Recent Results on Light Nuclei and Hypernuclei Production and Directed Flow in Au+Au Collisions at RHIC

Physics of High Net-Baryon Densities (PHD2025)

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17th Oct, 2025

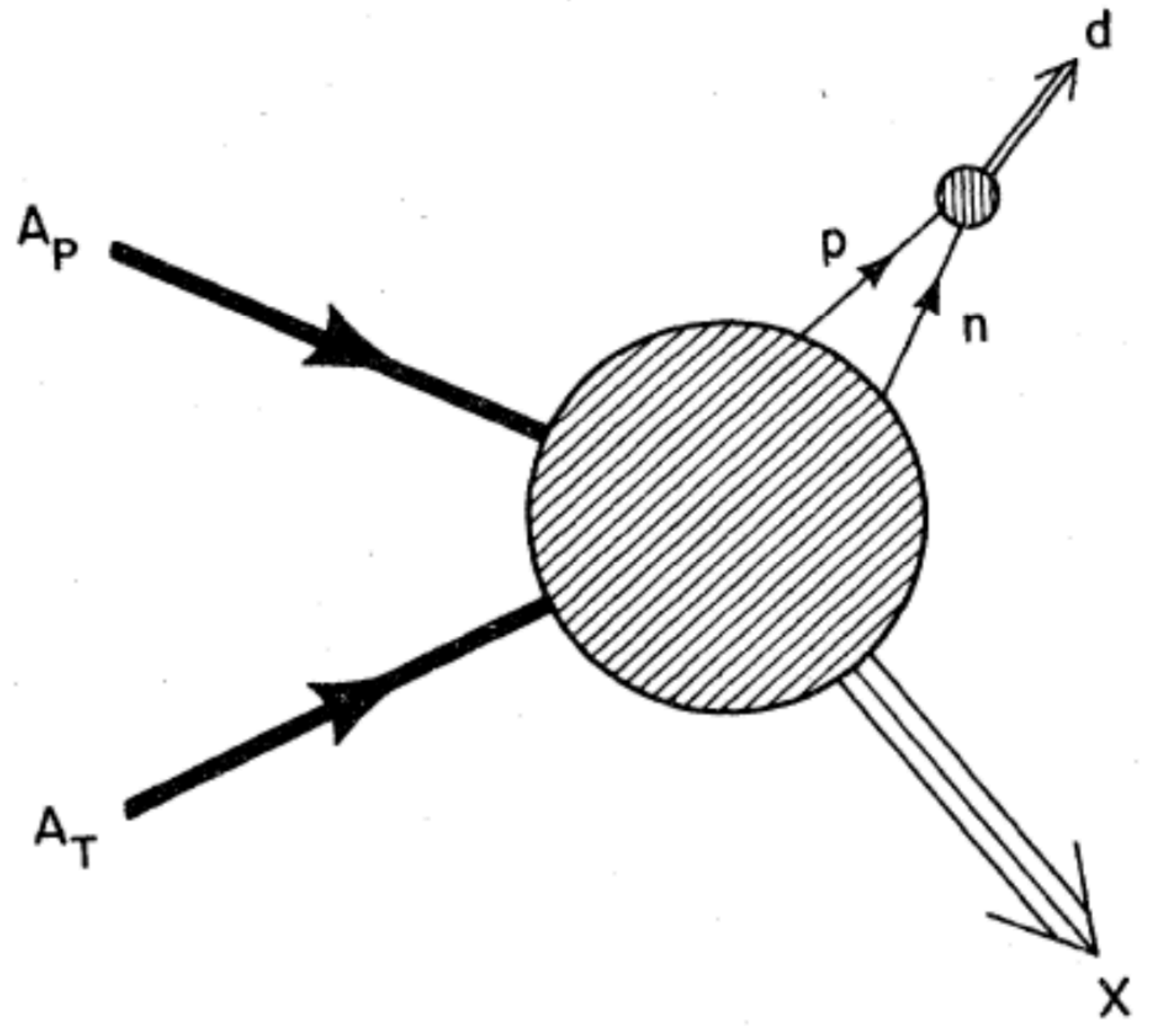
Outline

- Introduction
- Results
    - Production Yields
        - Transverse Momentum Distributions
        - Rapidity Distributions
    - Directed Flow
- Summary and outlook

Introduction

0. Production mechanisms

- Thermal model
    - Particle yields predicted with thermal equilibrium assumptions
        - Chemical freeze-out temperature T_{ch}
        - Baryo-chemical potential μ_B
        - Volume V
        - Strangeness correlation length r_C
- Coalescence model
    - Formed by nucleons (and hyperons) which are nearby in phase space after kinetic freeze-out
        - Nucleon distributions at freeze-out
        - Nuclear wave function



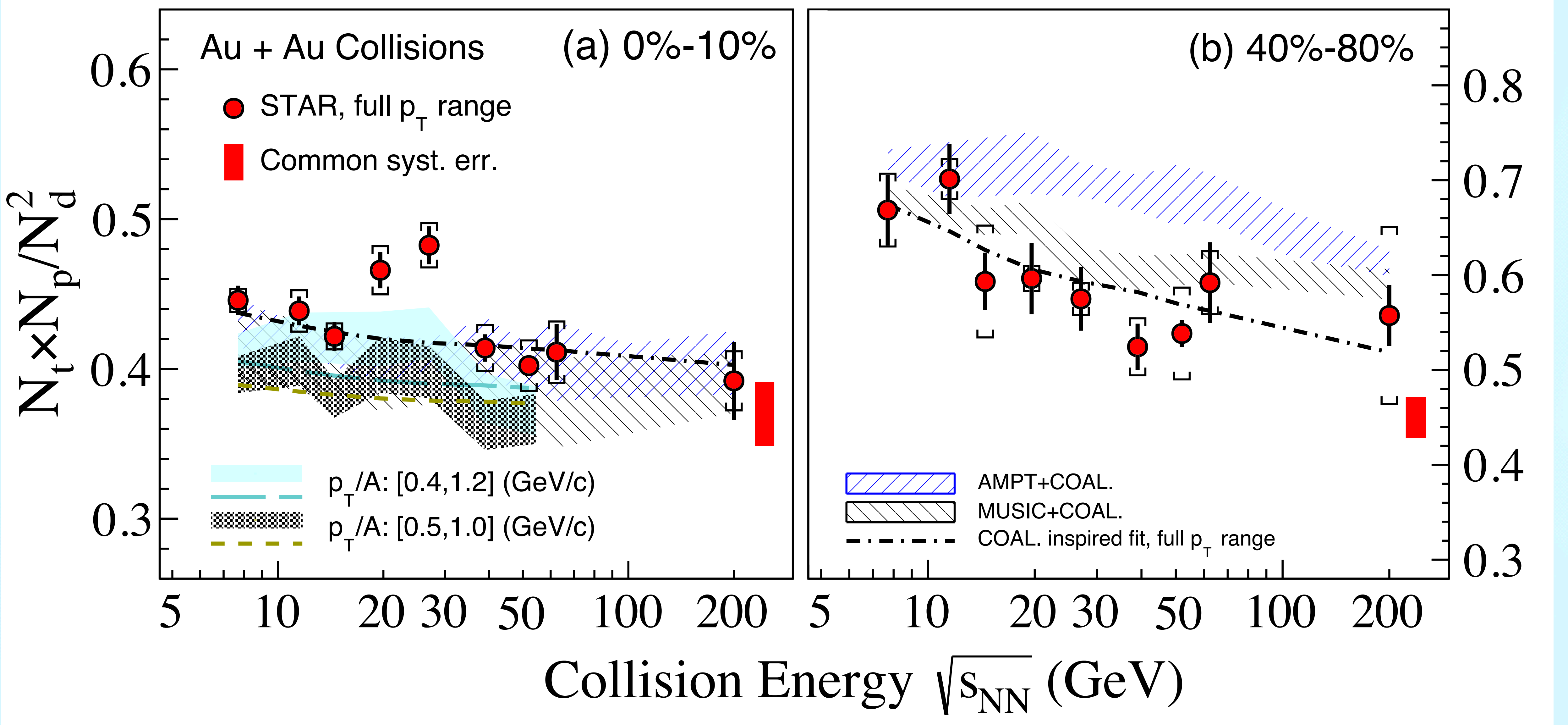
J. I. Kapusta, PRC 21, 1301 (1980)

- Others (hadronic scattering, potential mechansim, spectator fragmentation, etc.)

Motivations

1. Probing critical point/phase transition

- The compound ratio $\frac{N_t N_p}{N_d^2}$ has been proposed to be sensitive to **neutron density fluctuations**



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

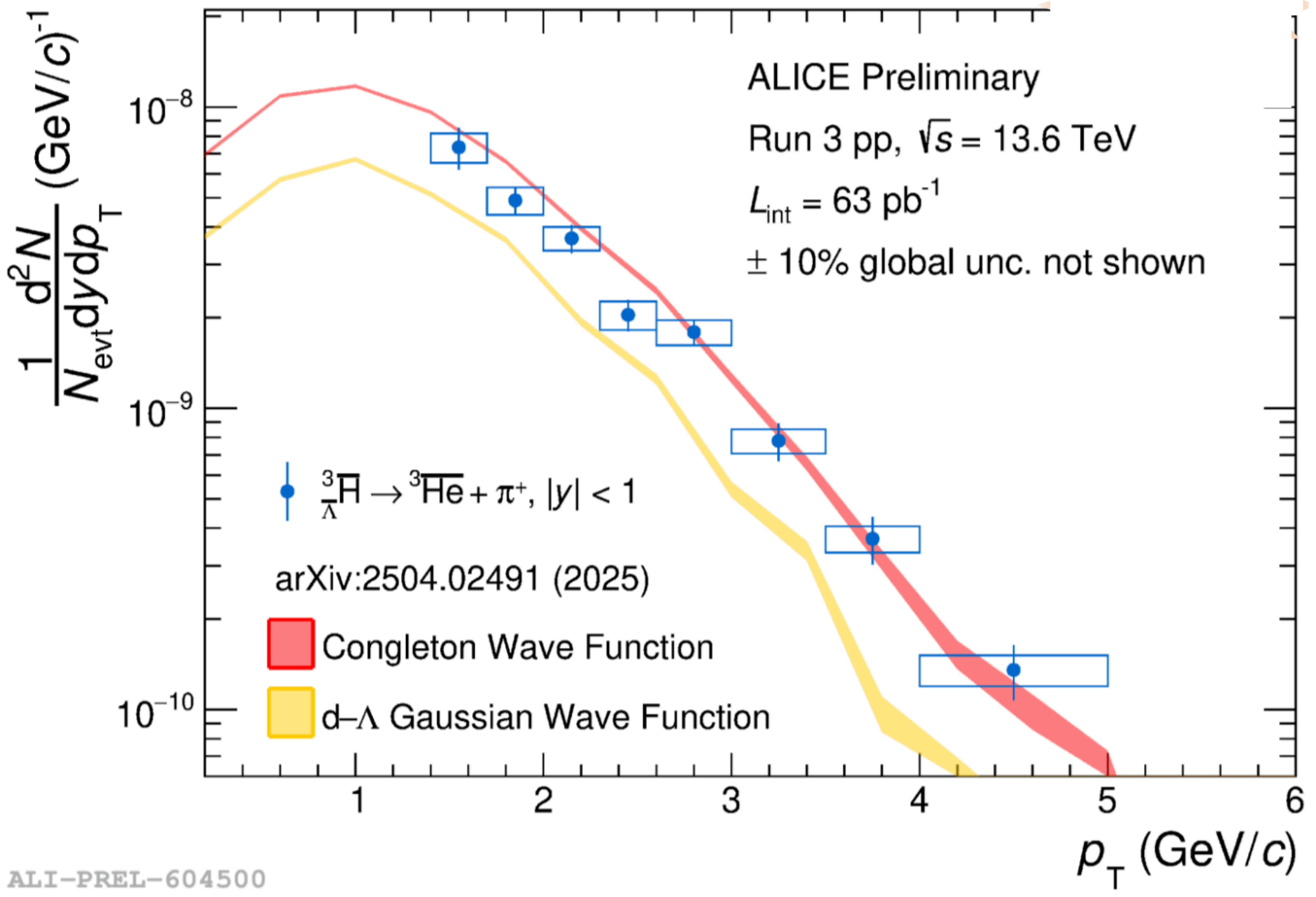
- Enhancements at 19.6 GeV and 27 GeV (4.1σ combined) from BES-I

2. Probing hypernuclei wave functions

- Structure of hypernuclei are connected to **YN** and **YNN** interactions

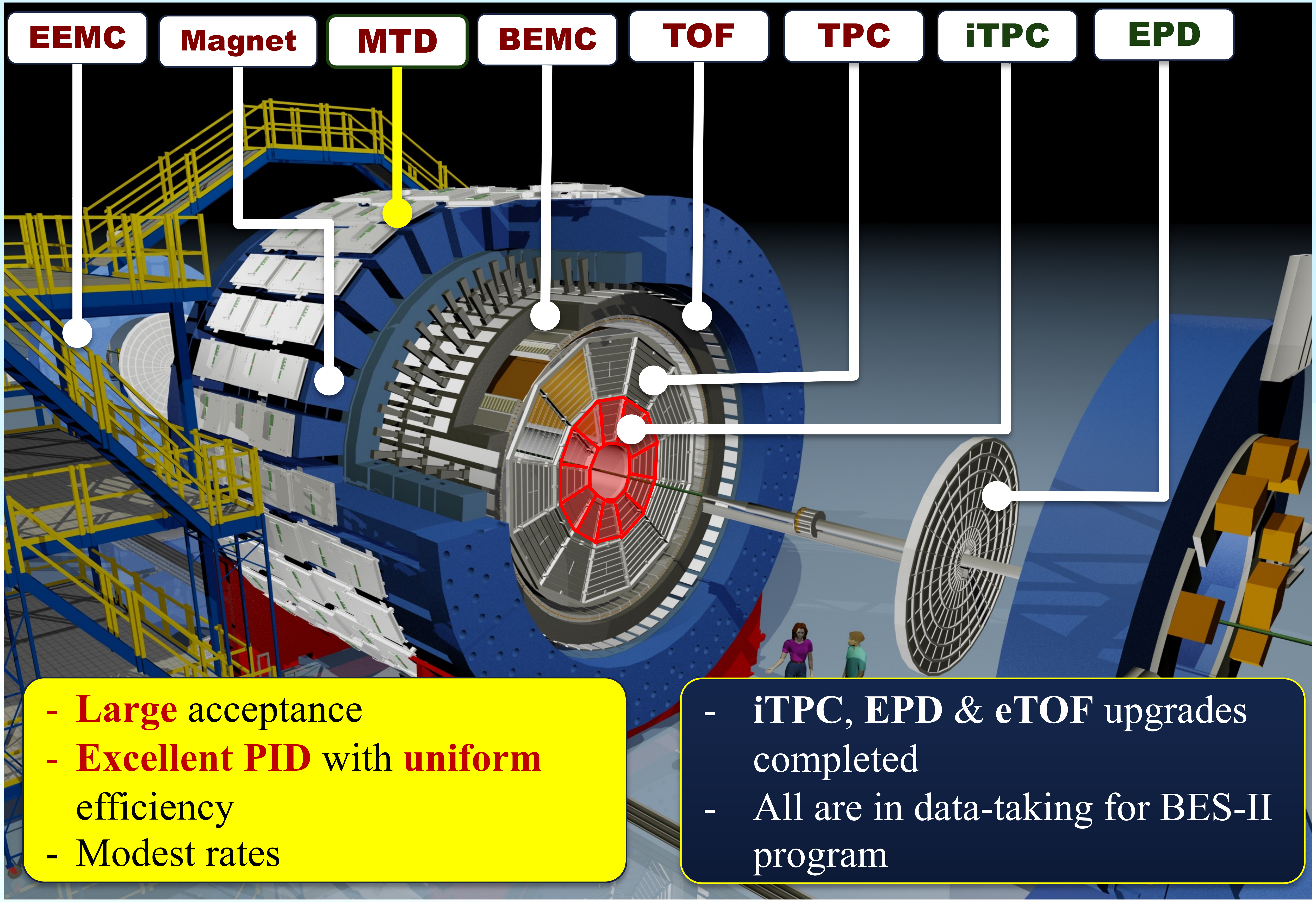
- Hypernuclei yield in **small systems**
  - probe short-distance structure of hypernuclear wavefunctions

Phys.Rev.C 103, 014907 (2021)



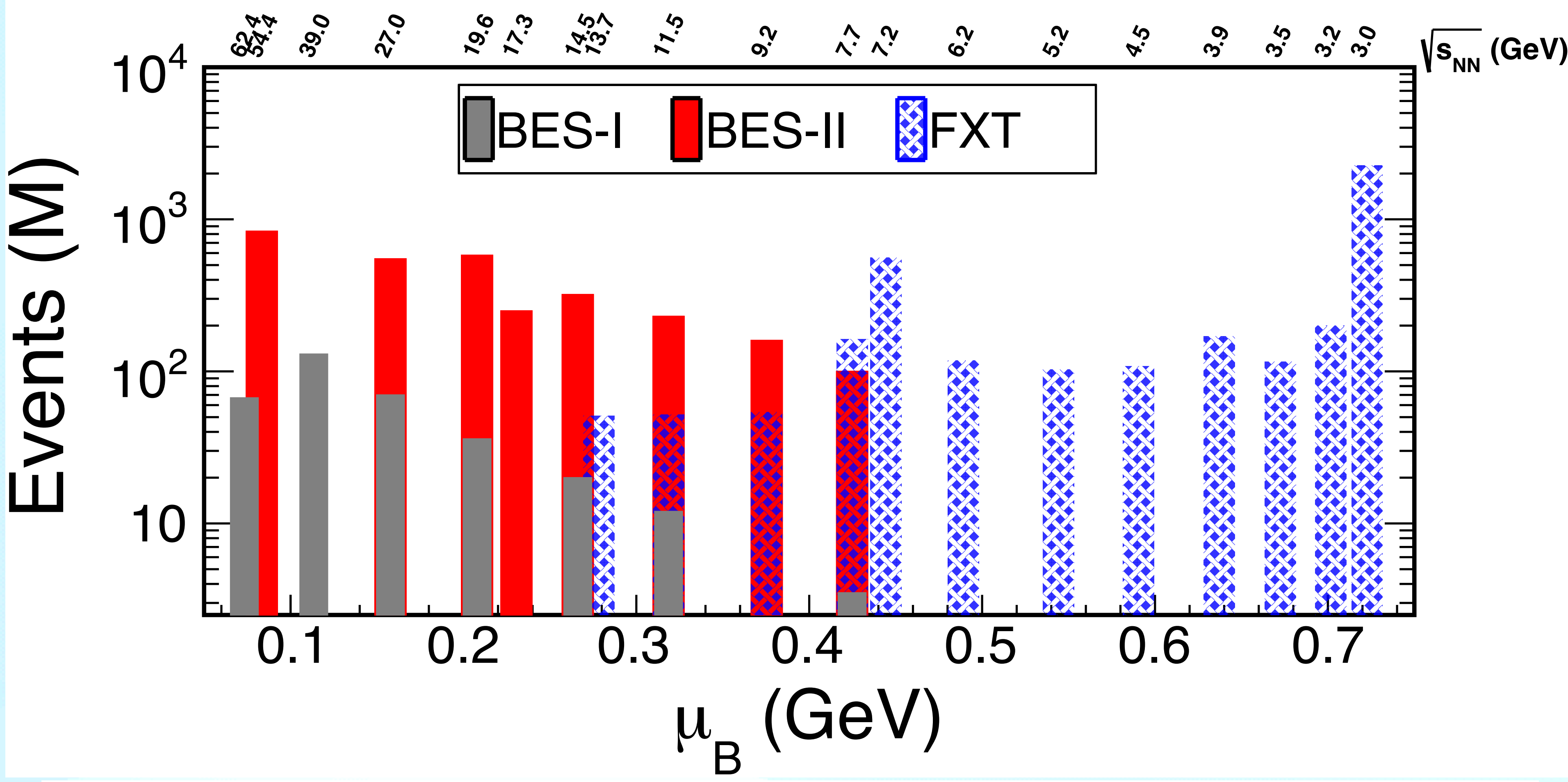
Janik Ditzel (ALICE), QM2025

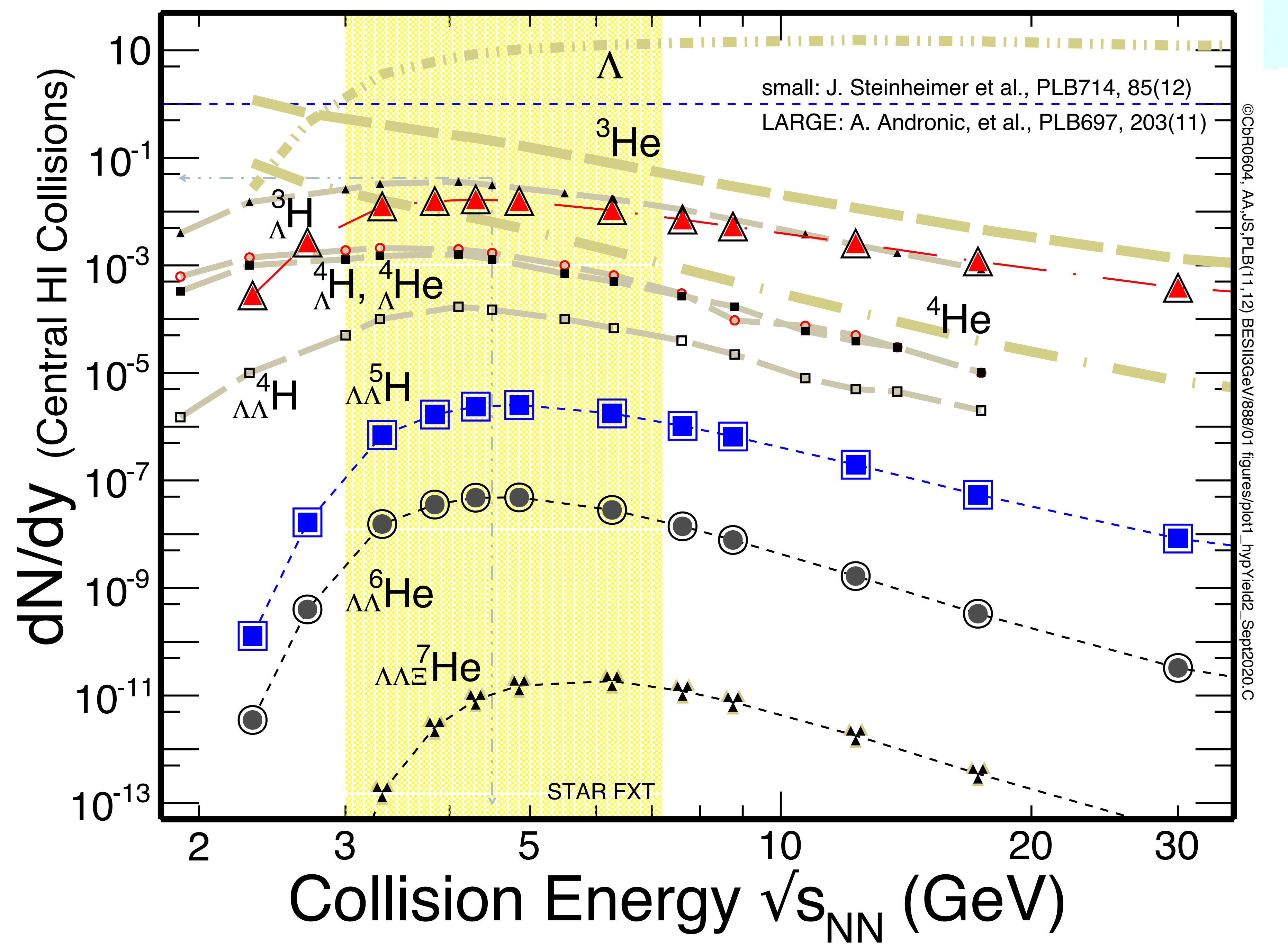
STAR Beam Energy Scan II (2018-2021)



- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC**, **EPD** & **eTOF** upgrades completed
- All are in data-taking for BES-II program

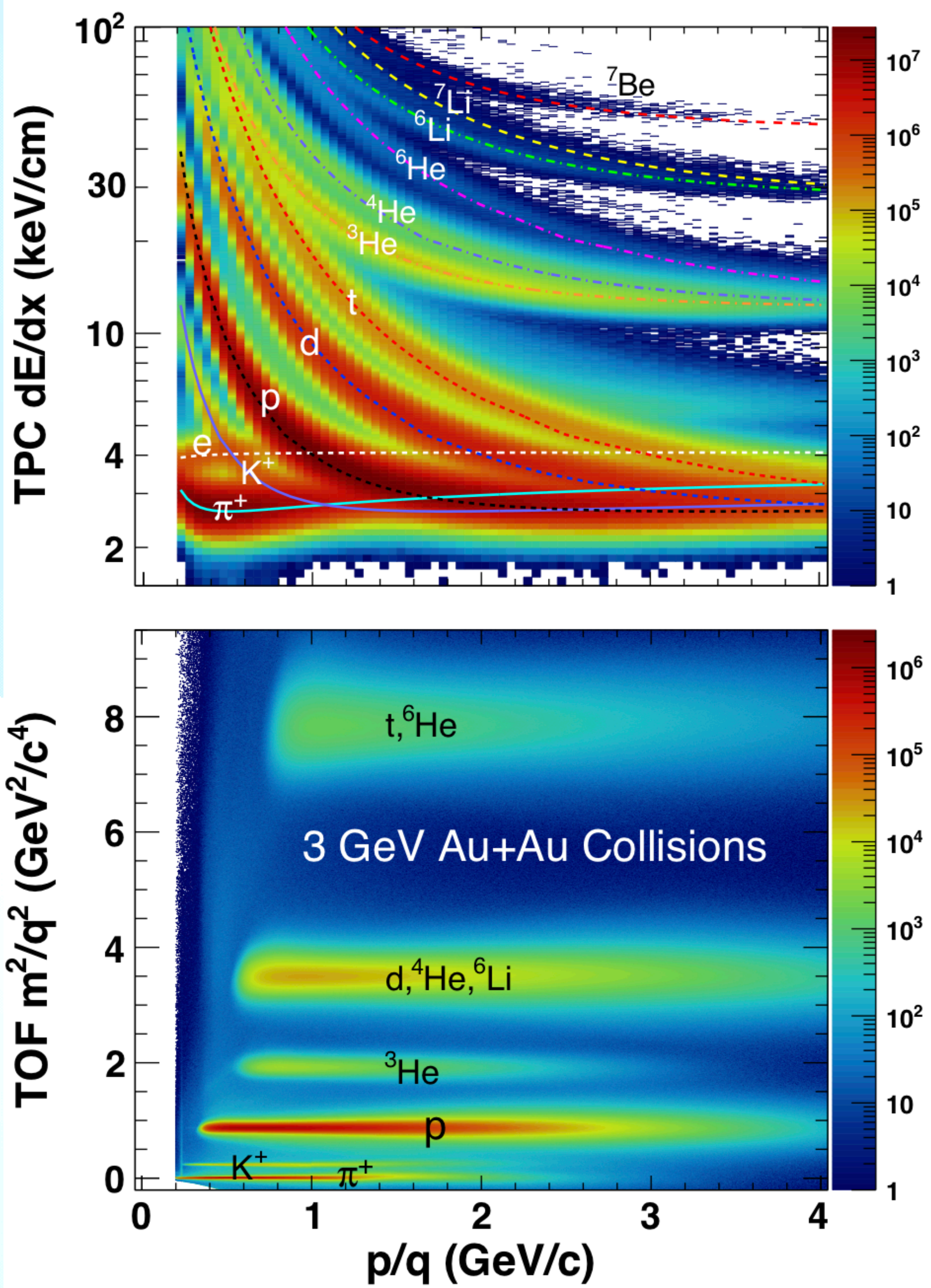


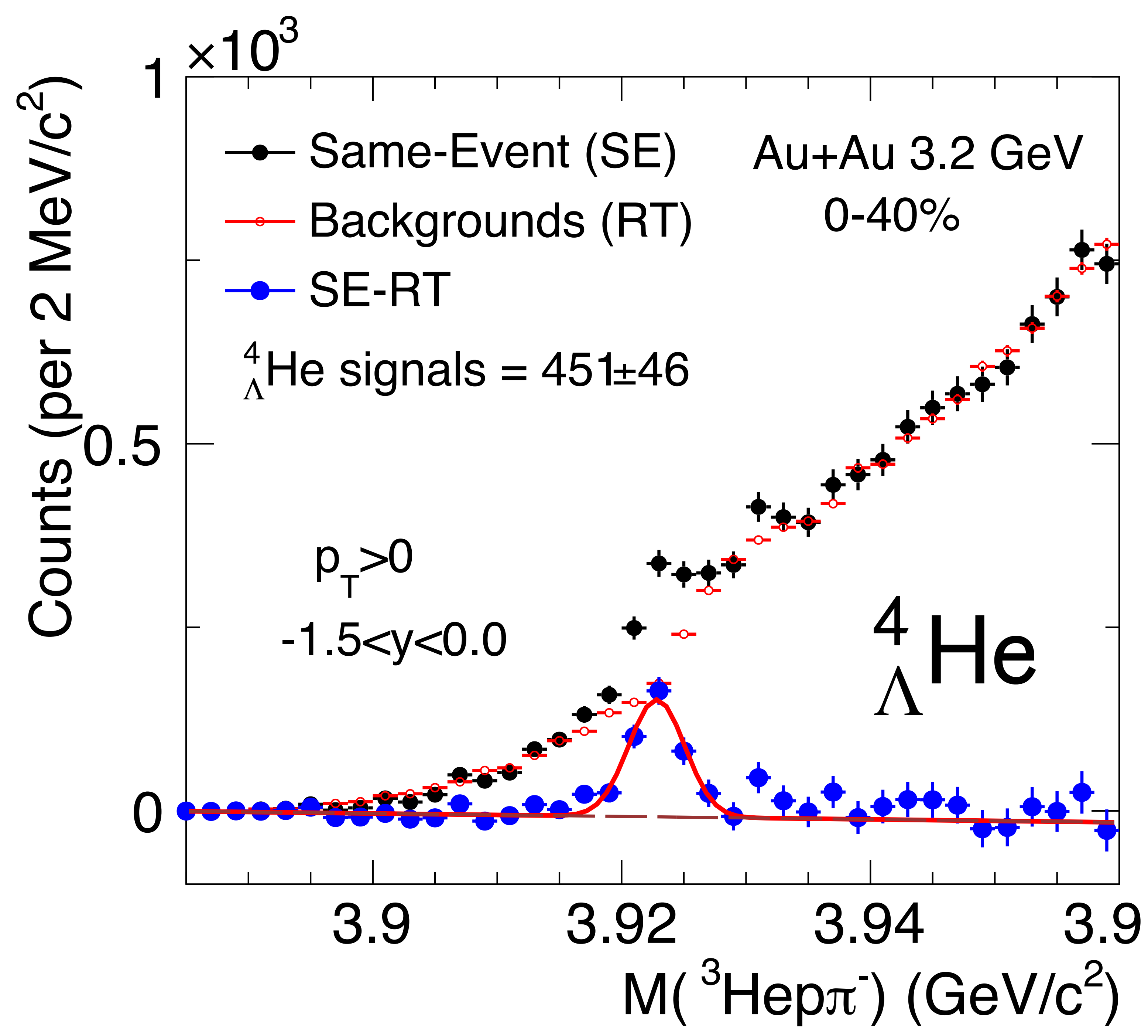


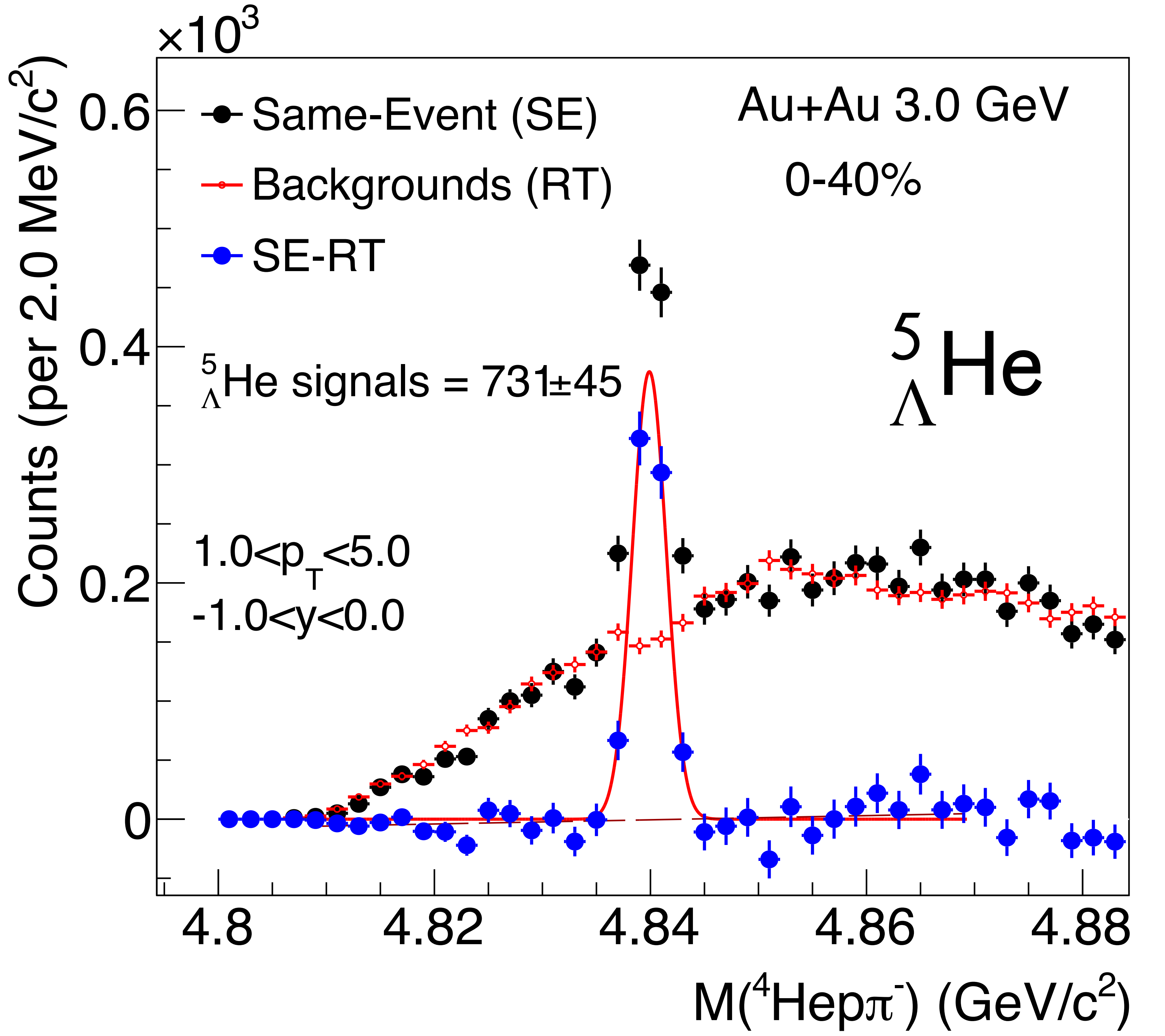
- Mid-rapidity coverage from 3-4.5 GeV in FXT

A. Andronic et al. Phys.Lett.B 697, 203 (2011)
J. Steinheimer et al. Phys.Lett.B 714, 85 (2012)

Particle Identification and Hypernuclei Reconstruction







- Hypernuclei reconstructed via weak decay channels

  e.g.: ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + p + \pi^{-}$, ${}^{5}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + p + \pi^{-}$

- *KFParticle package* utilizing information from error matrices applied to maximize significance

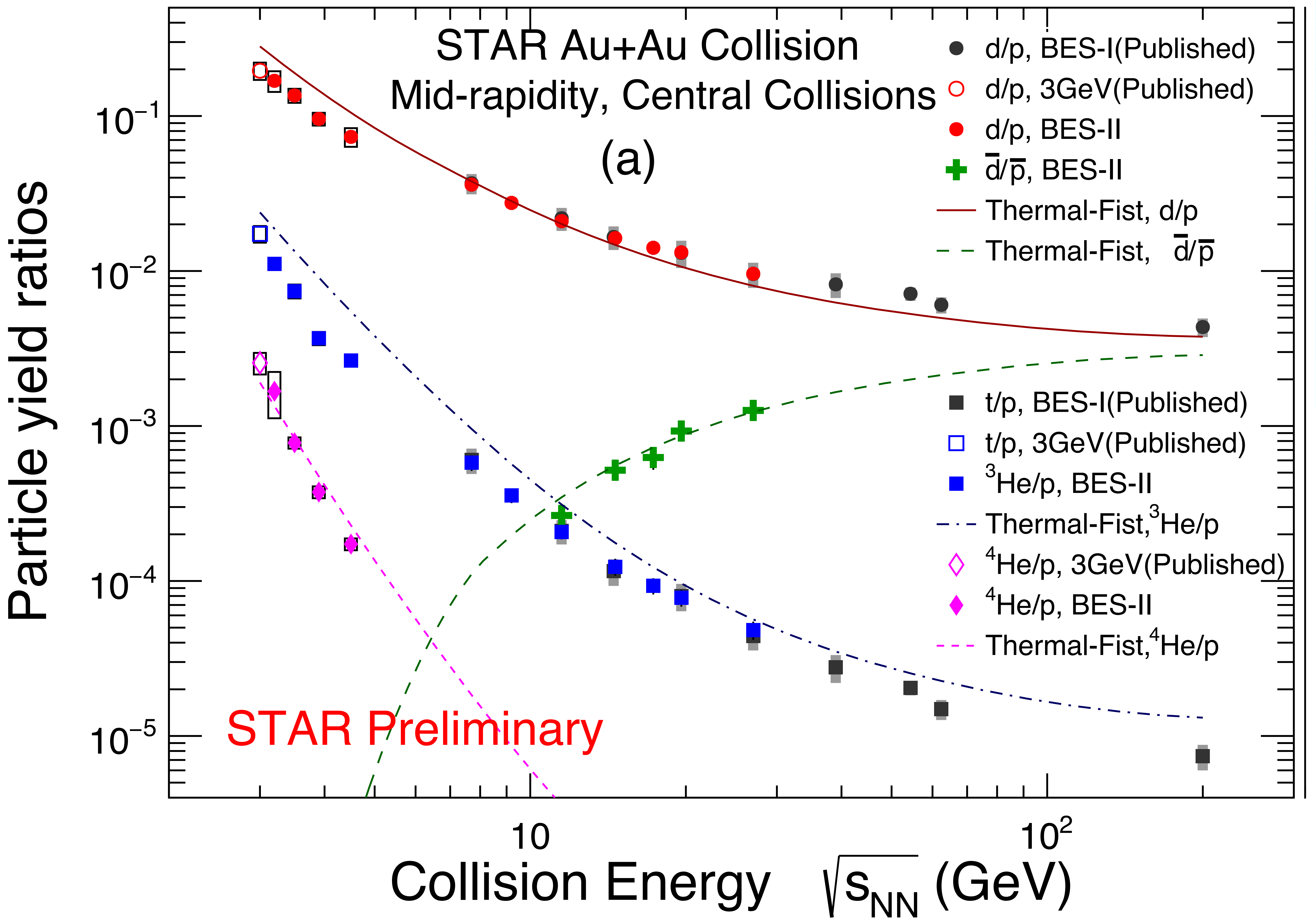
Nucl.Sci.Tech. 34 (2023) 10, 158

- TPC and (e)TOF used for particle identification

Nuclei-to-Nucleon Yield Ratios

STAR, Phys.Rev.C 110, 054911 (2024)
STAR, Phys.Rev.Lett. 130, 202301 (2023)

- d/p fairly well described by thermal model for $\sqrt{s_{NN}} \geq 7.7$ GeV, but overestimated $\leq$7.7 GeV
- t/p and $^3\mathrm{He}/p$ overestimated by factor of 2 for all energies
- Only slight overestimation of $^4\mathrm{He}/p$
- $\bar{d}/\bar{p}$ well described for $\sqrt{s_{NN}} \geq 7.7$ GeV



