Physics Motivation for an EIC fixed target program from the STAR BES perspective

(my personal view)

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CFNS - FXT and the EIC - Sept 29 2025

Well known but worth repeating

iTPC:

- $|y| < 1.5$
- $p_T > 60$ MeV/c
- Improved dE/dx

eTOF:

- Wide PID range

EPD:

- Triggering
- EP resolution

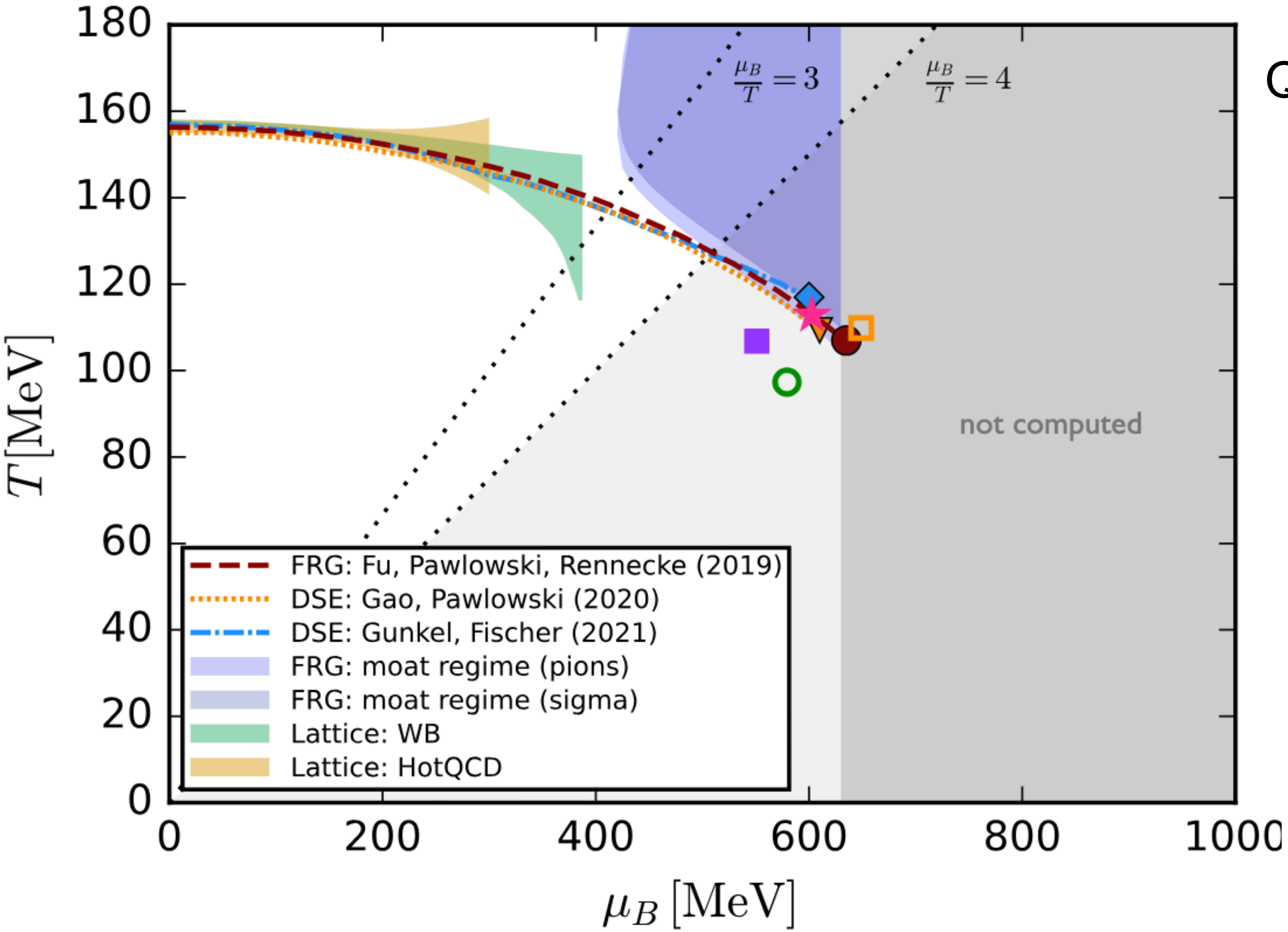
Critical features for future nFXT experiment(s)

Max $\sqrt{s_{NN}}$ =17.3 GeV

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M ->	Run-18+21

Motivation for Continued CP and Ordered Phase Transition Studies

Theory - current status



QM25: CP constrained to:

$\sqrt{s_{NN}}$ ~ 3-4 GeV

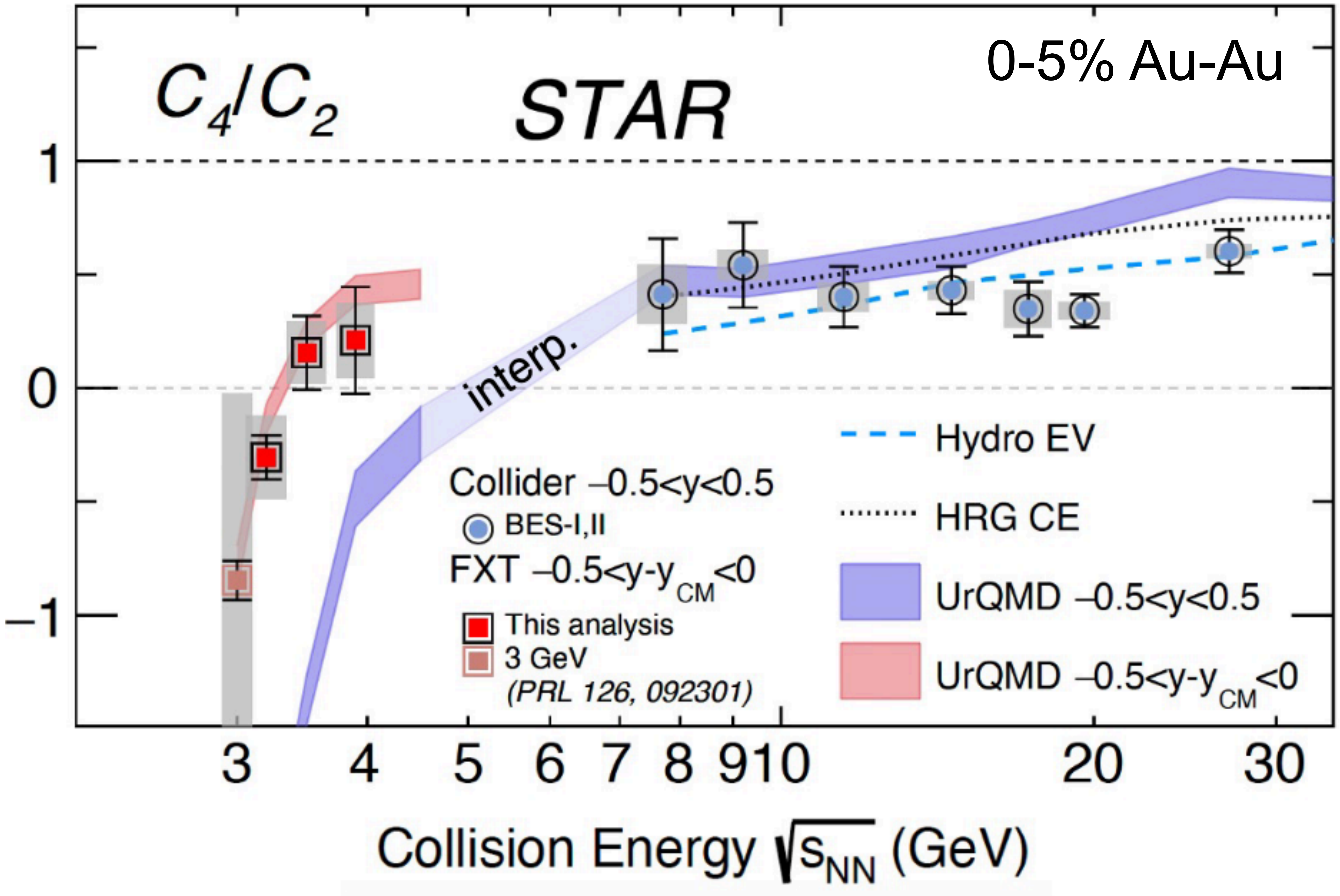
μ_B ~ 630 MeV, T ~110 MeV

2σ exclusion of μ_B < 450 MeV

In region accessible to FXT program at RHIC

arXiv: 2502.10267 S. Borsanyi et al

Net-proton fluctuation final results



N.B. Different rapidity range for FXT

Precision final measurements from BES-II:

$\sqrt{s_{NN}}$ = 7.7-27 GeV (collider)

$\sqrt{s_{NN}}$ = 3.2-3.9 GeV (FXT)

Still to come:

$\sqrt{s_{NN}}$ = 4.5 GeV (acceptance gaps)

$\sqrt{s_{NN}}$ = 3 GeV (-0.5 <y-y_{cm} < 0.5, and 2B events)

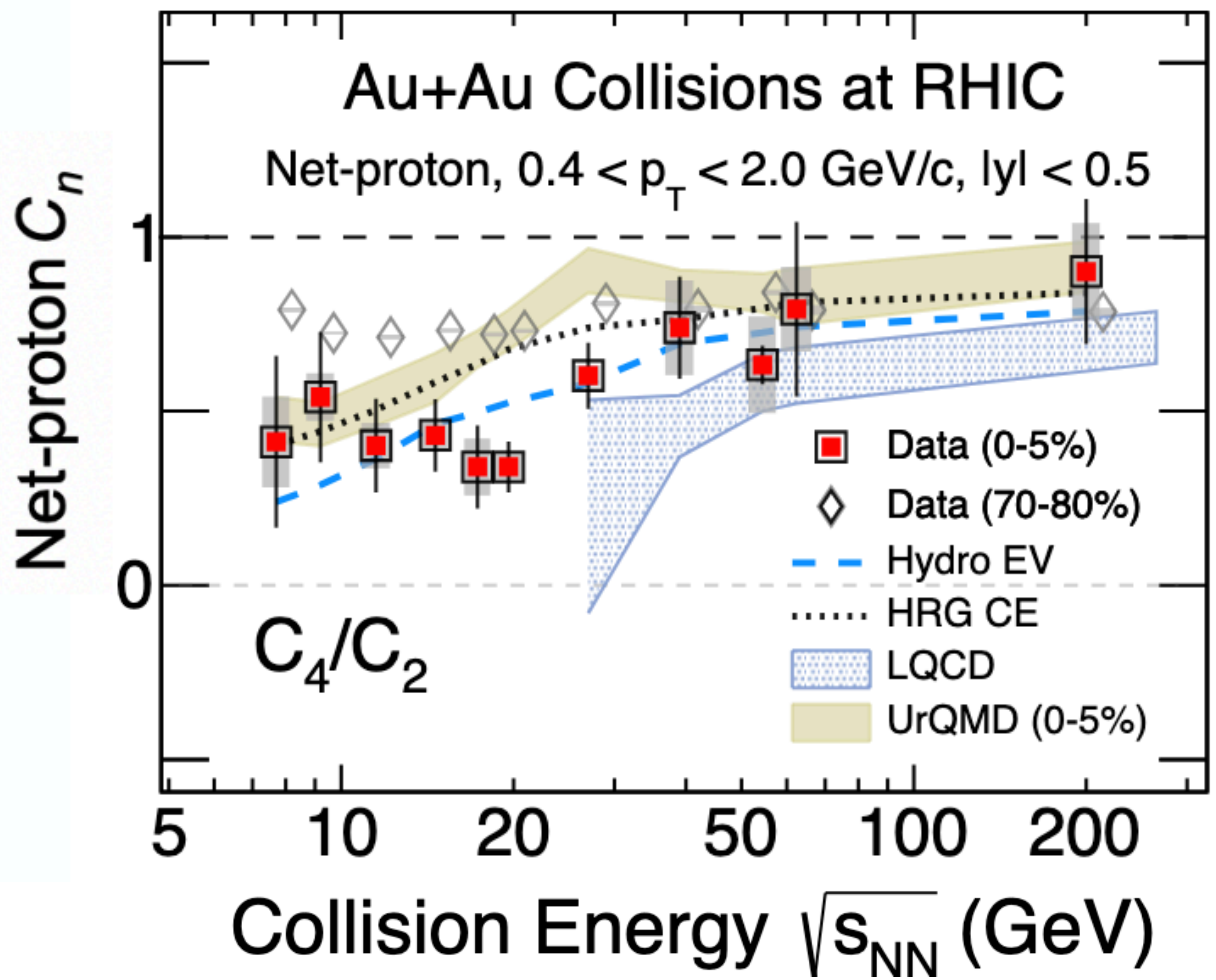
$\sqrt{s_{NN}}$ = 3.2-3.9 GeV:

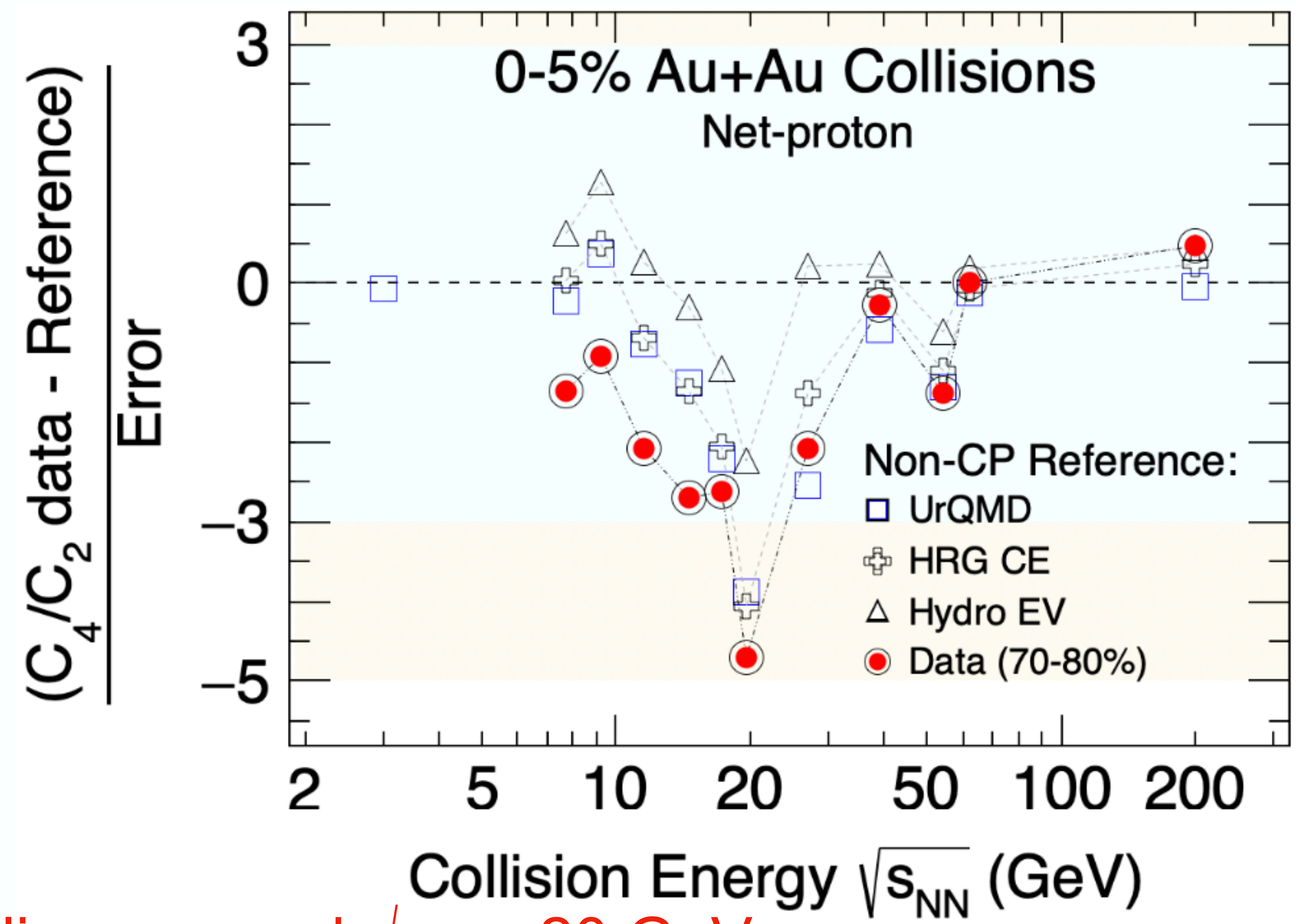
Consistent with UrQMD baseline

No data in the "gap" - opportunity for nFXT program

STAR: arXiv: 2504.00817

Zooming in on higher beam energy region





2-5σ deviations non-CP baselines around $\sqrt{s_{NN}}$ ~20 GeV

Theory shows "nothing exciting" in this range

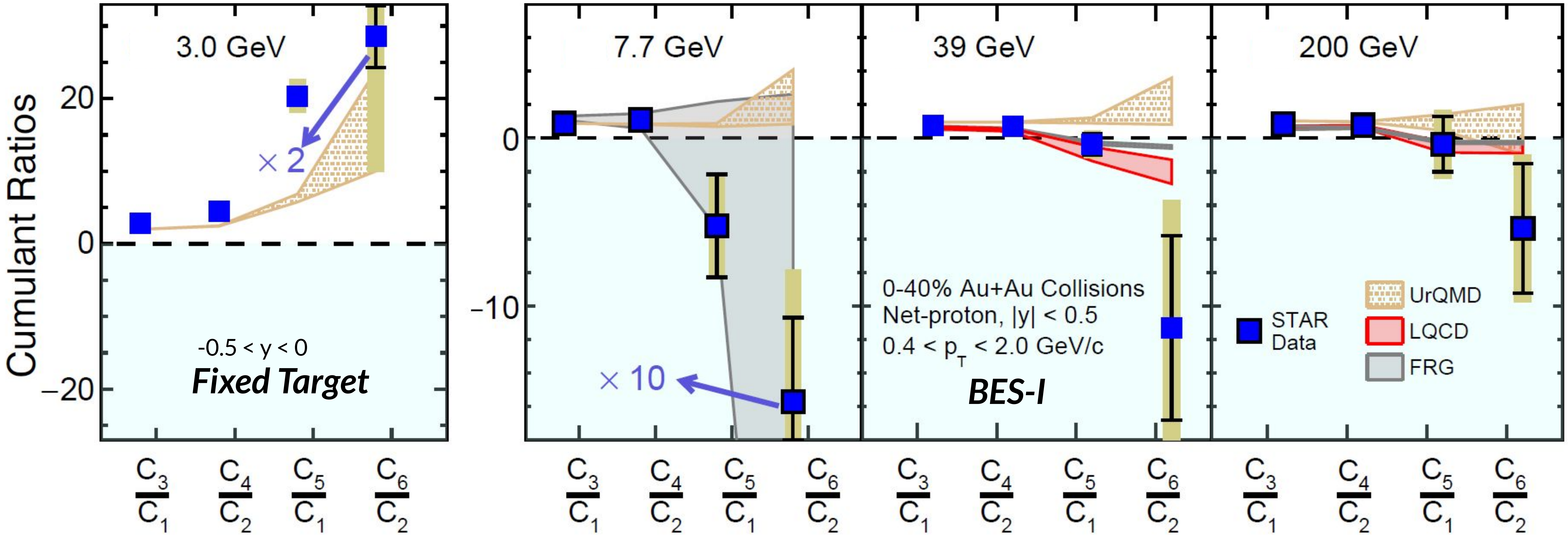
What's happening? Need more dynamical CP calculations

nFXT possible to $\sqrt{s_{NN}}$ = 17 GeV

STAR: arXiv: 2504.00817

Nature of medium produced

Cumulant ratios sensitive to nature of phase transition



$\sqrt{s_{NN}}$ =7.7-200 GeV: falling trend with rising order - trend predicted by Lattice

$\sqrt{s_{NN}}$ = 3 GeV (FXT): rising trend with rising order - trend in agreement with UrQMD

LQCD: HotQCD, PRD101,074502 (2020)
FRG: Wei-jie Fu et. al, PRD 104, 094047 (2021)
STAR: PRL 130, 082301 (2023)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

nFXT: precision study of $\sqrt{s_{NN}}$ ~10 GeV

Softening of Equation of State

Fermi-Landau initial conditions with ideal hydro expansion : $c_s^2 = \partial P/\partial \varepsilon$

$c_s^2 = 0$ for a sharp phase transition

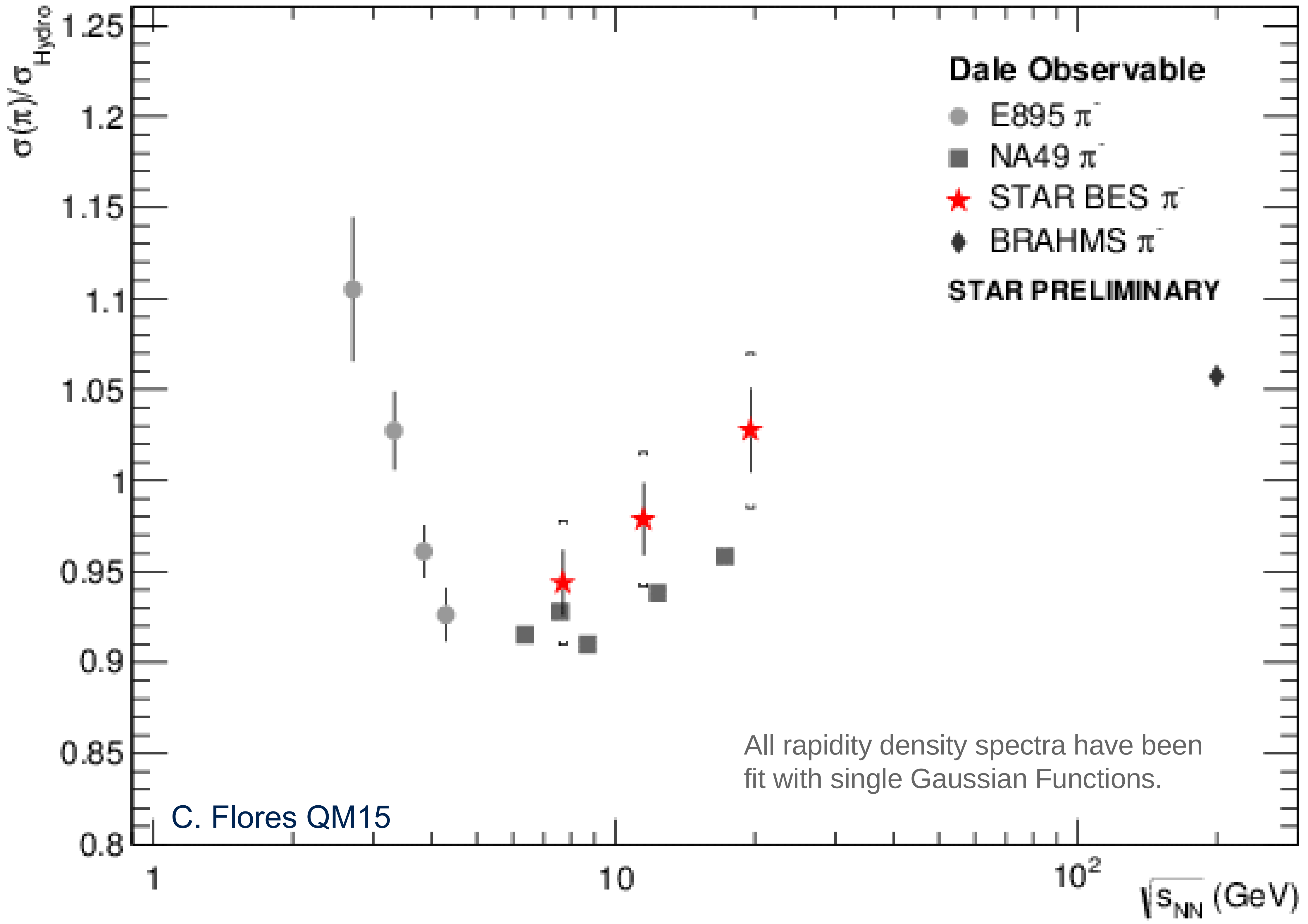
Softest Point: minimum in c_s^2

$$\frac{dn}{dy} = \frac{K s_{NN}^{1/4}}{\sqrt{2\pi\sigma_y^2}} e^{-\frac{y^2}{2\sigma_y^2}} \qquad \sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\frac{\sqrt{s}}{2m_N}\right)$$

Minimum observed at $\sqrt{s}$ = ~7 GeV

Minimum in the speed of sound?

$c_s^2 \sim 0.26$



E895: J. L. Klay et al, PRC 68, 05495 (2003)
NA49: S. V. Afanasiev et al. PRC 66, 054902 (2002)
BRAHMS: I.G. Bearden et al., PRL 94, 162301

Indication of softening of EoS?

NA61/SHINE see minima in similar place for pp data

Confirm c_s in other ways?

Directed flow

Sensitive probe of early time interactions and EOS

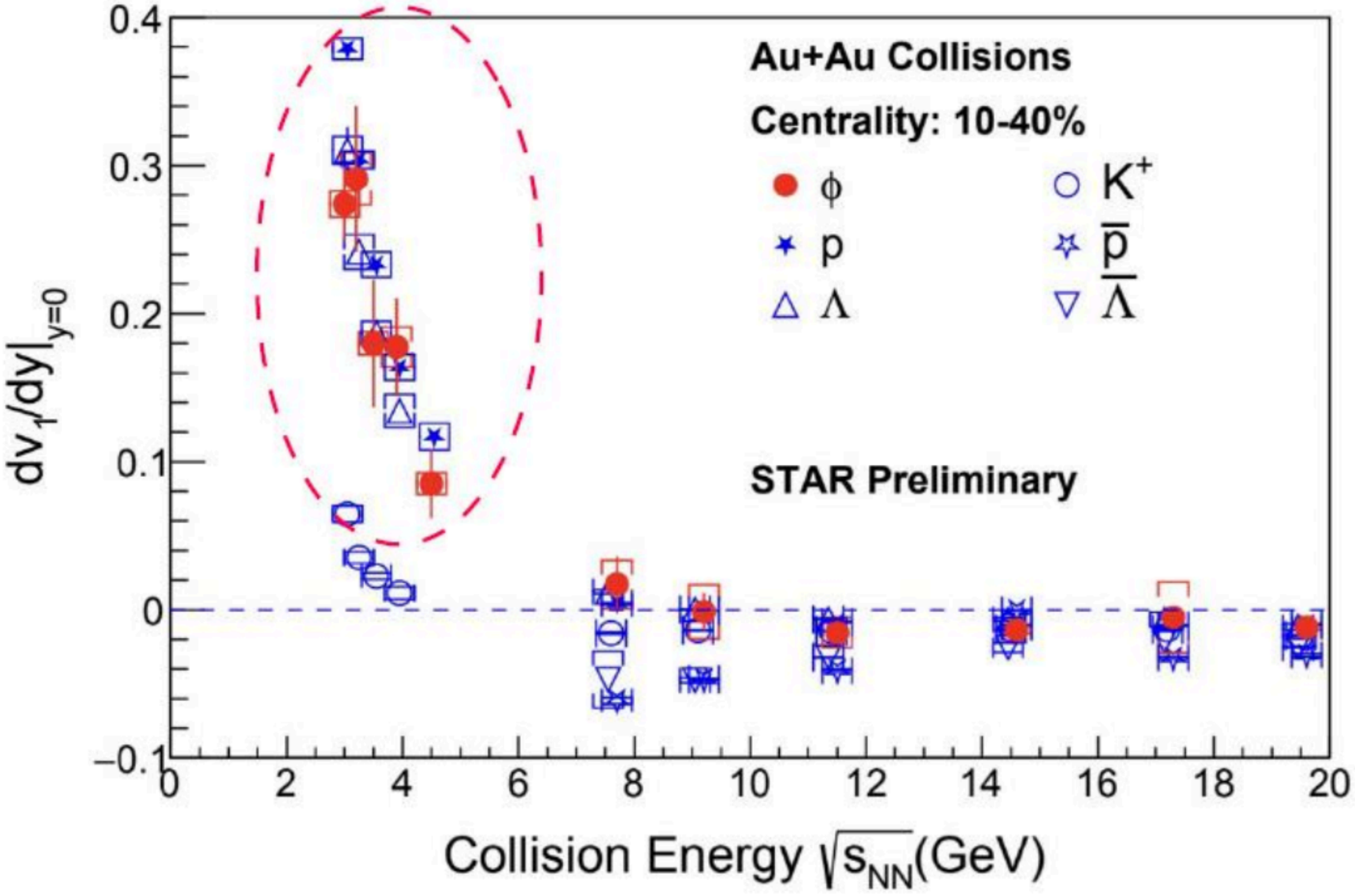
Kaons:

- sign change in FXT region
- where exactly does this occur?
- spectator shadowing at play?

ϕ:

- unexpectedly large v_1 in FXT region
- similar magnitude to p and Λ

Mass effect not baryon/meson?

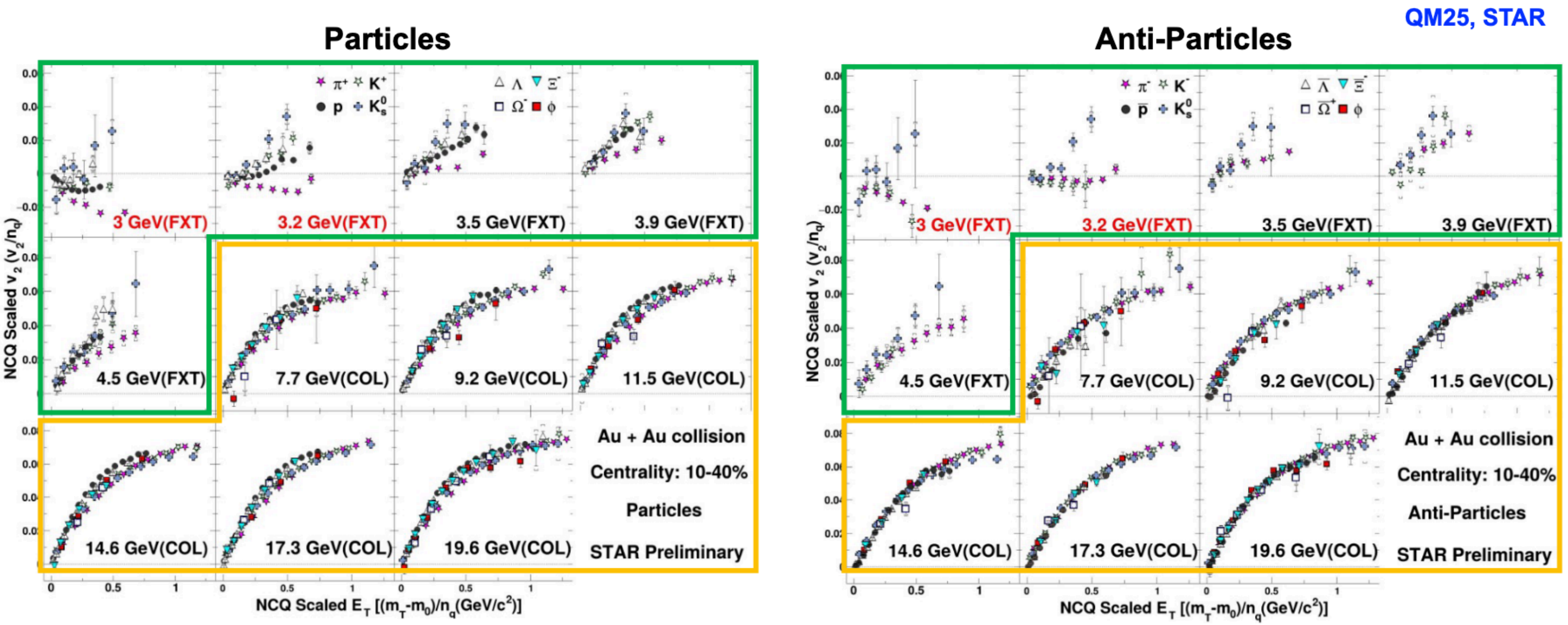


nFXT fills the gap

STAR: arXiv: 2503.23665

Motivation for Continued QGP Formation Studies

Disappearance of partonic collectivity



Particles and antiparticles no longer consistent with single-particle NCQ scaling for $\sqrt{s_{NN}} < 7$GeV

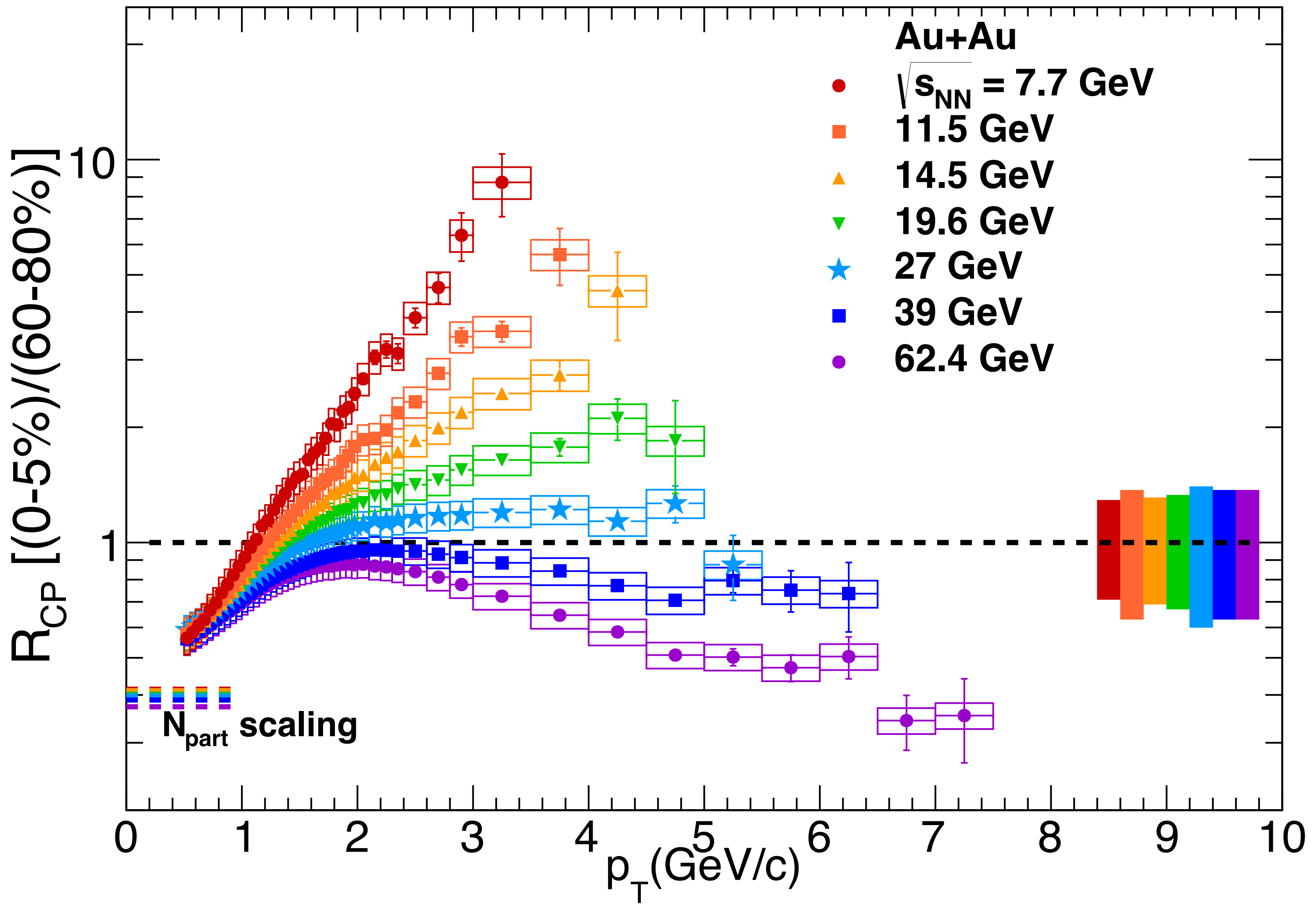
Dominance of hadronic interactions at $\sqrt{s_{NN}} < 3.5$ GeV

