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Measurement of Hypertriton Production at RHIC

Xiujun Li (李秀君)
University of Science and Technology of China

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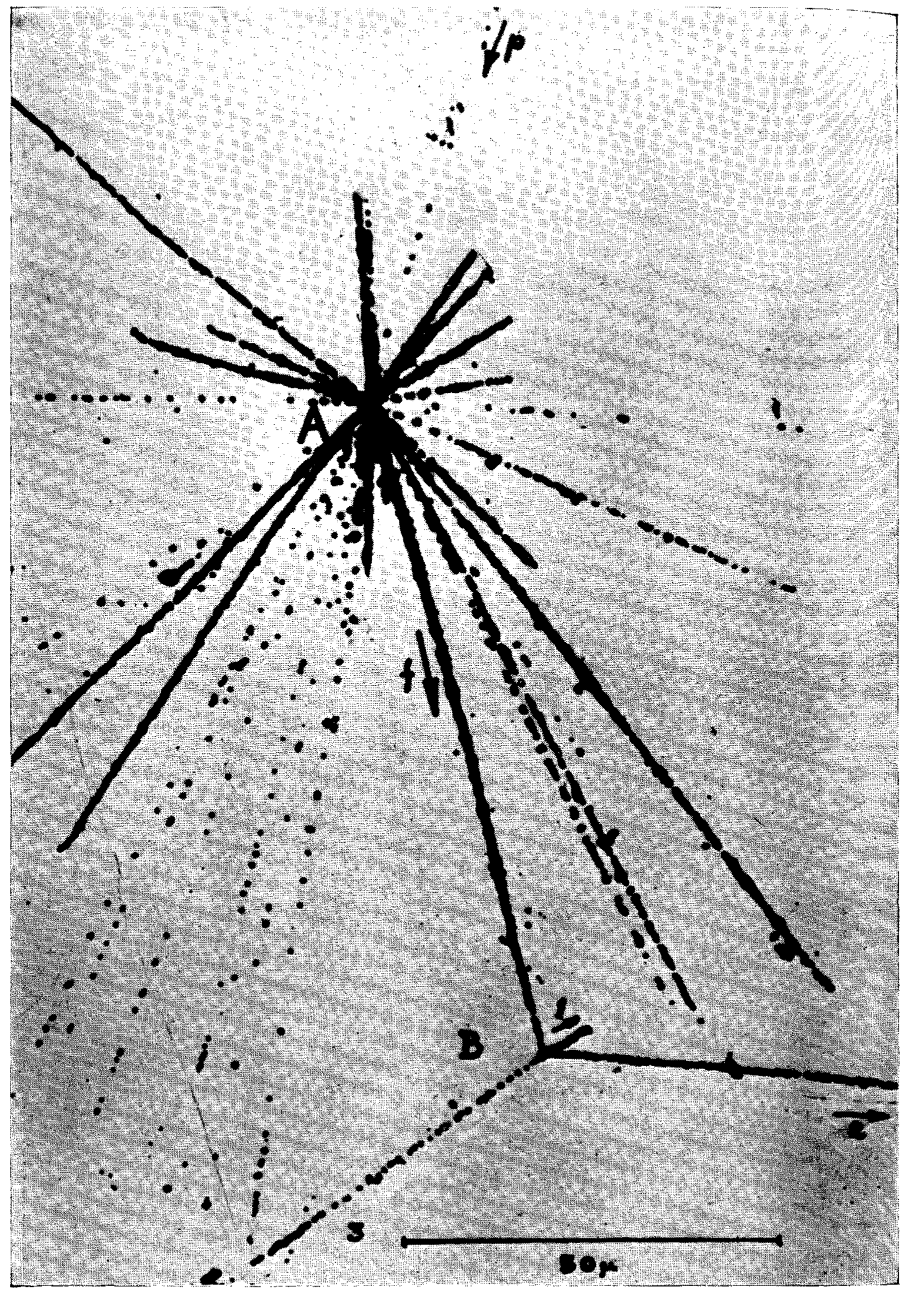
中国科学技术大学
1958
University of Science and Technology of China

Introduction: hypernuclei

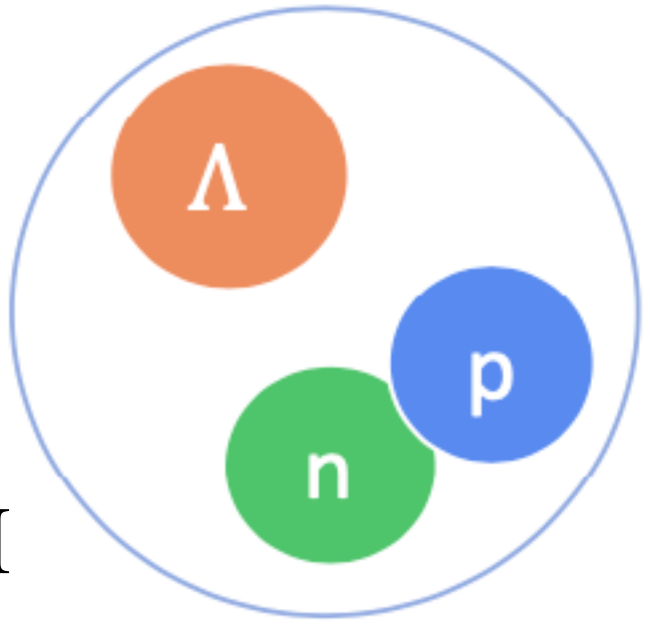
- Hypernuclei: bound nuclear systems of non-strange and strange baryons

