Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

NATIONAL SCIENCE CENTRE
POLAND

Correlations and fluctuations measured by the STAR experiment

Daniel Wielanek for the STAR Collaboration

New Trends in High-Energy and Low-x Physics

1-5th September 2024

Warsaw University of Technology

partially funded by DoE

U.S. DEPARTMENT OF ENERGY | Office of Science

RESEARCH UNIVERSITY
EXCELLENCE INITIATIVE

Outline

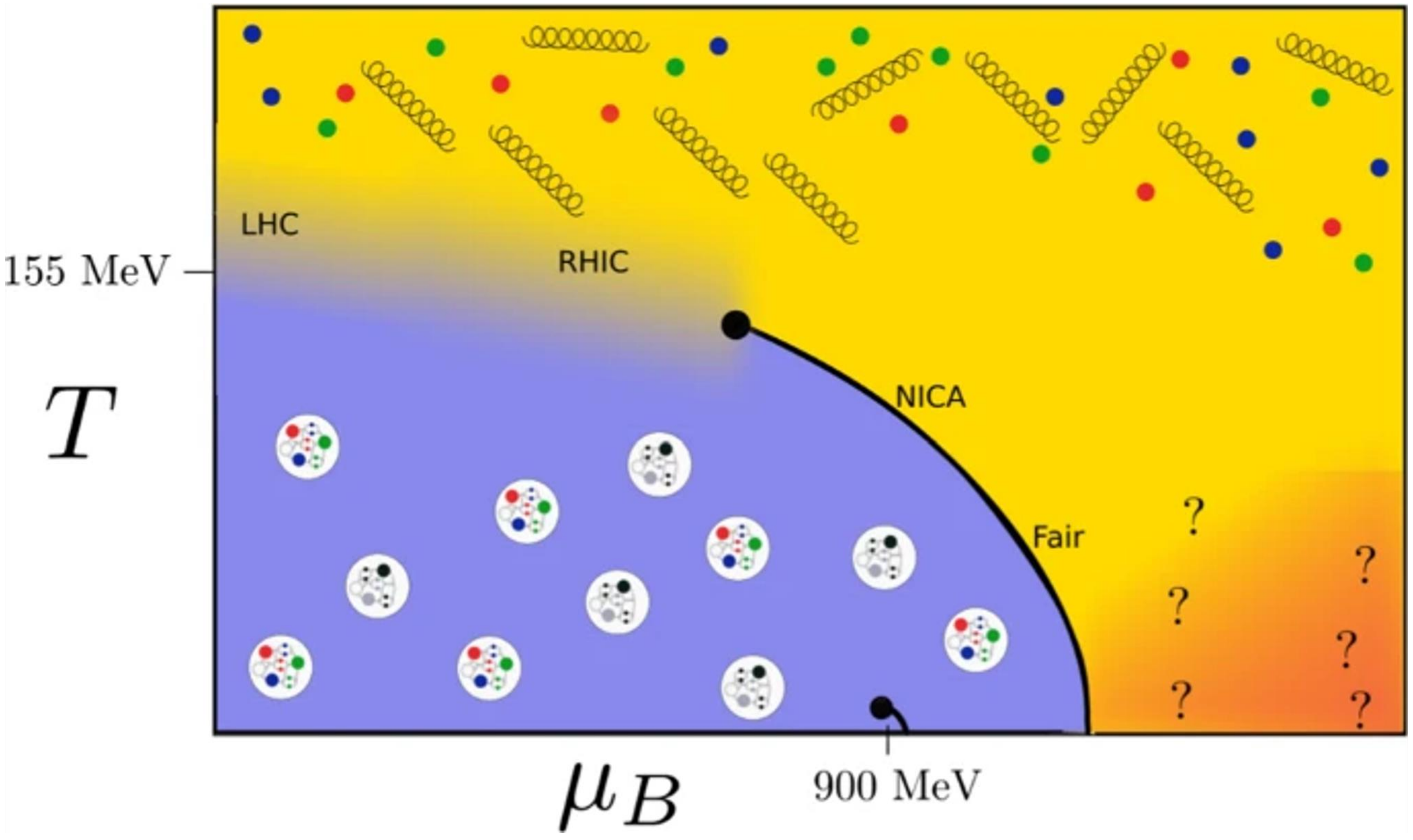
- Motivation
- STAR experiment
- Results
  - Fluctuations & criticality
  - Femtoscopy & interactions
- Summary & plans

Motivation

Motivation

Probing phase diagram of QCD matter

- High $\sqrt{s_{NN}}$ →high T, low μ_B
  - Lattice QCD calculations available
  - Crossover transition
  - Early Universe
- Medium $\sqrt{s_{NN}}$ → medium μ_B & T
  - Critical Point?
  - 1st order PT/crossover
- Low $\sqrt{s_{NN}}$ → high μ_B , low T
  - Nature of neutron stars
  - Onset of deconfinement
- Different collision energies → probing QCD phase diagram

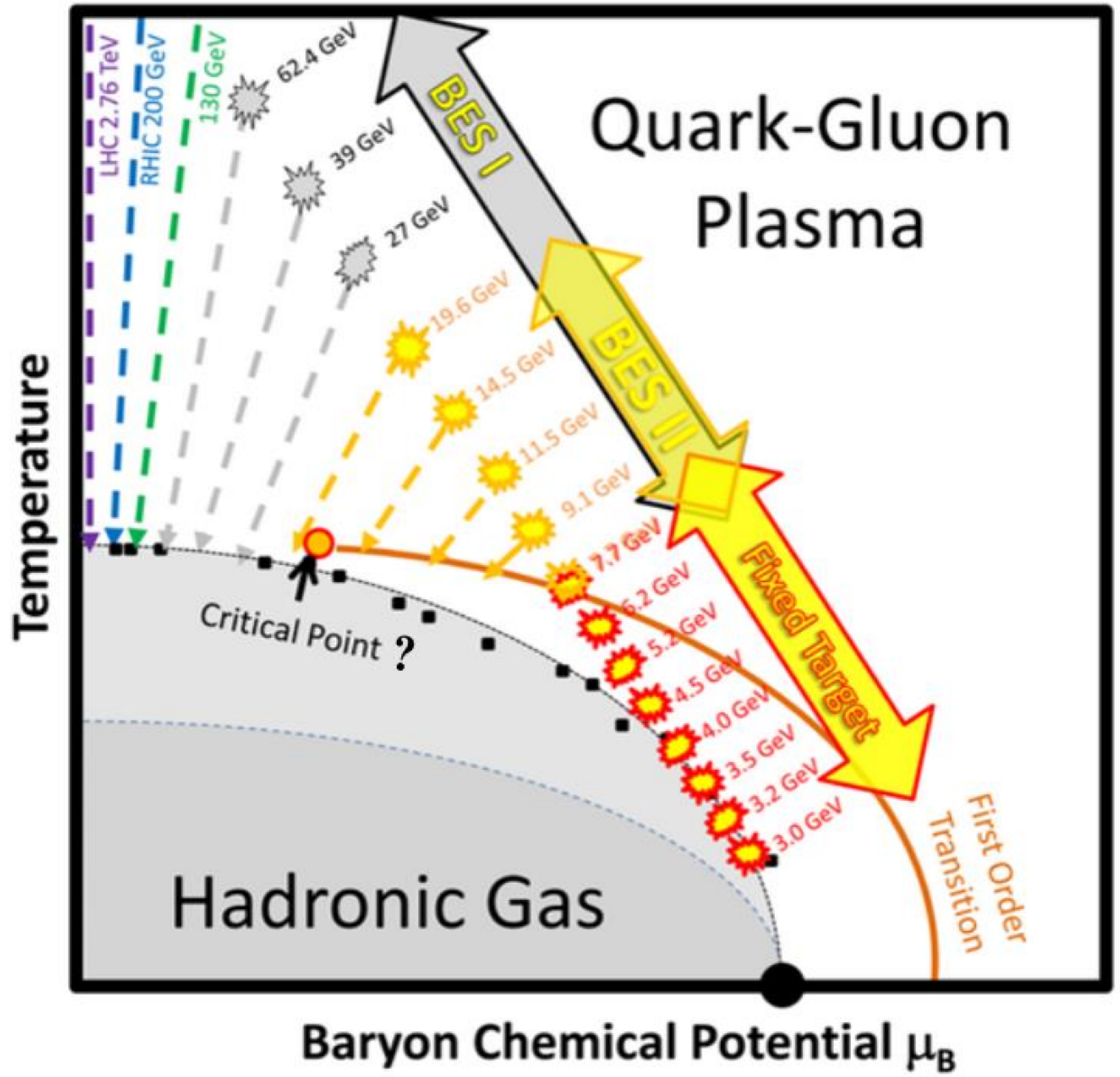


Overview of the QCD phase diagram, Recent progress from the lattice, The European Physical Journal A,
•Volume 57, article number 136, (2021) , Jana N. Guenther

Motivation

STAR program:

- High collision energies -> QGP properties
- Beam Energy Scan I, II and Fixed Target
  - onset of deconfinement
  - 1st order phase transition signatures
  - Critical Point



The STAR detector upgrade and future plan, Chi Yang, ICNFP2017

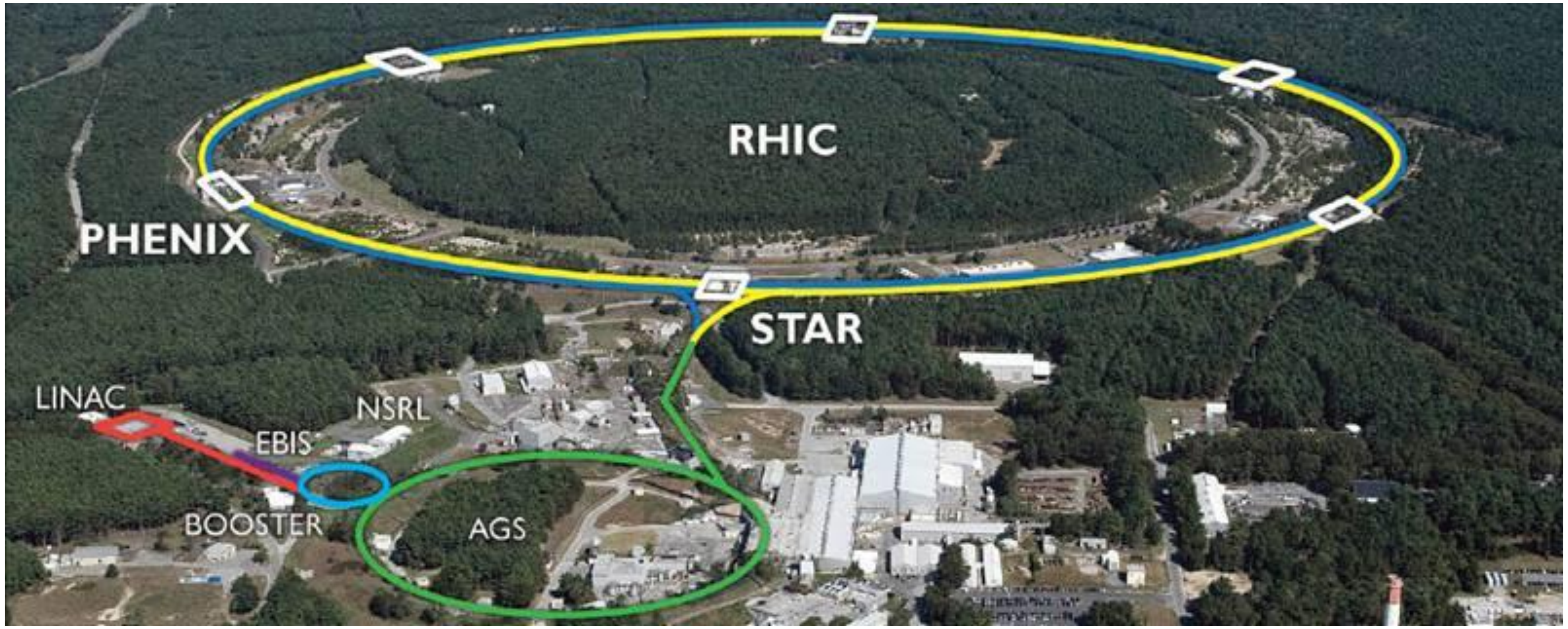
Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

STAR detector

Warsaw University of Technology

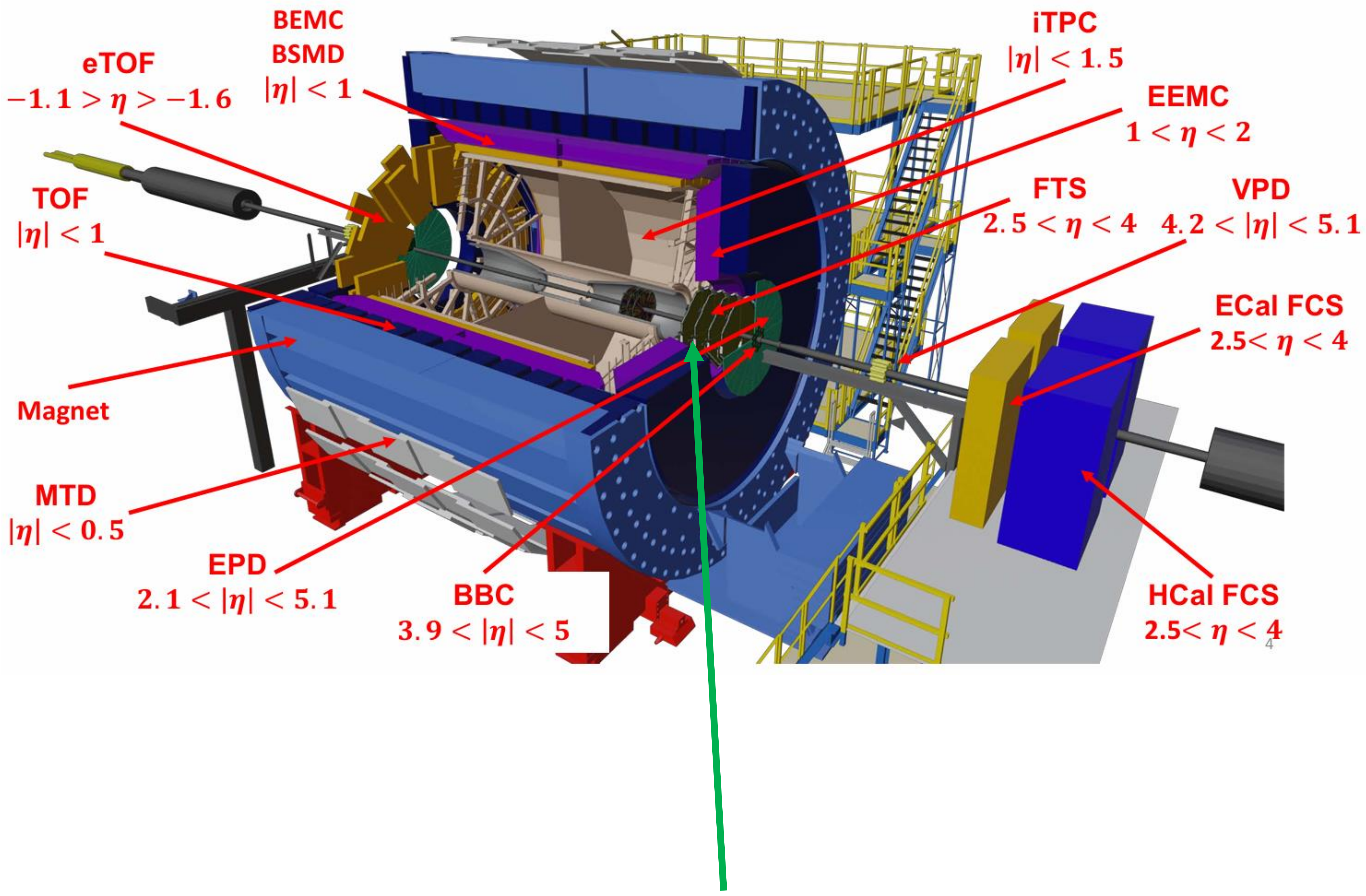
STAR experiment

STAR = Solenoidal Tracker At RHIC



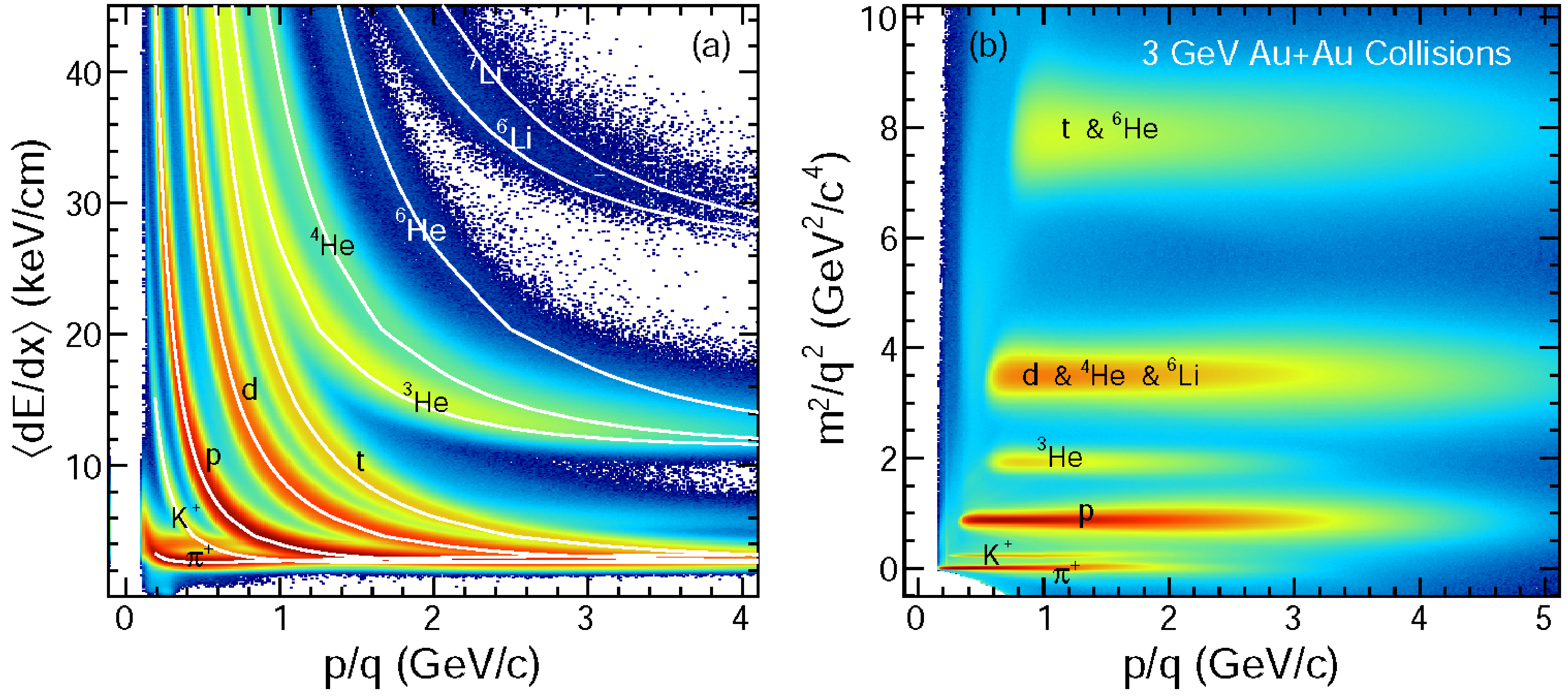
https://science.osti.gov/np/Facilities/User-Facilities/RHIC

STAR detector



Target (Fixed Target mode)

- Complex subdetectors system
- Excellent particle identification
- Numerous detectors upgrades tailored to achieve unique physics goals
- Full azimuthal acceptance



Light nuclei collectivity from √sNN = 3 GeV Au+Au collisions at RHIC, Physics Letters B Volume 827, STAR Collaboration

Warsaw University
of Technology

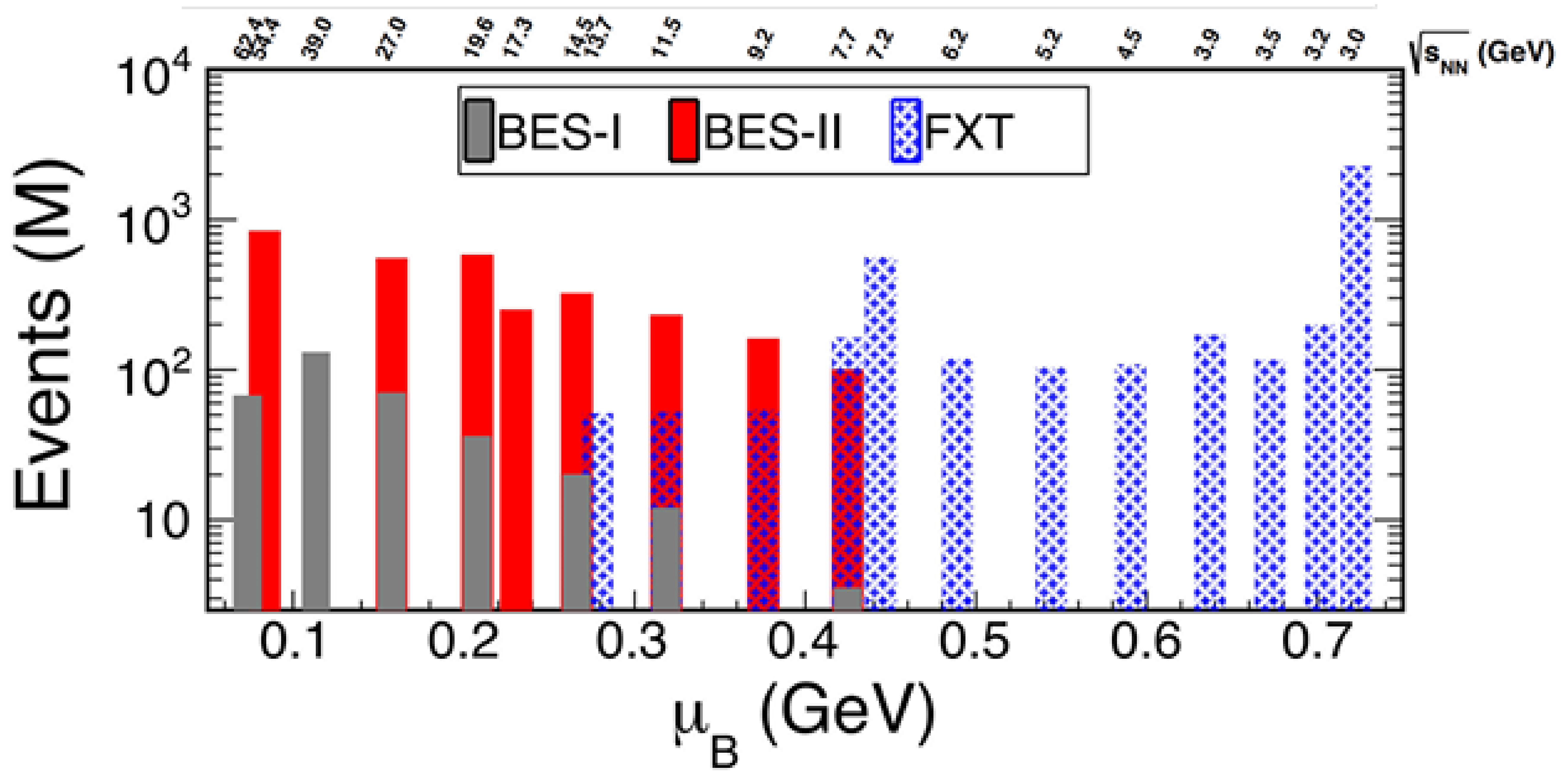
BES program

Beam Energy Scan I

- Scan of QCD phase diagram

Beam Energy Scan II/Fixed Target (FXT)

- more events registered
- better data quality e.g., increased acceptance (detector improvements iTPC, eTOF, EPD...)
- lower collision energies- extending the μ_B up to 750 MeV with FXT program



Korobitsyn, A. STAR Experiment Results from BES Program. *Phys. Part. Nuclei* **55**, 1037–1042 (2024).

