Hypernuclei Production and Decay Mode Measurements at Intermediate to Low Energy Collisions

UCAS seminar

Yue-Hang Leung

University of Heidelberg

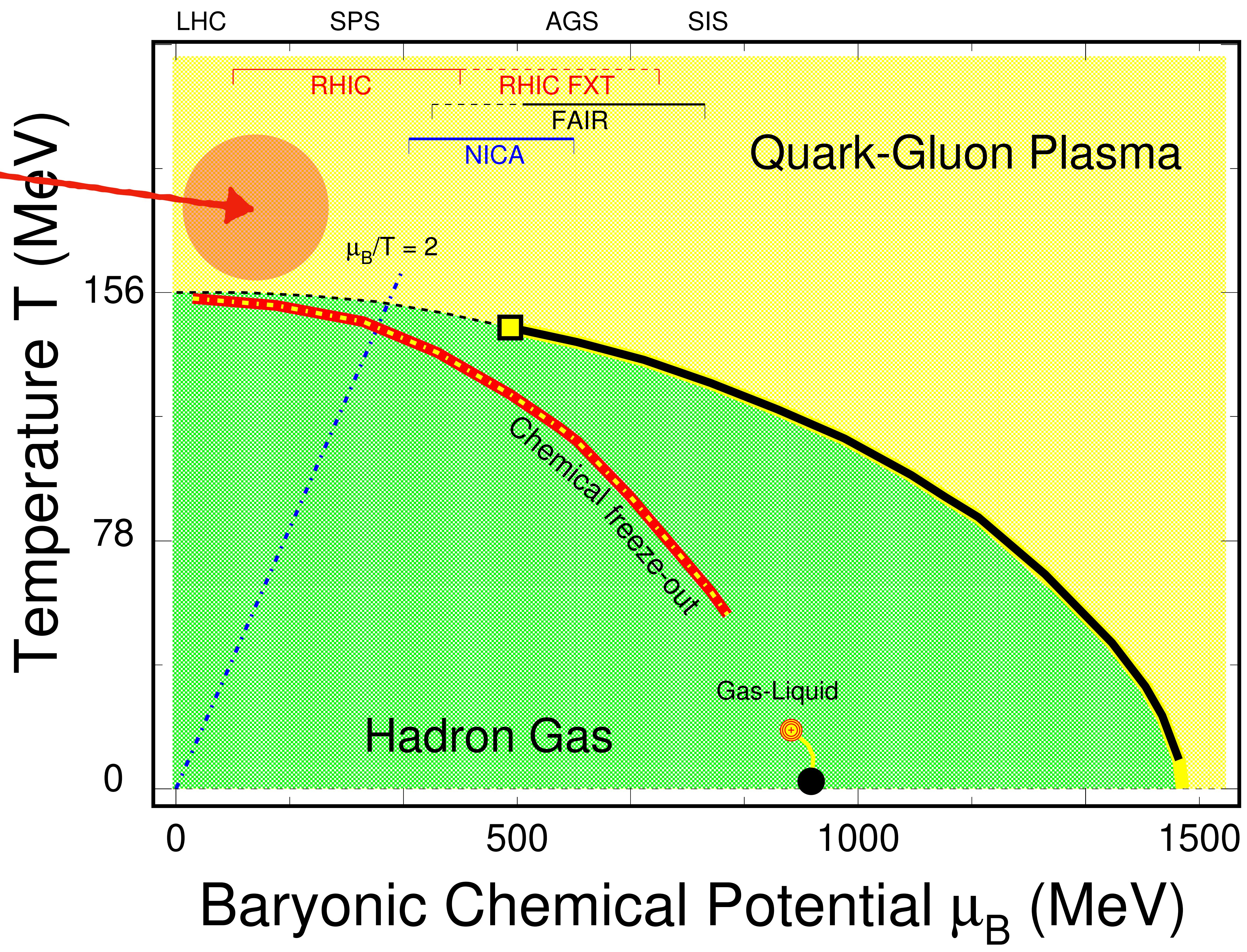
27th Dec, 2023

Outline

- **Introduction**
- **Experimental observables**
  - Strange Hadron Production in 3 GeV Au+Au collisions
  - Hypernuclei Production ($^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$) in 3-27 GeV Au+Au collisions
  - Aside: Hypernuclei Properties
- **Summary**
- **Outlook**

Probing the QCD Phase Diagram

- **QGP formation at top RHIC energies**
  $\sqrt{s_{NN}}$ = 200 GeV, μ_B = 20 MeV
    - Probe characteristics with heavy flavor, strangeness, jets etc.

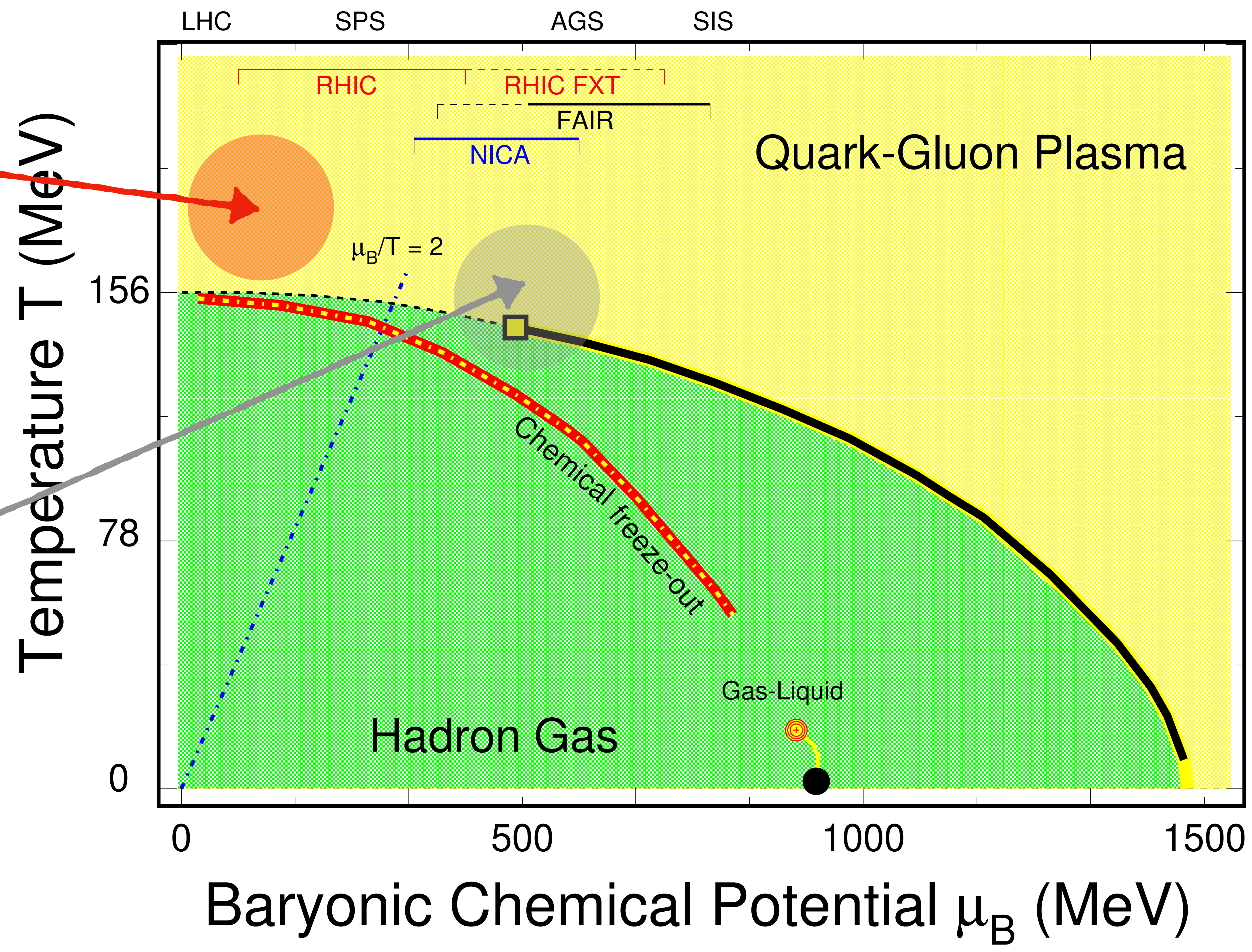


STAR, PRL126,9,092301(2021)

Probing the QCD Phase Diagram

- **QGP formation at top RHIC energies**
  $\sqrt{s_{NN}}$ = 200 GeV, μ_B = 20 MeV
  - Probe characteristics with heavy flavor, strangeness, jets etc.

- **Intermediate μ_B region: STAR collider mode**
  $\sqrt{s_{NN}}$ = 7.7-27 GeV, μ_B = 420 - 200 MeV
  - Probe onset of deconfinement
  - Search for critical phenomena



STAR, PRL126,9,092301(2021)

Probing the QCD Phase Diagram

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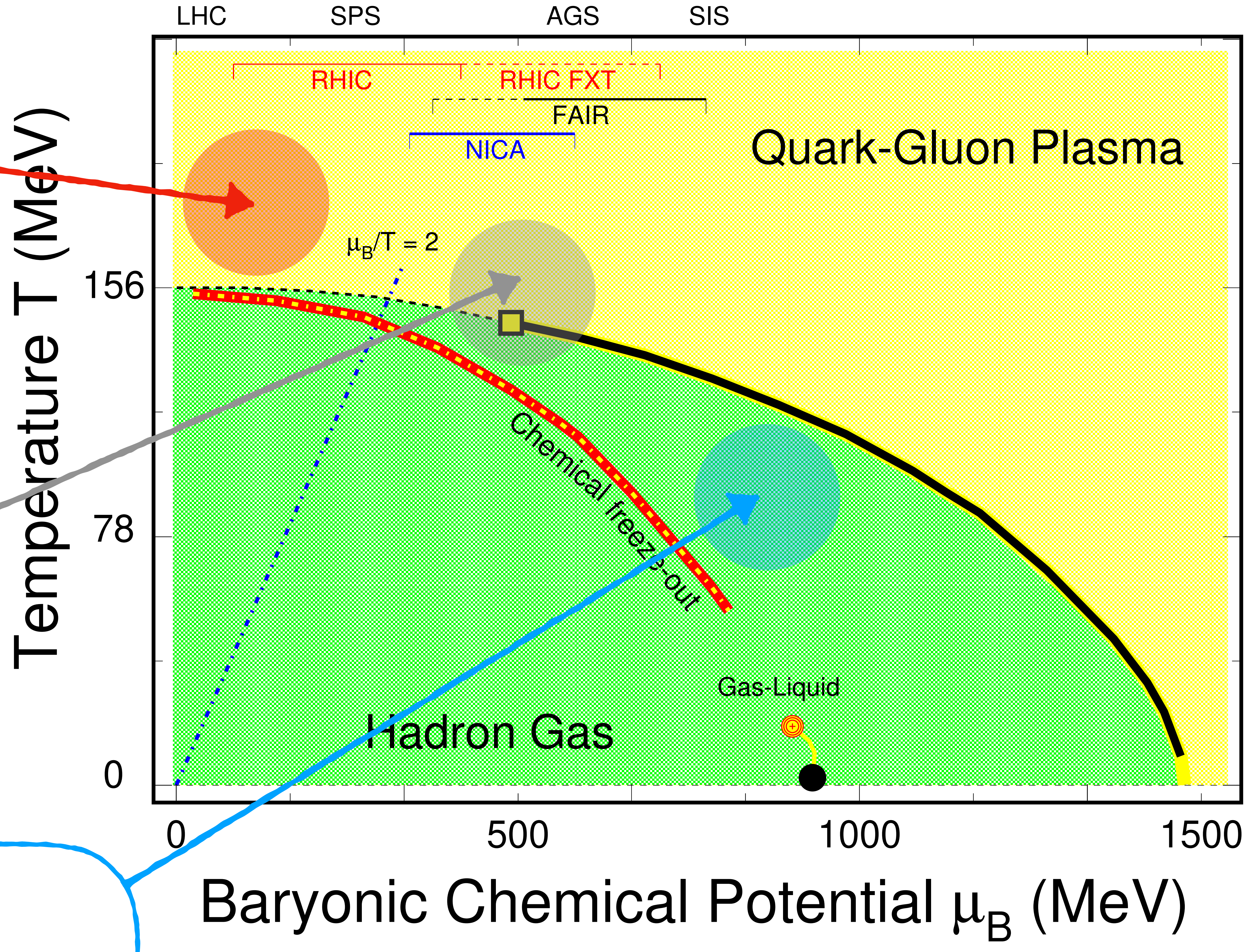
- **High μ_B region: STAR fixed-target (FXT)**
  $\sqrt{s_{NN}}$ = 3.0-13.7 GeV, μ_B = 750 - 280 MeV
  - Nature of produced medium (hadronic vs partonic?)
  - Investigate properties of dense baryonic matter



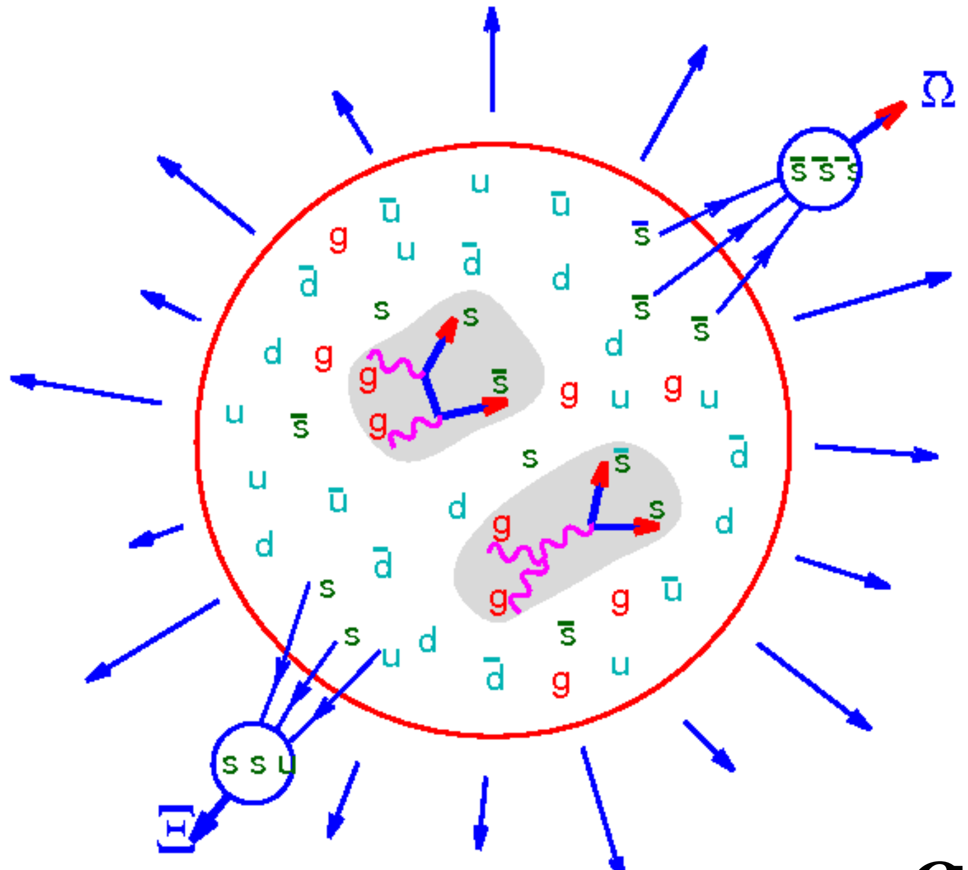
STAR, PRL126,9,092301(2021)

Motivations: Strangeness as a Probe to Study Nuclear Matter

- 1. Strangeness enhancement is originally proposed as a signature for QGP formation

  - Studying strangeness production as a function of energy may help us probe the **onset of deconfinement**

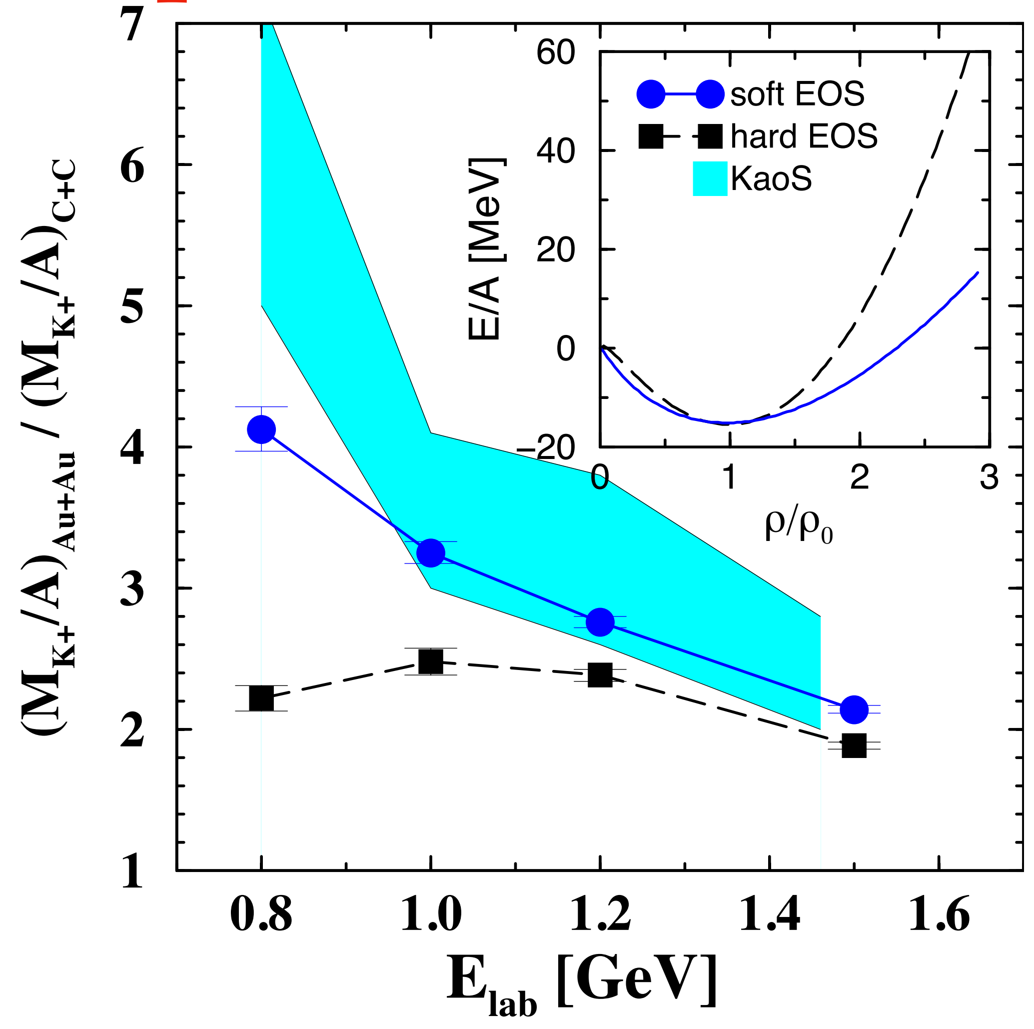
  - Issue: Strangeness enhancement has been observed in small systems → *what is the proper baseline?*



$$gg \rightarrow s\bar{s}$$

- 2. Near/Sub-threshold production of strange hadrons is sensitive to nuclear equation of state

  - Yield is strongly suppressed near NN-threshold ⟶ very few measurements available

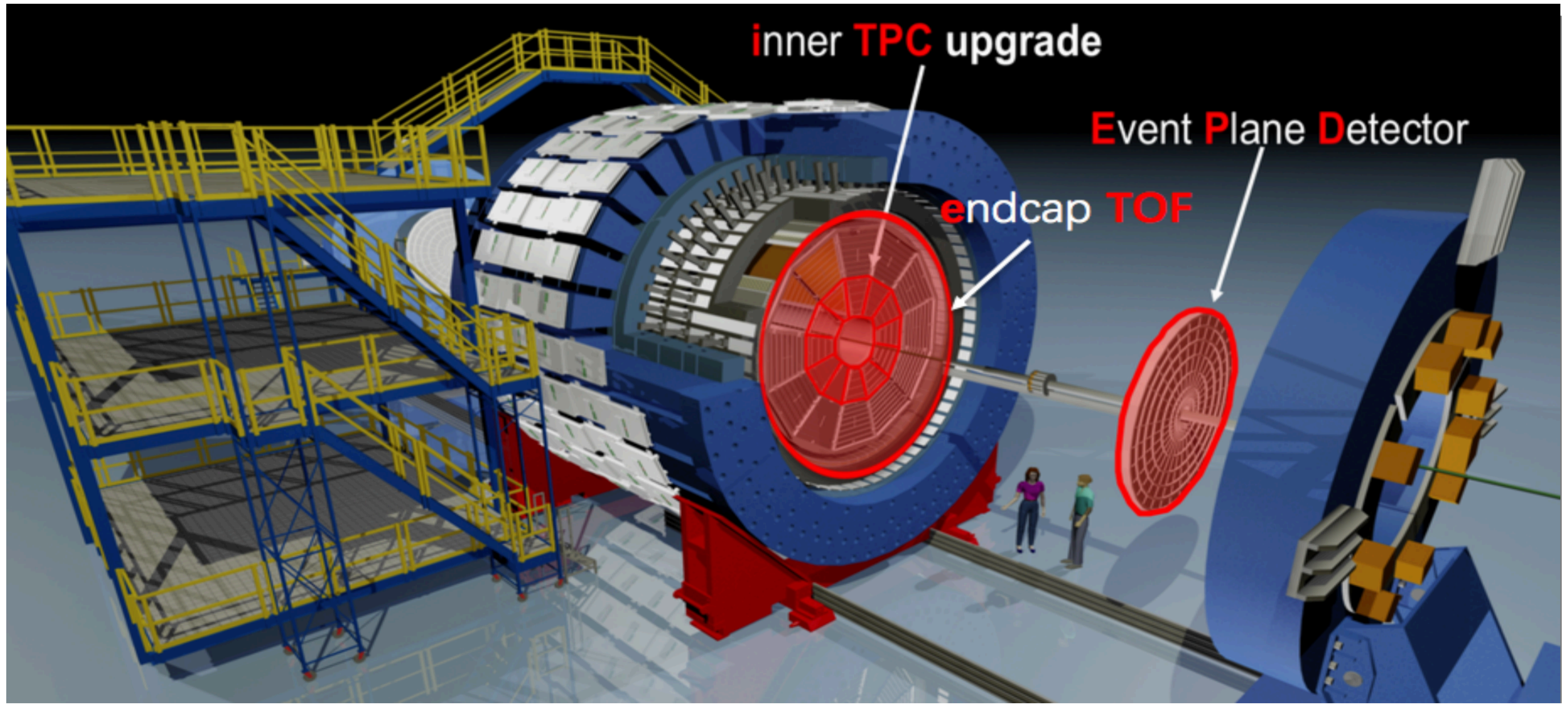


Phys. Rev. Lett. 86(2001)339

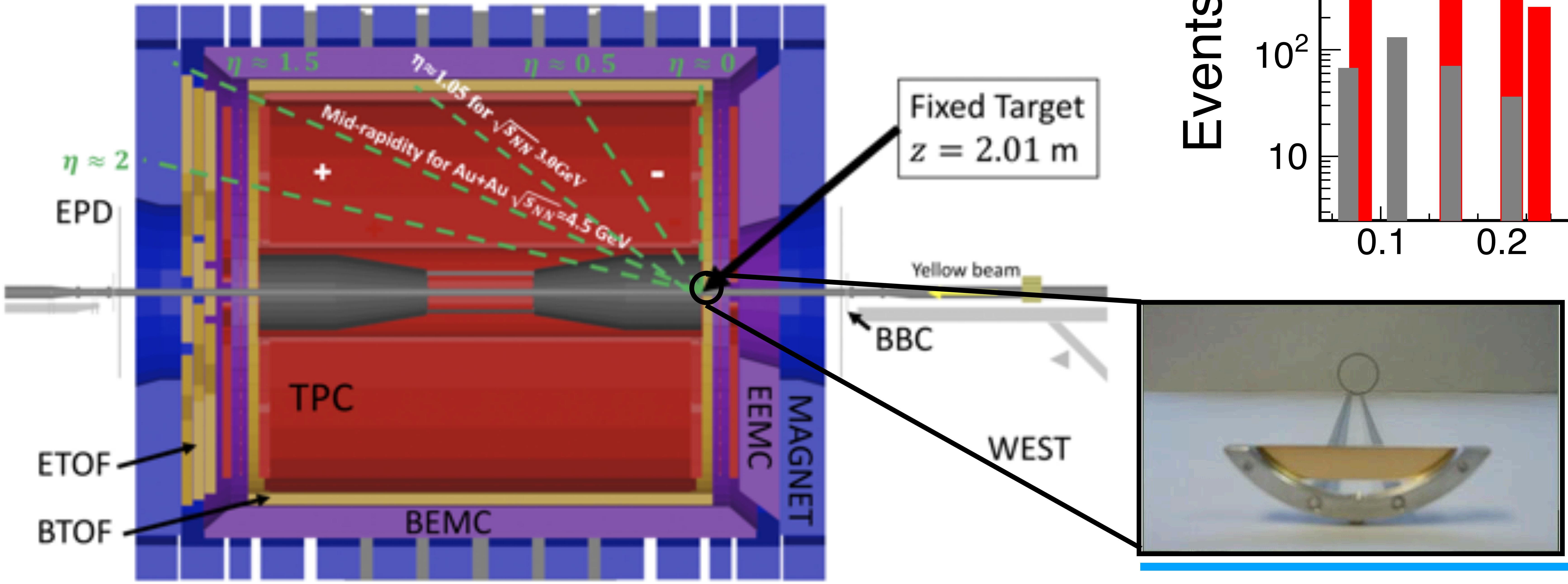
Phys. Rev. Lett. 86(2001)1974

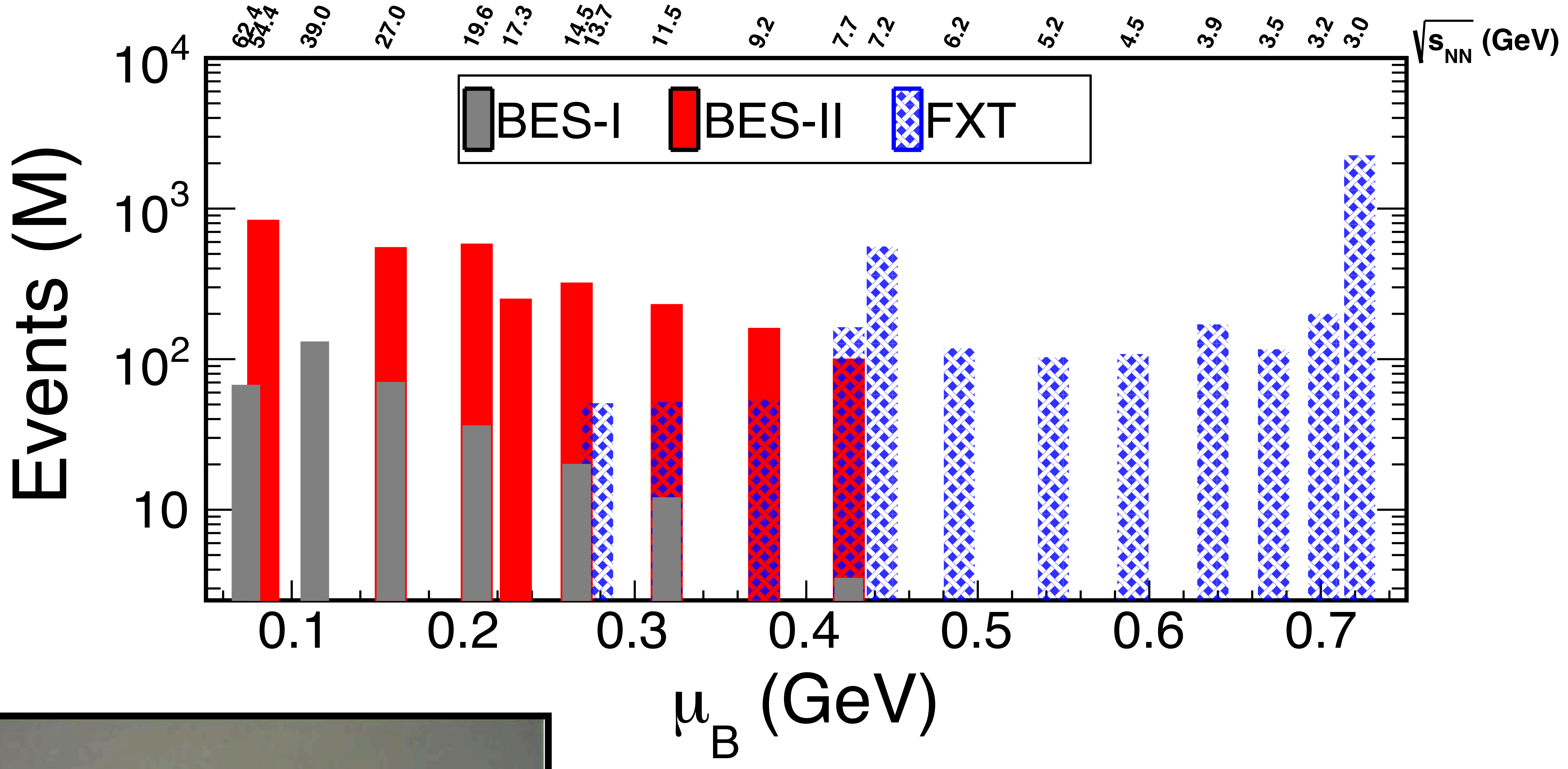

RHIC
sPHENIX
ASSEMBLY
UNDERWAY
STAR
LINAC
EBIS
NSRL
BOOSTER
AGS
Relativistic Heavy Ion Collider (RHIC)
• Located at Brookhaven National Laboratory
• STAR+sPHENIX (currently running)
• Collision species (p+p, p+Au, Au+Au, ...)
• Collision energies ($\sqrt{s_{NN}}$=3-200 GeV for Au+Au)

STAR Detector and BES-II



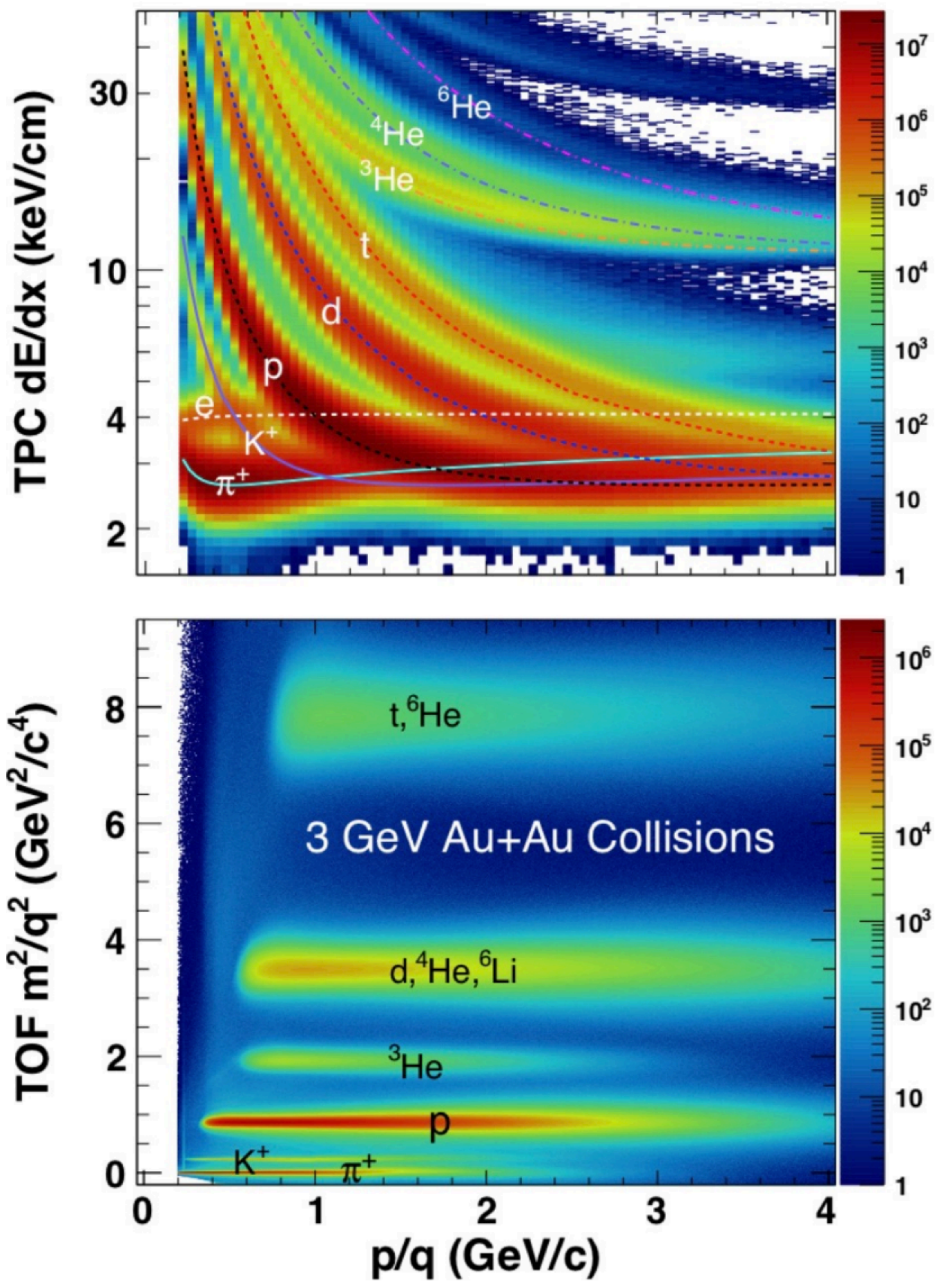
- STAR BES-II ($\sqrt{s_{NN}}$ = 3-54 GeV)
  - 10X statistics compared to BES-I
  - Detector upgrades: iTPC, eTOF
  - FXT extends energy reach down to 3 GeV