  — **Natural hyperon-baryon correlation system**



The first discovery of hypernucleus by Marian Danysz (right) and Jerzy Pniewski (left) in 1952

M. Danysz, J. Pniewski, Philos. Mag. 44 (1953) 348.

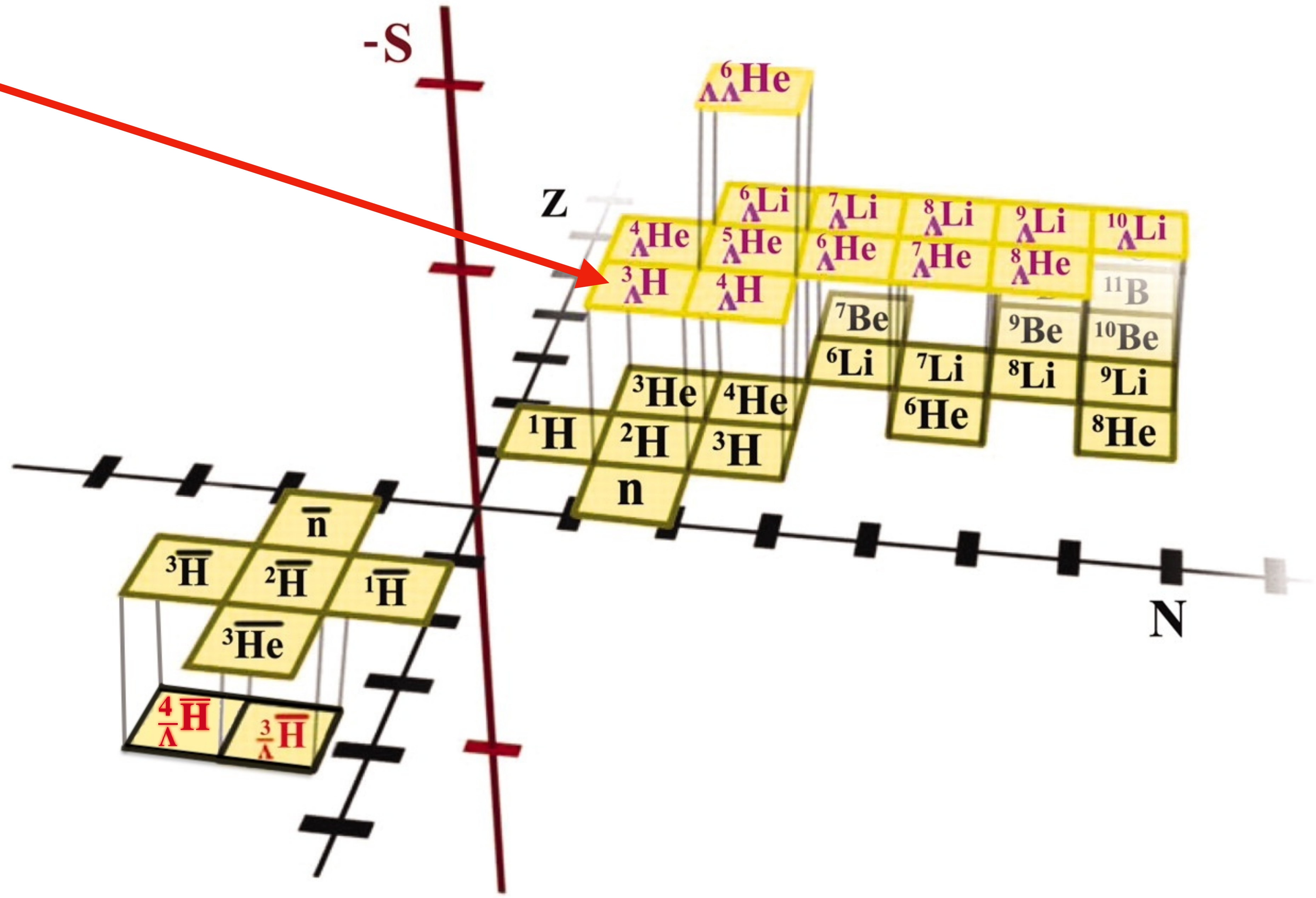


$^{3}_{\Lambda}\mathrm{H}$

lightest hypernucleus

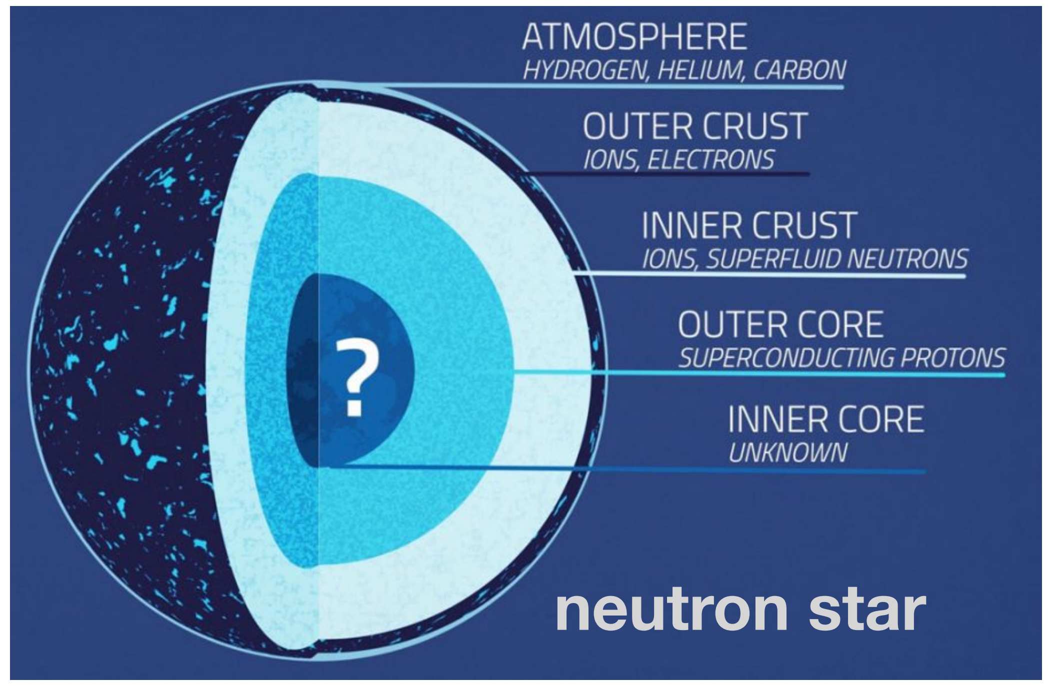
$B_\Lambda \sim 0.15\mathrm{MeV}$

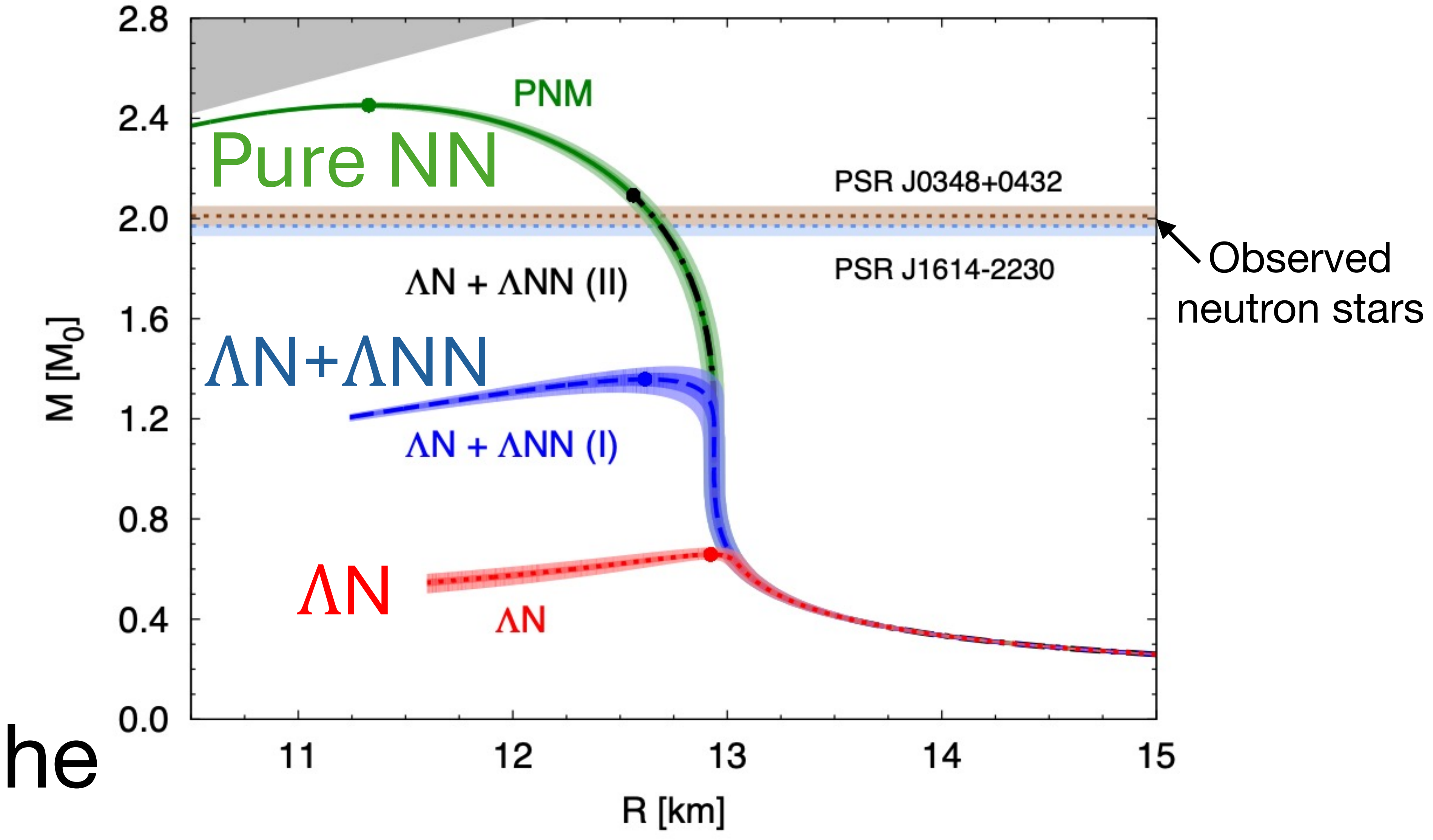
RMS radius $5 \sim 10$ fm



Introduction: YN interaction in dense matter

- Hypernuclei serve as a laboratory to study the hyperon–nucleon (YN) interaction
  - YN interaction is essential in probing dense inner core of neutron star
    - **Hyperon puzzle**: do hyperons exist in the dense inner core of neutron stars?
      - No direct method to probe inner core
        - Rely on theoretical models compared with observations
      - Lack of experimental data of YN, YNN, YY interactions to constrain theoretical models of the dense matter equation of state (EoS)



