Transverse Momentum Dynamics in $\sqrt{s_{NN}}$ = 3.0 GeV Au+Au collisions @ RHIC

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Outline

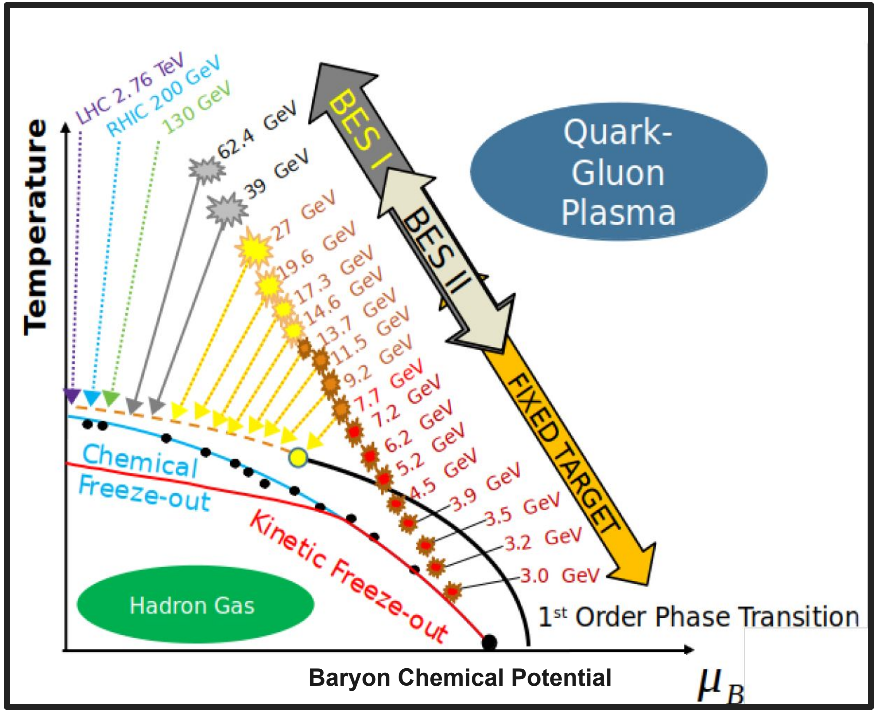
- Introduction
- STAR-FXT Setup
- Transverse Momentum Fluctuations
- Transverse Momentum Correlations
- Conclusions
- Outlook

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.

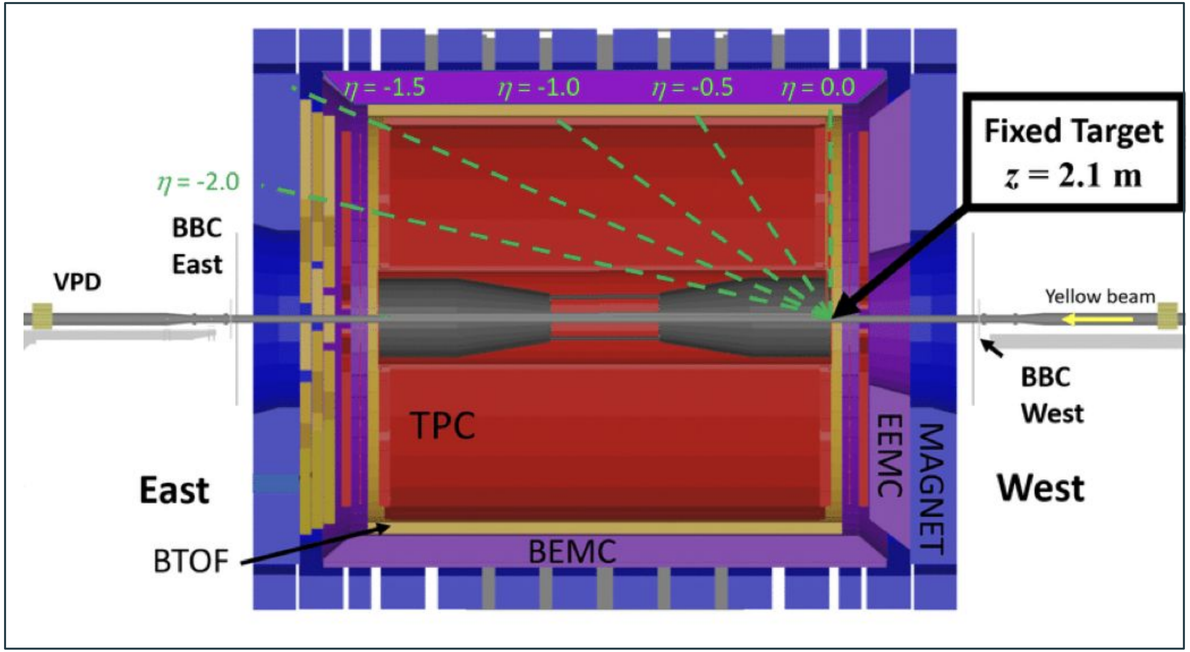
- The BES-II program provided the energies >=7.7 GeV and the BES-II FXT program provided the ones below, down to $\sqrt{s_{NN}} = 3$ GeV.



STAR-FXT Setup

- Gold Target fixed at west end of the detector
- TPC Acceptance ➤ η : [-2,0] (lab frame)
- PID Acceptance ➤ η : [-1.4,0] (lab frame)
- Mid rapidity ➤ $\eta \cong -1.05$

$\sqrt{s_{NN}}$	3.0 GeV
Year	2018
# of Events used	150 M



https://www.star.bnl.gov

Centrality Definition

- All primary charged particles within TPC acceptance
- Pile-up cut at N_{ch} =195
- We use the correlation between the TPC and ToF to reject the pileup events.