Mixing of transported and produced quarks changing

nFXT what energy does NCQ return? Also particle vs anti-particle

STAR: PRL. **135** (2025) 72301, PLB **827** (2022) 137003

Disappearance of partonic energy loss



For $\sqrt{s_{NN}}$ > 27 GeV suppression observed

STAR: PRL **121** (2018) 32301

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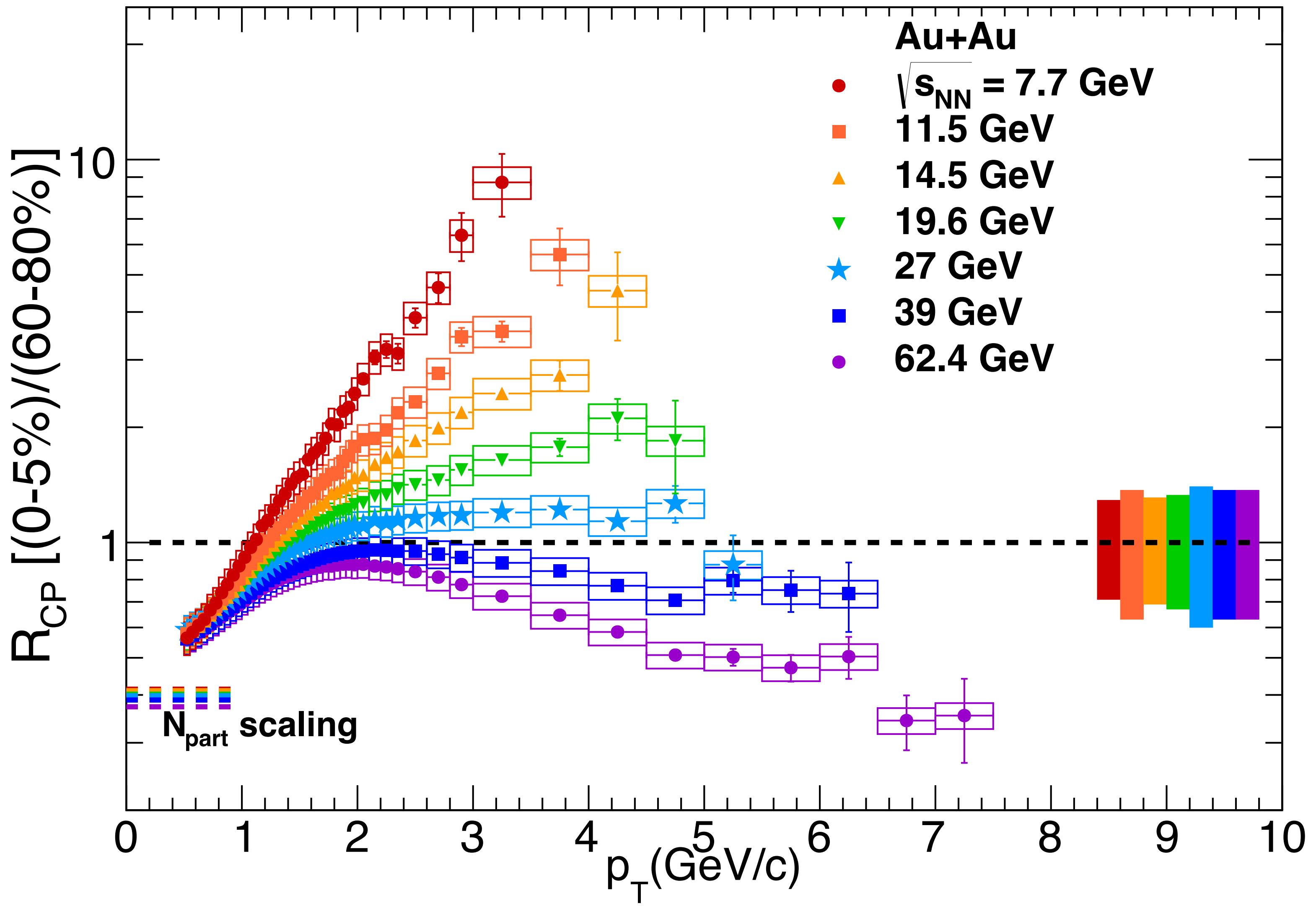
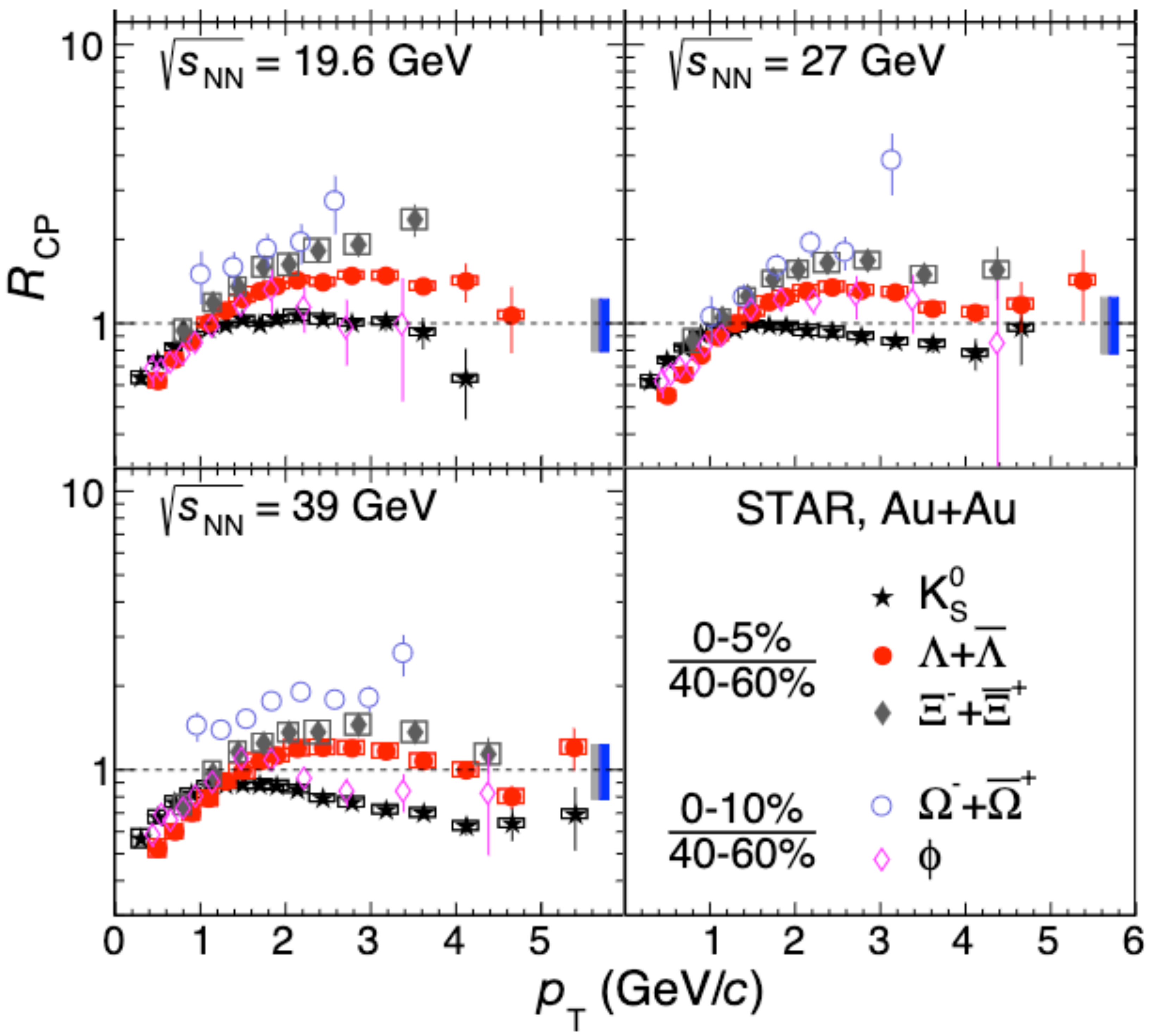


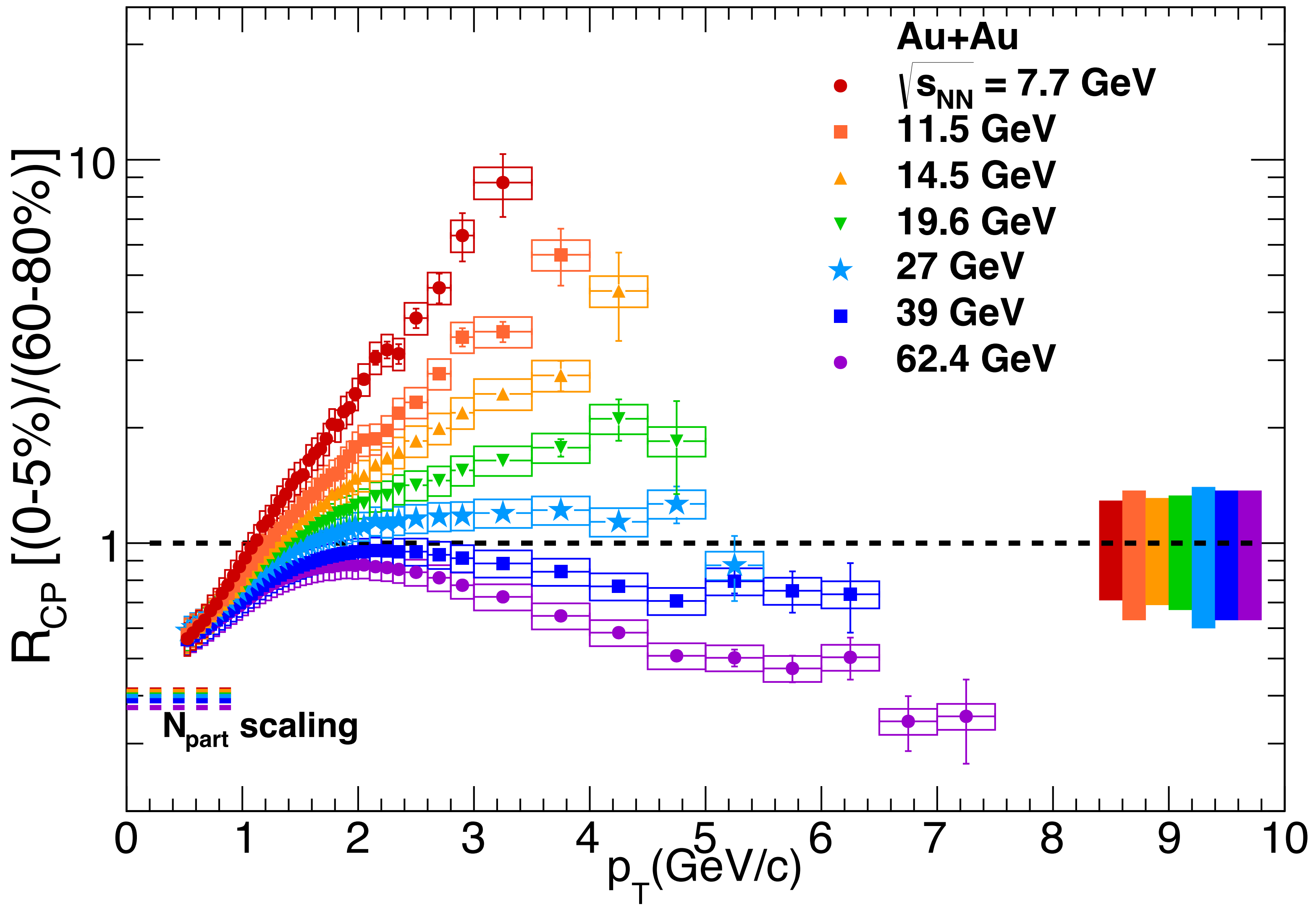


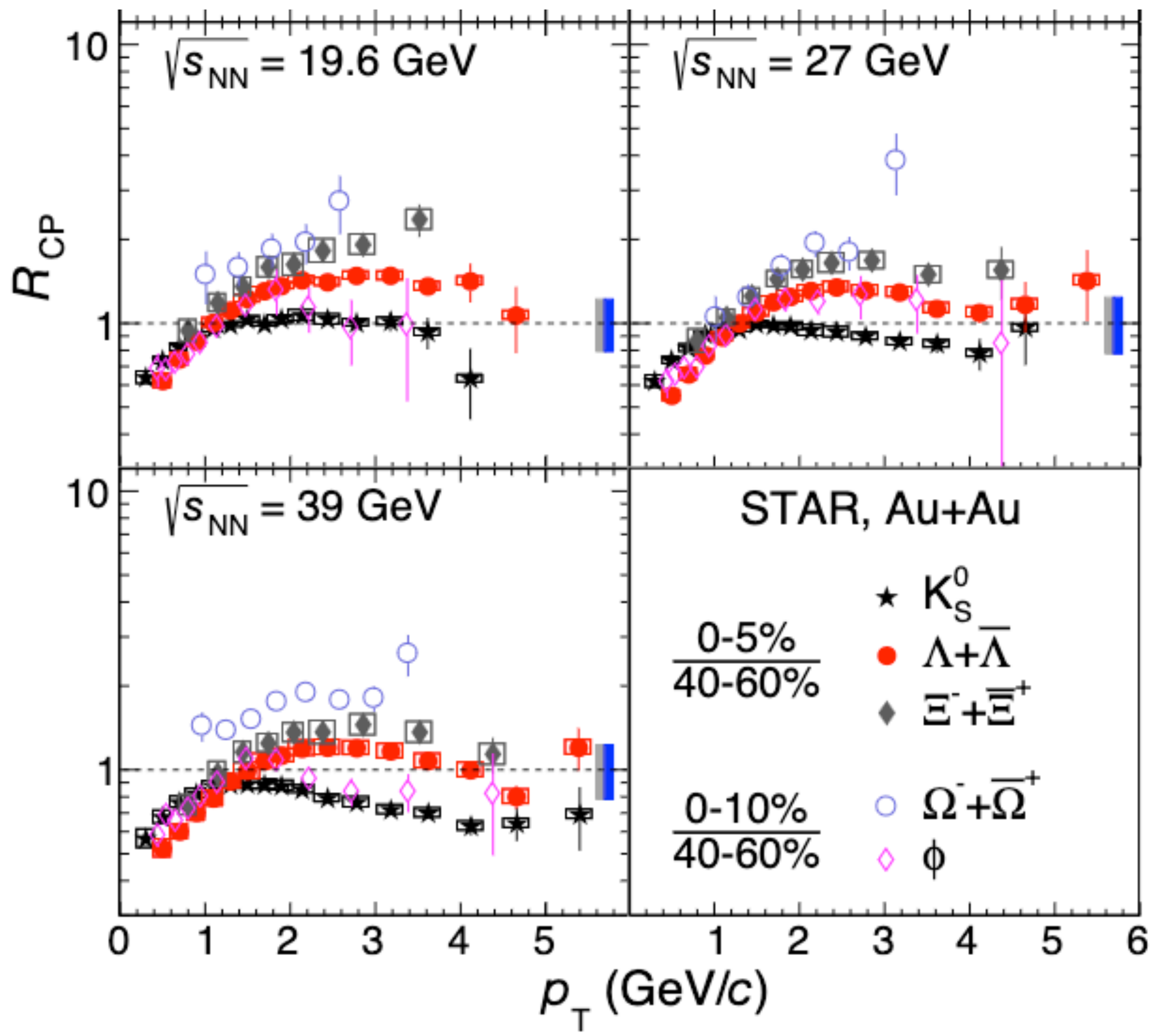
For $\sqrt{s_{NN}}$ > 27 GeV suppression observed

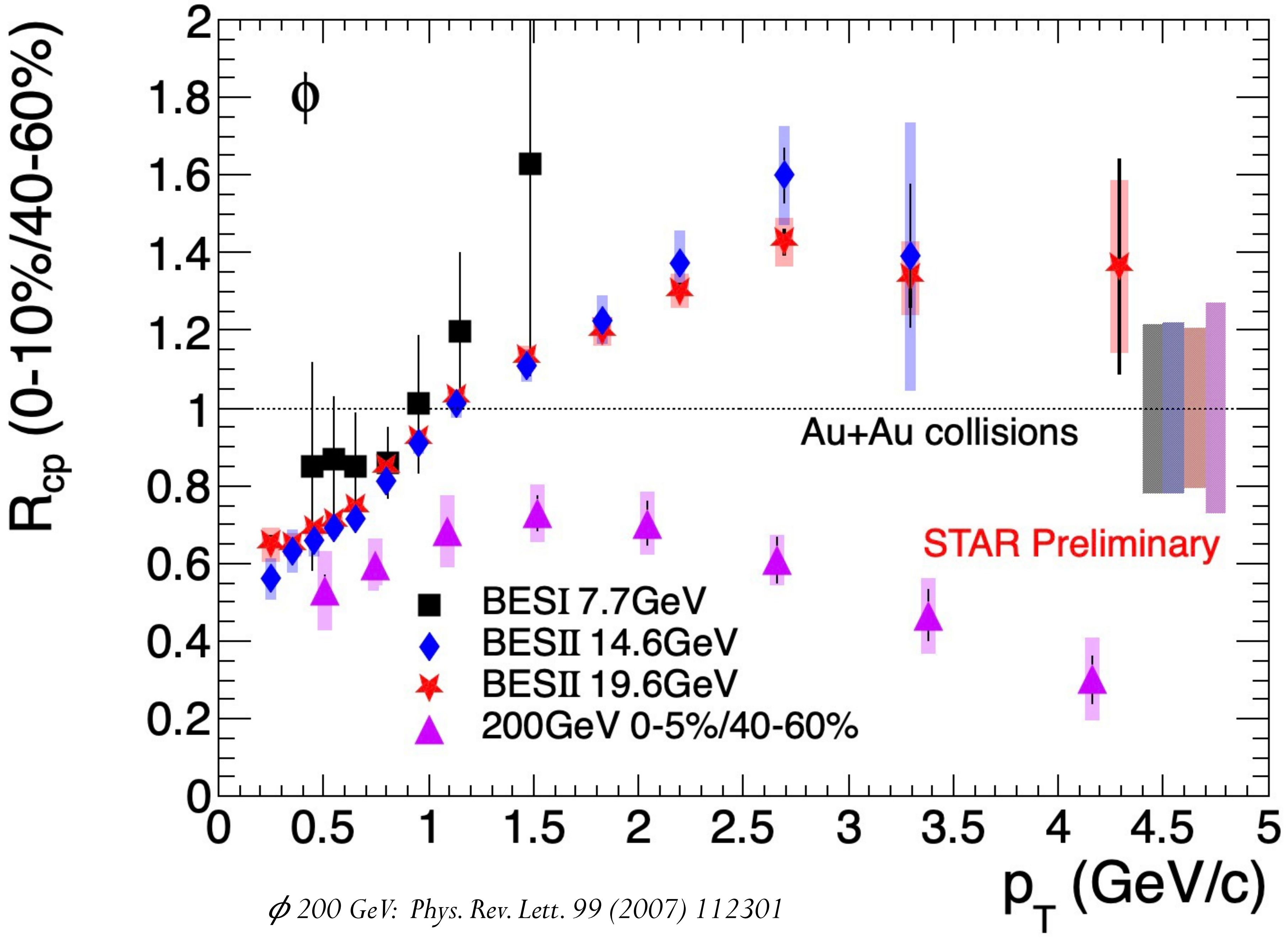
Differences for baryons and mesons

STAR: PRL **121** (2018) 32301

Disappearance of partonic energy loss







For $\sqrt{s_{NN}}$ > 27 GeV suppression observed

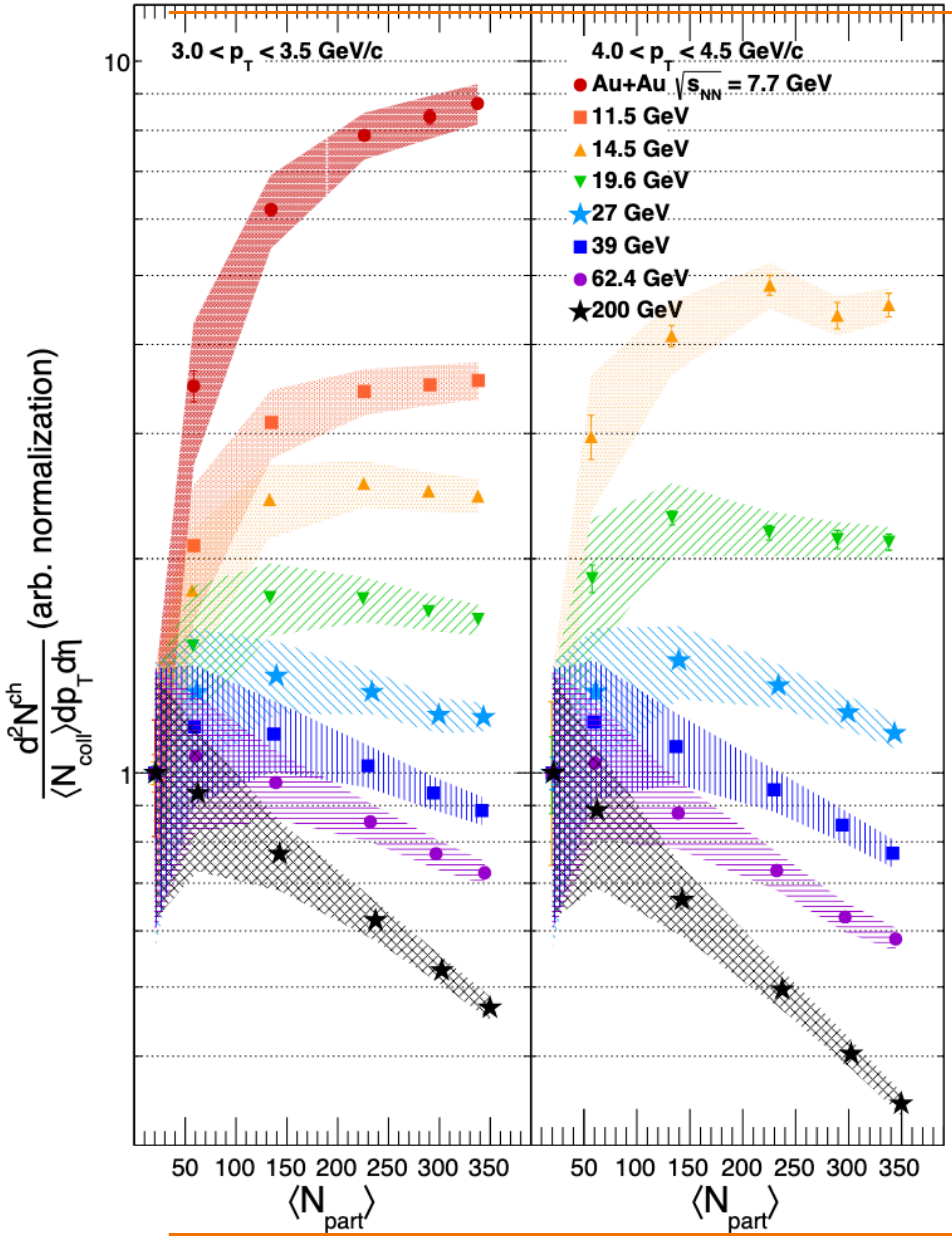
Differences for baryons and mesons

nFXT improve baseline

New ϕ data indicate mass not baryon/meson effect?

STAR: PRL **121** (2018) 32301

Disappearance of partonic energy loss?



Is flow/Cronin hiding E_{loss}?

Interesting idea:

For each energy normalize to peripheral data

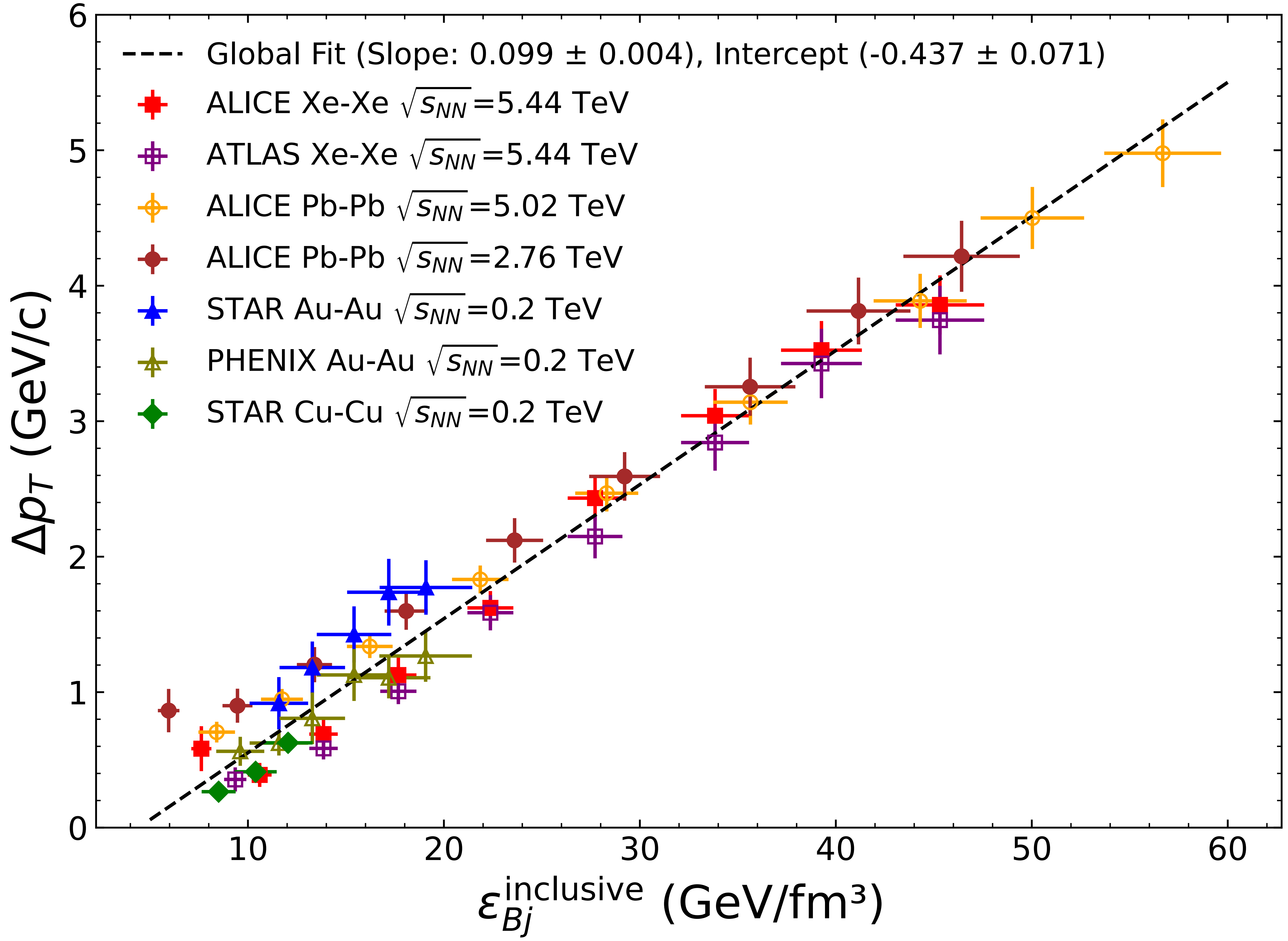
High p_T suppression in central events for all energies down to $\sqrt{s_{NN}}$ ~14.5 GeV

Many results reveal something interesting in $\sqrt{s_{NN}}$ =10-20 GeV range

nFXT: Where to other systems, especially pA sit?

STAR: PRL **121** (2018) 32301

Energy loss vs energy density



Link between entropy and charged particle density very sensitive to viscosity

More careful calculation needed

E_{Loss} from shift of p_T spectra

Approximate energy density from Glauber and charged particle yields

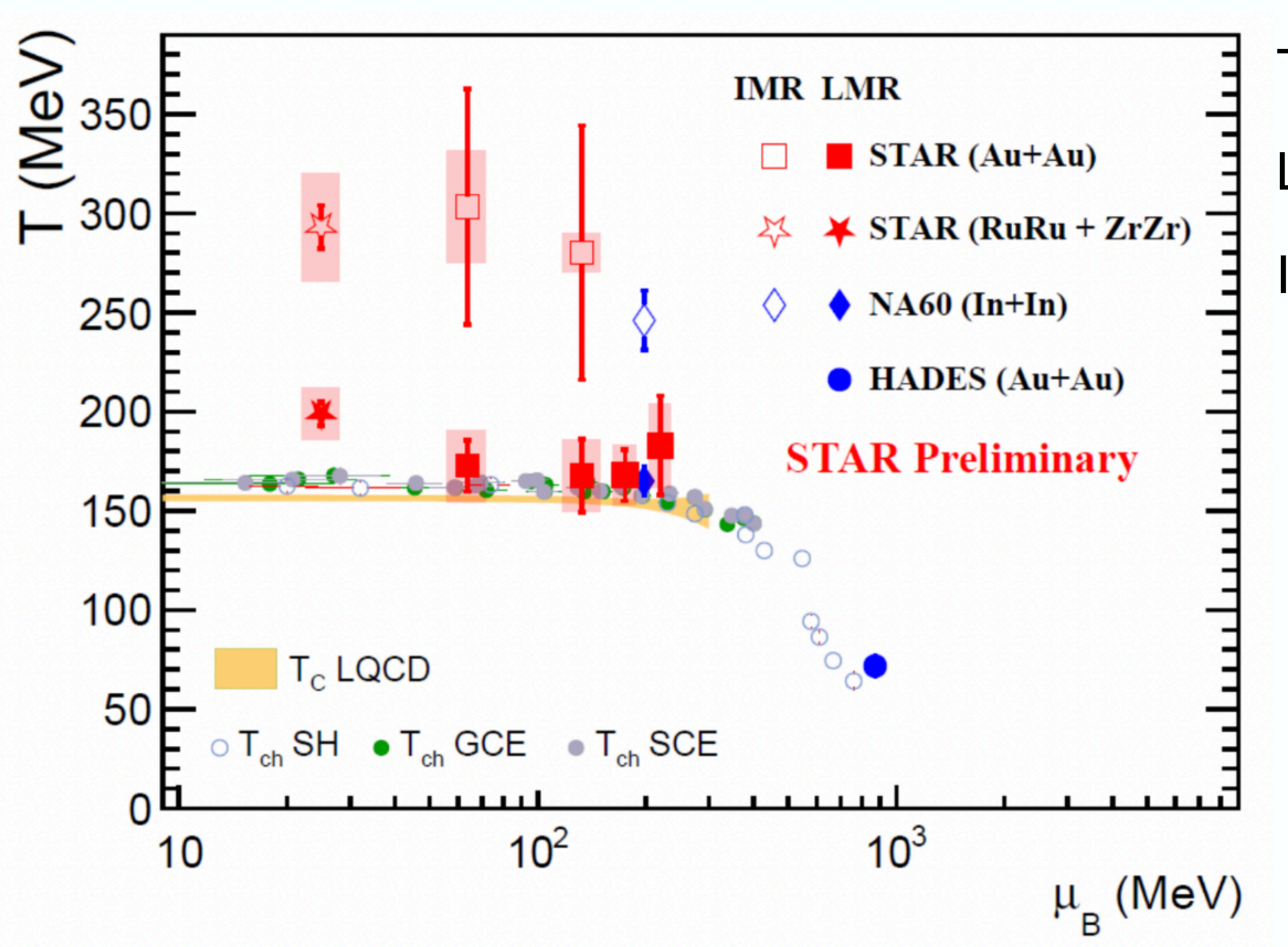
Given number of approximations strong correlation between E_{Loss} and ε_{init} over different species and collision energies

Partonic energy loss scales with initial energy density

Evidence of jet quenching in O+O (see QM and IS)

nFXT: Does scaling breakdown?

Initial temperature of medium



Thermal di-electrons:

LMR: Transition thermal radiation

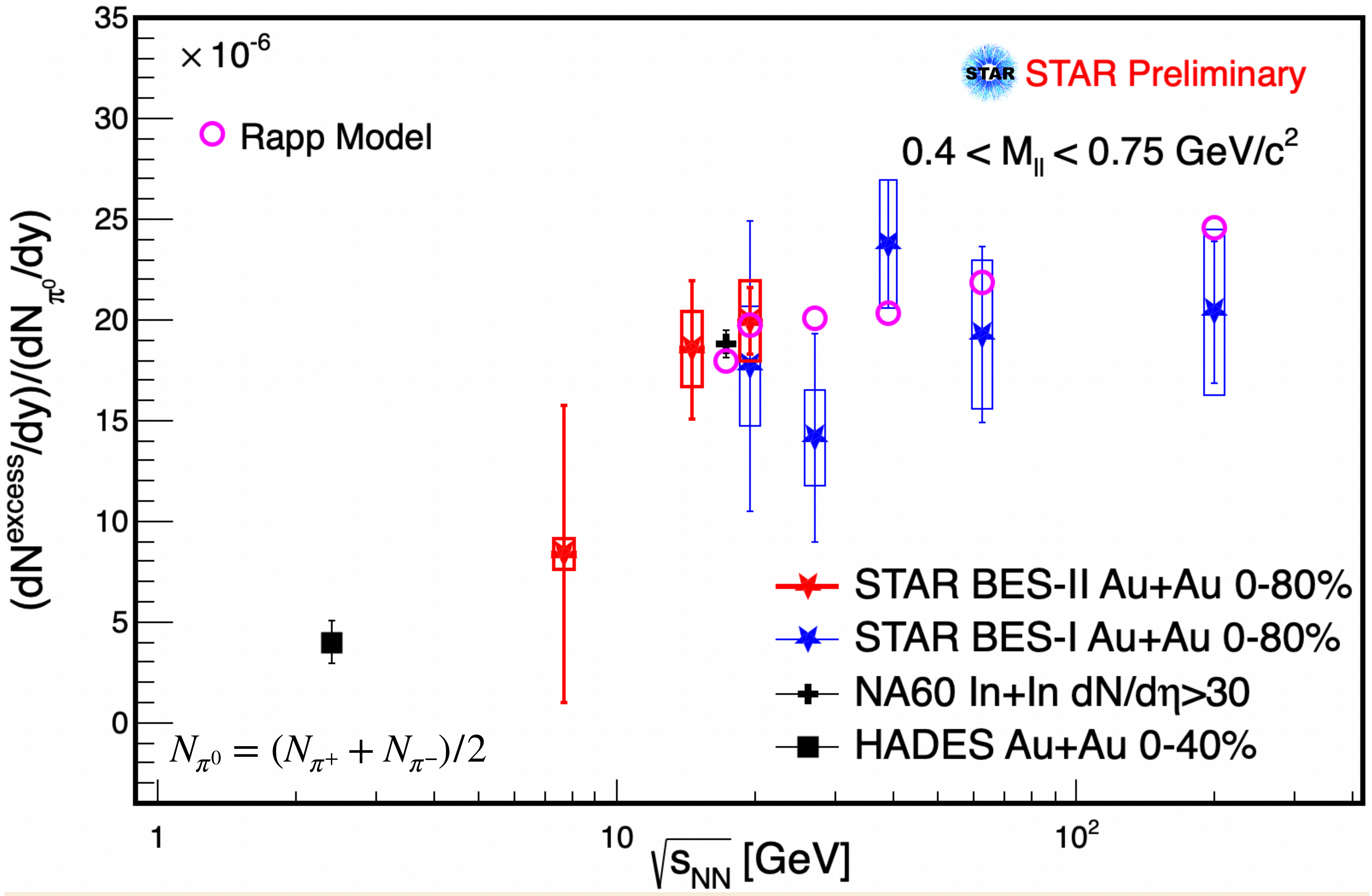
IMR: QGP thermal radiation

Need to cross into QGP regime to see CP

$\sqrt{s_{NN}}$ < 20 GeV possible with nFXT?

