SQM 2022
The 20th International Conference on Strangeness in Quark Matter
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Light and strangeness production and collectivity at high μ_B region

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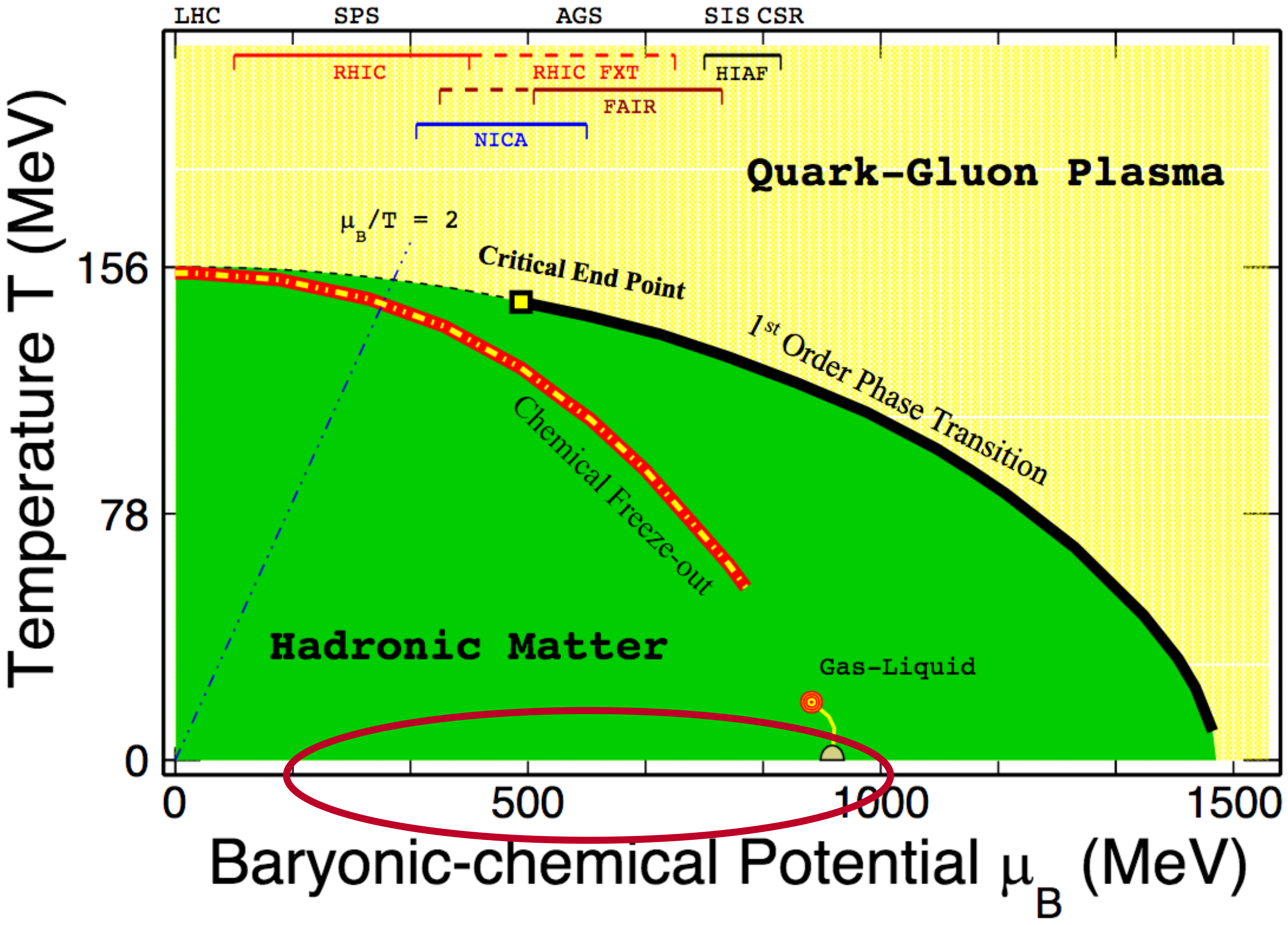
BERKELEY LAB

Nuclear collisions at high baryon density

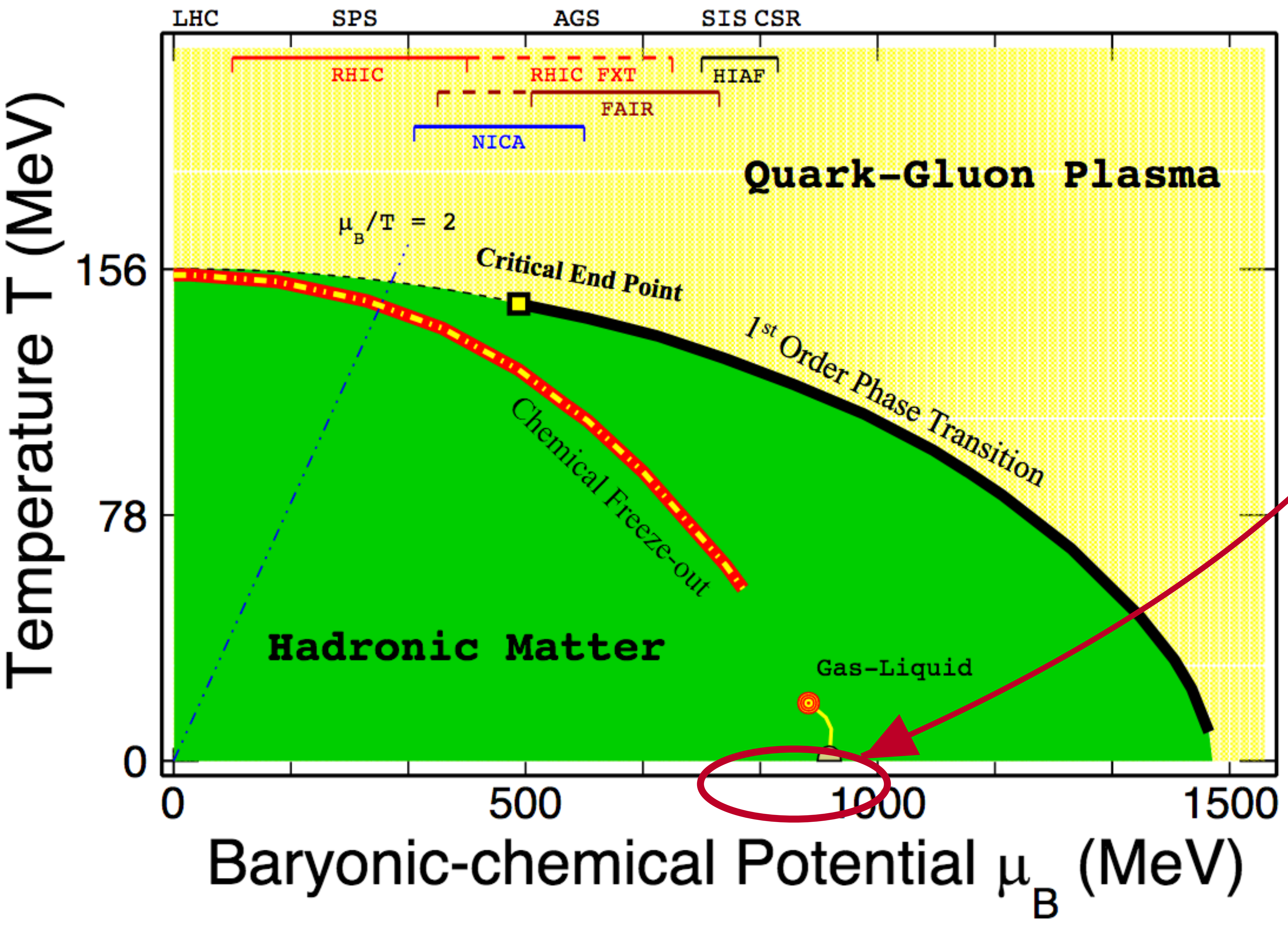


Phys. Rev. Lett.126 (2021), 092301

- What is the state of matter in the high μ_B region?
- What is its equation of state?
- What are its temperature and thermodynamic properties?
- Is there a first order phase transition to the QGP phase?
- Do we understand strangeness production in this region?

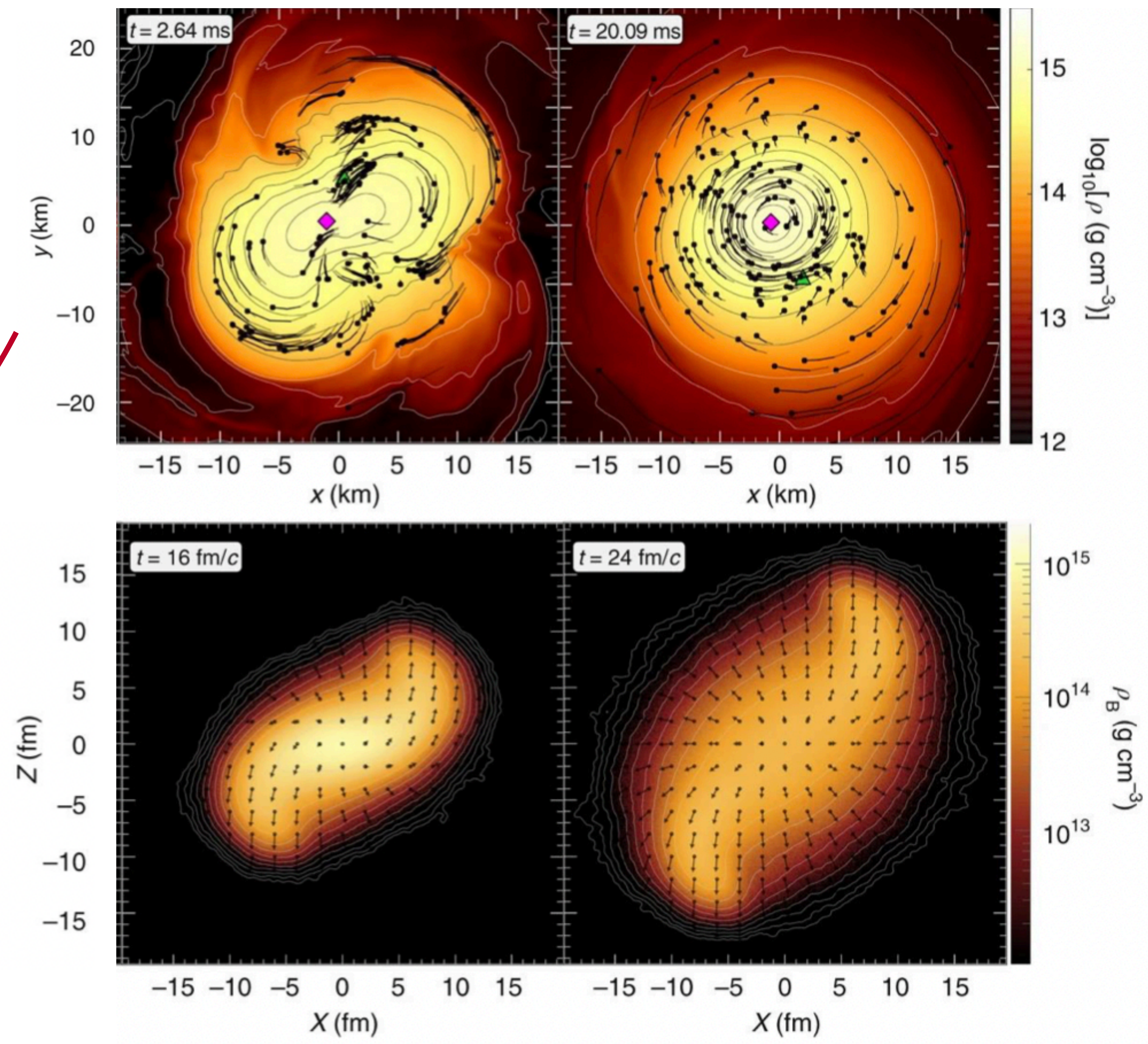
- Bulk particle (light and strange flavor) production and collectivity measurements key to answer these questions

Nuclear collisions at high baryon density



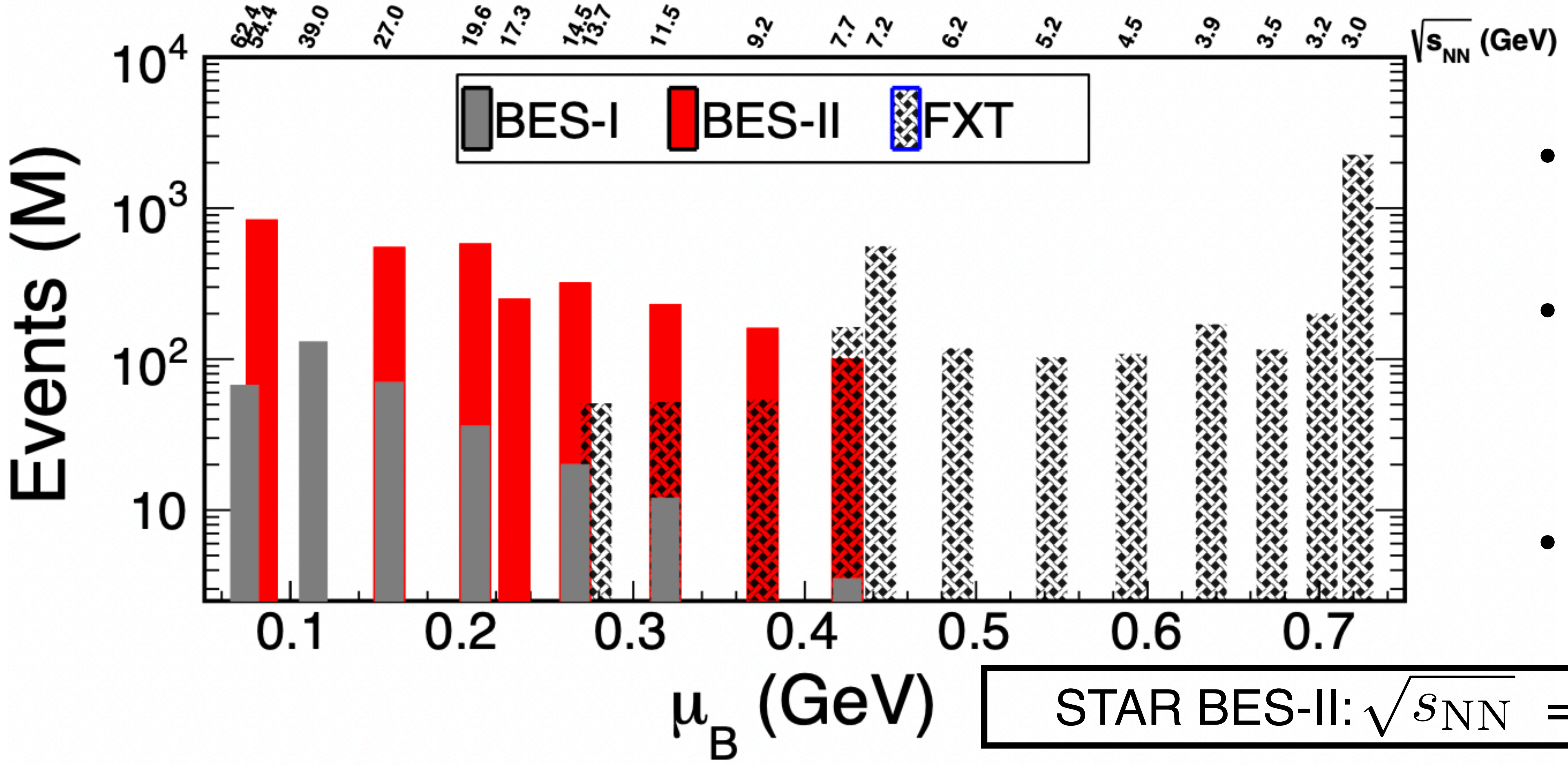
Phys. Rev. Lett.126 (2021), 092301

Nature Physics15,1040–1045 (2019)



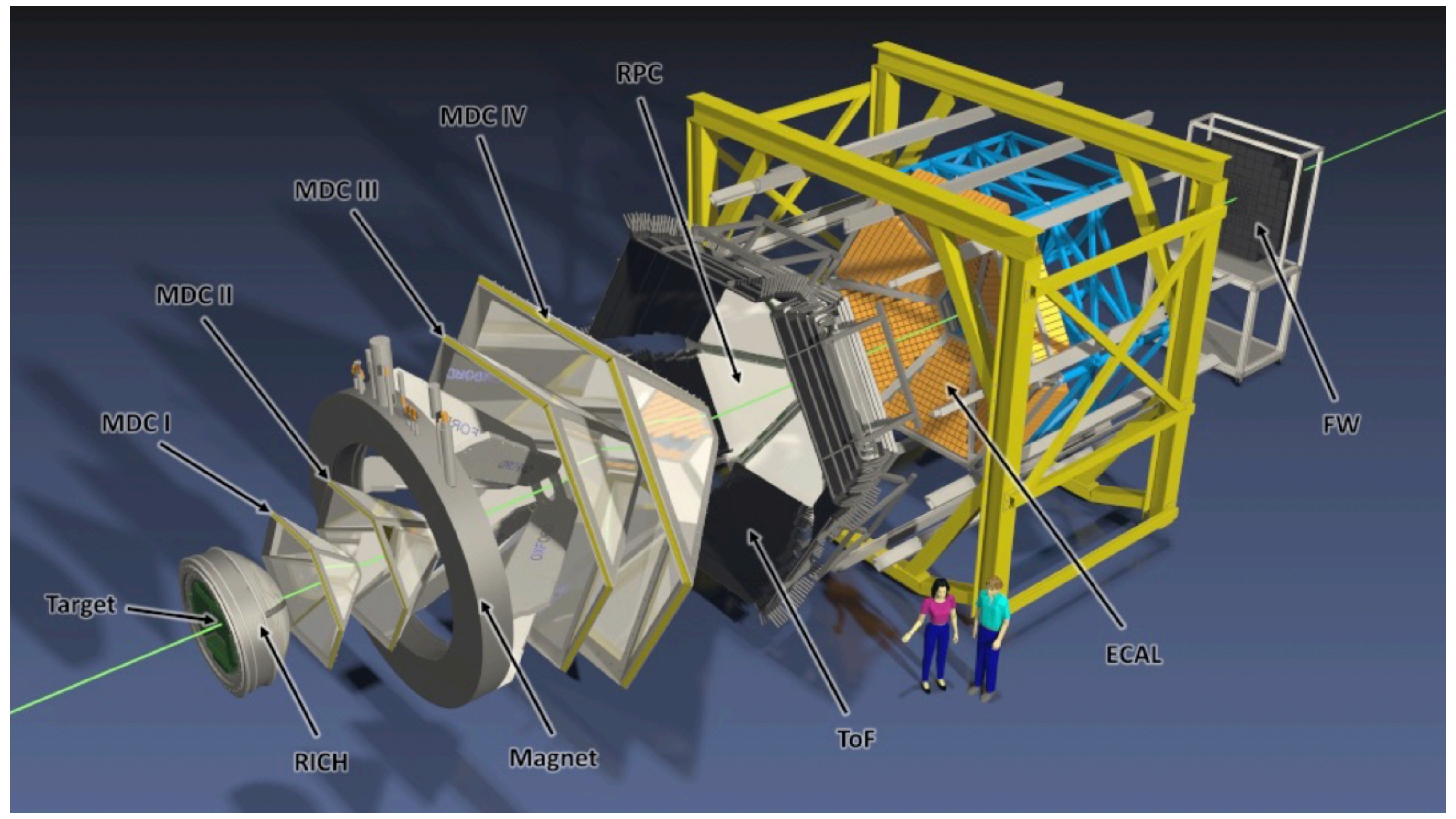
- Not just important for understanding of QCD, similar densities in HIC at high μB as in outer regions of a neutron star merger

Nuclear collisions at high baryon density

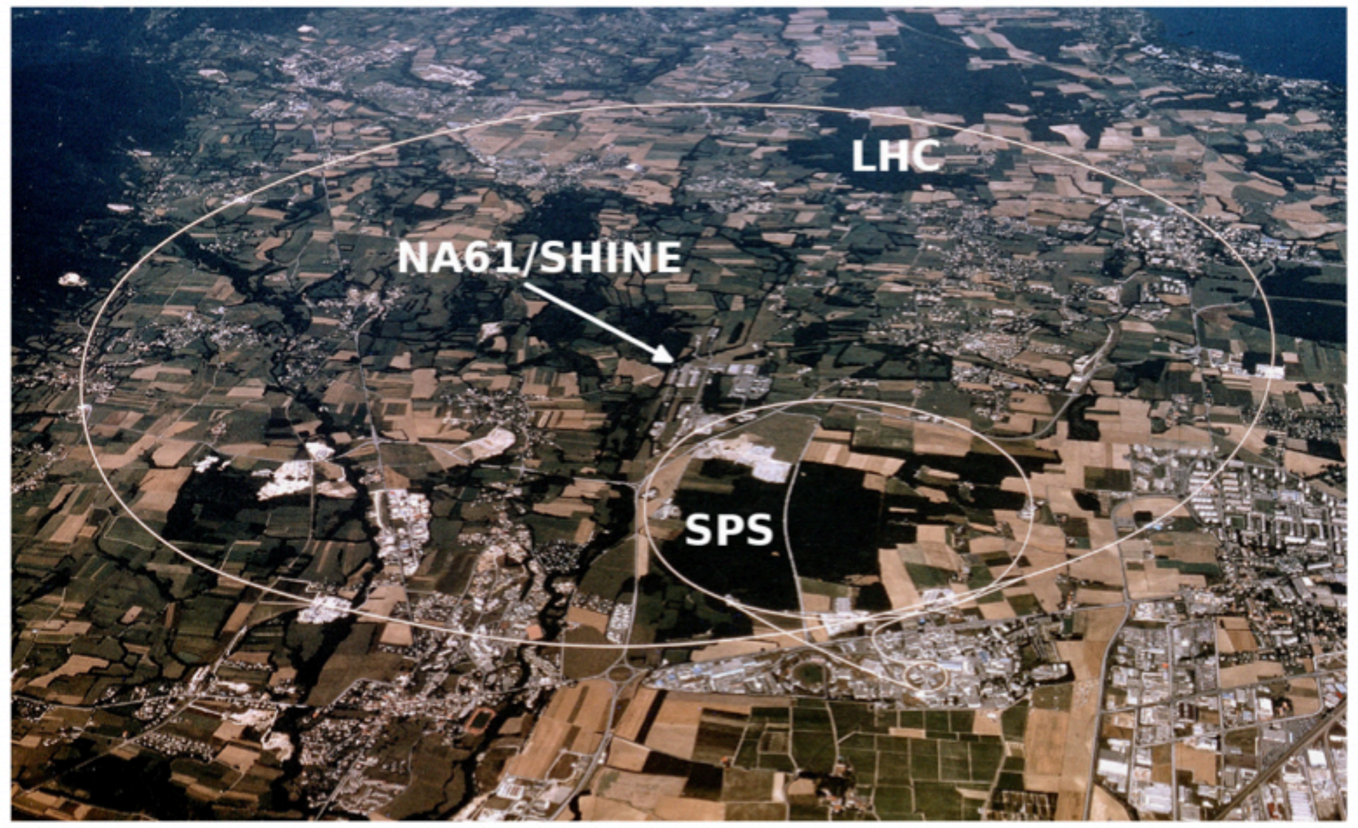


- STAR Beam Energy Scan-II has completed data taking
- With FXT program extending the reach to $\mu_B \sim$ 720 MeV and $\sqrt{s_{NN}}$ down to 3 GeV
- Lots of experimental focus in the region!