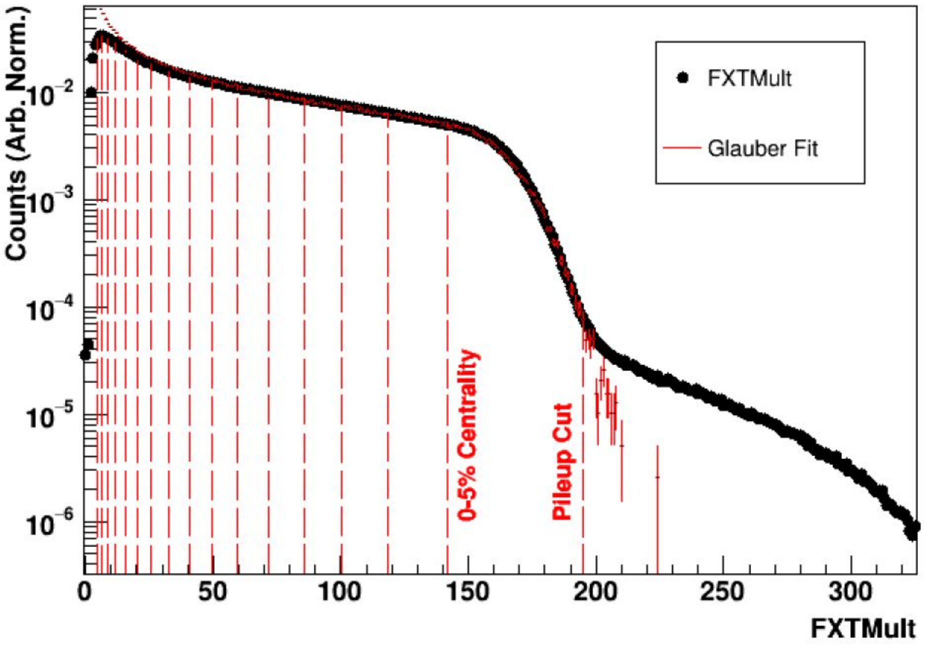


Image credits: Z. Sweger

Transverse Momentum Fluctuations

- Predominantly p_T distributions are thermal, so their shape is determined principally by the masses of the particles and the temperature of the body from which they were emitted.
- The existence of a critical point in the phase diagram of strongly interacting matter may go along with critical fluctuations of thermodynamic quantities such as temperature.[1]
- This could be reflected in dynamical event-by-event fluctuations of the mean transverse momentum of final-state charged particles.

Dynamical Fluctuations → σ_{dyn}

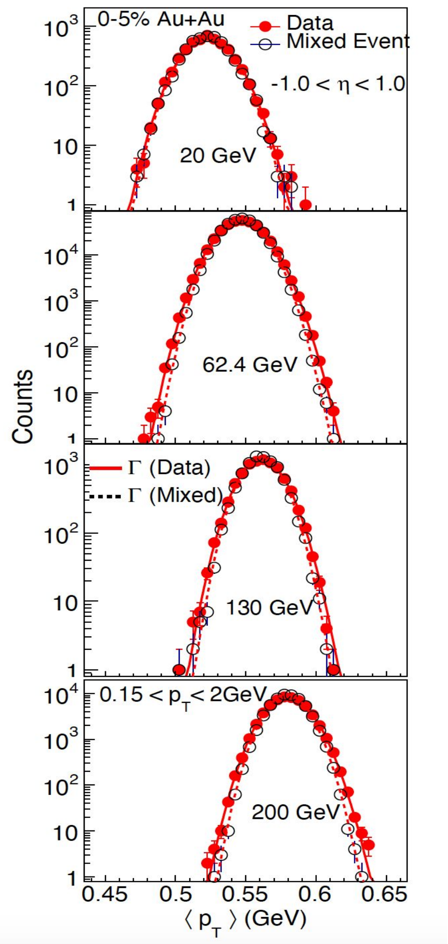
[1]: L.Stodolsky, *Phys.Rev.Lett.* 75,1995

Methodology

- Fluctuations involve a purely statistical component arising from the stochastic nature of particle production and detection processes, as well as a dynamic component arising from thermal fluctuations.

- We compare $<p_T>$ distributions from Data and from Mixed events to quantify possible dynamical fluctuations in the system.

- Dynamical fluctuations have been established for collision energies by different experiments.

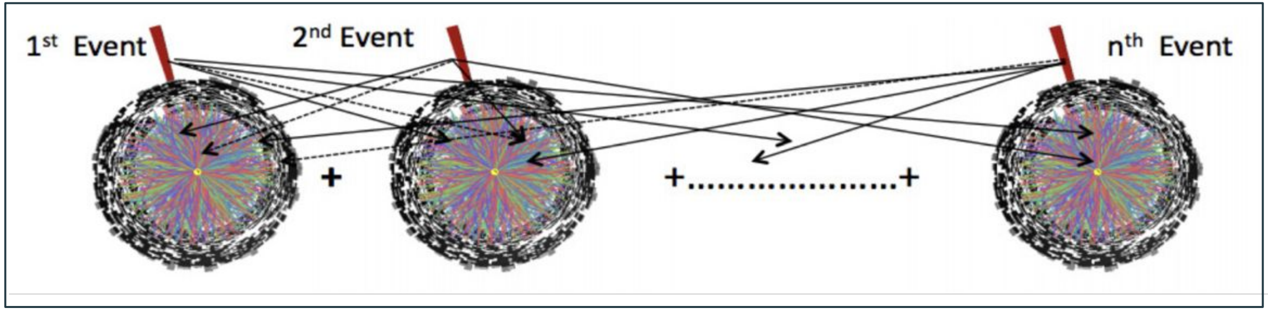


STAR,Phys.Rev.C72:044902,2005

Mixed Events Analysis

- ❖ In order to establish whether the observed fluctuations are partly dynamical in nature, we need to disentangle statistical effects i.e. effects due to the finite number of particles in the final state of the collision.

