Recent highlights from the STAR Experiment

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for the STAR Collaboration

Supported in part by
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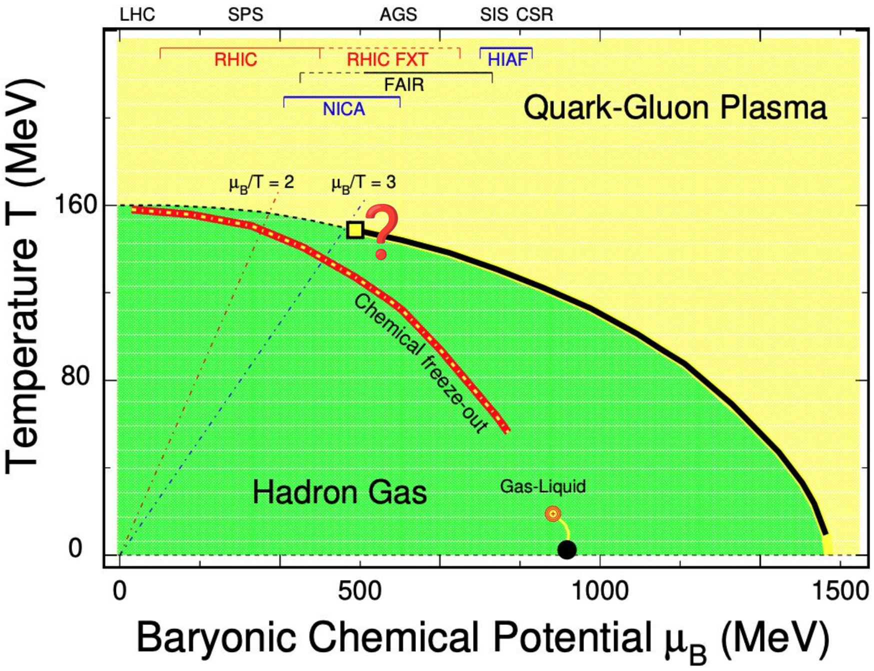
ENERGY

Outline

- ❖ Introduction
- ❖ STAR Experiment
- ❖ Results:
  - ➢ Proton Multiplicity Fluctuations
  - ➢ Transverse Momentum Correlations
- ❖ Summary

Introduction

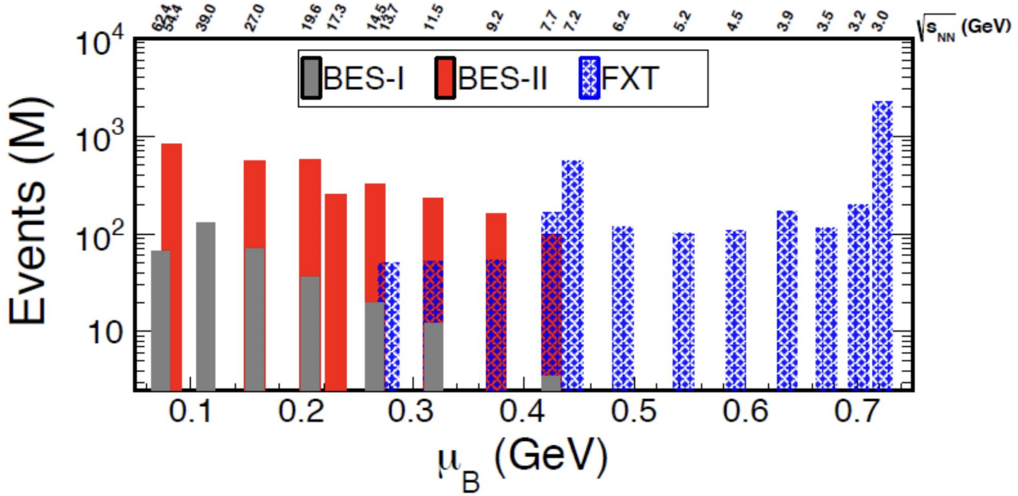
- Two distinct phases of matter confirmed
- Crossover at low $\boldsymbol{\mu}_B$ ($\boldsymbol{\mu}_B/T < 2$)
- Predictions of 1st order phase transition at high $\boldsymbol{\mu}_B$
- RHIC collider energies cover up to 420 (MeV) $\boldsymbol{\mu}_B$
- RHIC FXT extends coverage up to 750 (MeV) $\boldsymbol{\mu}_B$
- CBM experiment at FAIR extends coverage even further



B. Mohanty, N. Xu, arXiv:2101.09210

STAR Experiment

- STAR: Solenoidal Tracker At RHIC.
- Heavy ion collisions of Au,Cu,Zr,Ru etc ...
- Energy range from 3 GeV - 200 GeV ($\sqrt{s_{NN}}$).
- BES-II, detector upgraded, high statistics data recorded.
- Experiment has Collider and Fixed-Target modes.

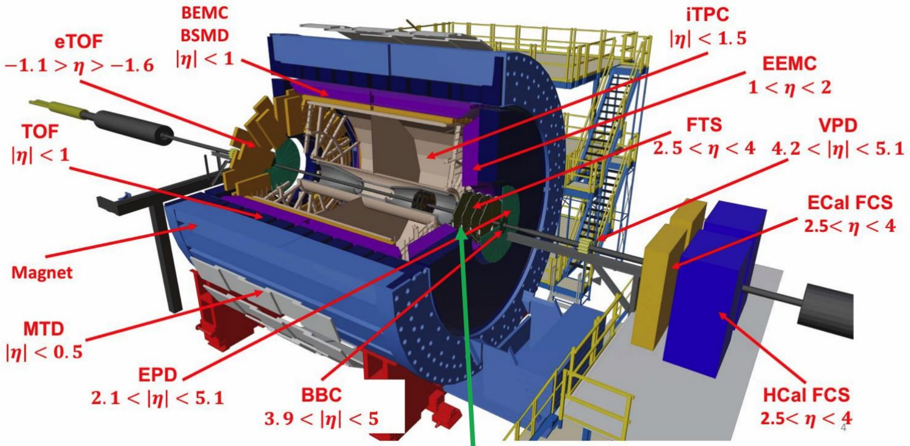


https://www.star.bnl.gov

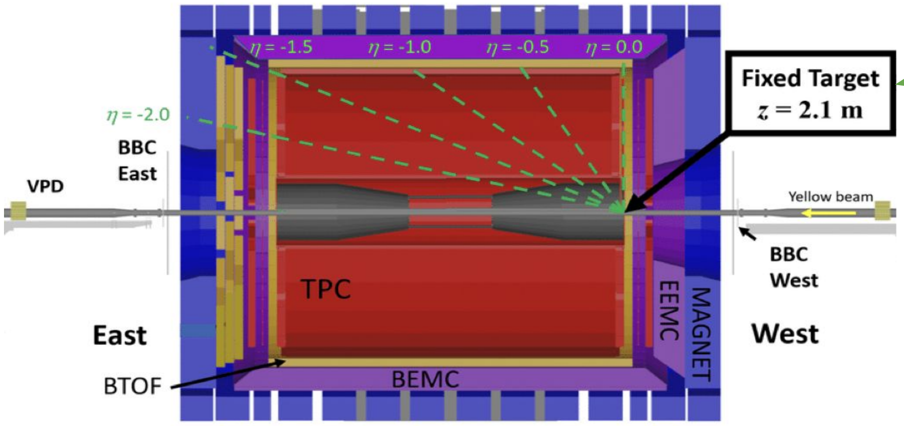
- Located at Brookhaven National Laboratory (BNL).
- Long Island, New York, USA.

STAR Detector

- Multiple sub detector systems
- Excellent particle identification capabilities
- Full azimuthal acceptance



Target (Fixed Target mode)



- Gold Target fixed at west end of the detector
- TPC Acceptance :
  - ➢ η : [-2,0] (lab frame)
- PID Acceptance (TPC + ToF):
  - ➢ η : [-1.5,0] (lab frame)

STAR

Results:
Proton Multiplicity Fluctuations

Proton Multiplicity Cumulants

Cumulants:

n = net-proton multiplicity in an event

$$\delta n = n - < n >$$

$$C_1 = < n >$$

$$C_2 = < \delta n^2 >$$

$$C_3 = < \delta n^3 >$$

$$C_4 = < \delta n^4 > - 3 < \delta n^2 >$$

Factorial Cumulants:

$$\kappa_1 = C_1$$

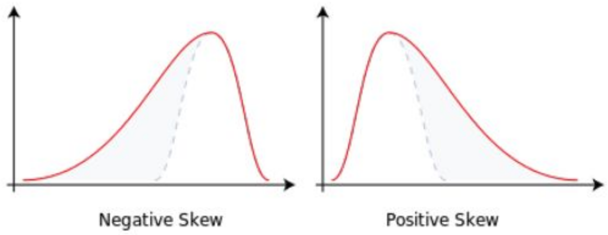
$$\kappa_2 = -C_1 + C_2$$

$$\kappa_3 = 2C_1 - 3C_2 + C_3$$

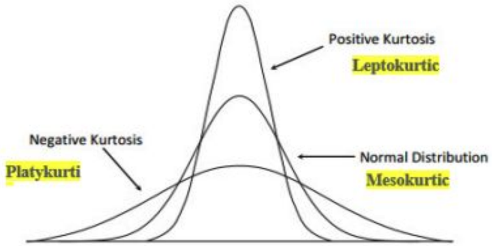
$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$$

Cumulants quantify characteristics of distributions:

Skewness: C_3/C_2



Kurtosis : C_4/C_2



Cumulants for CP Search

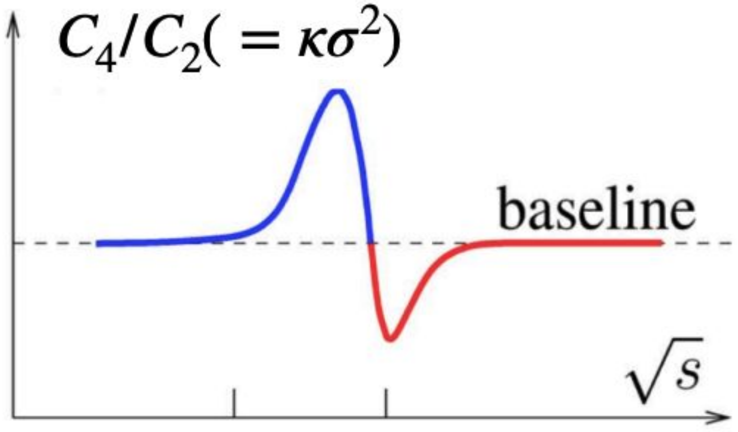
Cumulants are related to the correlation length

$$C_2 \sim \zeta^2$$

$$C_4 \sim \zeta^7$$

Cumulants ratios are related to ratios of susceptibilities

$$\frac{C_{4q}}{C_{2q}} = \frac{\chi_4^q}{\chi_2^q}$$

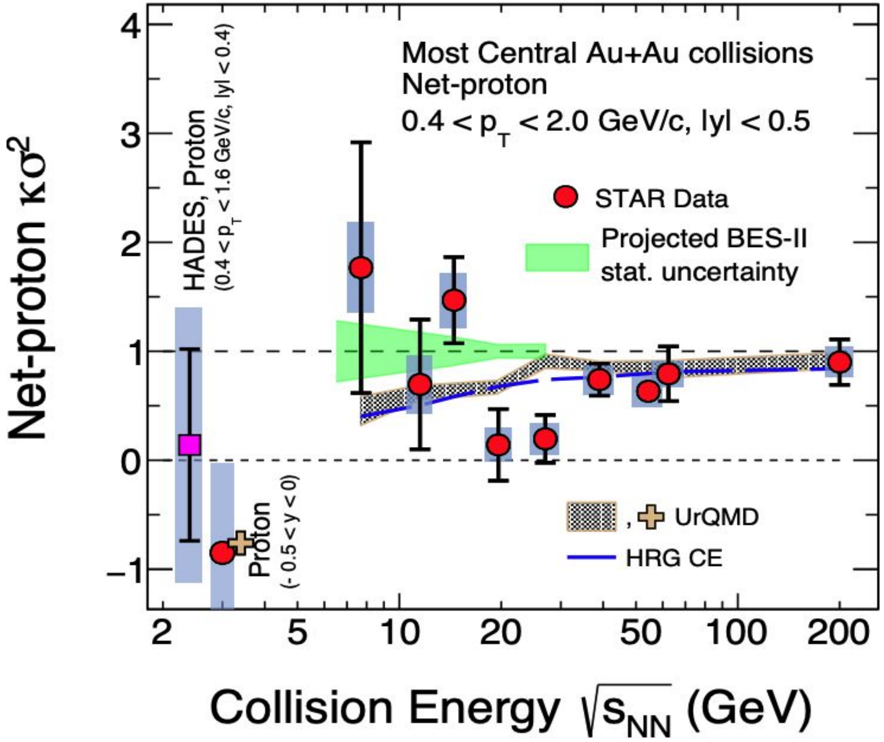


Non-monotonic dependence on collision energy ($\sqrt{s}$) predicted to be a signature of critical behaviour

M. A. Stephanov, PRL 107 (2011) 052301

BES-I Measurement of Kurtosis

- Observed hint of non-monotonous trend in BES-I (3σ)
- Robust conclusion requires confirmation from precision measurement from BES-II.
- Extend reach to even lower collision energies with FXT energies