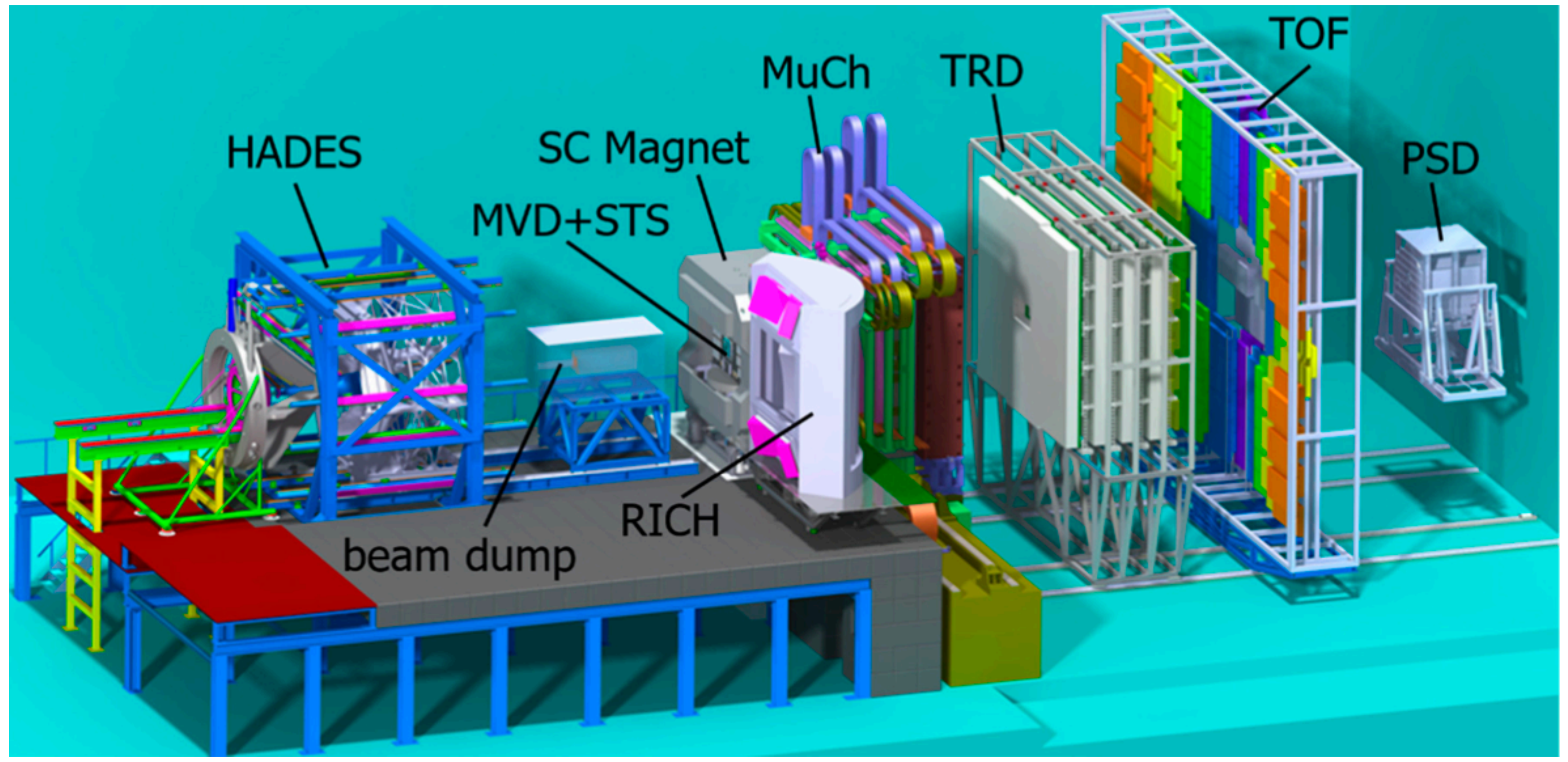
STAR BES-II: $\sqrt{s_{NN}}$ = 3 - 54.4 GeV



HADES: HIC with $\sqrt{s_{NN}}$= 2 - 2.55 GeV



$\sqrt{s_{NN}}$ = 5.1–17.3(27.4) GeV

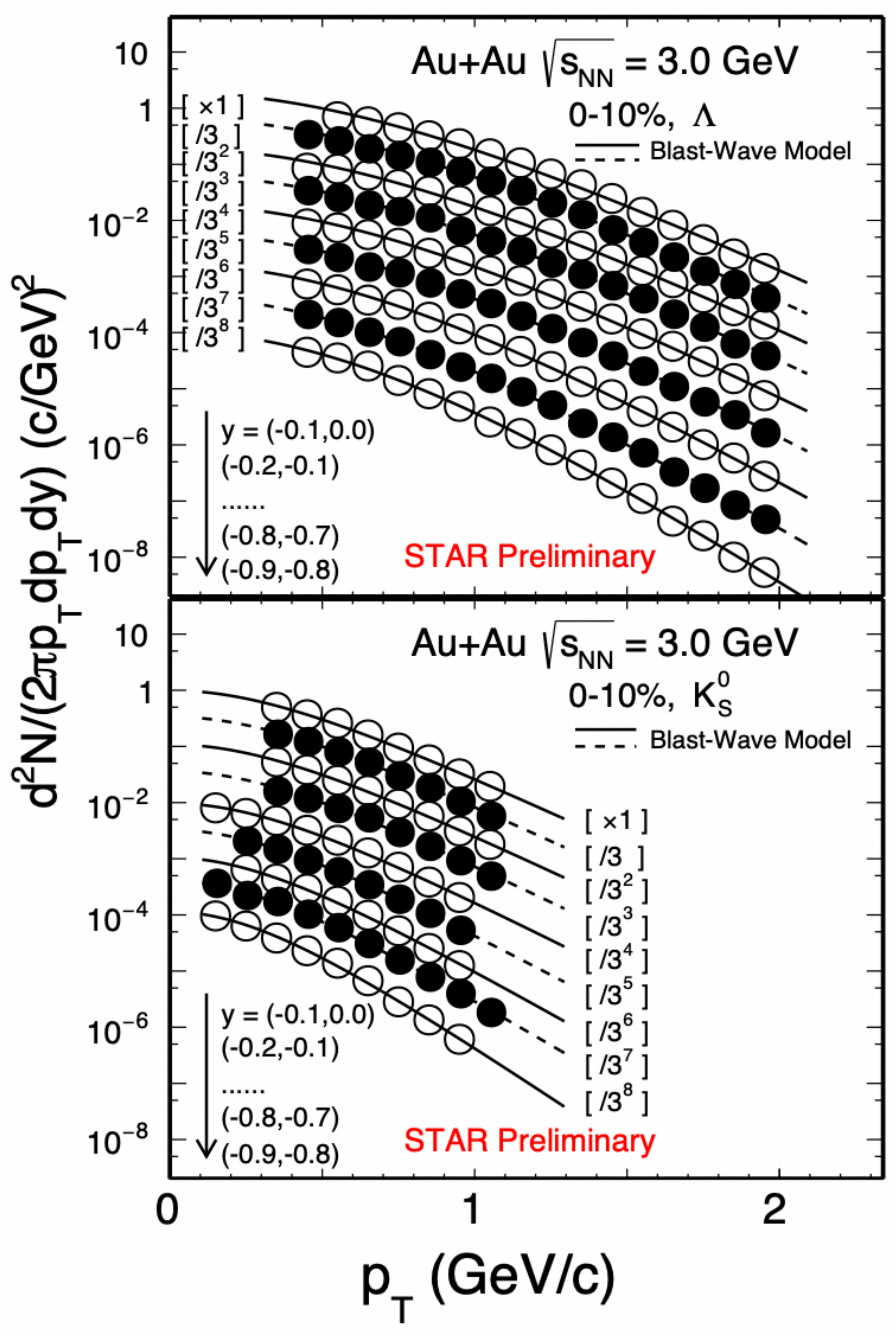


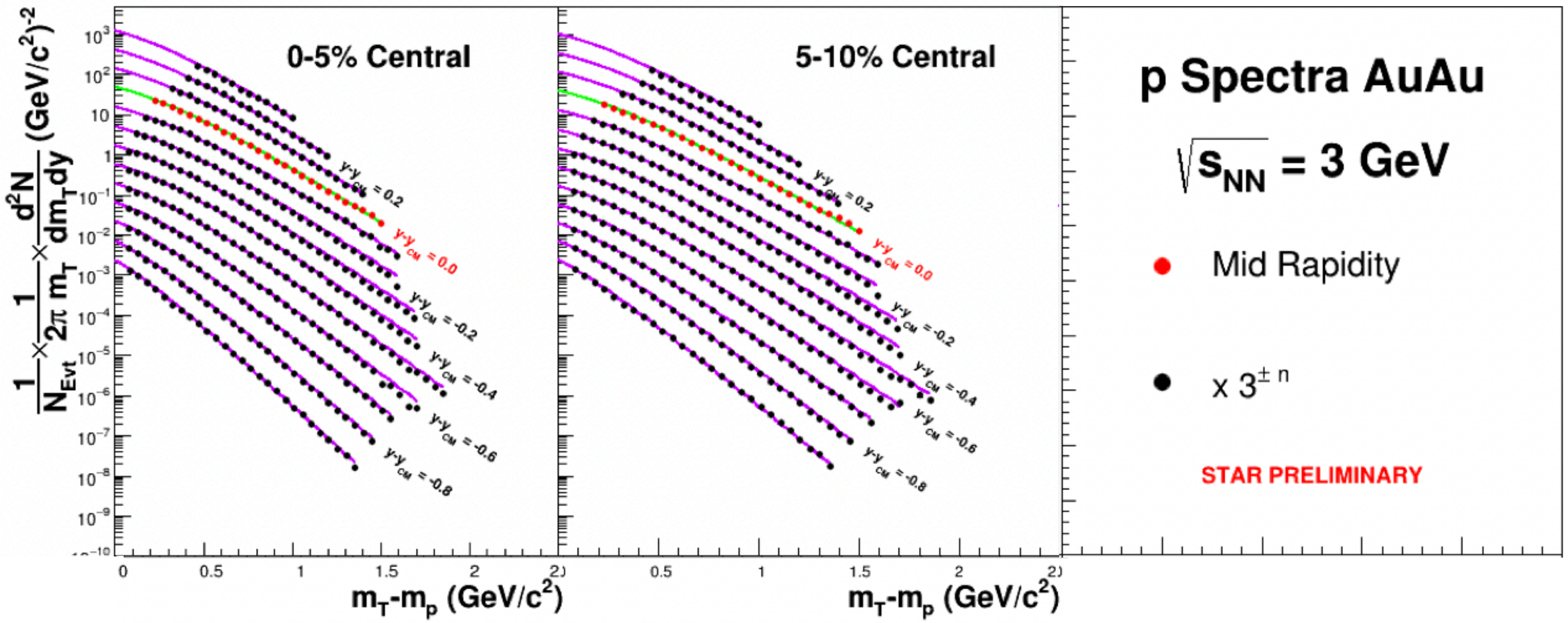
CBM: $\sqrt{s_{NN}}$ = 1.9 - 9 GeV

Light and strange particle production

Particle production at 3 GeV from STAR

- High statistics dataset and mid-rapidity acceptance



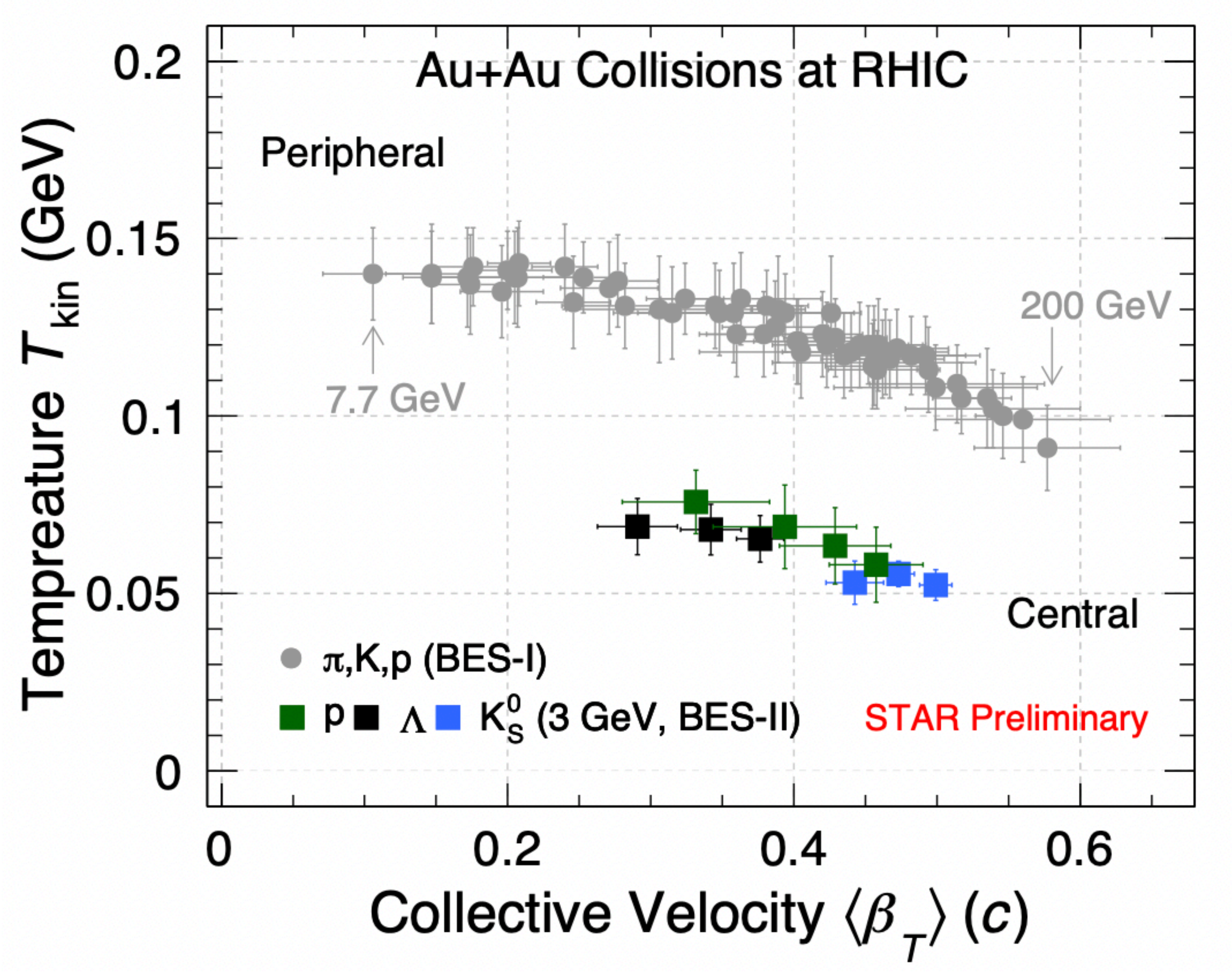


- p_T spectra well described by Blast Wave fits

$$\frac{d^2N}{2\pi p_T dp_T dy} = A\int_0^R r dr m_T \times I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right)K_1\left(\frac{m_T p \cosh\rho(r)}{T_{kin}}\right)$$

Kinetic freeze out parameters at 3 GeV

Talk by Y. Zhou, Tue, 14.00

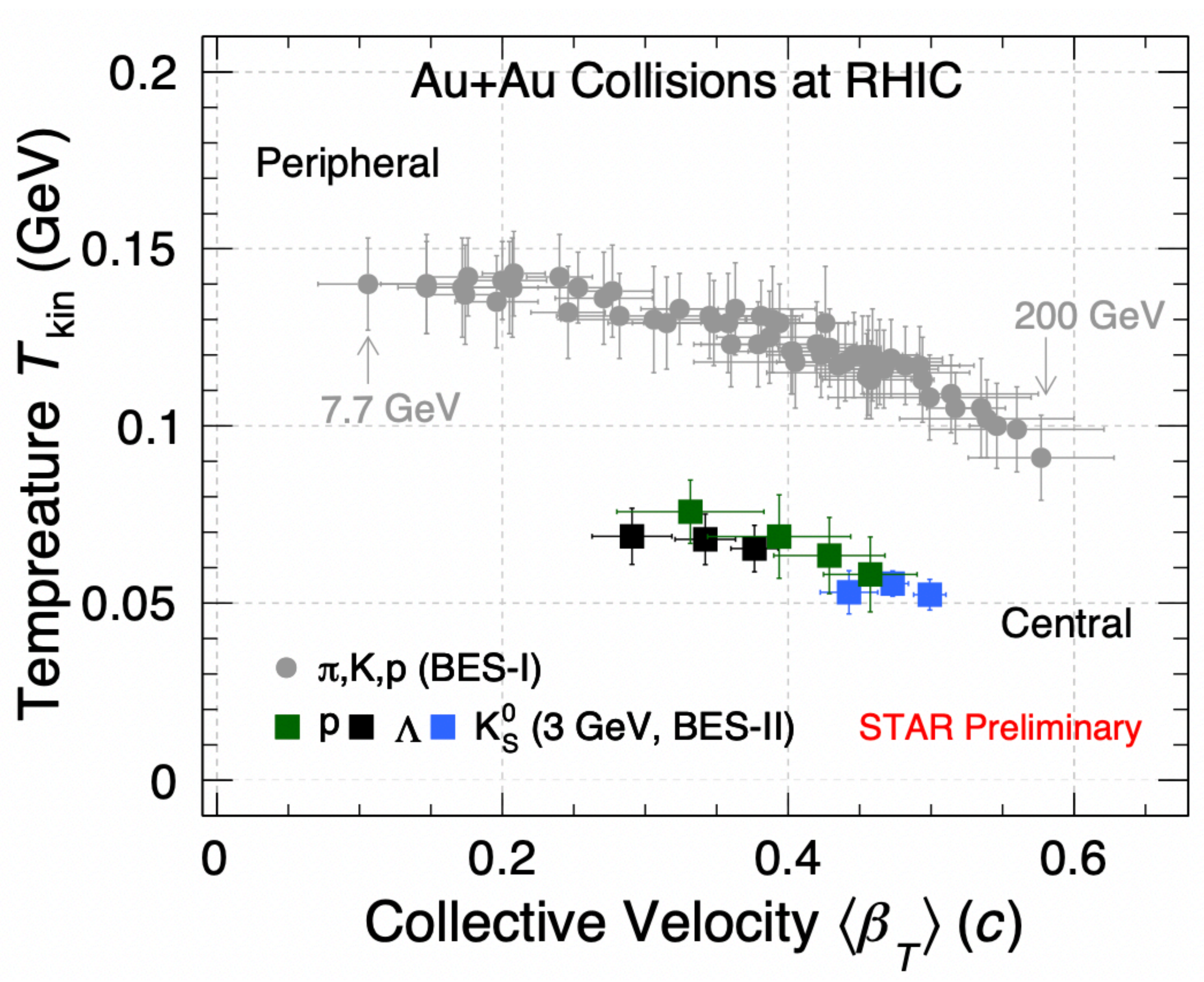


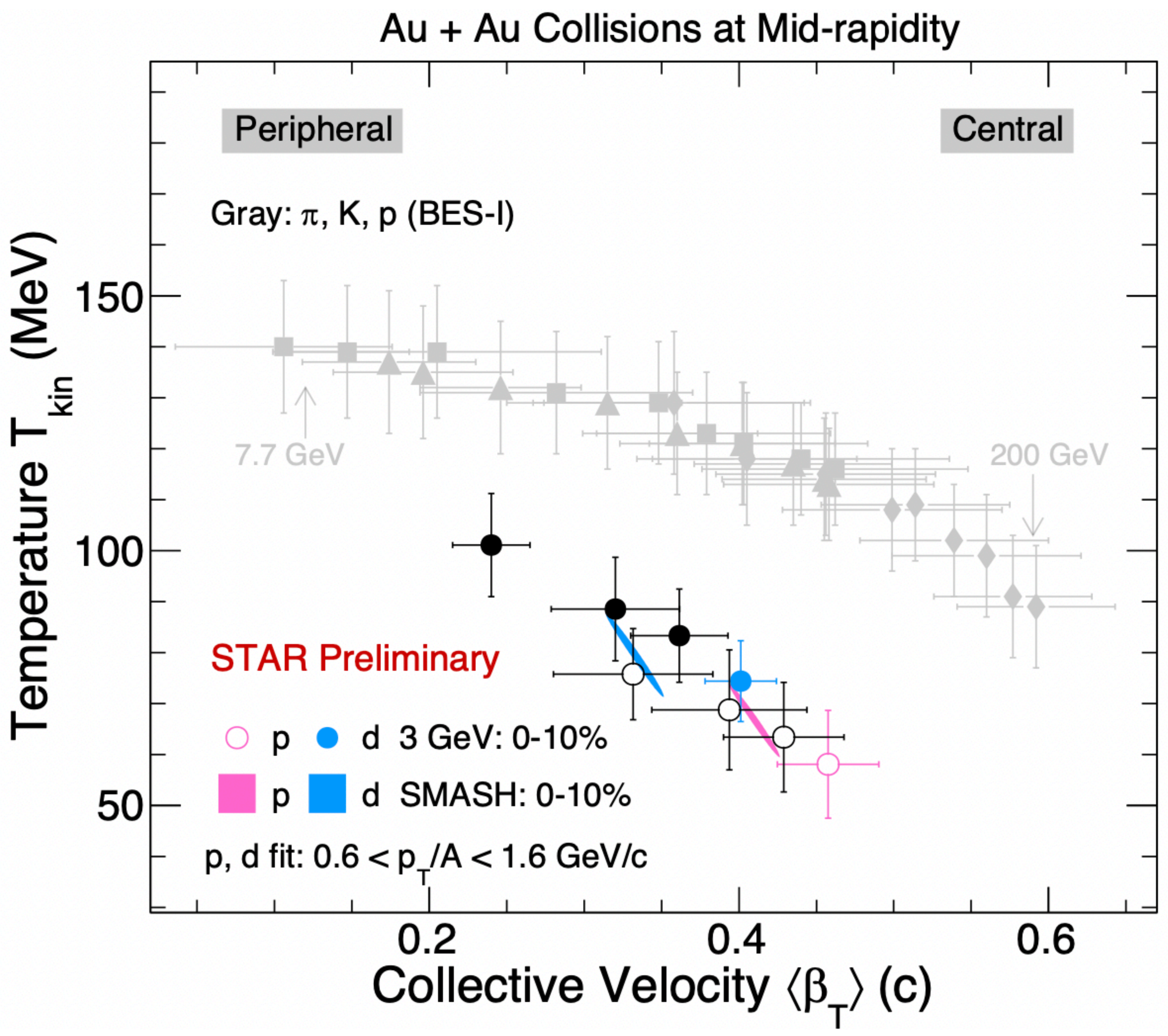
STAR BES-I: Phys. Rev. C. 96. (2017) 044904, Phys. Rev. C 102 (2020), 034909

- Similar value for freeze-out velocity but much lower temperatures at 3 GeV compared to BES-I
- Indication of different EoS at freeze-out at 3 GeV