- ❖ Creating ‘data’ which have all of the same detector effects, analysis effects, as the real data, but without any correlations.



A schematic representation of event mixing

*select 1 particle from each event

Gamma Distribution

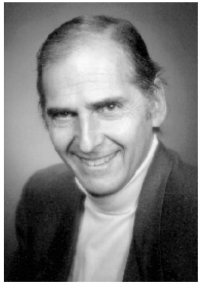
- We fit the $\langle p_T \rangle$ distributions with the gamma function to obtain the mean and sigma of the distributions.

- We can calculate μ and σ:
  - $\mu = \alpha\beta$
  - $\sigma^2 = \alpha\beta^2$

$$f(x) = \frac{x^{\alpha-1} e^{\frac{-x}{\beta}}}{\Gamma(\alpha)\beta^{\alpha}}$$

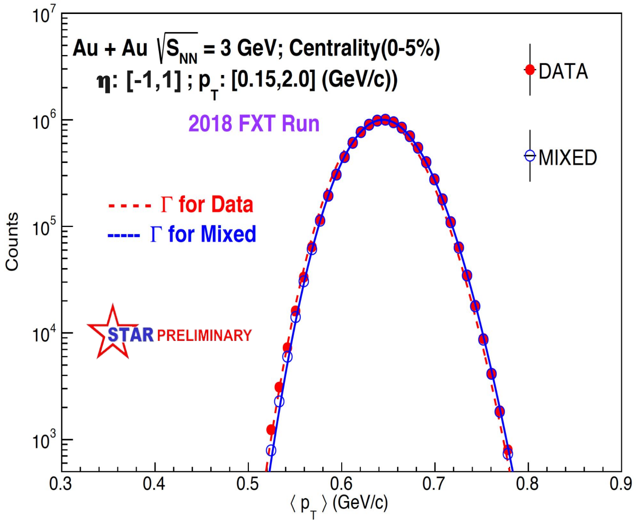
- $$\sigma_{dyn} = \sqrt{\left(\frac{\sigma_{data}}{\mu_{data}}\right)^2 - \left(\frac{\sigma_{mix}}{\mu_{mix}}\right)^2}$$

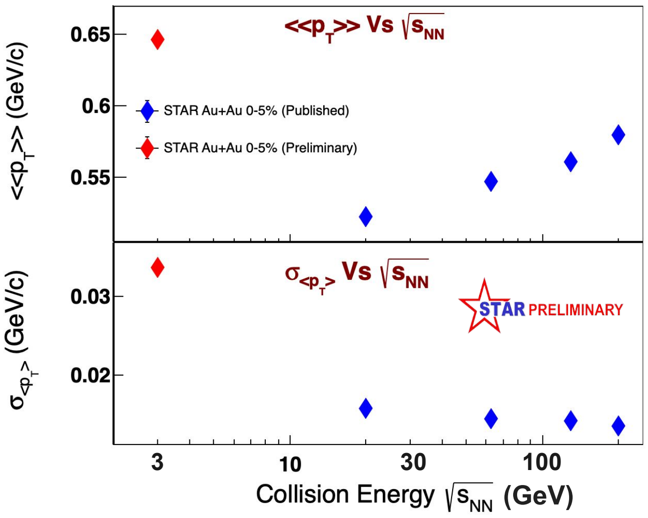
It's not a Gaussian…it's a Gamma distribution!



M.J.Tannenbaum Phys.Lett.B 498, 2001

Transverse Momentum Distributions



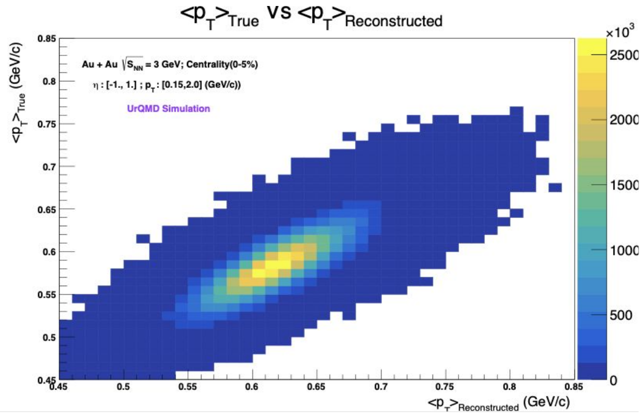


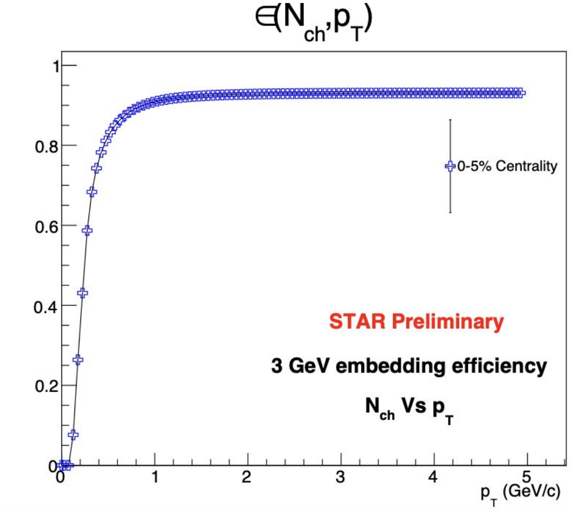
- ❖ 3 GeV is proton dominated as opposed to the collider energies.
- ❖ Mixture of primordial and produced particles.

