STAR Highlights

Sooraj Radhakrishnan
(for the STAR Collaboration)
Kent State University/
Lawrence Berkeley National Laboratory

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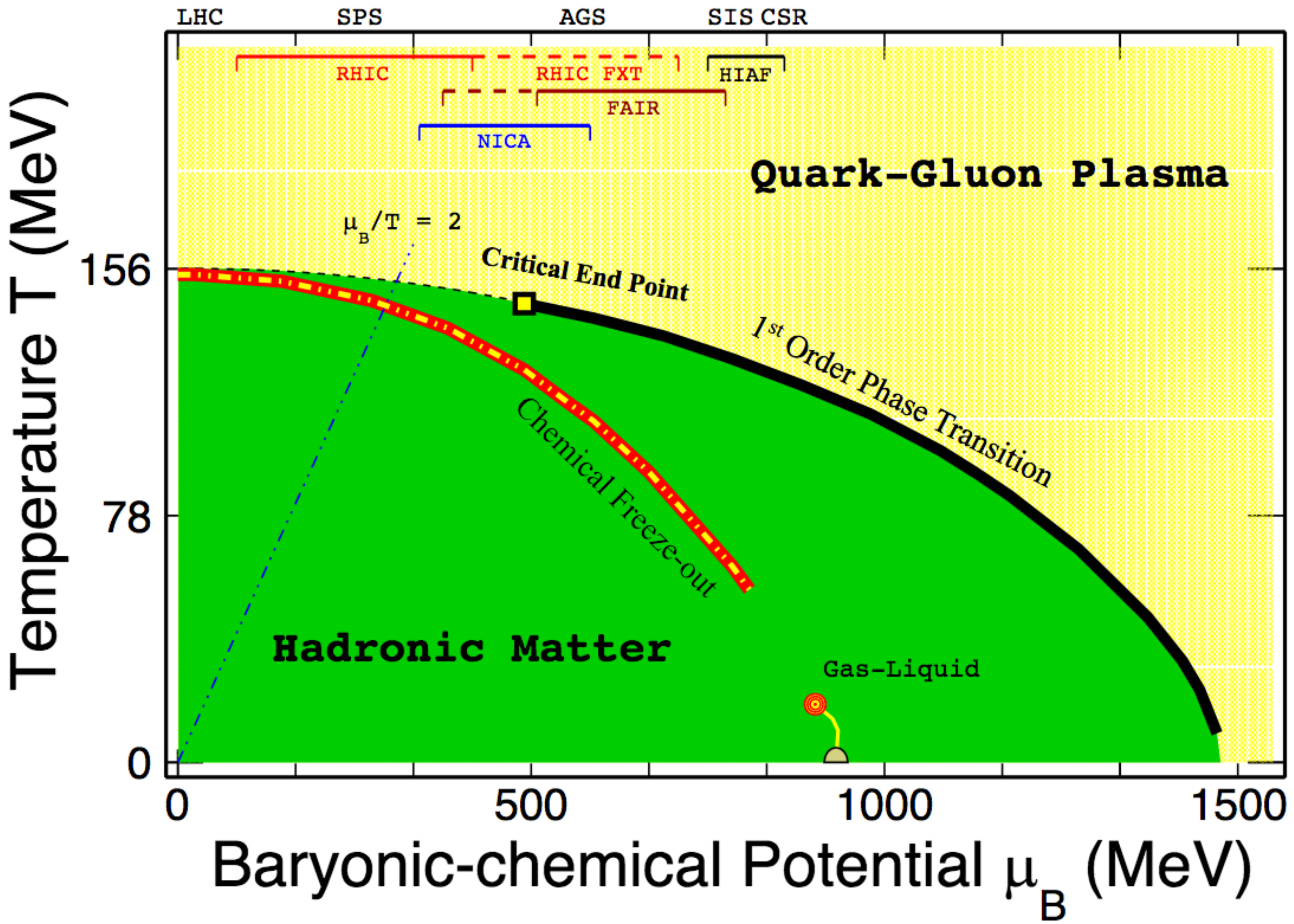
Supported in part by

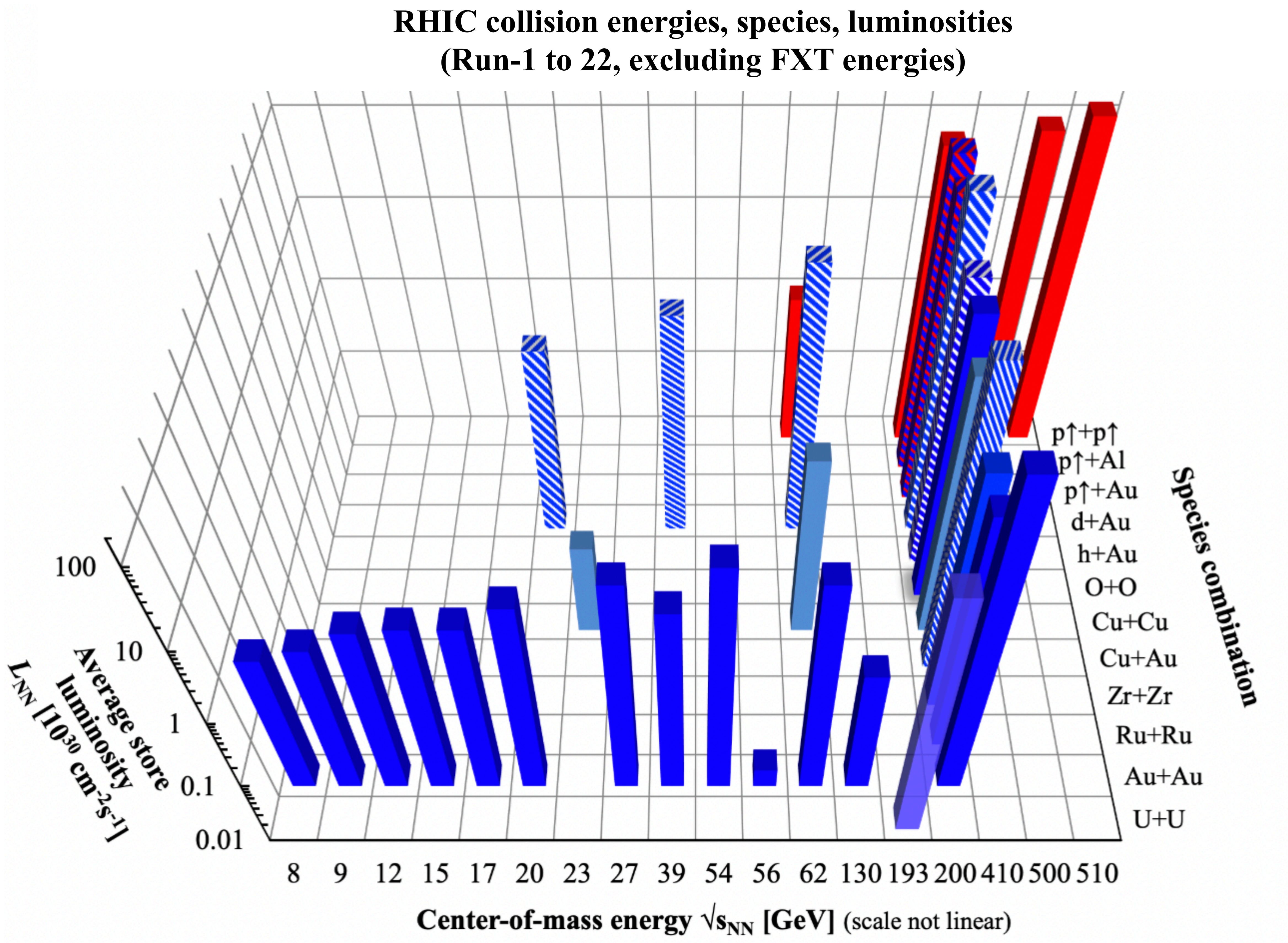
STAR - A Versatile Experiment

24 years of exploring QCD in its fullest! From QGP to QCD phase structure to confined hadronic matter

Varied collision systems, energies, programs, targeted upgrades

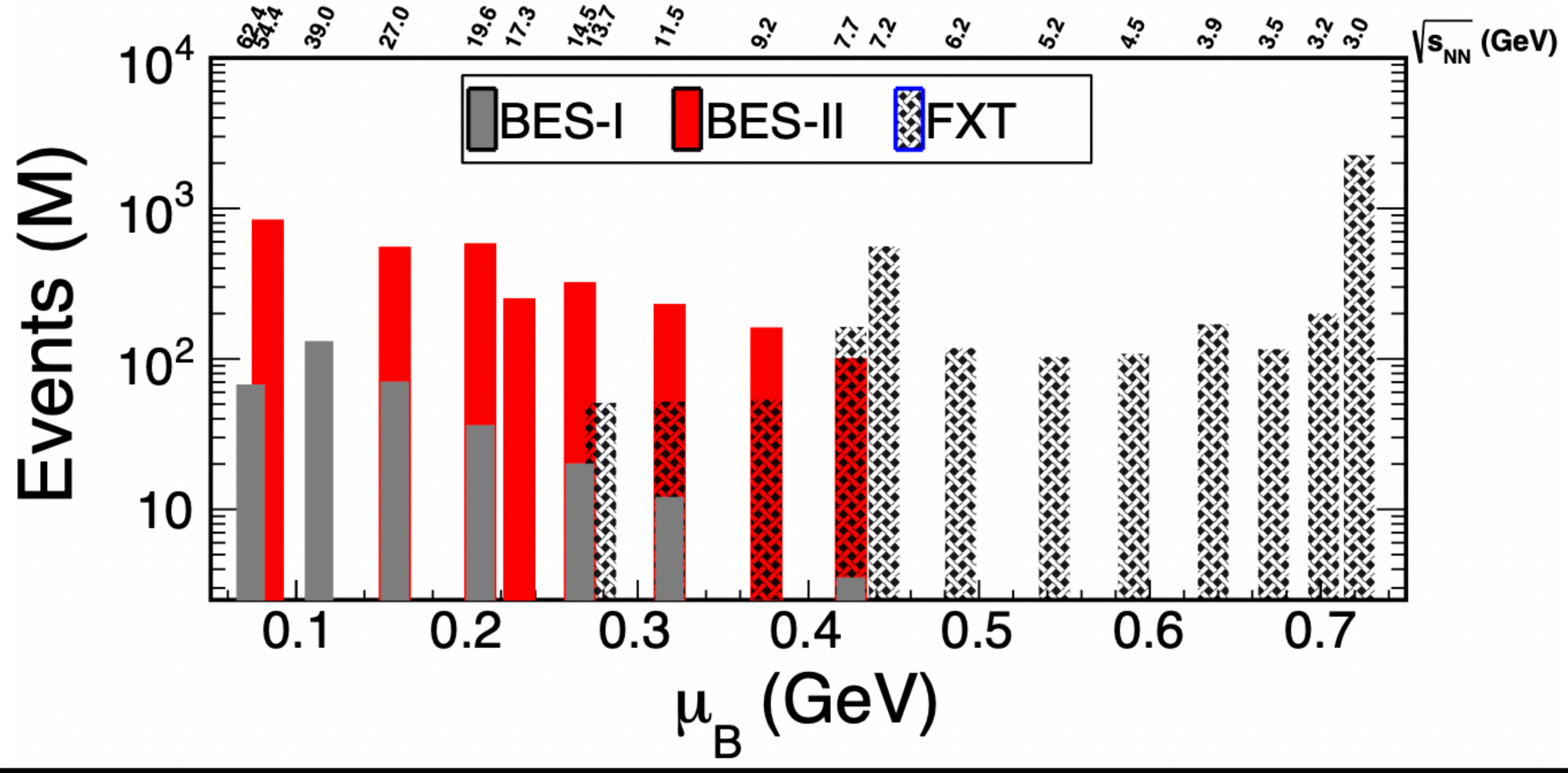


Phys. Rev. Lett.126 (2021), 092301

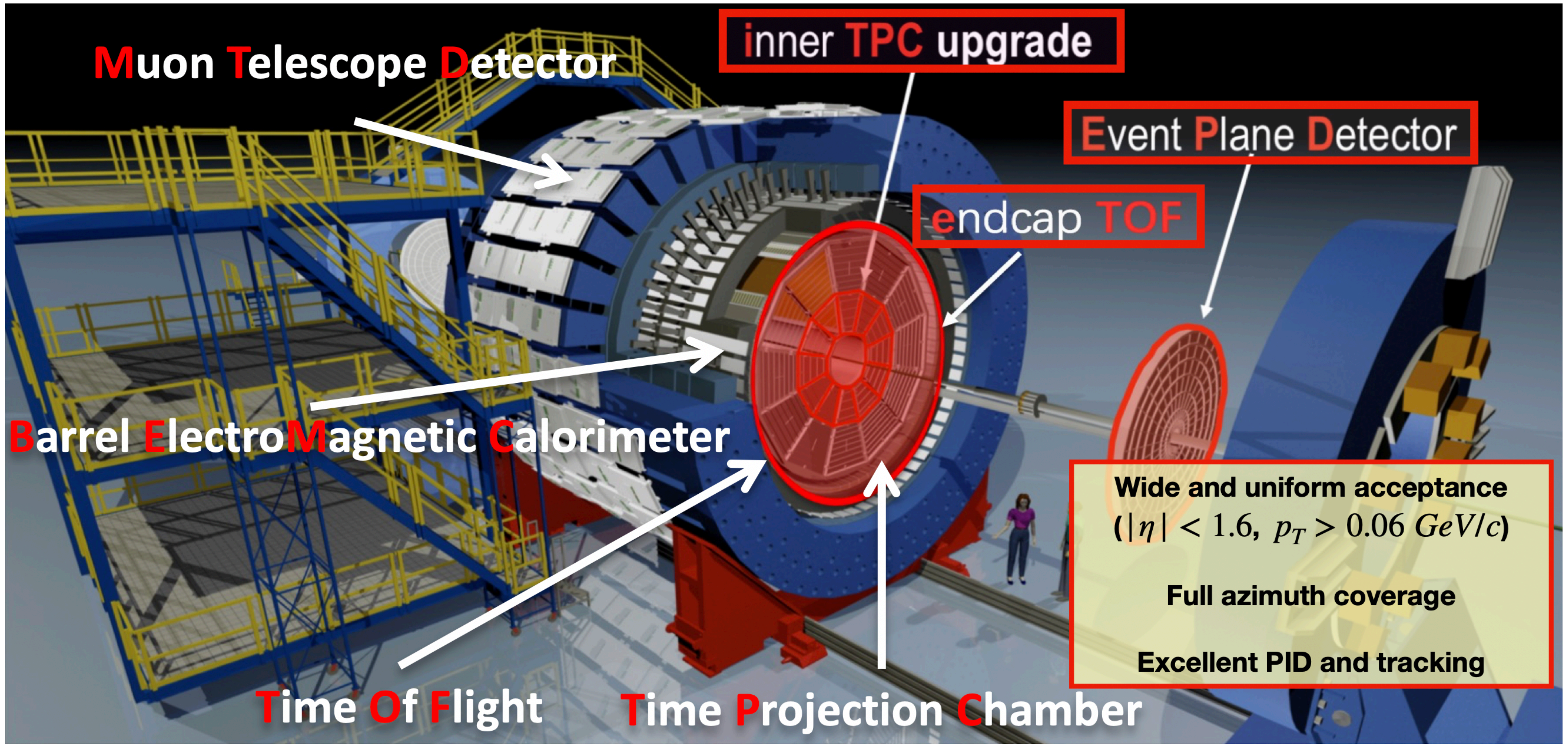


Sooraj Radhakrishnan

STAR: Beam Energy Scan - II



- Systematically explore high baryon density region (200 < μ_B < 750 MeV)
- FXT program extends the reach to μ_B = 750 MeV
- Search for CEP, phase boundary, signal for 1st order phase transition …



- Detector upgrades for BES-II:
    - iTPC, ETOF, EPD

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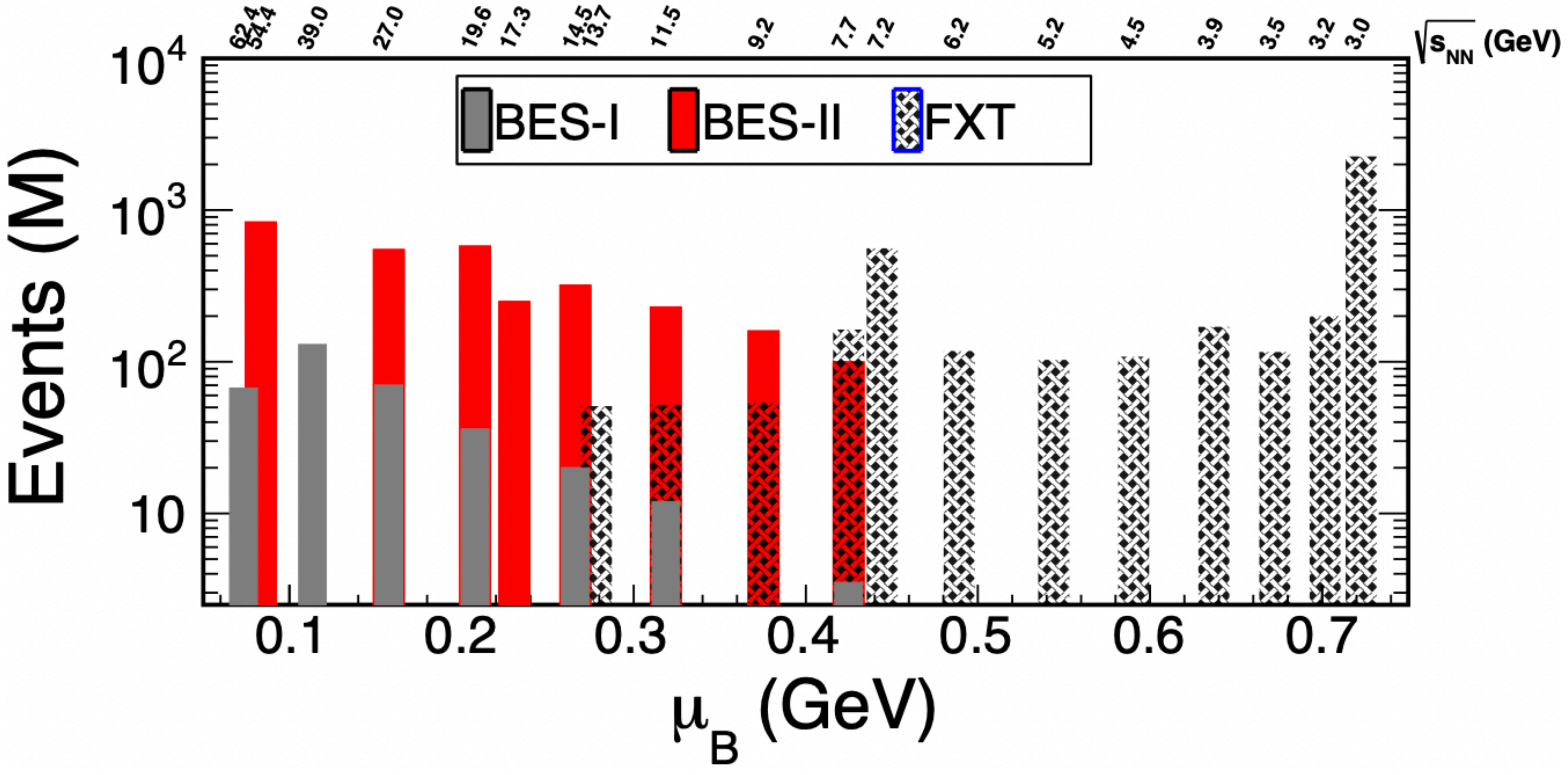