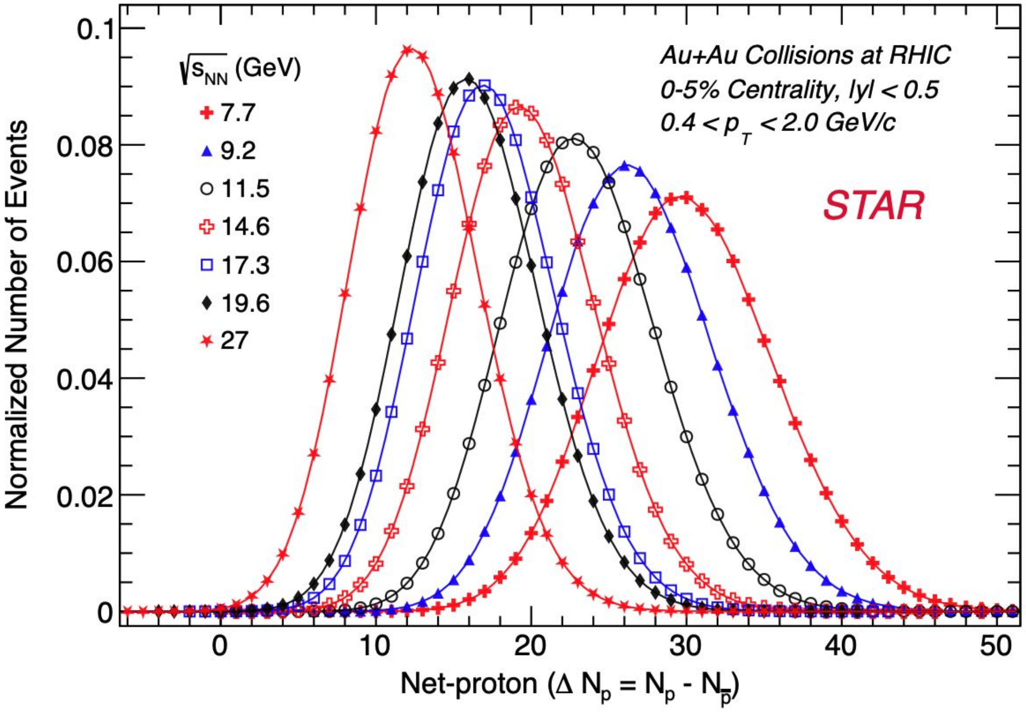


STAR : PRL 127, 262301 (2021), PRC 104, 24902 (2021) ,PRL 128, 202302 (2022), PRC 107, 24908 (2023)
HADES: PRC 102, 024914 (2020)

BES-II Scan of Proton Cumulants

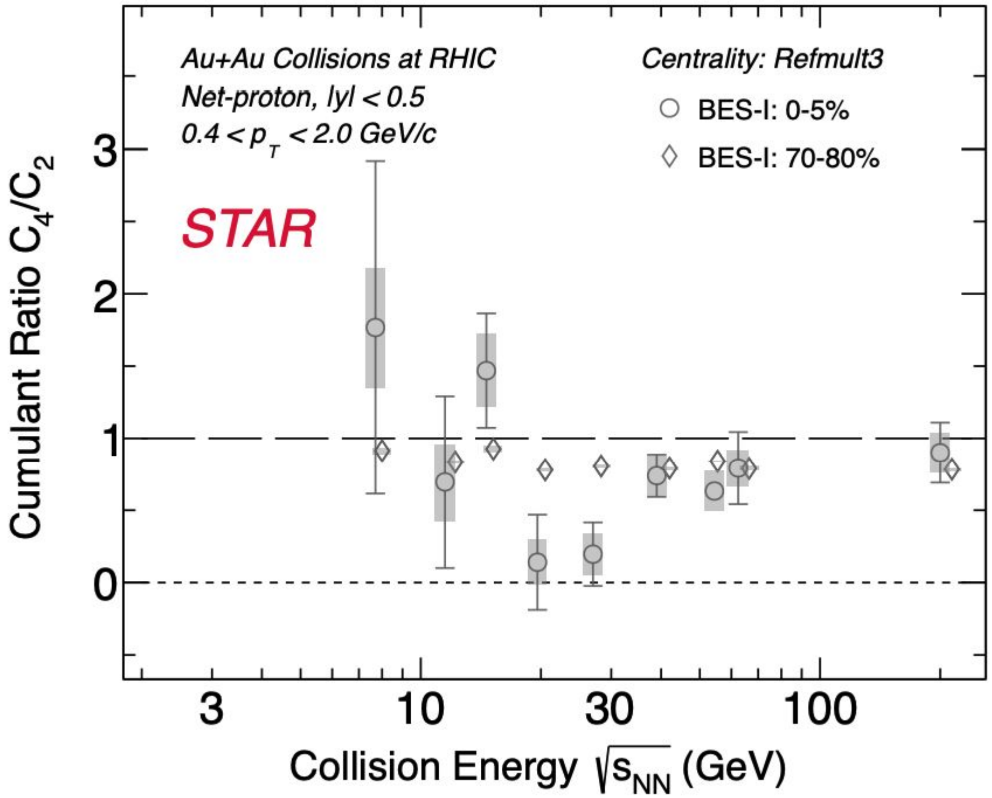
Net-proton Distributions:

- Raw net-proton distributions from BES-II (Collider): Uncorrected for detector efficiency.
- Mean increases with decreasing collision energy (baryon stopping).
- Larger width leads to larger Stat. uncertainties.



BES-II Vs BES-I

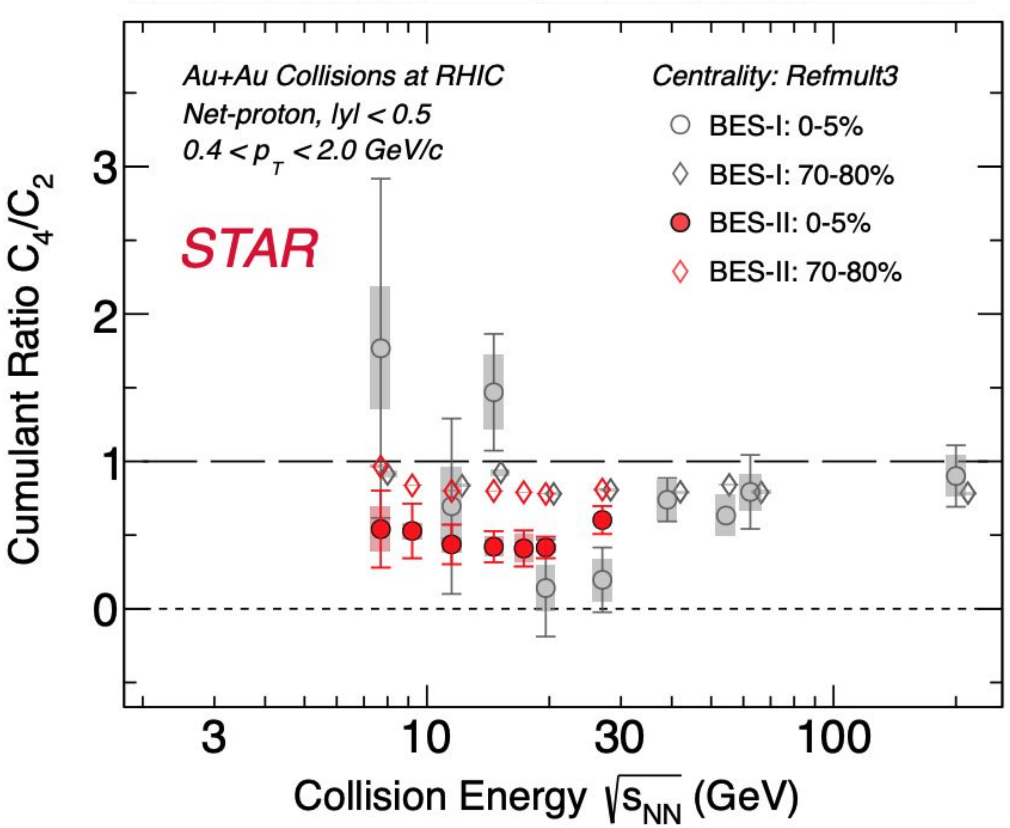
- ❖ Two different centrality classes shown



BES-II Vs BES-I

- Two different centrality classes shown
- Results consistent between BES-I and BES-II:

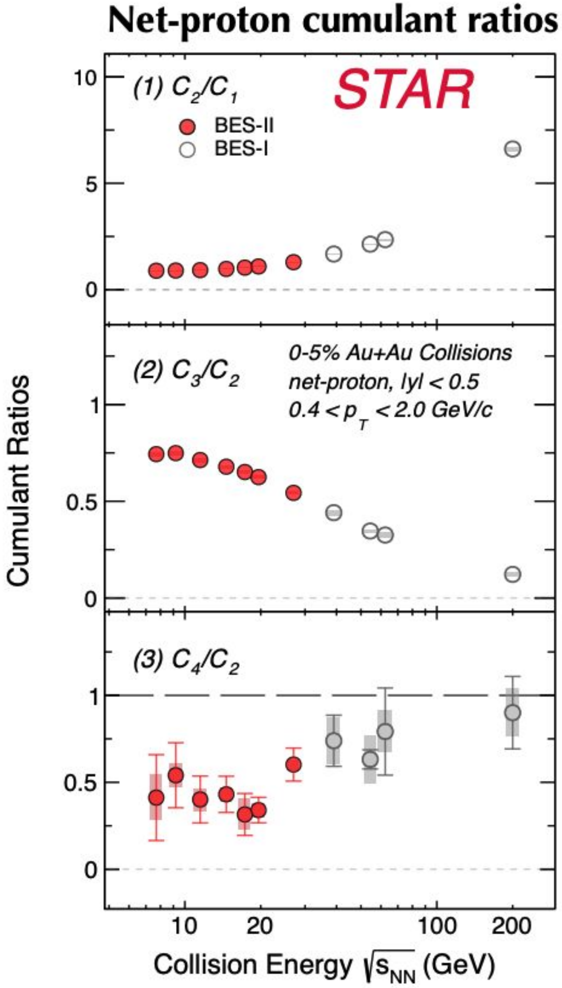
$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ



- Here on only BES-II results are discussed.

Model Comparisons

1. Smooth variation vs $\sqrt{s_{NN}}$ in C_2/C_1
   and C_3/C_2 observed.



Model Comparisons

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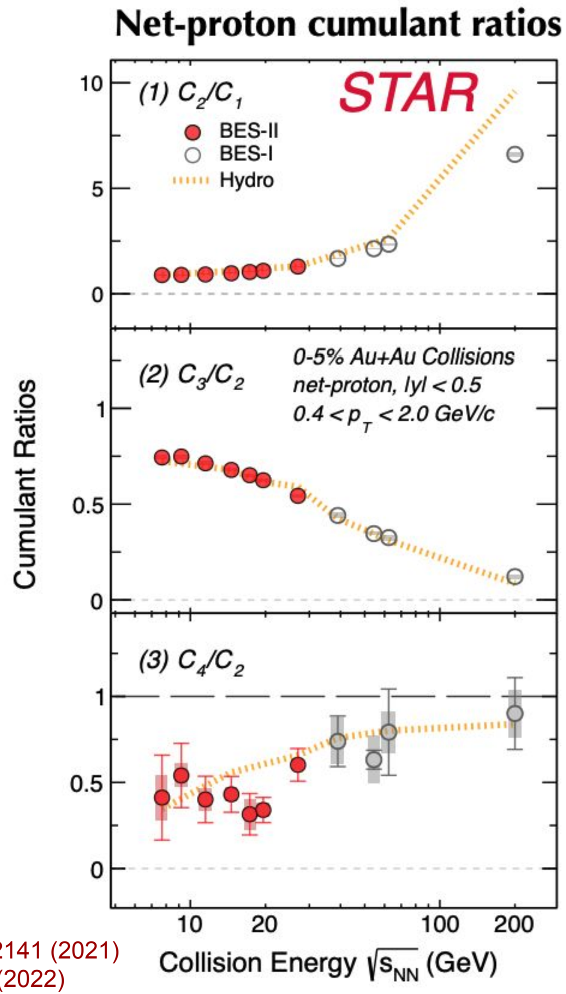
2. Non-CP models used for comparison:
   Hydro :Hydrodynamical model



HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)
UrQMD: M. Bleicher et al. J.Phys.G25:1859-1896,(1999)

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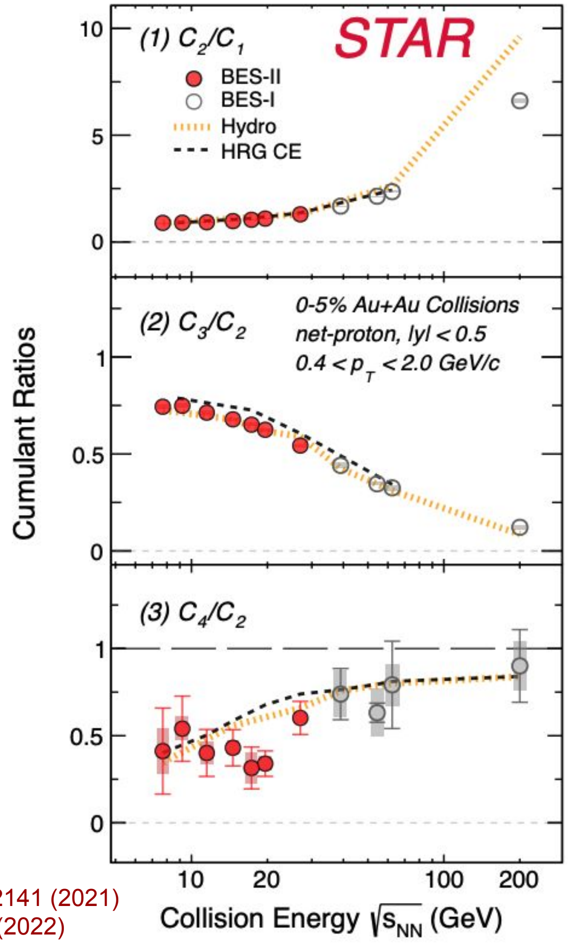
Net-proton cumulant ratios