STAR: arXiv:2402.01998

Normalized dilepton low mass excess



BES-I:

- No clear $\sqrt{s_{NN}}$ dependence
- Well described by in-medium ρ + QGP emission models

BES-II + HADES

- Decrease below $\sqrt{s_{NN}}$ ~ 10 GeV

STAR: PRC **107** (2023) 0

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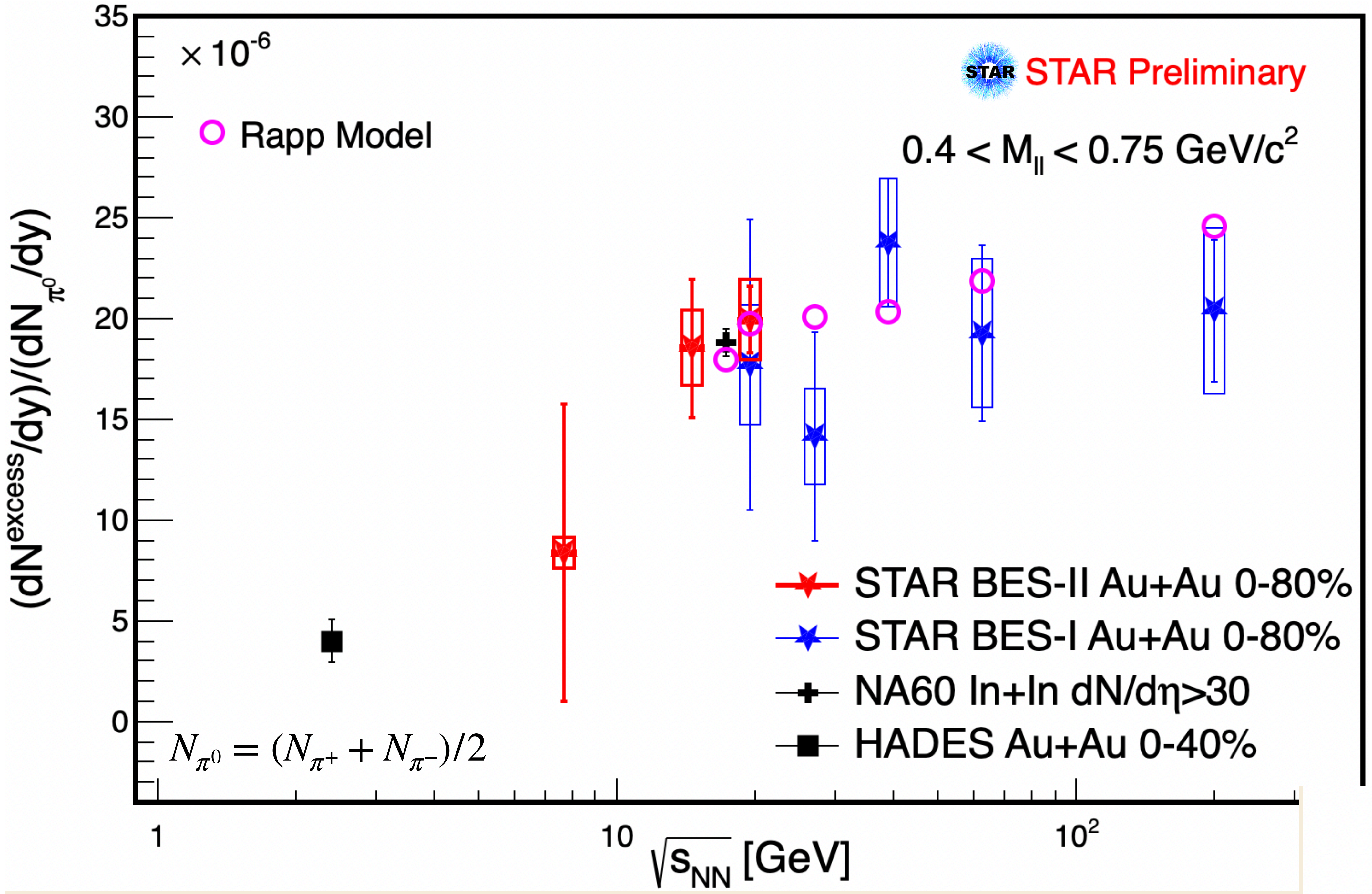

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BES-II + HADES
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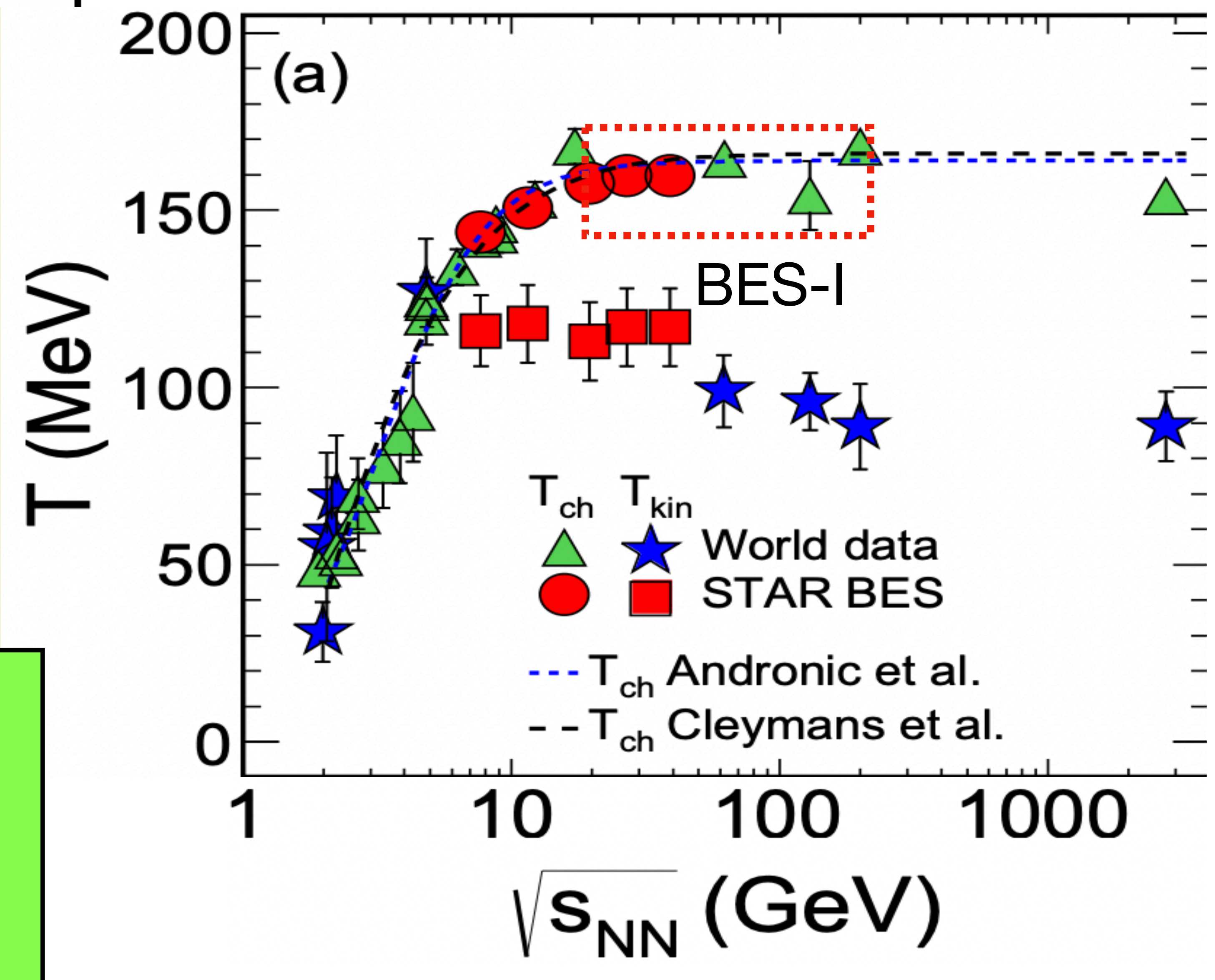
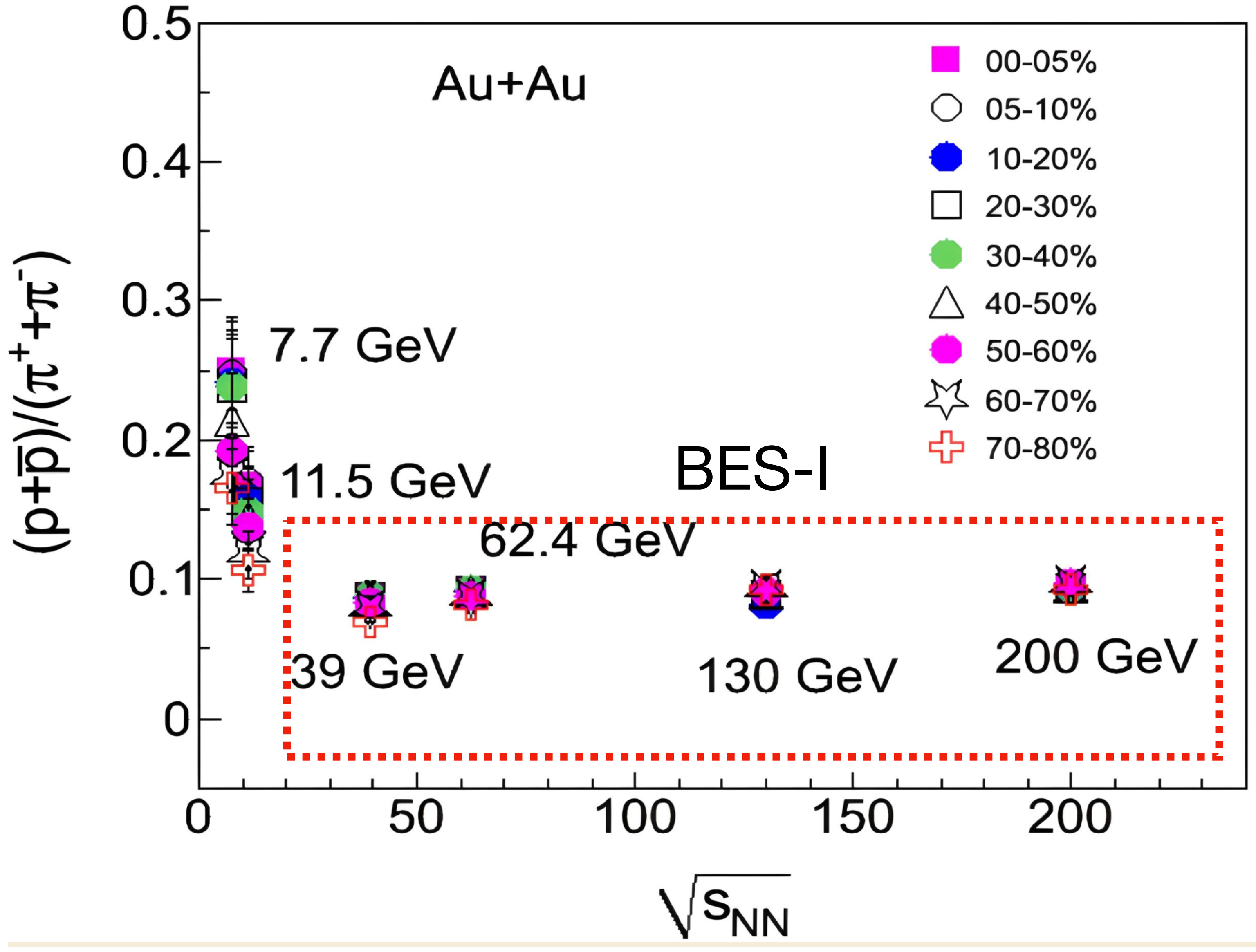
At about same location:
- Baryon density rises
- T_{ch} drops



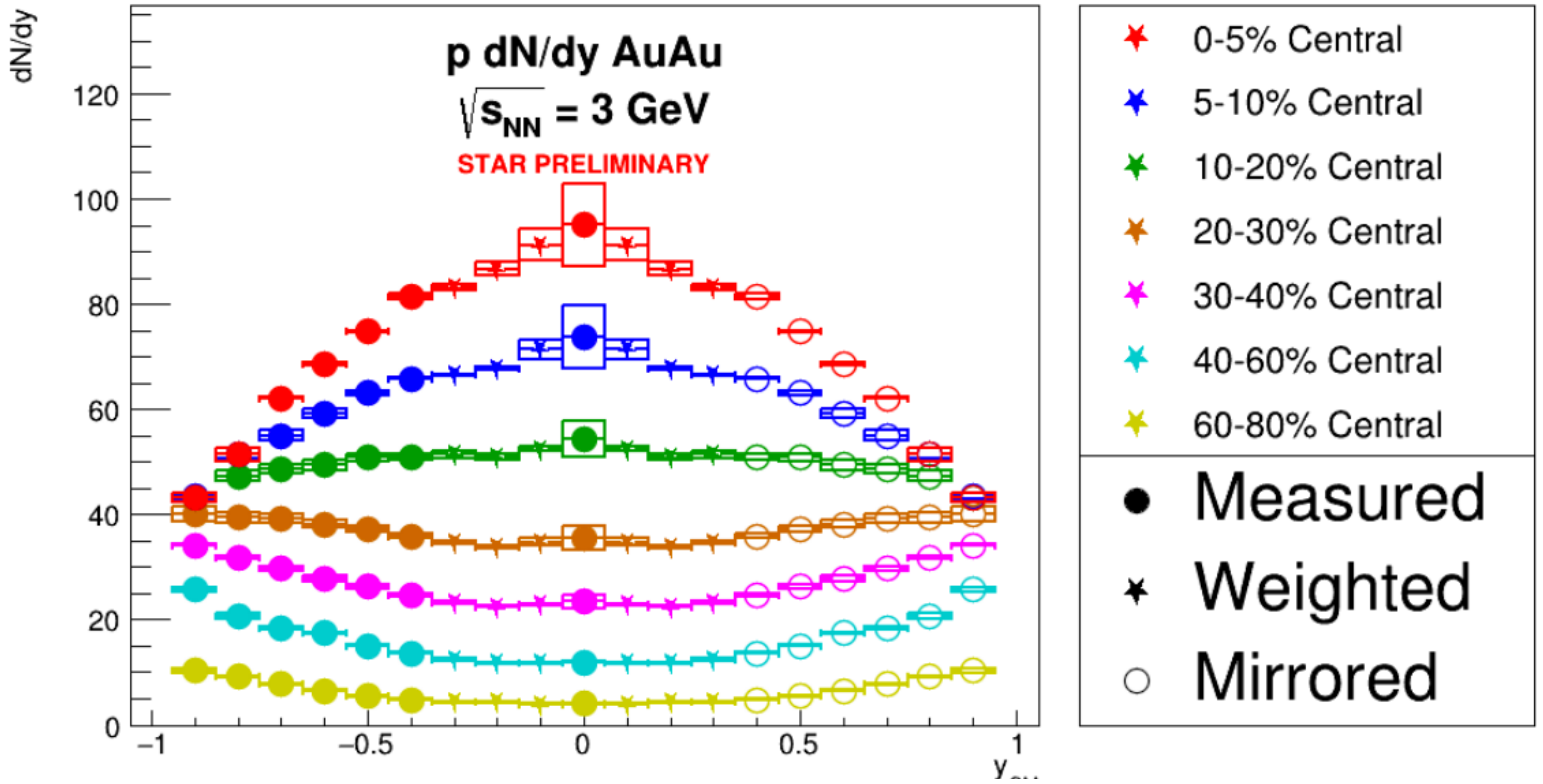


nFXT: With precision data can we disentangle different medium effects on LME?

STAR: PRC **107** (2023) 0

Motivation for Continued Particle Production Studies

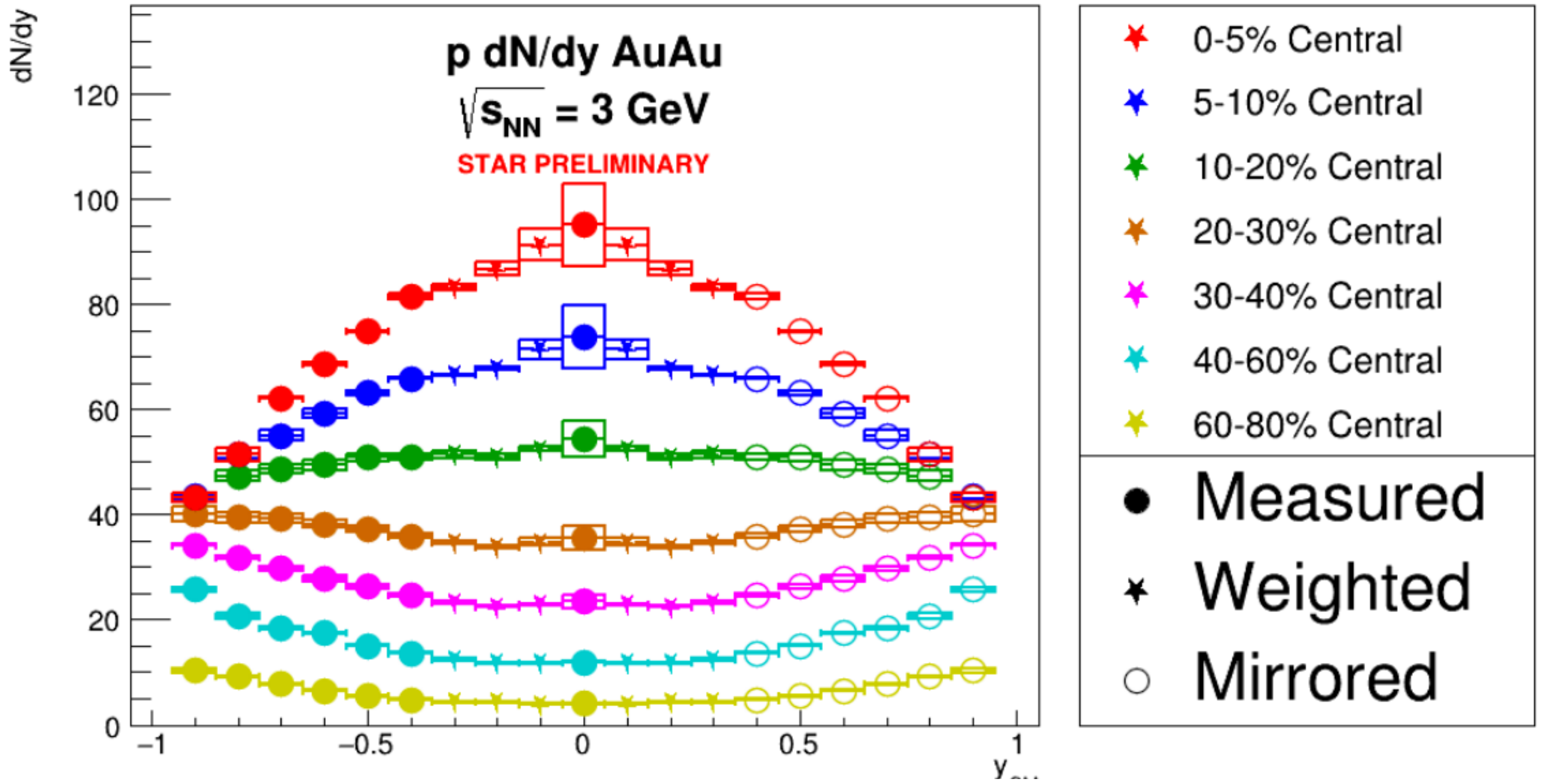
Renewed interest in baryon stopping/transport



FXT data Au+Au $\sqrt{s_{NN}}$ = 3 GeV:
Centrality dependence of proton rapidity distribution width

Proton peak shifts away from mid-rapidity for more peripheral collisions
- less stopping

Renewed interest in baryon stopping/transport



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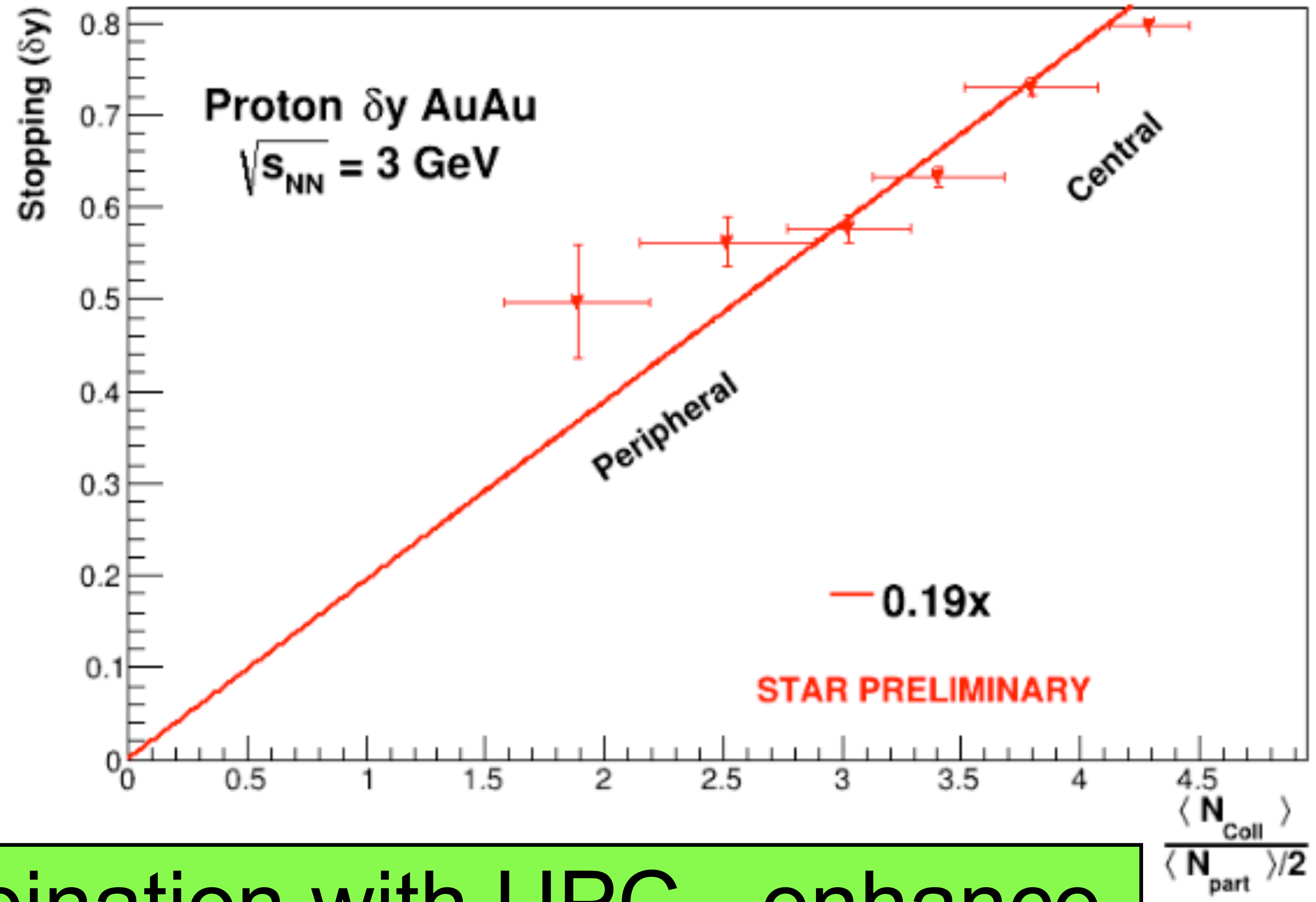


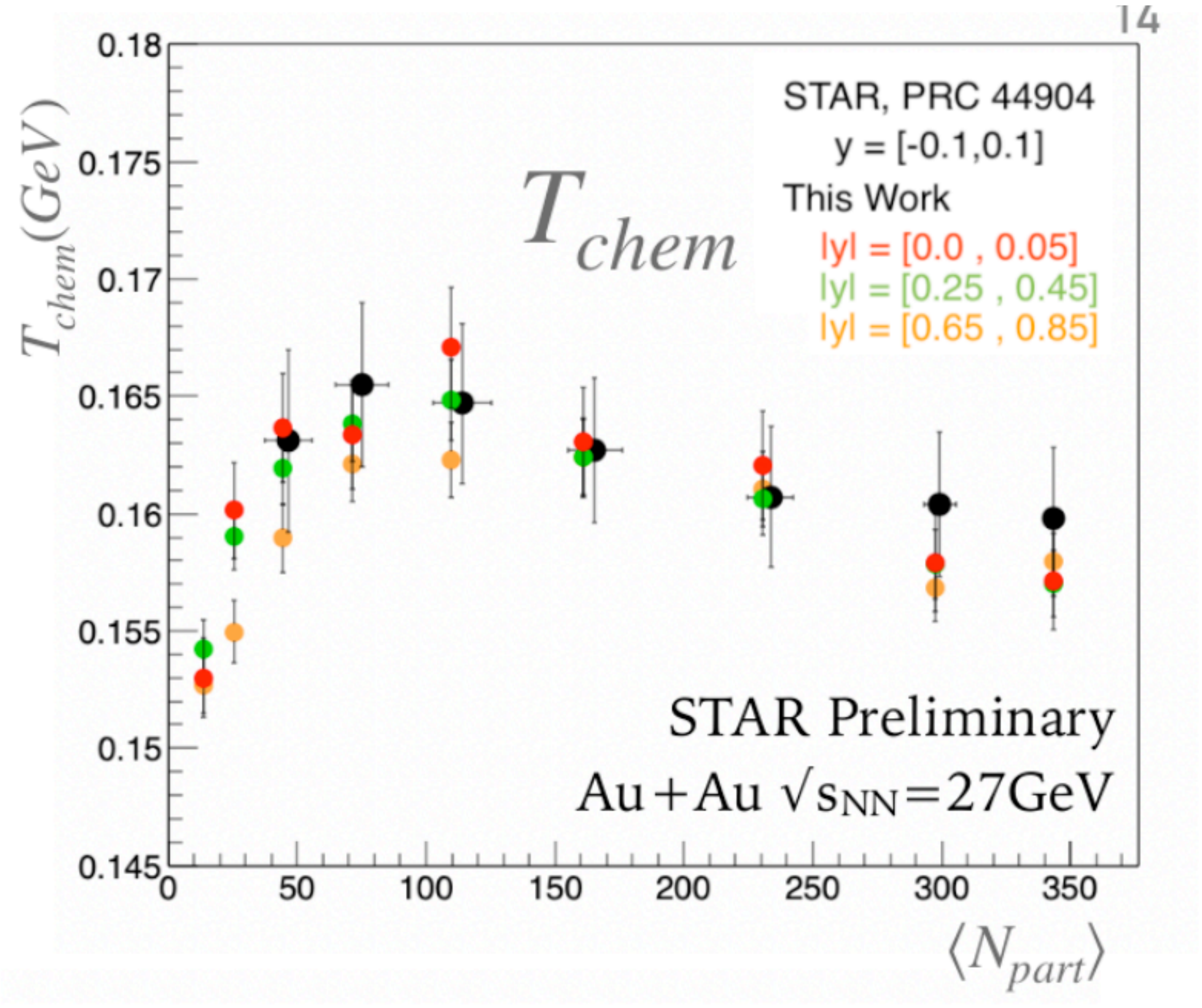
Define stopping, δy, via the shift of the participant proton peak from beam rapidity

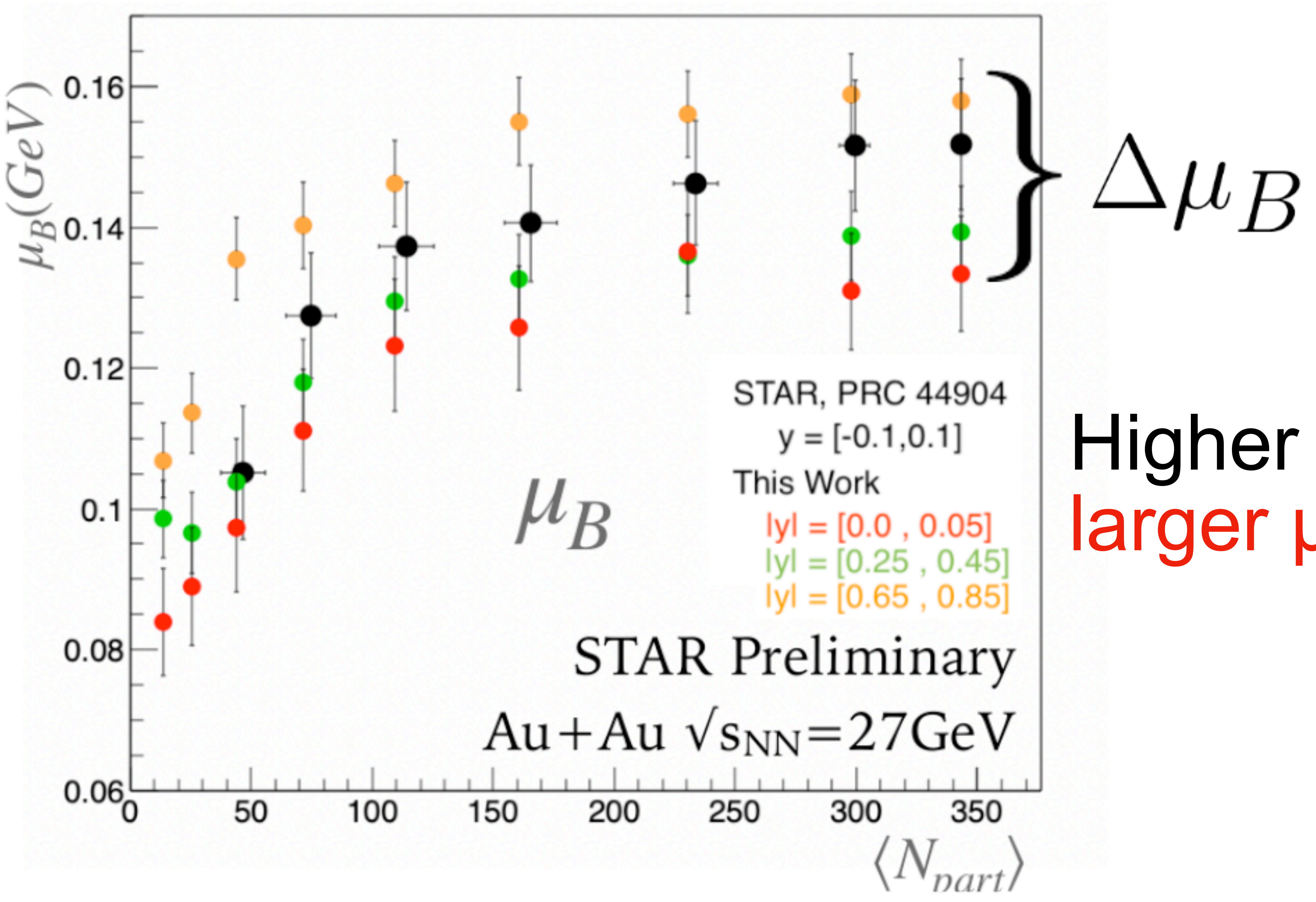
Average loss of 0.19 ± 0.01 units of rapidity per nucleon-nucleon collision

consistency with other experiments at similar energies

In combination with UPC - enhance understanding of baryons

Trajectory through the phase diagram?





Higher rapidity —>
larger μ_B, similar T_{ch}

Next step: Compare mid-rapidity/low $\sqrt{s_{NN}}$ and high rapidity/high $\sqrt{s_{NN}}$

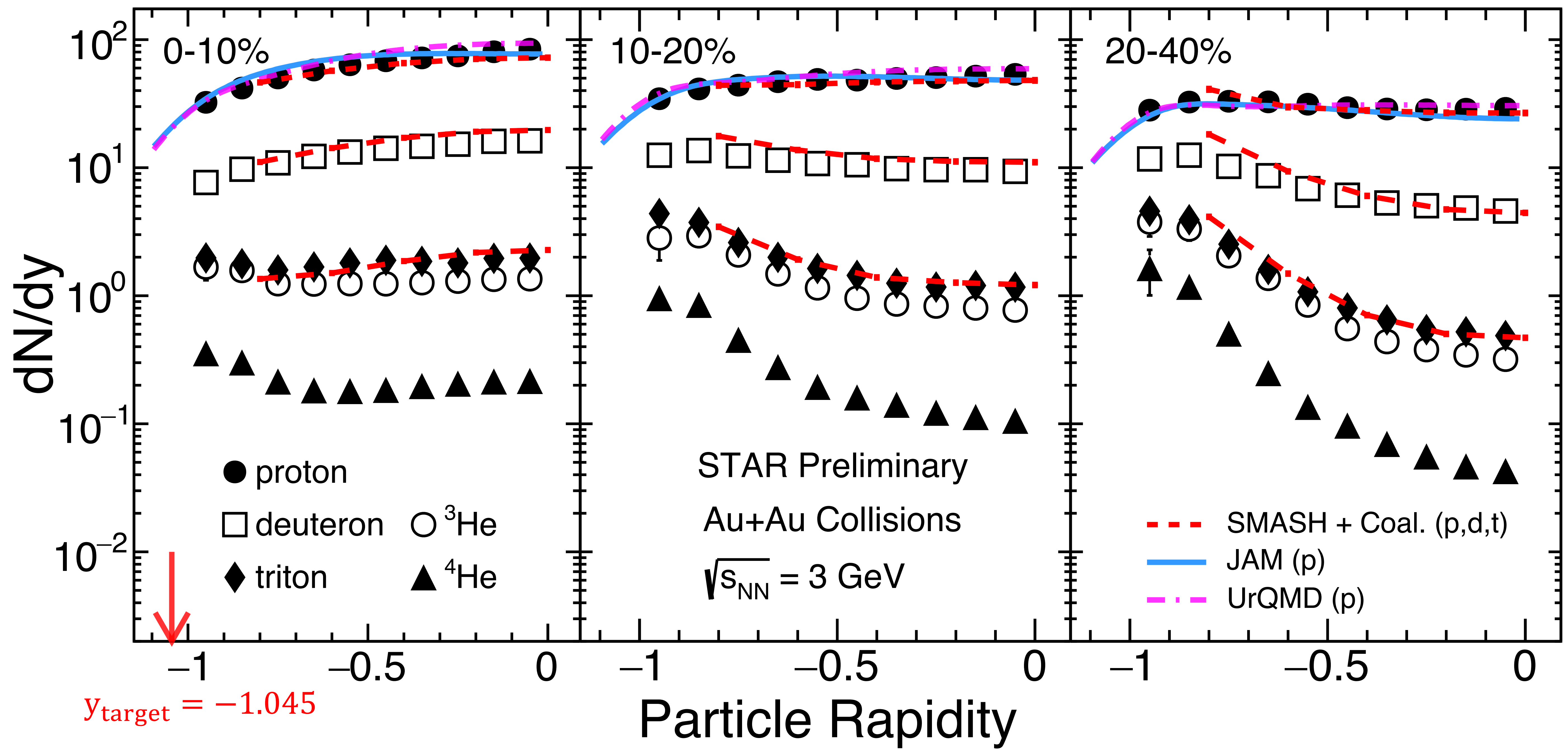
Chemical freeze-out parameters match but initial conditions differ.
Can we see the difference imprinted elsewhere?