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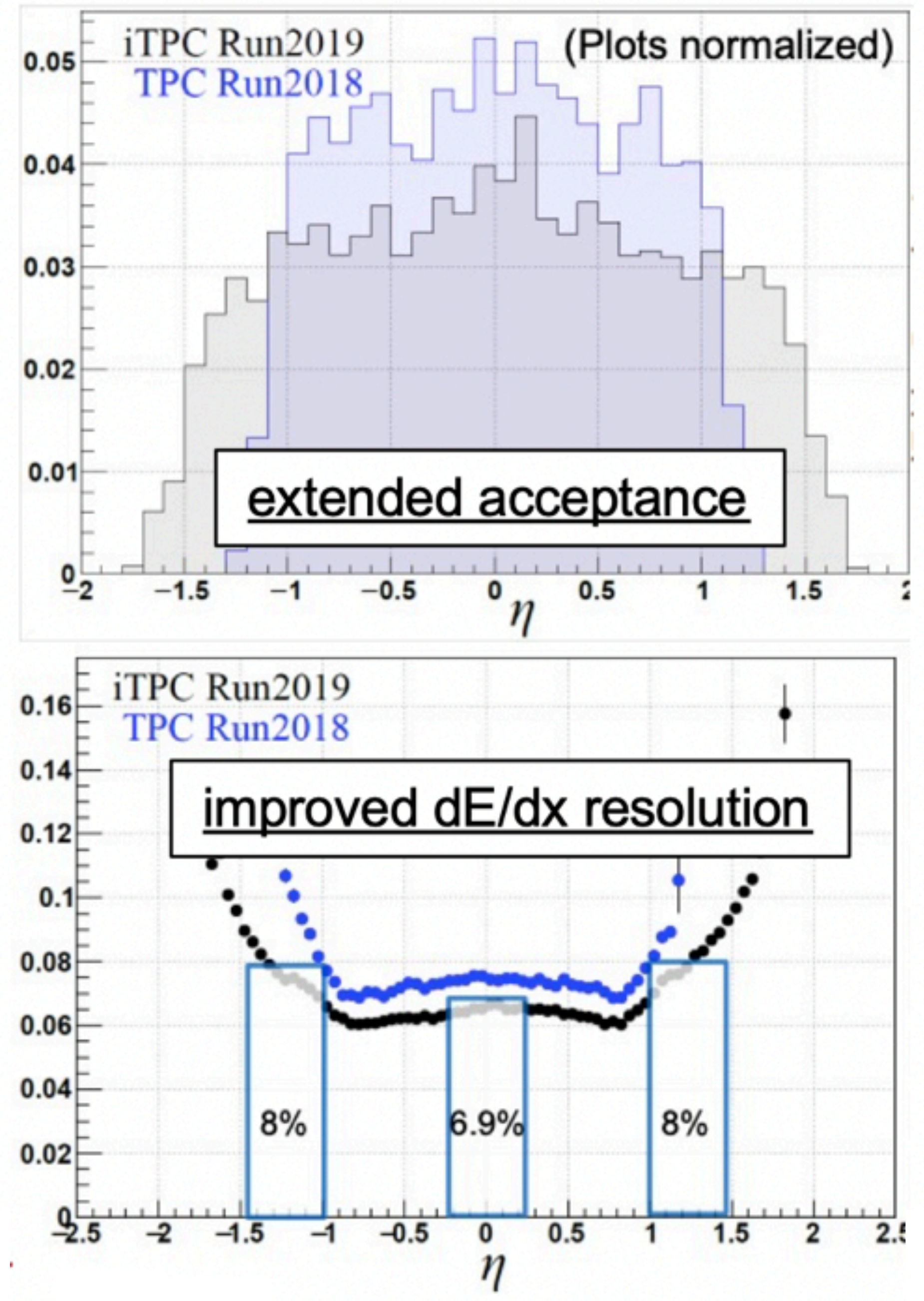
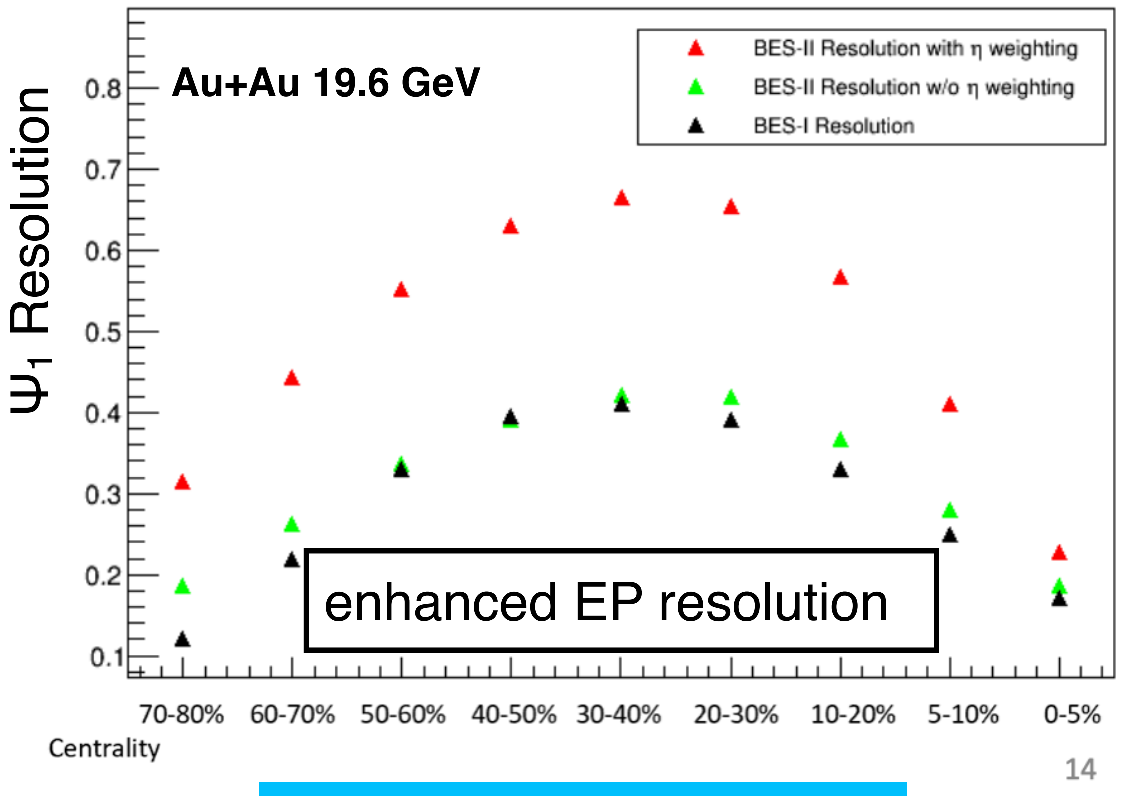
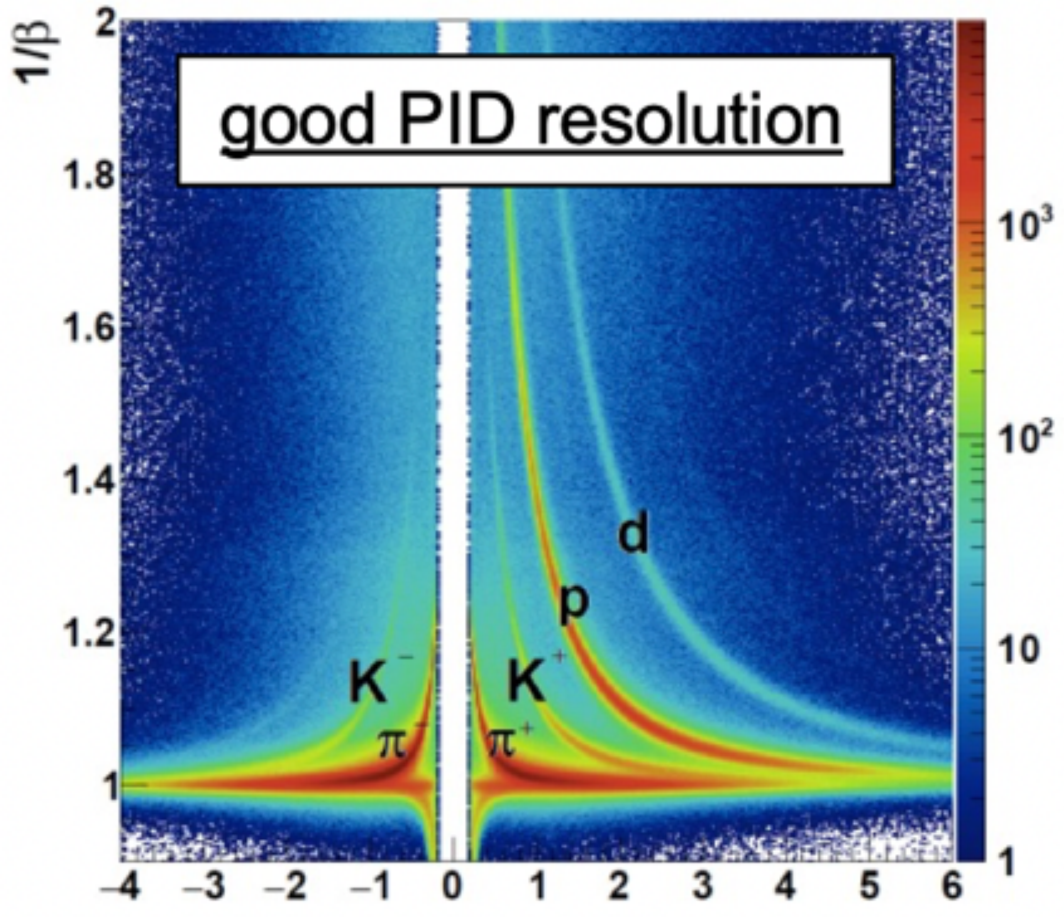




EPD ($2.1 < |\eta| < 5.1$)

iTPC ($|\eta| < 1.5$)

eTOF ($-1.5 < \eta < -1.05$)



- Detector upgrades for BES-II:
  - iTPC: ($|\eta|<1$ —> $|\eta|<1.5$, lower p_T reach, improved dE/dx resolution),
  - ETOF: (PID at forward η),
  - EPD: EP determination, trigger

STAR Highlights: Overview

- **Exploring the QCD phase structure**
  - CEP search, fluctuations of conserved charges, collectivity and EoS
- **Particle production and thermodynamic properties**
  - HBT correlations, strangeness production, baryon stopping
- **Hyperon interactions at high baryon density**
  - Baryon - hyperon correlations, light and hyper-nuclei production

Exploring the QCD phase structure
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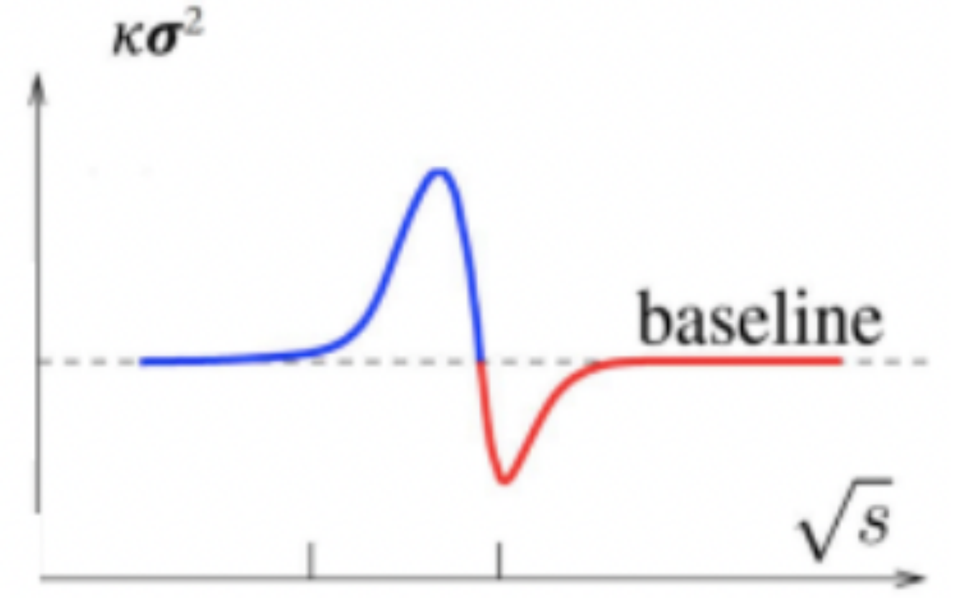
Baryon - hyperon correlations, light and hyper-nuclei production

Search for CEP: Net-proton cumulants

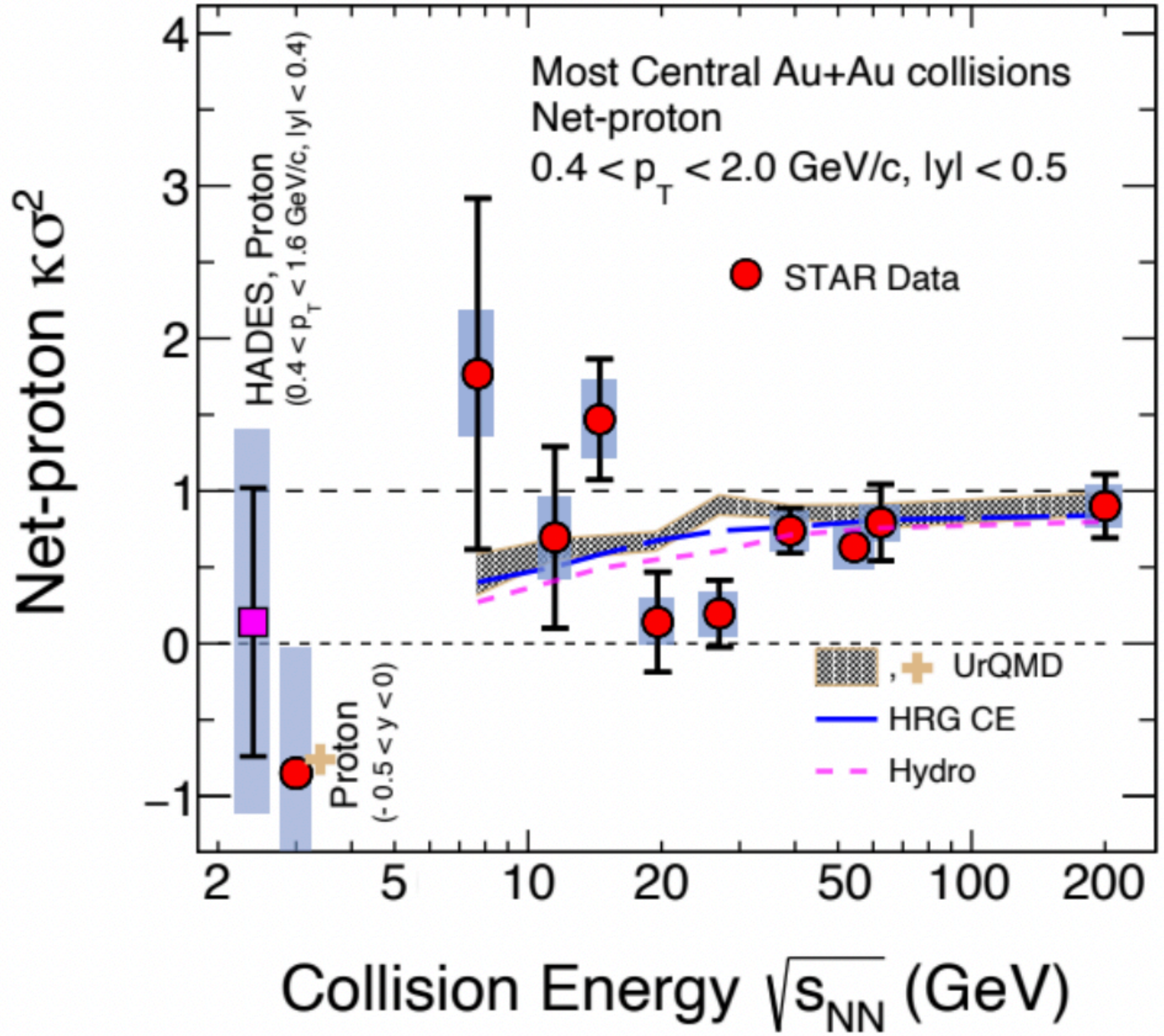
$C_2 \sim \xi^2, C_4 \sim \xi^7$

- Cumulants of conserved charge distributions relate to correlation length in the medium
- C_4/C_2 predicted to be non-monotonous in collision energy near CEP

M. A. Stephanov, Phys.Rev.Lett. 107 (2011)



- Indication of non-monotonous energy dependence from STAR BES-I measurements
- Falls back to baseline at 3 GeV



STAR, Phys. Rev. Lett.127, 262301 (2021)
STAR, Phys. Rev. Lett. 128, 202302 (2022)

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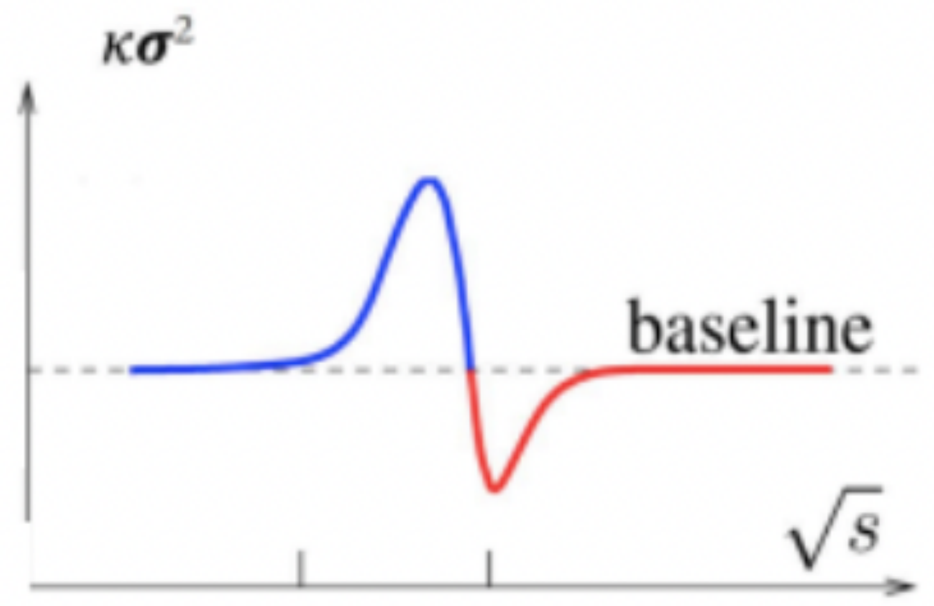
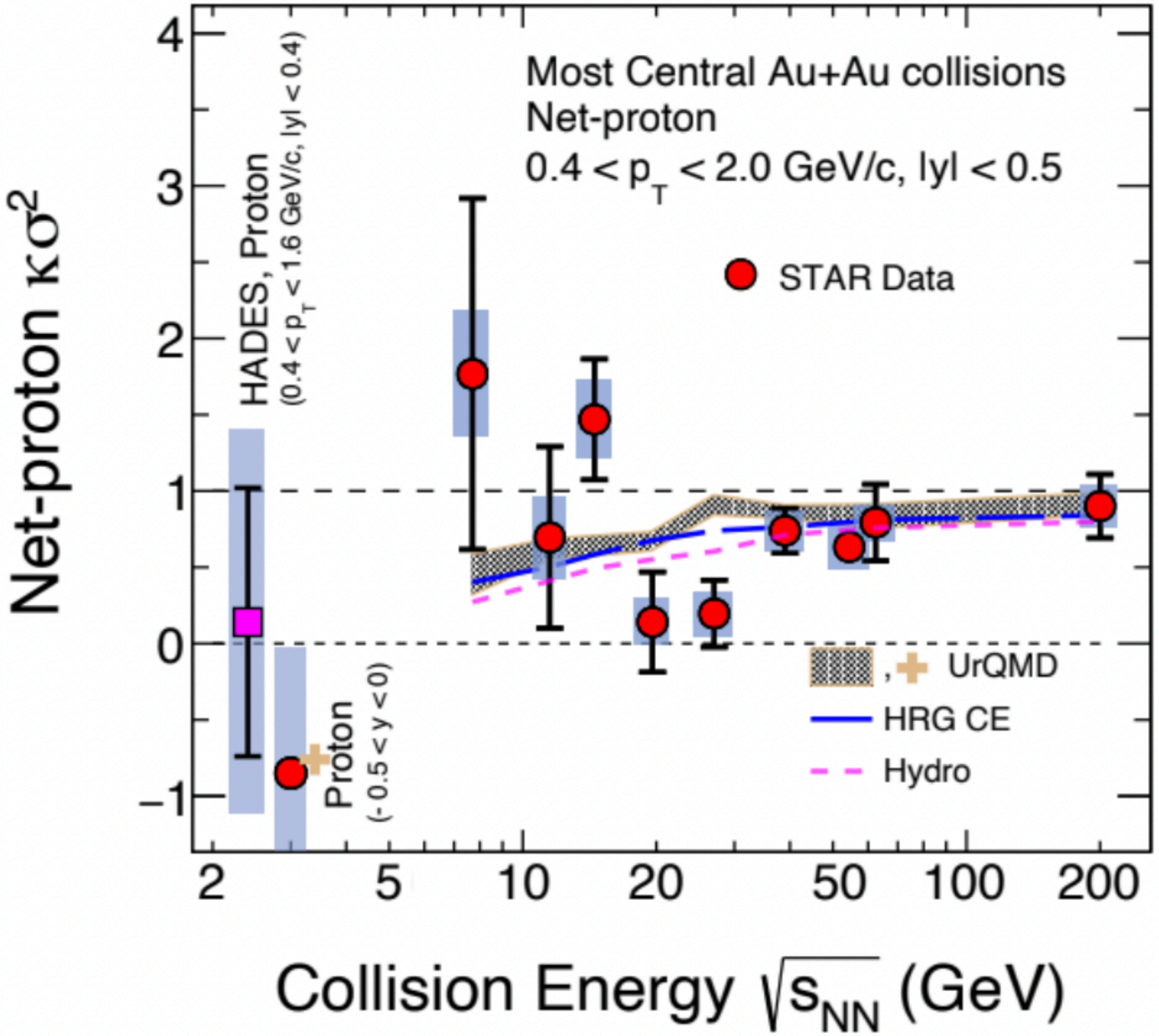