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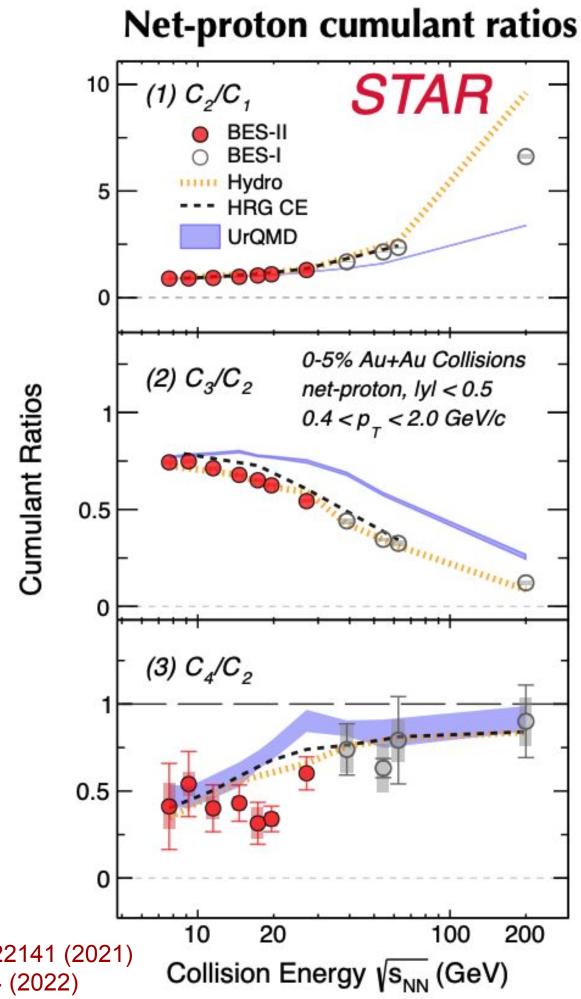

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2. Non-CP models used for comparison:

    Hydro :Hydrodynamical model

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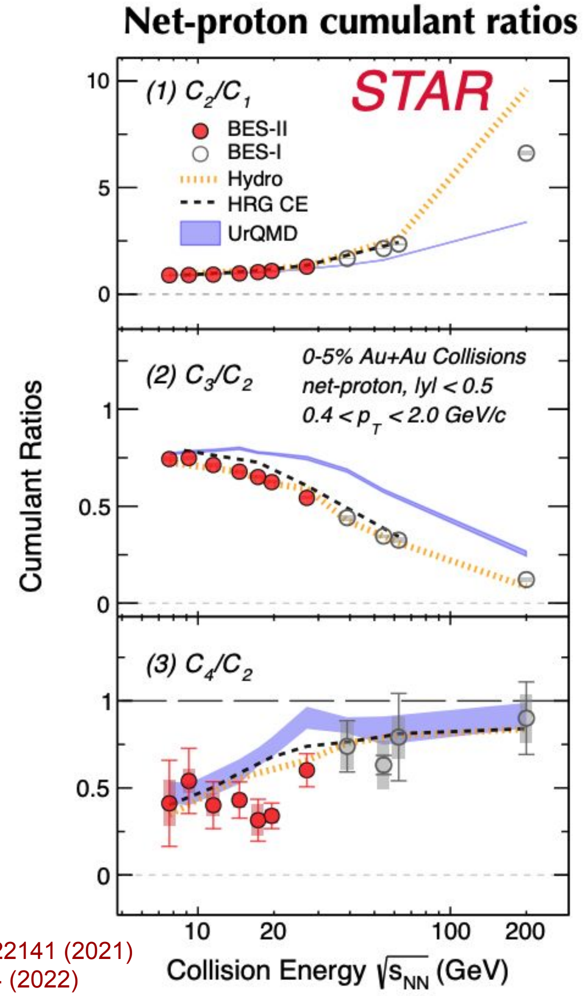
    UrQMD: Hadronic transport model

3. Qualitative trend described by model except for C_4/C_2. Quantitative differences exist b/w data and non-CP model.



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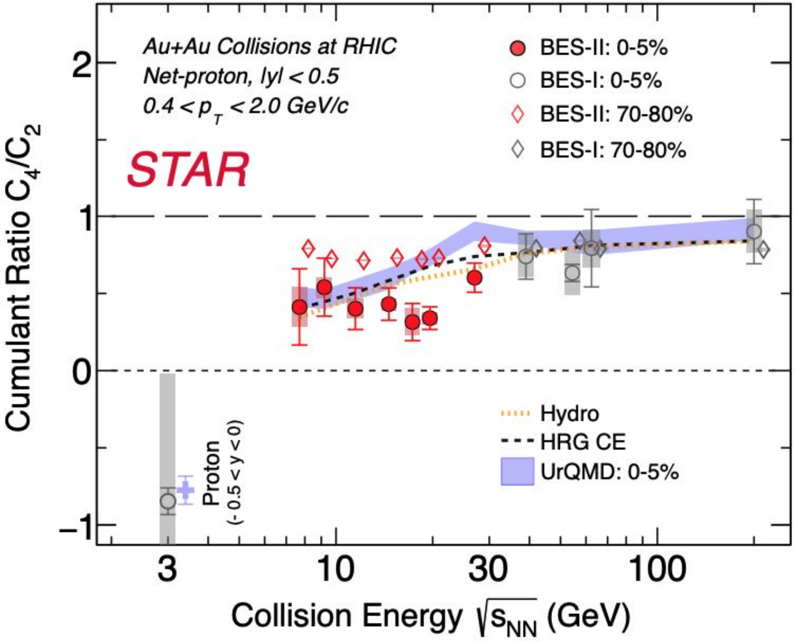
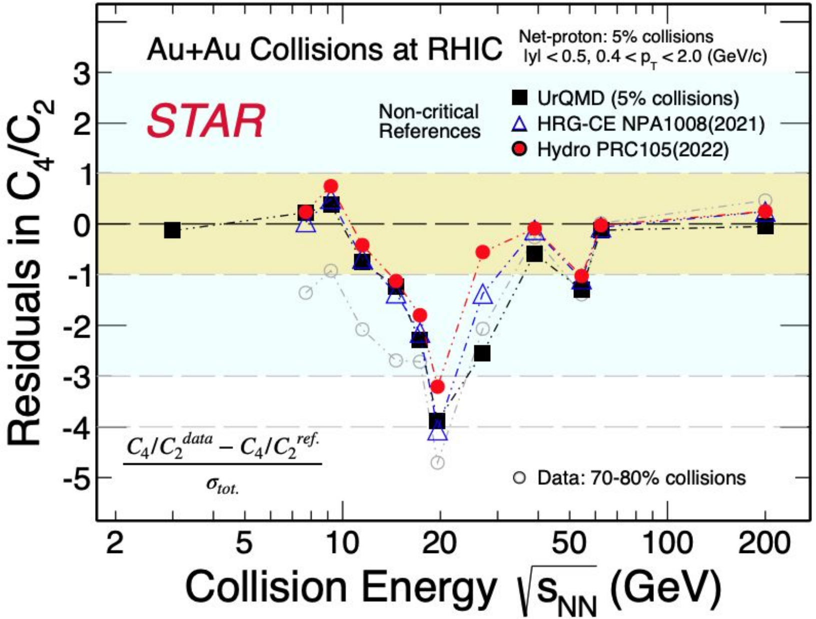
Conclusions





C_4/C_2 shows minimum around ~20 GeV comparing to non-CP models, 70-80% data

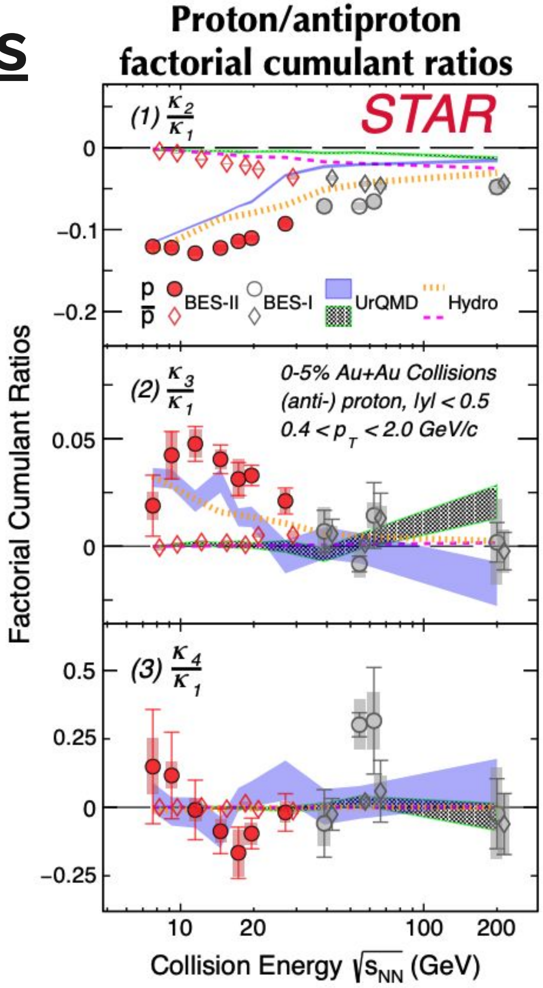
1. Maximum deviation: 3.2 -4.7σ at $\sqrt{s_{NN}}$ = 19.6 GeV (1.3 - 2.0σ for BES-I)

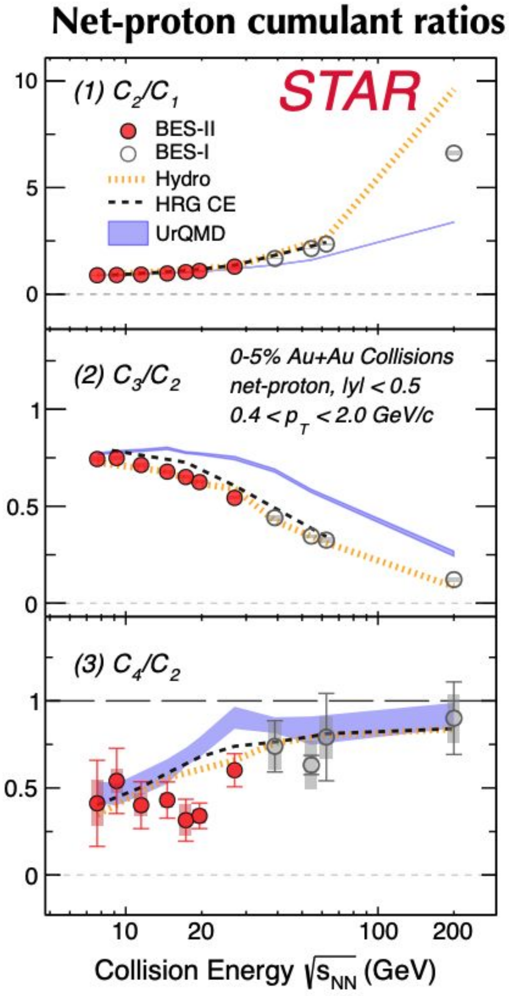
Factorial Cumulants

1. Factorial cumulants for protons and antiprotons.

2. Proton factorial cumulant ratios deviates from poisson baseline at 0.

3. Antiproton $\kappa_3/\kappa_1, \kappa_4/\kappa_1$ closer to 0.





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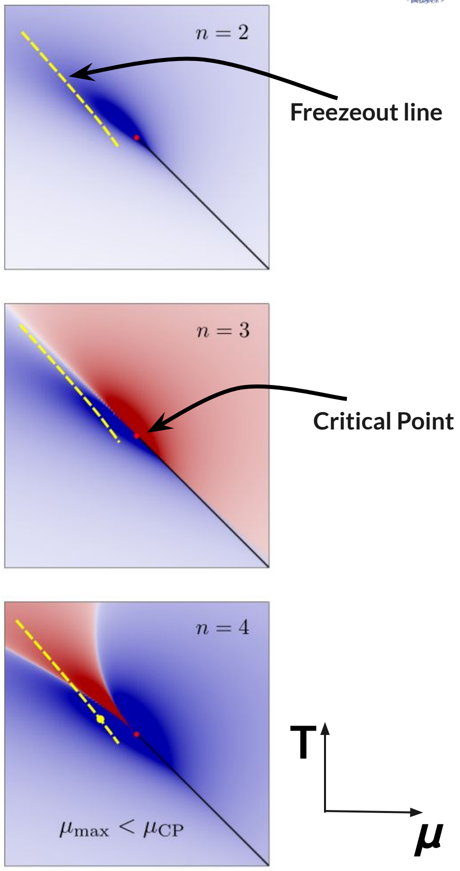
BES-II data Vs Theory

- Density plot of the quartic cumulant of the order parameter obtained by mapping of the Ising equation of state onto the QCD equation of state near the critical point.
- The freeze out point moves along the dashed yellow line as $\sqrt{s_{NN}}$ is varied during the beam energy scan.
- Susceptibilities extracted from universal EOS

