GSI Helmholtzzentrum für Schwerionenforschung GmbH

Strange Hadron Production at High Baryon Density

Yingjie Zhou
for the STAR collaboration

z.yingjie@gsi.de

20th May, 2024

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

CPOD 2024 - The 15th Workshop on Critical Point and Onset of Deconfinement

Outline

1) **Motivation**

2) **Datasets and Experimental Setup**

3) **Results and Discussion**

   I) Yields

   - Excitation function, yield ratios
   - Centrality dependence
   - Baryon to meson yield ratio

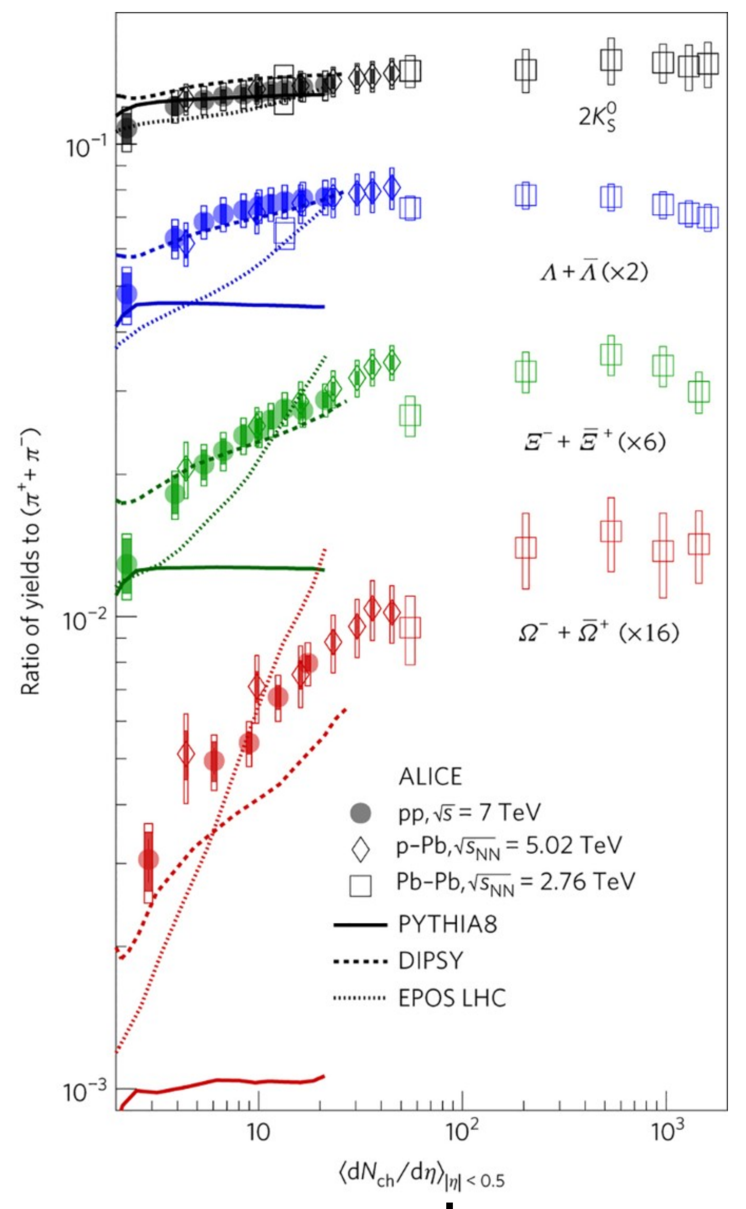
   II) Transverse distribution

4) **Summary and Outlook**

Explore QCD Phase Diagram at RHIC

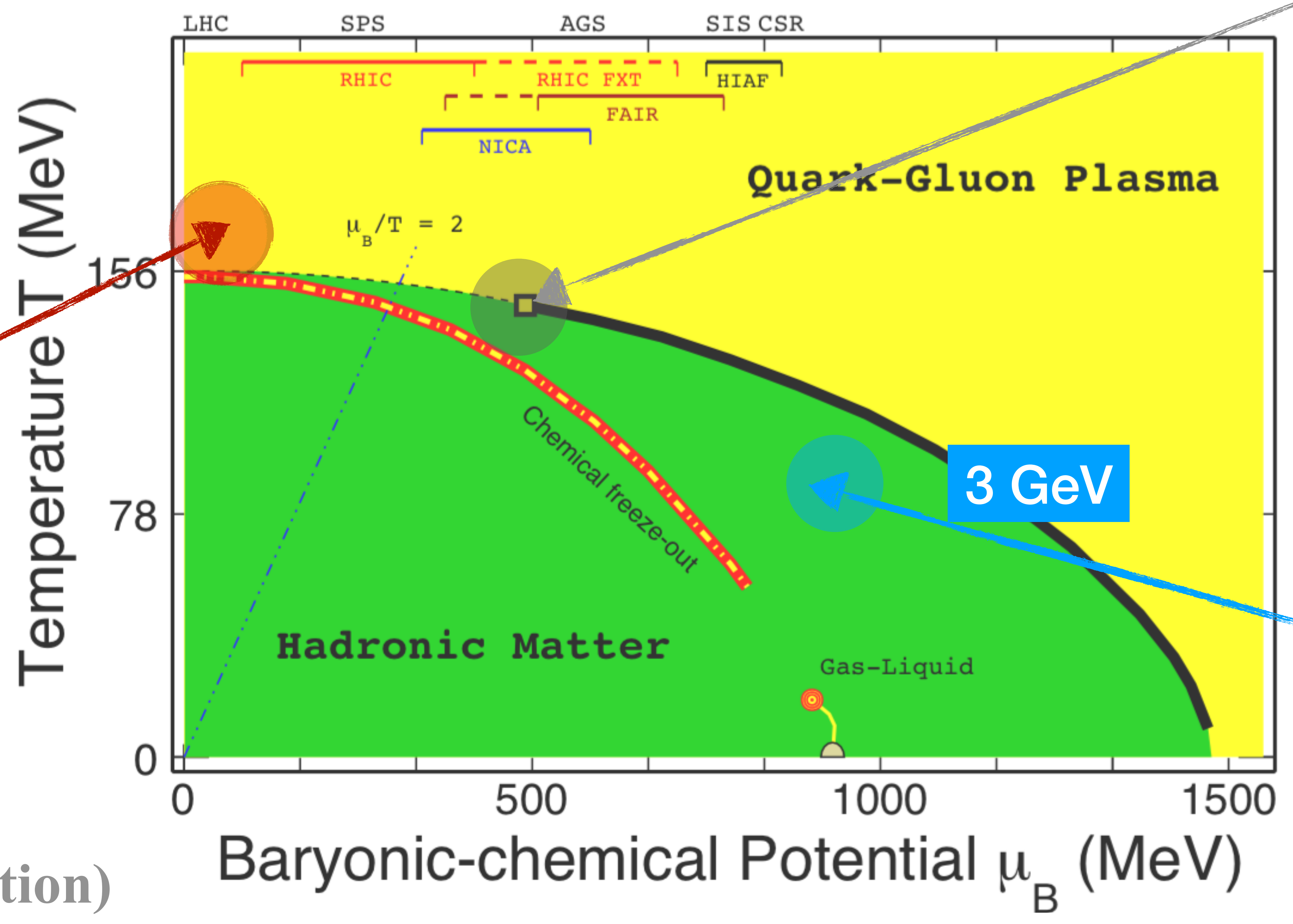
- **Formation of QGP in high energy heavy ion collisions** ($\sqrt{s_{NN}}$ = 200 GeV, μ_B = 25 MeV)
  - Strangeness enhancement, flow NCQ scaling, R_{AA}, R_{cp}, etc.
- **Search for the critical point** ($\sqrt{s_{NN}}$ = 3 - 27 GeV, μ_B = 750 - 200 MeV)
  - Possible signatures: net-proton fluctuation
- **Formation of high baryon density matter** ($\sqrt{s_{NN}}$ = 3.0 - 13.7 GeV, μ_B = 750 - 280 MeV)
  - Nature of produced medium (hadronic or partonic)
  - Investigate properties of dense baryonic matter

ALICE: Nature Phys 13, (2017) 535–539

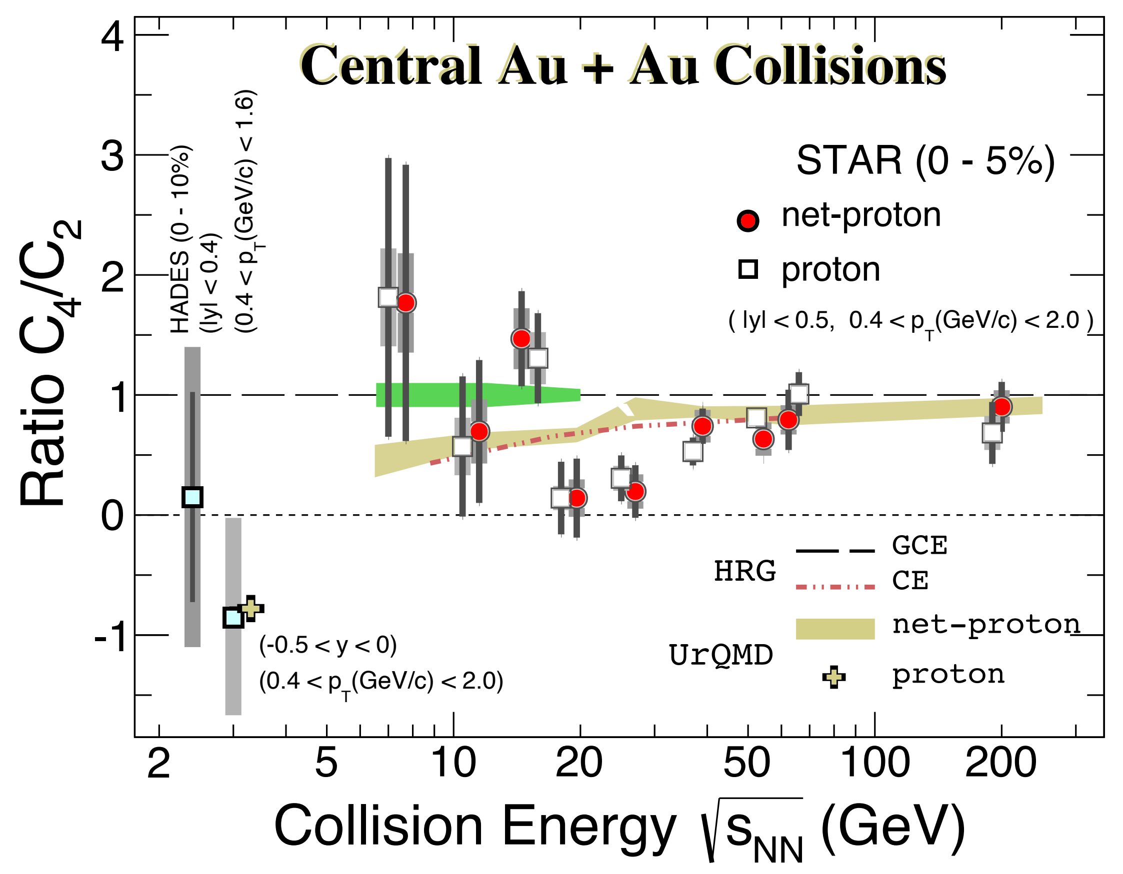


- Strangeneess enhancement

Figure, courtesy of Nu Xu

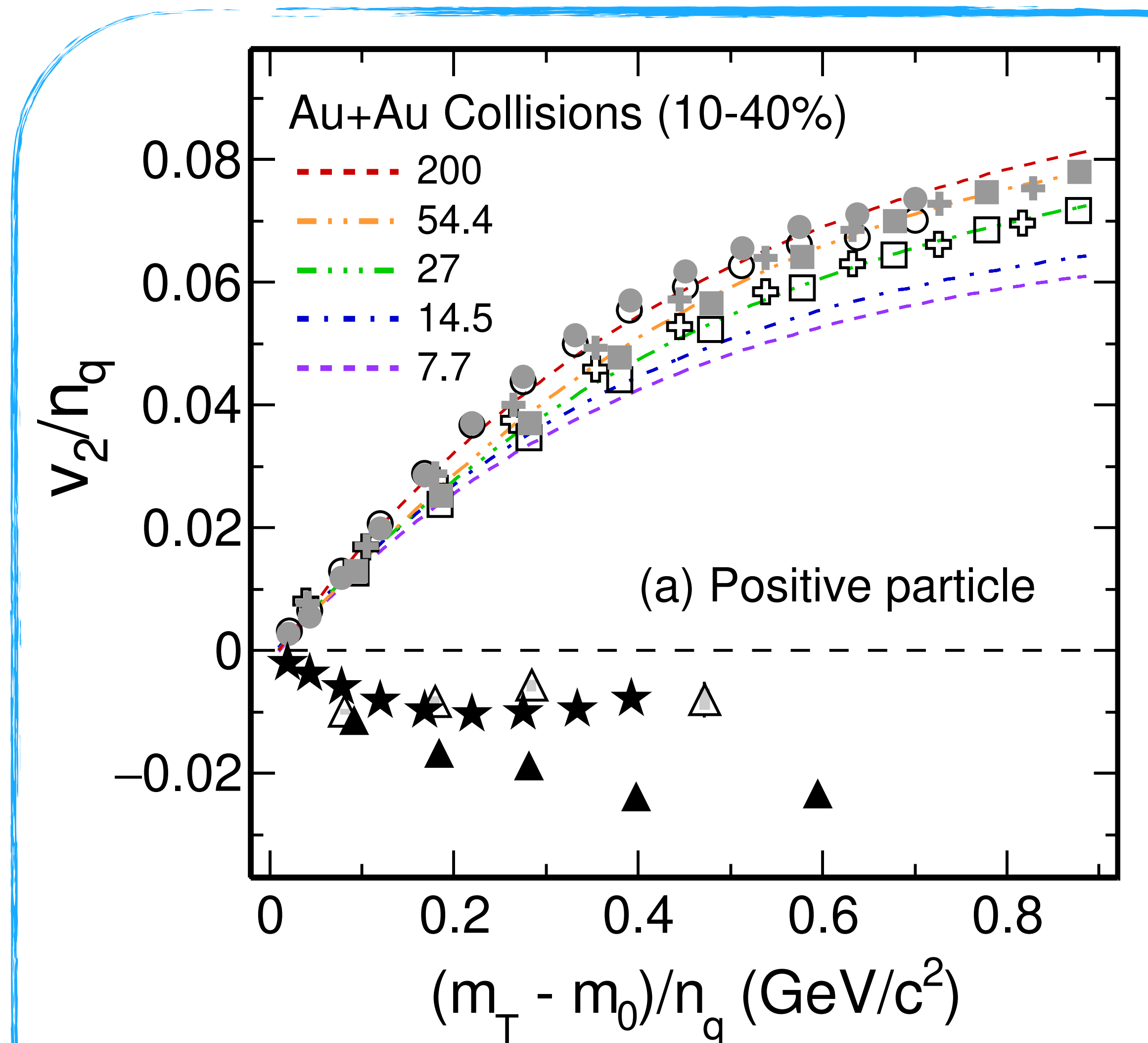


STAR: Phys. Rev. Lett. 128, 202303 (2022)



- Hint of critical fluctuations

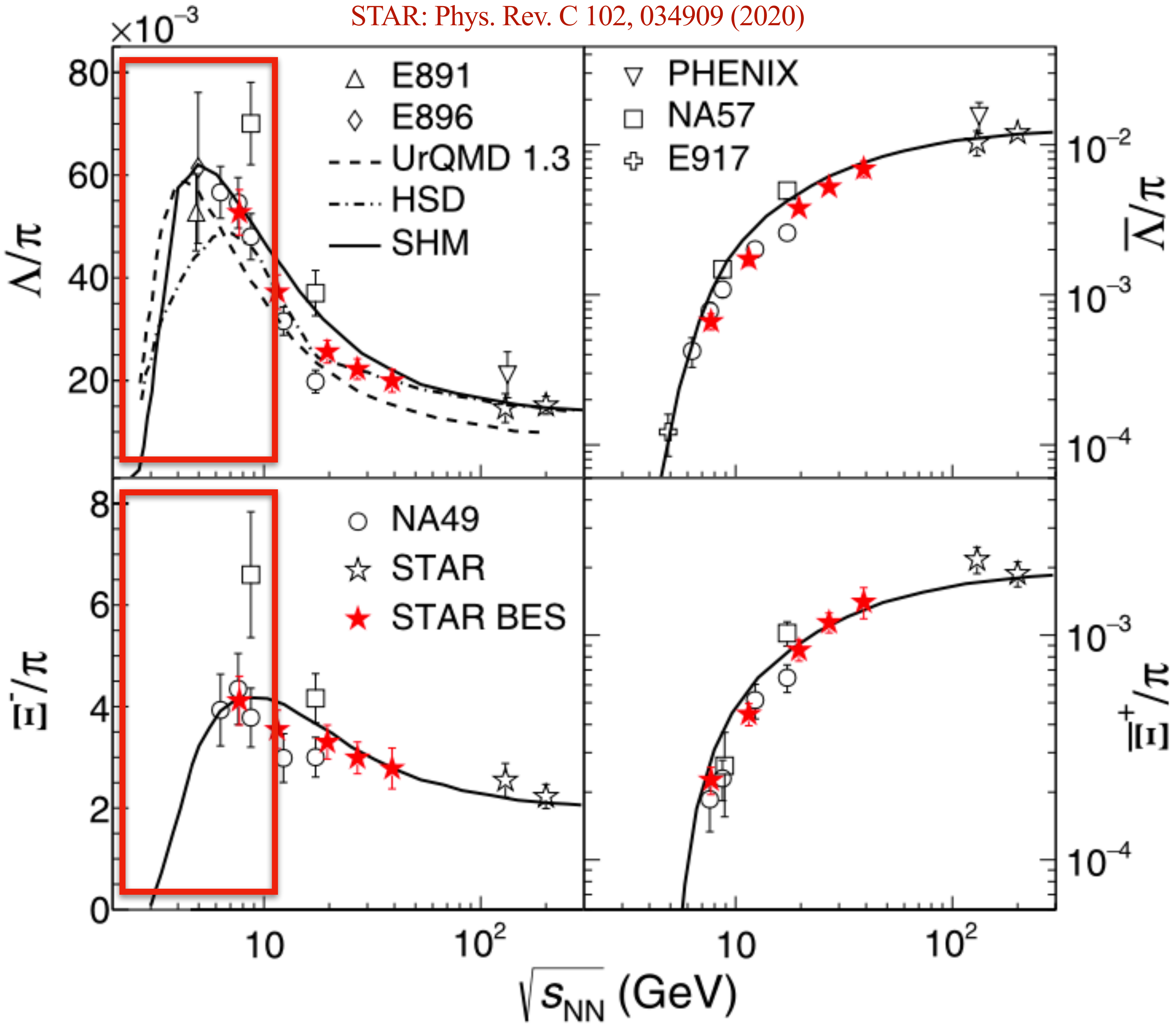
STAR: Phys. Lett. B 827, 137003 (2022)



- Disappearance of partonic collectivity at $\sqrt{s_{NN}}$ = 3 GeV

Strangeness as a Probe to Study the Nuclear Matter

STAR: Phys. Rev. C 102, 034909 (2020)



- **Rich structure in these excitation functions**
  - **Production mechanism is different at high and low baryon density**

    pair production: $gg \to s\bar{s}$, $q\bar{q} \to s\bar{s}$
    hadronic interaction: $BB \to BYK$, $BB \to BBK\bar{K}$
    B: N, p, Δ etc. Y: Λ, Ξ, etc. K: K^0, K^+

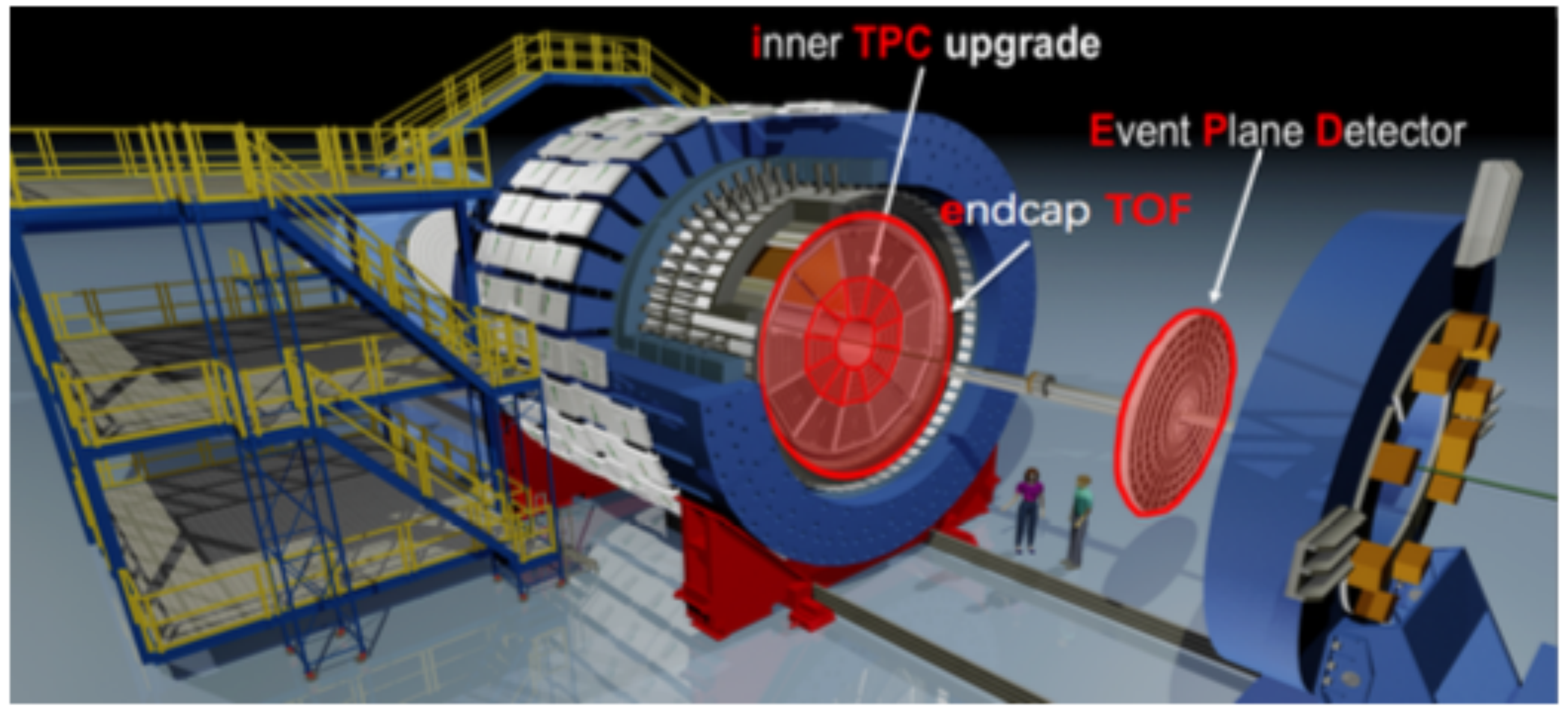
  - **Λ/π peaks at $\sqrt{s_{NN}} \sim 8$ GeV**
    Model: Baryon density maximal at $\sqrt{s_{NN}} \sim 8$ GeV[1]

➡**Scarce data at low energy, more data is needed!**

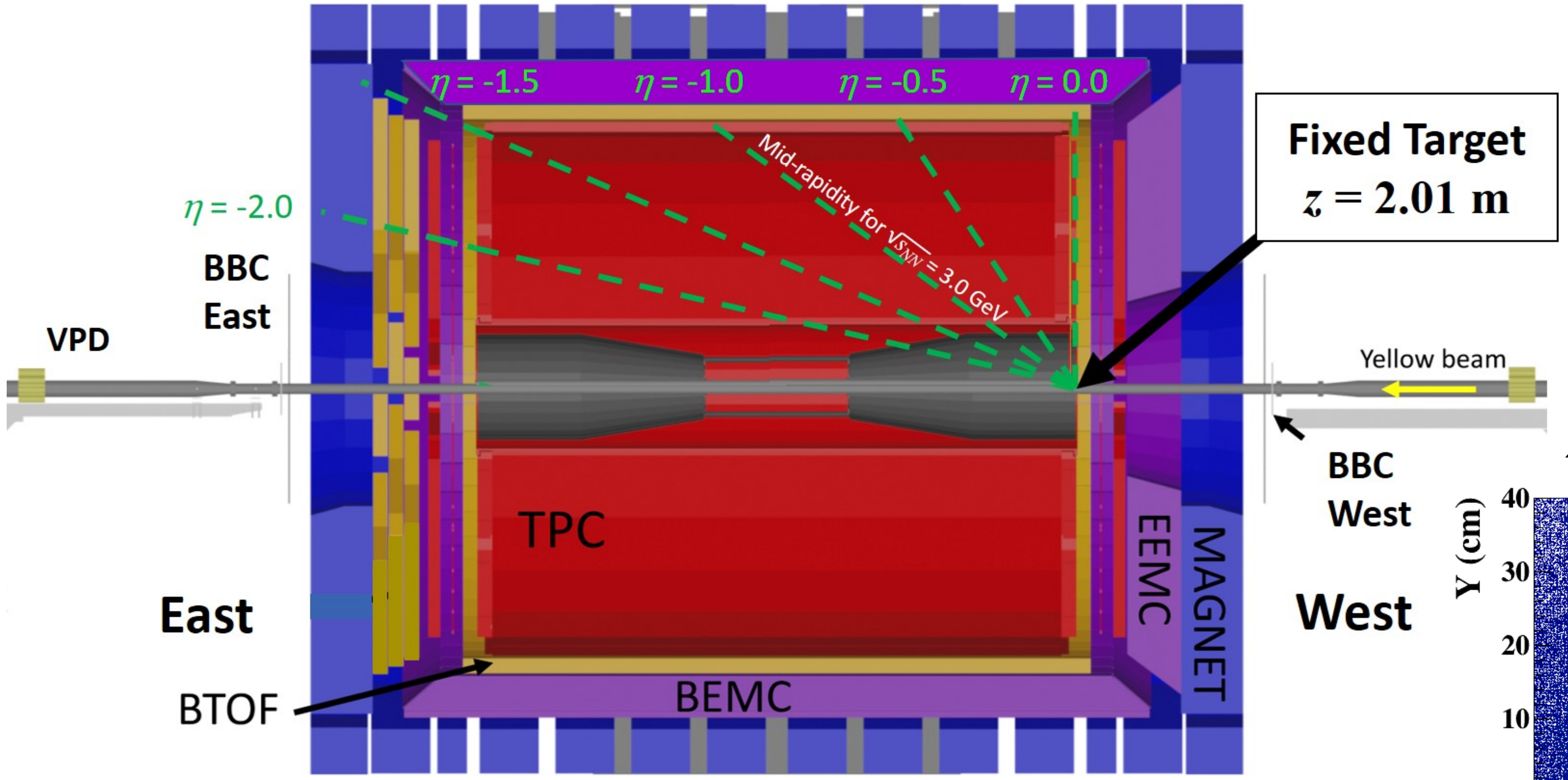
➡**Connections to the softness of dense nuclear matter, phase boundary, and onset of deconfinement**