Kinetic freeze-out of light nuclei

At $\sqrt{s_{NN}}$ = 3 GeV

Yields of proton & light nuclei well described by models

Significant centrality and rapidity dependence



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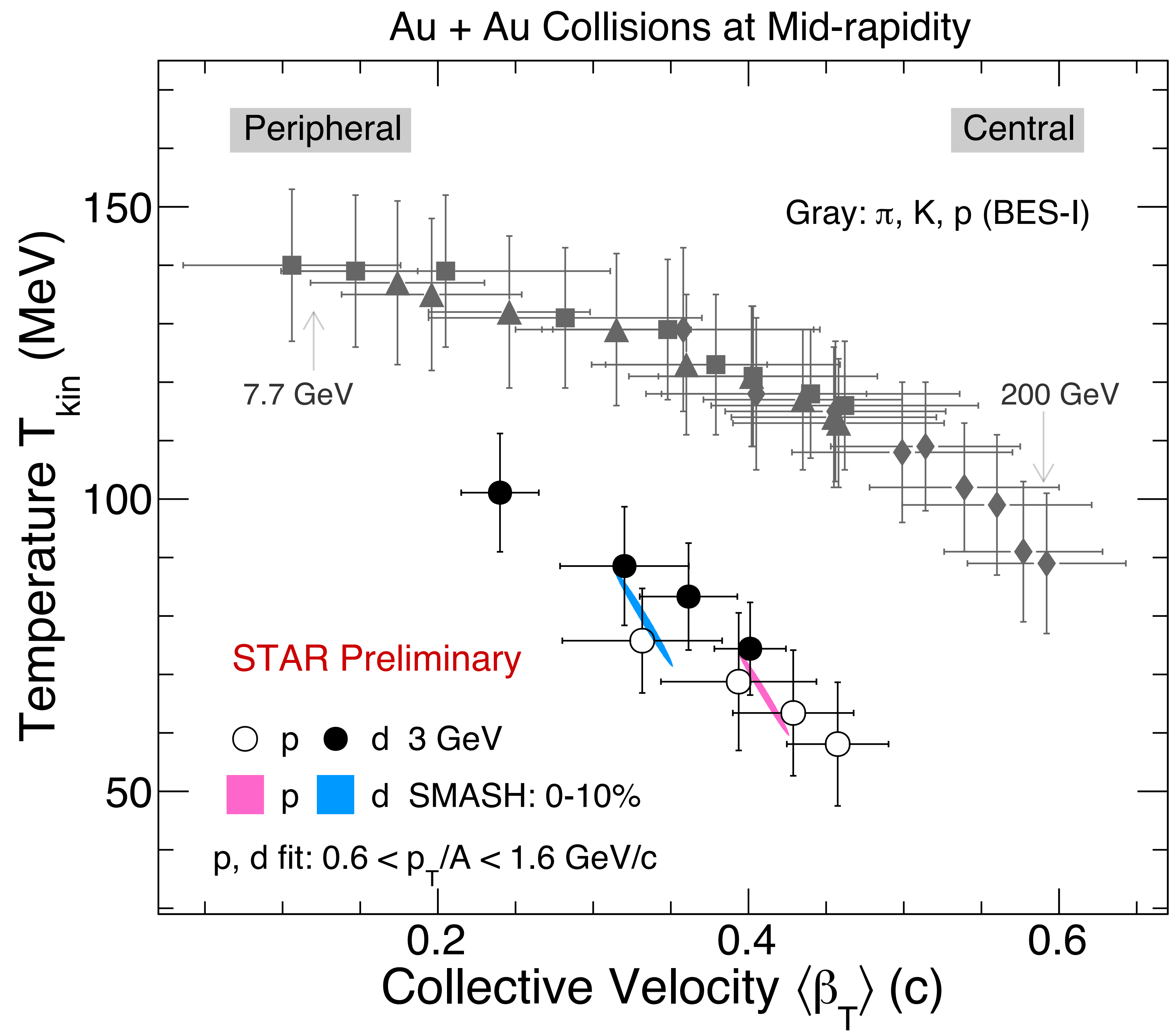
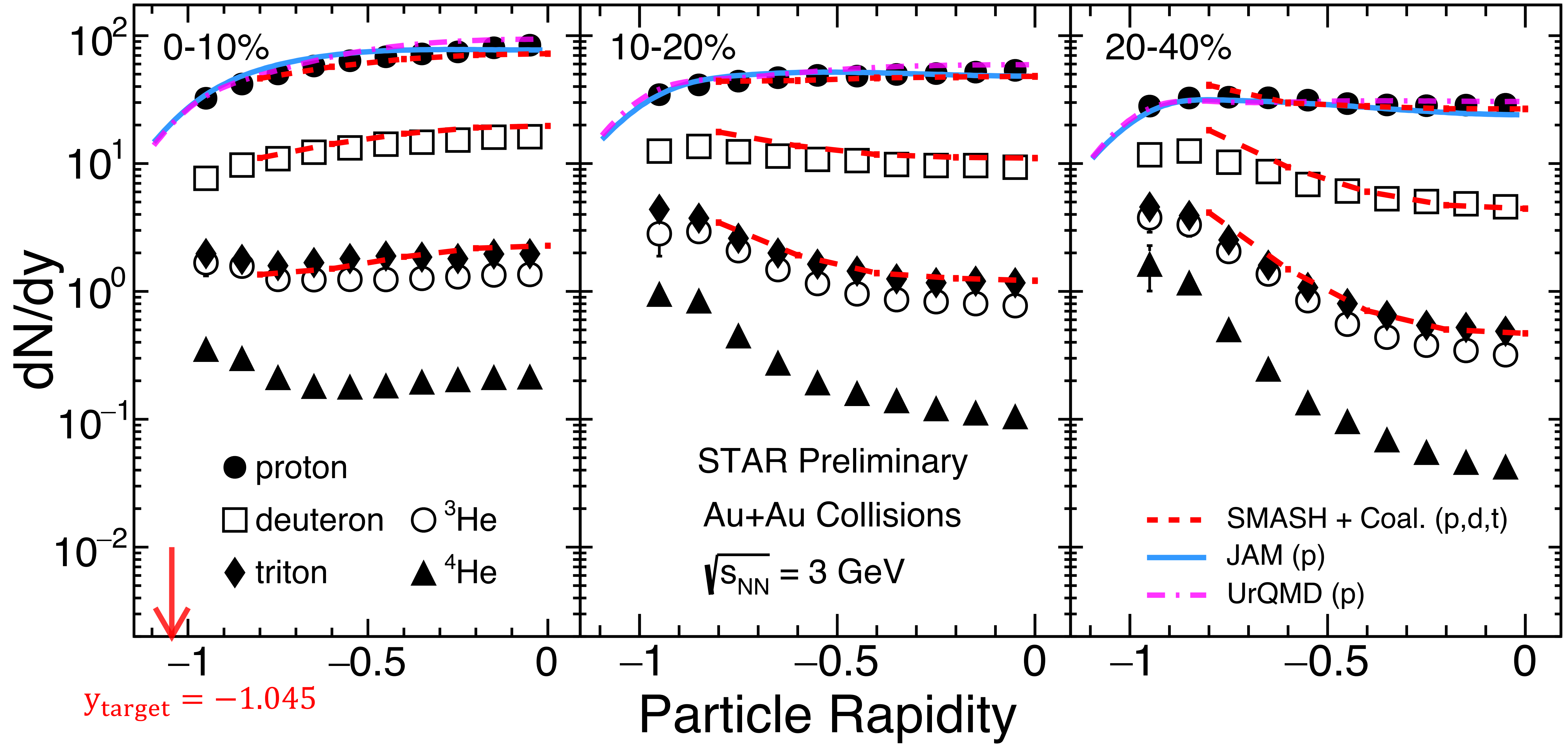


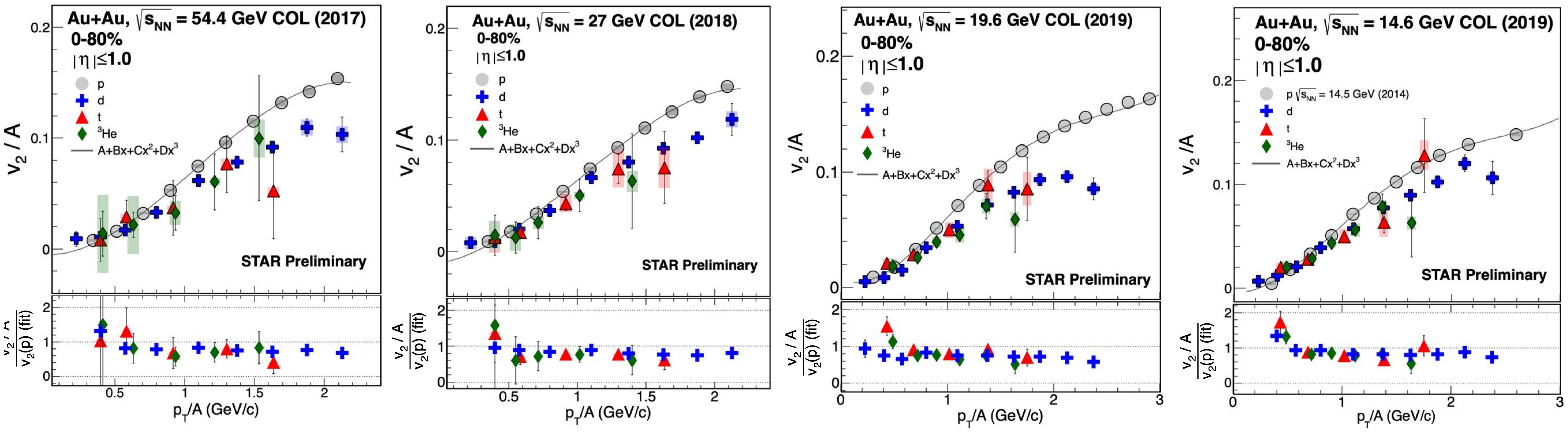


Effective average kinetic freeze out parameters extracted using cylindrical blast wave fits

$\sqrt{s_{NN}}$ = 3 GeV different trend to higher energies. Different EoS?

Effective $T_{kin}(d) > T_{kin}(p)$
$\beta_T(d) < \beta_T(p)$

Light nuclei collective motion

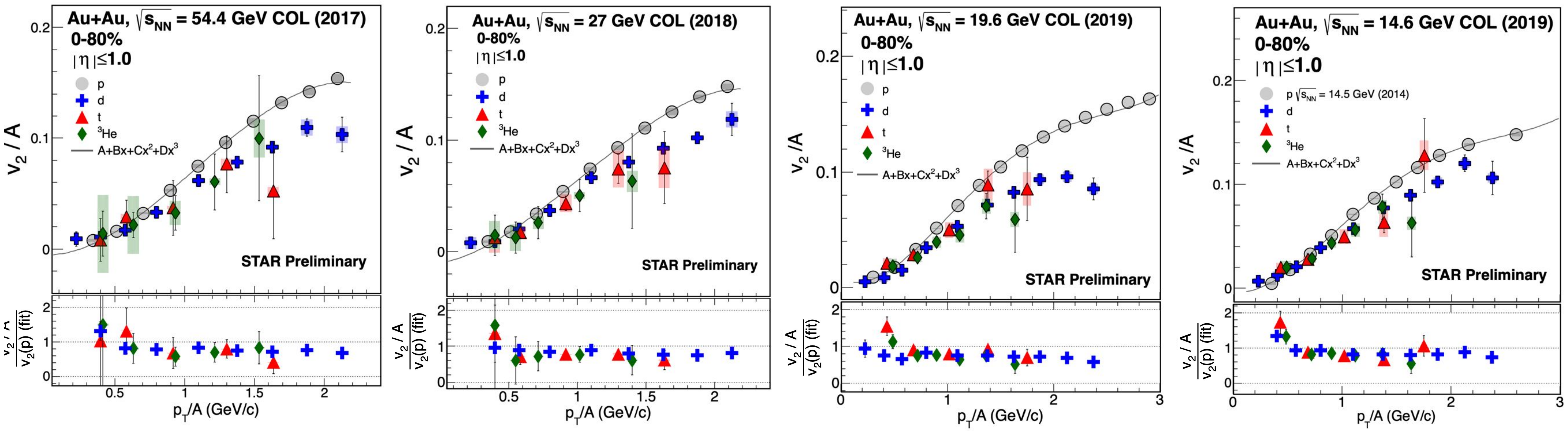


A-scaling:

v_2 for $\sqrt{s_{NN}}$ = 54-14.6 GeV

(also for v_3)

Light nuclei collective motion



A-scaling:

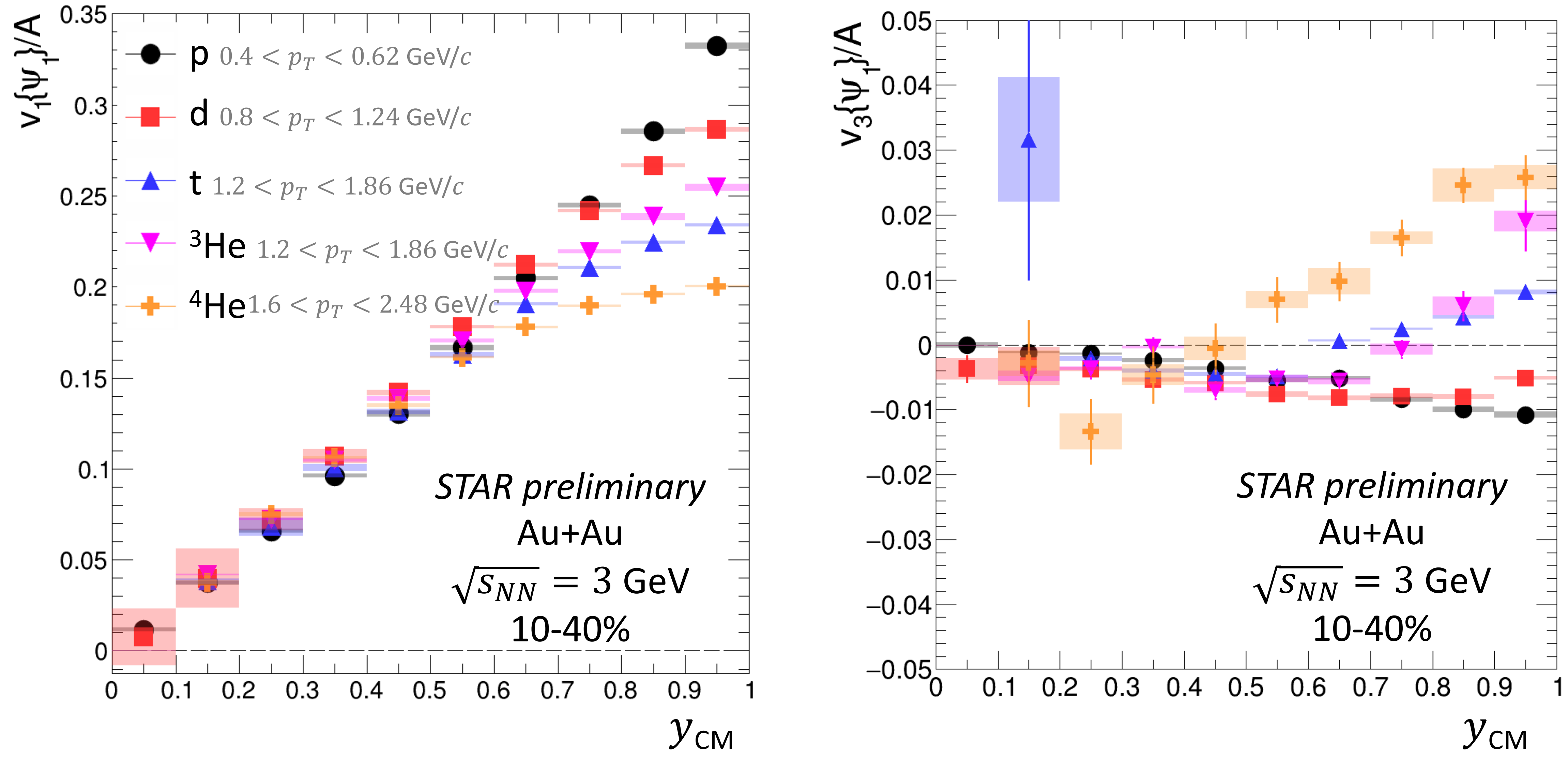
v_2 for $\sqrt{s_{NN}}$ = 54-14.6 GeV

(also for v_3)

A-scaling at $\sqrt{s_{NN}}$ = 3 GeV

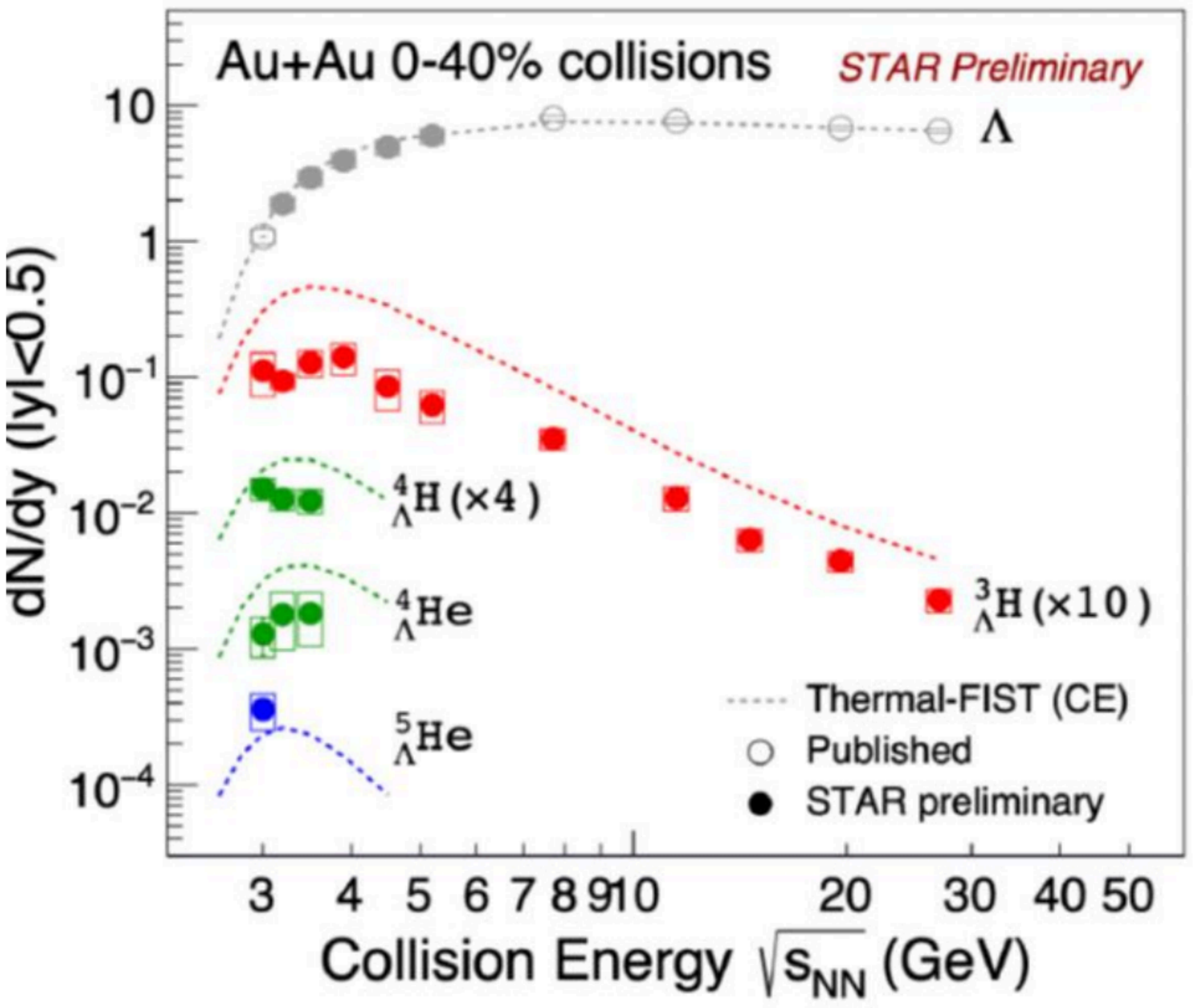
Reasonable for v_1 and $v_3\{\Psi_1\}$ at $y_{cm}<0.5$
Breaks for v_1 and $v_3\{\Psi_1\}$ $y_{cm}>0.5$

v_1 of hypernuclei similar trend



Consistent with late-stage coalescence
- high y nuclear fragments

Y-N interaction



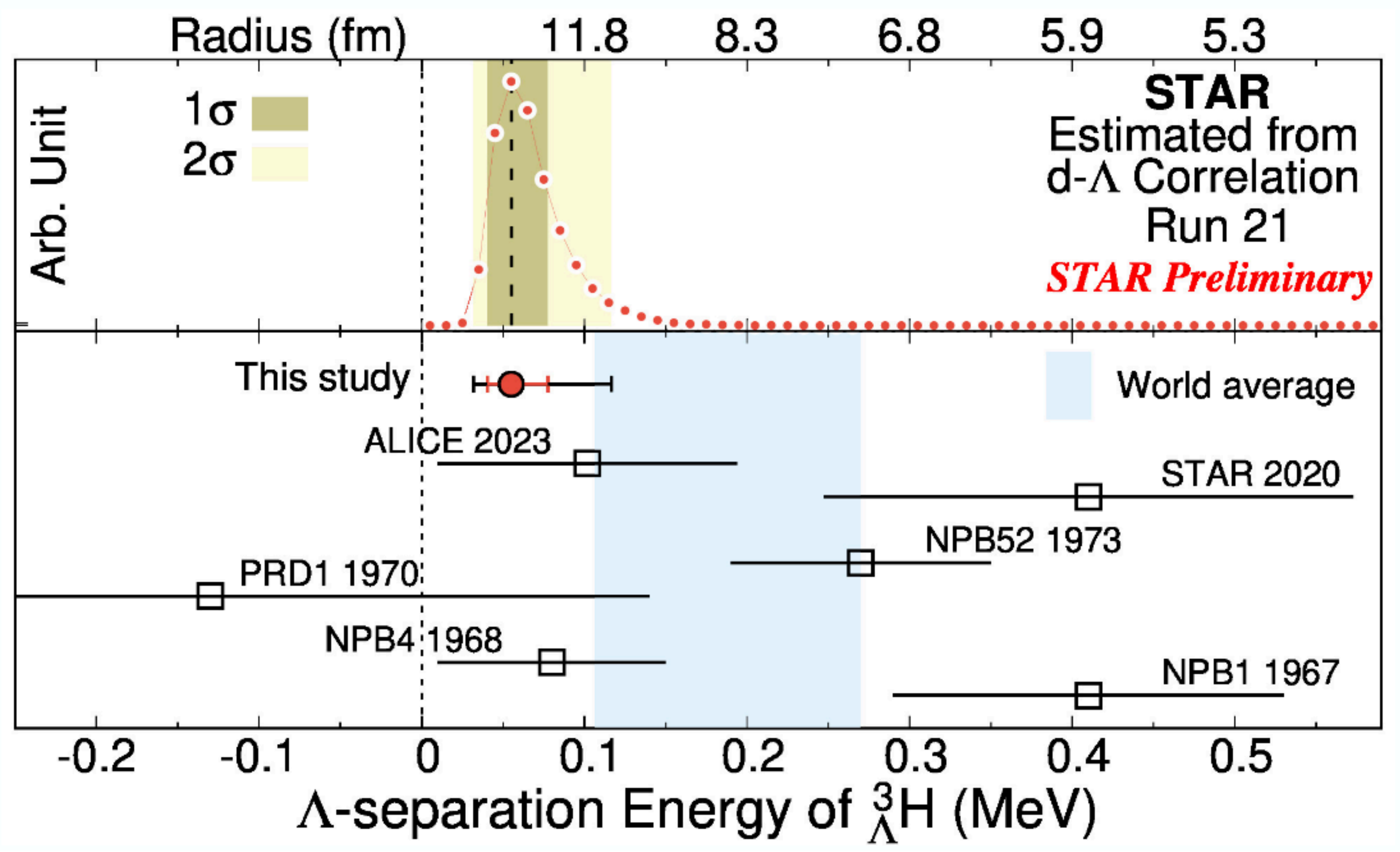
Critical to inform neutron star EOS

Probe using hypernuclei

- Thermal model over predicts all yields
- Evidence of excited states
- Extraction of BE possible in high μ_B region

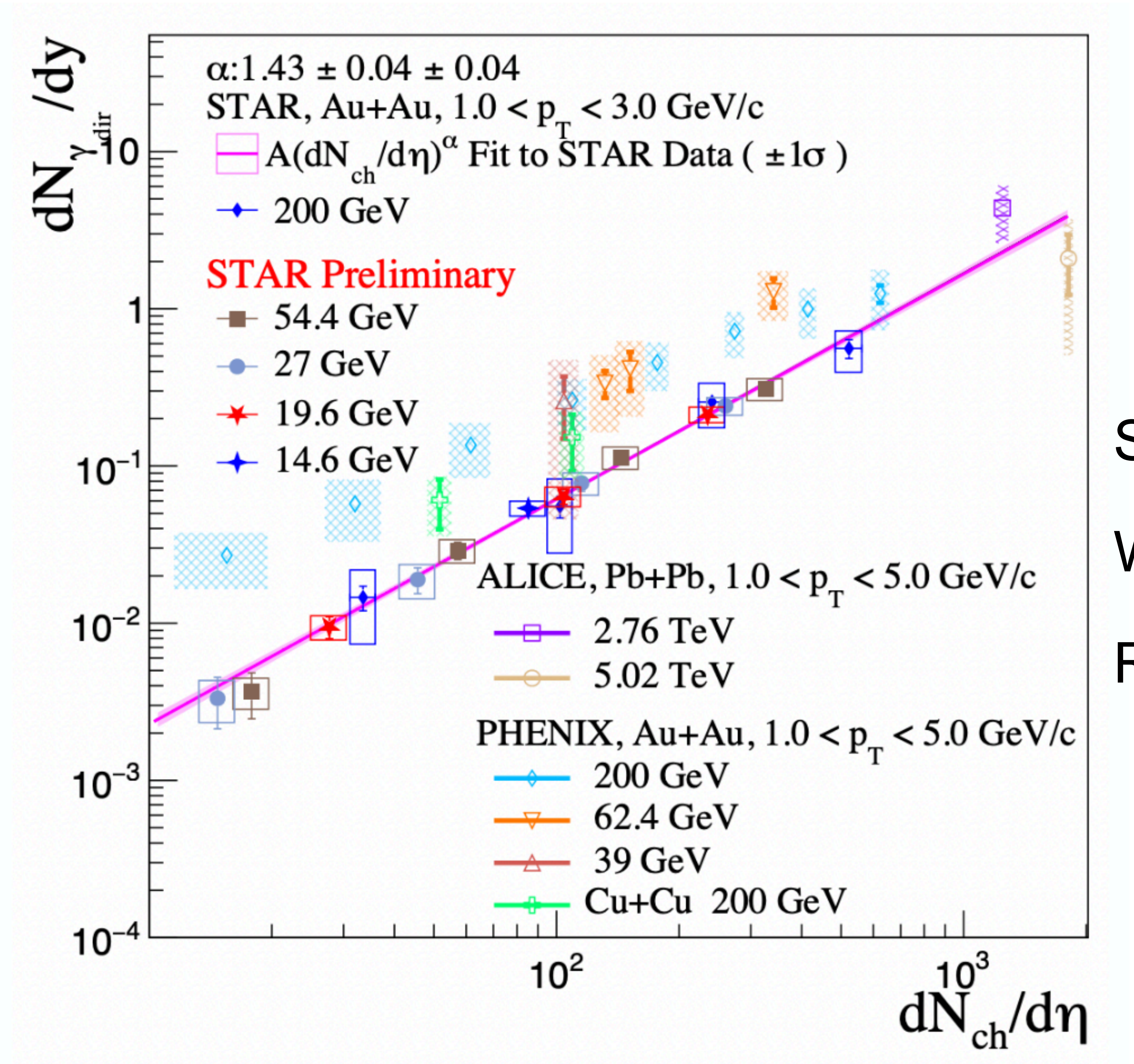
Precision studies are just beginning

nFXT region where production maximal



Other Open Questions

Direct virtual photons



Yield scales with multiplicity from
$\sqrt{s_{NN}}$ =14.6 GeV - 5 TeV

α = 1.43 0.04 0.02

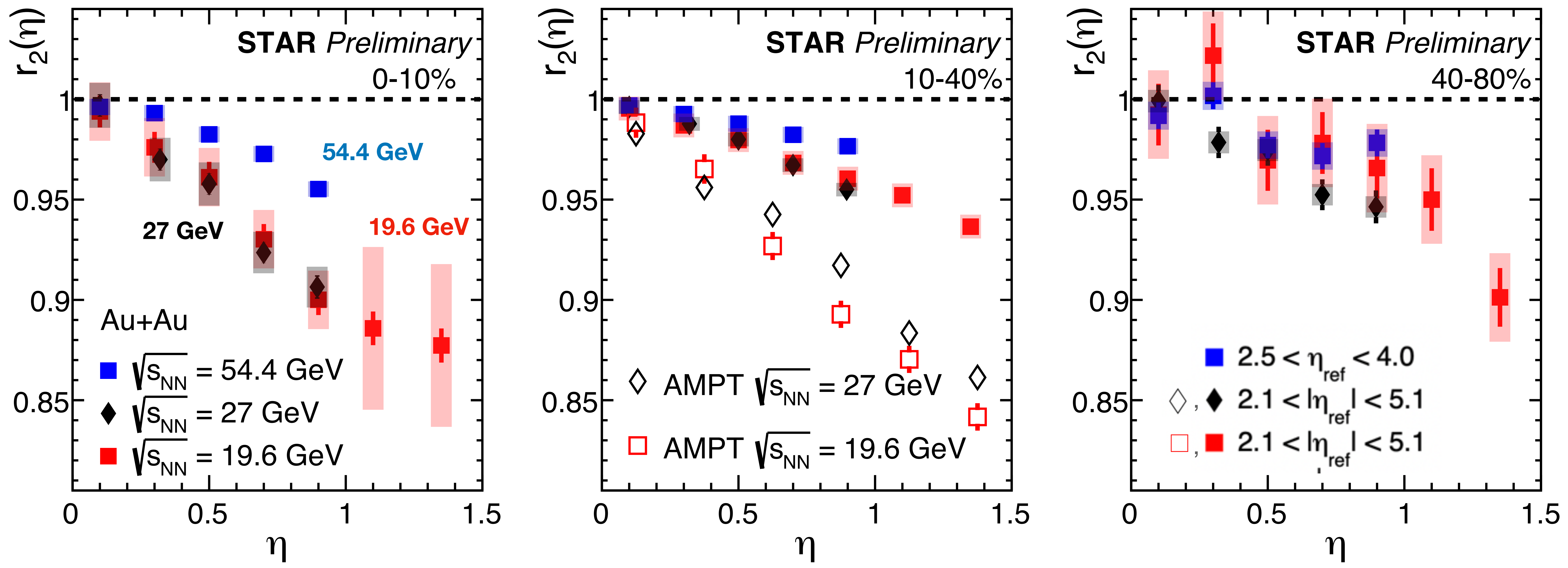
Scaling continues at lower collision energy?

What about other beam species?

Resolve offset between PHENIX and STAR

Asymmetric systems with nFXT?