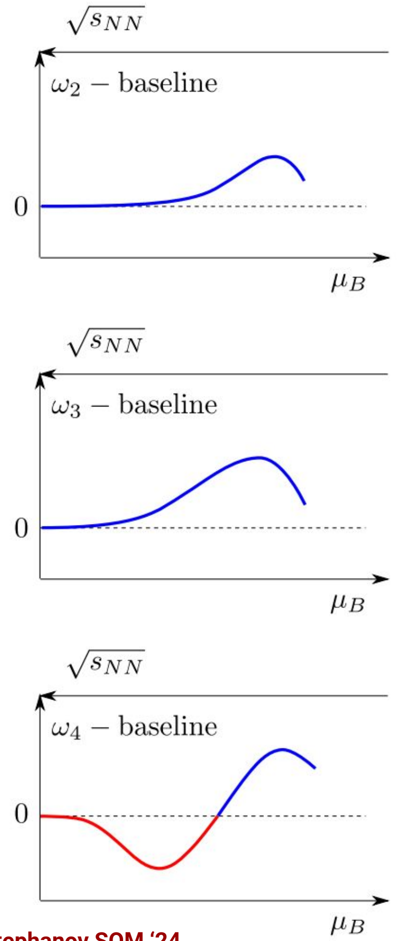
(universal EOS) critical χ_n:



A.Bzdak et. al. Phys.Rept. 853 (2020)

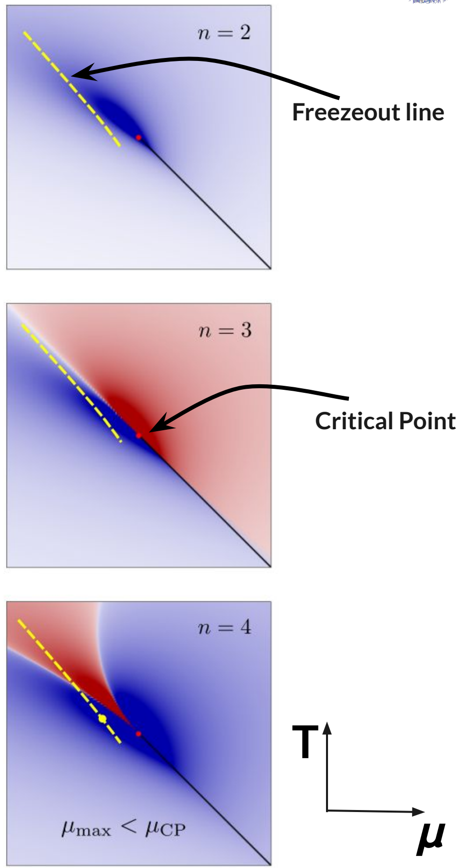
BES-II data Vs Theory

- Density plot of the quartic cumulant of the order parameter obtained by mapping of the Ising equation of state onto the QCD equation of state near the critical point.
- The freeze out point moves along the dashed yellow line as $\sqrt{s_{NN}}$ is varied during the beam energy scan.
- Susceptibilities extracted from universal EOS
- Susceptibilities along the freezeout line.



M. Stephanov SQM '24

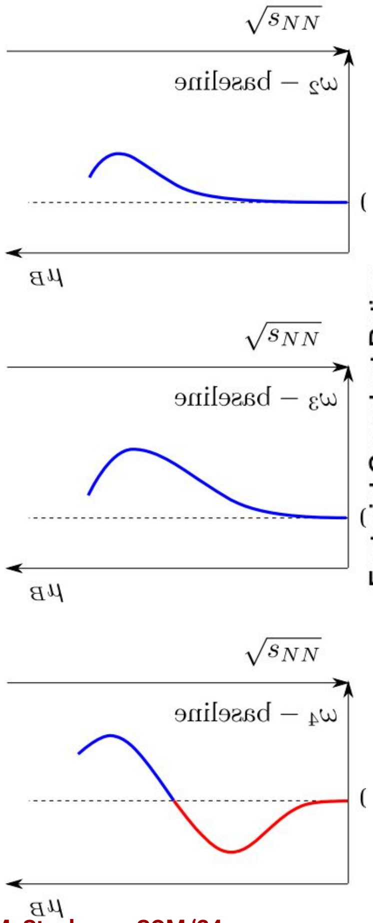
(universal EOS) critical χ_n:



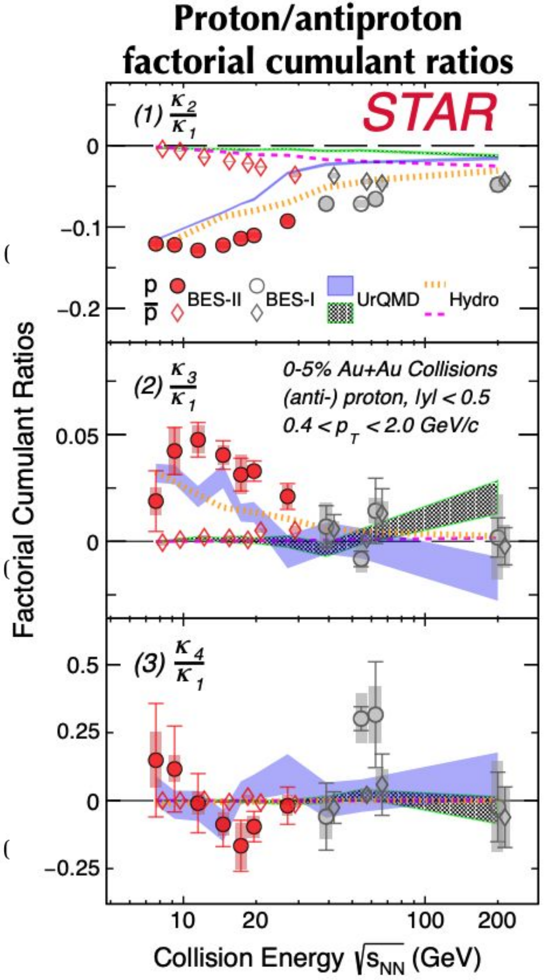
A.Bzdak et. al. Phys.Rept. 853 (2020)

BES-II data Vs Theory

- Susceptibilities along the freezeout line.
- Expected signatures: bump in ω_2 and ω_3, dip then bump in ω_4 for CP at μ_B > 420 MeV



M. Stephanov SQM ‘24
A.Bzdak et. al. Phys.Rept. 853 (2020)



HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
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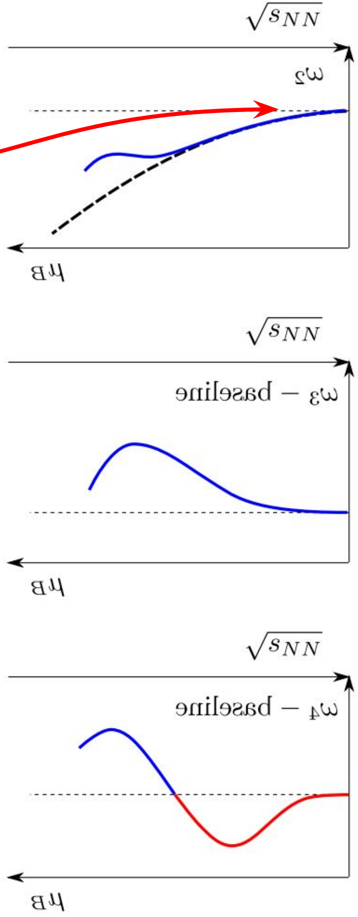
Conclusion

- Subtract the baseline
- Qualitatively agrees with non-monotonic expectations from CP, not only in n = 4 factorial cumulant, but n = 3 and n = 2.
- To produce such signatures the CP has to be at μB > 420 MeV. Agreement with recent theory estimates by different approaches.



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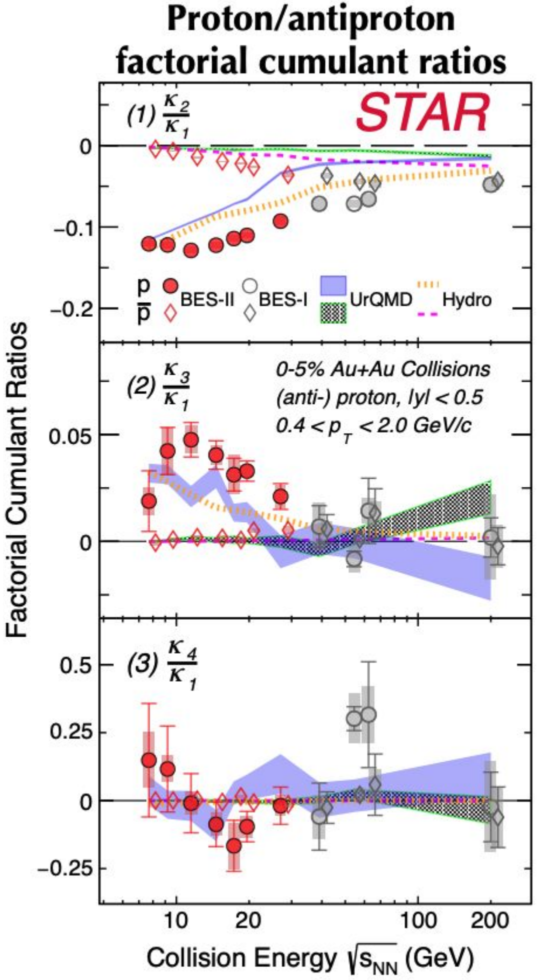

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
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Results:
Transverse Momentum Correlations

Transverse Momentum Correlations

- High-energy kinematics and Quantum Chromodynamics (QCD) generate correlations between the first partons produced at the onset of a nuclear collision [1].

- Transverse momentum correlators have been proposed as a measure of these correlations and as a probe for the critical point of quantum chromodynamics [2].

$$C_m = \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$$

$$\langle (p_{t,i} - \langle p_t \rangle)(p_{t,j} - \langle p_t \rangle) \rangle$$

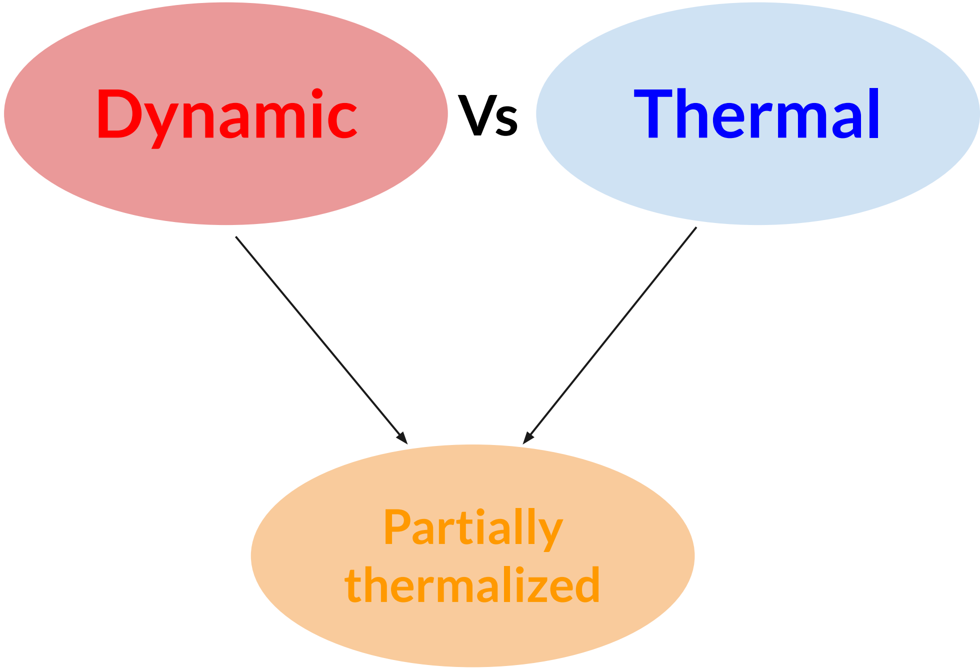
$i \neq j$

[1]: S. Gavin. Physical Review Letters, 92(16)

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

Correlator Contributions

- ❖ Correlators have contributions from dynamic correlations from the first partons produced.
- ❖ These correlations get erased by scattering and thermalization.
- ❖ The rapid expansion and short lifetime of the system fight the forces of isotropization, preventing certain correlations from being completely thermalized.
- ❖ To understand early correlations, study rapidity dependence!



Correlator Contributions

- Correlators have contributions from dynamic correlations from the initial partons produced.
- These correlations get erased by scattering and thermalization.
- The rapid expansion and short lifetime of the system fight the forces of isotropization, preventing certain correlations from being completely thermalized.
- Determined by particle production mechanisms.
- Determined by thermalization and equilibrium fluctuations.

$$< p_T > = < p_T >_o S + < p_T >_e (1 - S)$$

$$S \propto e^{-N}$$ (Collision probability)

$$< \delta p_T \delta p_T > = < \delta p_T \delta p_T >_o S^2 + < \delta p_T \delta p_T >_e (1 - S)^2$$

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

o: original
e: equilibrium

Correlator Contributions

❖ Transverse momentum fluctuations have contributions from multiplicity fluctuations as well

➢ R is the robust variance and depends on N_{part}

➢ Measures deviation from Poissonian statistics

➢ Robust quantity (independent of detector efficiency)

➢ Roughly constant for a given centrality class.

Quantified

$$R = \frac{<N(N-1)> - <N>^2}{<N>^2}$$

C. Pruneau et. al. Phys.Rev.C 66 (2002) 044904

Correlator Baseline Expectations

- Approximation

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

- $F(\zeta_T)$ function of ratio of the correlation length (ζ_T) to the transverse size.