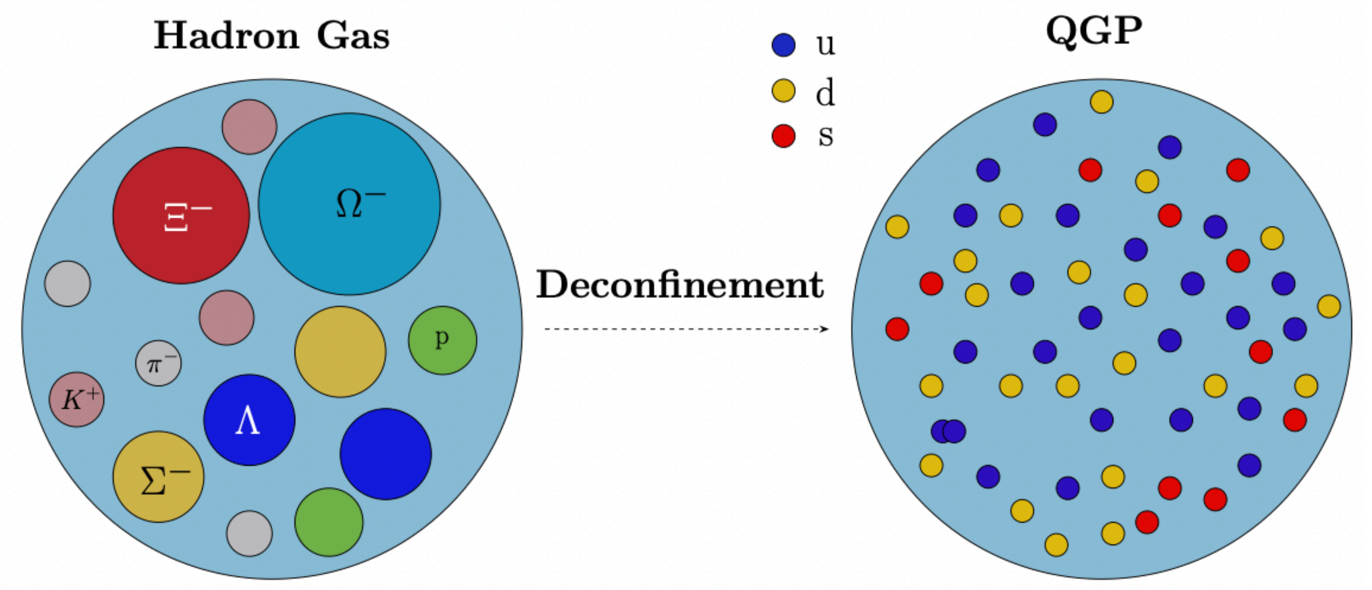


- Indication of non-monotonous energy dependence from STAR BES-I measurements
- Falls back to baseline at 3 GeV

Precision measurements from BES-II: new STAR results in Ashish Pandav's talk, 5/21, 09:00

STAR, Phys. Rev. Lett.127, 262301 (2021)
STAR, Phys. Rev. Lett. 128, 202302 (2022)

Baryon - Strangeness correlations



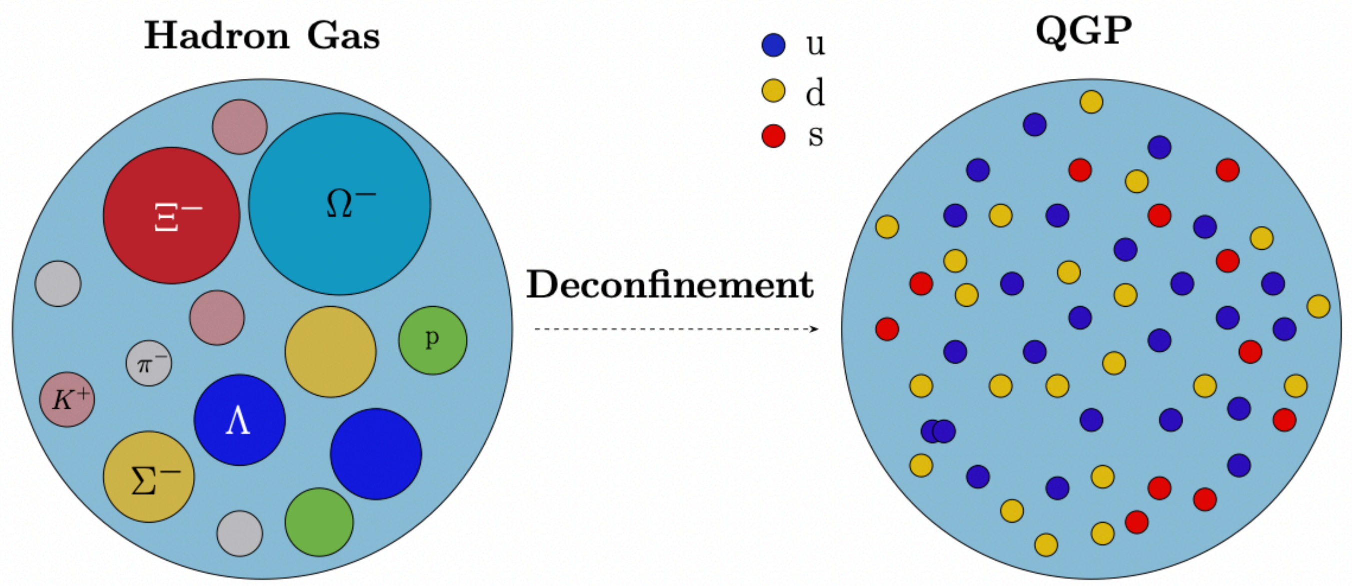
$$C_{BS} = -3\frac{\langle BS\rangle_c}{\langle S^2\rangle_c} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$

B-S correlations

- Strangeness carried by different degrees of freedom in hadron gas and QGP
- Can be sensitive probe of deconfinement

V. Koch et al., Phys. Rev. Lett. 95.182301 (2005)

Baryon - Strangeness correlations



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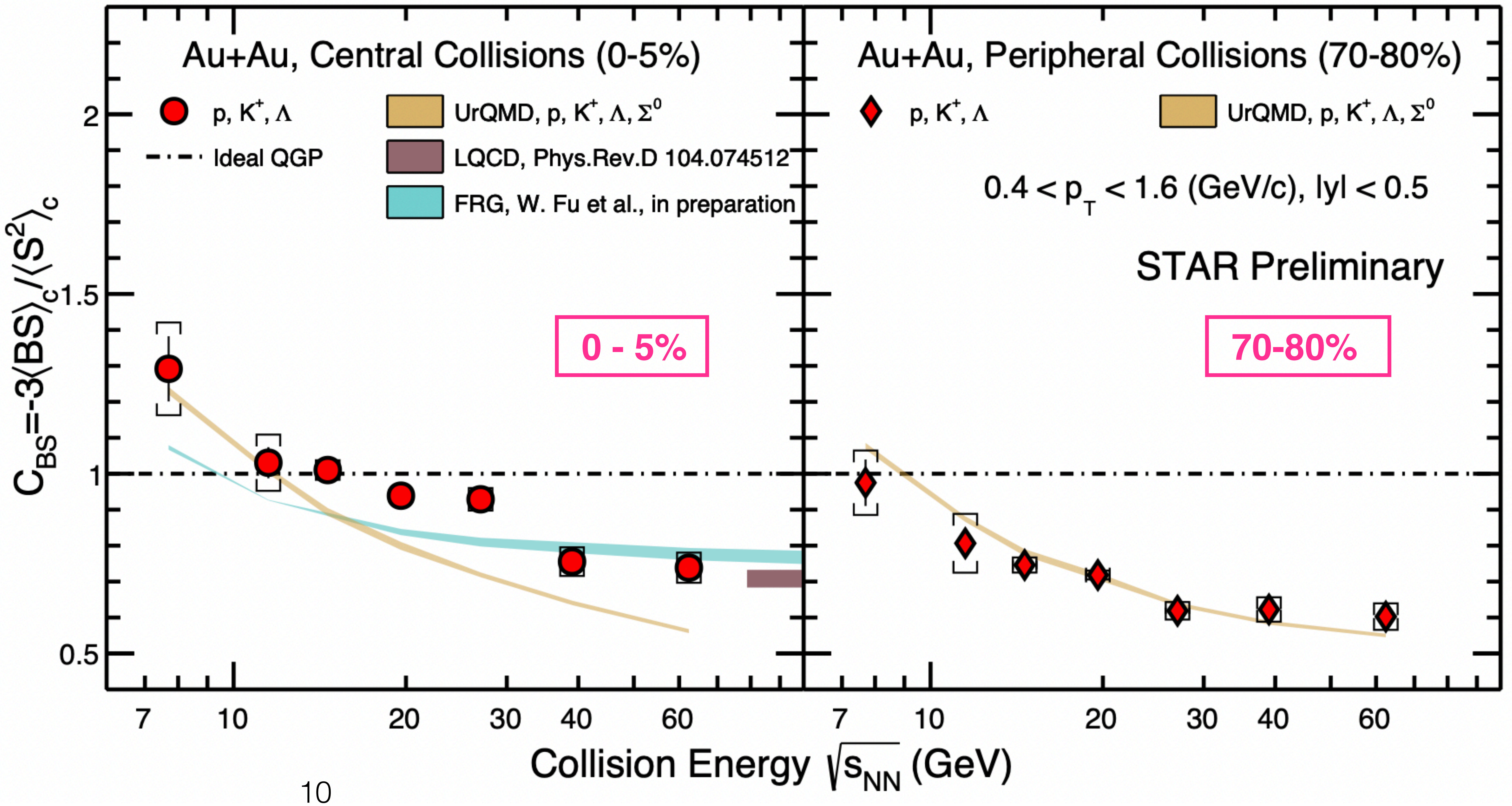
B-S correlations

- Strangeness carried by different degrees of freedom in hadron gas and QGP
- Can be sensitive probe of deconfinement

- C_{BS} in peripheral collisions reproduced by UrQMD
- In central collisions, UrQMD fails to describe above 10 GeV. C_{BS} at higher energy consistent with FRG and LQCD

net-B : $\delta p + \delta\Lambda(+\delta\Xi^-)$ net-S : $\delta K^+ - \delta\Lambda(-2\delta\Xi^-)$



Talk by Hanwen Feng, 5/22, 11:30

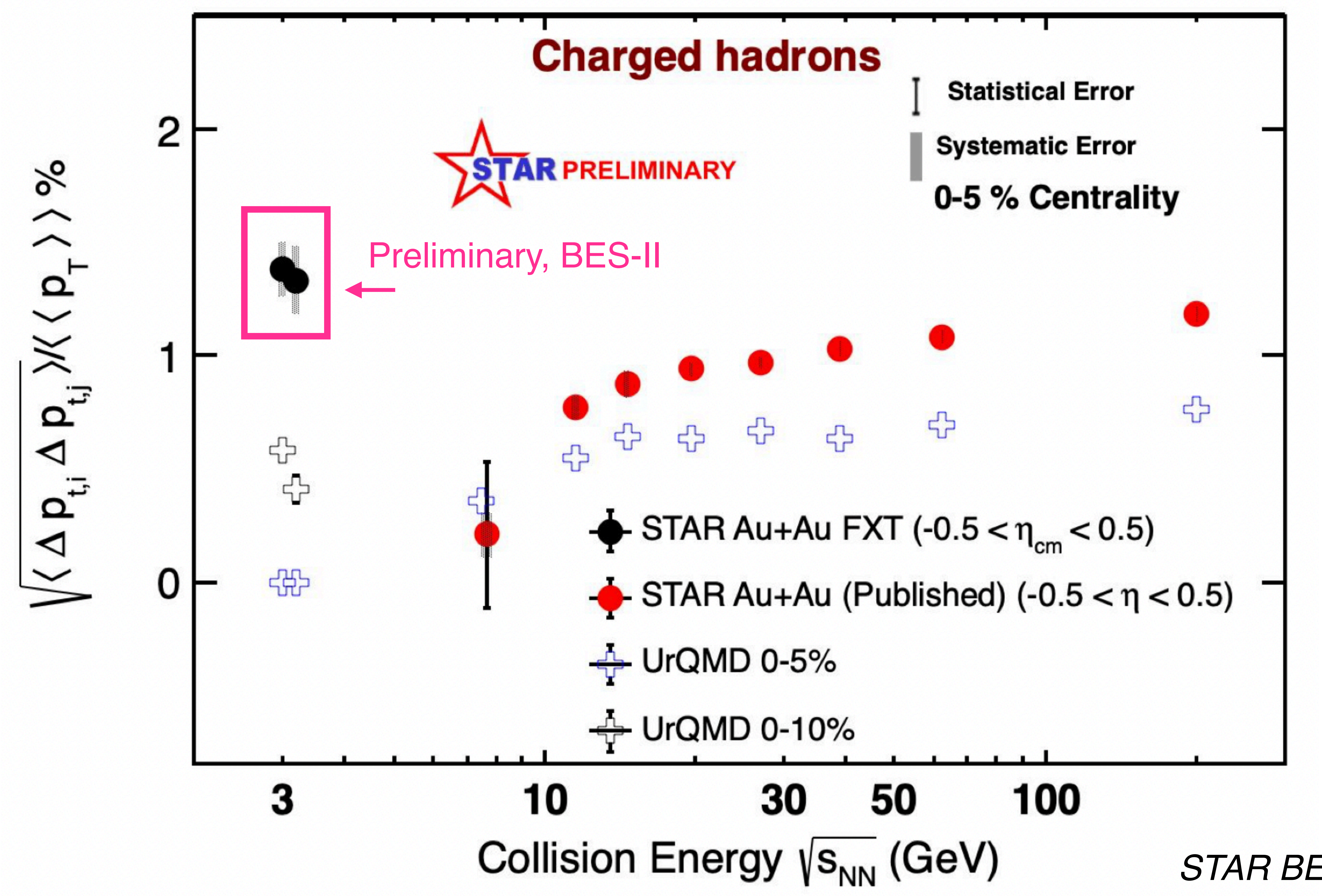
Sooraj Radhakrishnan

Momentum correlations

- In thermalized systems, sensitive to ratio of correlation length to transverse size

$$C_m \equiv < \Delta p_{T,i}, \Delta p_{T,i} >$$

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



- Non-monotonous in collision energy
- UrQMD fails to describe data

- More studies needed to understand data - model comparisons

STAR BES-I: Phys.Rev.C 99, 2019

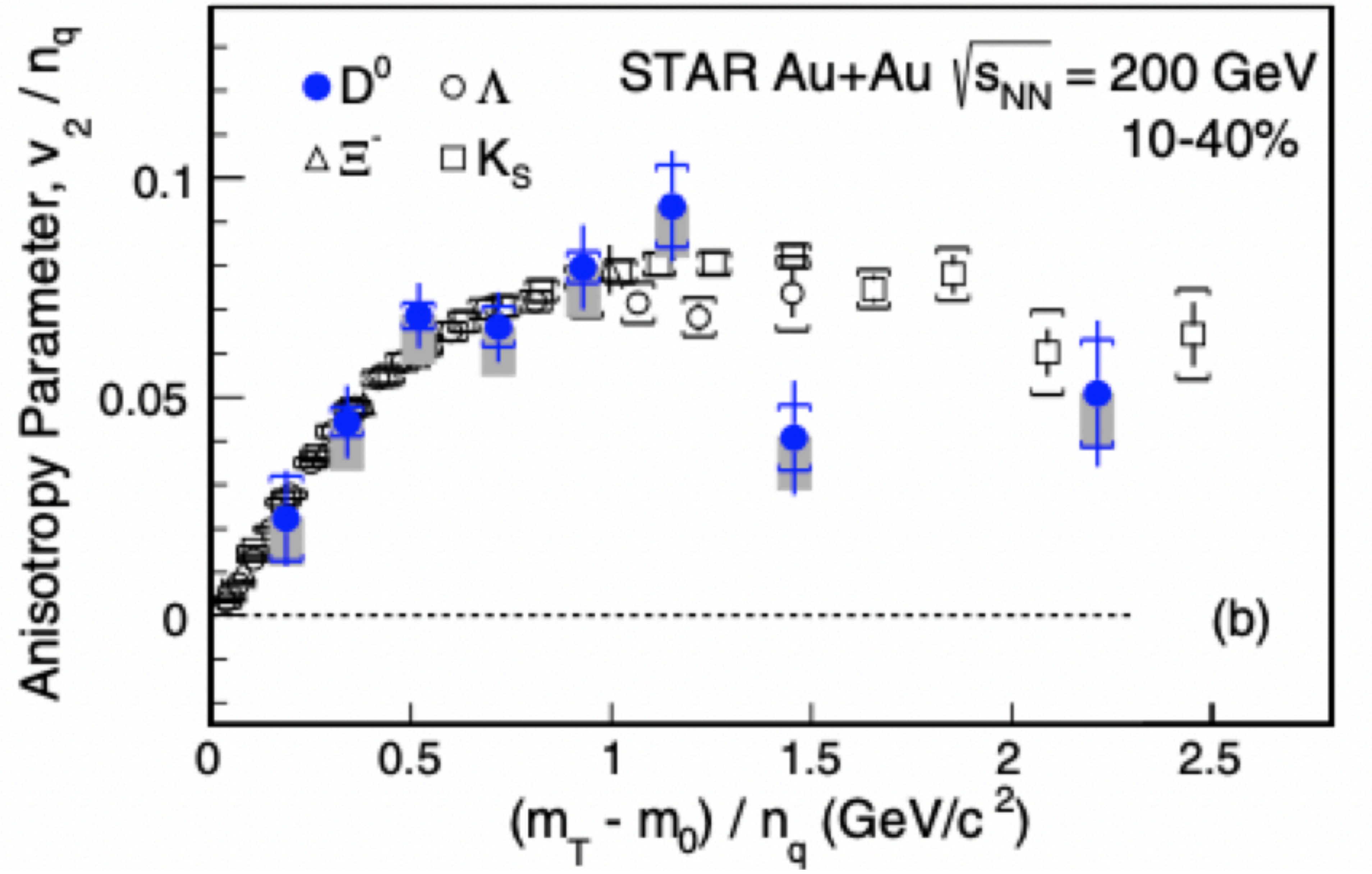
Talk by Rutik Manikandan, 5/21, 17:00

Collectivity and EoS: Onset of partonic collectivity

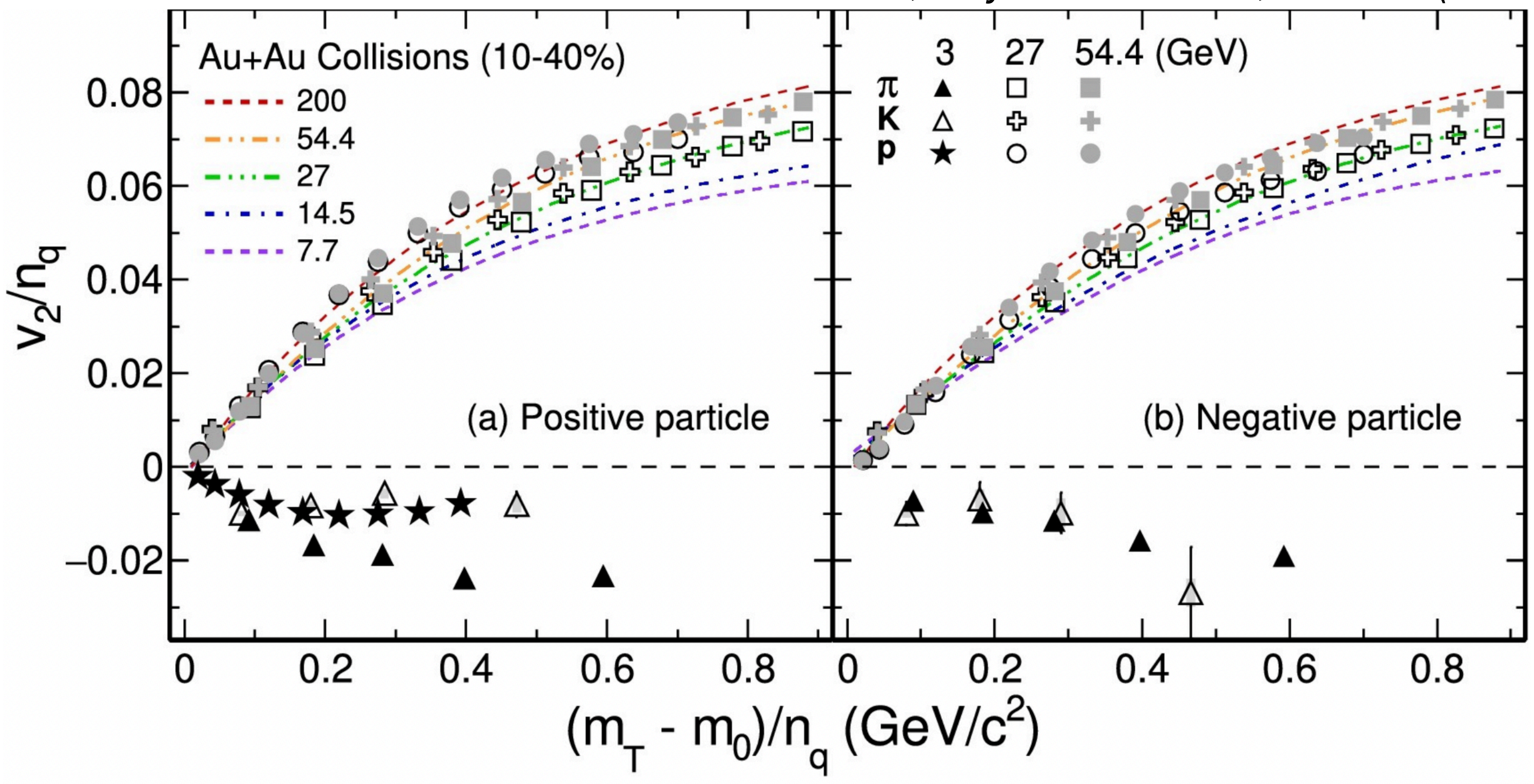
Anisotropic flow: tools to probe EoS of the matter

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n)$$

STAR, Phys. Rev. Lett. 118, 212301 (2017)