Kinetic freeze out parameters at 3 GeV

Talk by Y. Zhou, Tue, 14.00; H. Liu, QM 2022



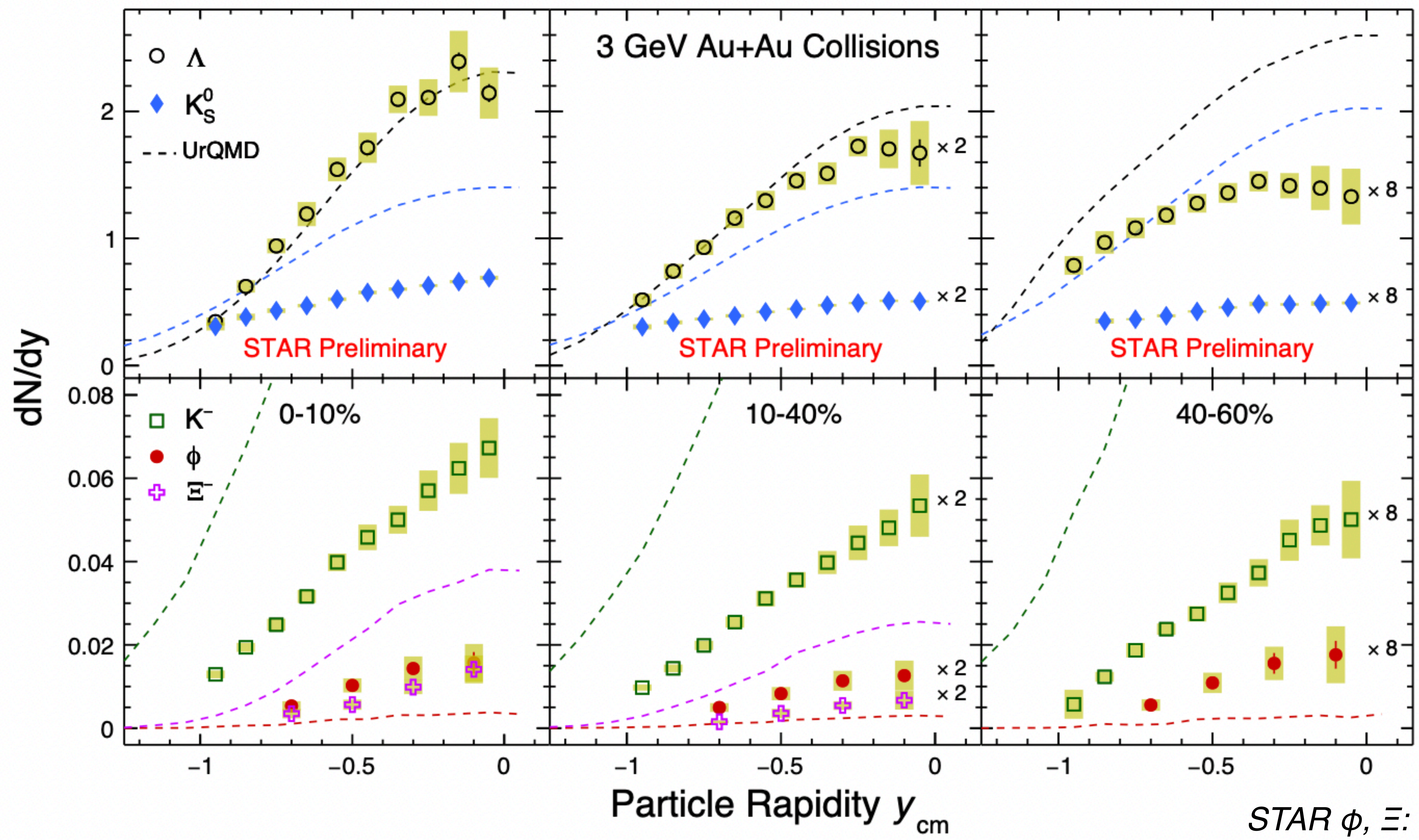


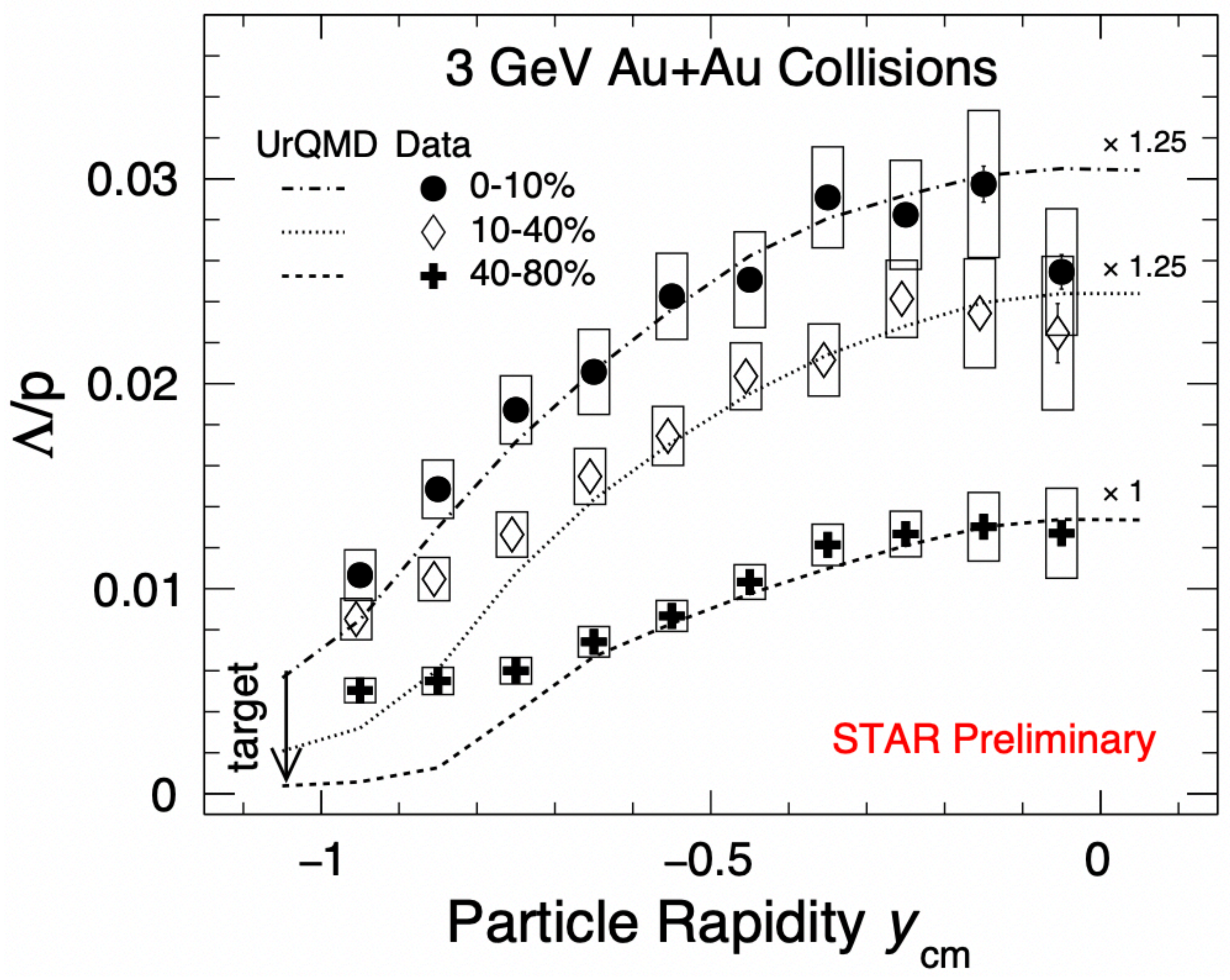
STAR BES-I: Phys. Rev. C. 96. (2017) 044904, Phys. Rev. C 102 (2020), 034909

- Similar value for freeze-out velocity but much lower temperatures at 3 GeV compared to BES-I
- Freeze-out T_{kin} and <β_T> for light nuclei also show similar trend
- Indication of different EoS at freeze-out at 3 GeV

Strangeness production: particle yields vs rapidity

Talk by Y. Zhou, Tue, 14.00





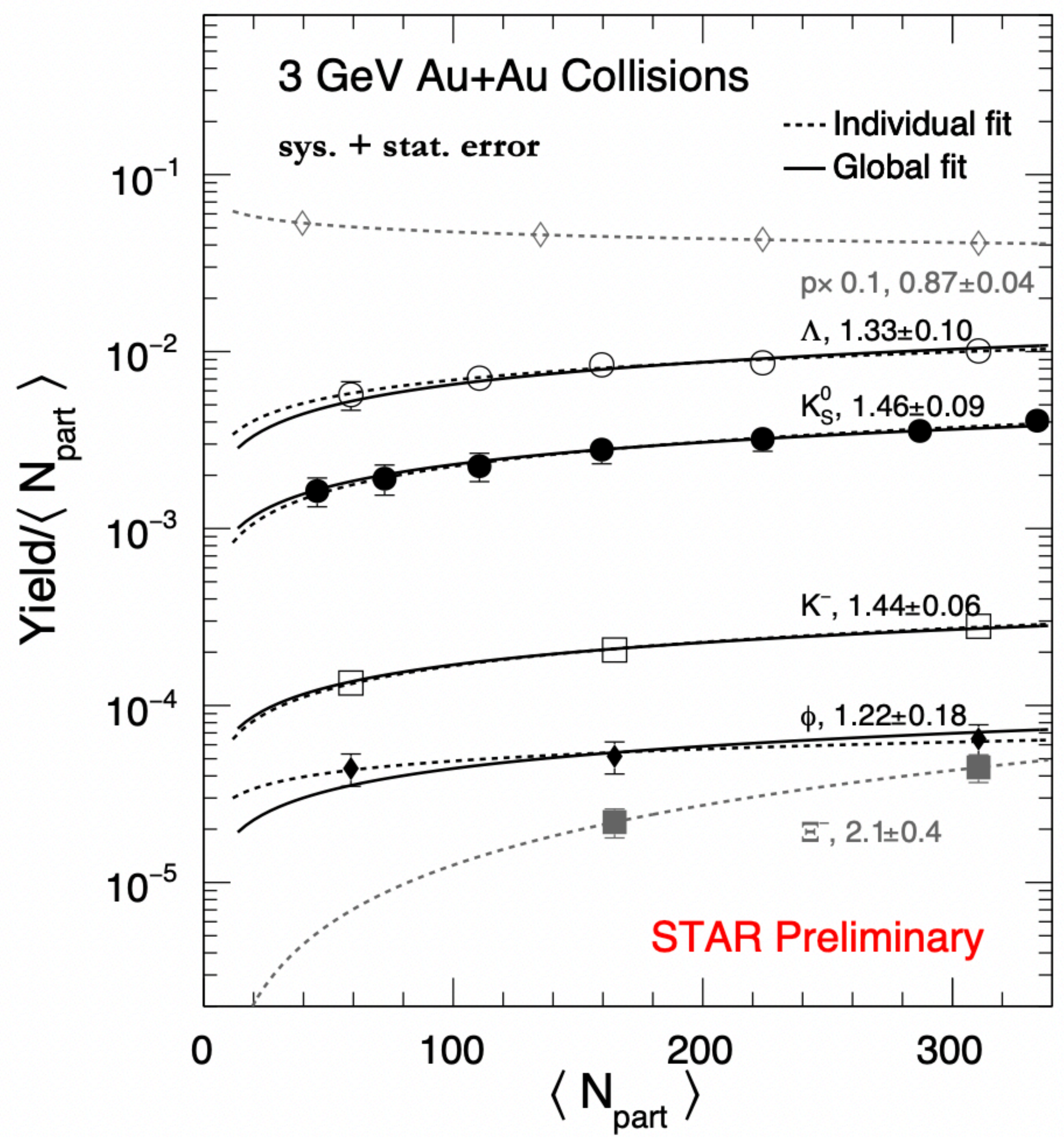
STAR ϕ, Ξ: Phys. Lett. B 831 (2022),137152

- Measurements from mid-rapidity to target rapidity
- UrQMD reproduces Λ yield in central collisions, but over-estimates K^0_S, K^-, Ξ^- and under-estimates ϕ production
- Λ/p ratio larger at mid-rapidity: constraints for strangeness and hypernuclei production at high μ_B