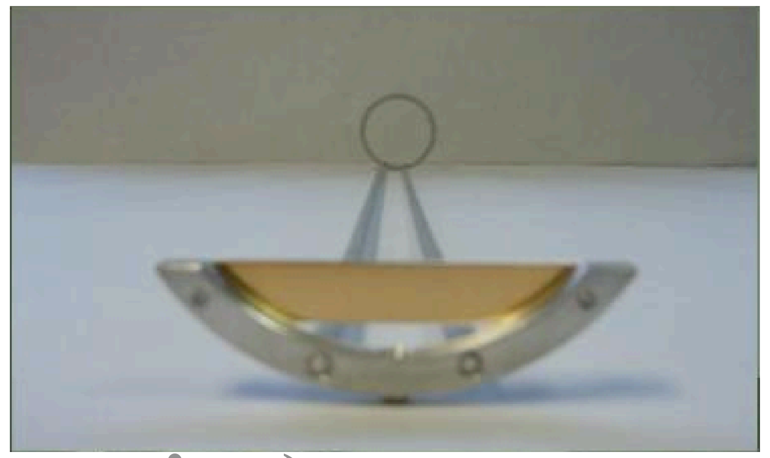
[1] J. Randrup, et al. Phys. Rev. C74, 047901 (2006)

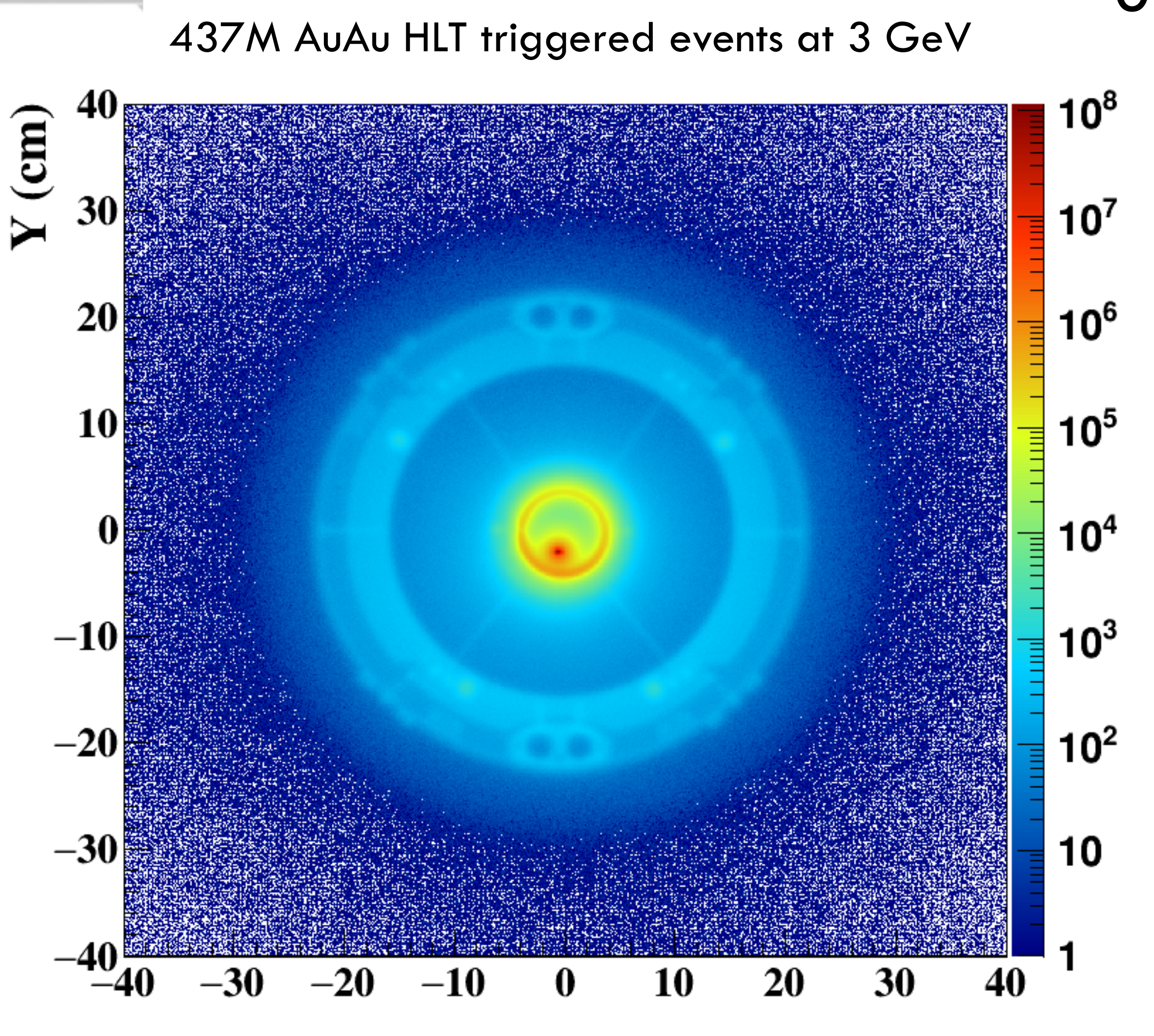
STAR Detector and BES-II

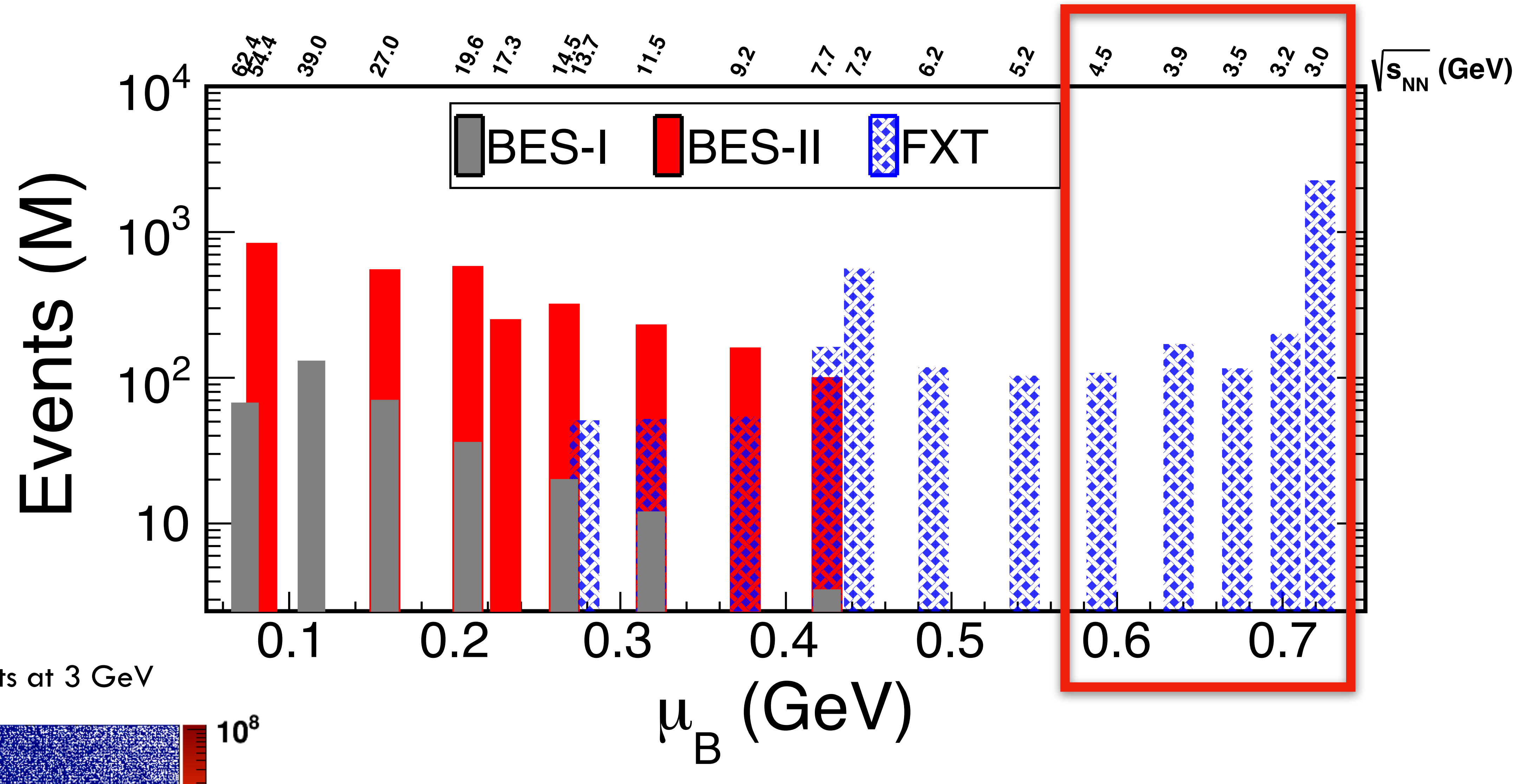


- STAR BES-II ($\sqrt{s_{NN}}$ = 3-54.4 GeV)
  - 10× statistics compared to BES-I
  - Detector upgrades: iTPC, eTOF
  - FXT extends energy down to 3 GeV



