucial to understand.
- Account for detector acceptance effects.
- Look into higher order moments.
- Thermal model predictions.



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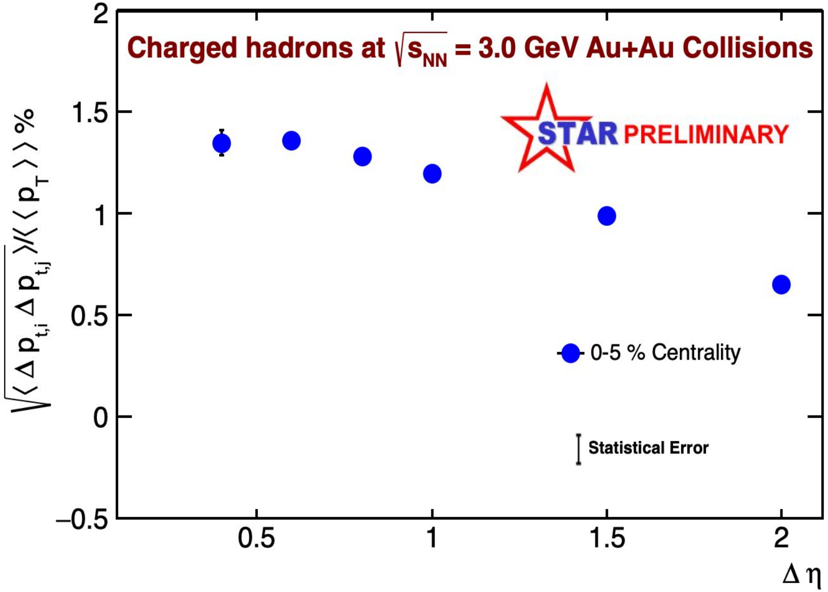
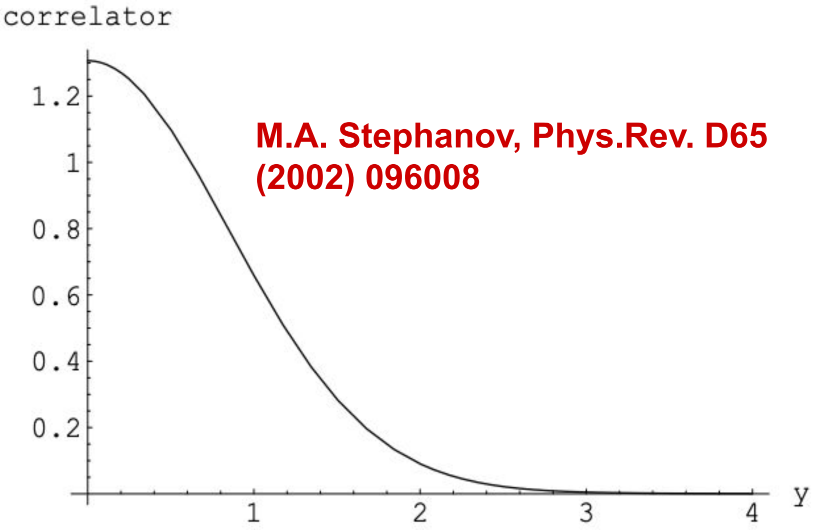
2. Incident energy dependence of pt correlations at relativistic energies - Phys.Rev.C72:044902,2005
3. Event-by-event fluctuations in mean p_T and mean e_T in s(NN)**(1/2) = 130-GeV Au+Au collisions - Phys.Rev.C 66 (2002) 024901
4. Collision-energy dependence of p_T correlations in Au + Au collisions at energies available at the BNL Relativistic Heavy Ion Collider - Phys.Rev.C 99 (2019) 4, 044918
5. Event-by-event mean p_T fluctuations in pp and Pb-Pb collisions at the LHC - Eur. Phys. J. C 74 (2014) 3077
6. Specific Heat of Matter Formed in Relativistic Nuclear Collisions - Phys.Rev.C 94 (2016) 4, 044901
7. Baryon Stopping and Associated Production of Mesons in Au+Au Collisions at s(NN)**(1/2)=3.0 GeV at STAR - Acta Phys. Pol. B Proc. Suppl. 16, 1-A49 (2023)
8. Traces of Thermalization from p_T Fluctuations in Nuclear Collisions - S. Gavin, Phys. Rev. Lett. 92, 162301 (2004)

BACKUP

Acceptance dependence





M.A. Stephanov, Phys.Rev. D65 (2002) 096008

- The effect of primordial protons bring the correlator down for the whole acceptance.