STAR,Phys.Rev.C72:044902, 2005

Efficiency Correction

- Mean values of multiplicity and spectra functions were obtained from UrQMD.
- Poissonian distributions were generated from these mean values.
- Detector effects were applied.
- Response Matrix with generated $<p_T>$ and reconstructed $<p_T>$ was calculated.
- 1D Bayesian Unfolding was performed with the Response Matrix.
- At least 10x Statistics was ensured.
- Response matrix has wider $<p_T>$ distributions as compared to data.





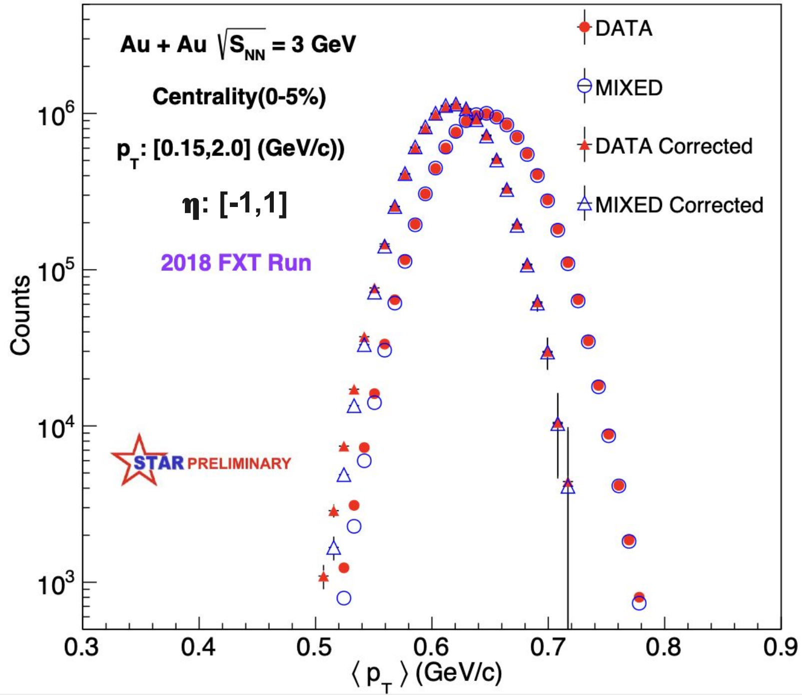
Acta Phys. Pol. B Proc. Suppl. 16, 2023

Efficiency Correction

❖ Efficiency correction decreases the mean and the sigma of the distribution.

❖ Dynamical fluctuations are the same (within error bars).

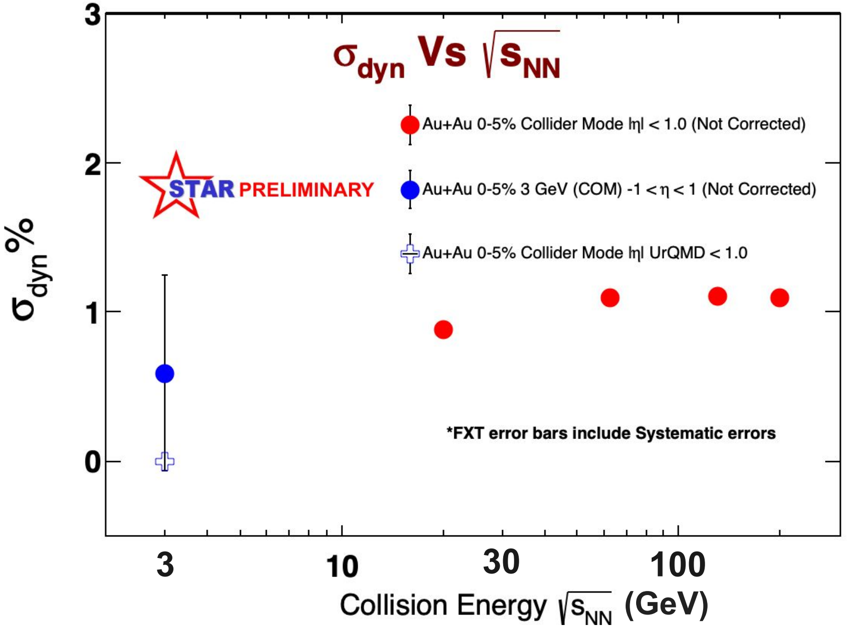
Case	μ (GeV)	σ (GeV)
3 GeV, real	0.6461	0.03365
3 GeV, mixed	0.6460	0.03342
3 GeV, real, corrected	0.6187	0.02935
3 GeV, mixed, corrected	0.6186	0.02903



Dynamical Fluctuations Vs $\sqrt{s_{NN}}$

- No signature of p_T fluctuations diverging is observed.
- Transport Model (UrQMD) at 3 GeV shows no dynamical fluctuations.

$$\sigma_{dyn} = \sqrt{\left(\frac{\sigma_{Data}}{\mu_{Data}}\right)^2 - \left(\frac{\sigma_{Mixed}}{\mu_{Mixed}}\right)^2}$$



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.[2]
- Correlation measurements generally have finer ‘resolution’ than fluctuation measurements and can be looked at more differentially.
- The correlator is the mean of covariances of all pairs of particles i and j in the same event with respect to the mean.