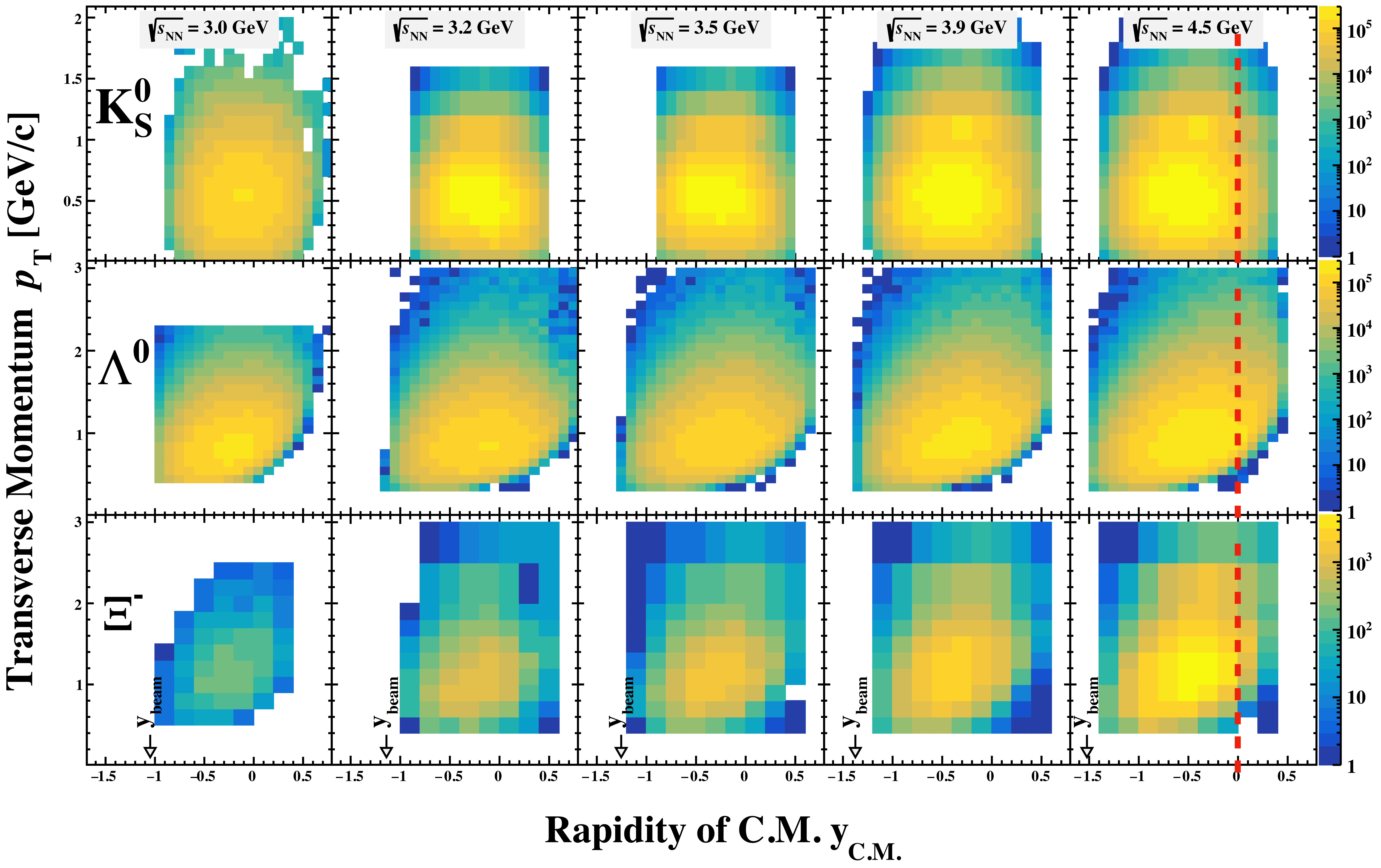






- **New results from BES-II data at: 3.0, 3.2, 3.5, 3.9, 4.5 GeV**

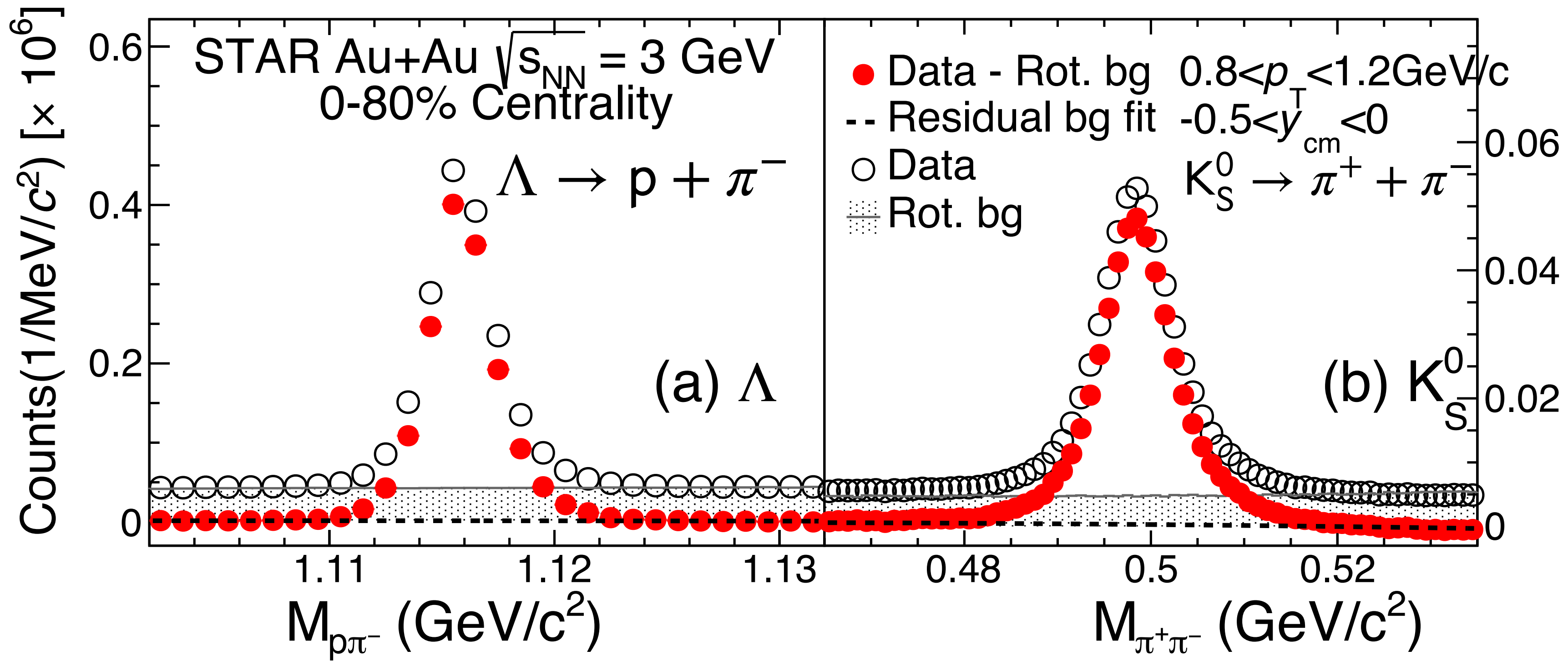
Particle Acceptance

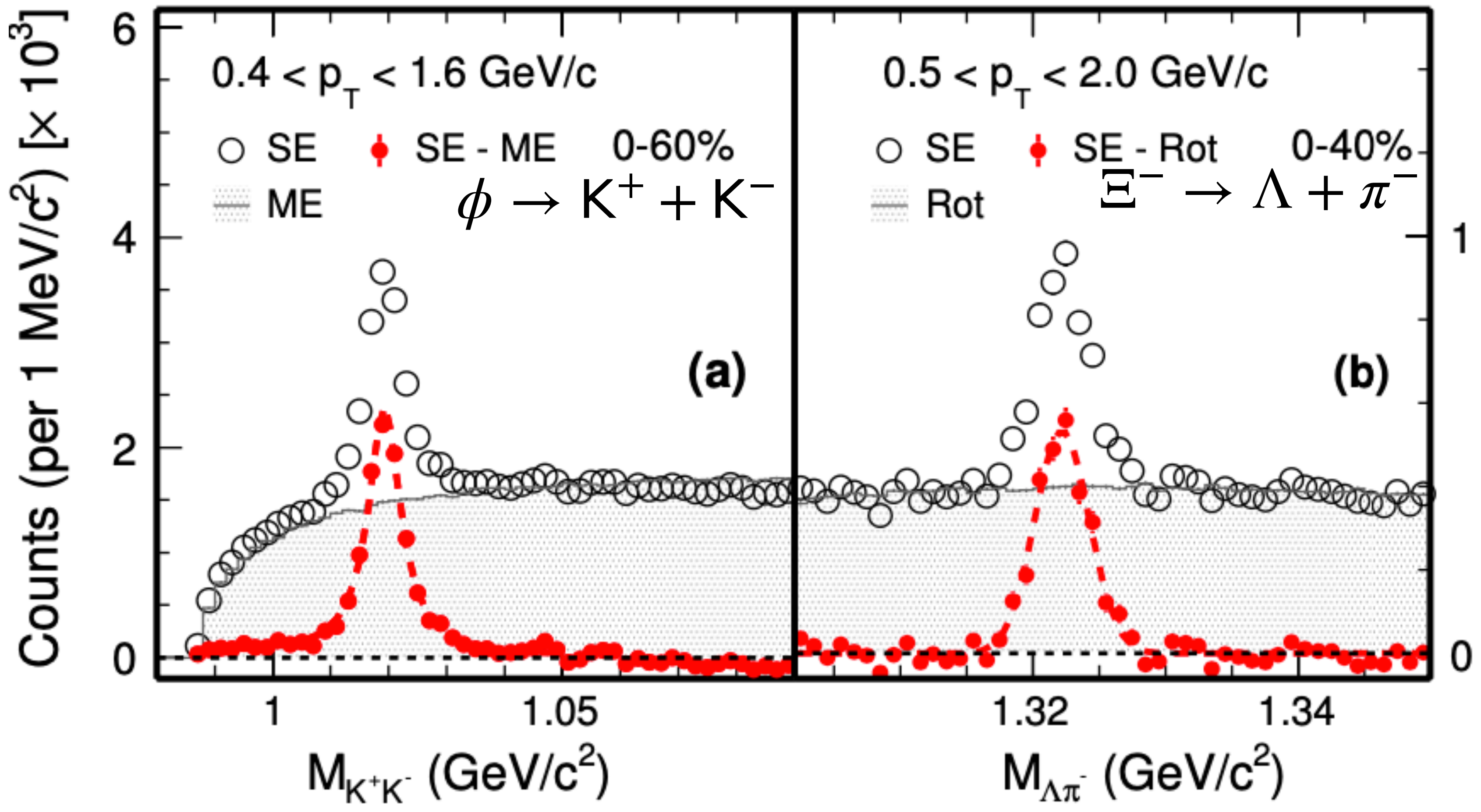


- Particle rapidity coverage from beam rapidity to mid-rapidity

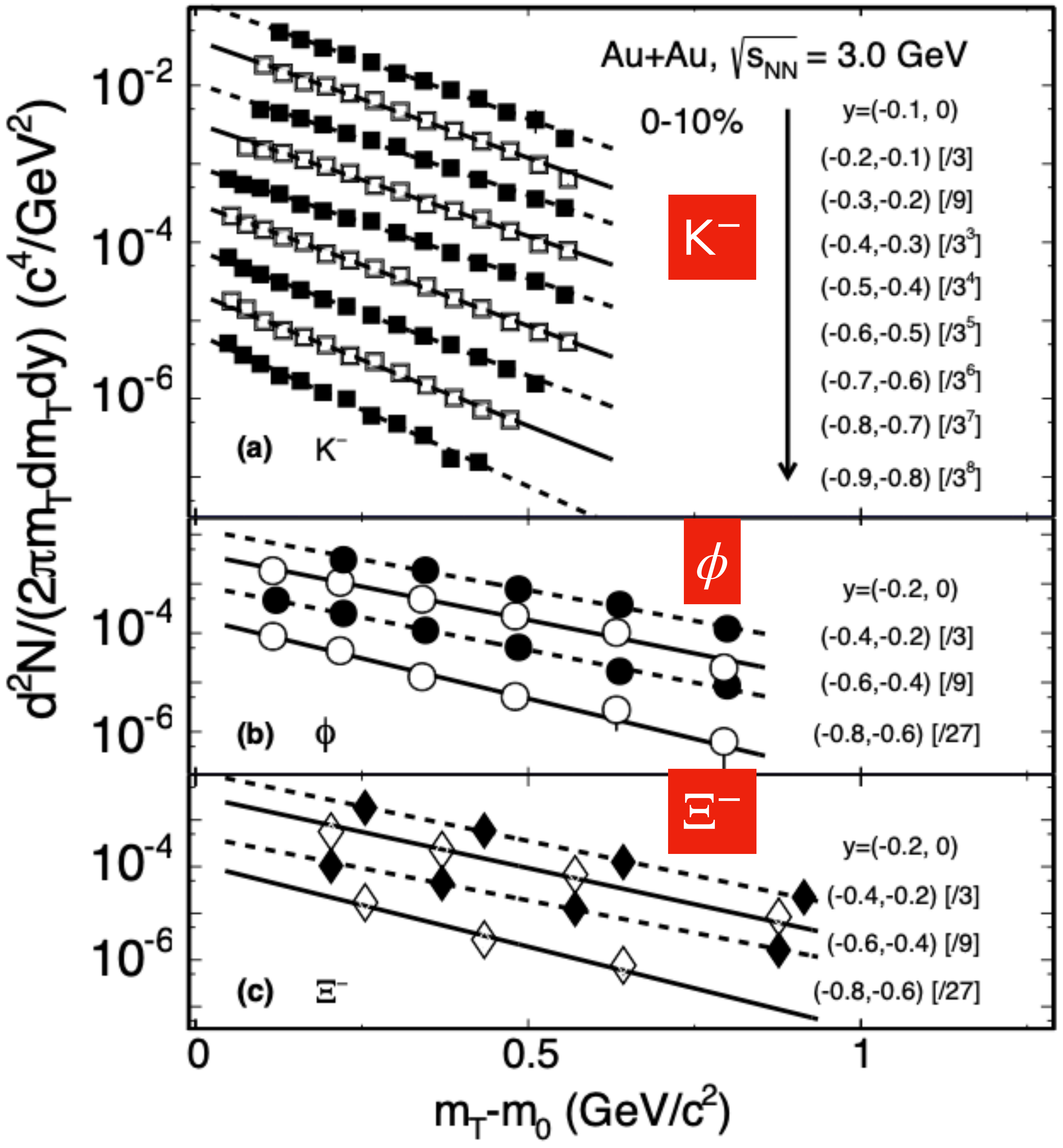
Strangeness Reconstruction

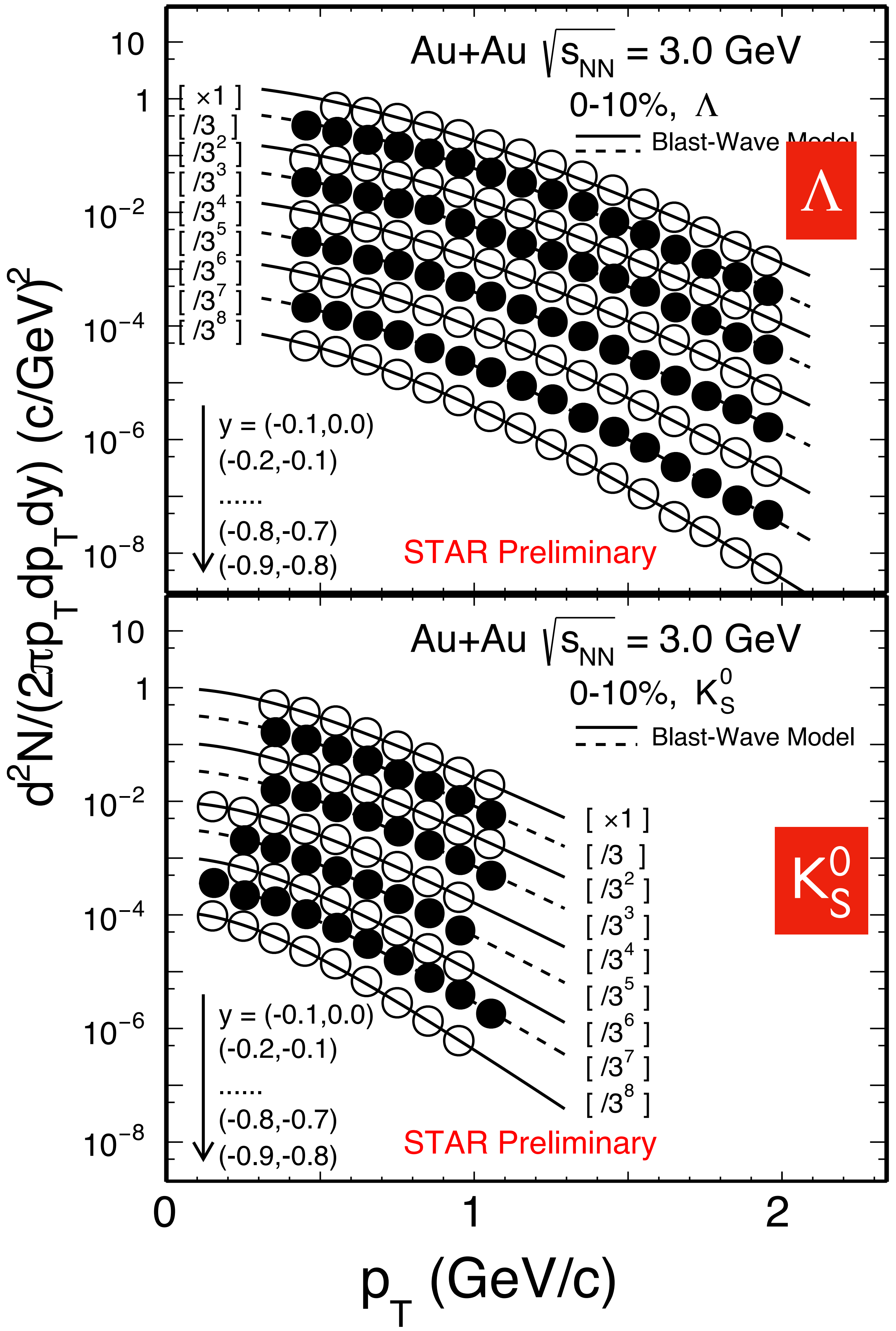
Au+Au 3 GeV





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

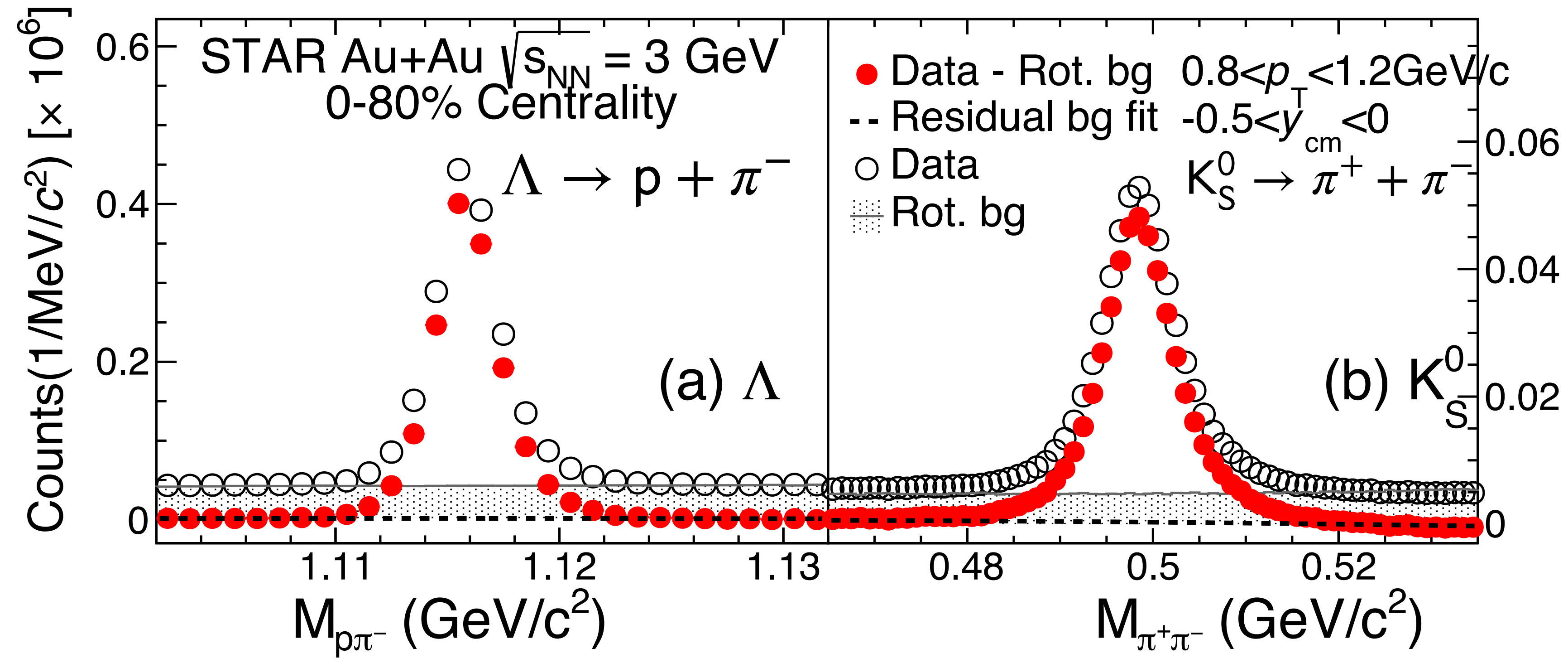


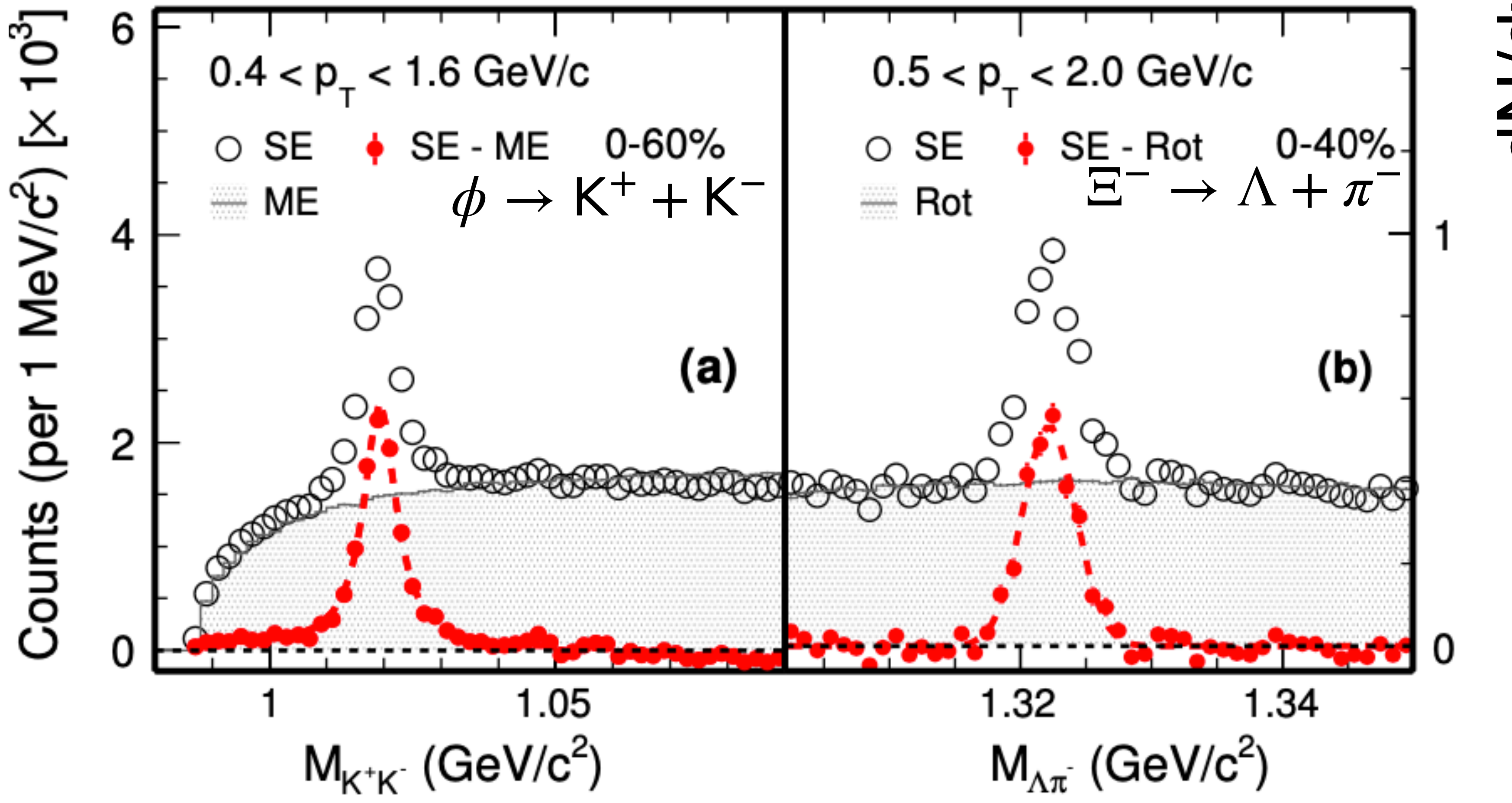


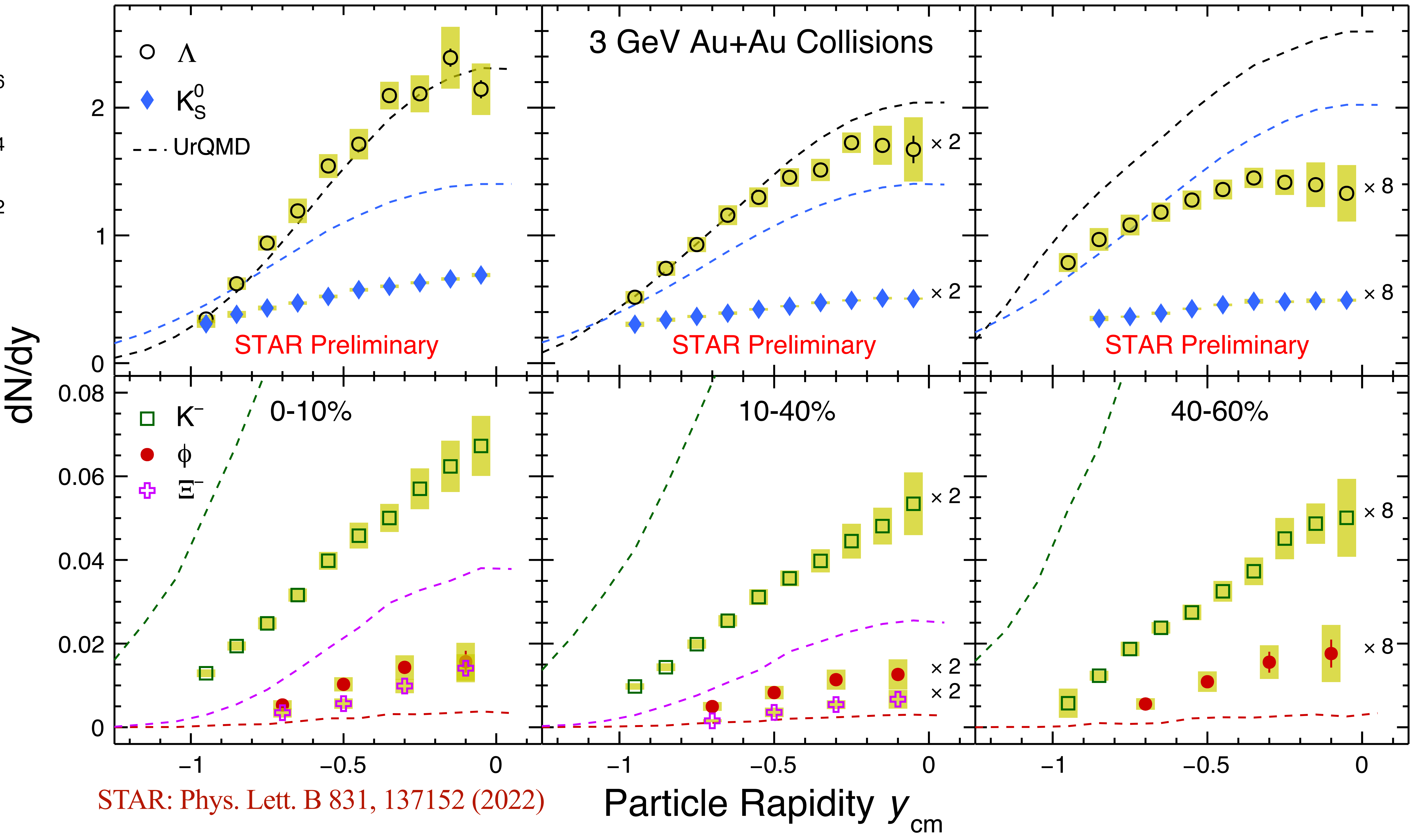
- **Comprehensive strangeness (K^-, K^0_S, Λ, ϕ, Ξ^-) measurements at different energies from 3 to 4.5 GeV**

Strangeness Reconstruction

Au+Au 3 GeV



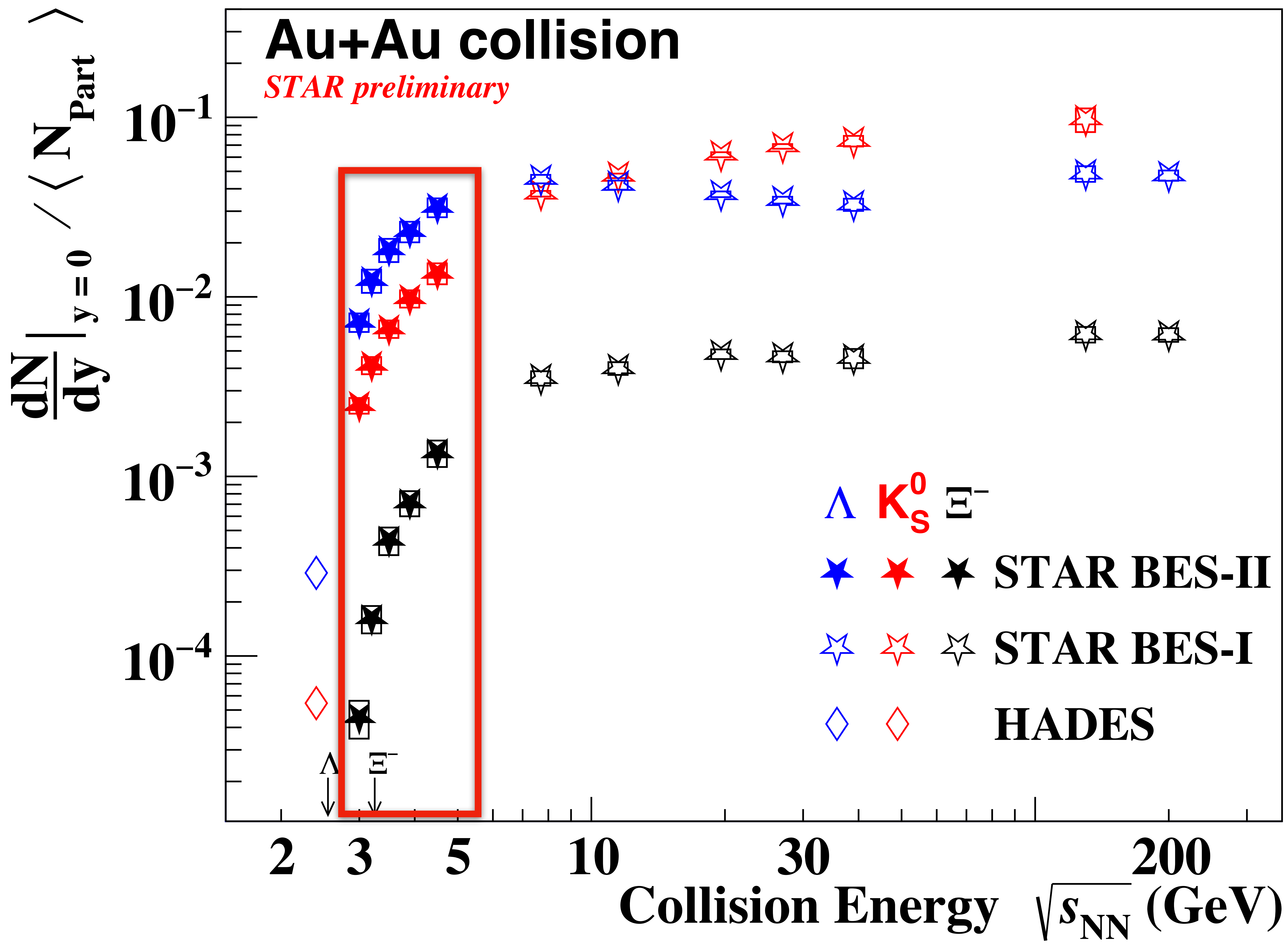




STAR: Phys. Lett. B 831, 137152 (2022)

- **Comprehensive strangeness (K^-, K^0_S, Λ, ϕ, Ξ^-) measurements at different energies from 3 to 4.5 GeV**

Strangeness Excitation Function



- Rich structure in these excitation functions

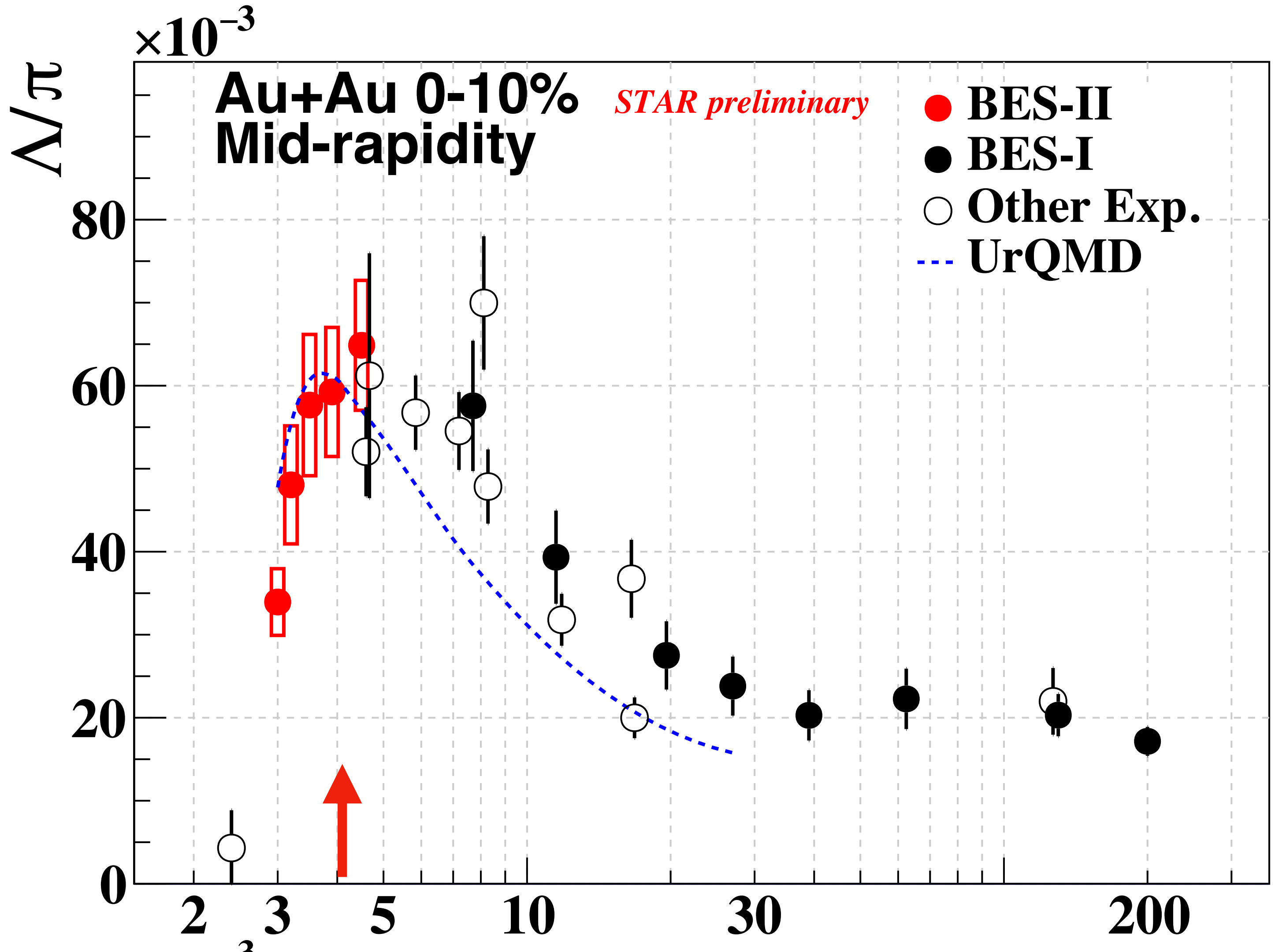
➡Connections to the softness of dense nuclear matter, phase boundary, and onset of deconfinement

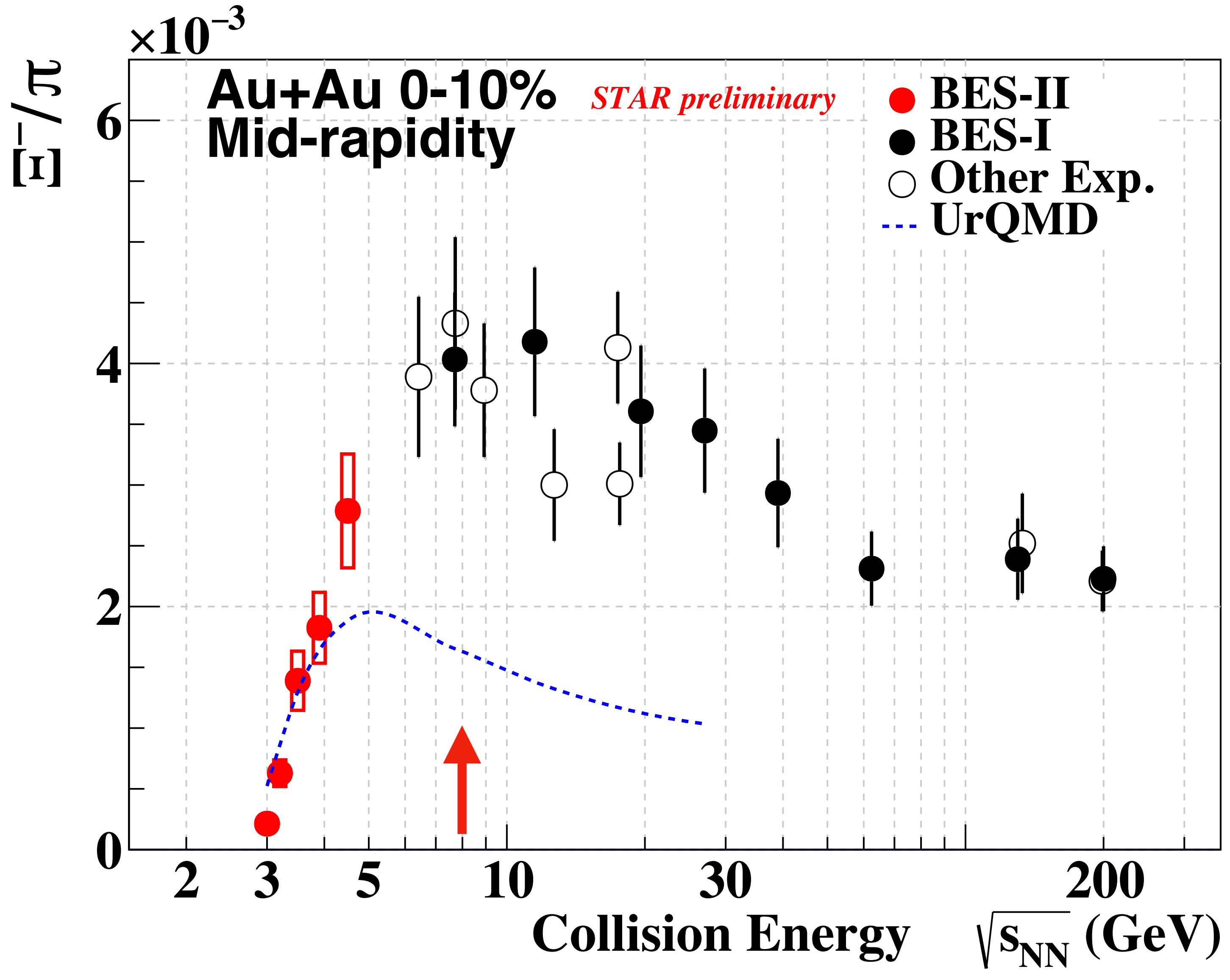
1) Λ and K^0_S cross at $\sqrt{s_{NN}} \sim 8$ GeV: baryon-dominated ↔ meson-dominated

2) First measurement of Ξ^- near- or sub-threshold energies in Au+Au collisions

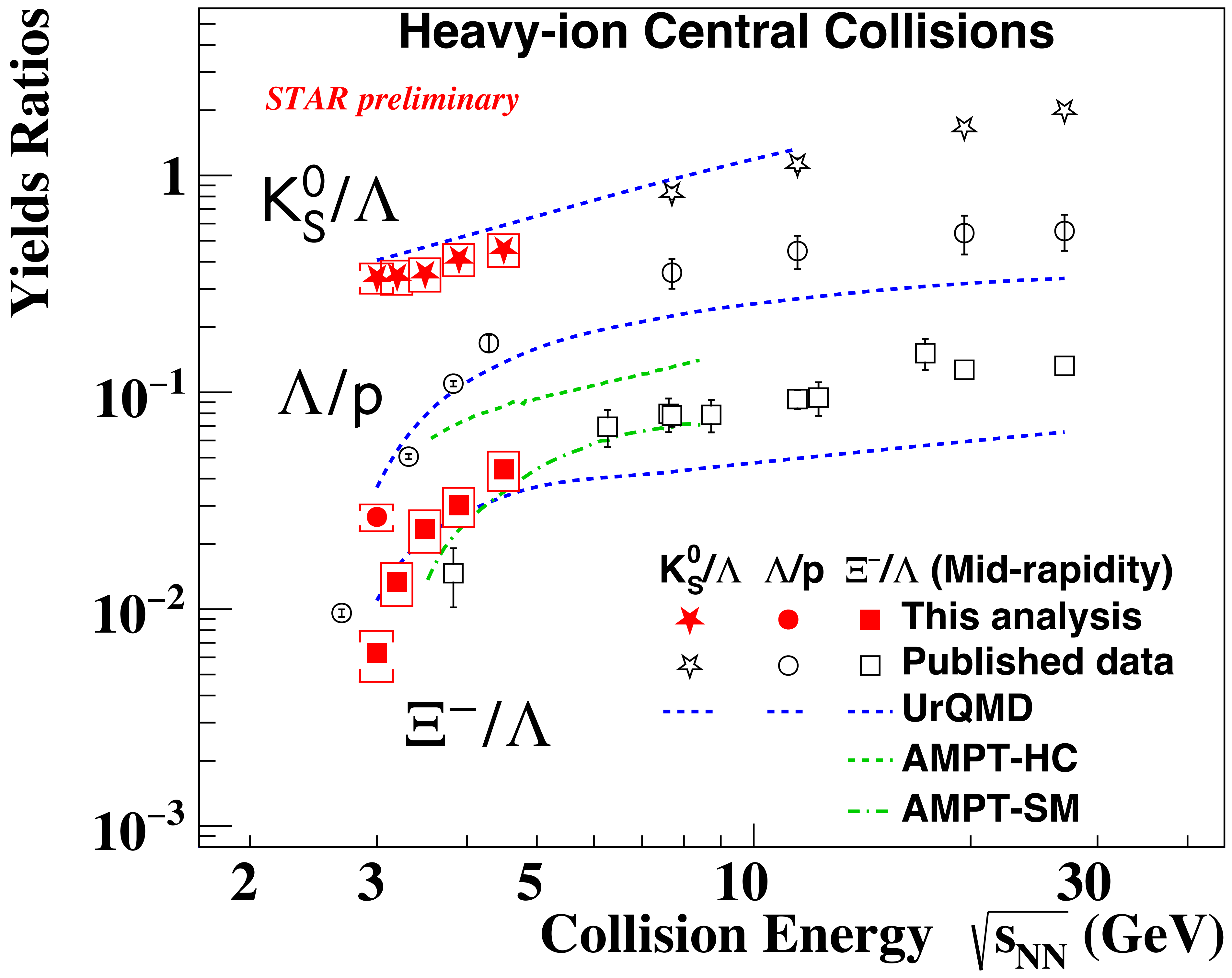
STAR: Phys. Lett. B 831, 137152 (2022)
STAR: Phys. Rev. C 102, 034909 (2020)
HADES: Phys.Lett.B 793 (2019) 457-463

Mid-rapidity Yield Ratio





UrQMD: cascade mode, hard EOS



STAR: Phys. Rev. C 102, 034909 (2020)
(UrQMD) S. A. Bass, et al. Prog. Part. Nucl. Phys. 41 (1998)
(AMPT) GC Yong, Phys.Lett.B 843, 138051 (2023)

1) Λ/π and Ξ^-/π seems to show a different maximum position

- π extracted from published data fit[1]