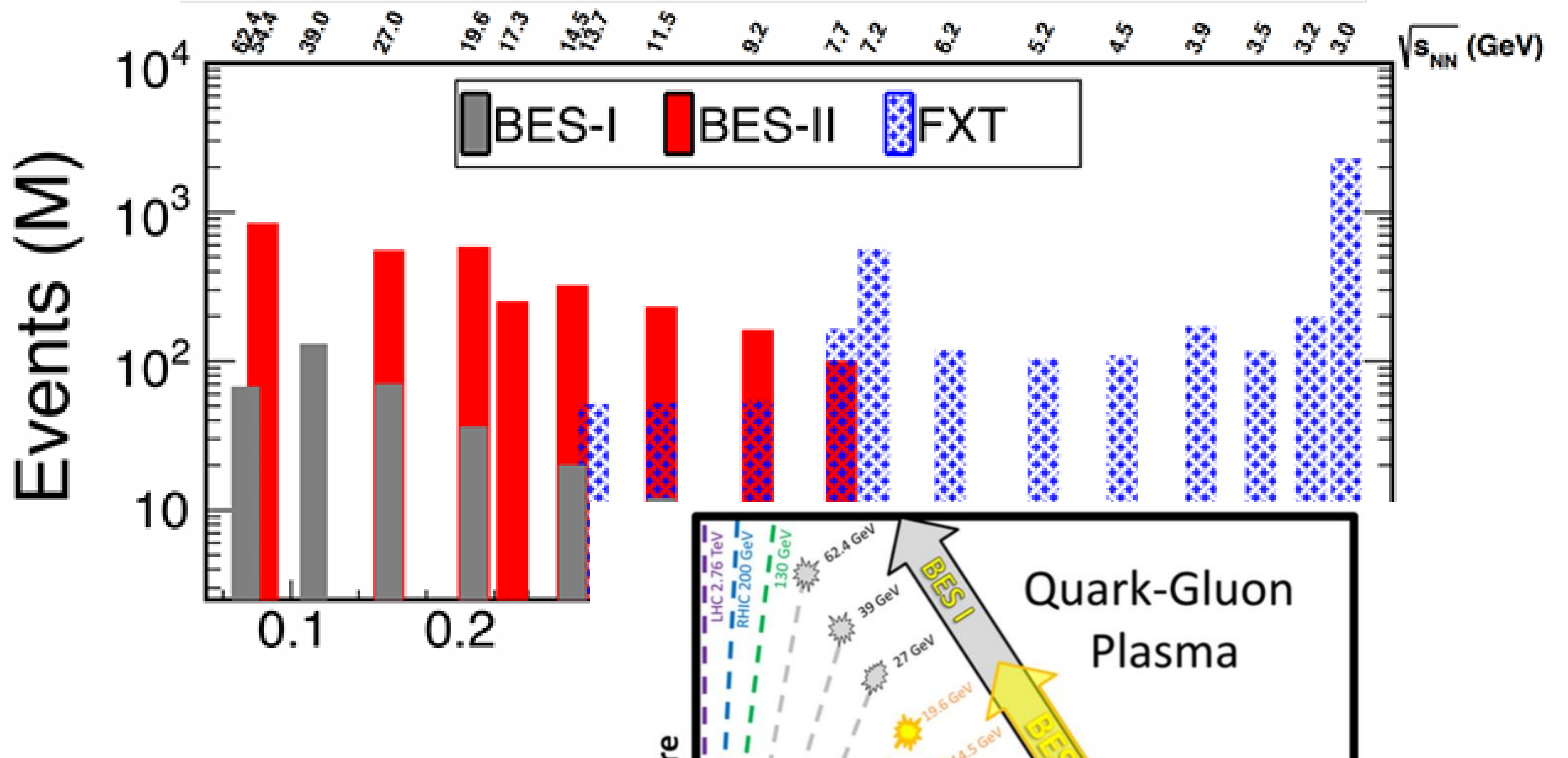
BES program

Beam Energy Scan I

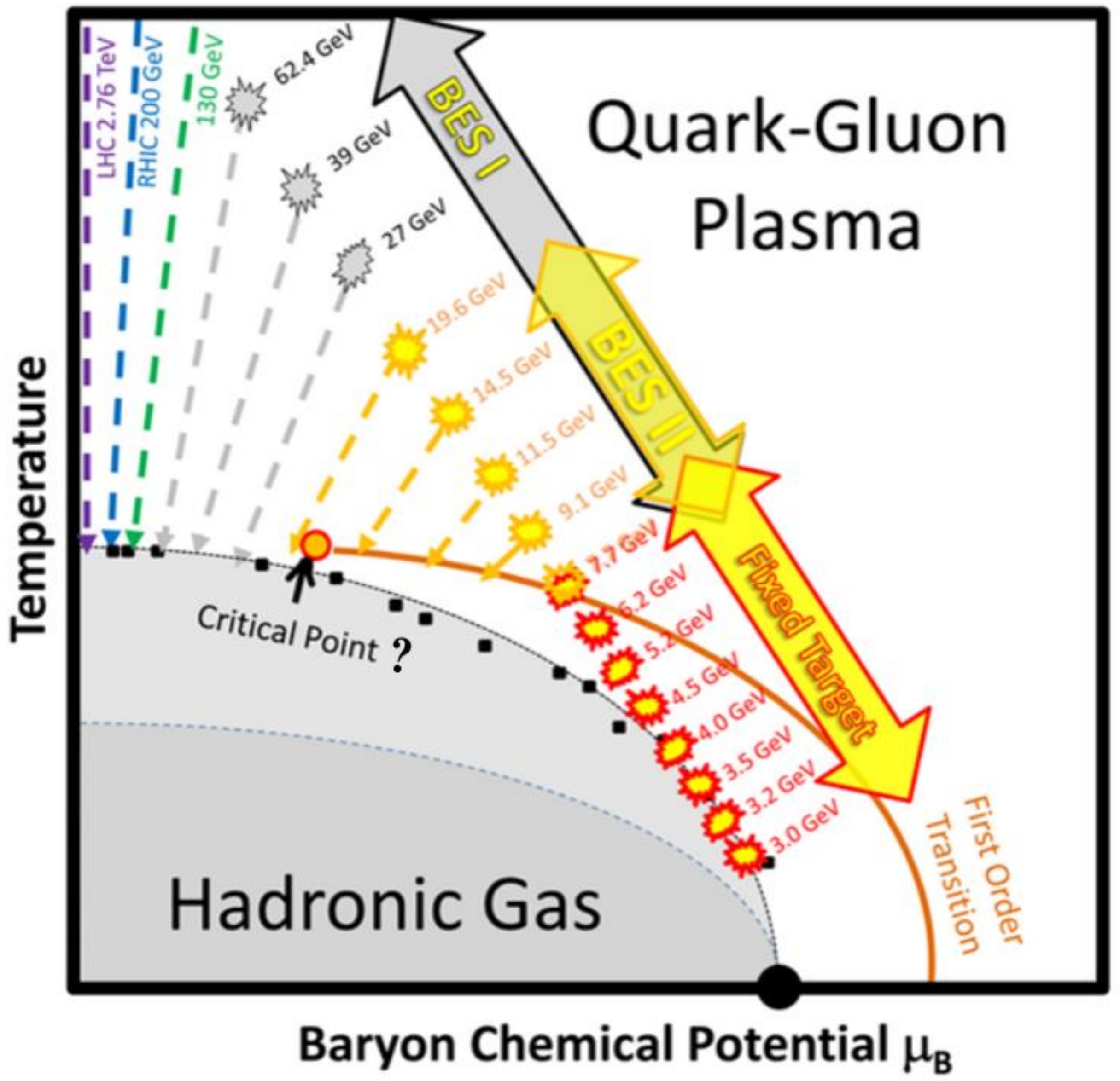
- Scan of QCD phase diagram

Beam Energy Scan II/Fixed Target (FXT)

- more events registered
- better data quality e.g., increased acceptance (detector improvements iTPC, eTOF, EPD...)
- lower collision energies- extending the μ_B up to 750 MeV with FXT program



Korobitsyn, A. STAR Experiment Re:



The STAR detector upgrade and future plan, Chi Yang, ICNFP2017

Fluctuations

Fluctuations

Fluctuations are sensitive to the correlation length (ξ).

$C_n^q = VT^3\chi_n^q$

Cumulants n=1-6:

$C_1 = \langle N\rangle$

$C_2 = \langle \delta N^2\rangle$

$C_3 = \langle \delta N^3\rangle$

$C_4 = \langle \delta N^4\rangle - 3\langle \delta N^2\rangle^2$

$C_5 = \langle \delta N^5\rangle - 5\langle \delta N^3\rangle\langle \delta N^2\rangle$

$C_6 = \langle \delta N^6\rangle - 15\langle \delta N^4\rangle\langle \delta N^2\rangle - 10\langle \delta N^3\rangle^2 + 30\langle \delta N^2\rangle^3$

$\delta N = N - \langle N\rangle$

Ratio of cumulants – no volume dependency -> cleaner signature of CP.

Some of them are well known:

Variance : $\sigma = \langle \delta N^2\rangle$

Skewness:

$S = \frac{\langle \delta N^3\rangle}{(\langle \delta N^2\rangle)^{3/2}}$ $S\sigma = \frac{C_3}{C_2}$

Kurtosis:

$\kappa = \frac{\langle \delta N^4\rangle}{(\langle \delta N^2\rangle)^2}$ $\kappa\sigma^2 = \frac{C_4}{C_2}$

Fluctuations

Fluctuations are sensitive to the correlation length (ξ).

$C_n^q = VT^3\chi_n^q$

Cumulants n=1-6:

$C_1 = \langle N \rangle$

$C_2 = \langle \delta N^2 \rangle$

$C_3 = \langle \delta N^3 \rangle$

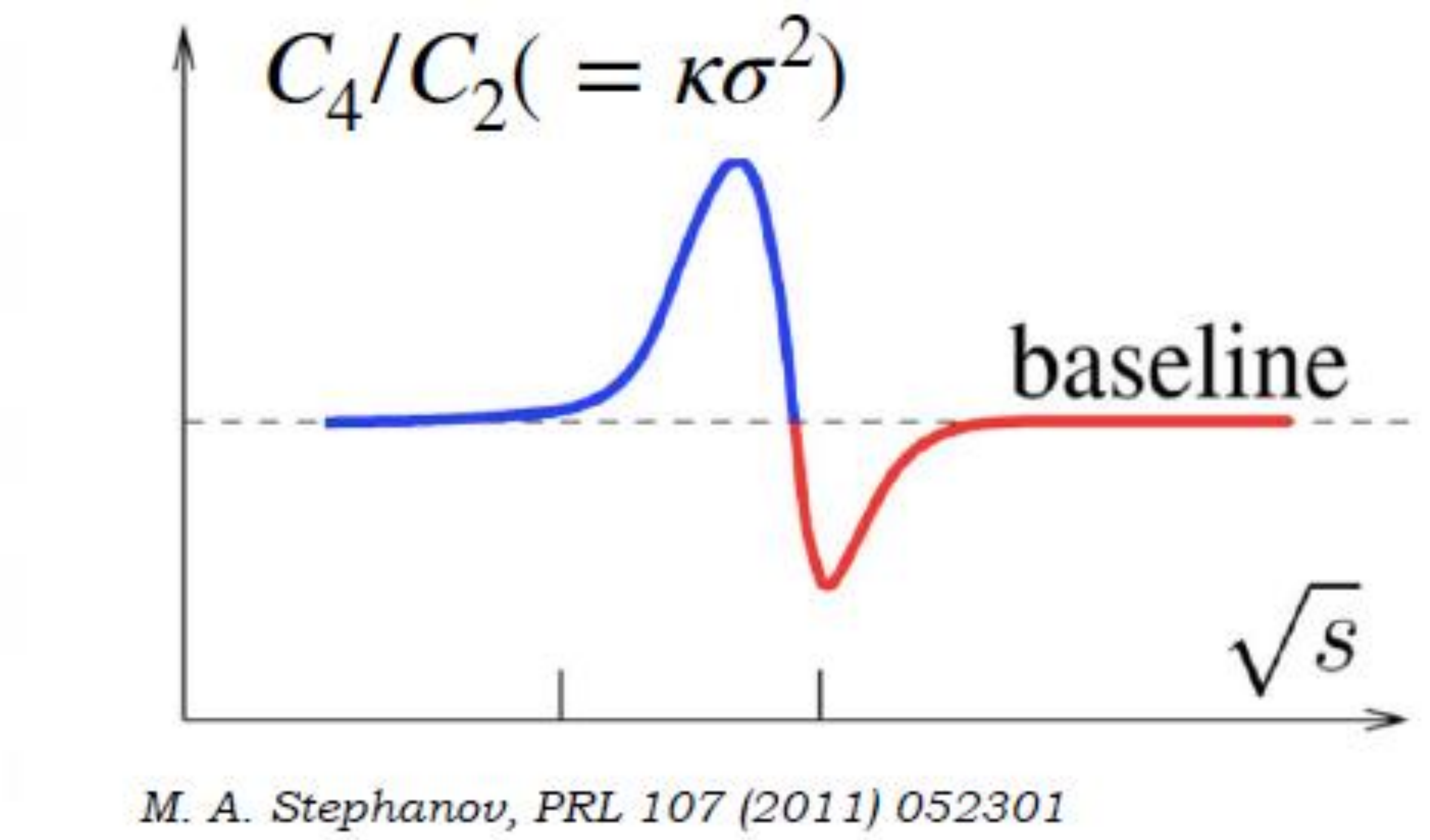
$C_4 = \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2$

$C_5 = \langle \delta N^5 \rangle - 5\langle \delta N^3 \rangle\langle \delta N^2 \rangle$

$C_6 = \langle \delta N^6 \rangle - 15\langle \delta N^4 \rangle\langle \delta N^2 \rangle - 10\langle \delta N^3 \rangle^2 + 30\langle \delta N^2 \rangle^3$

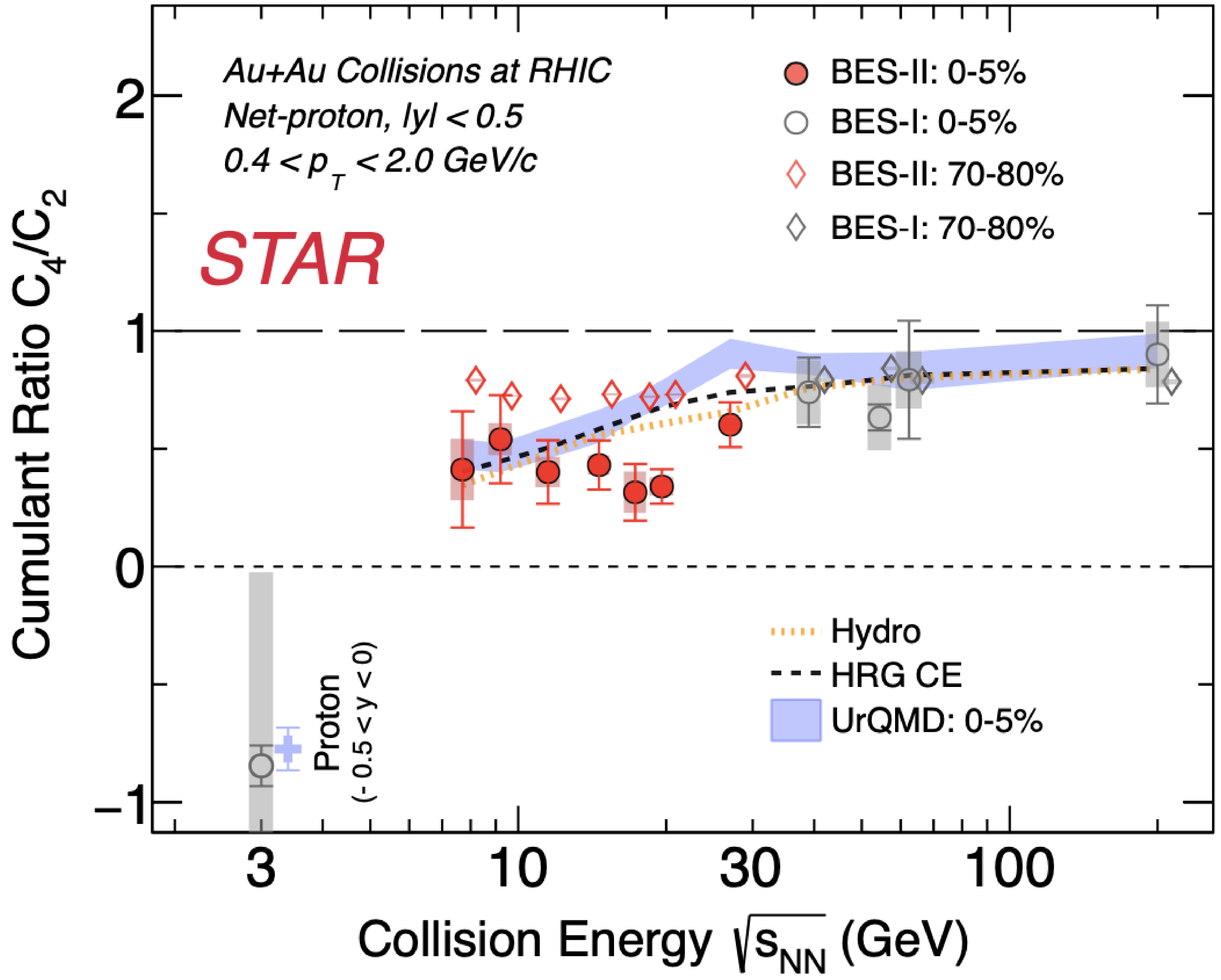
$\delta N = N - \langle N \rangle$

Ratio of cumulants – no volume dependency -> cleaner signature of CP.



CP – non-monotonic behavior of C_4/C_2 ratio.