A=2,4: fairly well described; A=3: strongly overpredicted

Energy Dependence of Compound Ratio

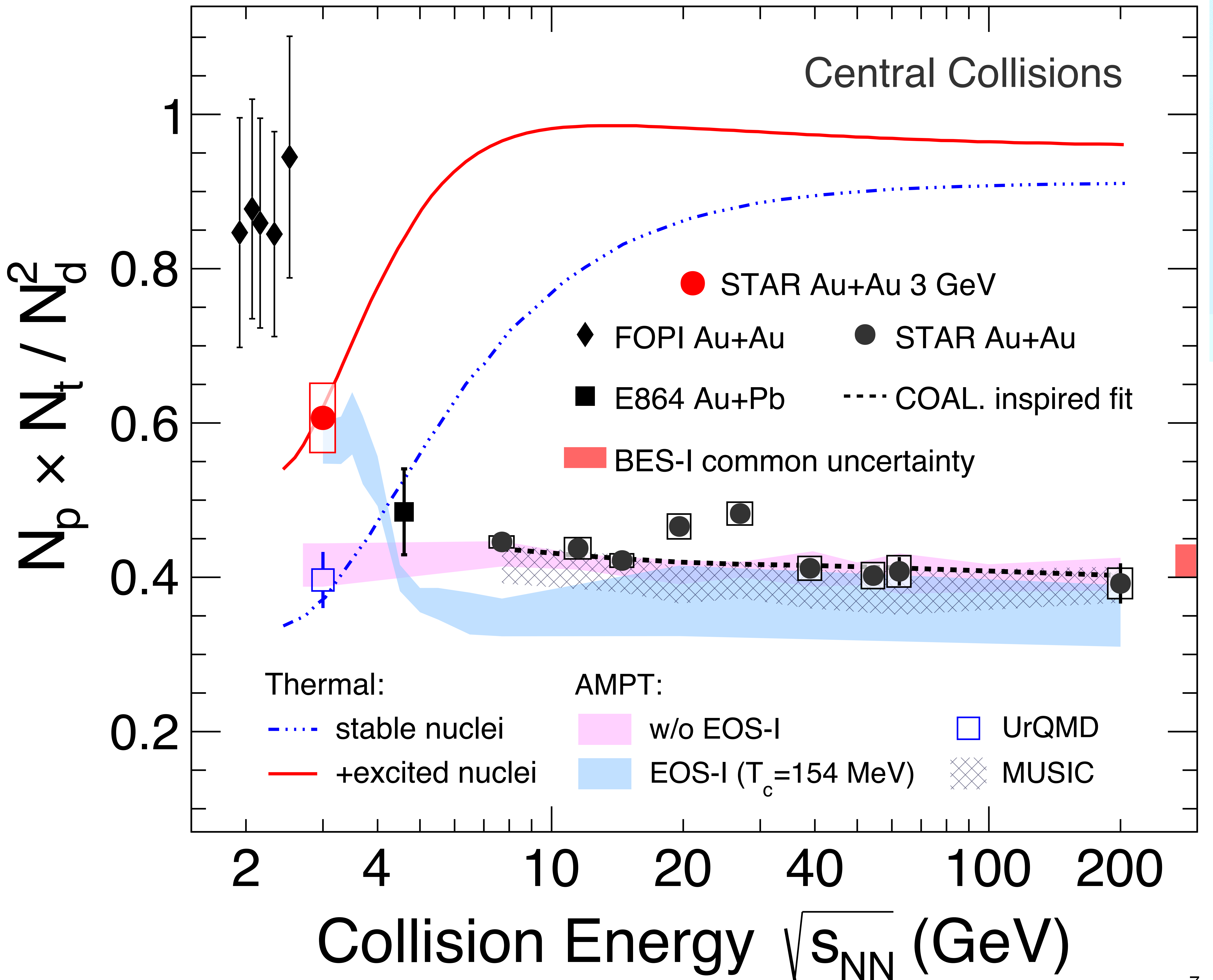
- $N_t N_p / N_d^2$ at $\sqrt{s_{NN}} = 3$ GeV is higher compared to 7.7 GeV and above
- Coalescence calculations incorporating **1st order phase transition** describes the ratio at 3 GeV

arXiv:2205.11010

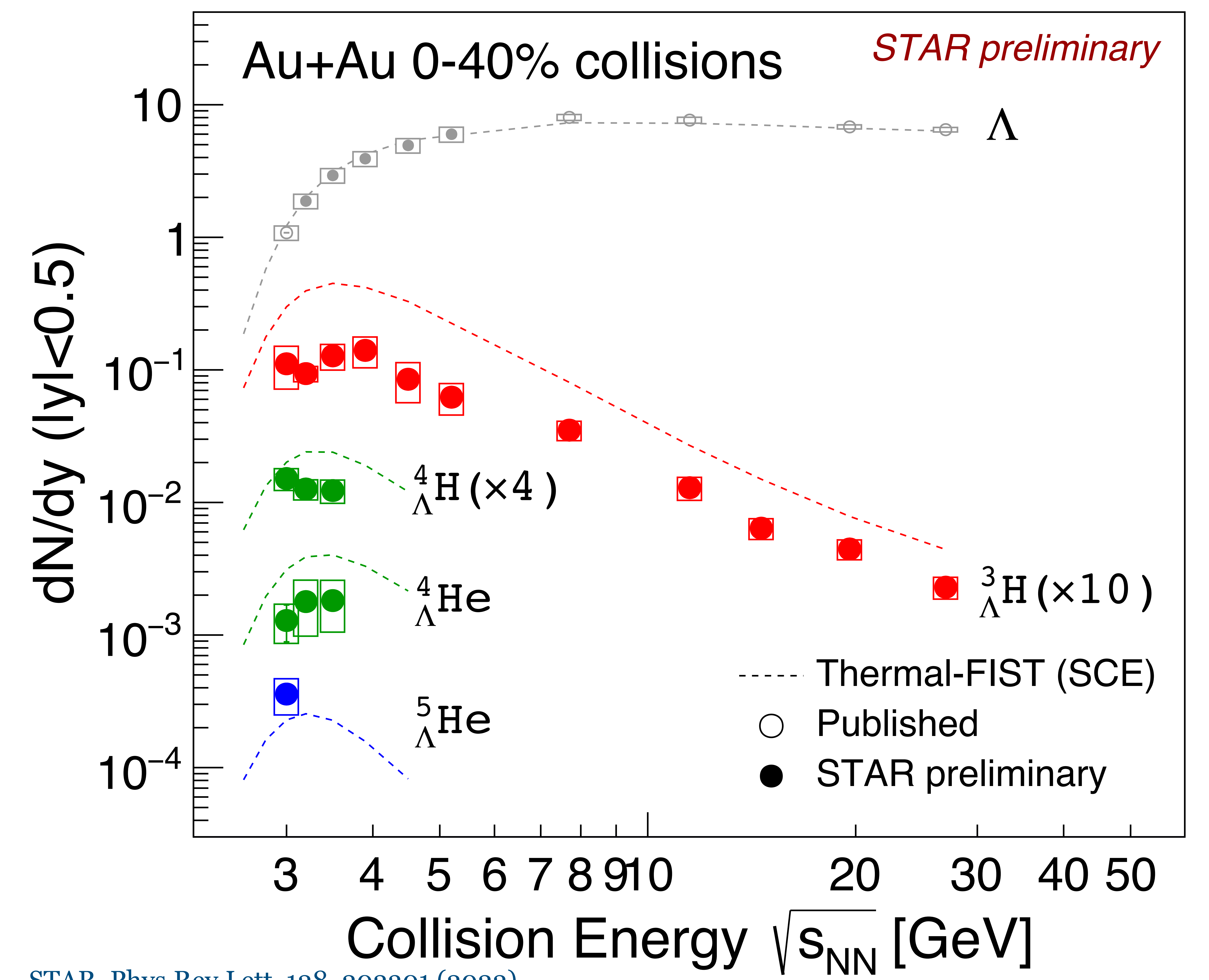
- Enhancement could be partially arising from **decay of unstable nuclei**

e.g.: $^4\text{He}^* \rightarrow p + t$

STAR, Phys.Rev.C 110, 054911 (2024)
STAR, Phys.Rev.Lett. 130, 202301 (2023)



Hypernuclei Excitation Functions



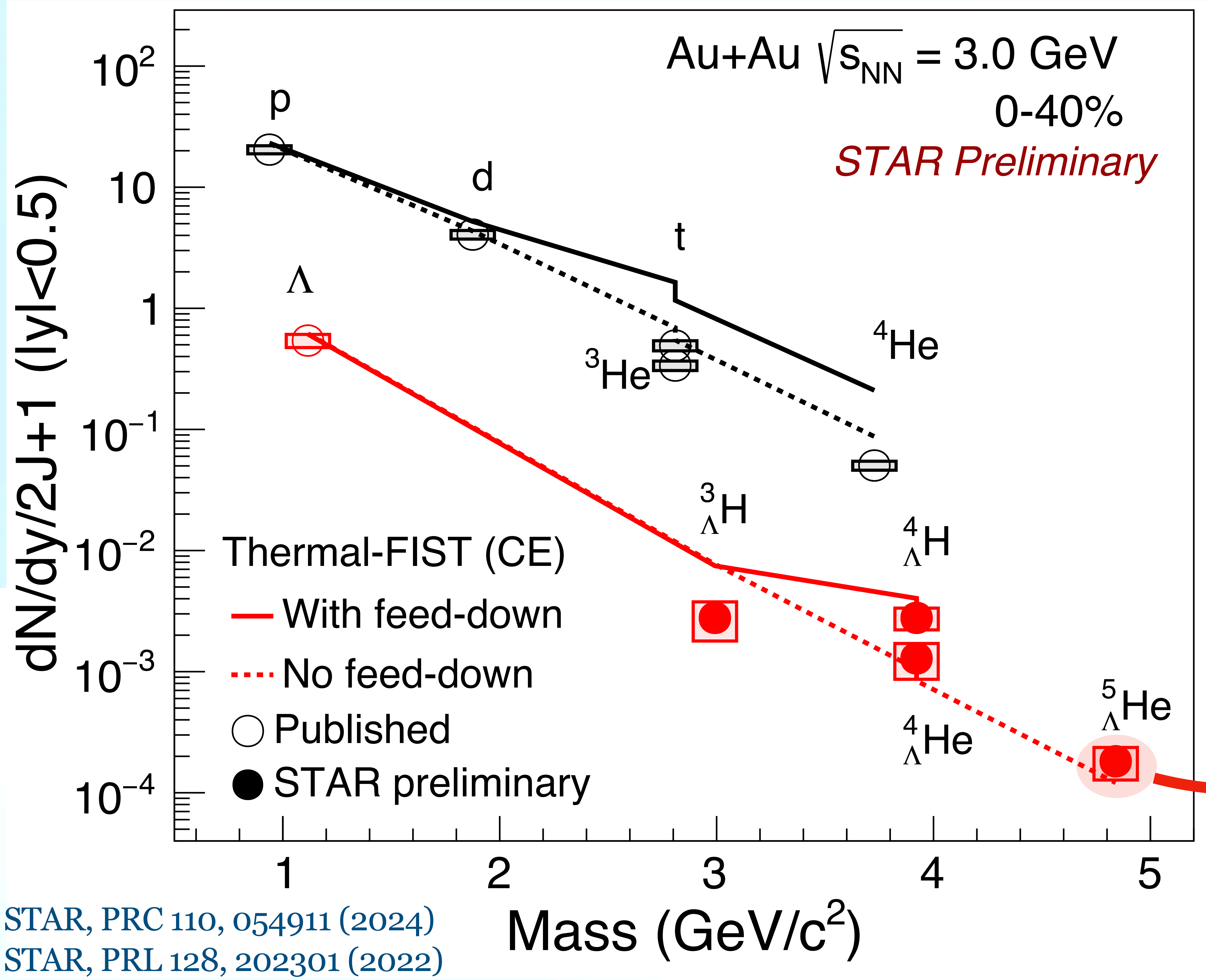
STAR, Phys.Rev.Lett. 128, 202301 (2022)
STAR, Phys.Rev.C 102, 034909 (2020)
STAR, JHEP 10, 139 (2024)

- Thermal model
  - strongly overestimates $^{3}_{\Lambda}$H
  - slightly overestimates $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He
  - slightly underestimates $^{5}_{\Lambda}$He

A=3 strongly overpredicted, A=4 show milder deviations,

similar to the trend for normal nuclei

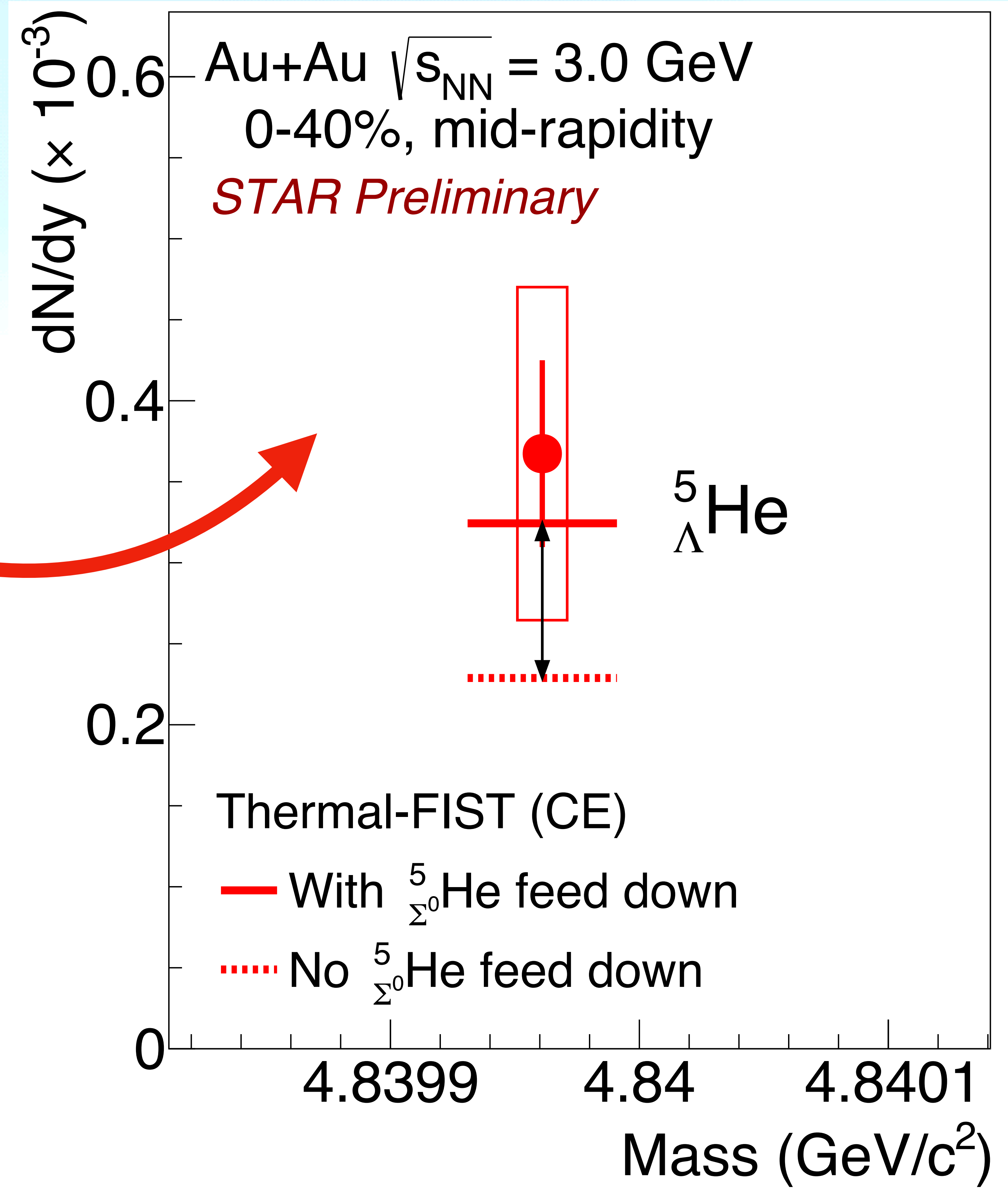
(Hyper)nuclei Mid-Rapidity Yields at $\sqrt{s_{NN}} = 3$ GeV



STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

- Inclusion of excited hypernuclear state production is crucial for models
- Thermal model overestimate $^4_\Lambda$H, $^4_\Lambda$He after including feed-down from excited states

$^4_\Lambda H^*(1^+) \rightarrow ^4_\Lambda H(0^+) + \gamma$
$^4_\Lambda He^*(1^+) \rightarrow ^4_\Lambda He(0^+) + \gamma$



Hint of possible feed-down from
$^5_{\Sigma^0}He \rightarrow ^5_\Lambda He + \gamma$

J. Johnstone et al., JPG 8, L105 (1982)

Probing the Hypertriton ($^3_\Lambda$H) Wave Function

- **Wigner-function coalescence:** coalescence probability given by overlap between $^3_\Lambda$H **wave function** and **nucleon/hyperon distributions** at freeze out

- $^3_\Lambda$H: loosely bound hypernuclei

  $(B_\Lambda = 0.164 \pm 0.043$ MeV)

- Gaussian: $\Phi_{^3_\Lambda\mathrm{H}}(r_{pn}, r_\Lambda) = \left(\frac{1}{3\pi^2 b_{pn}^2 b_\Lambda^2}\right)^{\frac{3}{4}} e^{-\frac{r_{pn}^2}{4b_{pn}^2}-\frac{r_\Lambda^2}{3b_\Lambda^2}}$

  $b_\Lambda = 7.2\mathrm{fm}$

  Phys.Rev.C 103, 014907 (2021)

- Congleton: $\hat{\Phi}_{^3_\Lambda\mathrm{H}(d\Lambda)}(q) = A\frac{e^{-\frac{-q^2}{Q_\Lambda^2}}}{q^2+\alpha_\Lambda^2}$

  - 2-body model of $^3_\Lambda$H

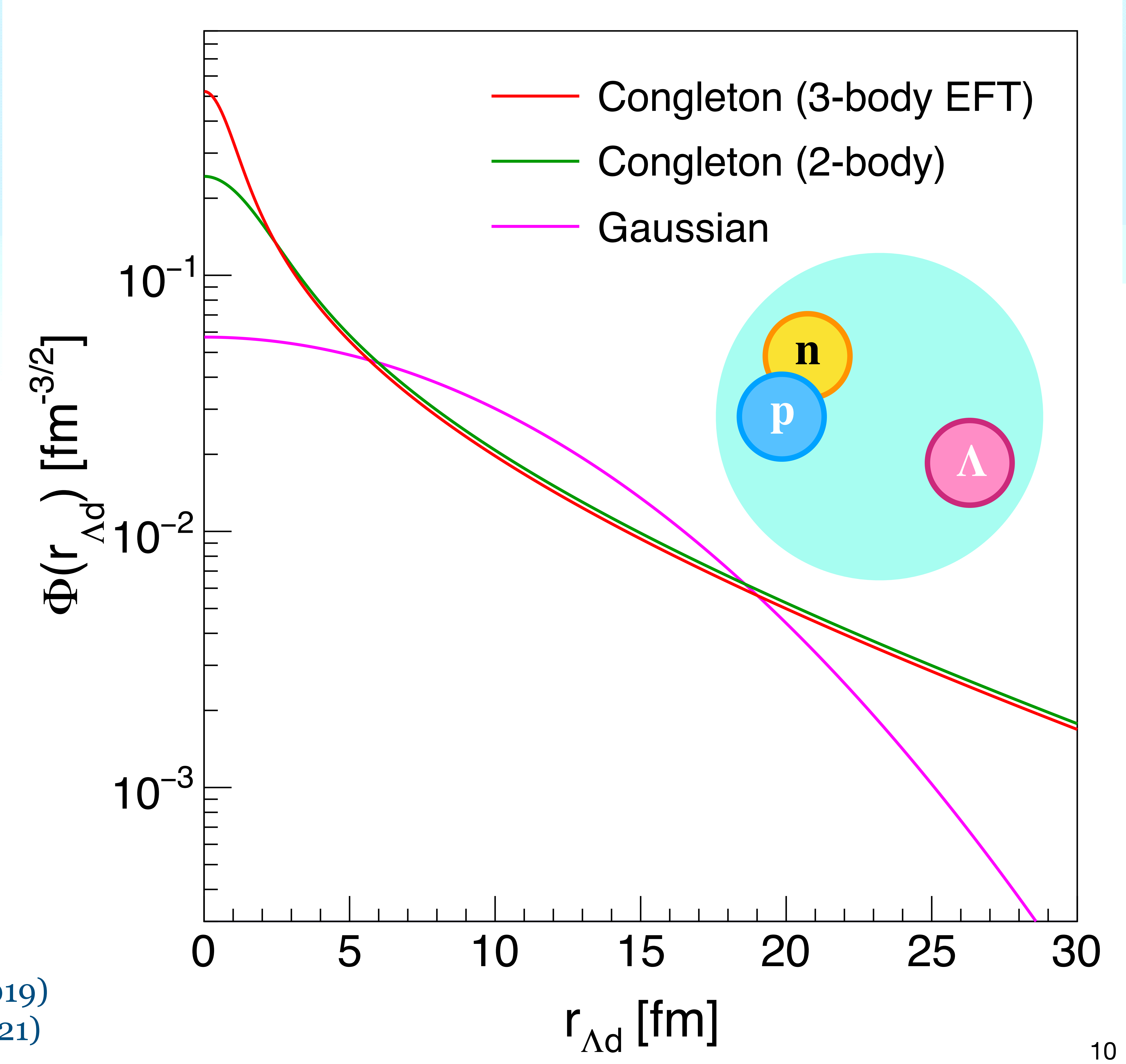
    J.Phys.G 18, 339-357 (1992)

    $(Q_\Lambda, \alpha_\Lambda) = (1.17{,}0.068)\mathrm{fm}^{-1}$

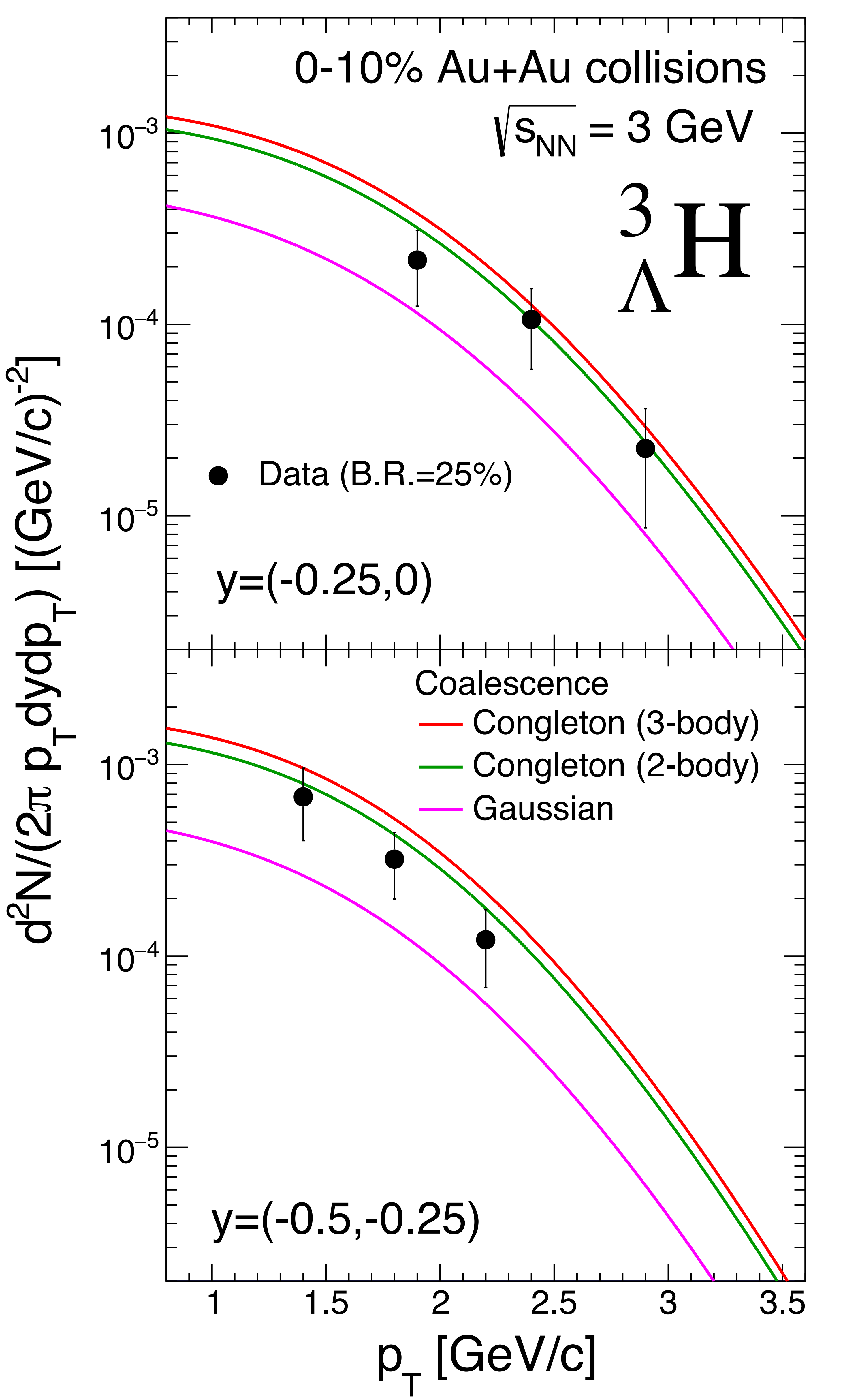
  - 3-body effective field theory

    $(Q_\Lambda, \alpha_\Lambda) = (2.5{,}0.068)\mathrm{fm}^{-1}$

    Phys.Rev.C 100, 034002 (2019)
    Phys.Rev.C 103, 014907 (2021)