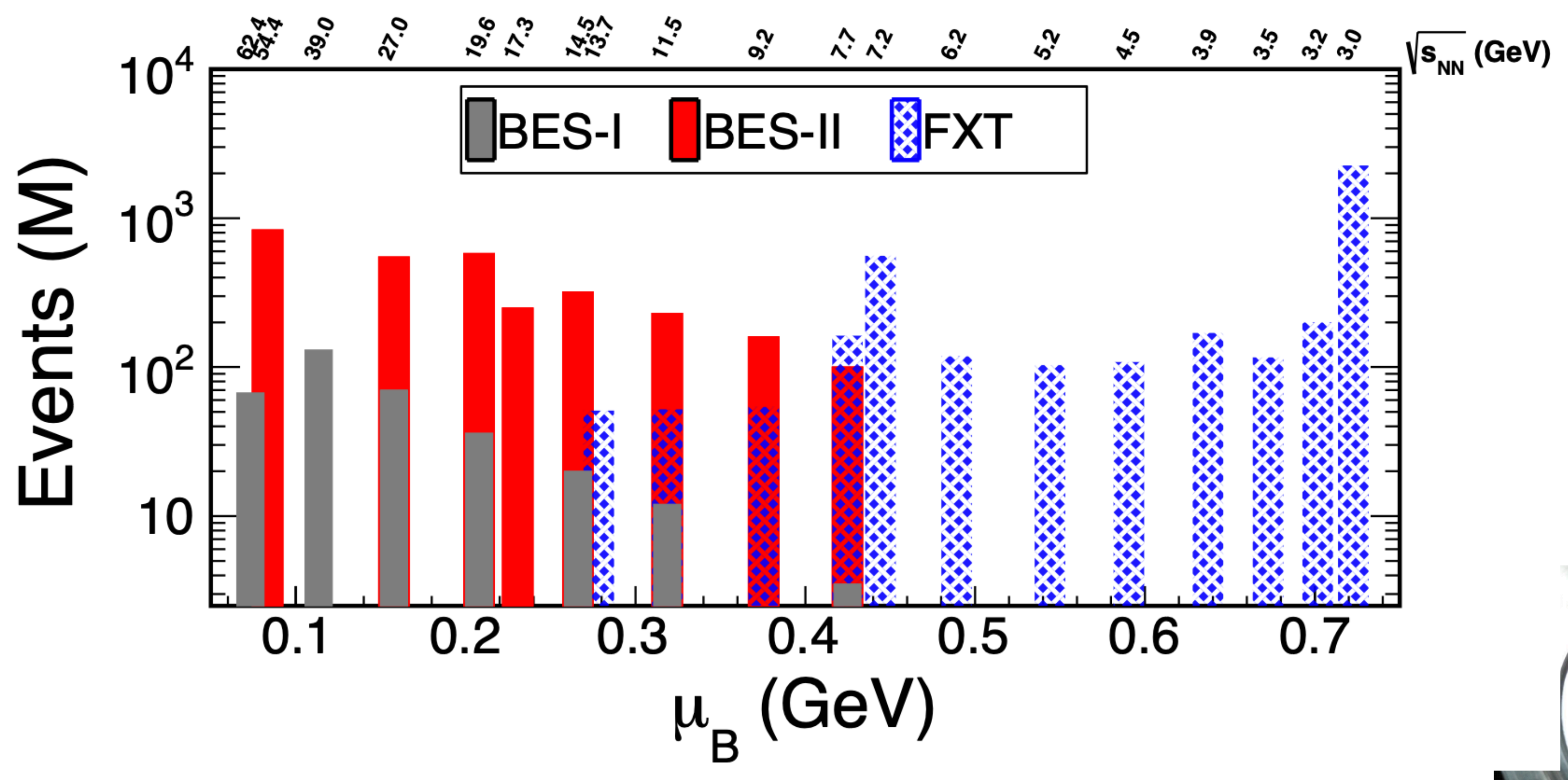


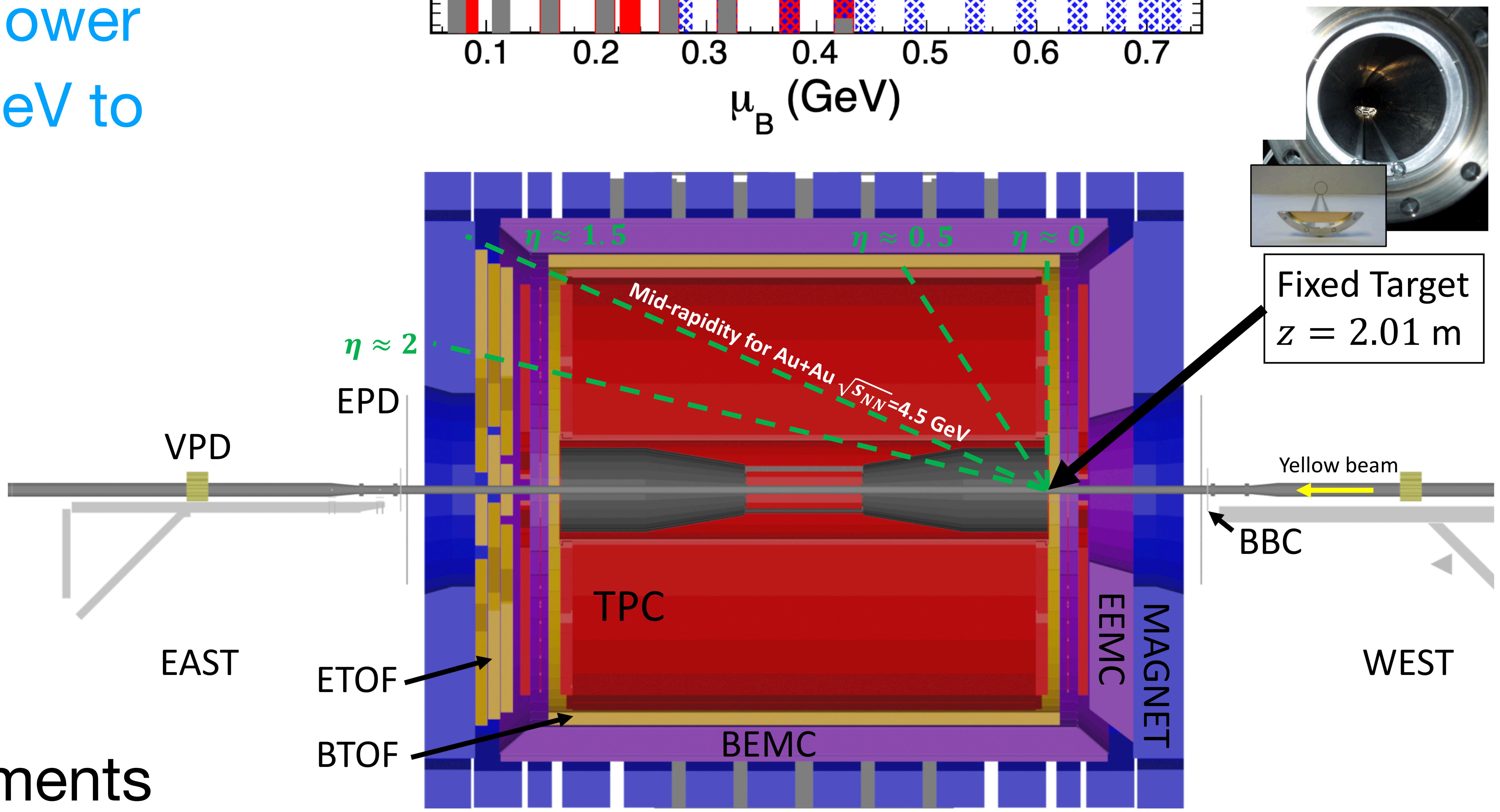
D. Lonardoni, et al. PRL 114, 092301 (2015)

Introduction: RHIC BES-II

- RHIC beam energy scan Phase II (BES-II):
  - Specific focus on low $\sqrt{s_{\mathrm{NN}}}$
    - Include fixed target (FXT) mode to reach lower energies, increase μ_{B} range from ~400 MeV to ~700 MeV
  - High statistics data
  - Improve systematics
    - Detector upgrade: iTPC, EPD, eTOF