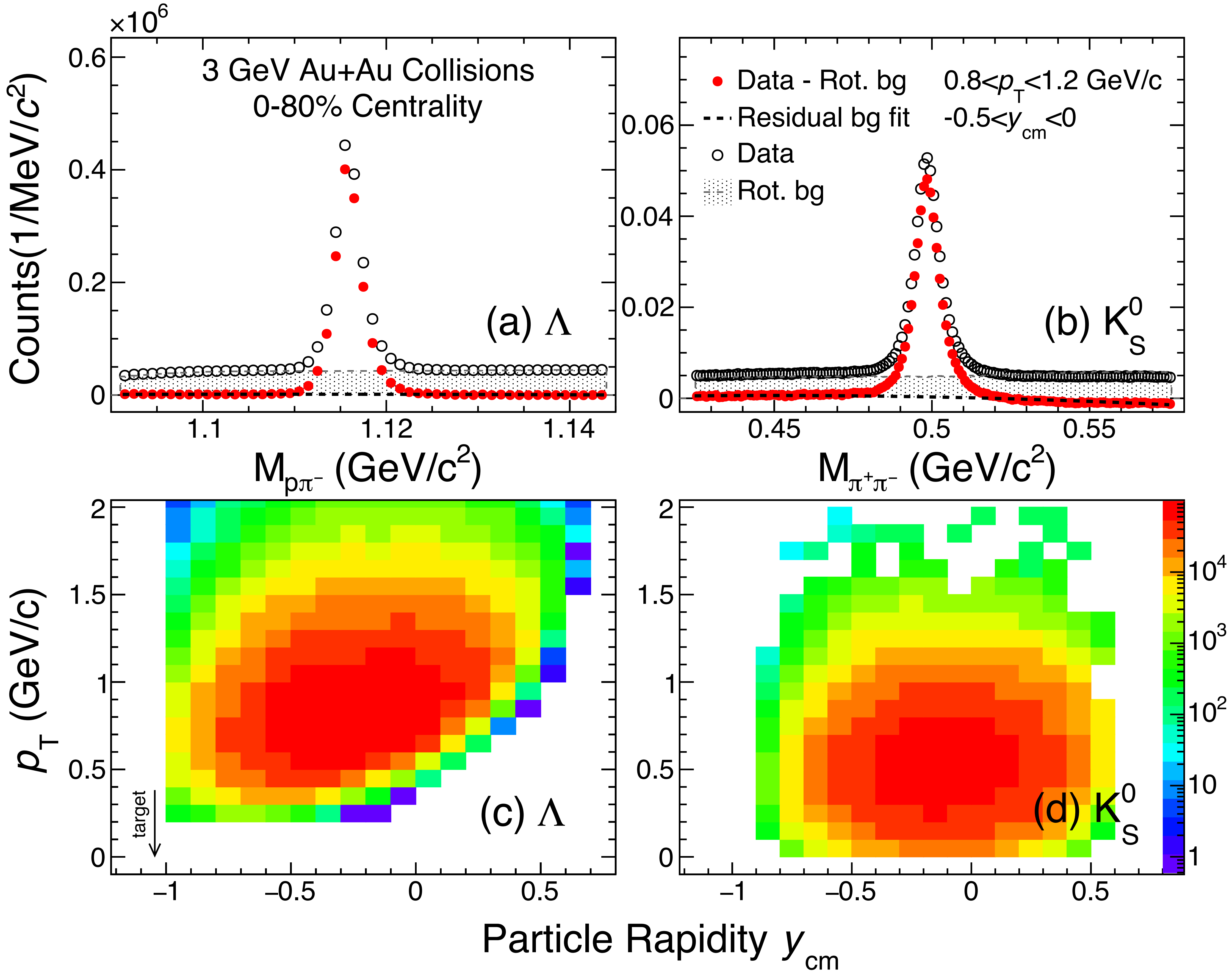




Particle Identification and Strange Hadron Reconstruction at 3 GeV

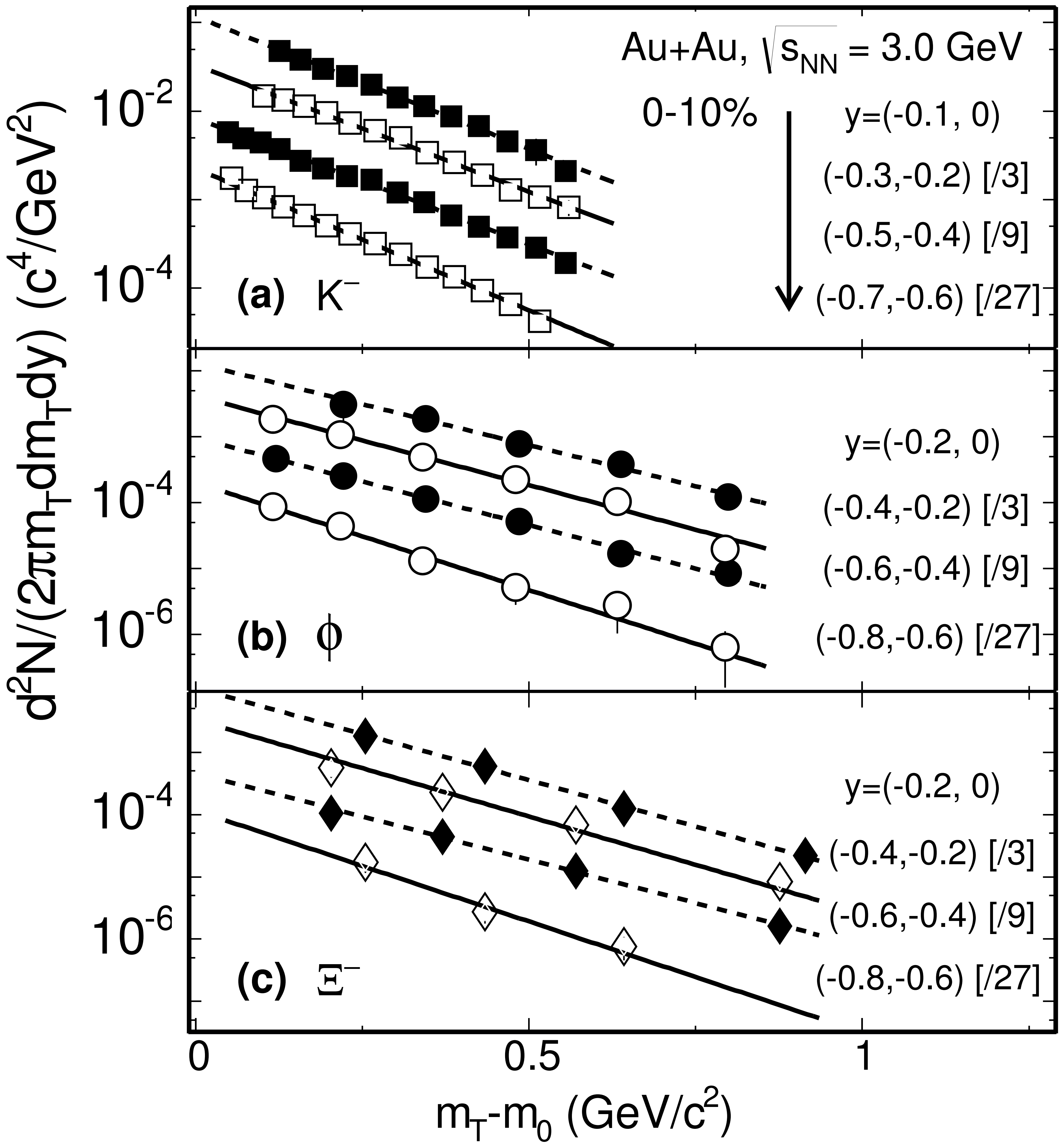
- TPC (dE/dx) and TOF (m^2/q^2) for pion, kaon, and proton identification

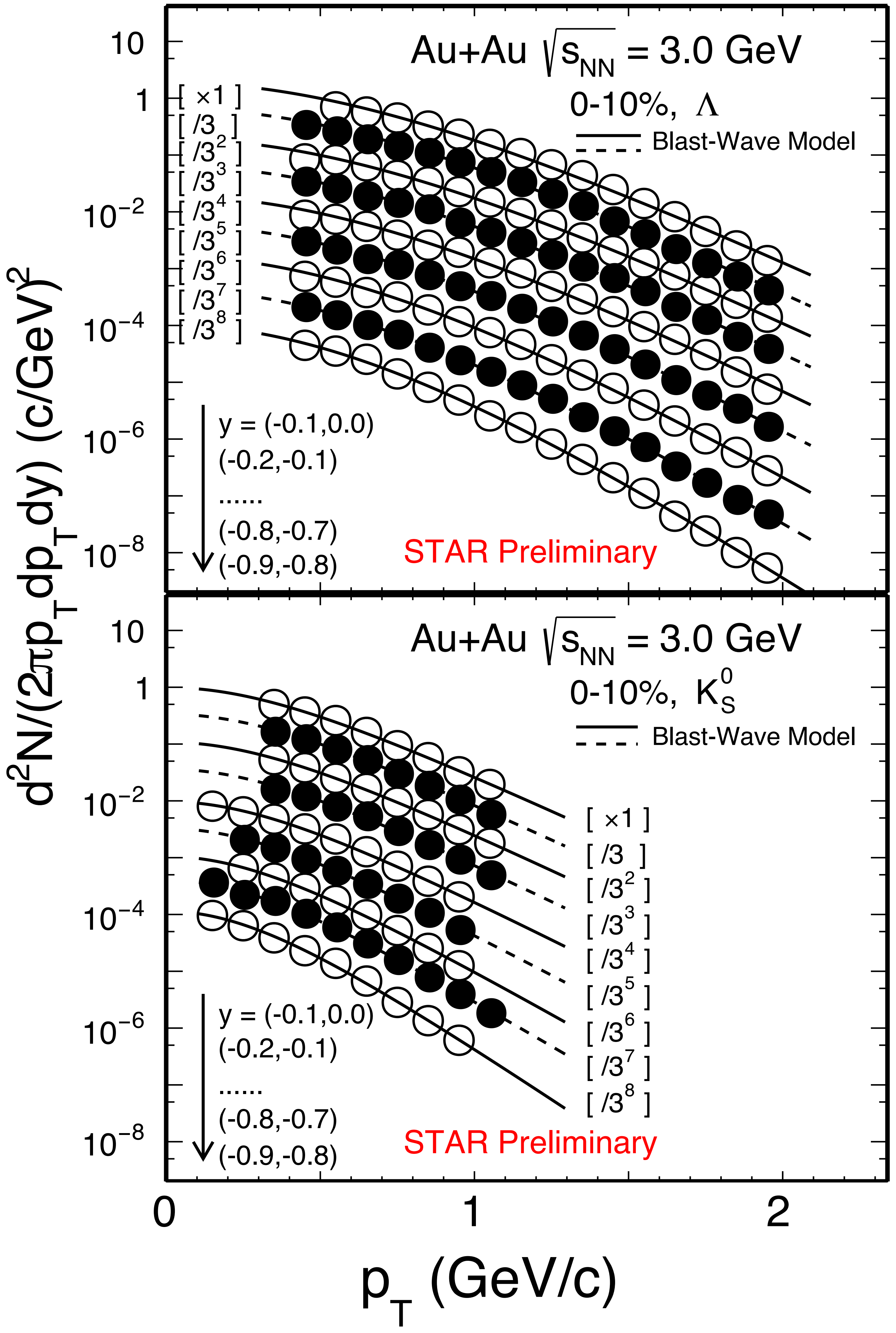




- Strange hadrons ($K_S^0, \phi, \Lambda, \Xi^-$) are reconstructed using the invariant mass method
- **Good mid-rapidity coverage for all particles**

Strange Hadron Transverse Momentum Spectra





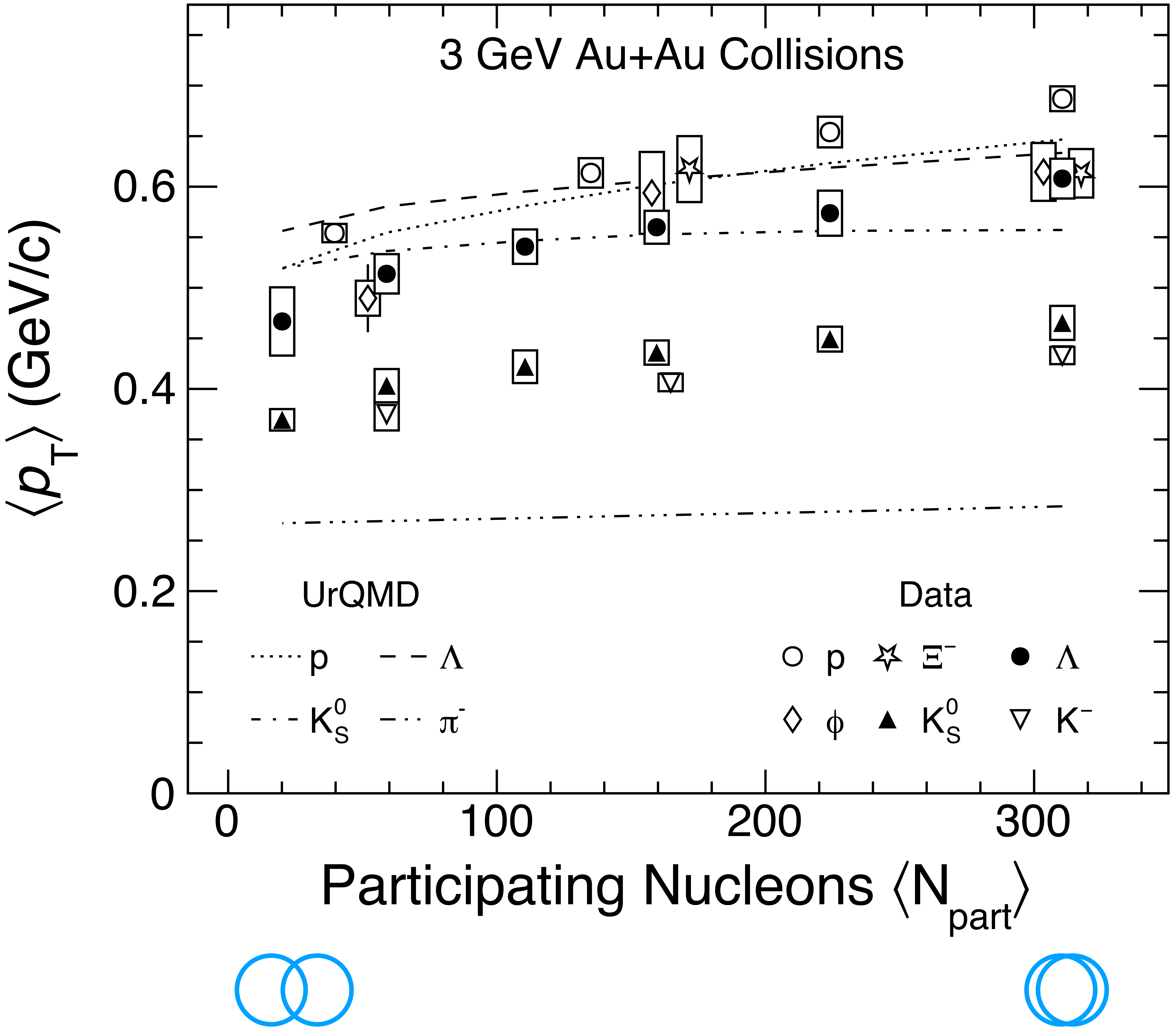
- Yields are extracted differentially in p_T, rapidity, and centrality
- The p_T integrated yield obtained from integrating data and function fits of spectra for the unmeasured region

- Tracking efficiency and detector acceptance are estimated with GEANT simulations embedded into real events

Blast-wave function (see S12):

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

Centrality Dependence of Mean Transverse Momentum

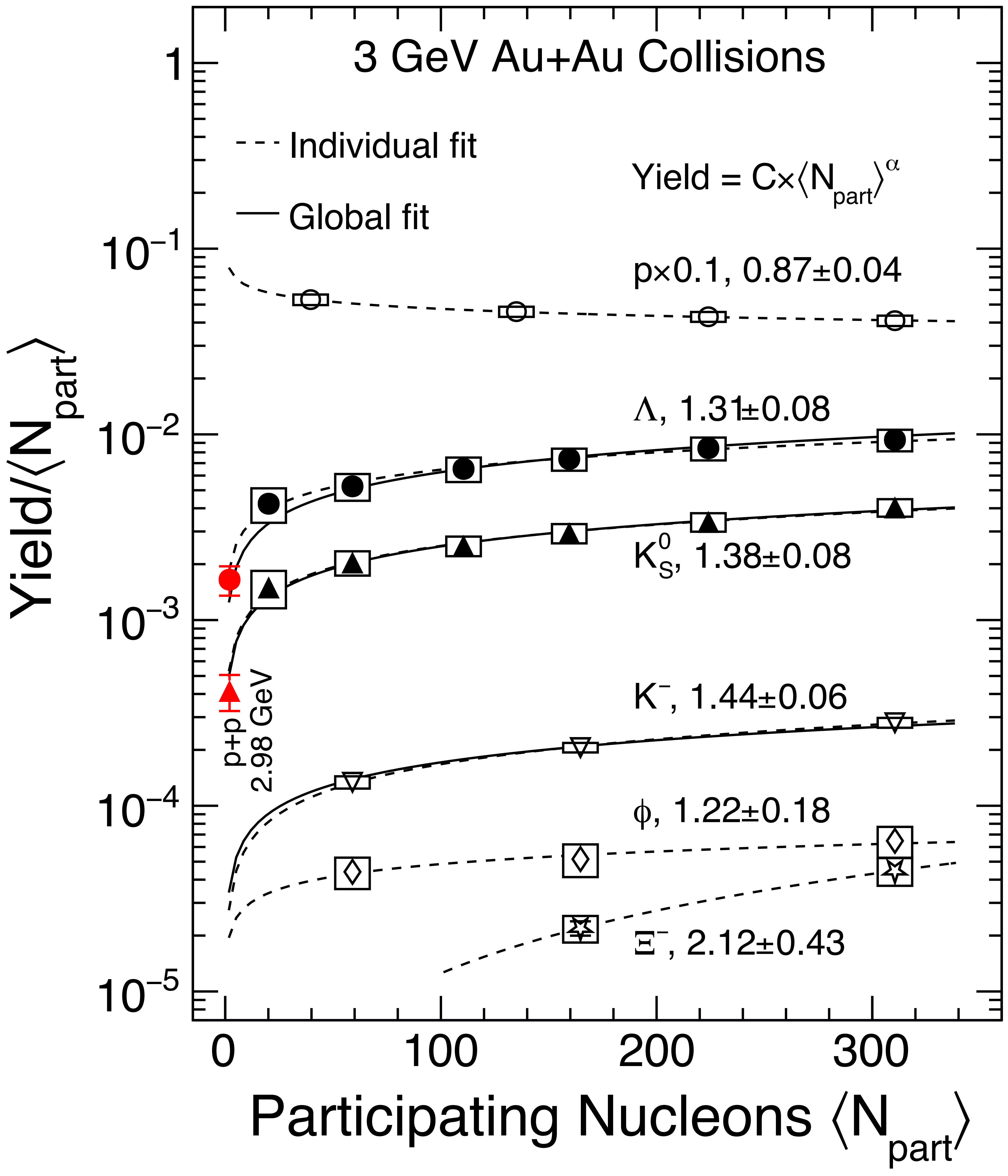


- Gradual increase in $\langle p_T \rangle$ vs $\langle N_{part} \rangle$ is observed for all strange particles →

Presence of radial flow in central collisions

- Mass ordering of $\langle p_T \rangle$
  - Violated for Λ and protons
  - Λ and protons do not share common collective radial flow
- UrQMD, a hadronic transport model, approx. describes the data

Centrality Dependence of Particle Yields

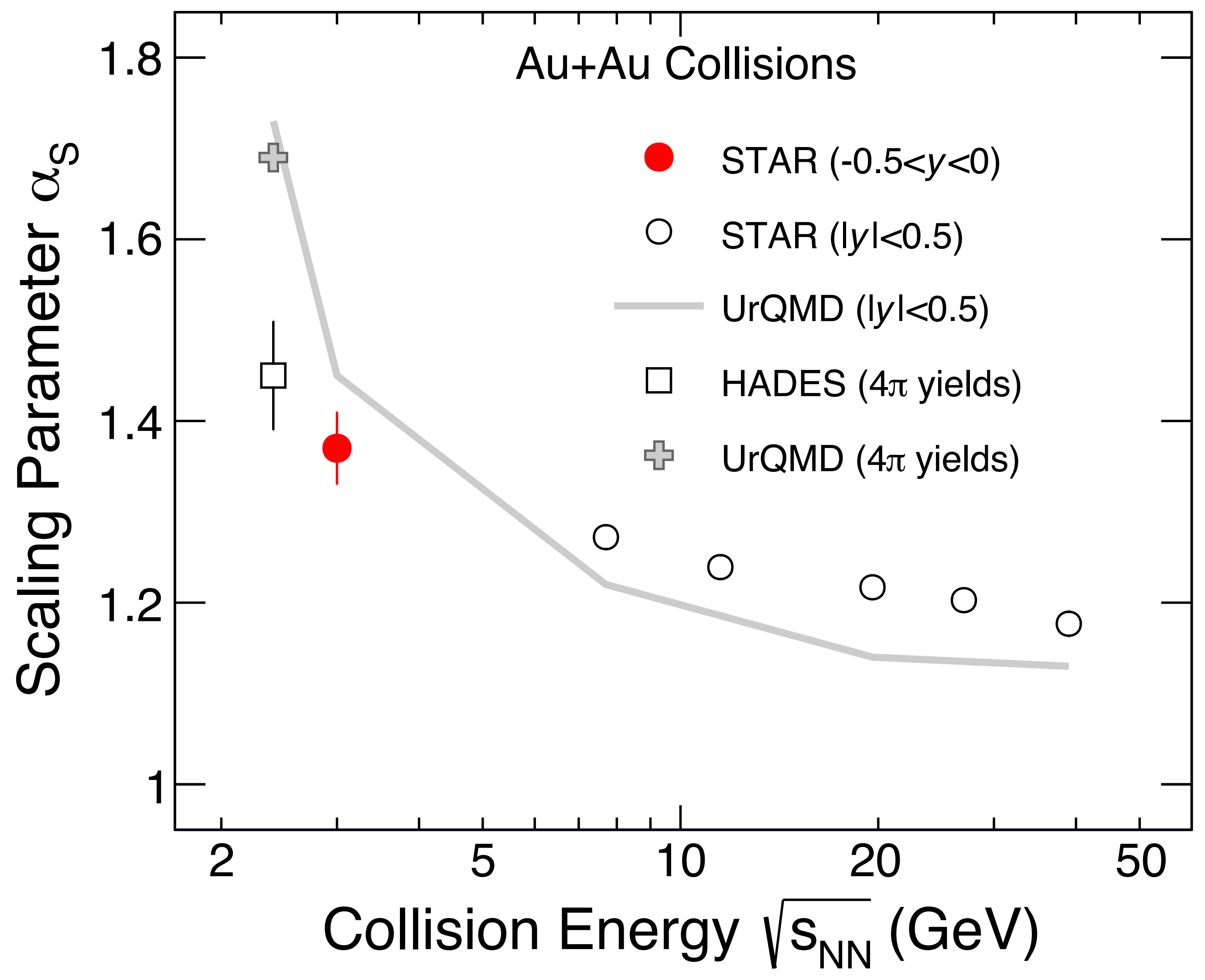


- Strange hadron yields (K^0_S, Λ, K^-) proportional to $\langle \mathrm{N_{part}} \rangle^{\alpha}$, with = 1.38 ± 0.04

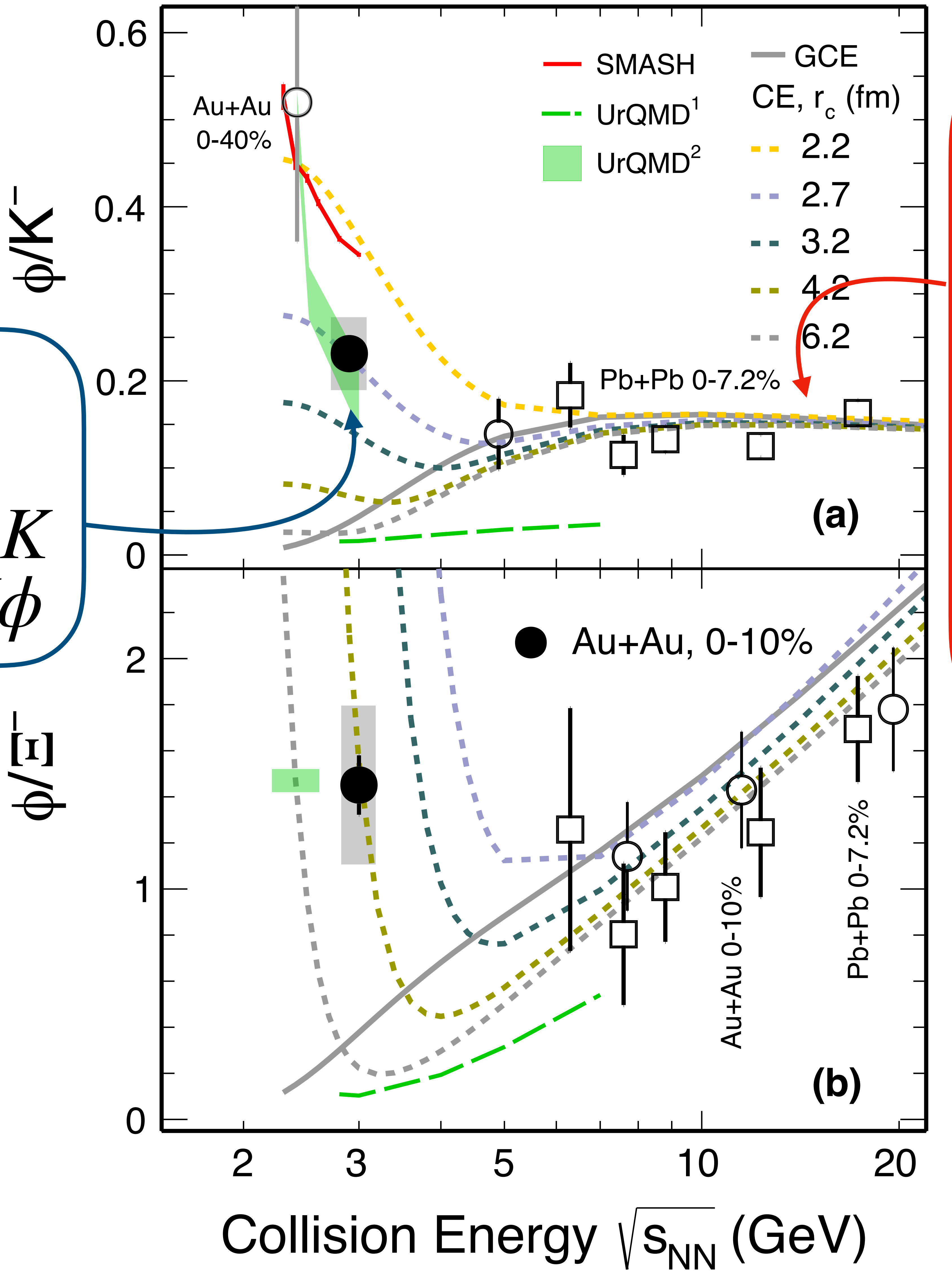
Similar production mechanism for S=1 hadrons

- Ξ^- seems to deviate from the scaling trend
  - Sub-threshold production

- UrQMD **only qualitatively** describes the energy trend of scaling of the strange hadron yields



Thermal Model Comparisons



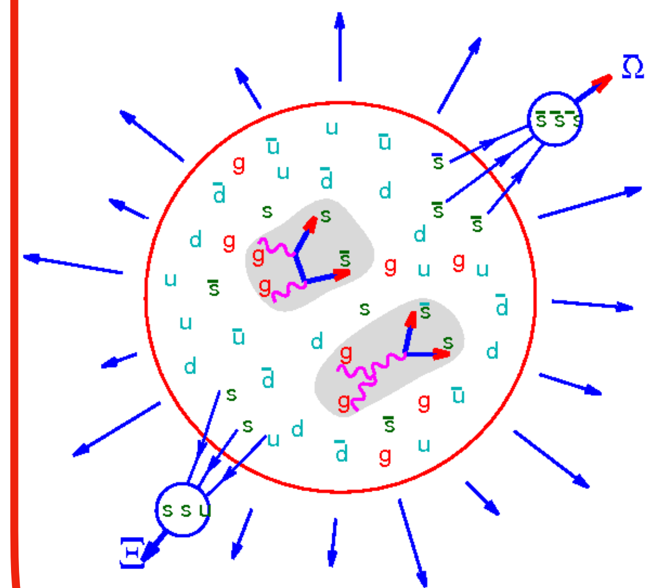
In hadronic matter:

$NN \rightarrow N\Lambda K$

$NN \rightarrow NN\phi$

In QGP:

$gg \rightarrow s\bar{s}$



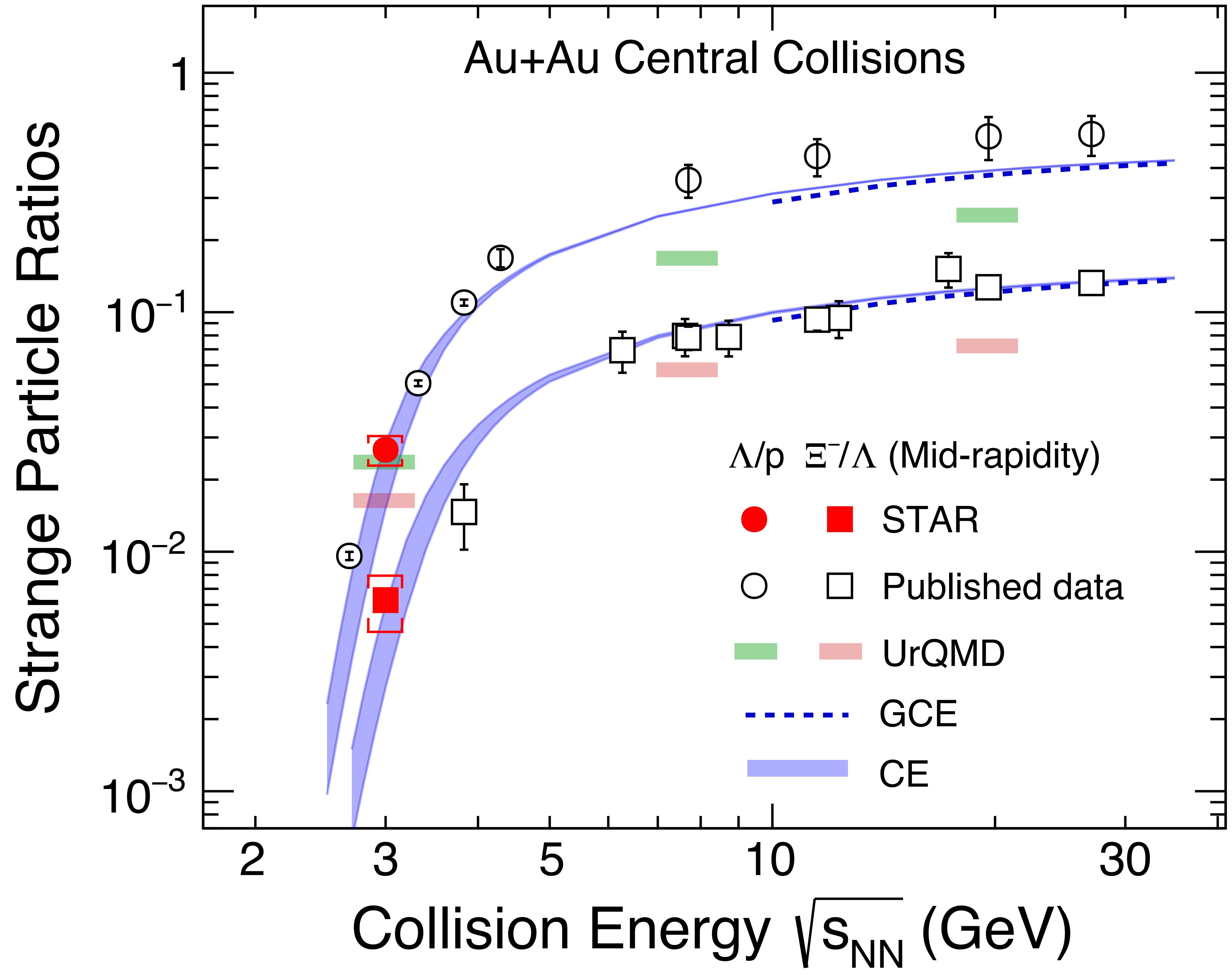
- Thermal model: assumes **all particles in chemical and thermal equilibrium at freeze-out**
  - Canonical ensemble: (CE) requires **local strangeness conservation** within a volume defined by the **strangeness correlation length** (r_c)
- Yield ratios $\phi/K^-, \phi/\Xi^-$ reflect **canonical suppression of strangeness** at 3 GeV

Implies the importance of local strangeness conservation at 3 GeV

May be an indication of a *change in medium properties*?

Wikipedia

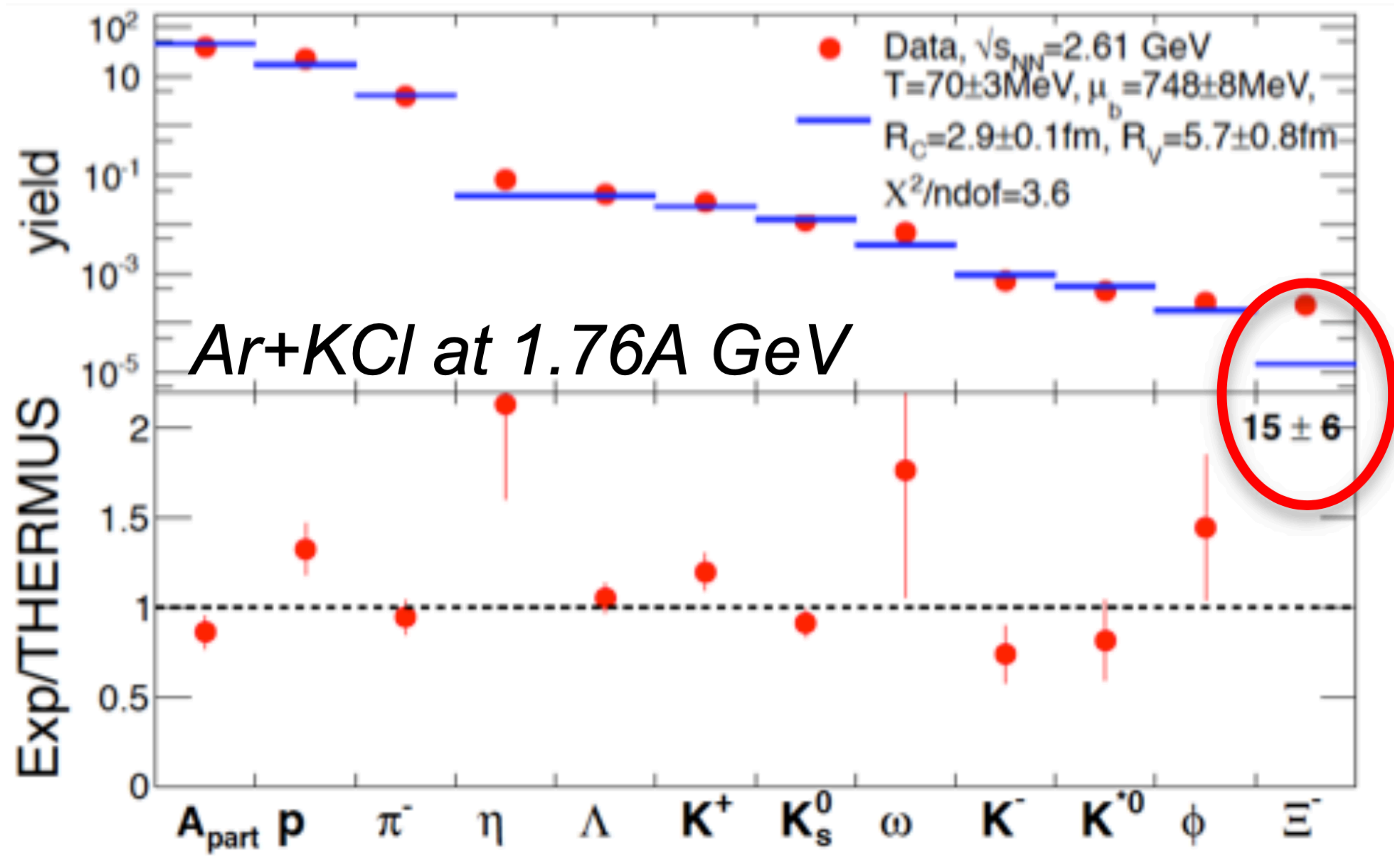
Thermal Model Comparisons



- CE with r_c from 5.2 to 6.2 fm simultaneously describes $\Lambda/p, \Xi^-/\Lambda$ in centrality collisions at mid-rapidity

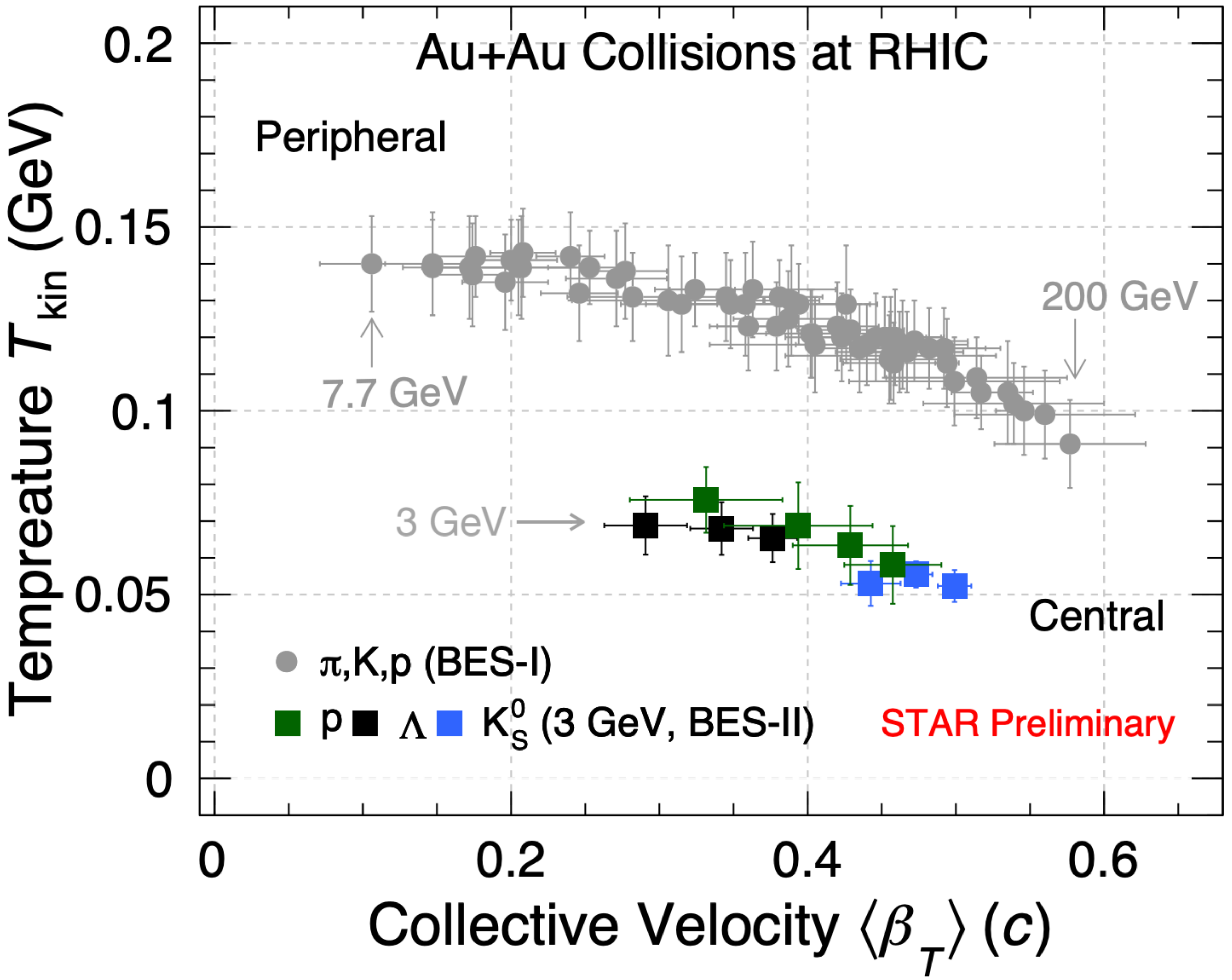
May indicate baryon (S=0,1,2) production approaches chemical equilibrium at 3 GeV Au+Au collisions