${}^{3}_{\Lambda}\mathrm{H}$ Spectra at 3 GeV

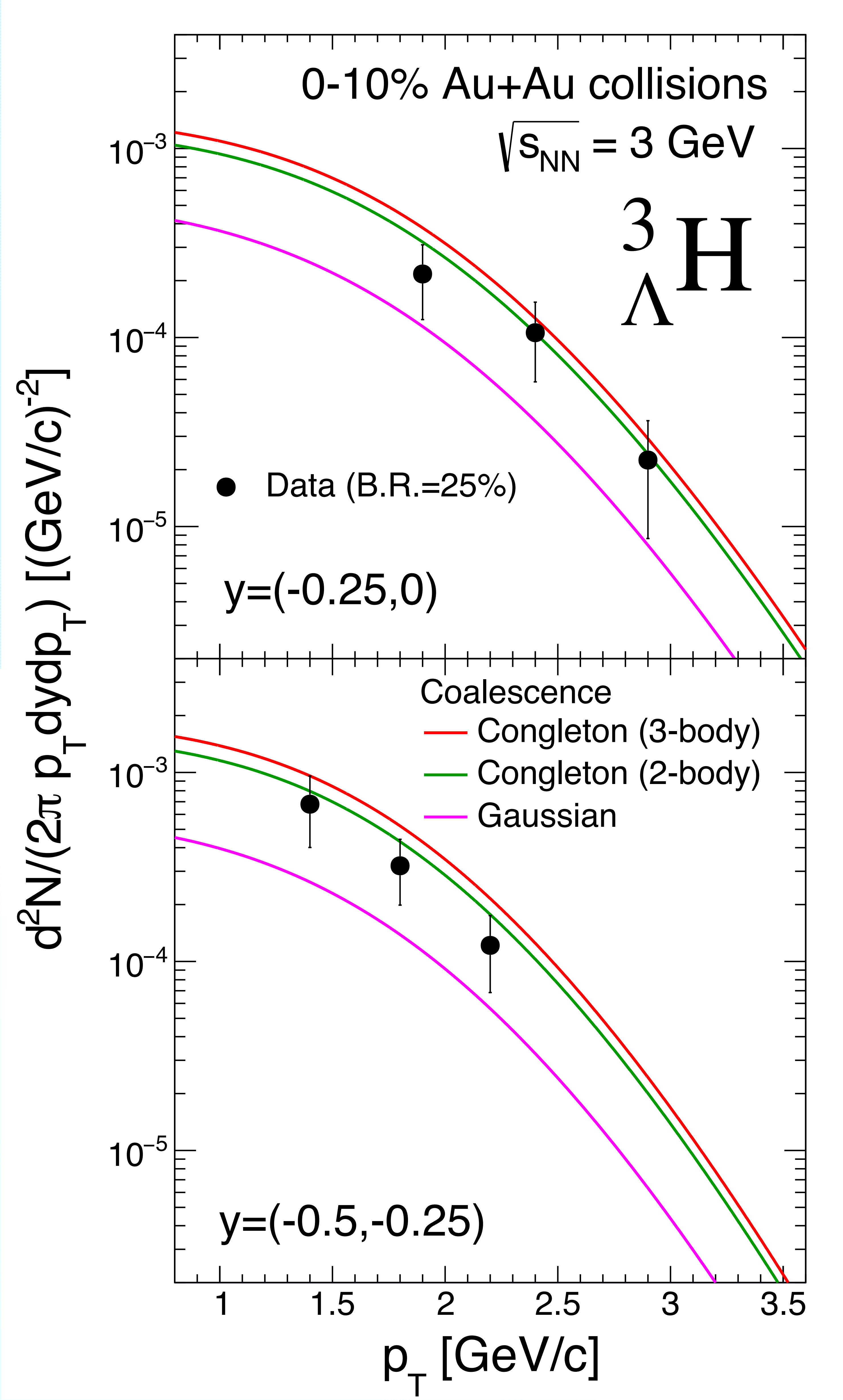


- Coalescence using Congleton wave function describe ${}^{3}_{\Lambda}\mathrm{H}$ spectra at $\sqrt{s_{NN}} = 3$ GeV

STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
Coalescence: arXiv: 2510.06758

Strangeness Population Factor

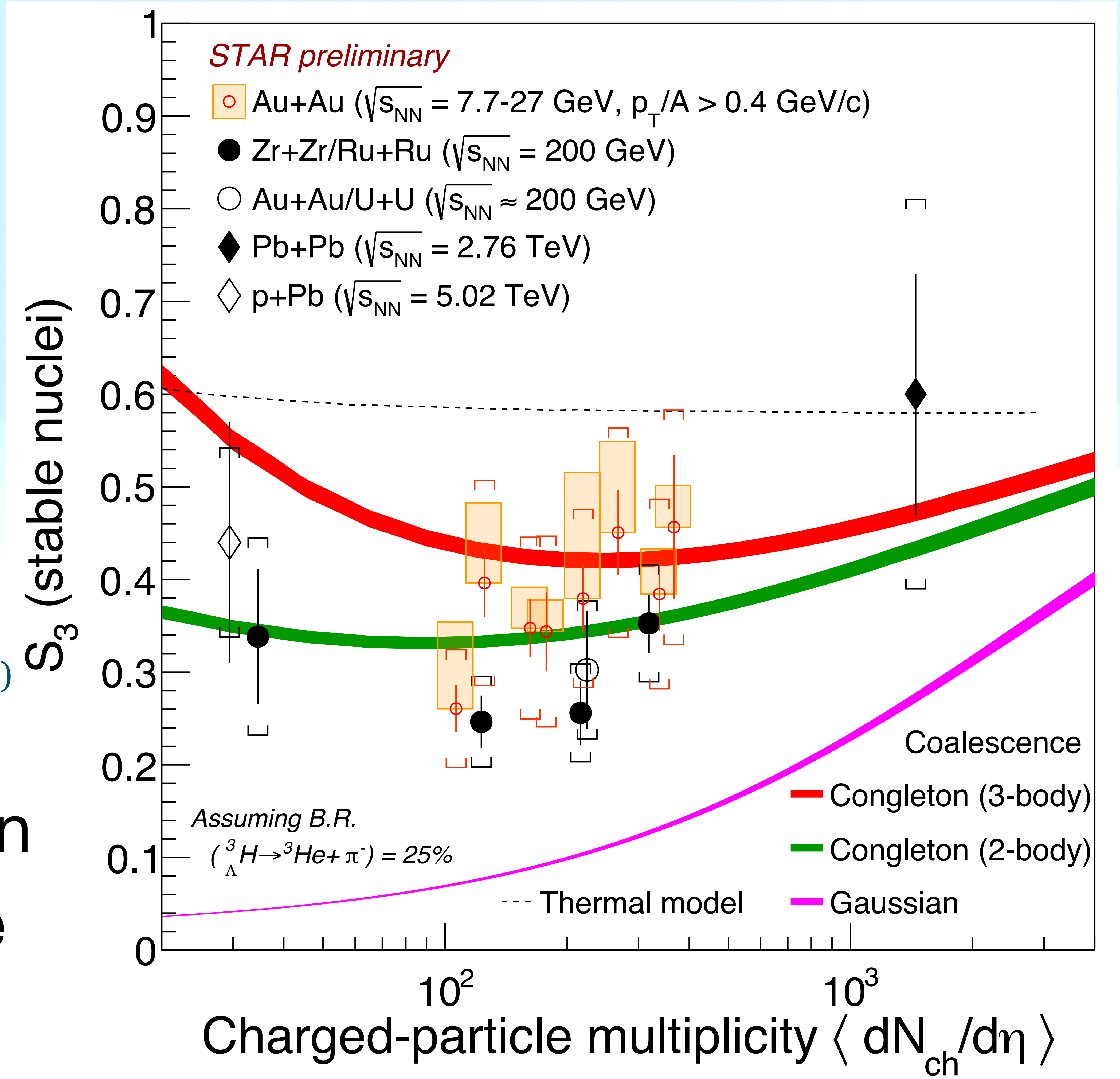
$$S_3 = \frac{^3_\Lambda\mathrm{H}}{^3\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$



- Coalescence using Congleton wave function describe $^3_\Lambda\mathrm{H}$ spectra at $\sqrt{s_{NN}} = 3$ GeV

STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
STAR, Nature 2024, 77 (2024)
ALICE, Phys.Rev.Lett. 128, 252003 (2022)
ALICE, Phys.Lett.B 754 (2016) 360-372
Coalescence: arXiv: 2510.06758
Thermal: Comput.Phys.Commun. 244, 295 (2019)

- Coalescence using Congleton wave function describe S_3 across wide range of energies

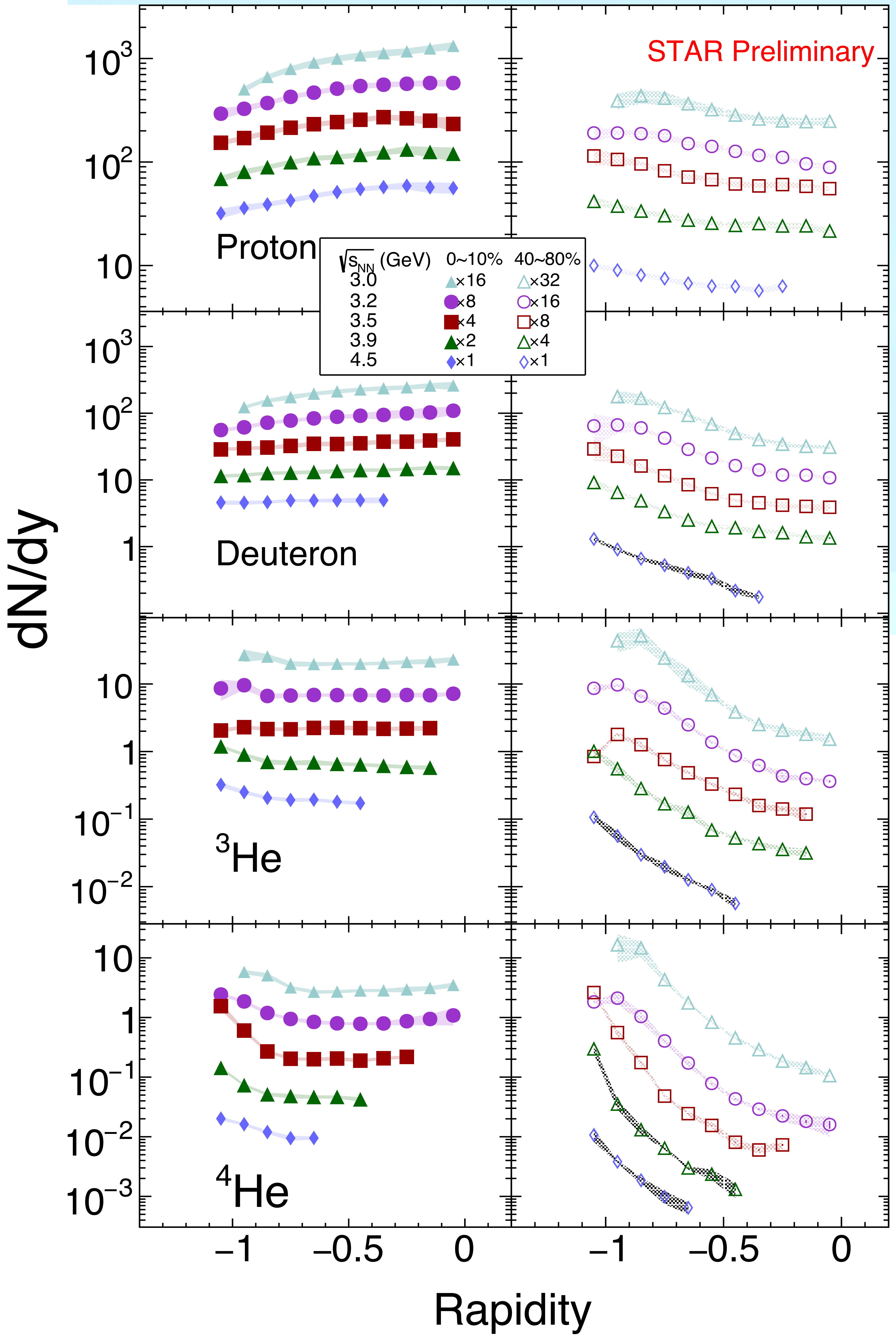


Sensitivity of $^3_\Lambda\mathrm{H}$ yields to short-distance structure of the wave function

Rapidity Dependence of Nuclei Production

- Peak structures at target rapidity are more prominent
    - in more peripheral collisions
    - for nuclei with higher mass

- Primarily due to the **fragmentation of spectators**



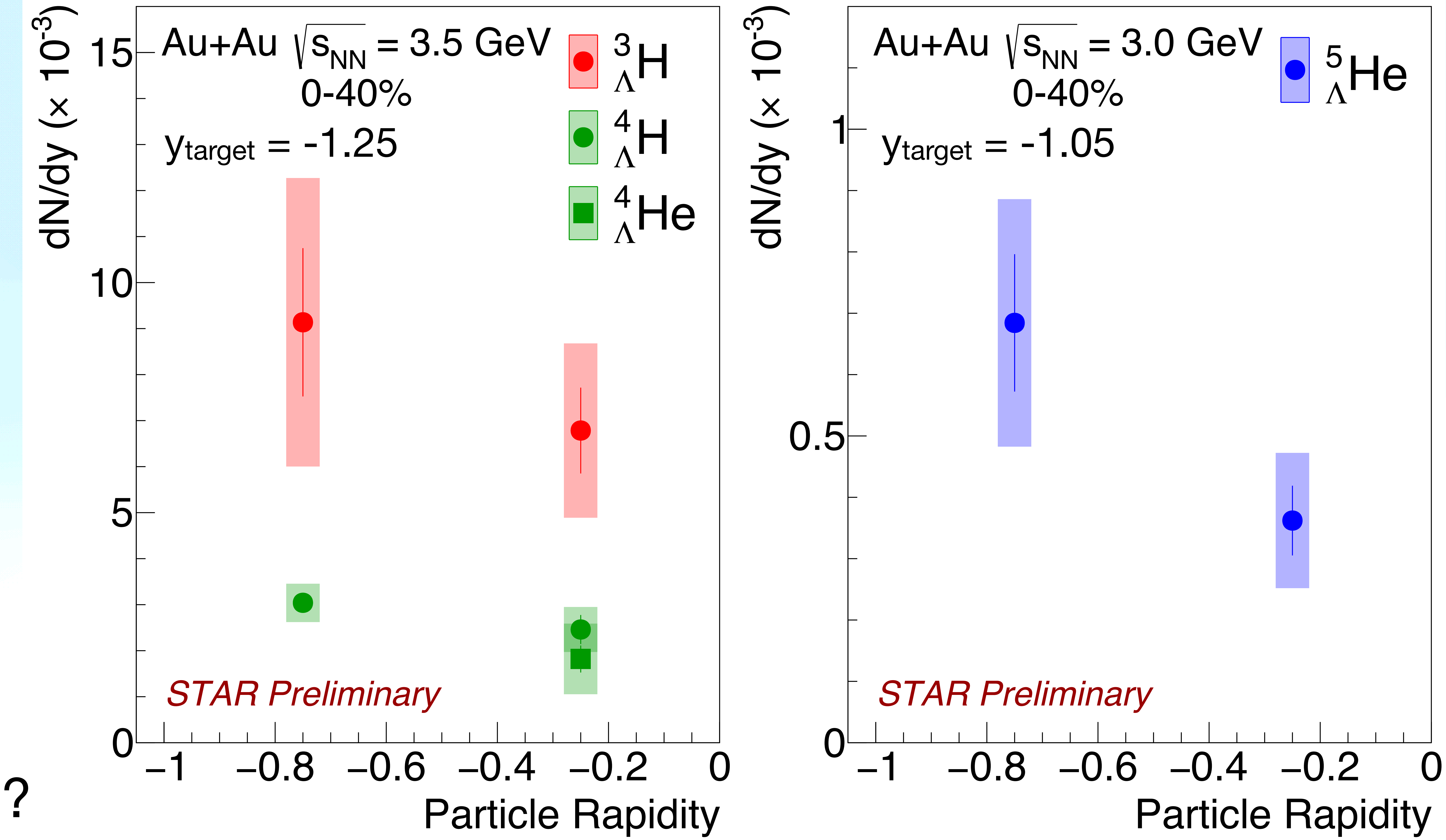
Rapidity Dependence of Hypernuclei Production

- Significant hypernuclei production near target rapidity

Spectators also play an important role in hypernuclei production

- Not "thermal"-like
- Coalescence? or
- Λ capture + fragmentation?