- Assumptions:
  - Central collisions are locally thermalized
  - Ratio of correlation length (ζ_T) to the transverse size remains constant.
  - R is constant

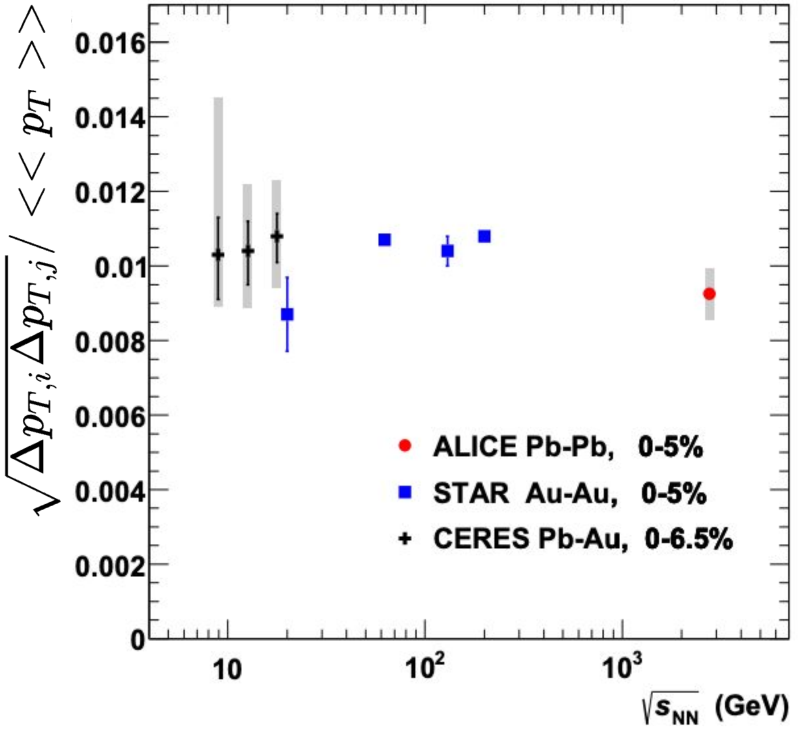
$$\frac{\sqrt{<\Delta p_{t,i} , \Delta p_{t,j}>}}{<p_t>} = \left(\frac{F(\zeta_T)R}{1+R}\right)^{1/2}$$

CONST of Collision Energy (BASELINE)

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

Correlator Vs Collision energy

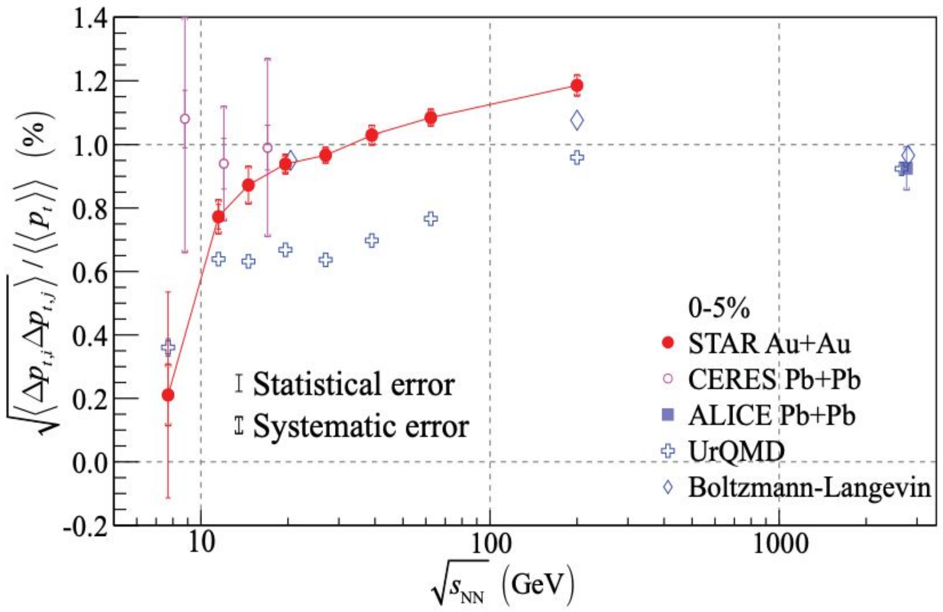
- The correlation observable may have a dependence on energy, so we scale it with $\langle\langle p_T \rangle\rangle$.
- Efficiency independent observable.
- Make a direct comparison with the CERES and ALICE.
- No dependence on collision energy observed. **(CONST!)**



STAR, Phys.Rev.C72:044902,2005
ALICE, Eur. Phys. J. C 74, 2014
CERES, Nucl.Phys.A811:179-196,2008

Correlator Vs Collision energy

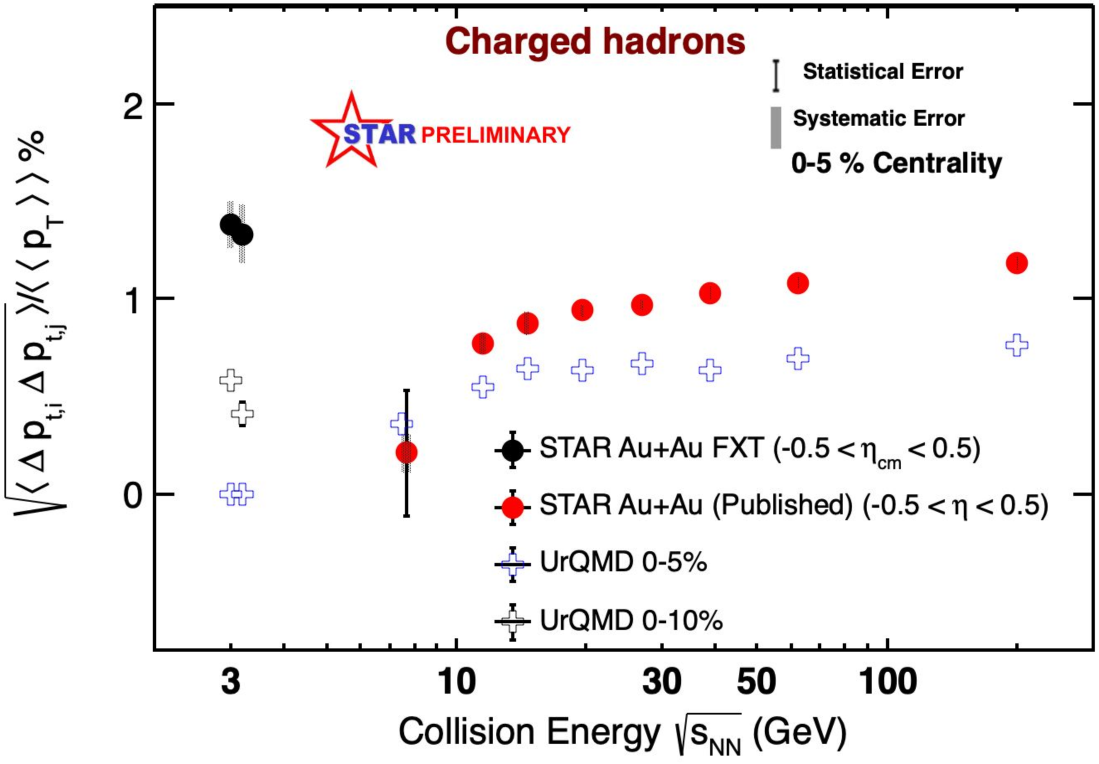
- Boltzmann-Langevin implies thermalized systems.
- UrQMD deviates from data consistently at all energies.
- A significant beam energy dependence was found for p_T correlations.



STAR, Phys.Rev.C 99, 2019
CERES, Nucl.Phys.A811:179-196,2008
ALICE, Eur. Phys. J. C 74, 2014

Correlator Vs Collision energy

- We see a departure from monotonicity
- Change in correlation length ζ_T ?
- p_T fluctuations has contributions from temperature and multiplicity fluctuations.

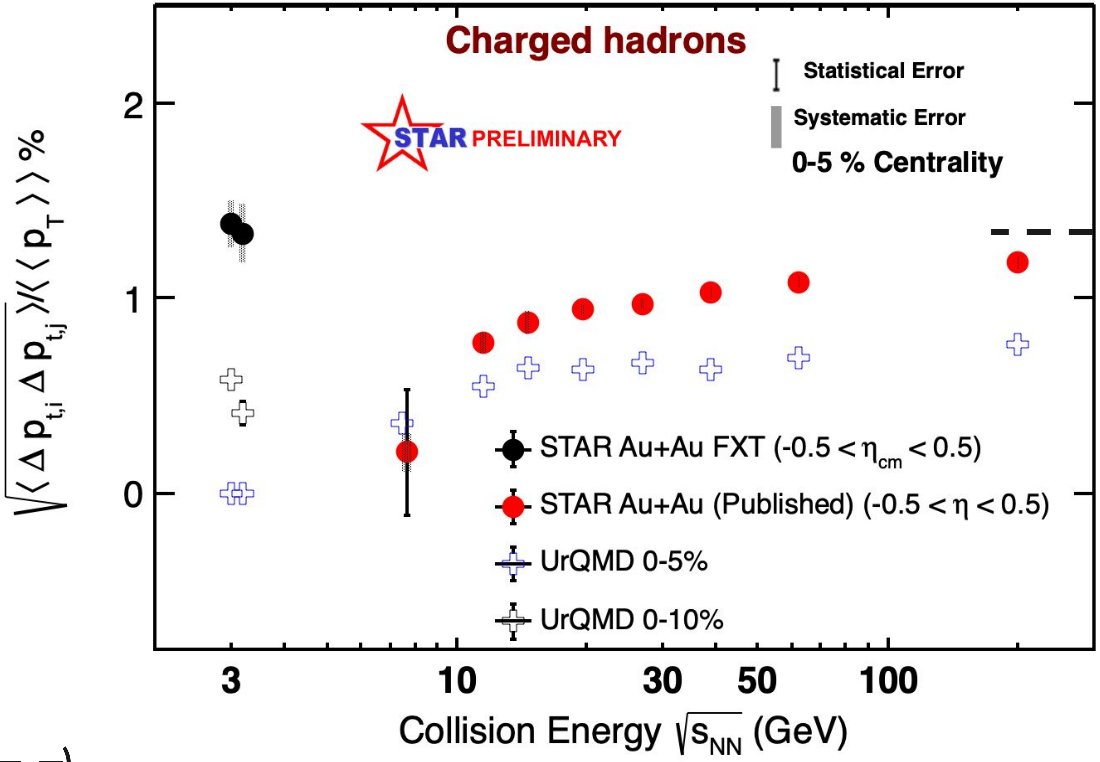


Sumit Basu et. al., Phys.Rev.C 94, 2016

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

Correlator Vs Collision energy

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

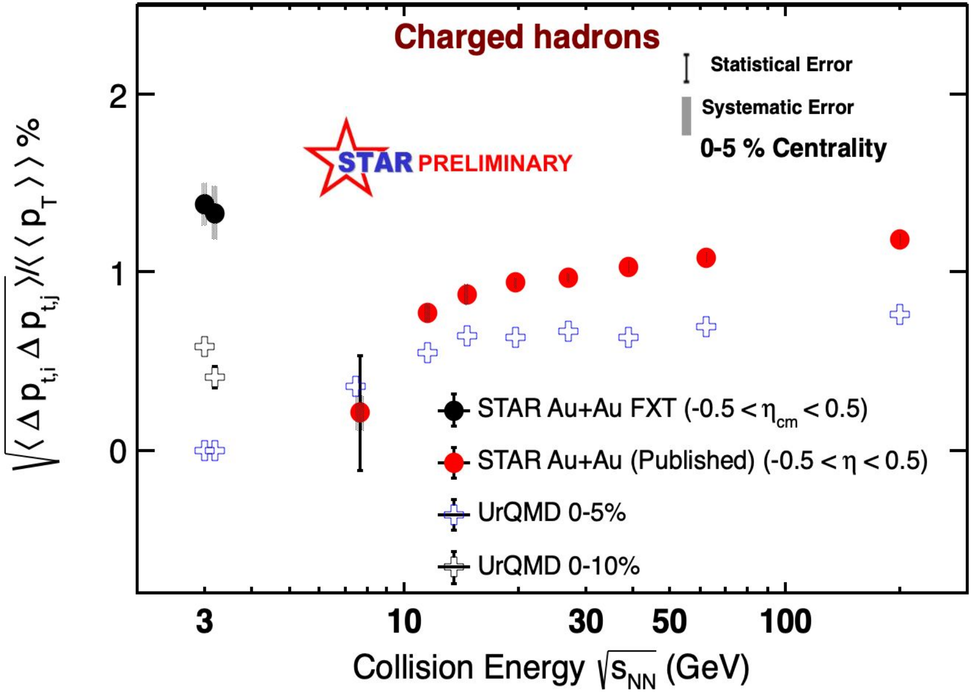


S. Gavin, Phys. Rev. Lett. 92, 162301

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

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.



Summary

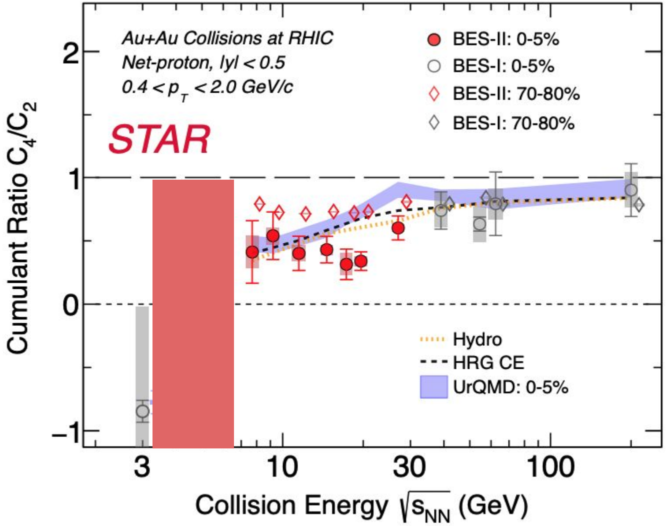
1. Precision measurement of net-proton number fluctuations in Au+Au collisions from STAR BES-II reported. Centrality and energy dependence discussed.