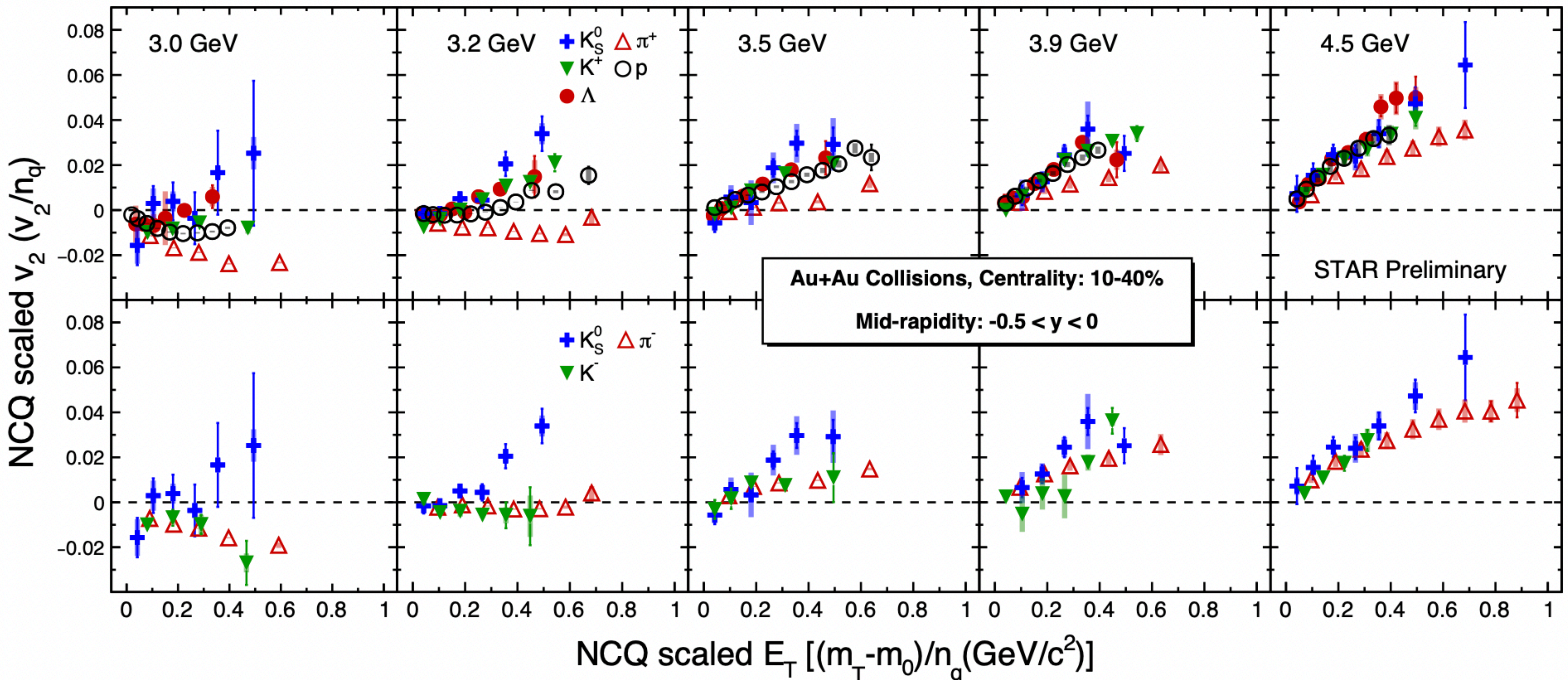


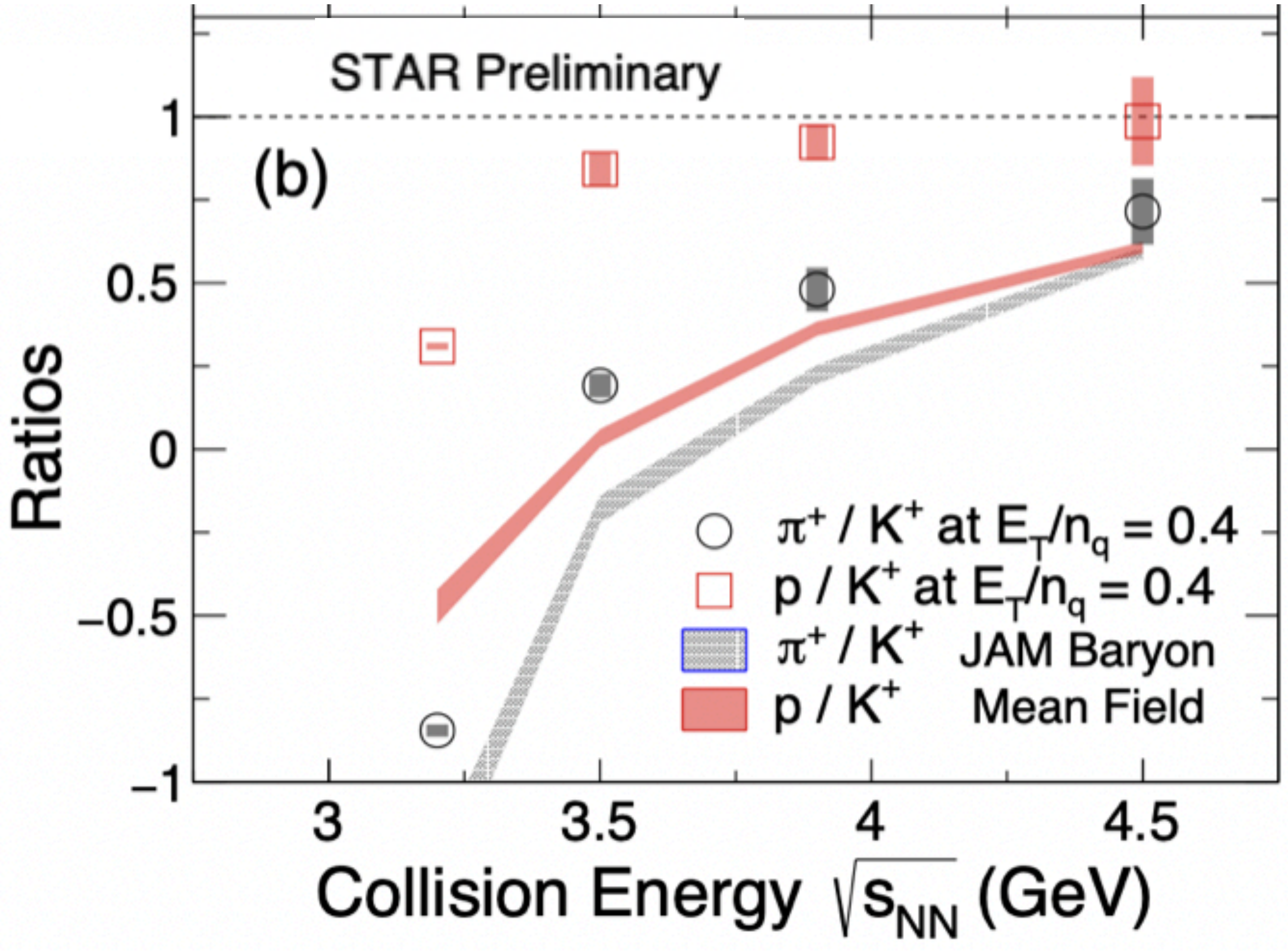
STAR, Phys. Lett. B 827, 137003 (2022)



- Constituent quark scaling holds at higher energies —> partonic collectivity
- Broken at 3 GeV —> dominance of hadronic interactions

Onset of partonic collectivity

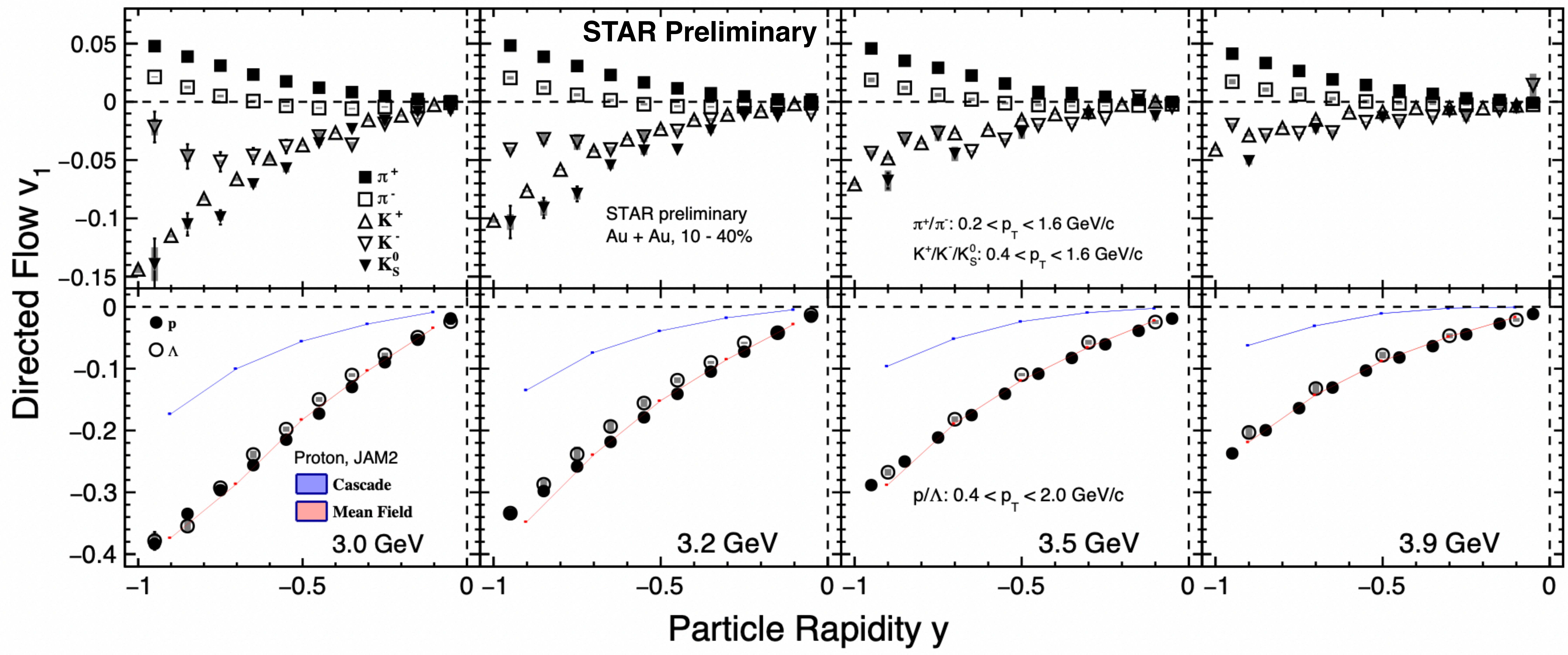




- NCQ scaling completely broken at and below 3.2 GeV
- Scaling gradually restores at 4.5 GeV
- Indication of change from hadron dominated matter —> parton dominated matter

Talk by Like Liu, 5/21, 14:30

Directed flow measurements at high baryon density

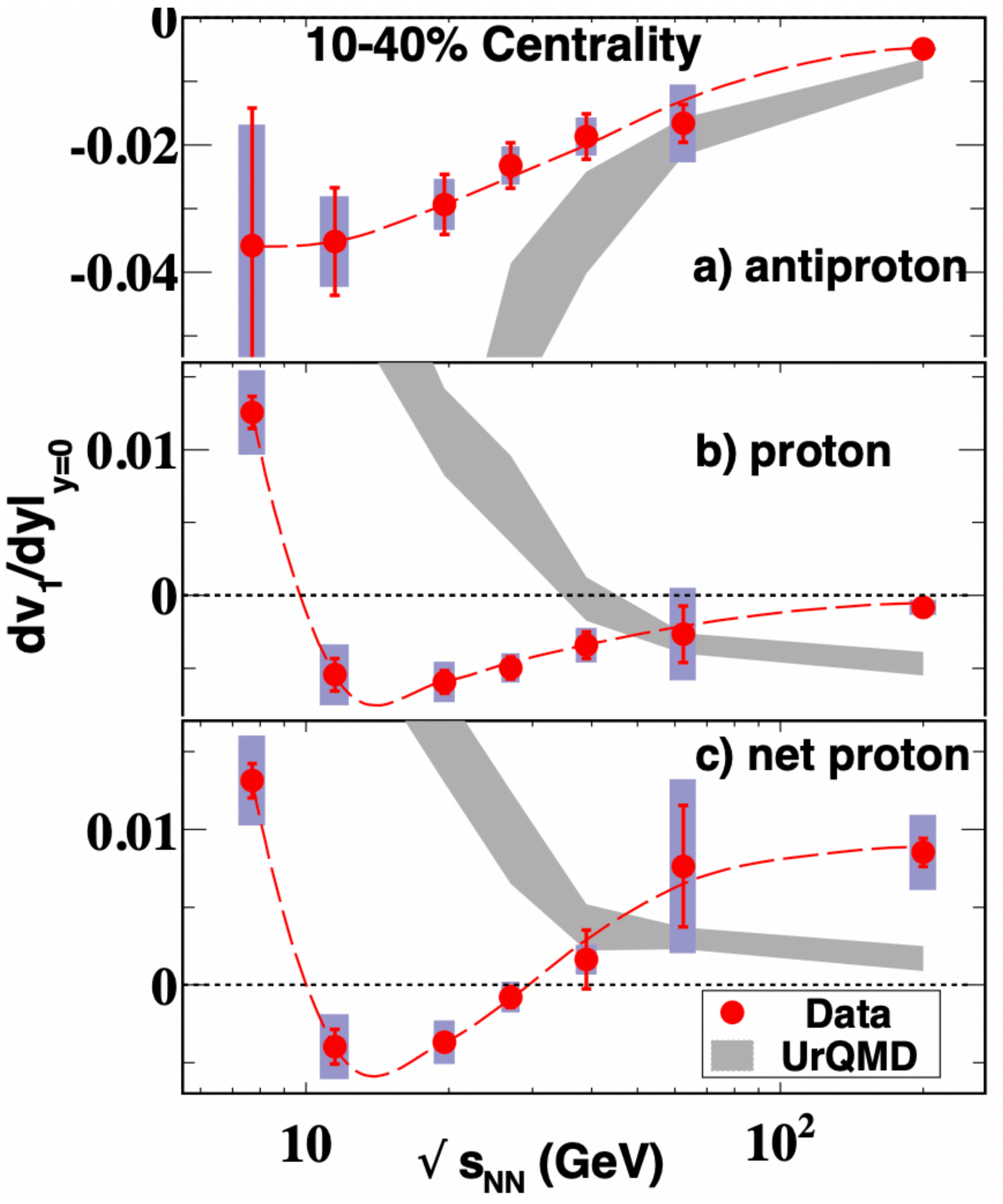


JAM MF: momentum dependent soft EoS; K = 210 MeV

- π, K, p, Λ measured across collision energies at high μ_B
- JAM with mean field interactions can describe the baryon flow

Talk by Like Liu, 5/21, 14:30

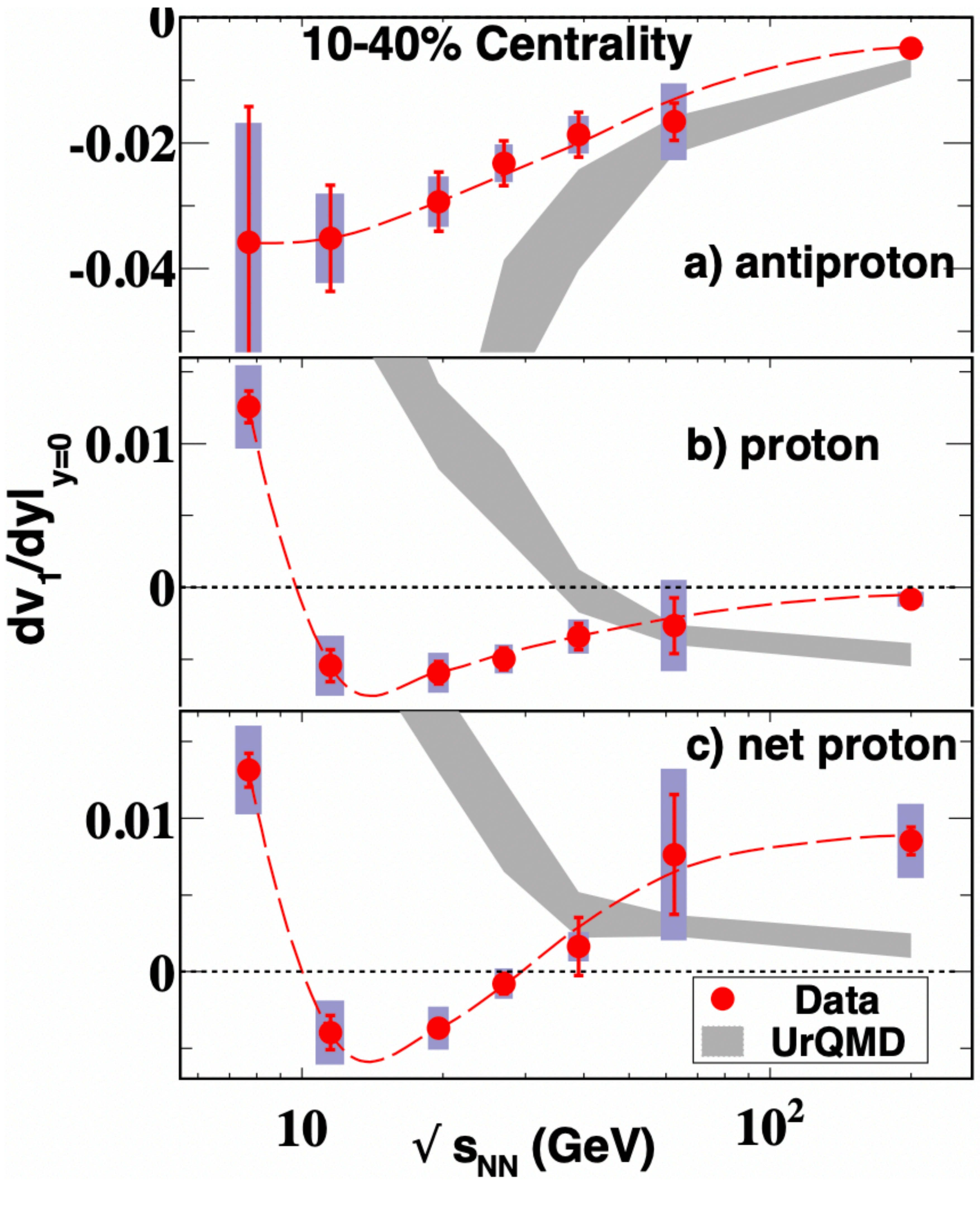
Proton directed flow



- Directed flow of protons predicted to be sensitive to softening of EoS near a first order PT
- Non-monotonous collision energy dependence for proton v_1 in BES-I

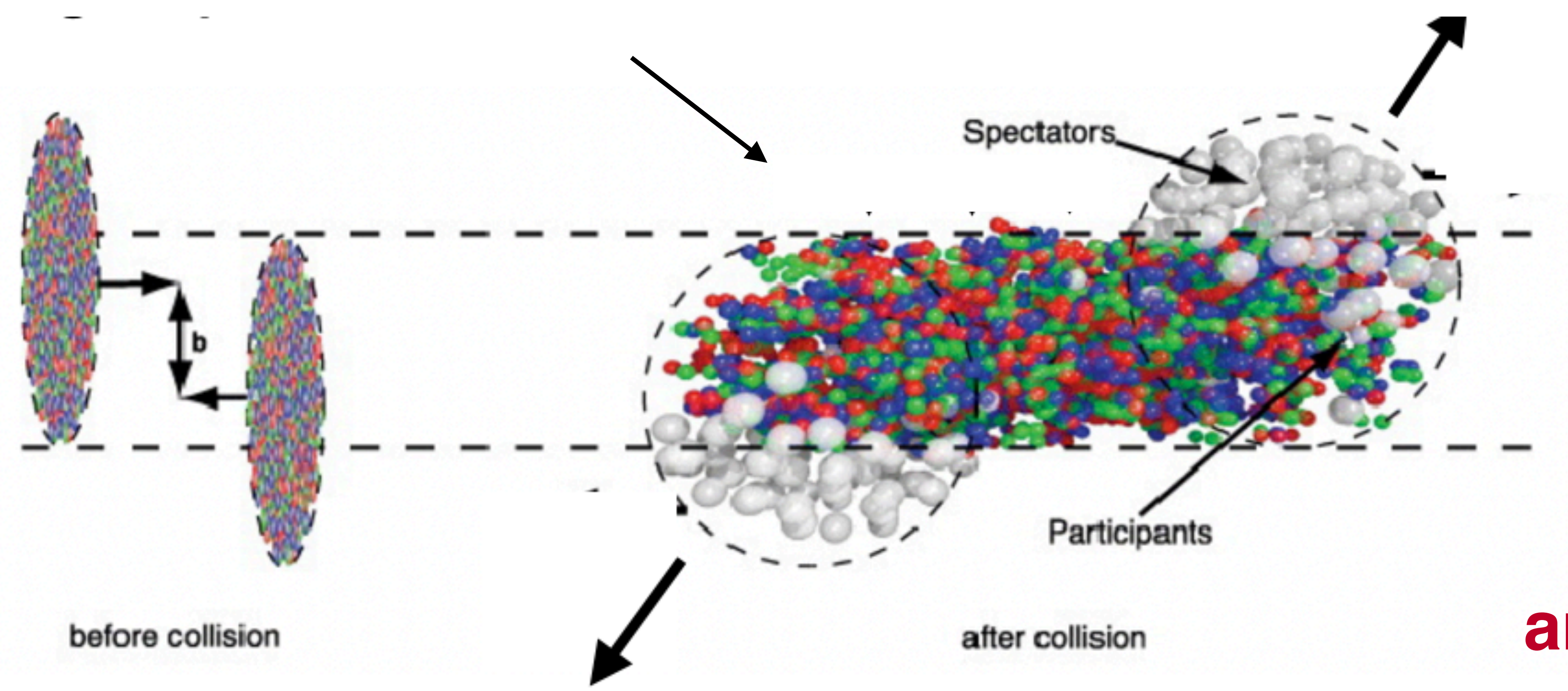
STAR, Phys. Rev. Lett. ***112*** *(2014) 162301*