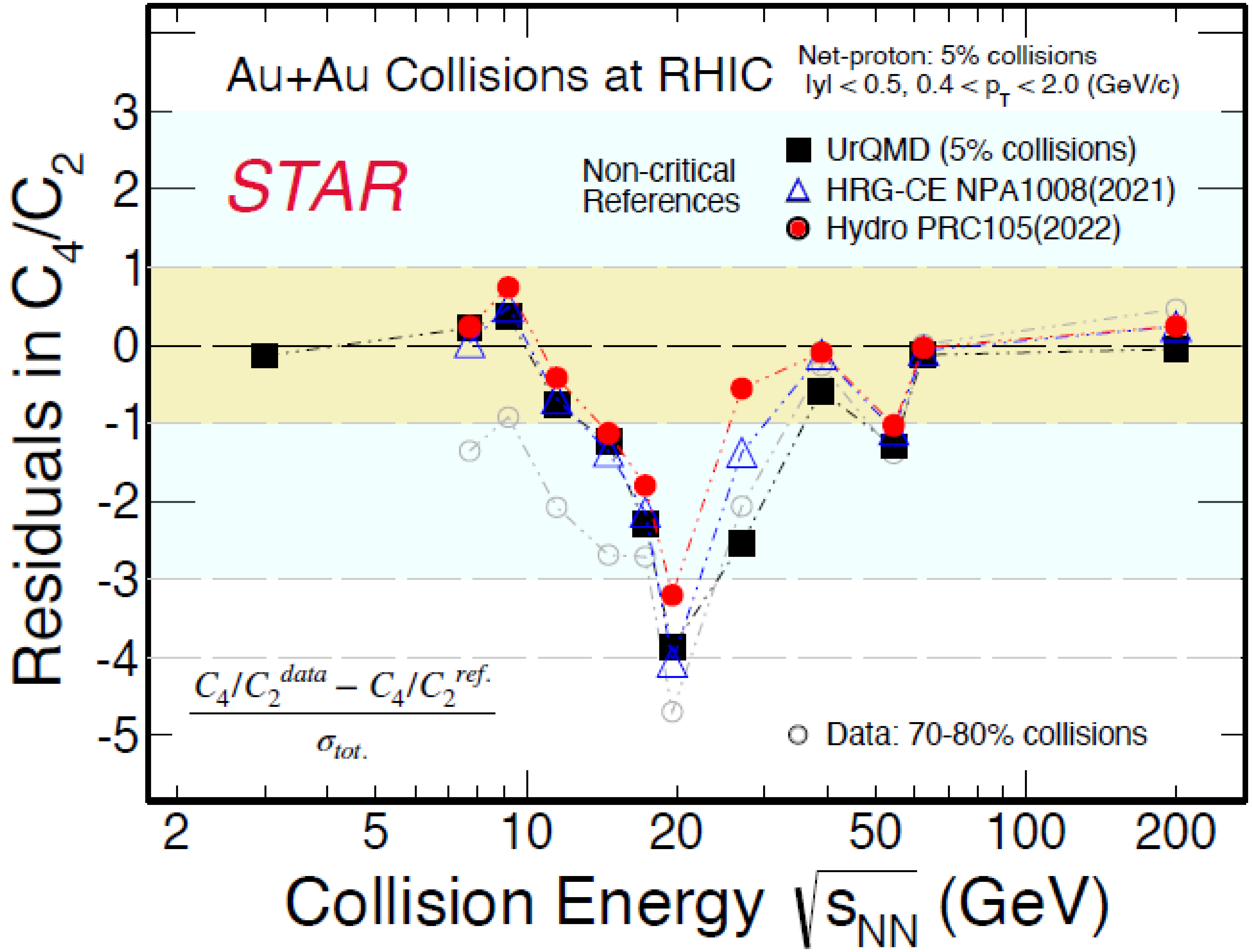
Fluctuations (net-proton)



- Comparison of STAR data with models without CP
- Greater measurement precision in BES-II
- Deviation of data at $\sqrt{s_{NN}}$≈20 GeV!
- Analysis of FXT data ongoing

Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC, CPOD 2024

Fluctuations (net-proton)



- Comparison of STAR data with models without CP
- Greater measurement precision in BES-II
- Deviation of data at $\sqrt{s_{NN}}$≈20 GeV!
- Analysis of FXT data ongoing

Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Femtoscopy

Warsaw University of Technology

How femtoscopy works?
What can we measure with femtoscopy?

Femtoscopy

Femtoscopy uses the Correlation Function defined as:

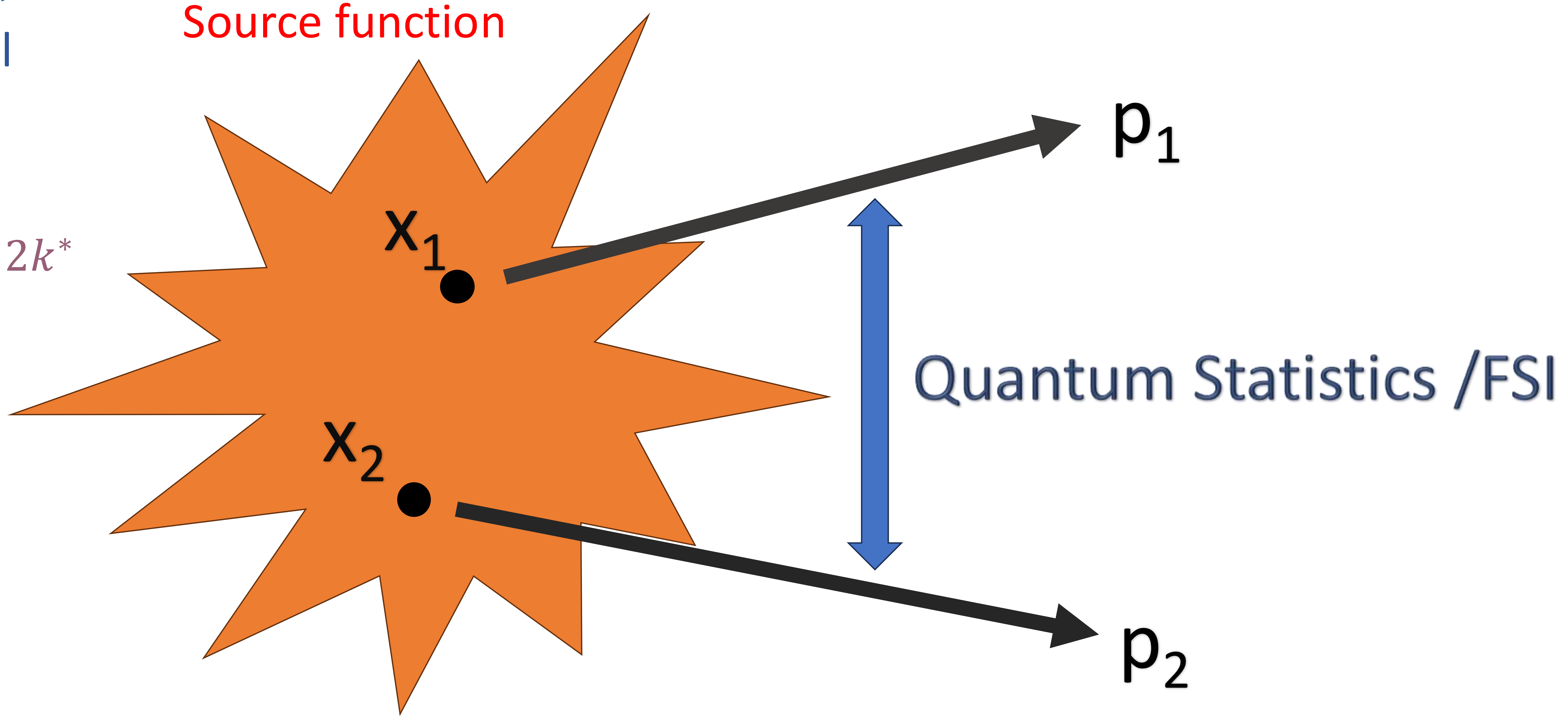
Two particle interactions/quantum statistics effect

$$C(q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \int \rho(x_1, p_1)\rho(x_2, p_2)\left|\Psi(x_1, p_1, x_2, p_2)\right|^2 dx_1 dx_2$$

Experimental definition

Source function

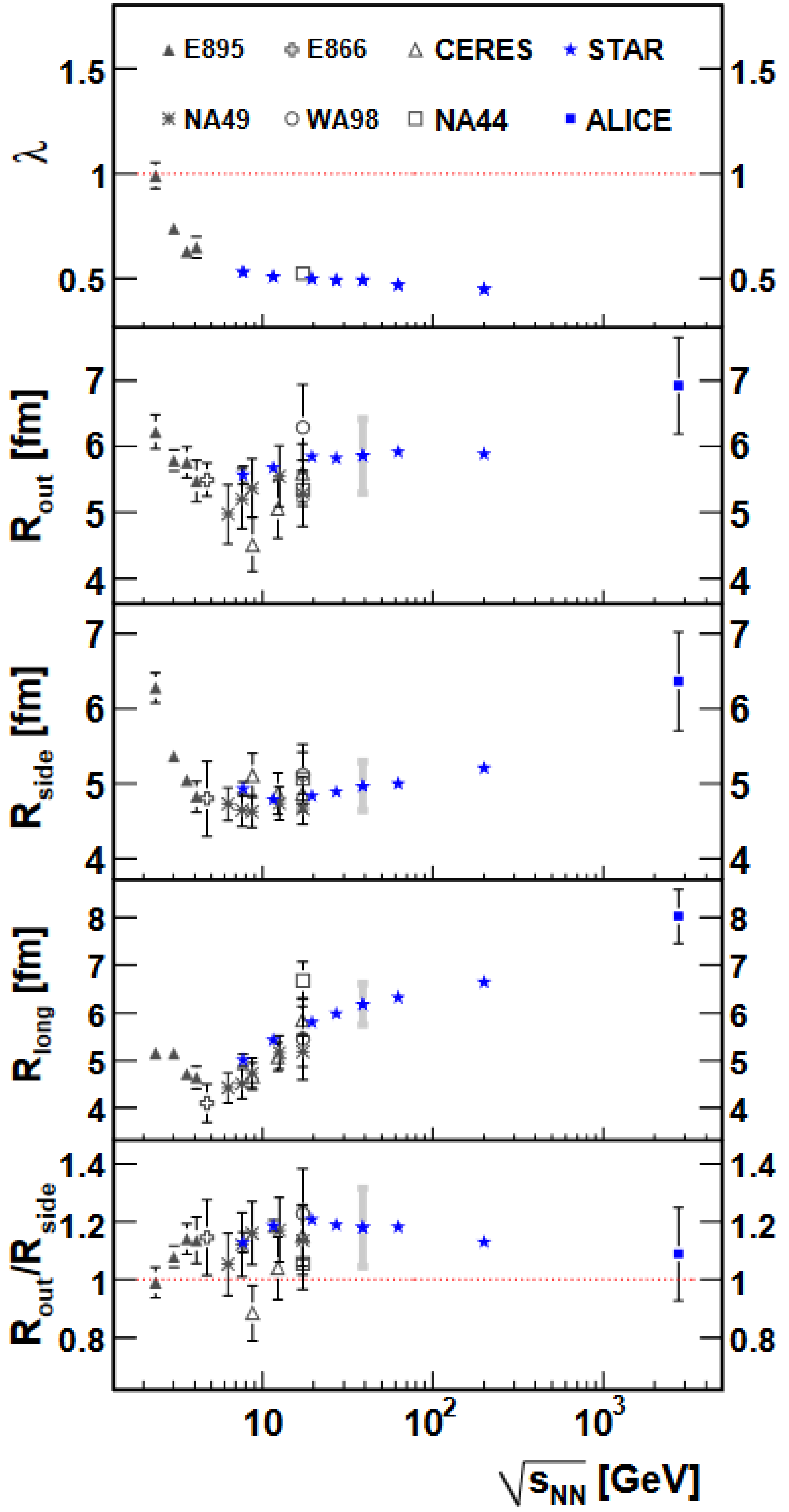
$$q = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2} = 2k^*$$



Femtoscopy

- Probing spatio-temporal structure of the collision
  - STAR measurements done for various energies, estimated the sizes of the sources in Au+Au collisions at RHIC
  - Maximum of R_{out}/R_{side} ratio visible at $\sqrt{s_{NN}} \approx$ 20GeV, critical behavior?
  - Minimum of R_{long} at $\sqrt{s_{NN}} \approx$ 5-10GeV – transition from QGP to HG?
  - **Currently working with analysis of data for lower energies**

R_{long} - size parallel the beam
R_{out} - size perpendicular to beam
R_{side} - size perpendicular to out/long



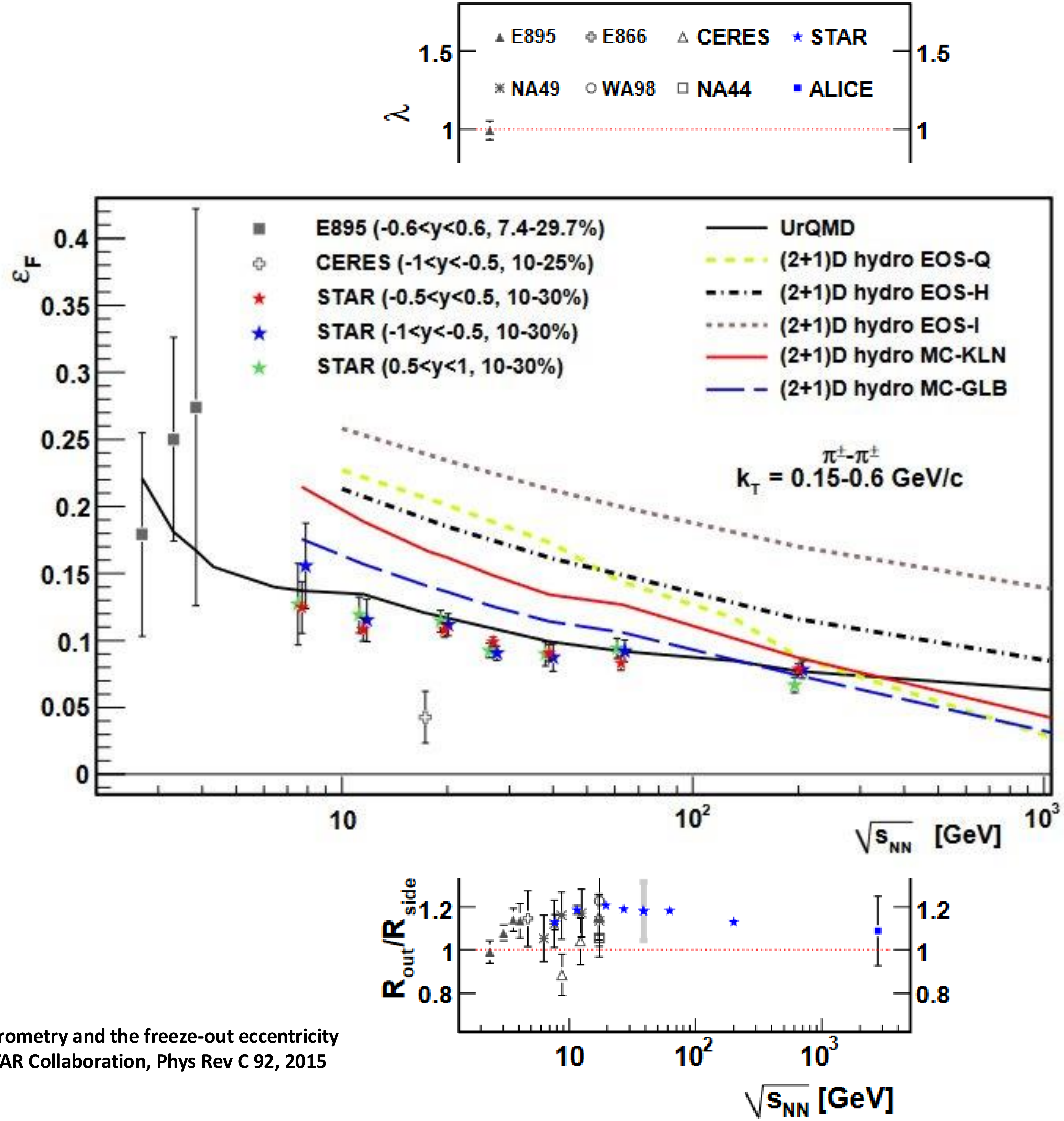
Beam energy dependent two-pion interferometry and the freeze-out eccentricity of pions in heavy ion collisions at STAR, STAR Collaboration, Phys Rev C 92, 2015

Femtoscopy

Eccentricity measured by STAR compared to various theoretical models.

Size of fireball:
σ_x – in the reaction plane
σ_y – out of the reaction plane

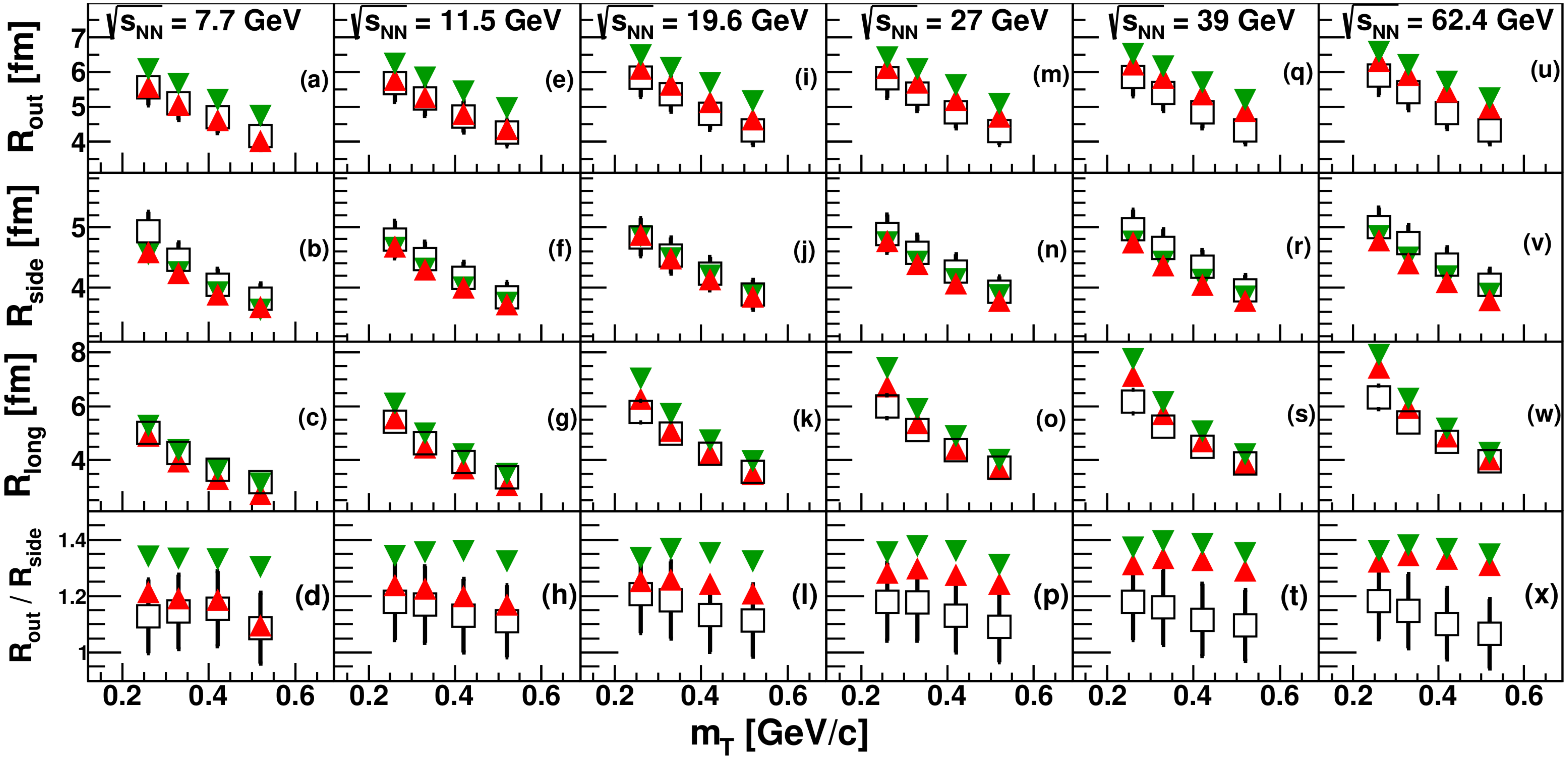
$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2}$$



Beam energy dependent two-pion interferometry and the freeze-out eccentricity of pions in heavy ion collisions at STAR, STAR Collaboration, Phys Rev C 92, 2015

Femtoscopy

vHLLE+UrQMD calculations with different Equation of State gives different femtoscopic radii.



Crossover EoS

1st order EoS

STAR data

Correlation femtoscopy study at energies available at the JINR Nuclotron-based Ion Collider fAcility and the BNL Relativistic Heavy Ion Collider within a viscous hydrodynamic plus cascade model, P. Batyuk et al. Phys. Rev. C 96, 024911

J. Steinheimer, S. Schramm, and H. St¨ocker, J. Phys. G 38, 035001 (2011)

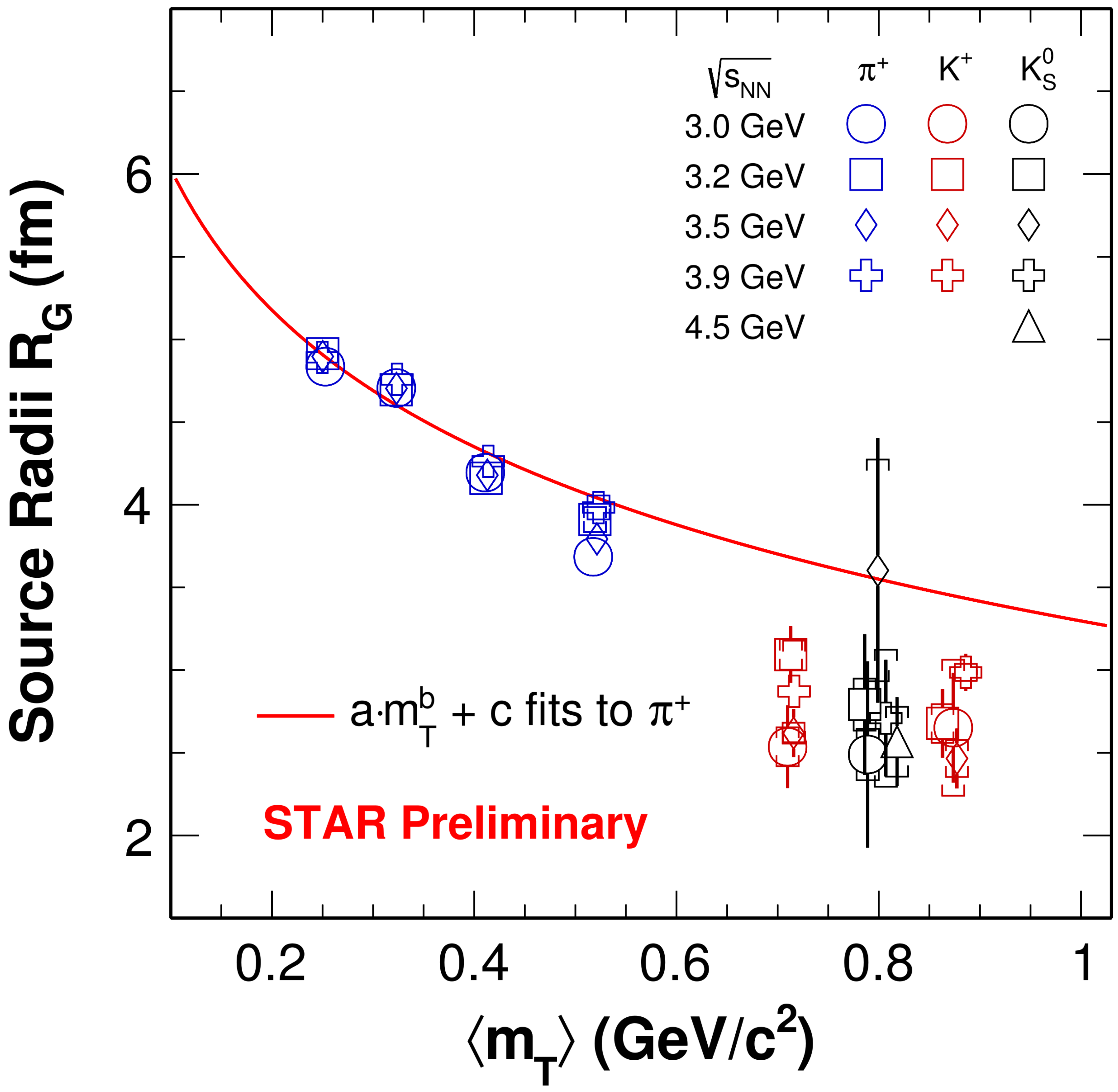
1PT Eos P. F. Kolb, J. Sollfrank, and U. W. Heinz, Phys. Rev. C 62, 054909 (2000).