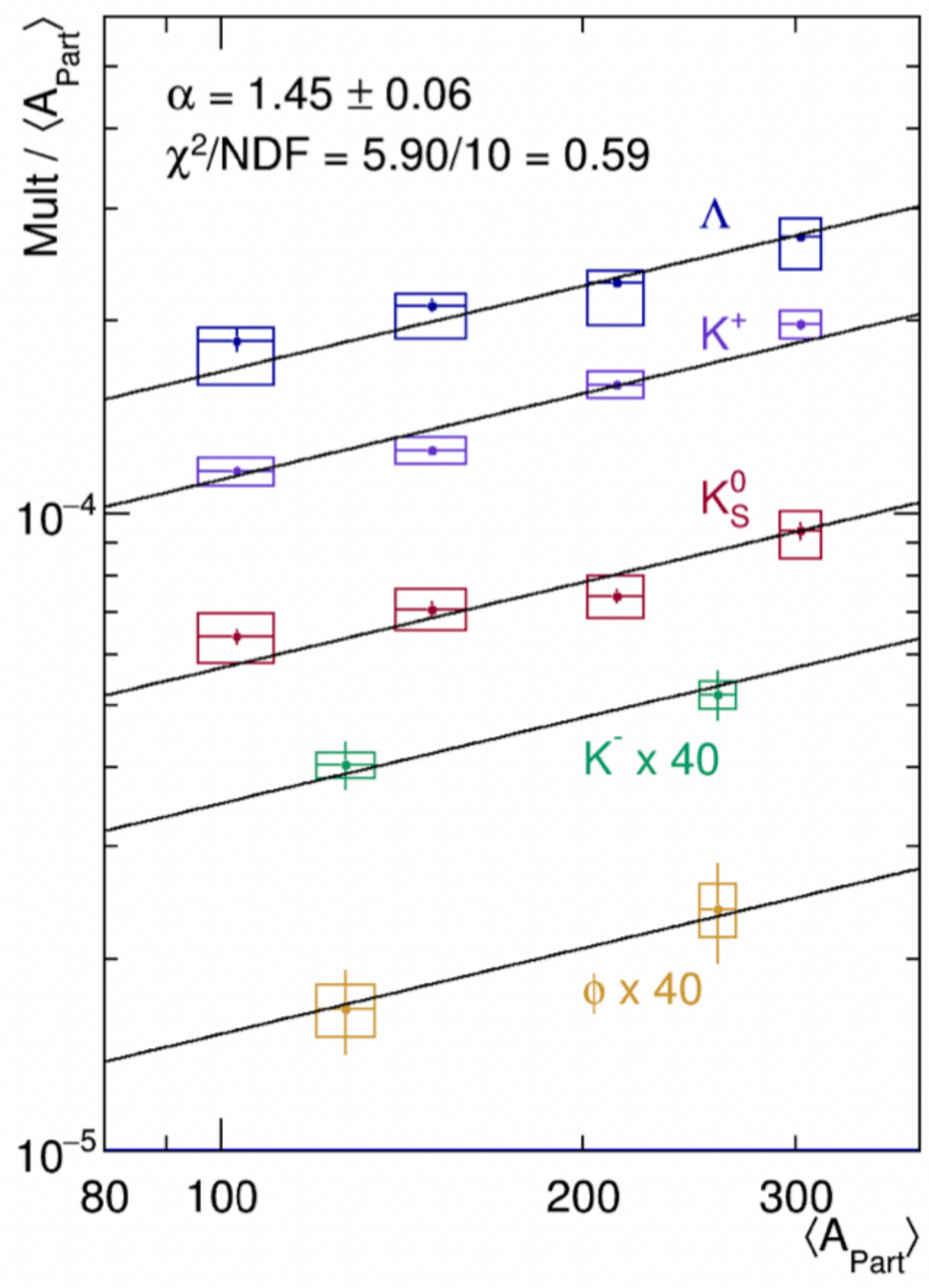
Strange hadron yields vs N_{part}

Talk by Y. Zhou, Tue, 14.00;
S. Spies, Thu 16.30

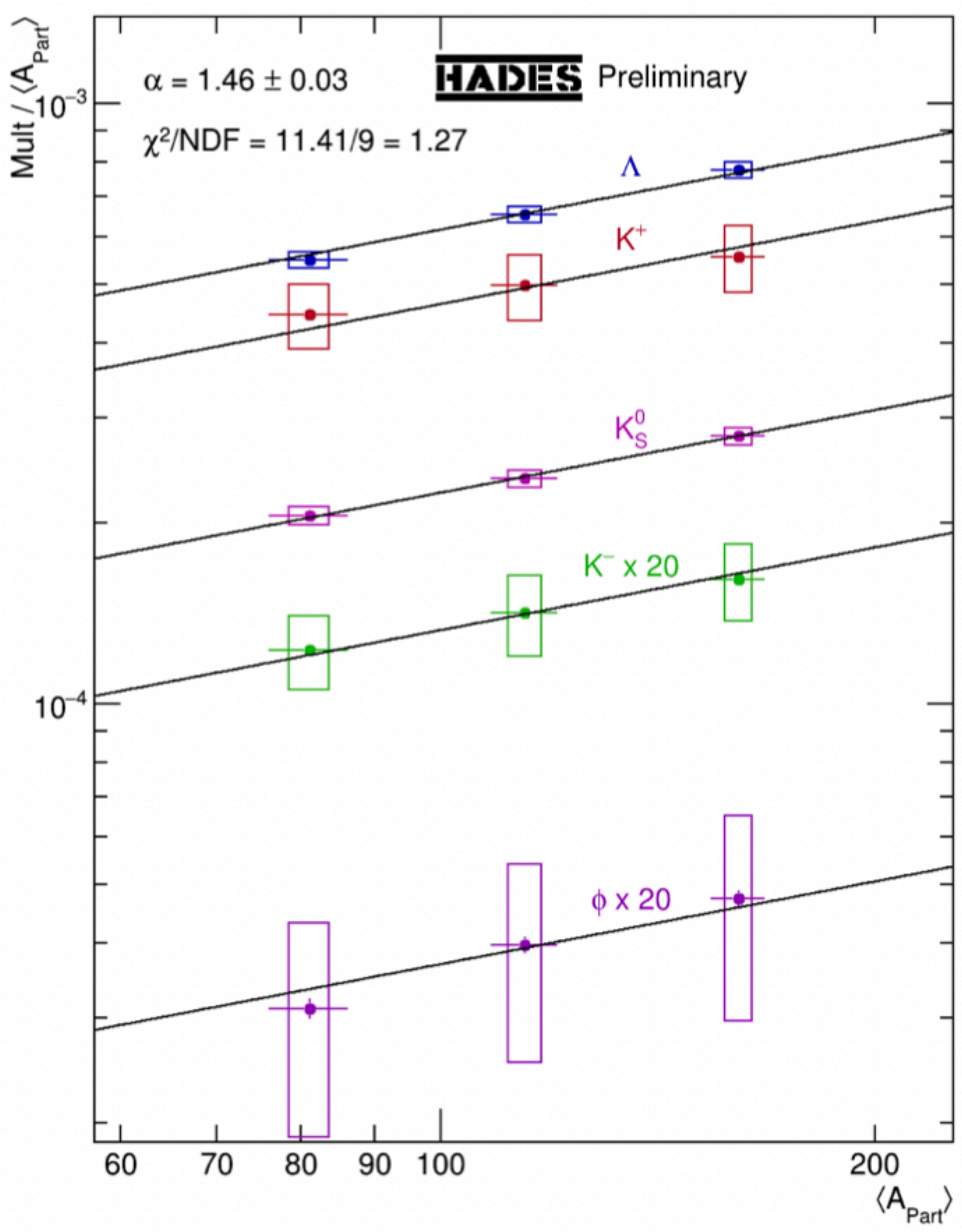
STAR: Au+Au 3.0 GeV



HADES: Au+Au 2.42 GeV

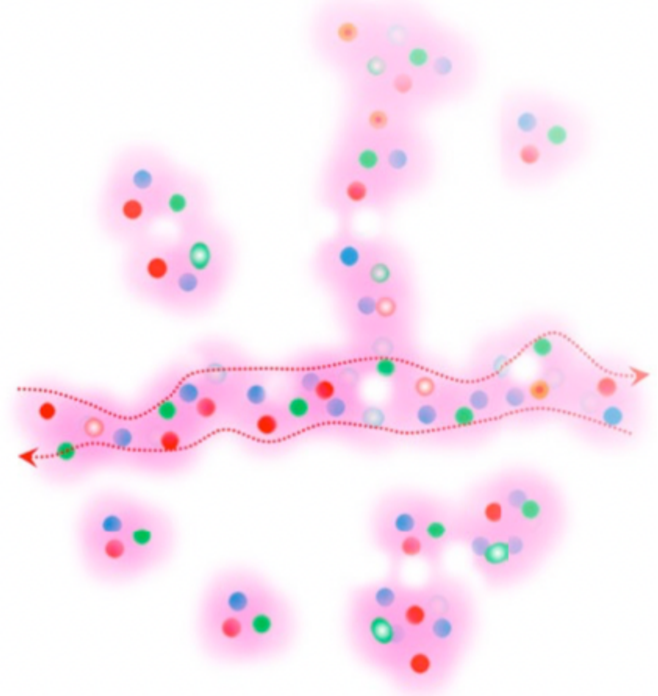


HADES: Ag+Ag 2.55 GeV



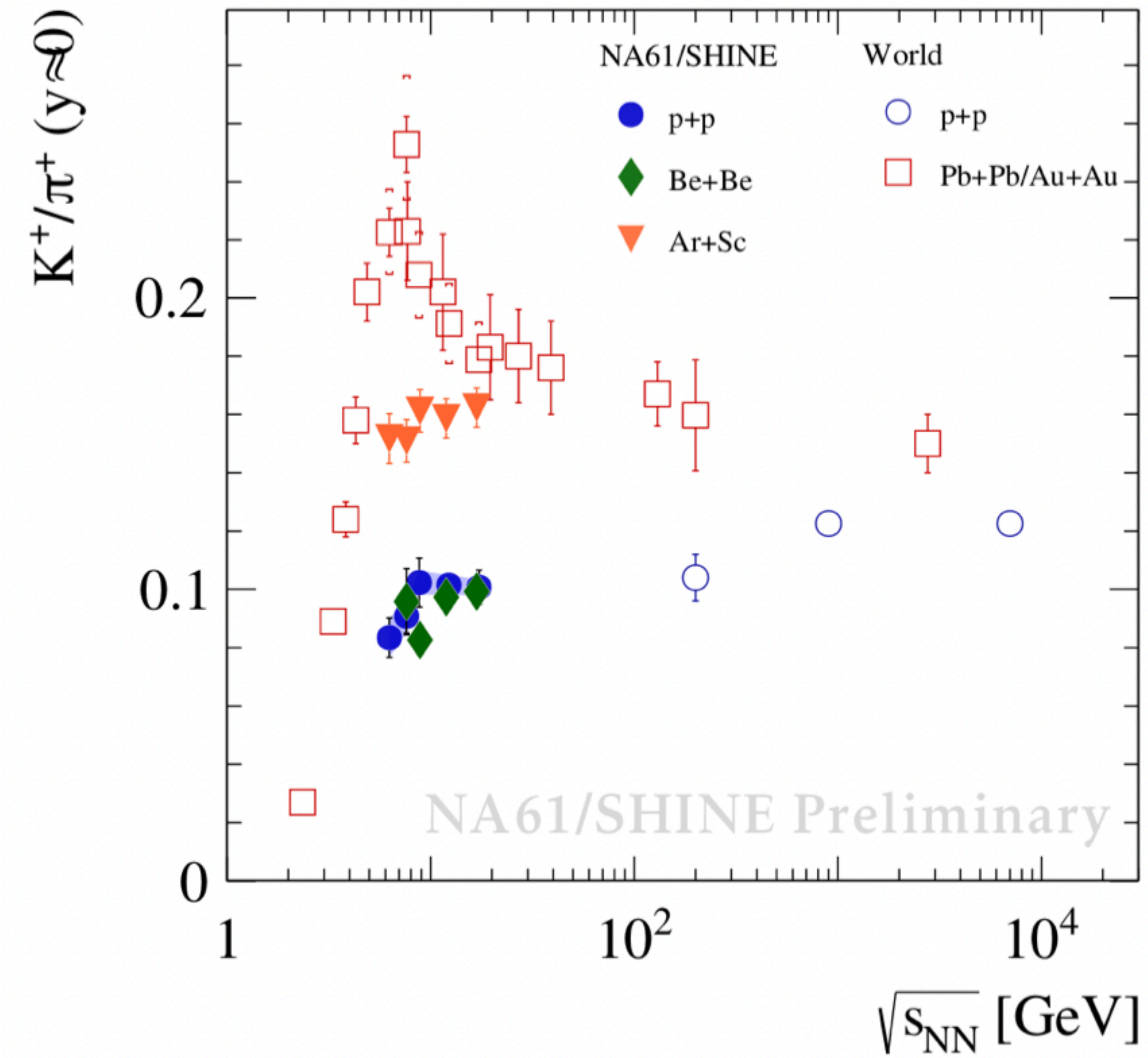
HADES, Phys. Lett. B 793 (2019) 457

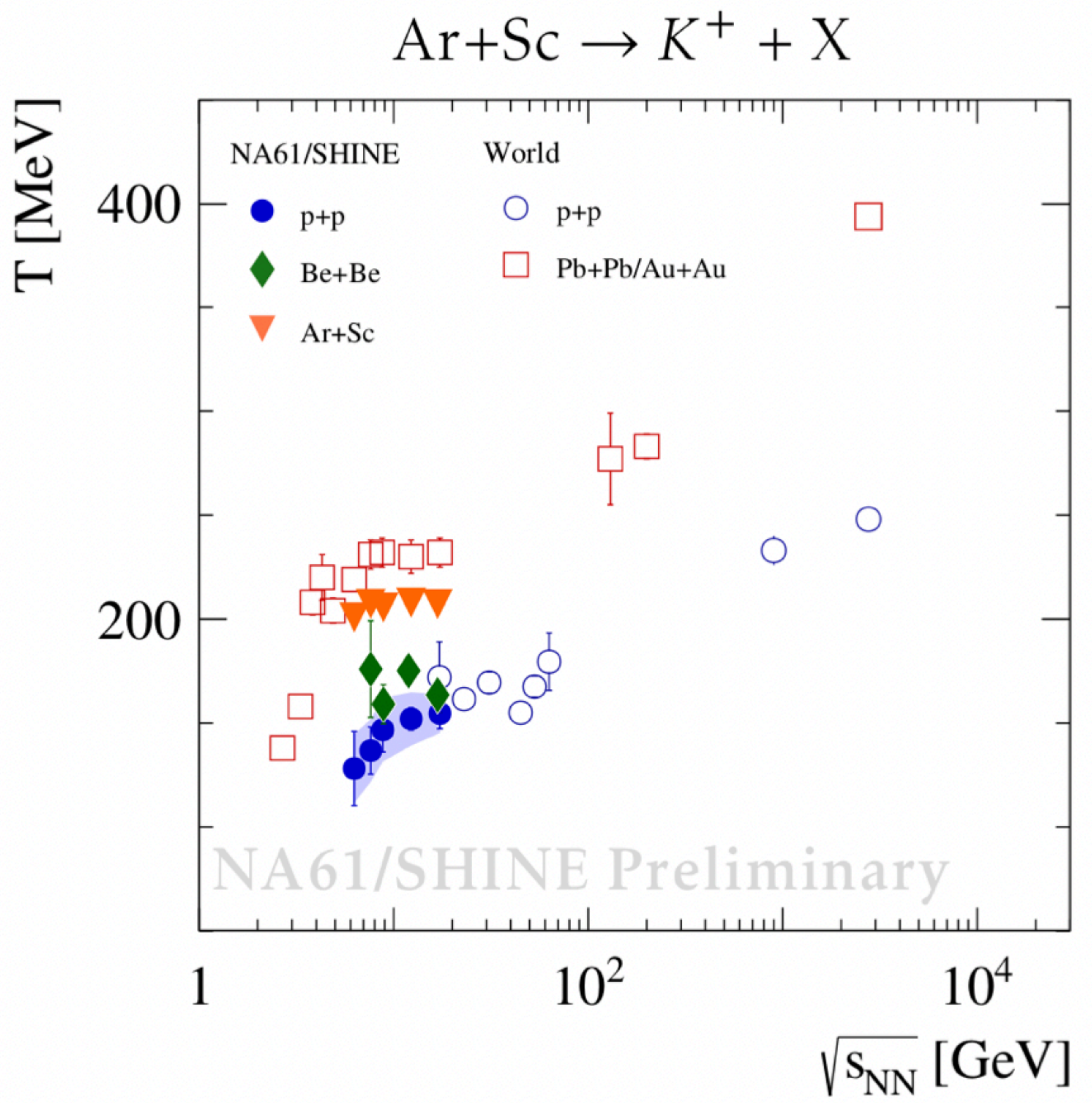
- Strange hadron yields proportional to $<N_{part}>^{\alpha}$, with α ~ 1.4, despite different production thresholds
- Yields scale with total strangeness production: Percolation of meson cloud? Soft deconfinement? *K. Fukushima, et al, Phys. Rev. D 102, 096017 (2020)*



Strangeness enhancement at SPS energies

Talk by P. Podlaski, Tue, 15.20

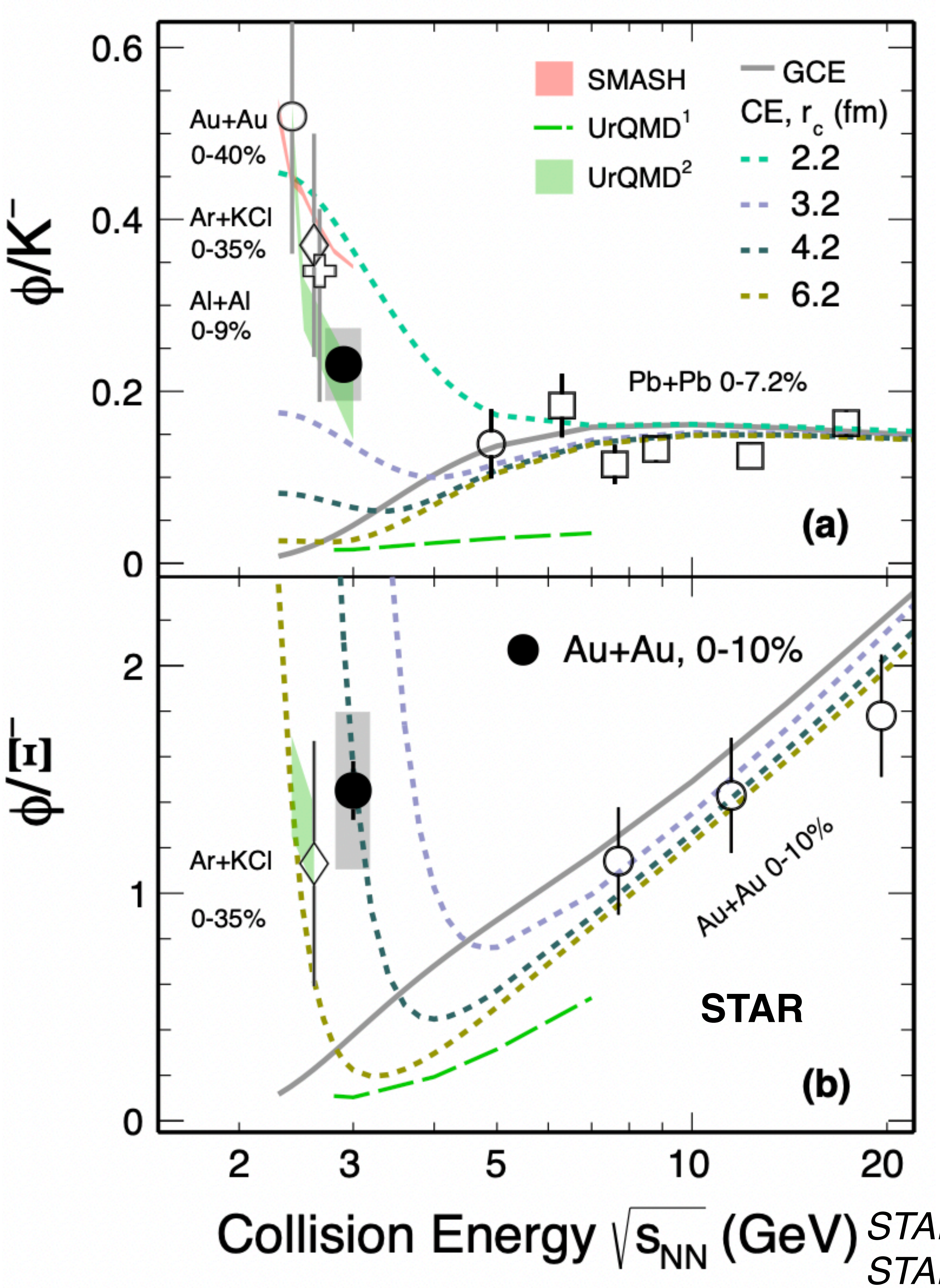


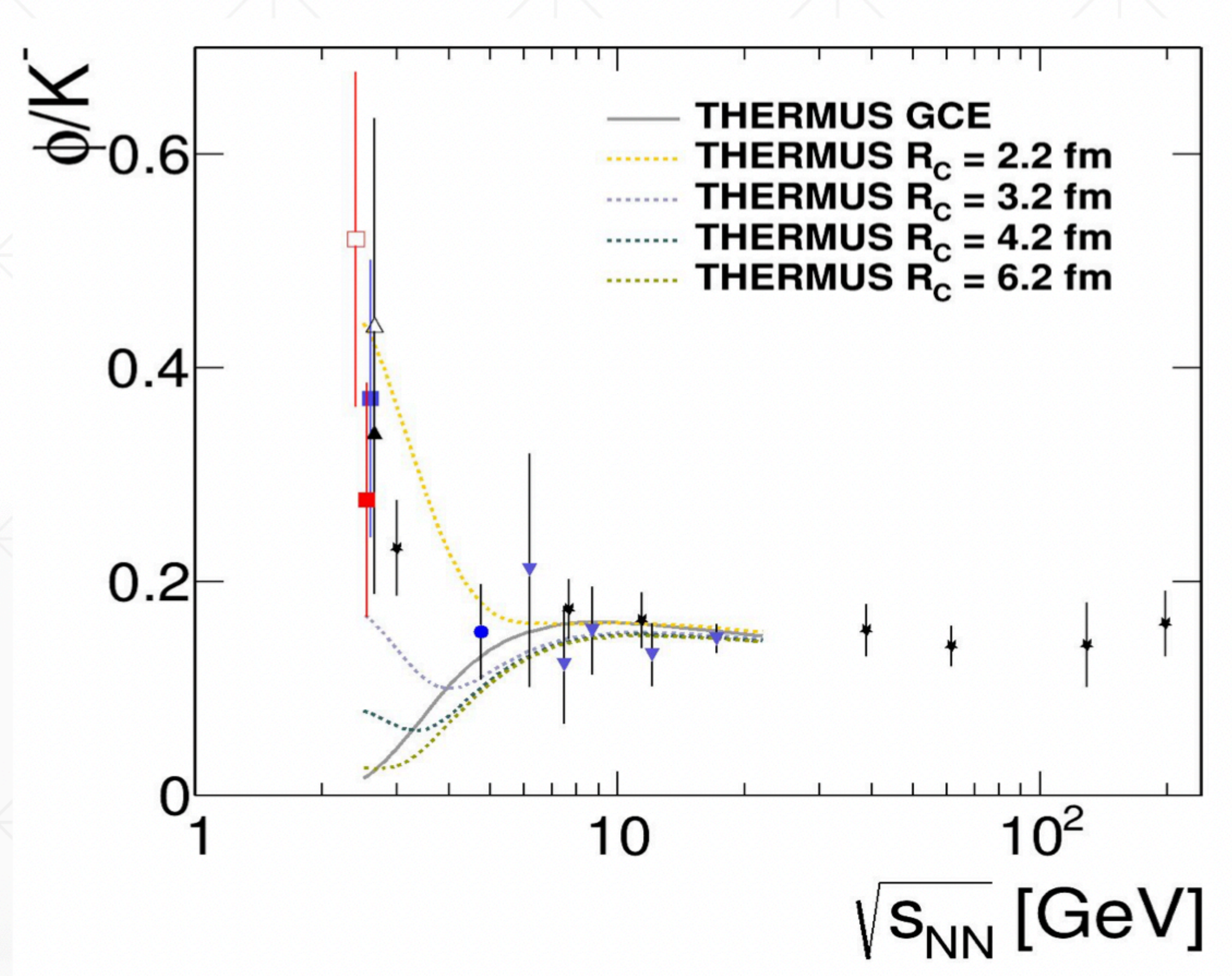


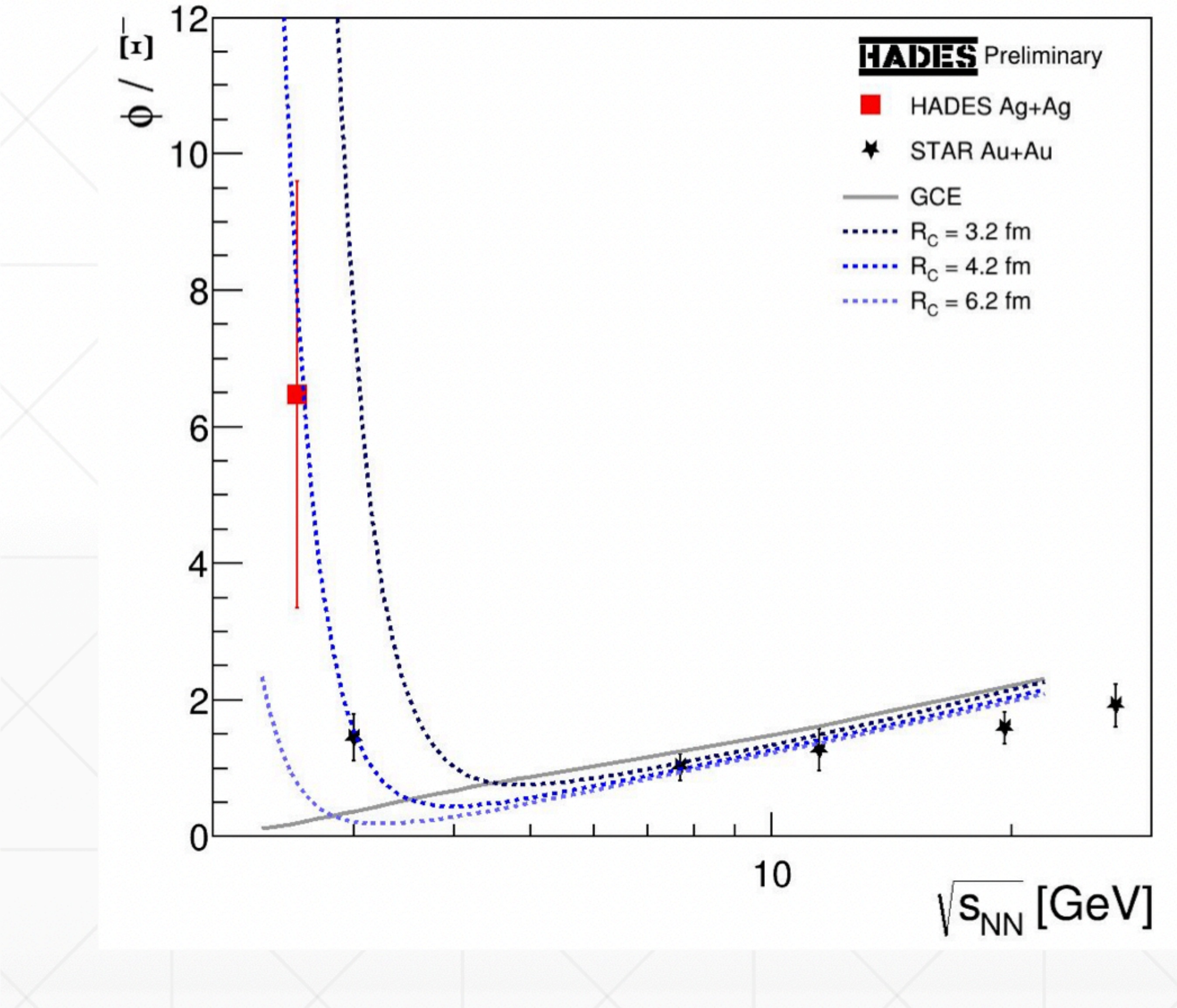
NA49 Pb+Pb, Phys. Rev. C 66, 054902 (2002)

- Yield ratio of K^+/π^+: rapid increase with collision energy till $\sqrt{s_{NN}}$ ~ 8 GeV and then plateaus. Argued to be from deconfinement and enhancement of strangeness (SMES model)
- T from inverse slope of kaon m_T spectra also shows similar collision energy dependence
- Strong system size dependence for the yield ratio and T

Multi-strange hadron yield ratios







- Yield ratios show canonical suppression of strangeness at 3 GeV
- Can help constrain strangeness correlation length in the medium

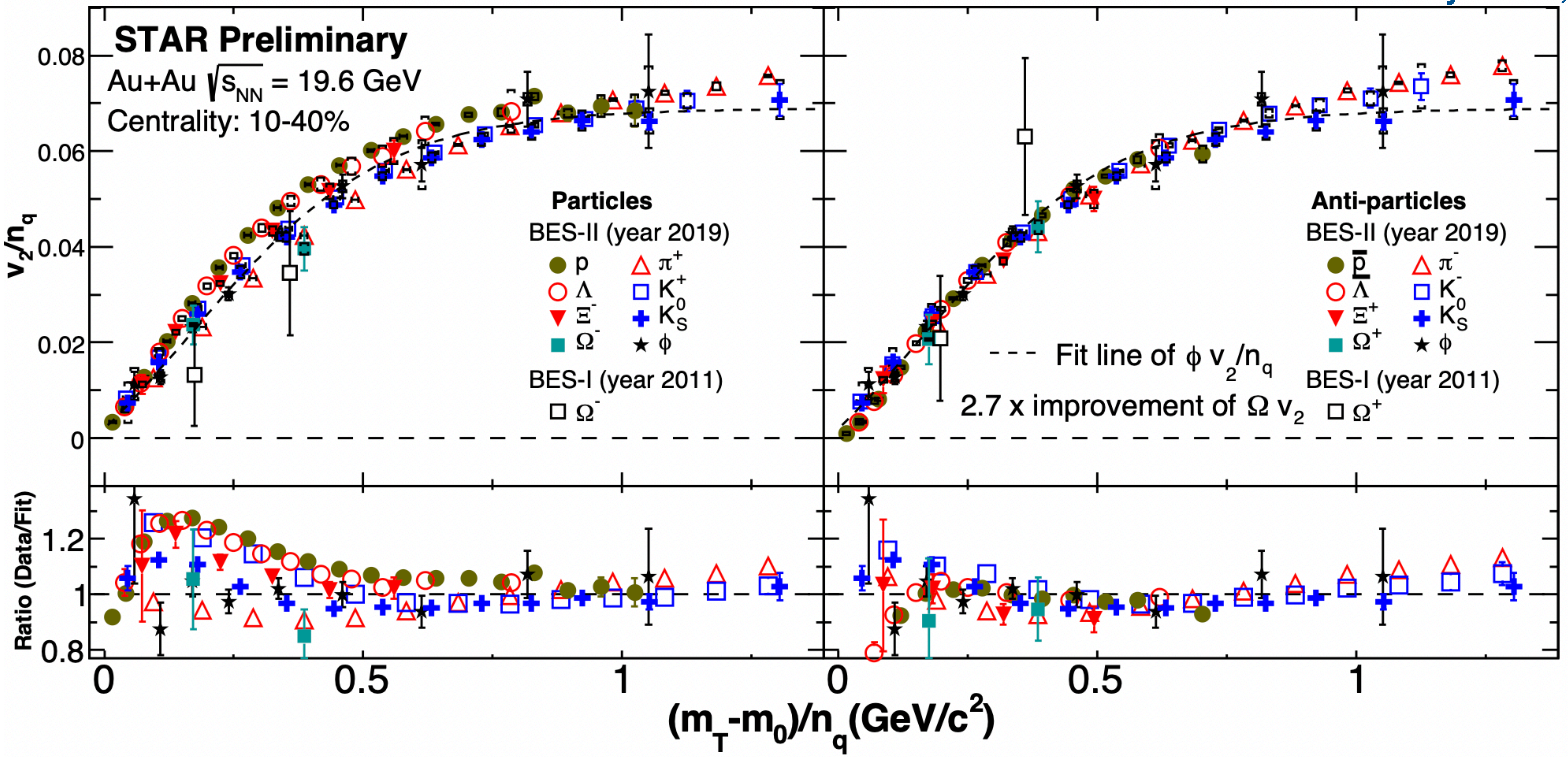
- Default UrQMD fails to describe the data
- Transport models with high mass resonance decays included can describe the ϕ/K^- yield ratio

STAR: Phys. Lett. B 831 (2022) 137152
STAR (BES-I): Phys. Rev. C 102 (2020) 34909
HADES: Eur. Phys. J. A (2016) 52: 178
UrQMD[1](default): Prog. Part. Nucl. Phys. 41 225-370
UrQMD[2]: J. Phys. G: Nucl. Part. Phys. 43 015104
Thermal CE: Phys. Lett. B 603, 146 (2004)