$$C_m = \langle \Delta p_{Ti} \, , \Delta p_{Tj} \rangle$$

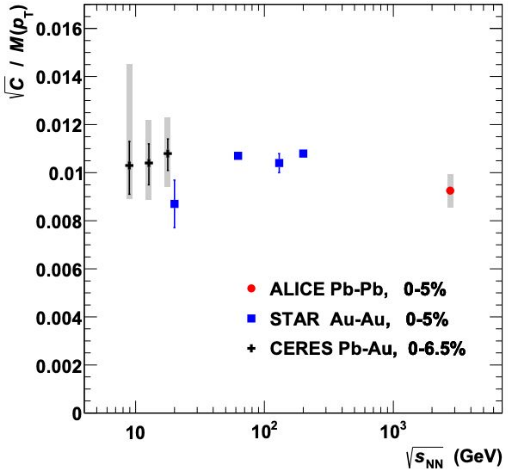
$$< (p_{T,i} - < p_T >)(p_{T,j} - < p_T >) >$$

$$i \neq j$$

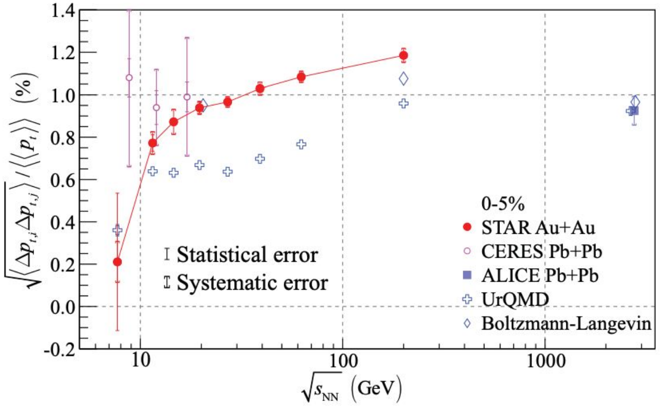
[2] : ALICE, *Phys. Part. Nuclei* 51,2020

Transverse Momentum Correlations

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



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



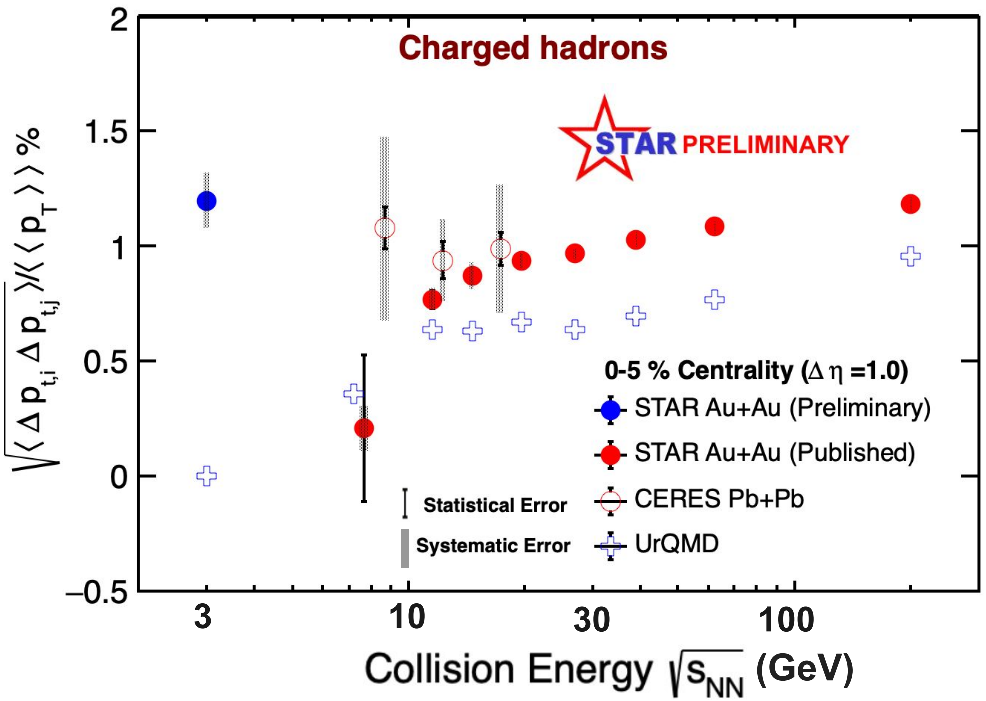
STAR,Phys.Rev.C 99, 2019

Correlator Vs Collision energy

- We see a departure from monotonicity
- Calculations from transport codes do not reproduce the data.
- Temperature fluctuations should be reflected in p_T fluctuations.