Phys.Rev.C 76, 024909 (2007)



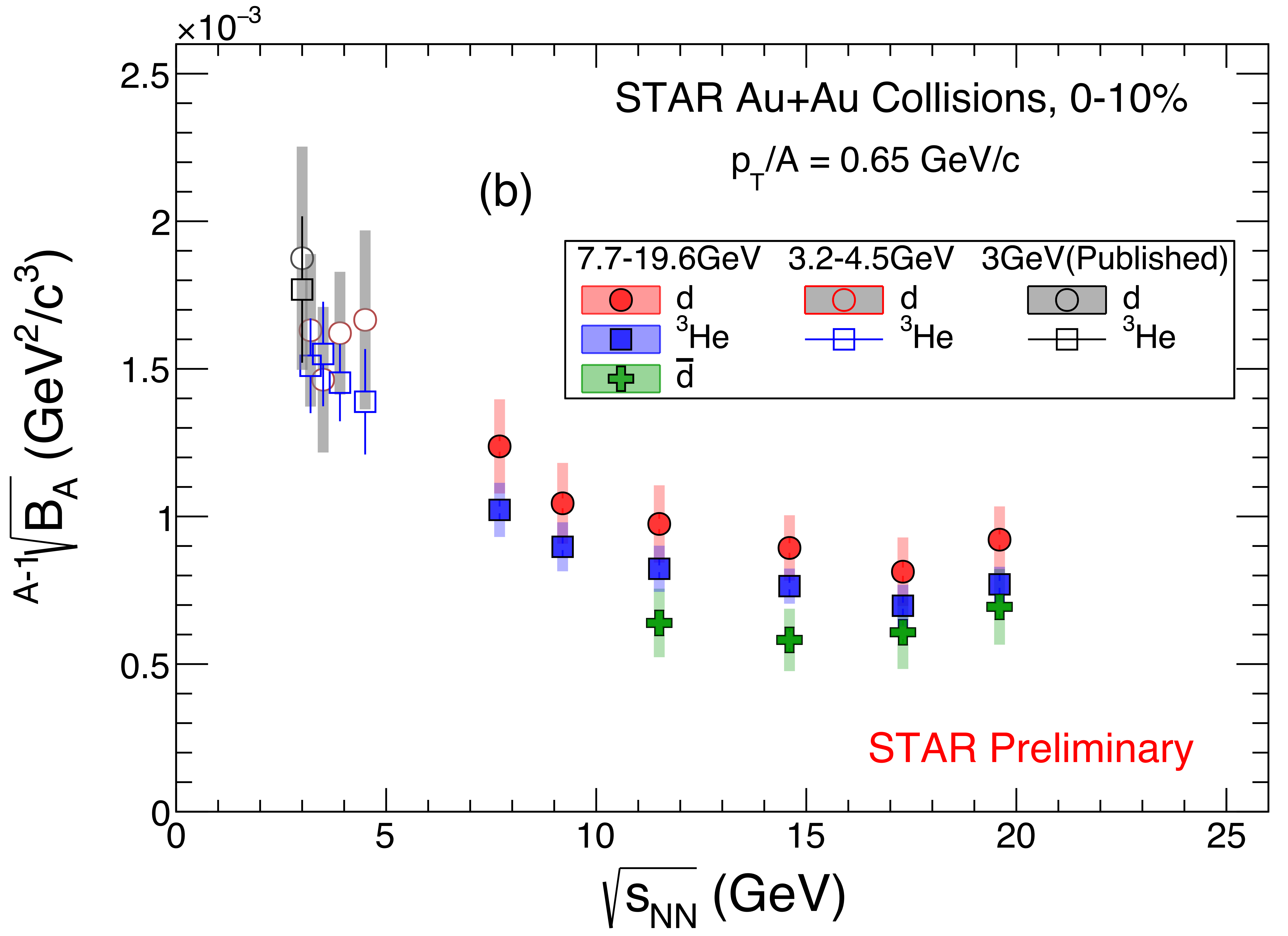
- *More differential measurements underway!*

Coalescence Parameters (B_A)

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^Z \left(E_n \frac{d^3N_n}{d^3p_n}\right)^{A-Z}}$$

$$p_A/A = p_p = p_n$$

- Coalescence parameters (B_A) reflect the coalescence probability
- $\sqrt[A-1]{B_A}$ decrease with increasing energy
    - effective volume increases with increasing energy



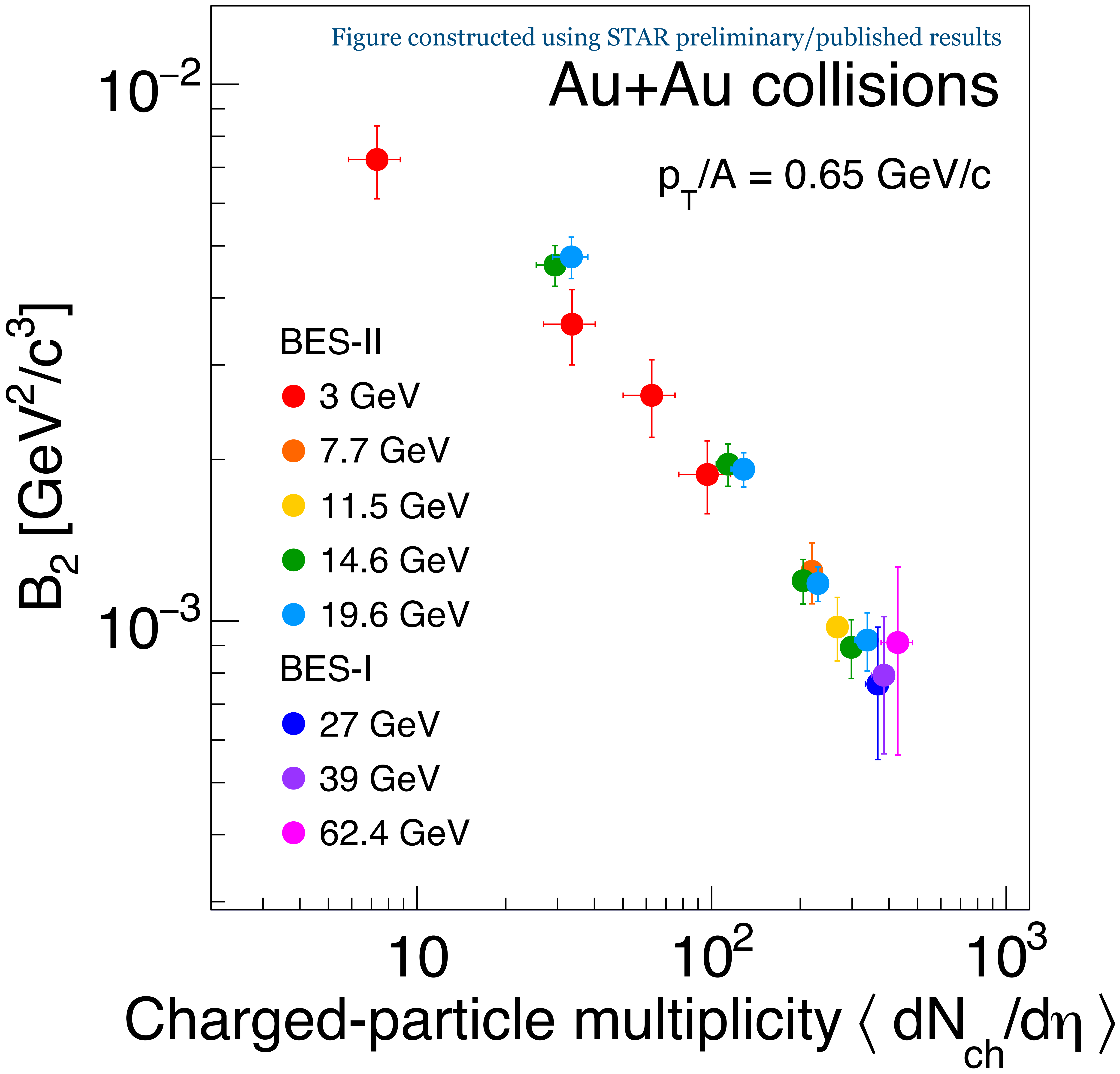
STAR, Phys.Rev.C 110, 054911 (2024)

Coalescence Parameters (B_A)

- $dN_{ch}/d\eta$ is a proxy of the volume of the system
- B_2 decreases with $dN_{ch}/d\eta$
    - Different collision energies approx. follow a global trend

Probability of coalescence is anti-correlated with the size of the system

STAR, Phys. Rev. C 99, 64905 (2019)
STAR, Phys.Rev.C 110, 054911 (2024)



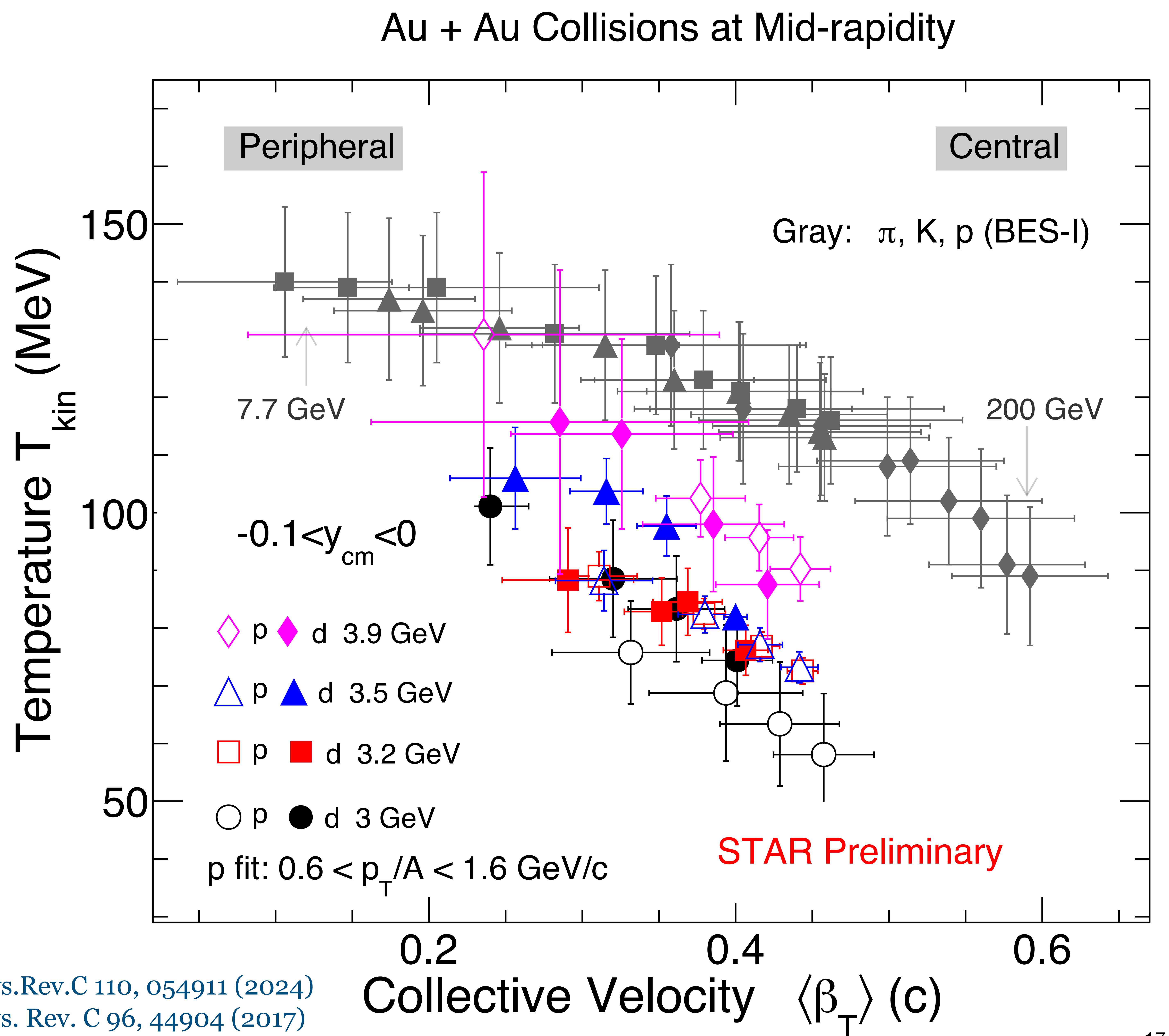
Deuteron Kinetic Freeze-out Parameters

- **Hydrodynamic-inspired Blast-Wave model**: assumes particles are emitted **thermally** from an expanding source with a common T_{kin} and $\langle \beta_T \rangle$

- Fit p and d spectra separately to obtain kinetic freeze-out parameters

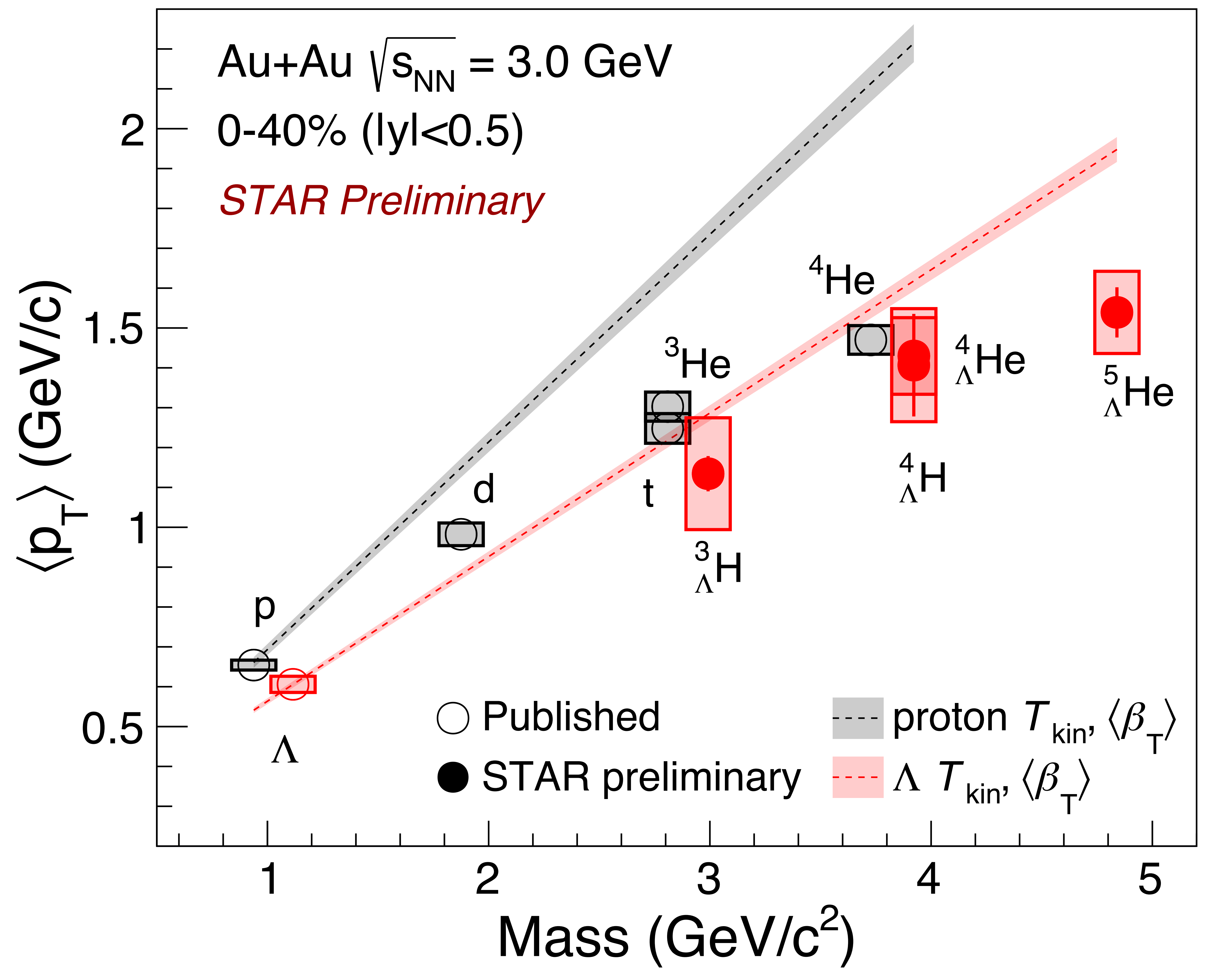
- Distinct kinetic freeze-out surfaces for p and d

Deuterons deviate from the hydrodynamical blast-wave picture



STAR, Phys.Rev.C 110, 054911 (2024)
STAR, Phys. Rev. C 96, 44904 (2017)

Mean Transverse Momentum $\langle p_T \rangle$ at 3 GeV



- Vary mass to construct blast-wave predictions using p(Λ) freeze-out parameters

	p	Λ
$\langle \beta_T \rangle$ (c)	0.43	0.33
T_{kin} (GeV)	0.065	0.076

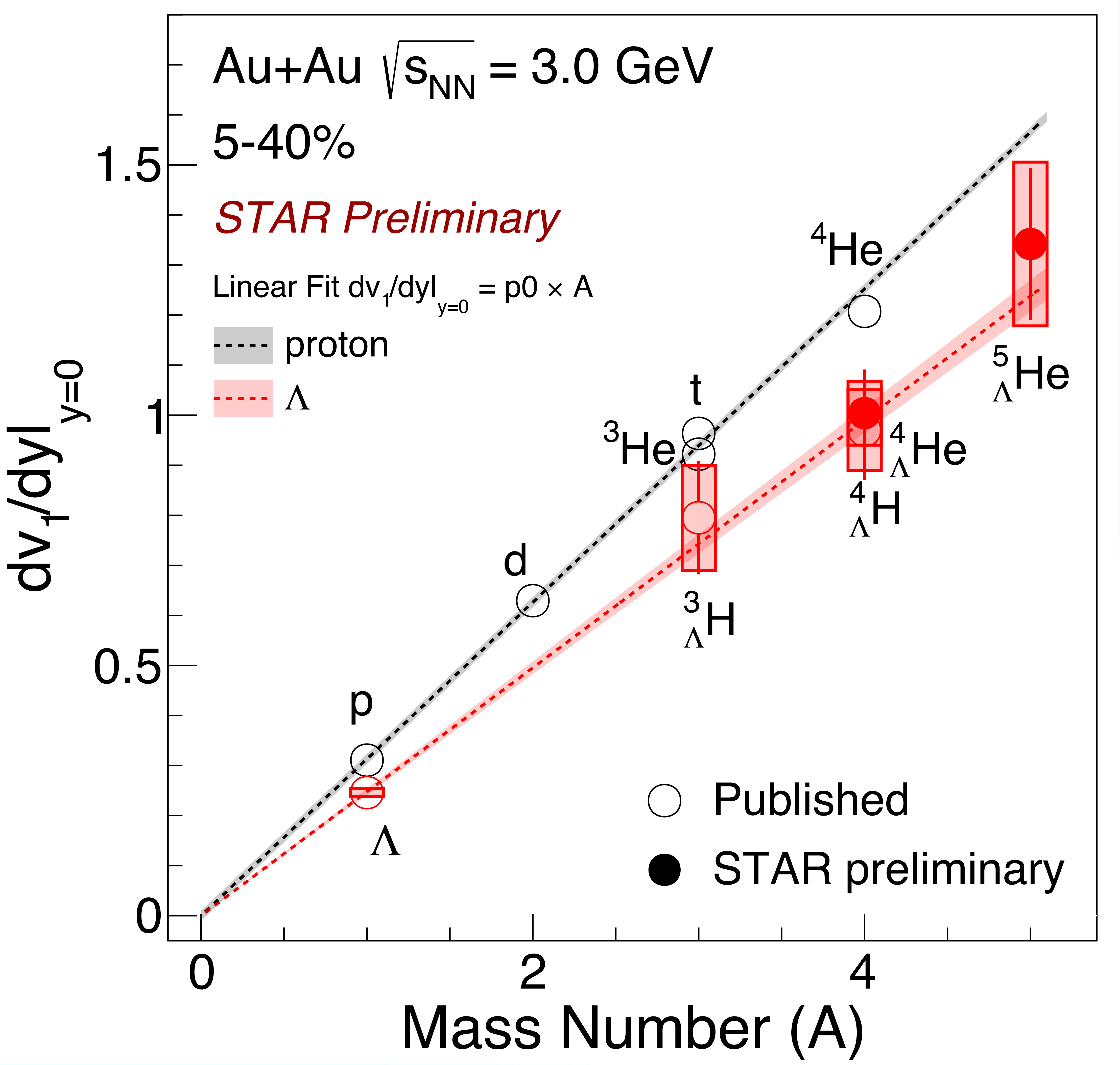
E. Schnedermann et al., PRC 48, 2462 (1993)
ALICE, PLB 794, 50–63 (2019)

- Hypernuclei closer to Λ blast-wave ansatz

Kinematics of (hyper)nuclei deviate from the collective expansion of the bulk matter

STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

Mass Number Scaling of Directed Flow at 3 GeV

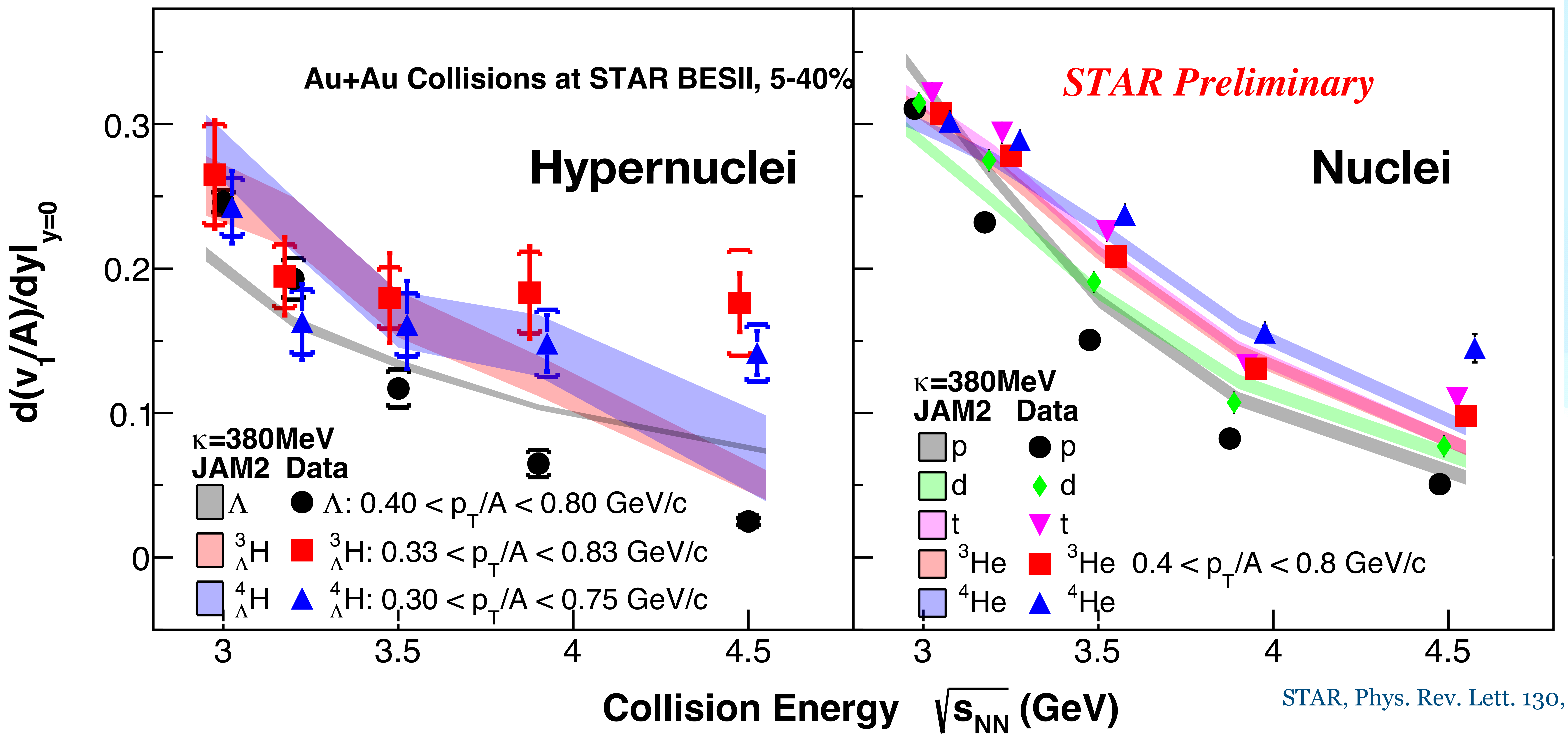


STAR, Phys. Rev. Lett. 130, 212301 (2023)