Proton directed flow



STAR, Phys. Rev. Lett. ***112*** *(2014) 162301*

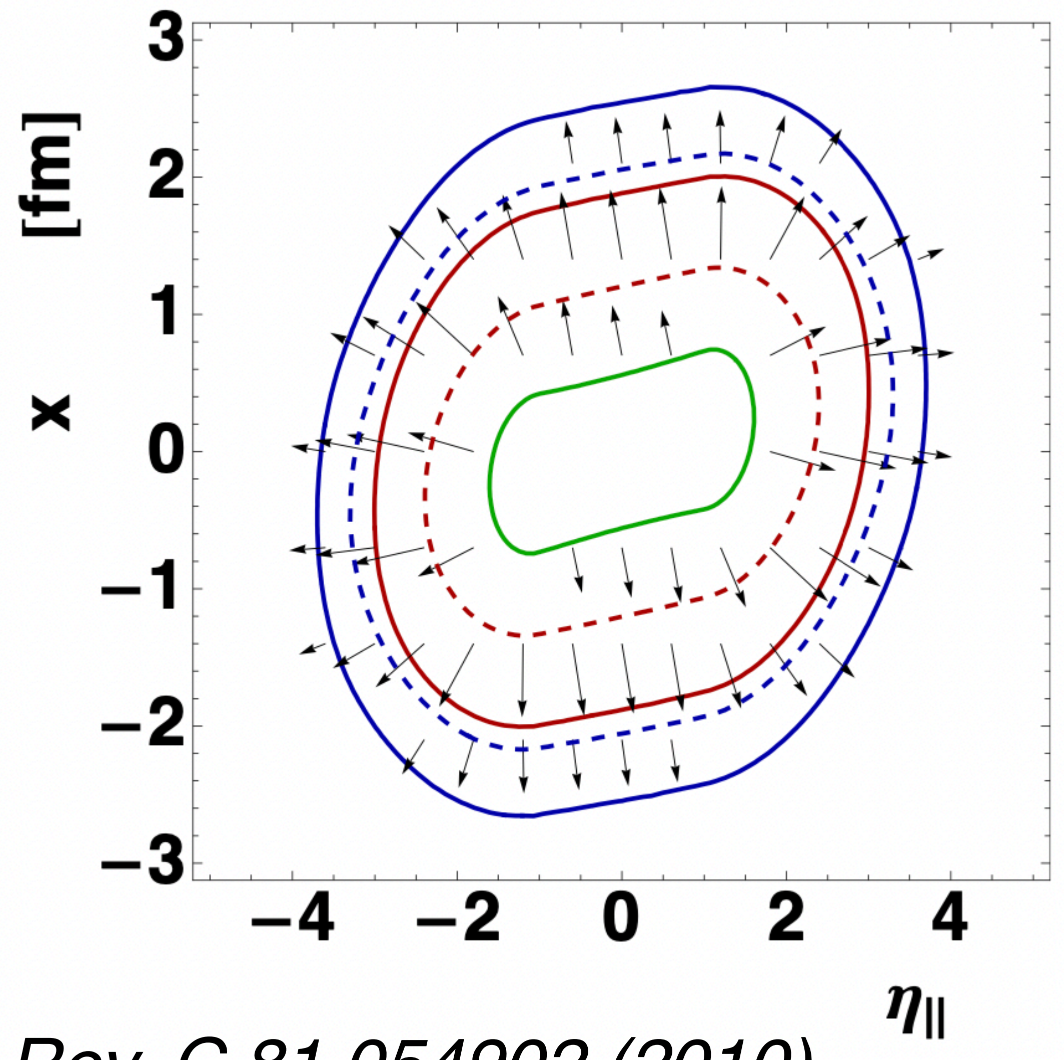
- Non-monotonous collision energy dependence for proton and net-proton v_1 in BES-I



- Interplay of positive contribution during initial compression stage, anti-flow from tilted source during expansion stage

Also see: Y. Nara et al, Phys. Rev. C.105.014911 (2021)

anti-flow from tilted source



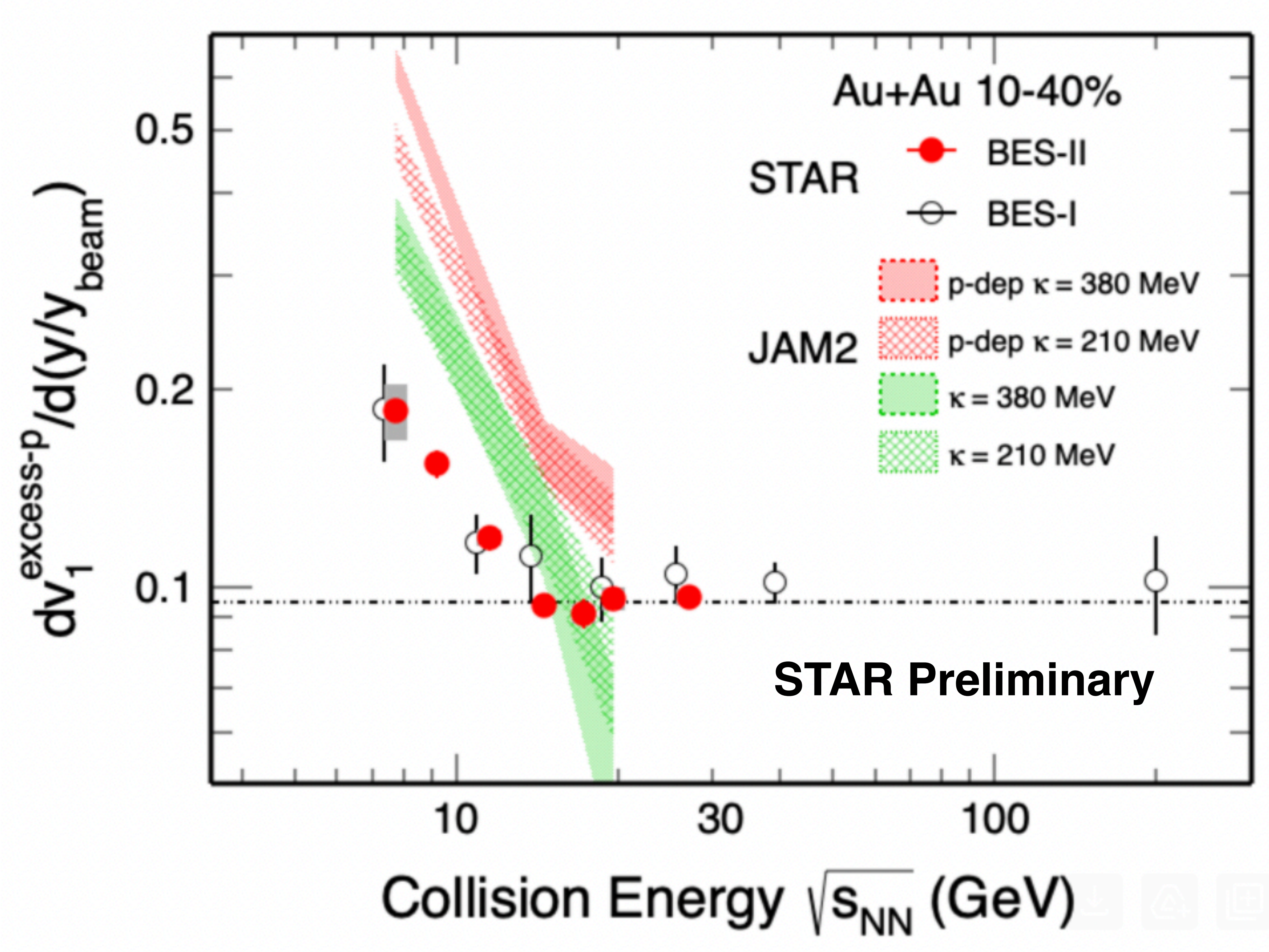
P. Bozek et al, Phys. Rev. C.81.054902 (2010)

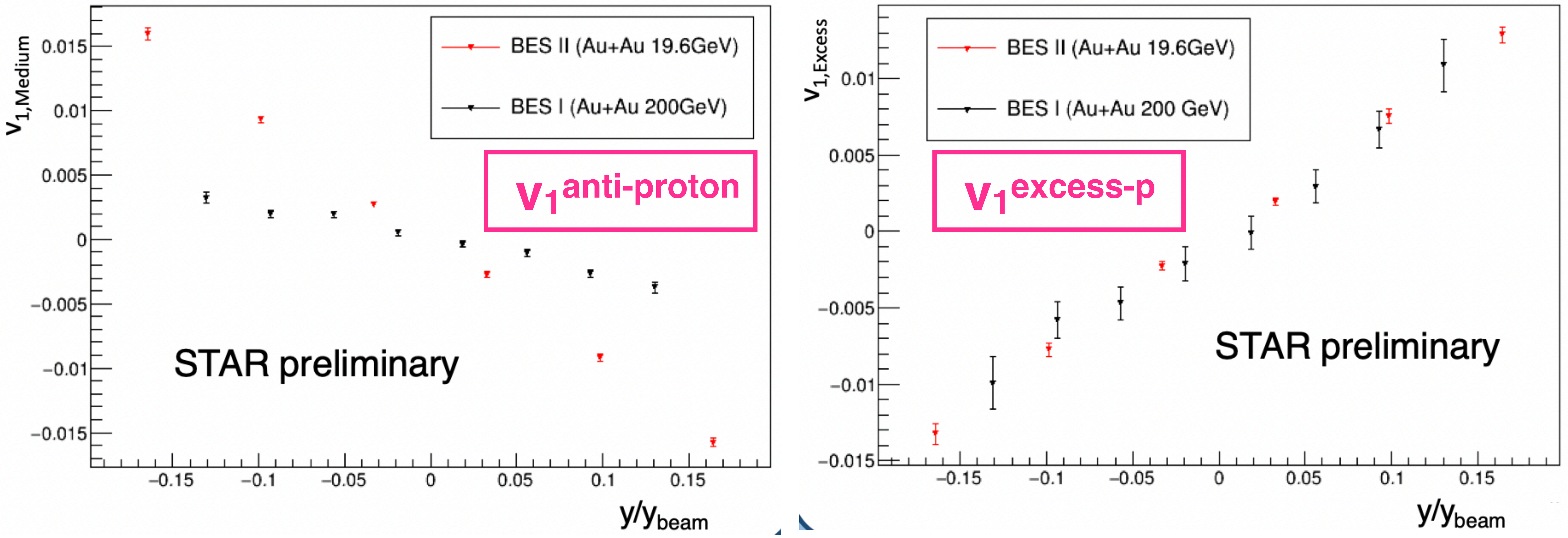
Proton directed flow

- Positive flow contributes more to transported protons
- Later medium component contributes to all protons and anti-protons

$$N_p v_1(p) = N_p v_1(\bar{p}) + (N_p - N_{\bar{p}}) v_1^{excess}(p)$$

$$v_1^{excess}(p) = (v_1(p) - v_1(\bar{p})) / (1 - N_{\bar{p}}/N_p)$$





- Constant value for the excess contribution to transported portions from 200 — 14 GeV
- No scaling for anti-proton v_1

- JAM mean field (K = 210 MeV) over-predicts the data

Talk by Emmy Duckworth, 5/24, 09:30

Exploring the QCD phase structure

CEP search, fluctuations of conserved charges, collectivity and EoS

Particle production and thermodynamic properties

HBT correlations, strangeness production, baryon stopping

Hyperon interactions at high baryon density

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Source size: Kaon HBT at high μ_B

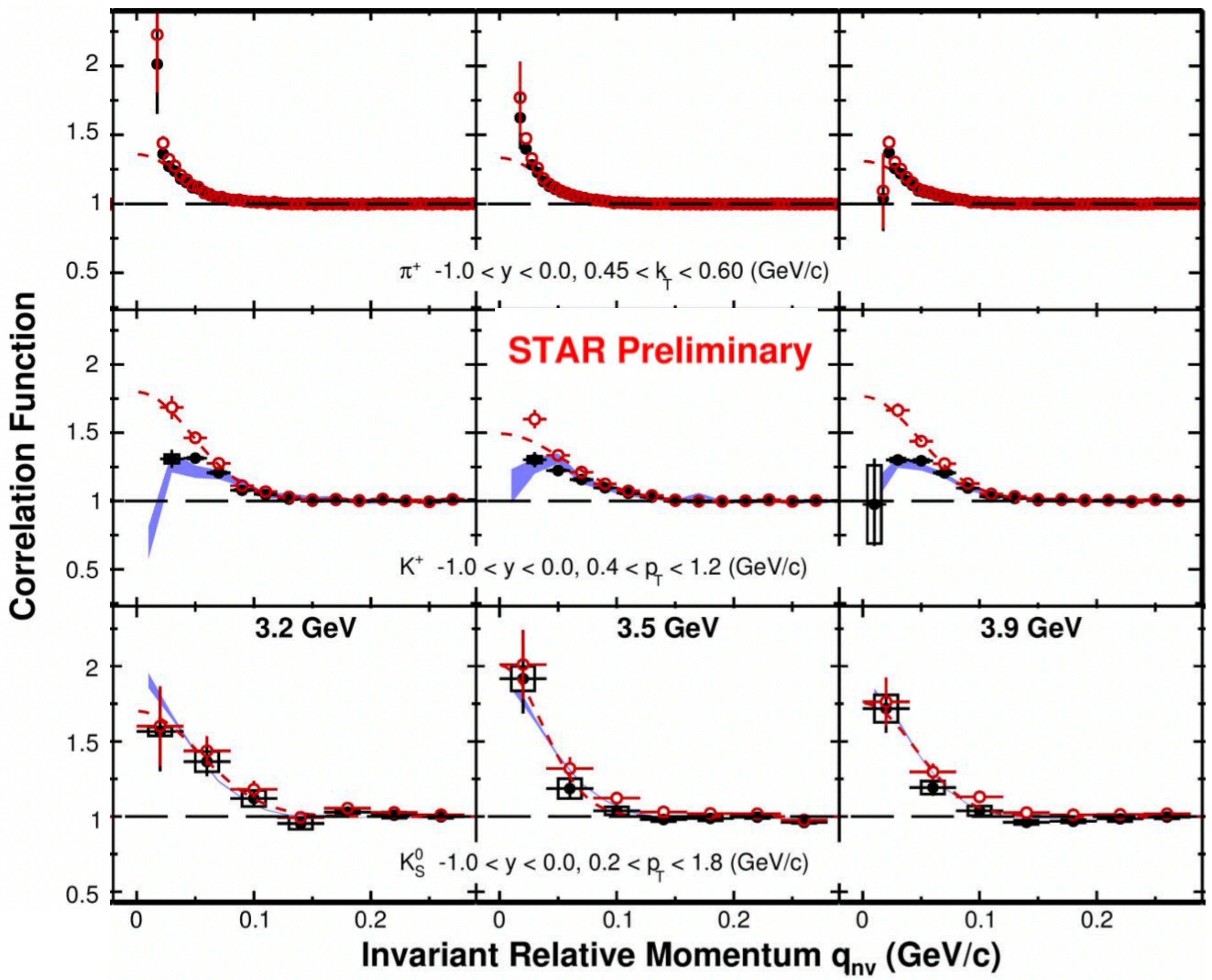
Femtoscopic correlations can inform on source size and dynamics

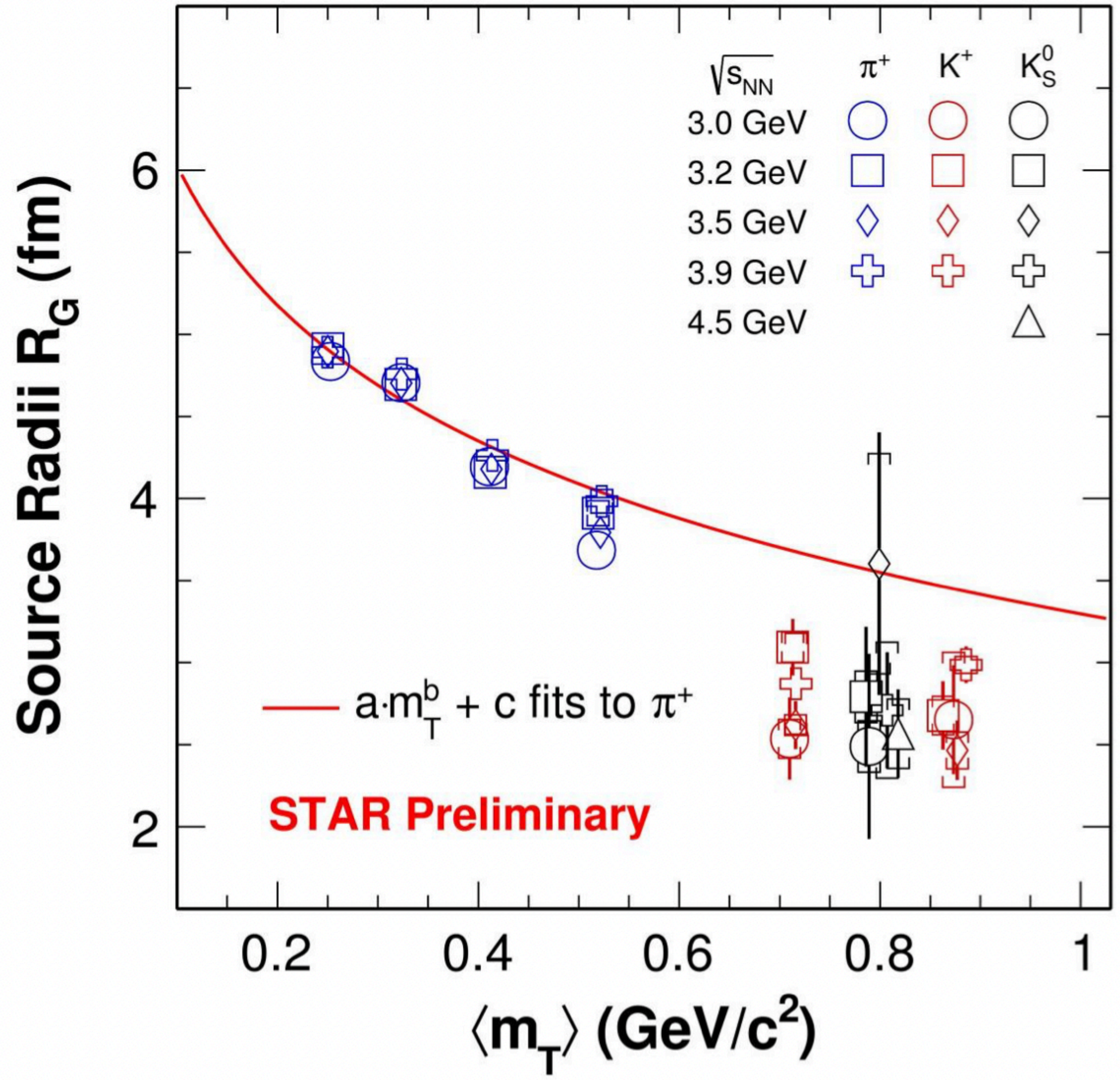
$$C(k^*) = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

- Sinyukov-Bowler[1] approach used for K^+- K^+ CF

$$CF(q_{inv}) = N[(1-\lambda) + \underbrace{K_{coul}(q_{inv}, R_G)}_{\text{Coulomb interaction part}}\lambda(\underbrace{e^{[-R_G^2 q_{inv}^2]}}_{\text{QS part}} + 1)]$$

- Fit correlation functions to extract source size
- Kaons do not follow the same m_T scaling as pions at high μ_B - kaon source size smaller at freeze out