$<p_T> \rightarrow T_{eff}$

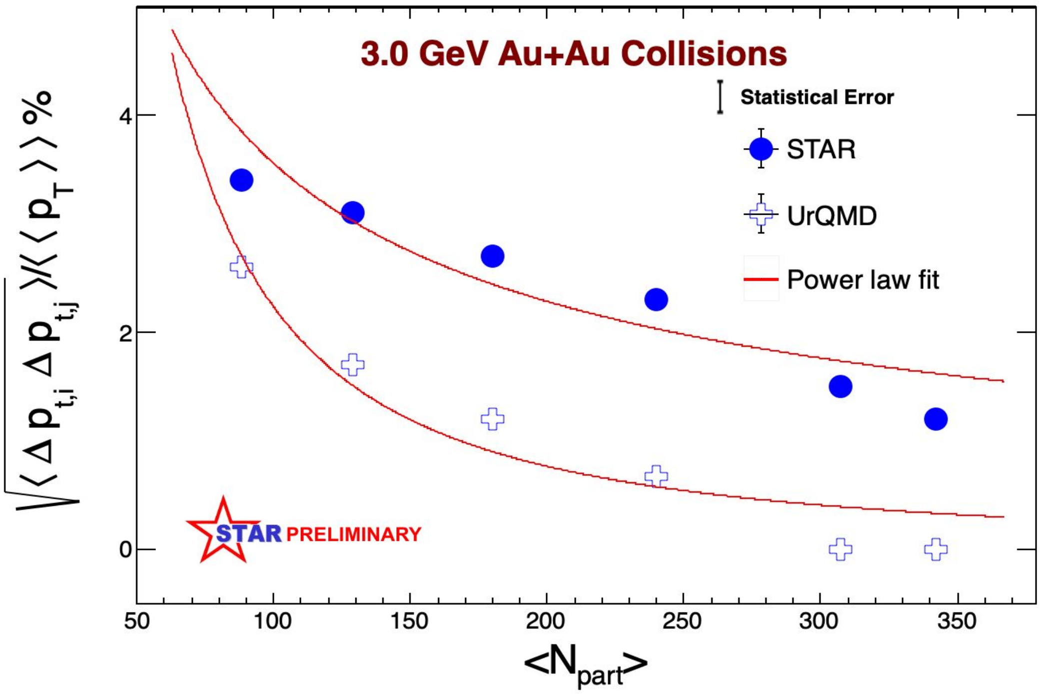
$$T_{eff} = T_{kin} + m_0 < \beta_T >^2$$



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

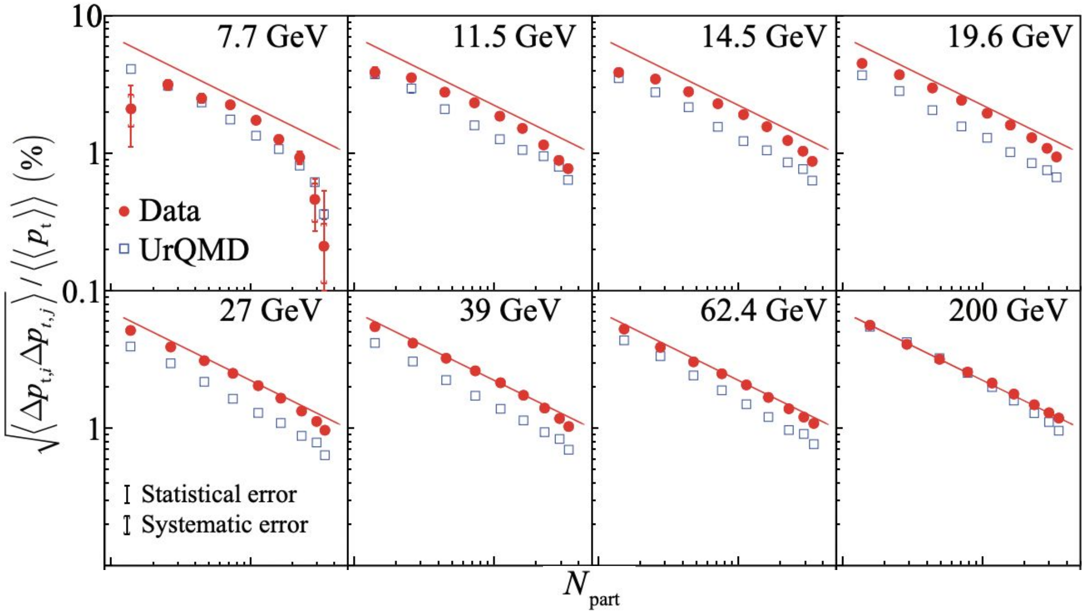
Correlator Vs Centrality

- ❖ Monotonic increase in decreasing centrality.
- ❖ UrQMD underpredicts the data.
- ❖ Power law fits do not capture the data.
- ❖ We lose sensitivity for UrQMD at central collisions.



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.