- Ξ^- are produced below threshold, may be **sensitive to the equation-of-state**



- *HADES measurement of Ξ^- in Ar+KCL at 1.76A GeV are not compatible with CE calculations(?)*

Kinetic Freeze-out Properties



- T_{kin} of Λ, K^0_S and p are lower than π, K, p in higher energy collisions
- *Might suggest a different EOS at high baryon density*

- Extract common kinetic freeze-out temperature T_{kin} and average transverse radial flow velocity β combined Blast-Wave fit to spectra

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

Phys. Rev. C. 96. (2017) 044904
Phys. Rev. C 102 (2020) 34909

Summary I

- Strange hadron yield measurements at 3 GeV indicate the presence of radial flow in central collisions

- Common centrality dependence for S=1 hadrons → similar production mechanism

- CE describes strange hadron yield ratios at mid-rapidity → Ξ^-, Λ, p approaches chemical equilibrium in high baryon density nuclear matter created in 3 GeV Au+Au collisions

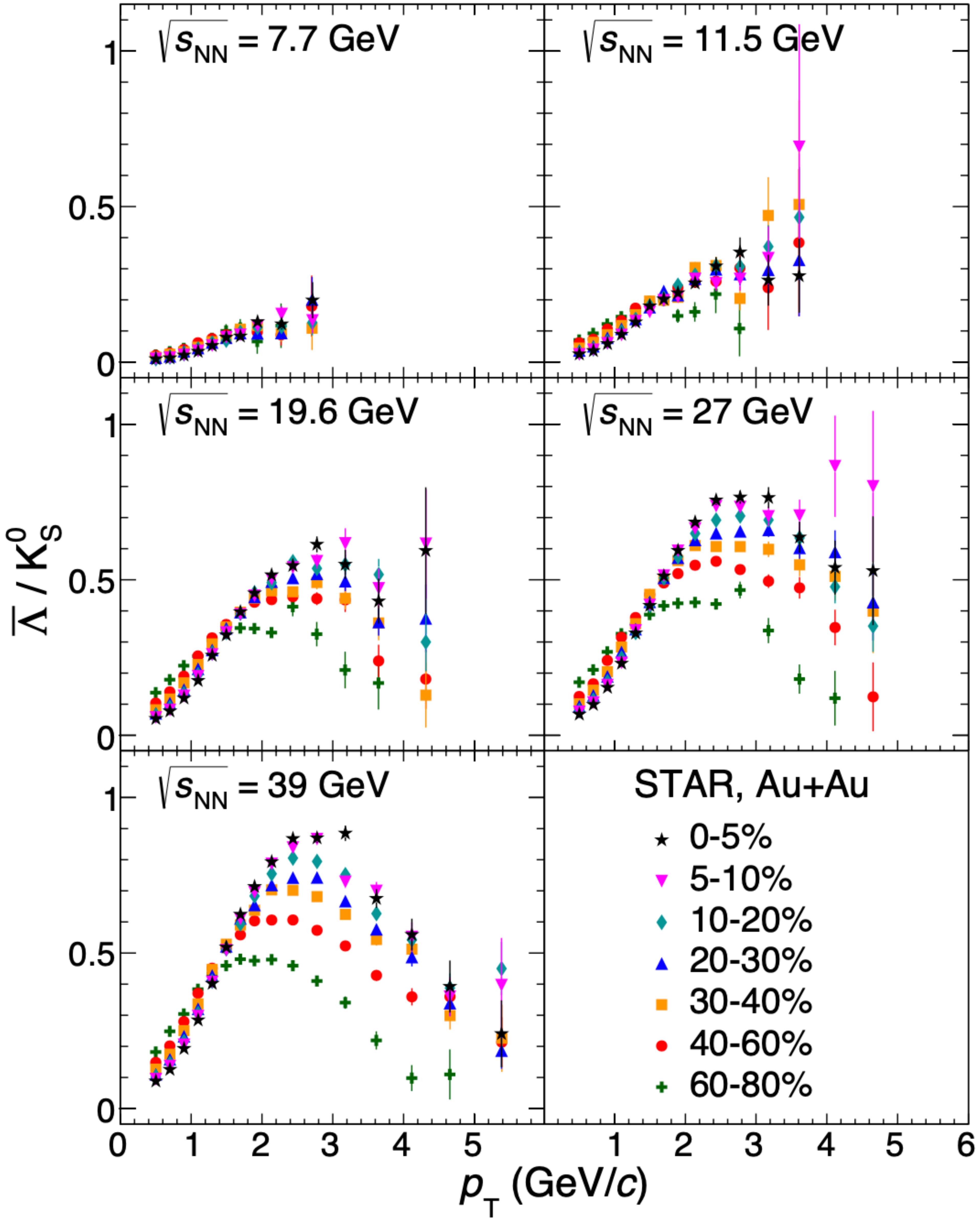
- Blast-wave analysis of Λ, K_S^0, p spectra indicate lower kinetic freeze-out temperature than those obtained from π, K, p spectra at collision energies above 7.7 GeV
    - Might suggest a different EOS at high baryon density

Outlook I: Baryon-to-Meson Ratio and Onset of Deconfinement

- $\bar{\Lambda}/K_S^0$ or Λ/K_S^0 ratio is often used as a probe for QGP formation
- Baryon-to-meson enhancement at intermediate p_T observed for energies above 19.6 GeV → may be interpreted as parton recombination
  - Recently observed at 14.6 GeV as well

    Y. Fang for STAR collaboration, QM2023

  - Energies b/w 3 and 14.6 GeV requires further investigation



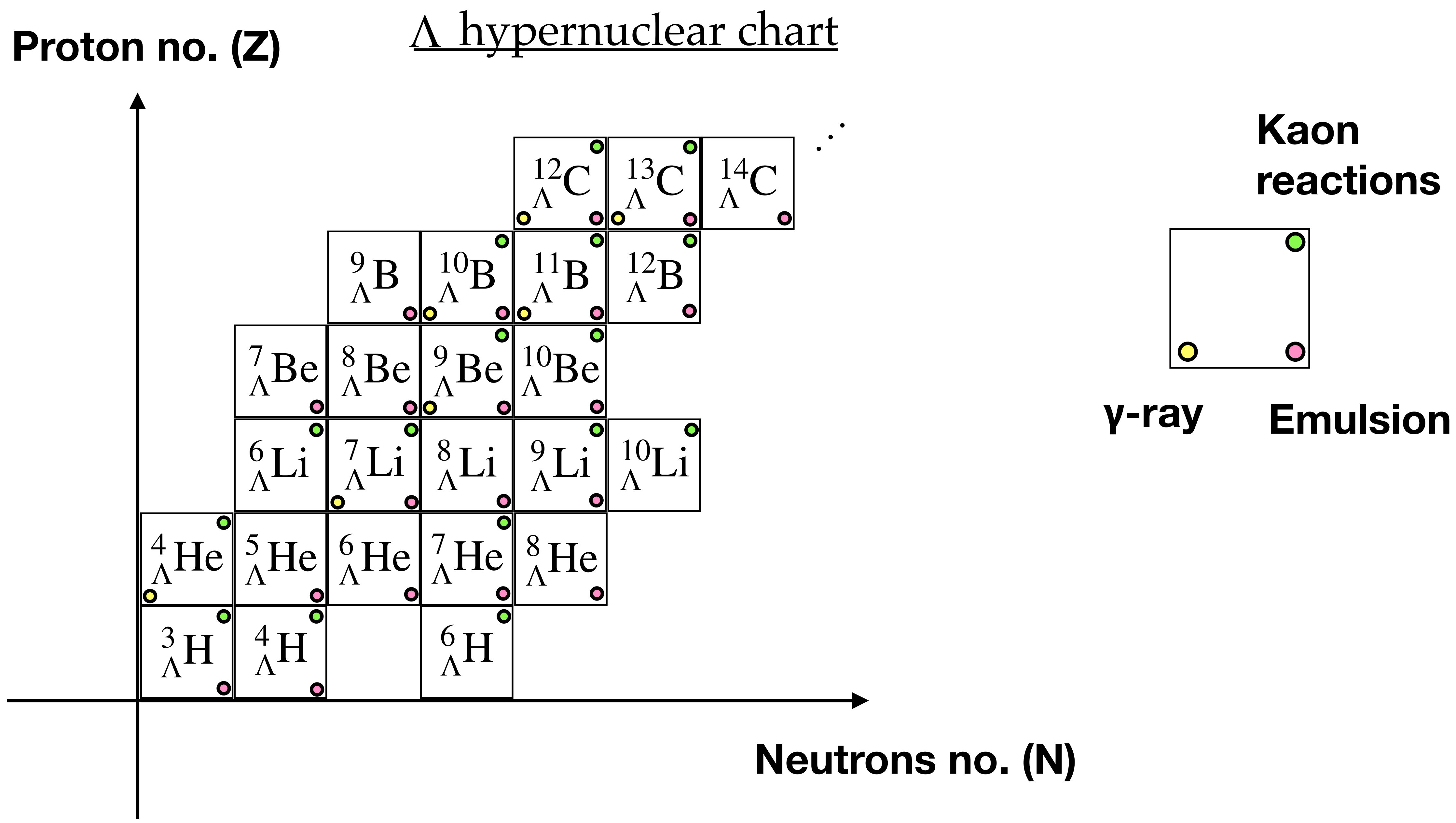
Phys. Rev. C 102 (2020) 34909

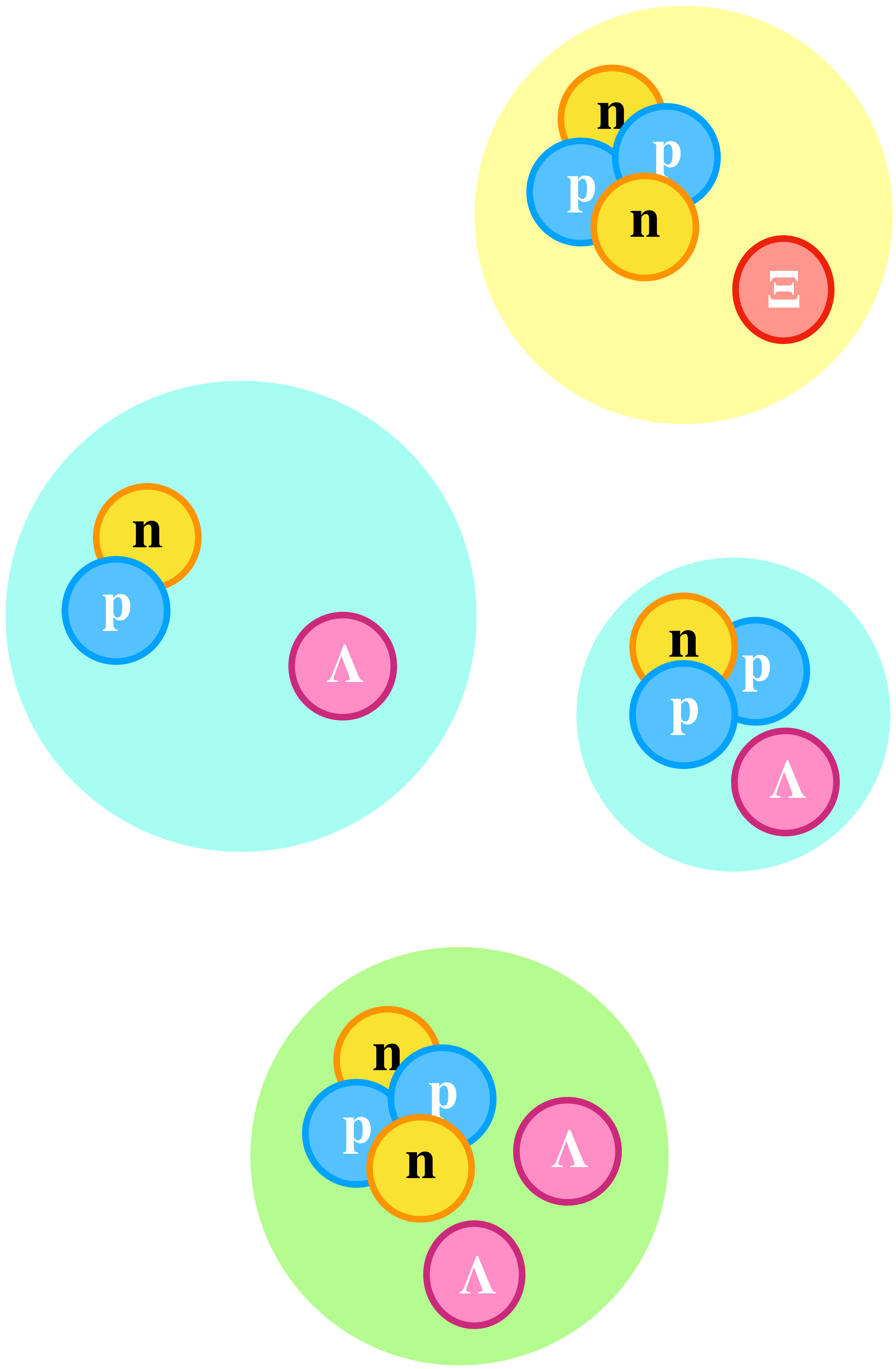
Hypernuclei

Hypernuclei are nuclei containing at least one hyperon

- Provide access to the hyperon–nucleon/hyperon (Y-N/Y) interaction

- Around 40 single-Λ hyypernuclei have been discovered so far
  - Very few double-Λ or Ξ hypernuclei have been confirmed to exist



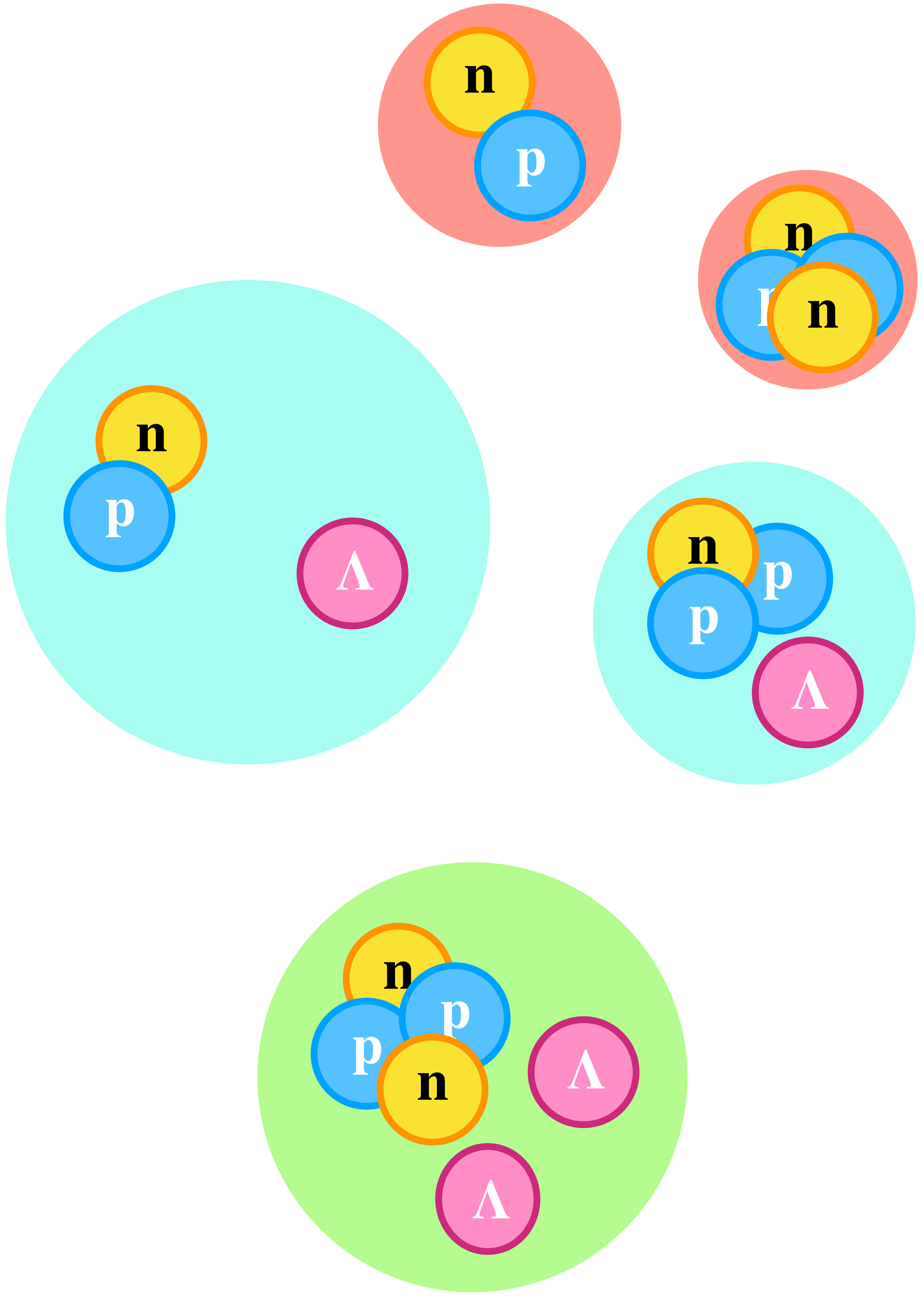


Motivations

1. What can light nuclei production in heavy-ion collisions tell us about the QCD phase diagram and the nuclear equation-of-state?

- Nuclei and hypernuclei yields have been suggested to be sensitive to **critical fluctuations** and the **onset of deconfinement**

  - *Assume coalescence formation of nuclei*



$$\frac{t \times p}{d^2}$$

Sensitive to neutron density fluctuations

$$\frac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

Sensitive to baryon-strangeness correlations

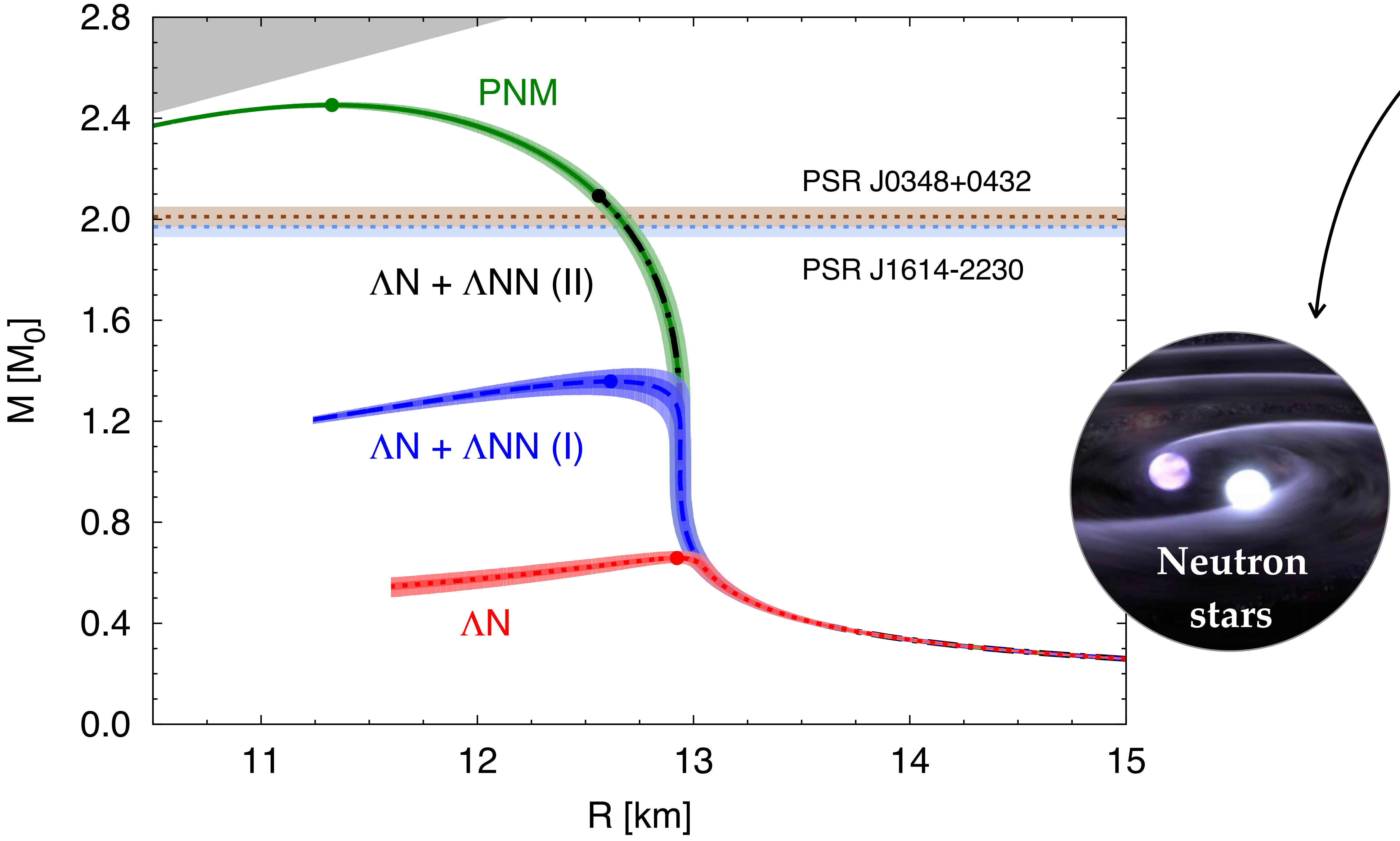
Phys. Lett. B 781 (2018) 499

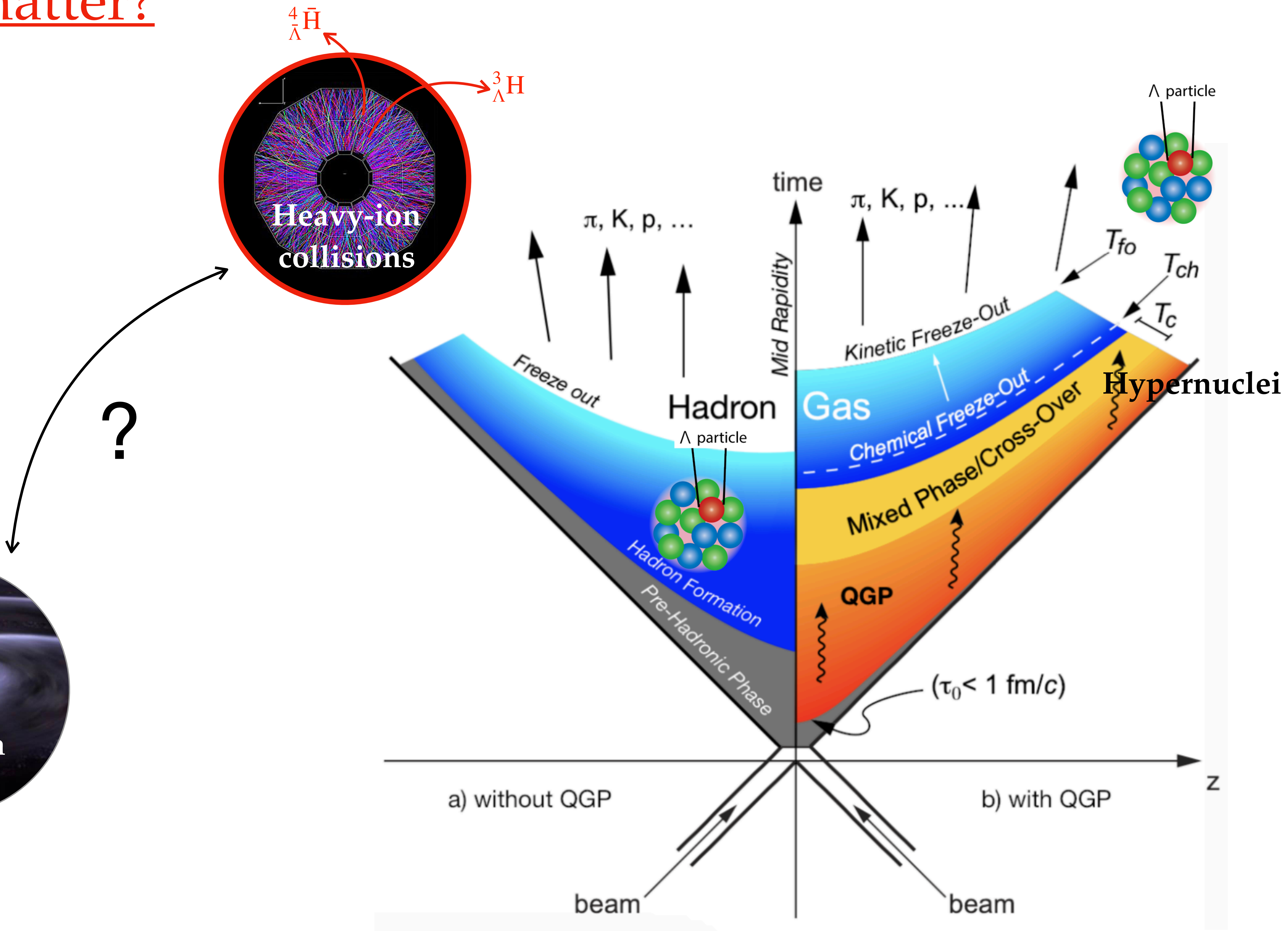
Phys. Lett. B 684 (2010) 224

Motivations

2. What is the role of hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction in the equation-of-state of high baryon density matter?

- **Hyperon Puzzle:** difficulty to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors





- Density dependent YN, YNN and YYN are essential input for solving the **Hyperon Puzzle**

When are hypernuclei formed? At freezeout? Or in medium?

Motivations

- 0. How and when are light nuclei formed in heavy ion collisions?

Light Nuclei Production Models

Thermal models

- Nuclei are formed earlier at the hadronic chemical freeze-out
- Thermal and chemical equilibrium (T, μ_B)

Coalescence models

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Dynamical models

$$\pi d \leftrightarrow \pi np$$
$$\pi t \leftrightarrow \pi nnp$$
$$\pi {}^3\mathrm{He} \leftrightarrow \pi npp$$
$$\ldots$$

- Disintegration cross-sections are large

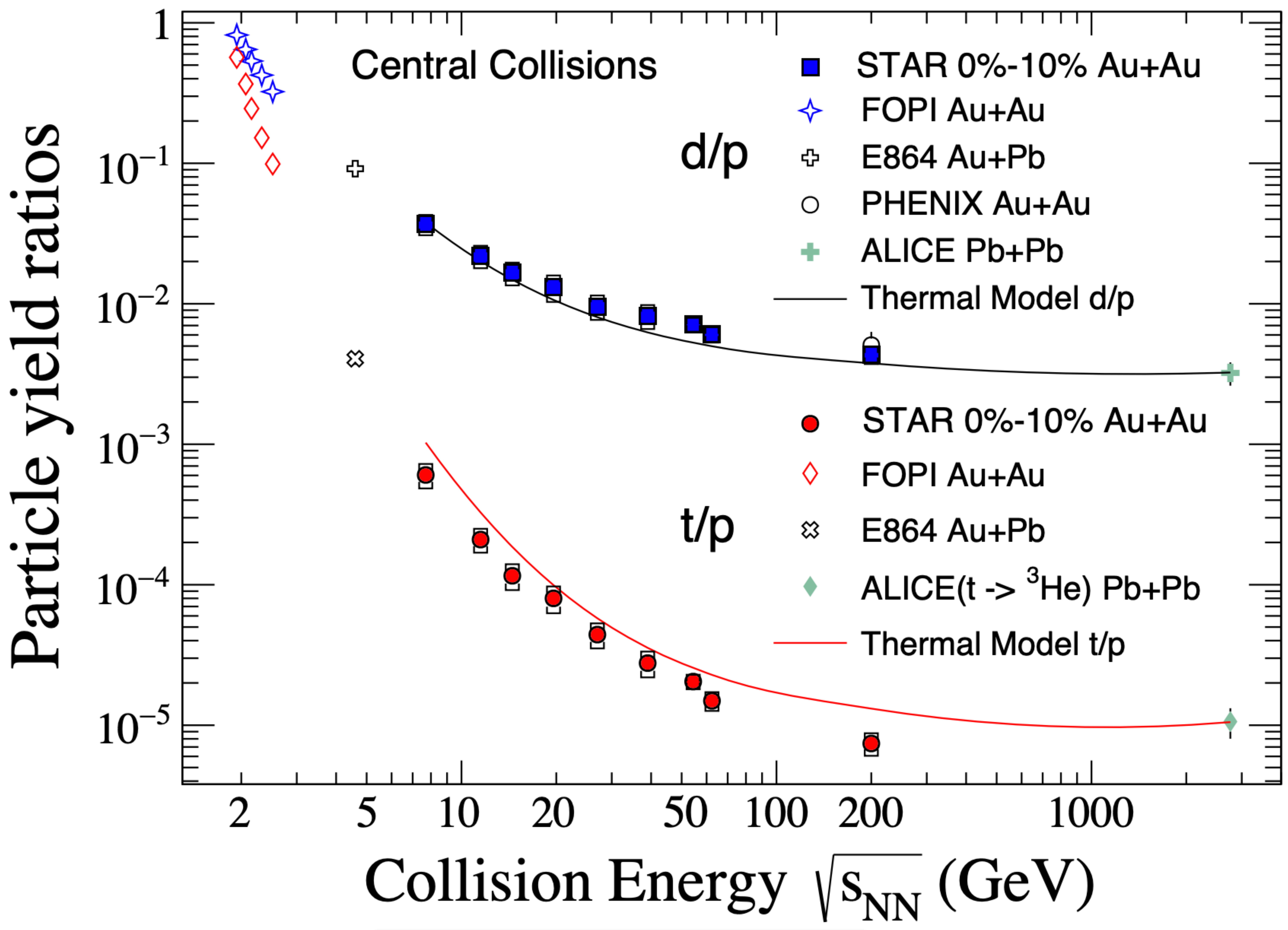
Nucl. Phys. A 1005 (2021) 121754

Multi-fragmentation

- Hyperon capture by excited "spectators" can lead to hypernuclei formation

Phys.Rev.C 76 (2007) 024909

Light Nuclei Ratios in Central Collisions



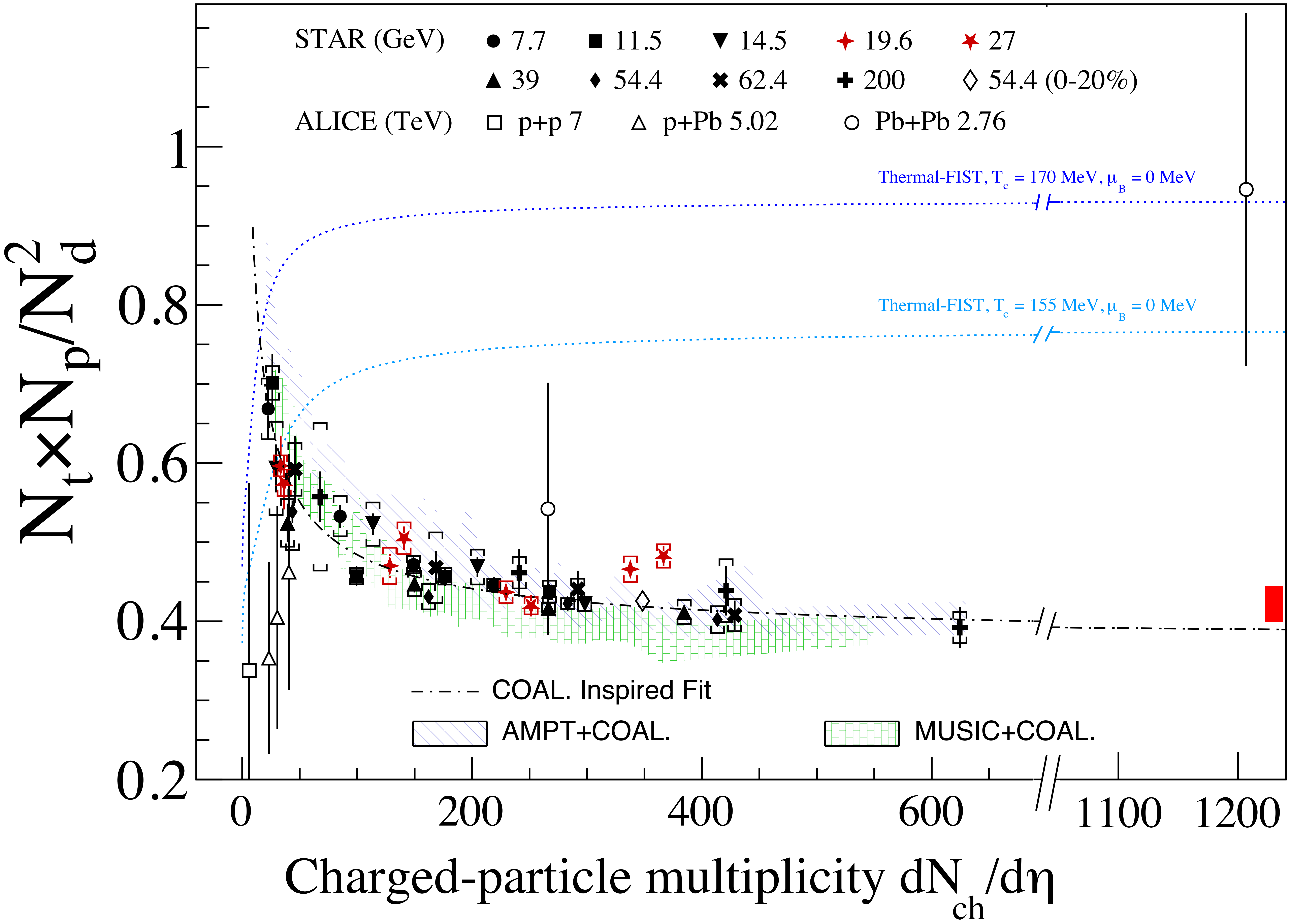
STAR, Phys. Rev. Lett. 130 (2023) 202301

- d/p fairly well described by thermal model, but t/p is overestimated

Effects from hadronic re-scattering?