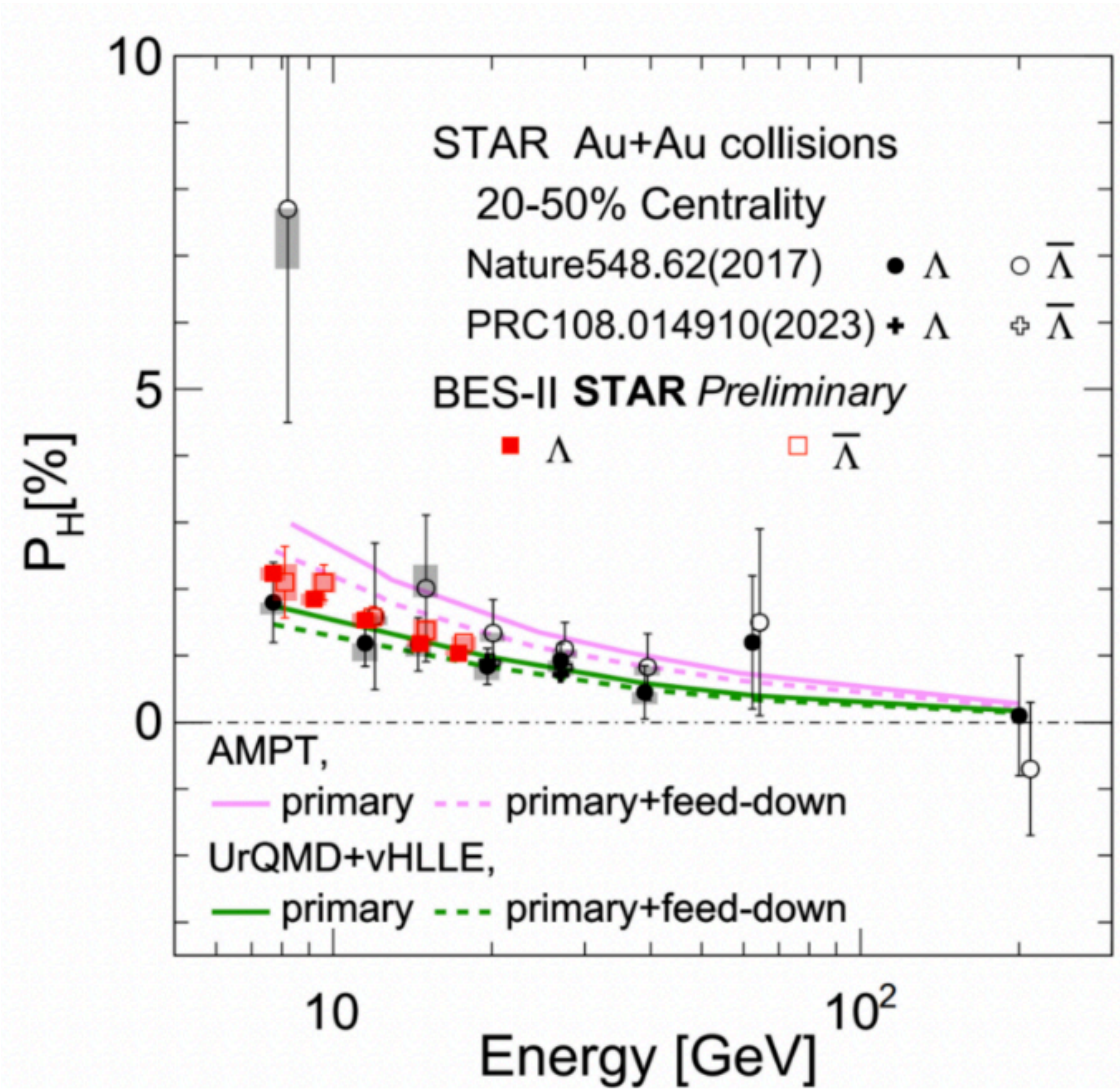
Longitudinal decorrelation

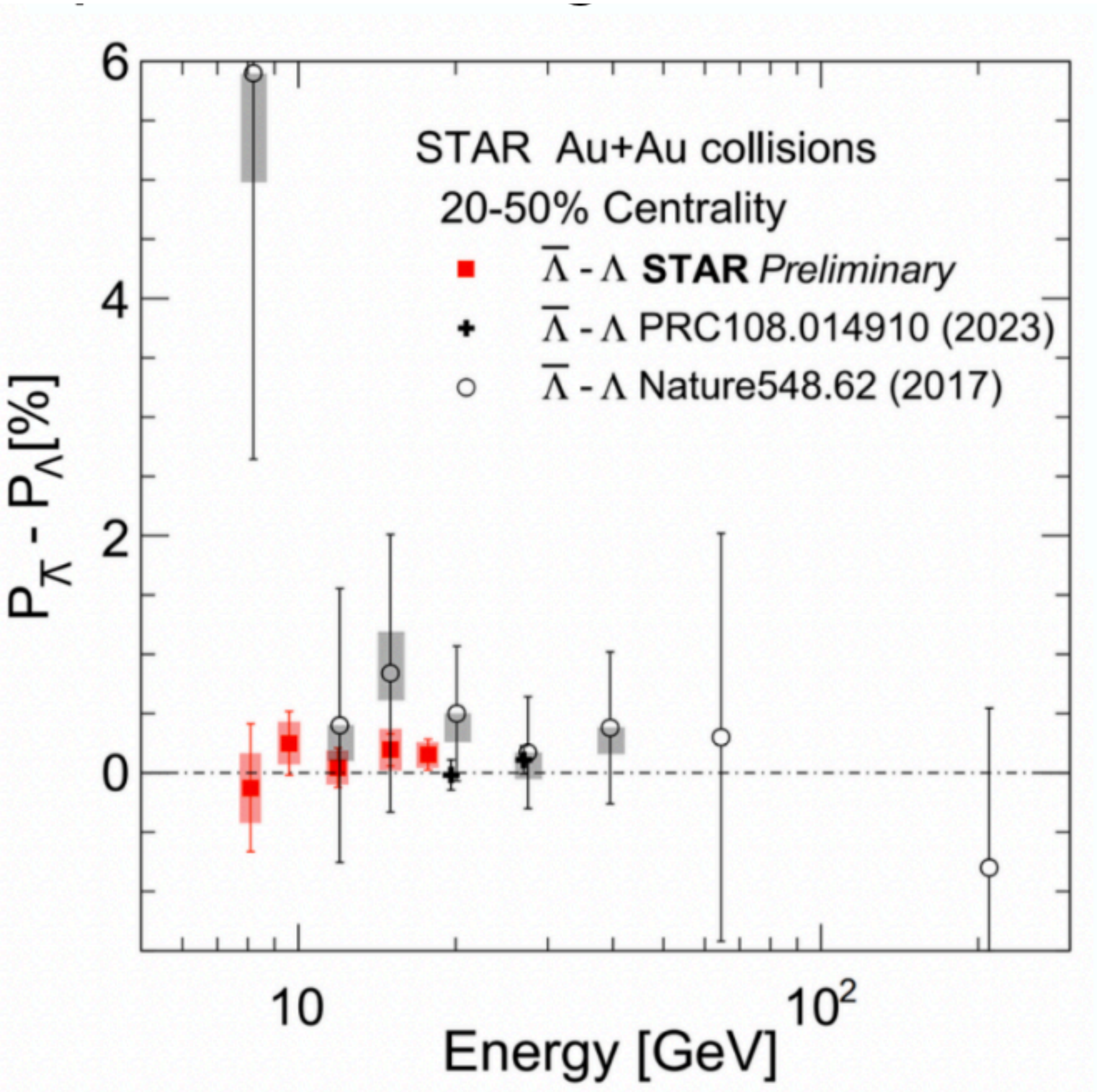


Strong decorrelation at RHIC energies (even stronger for r_3)
- Strongest in central events
- Increasing with decreasing collision energy
- AMPT too strong

3D dynamics important

What is the Magnetic Field Strength





$$(P_{\bar{\Lambda}} - P_{\Lambda}) \approx \frac{2|\mu_{\Lambda}|B}{T}$$

$$T = 150 \text{ MeV}$$

$$\mu_{\Lambda} = -1.93 \times 10^{-14} \text{ MeV/Tesla}$$

T - Temperature of emitting source
μ_{Λ} - magnetic moment of Λ

No global polarization splitting observed

Upper limit on late stage B-field B < 10^{13} Tesla (95% confidence)

Must be a magnetic field - dies away too quickly?
Can nFXT detect it? More theory needed

Summary

STAR BES-II

RHIC and STAR operated beyond our imagination

Motivating measurements achieved with precision stated

Despite incredible success of BES-II program many open questions remain and others have been generated

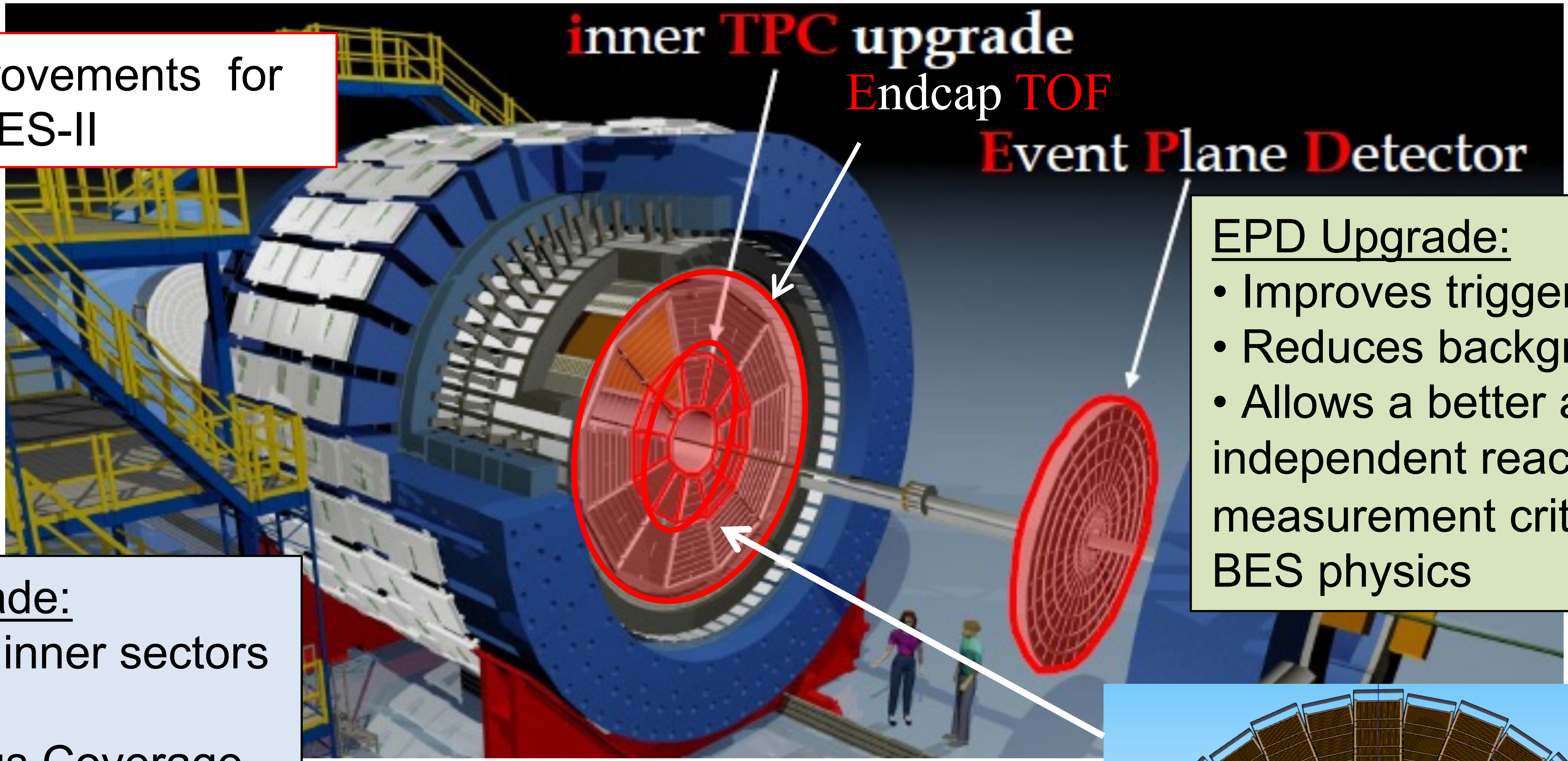
nFXT program will provide multiple unique opportunities over and above those from CBM, SHINE, HADES, NA60+

Possibility to answer what happens in the gap, provide pp(?) and pA baselines, other species

END IS HERE

The upgrades

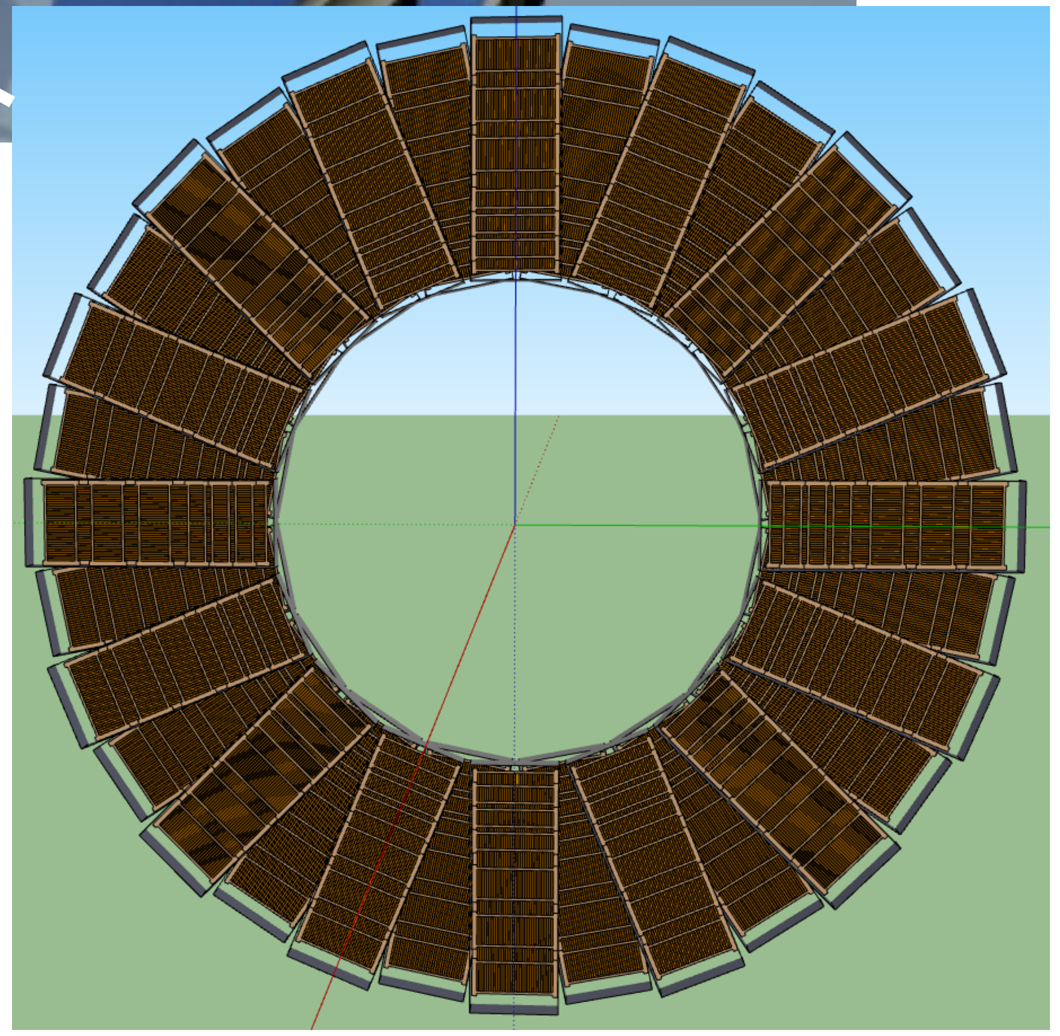
Major improvements for BES-II



EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

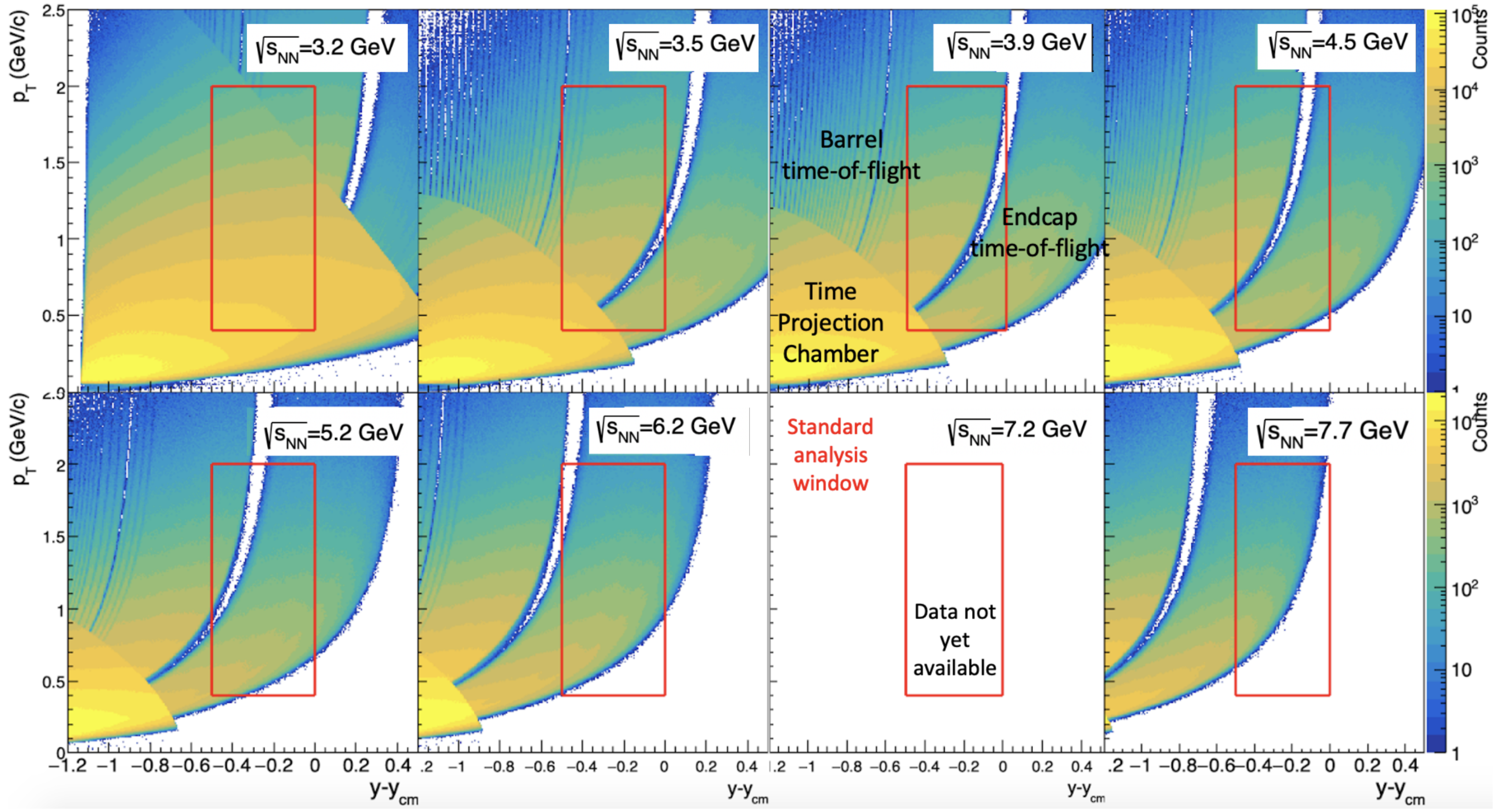
iTPC Upgrade:
- Replaced inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



All worked during BES-II

FXT proton acceptance



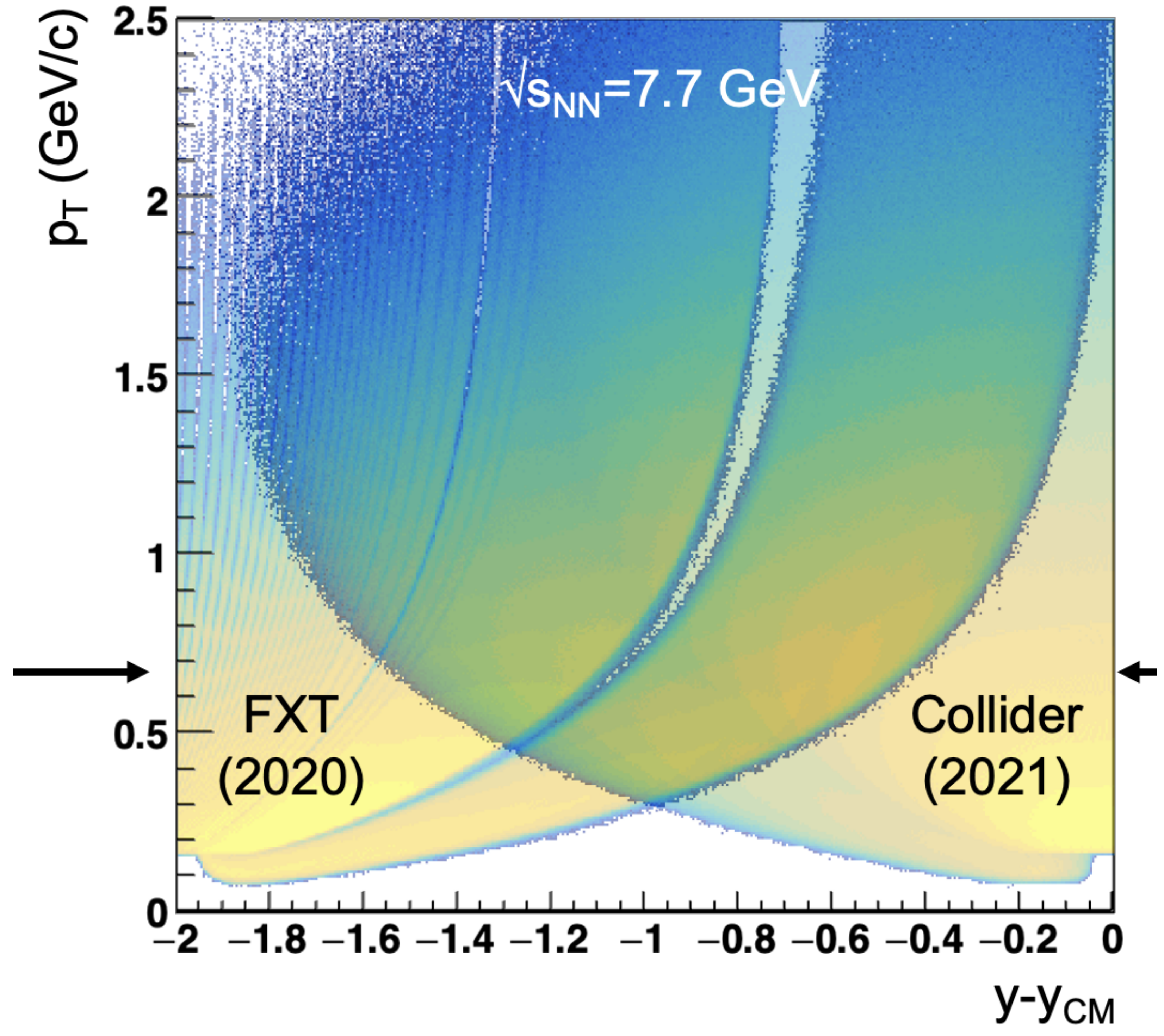
Red box: Standard analysis window

0.4< p_T < 2 GeV/c

-0.5 < y-y_{cm} < 0

Near-full acceptance to 4.5 GeV

Top energies need to move away from mid-rapidi



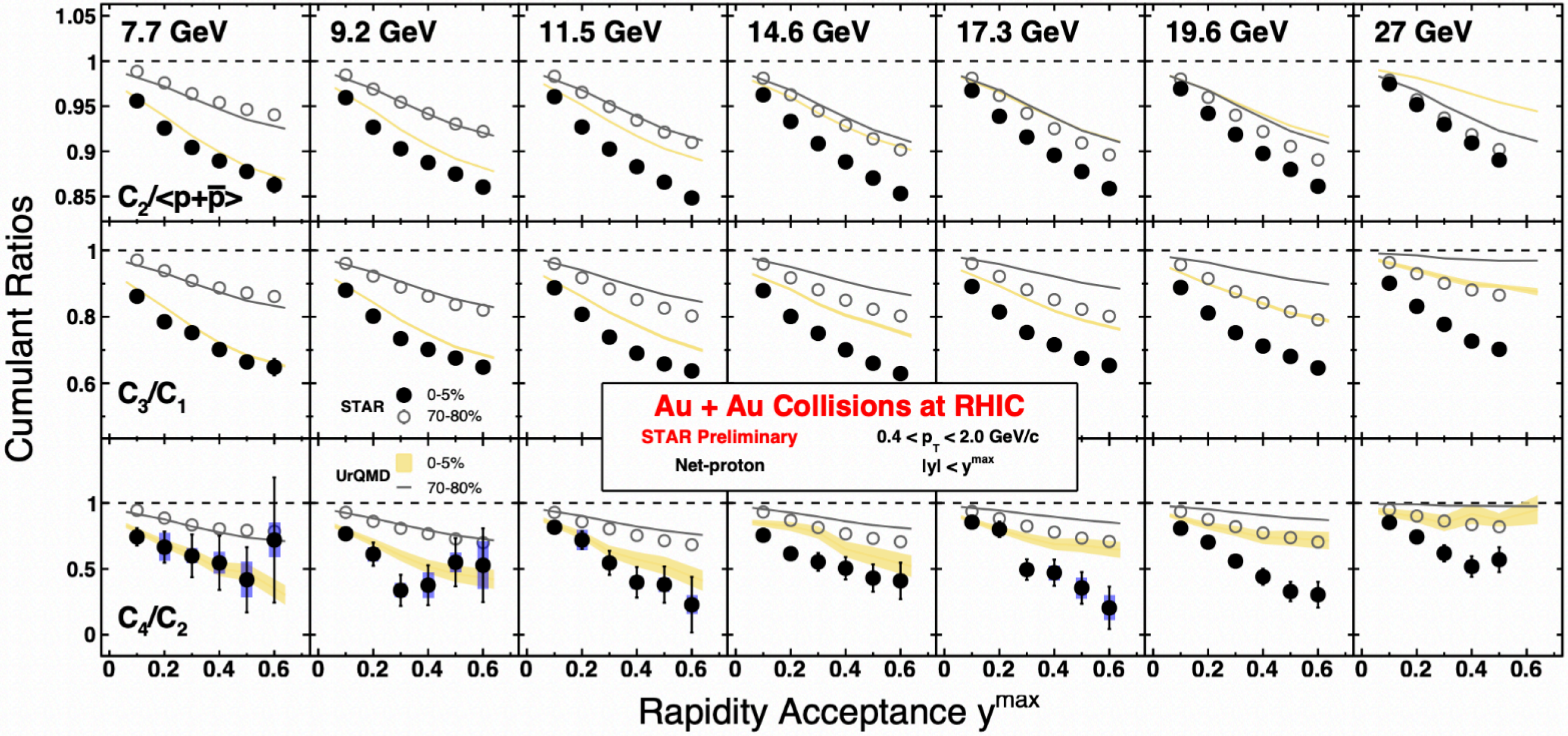
7.7 taken in both FXT and collider mode

Good overlap in acceptance

Critical for methodology comparison

Cumulants vs Acceptance

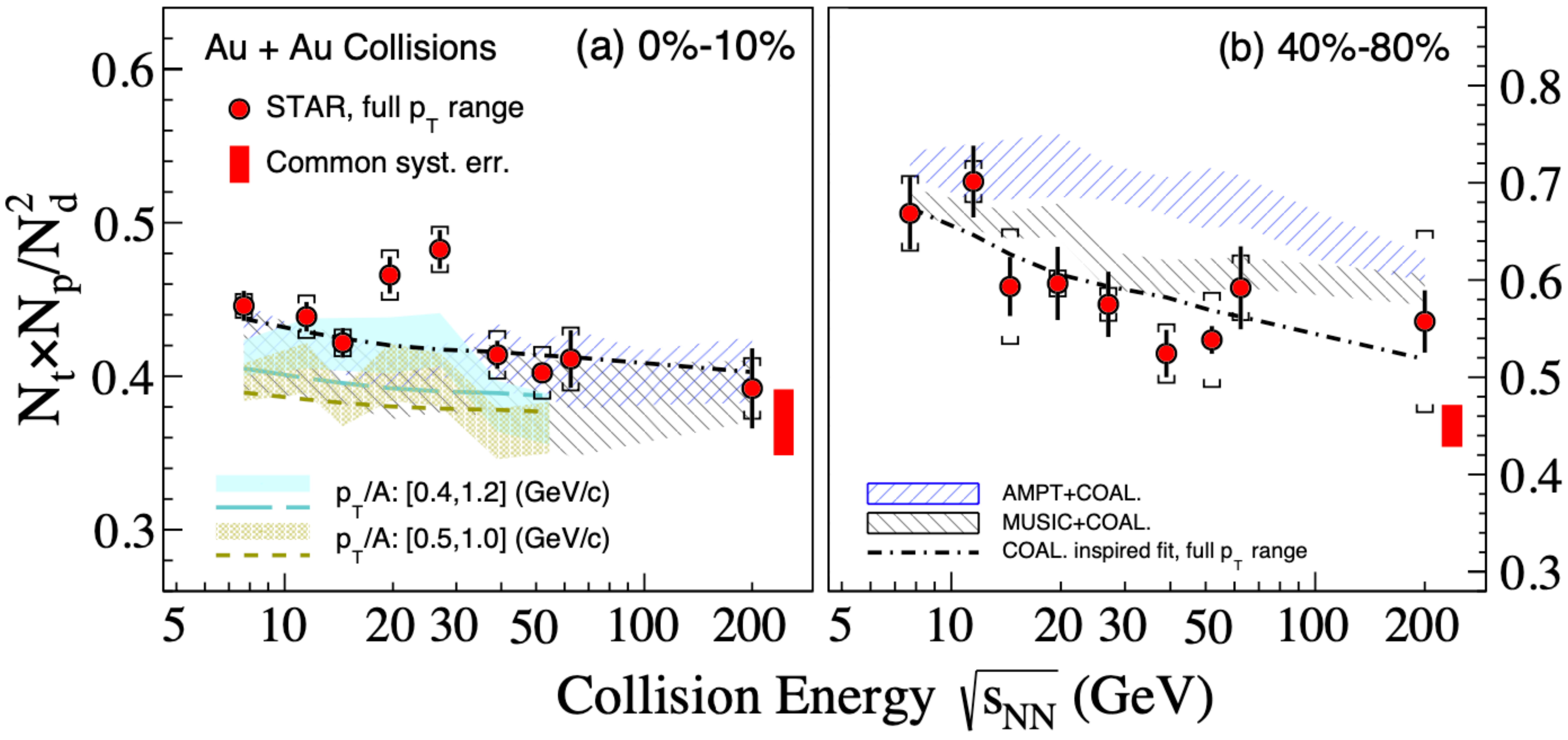
- Widening y, p_T windows of measurement enhances potential critical contributions



- Deviation from UrQMD increases with y acceptance and near 20 GeV

Light nuclei Ratio

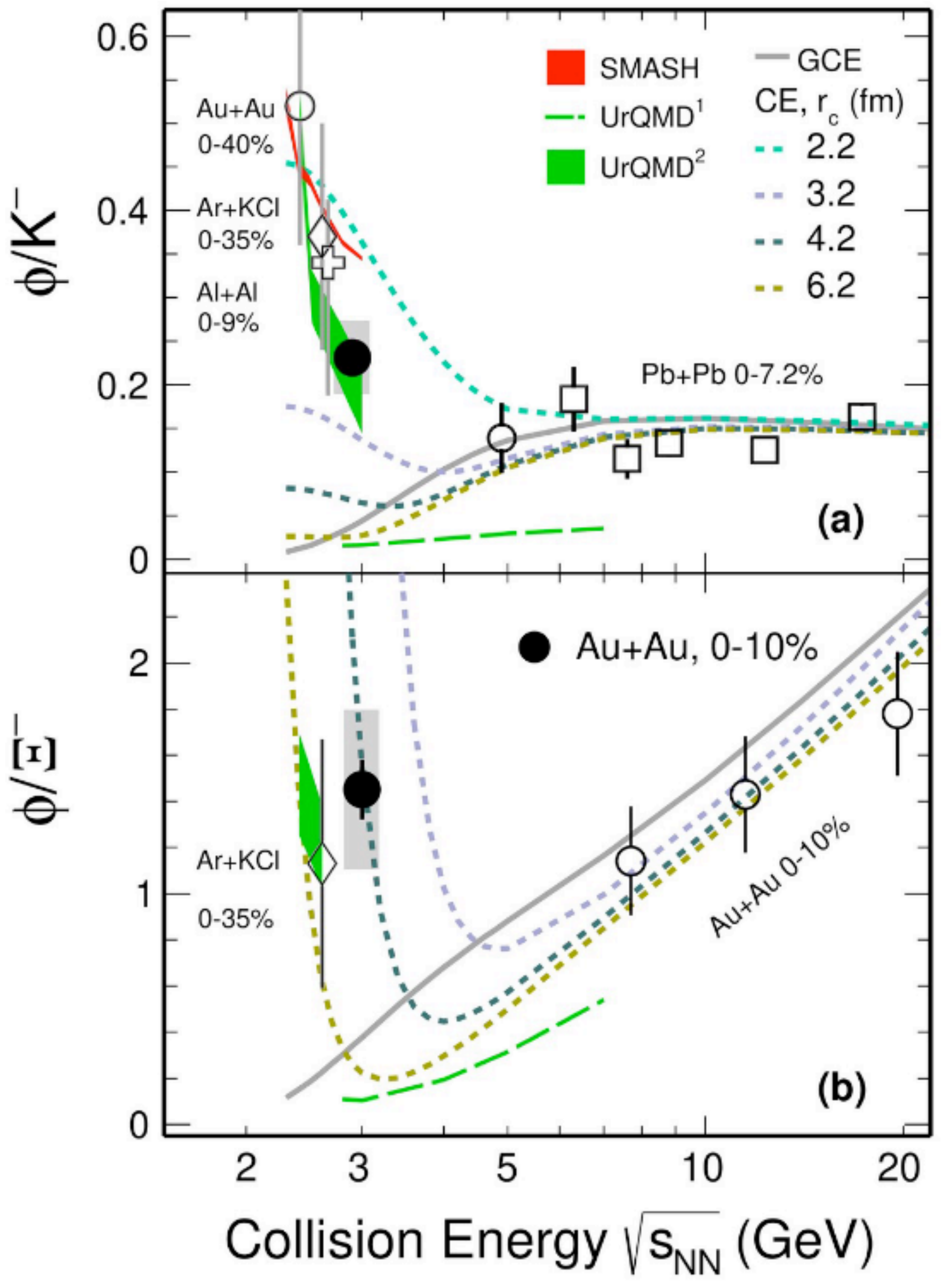
PRL 130 (2023) 202301

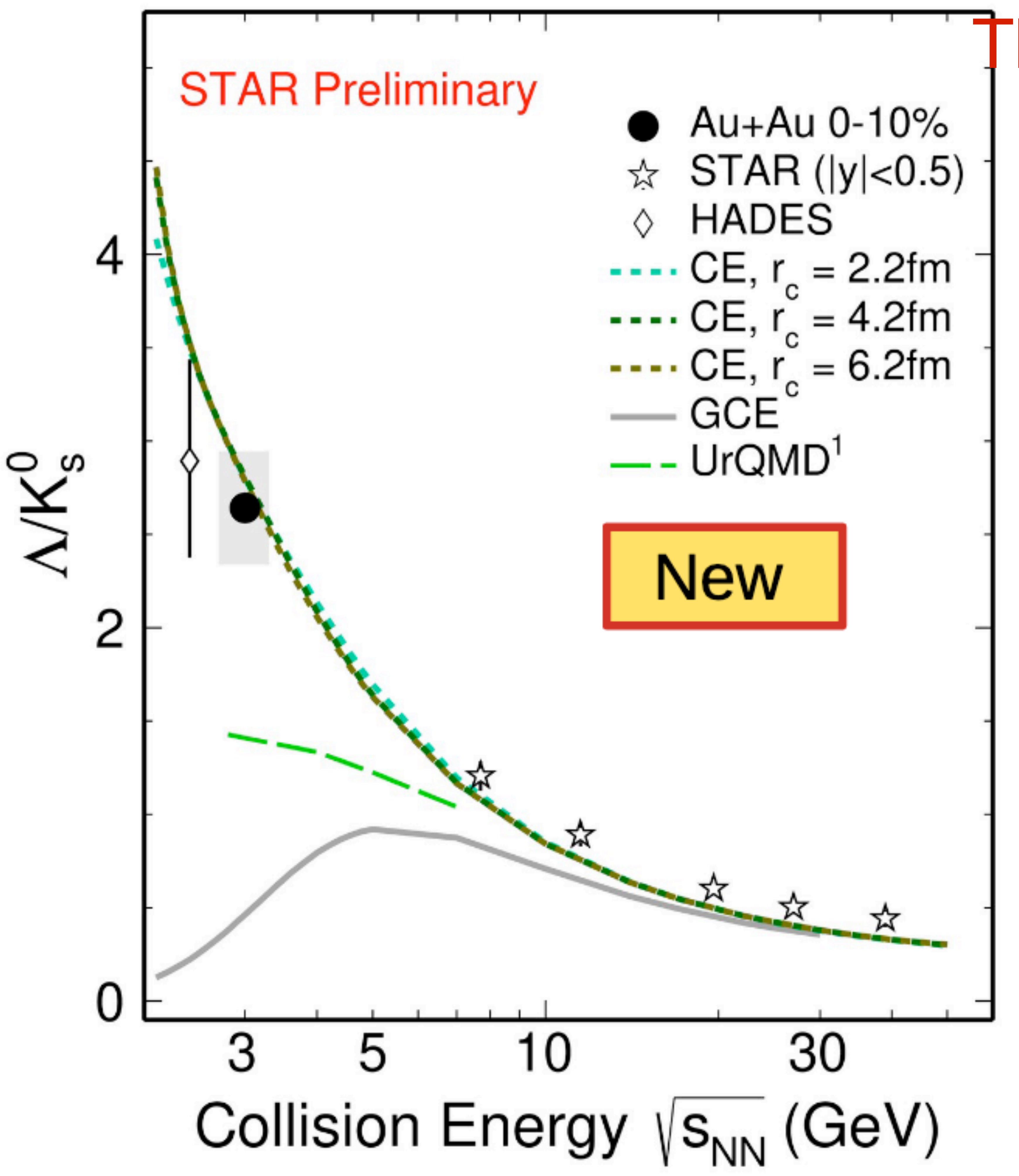


N_tN_p/N_d^2, sensitive to fluctuations of the local neutron density shows enhancements relative to the coalescence baseline with a significance of 2.3σ and 3.4σ respectively in 0 –10% central Au+Au collisions at 19.6 and 27 GeV.