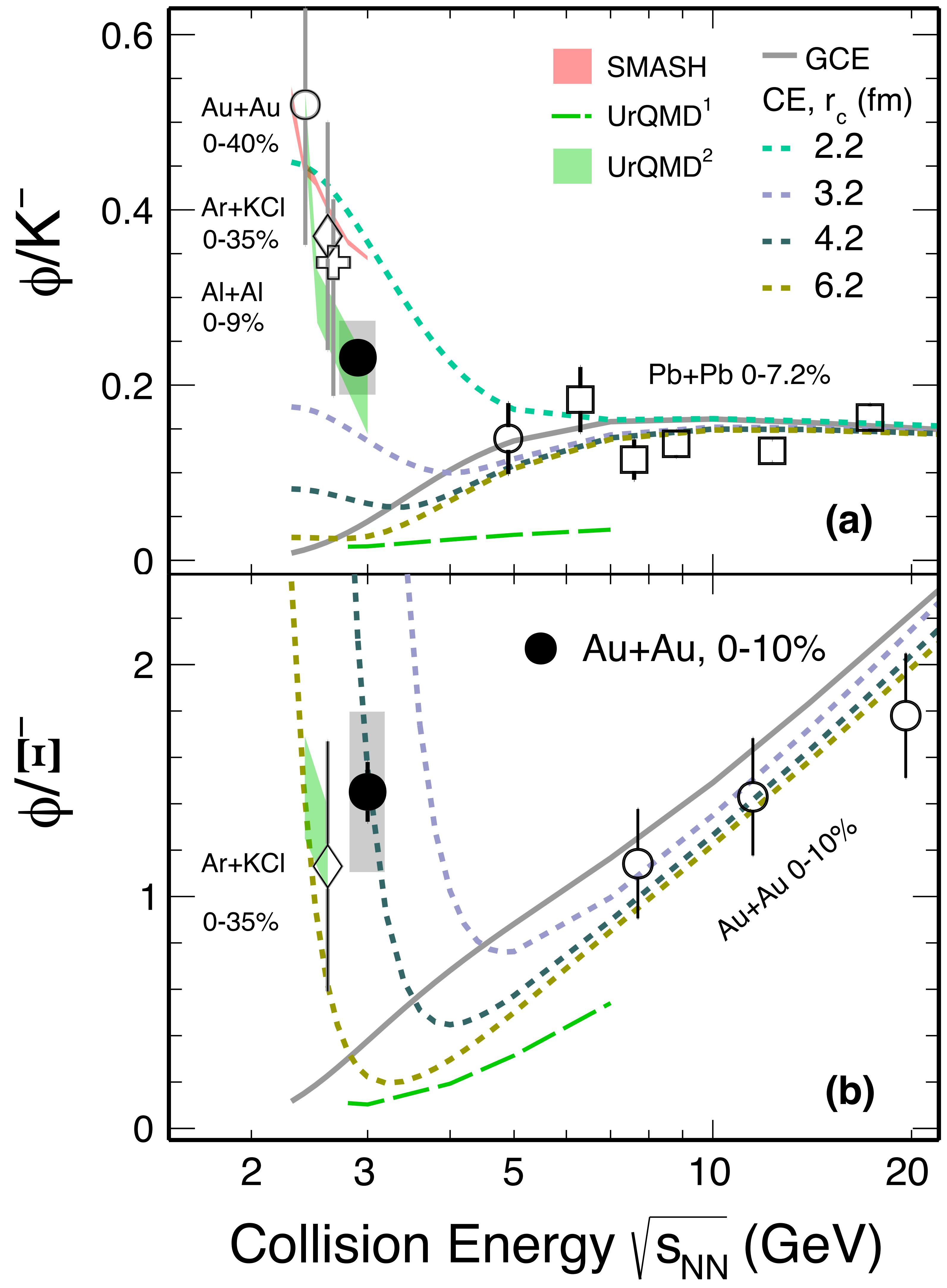
2) Present transport models (UrQMD, AMPT) cannot consistently describe all data

- **Strange baryons, especially the double strangeness Ξ^-, are sensitive probes to the medium properties**

[1] S. Chatterjee et al. Adv.High Energy Phys. 349013 (2015)

Mid-rapidity Yield Ratio

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



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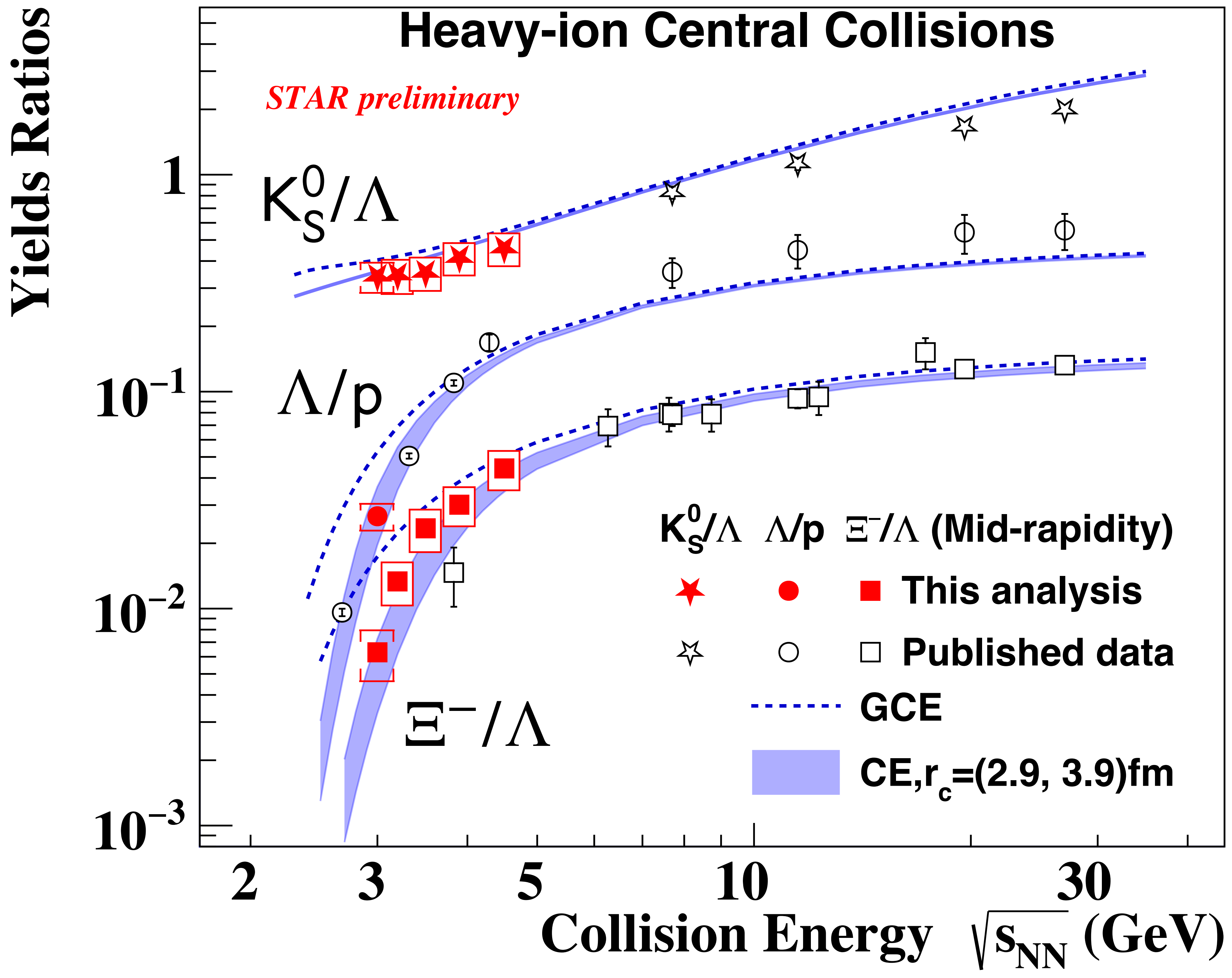


STAR: Phys. Rev. C 102, 034909 (2020)
(THERMUS) S. Wheaton, et al. Comput.Phys.Commun. 180 (2009)

Thermal model parameters: T and μ_B taken from [1], with net S = 0

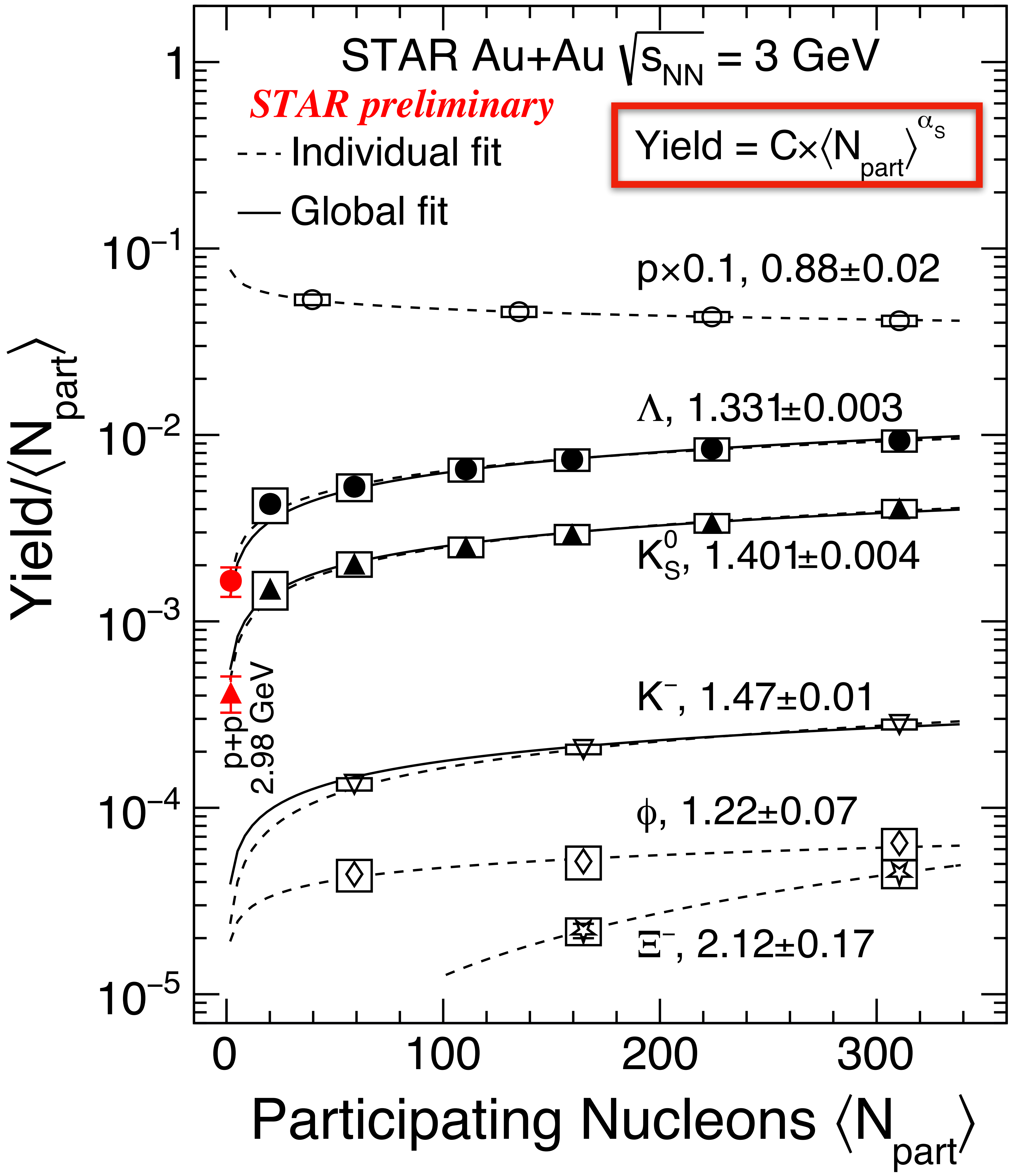
1) Canonical Ensemble (CE) with strangeness correlation length 2.9 – 3.9 fm, simultaneously describes K^0_S/Λ, Λ/p, and Ξ^-/Λ in the measured energy range, GCE fails at low energies

- **Similar observations for ϕ/K^- and ϕ/Ξ^-**

➡Change of medium properties at the high-density region

[1] V. Vovchenko, et al. Phys. Rev. C 93, 064906 (2016)

Centrality Dependence of 4π Yields - 3 GeV



1) **Single strange hadron yields (K^-, K^0_S, Λ) follow common $\langle N_{part}\rangle$ scaling, but Ξ^- seems to deviate from the scaling trend** (2σ deviation from S=1)

Due to Ξ^- **Sub-threshold production?**
→ Multi-step collisions involving pions and Delta resonances → **sensitive to the baryon density, which depends on the EOS**[1]

$NN \rightarrow \Xi^- K^+ K^+ N$ $\sqrt{S_{thresh.}}$ = 3.25 GeV
$NN \rightarrow K^0 N \Lambda$ $\sqrt{S_{thresh.}}$ = 2.56 GeV

2) **p+p following the scaling trend**

➡ **Hadronic interactions drive the observed trends**

[1] T. Song, et al. Phys. Rev. C 103, 044901 (2021)
(p+p) V. Kolesnikov, et al. Phys. Part. Nuclei Lett. 17, (2020) 142–153
(PHQMD) J. Aichelin, et al. Phys. Rev. C 101, 044905 (2020)

Centrality Dependence of Mid-rapidity Yields

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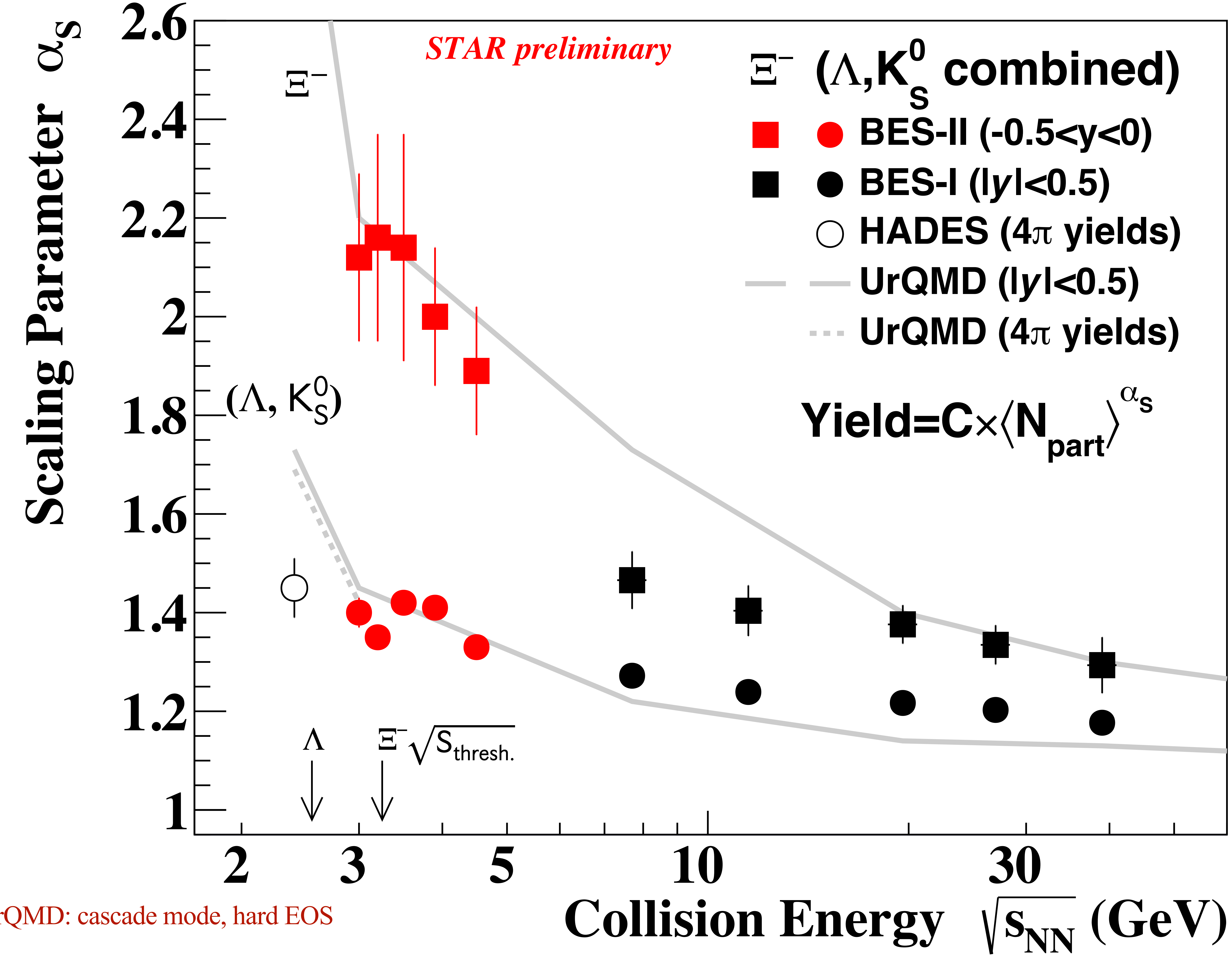


UrQMD: cascade mode, hard EOS

1) Rapid decrease of scaling parameter α_S for Ξ^- from 4.5 to 7.7 GeV, and saturate at high energy

➡Hadron dominated medium at $\sqrt{s_{NN}} < 4.5$ GeV

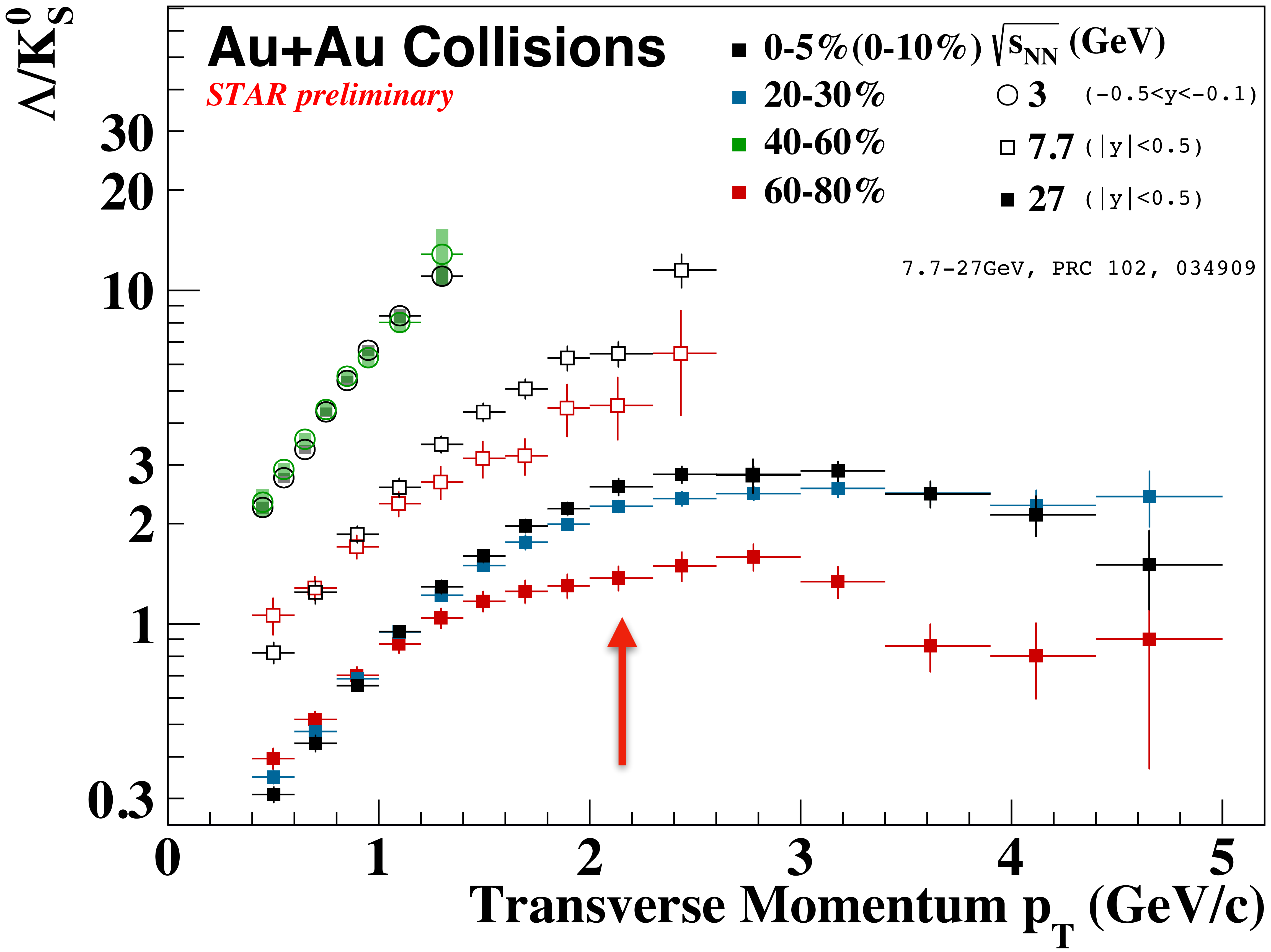
2) UrQMD qualitatively reproduces the energy dependence

- Quantitatively fails at 7.7 – 11.5 GeV, likely due to missing medium effects

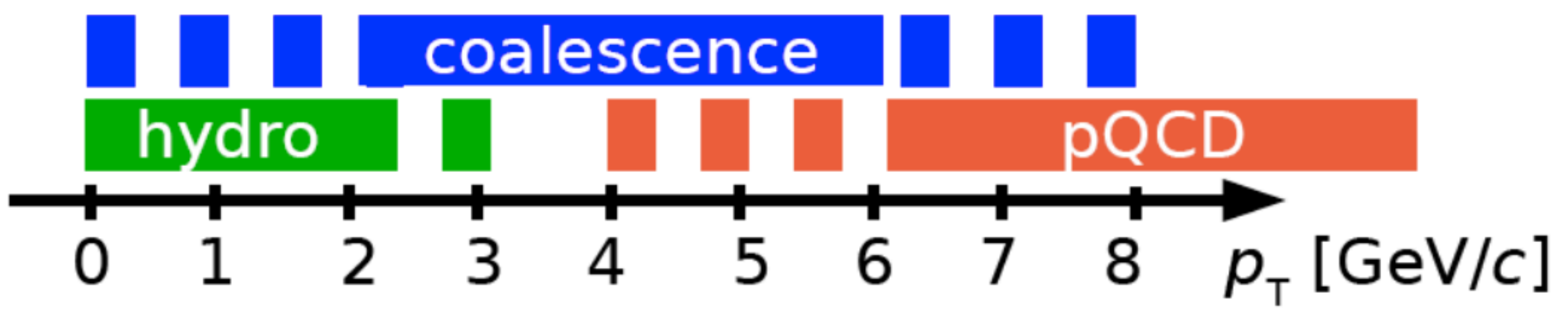
(UrQMD) S. A. Bass, et al. Prog. Part. Nucl. Phys. 41 (1998)

Baryon-to-Meson Yield Ratio

STAR: Phys. Rev. C 102, 034909 (2020)



Physics in high energy AA collisions



Figure, courtesy of Christoph Blume

Low p_T region: radial flow
mass dependent hardening of spectra

Intermediate p_T region[1,2,3]: quark recombination
Baryon enhancement

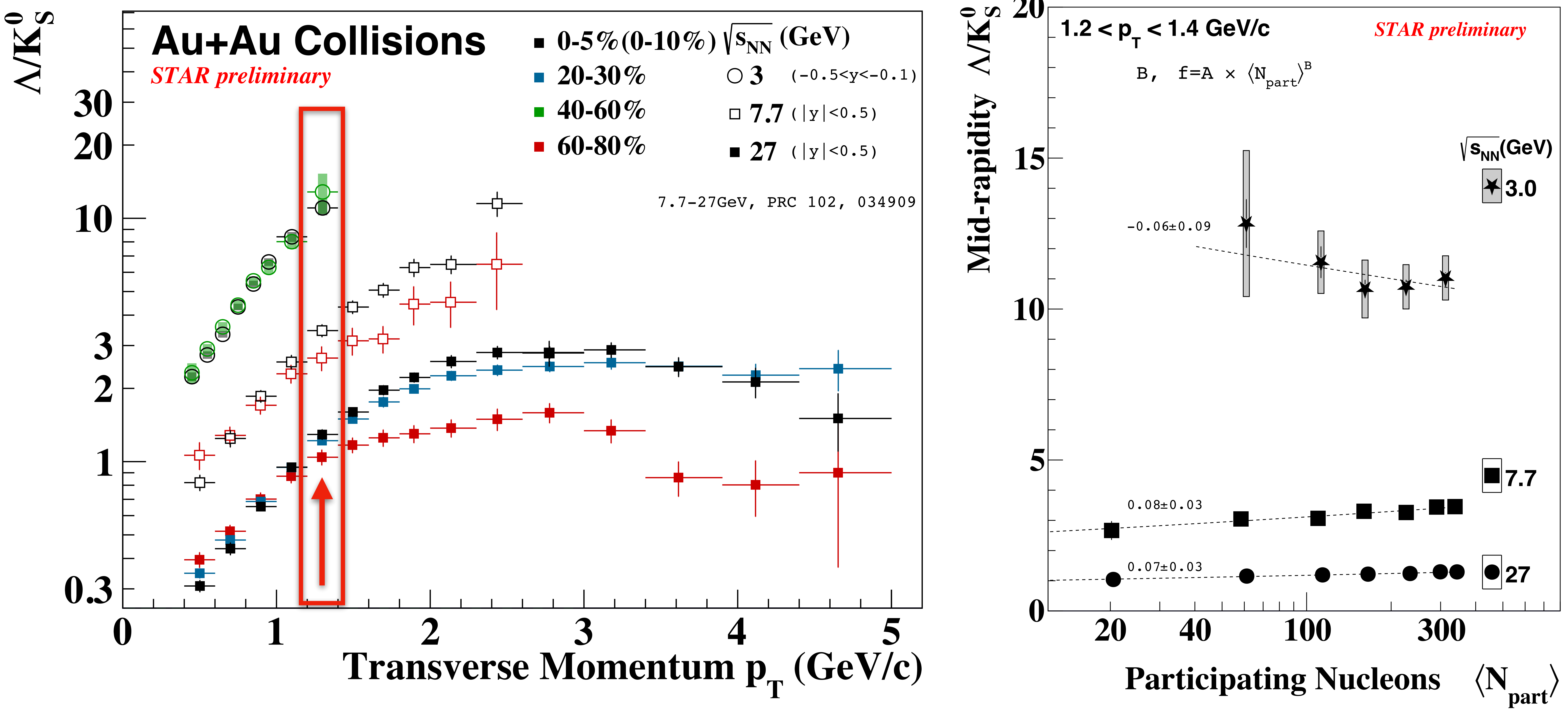
High p_T region: fragmentation
universal behaviour

1) At high energies ($\sqrt{s_{NN}} \geq 7.7$ GeV), Λ/K^0_S is enhanced in central collisions
- Parton recombination?