2. Measured net-proton C_4/C_2 in 0-5% central collisions shows clear deviation at $\sqrt{s_{NN}}$ = 19.6 GeV for all non-CP model calculations with a significance level of 3.2 – 4.7σ

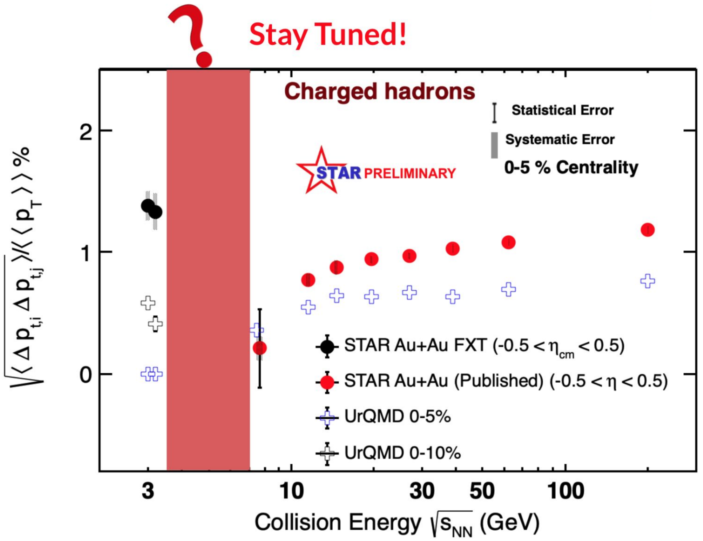
3. Factorial Cumulants are qualitatively described by CP signatures.

4. First measurement of Δp_T-Δp_T correlators at high baryon density region.

5. Δp_T-Δp_T show a non-monotonic behaviour in 0-5% central collisions a function of collision energy.



Stay Tuned!



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1. Temperature Fluctuations in Multiparticle Production - Phys. Rev. Lett. 75, 1044

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

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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)

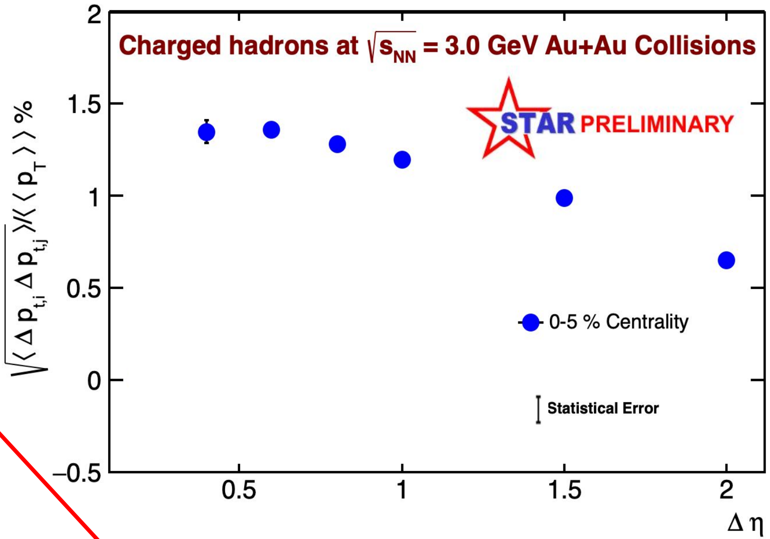
8. Traces of Thermalization from p_T Fluctuations in Nuclear Collisions - S. Gavin, Phys. Rev. Lett. 92, 162301 (2004)

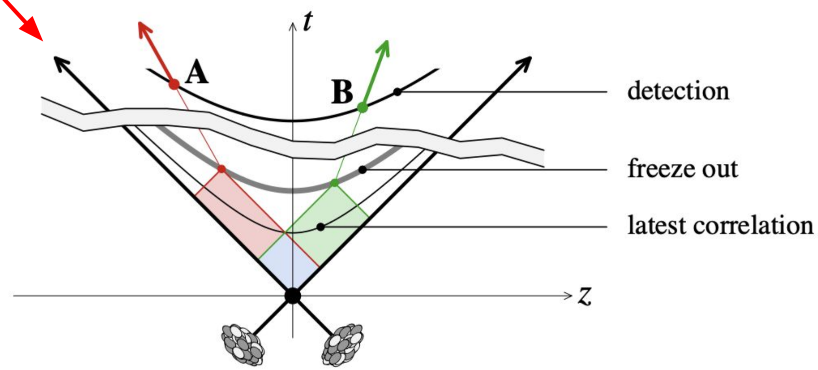
BACKUP

Correlator Vs Acceptance

- Long range rapidity correlations imply early correlations [1].
- Early correlations from hadronic or partonic interactions?
- Delve deeper into source for early correlations.

*Δη : Acceptance window around mid-rapidity

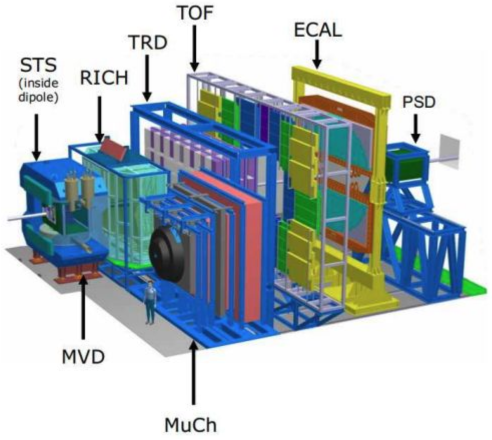




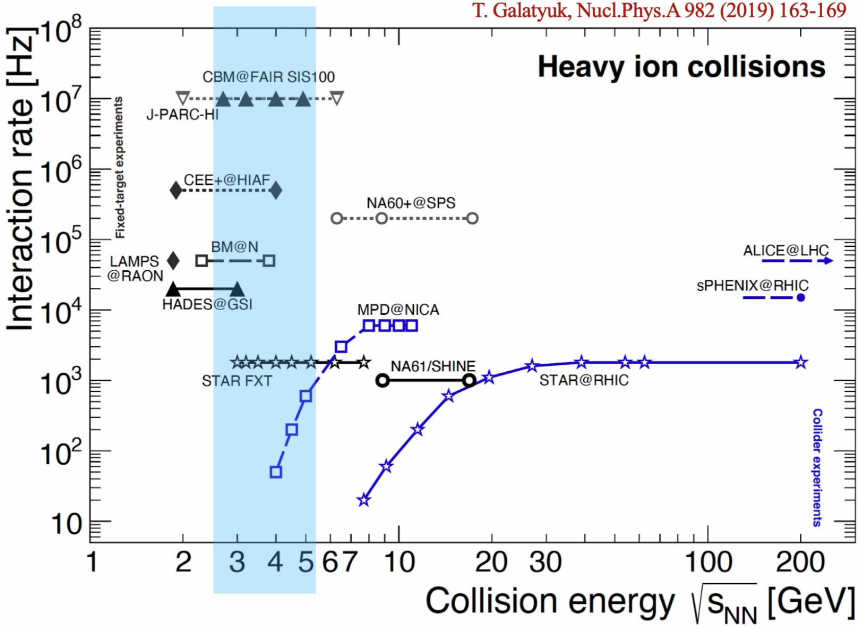
[1] : L. Mclerran et. al. Nucl.Phys.A810:91-108, 2008

Facility for Anti-proton and Ion Research

- $\sqrt{s_{NN}}$ = 2.5-4.9 GeV Au+Au
- Interaction rates upto 10 MHz
- Optimal for CP searches!



CBM at FAIR SIS100

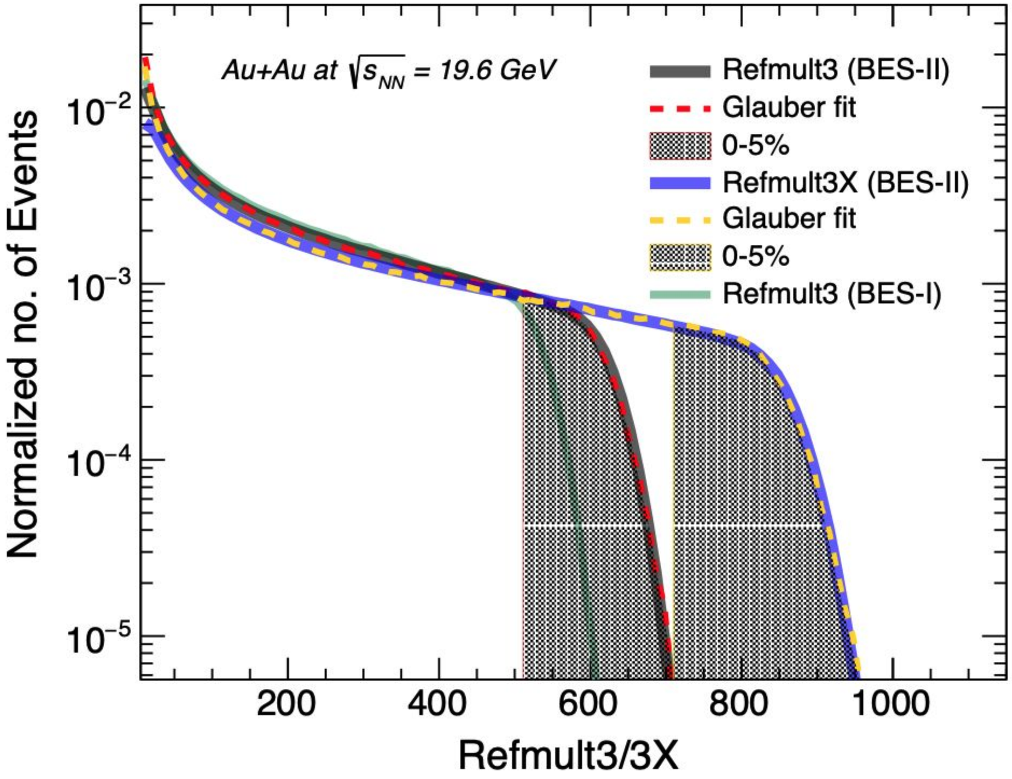


- Good low p_T coverage
- Mid-rapidity coverage

BES-II Scan of Proton Cumulants

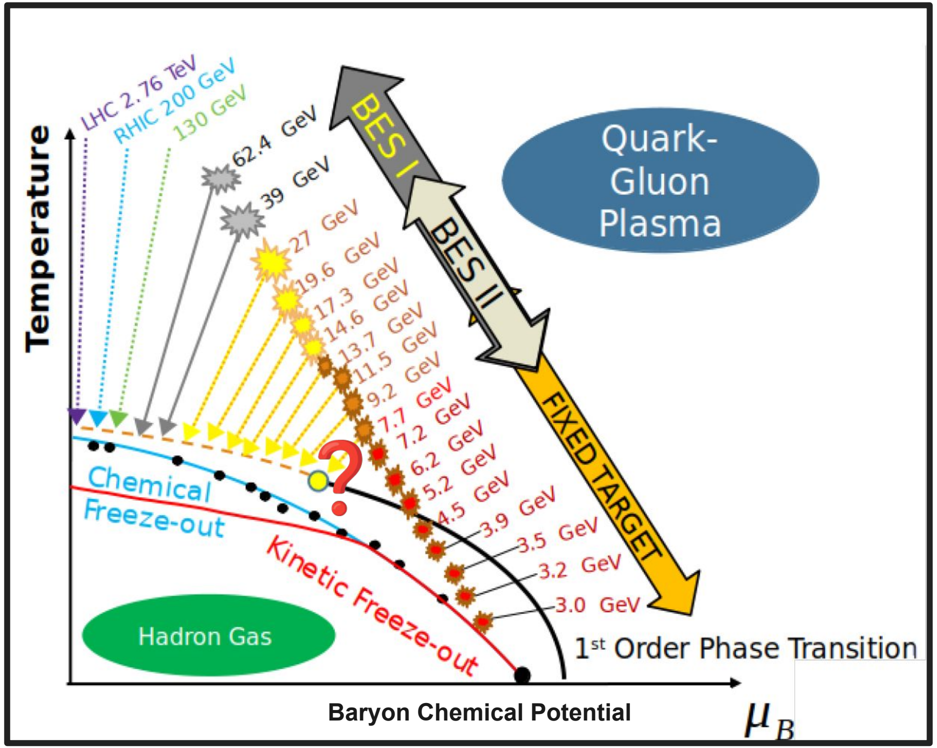
Centrality Definition:

- Defined using charged particle multiplicity measured by STAR
- Exclude protons and antiprotons to avoid self correlation
- **Refmult3:** Charged particle multiplicity excluding protons measured within $|\eta| < 1.0$
- **Refmult3X:** Charged particle multiplicity excluding protons measured within $|\eta| < 1.6$