Kai-Jia Sun et al, arXiv:2207.12532

Nuclear Compound Yield Ratio

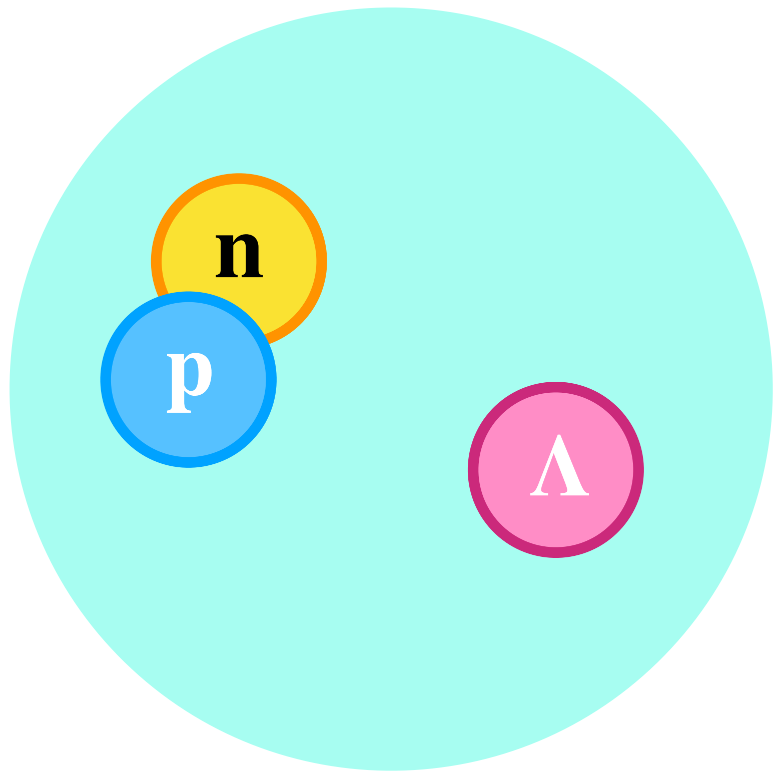
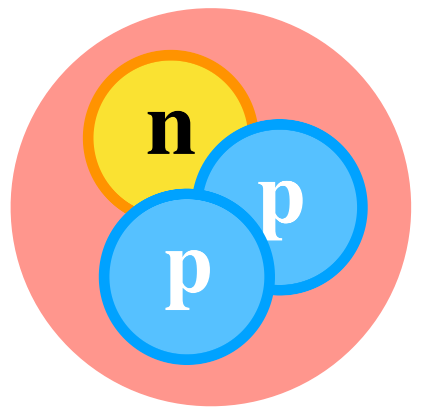


- Light nuclei yield ratio deviates strongly from thermal model from $\sqrt{s_{NN}}$ = 7.7-200 GeV
- Yield ratio exhibits approx. scaling behavior with $dN_{ch}/d\eta$

Data favors coalescence prescription

STAR, Phys. Rev. Lett. 130 (2023) 202301
THERMAL-fist: Comput. Phys. Commun. 244, 295 (2019)

The Hypertriton ($^3_\Lambda H$)

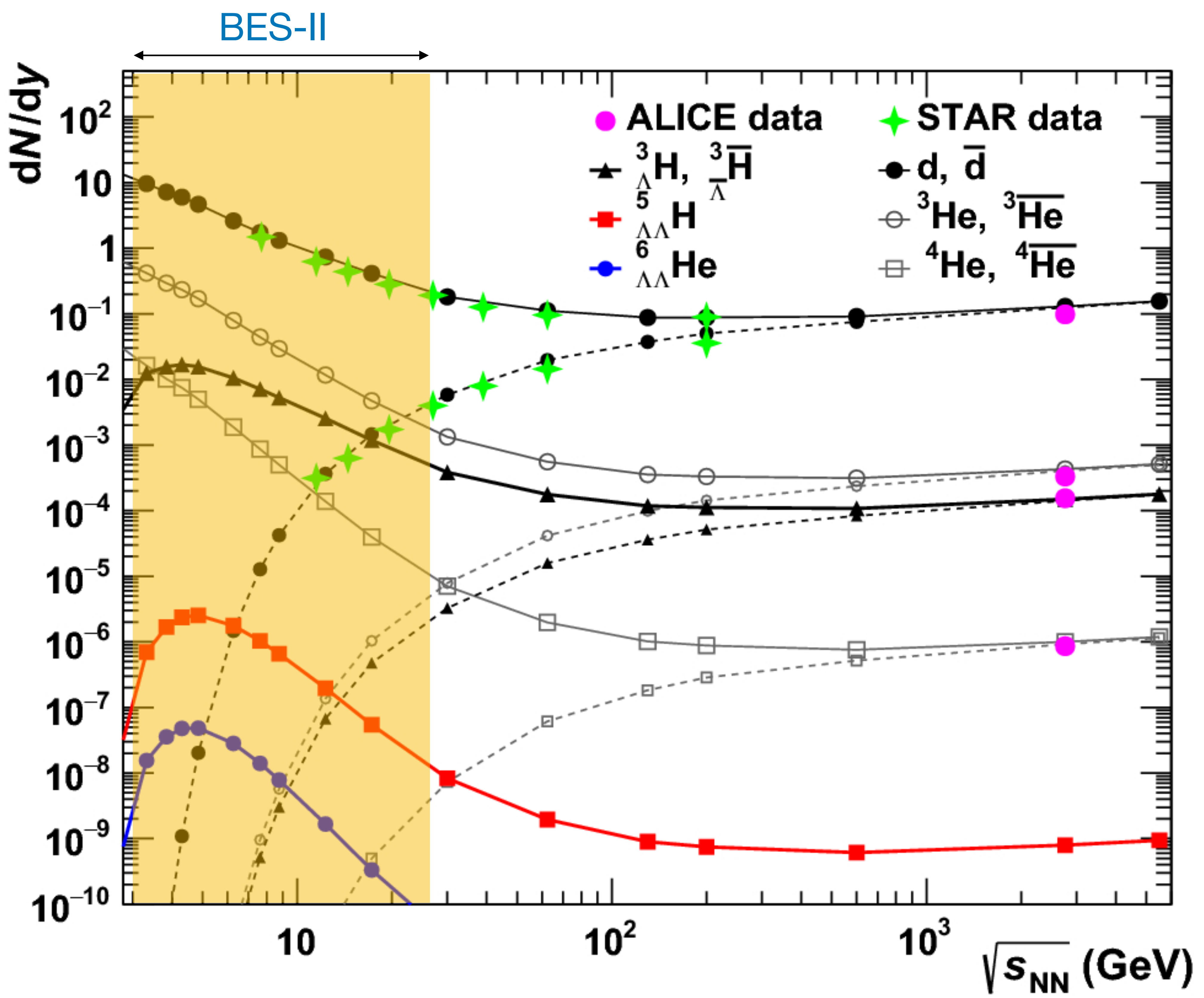
	$^3_\Lambda H$	^3H
		
Strangeness	+1	0
RMS Radius	~4.9 fm	1.15 fm

H. Nemura et al, Prog. Theor. Phys. 103, 929 (2000)

STAR and BES-II

B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al, PLB 697 (2011)203

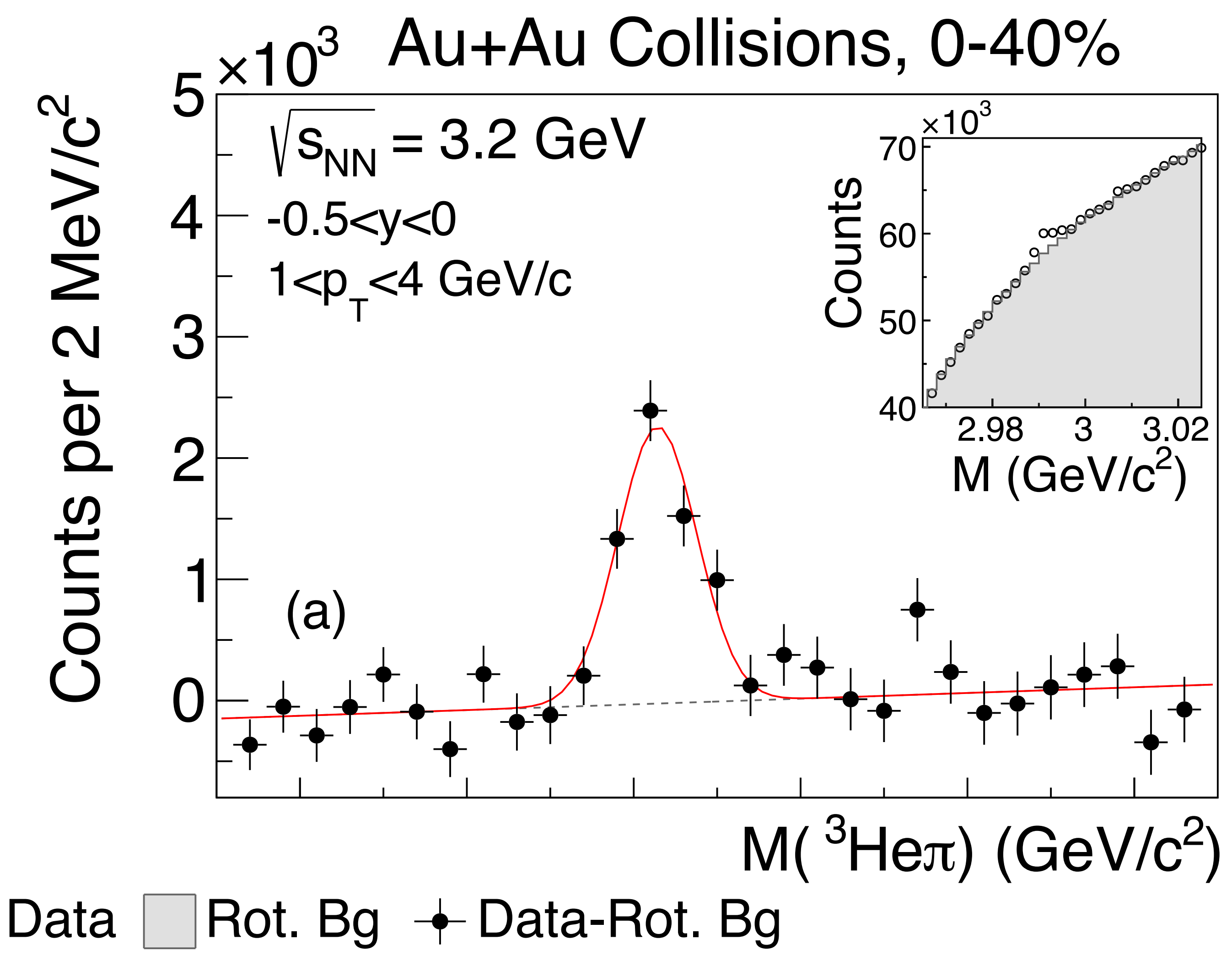
- Hypernuclei measurements are scarce in heavy-ion experiments
- At lower beam energies, hypernuclei yields are expected to be **enhanced due to baryon stopping**
  - STAR BES-II (2018-2021) -> great opportunity to study hypernuclei production



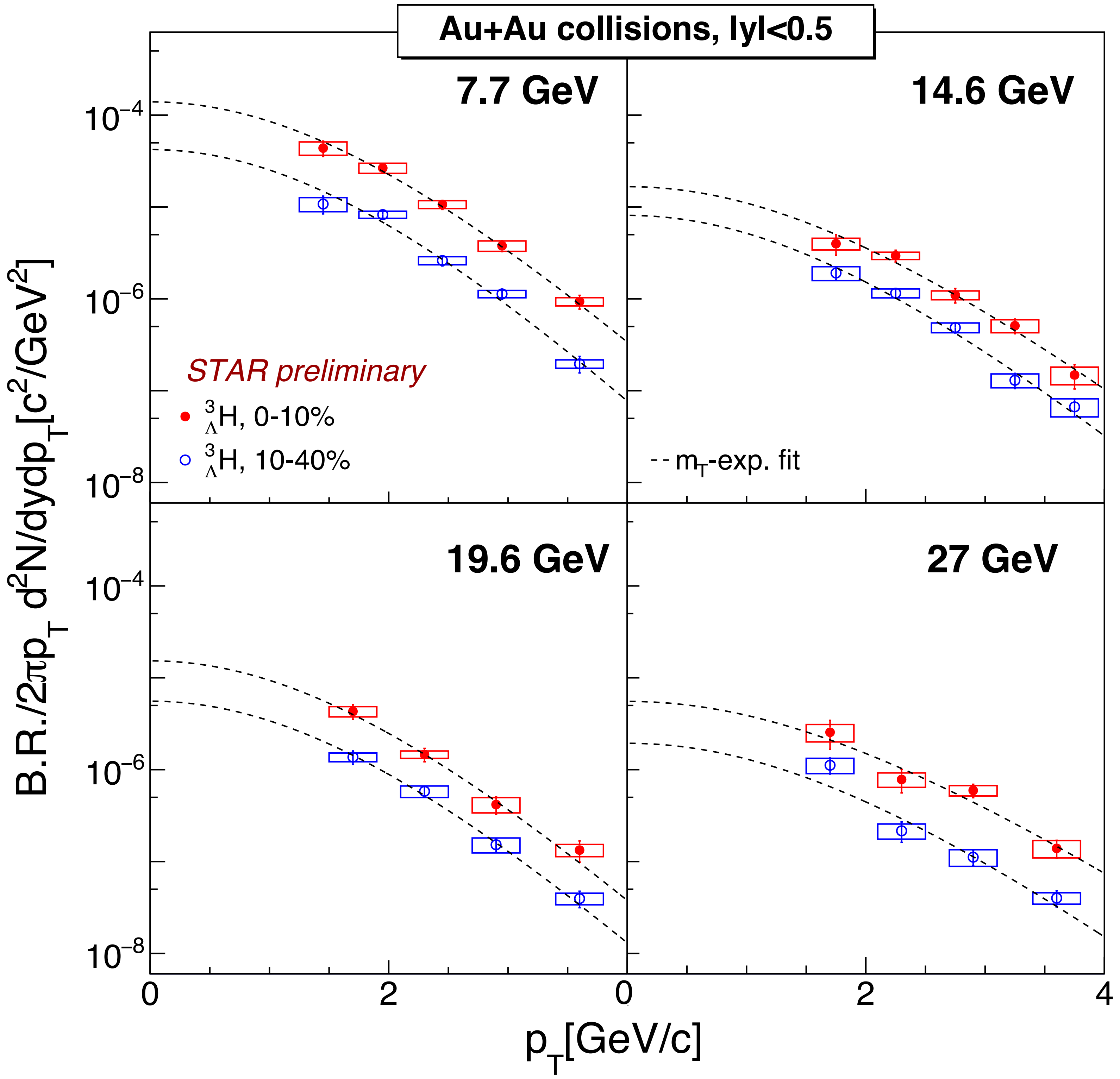
New results from BES-II data at:

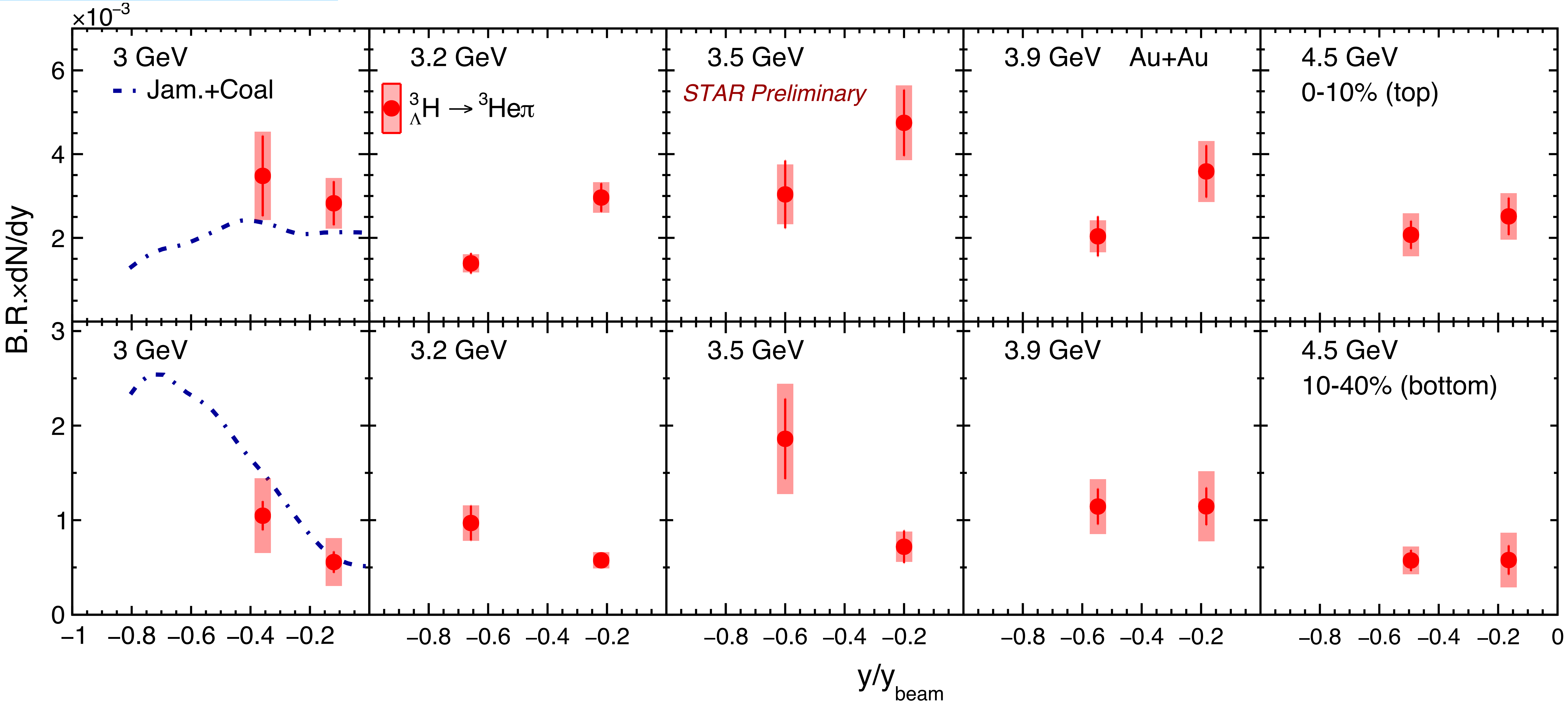
- **3.0, 3.2, 3.5, 3.9, 4.5 GeV (fixed-target mode)**
- **7.7, 14.6, 19.6, 27 GeV (collider mode)**

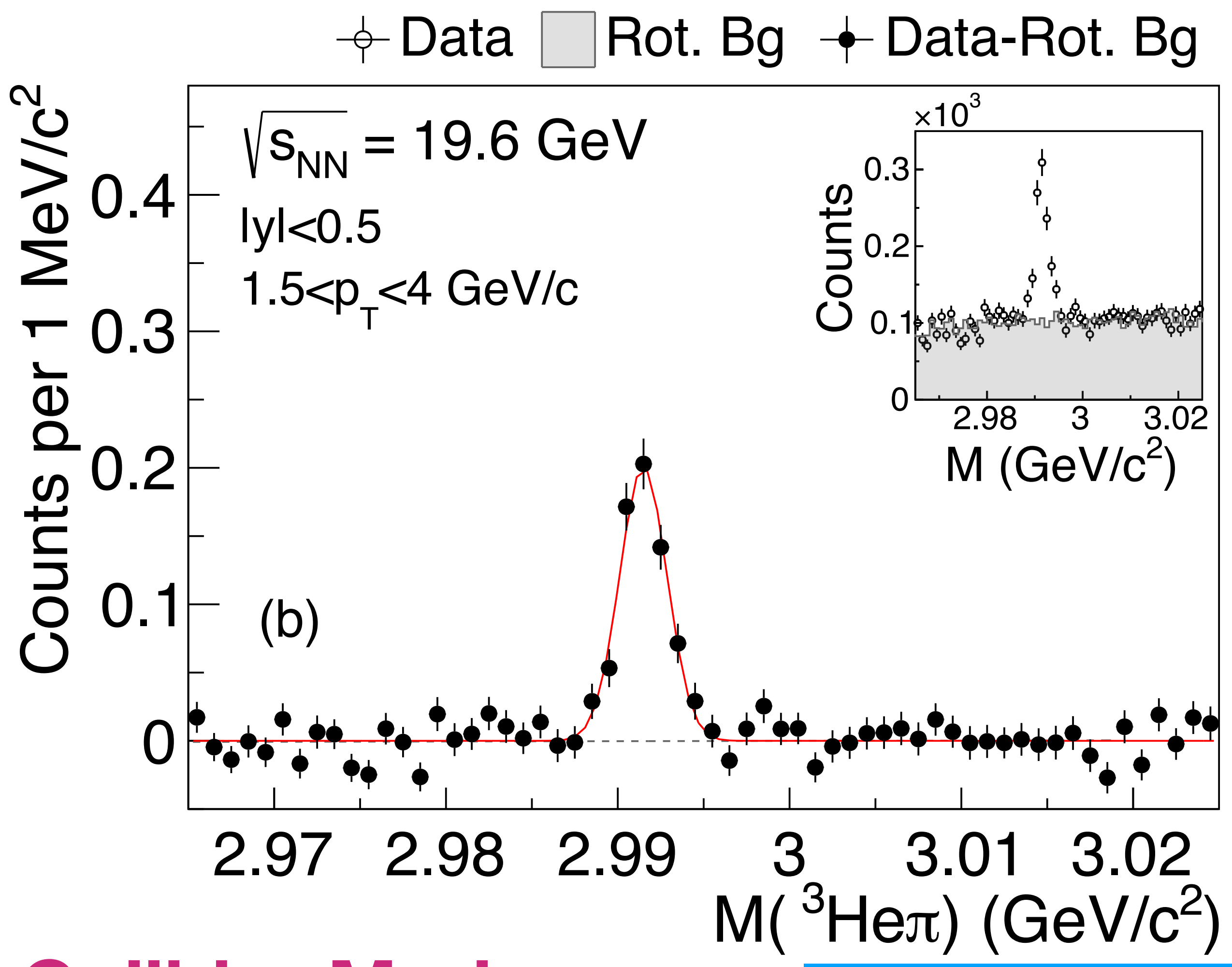
Rapidity Densities (dN/dy) and Transverse Momentum Spectra (dN/dpT)



Fixed-Target Mode



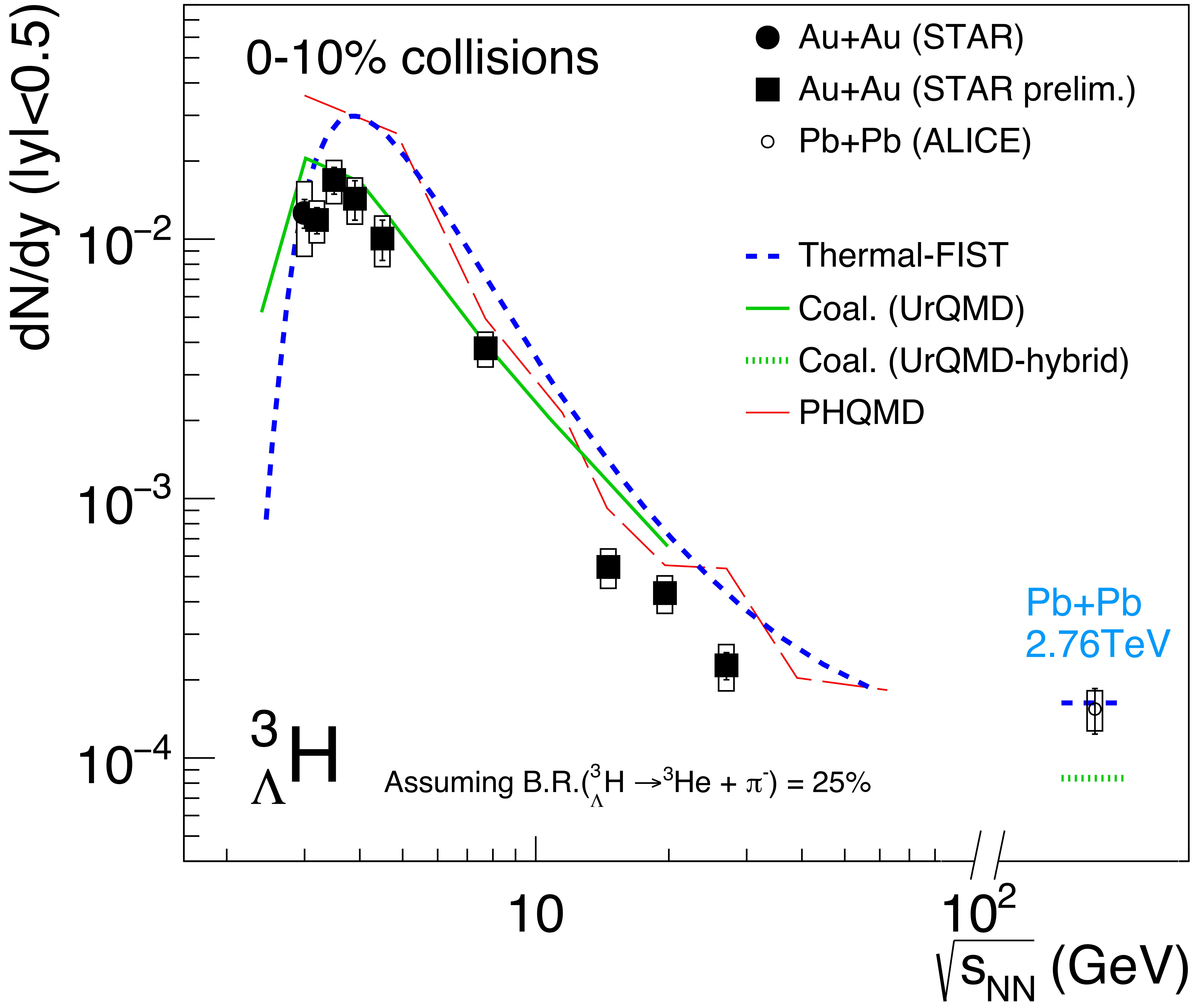




Collider Mode

Comprehensive measurements using fixed-target and collider data with <u>high significance</u>

$^{3}_{\Lambda}H$ Excitation Function



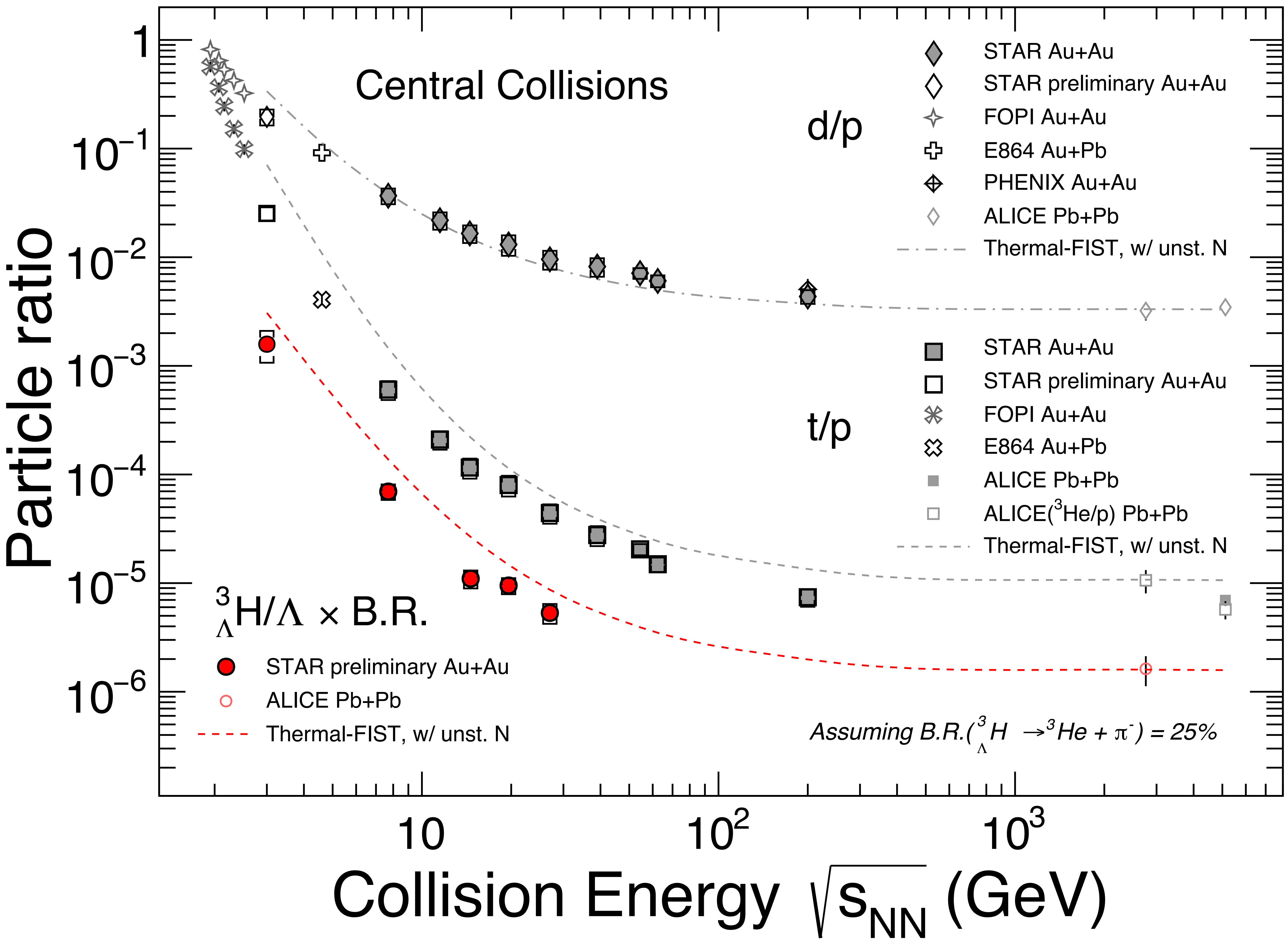
- Yield increases strongly from 27 GeV to 7.7 GeV
- Maximum is reached at ~3-4 GeV
- Qualitatively consistent with thermal and coalescence models

Trend in data can be interpreted as an interplay b/w

increasing baryon density and **stronger strangeness canonical suppression**

towards low energies

Nuclei-to-Hadron Ratios



- At RHIC energies, similar to t/p, $^{3}_{\Lambda}$H/Λ is overestimated by a factor of ~2 by the thermal model
- Situation in Pb+Pb collisions at LHC energies is less clear

Data are **in contradiction** to the scenario where $^{3}_{\Lambda}$H is **in equilibrium and frozen** at the **conventional chemical freezeout**

Strangeness Population Factor as a Probe for Medium Properties?

- The strangeness population factor S_3:

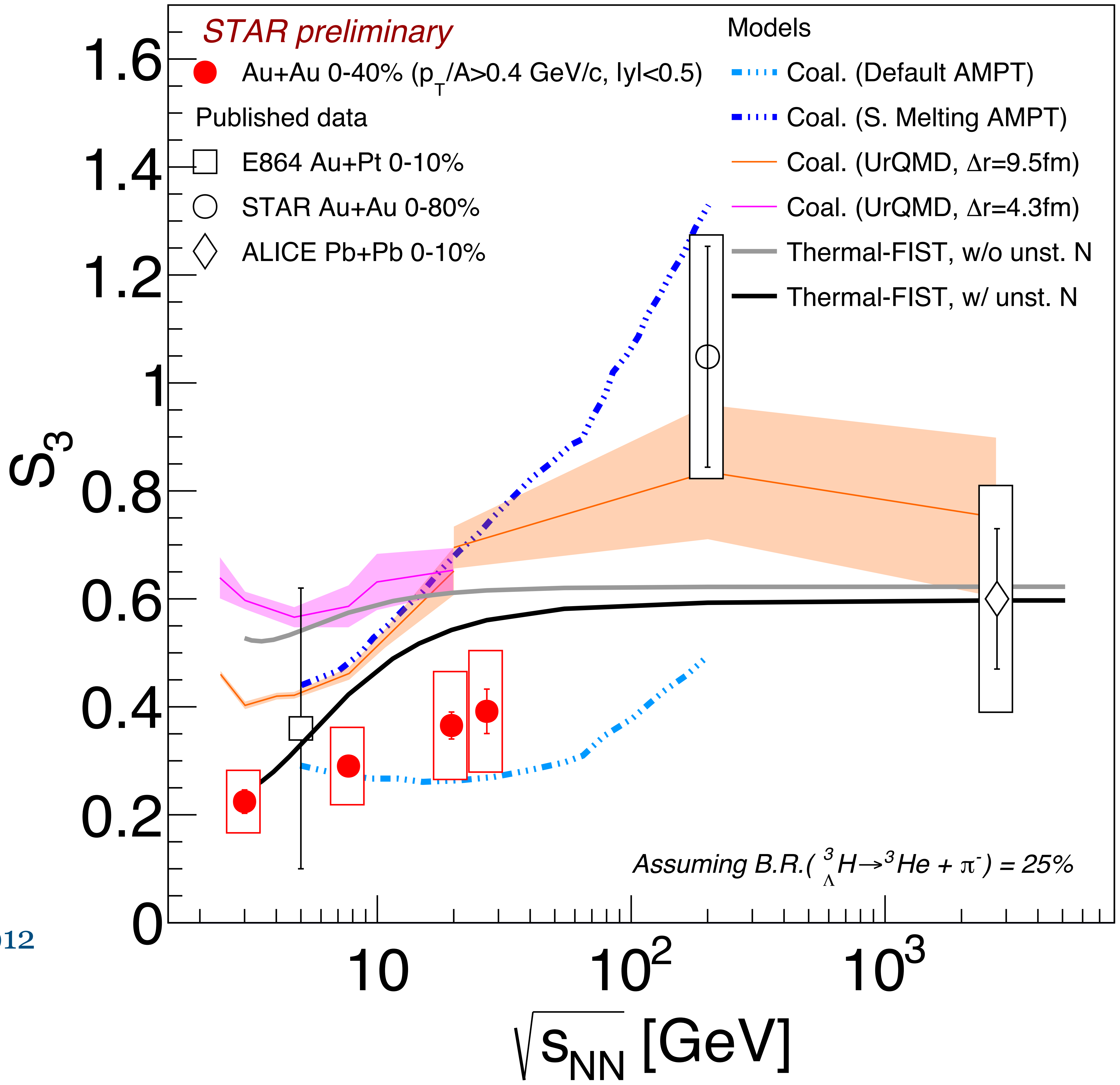
$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

is often used to compare nuclei production with hypernuclei production

Increasing trend of S_3 originally proposed as a signature of onset of deconfinement

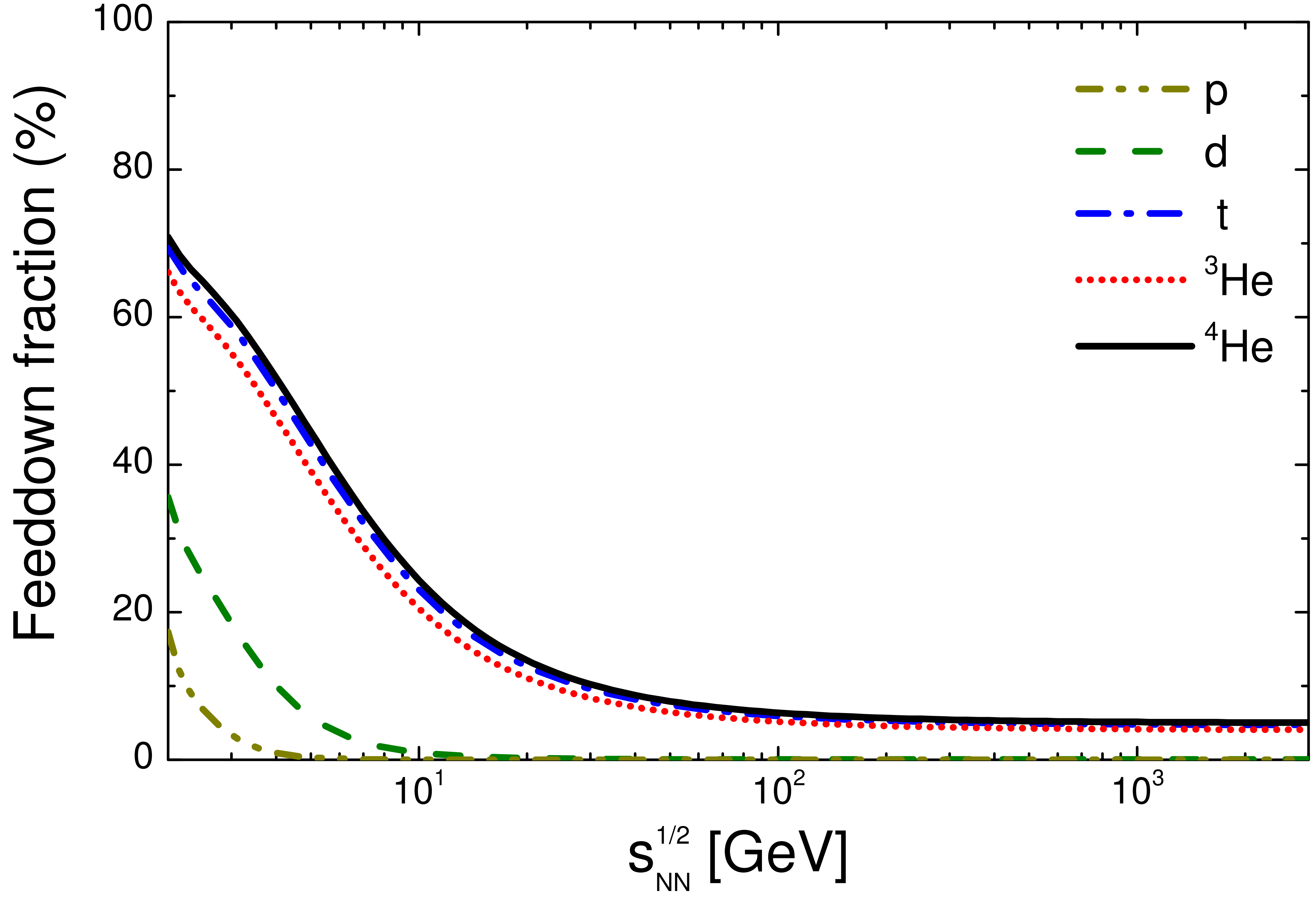
Phys. Lett. B 684 (2010) 224

- Data shows a hint of an increasing trend
- Coalescence+transport also suggest increasing trend Phys. Rev. C 107 (2023) 1, 014912
    - Suppression of ${}^{3}_{\Lambda}\mathrm{H}$ due to large size