Recent results from STAR.

Femtoscopy

Kaon Femtoscopy:

- Kaons are less contaminated by resonances than pions
- It is observed that Kaons R_G do not follow the power-law distributions extracted from pions at the same collisions implying lack of equilibrium among different particle species in such collisions



Kaon Femtoscopy at High Baryon Density Region – Li'Ang Zhang, CPOD 2024

Warsaw University of Technology

Femtoscopy

Asymmetry in kaon production:

We measure K^0_S or K^0_L states, they are mixtures of K^0 and anti-K^0

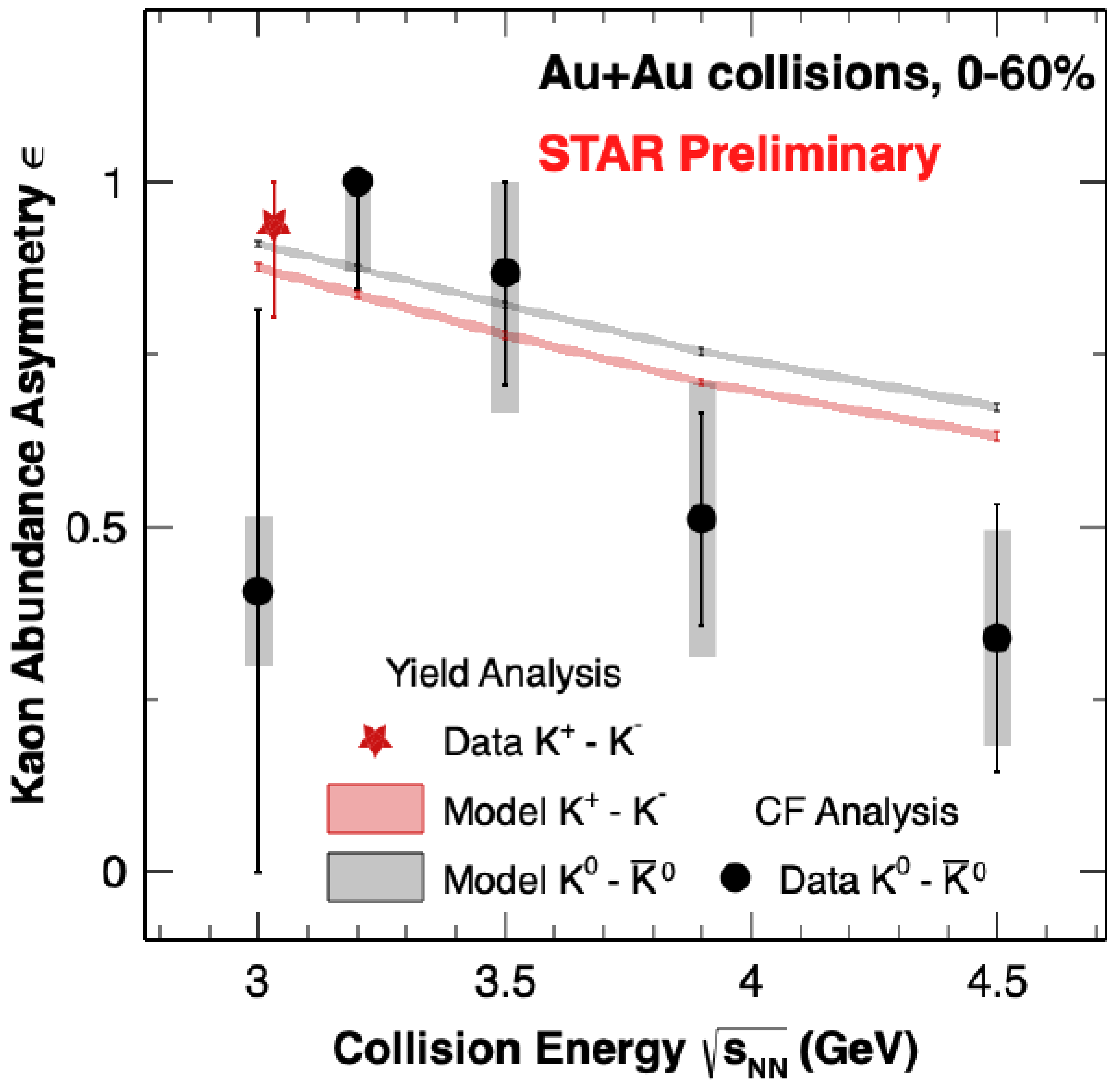
Correlation function for kaons*:

$$C(q) = \lambda[e^{-q^2R^2} + \frac{1-\epsilon^2}{2} SI(q)]$$

Quantum statistic

$SI(q)$ – *Strong Interaction*

$$\epsilon = \frac{K - \overline{K}}{K + \overline{K}}$$



Kaon Femtoscopy at High Baryon Density Region – Li'Ang Zhang, CPOD 2024

STAR data show that asymmetry increases when collision energy decreases; this trend can be reproduced by models.

**full formula in backup slides*

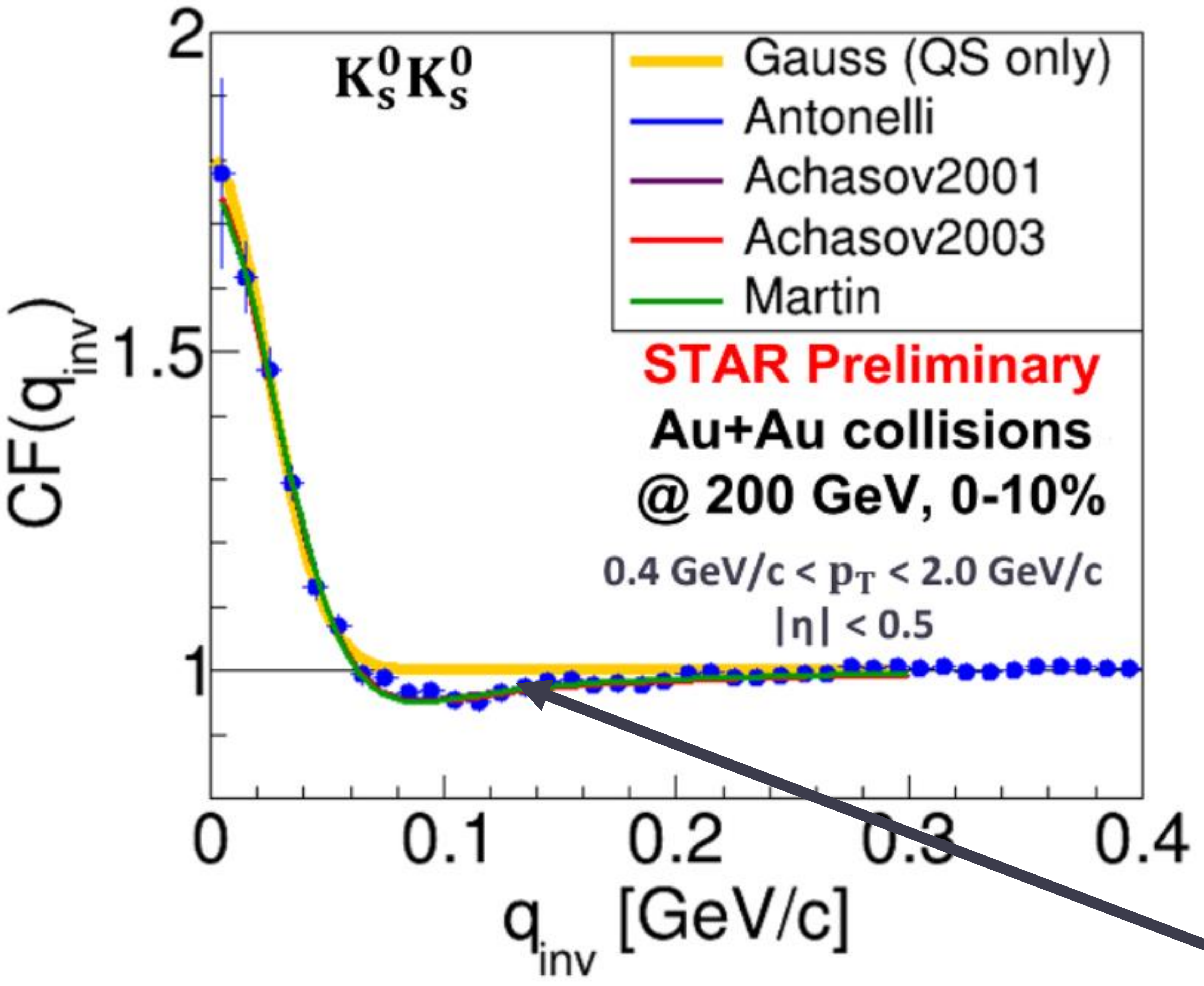
Femtoscopy

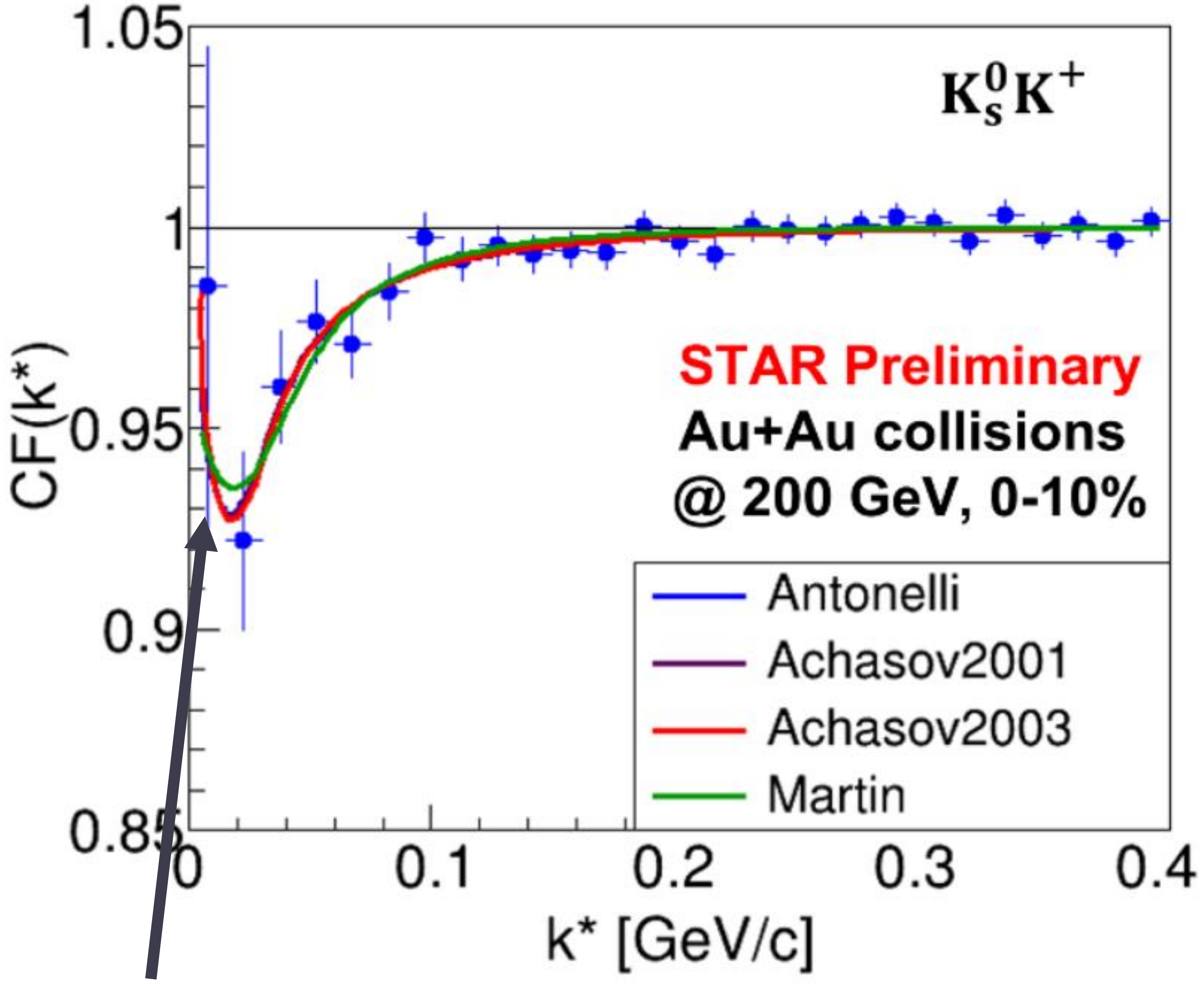
	$m_{f_0}\left[\frac{GeV}{c^2}\right]$	$\gamma_{f_0K\bar{K}}$	$\gamma_{f_0\pi\pi}$	$m_{a_0}\left[\frac{GeV}{c^2}\right]$	$\gamma_{a_0K\bar{K}}$	$\gamma_{a_0\pi\pi}$
Antonelli [1]	0.973	2.763	0.5283	0.985	0.4038	0.3711
Achasov2001 [2]	0.996	1.305	0.2684	0.992	0.5555	0.4401
Achasov2003 [3]	0.996	1.305	0.2684	1.003	0.8365	0.4580
Martin [4]	0.978	0.792	0.1990	0.974	0.3330	0.2220

[1] eConf C020620, THAT06 (2002), [2] Phys. Rev. D 63, 094007 (2001)
[3] Phys. Rev. D 68, 014006 (2003), [4] Nucl. Phys. B 121, 514–530 (1977)

- Neutral kaons interact by $a_0(980)$ resonace
- CF shape →a_0 properties
- Is a_0 a $(q_1, \bar{q}_2)$ or tetraquark state $(q_1, \bar{q}_2, s, \bar{s})^*$?
- Current data suggest that a_0 is a tetraquark

*q_1,q_2 – u or d quark





Strong interaction

Femtoscopy measurements of two-kaon combinations in Au+Au collisions at the STAR experiment, D. Pawłowska, EPJ Web of Conferences 276, 01016 (2023)

Femtoscopy - baryons

Lednicky-Lyuboshitz:

$$C(k^*) \approx 1 + \frac{|f(k^*)|}{2R^2} F(d_0) + \frac{2Re\big(f(k^*)\big)}{\sqrt{\pi}R} F_1(2k^*R) - \frac{Im\big(f(k^*)\big)}{R} F_2(2k^*R)$$

$$f(k^*)^{-1} = \frac{1}{f_0} + \frac{d_0 k^*}{2} - ik^*$$

*R. Lednicky and V. L. Lyuboshits, Final State Interaction Effect on Pairing Correlations Between Particles with Small Relative Momenta, Yad. Fiz. 35 (1981) 1316, JINR-E2-81-453

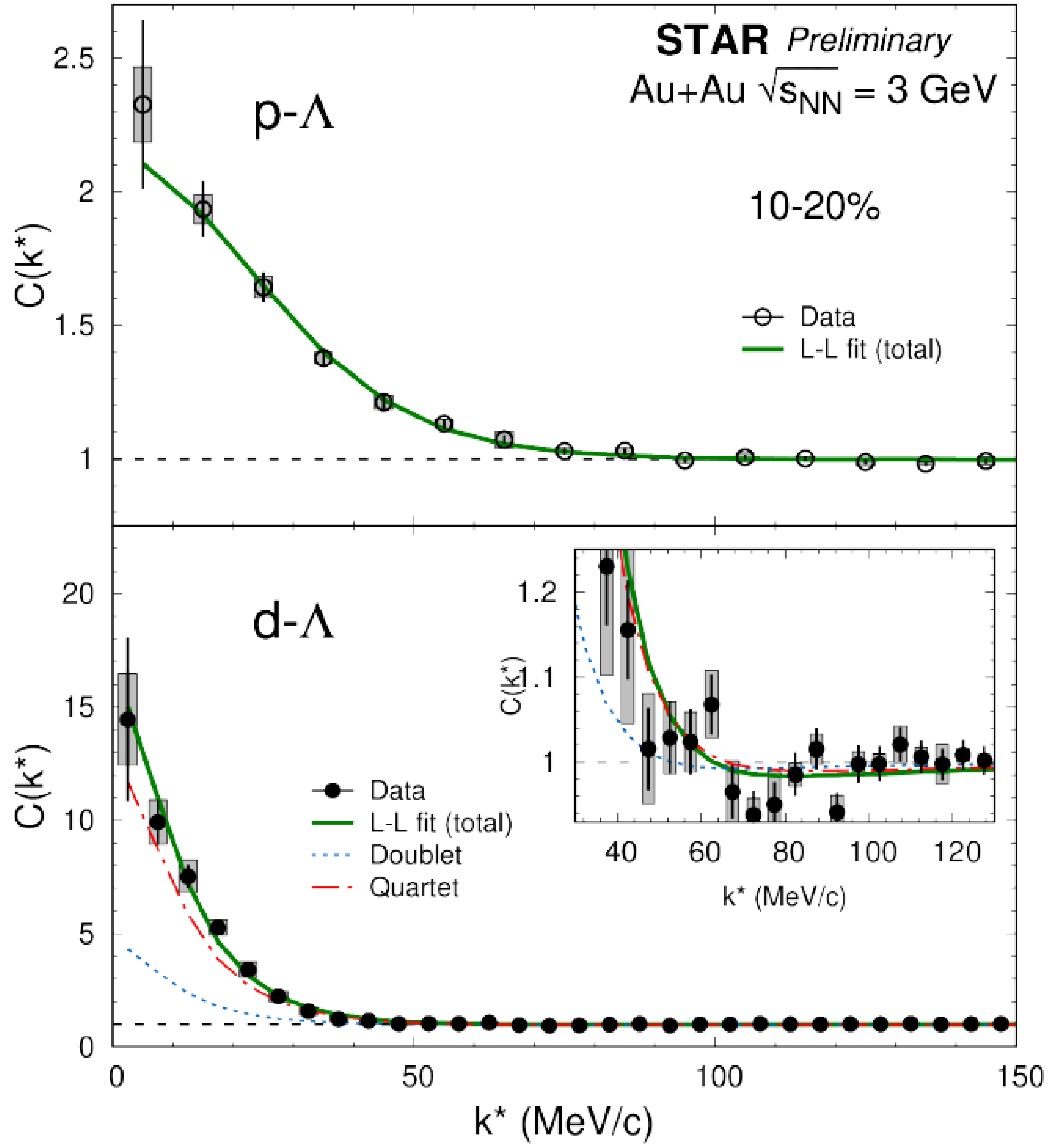
d_0, f_0 – effective range, scattering length – parameters that describe the interaction

R – size of source

p-Λ = 1/4 singlet + 3/4 triplet

d-Λ = 1/3 doublet + 2/3 quartet – statistic big enough to perform spin-separated fits

p-d and d-Λ system

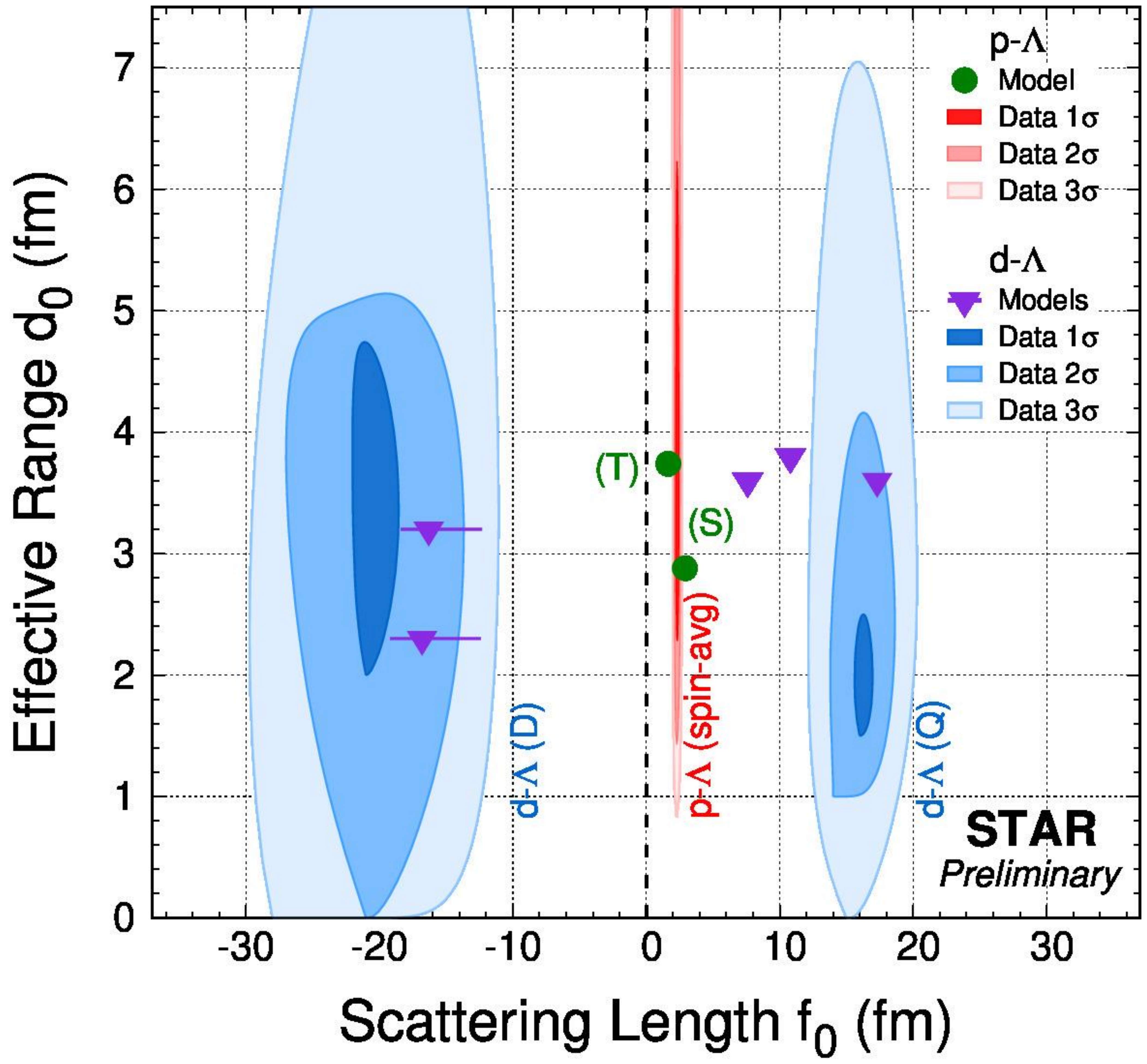


First extraction of the strong interaction parameters for d-Λ. Measured spin separated parameters for d-Λ and spin averaged for p-Λ.