Sooraj Radhakrishnan

Talk by Liang Zhang, 5/20, 15:00

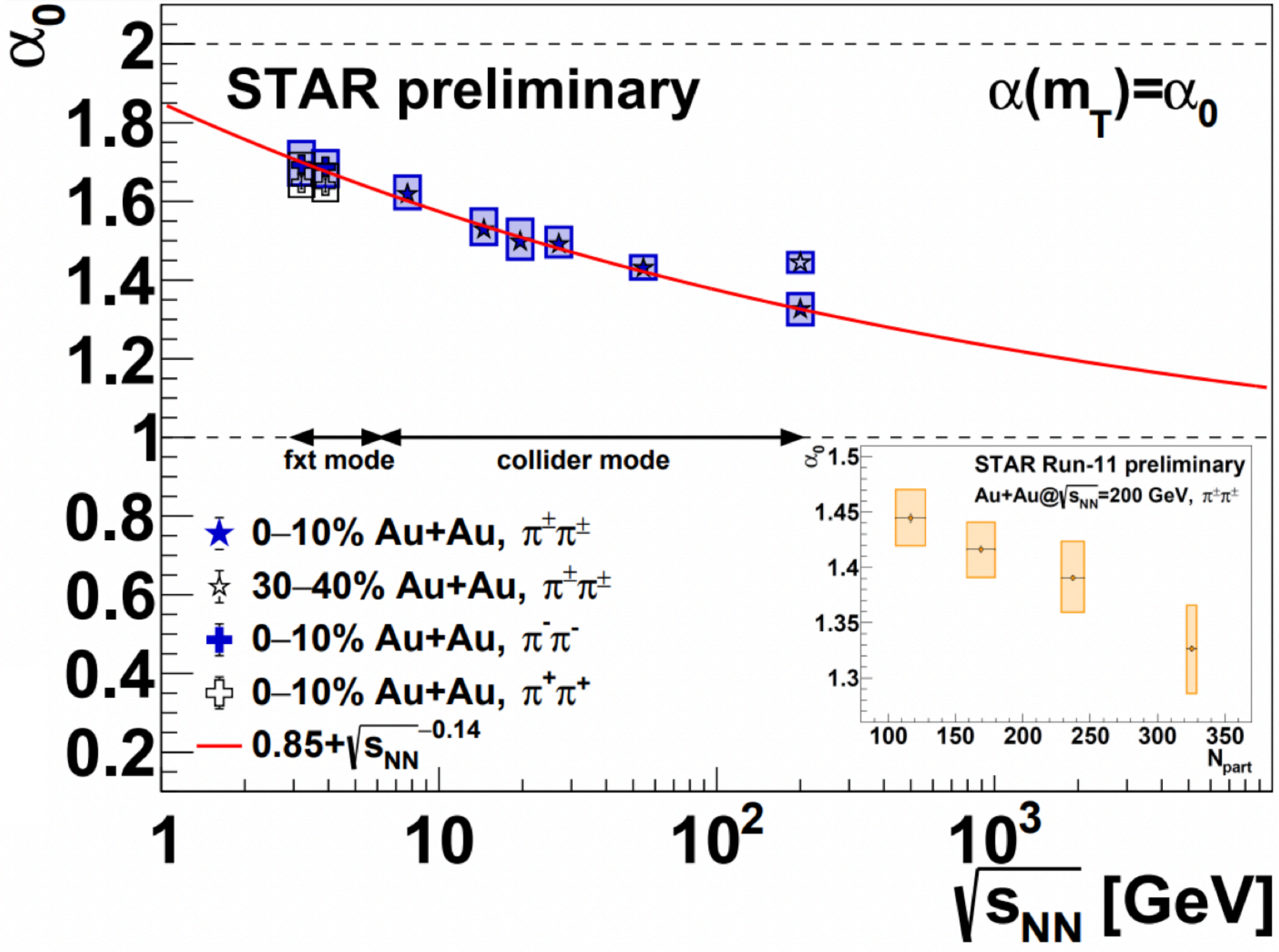
Pion HBT with Levy-stable source

- HBT source size extractions usually assume Gaussian source
- Distributions could have power law tails, evaluate through fits to Levy-stable source

$$C(Q) = \left(1 - \lambda + \lambda \cdot K(Q;\alpha,R) \cdot \left(1 + e^{-|RQ|^{\alpha}}\right)\right) \cdot N \cdot (1 + \varepsilon Q)$$

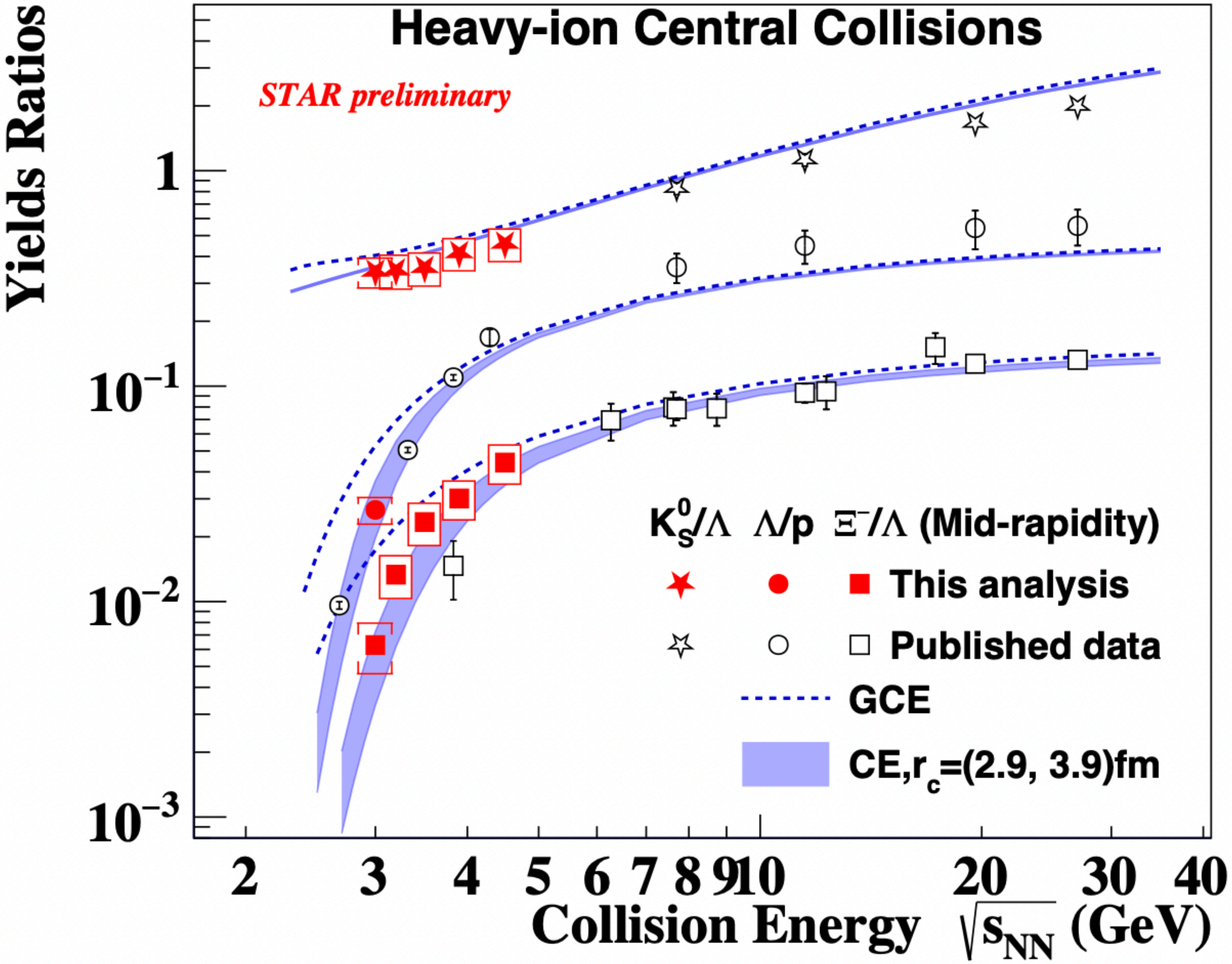
α: Levy exponent
R: Levy scale parameter
α = 2 —> Gaussian source

- Fits indicate non Gaussian source (α < 2)
- α decreases with increase in collision energy, and from peripheral to central collisions



Talk by Daniel Kincses, 5/21, 17:20

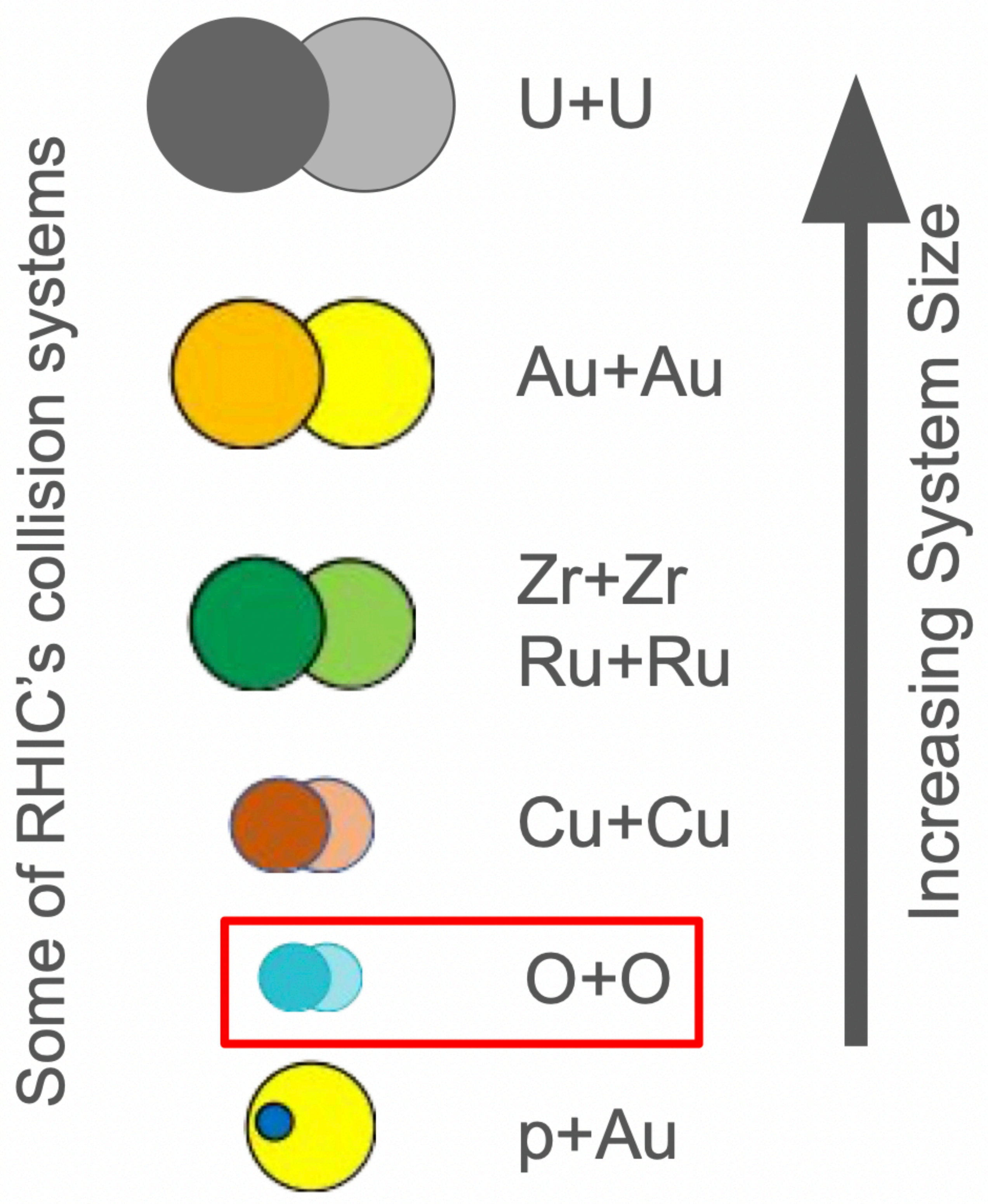
Strangeness production at high μ_B



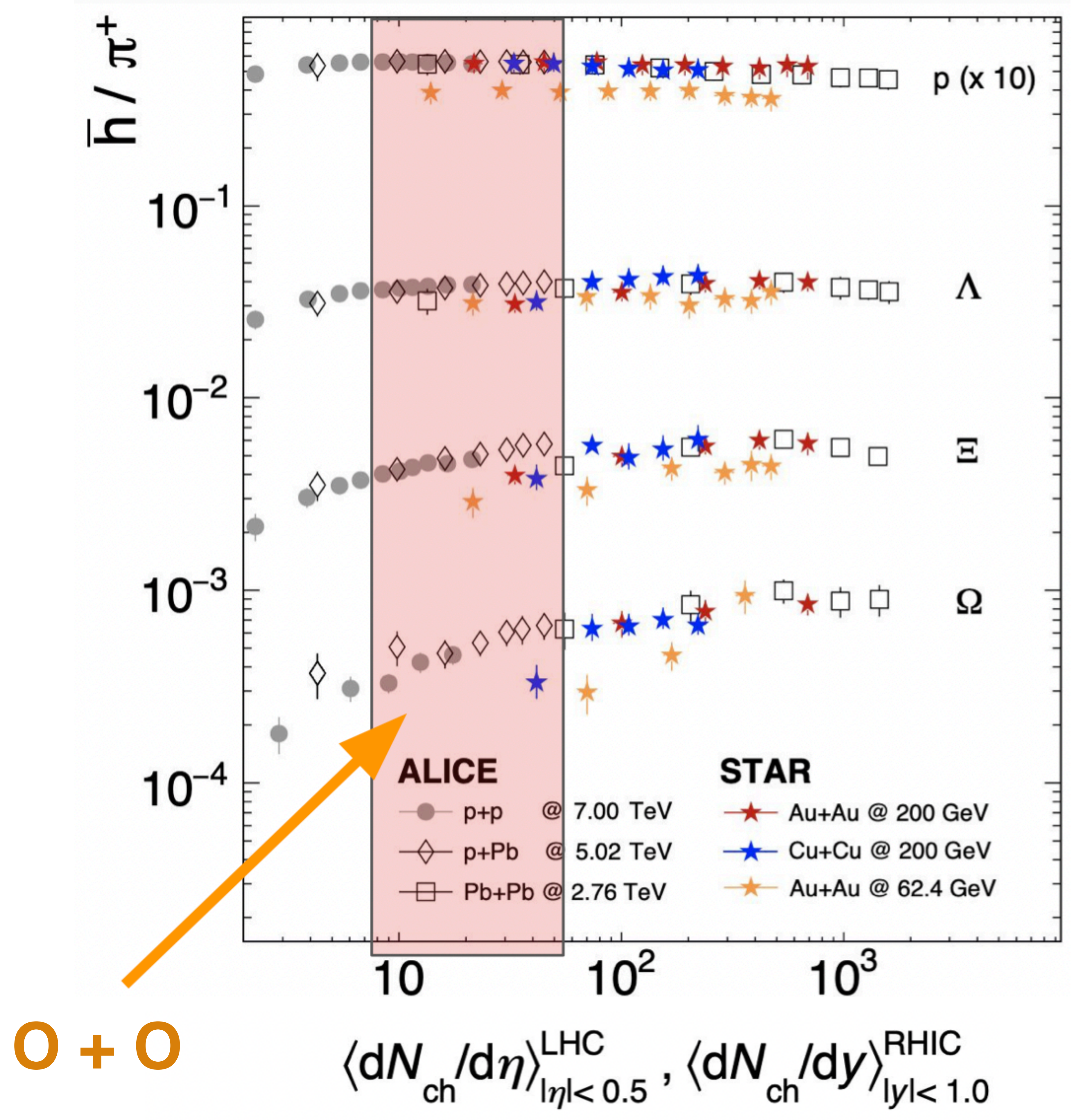
- Comprehensive measurements of strange hadron production at FXT energies
- Canonical suppression of strangeness production at high μ_B
- Strangeness correlation length 2.9 — 3.9 fm

Talk by Yingjie Zhou, 5/20, 17:00

Strangeness production in O+O



*[X. Zhu, BNL Nucl. Phys. Seminar. (2021)](#)

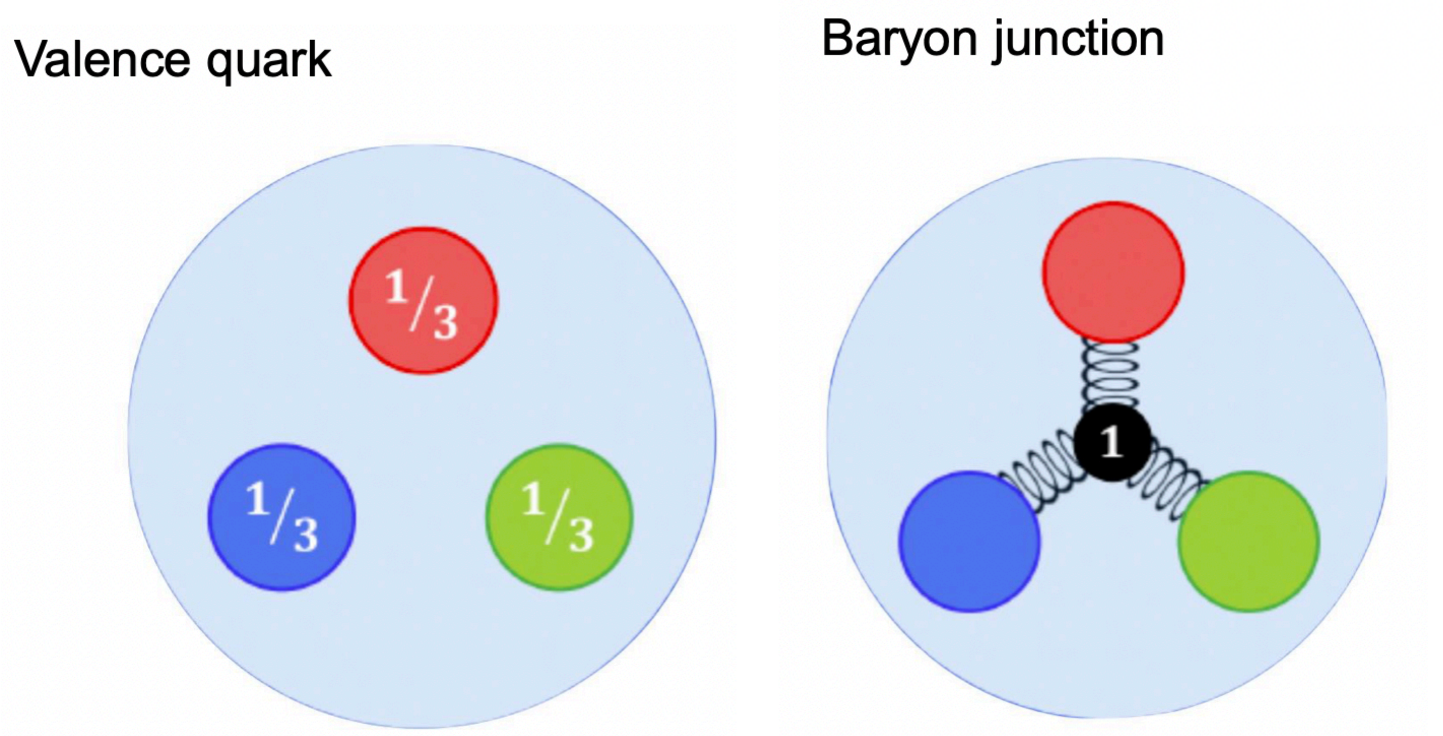


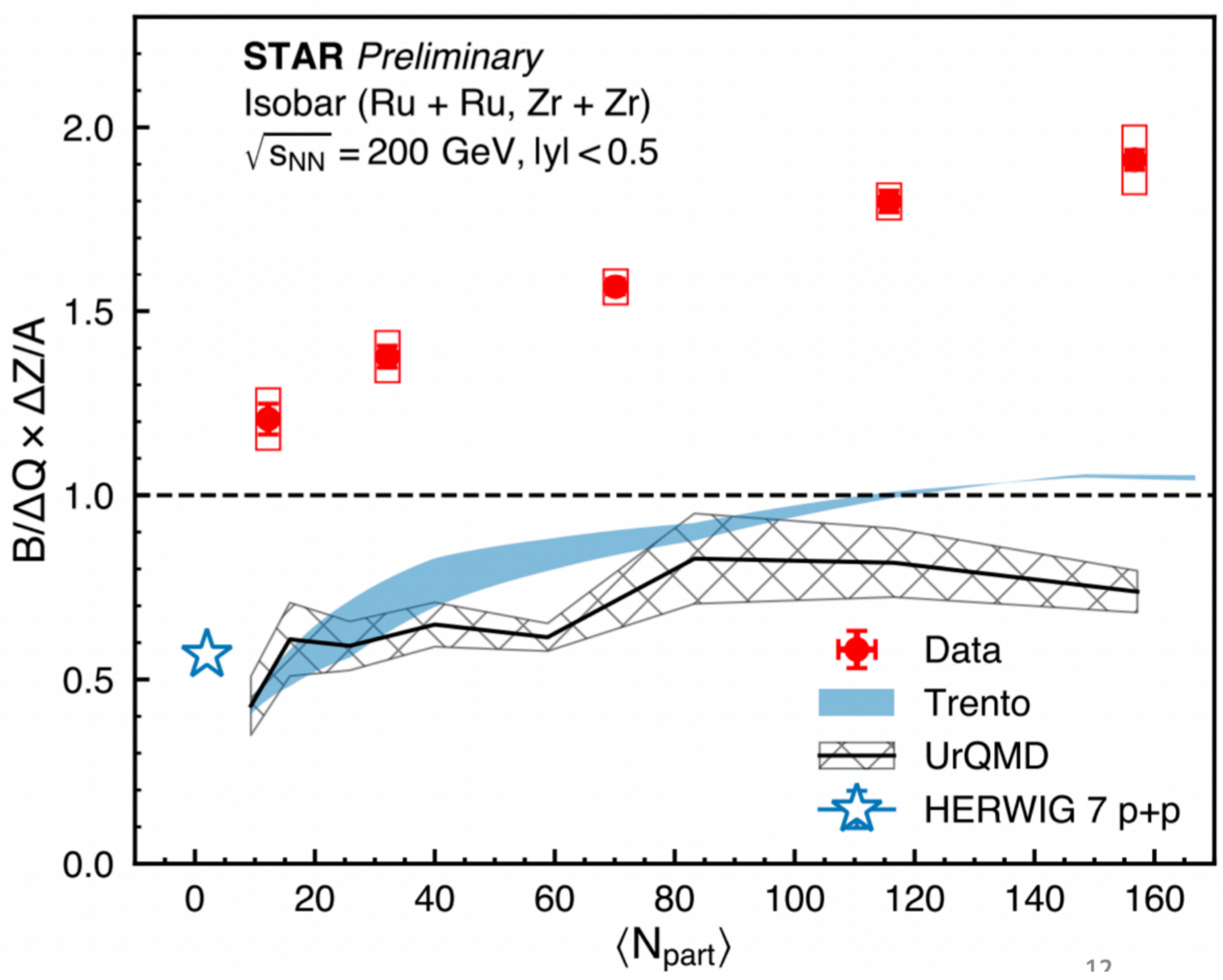
- O+O - explore strangeness production at lower multiplicities and smaller collision systems at RHIC

Talk by Iris Daniela Ponce Pinto, 5/23, 15:20

Baryon stopping and search for baryon junction

- Are baryon junctions carrying baryon number?
- Can we answer from baryon stopping?