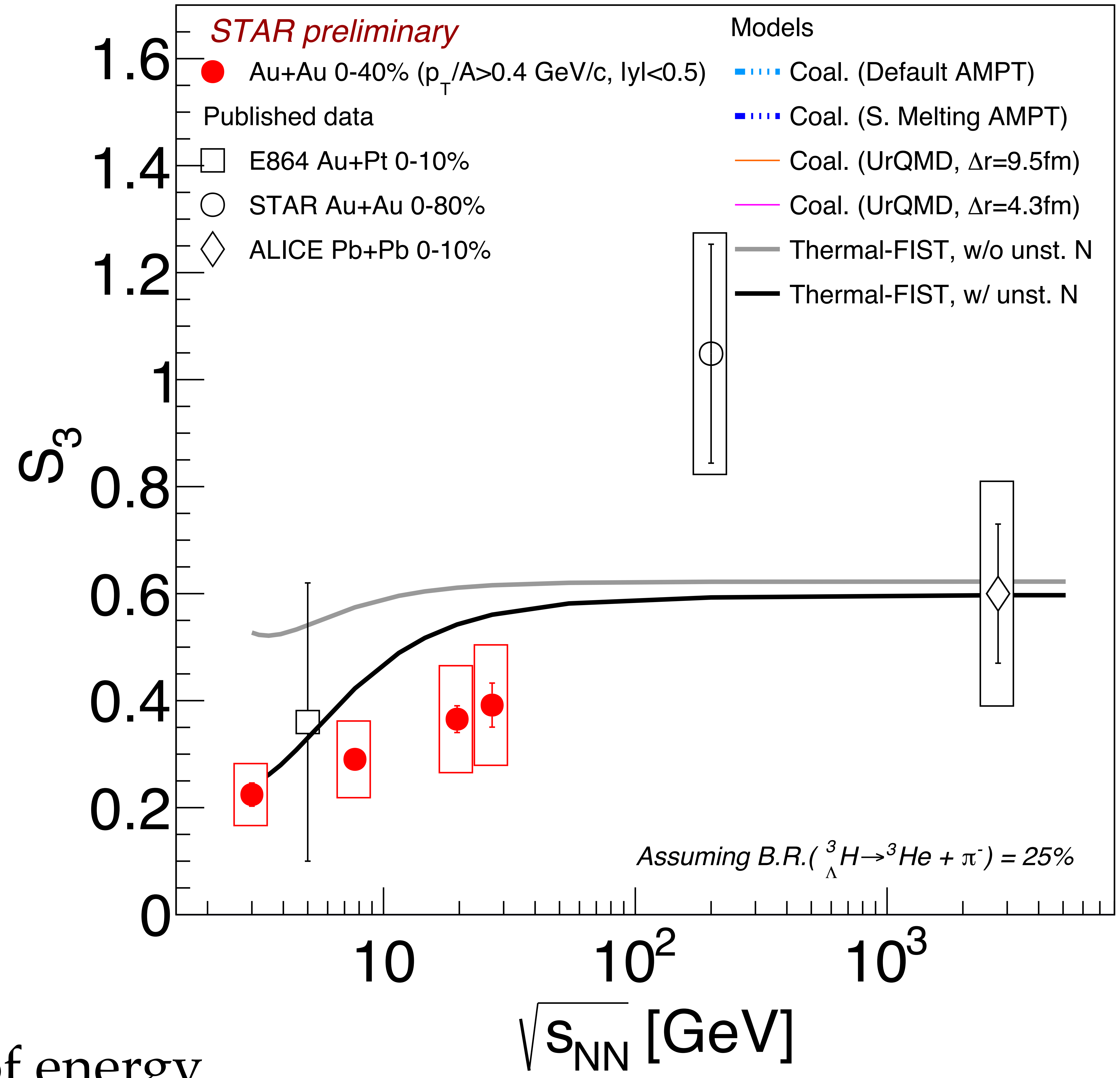


Role of unstable nuclei feed-down at low energies

- Thermal-FIST also suggest increasing trend
  - Unstable nuclei breakup enhance ^{3}He yields? $e.g.\ ^4\text{Li} \rightarrow\ ^3\text{He} + p$

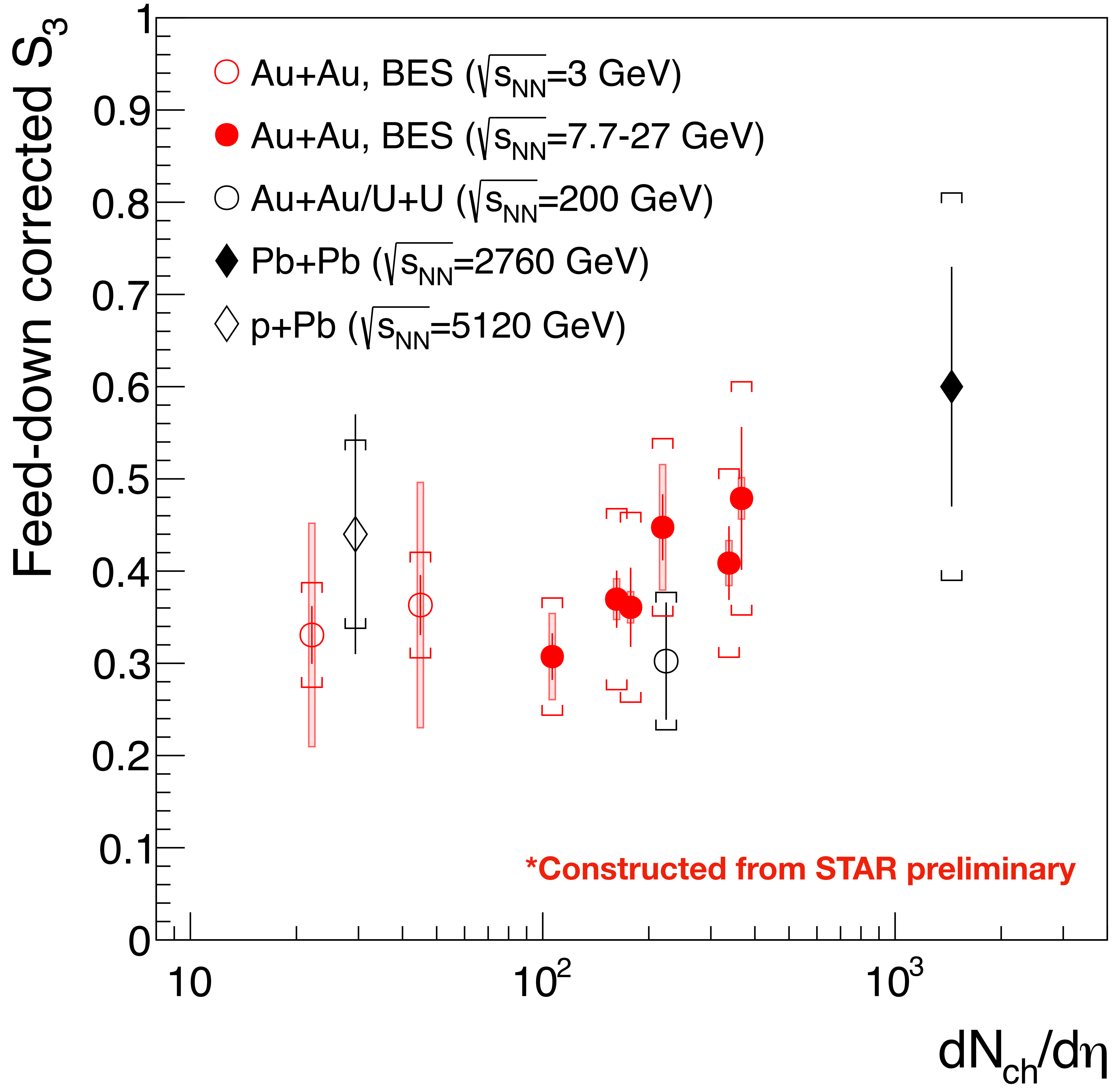


V. Vovchenko et al, Phys. Lett. B 809 (2020) 135746

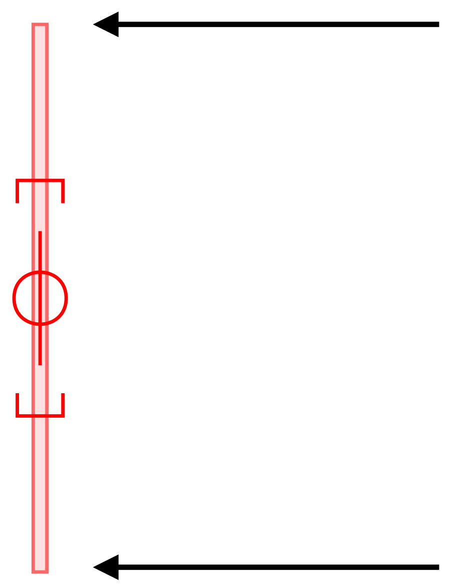


- Feed-down corrected S_3 is *almost* independent of energy

Multiplicity Dependence of S_3 with Considering Different Feed-down Scenarios



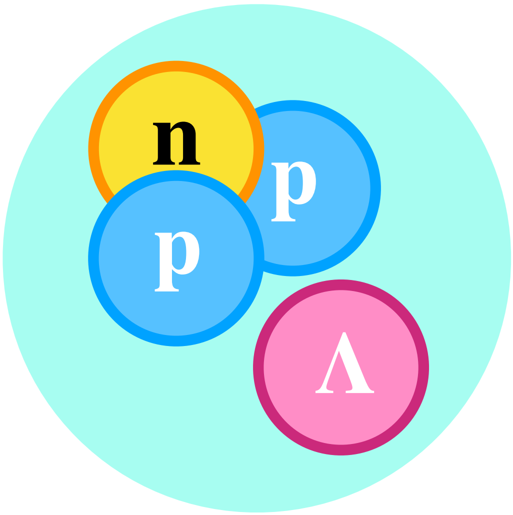
- The filled red rectangles represents possible feed-down contributions
- The central values (red circles) are adjusted to the middle of the red rectangle



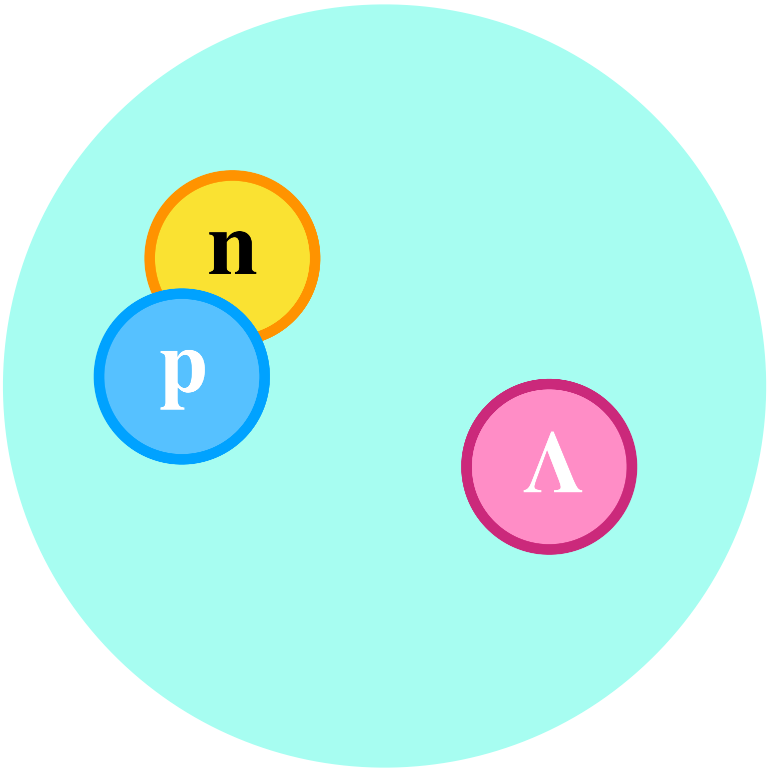
- Feed-down corrected S_3 from low energies (Au+Au 3 GeV) to high energies (200 GeV), from large (Pb+Pb) to small (p+Pb) systems, are all consistent with each other **within sizable uncertainties**

HyperHydrogen-4 $({}^4_\Lambda\mathrm{H})$

$^4_\Lambda\mathrm{H}$

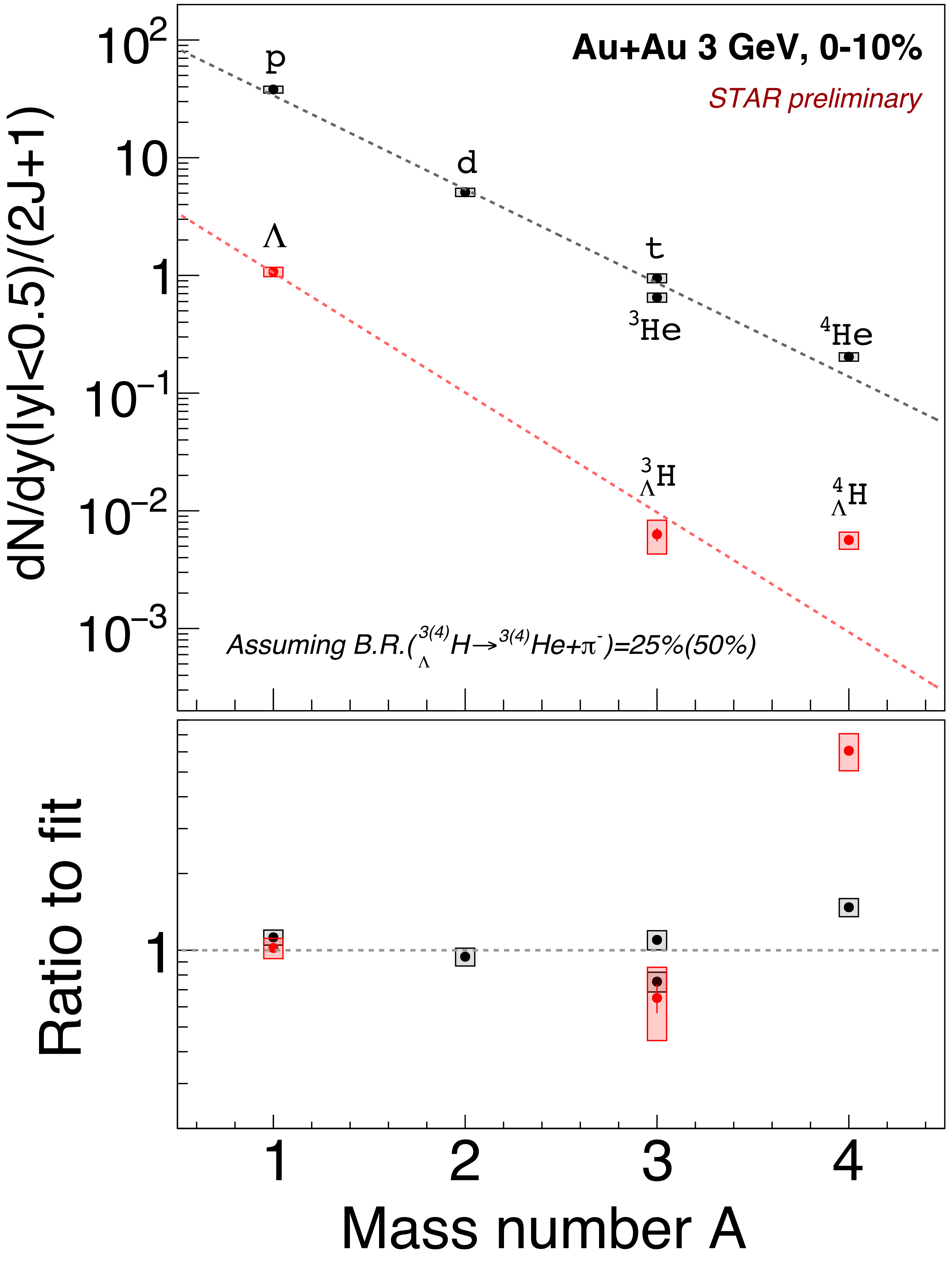


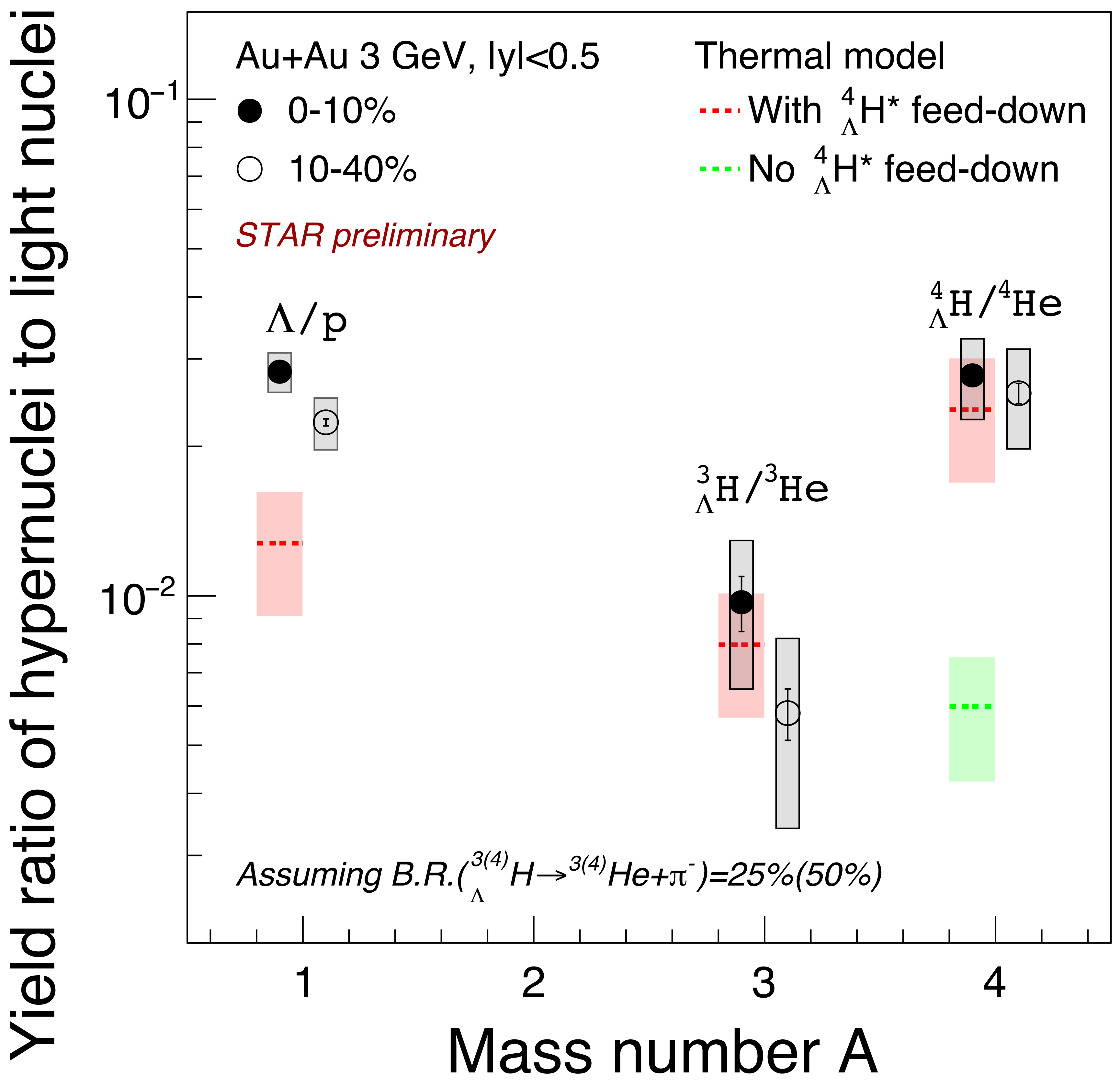
$^3_\Lambda\mathrm{H}$



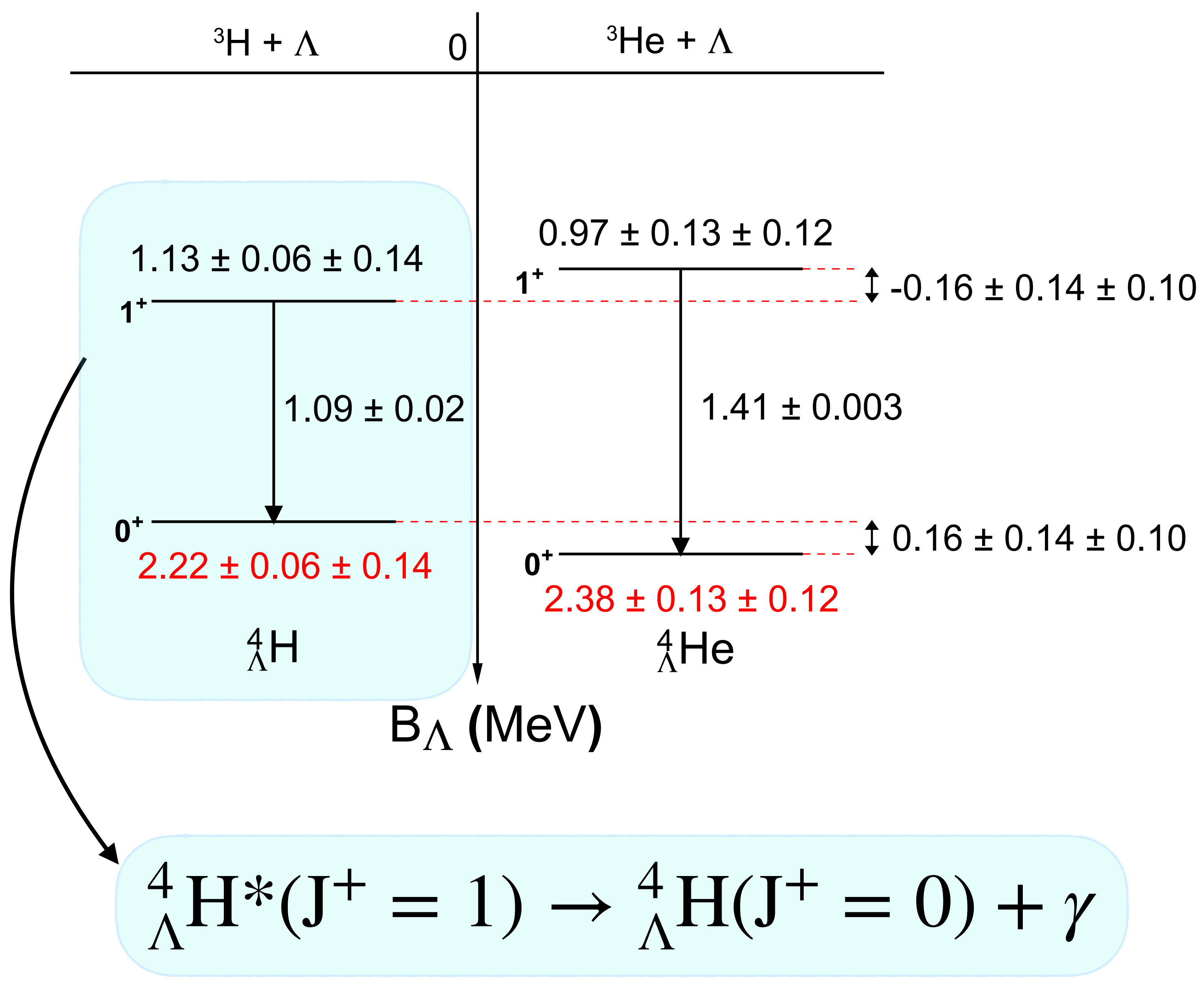
	$^4_\Lambda\mathrm{H}$	$^3_\Lambda\mathrm{H}$
Λ binding energy	2.2 MeV	~0.1-0.2 MeV
Excited states	$^4_\Lambda\mathrm{H}^*(1^+) \rightarrow {}^4_\Lambda\mathrm{H}(0^+) + \gamma$	Not observed

Comparison to Λ and light nuclei at 3 GeV





Level diagram of A=4 hypernuclei



STAR, PLB 834 (2022) 137449

- Thermal/coalescence models predict approx. exponential dependence of yields/(2J+1) vs A
- $^4_\Lambda$H lies a factor of 6 above exponential fit to ($\Lambda, {}^3_\Lambda H, {}^4_\Lambda H$)

- Non-monotonic behavior in light-to hyper-nuclei ratio vs A observed
  - Thermal model calculations including excited $^4_\Lambda H^*$ feed-down show a similar trend

Data support creation of excited A=4 hypernuclei from heavy-ion collisions

A. Andronic et al, PLB 697 (2011)203 (updated, preliminary) (Thermal Model)

Strangeness Population Factors S_3 and S_4 at 3 GeV

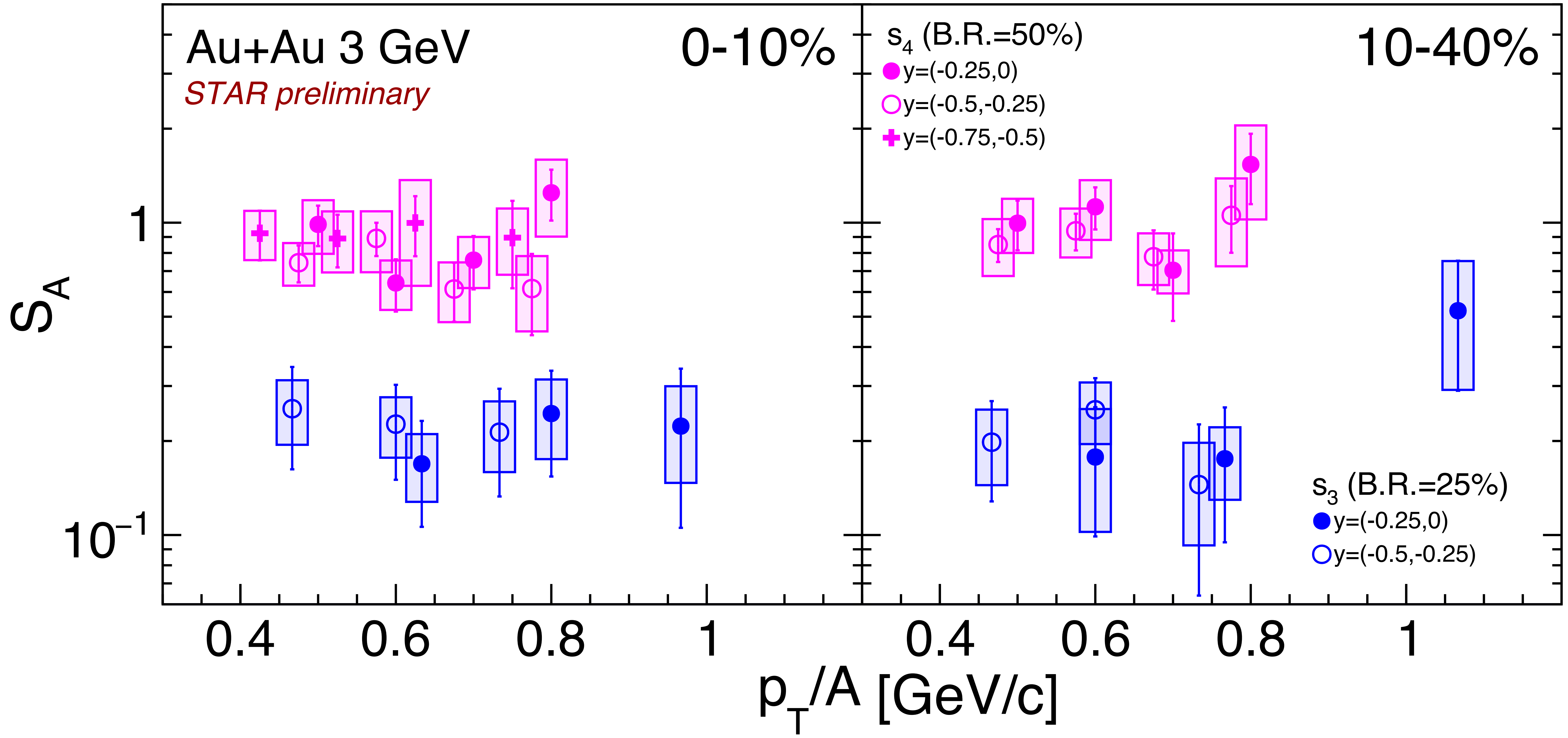
S. Zhang et al, PLB 684(2010)224

- Strangeness population factor:

$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

- Ratio of coalescence parameters B_A:

$$S_A(p_T/A) = \frac{{}^{A}_{\Lambda}\mathrm{H}(p_T)}{{}^{A}\mathrm{He}(p_T) \times \frac{\Lambda}{\mathrm{p}}(p_T/A)} = \frac{B_A({}^{A}_{\Lambda}\mathrm{H})(p_T/A)}{B_A({}^{A}\mathrm{He})(p_T/A)}$$



- B_A of light nuclei and hypernuclei follows similar trends in p_T, rapidity, centrality

Mechanics behind **formation of hypernuclei** and **nuclei** are **similar**

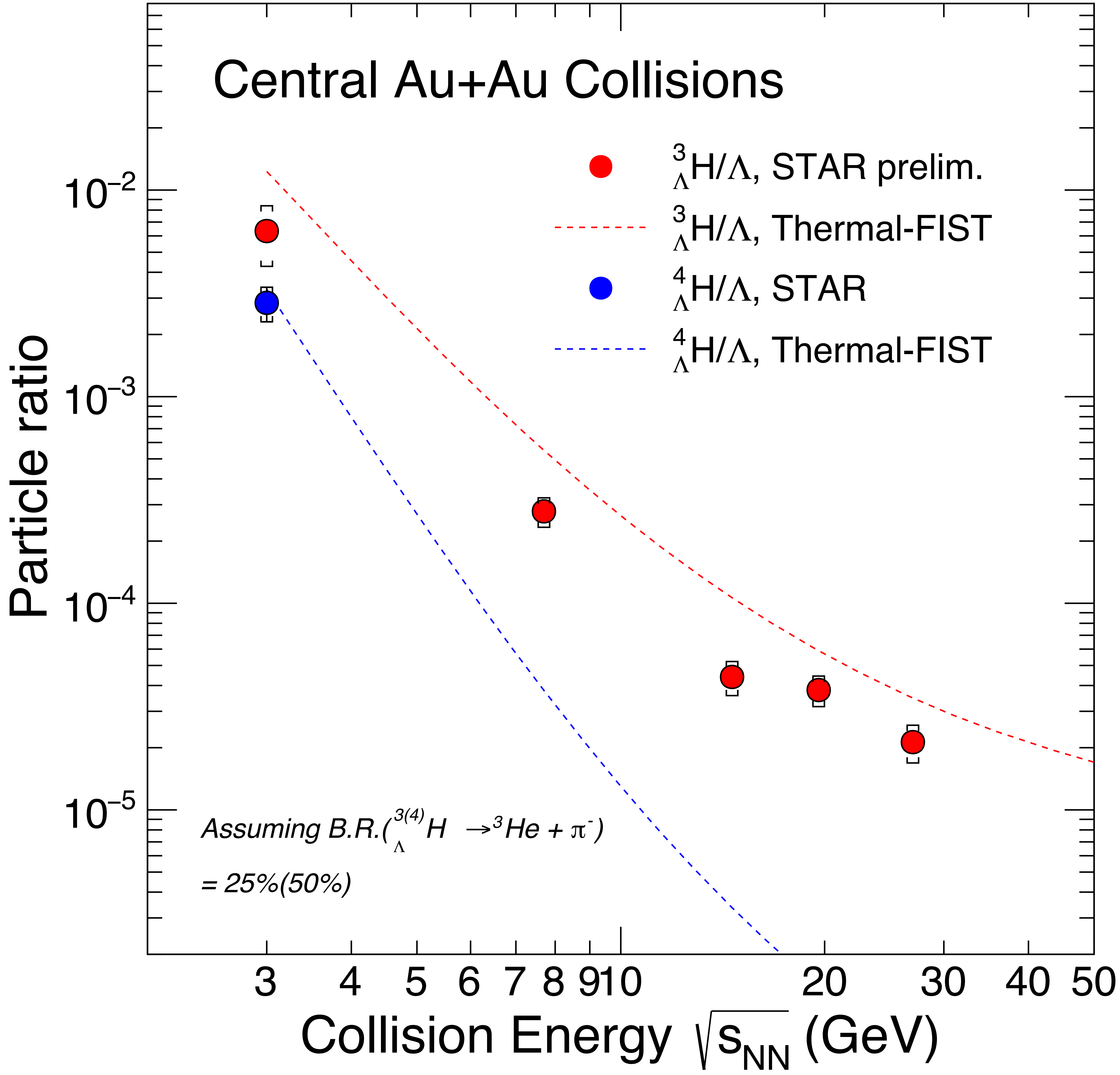
- $S_4 \approx 4\, S_3$

$${}^{4}_{\Lambda}\mathrm{H}^*(1^+) \rightarrow \gamma$$

$${}^{4}_{\Lambda}\mathrm{H}^*(1^+) \rightarrow {}^{4}_{\Lambda}\mathrm{H}(0^+)$$

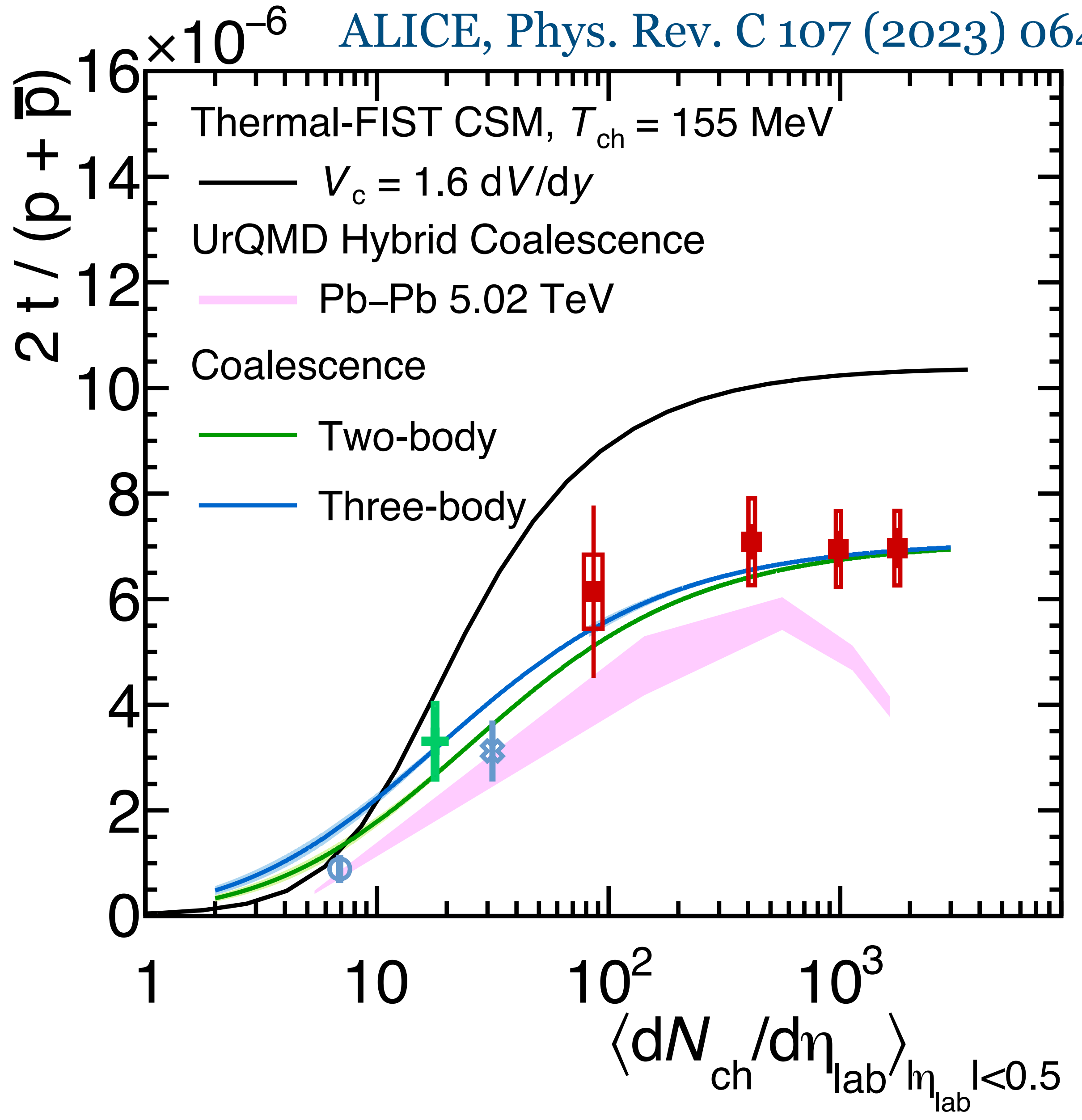
Supports **creation** of **excited hypernuclei**