p-Λ
- $f_0 = 2.32^{+0.12}_{-0.11}\ fm$
- $d_0 = 3.5^{+2.7}_{-1.3}\ fm$

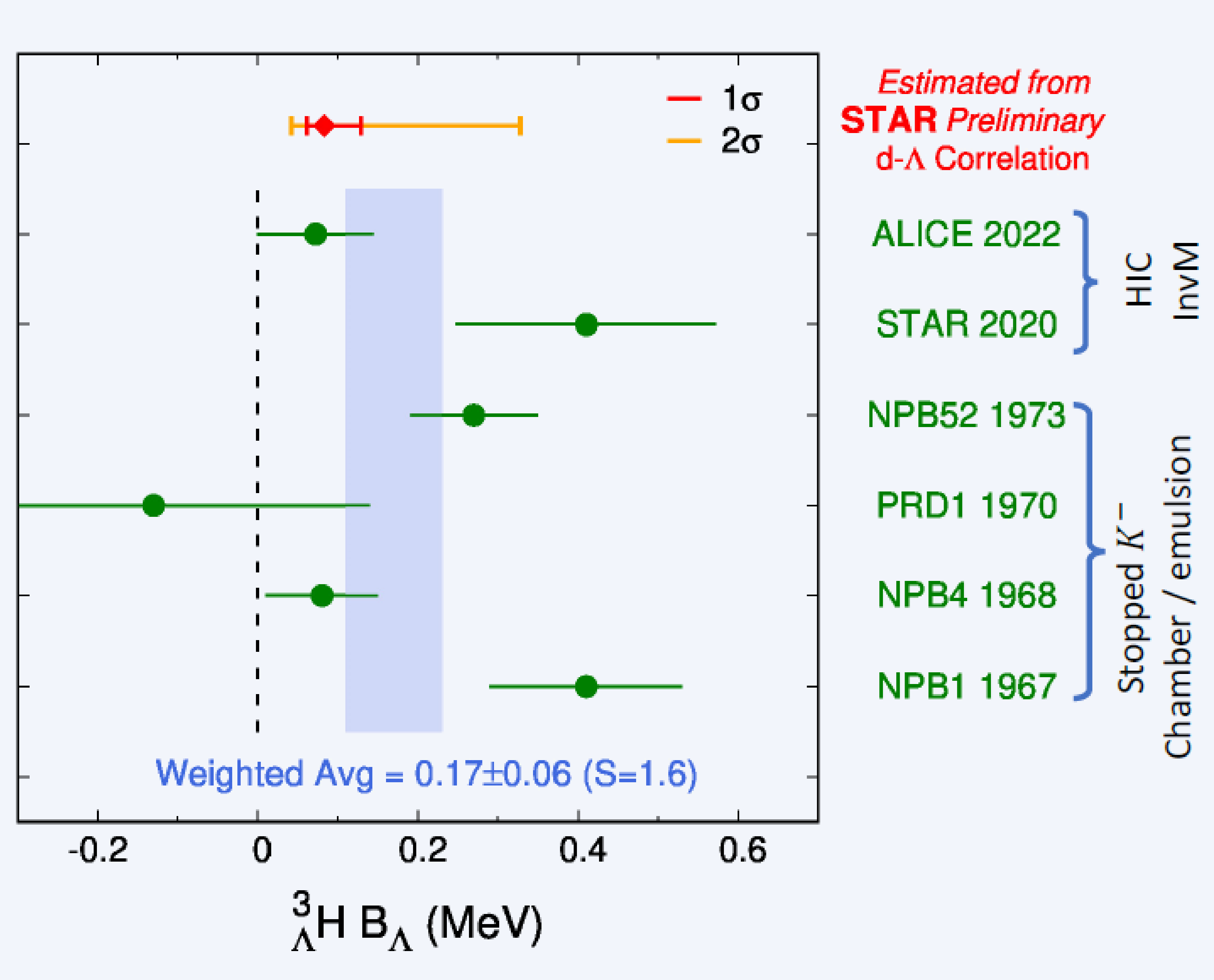
d-Λ
- $f_0(D) = -20^{+3}_{-3}\ fm$
- $d_0(D) = 3^{+2}_{-1}\ fm$
- $f_0(Q) = 16^{+2}_{-1}\ fm$
- $d_0(Q) = 2^{+1}_{-1}\ fm$

Measurements of p-Λ and correlations in 3 GeV Au+Au collisions at STAR, Yu Hu, QM 2023

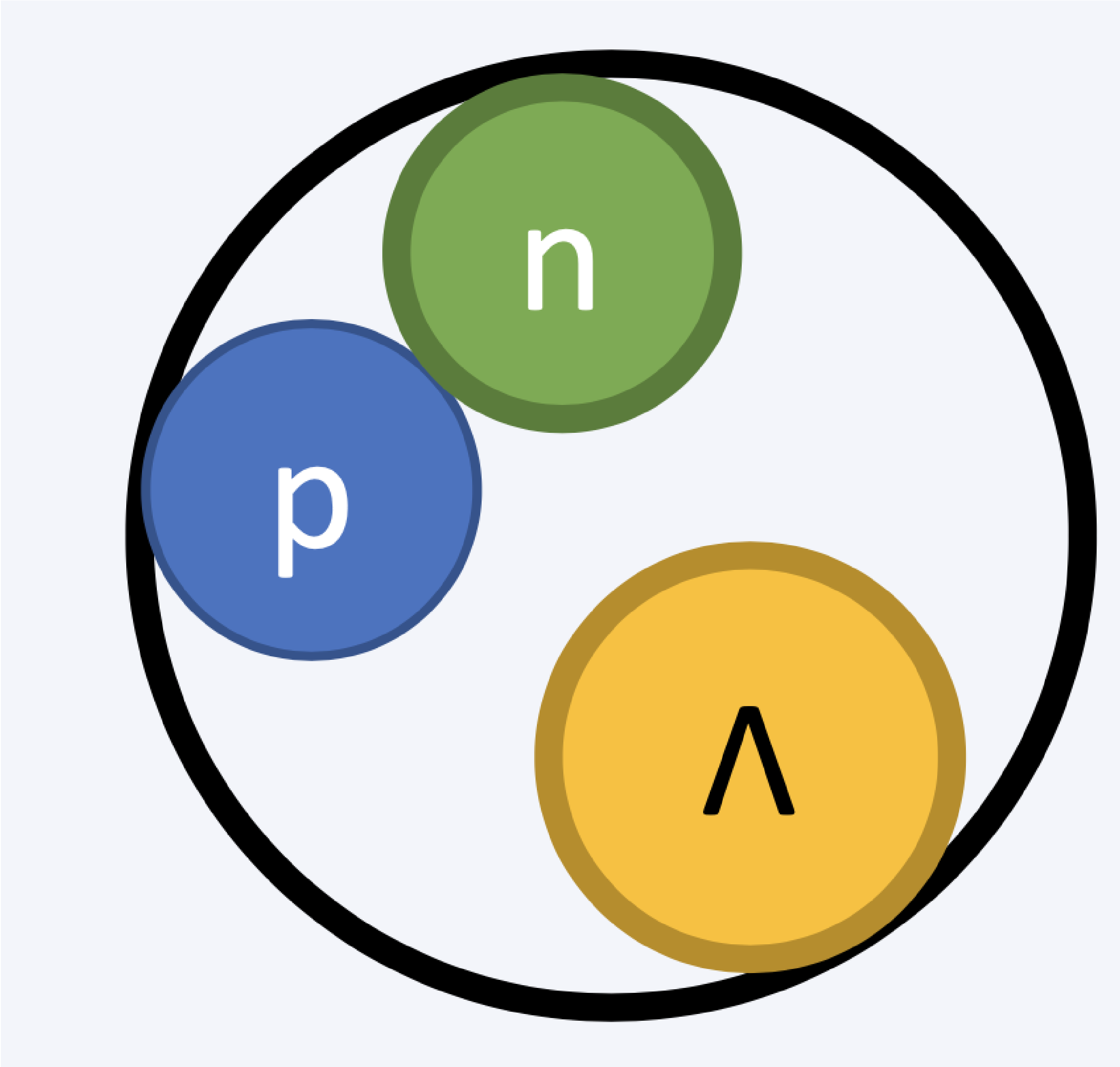


Measurements of p-Λ and correlations in 3 GeV Au+Au collisions at STAR, Yu Hu, QM 2023

p-d and d-Λ system



Measurements of d-Λ correlations allow to extract the binding Energy of $^{3}_{\Lambda}H$.
Result consistent with previous measurements.



Measurements of p-Λ and correlations in 3 GeV Au+Au collisions at STAR, Yu Hu, QM 2023

Faculty of Physics

WARSAW UNIVERSITY OF TECHNOLOGY

Summary

Warsaw University of Technology

Summary

STAR highlights on fluctuations and correlations were shown:

- Fluctuations
  - The C_4/C_2 cumulants were measured, BES-II allowed to increase the precision of measurements
  - There is a visible "nσ deviation" from non-CP models around $\sqrt{s_{NN}}$ ≈20 GeV
  - Plans: complete analysis of FXT data ($\sqrt{s_{NN}}$ =3-4.5 GeV)
- Correlations
- Kaons measurements at FXT program were reported:
  - Scaling of R_{inv} with m_T with kaons is broken between pions and kaons
  - Charged and neutral kaons gives similar results as expected
  - Measurement of kaon abundance asymmetry at low energies
- p-Λ and d- Λ correlations were measured:
  - For the first time interaction parameters were extracted for d-Λ
  - Spin averaged parameters extracted for p-Λ
  - Binding Energy of $^{3}_{\Lambda}H$ was extracted
  - $\sqrt{s_{NN}}$ =3 GeV data with higher statistics will be analyzed to improve precission of the measurements and measure correlations with heavier baryons

Thank you!

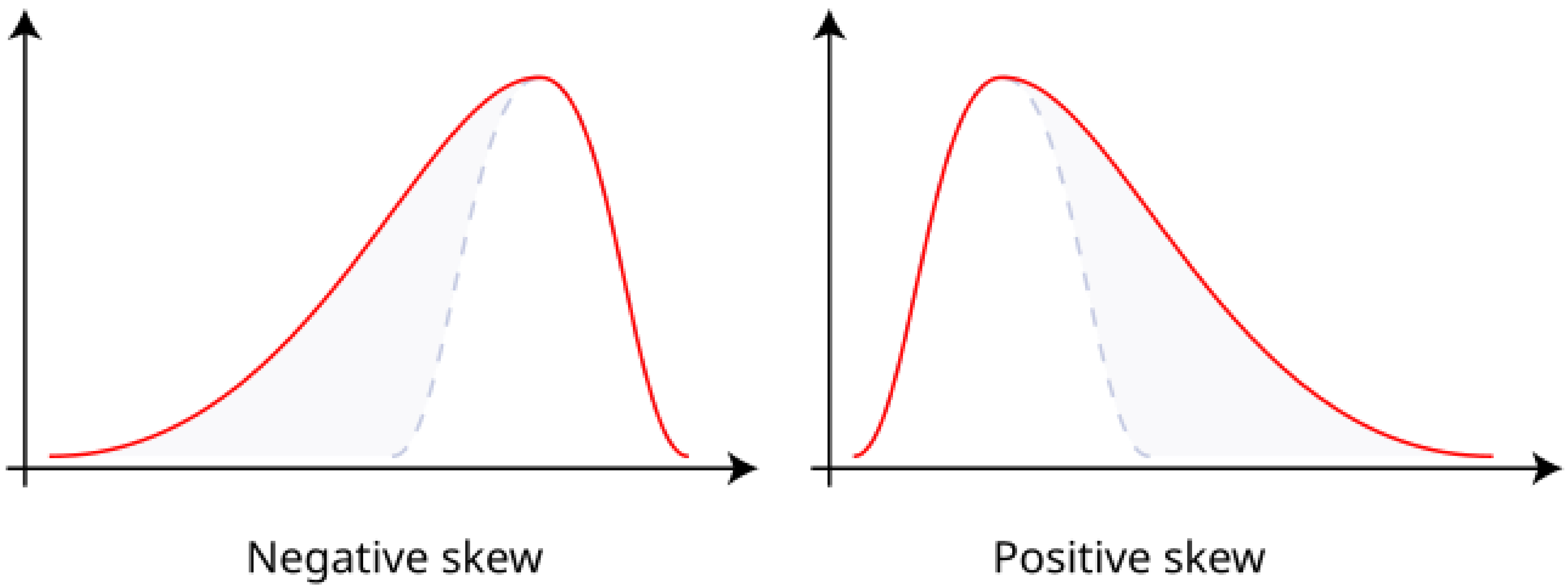
Backup slides

STAR experiment

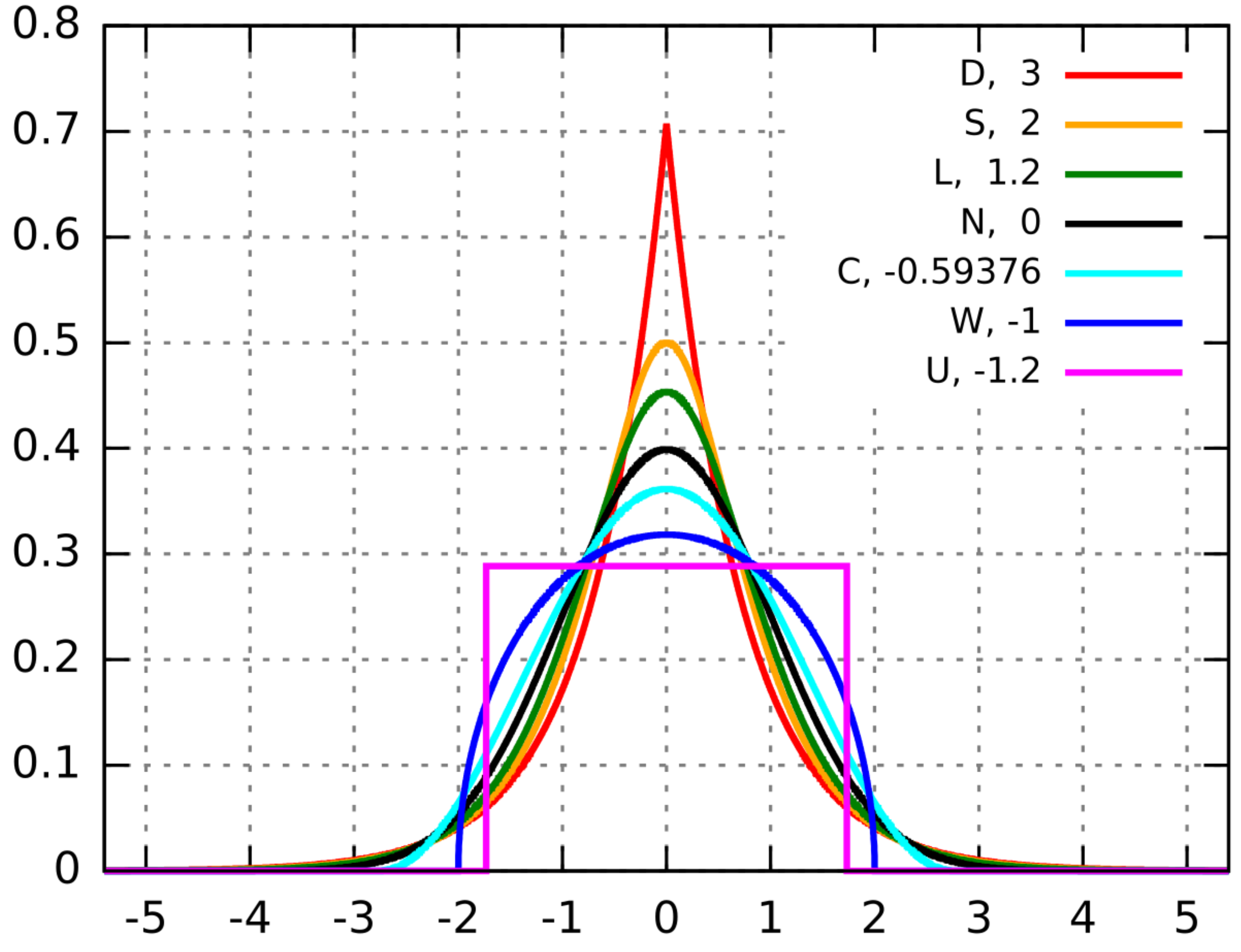
Au+Au Collisions at RHIC							
Collider Runs				**Fixed-Target Runs**			
Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)	Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)
1	200	380	25	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440
6	19.6	595	206	6	6.2 (19.5)	120	490
7	17.3	256	230	7	5.2 (13.5)	100	540
8	14.6	340	262	8	4.5 (9.8)	110	590
9	11.5	257	316	9	3.9 (7.3)	120	633
10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
				12	3.0 (3.85)	260 + 2000	750

BES II

Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC, Ashish Pandav, CPOD 2024 c



https://en.wikipedia.org/wiki/Skewness

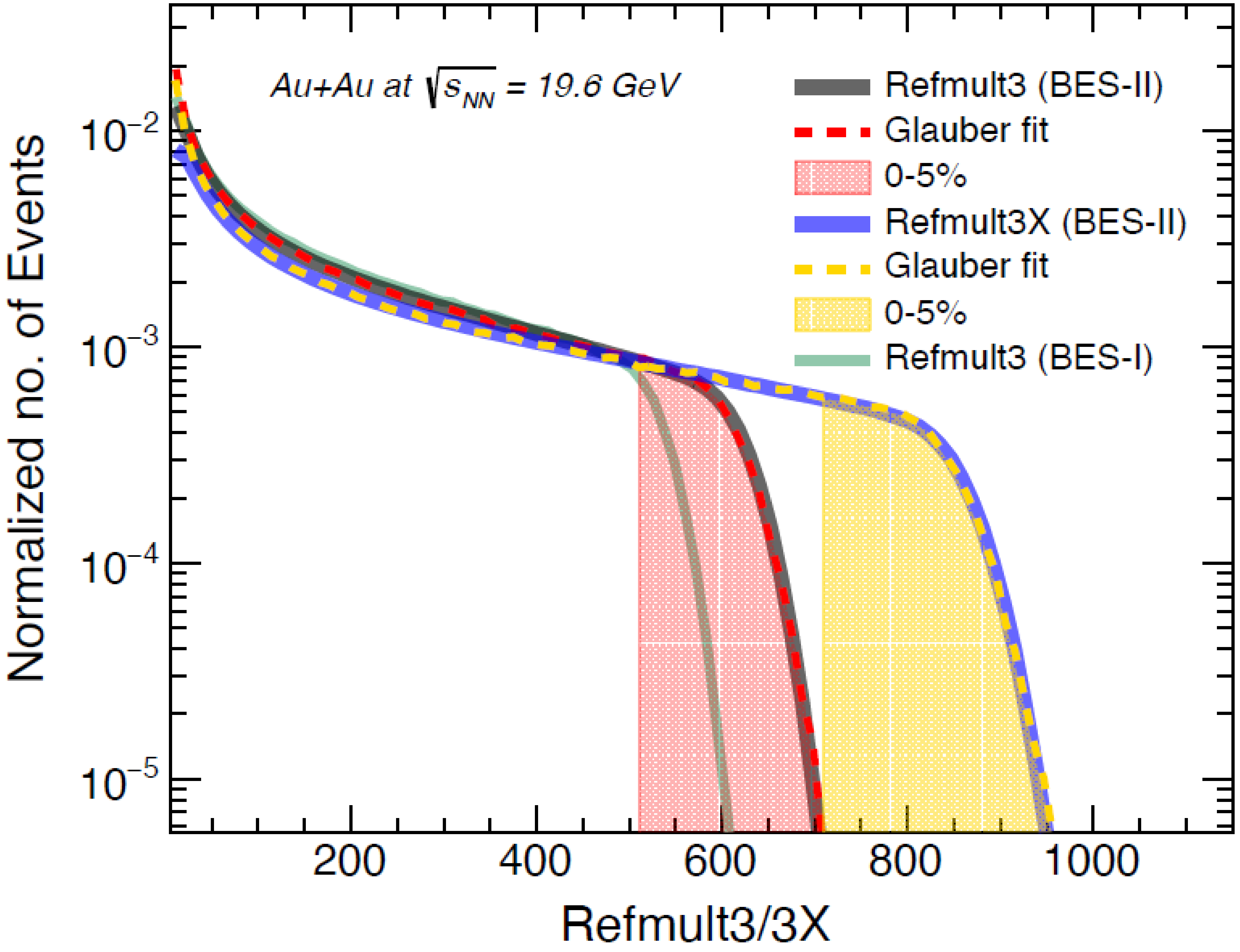


https://en.wikipedia.org/wiki/Kurtosis

Fluctuations (net-proton measurements)