- Closer to mid-rapidity where majority of the particle production takes place the value saturates.

Closure Test

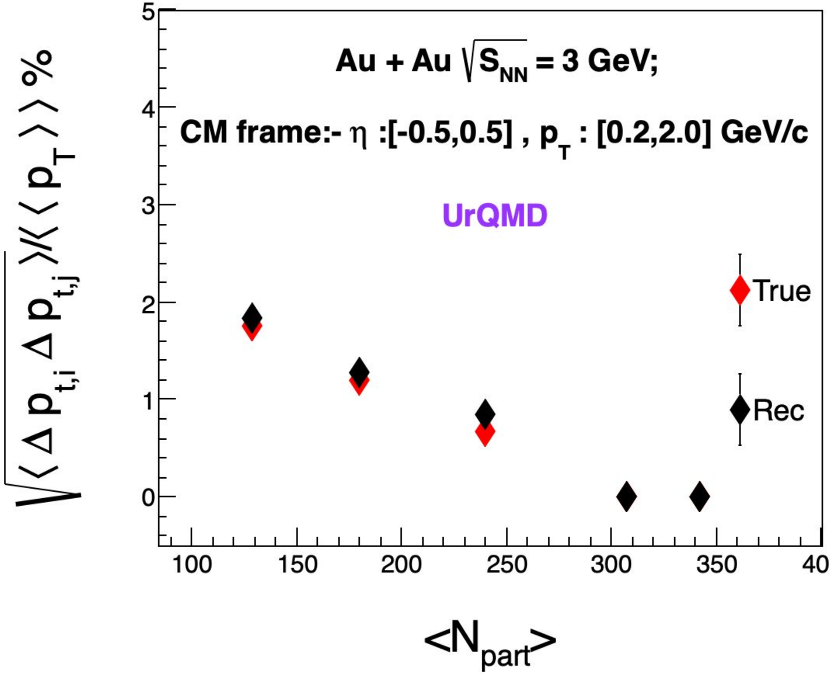
- The relative uncertainties $\sqrt{C_m}/\langle\langle p_T \rangle\rangle$ on are generally smaller than those on C_m because most of the sources of uncertainties lead to correlated variations of $\langle\langle p_T \rangle\rangle$ and C_m that tend to cancel in the ratio.

- Closure test was performed with UrQMD data, by incorporating 3.0 GeV efficiency curves.

- We see closure within the statistical error bars.

- No efficiency correction was employed on STAR Data.

$\sqrt{\langle \Delta p_{t,i} \Delta p_{t,j} \rangle} / \langle \langle p_T \rangle \rangle$ Vs N_{part}