— Enhances the capability of various measurements with excellent precision



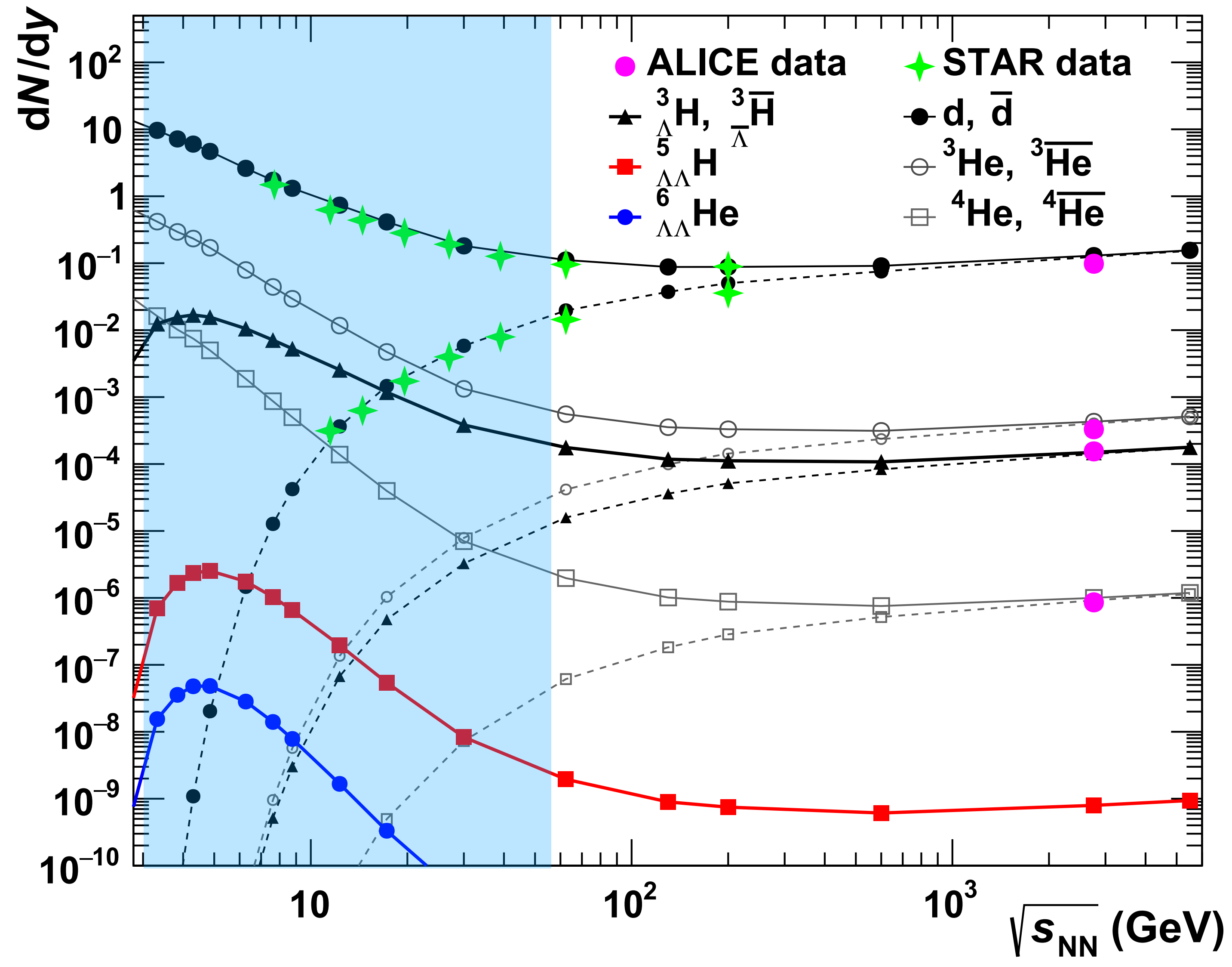


Introduction: hypernuclei in HI collisions

Production mechanism of hypernuclei is still not well understood.