Thermal Model Comparisons

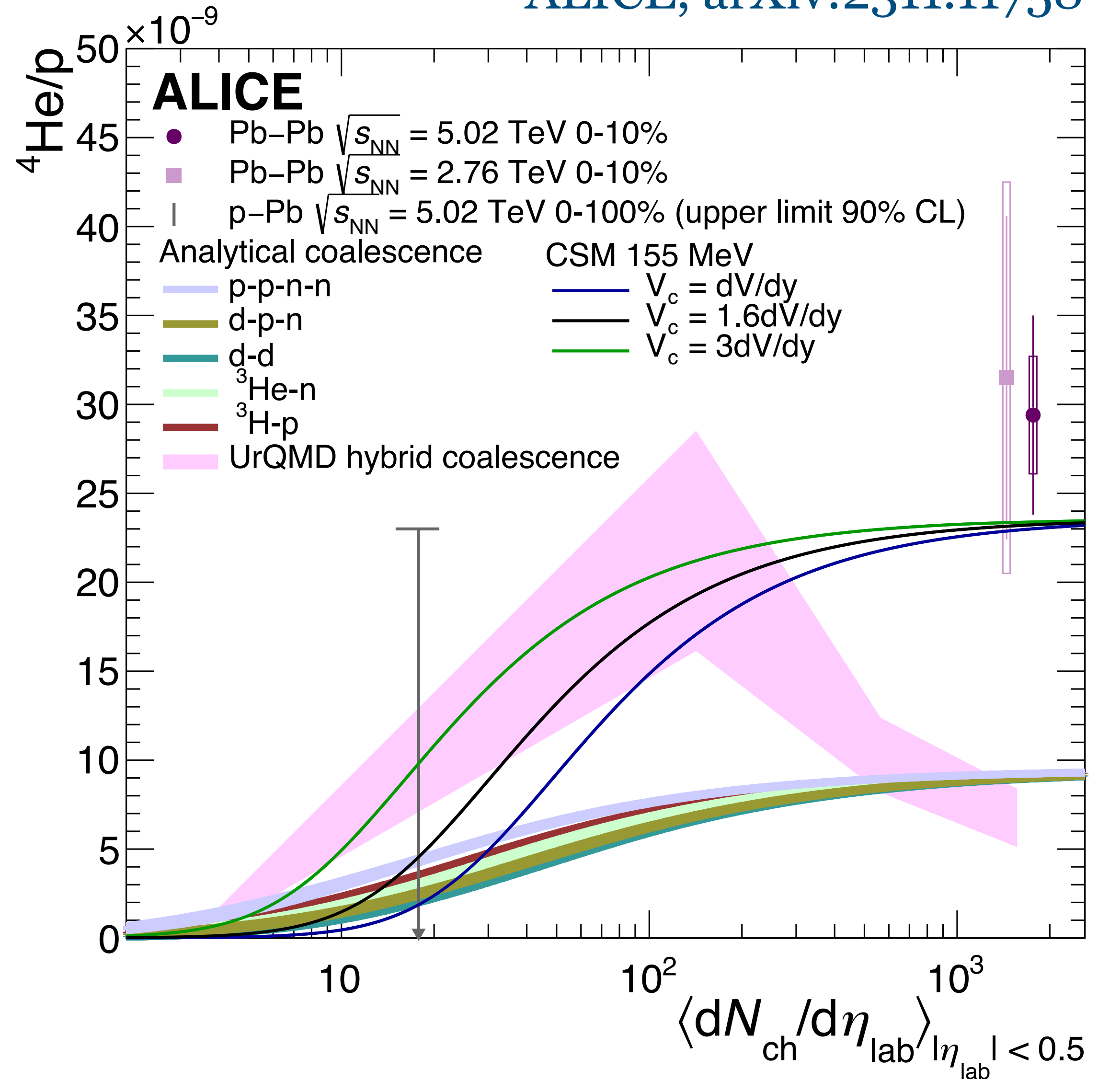


- The thermal model cannot describe t or $^{3}_{\Lambda}\mathrm{H}$, but can describe d and $^{4}_{\Lambda}\mathrm{H}$
- At 5.02 TeV, thermal model apparently cannot describe t or $^{3}\mathrm{He}$, but can describe $^{4}\mathrm{He}$

ALICE, Phys. Rev. C 107 (2023) 064904

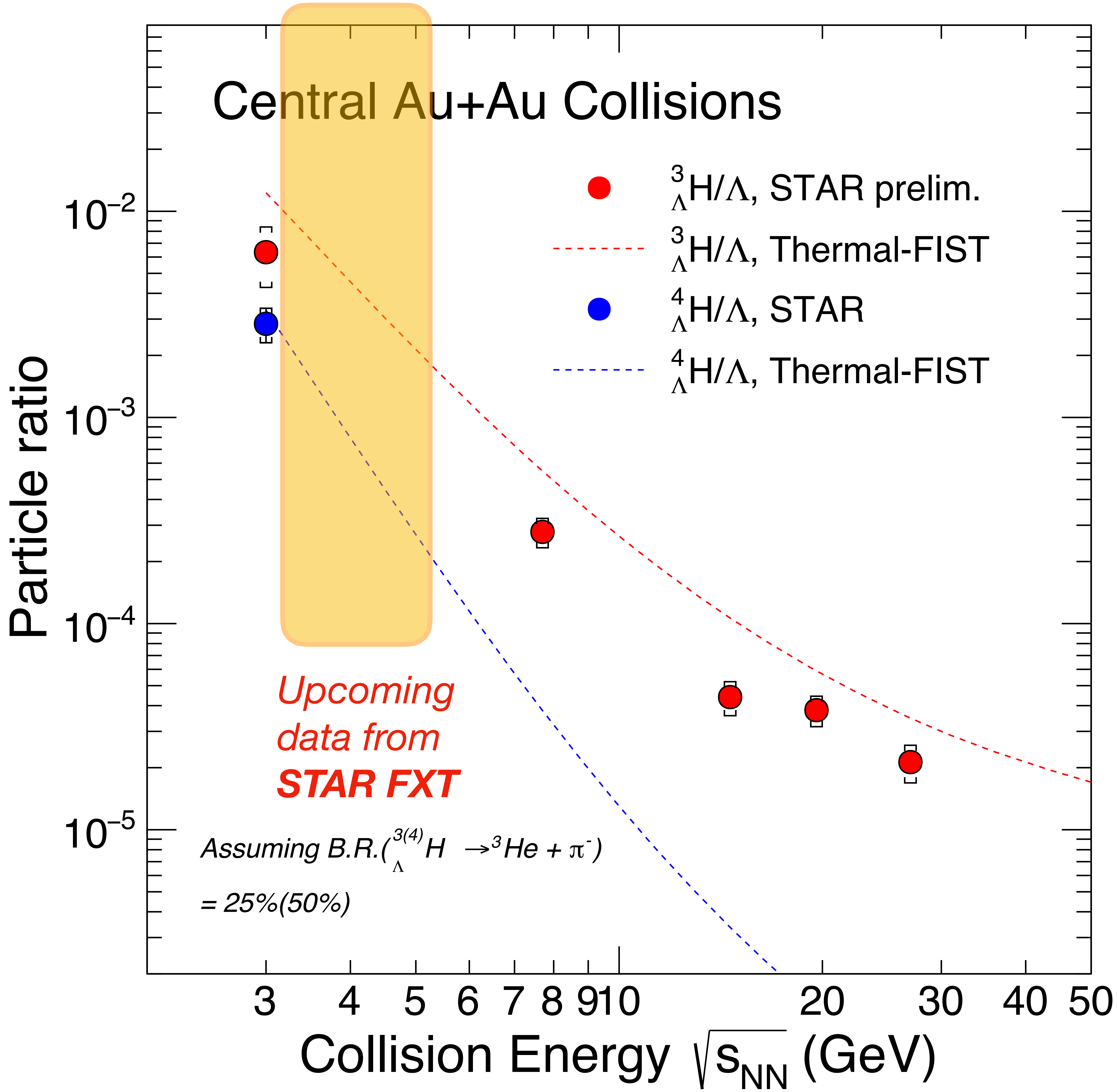


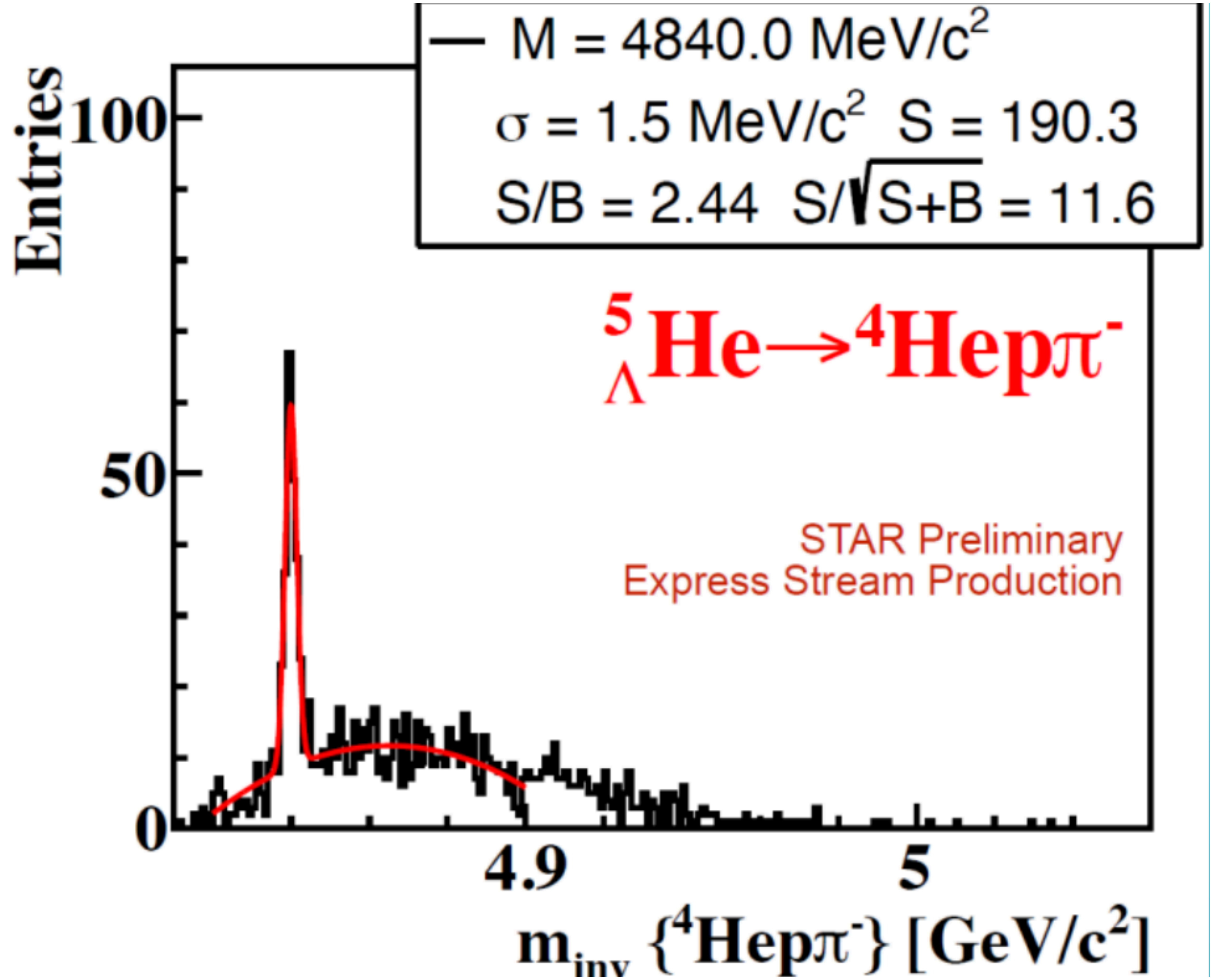
ALICE, arXiv:2311.11758



Is it a coincidence that thermal model works for A=4 but not A=3?

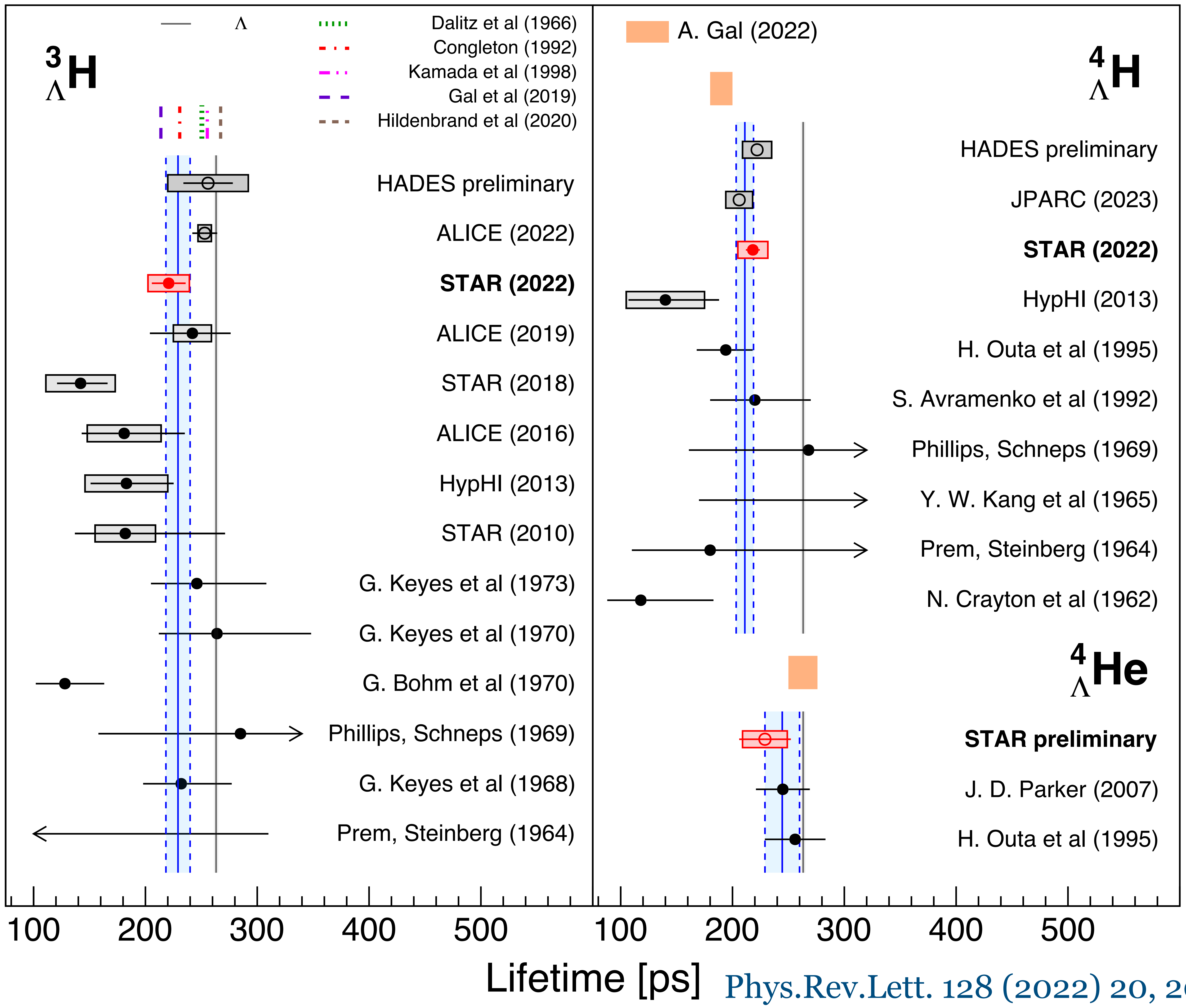
Thermal Model Comparisons



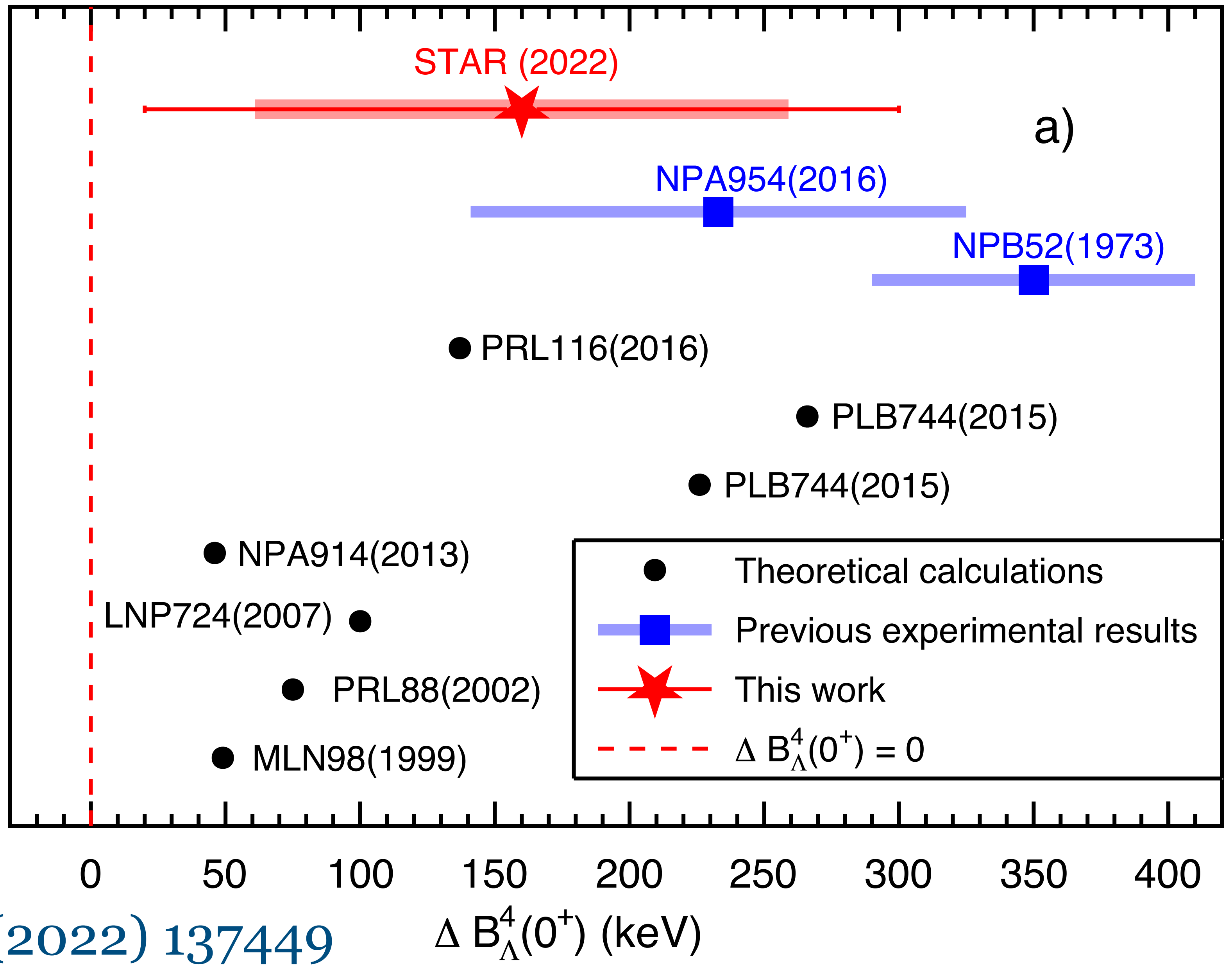


Is it a coincidence that thermal model works for A=4 but not A=3? More data in the near future

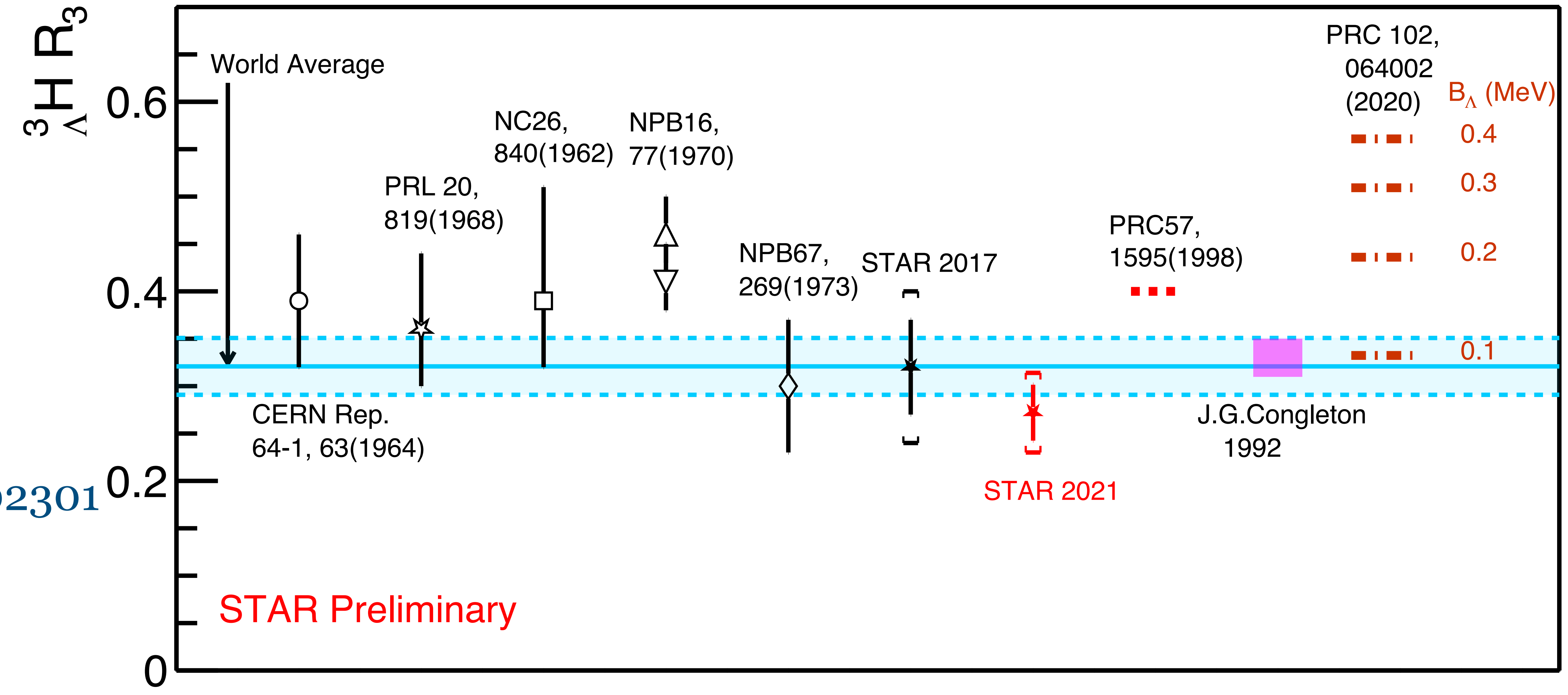
Aside: Hypernuclei Lifetime, Branching Ratio and Binding Energy



Phys.Rev.Lett. 128 (2022) 20, 202301



Phys. Lett. B 834 (2022) 137449



BES-II data improves our understanding of hyperrnuclei structure

Summary II

- We have shown comprehensive measurements of the **collision energy dependence of $^{3}_{\Lambda}H$ production** in Au+Au collisions and compared with triton production and $^{4}_{\Lambda}H$ yields at 3 GeV
- **Thermal model** systematically **over-predict the triton and hypertriton yield by a factor of ~2** in Au+Au collisions
    - Suggests **dynamics that take place after chemical freeze-out** playing a strong role in nuclei formation
- The **strangeness population factor S_3**, when possible feed-down are considered, is **similar (~0.4)** for data from **low to high collision energy and multiplicity**
- In contrast to A=3 $(t, {}^{3}He, {}^{3}_{\Lambda}H)$, **A=4** $({}^{4}He, {}^{4}_{\Lambda}H)$ yields are **surprisingly consistent** with thermal model
- Branching ratio measurements are important to help minimize the uncertainty in the hypernuclei yields

Summary II

- We have shown comprehensive measurements of the **collision energy dependence of ${}^{3}_{\Lambda}\mathrm{H}$ production** in Au+Au collisions and compared with triton production and ${}^{4}_{\Lambda}\mathrm{H}$ yields at 3 GeV
- Thermal model systematically overpredict the triton and hypertriton yield by a factor of ~2 in Au+Au collisions
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- Branching ratio measurements are important to help minimize the uncertainty in the hypernuclei yields

Very high statistics data are needed!

Can be achieved by

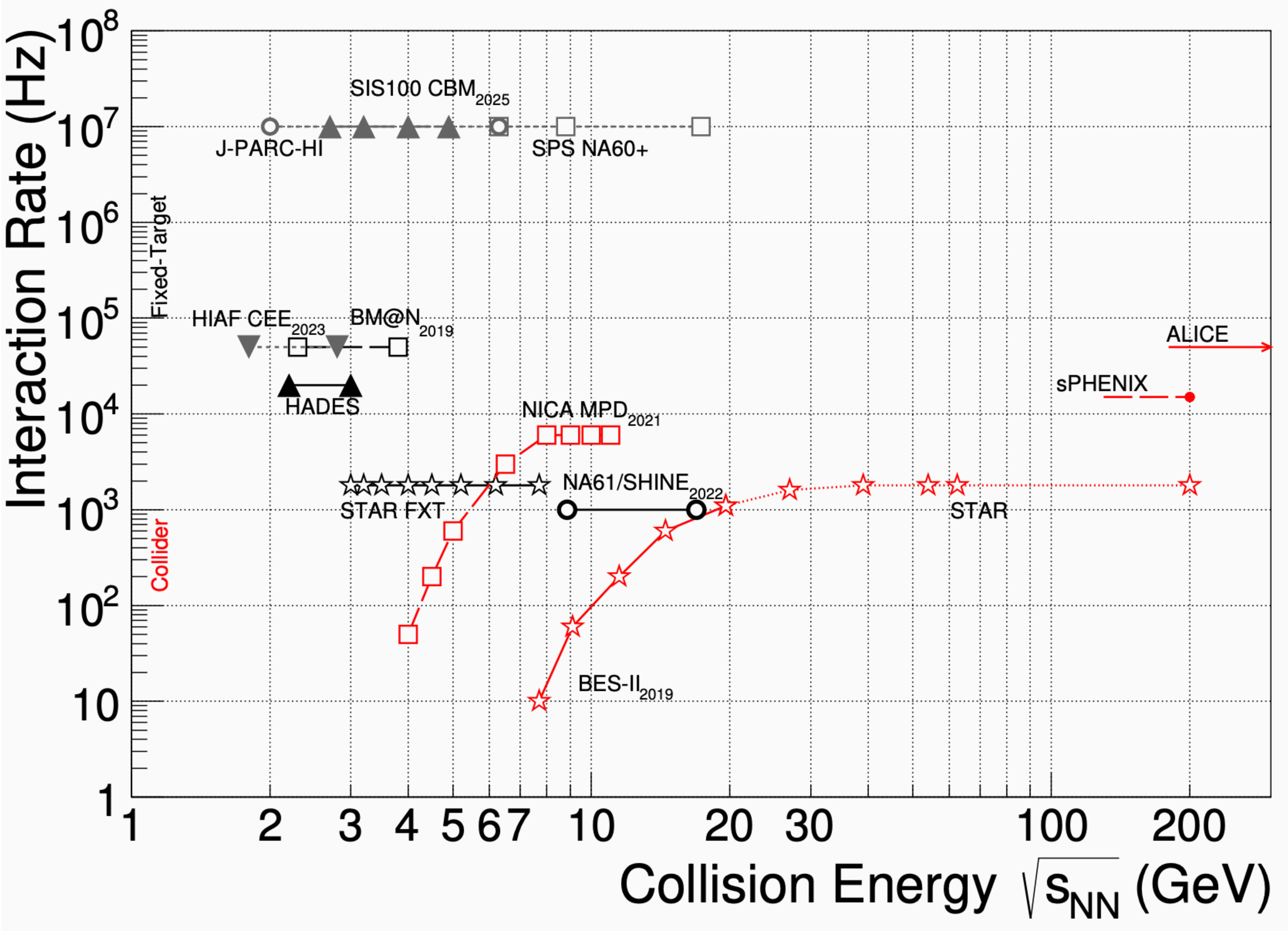
increasing interaction rates

- *ΛΛ, pΞ, etc. interactions necessary to solve the hyperon puzzle*
- *More precise measurements of strangeness population factor are needed*

Outlook: Future Facilities

HIAF experiments	HIAF, China
J-PARC-HI	J-PARC, Japan
NA60+	SPS, CERN, Switzerland
CBM	SIS100, GSI, Germany

Interaction rates up to 10MHz!!

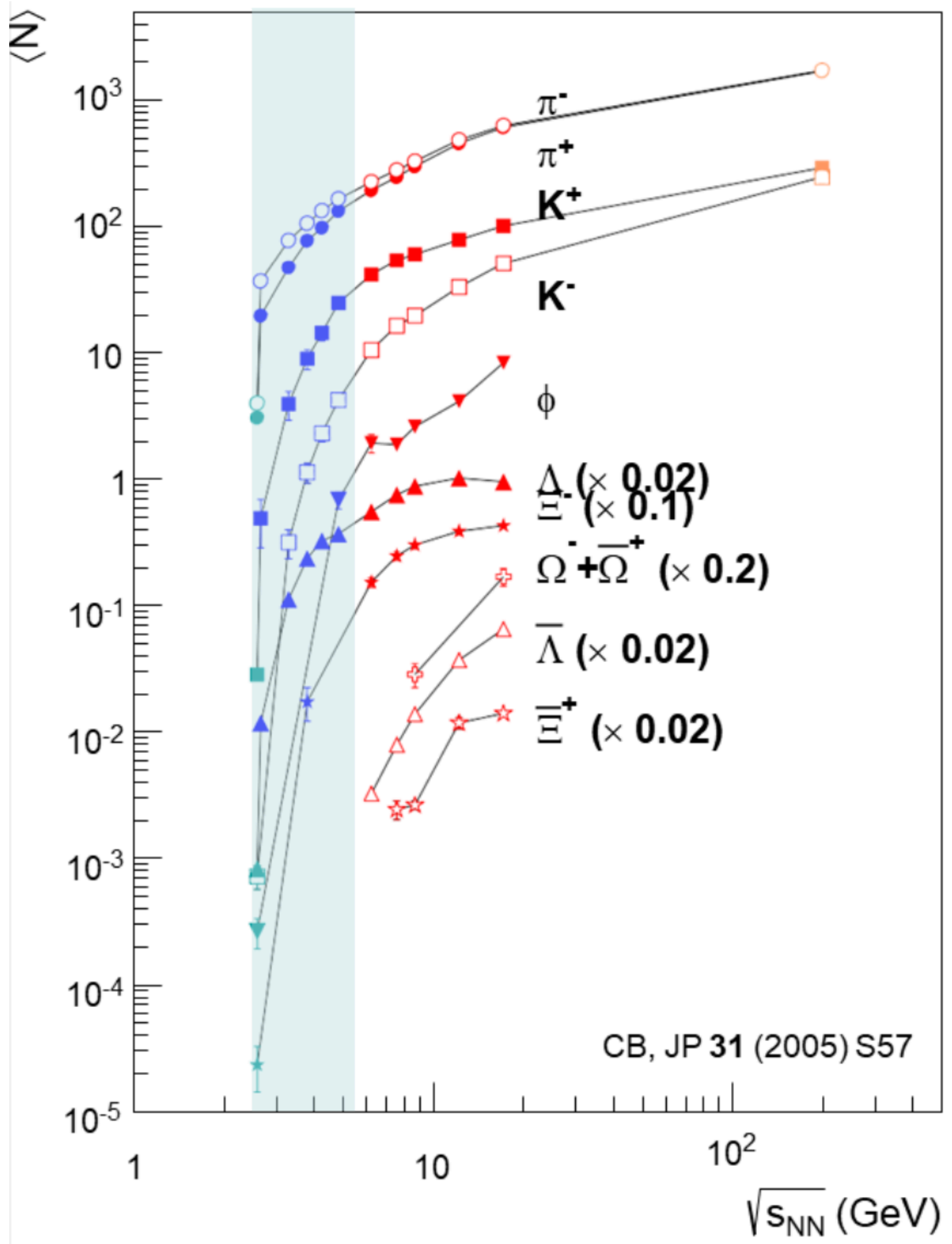


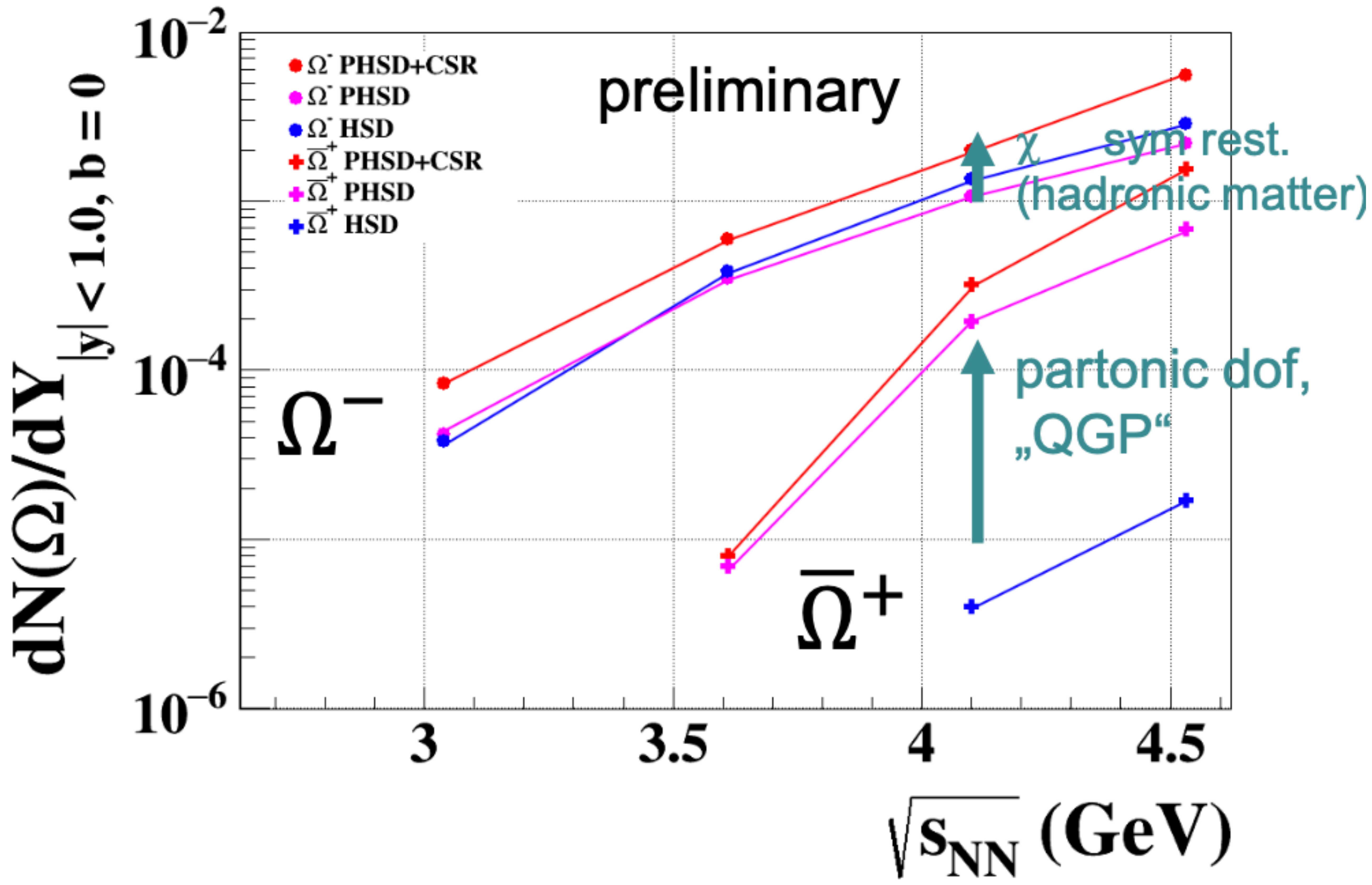
T. Galatyuk, Nucl. Phys. A 982 (2019) 163

NA60+ LoI: arXiv:2212.14452

Outlook: Strange Hadrons

- **<u>Sub-threshold strange hadron production to study the EoS at high baryon density</u>**





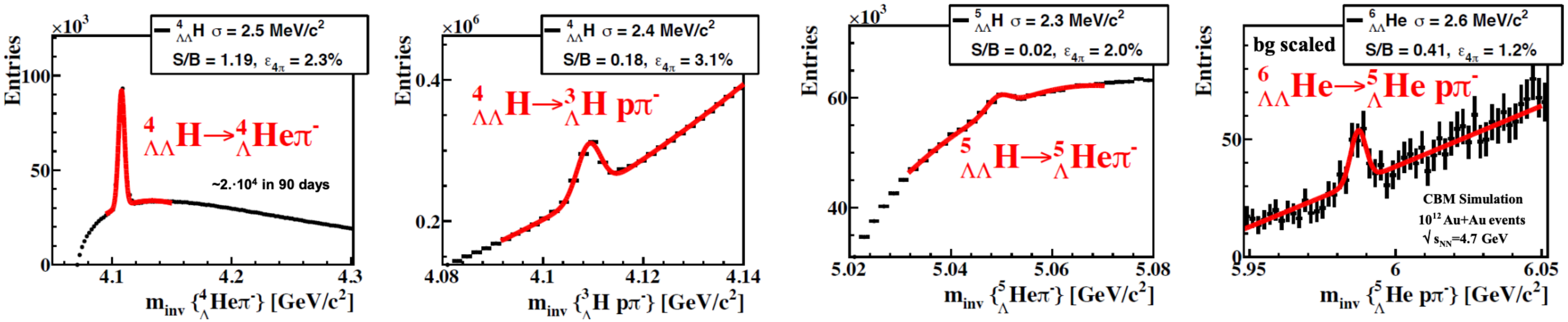
- Measurement beneath threshold are very scarce