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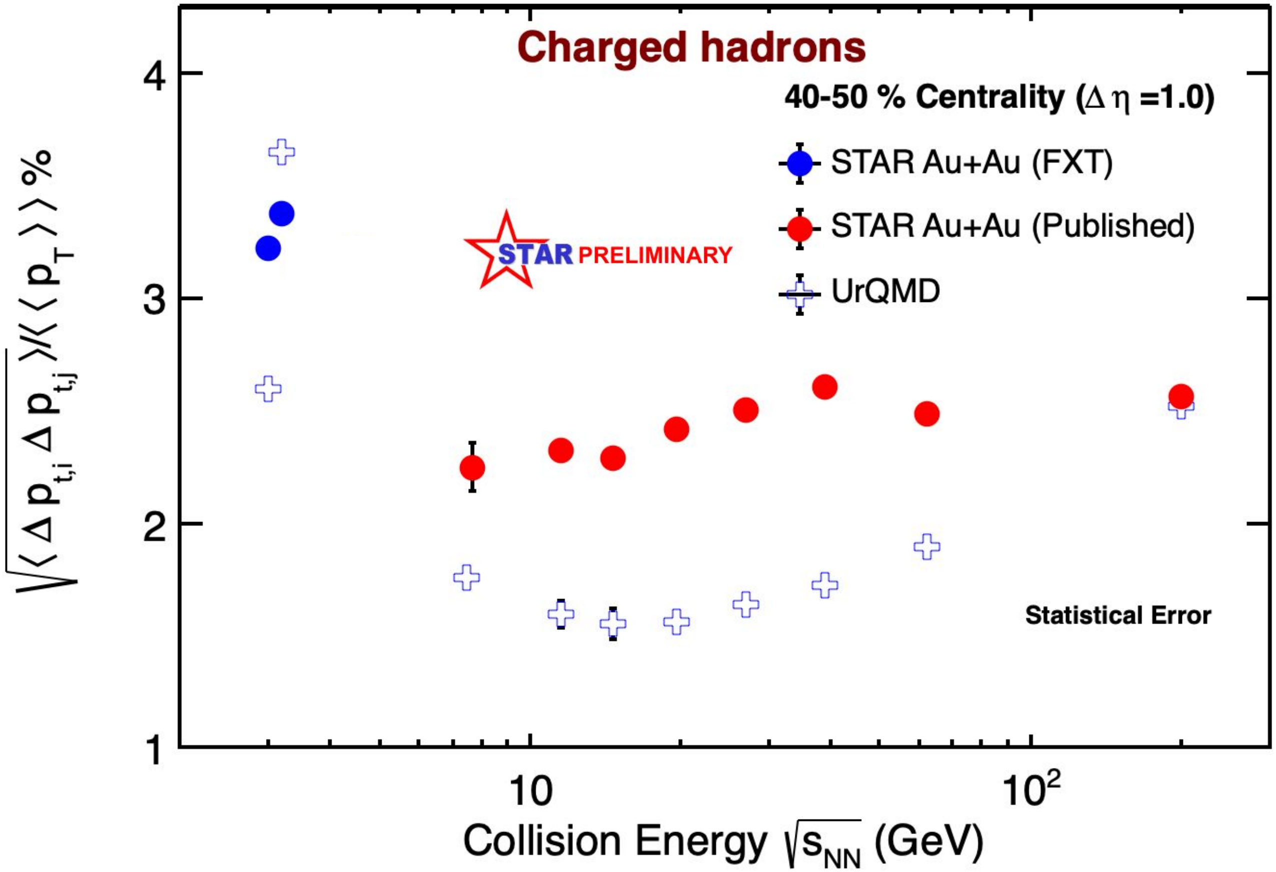
Cumulants from moments

$$\langle \Delta p_{\mathrm{T},i}\Delta p_{\mathrm{T},j}\rangle = \left\langle \frac{\sum_{\substack{i,j,\\ i\neq j}}^{N_{\mathrm{ch}}} (p_{\mathrm{T},i} - \langle\langle p_{\mathrm{T}}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_{\mathrm{T}}\rangle\rangle)}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)} \right\rangle_{\mathrm{ev}} = \left\langle \frac{Q_1^2 - Q_2}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)}\right\rangle_{\mathrm{ev}} - \left\langle \frac{Q_1}{N_{\mathrm{ch}}}\right\rangle_{\mathrm{ev}}^2 , \tag{2}$$

$$\begin{aligned}\langle \Delta p_{\mathrm{T},i}\Delta p_{\mathrm{T},j}\Delta p_{\mathrm{T},k}\rangle &= \left\langle \frac{\sum_{\substack{i,j,k,\\ i\neq j\neq k}}^{N_{\mathrm{ch}}} (p_{\mathrm{T},i} - \langle\langle p_{\mathrm{T}}\rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_{\mathrm{T}}\rangle\rangle)(p_{\mathrm{T},k} - \langle\langle p_{\mathrm{T}}\rangle\rangle)}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)(N_{\mathrm{ch}}-2)} \right\rangle_{\mathrm{ev}} \\ &= \left\langle \frac{Q_1^3 - 3Q_2Q_1 + 2Q_3}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)(N_{\mathrm{ch}}-2)}\right\rangle_{\mathrm{ev}} - 3\left\langle \frac{Q_1^2 - Q_2}{N_{\mathrm{ch}}(N_{\mathrm{ch}}-1)}\right\rangle_{\mathrm{ev}} \left\langle \frac{Q_1}{N_{\mathrm{ch}}}\right\rangle_{\mathrm{ev}} + 2\left\langle \frac{Q_1}{N_{\mathrm{ch}}}\right\rangle_{\mathrm{ev}}^3 ,\end{aligned} \tag{3}$$