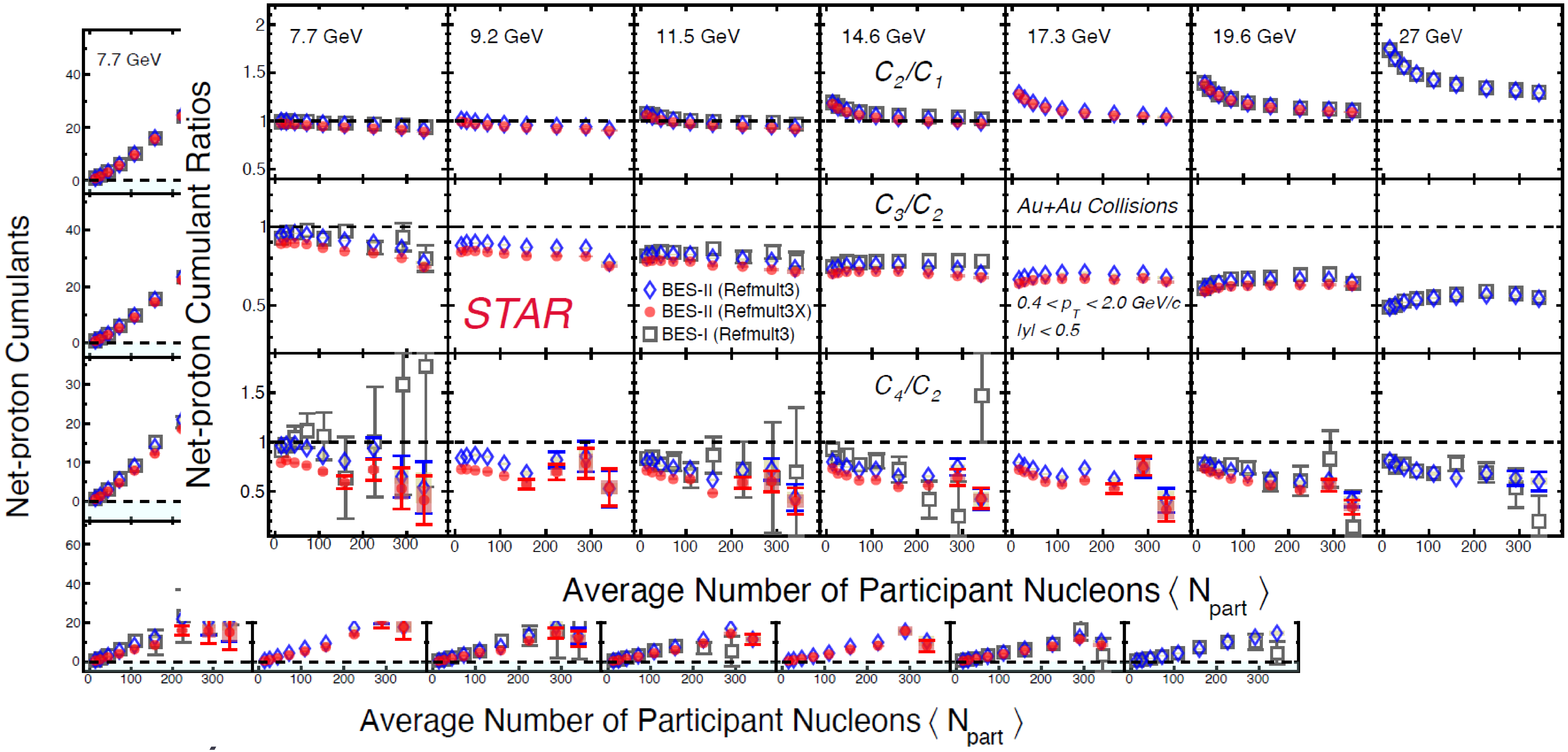
Centrality definitions at STAR used to study fluctuations:

- Refmult3 = charged particle multiplicity (excluding protons to avoid autocorrelations) |η|<1
- Refmult3X - |η|<1.6 due to iTPC upgrade



Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC, Ashish Pandav, CPOD 2024 c

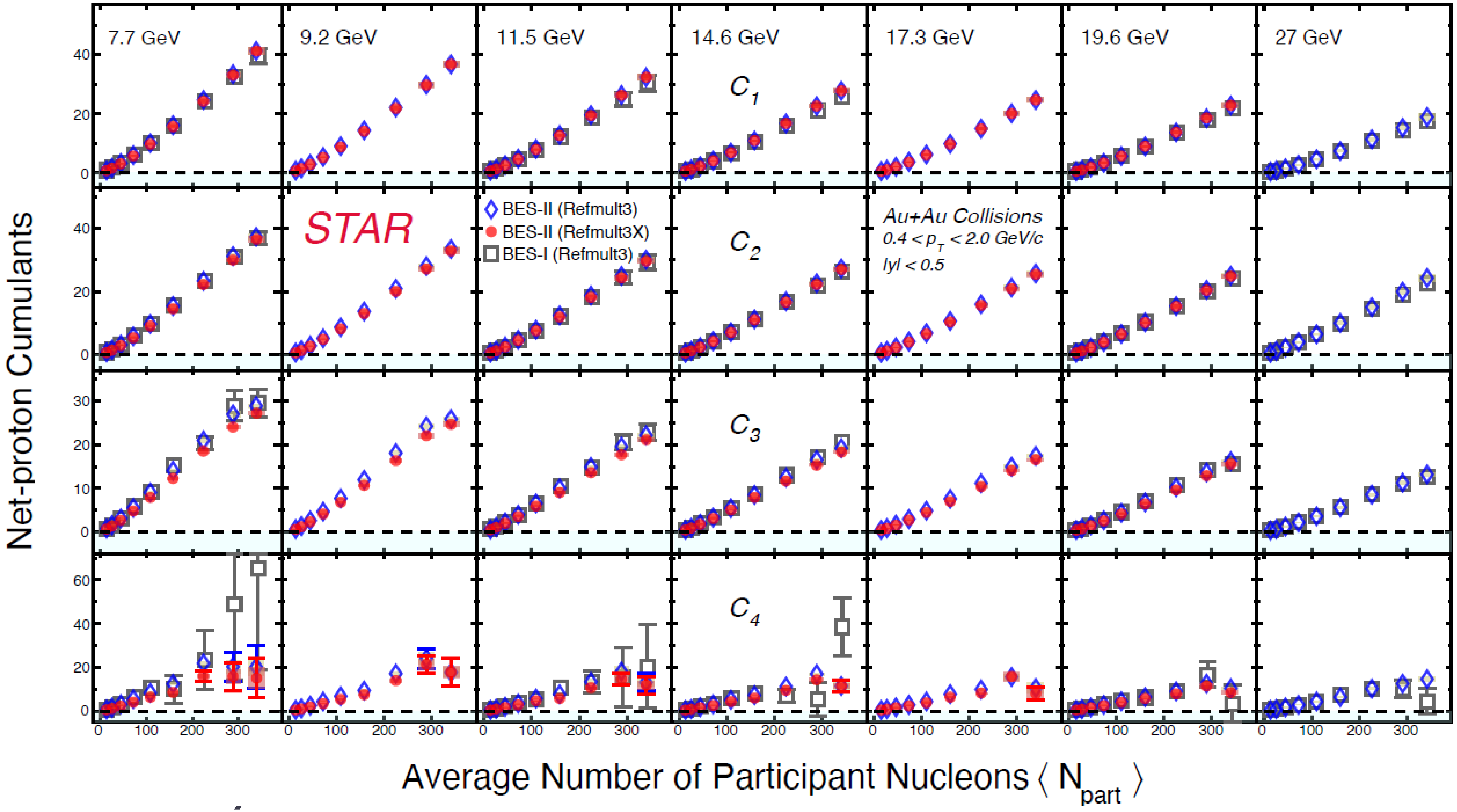
Centrality dependence of cumulants (net-proton)



of Technology

Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC, Ashish Pandav, CPOD 2024

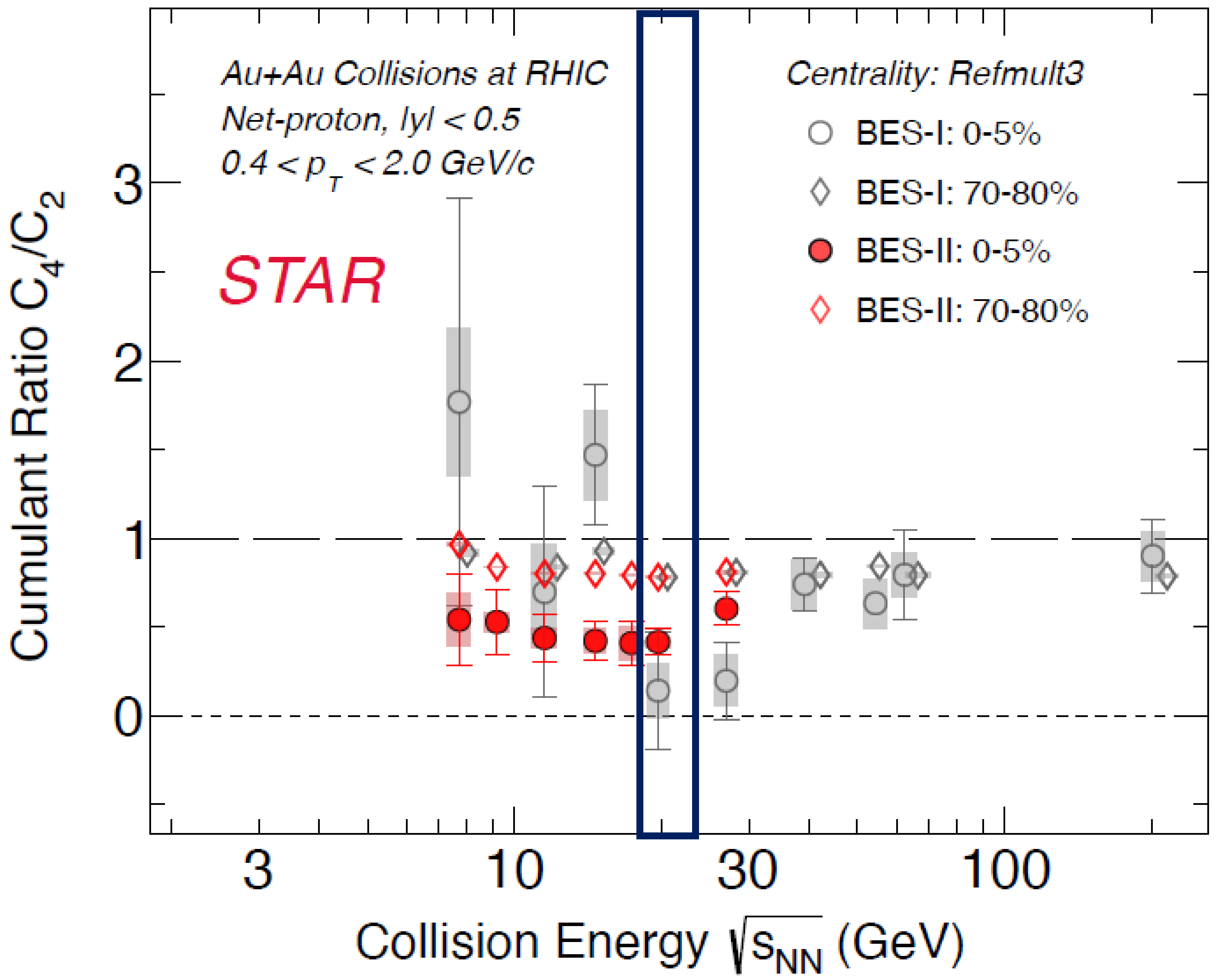
Centrality dependence of cumulants (net-proton)

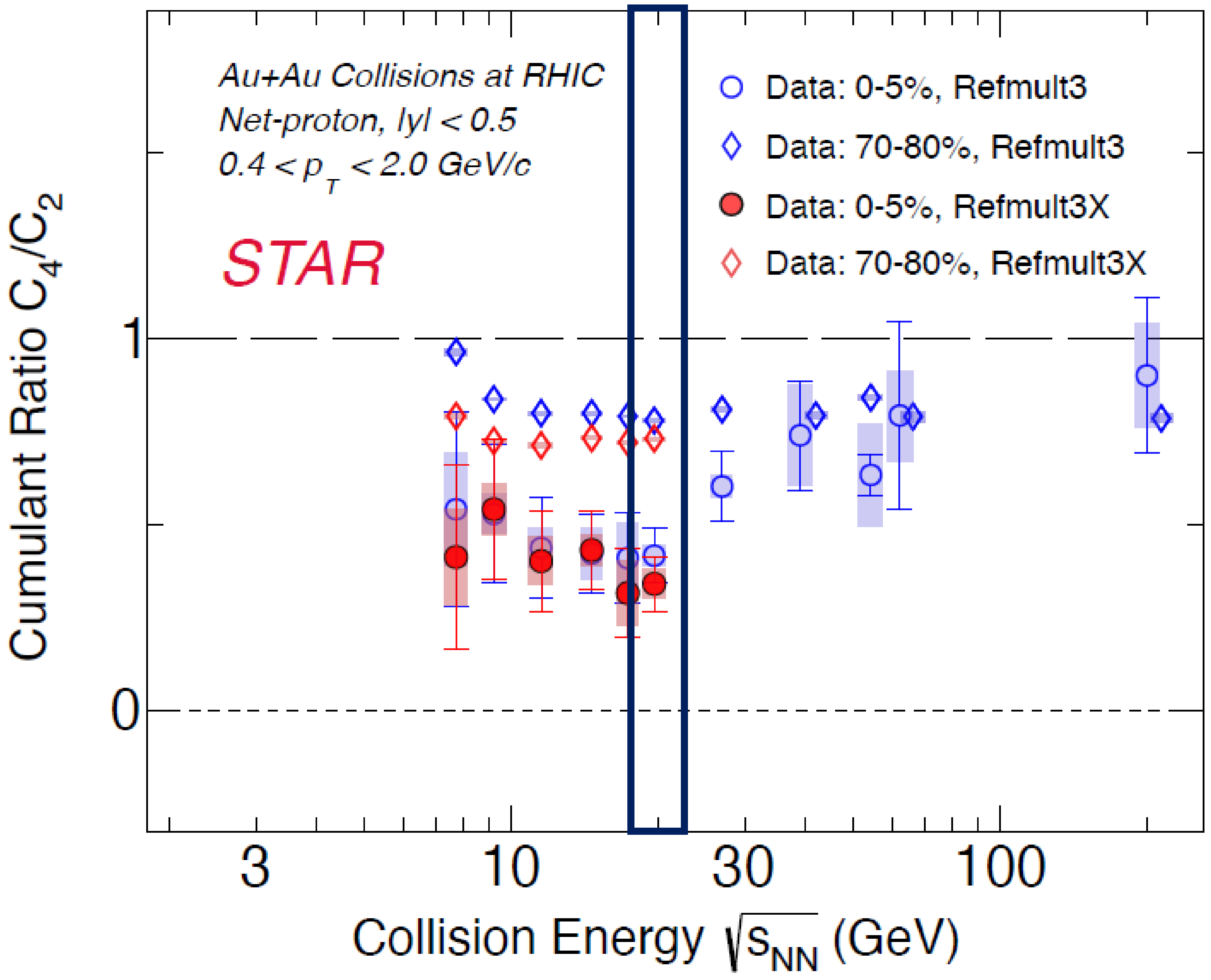


of Technology

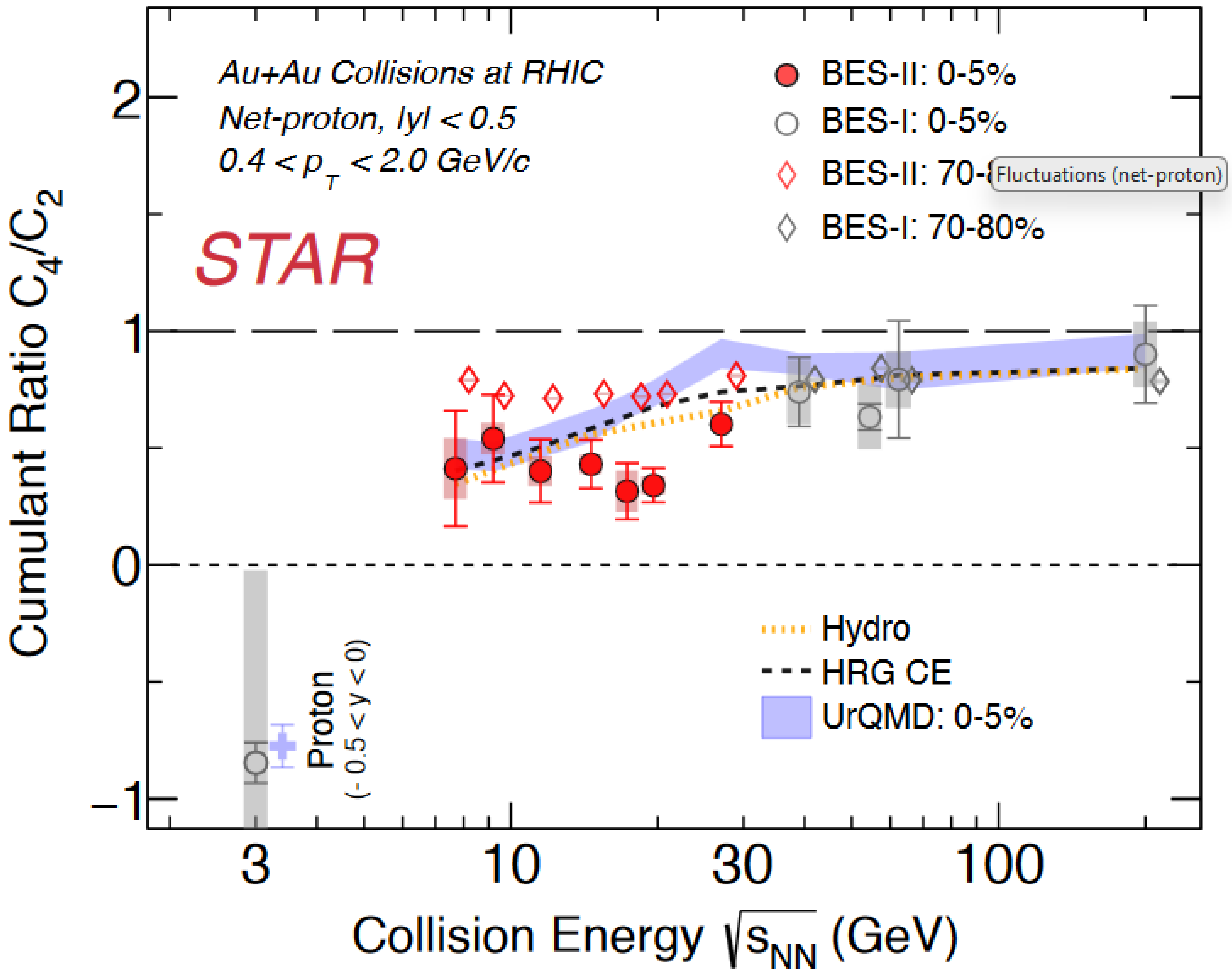
Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC, Ashish Pandav, CPOD 2024

Fluctuations (net-proton)





Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC, Ashish Pandav, CPOD 2024



Warsaw University of Technology

Higher-order cumulants (n=5,6)