Collectivity in the high μ_B region

BES-II elliptic and triangular flow measurements at lower μ_B

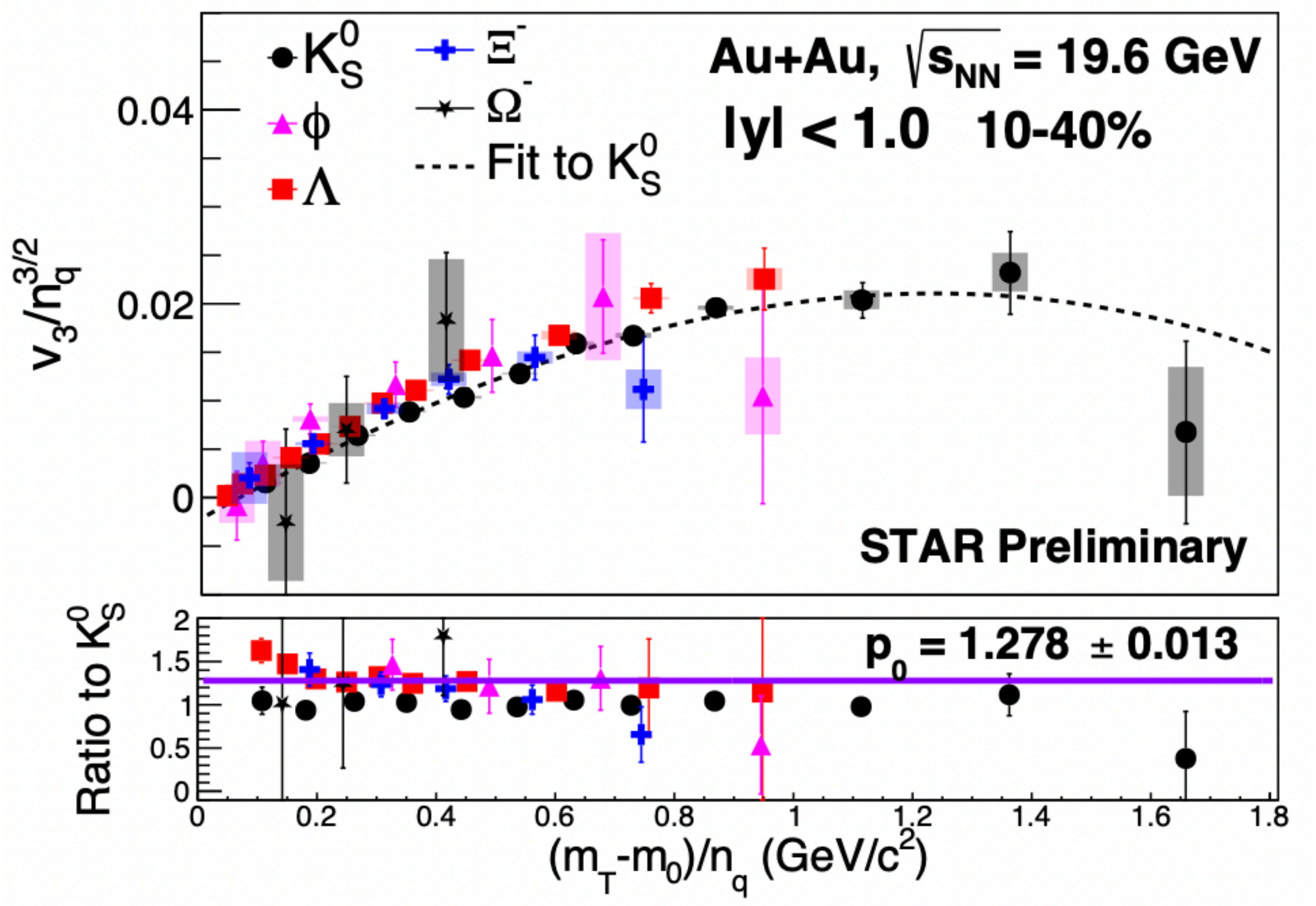
Talk by L. Liu, Tue, 15.00

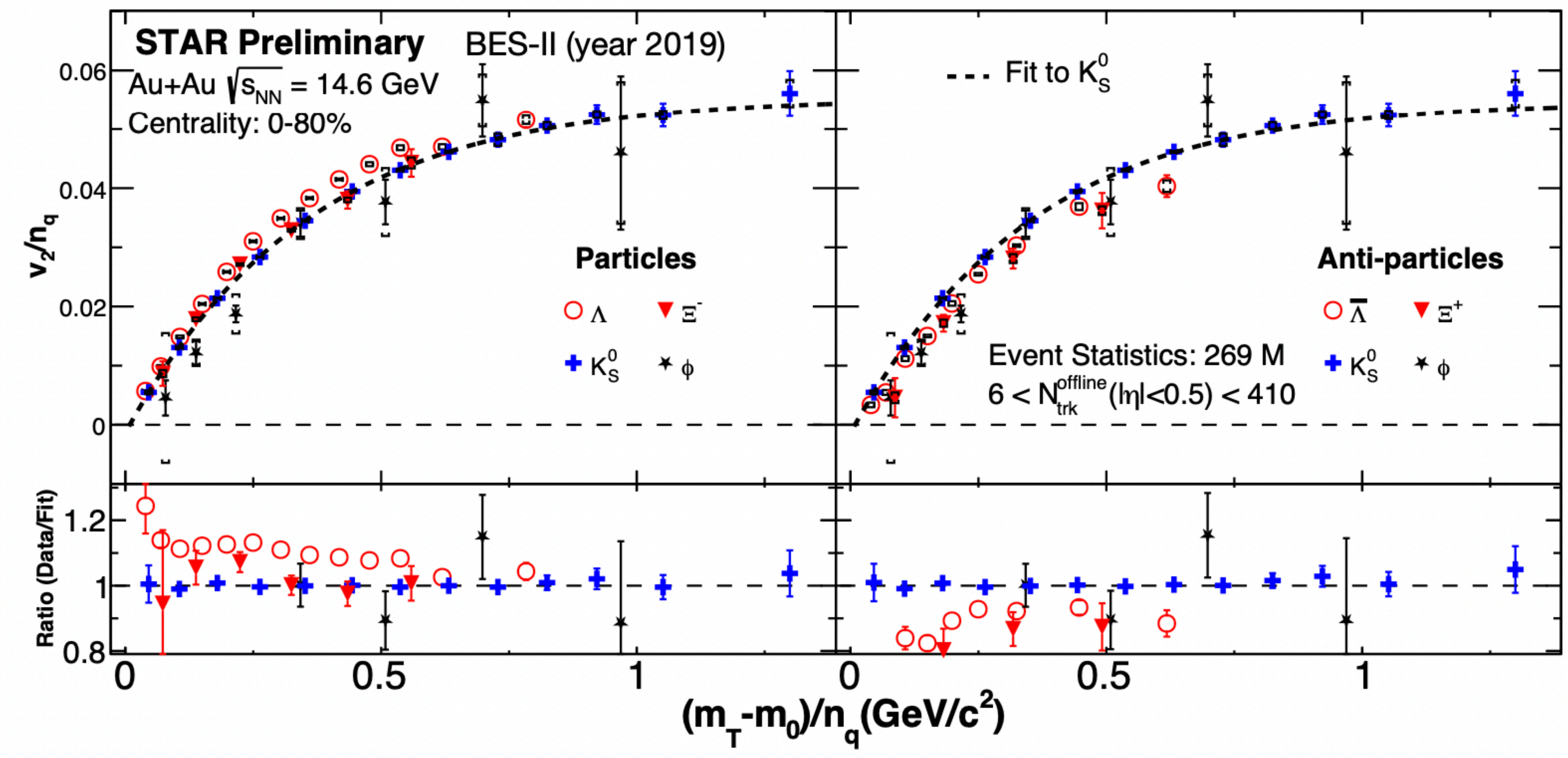


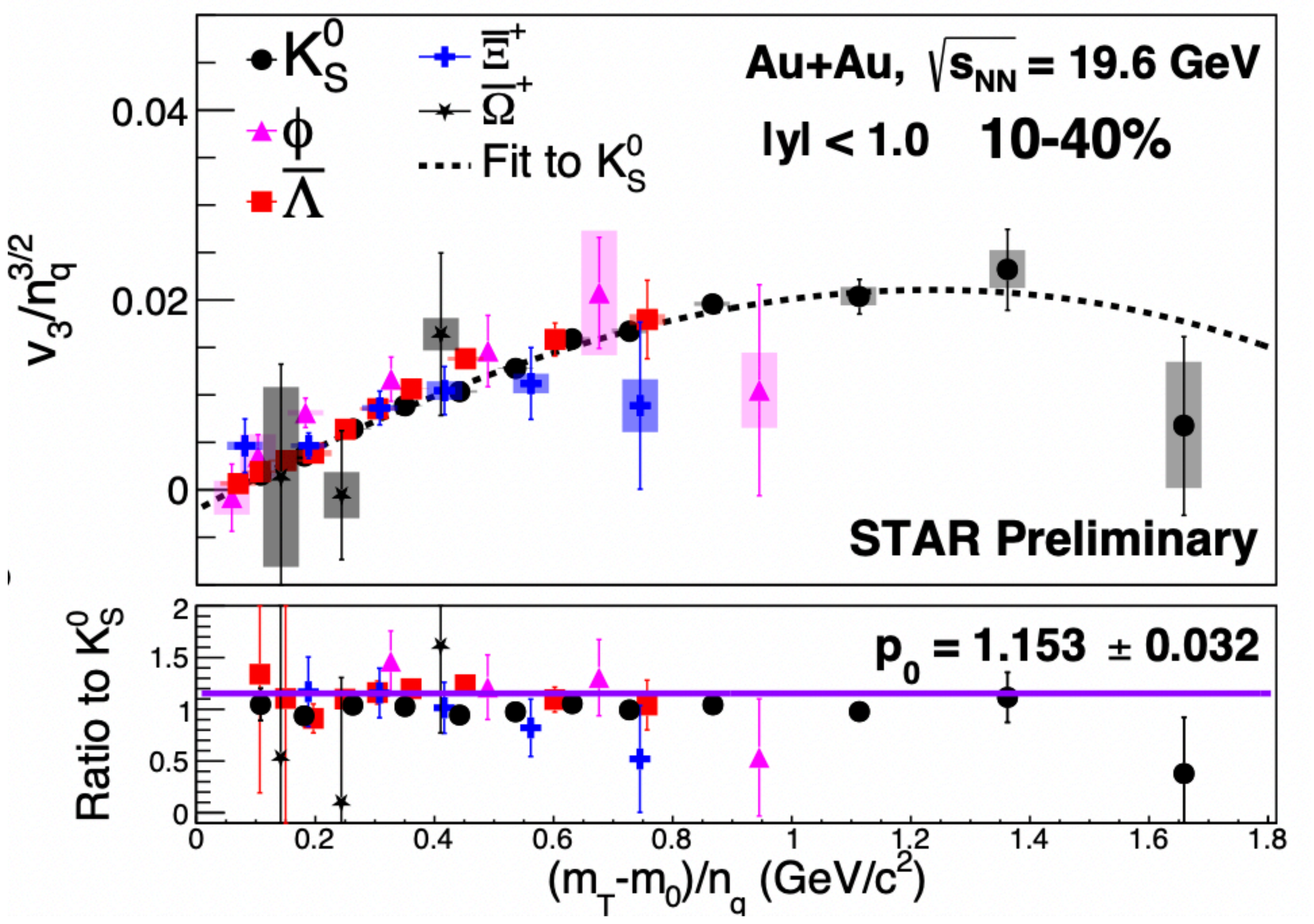
- Significant improvement of precision of v_2 measurements with BES-II data
- NCQ scaling observed to hold within 10% for anti-particles and within 20% for particles
- Dominance of partonic interactions in the generation of collective flow

BES-II elliptic and triangular flow measurements at lower μ_B

Talk by L. Liu, Tue, 15.00
Poster by P.Dixit

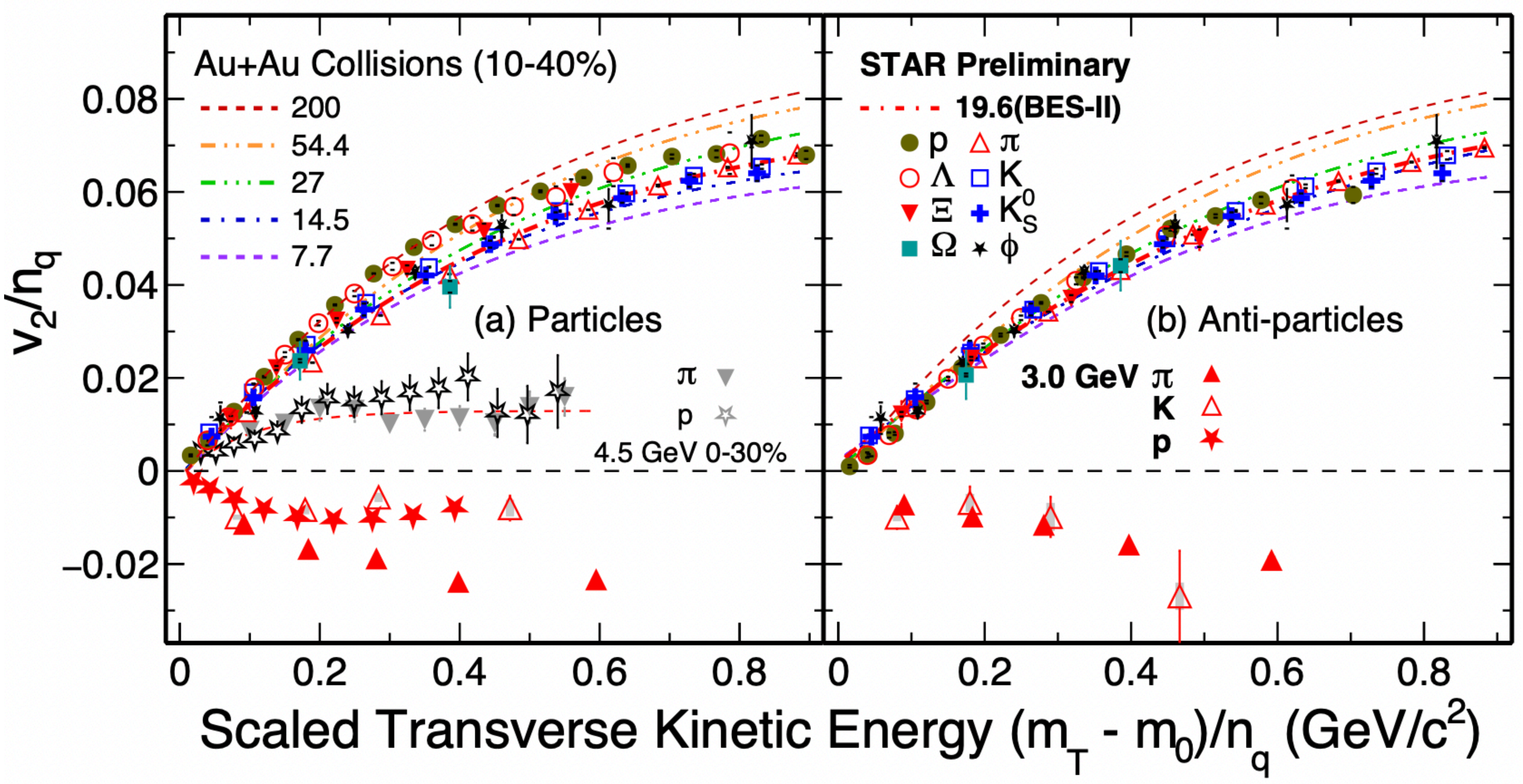






- NCQ scaling also for v_3 and at 14.6 GeV: partonic dominance
- v_2 and v_3 important to constrain EoS evolution
- Lower energy ϕ v_n measurements important to study relative contributions from partonic and hadronic stages vs $\sqrt{s_{NN}}$

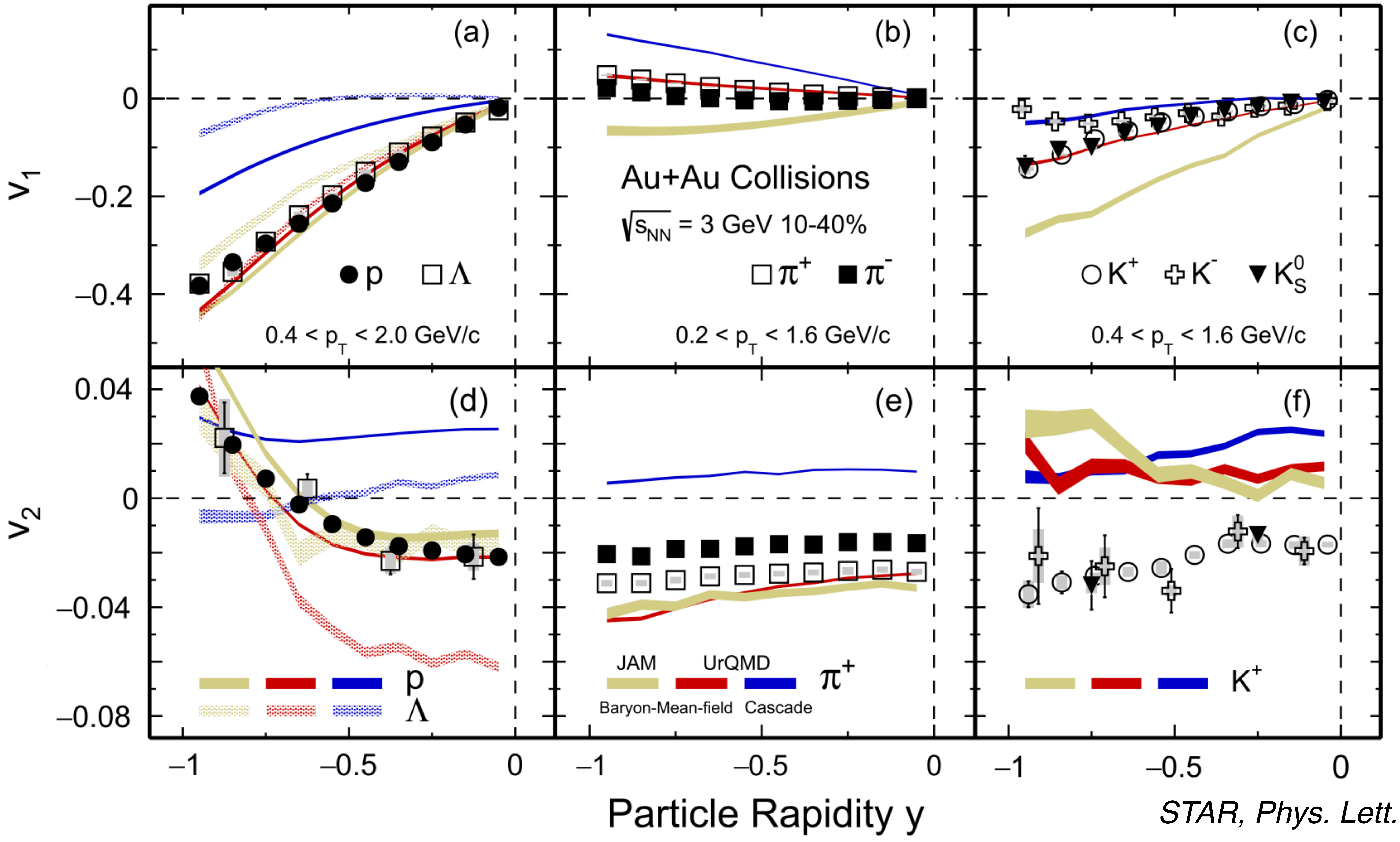
Collectivity measurements at 3 GeV

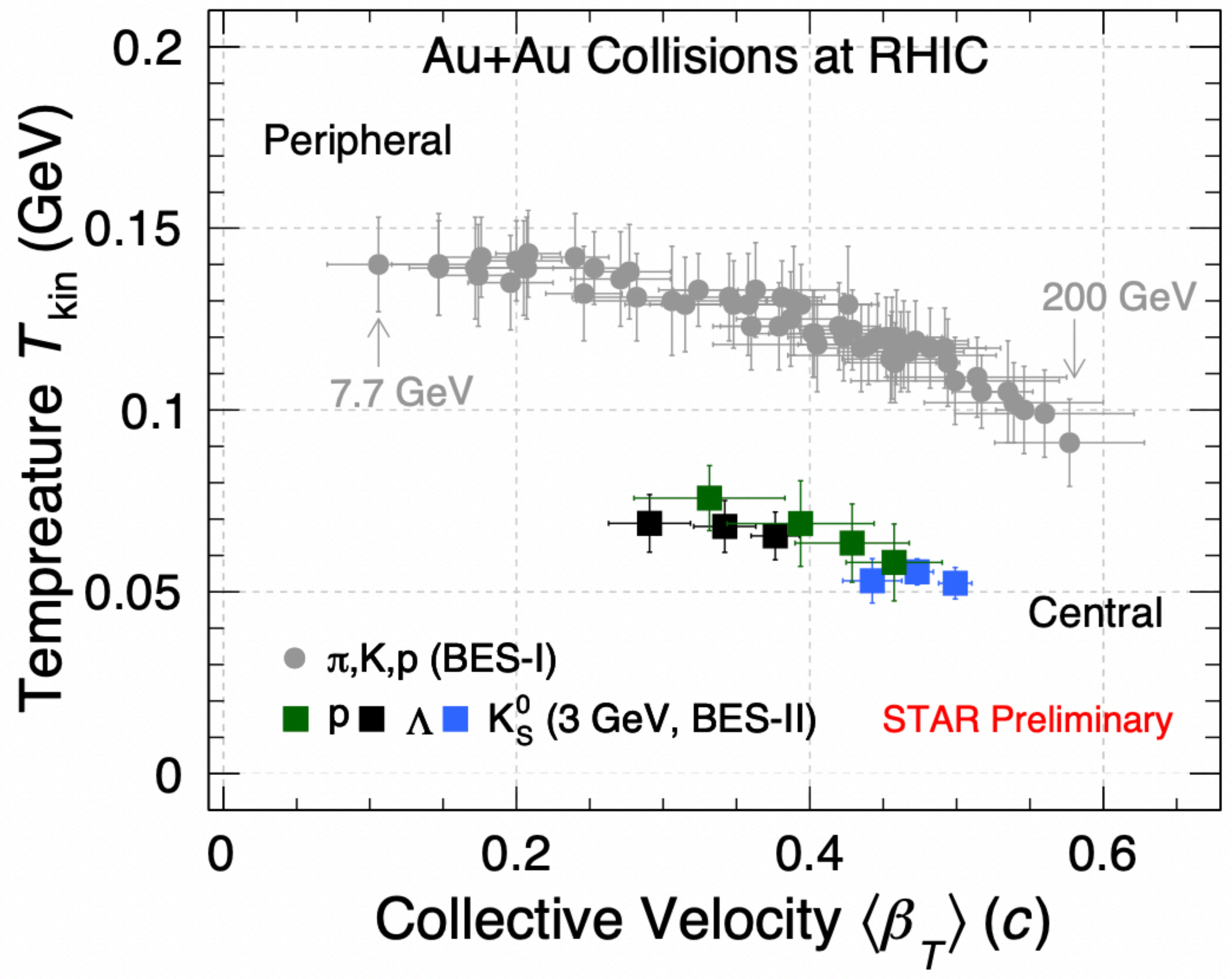


STAR, Phys. Lett. B 827, 137003 (2022)

- NCQ scaling holds within uncertainties till $\sqrt{s_{NN}}$ = 4.5 GeV
- Breaks for 3 GeV collisions: Medium not dominated by partonic interactions

Collectivity measurements at 3 GeV



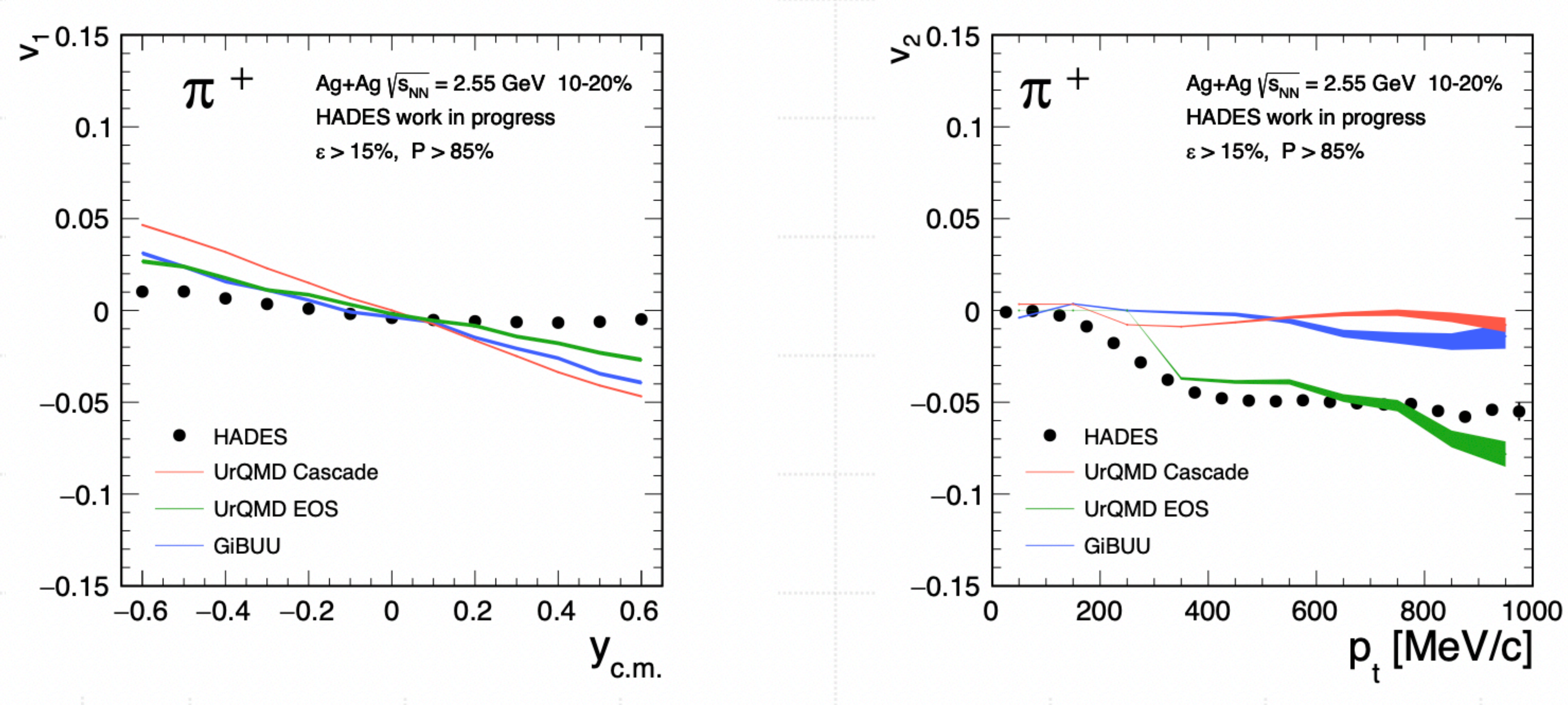


STAR, Phys. Lett. B 827, 137003 (2022)

- Good description of v_2 and v_1 measurements (except for kaons) by hadronic transport model calculations with baryonic mean-field interactions
- Medium dominated by hadronic interactions at 3 GeV