Constrain production dynamics of light nuclei and understanding of the QCD phase diagram

Strangeness production





Things change at $\sqrt{s_{NN}}$ = 3 GeV

Collision energy:

below threshold for Ξ

very close to threshold for ϕ

Small strangeness correlation radius preferred

$r_C \lesssim 4.2$ fm

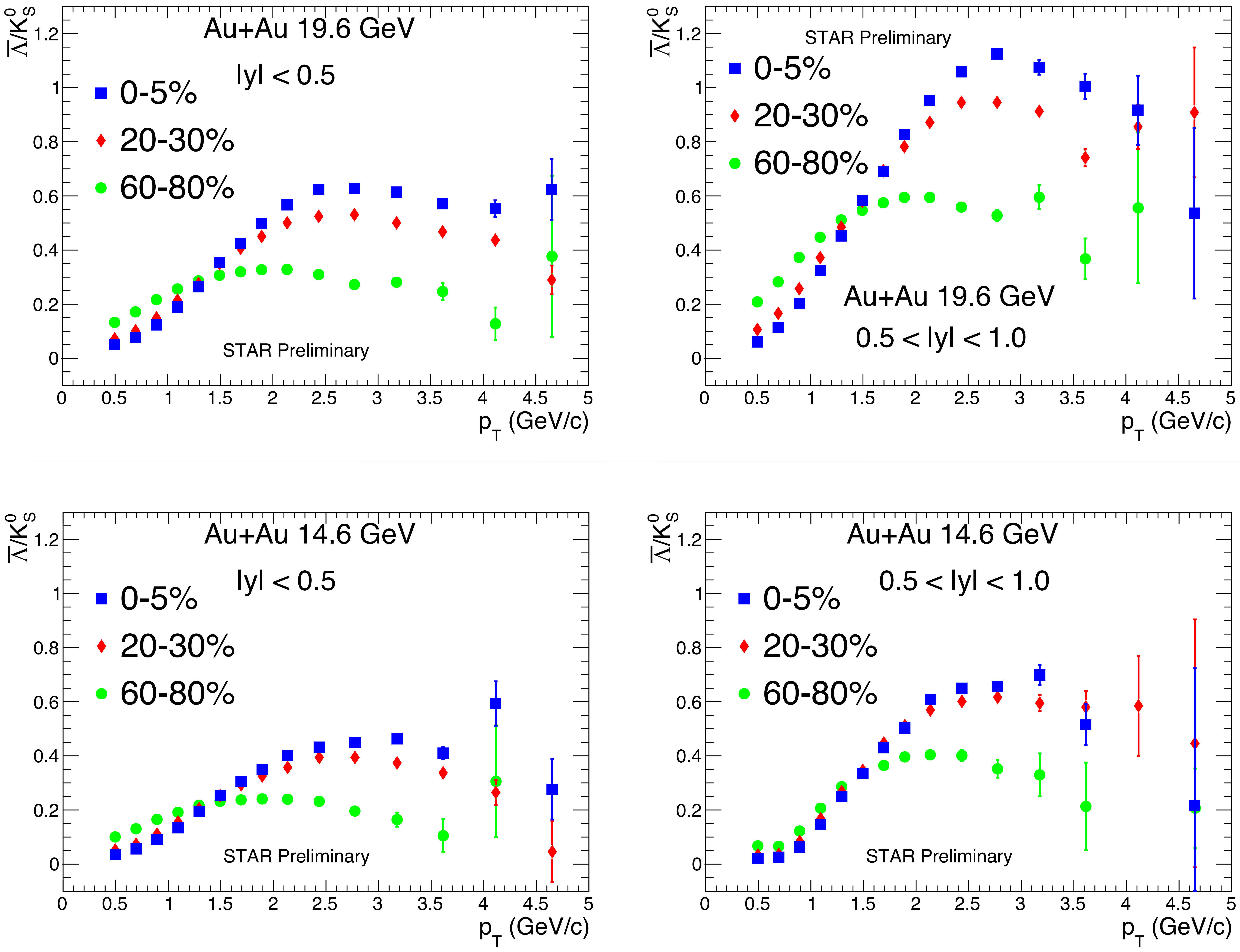
Local strangeness conservation is crucial

CE cannot simultaneously describe ϕ/K⁻ and ϕ/Ξ⁻ ratios

significant change in strangeness production at this low energy

ata compilation: arXiv: 2108.00924
TAR: Phys. Rev. C 102 (2020) 34909
ADES: Eur. Phys. J. A (2016) 52: 178
rQMD¹: Prog. Part. Nucl. Phys. 41
1998) 225-370
rQMD²: J. Phys. G: Nucl. Part. Phys.
3, 015104 (2015)
MASH: Phys. Rev. C 99, 064908
2019).
hermal CE: Phys. Lett. B 603, 146
2004)

Rapidity dependence of anti-baryon enhancement



Anti-Baryon/Meson ratio increases with:

- collision energy
- centrality
- rapidity

Increased coalesence or fragments at higher rapidity?

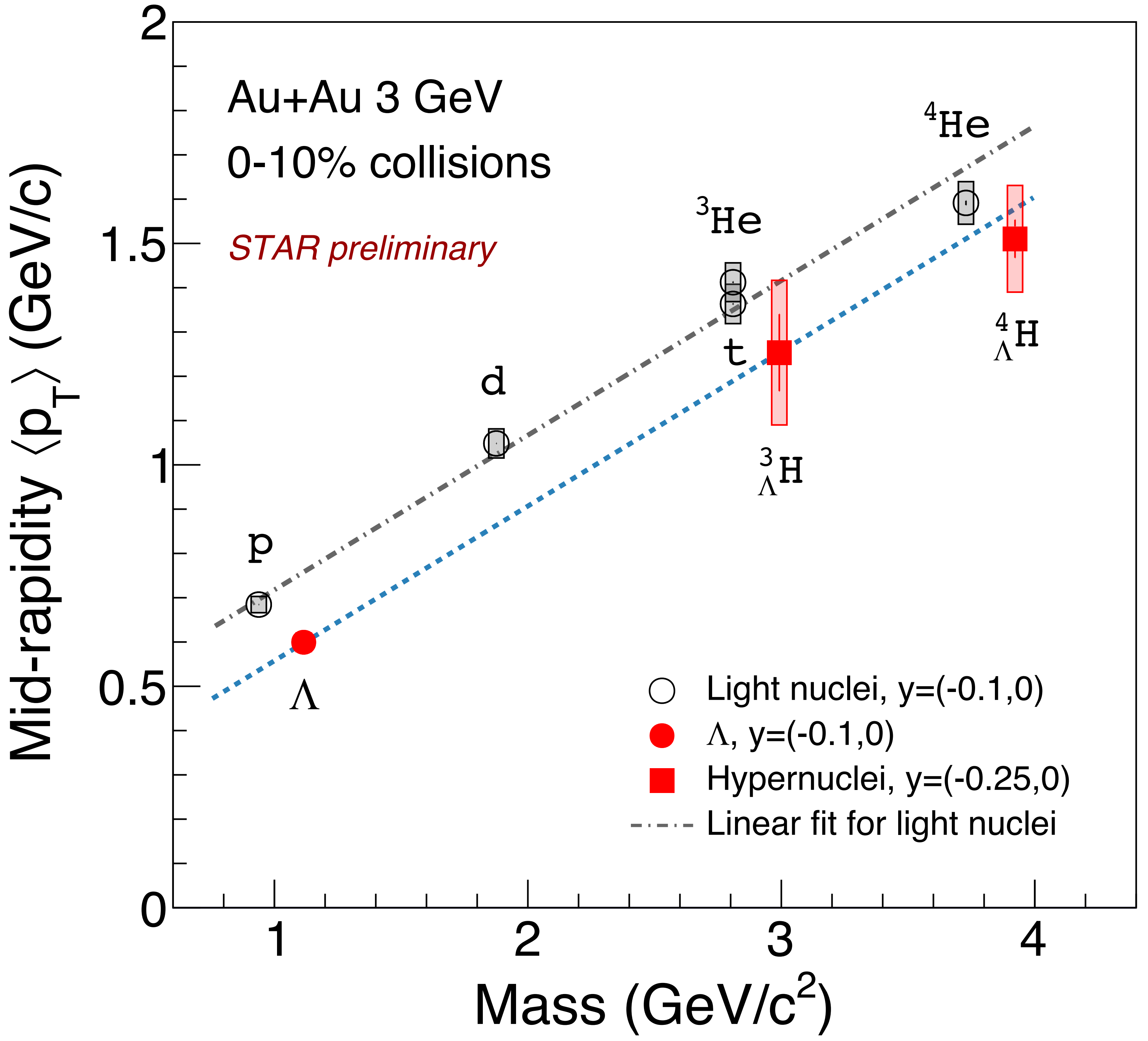
Significant enhancement above cocktail

Low mass range

Intermediate mass range

Something interesting occurring in both mass ranges for several collision energies

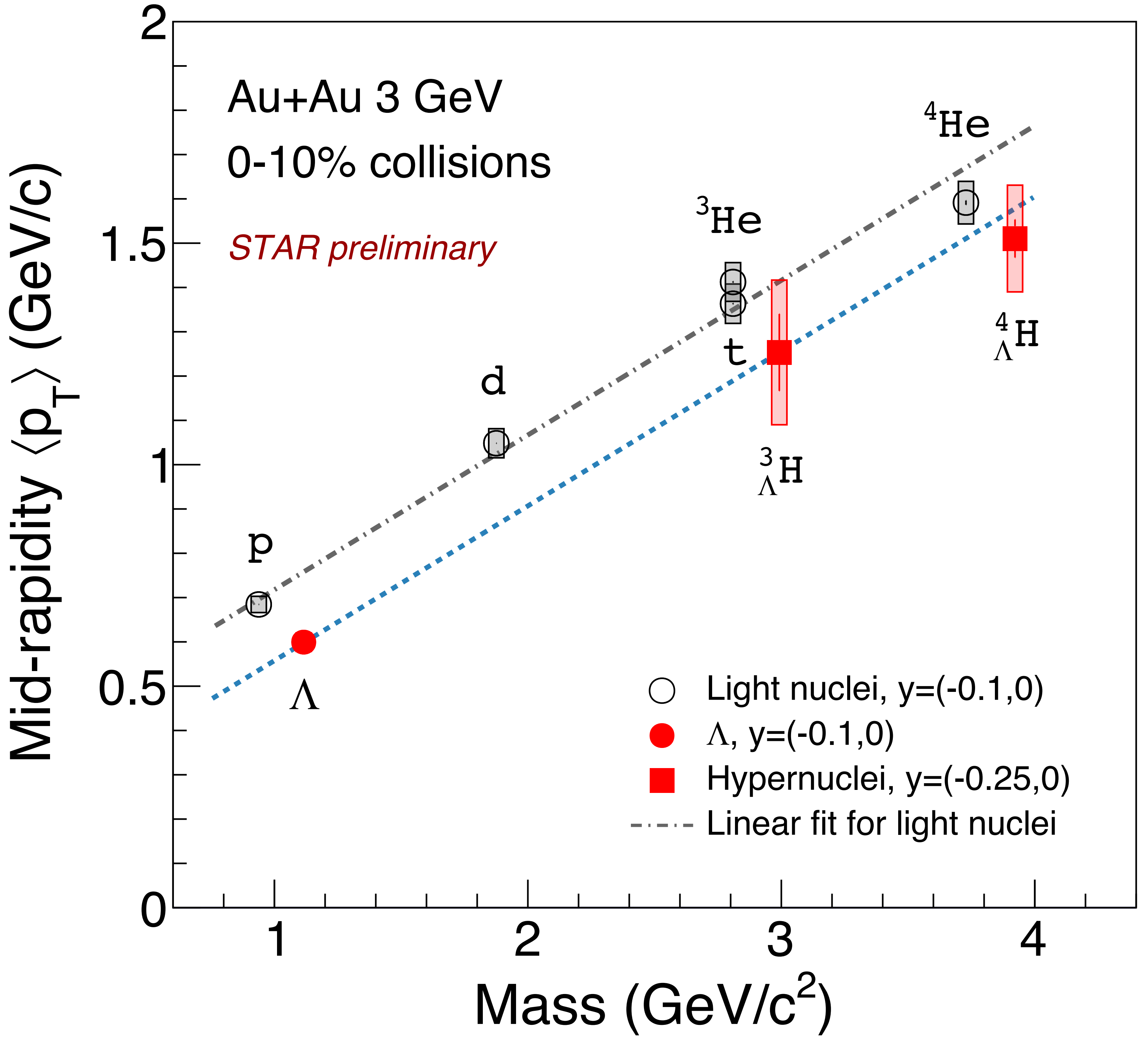
Hypernuclei kinematics

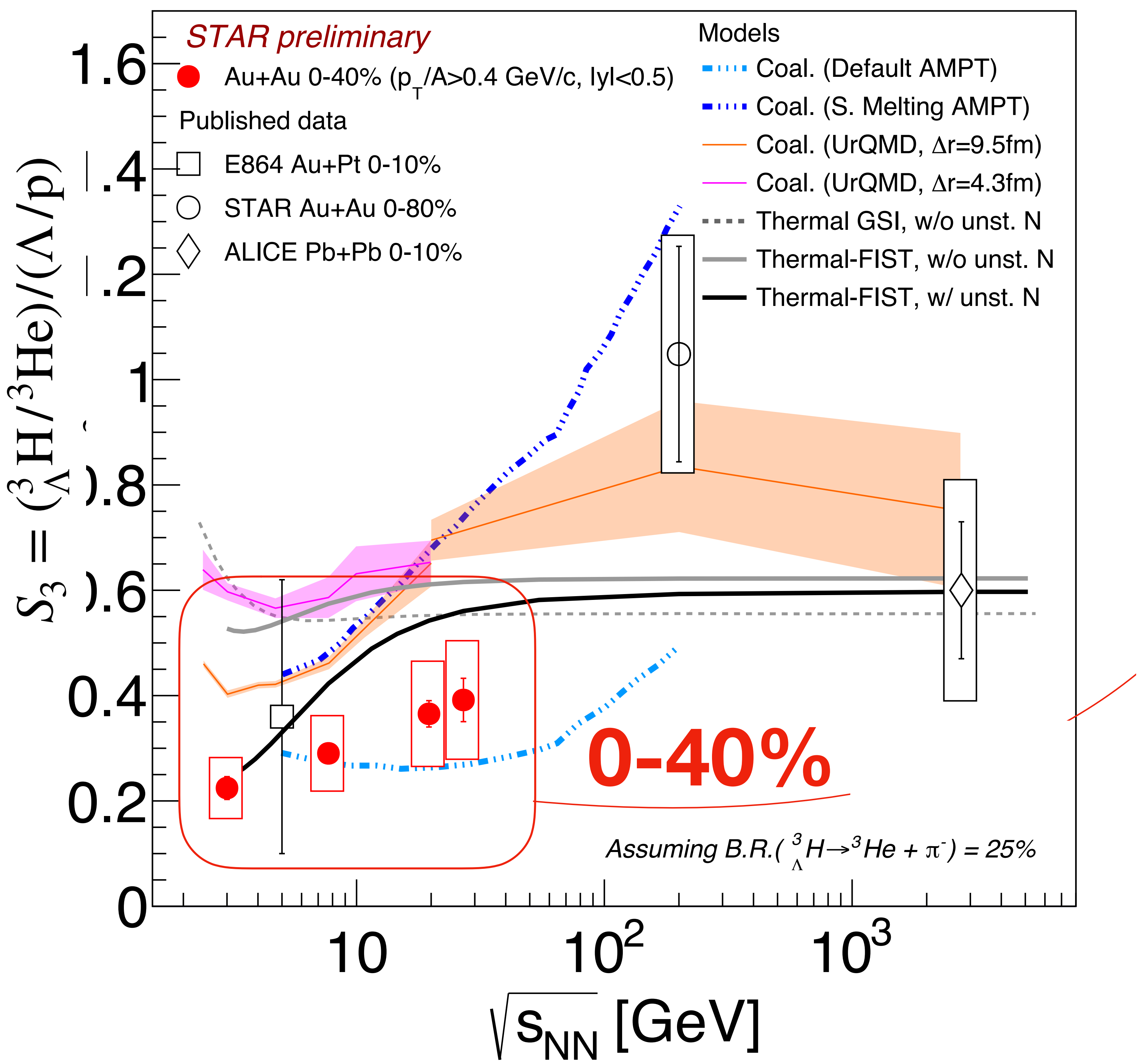


Including Λ reduces $<p_T>$

Mass number scaling preserved

Hypernuclei kinematics





Including Λ reduces $<p_T>$

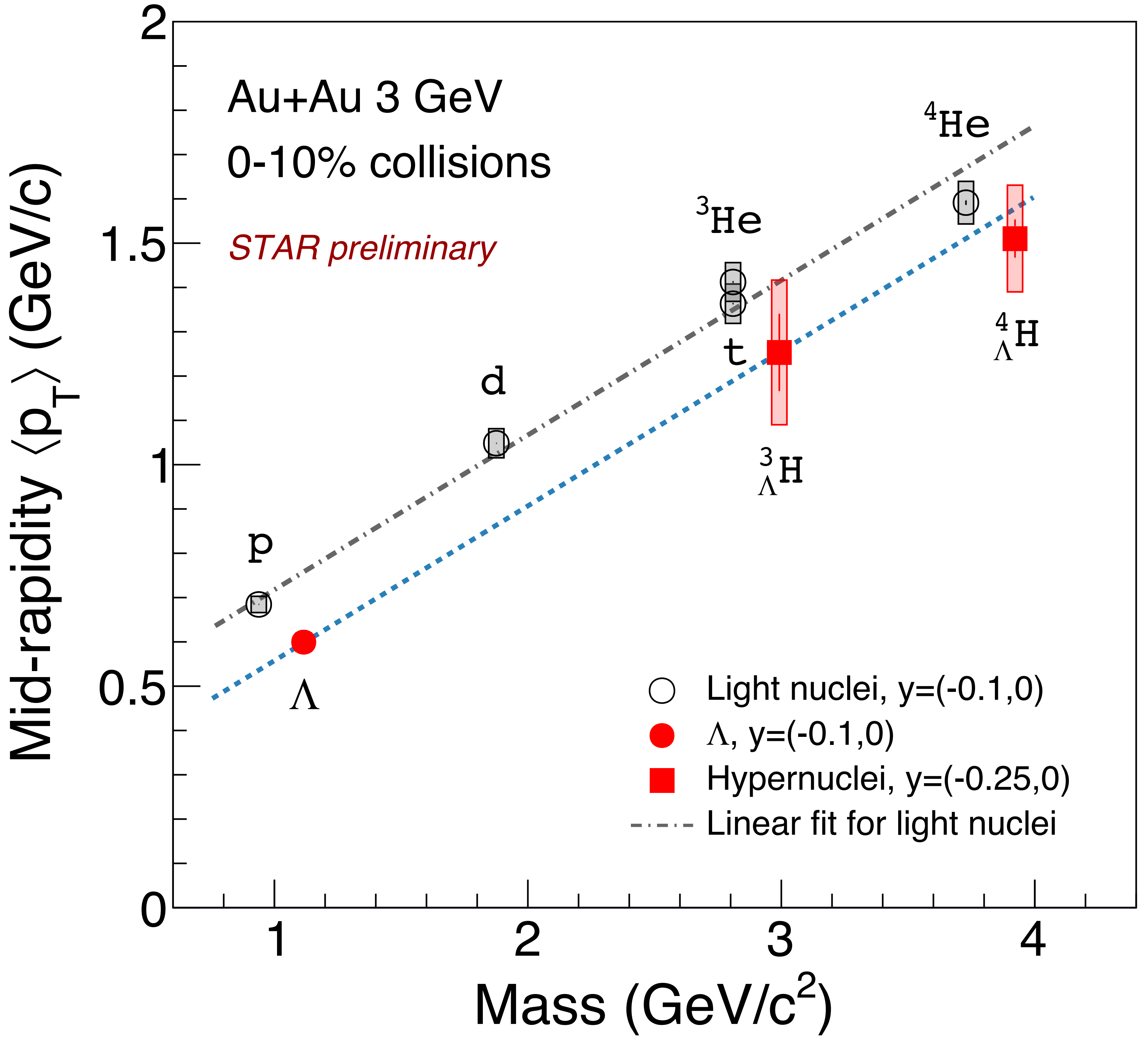
Mass number scaling preserved

S_3 increases with $\sqrt{s_{NN}}$

Increasing feed-down to ^{3}He from unstable nuclei?

Suppression at low $\sqrt{s_{NN}}$?

Hypernuclei kinematics



Including Λ reduces <p_T>

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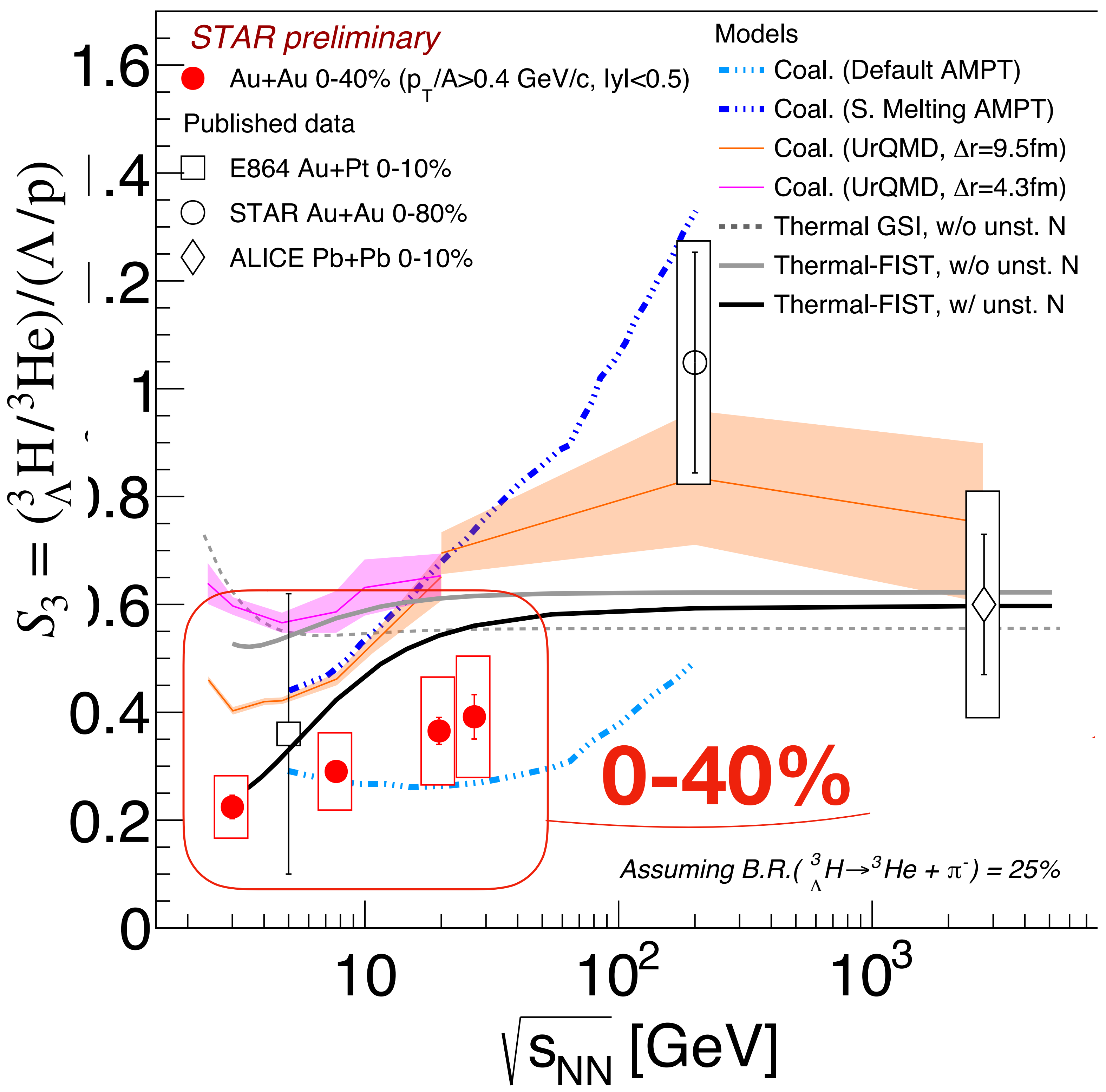

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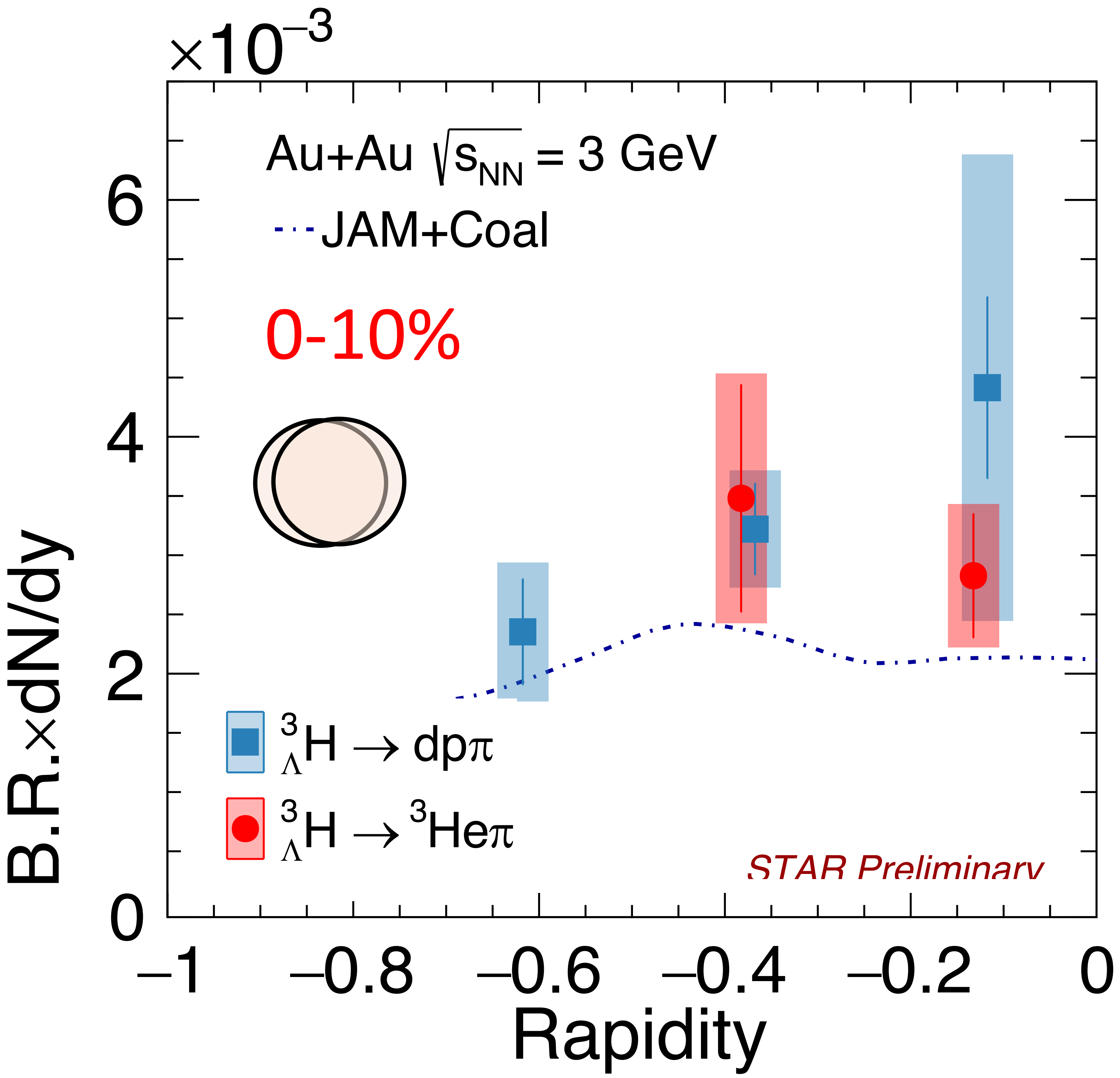
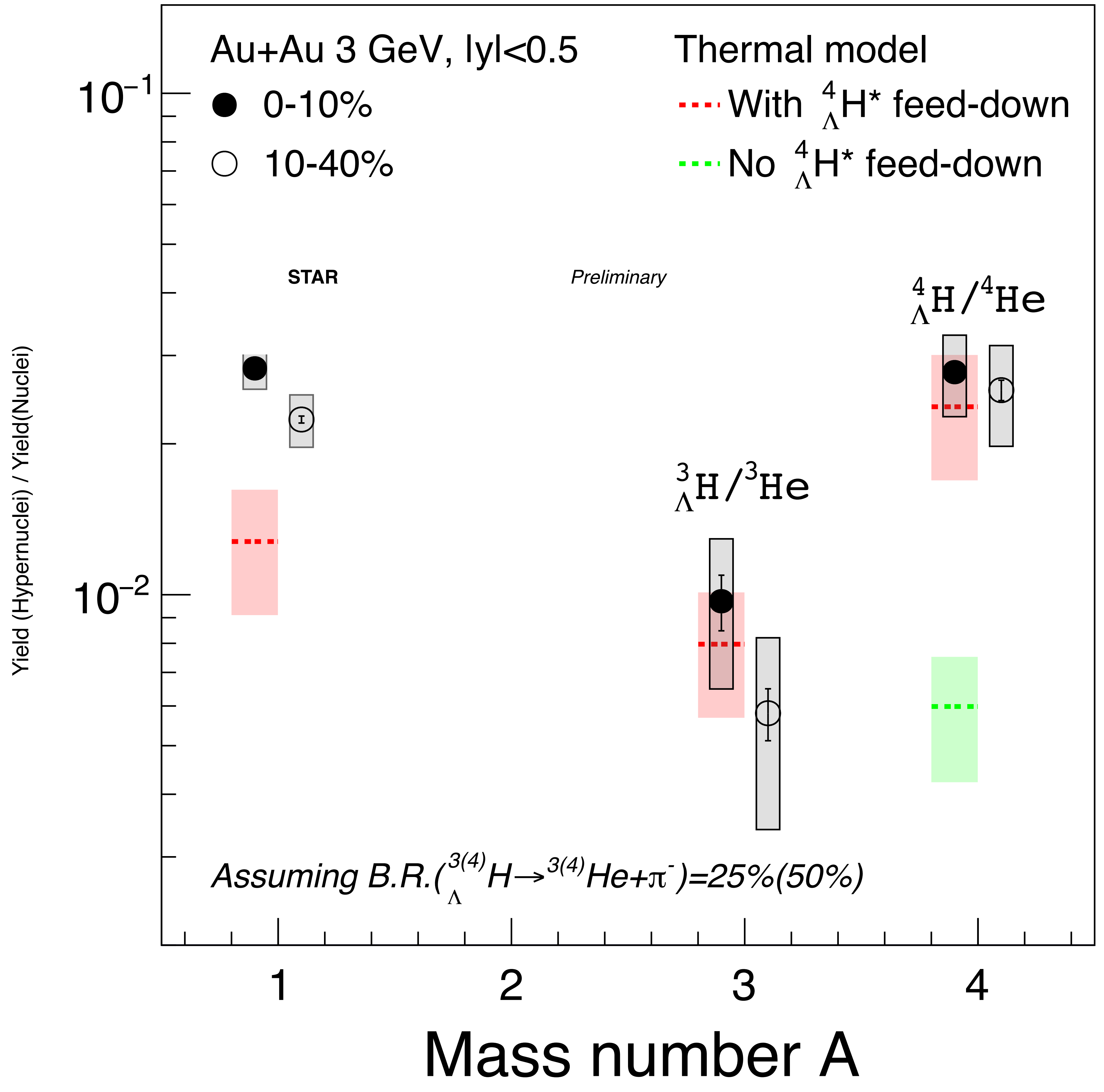


Different decay channels give consistent distribution

JAM + Coalescence give reasonable description

Adding a hyperon enhances sensitivity

Excited hypernuclei are also created



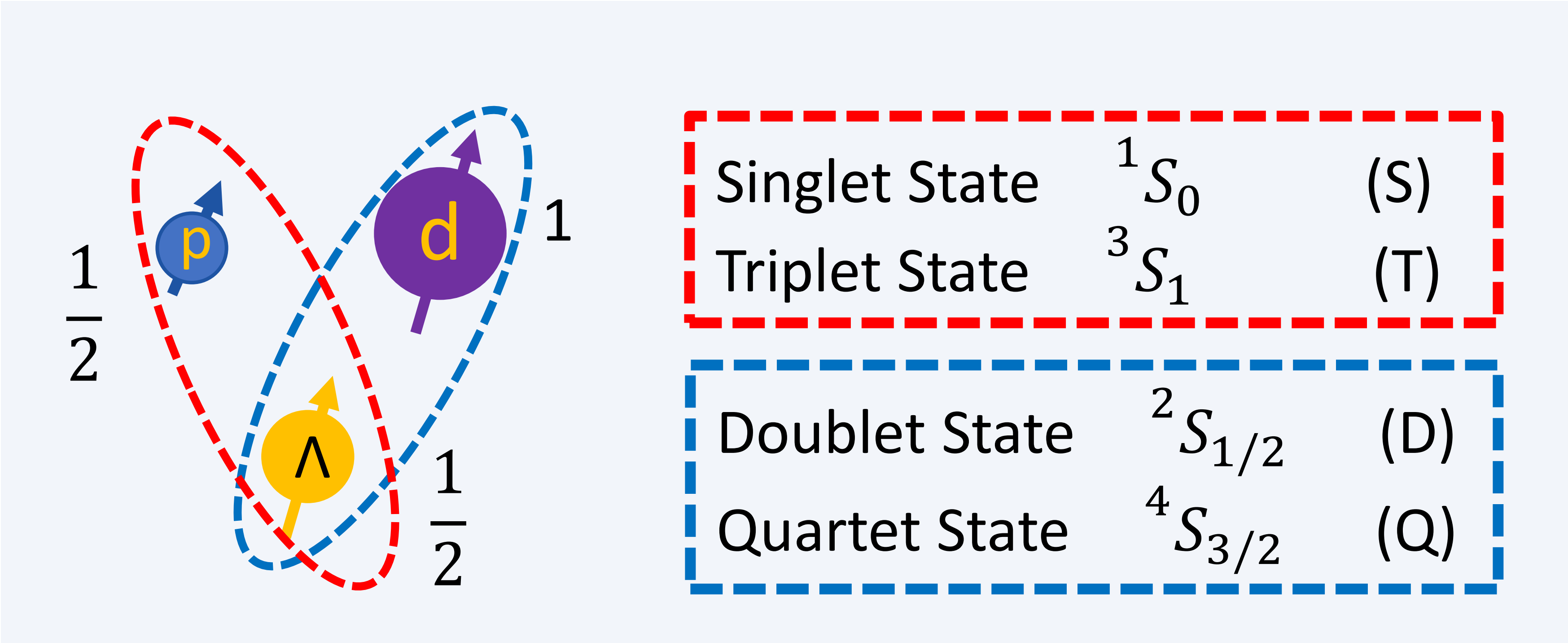
Evidence of formation of excited hypernuclei states in heavy ion collisions