[1] STAR: Phys. Rev. C 83, 24901 (2011)
[2] ALICE: Phys. Lett. B 728 (2014) 25-38
[3] ALICE: Phys. Rev. C 99, 024906 (2019)

Baryon-to-Meson Yield Ratio

STAR: Phys. Rev. C 102, 034909 (2020)



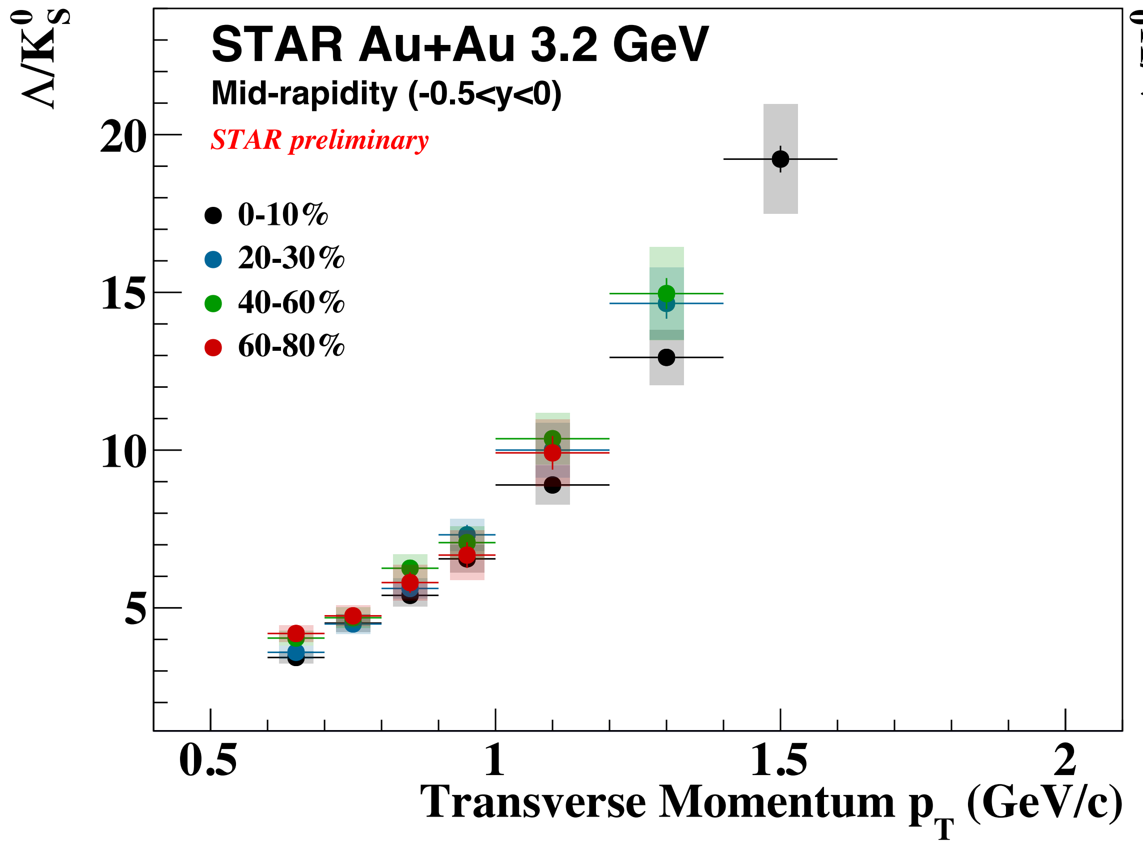
1) At high energies ($\sqrt{s_{NN}} \geq 7.7$ GeV), Λ/K^0_S is enhanced in central collisions

- Parton recombination?

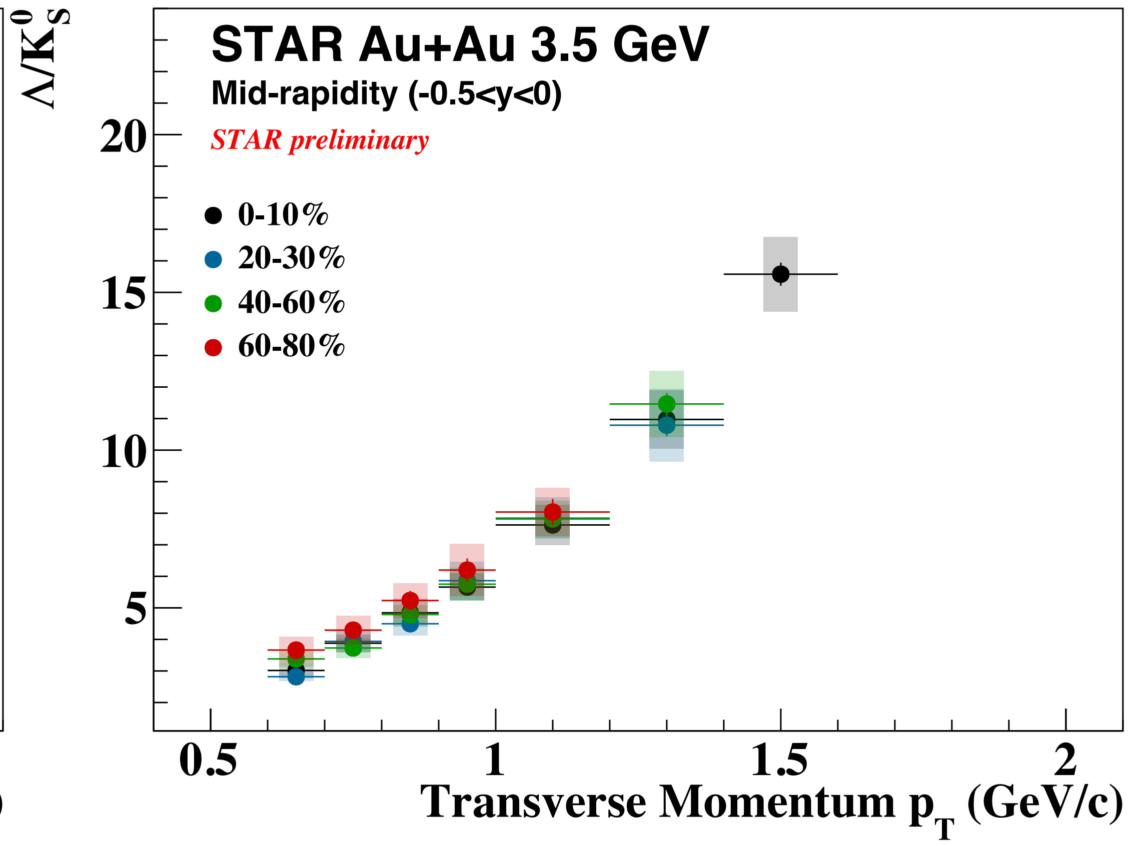
2) Λ/K^0_S enhancement not observed at 3 GeV in the measured p_T range

Baryon-to-Meson Yield Ratio

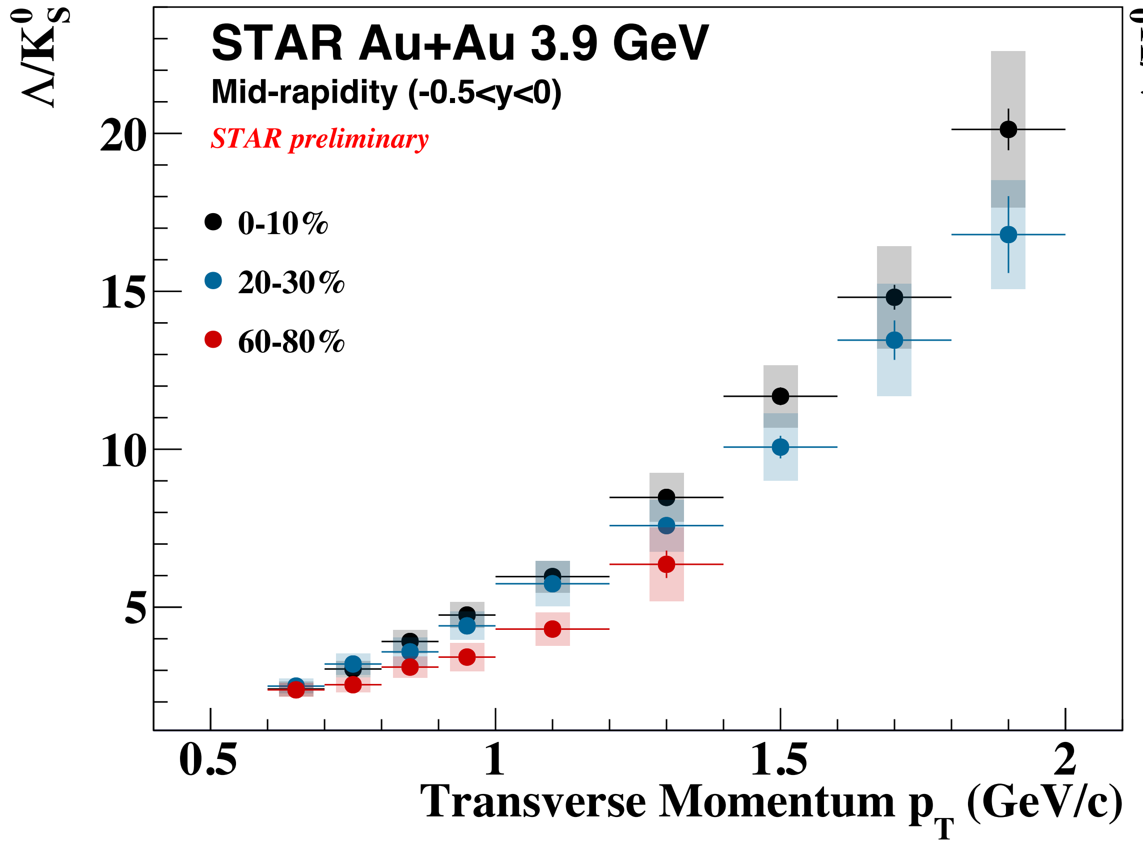
3.2 GeV



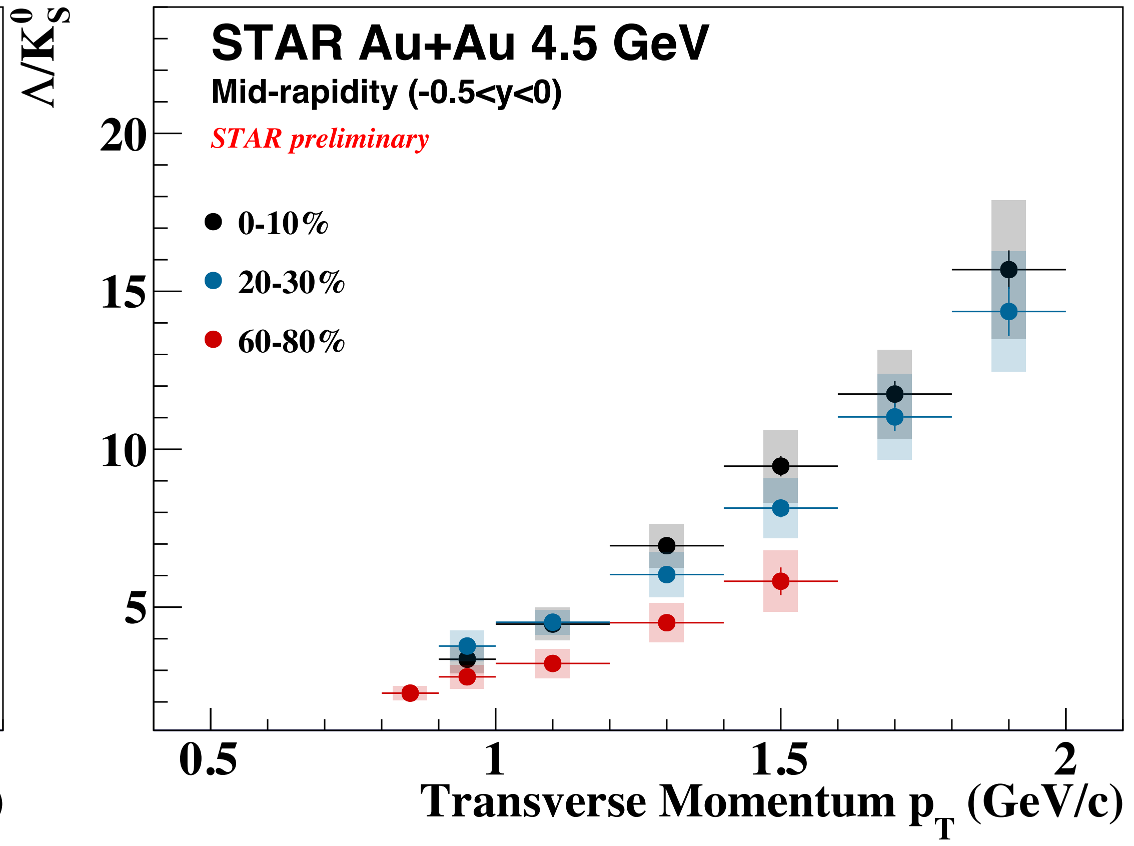
3.5 GeV

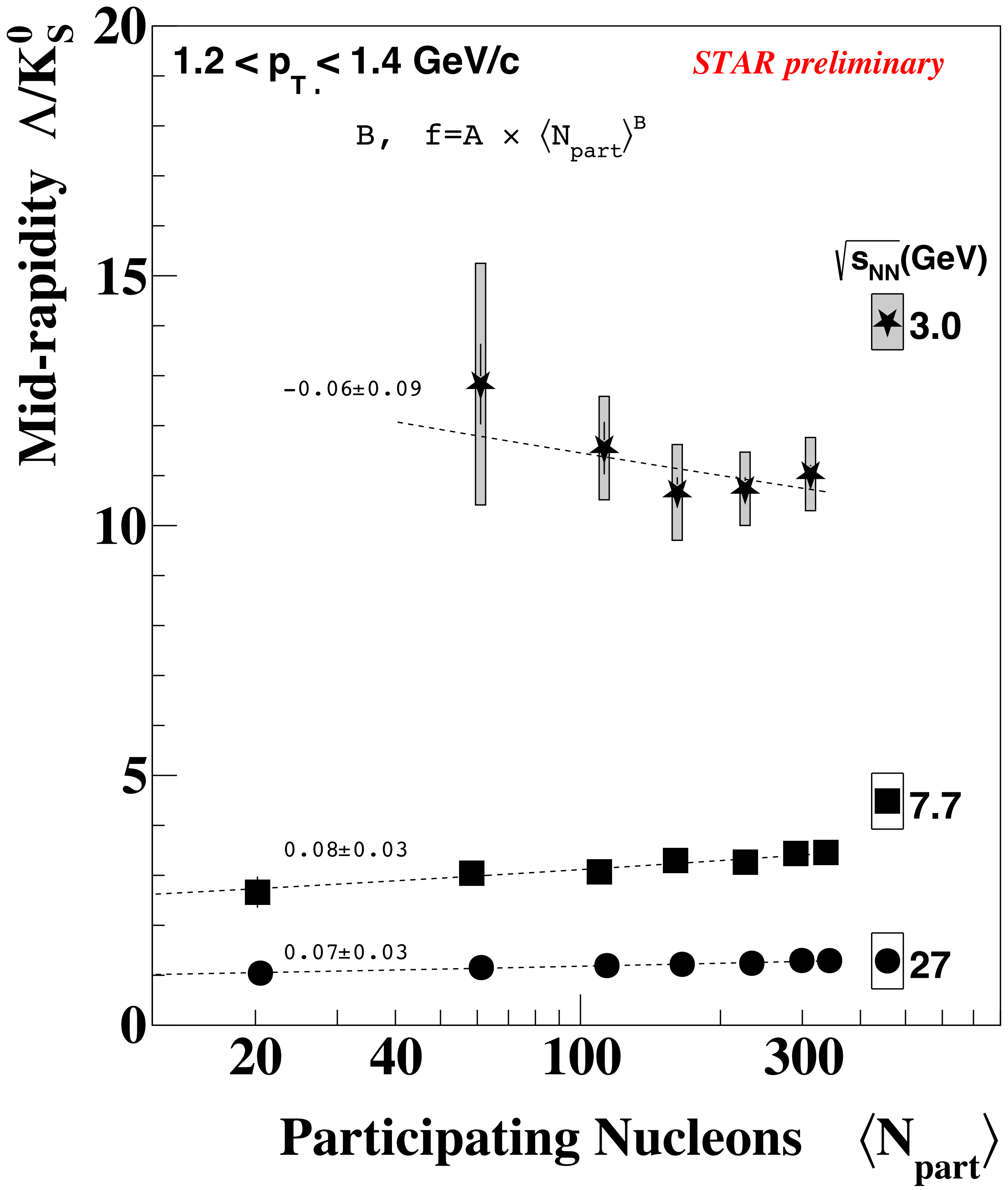


3.9 GeV

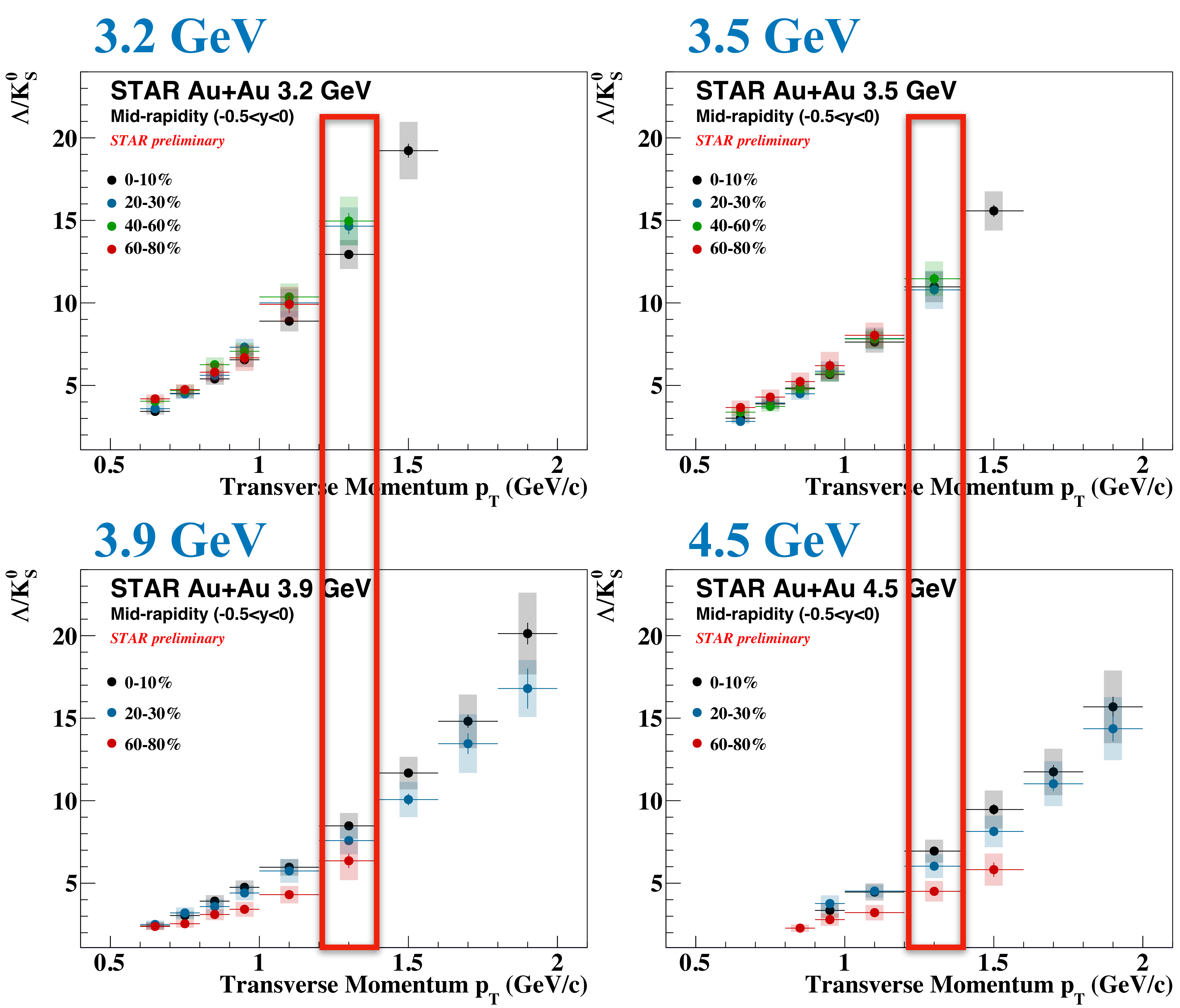


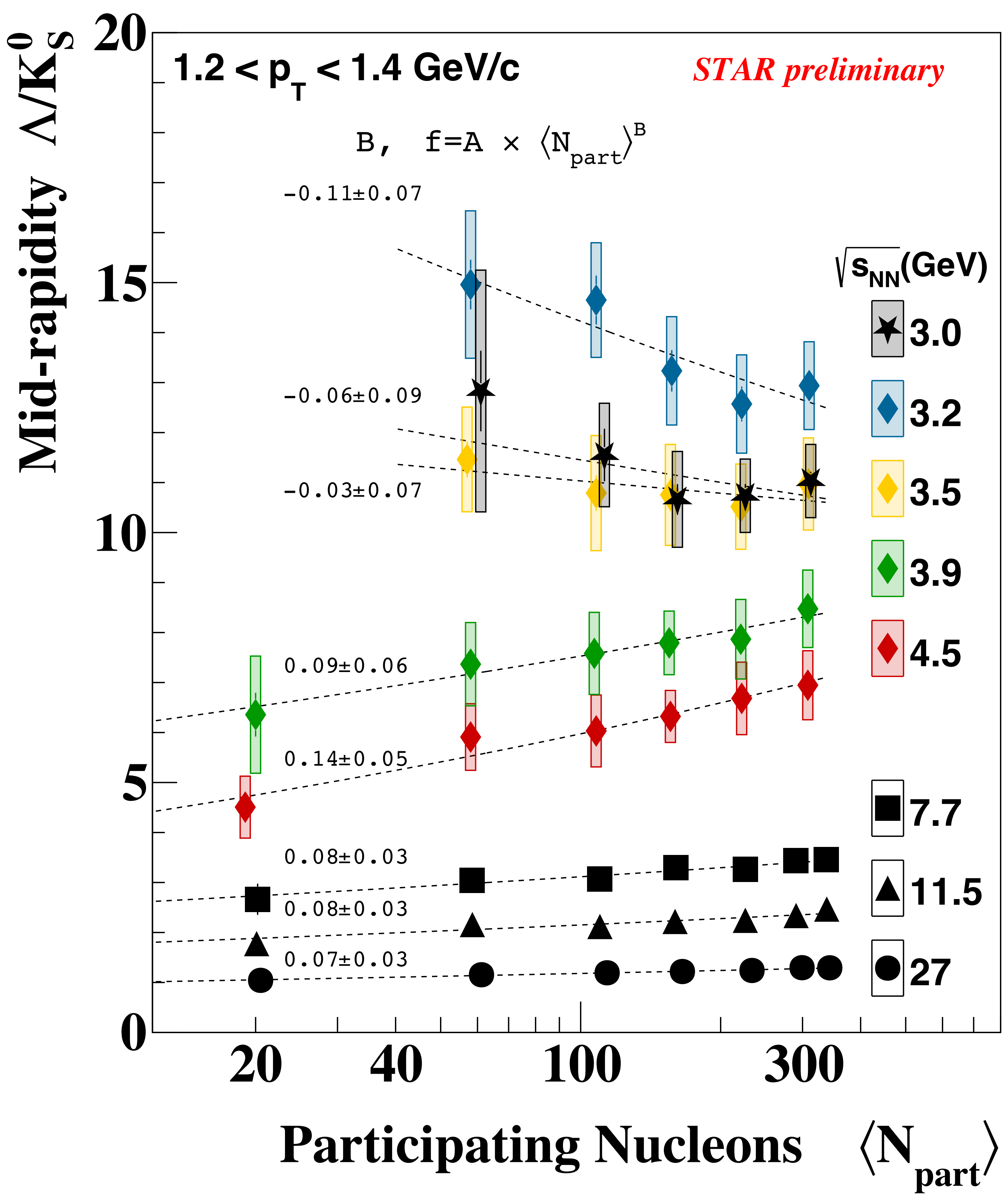
4.5 GeV

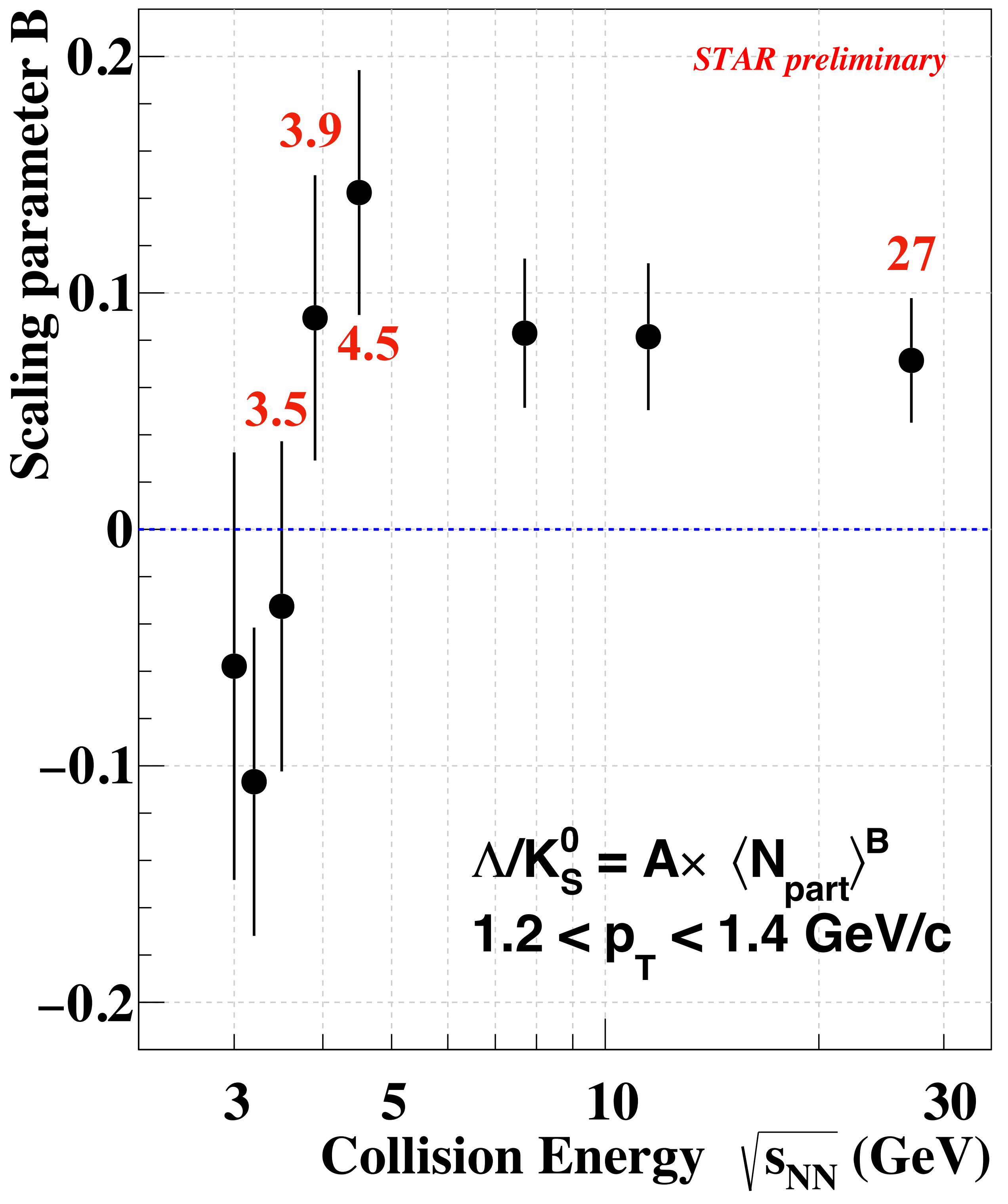




Baryon-to-Meson Yield Ratio



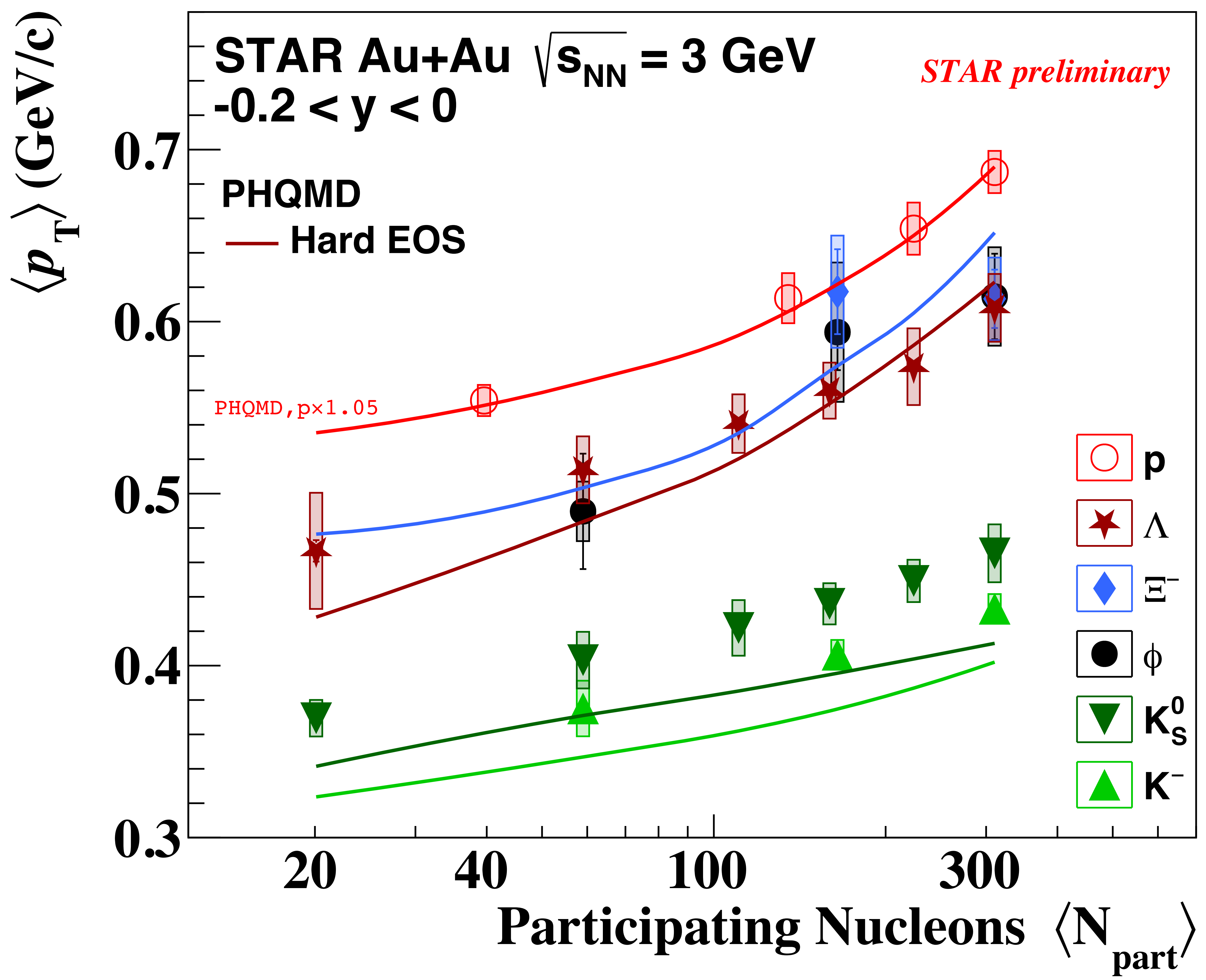




1) Λ/K^0_S is enhanced in p_T [1.2, 1.4] GeV/c at 4.5 GeV, but not observed below 3.9 GeV