$$Q_n = \sum_{i=1}^{N_{\mathrm{ch}}} p_{\mathrm{T},i}^n .$$

Correlator Vs Collision energy



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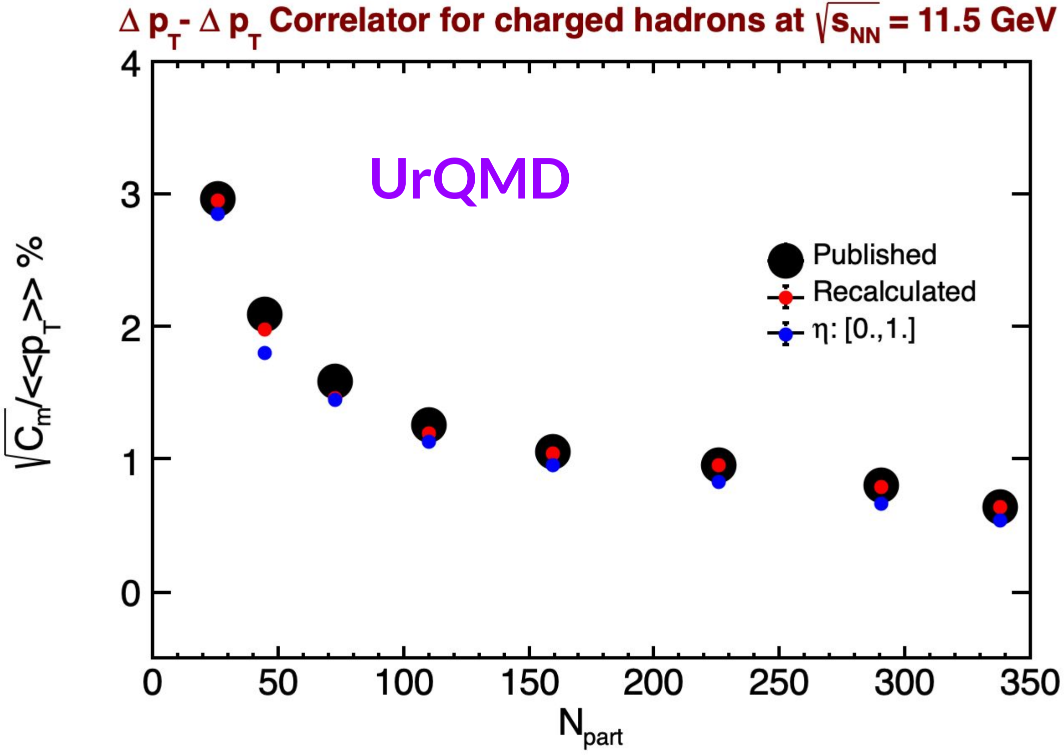
UrQMD with asymmetric Acceptance

- To verify the UrQMD calculations, the analysis was carried out at a published energy.

- The analysis was also done with an asymmetric acceptance of **η** : [0,1]