- Mid-rapidity v_1 slope of nuclei increase linearly with atomic mass number *A*
- Hypernuclei v_1 slope
  - systematically lower than light nuclei of similar *A*
  - compatible with Λ atomic mass number scaling, up to A=5

***A* scaling of v_1, qualitatively consistent with coalescence**

Collision Energy Dependence of (Hyper)nuclei Directed Flow



STAR, Phys. Rev. Lett. 130, 212301 (2023)

- Larger hypernuclei flow at 4.5 GeV than expected by JAM + coalescence

Agreement with *A* scaling deteriorates as the collision energy increases

Summary

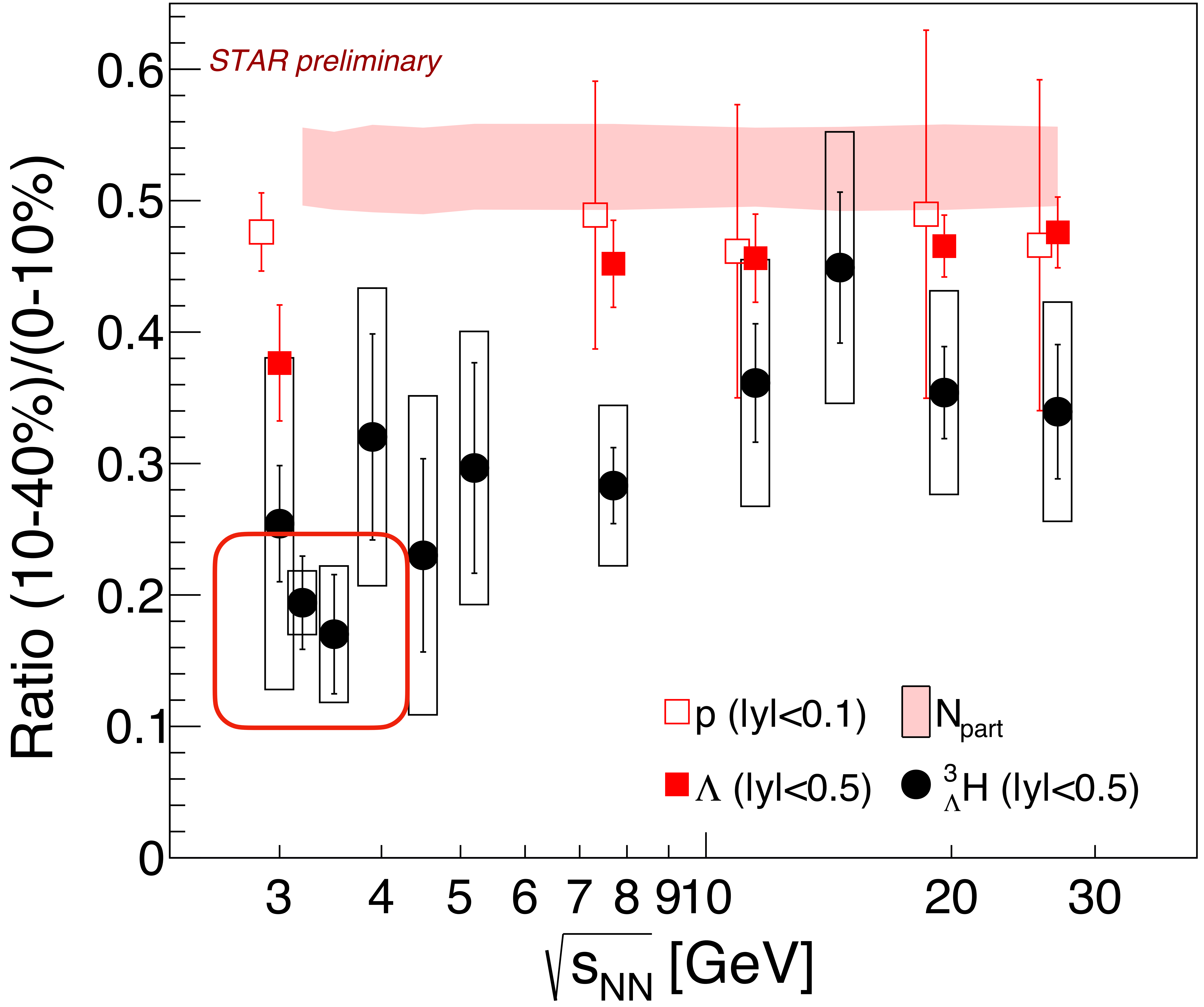
- Nuclei (d, t, ^{3}He, ^{4}He) and hypernuclei (${}^3_\Lambda$H, ${}^4_\Lambda$H, ${}^4_\Lambda$He, and ${}^5_\Lambda$He) yield and directed flow measurements from STAR BES-II at $\sqrt{s_{NN}}$ = 3-27 GeV
- Thermal model
  - Describes A=2, 4, 5 fairly well
  - **Strongly overpredicts A=3, N_tN_p/N_d^2, S_3**
- Blast-wave model
  - **Overpredicts ⟨p_T⟩ of (hyper)nuclei**
- Coalescence model
  - Describe N_tN_p/N_d^2 fairly well
  - **Describe S_3 well with Congleton wave function**
  - Qualitatively consistent with v_1 measurements, tension with hypernuclei data at 3.9-4.5 GeV

- **Data favors coalescence as the dominant production mechanism at midrapidity**
- **Coalescence calculations indicate sensitivity of ${}^3_\Lambda$H yields to its wave function in low multiplicity environments → opportunities to constrain YN(N) interactions**

Thank you for listening!!

Backup slides follow

Centrality Dependence



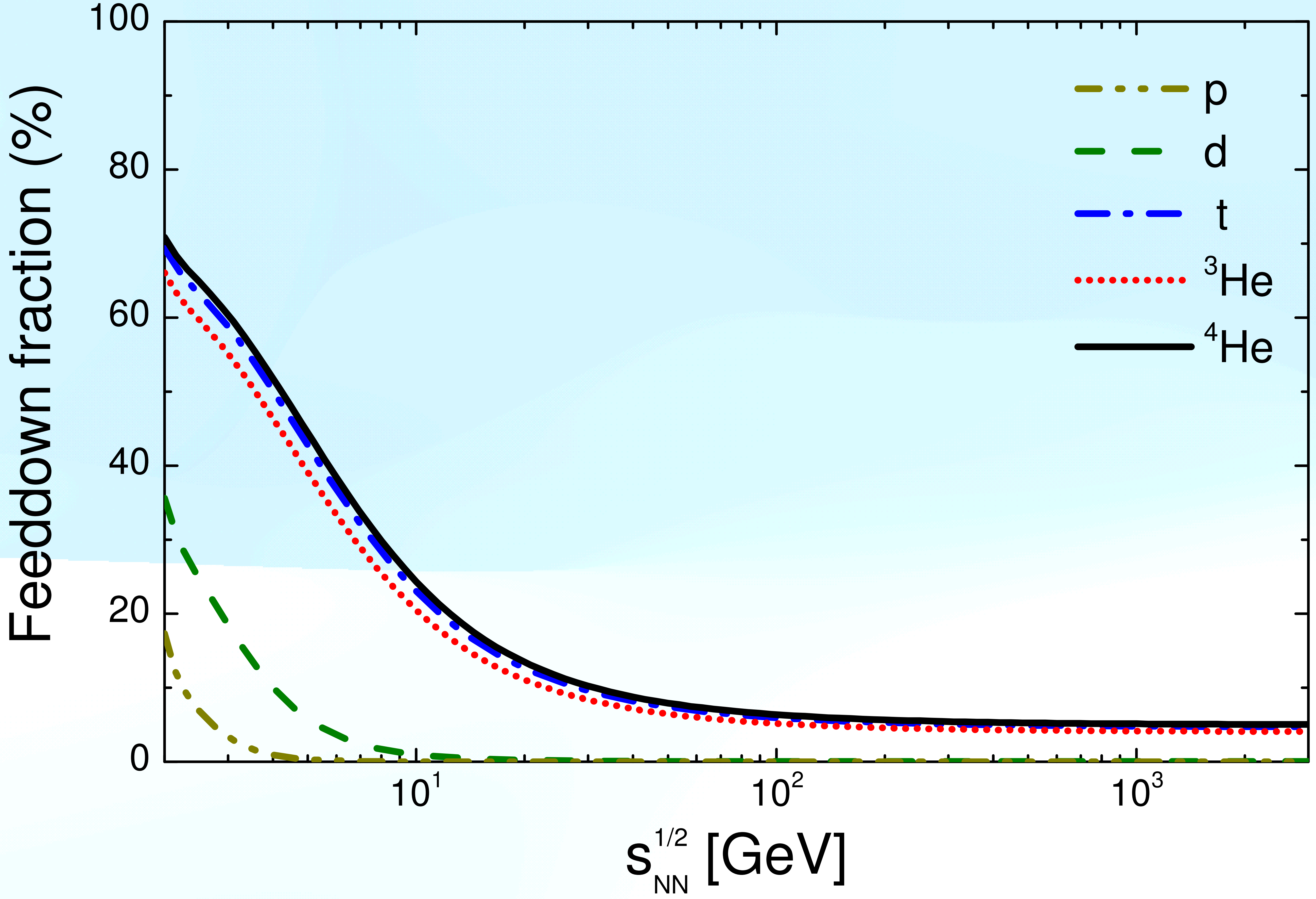
- Below $\sqrt{s_{NN}} \sim 4$ GeV, yield ratio (10-40%)/(0-10%) for $^{3}_{\Lambda}H$ is smaller compared to proton, Λ, and N_{part}

Suppression of $^{3}_{\Lambda}H$ production in more peripheral collisions compared to proton and Λ below $\sqrt{s_{NN}} \sim 4$ GeV

- Steep decline may be related to coalescence production and smaller source size in more peripheral collisions

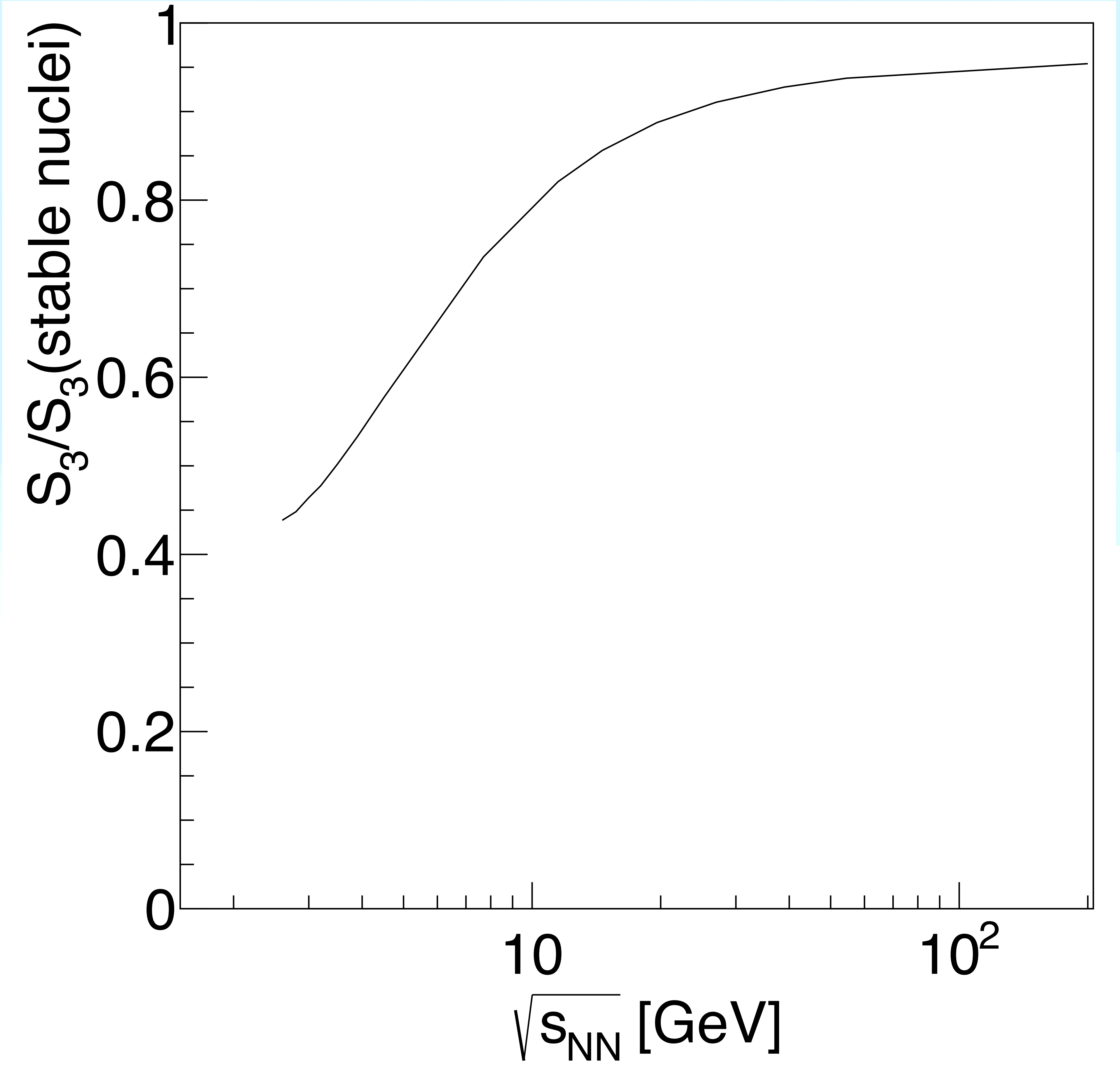
T. Reichert et al, Phys.Rev.C 107 (2023) 1, 014912
D. Liu et al, Phys.Lett.B 855 (2024) 138855

Feed-down from Unstable Nuclei



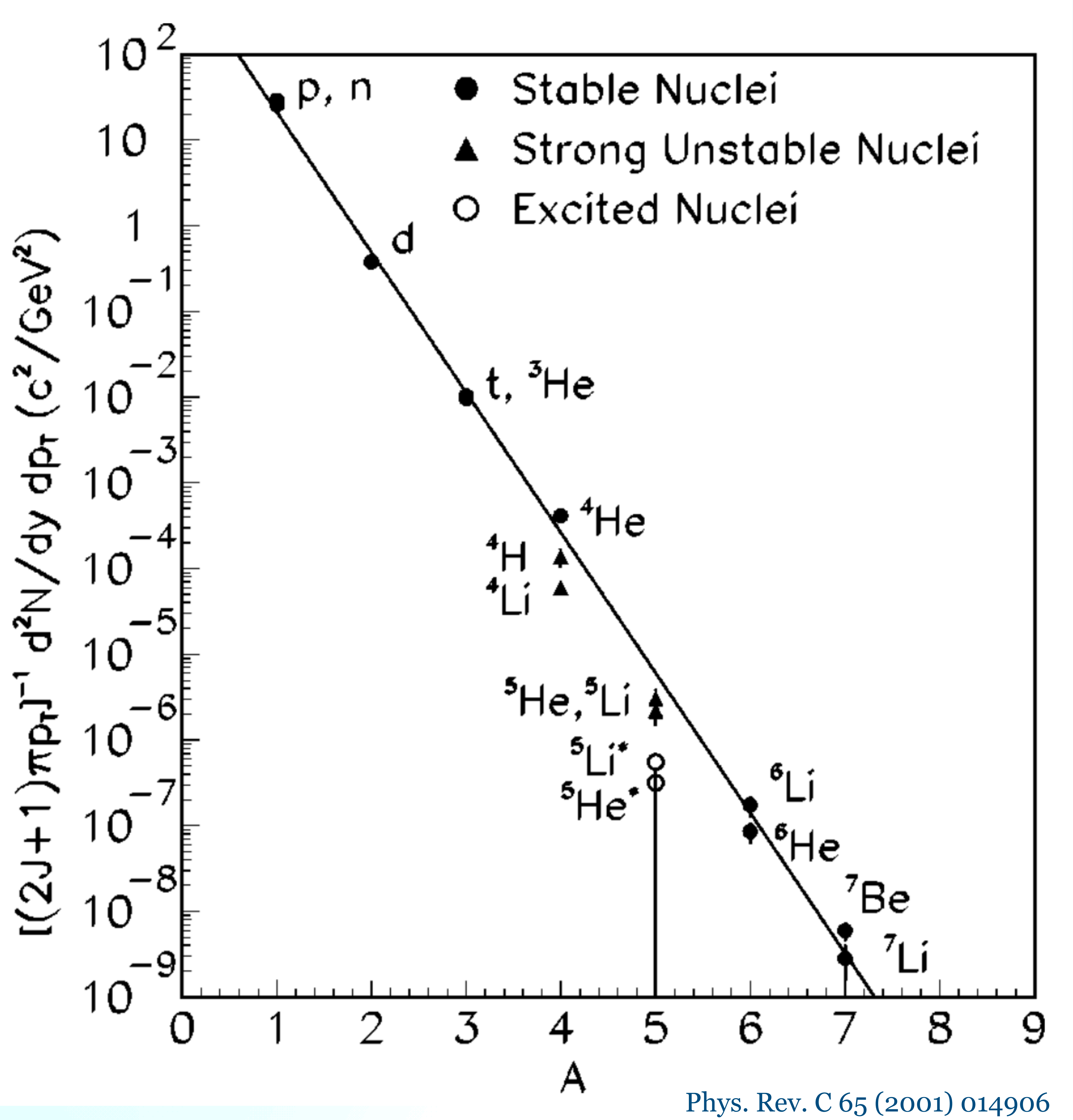
- Feed-down fractions estimated using Thermal-FIST