➡Possible change of medium properties

Average Transverse Momentum - 3 GeV



PHQMD, w/o momentum dependence
Hard: κ = 380 MeV

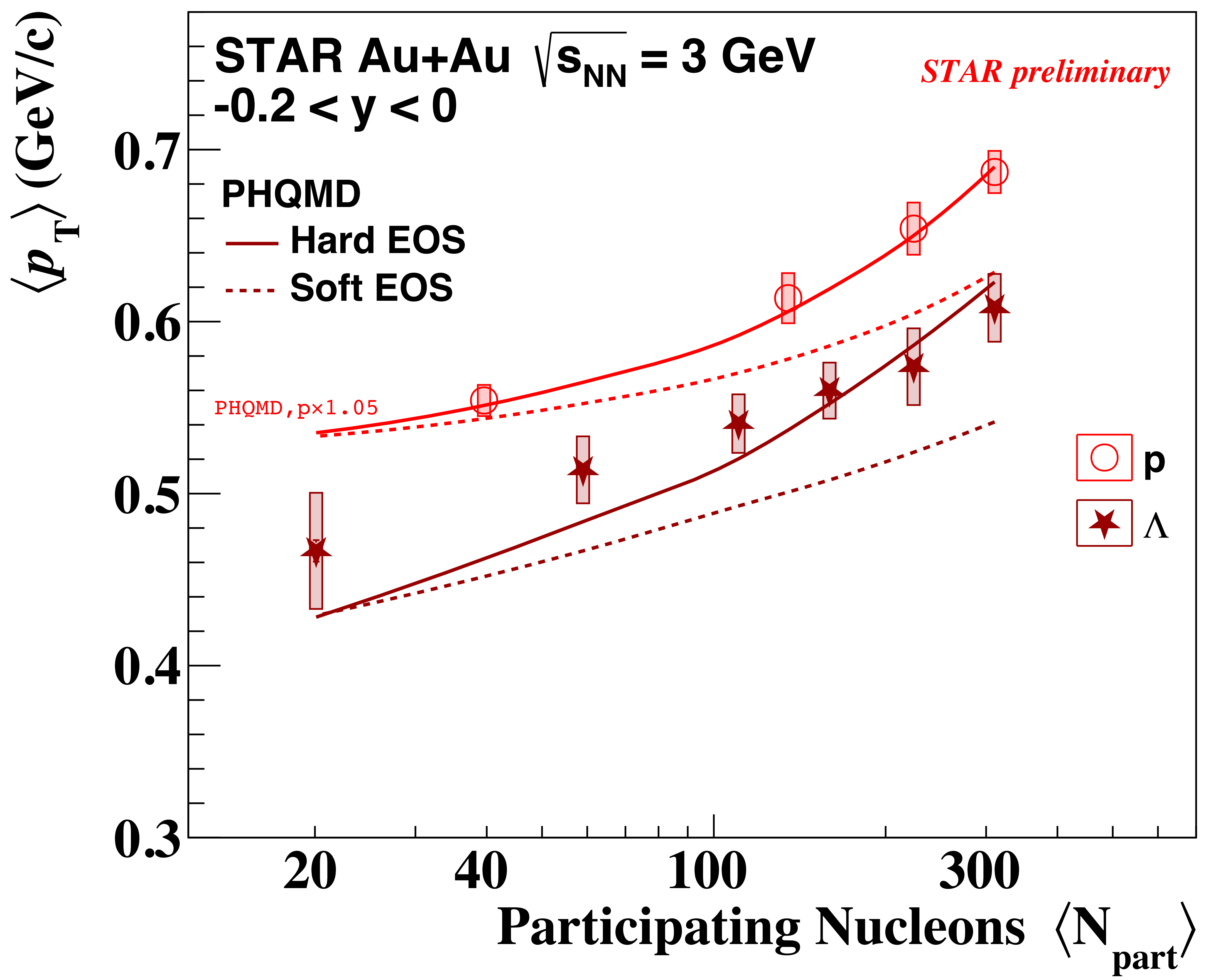
1) $\langle p_T \rangle$ **v.s.** $\langle N_{part} \rangle$ **consistent with radial flow caused by hadronic interactions**

- Gradual increase in $\langle p_T \rangle$ as $\langle N_{part} \rangle$ increase
- Data $\langle p_T \rangle^{K^-} \approx \langle p_T \rangle^{K^0_S} < \langle p_T \rangle^{\phi} \approx \langle p_T \rangle^{\Lambda} \approx \langle p_T \rangle^{\Xi^-}$ follow mass hierarchy
- Data show $\langle p_T \rangle^{\Lambda} < \langle p_T \rangle^{p}$
  - Possibly due to smaller Y-N interaction than N-N interaction?

2) Transport model (PHQMD) with baryon mean field offer consistent $\langle p_T \rangle$ **for p,** Λ **and** Ξ^-

(PHQMD) J. Aichelin, et al. Phys. Rev. C 101, 044905 (2020)

Average Transverse Momentum - 3 GeV



PHQMD, w/o momentum dependence
Hard: κ = 380 MeV; Soft: κ=200 MeV

1) $\langle p_T \rangle$ v.s. $\langle N_{part} \rangle$ consistent with radial flow caused by hadronic interactions

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2) Transport model (PHQMD) with baryon mean field offer consistent $\langle p_T \rangle$ for p, Λ and Ξ^-

- **$\langle p_T \rangle$ is sensitive to EOS**

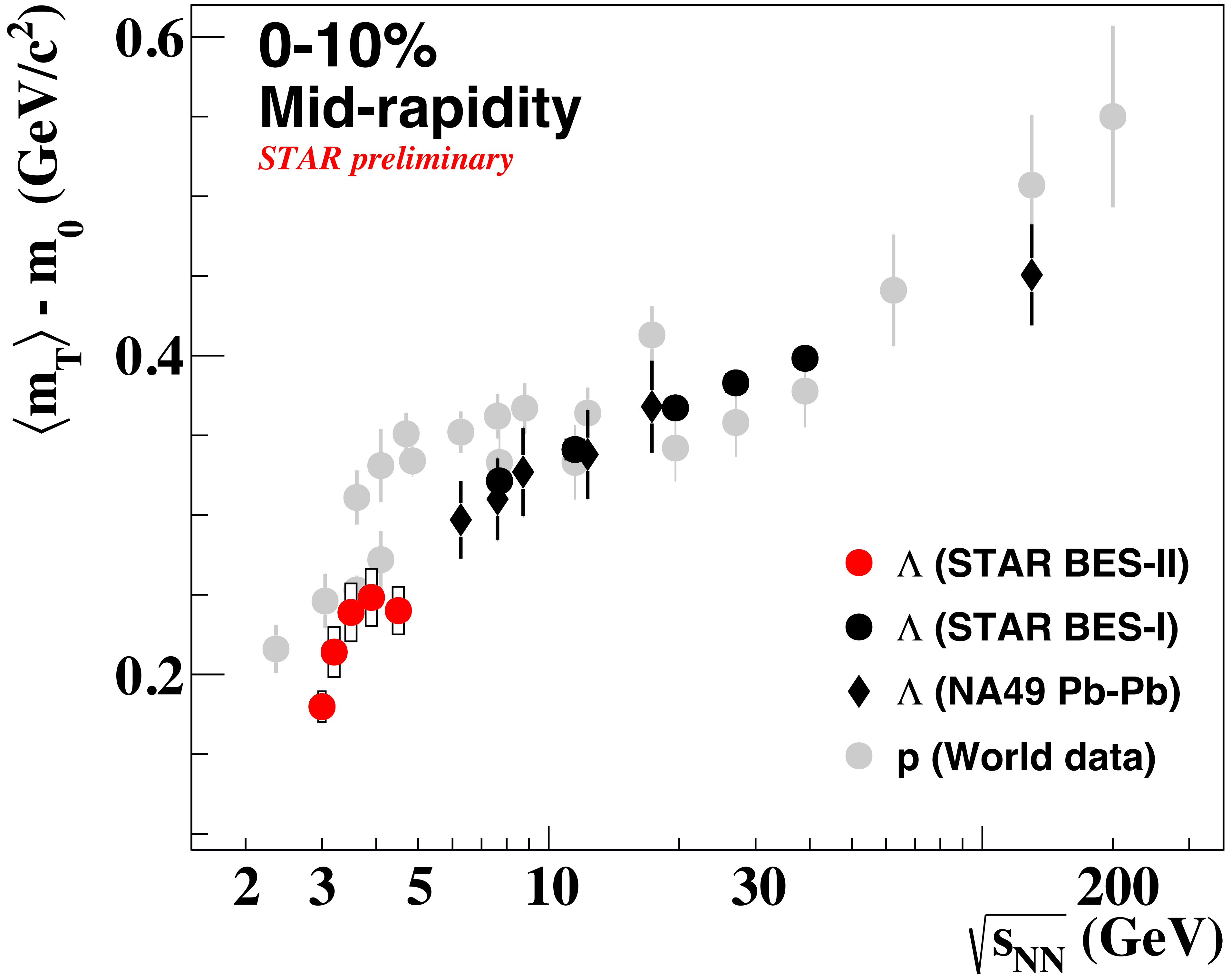
Stiff EOS implies a rapid increase in pressure with energy density, harder EOS will lead to harder p_T distribution, **larger $\langle p_T \rangle$** [1]

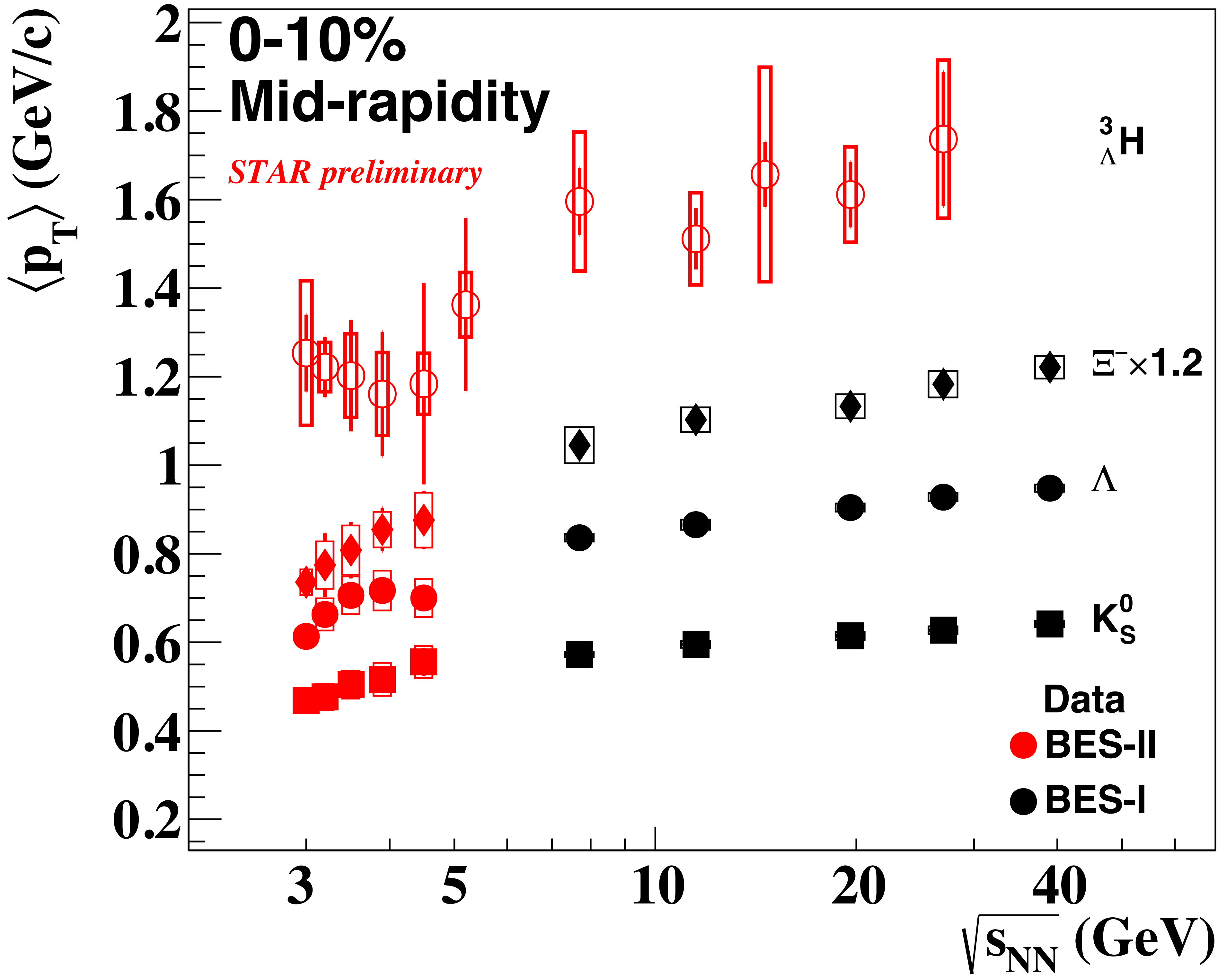
(PHQMD) J. Aichelin, et al. Phys. Rev. C 101, 044905 (2020)

[1] J Steinheimer, et al. Eur. Phys. J. C 82, 911 (2022)

Average Transverse Momentum

- $\langle m_T \rangle - m_0$ is an approximate representation of the temperature of the system[1]





1) Below 11.5 GeV, Λ $\langle m_T \rangle - m_0$ tends to be smaller than proton, while they are compatible at 11.5 GeV or higher

- Difference between Y-N and N-N potentials playing a role below 11.5 GeV?

[1] L. Van Hove, Phys. Lett. B 118, 138 (1982)
STAR: Phys. Rev. C 102, 034909 (2020)
STAR: Phys. Rev. C 96, 044904 (2017)

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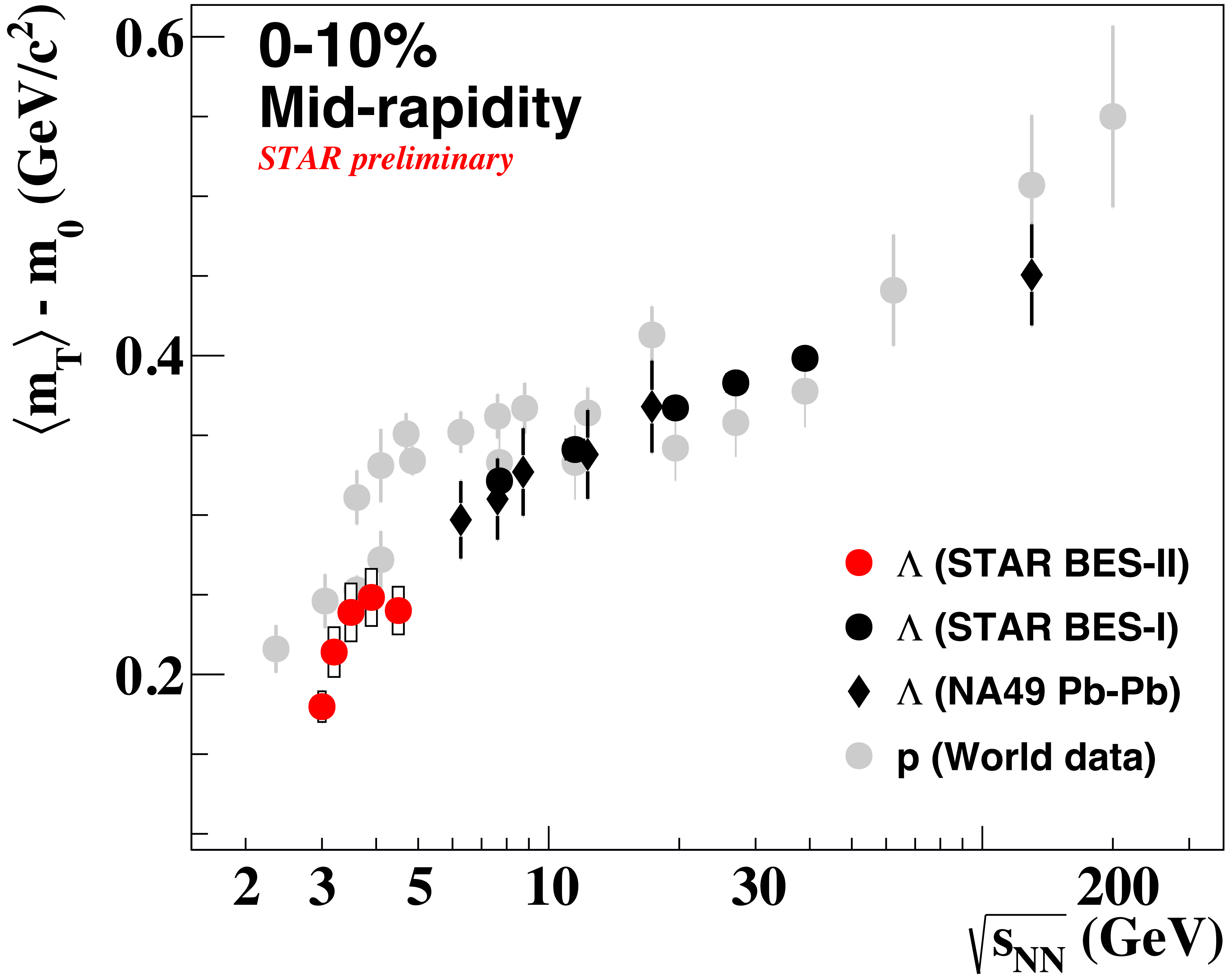
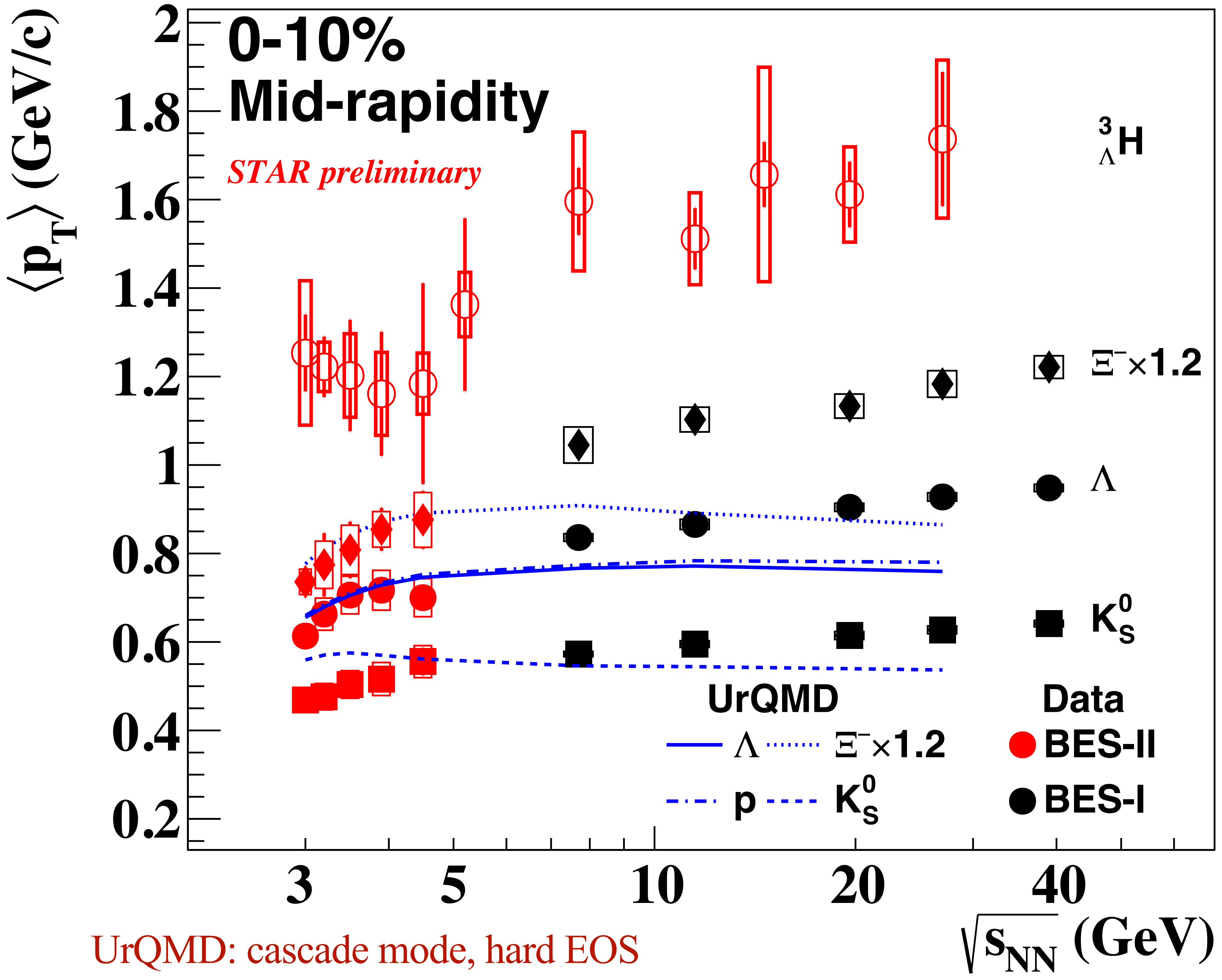




UrQMD: cascade mode, hard EOS

1) Below 11.5 GeV, Λ $\langle m_T \rangle - m_0$ tends to be smaller than proton, while they are compatible at 11.5 GeV or higher

- Difference between Y-N and N-N potentials playing a role below 11.5 GeV?

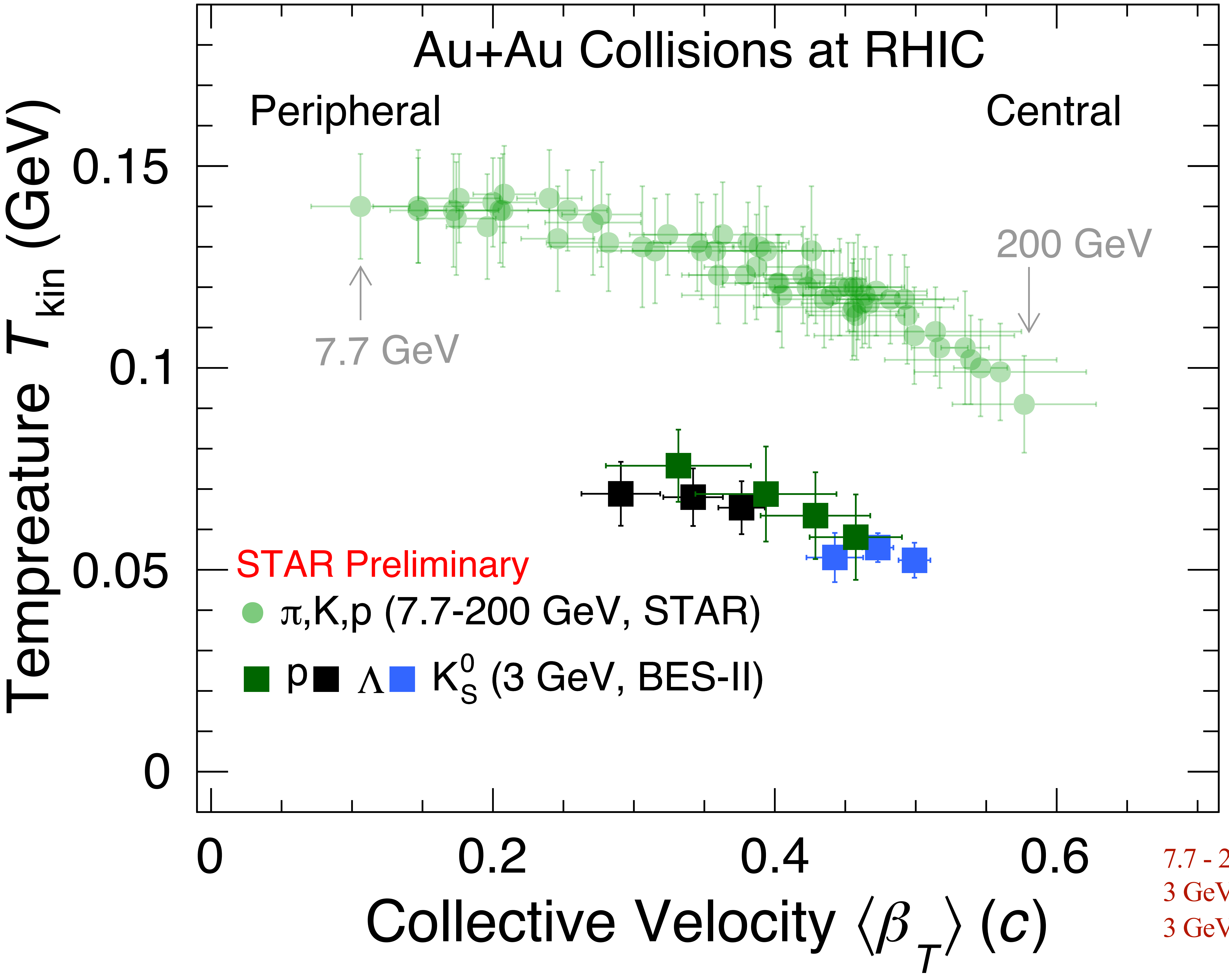
2) Transport model (UrQMD) offers consistent $\langle p_T \rangle$ for Λ and Ξ^- below 5 GeV, but fails at 7.7 GeV or higher

- Transition from a **hadronic interaction dominated matter** to **matter dominated by quark degrees of freedom** somewhere between 4.5 and 7.7 GeV?