Hypernuclei formation process in relativistic heavy-ion (HI) collisions

can be studied through measurements related to **spectra and collective flow.**

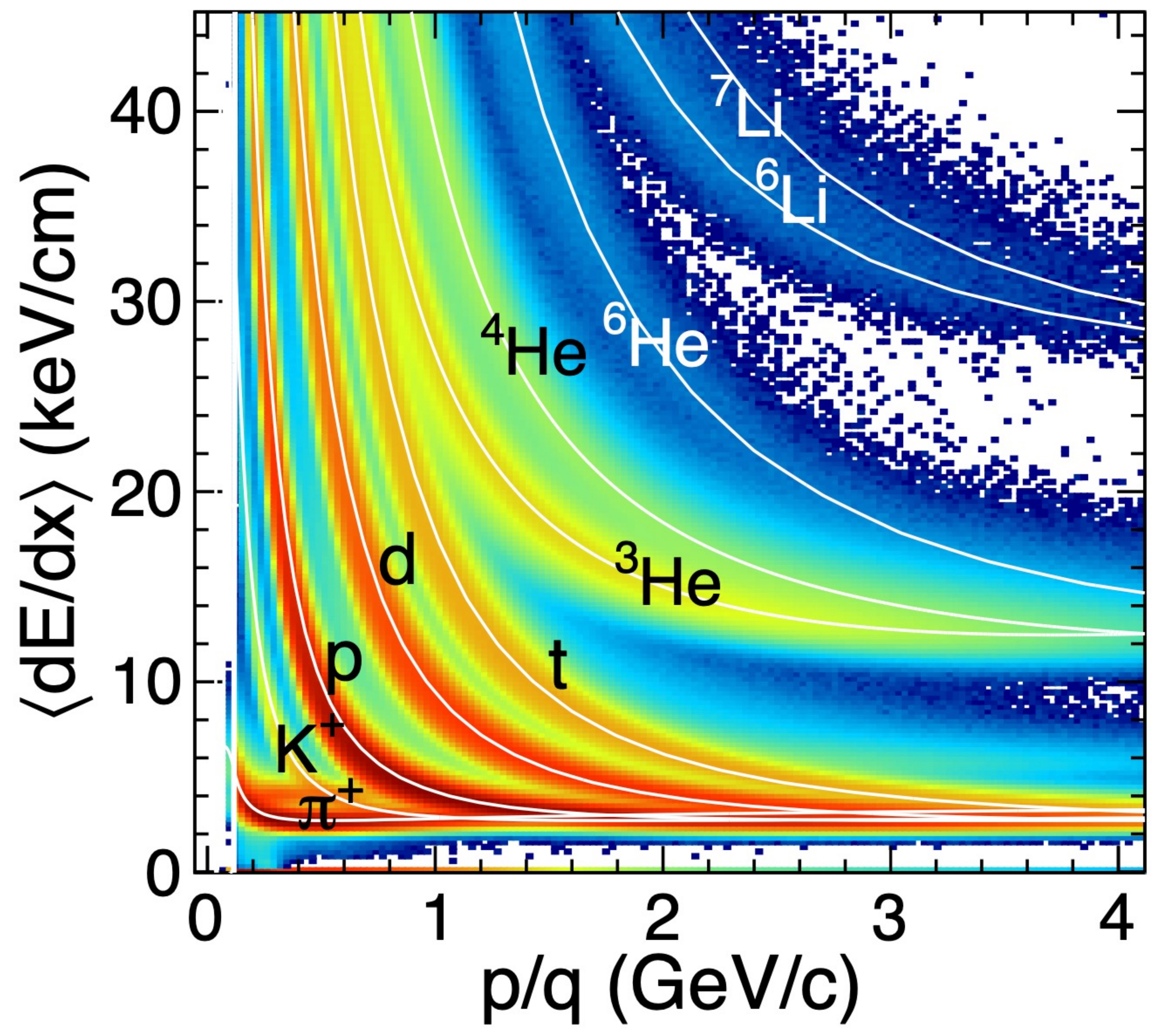


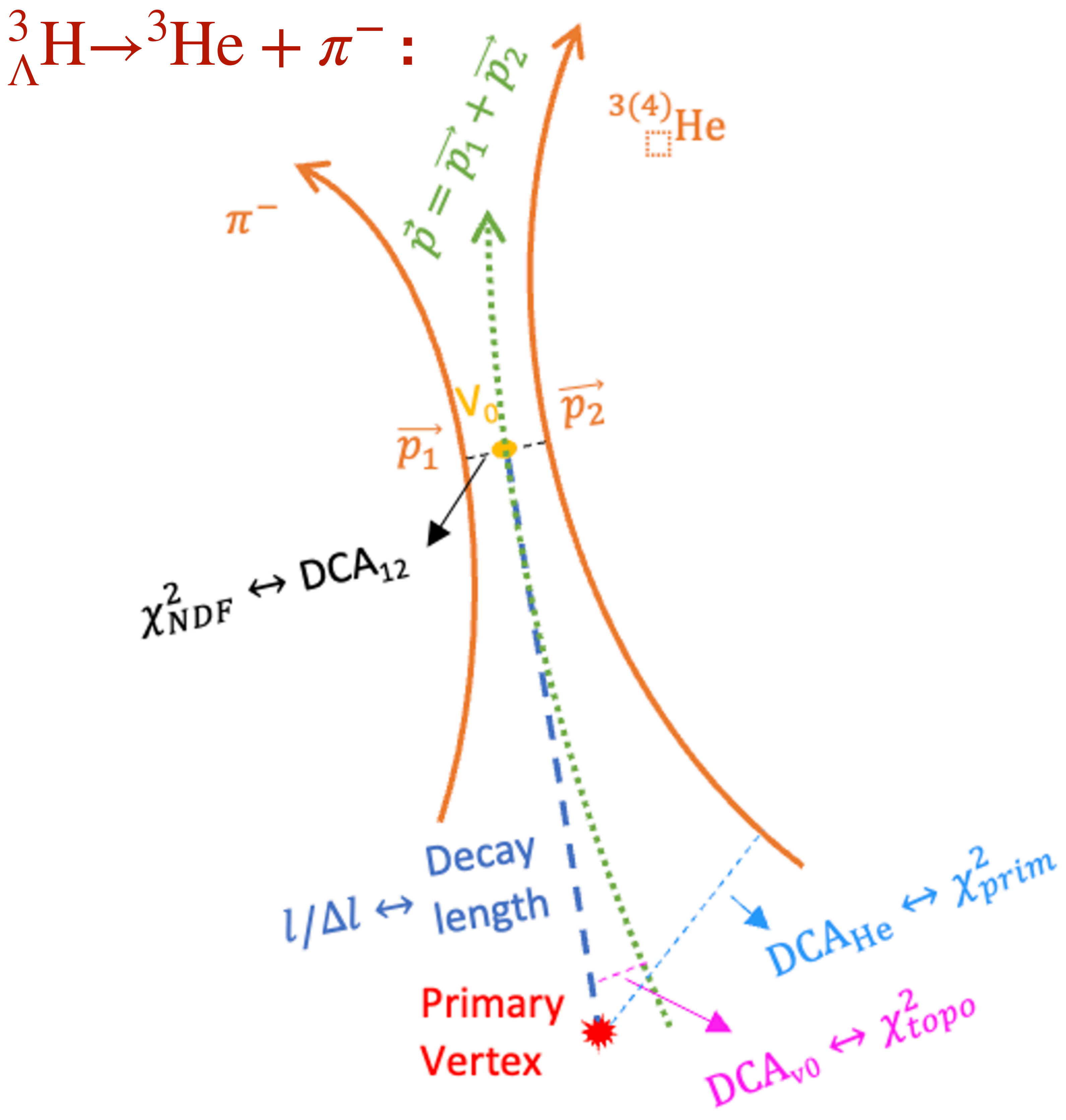
- Hypernuclei measurements are scarce in HI collision experiments
- At **low beam energies**, hypernuclei production is expected to be **enhanced** due to high baryon density