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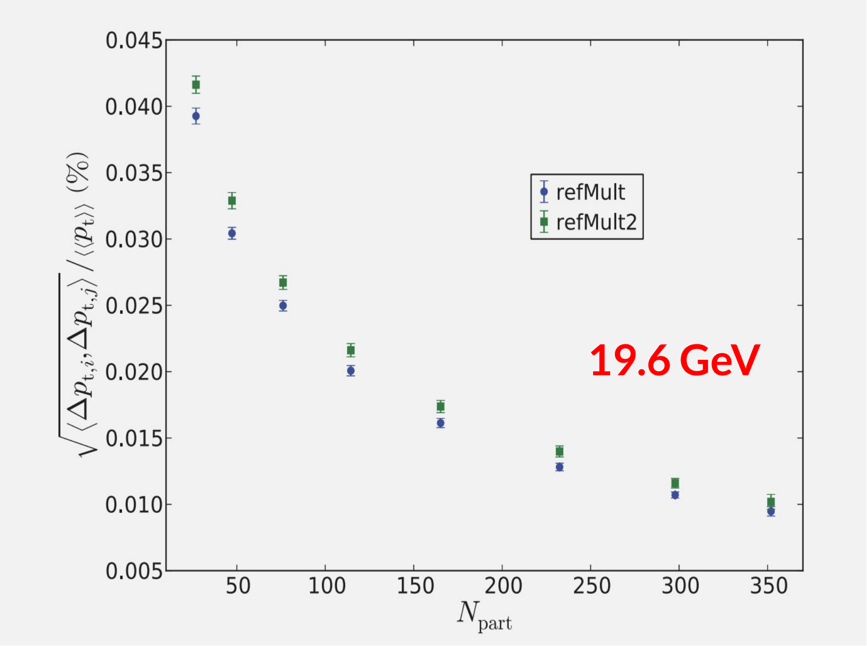