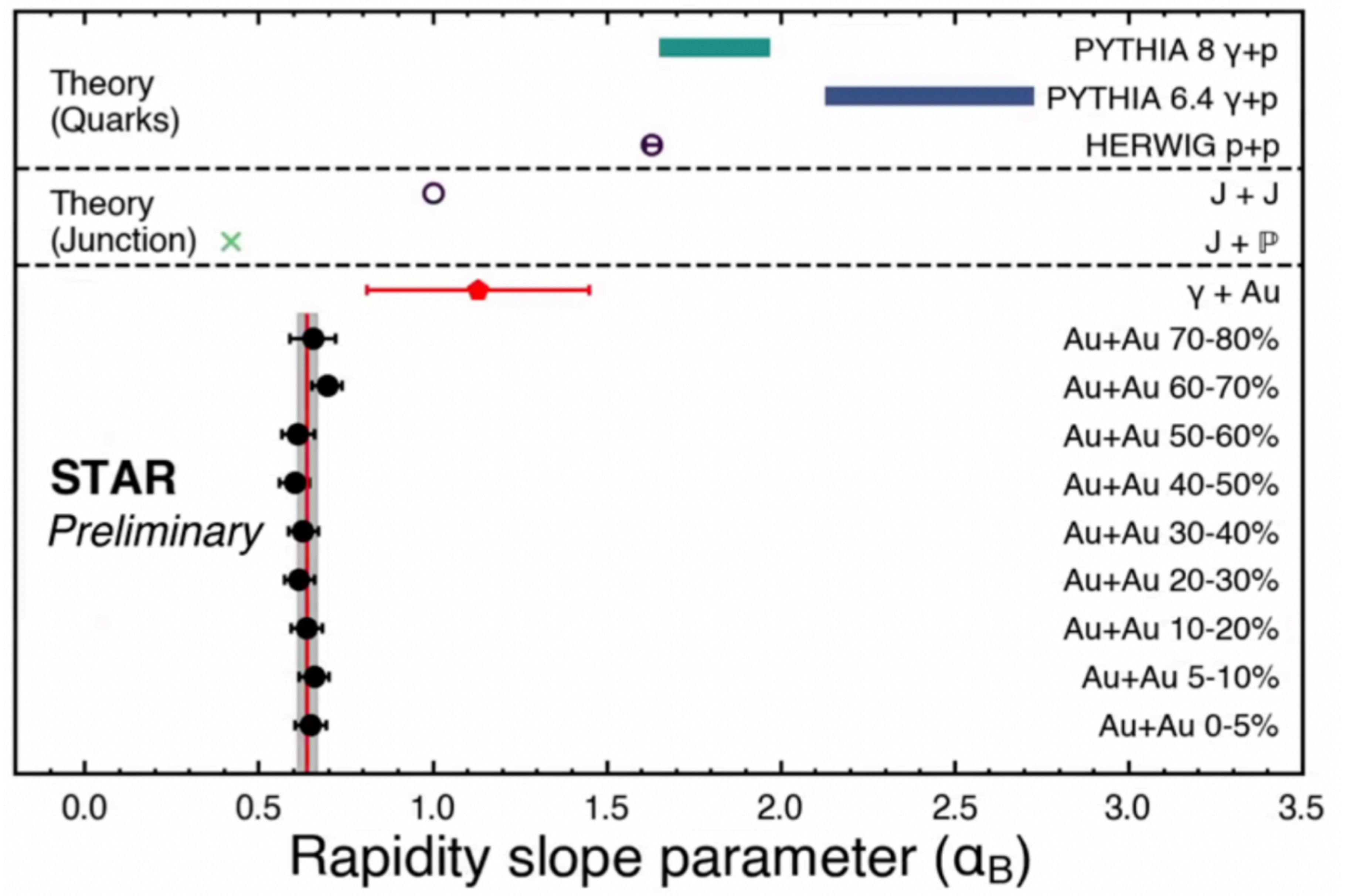




- More baryon stopping than charge stopping in data

$$dN/dy \propto e^{-\alpha_B \delta y} \qquad \delta y = y_{beam} - y$$

- Stronger stopping in A+A and γ+A data than in PYTHIA γ+A



Talk by Prithwish Tribedy, 5/22, 11:50

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Hyper-nuclei production

Hyper-nuclei production valuable tool to understand Y-N interactions and hyperon contribution to nuclear EoS and thus the 'hyperon puzzle'

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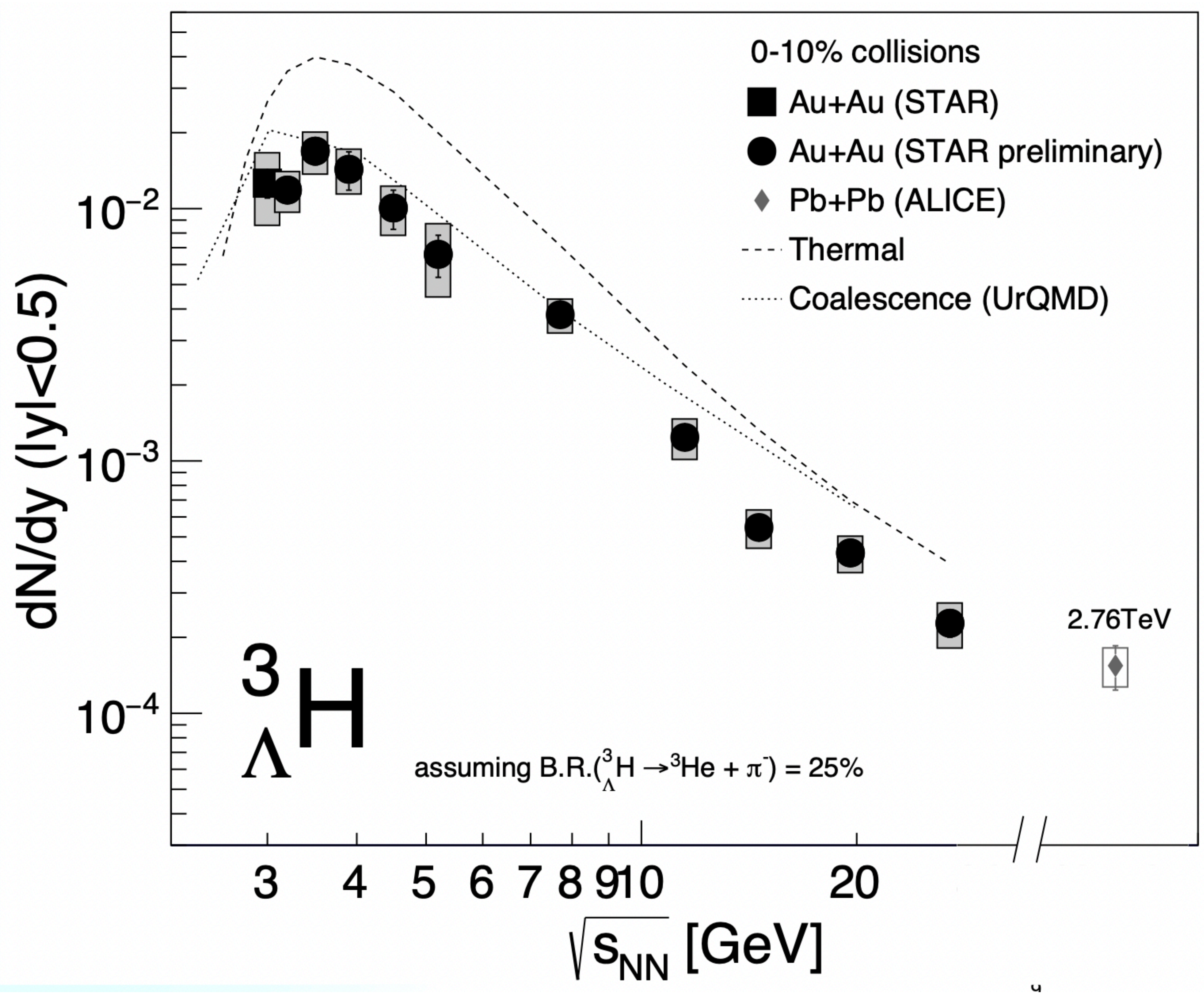


- Yield measurements over a broad range of collision energies
- Thermal models can’t describe the yields of 3HΛ

STAR, Phys. Rev. Lett. 130 (2023) 202301
STAR , arXiv: 2311.11020

Talk by Yue-Hang Leung, 5/20, 14:30

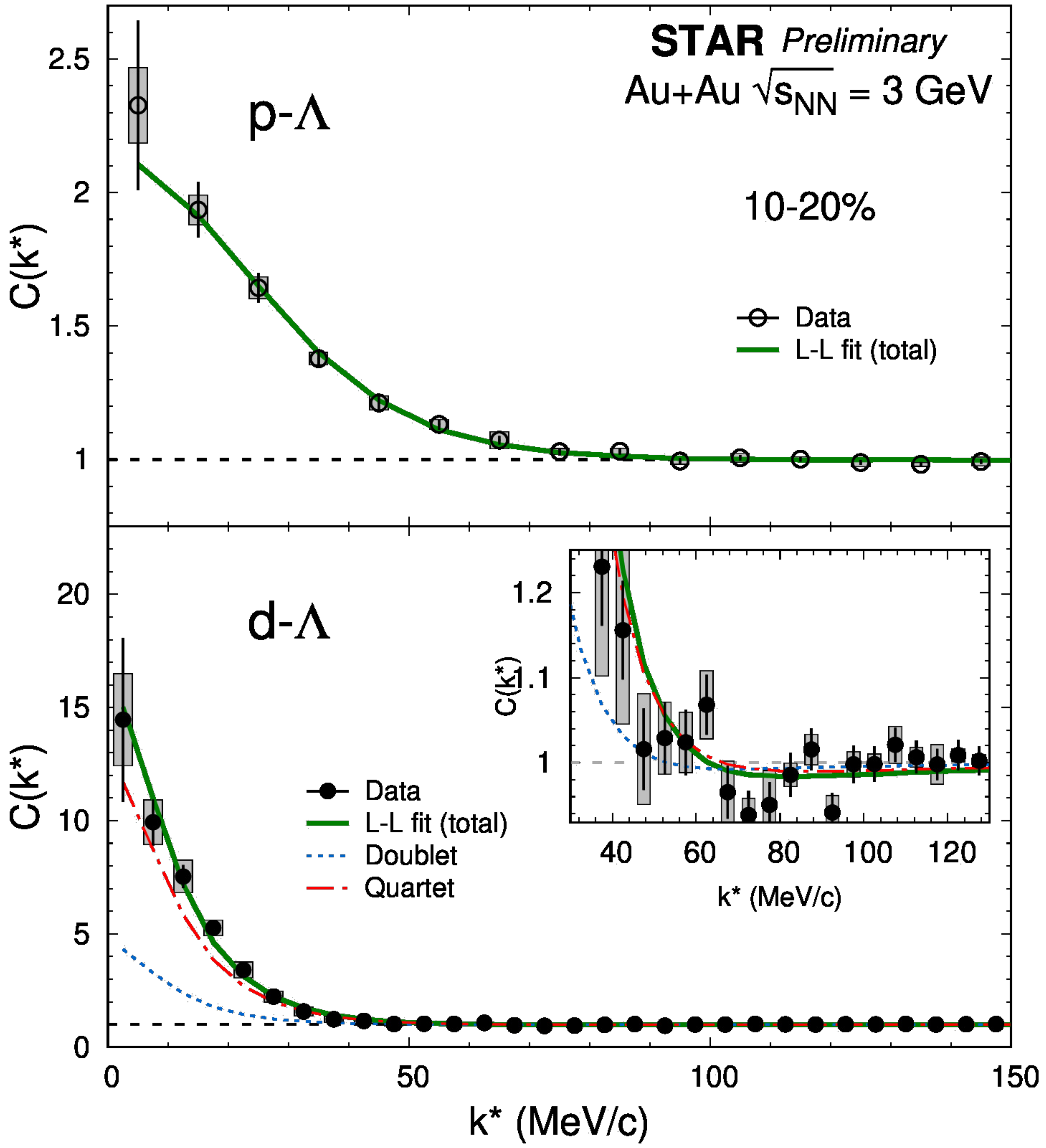
Proton/deuteron-Lambda correlations

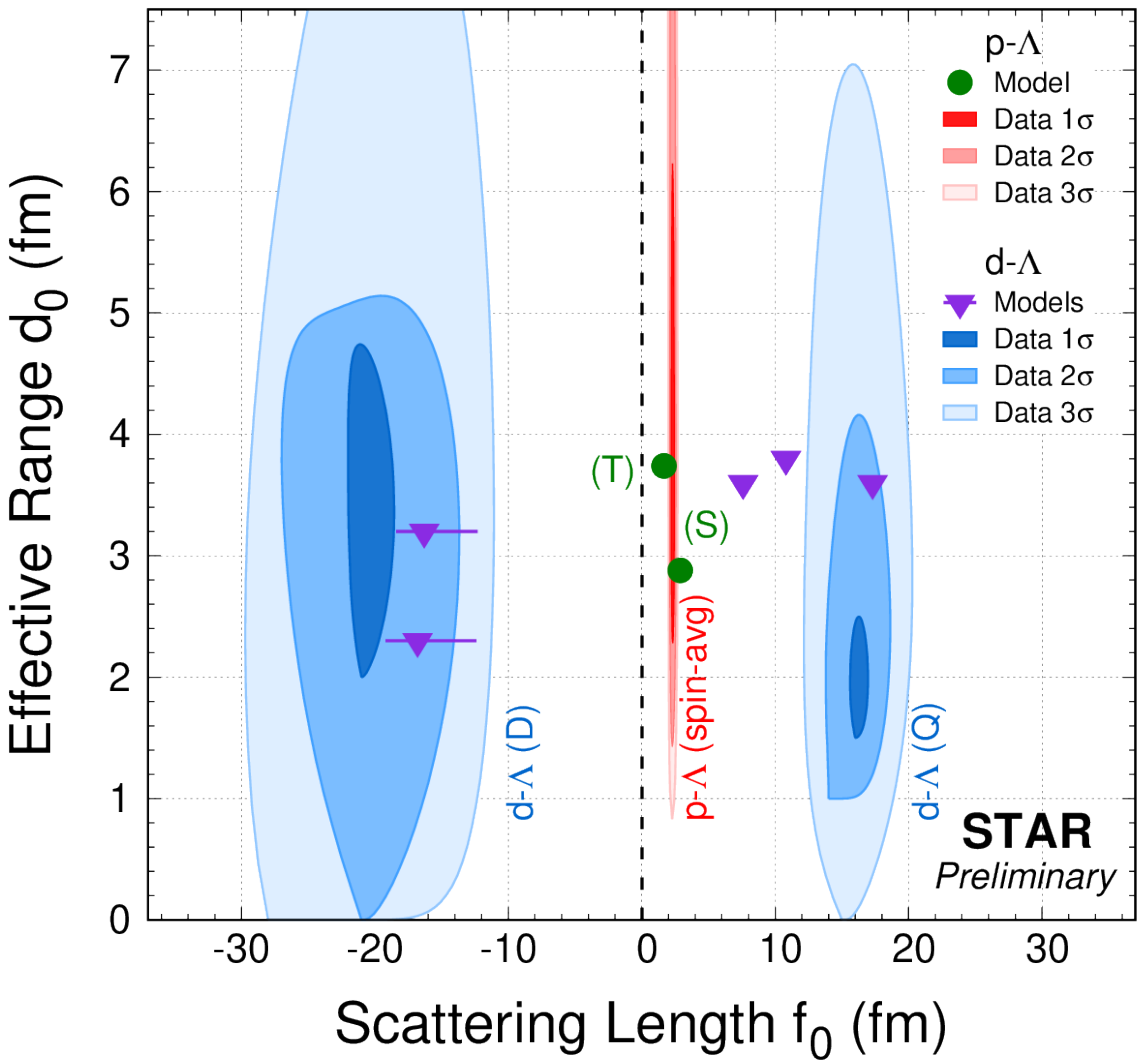
- Alternate way to study Y-N interactions is to use HBT correlations
- Lednicky - Lyuboshitz fits to correlations functions to extracts final state interactions

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

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

R_G : spherical Gaussian source of pairs
f_0 : scattering length
d_0 : effective range

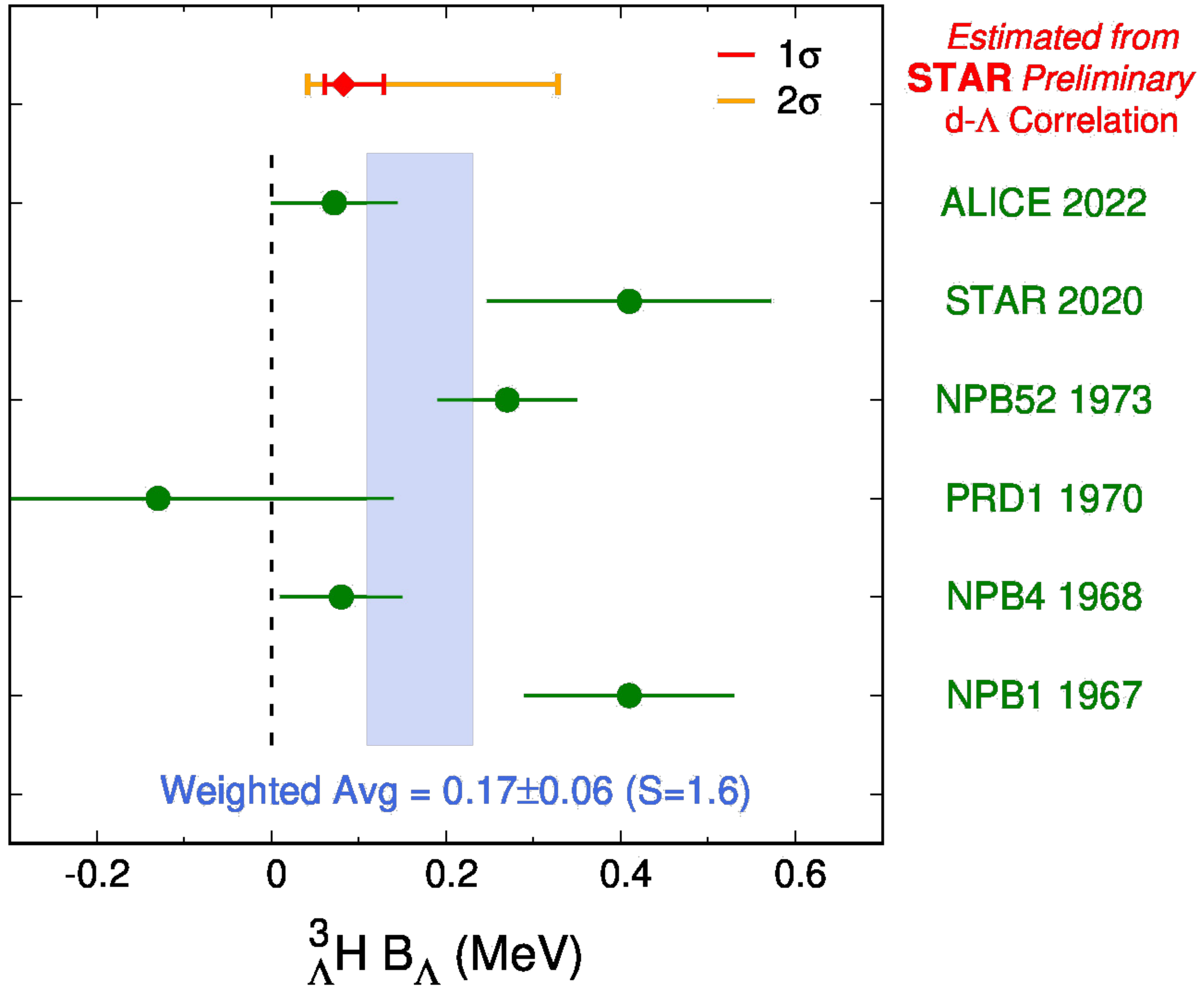




- d_0 and f_0 extracted for the two spin states from d - Λ correlations
- Spin averaged values for p - Λ
- Negative f_0 for D-state —> bound state