Correlations with hyperons

p-Λ and d-Λ correlations explore:
N-(-N)Y interactions and hyper nuclei structure

R_G : Spherical Gaussian source size
f_0 : scattering length
d_0 : effective range

Expect different f_0 and d_0 from difference spin states



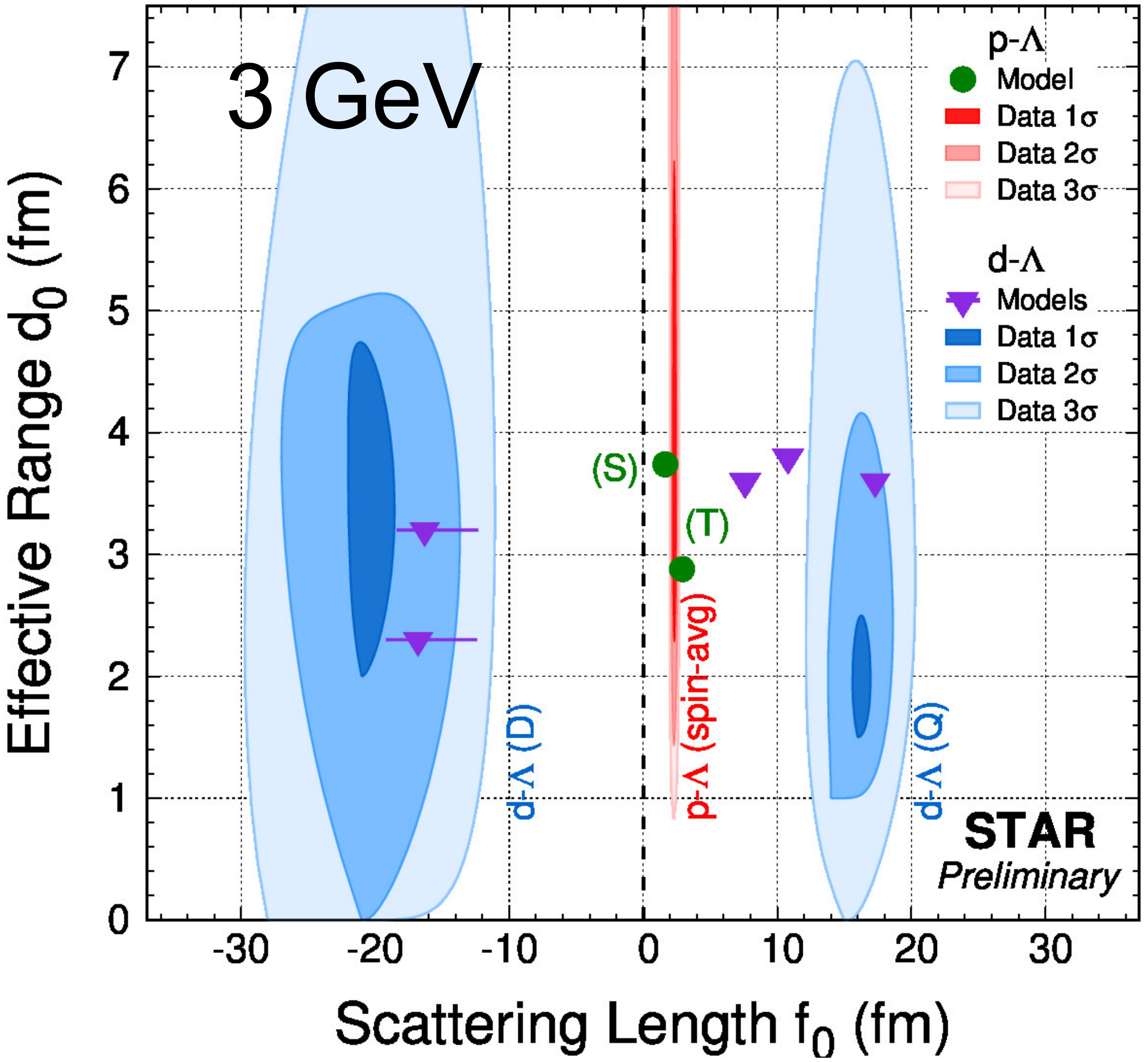
Separating source size and FSI

R_G ~ 2-3 fm

$R_G^{central} > R_G^{peripheral}$

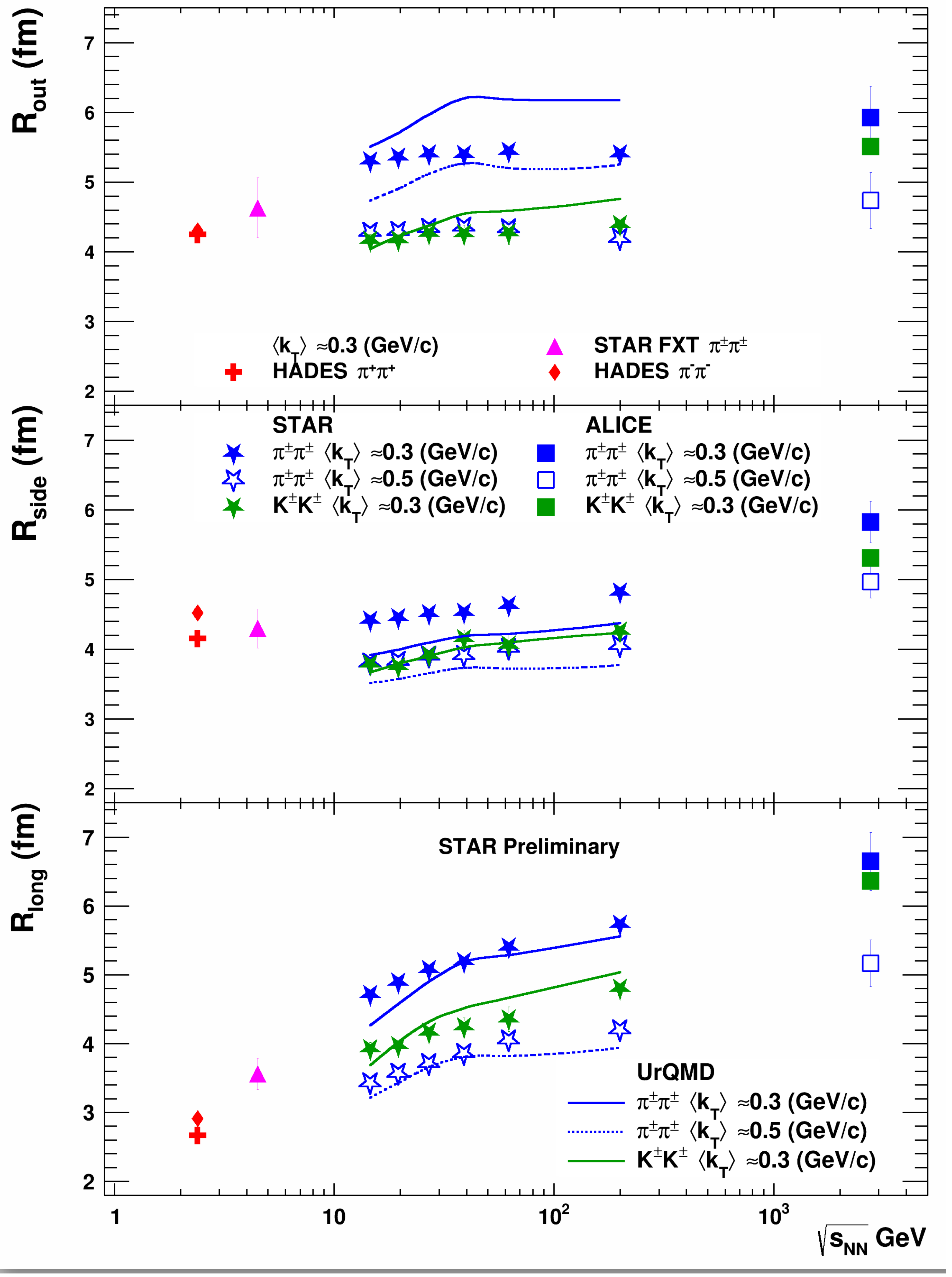
$R_G^{(p\text{-}\Lambda)} > R_G^{(d\text{-}\Lambda)}$

10x stats still to come



- Spin-avg for f_0 & d_0 p- system
- $f_0 = 2.32^{+0.12}_{-0.11}\text{fm},\ d_0 = 3.54^{+2.7}_{-1.3}\text{fm}$
- Separate two spin states in d-Λ
- $f_0(D) = -20^{+3}_{-3}\text{fm},\ d_0(D) = 3^{+2}_{-1}\text{fm}$
- $f_0(Q) = 16^{+2}_{-1}\text{fm},\ d_0(Q) = 2^{+1}_{-1}\text{fm}$

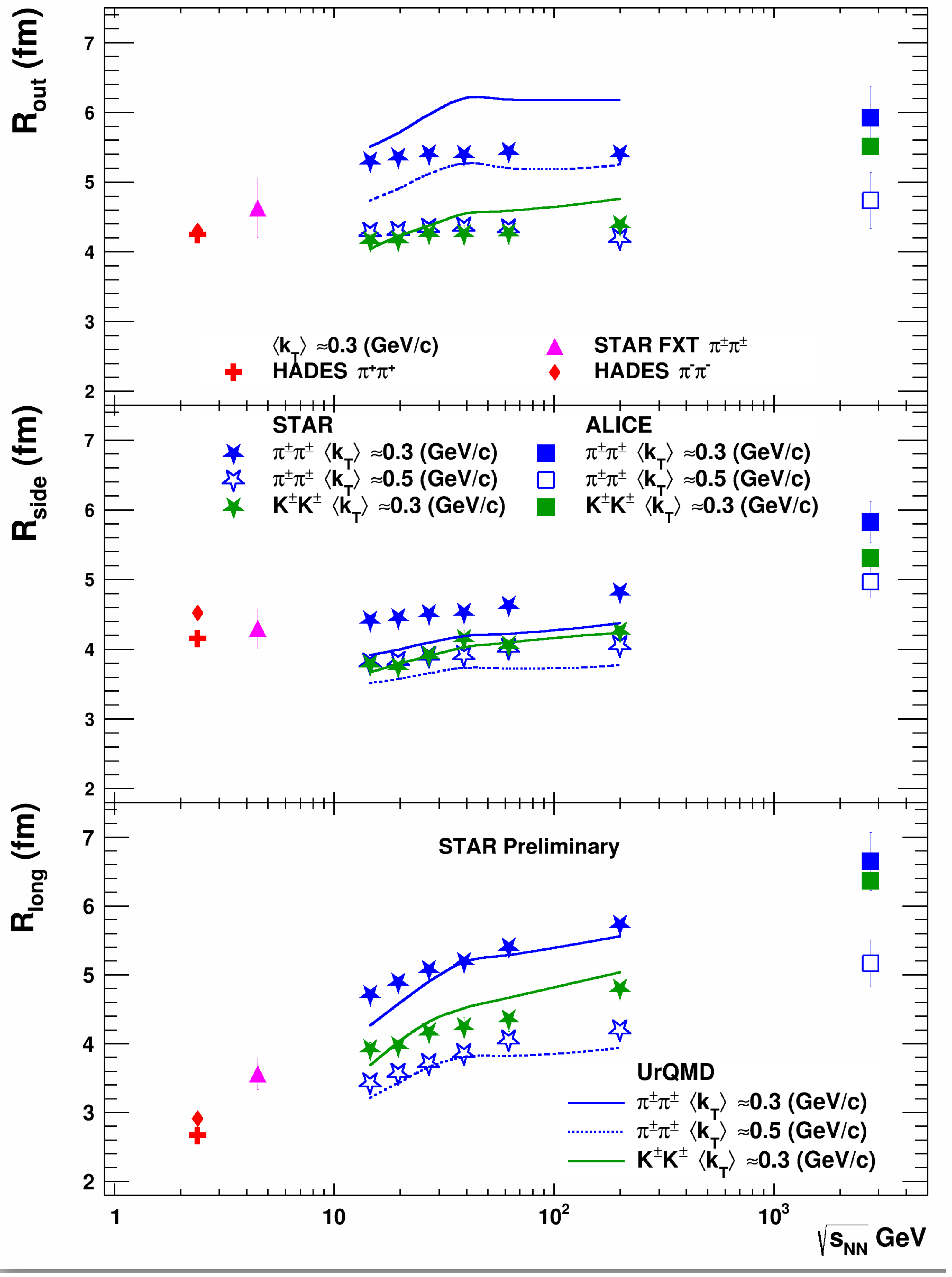
HBT - 3D femtoscopy

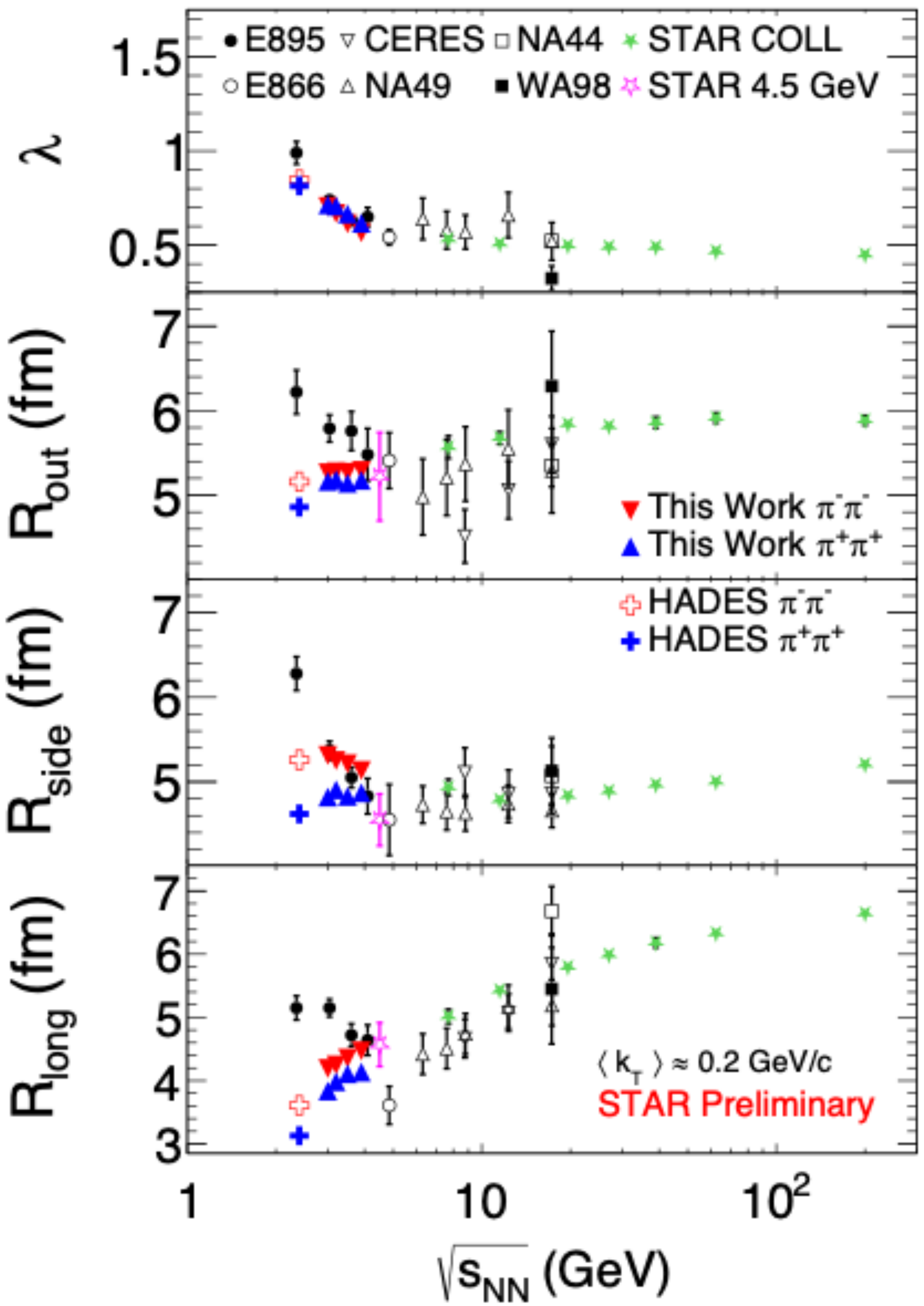


Radii:

- Increase with collision energy
- Decrease with transverse mass
- Larger for π than K
- UrQMD reasonable agreement

HBT - 3D femtoscopy

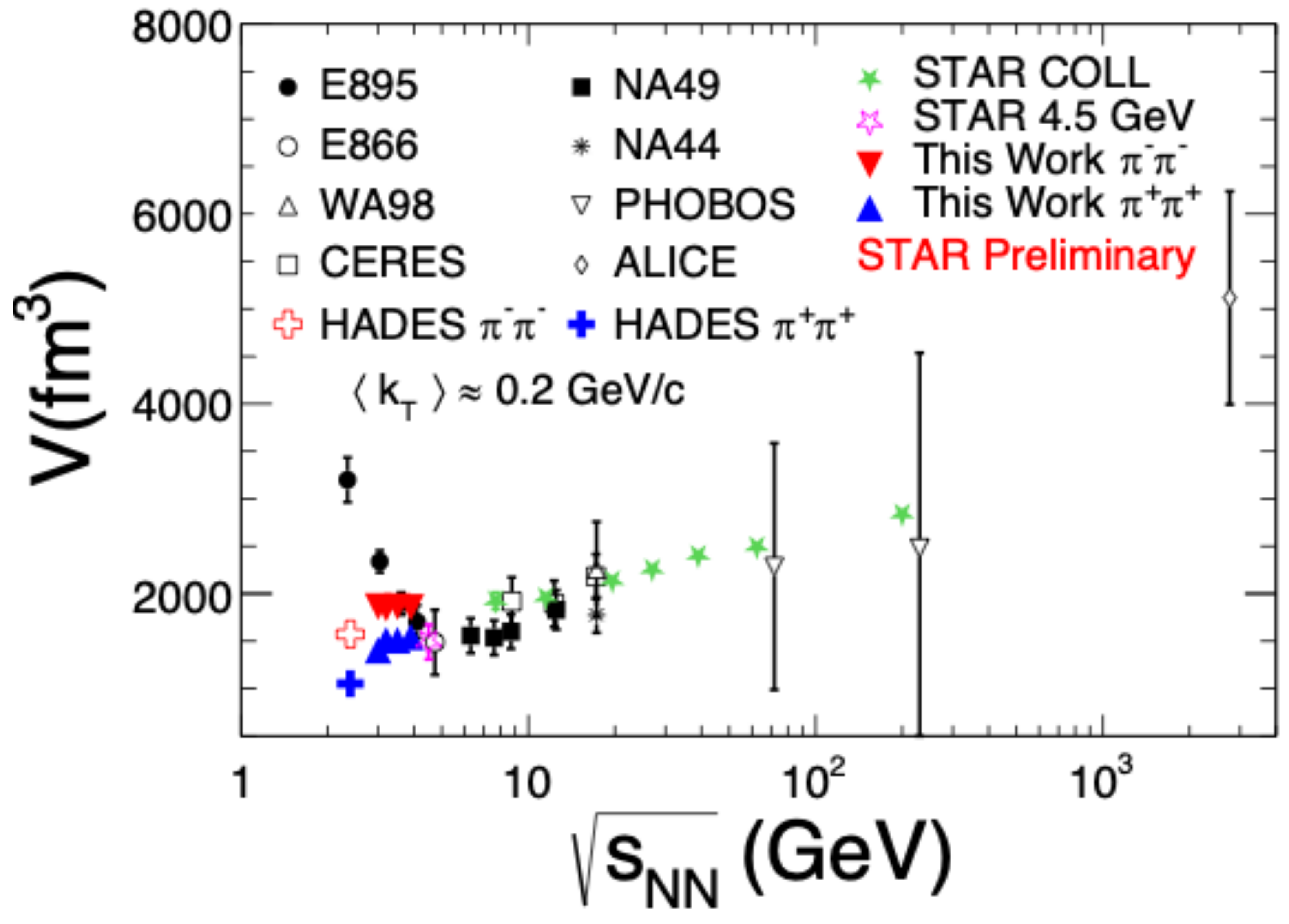




Radii:

- Increase with collision energy
- Decrease with transverse mass
- Larger for π than K
- UrQMD reasonable agreement

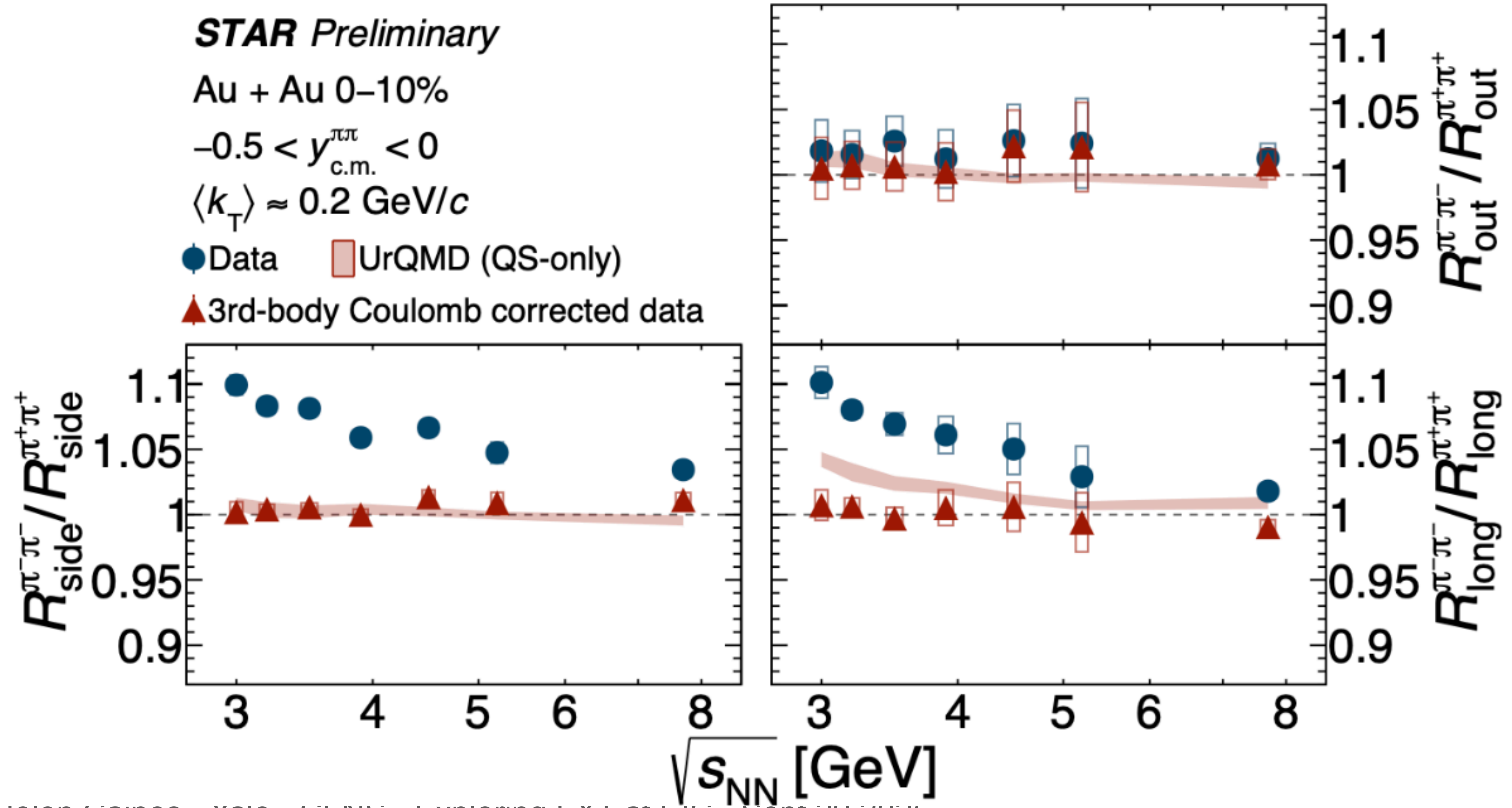
Tension emerging with E895



Slowly increasing volume from STAR and HADES

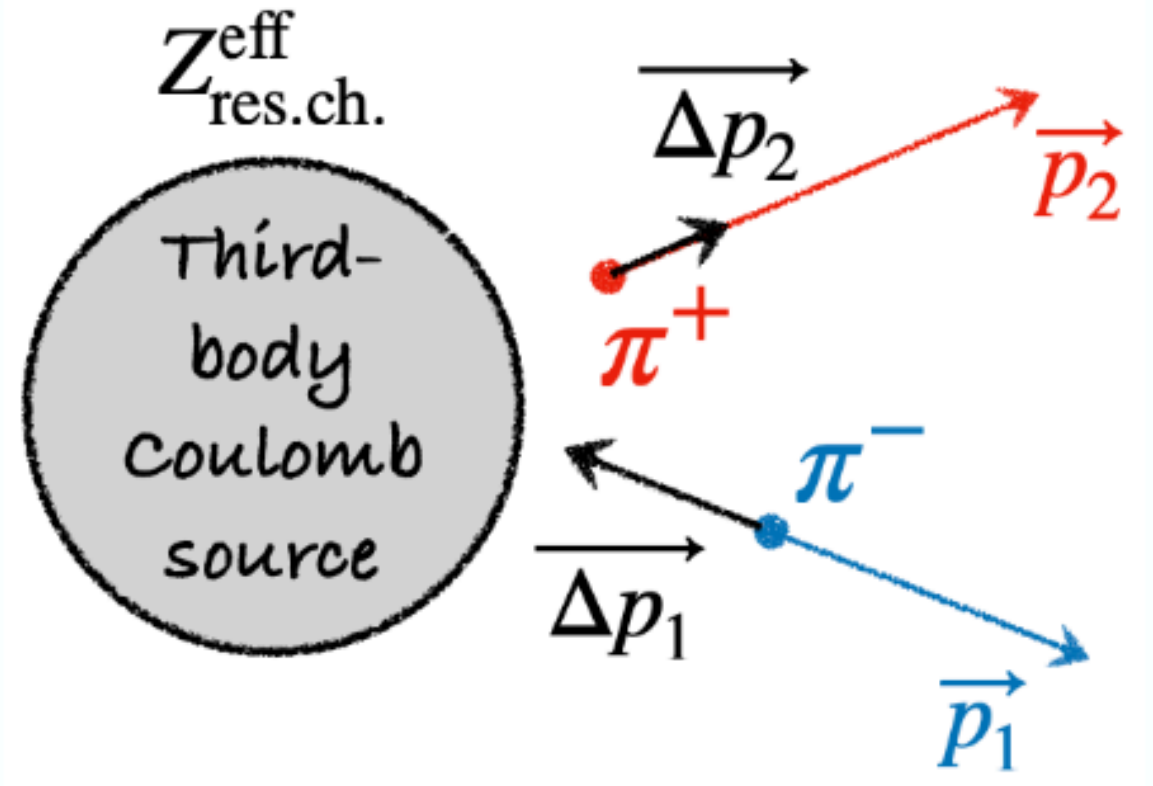
3rd body Coulomb interactions

- Isolate 3rd body Coulomb effect:
  - Extract Z_{res}^{eff} from π^+/π^- yield ratio,
  - Calculate Δp needed to produce the 3rd body Coulomb effect in UrQMD
  - Get correlation functions with the momentum shift



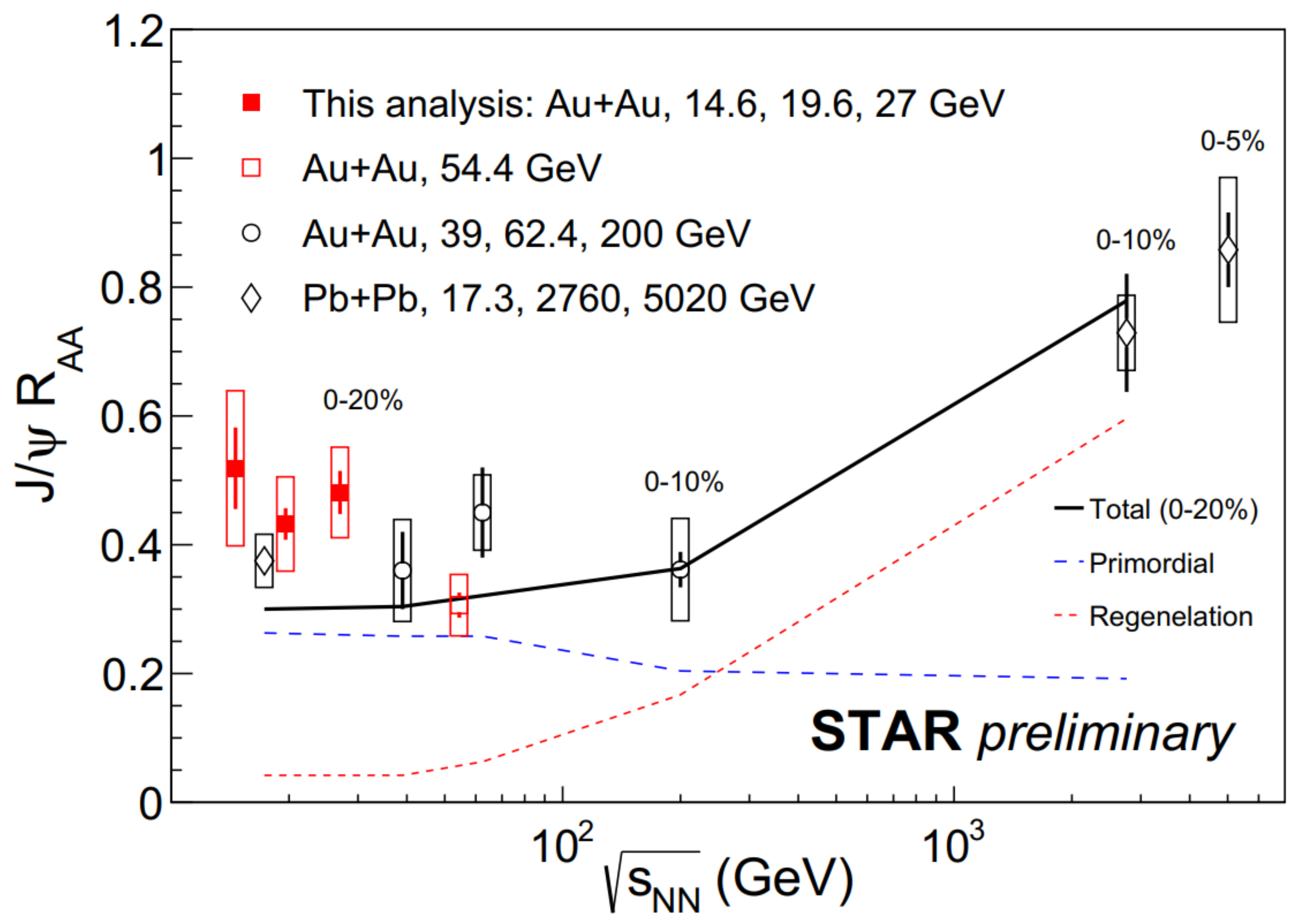
Measured femtoscopic source radii different for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs

3rd body Coulomb effect or isospin of the system?