1st order PT

→mixed phase

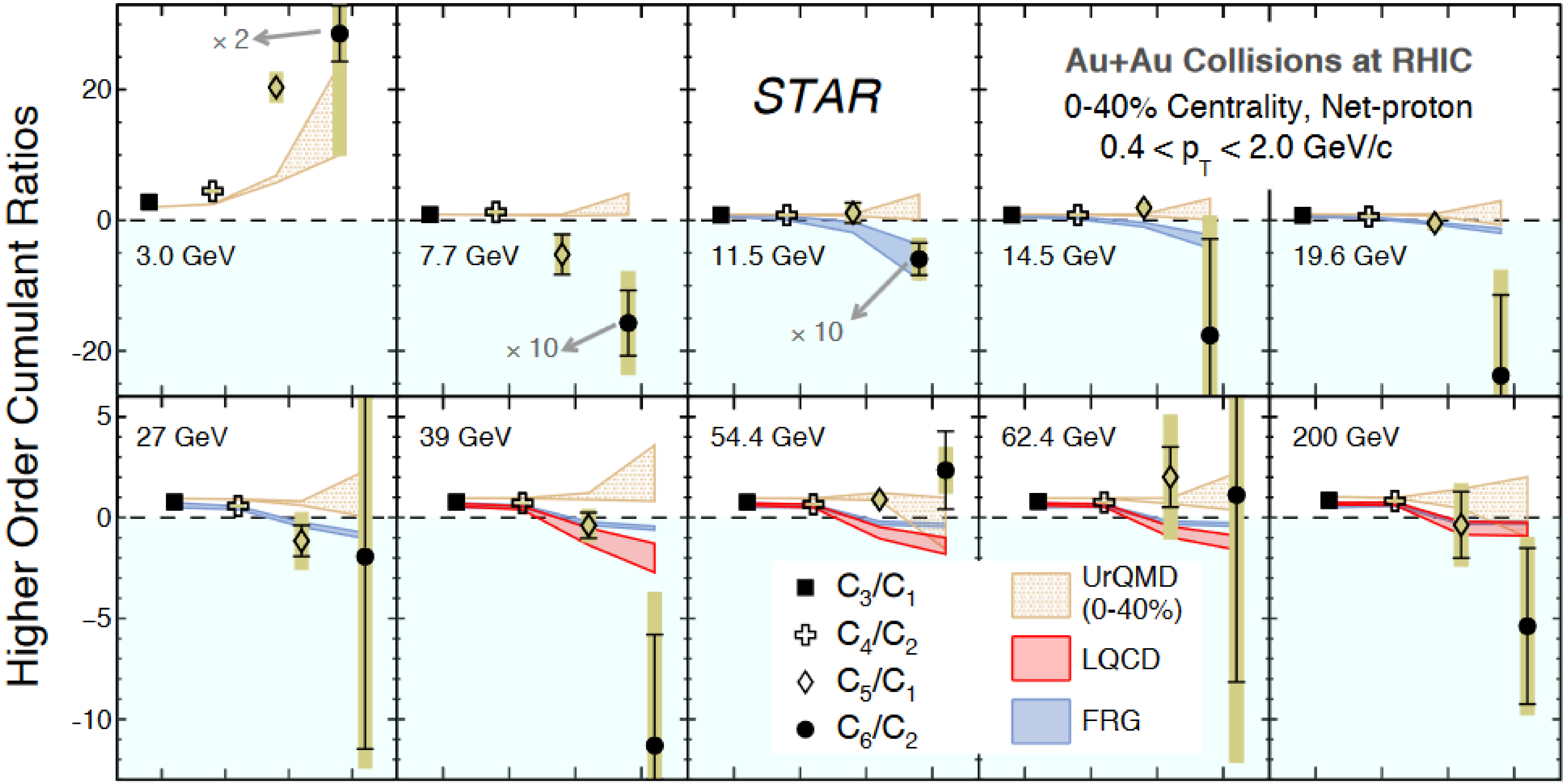
→ two phases

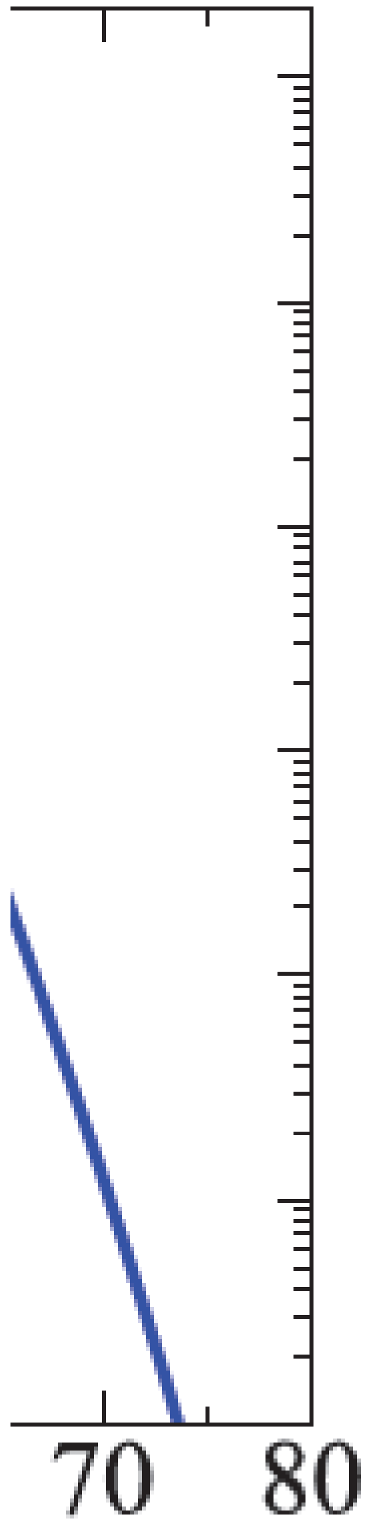
→ two distributions

→higher order cumulant

Analysis status: to be do

BES-I data

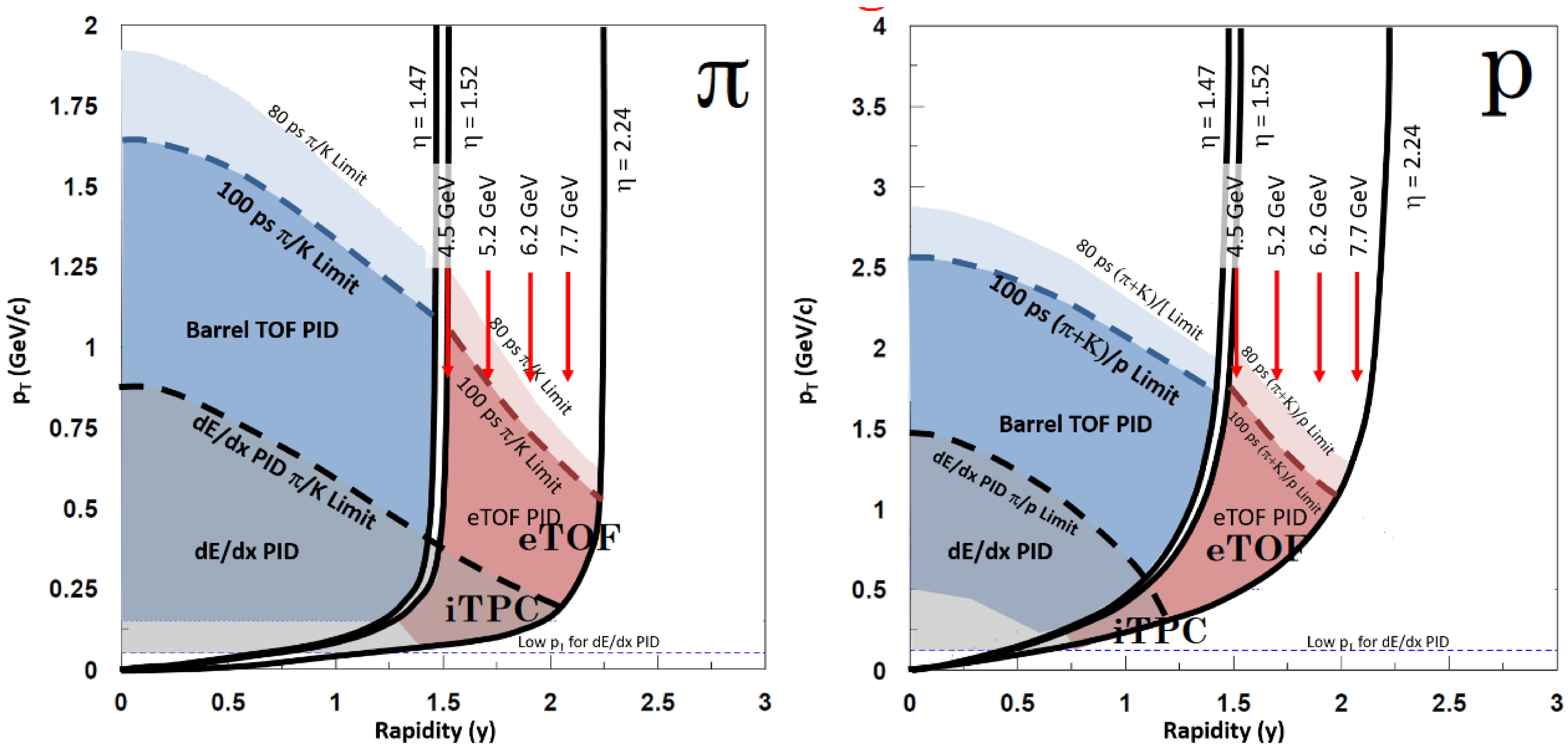




Beam Energy Dependence of Fifth and Sixth-Order Net-proton Number Fluctuations in Au+Au Collisions at RHIC- STAR Collaboration, 202

Fluctuations

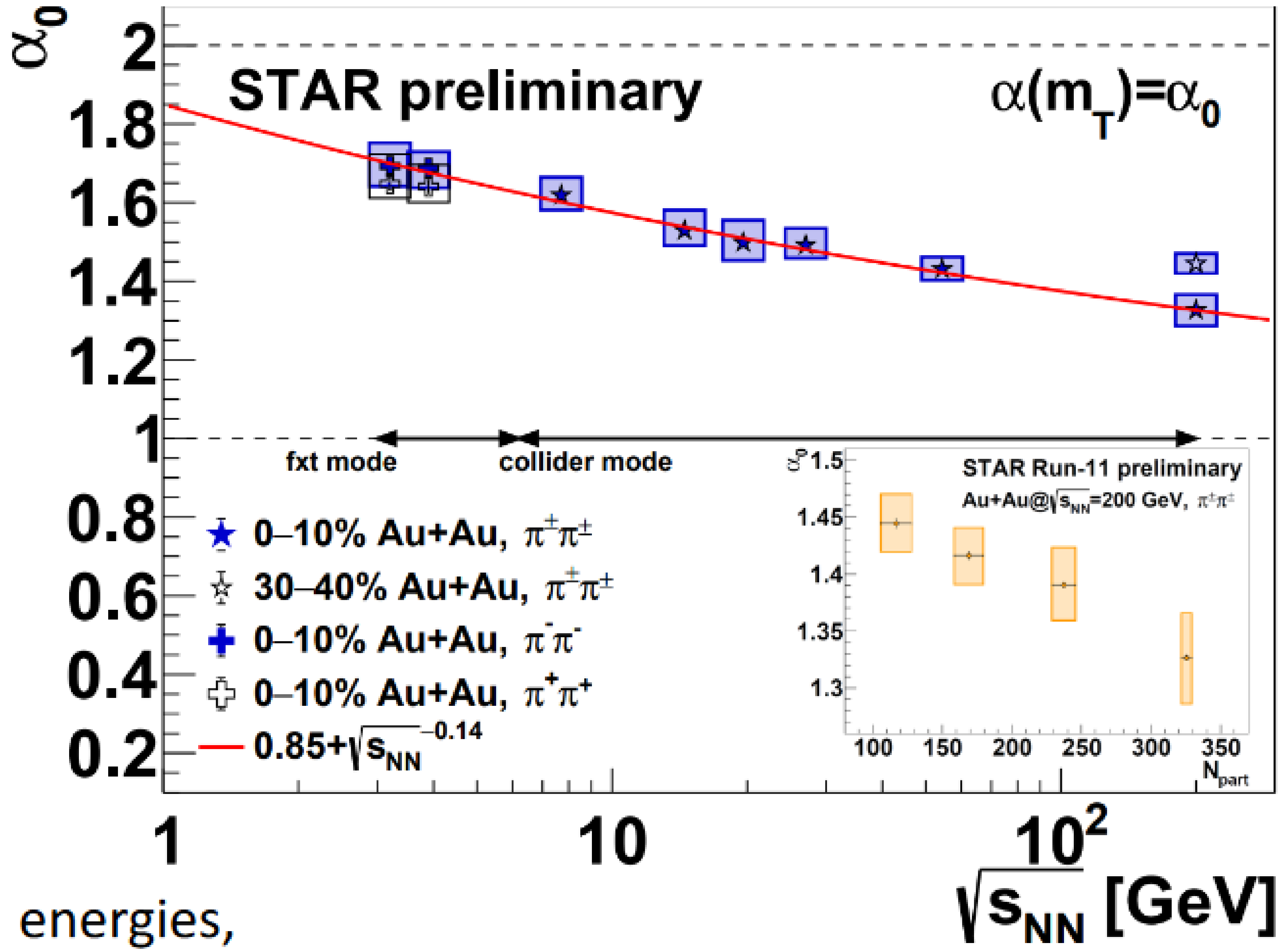
- BES-I – hint of possible non-monoton behavior of $\kappa\sigma^2$
- BES-II :
  - Better statistic
  - Larger acceptance:
    - iTPC measurements of particles witł lower p_T (125→ 60 MeV/c), extende rapidity coverage (|1|->|1.6|
    - eTOF PID measurements from η=1.(to 1.5
    - EPD – better reaction plane resolution, better event triggering



The STAR detector upgrade and future plan, Chi Yang for the STAR collaboration,6th International Conference on New Frontiers in Physics (ICNFP2027)

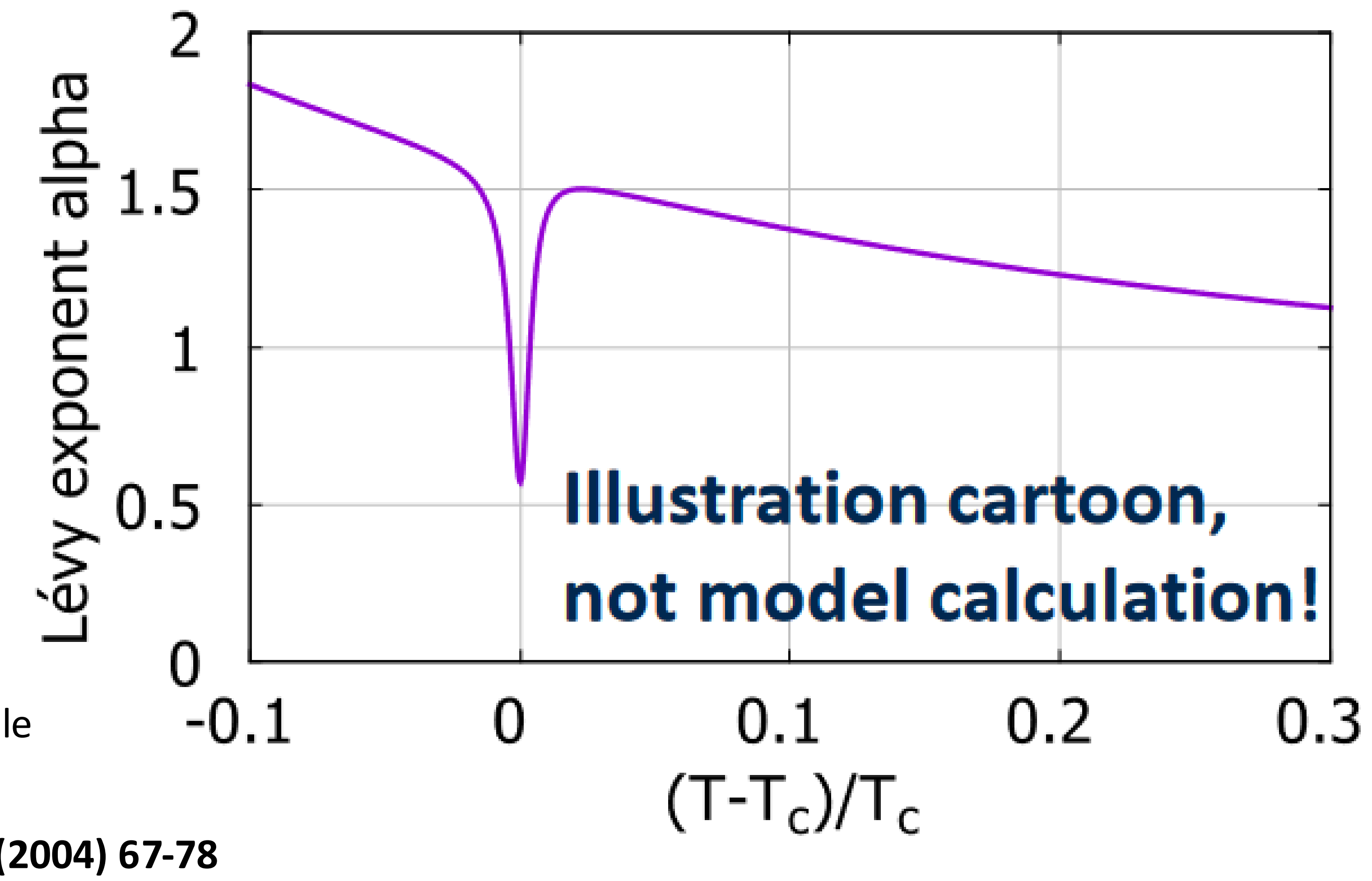
c

EoS, Critical Point



energies,

- Study of the shape of the source (not only the size) - (Lévy parametrization):*
  $$C(q) = 1 + \lambda e^{-|R_L q|^\alpha}$$
- α =2 → Gaussian source (standard parametrization)
- Strong decrease of α near the CP suggested** but not visible in analyzed data



Beam-Energy Dependent Pion Interferometry with Levy-Stable Sources at STAR, D. Kincses, CPOD 2024

**Bose-Einstein correlations for Levy stable source distributions, T. Csorgo, S. Hegyi, W. A. Zajc, Eur.Phys.J. C36 (2004) 67-78

** for clearance: neglected coulomb interaction*

Neutral kaons correlation functions:

$$C(q) = \lambda(e^{-q^2R^2} + \frac{1-\epsilon^2}{2}[\left|\frac{f(k^*)}{R}\right|^2 + \frac{4Re\big(f(k^*)\big)}{\sqrt{\pi}R}F_1(qR) + \frac{2Im\big(f(k^*)\big)}{R}F_2(qR)] \quad F_2(z) = \frac{1-e^{-z^2}}{z}$$

*R. Lednicky and V. L. Lyuboshits, Final State Interaction Effect on Pairing Correlations Between Particles with Small Relati
Momenta, Yad. Fiz. 35 (1981) 1316, JINR-E2-81-453

$f(k^*) - scattering\ amplitude$

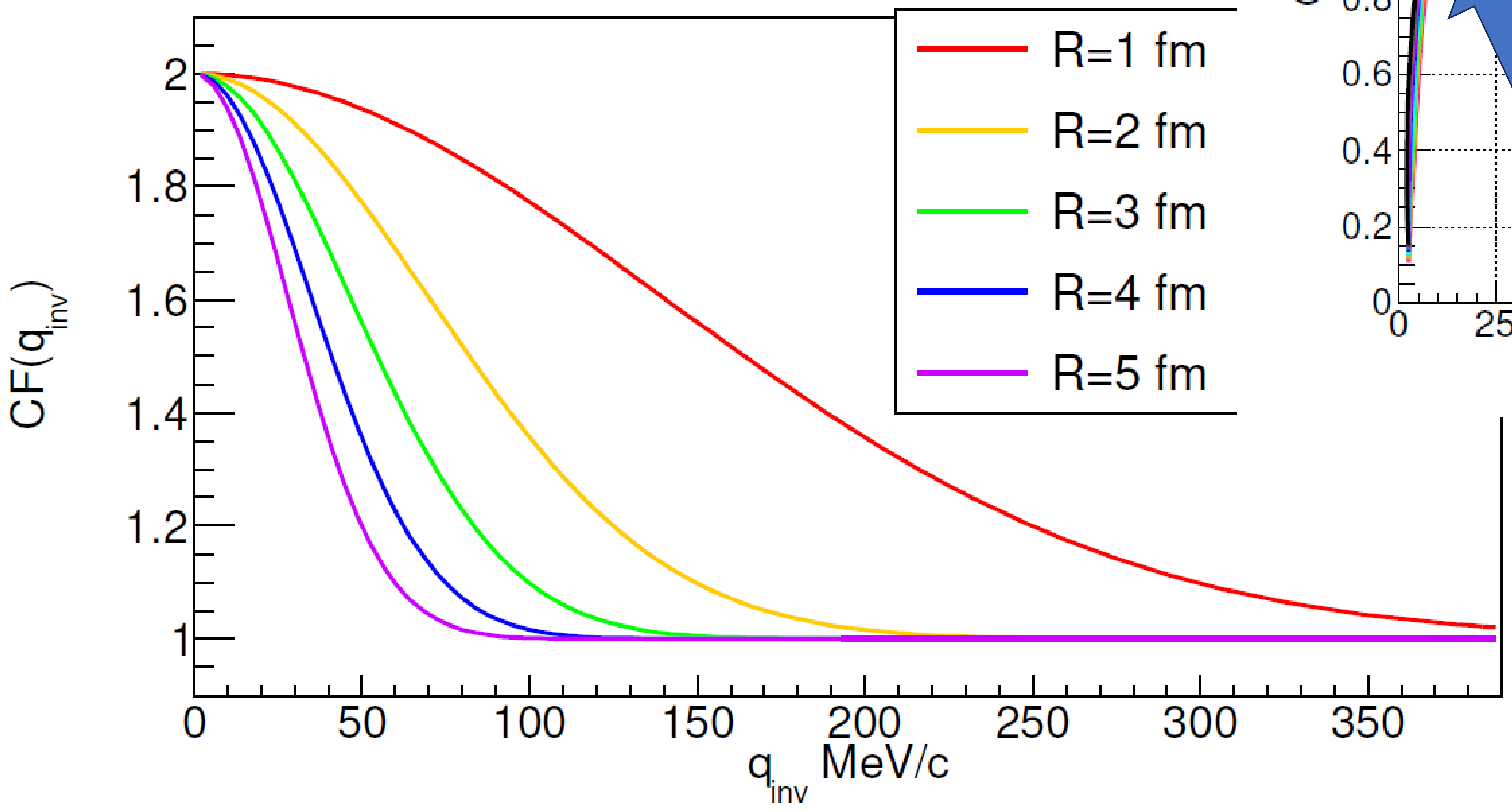
$R - size\ of\ source$

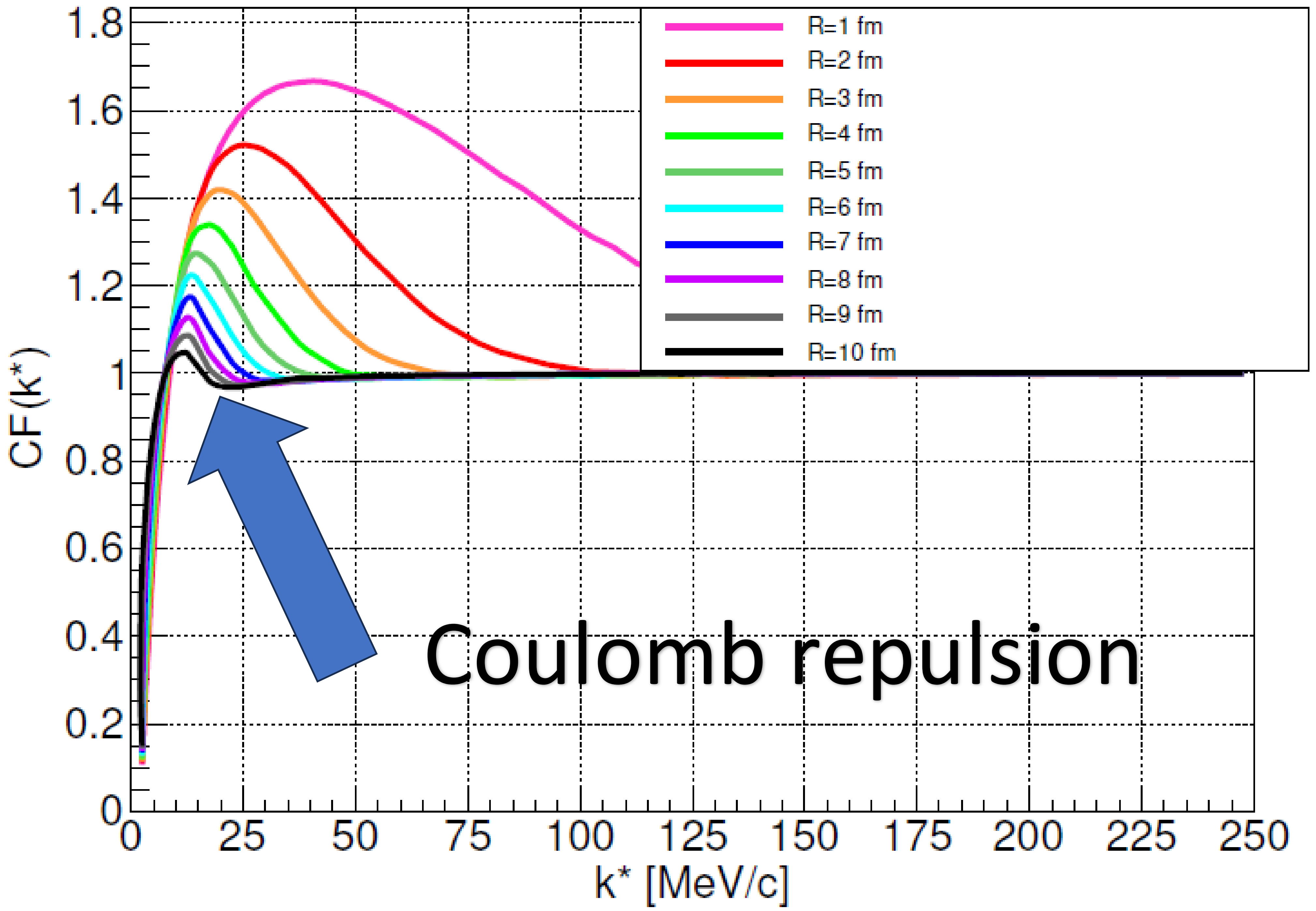
$\epsilon - assymetry\ in\ kaon\ production\ (see\ next\ slides)$