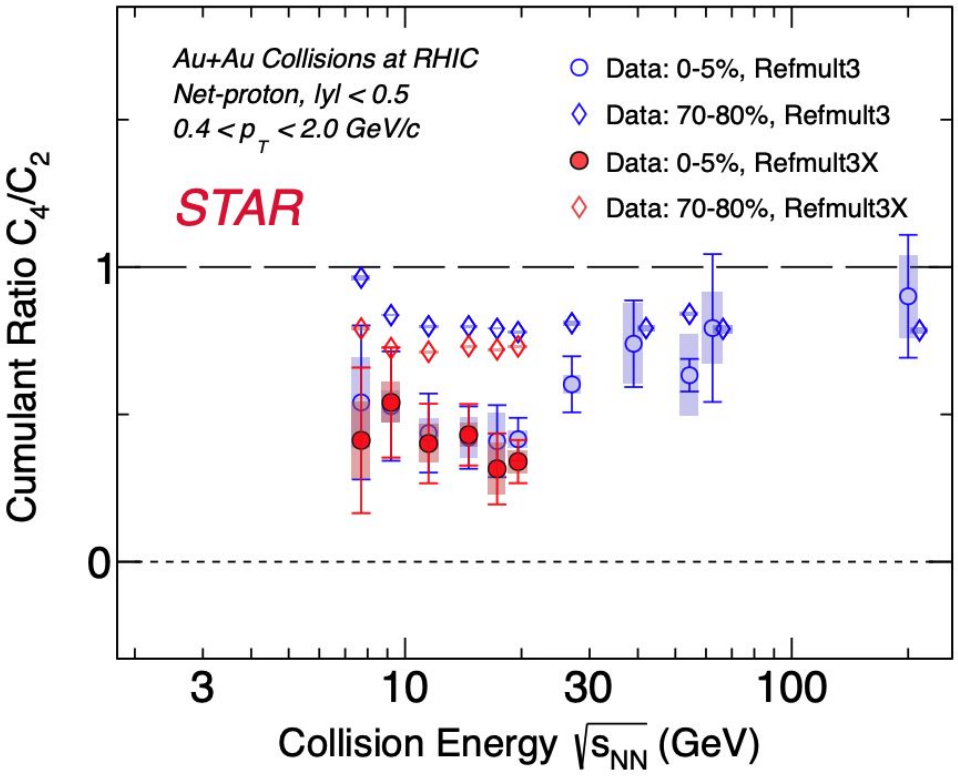


RHIC Beam Energy Scan

- 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 $\sqrt{s_{NN}}$ = 3.0 GeV.



Centrality resolution dependence on C_4/C_2



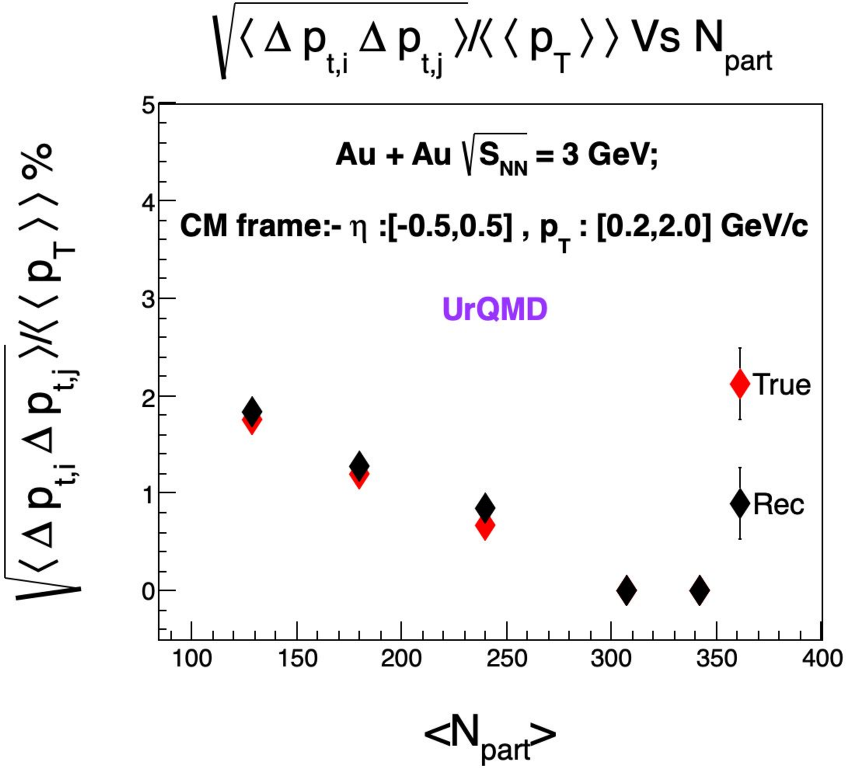
1. 0-5% centrality results show good agreement between Refmult3 and Refmult3X

2. Weak effect of centrality resolution on C_4/C_2 for central collisions.

3. BES-II results shown hereafter are with Refmult3X

Closure Test

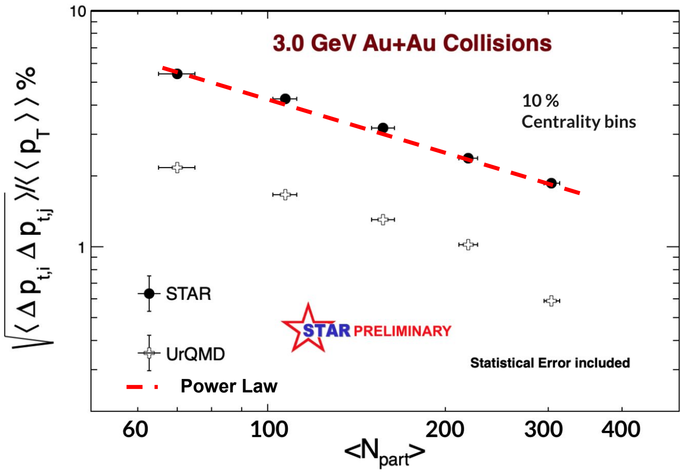
- The relative uncertainties $\sqrt{C_m}/\langle\langle p_T\rangle\rangle$ on are generally smaller than those on C_m because most of the sources of uncertainties lead to correlated variations of $\langle\langle p_T\rangle\rangle$ and C_m that tend to cancel in the ratio.
- Closure test was performed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

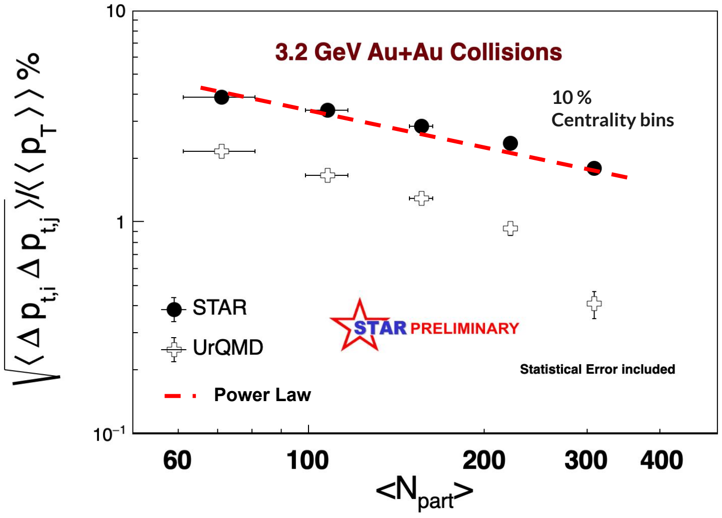


Correlator Vs Centrality

- **Monotonic increase** in decreasing centrality.
- UrQMD **underpredicts** the data at both energies.
- Power law **able to describe these energies**, need to delve deeper into centrality bin width dependence.

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





Partial Thermalization

- ❖ Scattering among these partons leads to dissipation that works to erase these correlations, making the system as thermal and locally isotropic as possible.

- ❖ The rapid expansion and short lifetime of the system fight the forces of isotropization, preventing certain correlations from being completely thermalized.

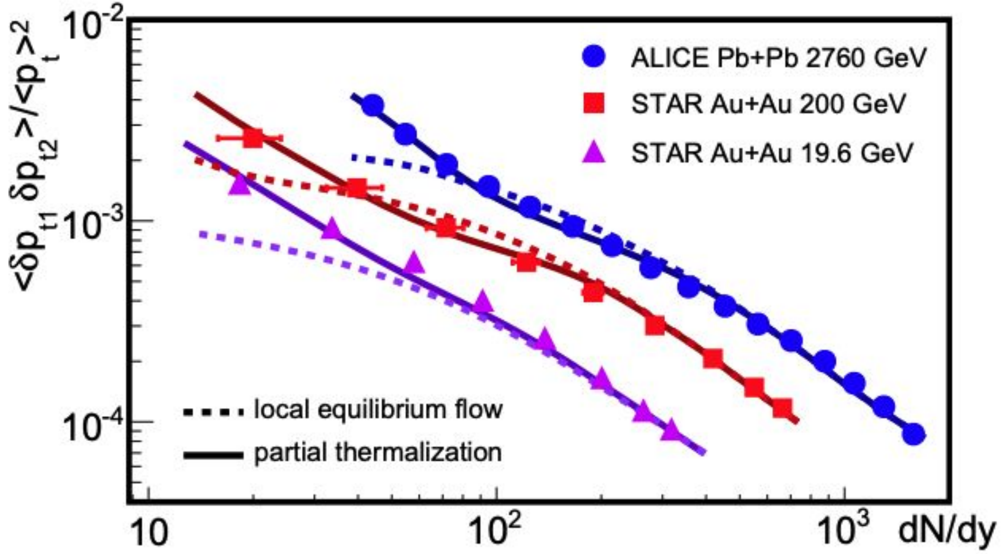
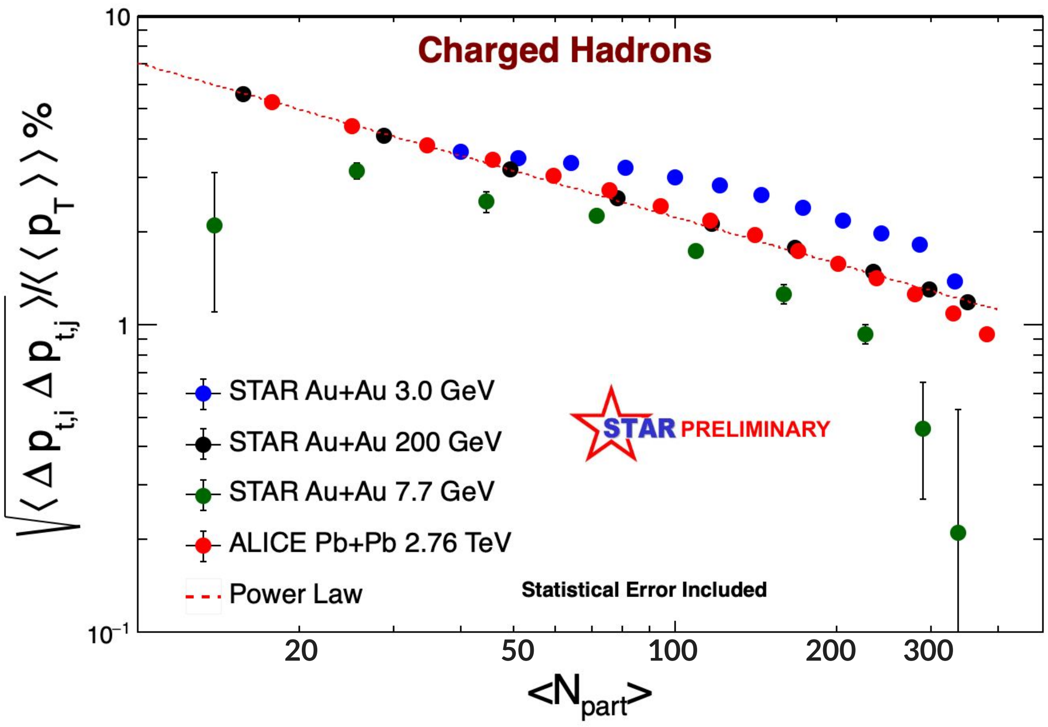


FIG. 1. (color online) Transverse momentum fluctuations as a function of the charged-particle rapidity density dN/dy for partial thermalization (solid curves) and local equilibrium flow (dashed curves). Data (circles, squares, and triangles) are from Refs. [27], [31], and [32, 33], respectively.

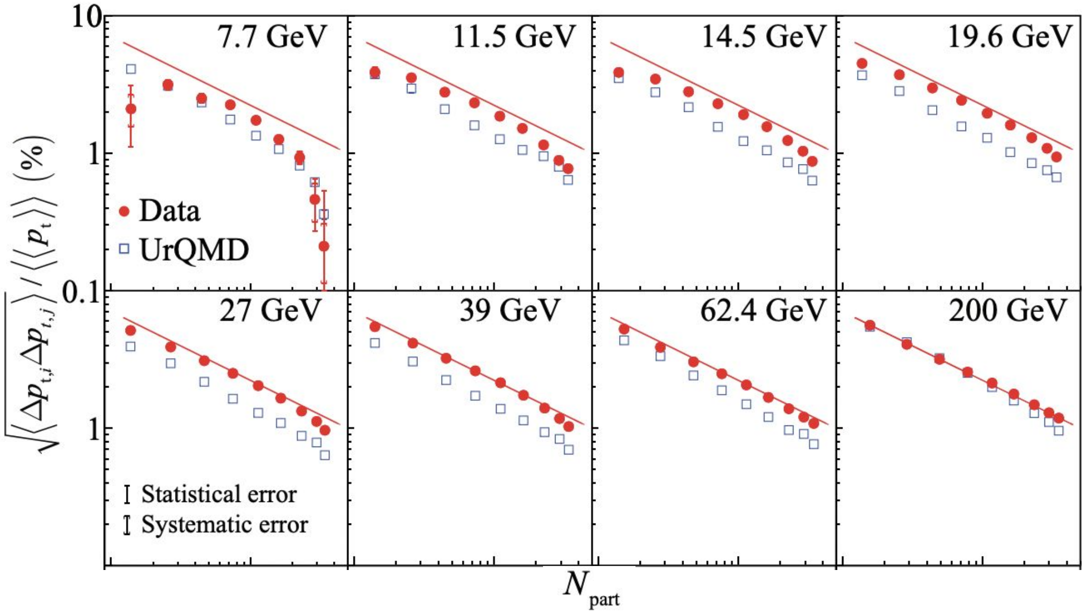
Correlator Vs Centrality

- 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 and 3.2 GeV Au+Au collisions as well.