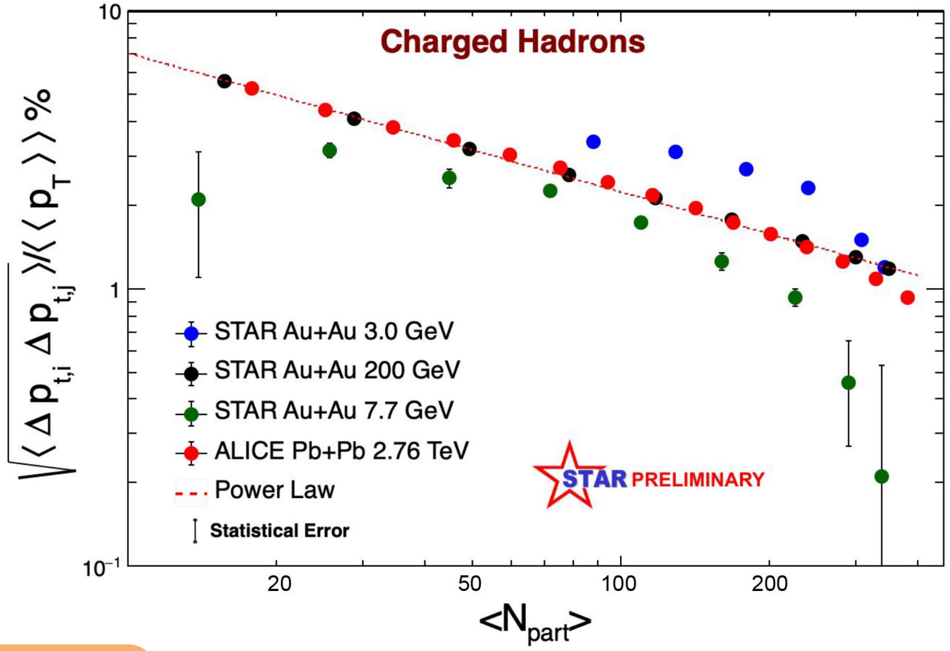


STAR,Phys.Rev.C 99, 2019

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

Correlator Vs Centrality

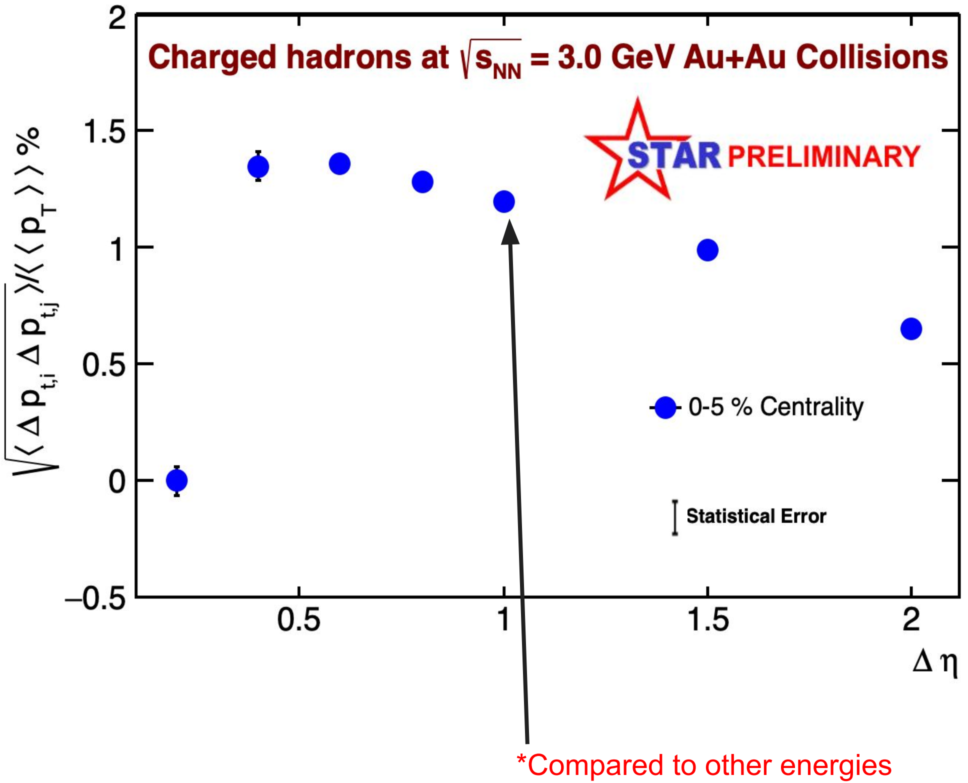
- Power law implies uncorrelated sources (b=-0.5).
- STAR data from 200 GeV Au+Au collision shows minimal deviation
- Deviation increases as we go down the collision energy
- Deviation holds at STAR 3 GeV Au+Au collisions as well.



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

Correlator Vs Acceptance

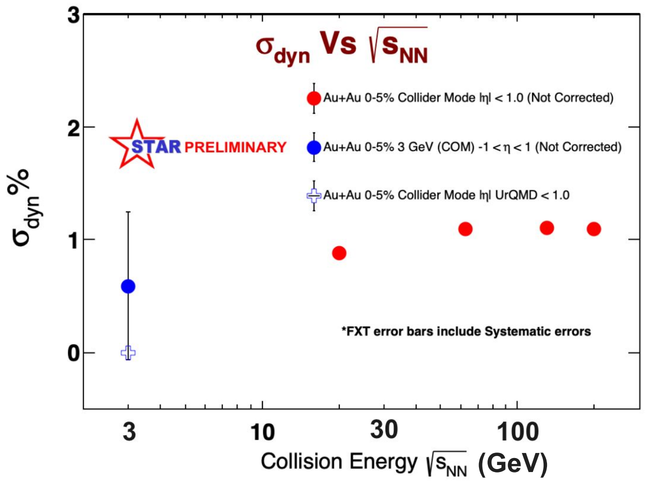
- The effect of primordial protons bring the correlator down for the whole acceptance.
- Closer to mid-rapidity where majority of the particle production takes place the value saturates.
- At lower acceptances we don't have enough particles to correlate.

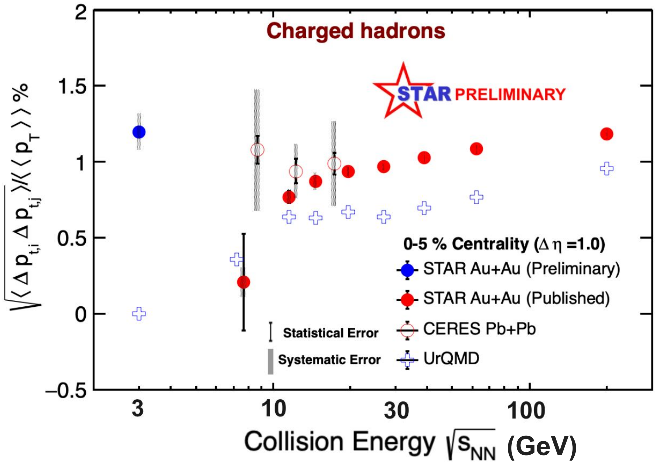


***Δη : Acceptance window around mid-rapidity**

Conclusions

- Transverse Momentum Dynamics were discussed.
  - $\boldsymbol{\sigma}_{dyn}$ do not show a non-monotonic behaviour.
  - Δp_T-Δp_T show a non-monotonic behaviour.
- We don't fully understand the discrepancy between Transport codes (UrQMD) and the data at 3.0 GeV Au+Au collisions.