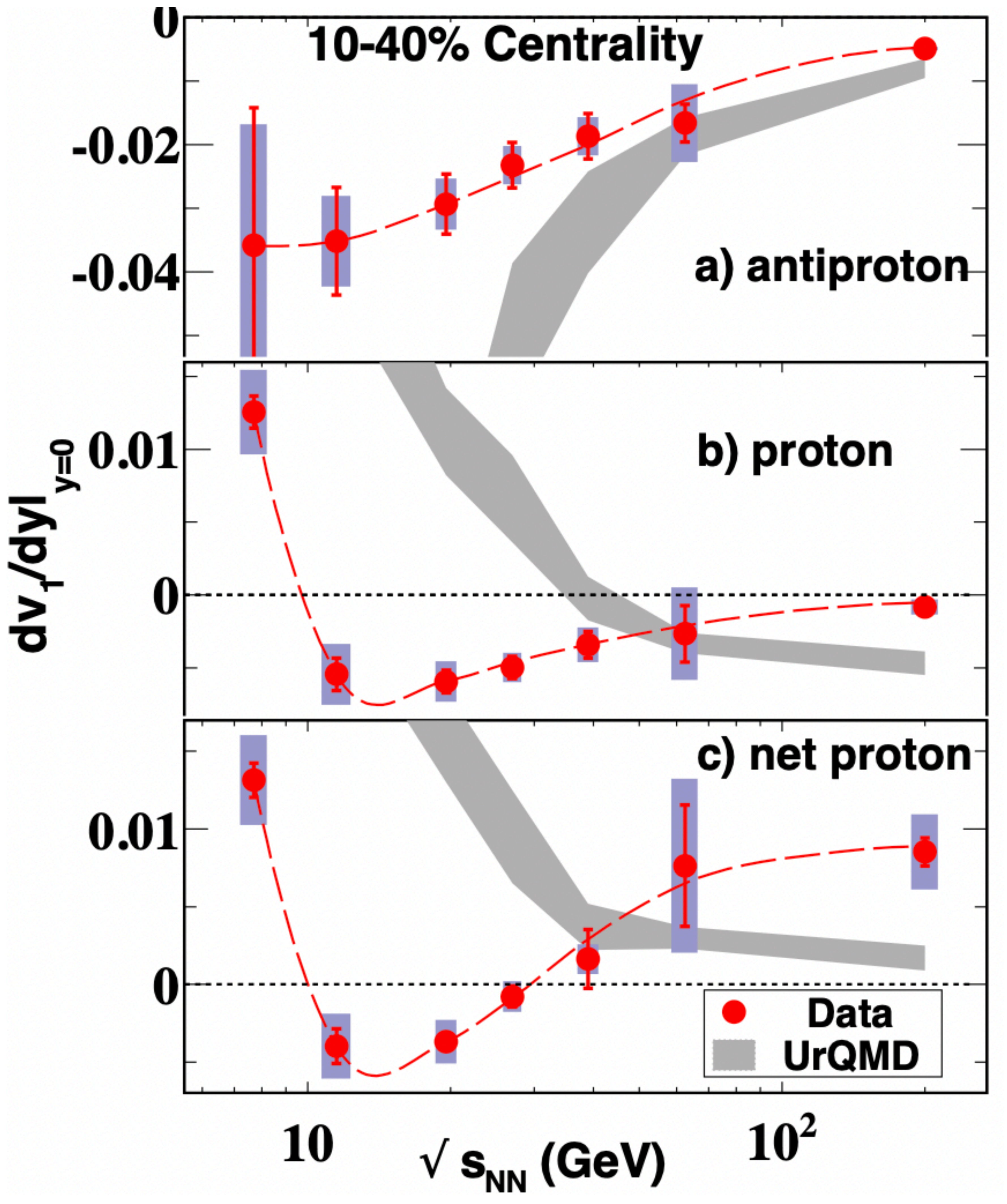
Collectivity measurements at lower energies

Talk by L. Chlad, Mon, 14.50



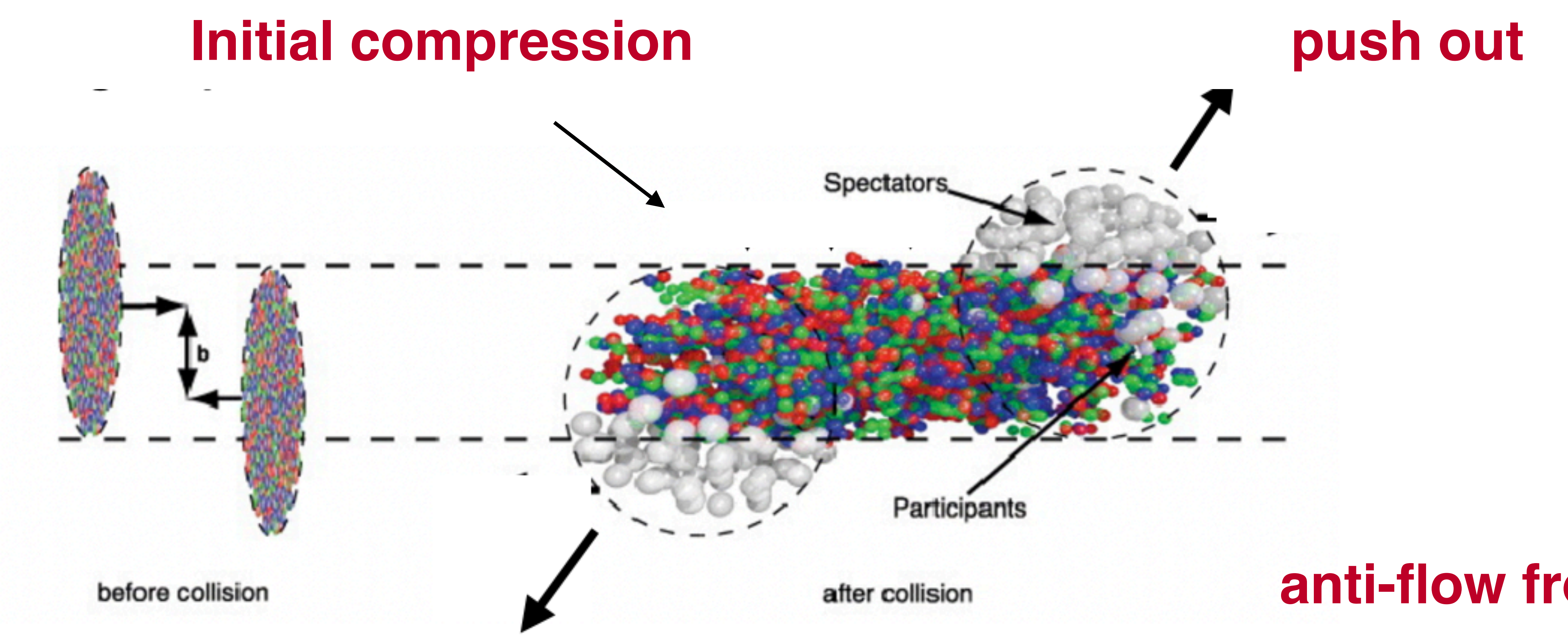
- Similar story from HADES measurements, UrQMD with baryonic interactions give better description of data
- Kaon measurements not well reproduced by mean-field calculations

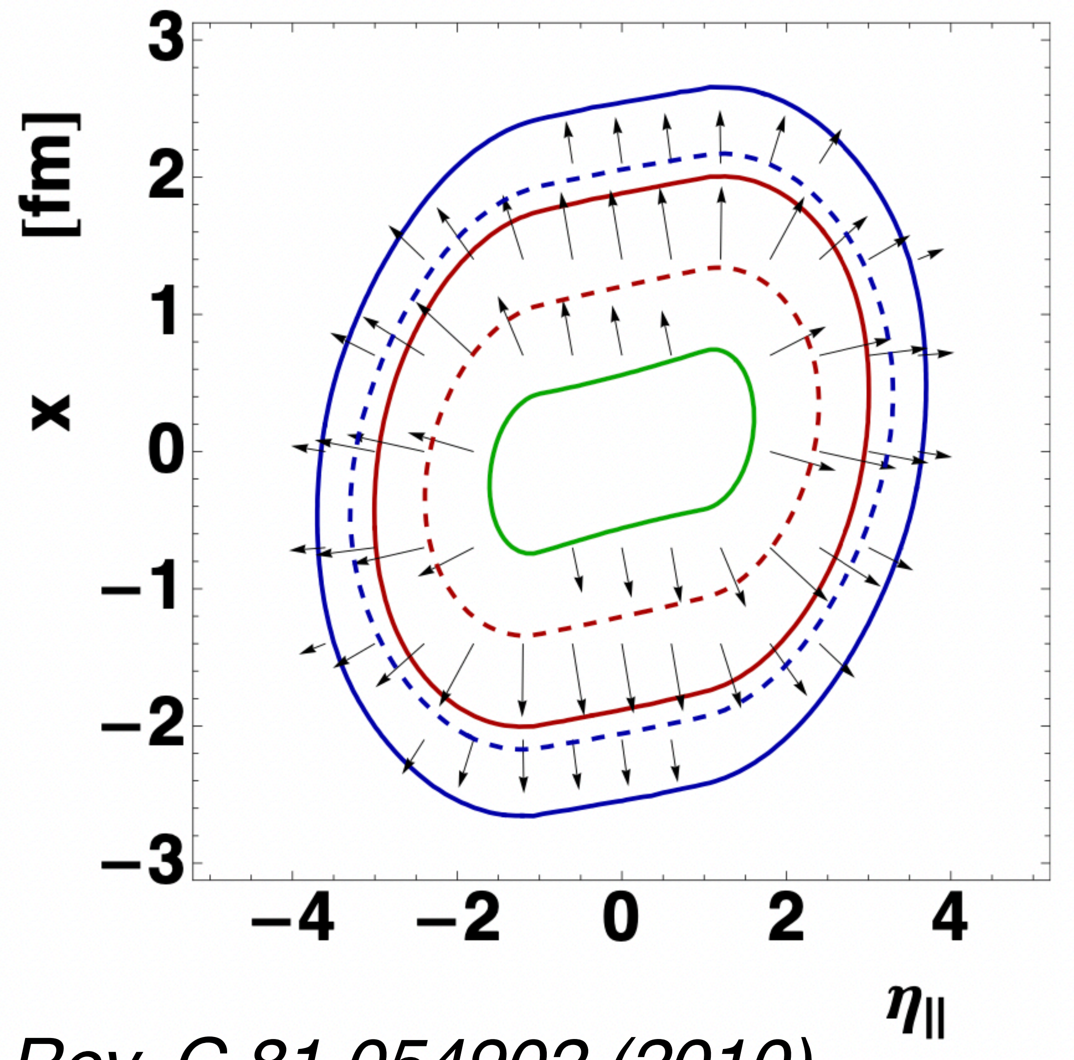
Initial directed flow of protons



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

- Non-monotonous collision energy dependence for proton and net-proton v_1





- 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)

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

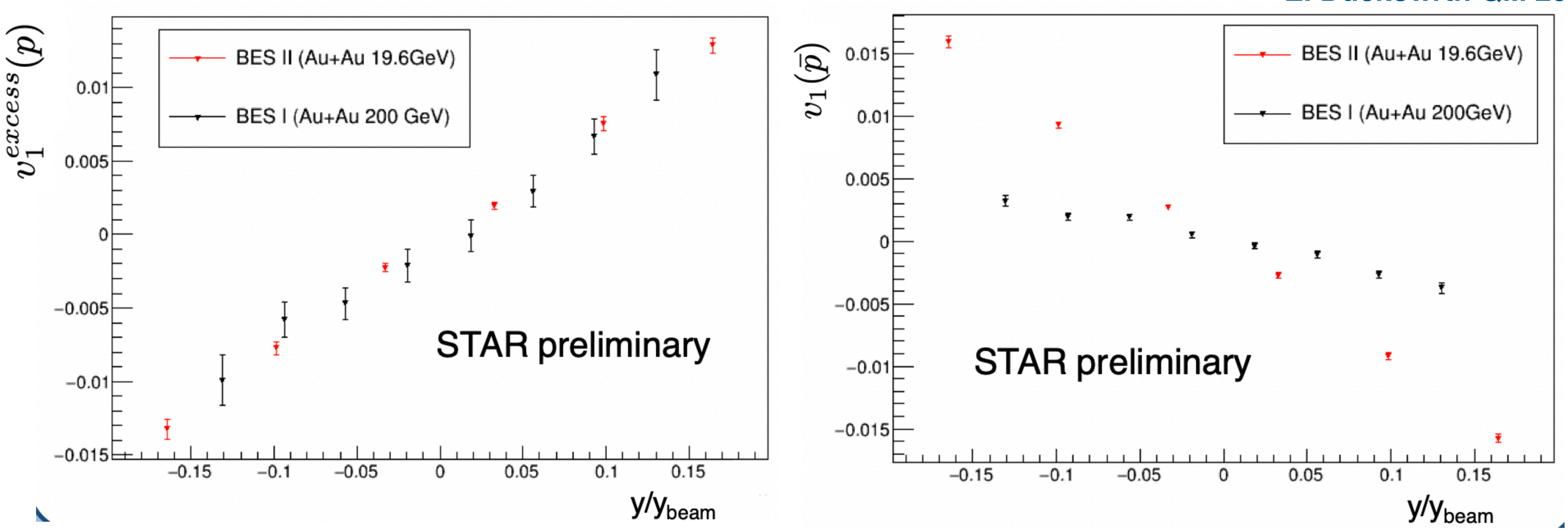
Initial directed flow of protons: scaling with collision energy

- Initial flow contributes only to transported protons
- Later medium component contributes to both protons and anti-protons

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

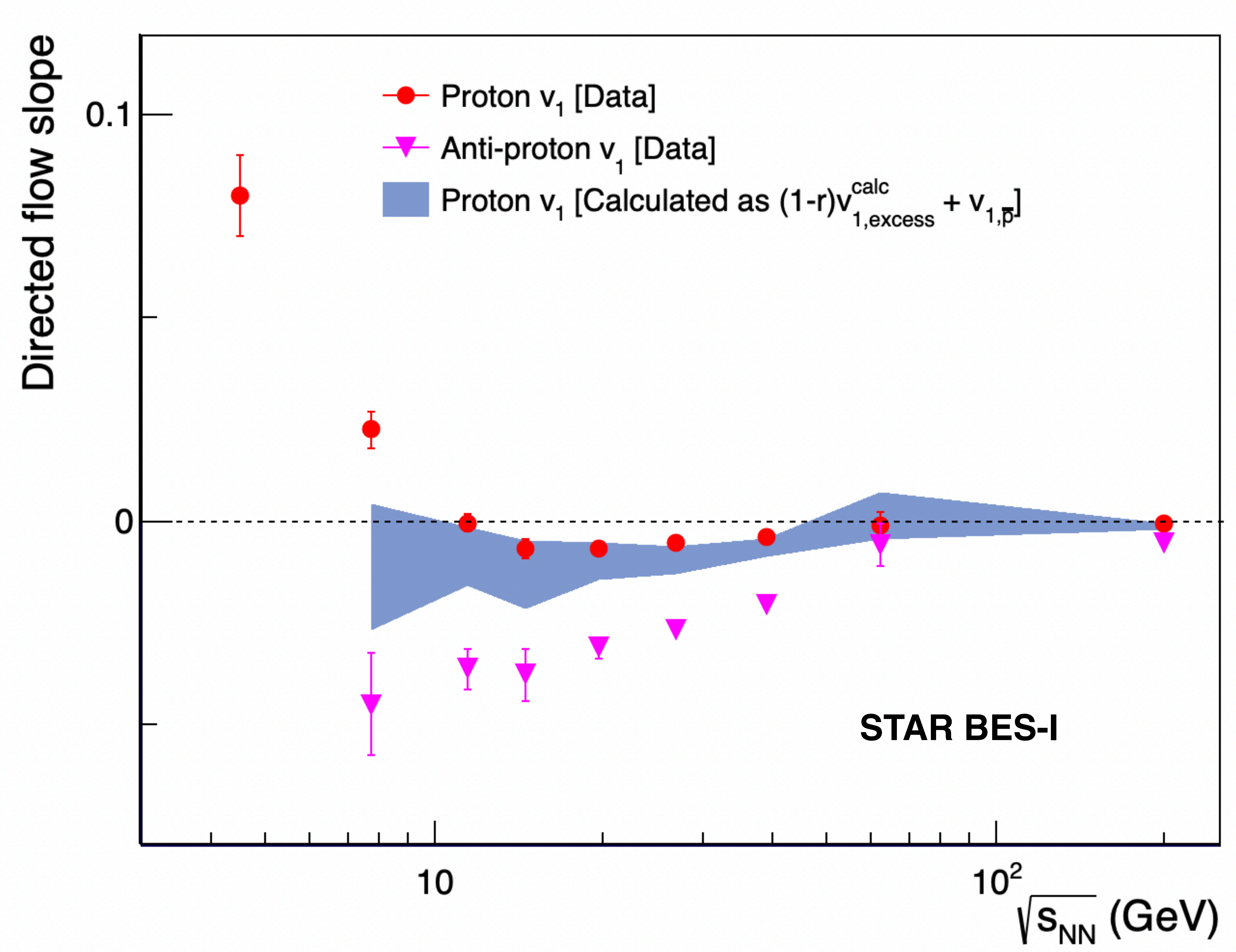
$$v_1^{excess}(p) = (v_1(p) - v_1(\bar{p})) / (1 - N_{\bar{p}}/N_p)$$

E. Duckowrth QM 2022



- Scaling of initial proton flow with collision energy. Anti-proton flow shows no scaling

Initial directed flow of protons: scaling with collision energy



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

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

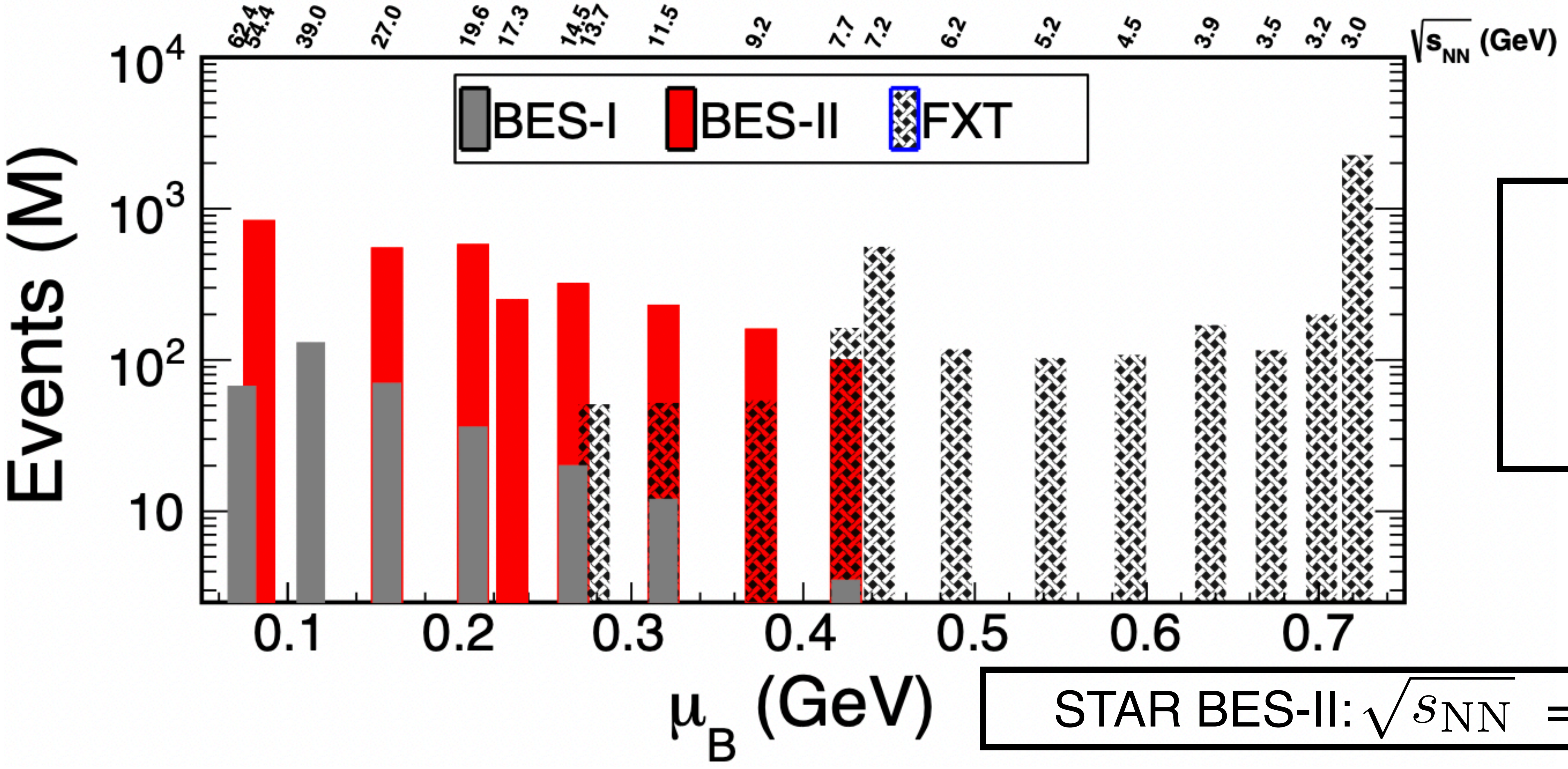
- Scaling of the initial v_1 observed till collision energy of ~10 GeV
  - Hint of scaling breaking at lower energies
  - Constraints for initial stages of collisions
- BES-II measurements with better precision will give more insights

Summary

- Indication of change in EoS of matter produced in 3 GeV (and below) collisions
  - Kinetic freeze-out parameters T and $\langle \beta_T \rangle$ show different trend at 3 GeV compared to higher energies
  - Disappearance of partonic collectivity at 3 GeV
  - Flow dominated by baryonic interactions at 3 GeV and below

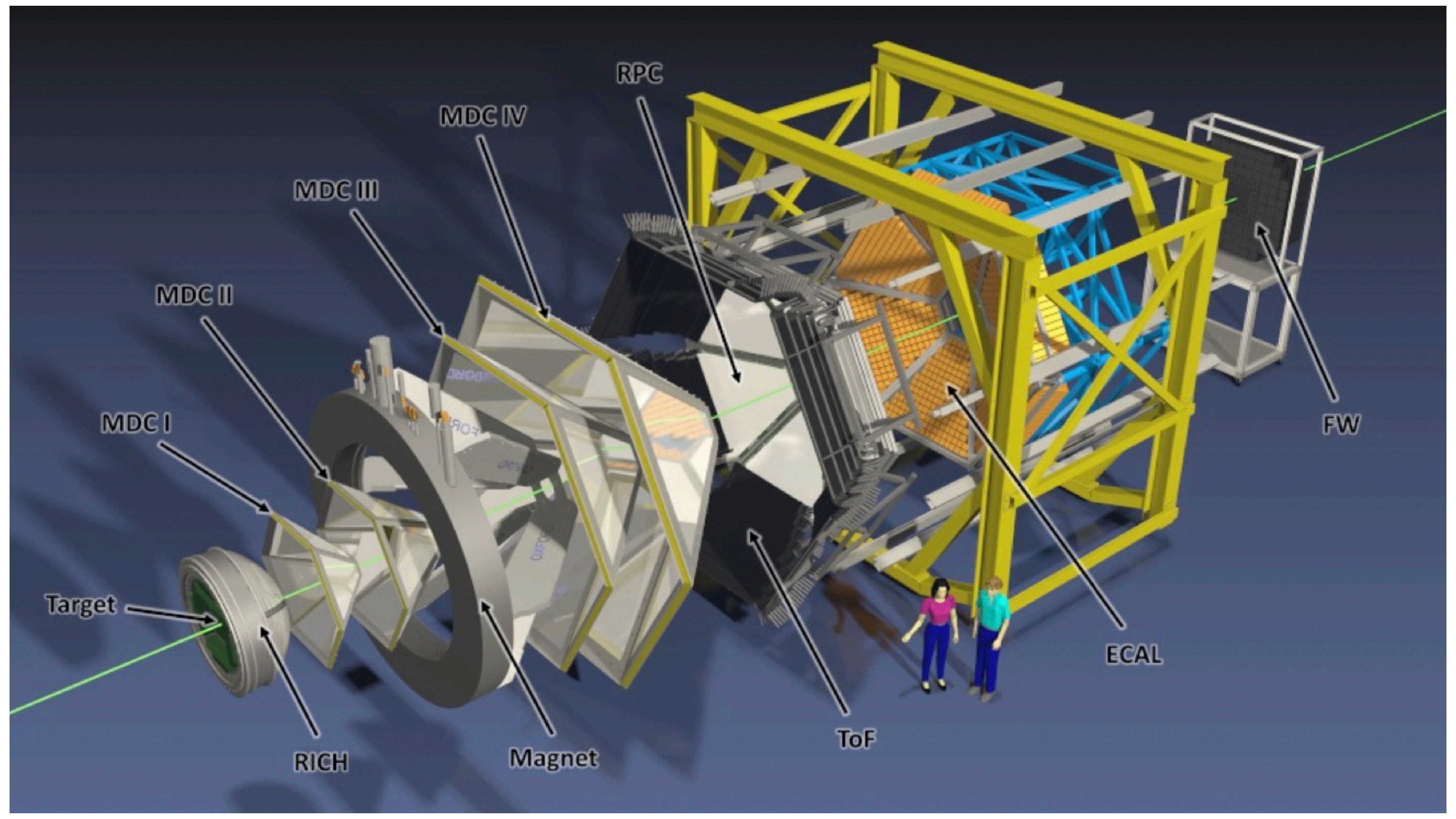
- Strangeness production at high μ_B
  - Canonical suppression of strangeness in 3 GeV collisions and below
  - Indication of meson cloud percolation

- Proton directed flow can be decomposed into an initial component and medium component
  - Same initial v_1 between collision energies 200 - 10 GeV
  - Hint of scaling breaking at lower collision energies
  - Can inform on initial conditions, change in phase of matter as function of collision energy



New measurements at several different energies ongoing, expect many more exciting results soon!!