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



- Feed-down correction of S_3 from unstable nuclei estimated using Thermal-FIST

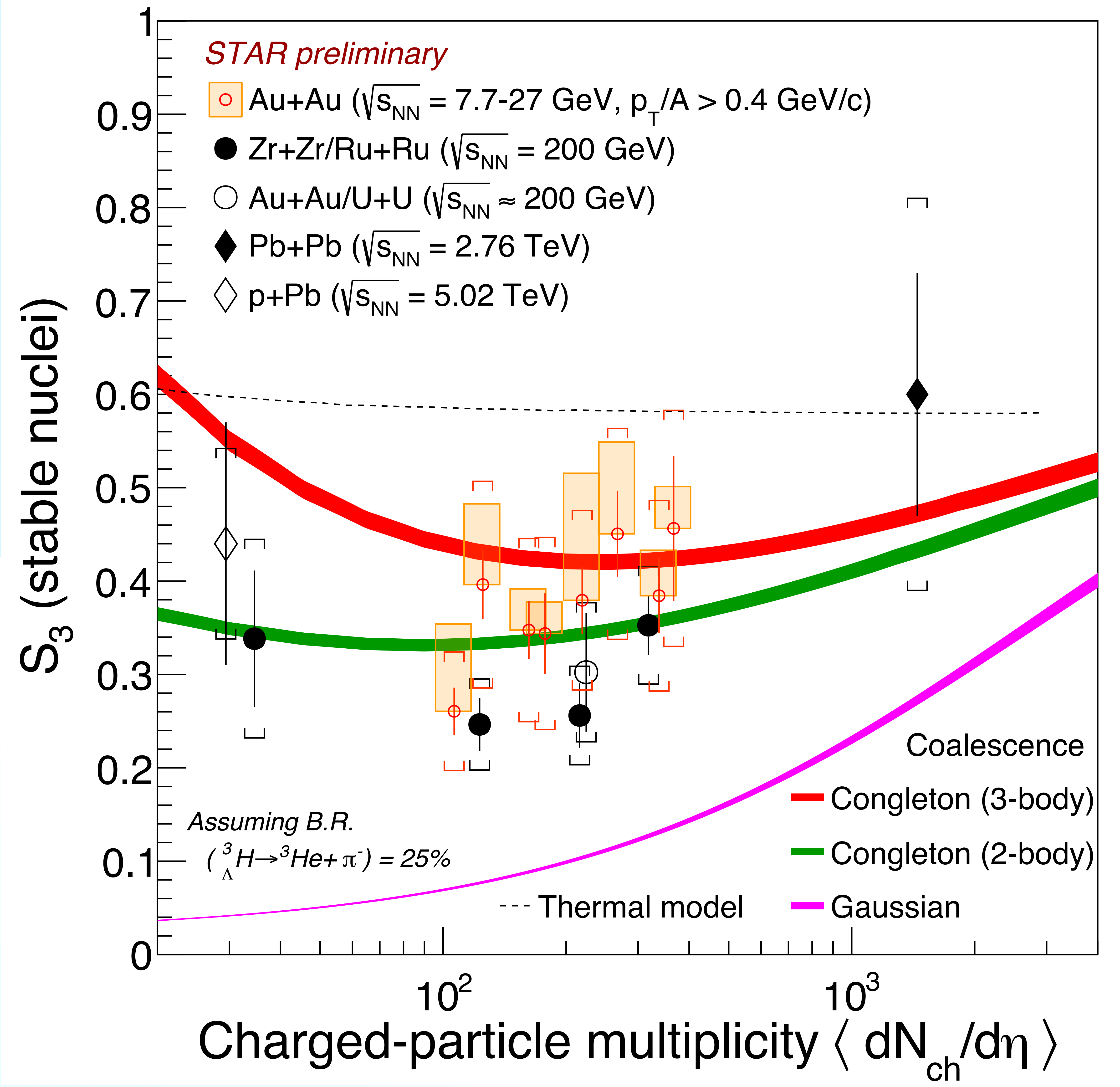
Feed-down from Unstable Nuclei

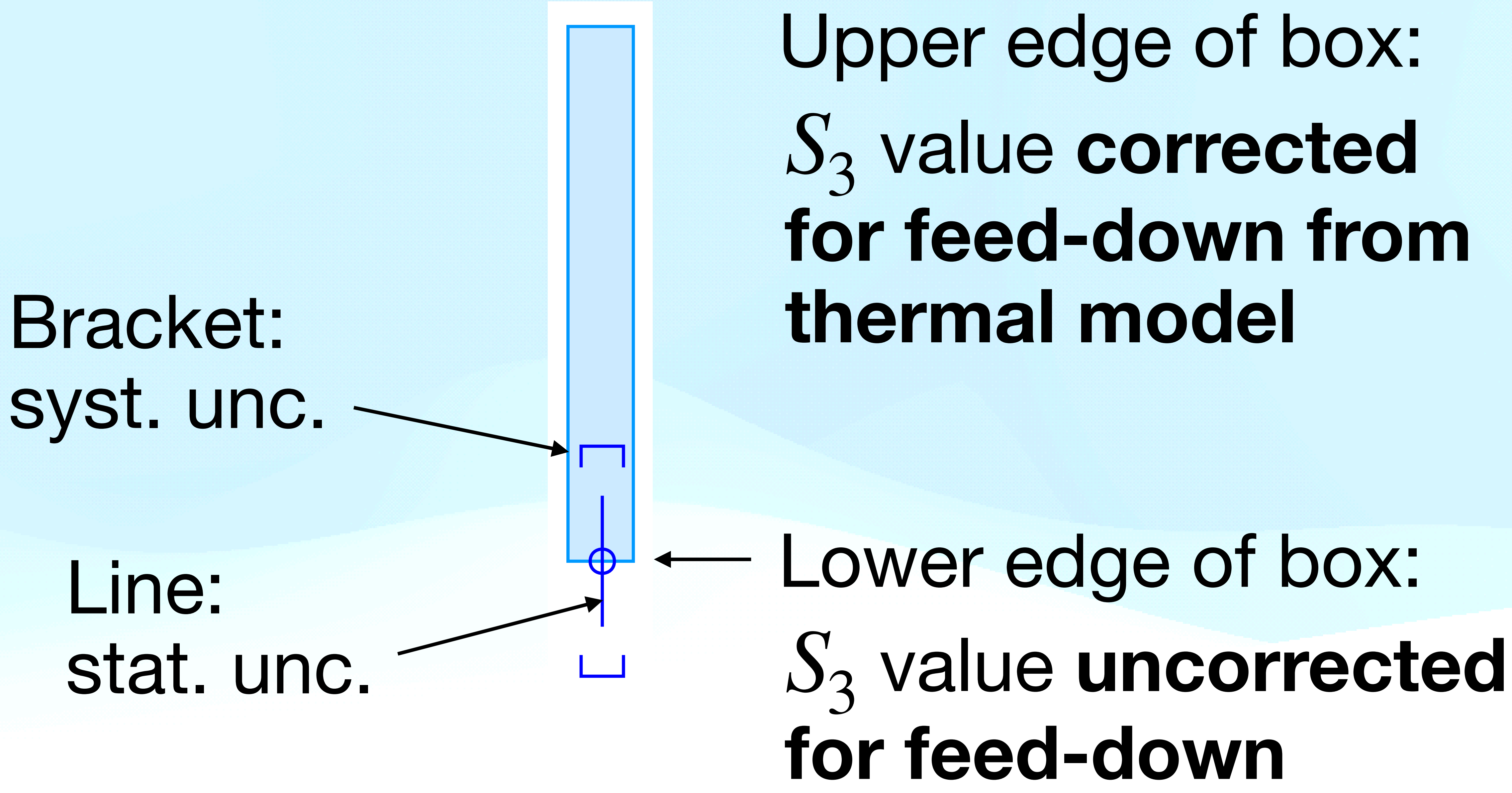


Phys. Rev. C 65 (2001) 014906

- Suppression of A=4 unstable states compared to ^{4}He ground state observed at E864

Strangeness Population Factor

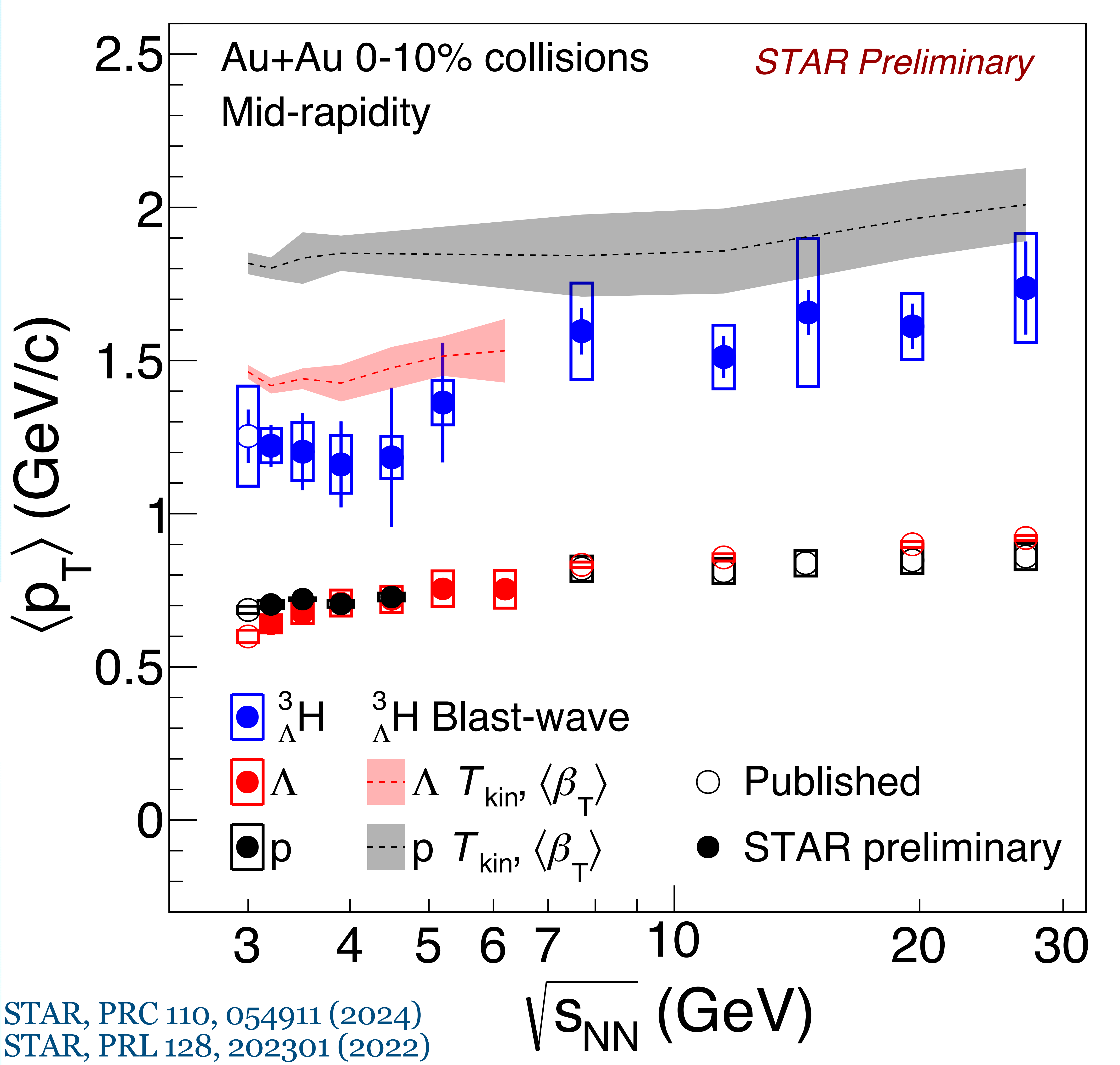




- Unstable nuclei production are suppressed relative to stable nuclei (see backup)
- The true value of S_3 (stable nuclei) very likely lies between the upper and lower limits

ALICE, Phys.Rev.Lett. 128(2022)252003
(Thermal) V. Vovchenko, Phys.Lett.B 785(2018)171
(Coalescence) K. Sun et al, Phys.Lett.B 792(2019)132

Insight from Blast-Wave Comparison



STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

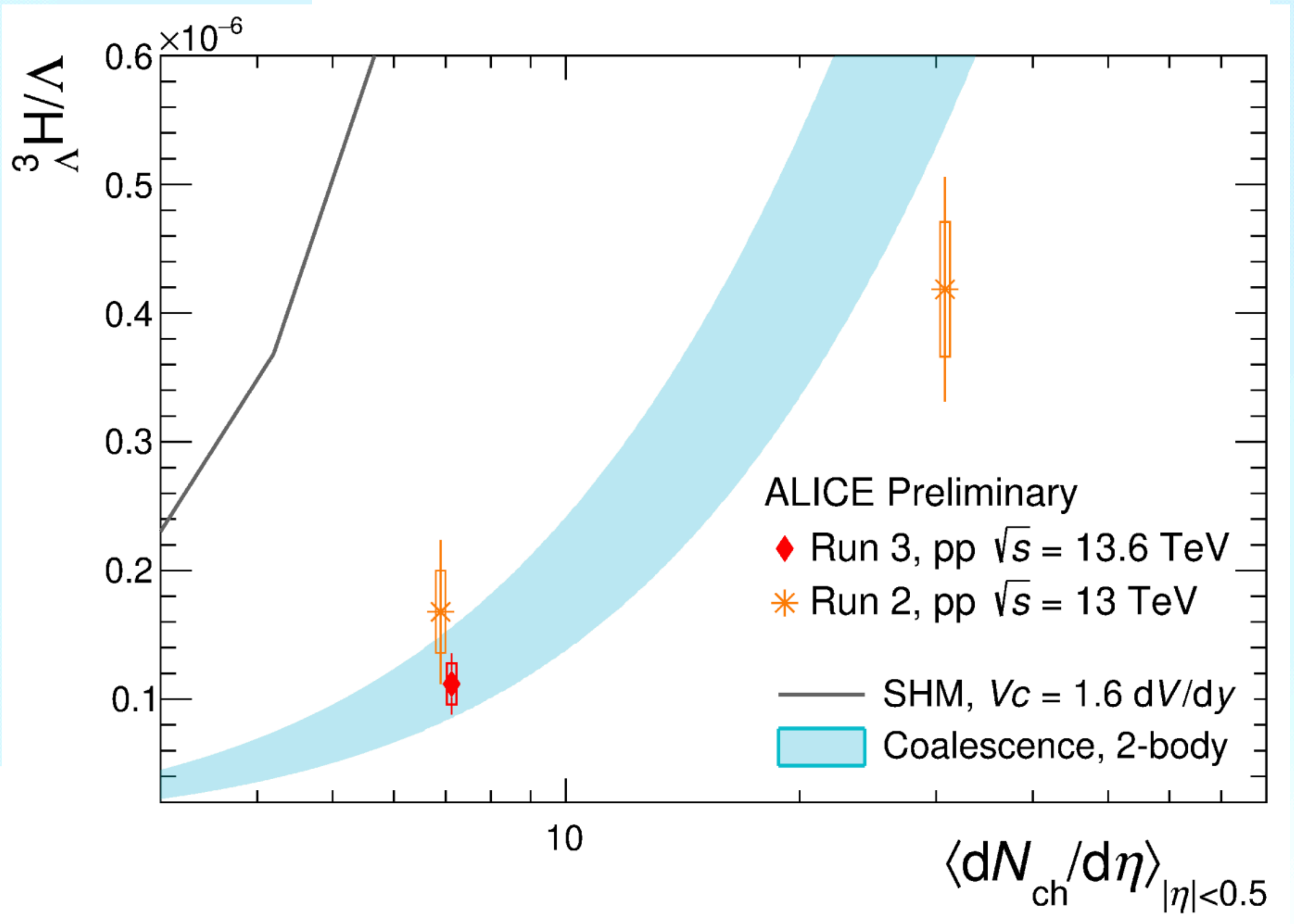
- At $\sqrt{s_{NN}} \geq 7.7$ GeV, $^{3}_{\Lambda}H$ $\langle p_T \rangle$ tends to approach the blast-wave prediction with proton freeze-out parameters
  - May be due to increasing effective volume for coalescence with increasing energy

D.-N. Liu et al., PLB 855, 138855 (2024)

- Noticeable change between 4.5 and 7.7 GeV

System Size Dependence at High Collision Energies

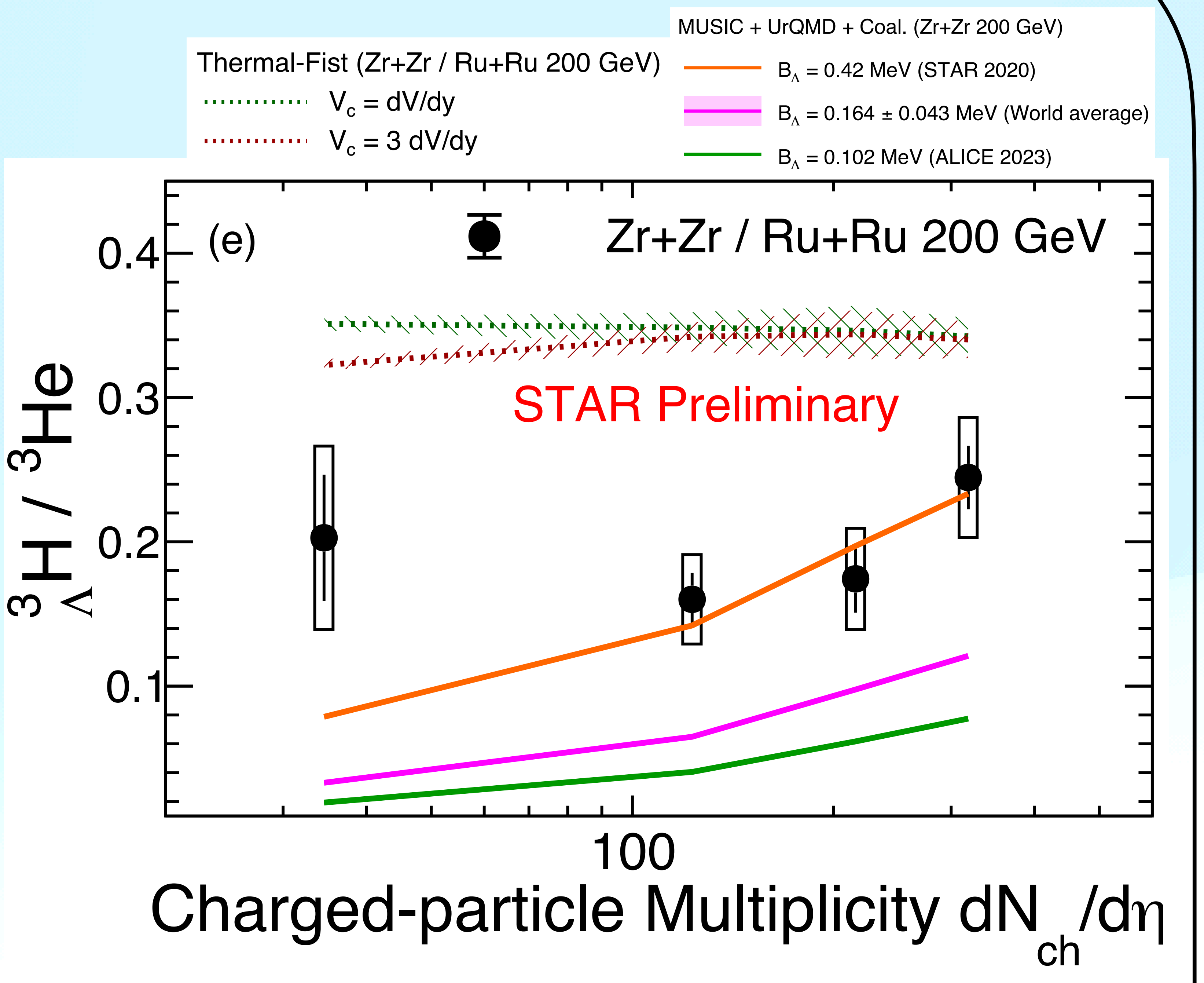
J. Ditzel (ALICE), QM2025



p+p @ $\sqrt{s}$ = 13, 13.6 GeV

$dN_{ch}/d\eta \sim O(10)$

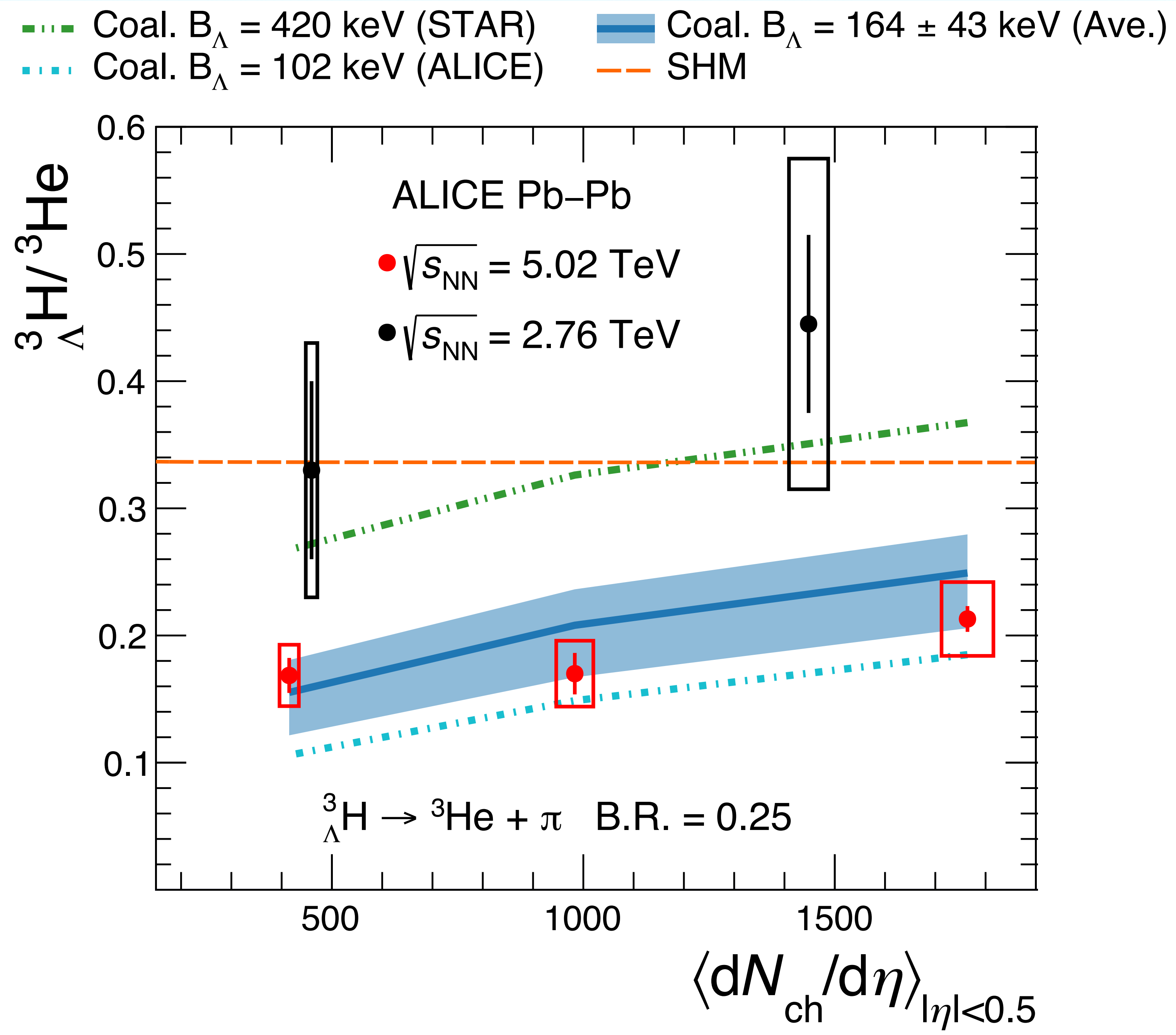
D. Li (STAR), SQM2024



Ru/Zr+Ru/Zr @ $\sqrt{s_{NN}}$ = 200 GeV

$dN_{ch}/d\eta \sim O(100)$

ALICE, Phys.Lett.B 860 (2025) 139066



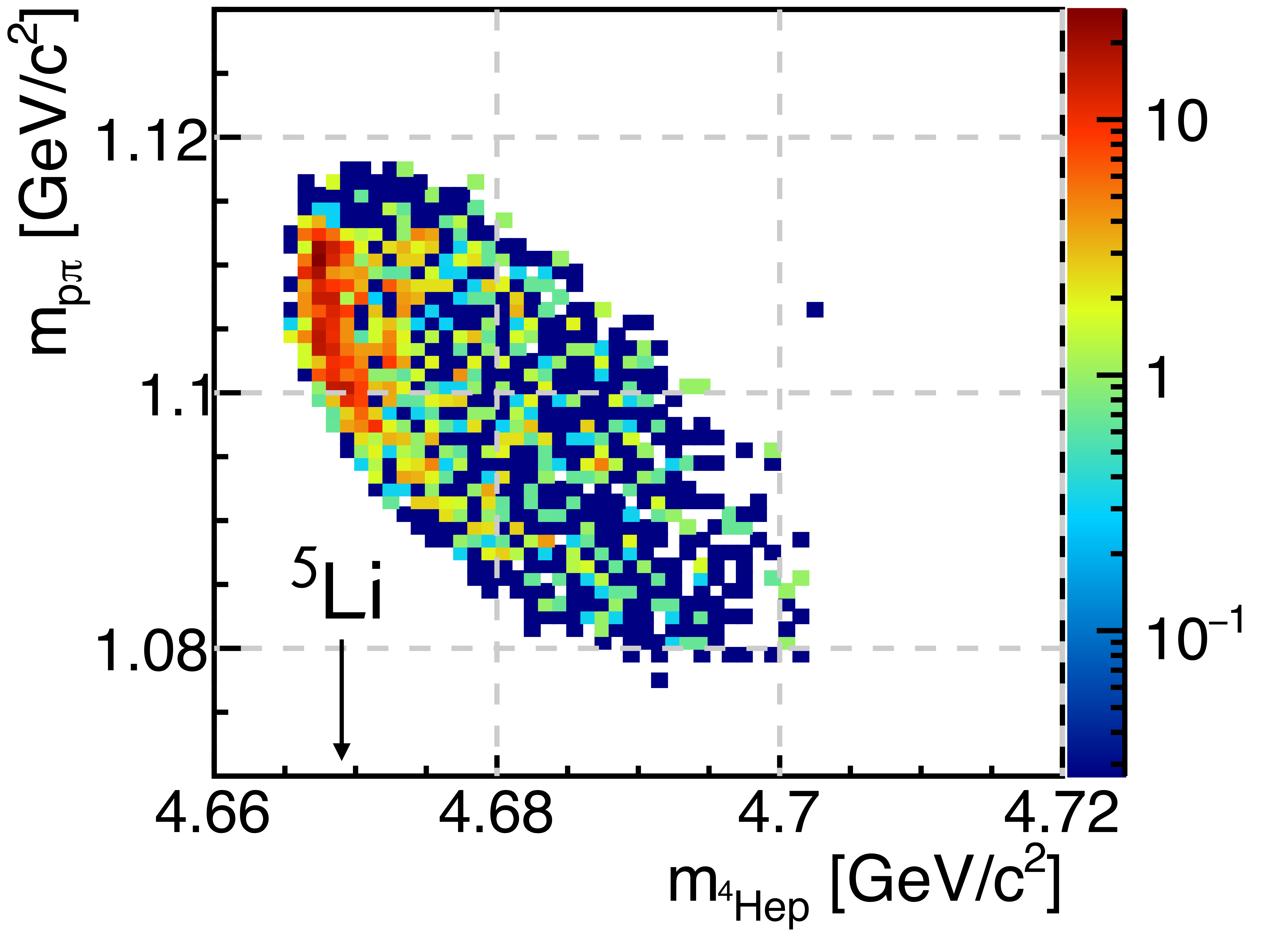
Pb+Pb @ $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