References

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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

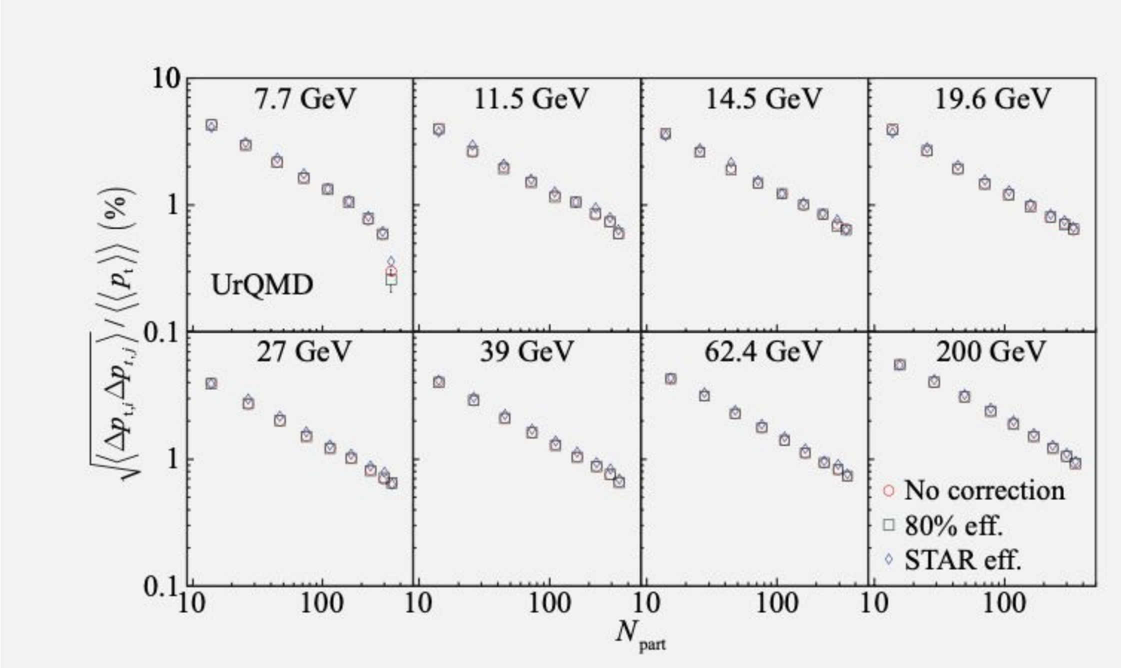
4. Collision-energy dependence of p_T correlations in Au + Au collisions at energies available at the BNL Relativistic Heavy Ion Collider - Phys.Rev.C 99 (2019) 4, 044918

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)

BACKUP



7.7 GeV
11.5 GeV
14.5 GeV
19.6 GeV
27 GeV
39 GeV
62.4 GeV
200 GeV
UrQMD
No correction
80% eff.
STAR eff.
$\sqrt{\langle \Delta p_{t,i} \Delta p_{t,j} \rangle} / \langle\langle p_t \rangle\rangle$ (%)
N_{part}
10
1
0.1
100

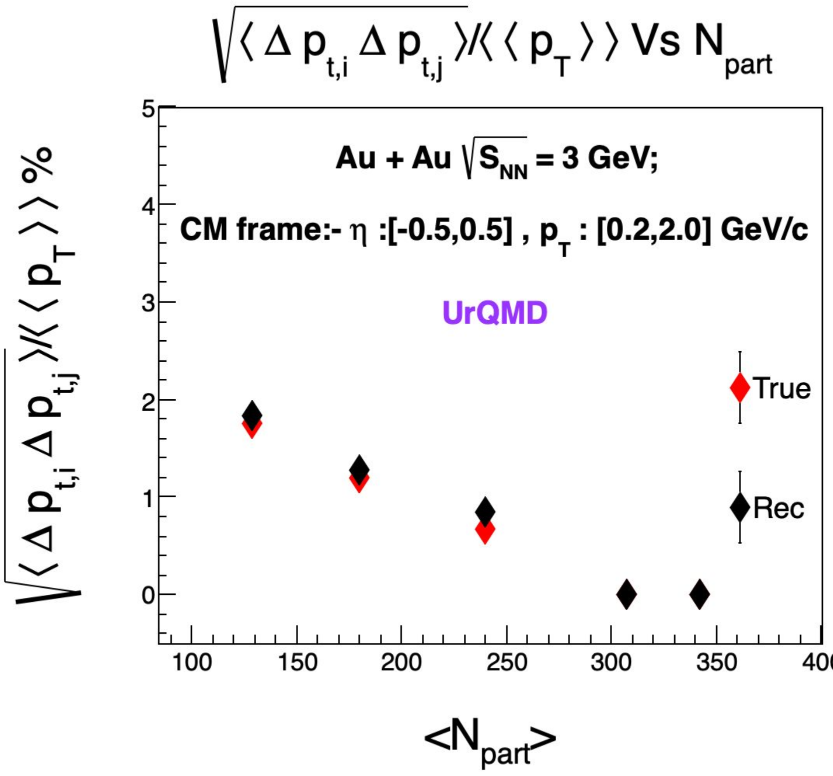
Closure Test

- 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.



Correlator Vs Collision energy