Correlator Vs Centrality

- Power law seems to describe the data at 200 GeV , implying an independent sources scenario.
- Most sources of p_T fluctuations are stochastic, encompassing fluctuations in nucleon and parton positions within the initial state [1].
- UrQMD tends to underpredict the data at all energies.



STAR, Phys.Rev.C 99, 2019

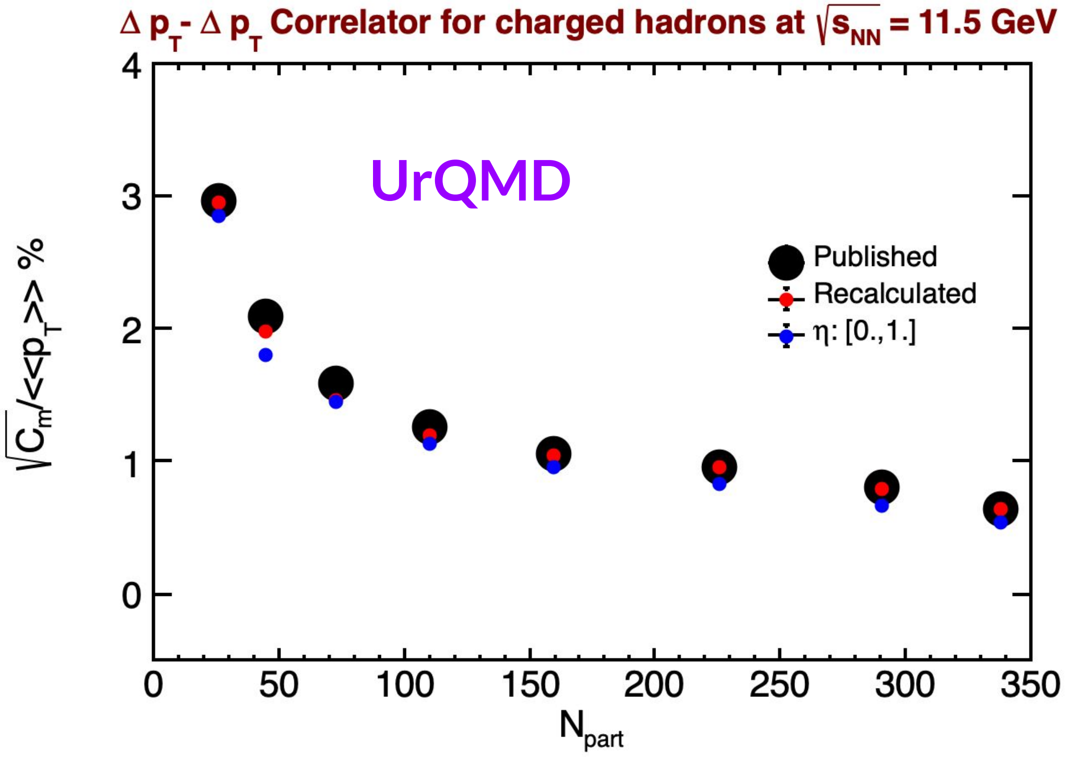
Power Law: $$\frac{\sqrt{C_m}}{<<p_T>>} \propto < N_{part} >^b$$

[1] : ATLAS-CONF-2023-061

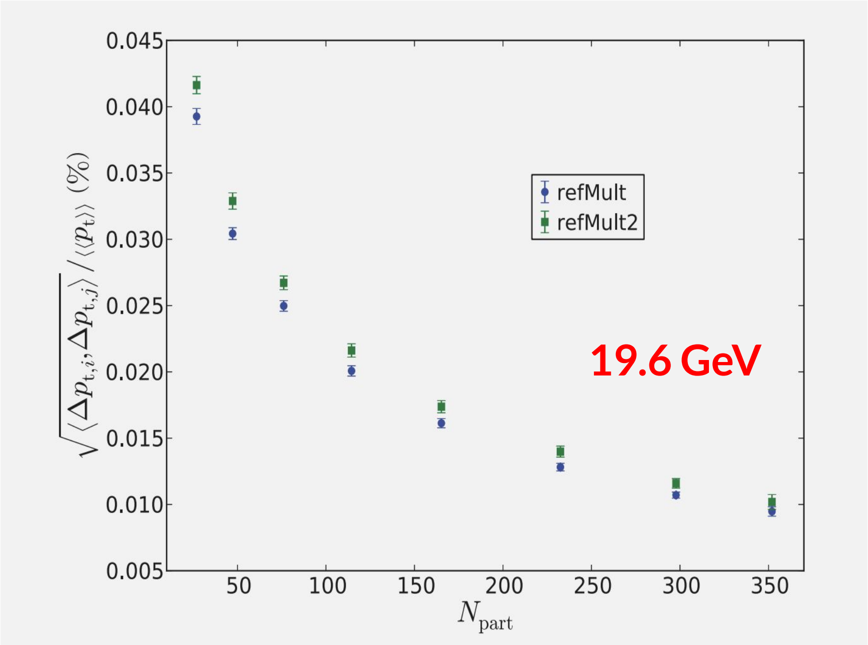
UrQMD with asymmetric Acceptance

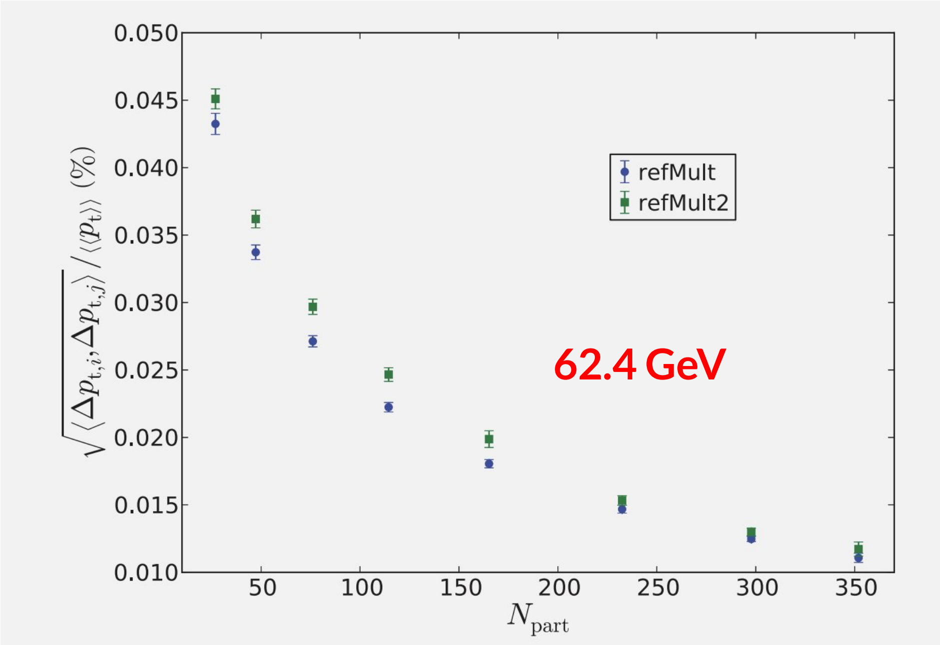
- To verify the UrQMD calculations, the analysis was carried out at a published energy.

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



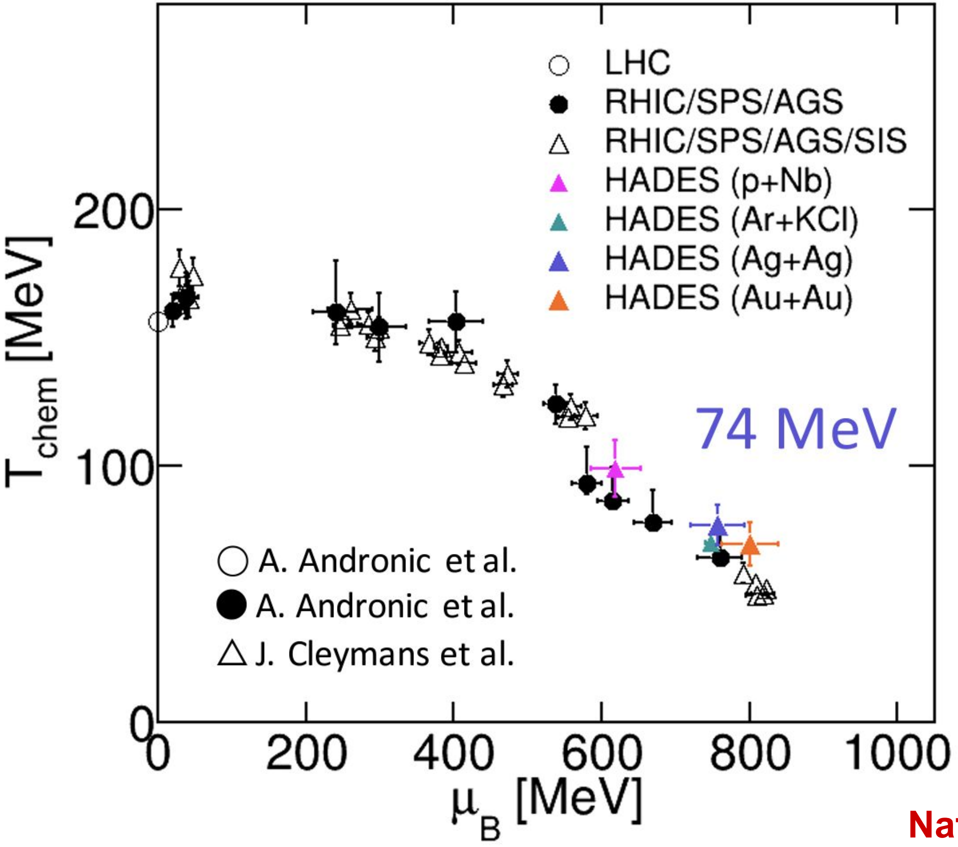
Auto Correlation Studies





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

T_{chem} Vs μ_B

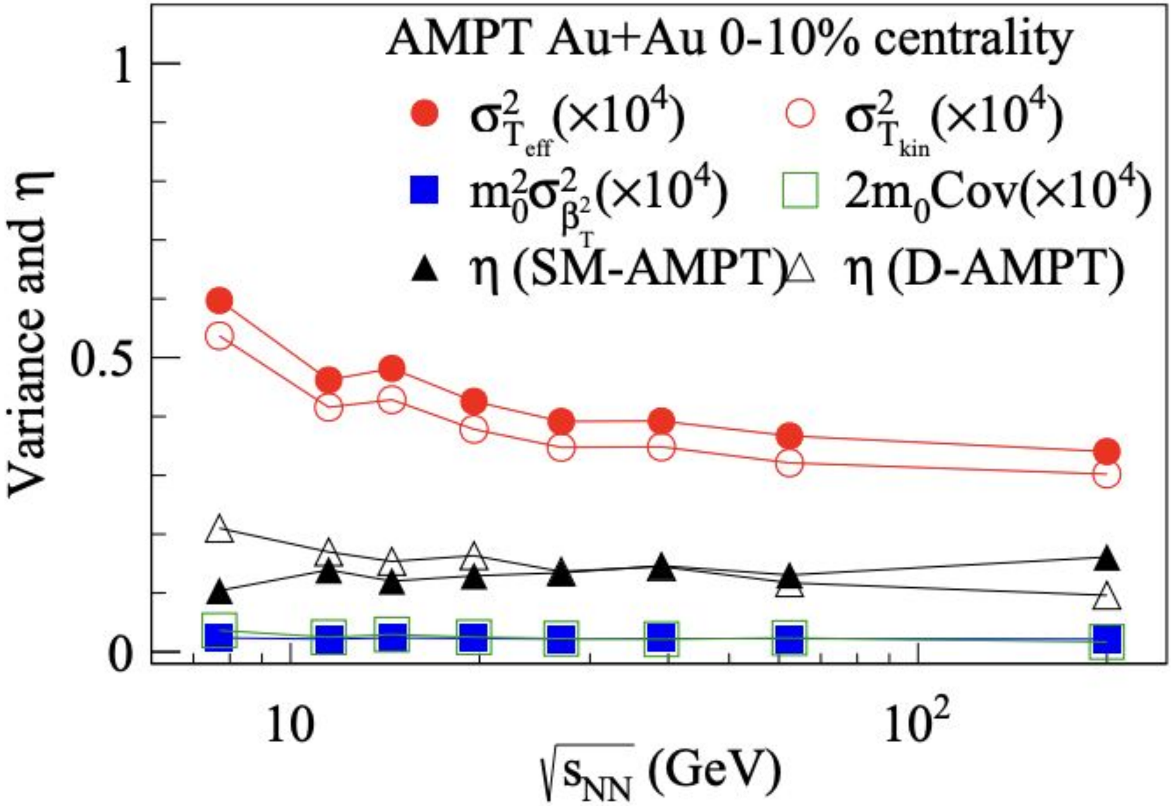


Nature Phys. 15 (2019) 10, 1040-1045

Contributions to temperature fluctuations

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

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



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