$dN_{ch}/d\eta \sim O(1000)$

Small systems ⟶ Large systems

Across all systems, thermal model overestimates $^{3}_{\Lambda}\mathrm{H}$ production

Dalitz plot for ${}^{5}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p} + \pi^{-}$



Nuclei Production at the LHC

d/p $\quad$ $^3He/p$ $\quad$ t/p $\quad$ $^4He/p$

A=2,4: fairly well described; A=3 nuclei: strongly overpredicted

Coalescence calculations (arXiv:2510.06758)

Phys.Rev.C 103, 014907 (2021)

$$B_3({}^3_\Lambda\mathrm{H}) \approx \frac{3}{m^2}\frac{2s_{{}^3_\Lambda\mathrm{H}}+1}{(2s_N+1)^3}(2\pi)^6\int d^3r_{pn}\int d^3r_\Lambda \underbrace{|\Phi_{{}^3_\Lambda\mathrm{H}}(r_{pn},r_\Lambda)|^2}_{\text{Wave function}}\ \underbrace{\mathcal{S}_3(r_{pn},r_\Lambda)}_{\text{Nucleon source}}$$

Wave function

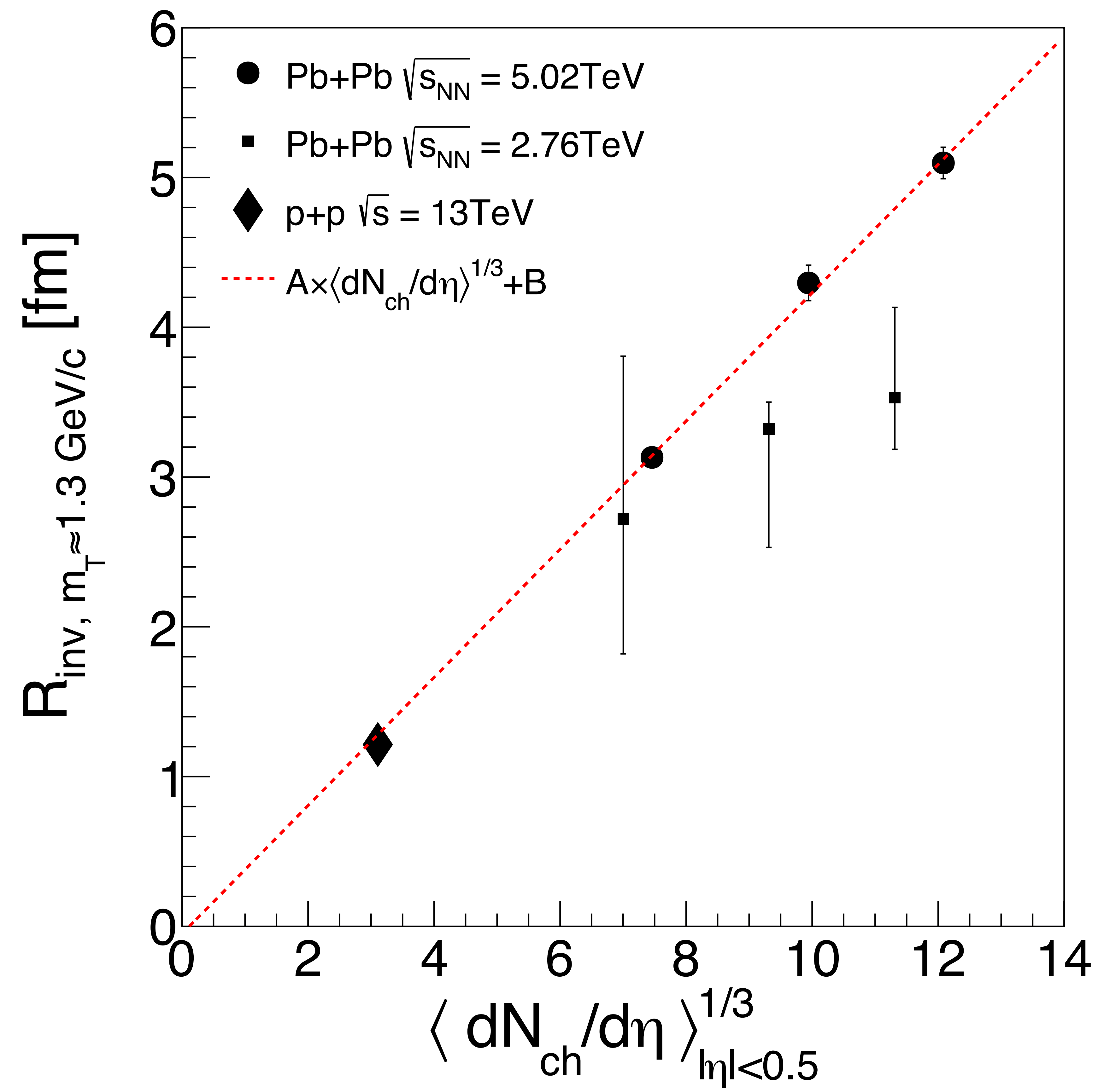
Nucleon source

- Assuming an isotropic Gaussian nucleon source

$$\mathcal{S}_3(r_{12},r_3) = \frac{1}{(12\pi^2 R_{\mathrm{inv}}^4)^{3/2}}\exp\left(-\frac{r_{12}^2+\frac{4}{3}r_3^2}{4R_{\mathrm{inv}}^2}\right)$$

- Use ALICE baryon-baryon **correlation function data** to estimate R_{inv} for **high energy collisions**

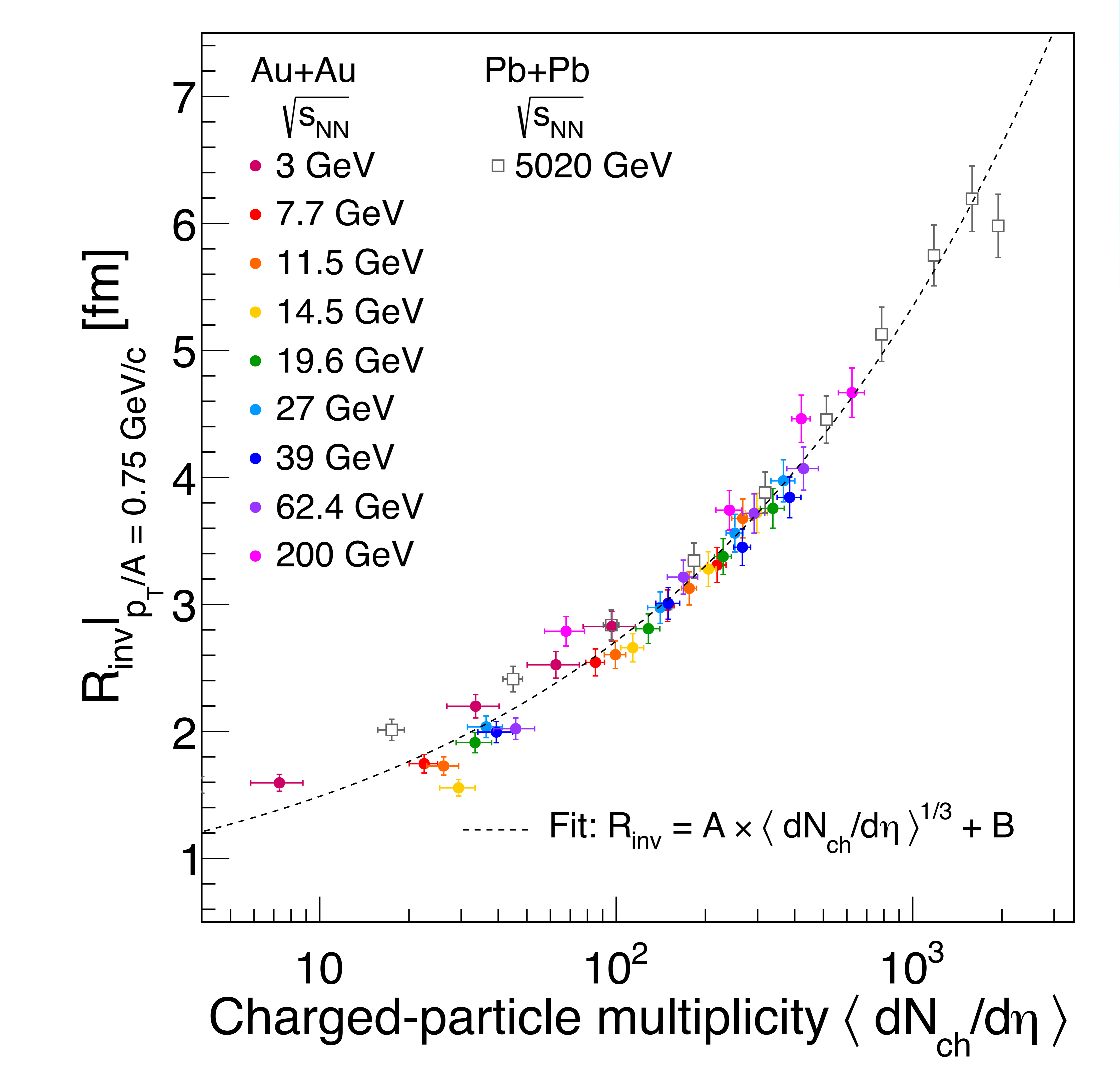
ALICE, arXiv:2505.01061

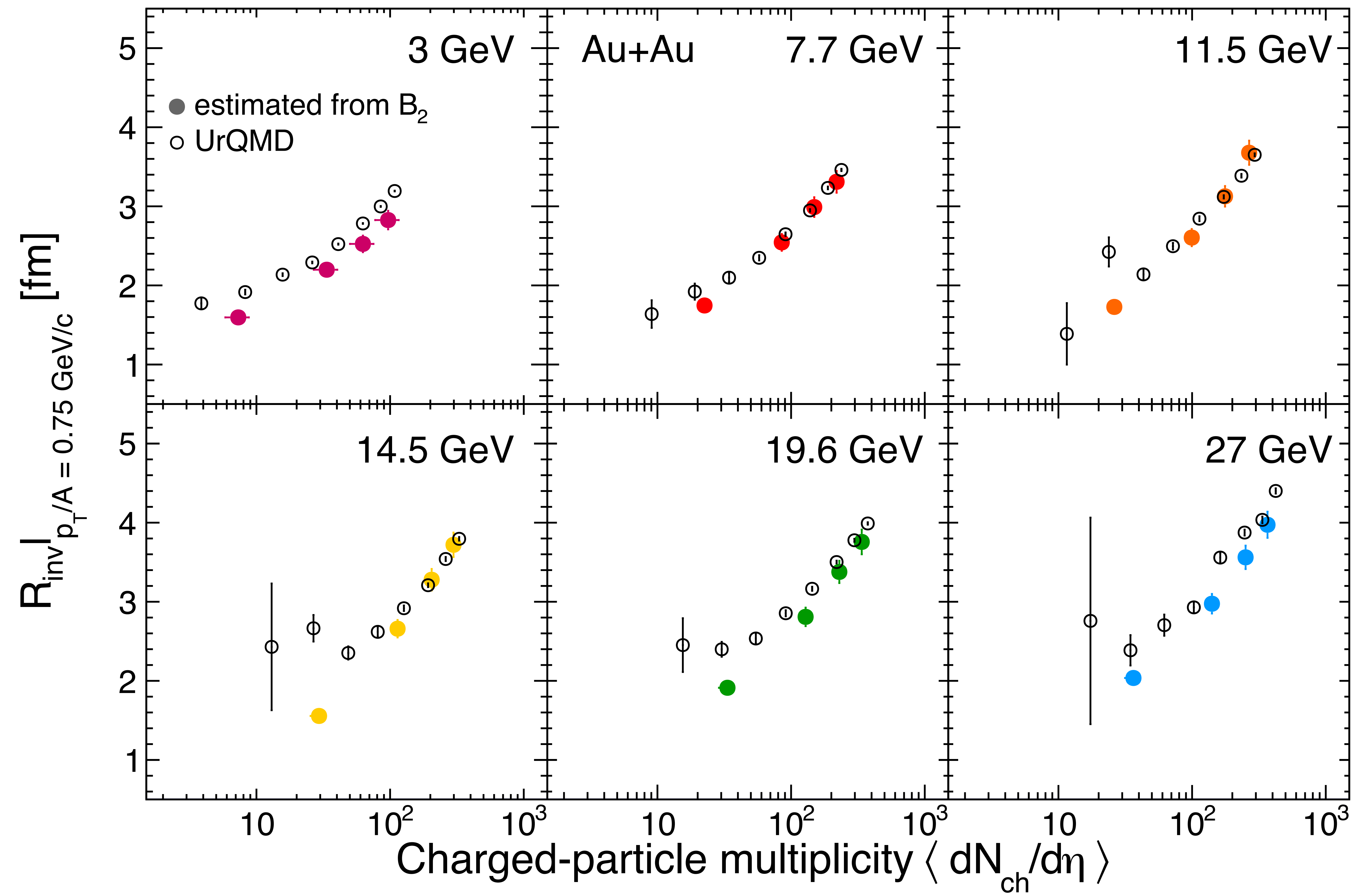


Coalescence calculations (arXiv:2510.06758)

- Use deuteron data to estimate R_{inv} **for BES energies**
- Calculate B_2 as function for pT and centrality using data
- Use coalescence formula with Argonne v_{18} wave function to obtain R_{inv}

$$B_2(d) \approx \frac{2(2s_d+1)}{m\,(2s_N+1)^2(2\pi)^3}\int d^3r|\Phi_d(r)|^2\,\mathcal{S}_2(r)$$





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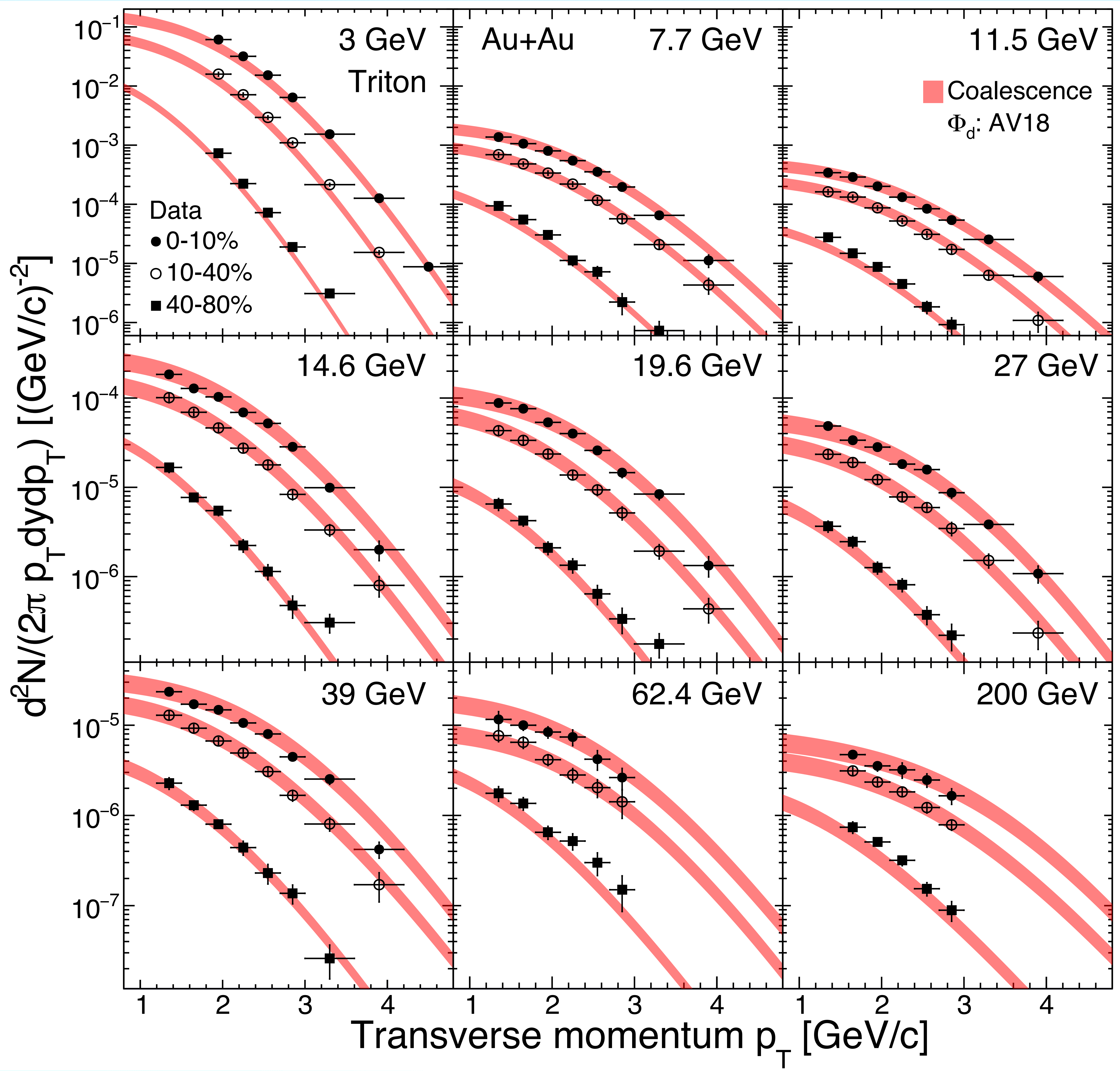

- Calculations describe triton data well

Overview of (Hyper)Nuclei Results from BES-II

$\sqrt{s_{NN}}$ [GeV]	d	t	^{3}He	^{4}He	$\bar{d}$	$^3_\Lambda$H	$^4_\Lambda$H	$^4_\Lambda$He	$^5_\Lambda$He
3	✅	✅	✅	✅		✅	✅	☑️	☑️
3.2	☑️	☑️	☑️	☑️		☑️	☑️	☑️	
3.5	☑️	☑️	☑️	☑️		☑️	☑️	☑️	
3.9	☑️	☑️	☑️	☑️		☑️	☑️		
4.5	☑️	☑️	☑️	☑️		☑️			
5.2						☑️			
7.7	☑️		☑️		☑️	☑️			
9.2	☑️		☑️		☑️				
11.5	☑️		☑️		☑️	☑️			
14.6	☑️		☑️		☑️	☑️			
17.3	☑️		☑️		☑️				
19.6	☑️		☑️		☑️	☑️			
27	☑️		☑️		☑️	☑️			

FXT: mid-rapidity to target rapidity from 3-4.5 GeV

COL: mid-rapidity

✅ : Published
☑️ : Preliminary