[1] L. Van Hove, Phys. Lett. B 118, 138 (1982)
STAR: Phys. Rev. C 102, 034909 (2020)
STAR: Phys. Rev. C 96, 044904 (2017)
(UrQMD) S. A. Bass, et al. Prog. Part. Nucl. Phys. 41 (1998)

Kinematic Freeze-out Properties

STAR: Phys. Rev. C 102, 034909 (2020); Phys. Rev. C 96, 044904 (2017); Phys. Rev. Lett. 108, 072301 (2012)



1) Freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) of p, Λ and K^0_S at 3 GeV do not follow the same trend as π, K, p at 7.7 – 200 GeV

➡Change in medium properties (EOS) or expansion dynamics

Blast wave function fit

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

T_{kin}: the kinetic freeze-out temperature

$\langle\beta_T\rangle$: average transverse radial flow velocity

n: the exponent of flow velocity profile, n=1

I_0 and K_1 are from Bjorken Hydrodynamic assumption

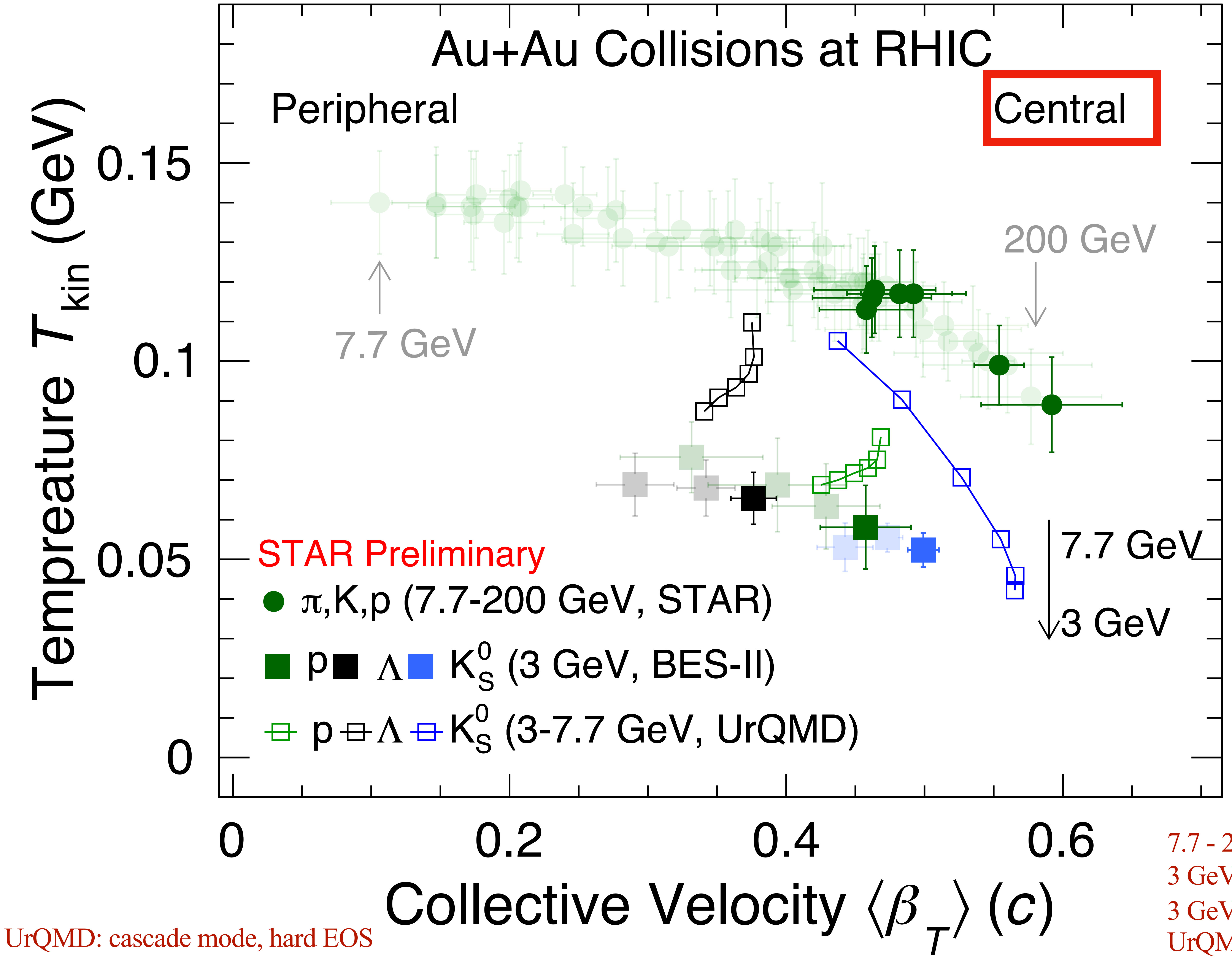
7.7 - 200 GeV: 0-5%, 5-10%, …60-80%

3 GeV Λ(K^0_S): 0-10%, 10-40%, 40-60%

3 GeV p: 0-10%, 10-20%, 20-40%, 40-80%

Kinematic Freeze-out Properties

STAR: Phys. Rev. C 102, 034909 (2020); Phys. Rev. C 96, 044904 (2017); Phys. Rev. Lett. 108, 072301 (2012)



UrQMD: cascade mode, hard EOS

1) Freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) of p, Λ and K^0_S at 3 GeV do not follow the same trend as π, K, p at 7.7 – 200 GeV

➡Change in medium properties (EOS) or expansion dynamics

2) Transport model (UrQMD) predicts decreasing T_{kin} from 7.7 – 3 GeV

- **Different freeze-out parameters for p, Λ and K^0_S, similar to 3 GeV data**

7.7 - 200 GeV: 0-5%, 5-10%, …60-80%
3 GeV Λ(K^0_S): 0-10%, 10-40%, 40-60%
3 GeV p: 0-10%, 10-20%, 20-40%, 40-80%
UrQMD: 0-10%

(UrQMD) S. A. Bass, et al. Prog. Part. Nucl. Phys. 41 (1998)

Summary

- Precision measurements of strangeness ($K^{\pm}$, K_S^0, Λ, ϕ and Ξ^-) production in 3 – 4.5 GeV Au+Au collisions

1) <u>Steeper centrality dependence</u> of mid-rapidity yields (α_S) at 3 – 4.5 GeV than that at higher energies

2) <u>Baryon-to-meson ratio (Λ/K_S^0) enhancement</u> not observed at 3 – 3.5 GeV, but observed at 4.5 GeV or higher energies

3) <u>Canonical suppression</u> of strangeness is observed at 3 GeV

4) <u>Freeze-out parameters</u> (T_{kin}, $\langle\beta_T\rangle$) of p, Λ and K_S^0 at 3 GeV do not follow the same trend as π, K, p at 7.7 – 200 GeV

➡Hadron dominated medium created in 3 GeV Au+Au collisions

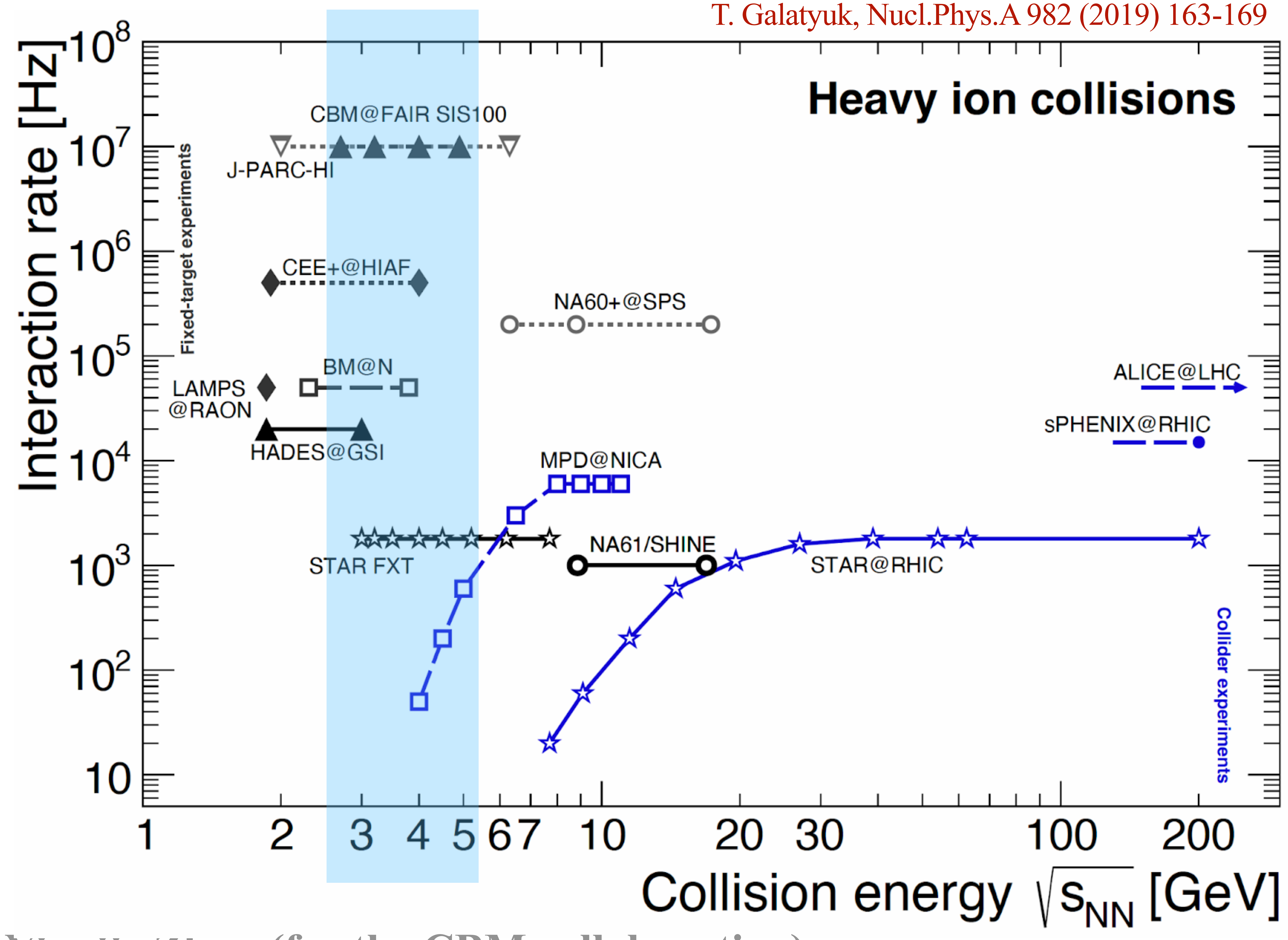
➡Onset of partonic degrees of freedom at ~ 3.9 GeV? Or are trends driven by expansion dynamics?

Future Strangeness Studies with CBM

- **Sub-NN-threshold particle production is sensitive to Equation-of-State (EOS)**
  - **$\sqrt{s_{NN}}$ = 2.5-4.9 GeV Au+Au**
  - **Interaction rates up to 10MHz**
  - **Gives access to rare probes**

reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
$pp \to K^+\Lambda p$	2.548	1.6
$pp \to K^+K^-pp$	2.864	2.5
$pp \to K^+K^+\Xi^-p$	3.247	3.7
$pp \to K^+K^+K^+\Omega^-n$	4.092	7.0
$pp \to \Lambda\bar{\Lambda}pp$	4.108	7.1
$pp \to \Xi^-\bar{\Xi}^+pp$	4.520	9.0
$pp \to \Omega^-\bar{\Omega}^+pp$	5.222	12.7
$pp \to J/\Psi\, pp$	4.973	12.2

T. Galatyuk, Nucl.Phys.A 982 (2019) 163-169



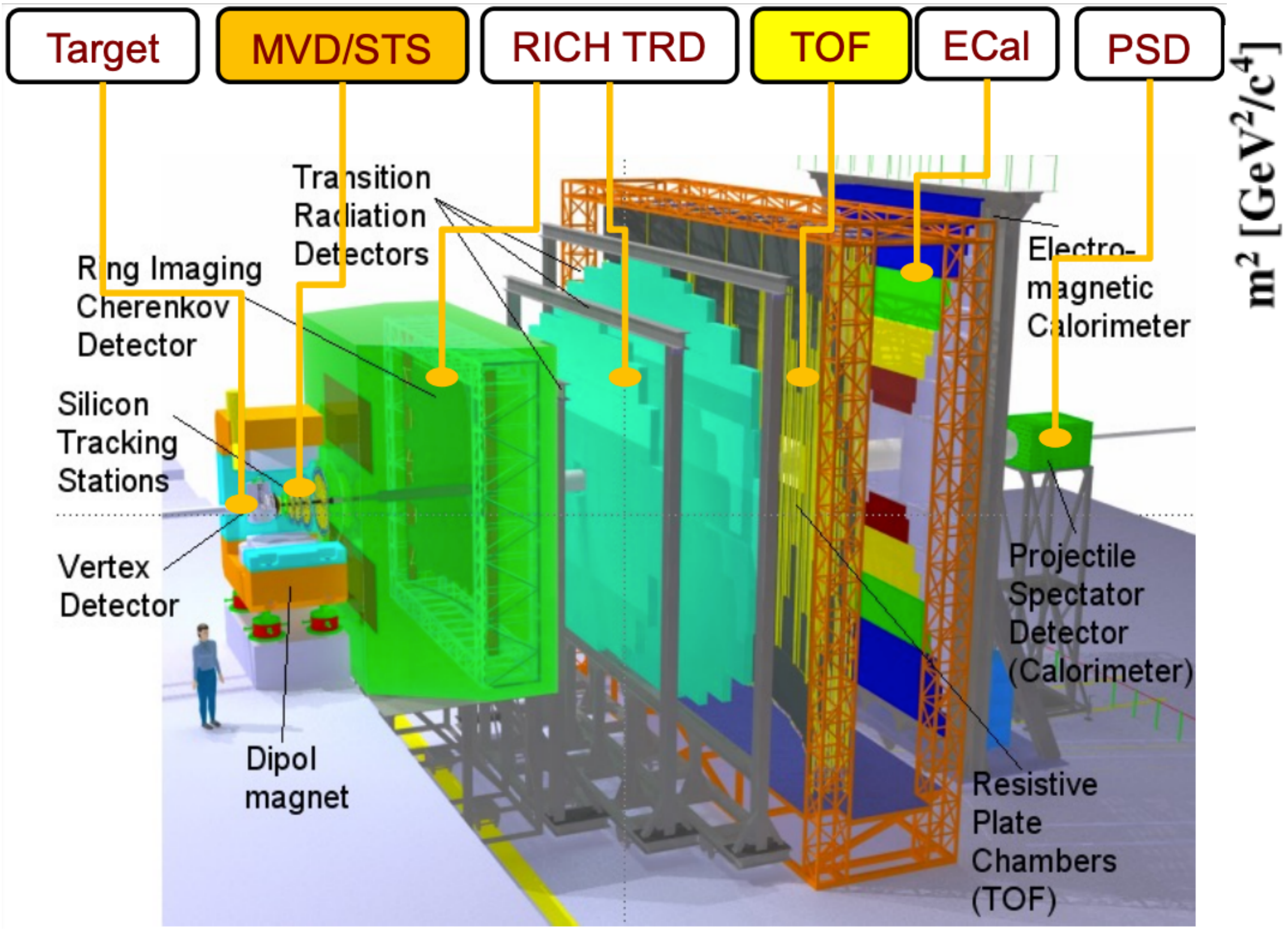
The equation-of-state at high ρ_B
collective flow of hadrons,
particle production at threshold energies:
multi-strange hyperons, hypernuclei

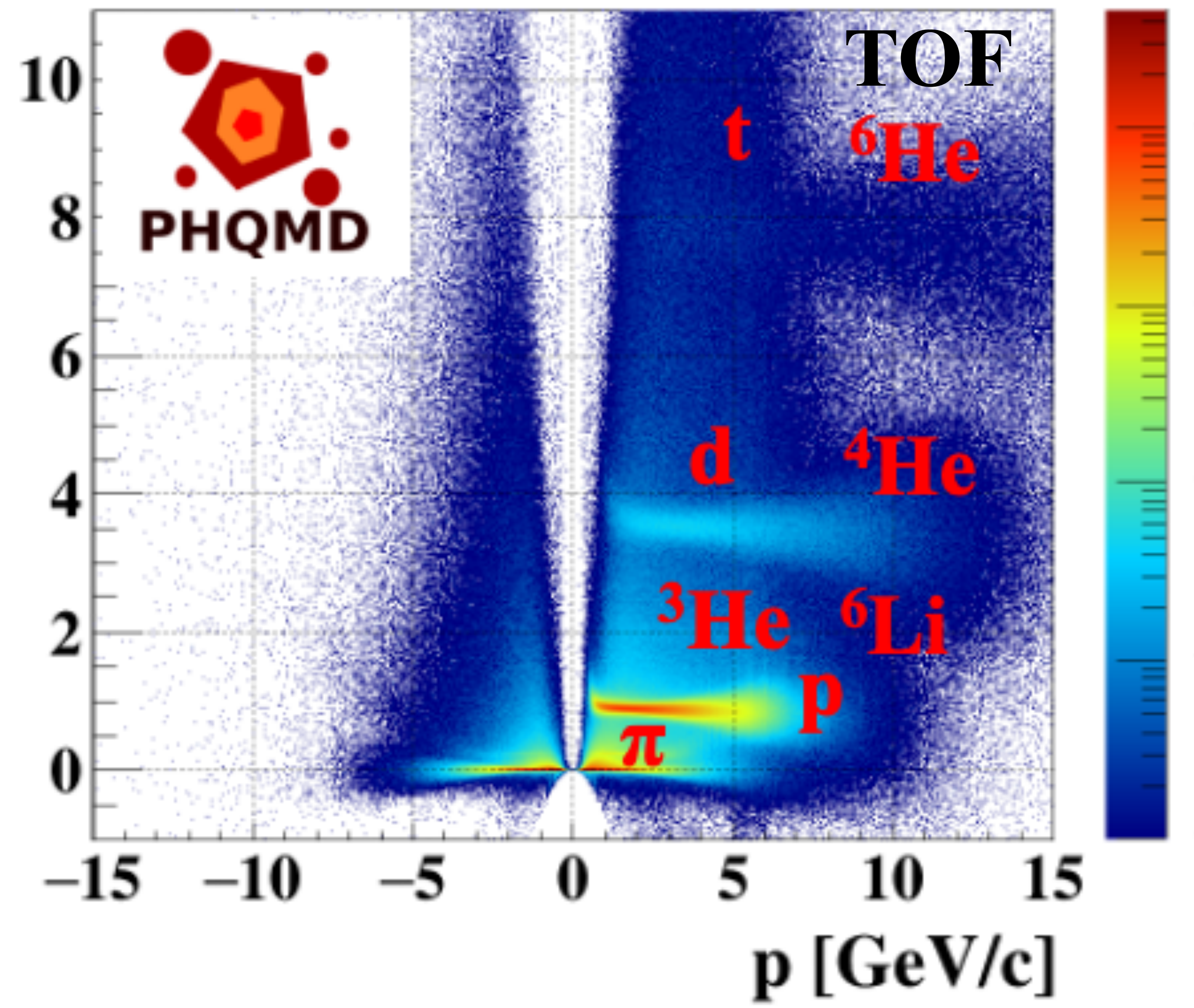
Deconfinement phase transition at high ρ_B
excitation function and flow of
strangeness (K, Λ, Σ, Ξ, Ω and ϕ)

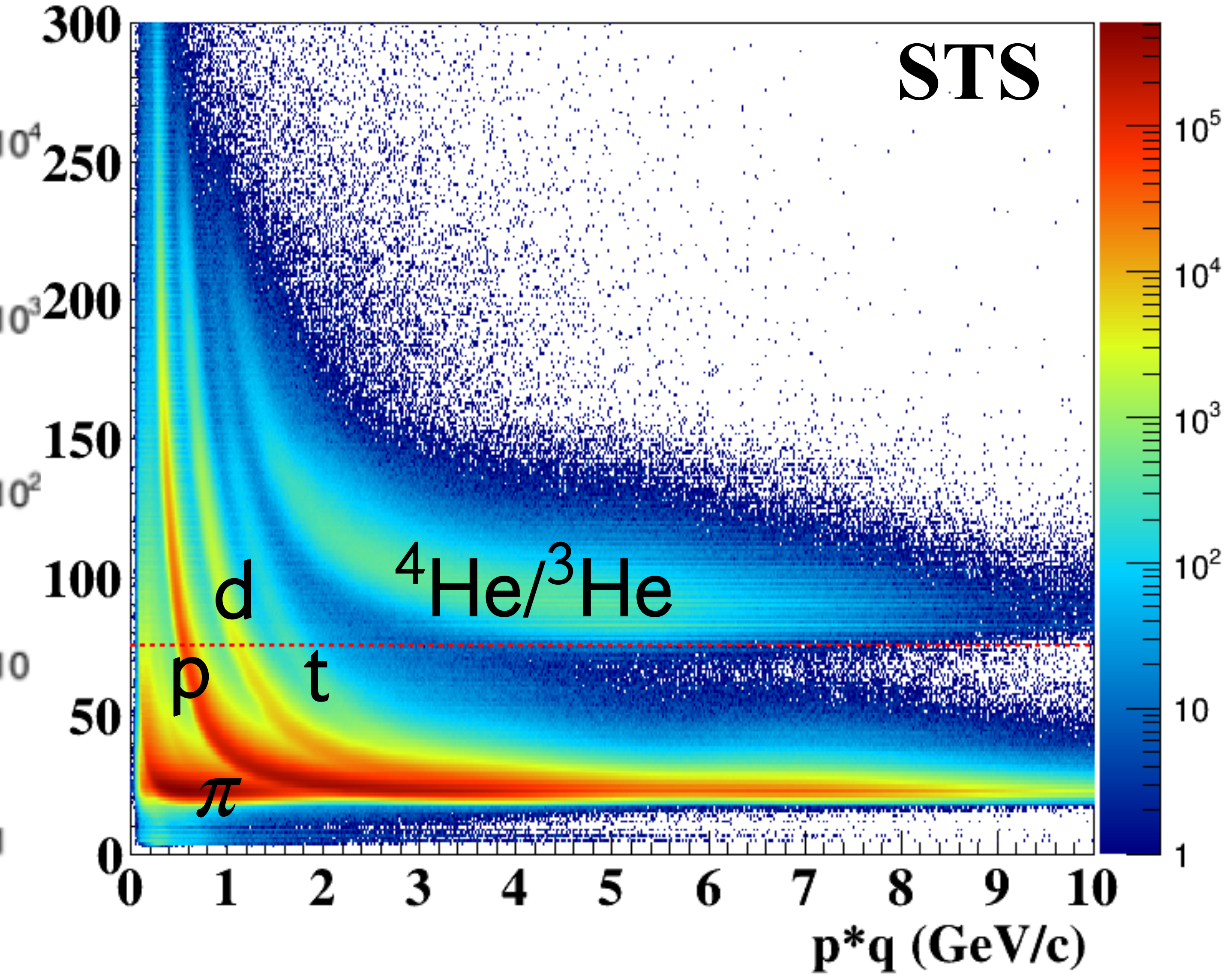
Chiral symmetry restoration at high ρ_B
in-medium modifications of hadrons (ρ, ω, ϕ)
excitation function of **multi-strange (anti)hyperons**

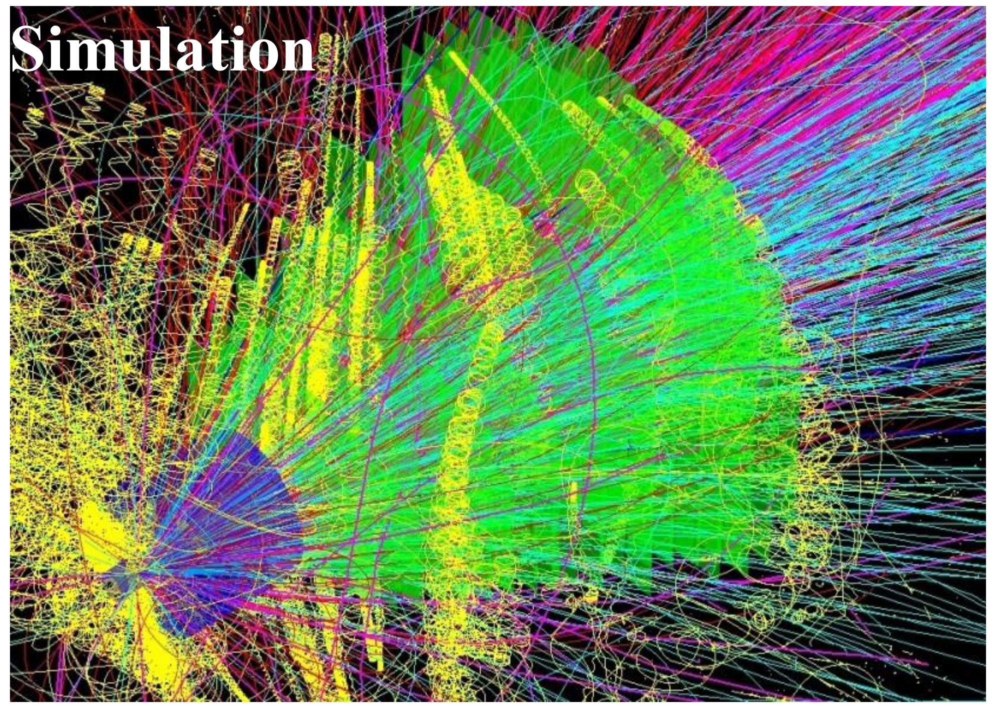
QCD critical endpoint
excitation function of event-by-event fluctuations
(π, K, p, **Λ, Ξ, Ω**…)