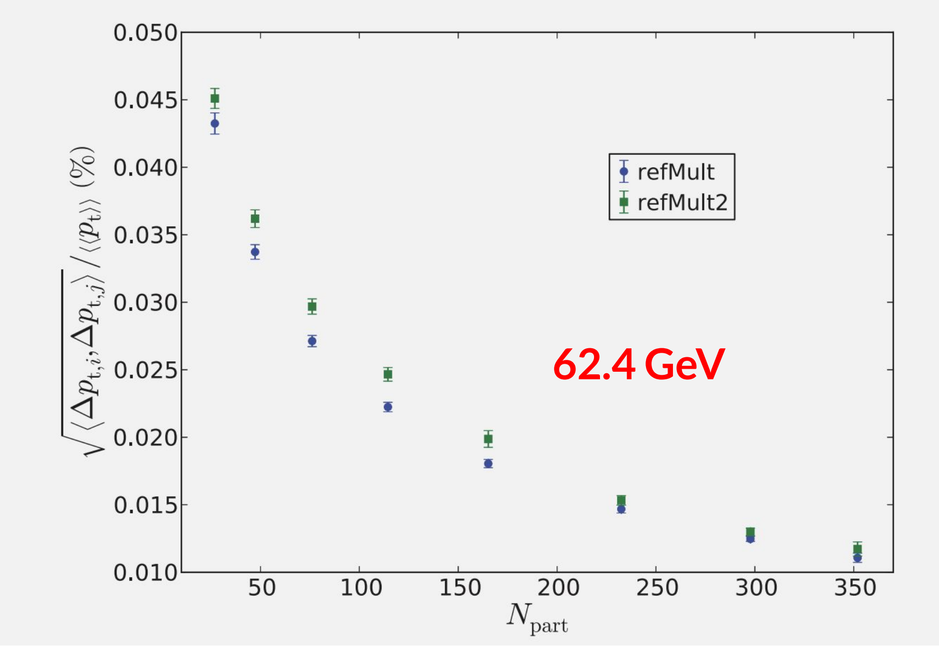
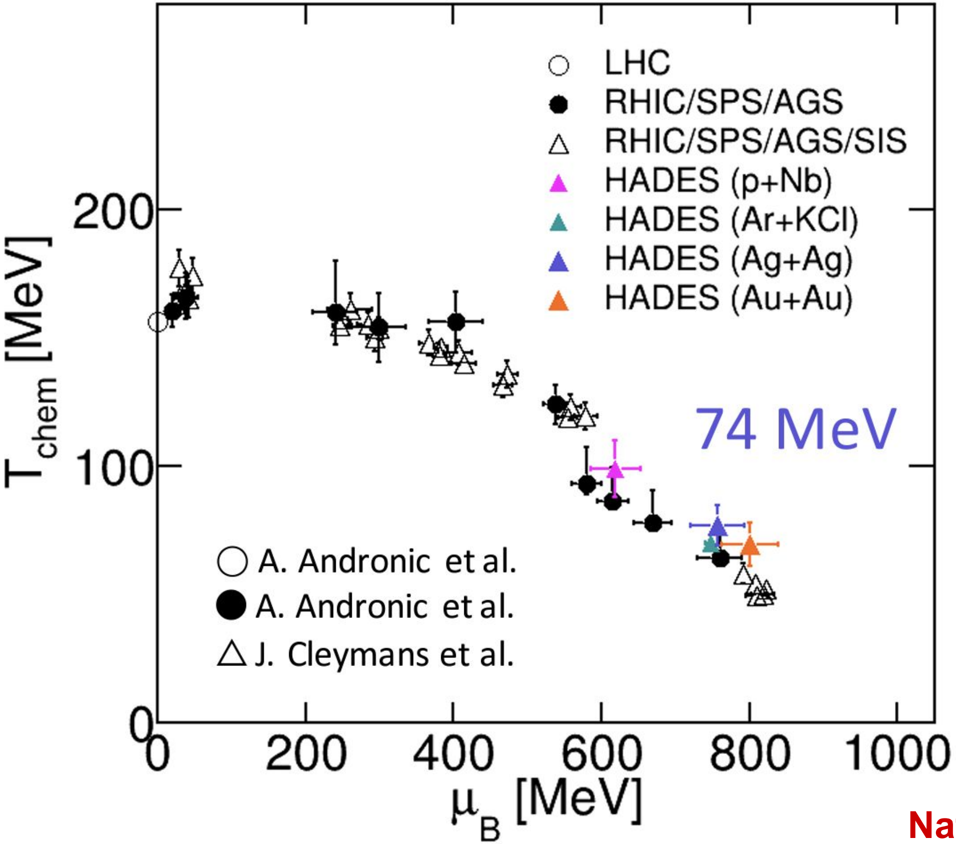
Auto Correlation Studies