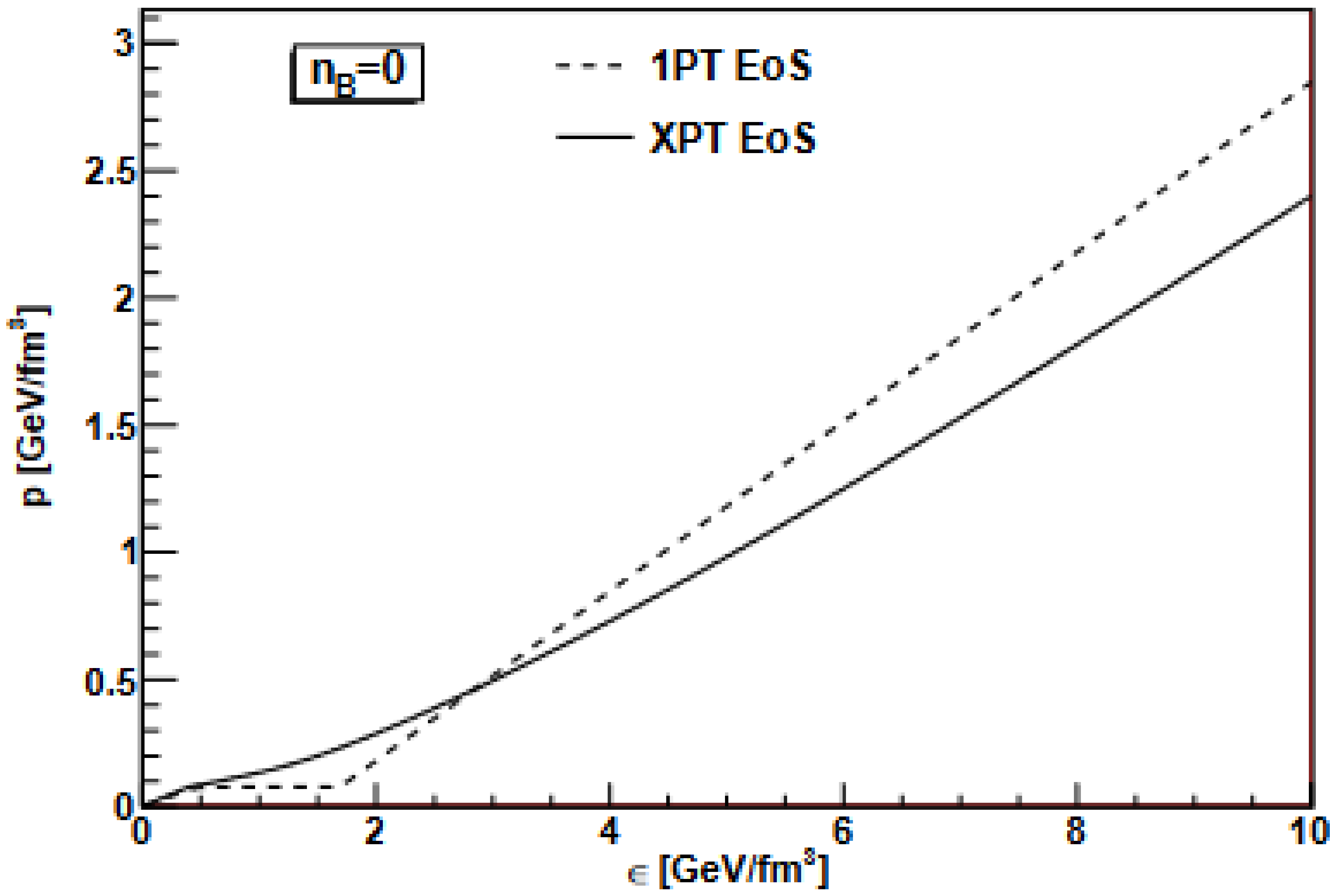
$q = 2k^* = p_1 - p_2$

$$F_1(z) = \int_0^z \frac{e^{x^2-z^2}}{z}dx$$

Femtoscopy


R=1 fm
R=2 fm
R=3 fm
R=4 fm
R=5 fm
CF(q_{inv})
q_{inv} MeV/c

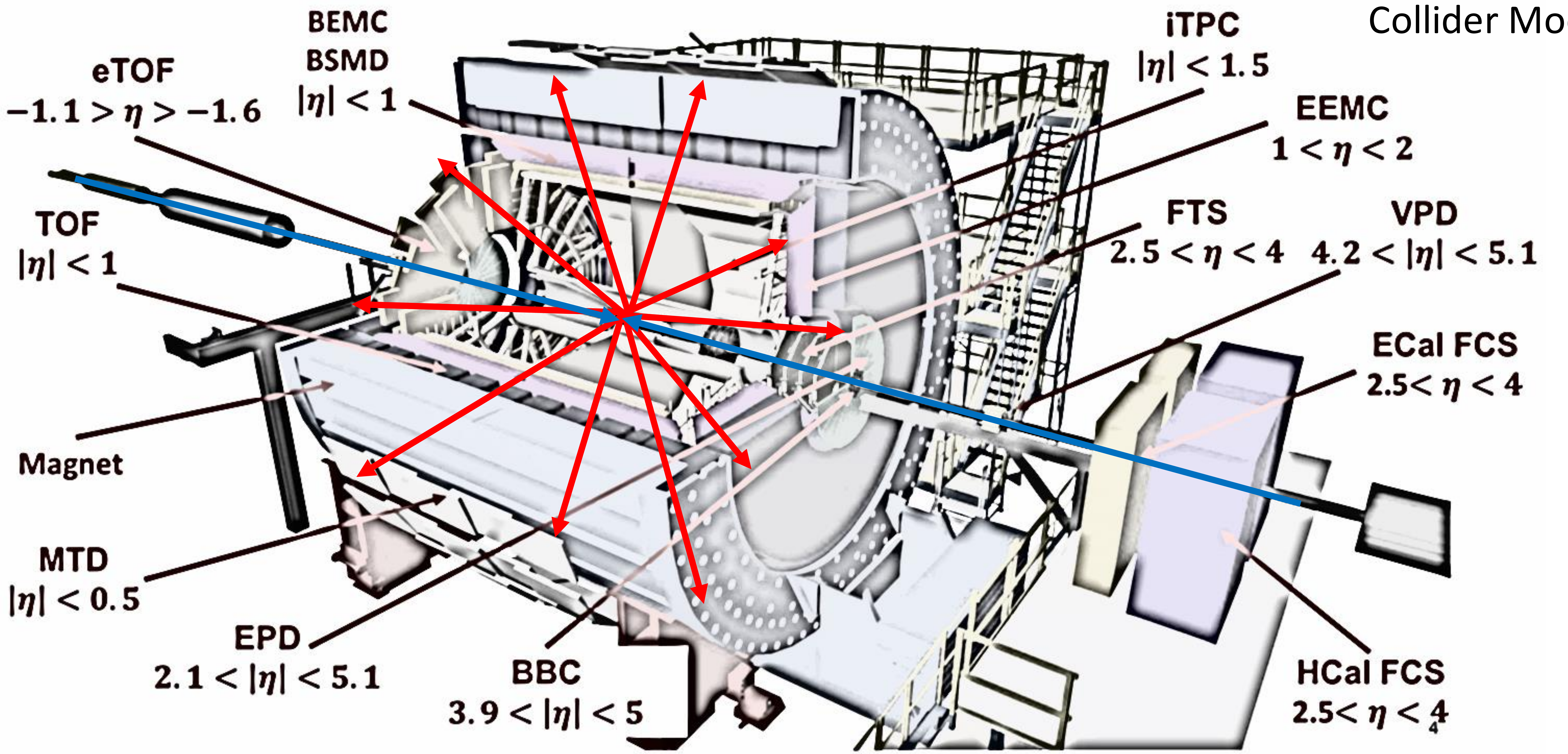

R=1 fm
R=2 fm
R=3 fm
R=4 fm
R=5 fm
R=6 fm
R=7 fm
R=8 fm
R=9 fm
R=10 fm
CF(k*)
k* [MeV/c]
Coulomb repulsion



n_B=0
1PT EoS
XPT EoS
p [GeV/fm³]
ε [GeV/fm³]
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10

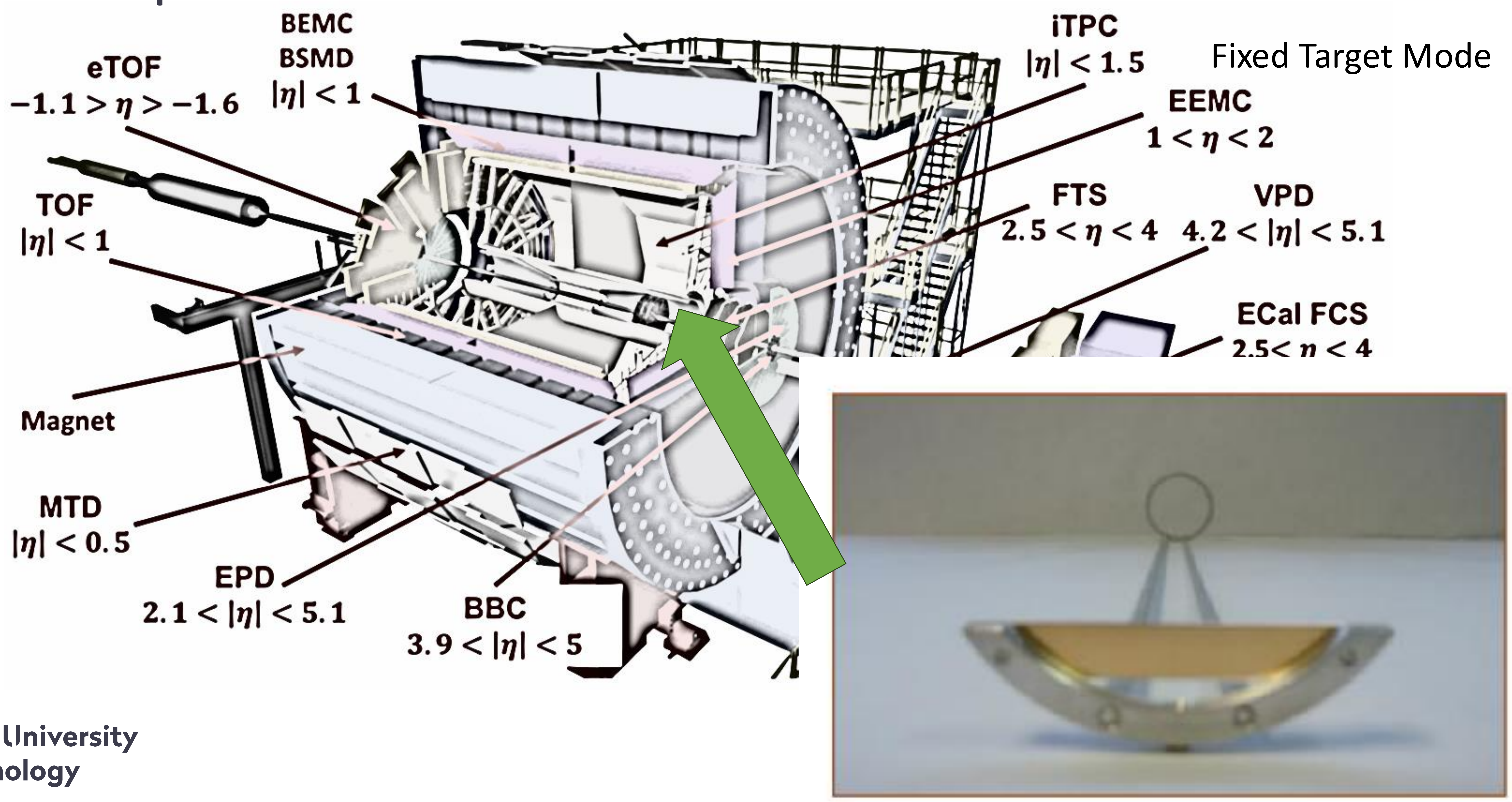
STAR experiment

Original design:
Collider Mode



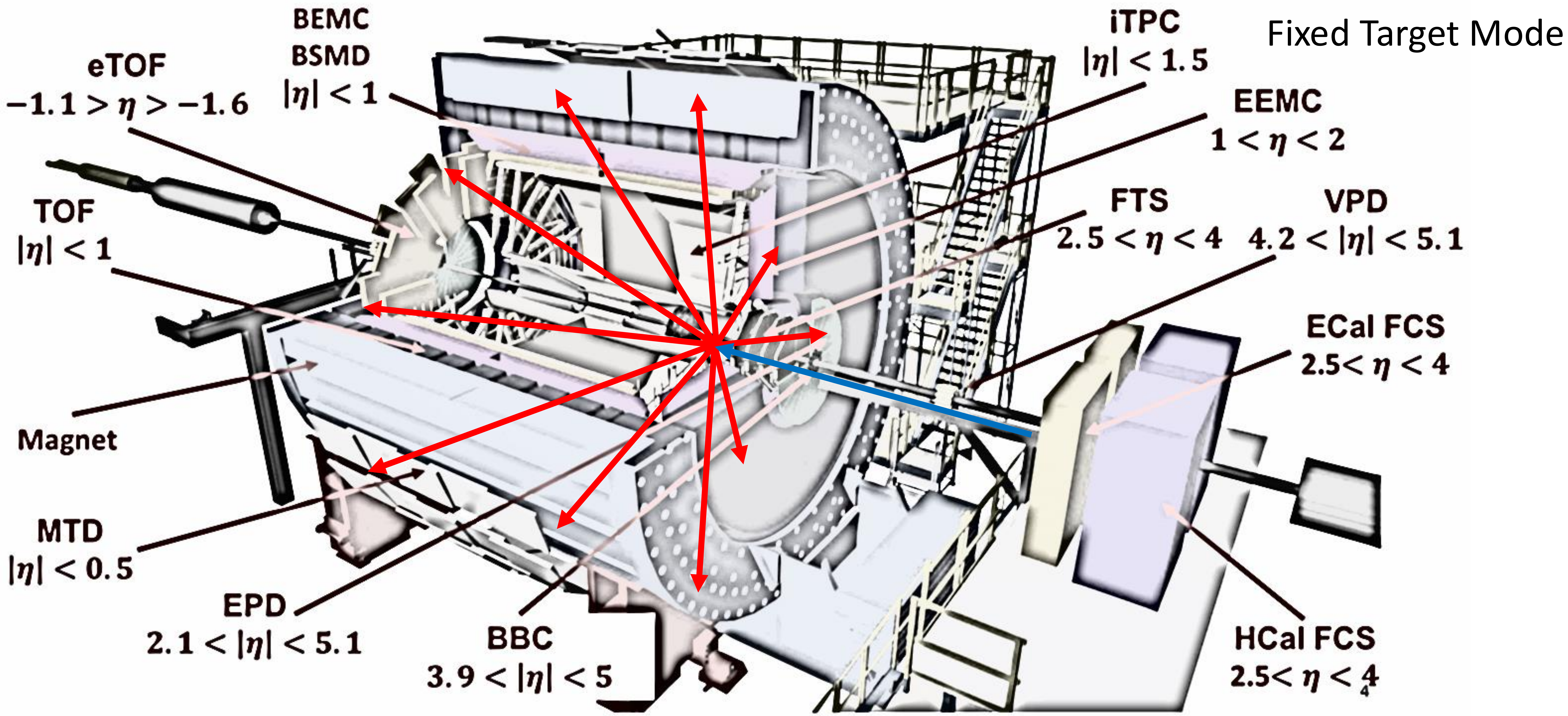
STAR experiment

Fixed Target Mode



The STAR detector upgrade and future plan, Chi Yang

STAR experiment

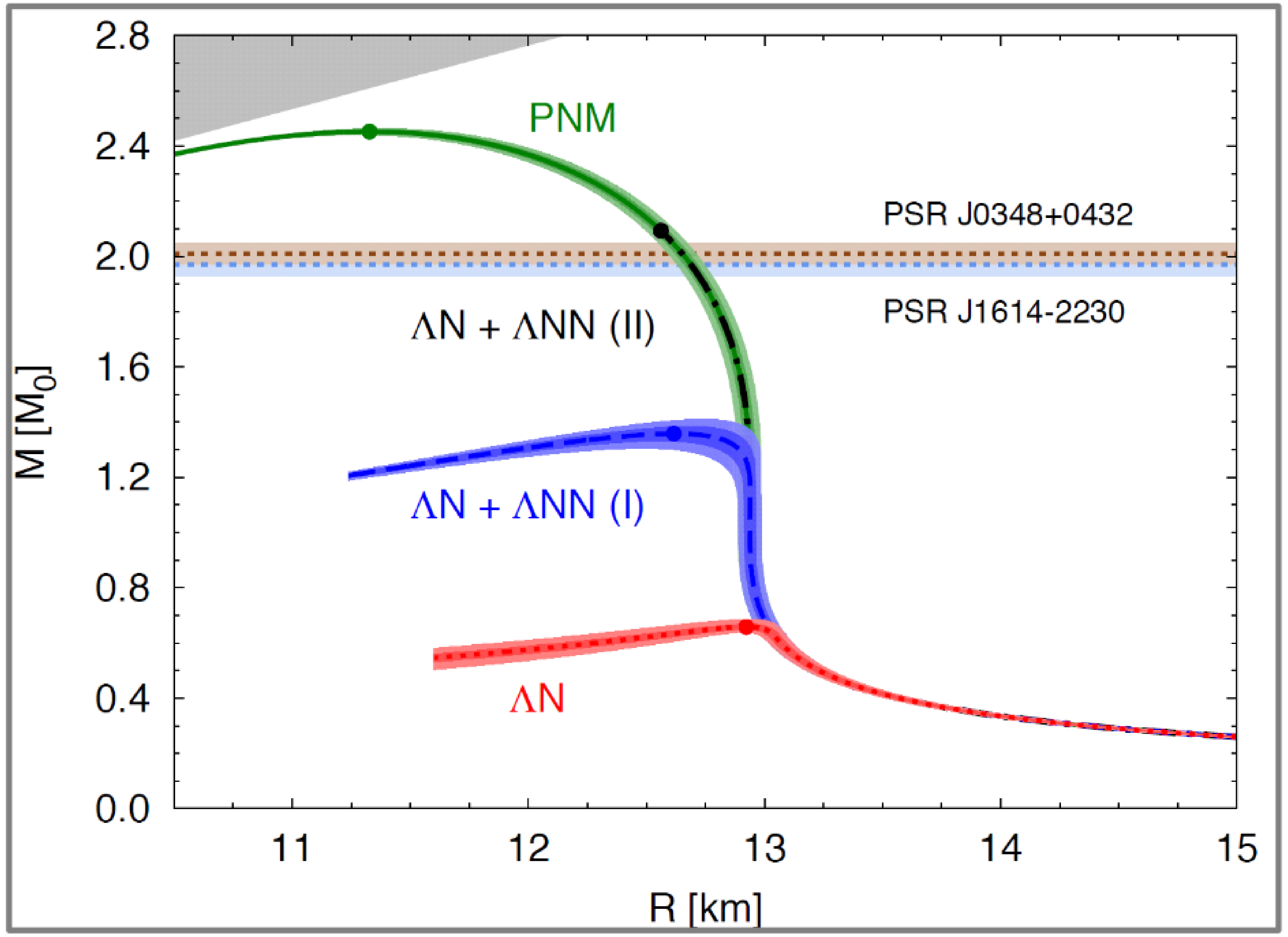


The STAR detector upgrade and future plan, Chi Yang

Femtoscopy

Probing interactions between particles:

- Protons, pions – possible to probe interactions by scattering experiments
- More exotic particles e.g., lambda, kaon –cannot produce a target/beam →**femtoscopy!**
- Interactions:
  - Attractive or repulsive?
  - Probing bound states (if exists)
  - Probing EoS of matter → better understanding of neutron stars



D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)