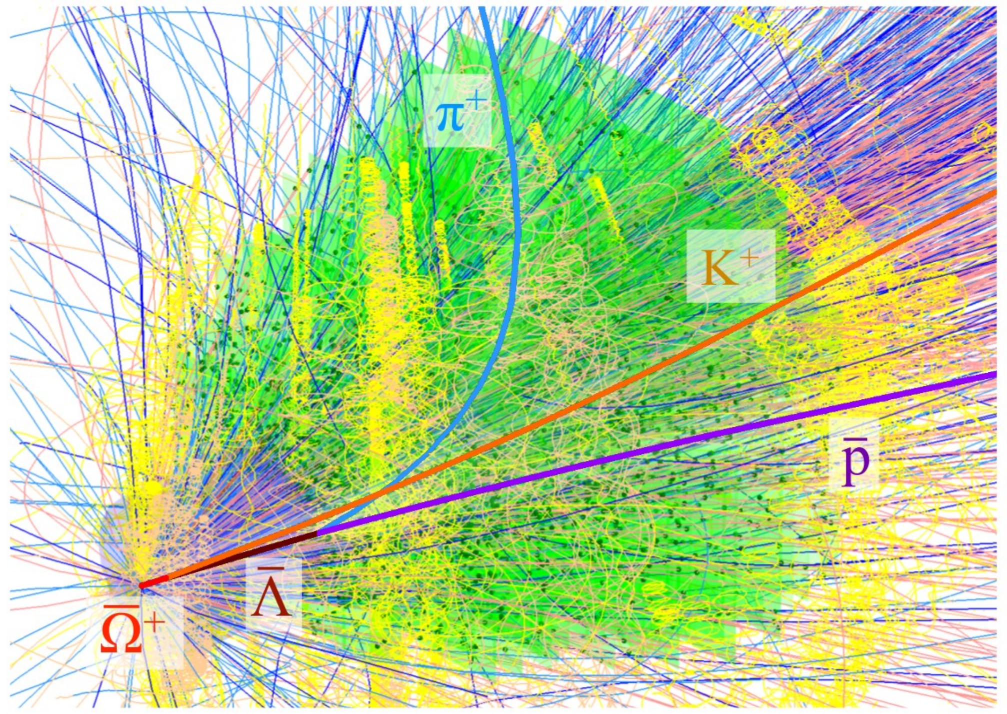
CBM Performance Study - Particle Identification with PID Detectors









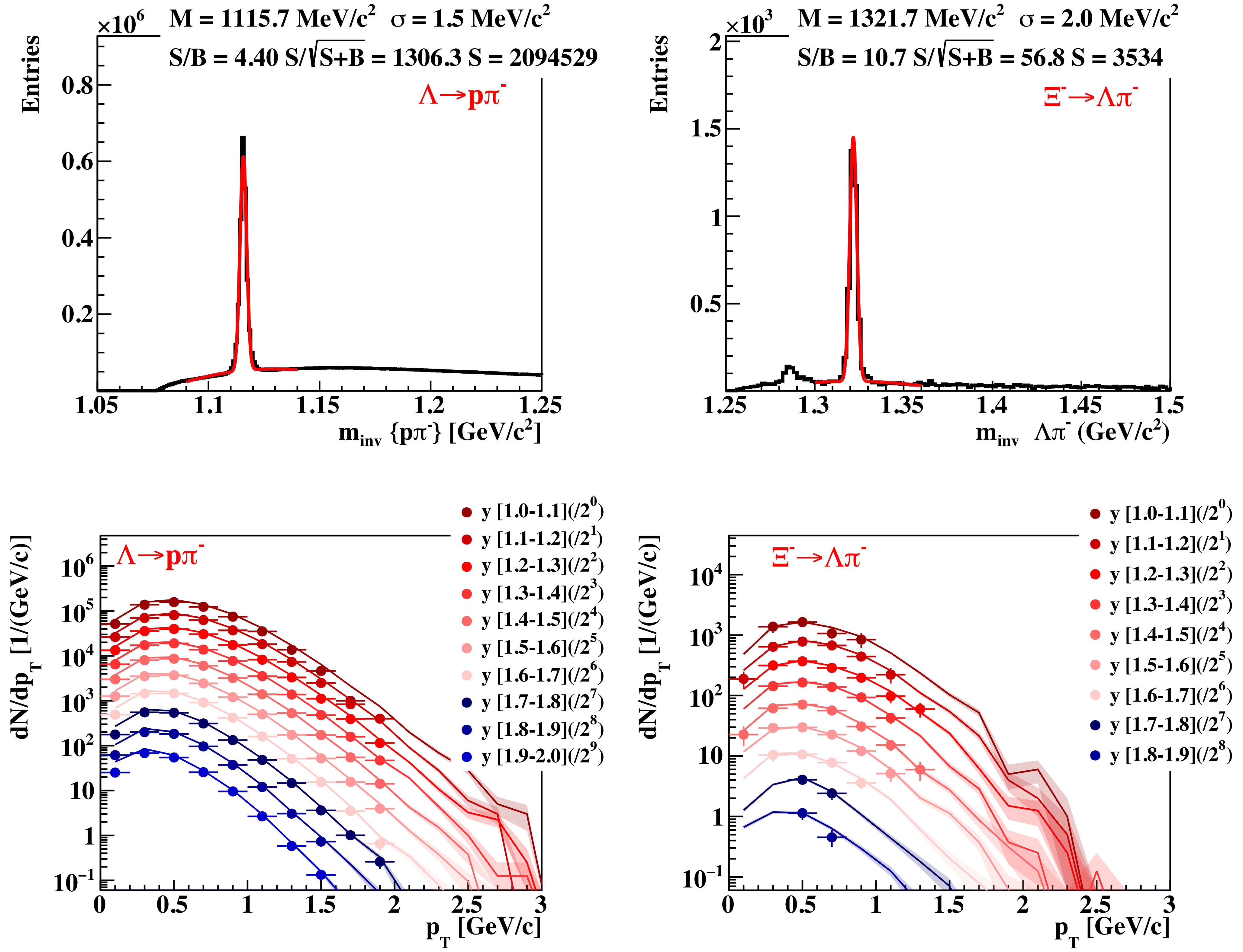


- **PHQMD Au+Au at $\sqrt{s_{NN}}$ = 3 GeV, b <15 fm, ~15 M events**
- **Transport to the CBM detector via GEANT3**
  - **Transport → digitisation → reconstruction**
- **PID detectors of CBM will allow a clear identification of charged tracks**
  - TOF (Time of Flight) — hadron identification
  - STS (Silicon Tracking System) — heavy fragments identification by dE/dX
  - TRD (Transition Radiation detector) — electron and heavy fragments identification

(PHQMD) J. Aichelin, et al. Phys. Rev. C 101, 044905 (2020)

CBM Performance Study - Strange Particle Reconstruction

PHQMD Au+Au 3 GeV **Blue open box: MC input acceptance** **Filled box: Simulation reconstructed acceptance**



integral efficiency ($\epsilon_{4\pi}$) = rec signal/input

Statistics estimation at R_{int} =10 MHz

$S_w = R_{av} * \epsilon_{duty} * P_{prod} * f_{mb/cent} * BR * \epsilon_{reco} * \Delta T$

Particle	Multiplicity	decay mode	BR	efficiency(4pi)	Signal counts per week
Λ	1.22	$p\pi^-$	63.9%	27 %	1.5e8
K^0_S	0.54	$\pi^+\pi^-$	69.2%	12 %	3.2e7
Ξ^-	6.5e-3	$\Lambda\pi^-$	99 %	5 %	3.5e7
$^3_\Lambda H$	3.9e-3	$^3He\pi^-$	25%*	9 %	9e6
$^4_\Lambda H$	1.9e-3	$^4He\pi^-$	50%*	8 %	8e6
$^4_\Lambda He$	1.5e-3	$^3Hep\pi^-$	23%*	5 %	1.8e6
$^5_\Lambda He$	4.5e-4	$^4Hep\pi^-$	34%*	3 %	5.1e5

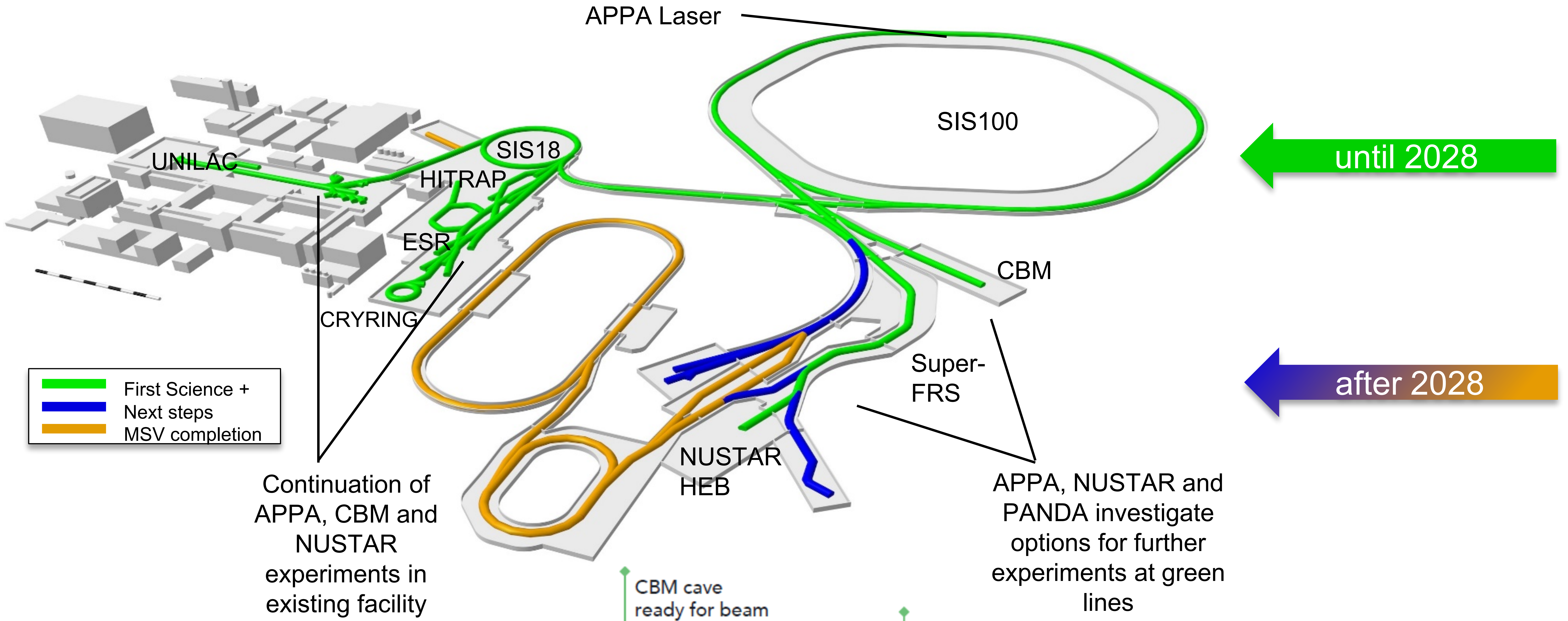
- **Good low p_T coverage, mid-rapidity coverage**
- **High statistics will be able to perform a comprehensive study of strangeness and hypernuclei**

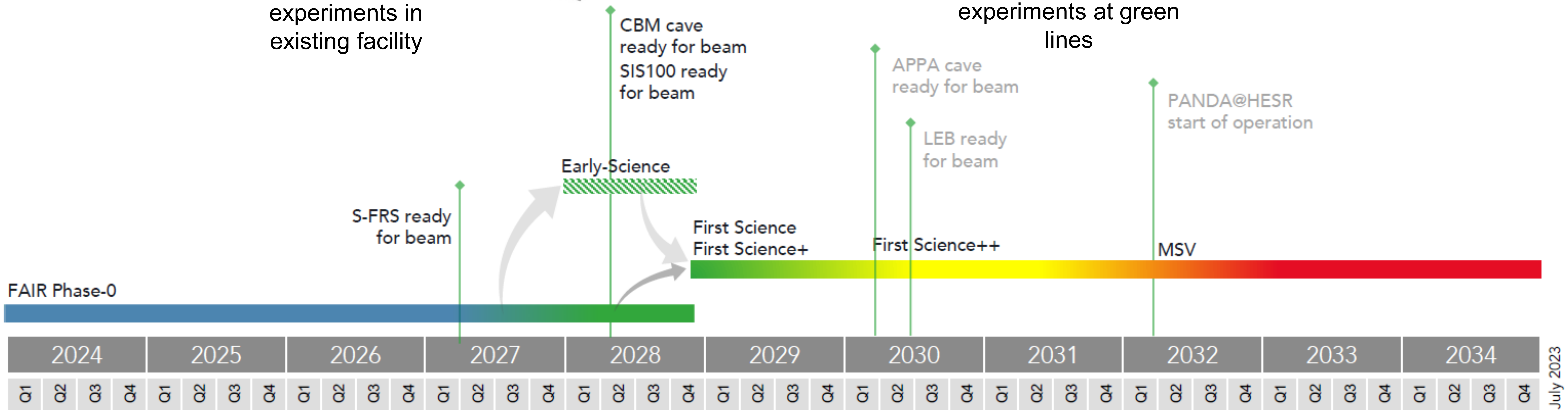
PHQMD, w/o momentum dependence
Hard: κ = 380 MeV

* B.R. estimated from https://hypernuclei.kph.uni-mainz.de/

FAIR facility

FAIR 2028 Plan





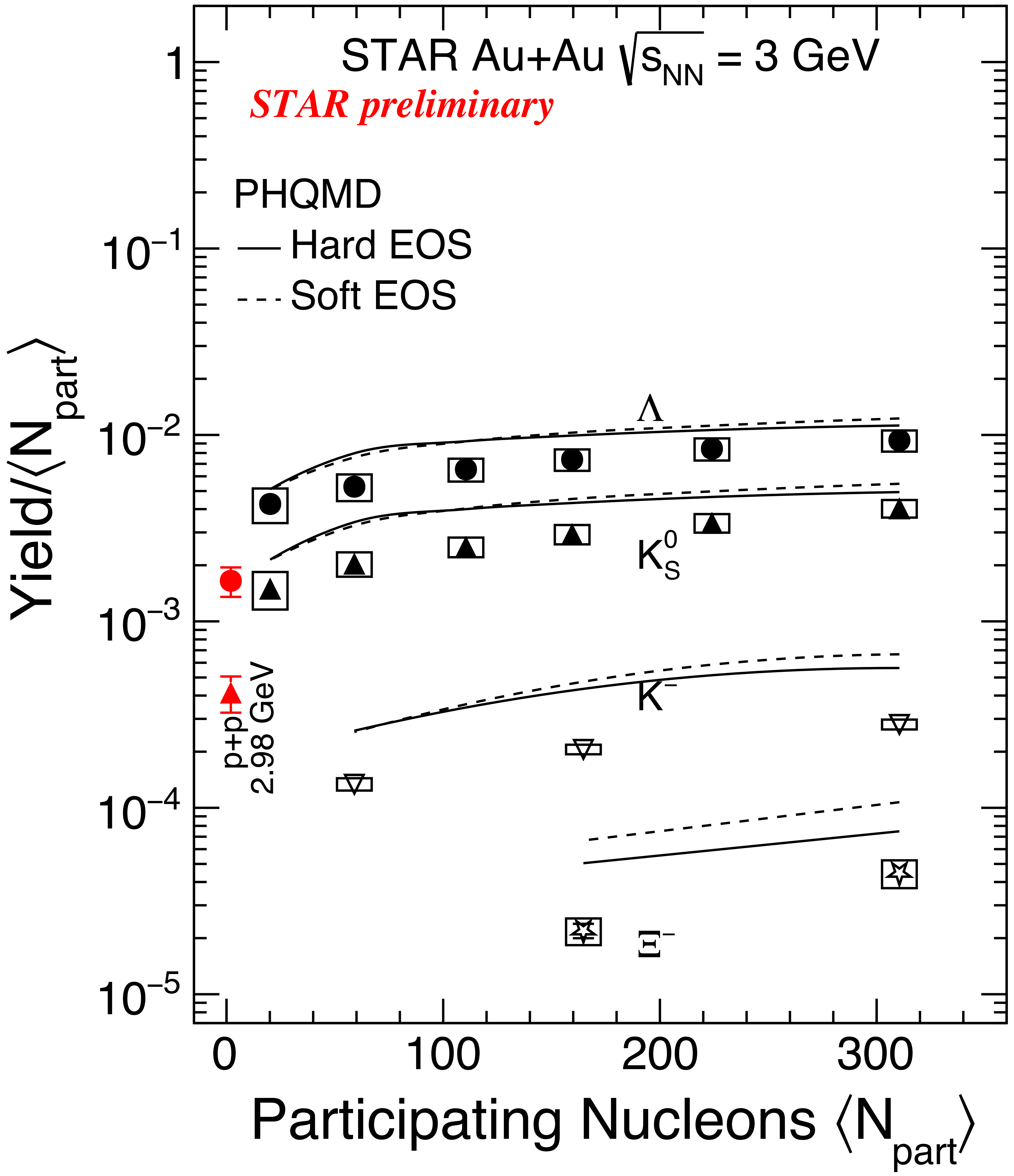
Outlook: Year 1 – 3 Proposed Scenario as of September 2023

*To be confirmed

Year	Setup	Reaction	T_{Lab} (AGeV)	Days on Target	Number of events	Remarks
0 (2028*)	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10, max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10, max	30 (5 each)	$2 \cdot 10^{10}$ each	EB mBias
1	ELEHAD	C+C	2,4,6,8,10, max	18 (3 each)	$4 \cdot 10^{10}$ each	mBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	$2 \cdot 10^{11}$ each	mBias
2	MUON	Au+Au	2,4,6,8,10, max	30 (5 each)	$2 \cdot 10^{11}$ each	mBias
2	MUON	C+C	2,4,6,8,10, max	18 (3 each)	$4 \cdot 10^{11}$ each	mBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	$2 \cdot 10^{12}$ each	mBias
3	HADR	Au+Au	2,4,6,8,10, max	12 (2 each)	$4 \cdot 10^{11}$ each	EB+ Selectors
3	HADR	C+C	2,4,6,8,10, max	6 (1 each)	$8 \cdot 10^{11}$ each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	$2 \cdot 10^{10}$ each	mBias

Backup

Centrality Dependence of 4π Yields - 3 GeV



1) Single strange hadron yields (K^-, K^0_S, Λ) follow common ⟨N_{part}⟩ scaling, but Ξ^- seems to deviate from the scaling trend (2σ deviation from S=1)

Due to Ξ^- **Sub-threshold production?**
→ Multi-step collisions involving pions and Delta resonances → **sensitive to the baryon density, which depends on the EOS**[1]

NN → $\Xi^- K^+ K^+ N$ $\sqrt{s_{thresh.}}$ = 3.25 GeV

NN → $K^0 N \Lambda$ $\sqrt{s_{thresh.}}$ = 2.56 GeV

2) p+p following the scaling trend

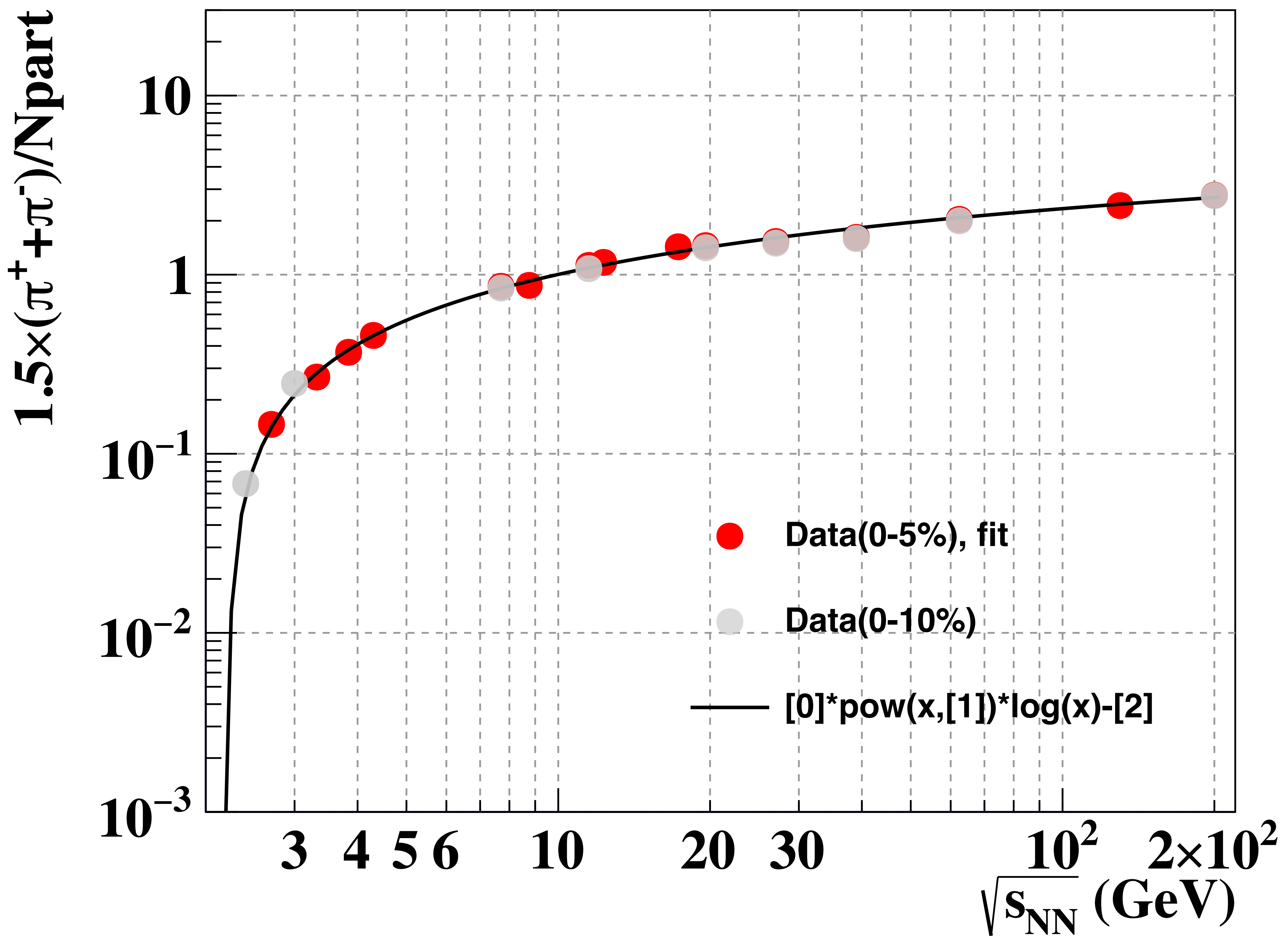
➡ Hadronic interactions drive the observed trends

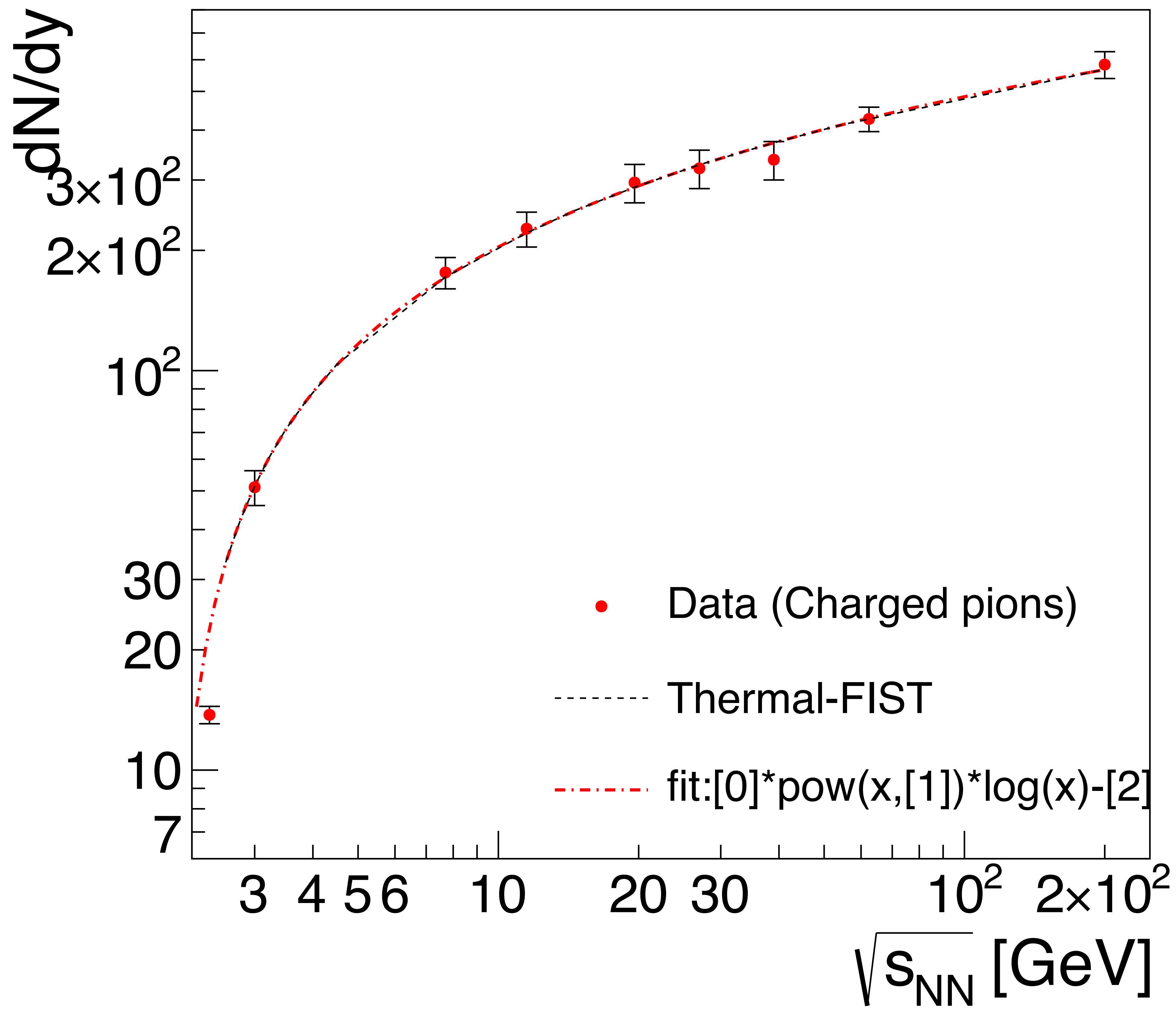
3) PHQMD over-estimate strange hadron yields, but reproduce the scaling trends

PHQMD, w/o momentum dependence
Hard: κ = 380 MeV; Soft: κ=200 MeV

[1] T. Song, et al. Phys. Rev. C 103, 044901 (2021)
(p+p) V. Kolesnikov, et al. Phys. Part. Nuclei Lett. 17, (2020) 142–153
(PHQMD) J. Aichelin, et al. Phys. Rev. C 101, 044905 (2020)

Pion yields





- **Pion: evaluated from power function which fits to data Collected in Adv.High Energy Phys. 2015 (2015) 349013**