- Correlation functions consistent after removal of 3rd body Coulomb effect
- No significant isospin contribution seen

Medium modification of J/ψ

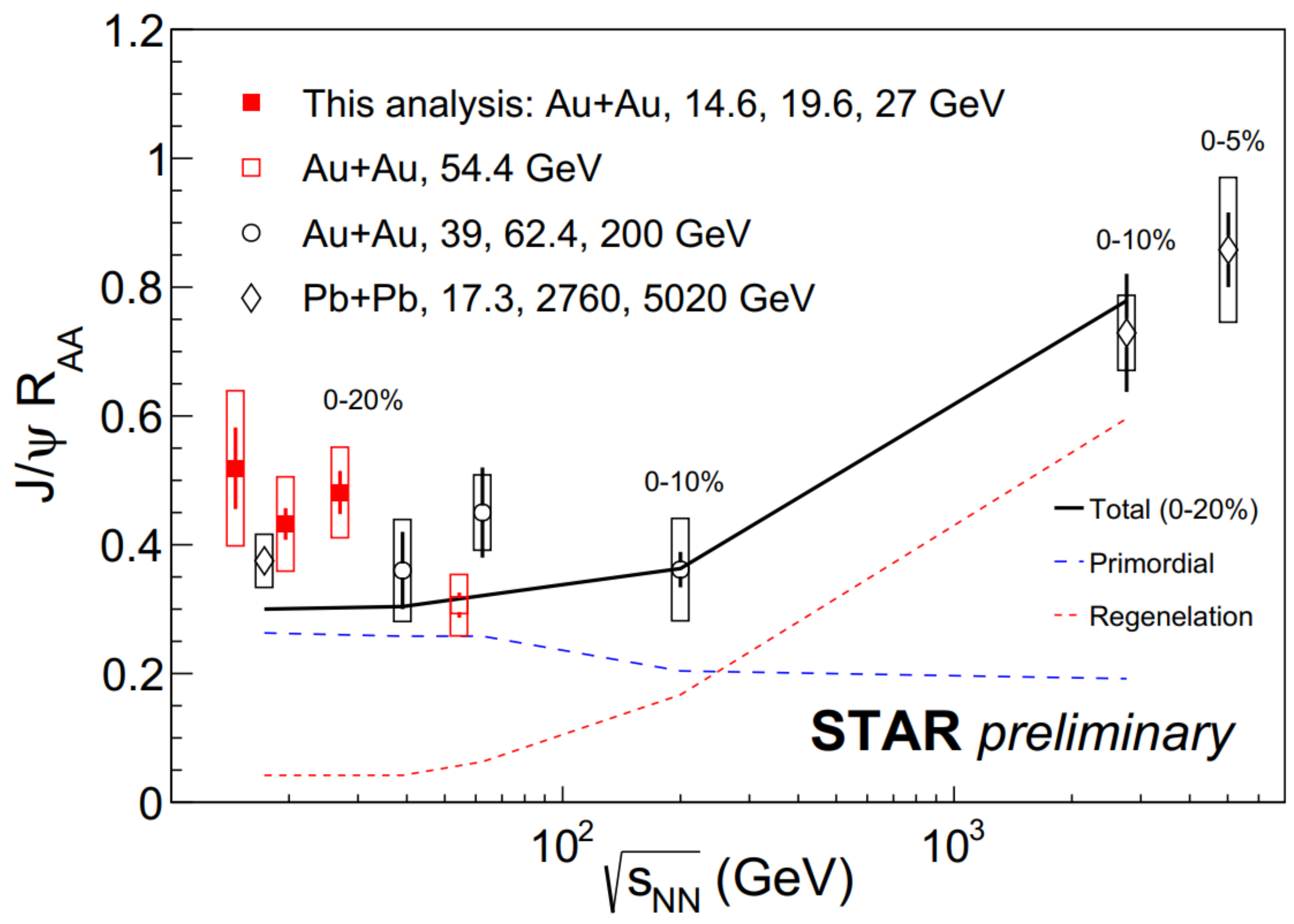


New data at 14.6, 19.6 and 27:

Confirm no significant energy dependence at RHIC energies

Interplay of dissociation, regeneration, CNM, spectra shape

Medium modification of J/ψ

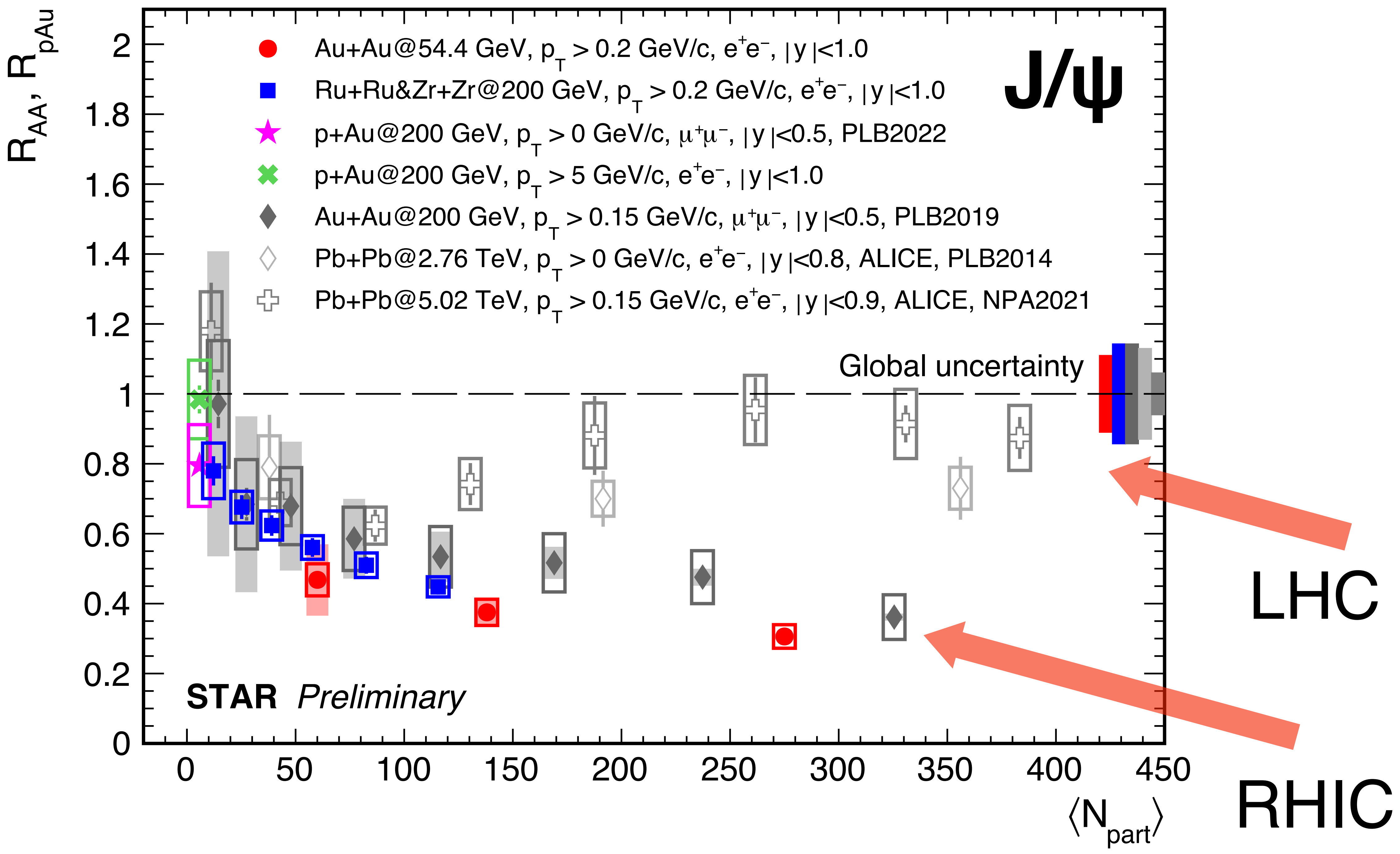


New data at 14.6, 19.6 and 27:

Confirm no significant energy dependence at RHIC energies

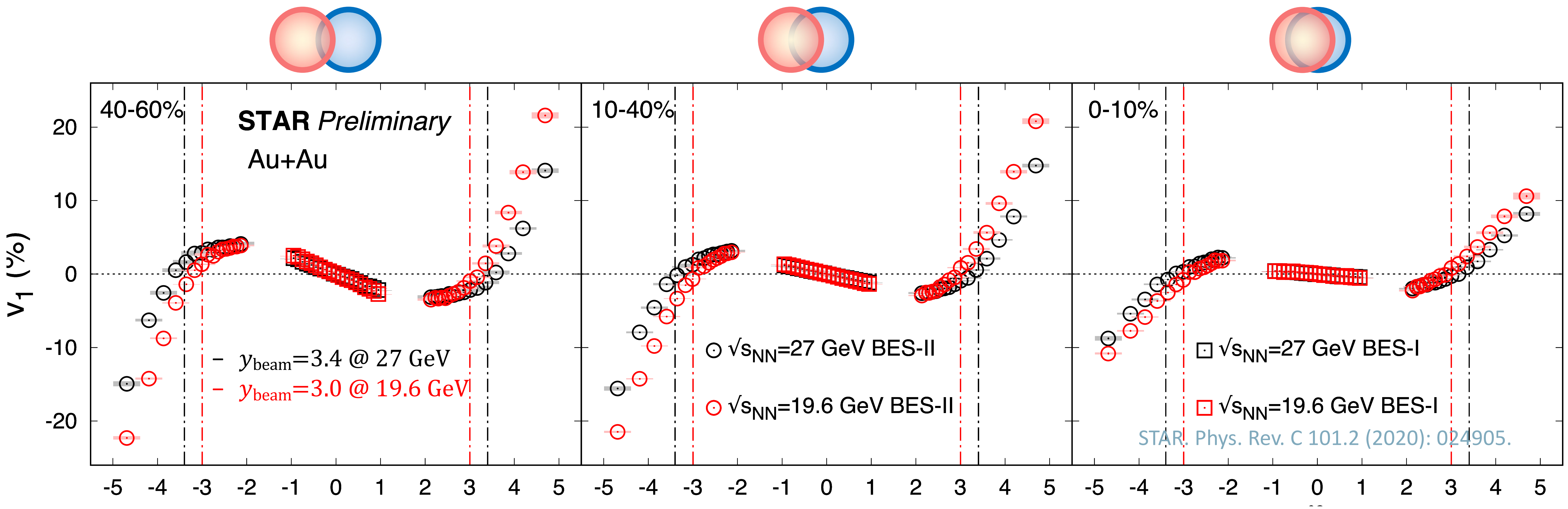
Interplay of dissociation, regeneration, CNM, spectra shape

Suppression at RHIC that scales with N_{part}

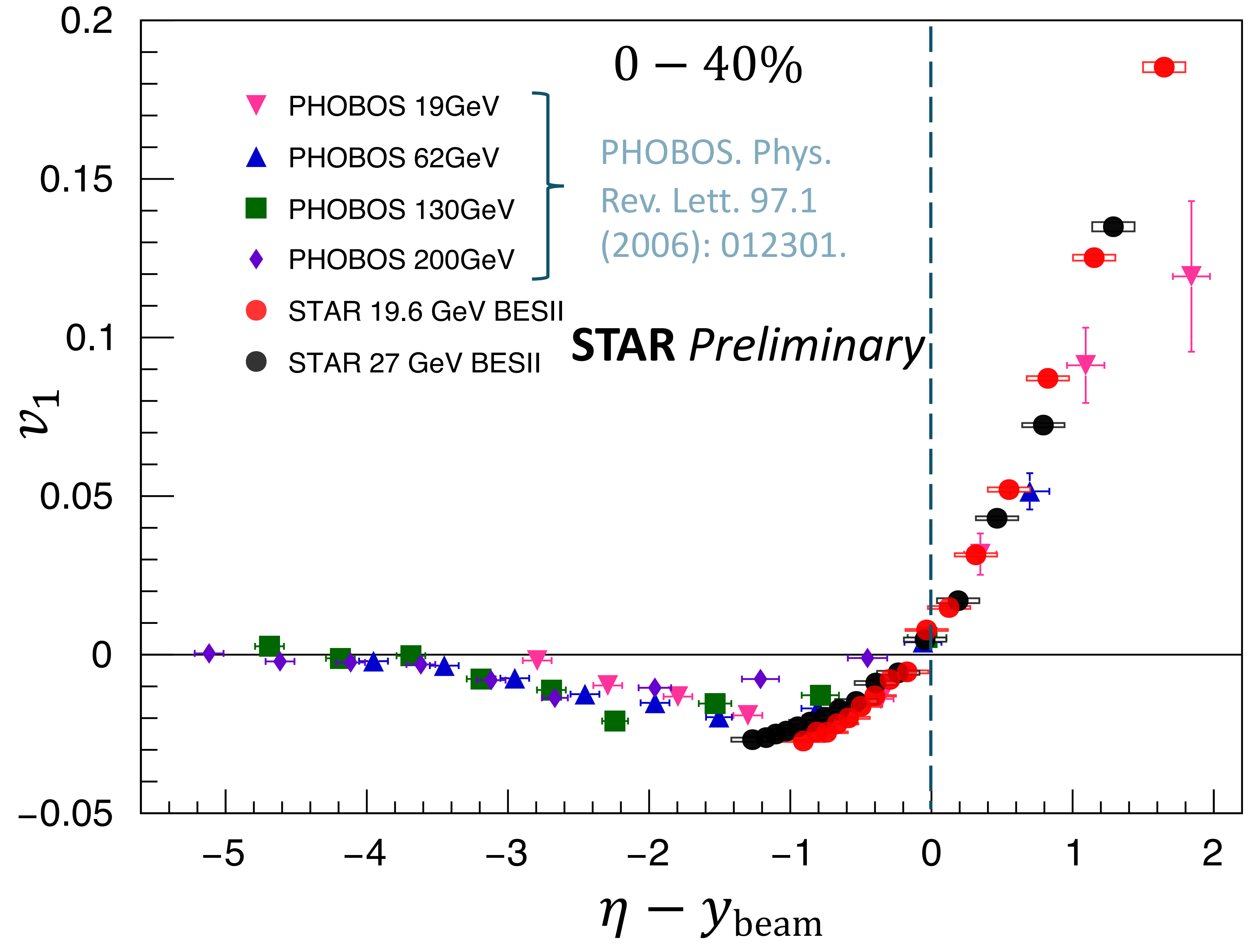


More suppression at RHIC due to much less regeneration in the medium

Limiting fragmentation



Results extended to more centralities



Scaling of v_1 observed for all centralities

Nuclei fragments contribute to v_1

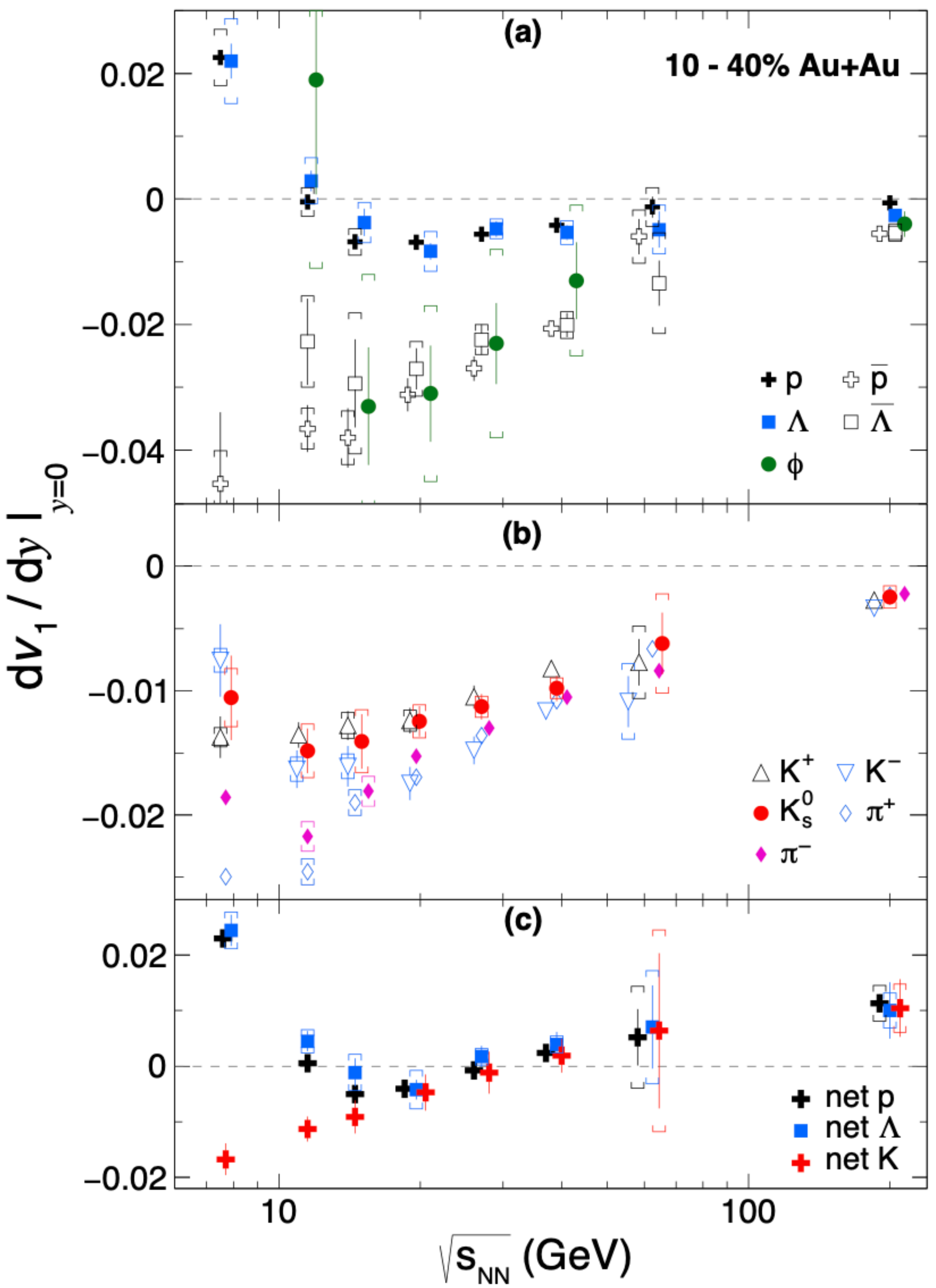
"Limiting fragmentation" a dynamical phenomenon

Change in since of net proton v1

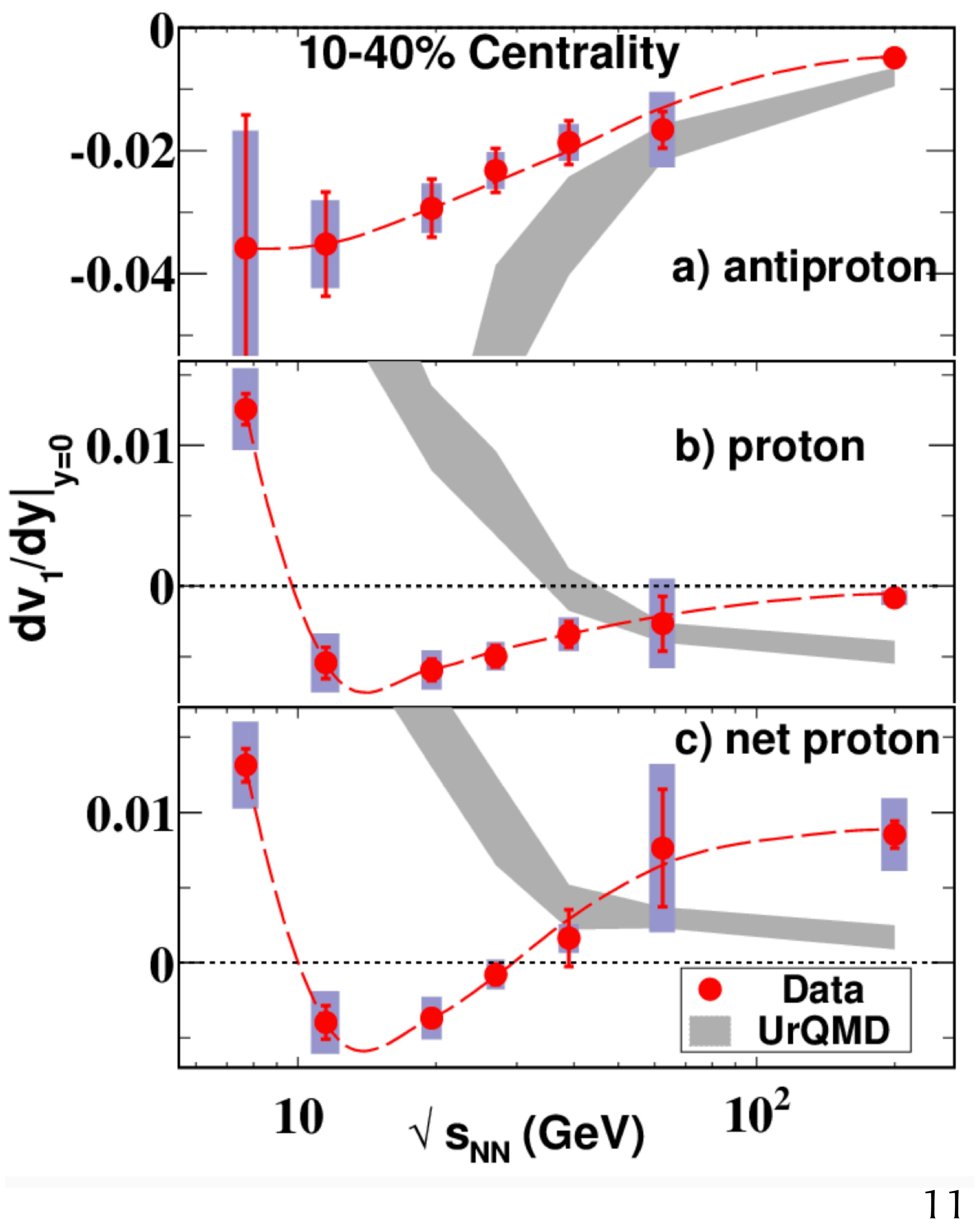
- Change of sign in the slope of $\frac{dv_1}{dy}$ (for baryons, or net-baryons) as a probe to the **softening of EoS** and/or **first-order phase transition;**

- If a system undergoes a first-order phase transition, due to formation of **mixed phase, pressure gradient is small (minimum** in the $\frac{dv_1}{dy}$ **slope** parameter);

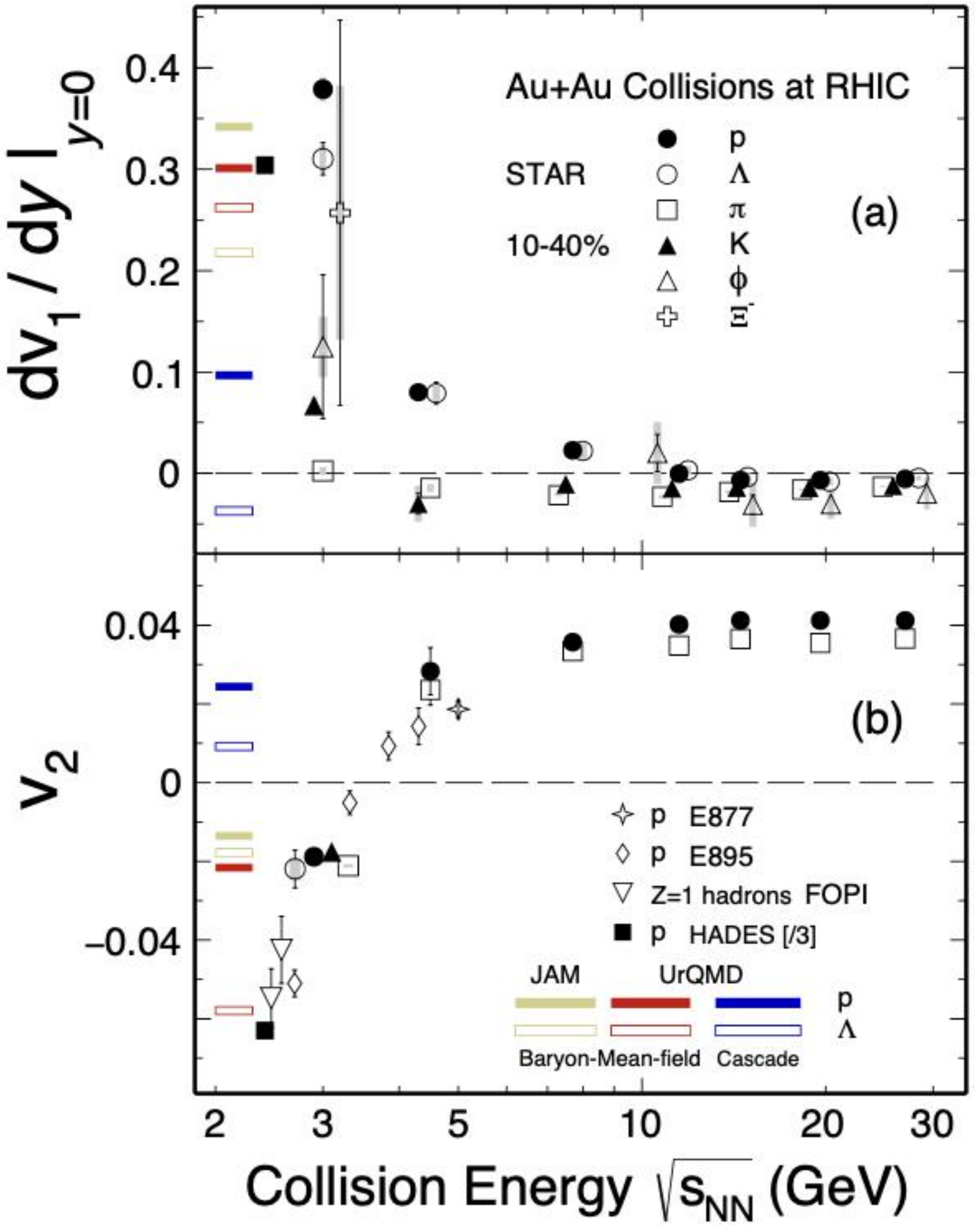
PRL 120 (2018) 6, 062301



PRL 112, 162301 (2014)



v_1 slope and v_2 sign change



- Negative v_1 slope and large positive v_2 in Au+Au collisions at high beam energies.
- Positive v_1 slope and negative v_2 for all measured particles in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV.
- hadronic transport model JAM and UrQMD with baryonic mean-field interactions qualitatively describe the data.

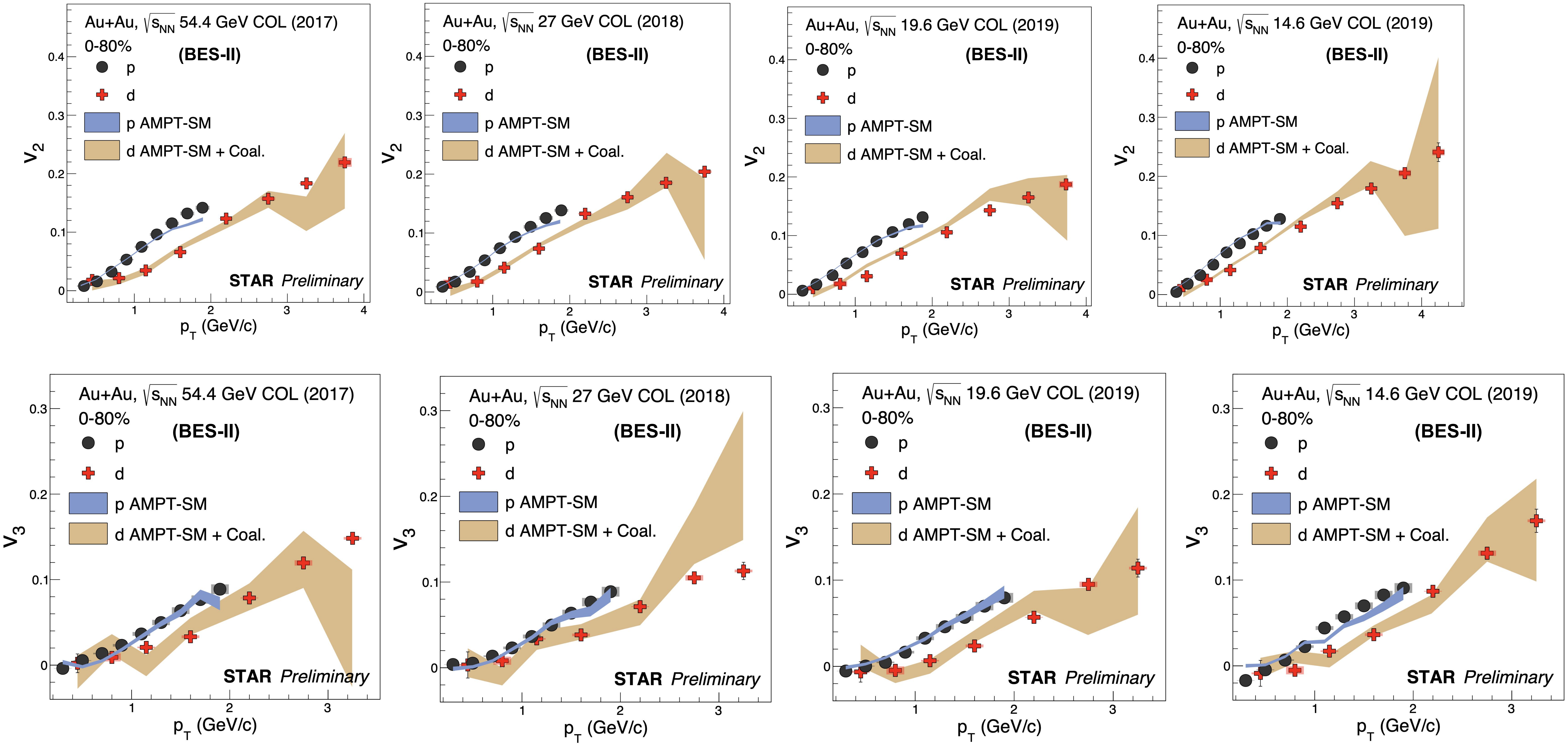
  → EoS dominated by baryonic interactions at 3 GeV

E877: Phys. Rev. C 56, 3254-3264
E895: Phys. Rev. Lett.85, 940
FOPI: Phys. Lett. B 612, 173
STAR: Phys. Lett. B 827, 137003, (2021)

v_2 light nuclei

1) Light-Nuclei elliptic flow v_2 measurements in 10-40% mid-central Au+Au Collisions at $\sqrt{s_{NN}}$= 3.0, 3.2, 3.5, 3.9 GeV
2) Mid-rapidity elliptic flow results indicate an out-of-plane expansion ($v_2 < 0$) at the lowest collision energy, whereas in-plane expansions ($v_2 > 0$) are evident at higher collision energies

Flow of light nuclei from coalescence - AMPT



R. Sharma: STAR QM Talks

v_1 and EM Fields

Quarks in the expanding medium experience different forces due to

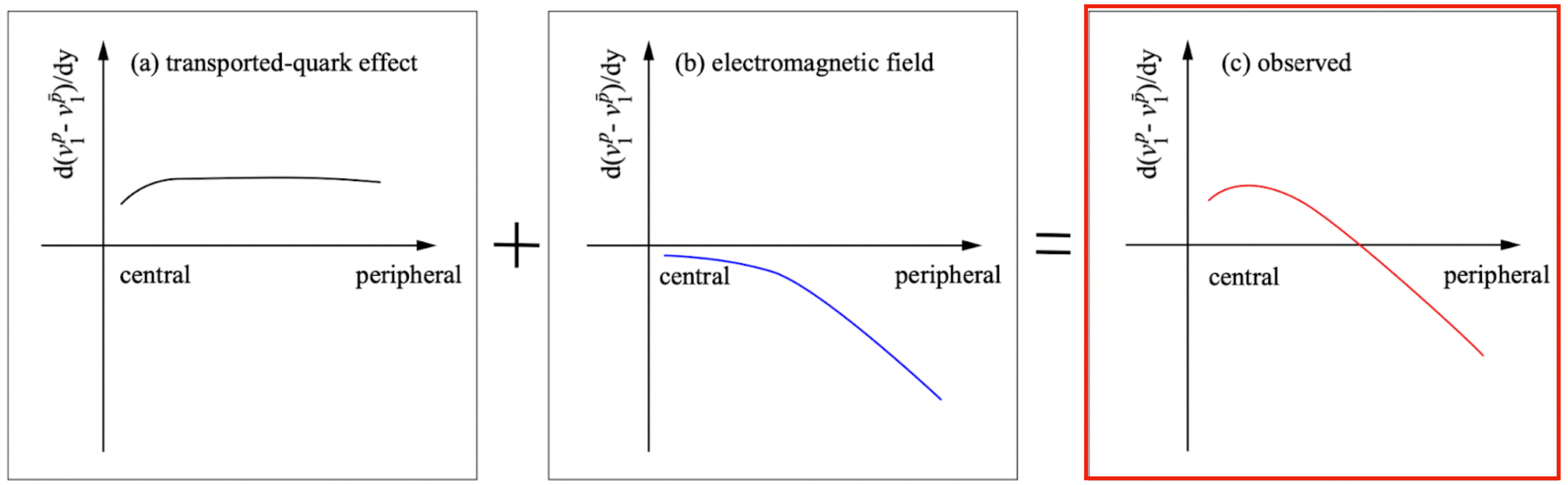
1. **Hall Effect**: **F**= q(**v**×**B**)
2. **Coulomb Effect**: **E** generated by spectators
3. **Faraday Induction**: Generated by decreasing magnetic field as spectators fly away

[U. Gürsoy et al. PRC 98,055201, PRC 89 054905]

These EM forces give opposite v_1 to particles with opposite charges and thus $v_1(h^+)$-$v_1(h^-)$ is sensitive to EM fields

Transported quark effect: Quarks transported from incoming nuclei can have different v_1 than that of quarks produced in the interaction region. **It can affect hadrons having u and d quarks.**

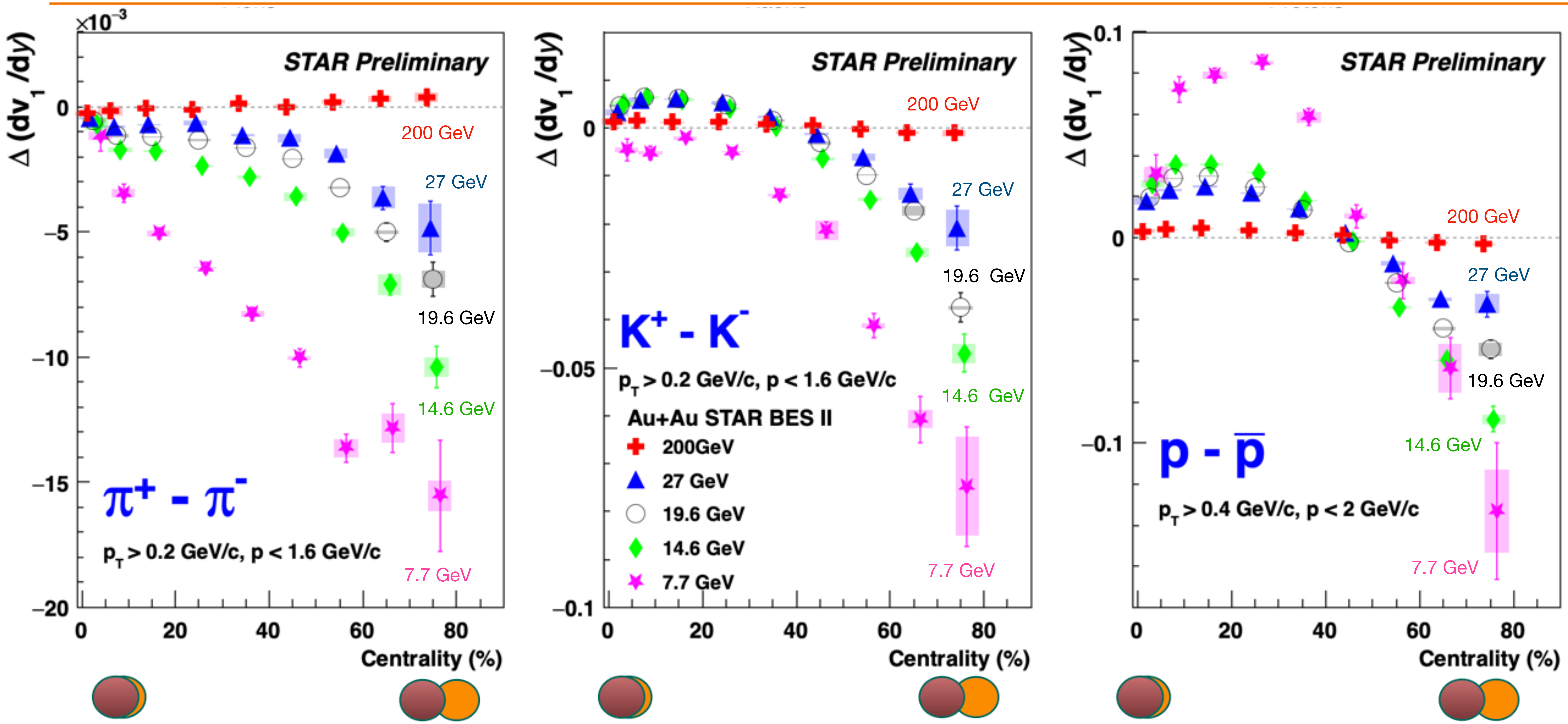
Demonstration for protons



$\Delta dv_1/dy = dv_1(h^+)/dy - dv_1(h^-)/dy$

[STAR, arXiv:2304.03430]

Directed flow difference



Different effects can/do dominate in different regimes - Have precision to hopefully disentangle

Difference in particle-anti-particle slope:

- Increases with decreasing centrality - Higher B-field
- Increases with decreasing beam energy - Increasing crossing time
- Has species dependence - transported vs created quarks