Talk by Yu Hu, 5/22, 10:00

Proton/deuteron-Lambda correlations



$$\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$

- ❖ $B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}}$
- ❖ $\mu_{d\Lambda}$: reduced mass
- ❖ γ: binding momentum

- Can extract the 3HΛ binding energy from measured f_0 d_0 from d - Λ correlations

- Consistent with previous measurements
- New way to study HN structure

Talk by Yu Hu, 5/22, 10:00

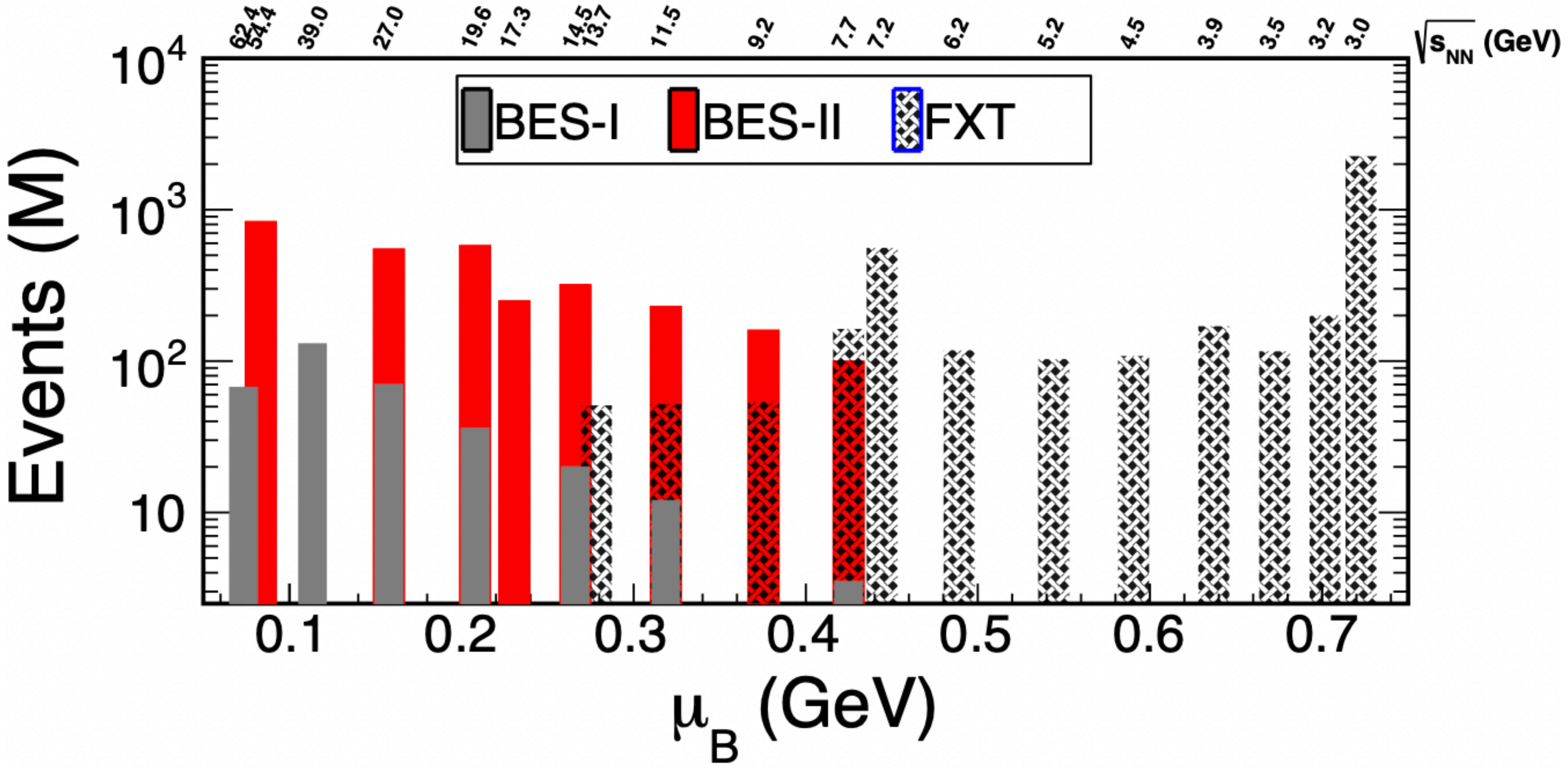
Summary

- **QCD phase structure**
  - B-S correlations in central collisions show deviations from UrQMD at energies > 10 GeV
  - v_2 measurements indicate hadronic interactions dominate below 3.2 GeV, partonic interactions becoming important ~ 4.5 GeV
  - New measurements of proton v_1 - constraints for EoS

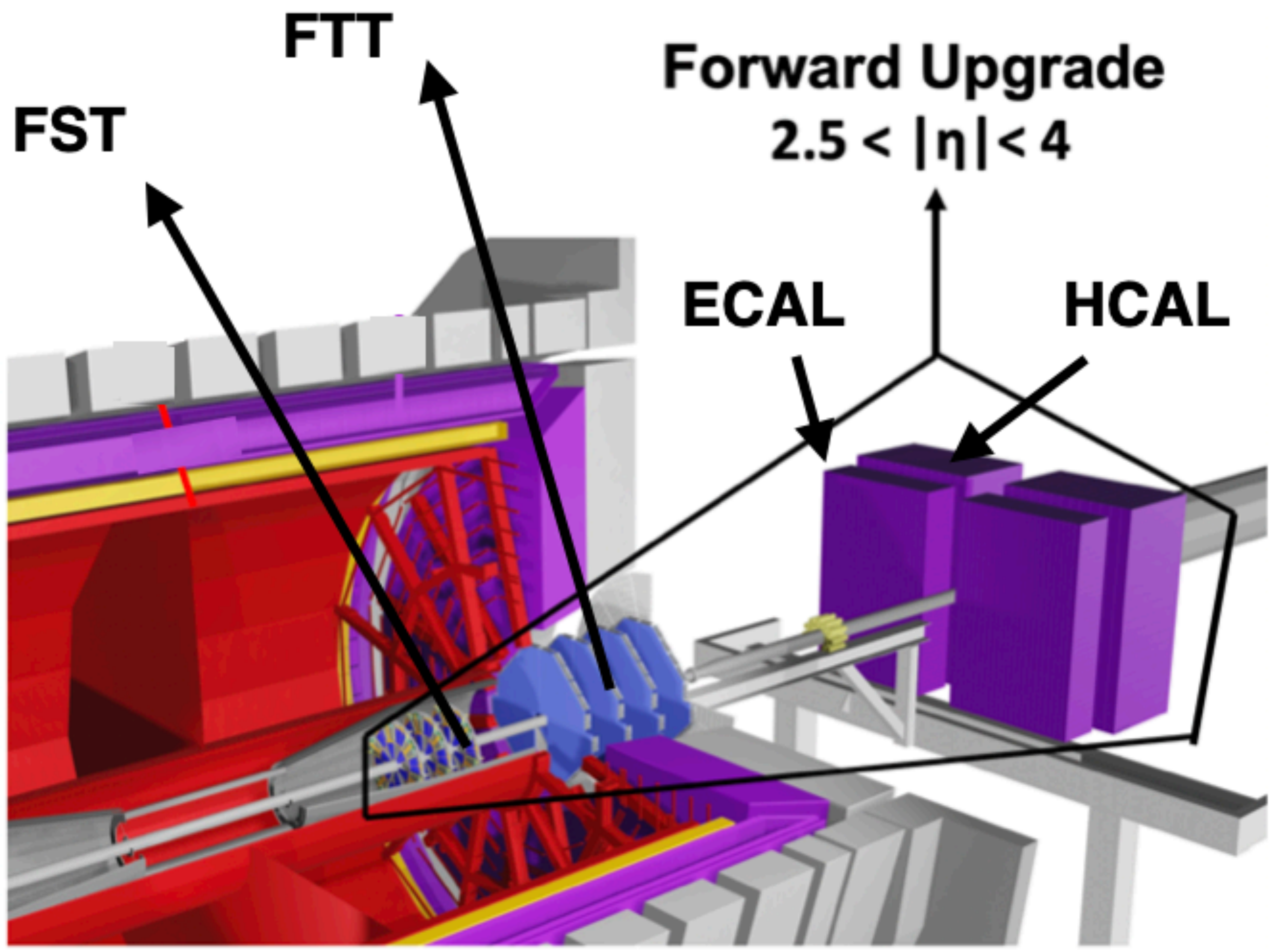
- **HBT, particle production**
  - Different source size for pions and kaons at freeze-out in large μ_B collisions
  - Canonical suppression of strangeness with correlation length 2.9 — 3.9 fm at high μ_B
  - Stronger baryon stopping than charge stopping, stronger stopping in γ+A data than PYTHIA

- **Hyperon interactions at high baryon density**
  - Thermal models cannot describe 3HΛ production at high μ_B
  - Strong interaction parameters extracted from p - Λ , d - Λ correlations

Outlook



- **More energies and many ongoing analyses from BES-II**
  - Also high statistics (2B MB events) at 3 GeV with mid to target rapidity acceptance at STAR

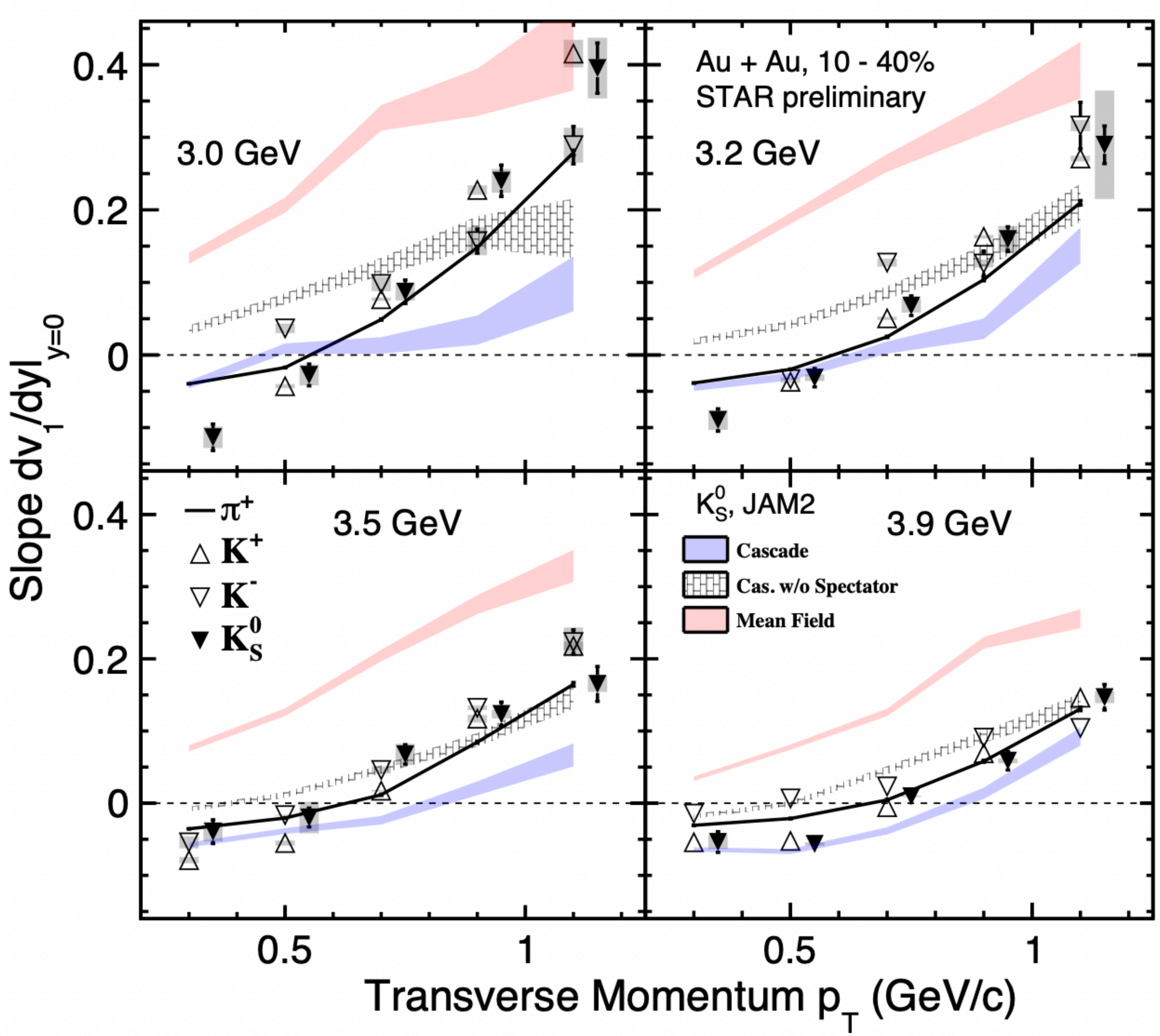


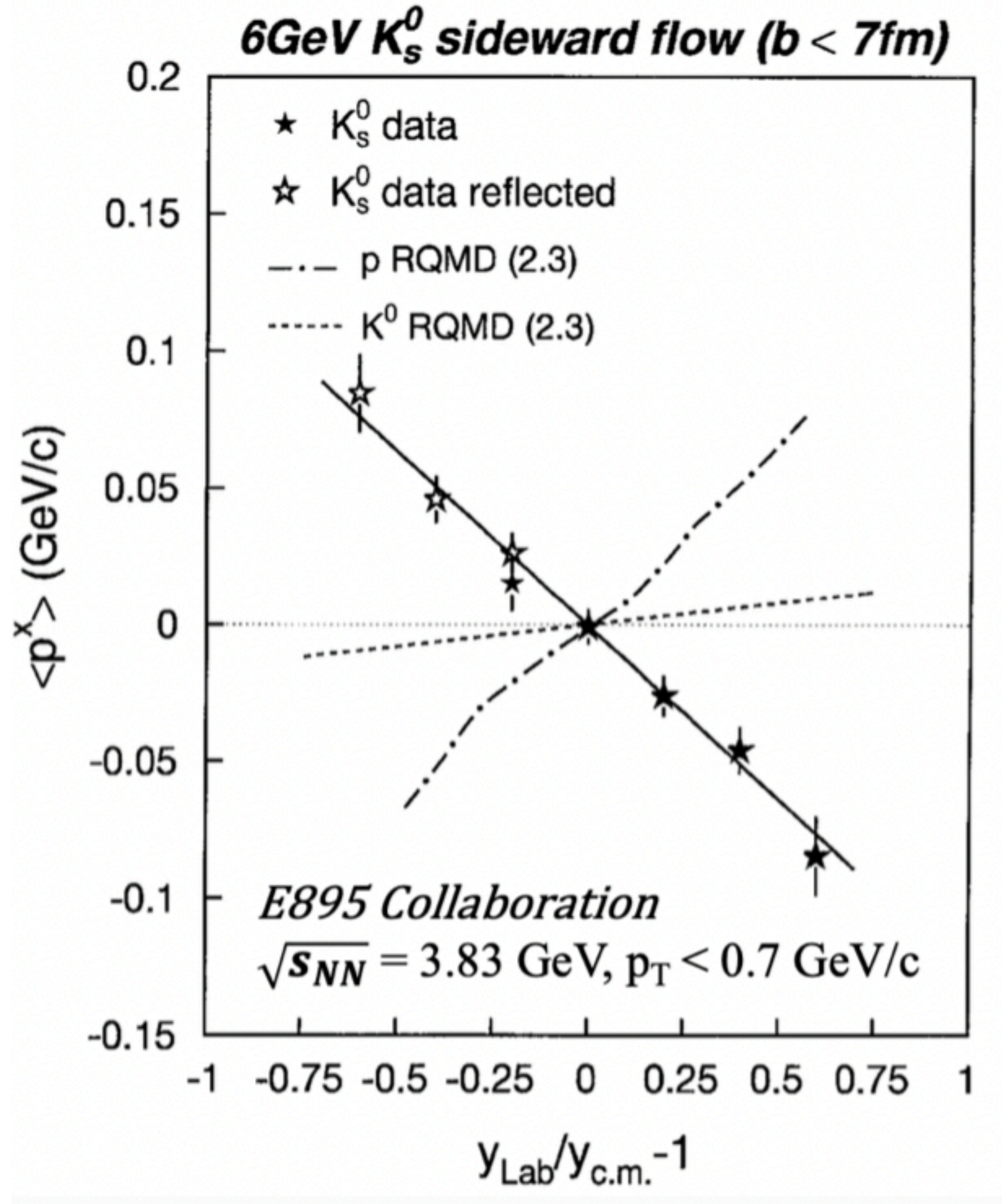
Locate at STAR west side, 2.5 < η < 4

- **High statistics p+p, p+A and Au+Au data taking (2023 - 25)**
  - Completed forward upgrade with tracking and calorimetery
  - Precision measurements of QGP properties, complement EIC

Back Up

Anti-flow of kaons





- Kaons and pions show strong anti-flow at low p_T
- Spectator shadowing can induce anti-flow at low p_T, without requiring additional kaon potential

Source size: Kaon HBT at high μ_B

Femtoscopic correlations can inform on source size and dynamics

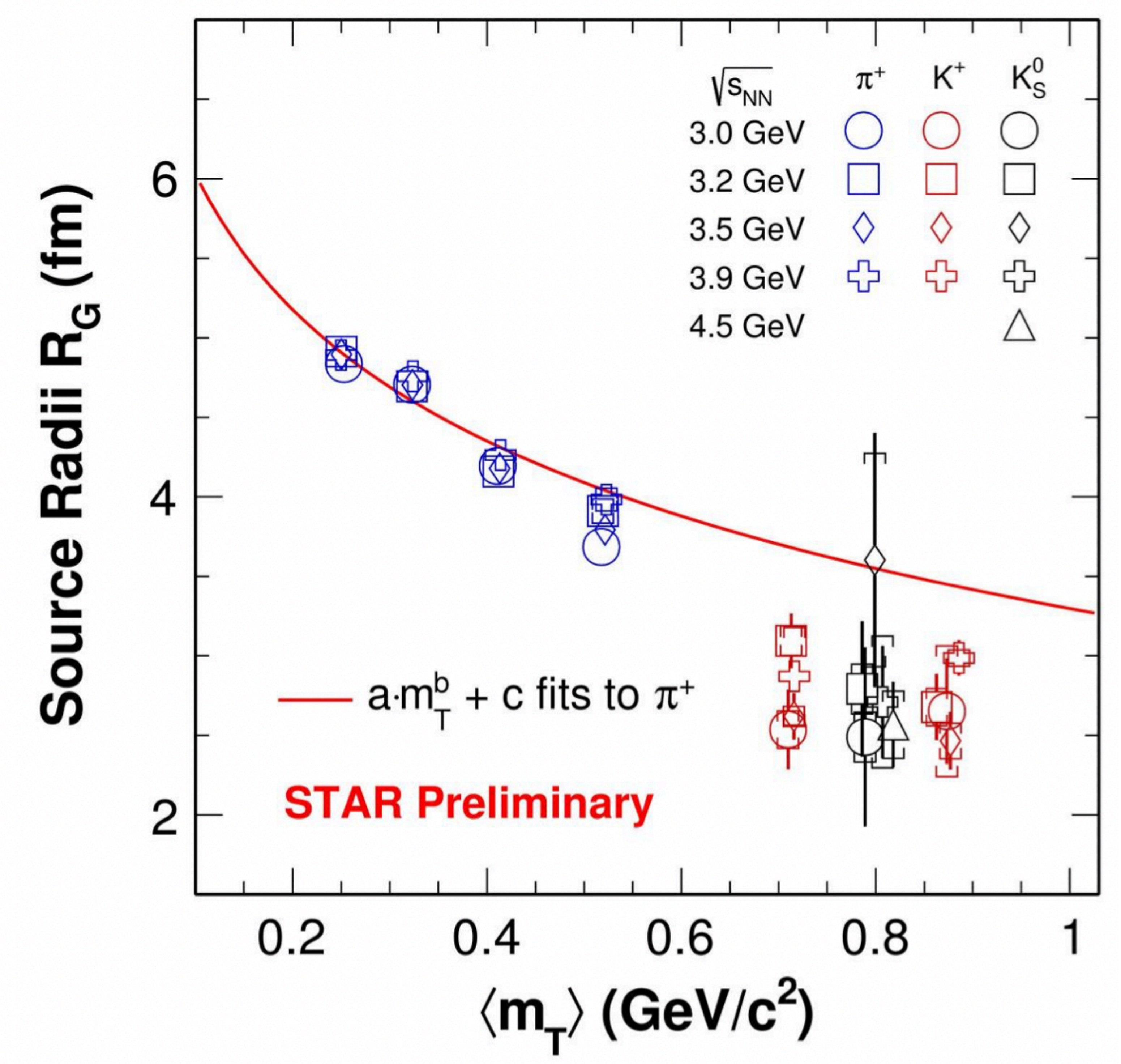
$$C(k^*) = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

- Sinyukov-Bowler[1] approach used for K^+- K^+ CF

$$CF(q_{inv}) = N[(1-\lambda) + \boxed{K_{coul}(q_{inv}, R_G)}\lambda(\boxed{e^{[-R_G^2 q_{inv}^2]}} + 1)]$$

Coulomb interaction part **QS part**

- Fit correlation functions to extract source size



- Kaons do not follow the same m_T scaling as pions at high μ_B
- No strong energy dependence at FXT energies