W. Cassing, E. Bratkovskaya et al., Phys.Rev. C93 (2016), 014902

Outlook: Hypernuclei

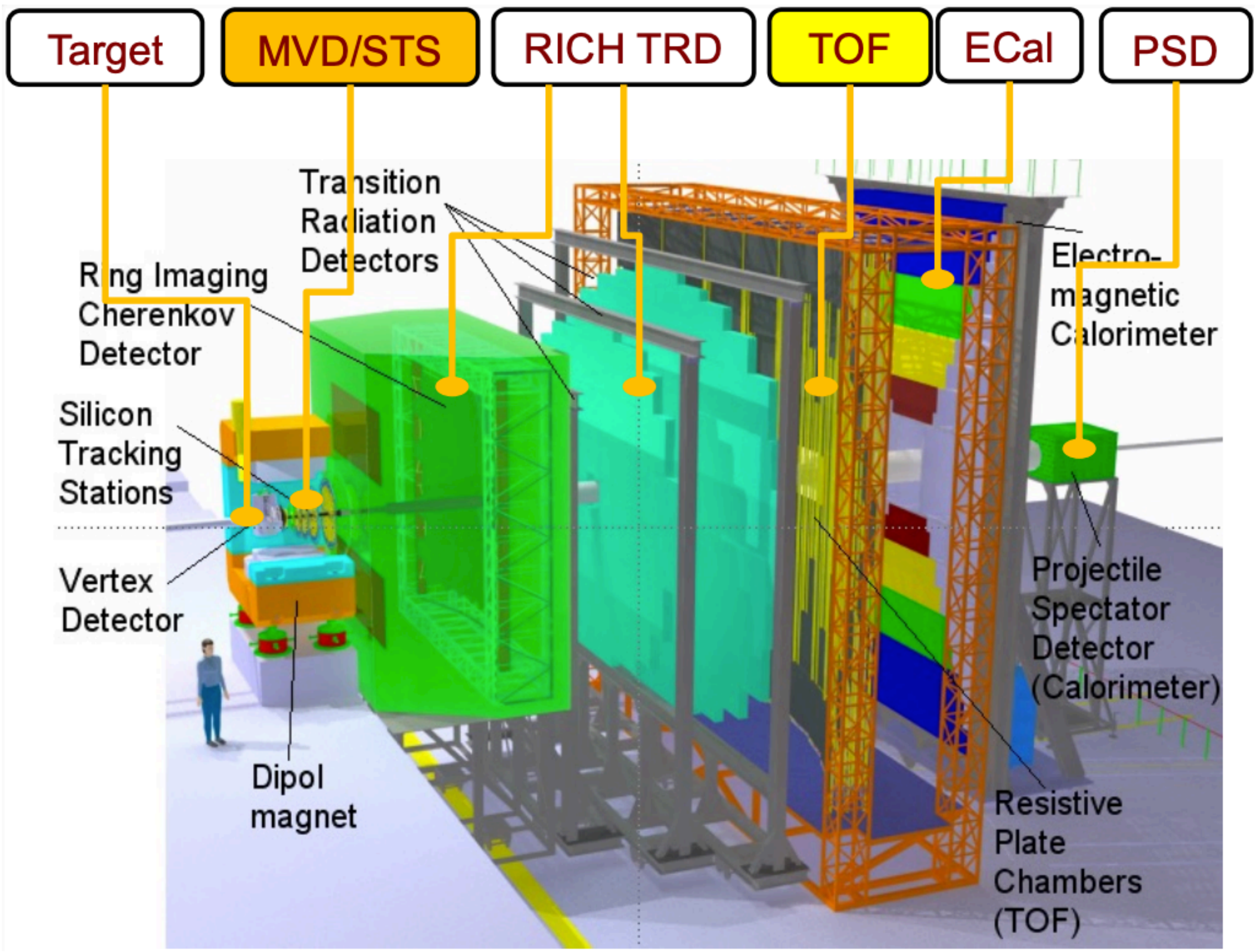
- **Hypernuclei Production mechanisms**
  - A>4 hypernuclei may give further insights

- **Hyperon interactions possibly relevant for neutron stars**
  - ΛΛ interaction: accessible with ΛΛ-hypernuclei
  - ΛN interaction in neutron-rich matter: accessible with neutron rich Λ-hypernuclei (e.g. ${}^{6}_{\Lambda}H$)



I. Vassiliev, CBM simulation

Compressed Baryonic Matter (CBM)



CBM (2028*-)

- $\sqrt{s_{NN}}$=2.5-4.9 GeV Au+Au
- Interaction rates up to 10MHz
- Gives access to rare probes

*To be confirmed

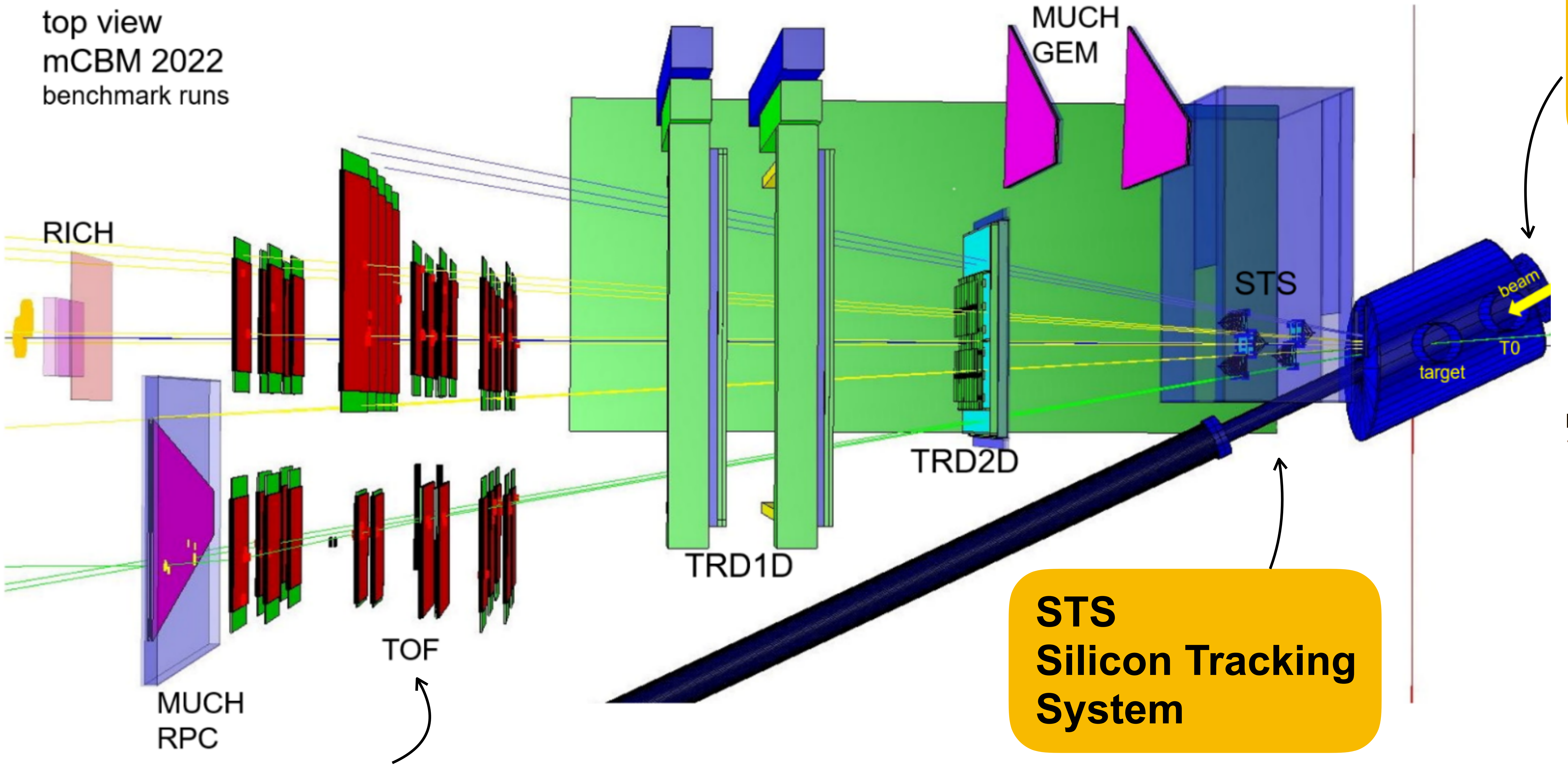
- Ongoing preparations for beamtime:
  1. FAIR Phase 0 @ STAR (2018-)
  2. mCBM (2017-)

mCBM (2017-)

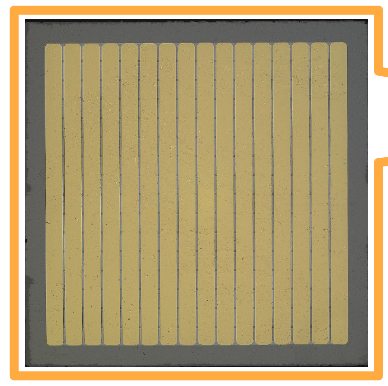
- Precursor experiment and demonstrator
  - Comprises prototypes/pre-series components of CBM detector subsystems

- Primary objectives:
  - To test detector prototypes and commission the triggerless streaming DAQ system
  - To develop, optimize and demonstrate online track and event reconstruction and event selection algorithms

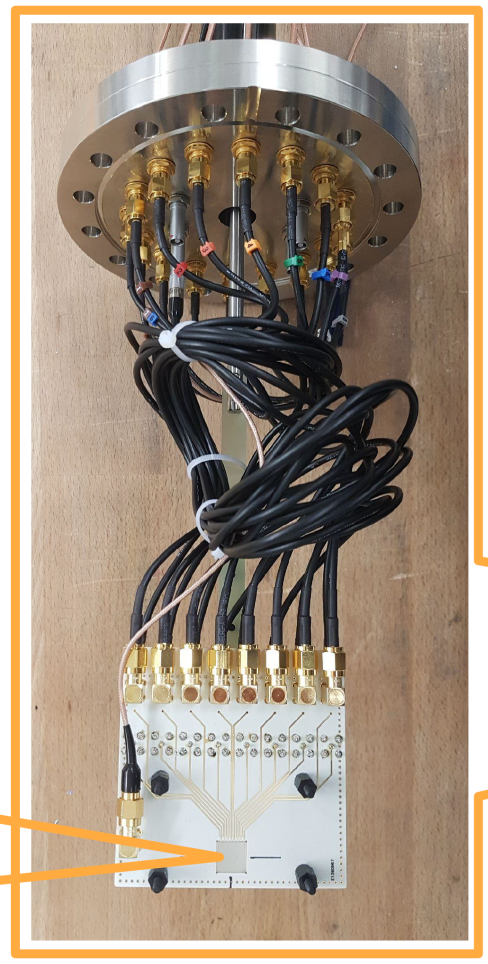
mCBM campaign 2022



**T0
Diamond
Counter**



New 10 mm x 10 mm x 80 μm
16-channels pcCVD diamond sensor

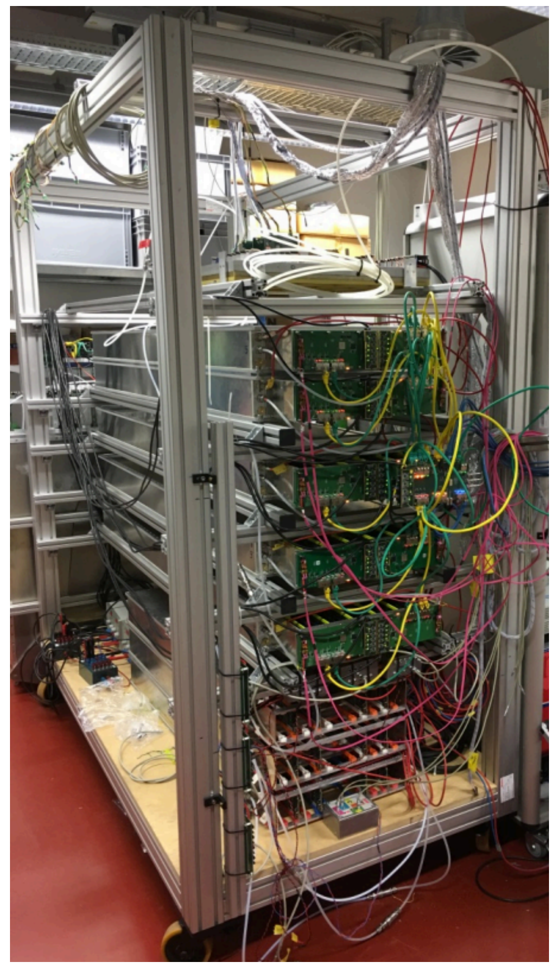


Diamond interface PCB
with pneumatic drive

15

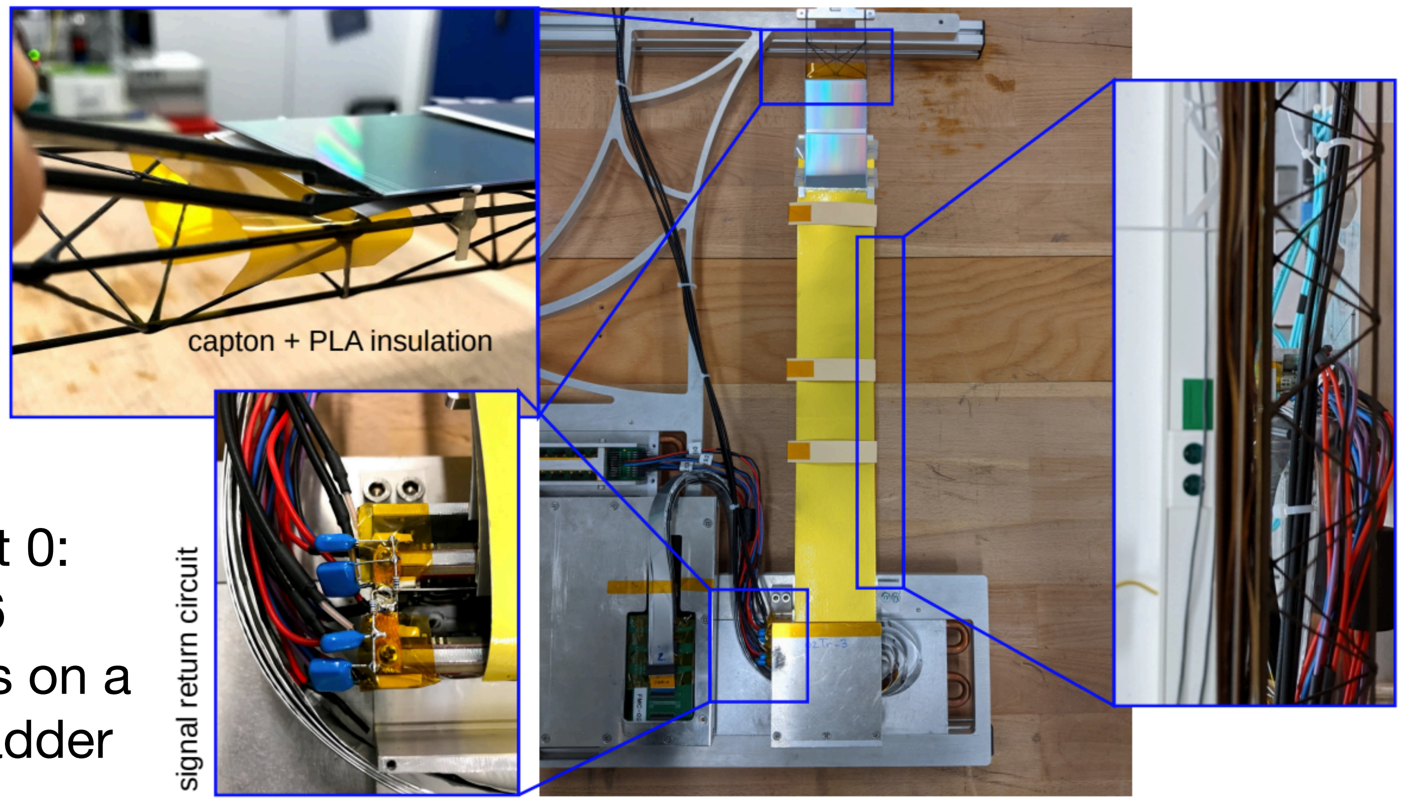
**STS
Silicon Tracking
System**

**TOF
Resistive Plate
Chambers**



Cosmics runs with
resistive plate
chambers in
Heidelberg

STS unit 0:
Two 6x6
modules on a
single ladder

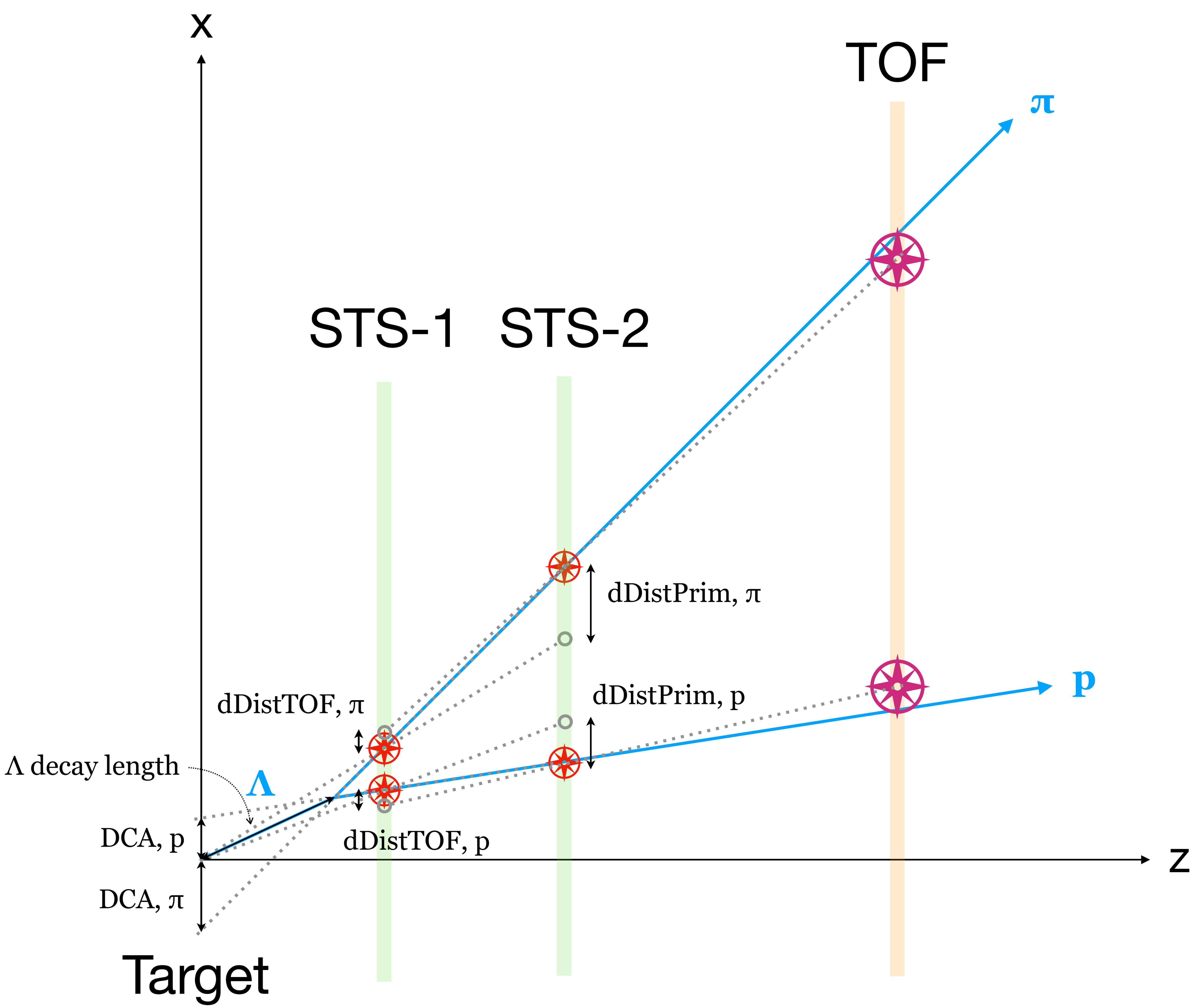


Benchmark runs 2022

Ni + Ni, T = 1.93 AGeV
May 26, 2022, total run duration: 5h 55m
avg. collision rate: **400kHz**
avg. data rate 1.5 GB/s to disk, 32 TB tsa files

Au + Au, T = 1.23 AGeV
June 17 - 18, 2022, total run duration: 34h 33m
avg. collision rate: **200 - 300kHz**
avg. data rate 1.4 - 2.2 GB/s to disk, 180 TB tsa files

Λ reconstruction from mCBM



- Challenge: No B-field or PID!

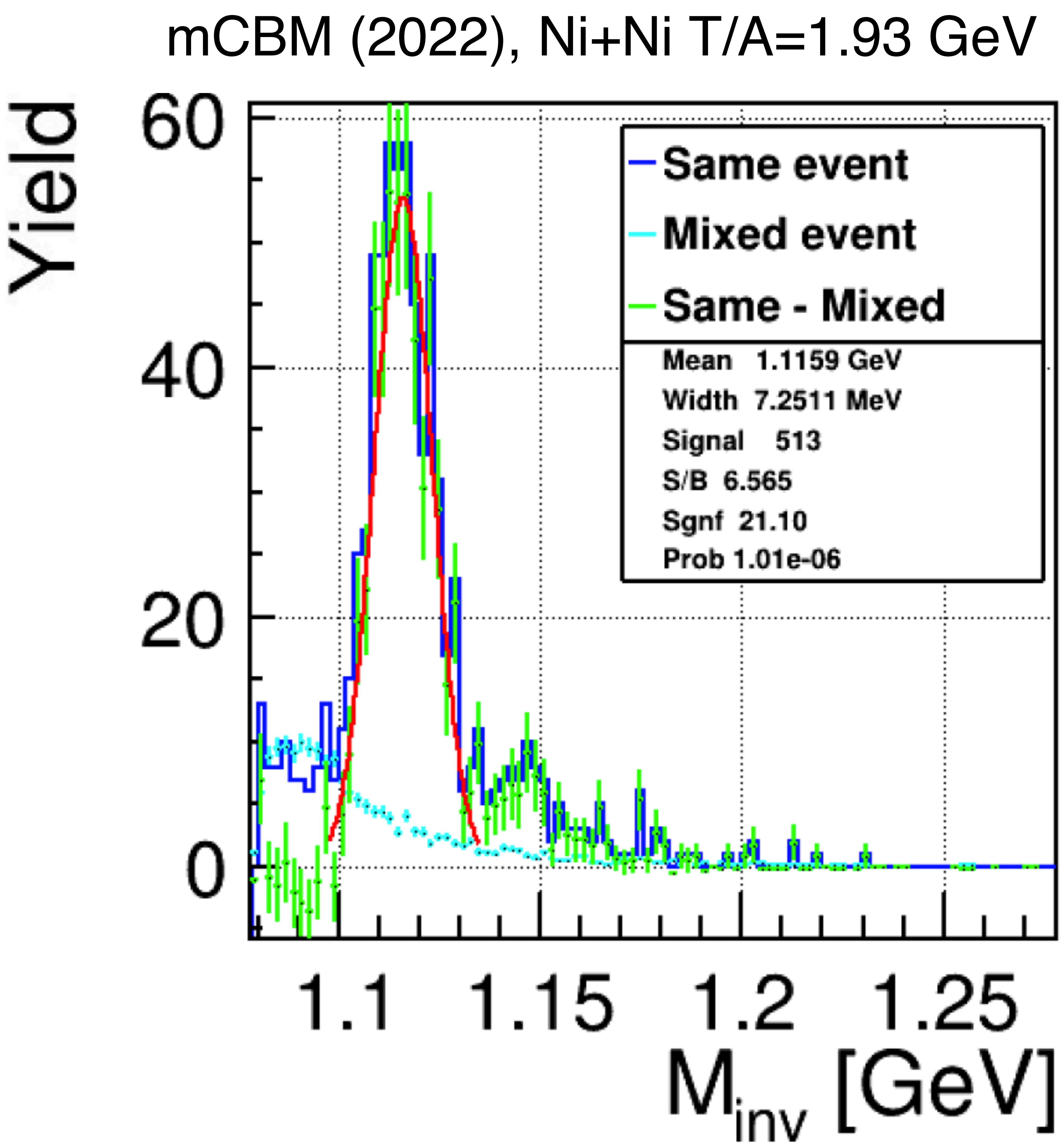
Calibration and alignment

- TOF calibration: provides accurate velocity (momentum) measurement
- Global alignment: accurate description of decay topology to reject primary backgrounds

Particle identification:

- Daughter protons and pions identified according to decay topology

Λ reconstruction from mCBM



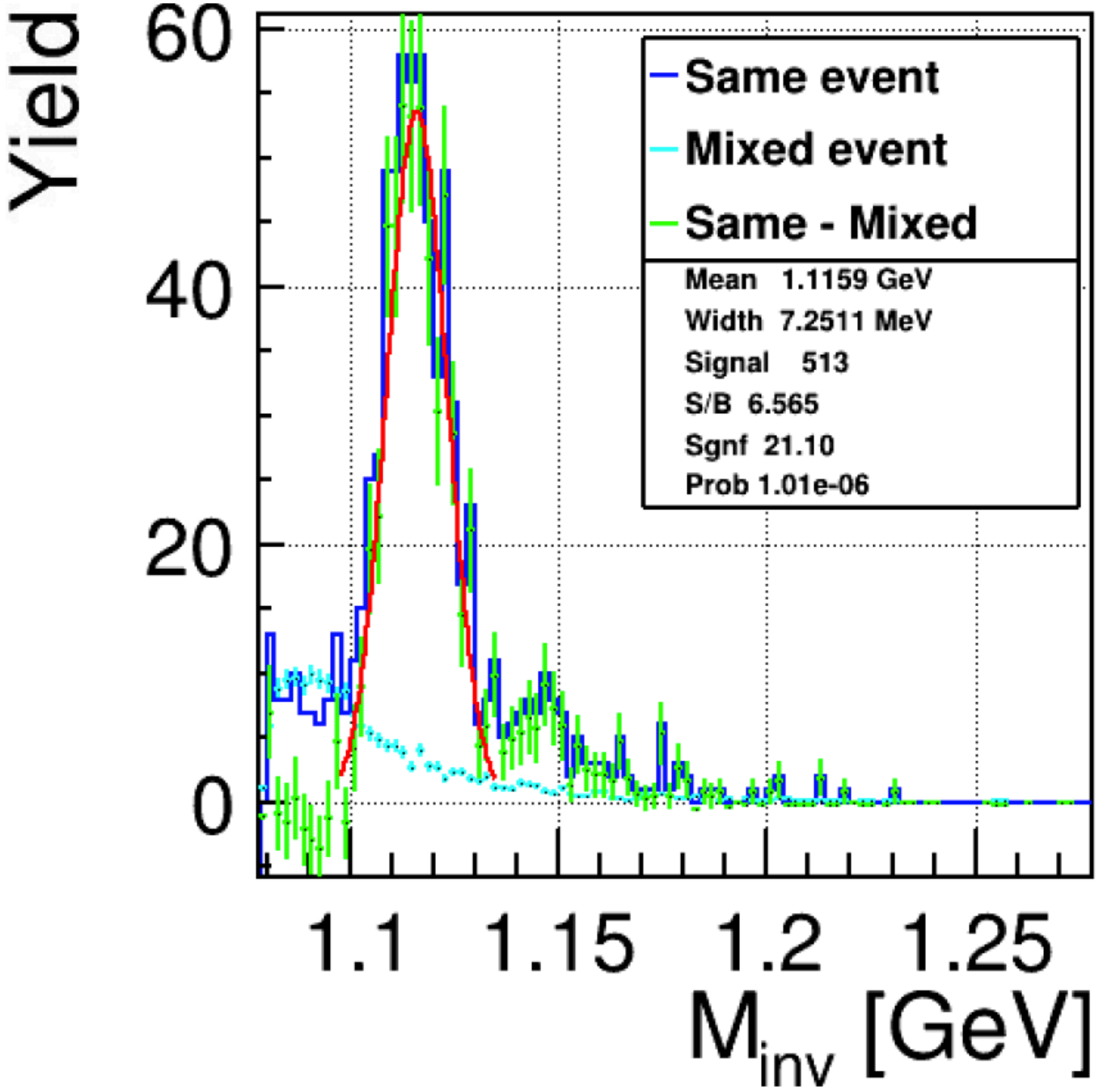
- mCBM: promising testbed for hardware and software
    - Detector alignment and calibration
    - KF Particle Finder application
    - Methods for efficiency correction
    - Methods for signal optimization

Data: run 2391, May 26, 2022, 03:19 - 05:16 CET, **duration 1:57h**
~5×10^7 ions per spill, 10s spill, 400 - 500 kHz collision rate

Clear Λ signal reconstructed from Ni+Ni data taken by mCBM in 2022

Λ reconstruction from mCBM

mCBM (2022), Ni+Ni T/A=1.93 GeV



- mCBM: promising testbed for hardware and software

Granted proposal (G-22-00110)

	Year	Objective	Projectile	Intensity per spill	Extraction	User type	Shifts
(1) →	2023 2024	high-rate detector studies	ions 1 - 2 AGeV, preferably: Au, Pb, U	10^7 - 10^9	slow, 10 s	secondary	6
(2) →	2023 2024	commissioning for benchmark run	ions 1 - 2 AGeV, preferably: Ni 1.93 AGeV	10^7 - 10^8	slow, 10 s	secondary	3
(3) →	2023 2024	benchmark runs, Λ production excitation function	Ni 1.93, 1.58, 1.23, 1.0 AGeV	10^8	slow, 10 s	main	~~18~~ 9
(4) →	2024 2025	high-rate detector studies	ions 1 - 2 AGeV, preferably: Au, Pb, U	10^7 - 10^9	slow, 10 s	secondary	6
(5) →	2024 2025	commissioning for benchmark run	ions 1 - 2 AGeV, preferably: Ag 1.58 AGeV	10^7 - 10^8	slow, 10 s	secondary	3
(6) →	2024 2025	benchmark runs, Λ production excitation function	Ag 1.58, 1.23, 1.0 AGeV	10^8	slow, 10 s	main	~~18~~ 9

- Next year: Develop and demonstrate full data analysis chain for streaming data

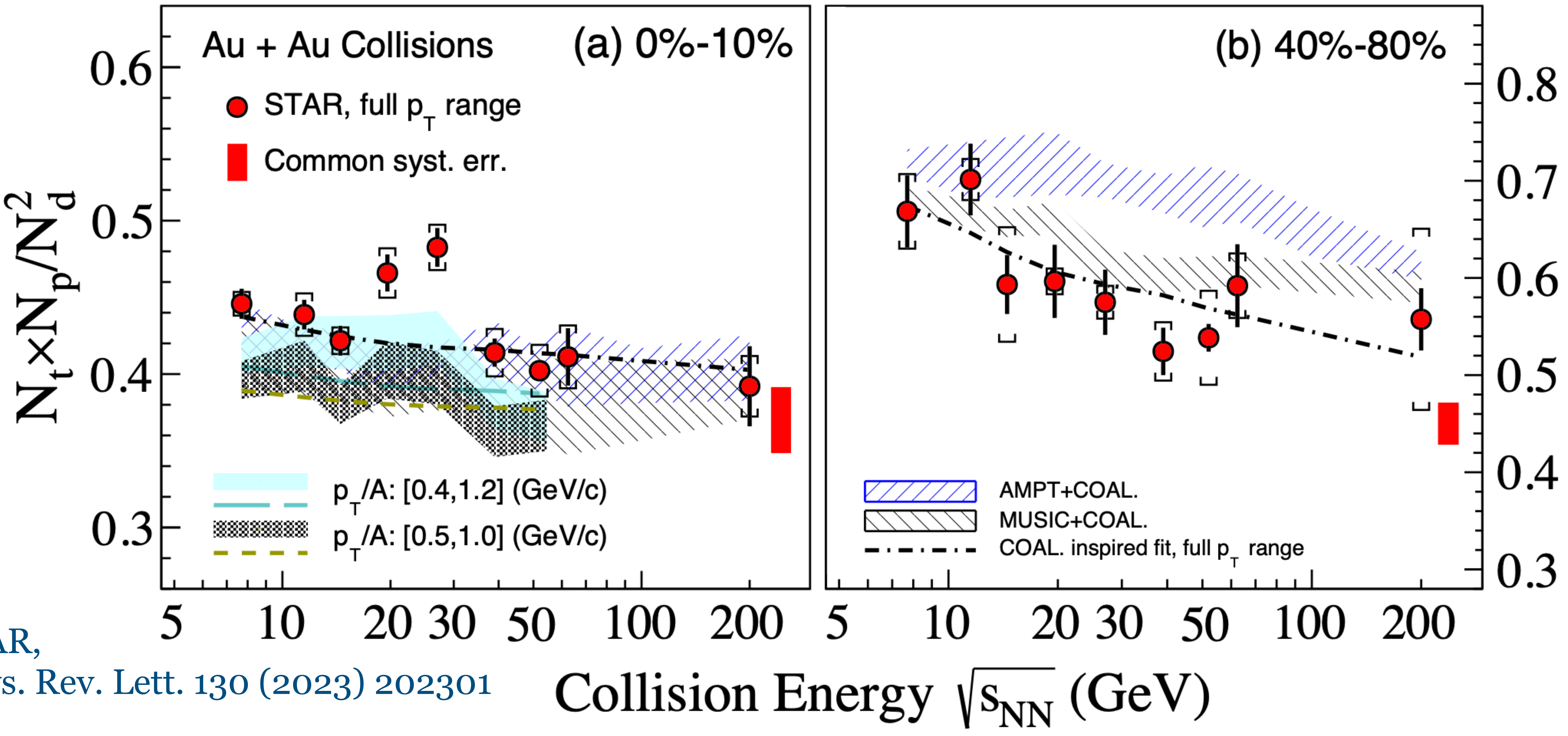
Main Takeaways

- Strange hadron production in 3 GeV collisions likely dominated by hadronic interactions
- Blast-wave analysis possibly suggests a change in EoS
- Further investigation from 3 to 14.6 GeV needed to probe the onset of deconfinement

- Comparison of triton and hypertriton yield data with thermal model suggests dynamics that take place after chemical freeze-out playing a strong role in nuclei formation
- In contrast to A=3 (t, ^{3}He, $^{3}_{\Lambda}$H) , A=4 (^{4}He, $^{4}_{\Lambda}$H) yields are surprisingly consistent with thermal model
- Further investigation of higher mass nuclei will likely give more insight on nuclei production mechanisms

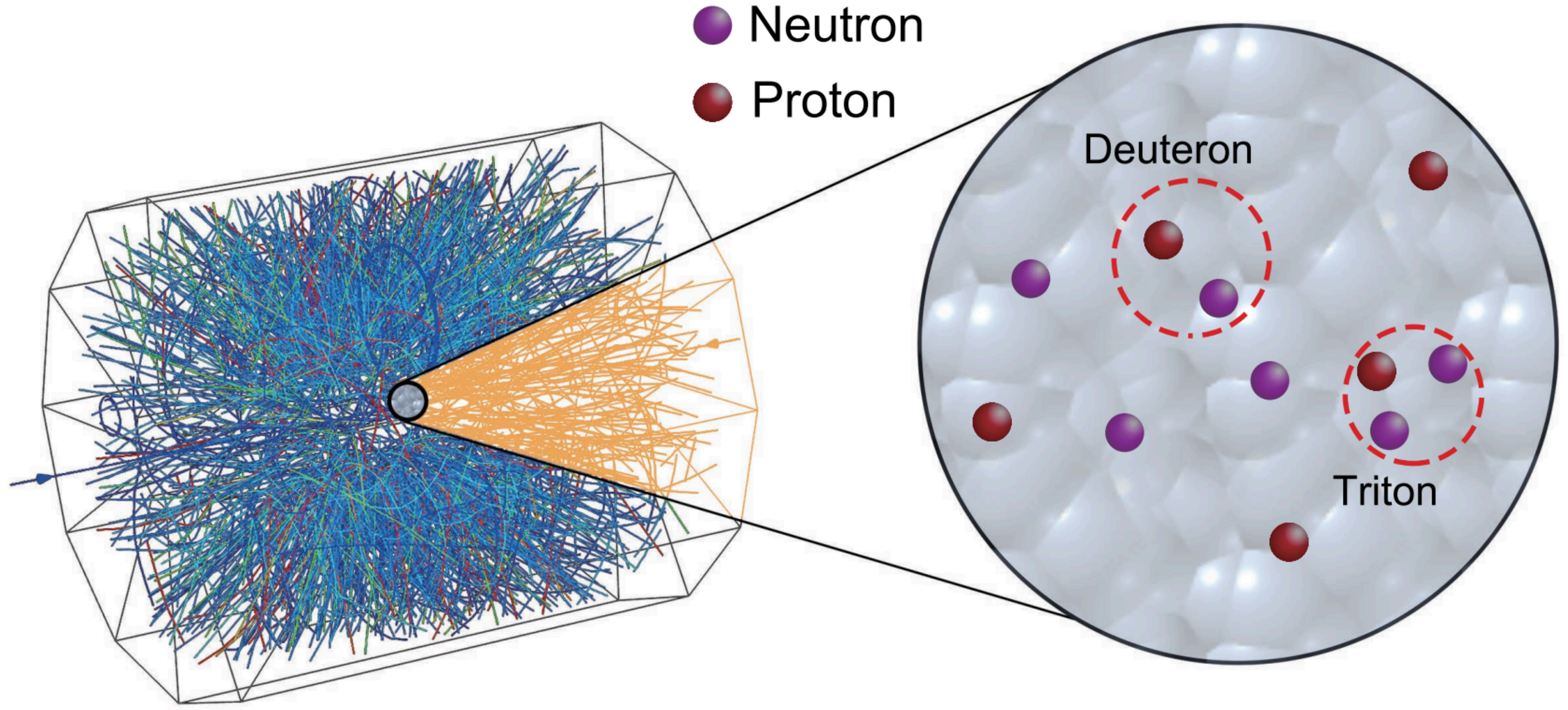
Backup slides follow

Energy Dependence of Nuclear Compound Yield Ratio



STAR,
Phys. Rev. Lett. 130 (2023) 202301

Figure credit: Yige Huang

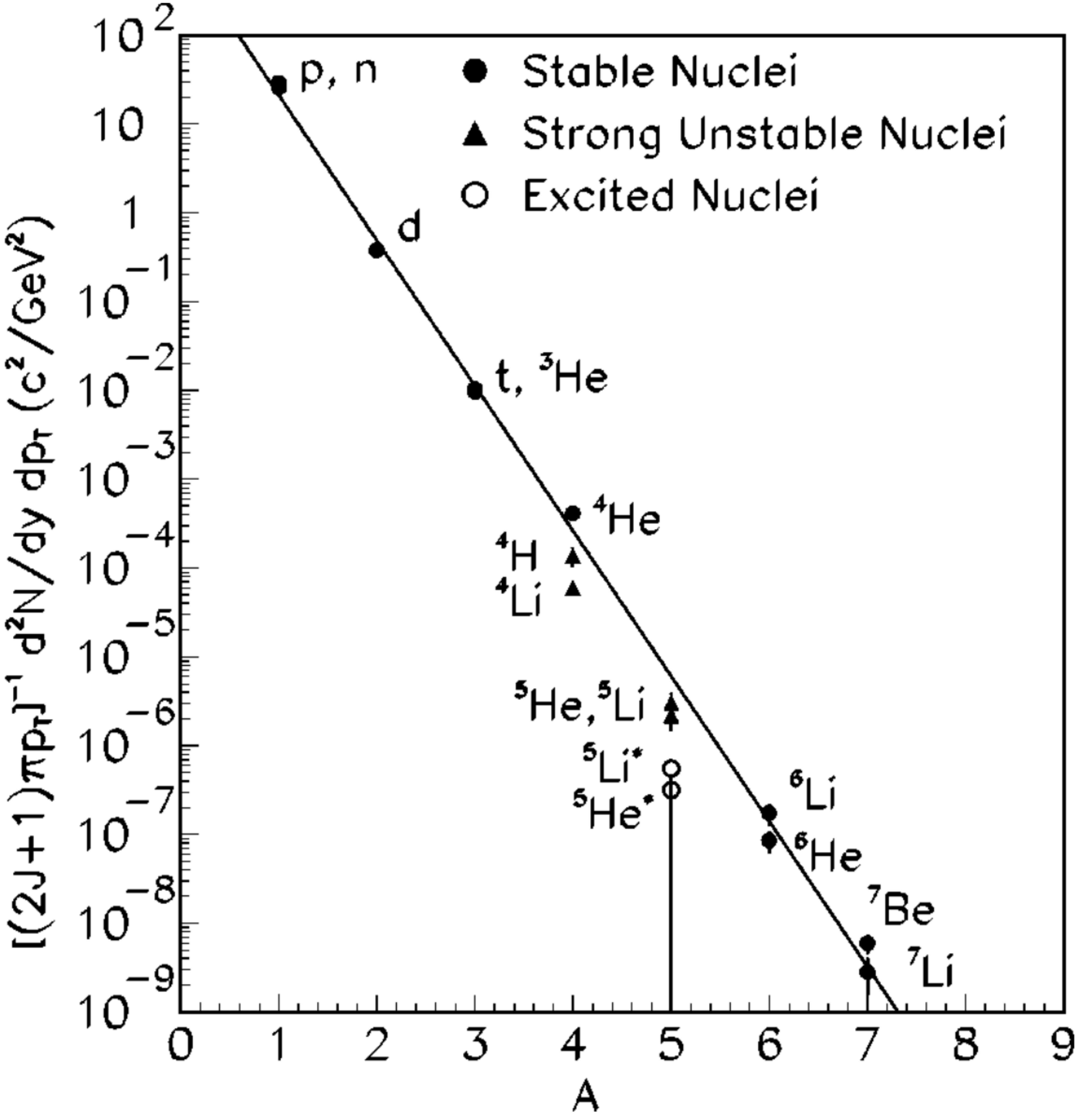


$$\frac{t \times p}{d^2} = g(1 + \Delta n)$$

Phys. Lett. B 781 (2018) 499

- In a coalescence picture, compound yield ratio is sensitive to baryon density fluctuations
  - **In the vicinity of the critical point, density fluctuations become larger**
- In central collisions, non-monotonic behavior around 19.6 and 27 GeV observed with a combined significance of 4.1σ
  - Enhancements decreases with decreasing p_T acceptance