https://groups.nscl.msu.edu/nscl_library/Thesis/Novak,%20John.pdf

T_{chem} Vs μ_B

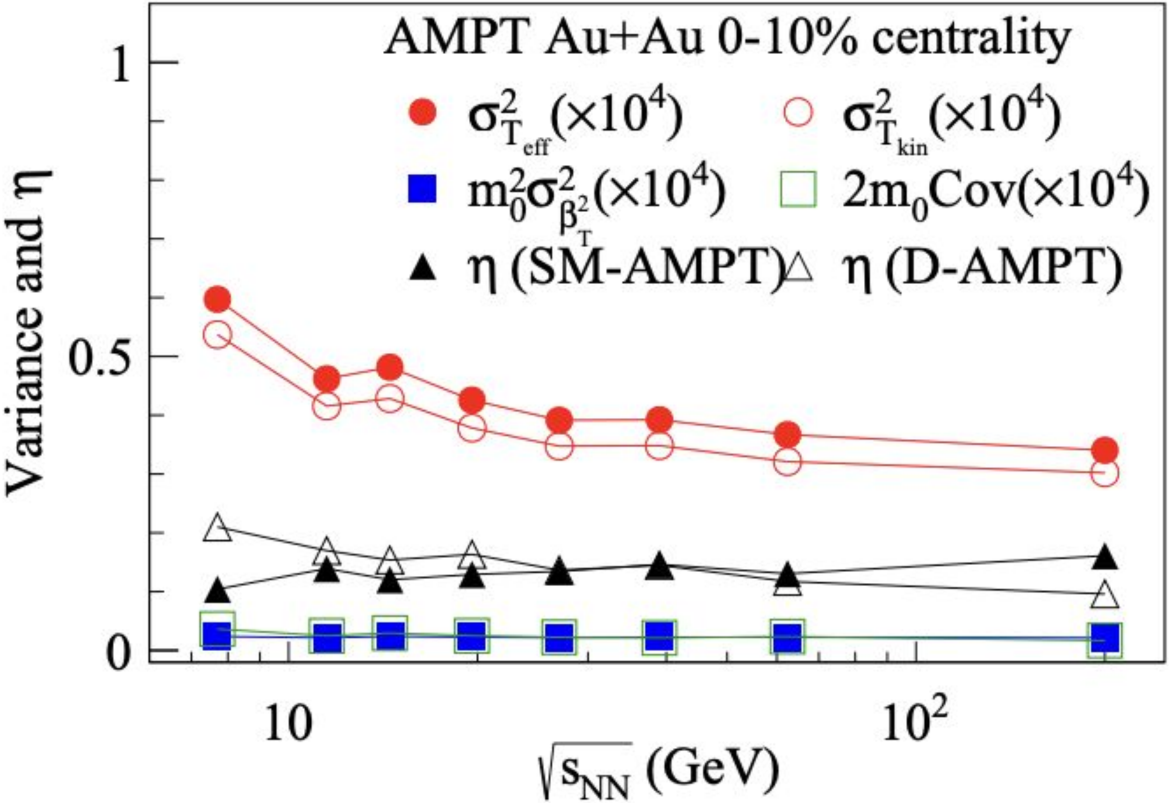


Nature Phys. 15 (2019) 10, 1040-1045

Contributions to temperature fluctuations

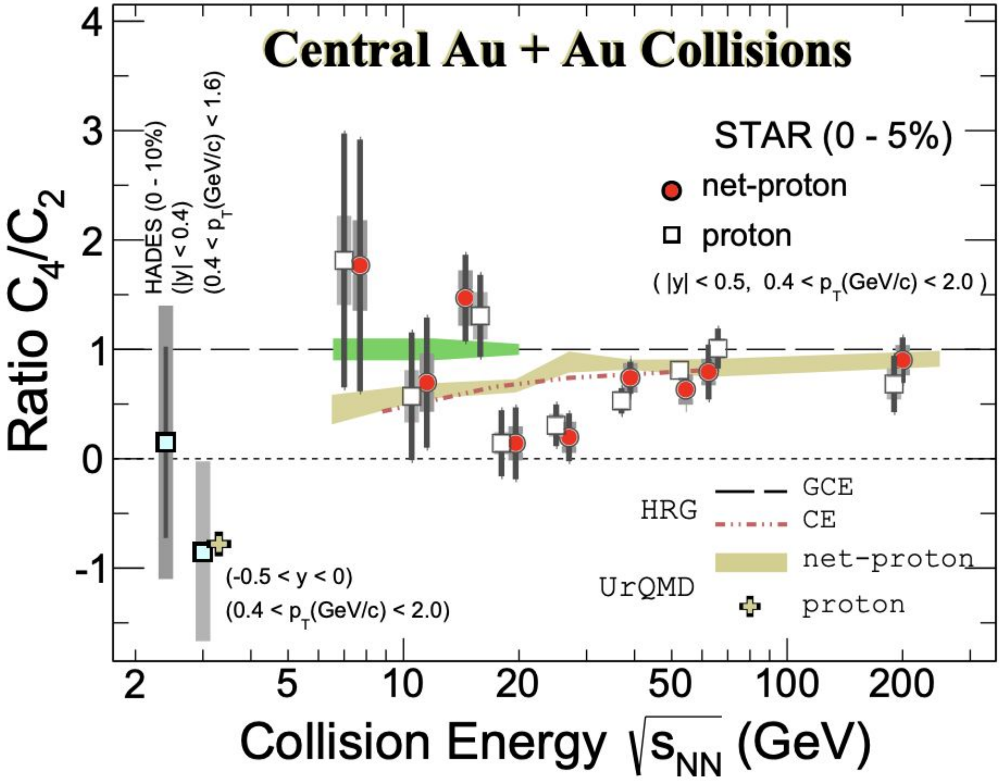
$$\sigma^2_{T_{eff}} \approx \sigma^2_{T_{kin}} + m_0^2\sigma^2_{\langle\beta_T\rangle^2}$$

$$+\, 2m_0\mathrm{Cov}\left(T_{kin}, \langle\beta_T\rangle^2\right)$$



Phys.Rev.C 106 (2022) 1, 014910

Proton Multiplicity fluctuations



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