STAR BES-II: $\sqrt{s_{NN}}$ = 3 - 54.4 GeV



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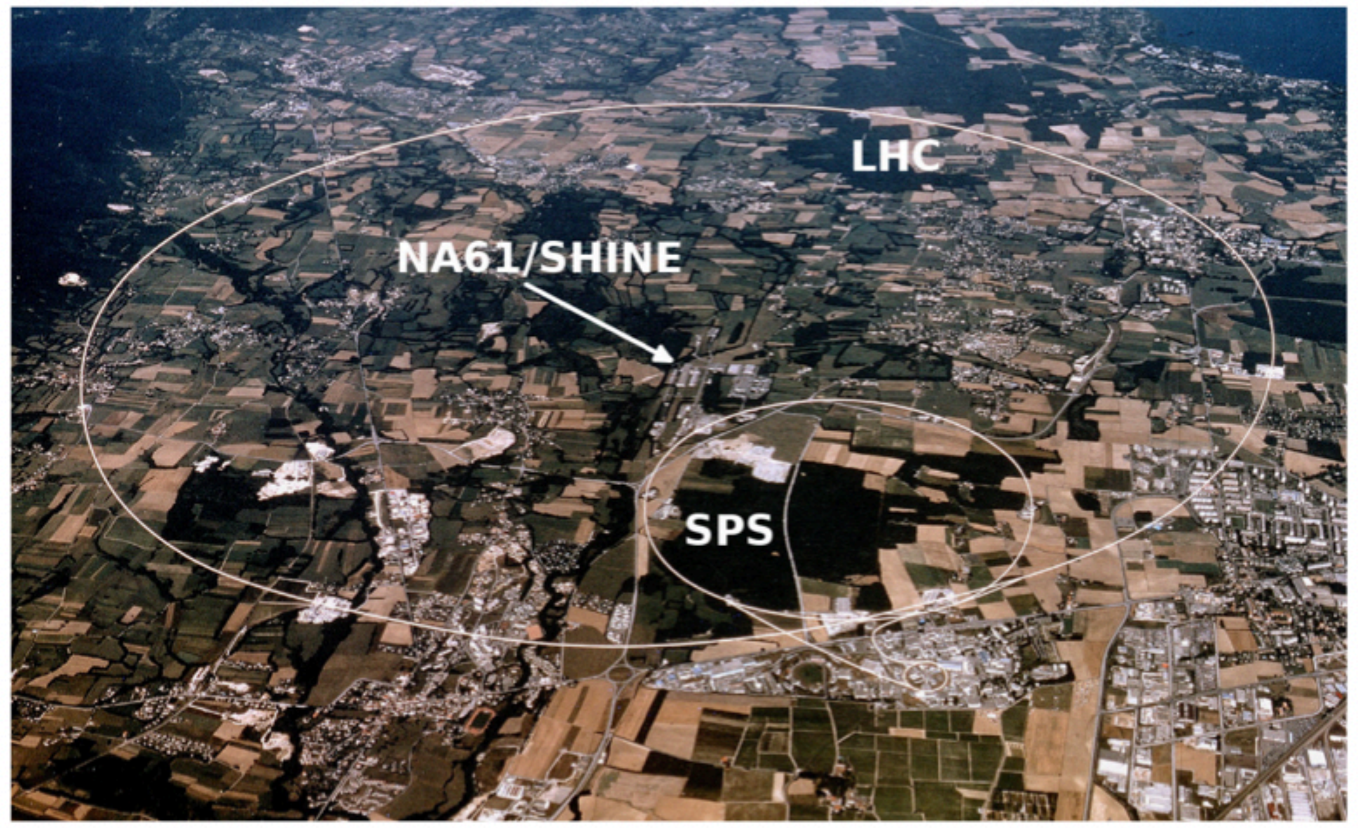
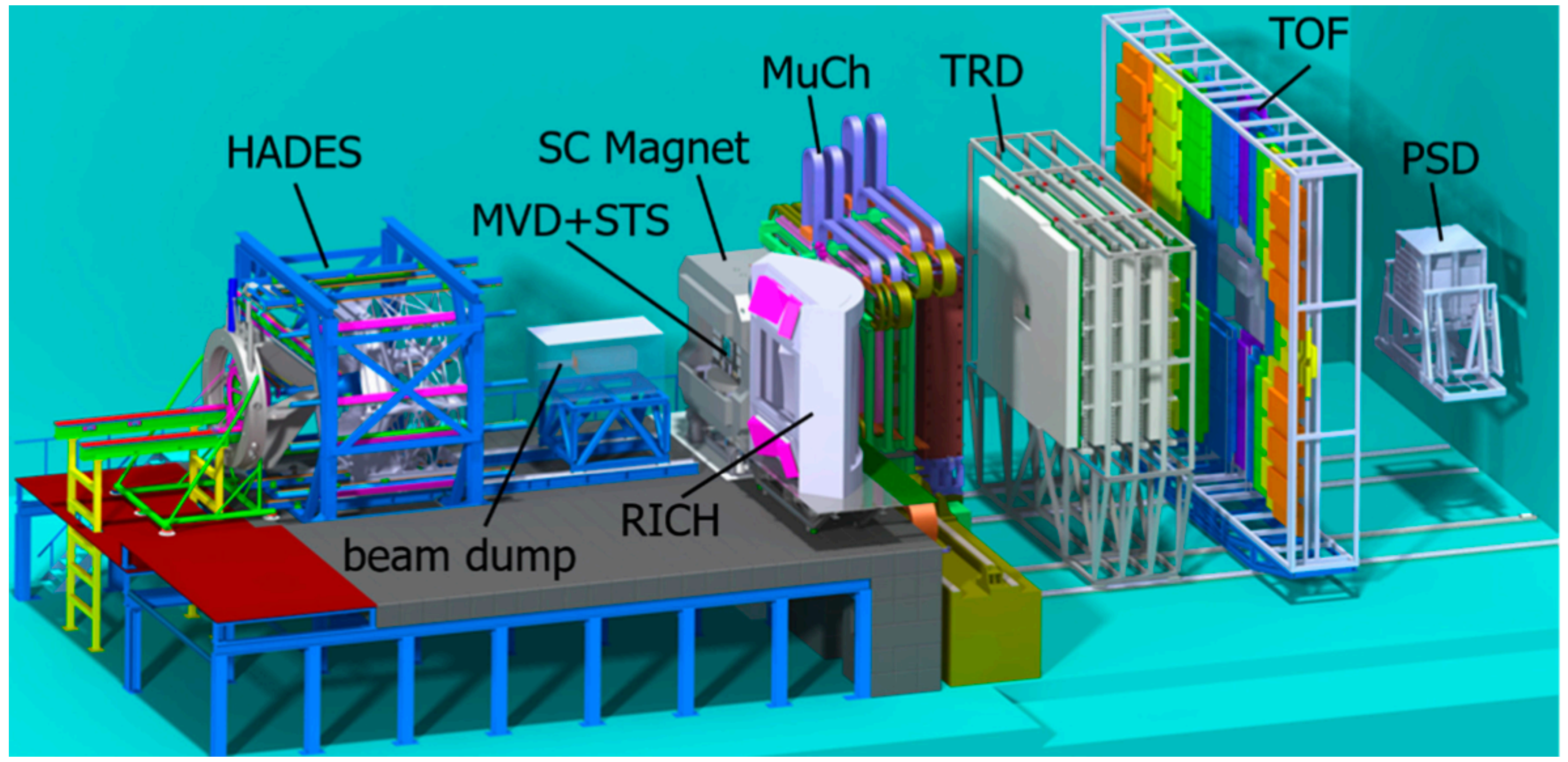