Measurements of Unstable Nuclei from AGS



Suppression of A=4 unstable states compared to ^{4}He ground state

$A=4$	E_x(MeV)	J^π	Decay channels
^{4}H	g.s.	2^-	n(100%)
	0.31	1^-	n(100%)
	2.08	0^-	n(100%)
	2.83	1^-	n(100%)
^{4}He	g.s.	0^+	stable
	20.21	0^+	p(100%)
	21.01	0^-	n(23.8%), p(76.2%)
	21.84	2^-	n(37.3%), p(62.7%)
	23.33	2^-	n(47.3%), p(52.7%)
	23.64	1^-	n(44.5%), p(55.5%)
	24.25	1^-	n(47.0%), p(50.5%), d(2.5%)
	25.28	0^-	n(48.3%), p(51.7%)
	25.95	1^-	n(48.5%), p(51.5%)
	27.42	2^+	n(3%), p(3%), d(94%)
	28.31	1^+	n(47%), p(48%), d(5%)
	28.37	1^-	n(2%), p(2%), d(96%)
	28.39	2^-	n(0.25%), p(0.25%), d(99.5%)
	28.64	0^-	d(100%)
	28.67	2^+	d(100%)
	29.89	2^+	n(0.4%), p(0.4%), d(99.2%)
^{4}Li	g.s.	2^-	p(100%)
	0.32	1^-	p(100%)
	2.08	0^-	p(100%)
	2.85	1^-	p(100%)

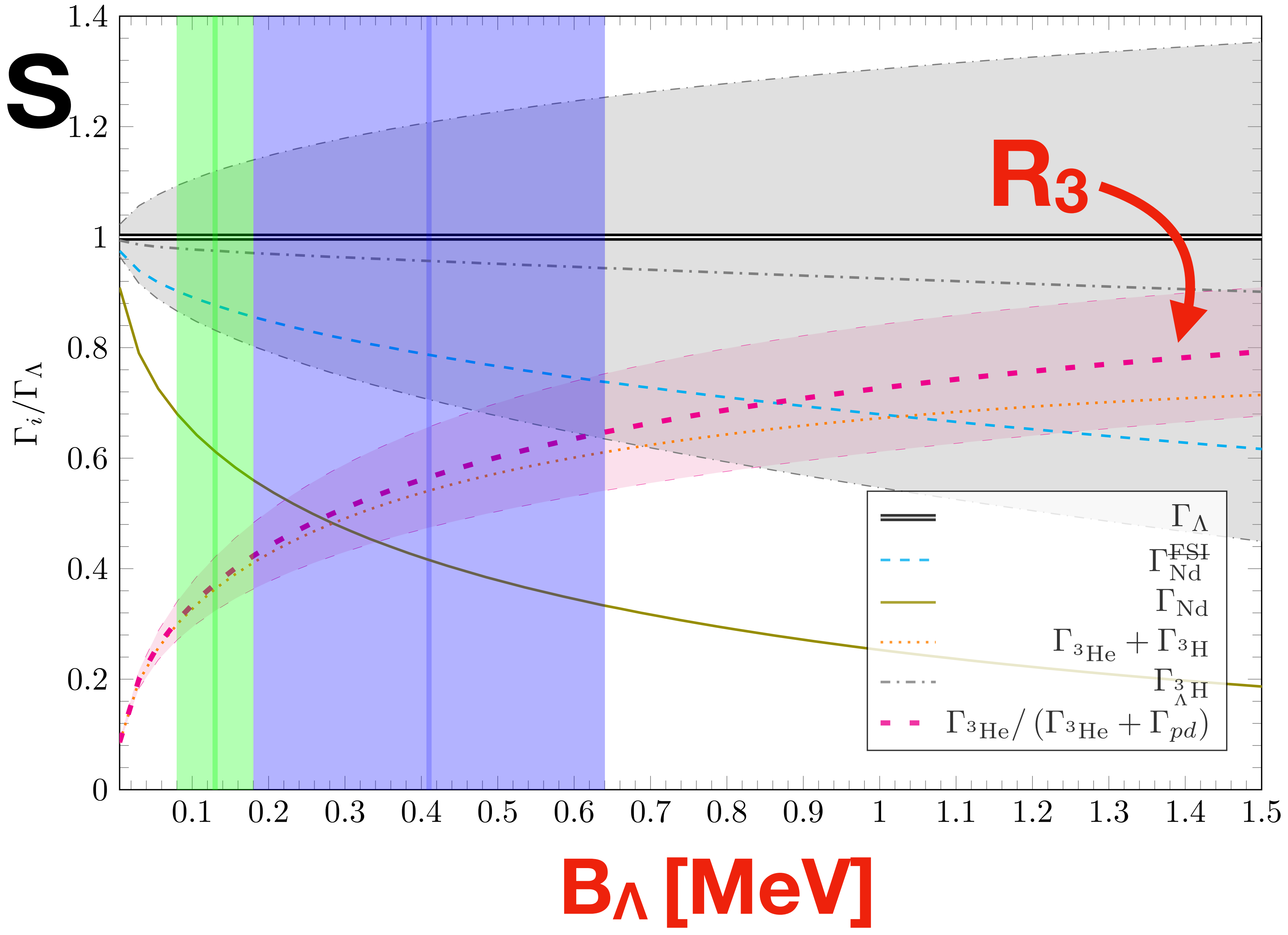
E864, Phys. Rev. C 65 (2002) 014906

Aside: Branching Ratio Measurements

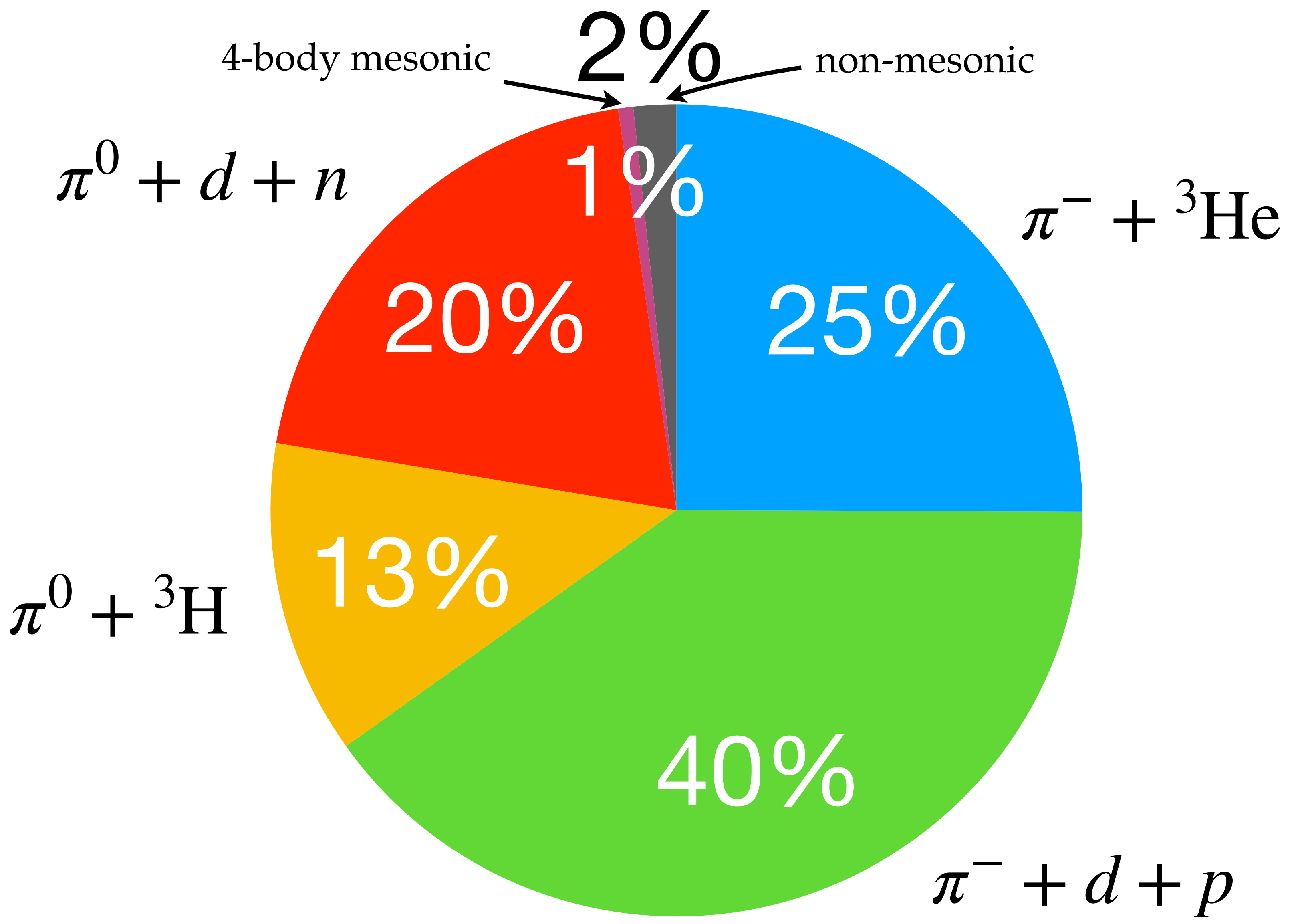
- The $^{3}_{\Lambda}H$ relative branching ratio, R_3, is defined as:

$$R_3 = \frac{B.R.(^{3}_{\Lambda}H \rightarrow {}^{3}He\pi^{-})}{B.R.(^{3}_{\Lambda}H \rightarrow {}^{3}He\pi^{-}) + B.R.(^{3}_{\Lambda}H \rightarrow dp\pi^{-})}$$

- Recent calculations predict a **strong dependence of R_3 on the binding energy** Hildenbrand et al, Phys. Rev. C 102 (2020) 064002
    - Indirect measurement of binding energy and give constraints to its structure
- The 2-body and 3-body mesonic decay channels are expected to contribute ~97% of the total decay rate Kamada et al, Phys. Rev. C 57 (1998) 1595
    - $\pi^{-} : \pi^{0}$ decay rates expected to follow isospin rule (2:1)
    - Give constraints on the absolute branching ratio, crucial for yield measurements



Calculated decay rates vs B_Λ from Hildenbrand et al.



Calculated decay B.R. from Kamada et al.

Aside: Branching Ratio Measurements

- Relative branching ratio:

$$R_3 = \frac{B.R.({}^3_\Lambda H \rightarrow {}^3He\pi^-)}{B.R.({}^3_\Lambda H \rightarrow {}^3He\pi^-) + B.R.({}^3_\Lambda H \rightarrow dp\pi^-)}$$

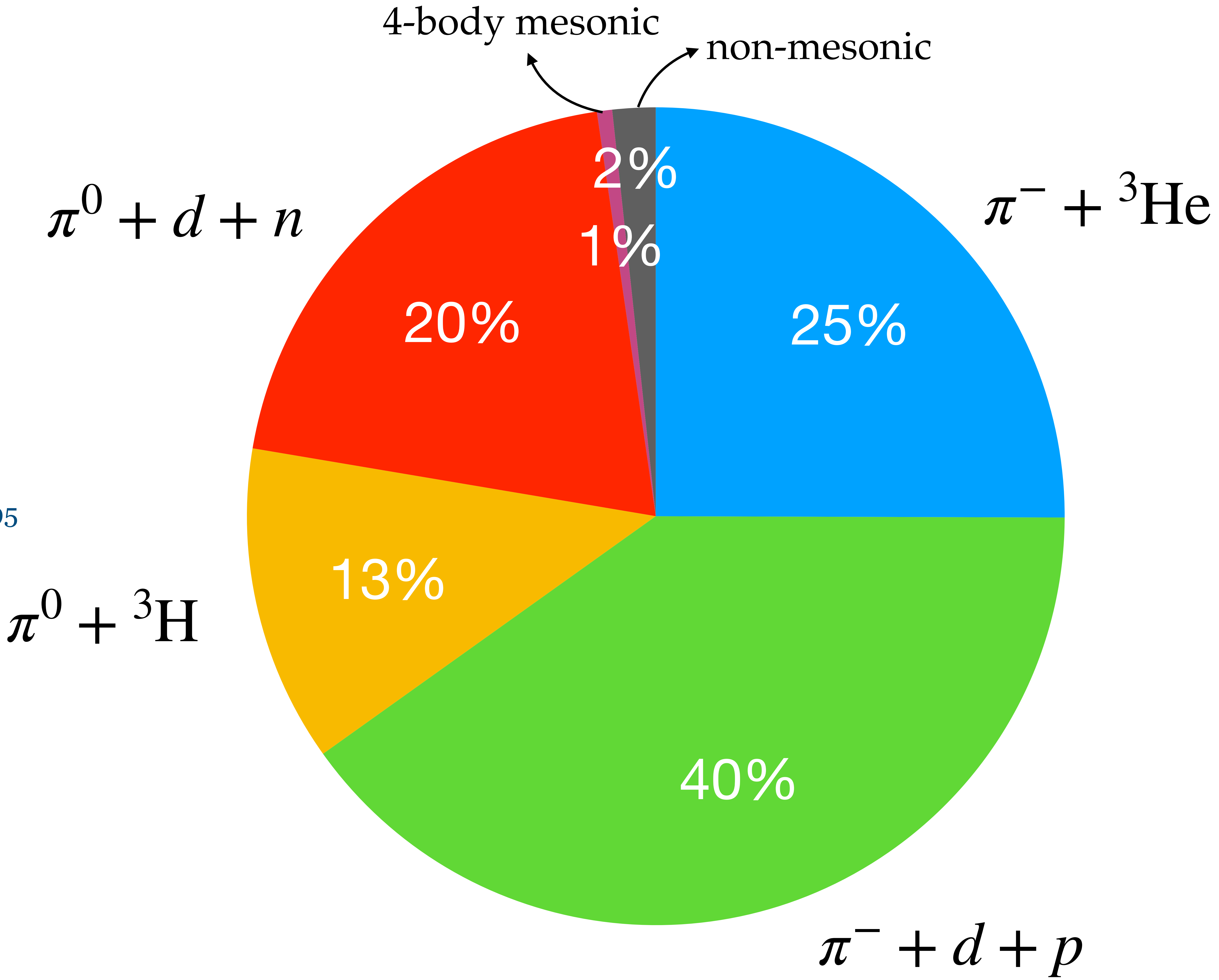
- The 2-body and 3-body mesonic decay channels are expected to contribute ~97% of the total decay rate

Kamada et al, Phys. Rev. C 57 (1998) 1595

- $\pi^- : \pi^0$ decay rates expected to follow isospin rule (2:1)

- Suggested to be sensitive to the radius of the hypertriton Hildenbrand et al, Phys. Rev. C 102 (2020) 064002

Calculated decay B.R. from Kamada et al

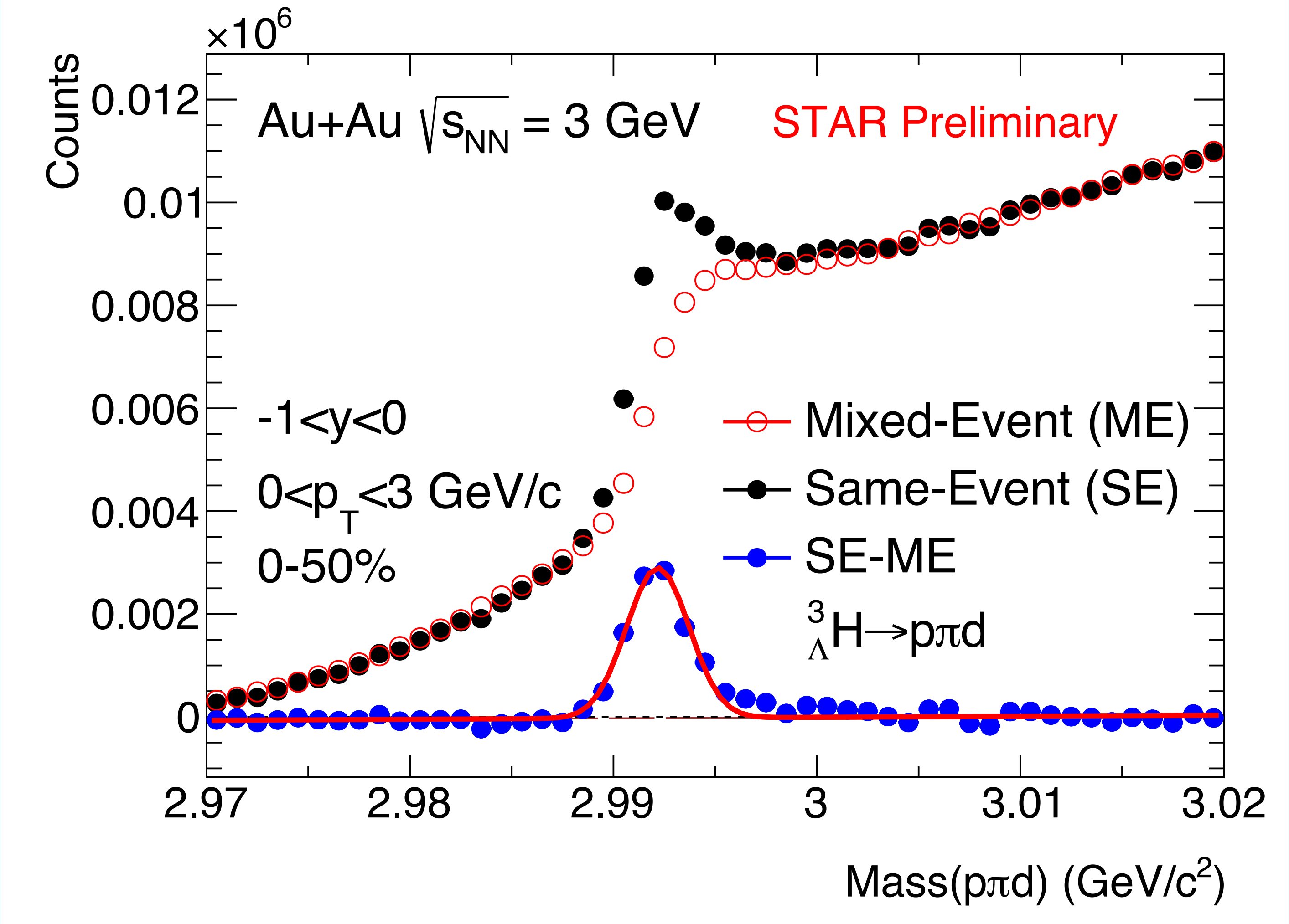


- Give constraints to **the absolute branching ratio**, crucial for yield measurements

${}^{3}_{\Lambda}$H reconstruction via 3-body decay

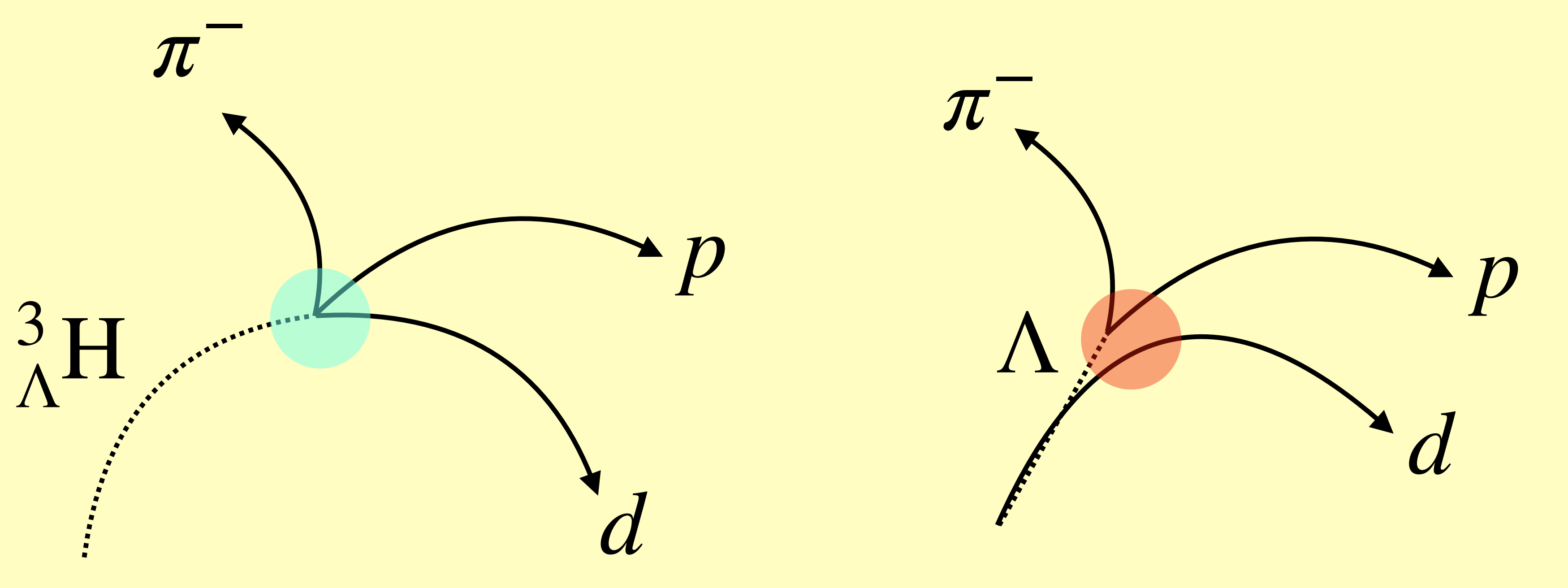
- To obtain corrected yields from hypertriton 3-body decay ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$:

1. Subtract uncorrelated background, estimated via event-mixing

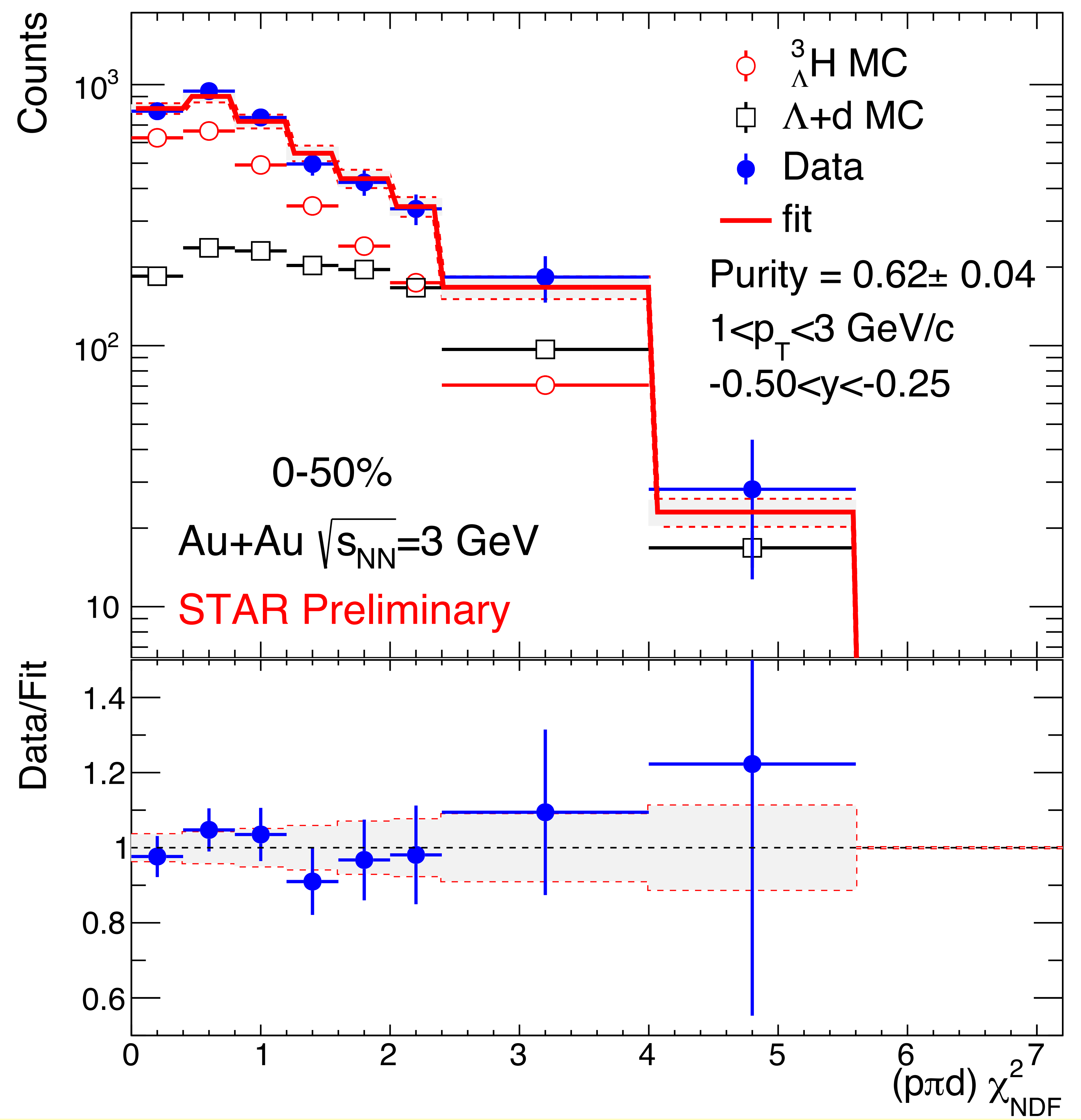


2. Excess around hypertriton peak contains correlated background

- Purity estimated via template fit to χ^2 of secondary vertex fit

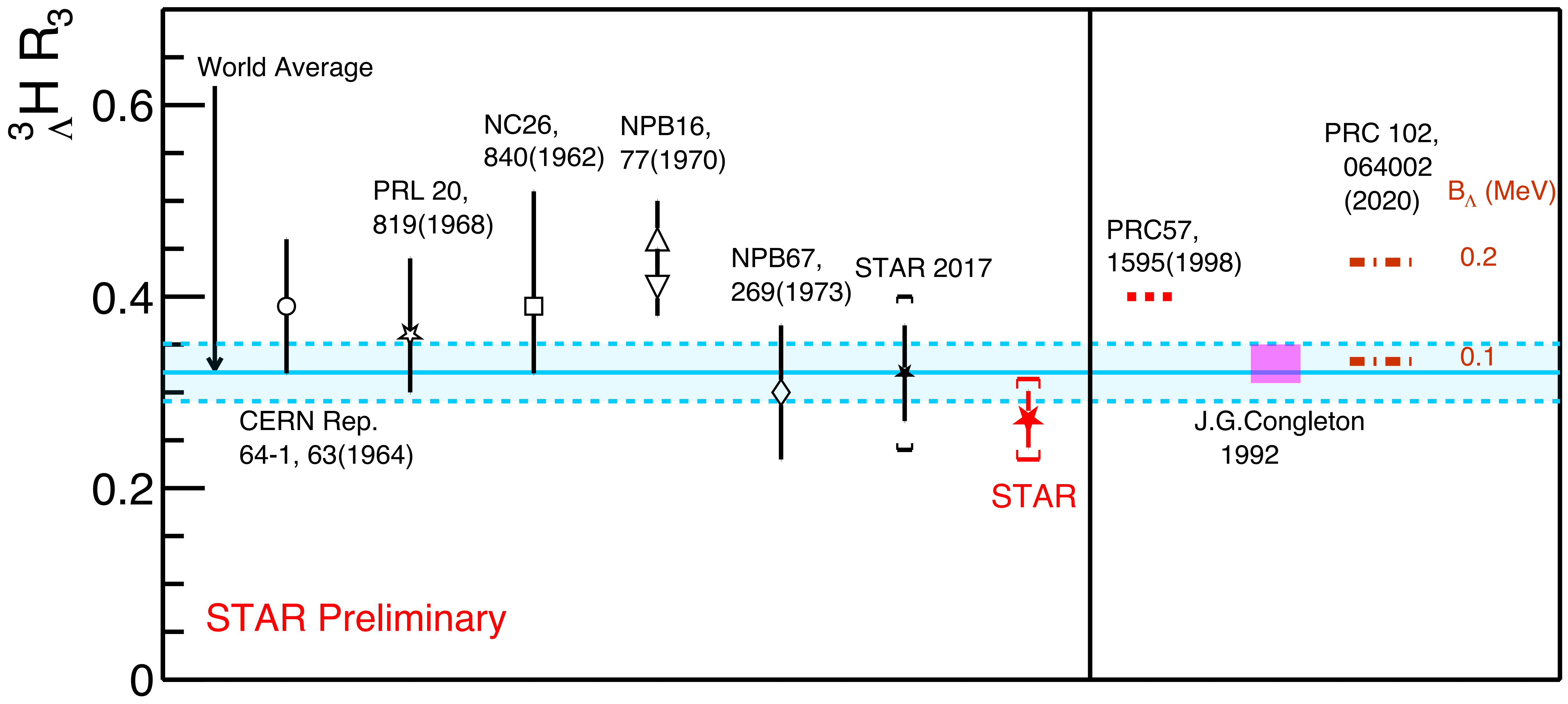


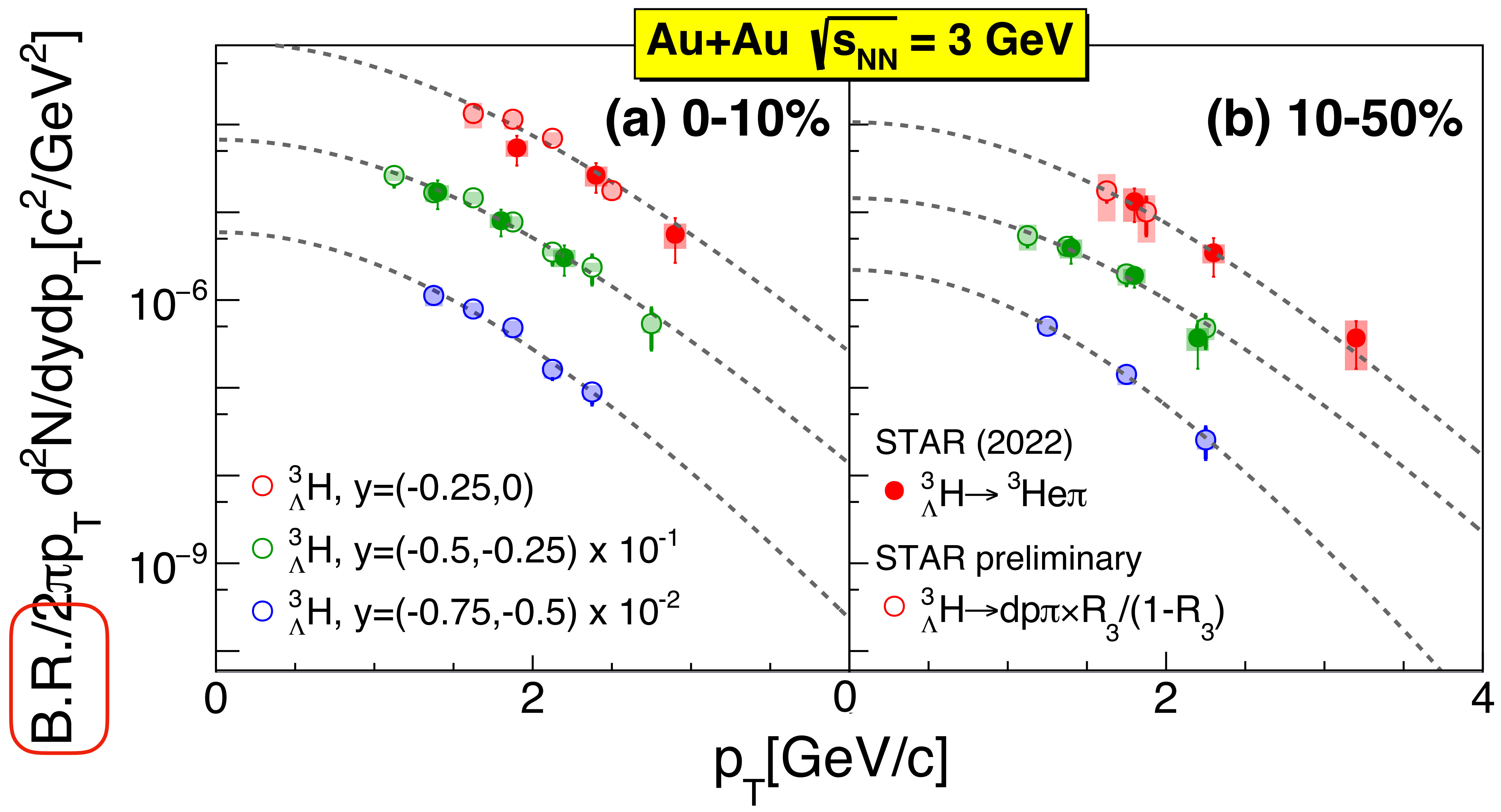
Real signal: lower χ^2 Background: higher χ^2



3. Correct for efficiency of real signal

Relative branching ratio R3 measurement





- Currently, there is NO absolute B.R. measurement of the hypertriton

Extrapolation to absolute B.R. from R3 measurement via isospin rule:

- R3 measurement is obtained by comparing the efficiency corrected yield from 3-body and 2-body decays

$$R_3 = 0.272 \pm 0.030 \pm 0.042$$

- Differential yield from 3-body and 2-body measurements agree with each other

4-body+ non-mes. ↓ Isospin rule ↓

$$e.g.: \mathrm{BR}\,.\,({}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}) \approx \mathrm{R}_3 \times (1 - 0.03) \times \frac{2}{3} = 0.21 \pm 0.02$$