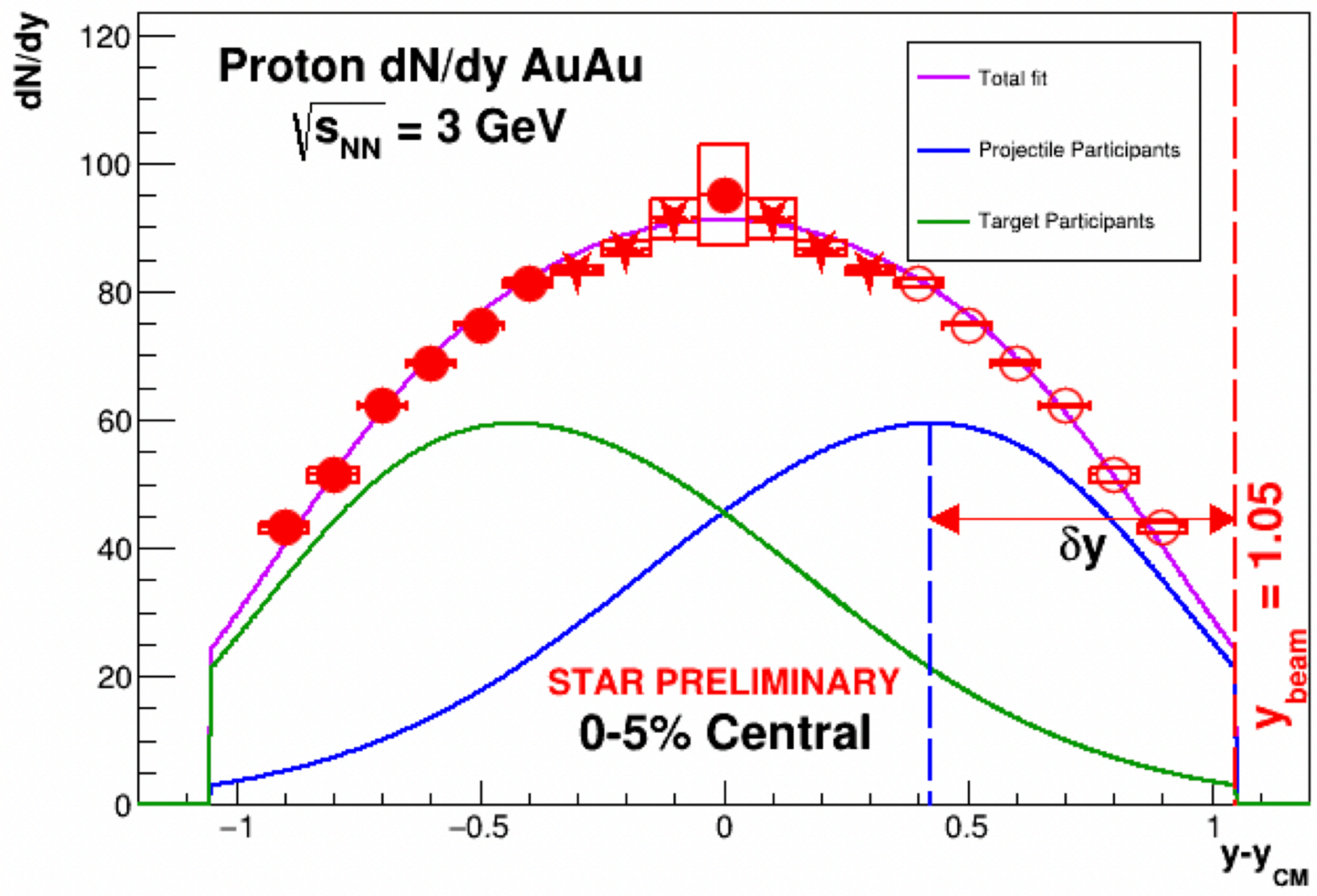
$\sqrt{s_{NN}}$ = 5.1–17.3(27.4) GeV

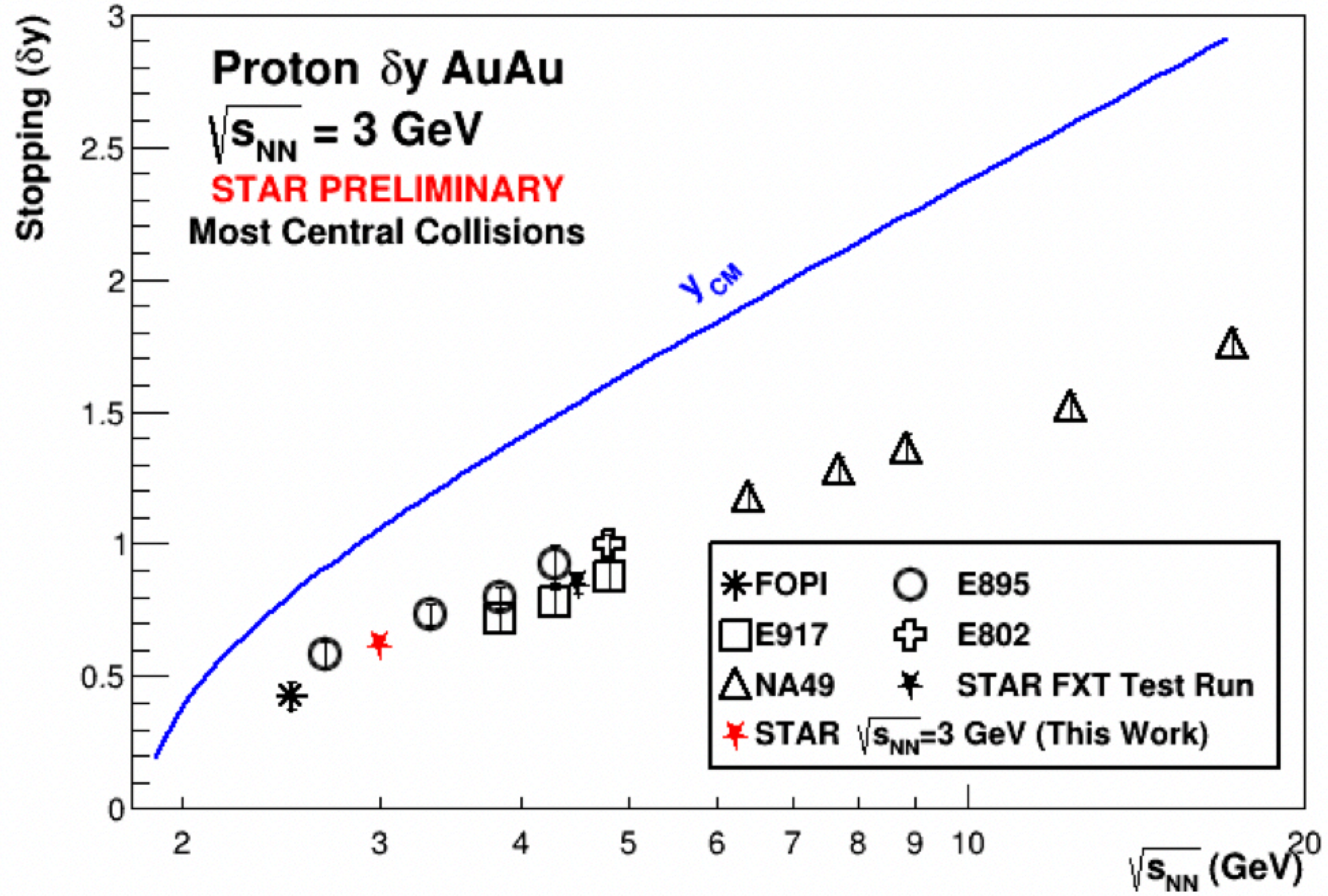


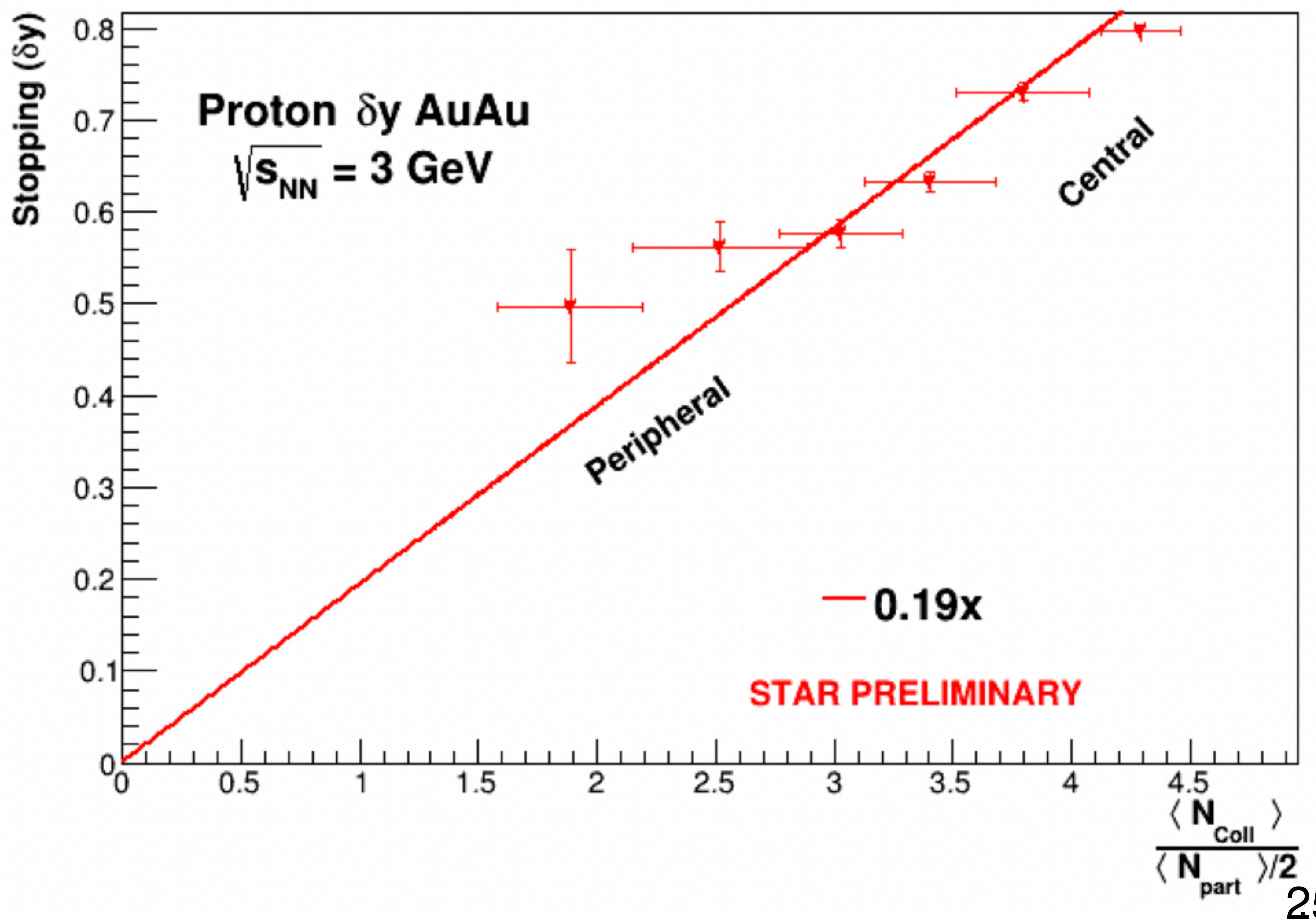
CBM: $\sqrt{s_{NN}}$ = 1.9 - 9 GeV

Back Up

Baryon transport in heavy-ion collisions

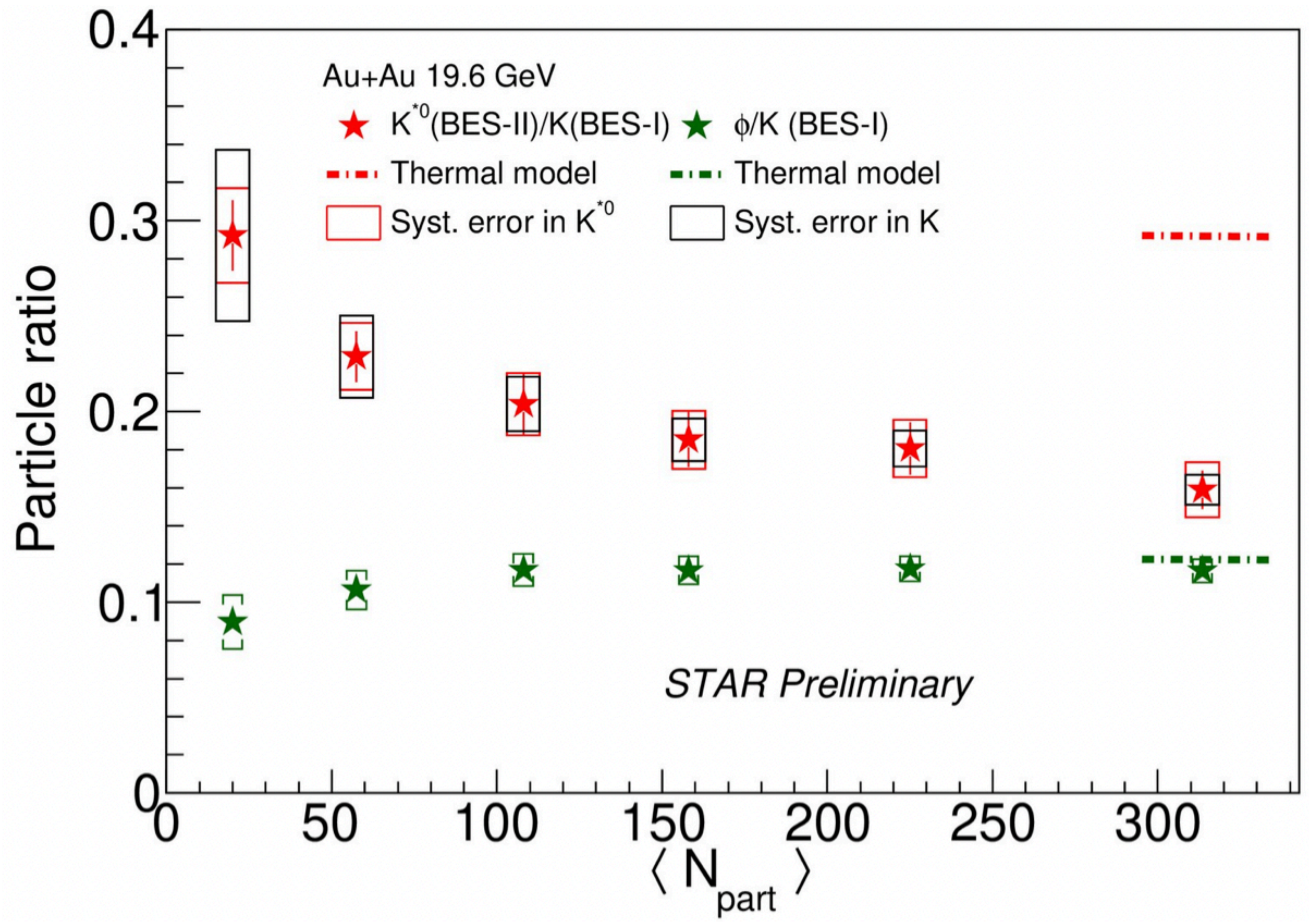


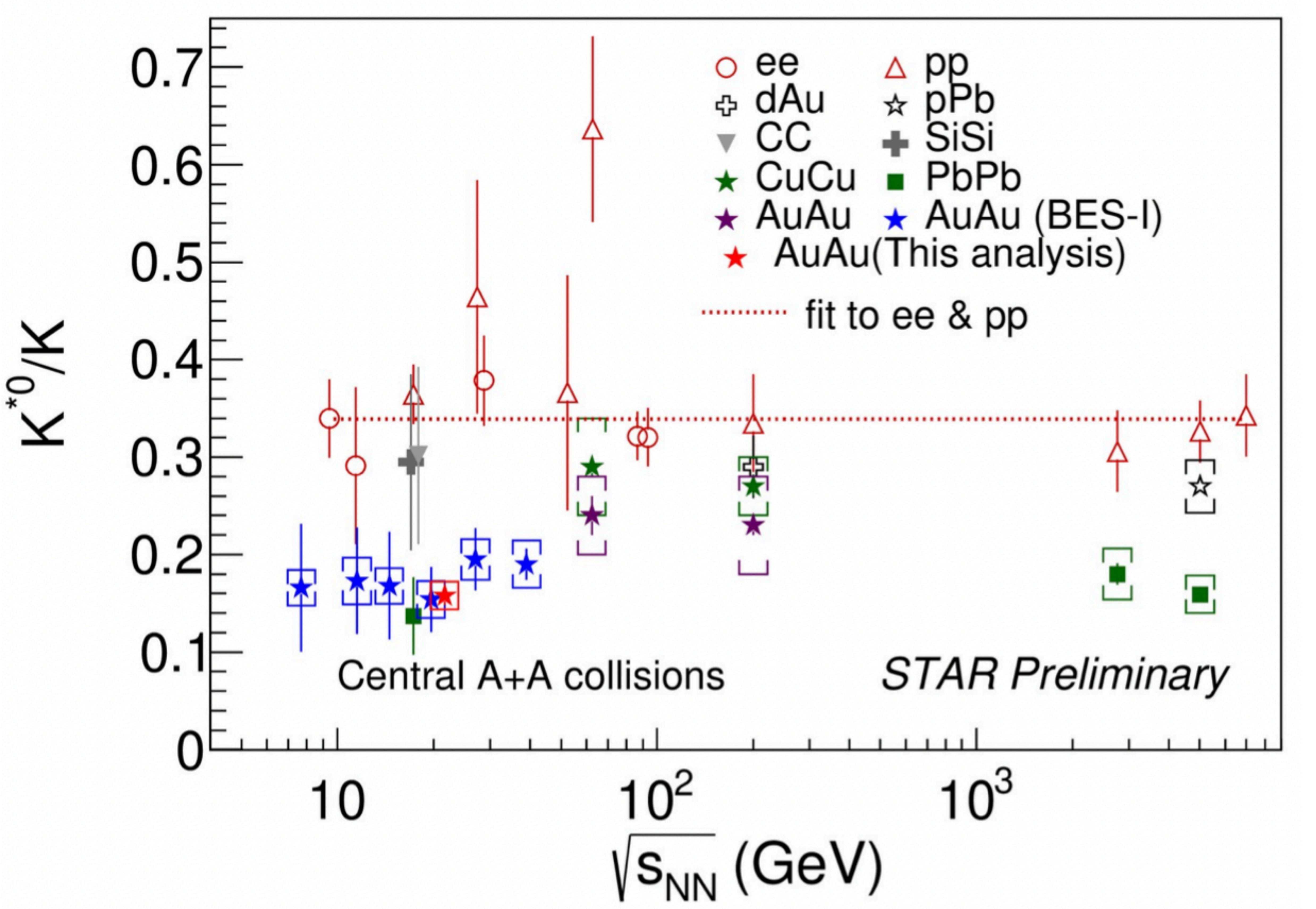




- Rapidity loss from baryon stopping evaluated from double Gaussian fit to proton dN/dy
- Extracted δy consistent with world data
- Also centrality dependence measurement, average loss of 0.19 +/- 0.01 units of rapidity per n-n collision

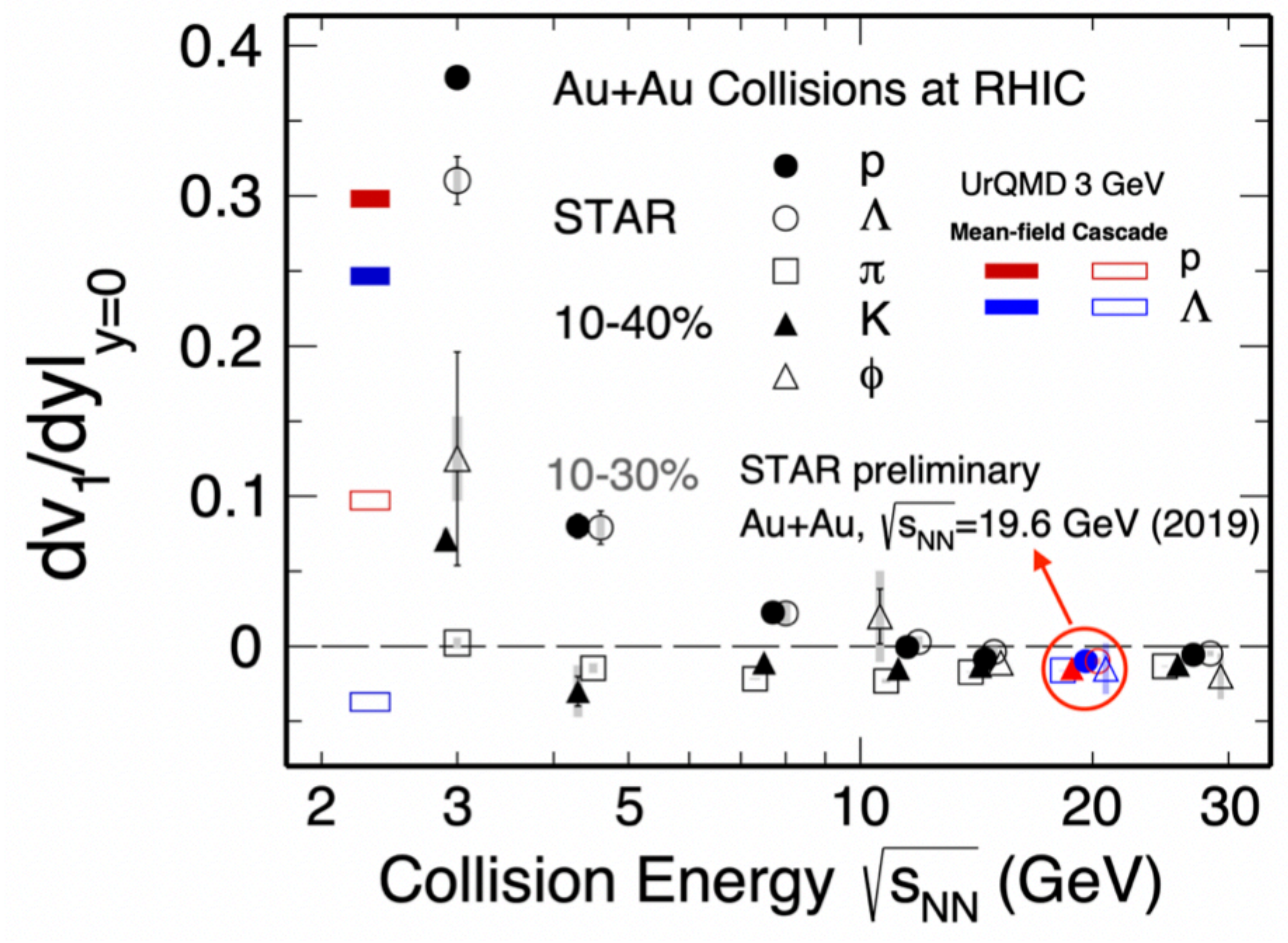
Hadronic rescattering and K^{*0} production

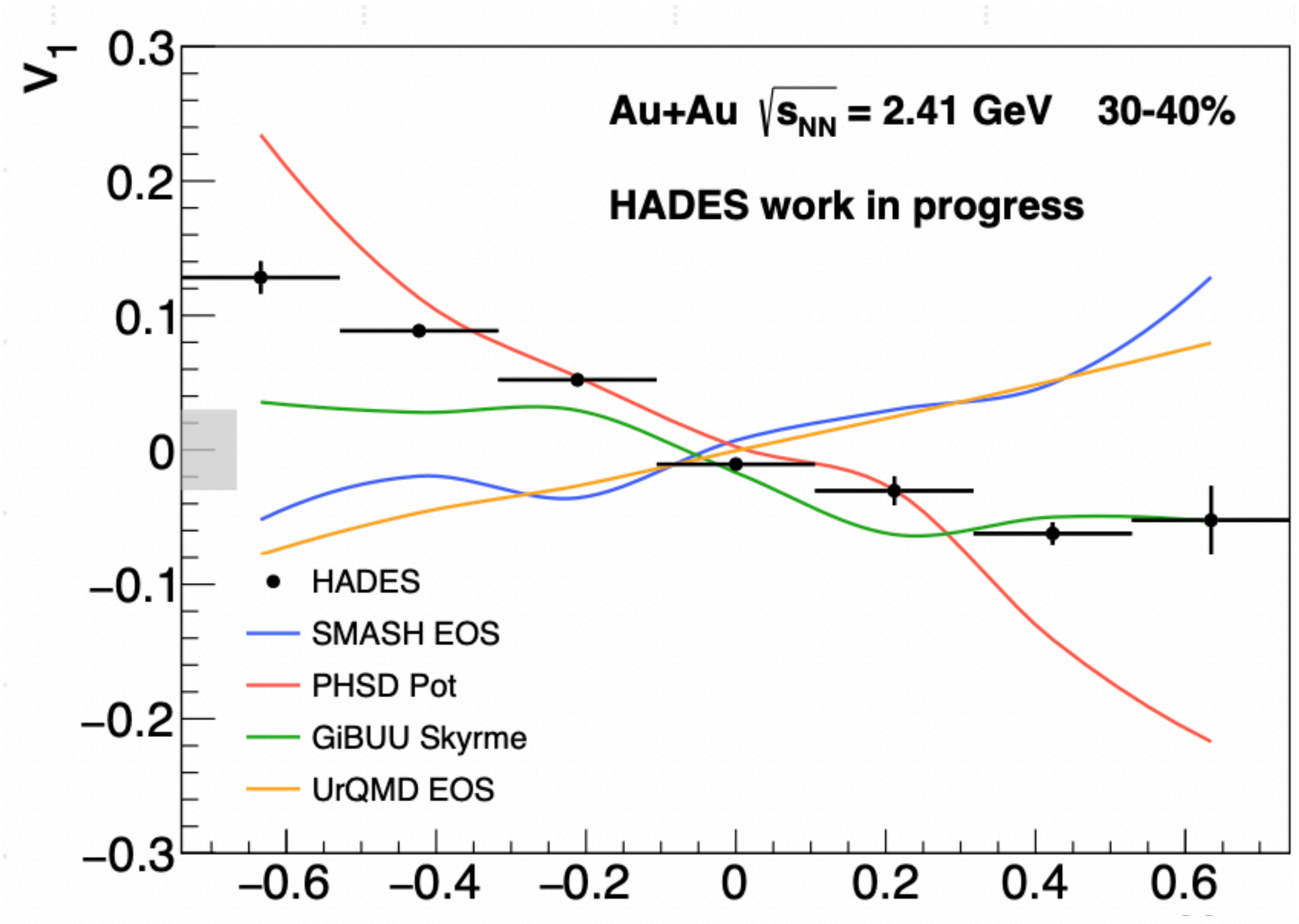


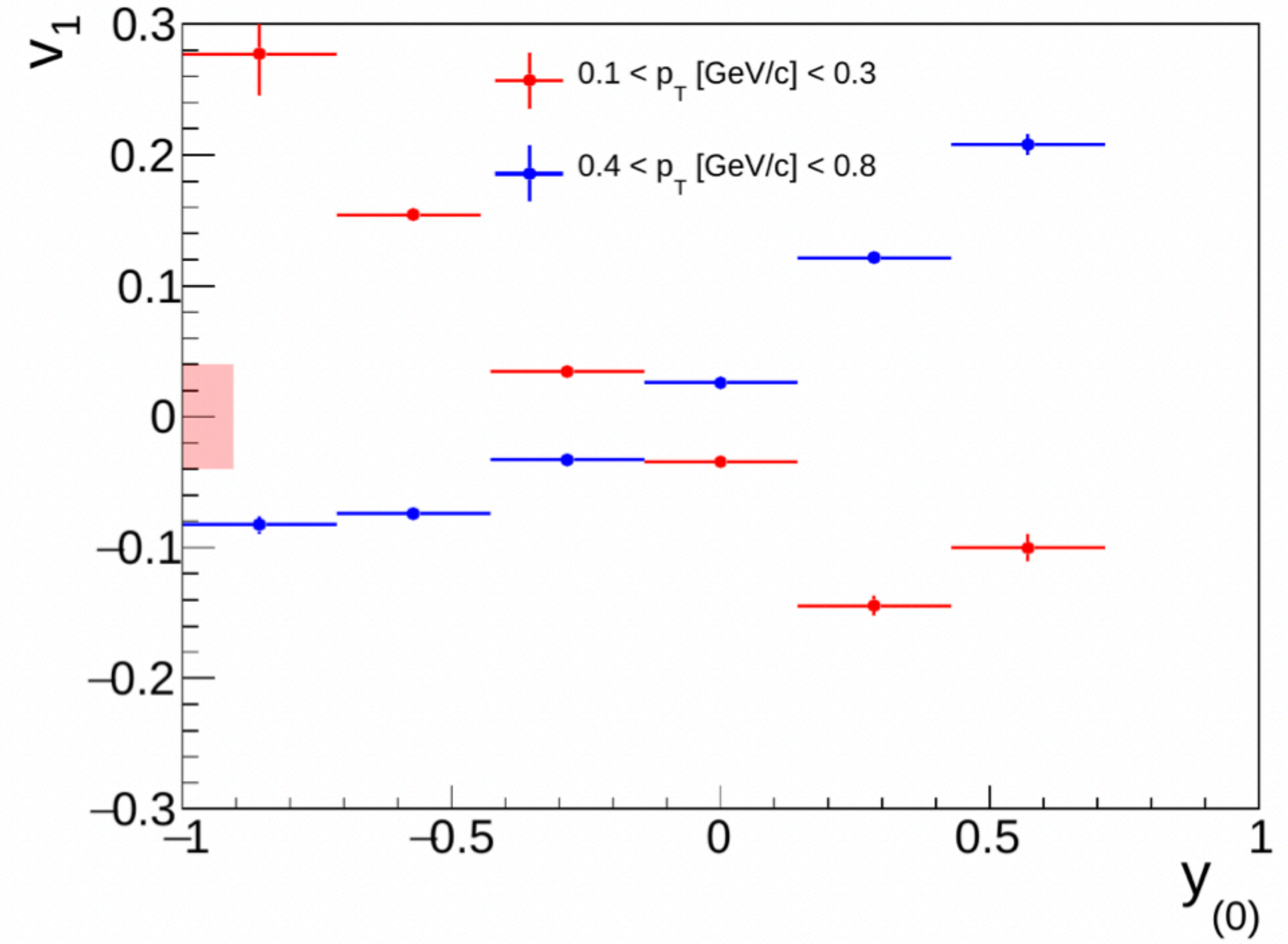


- Suppression of K^{*0} yield in central Au+Au relative to thermal model calculations
- From hadronic rescattering in Au+Au collisions
- No significant collision energy dependence from BES-I measurements? How about at lower energies? A dominance of hadronic phase could alter the ratio

Directed flow measurements at lower energies



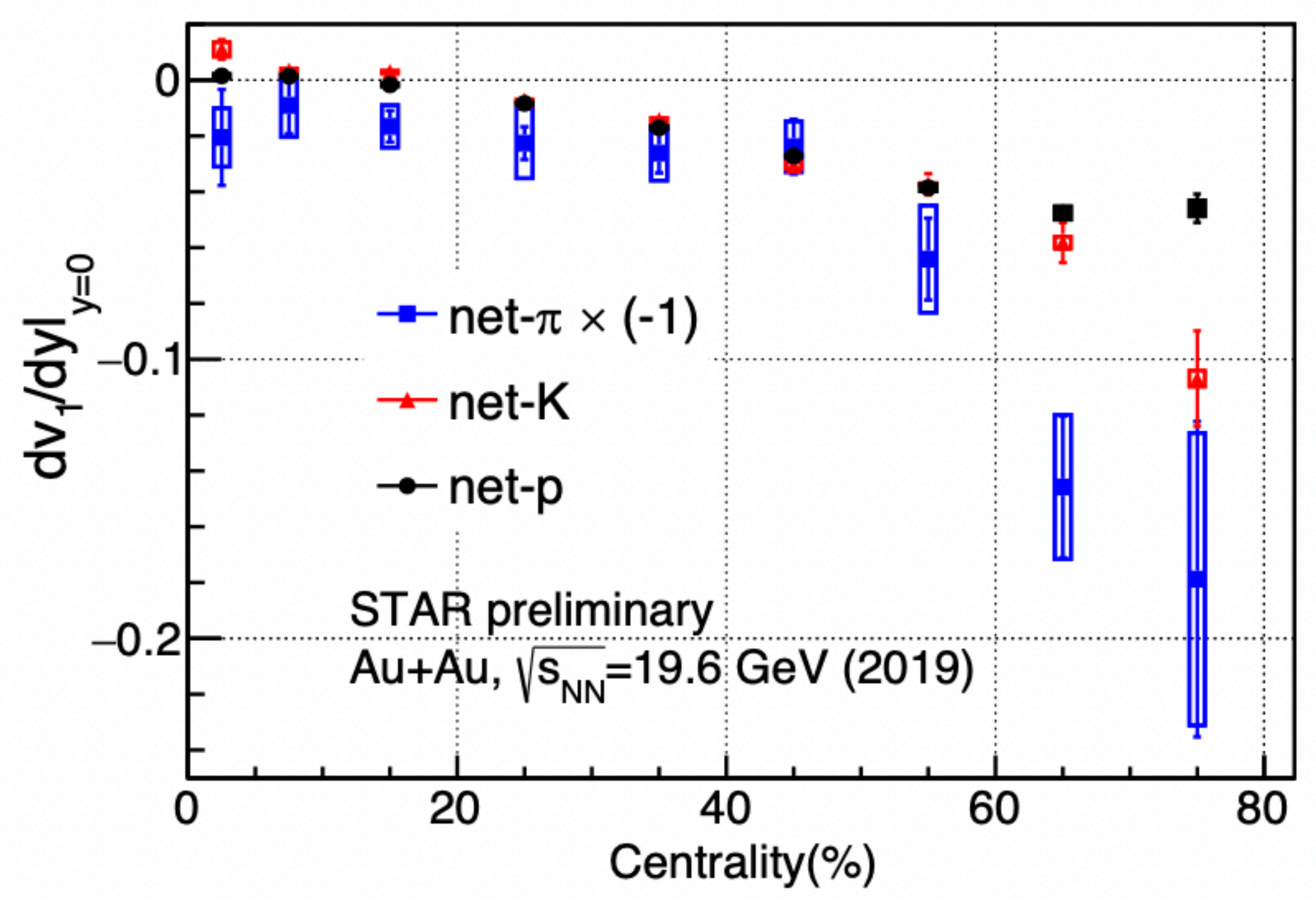




- Negative kaon v_1 at 2.5 GeV from HADES
- Has dependence on lower p_T cut
- STAR lower p_T cut for kaons 0.4 GeV/c

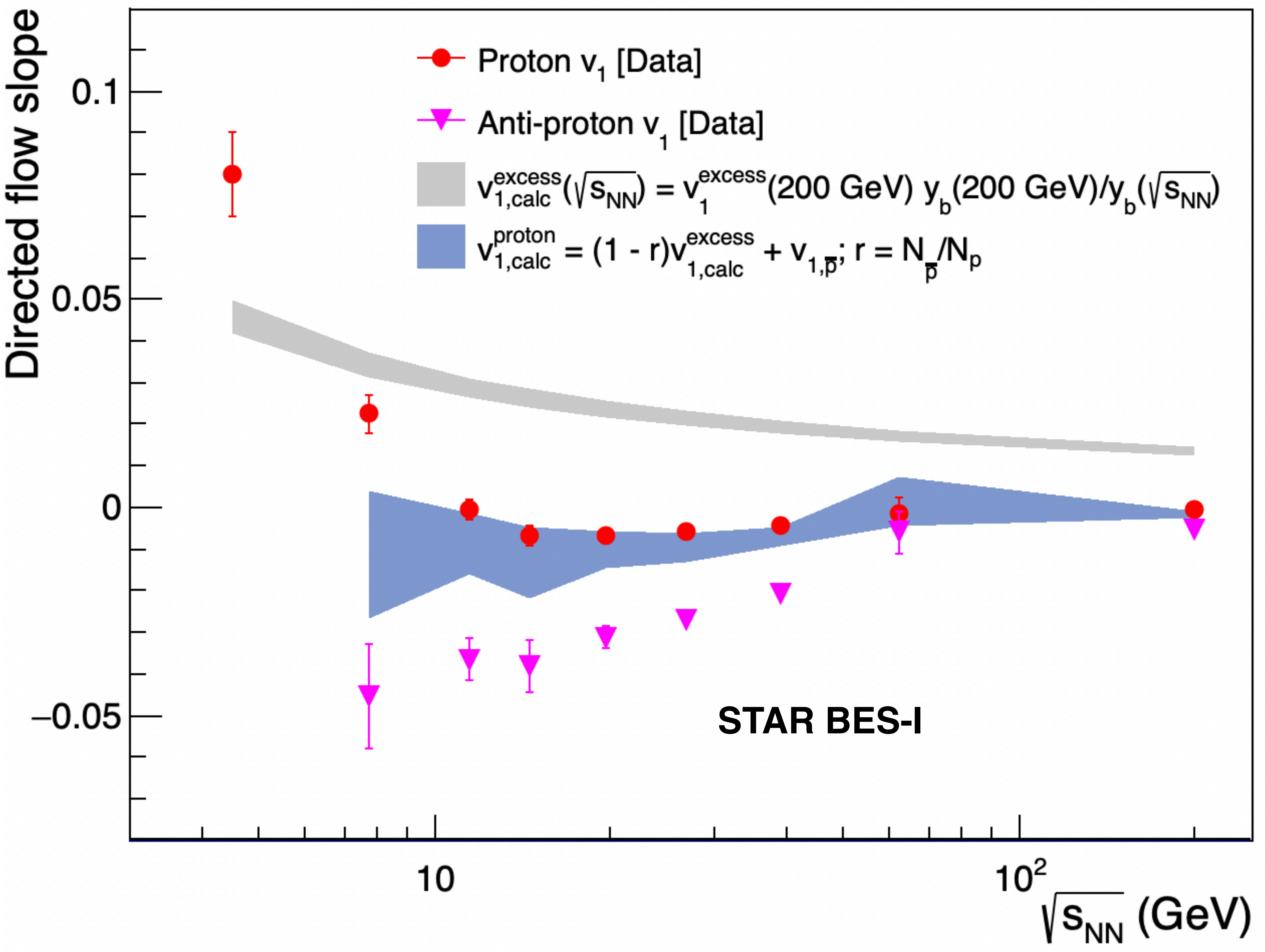
Directed flow of net particles at 19.6 GeV

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



- Improved precision to study centrality dependence of net-particle v_1 from BES-II

Initial directed flow of protons: scaling with collision energy



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