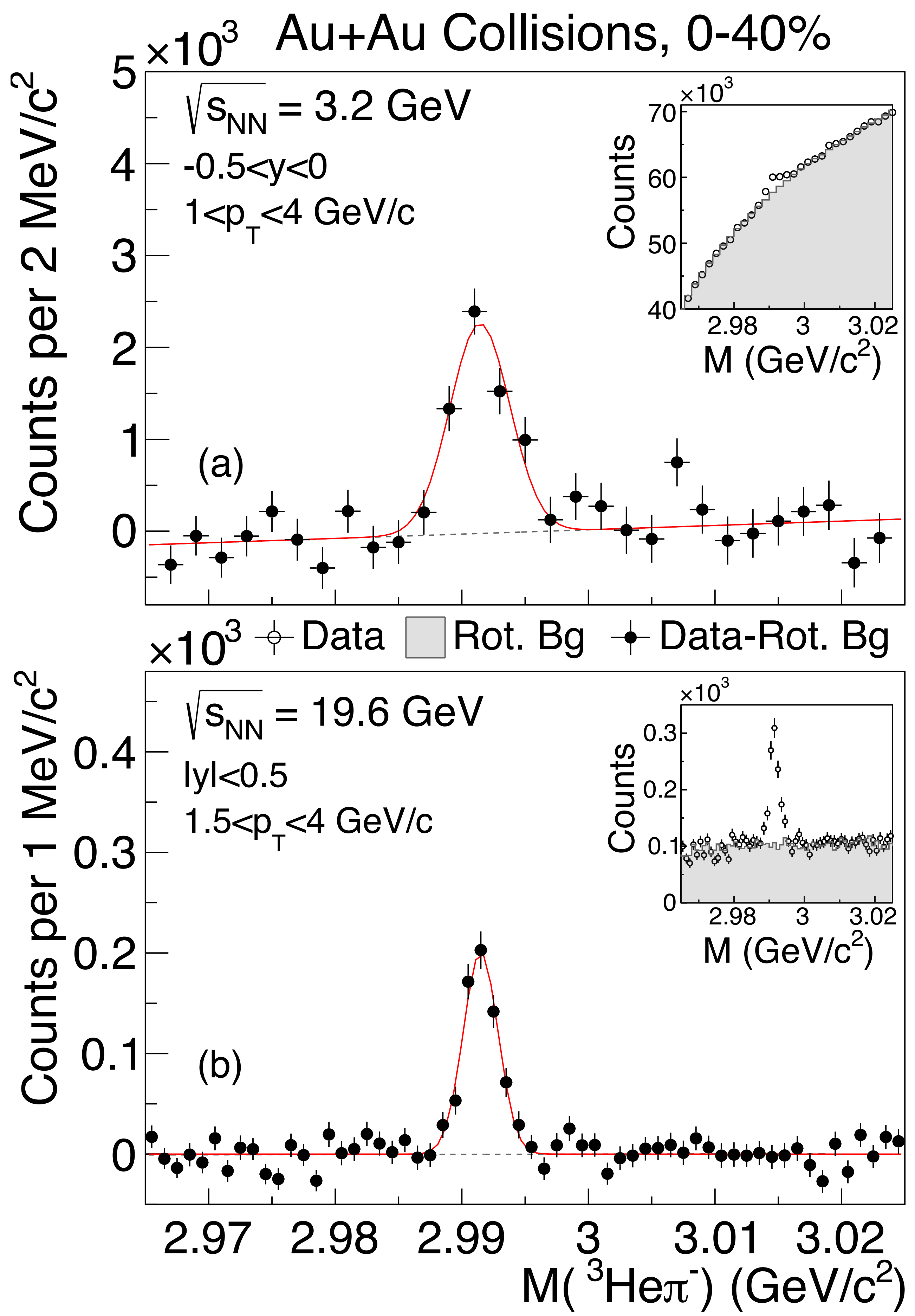
RHIC BES-II offers great opportunity for hypernuclei measurements.

B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207

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



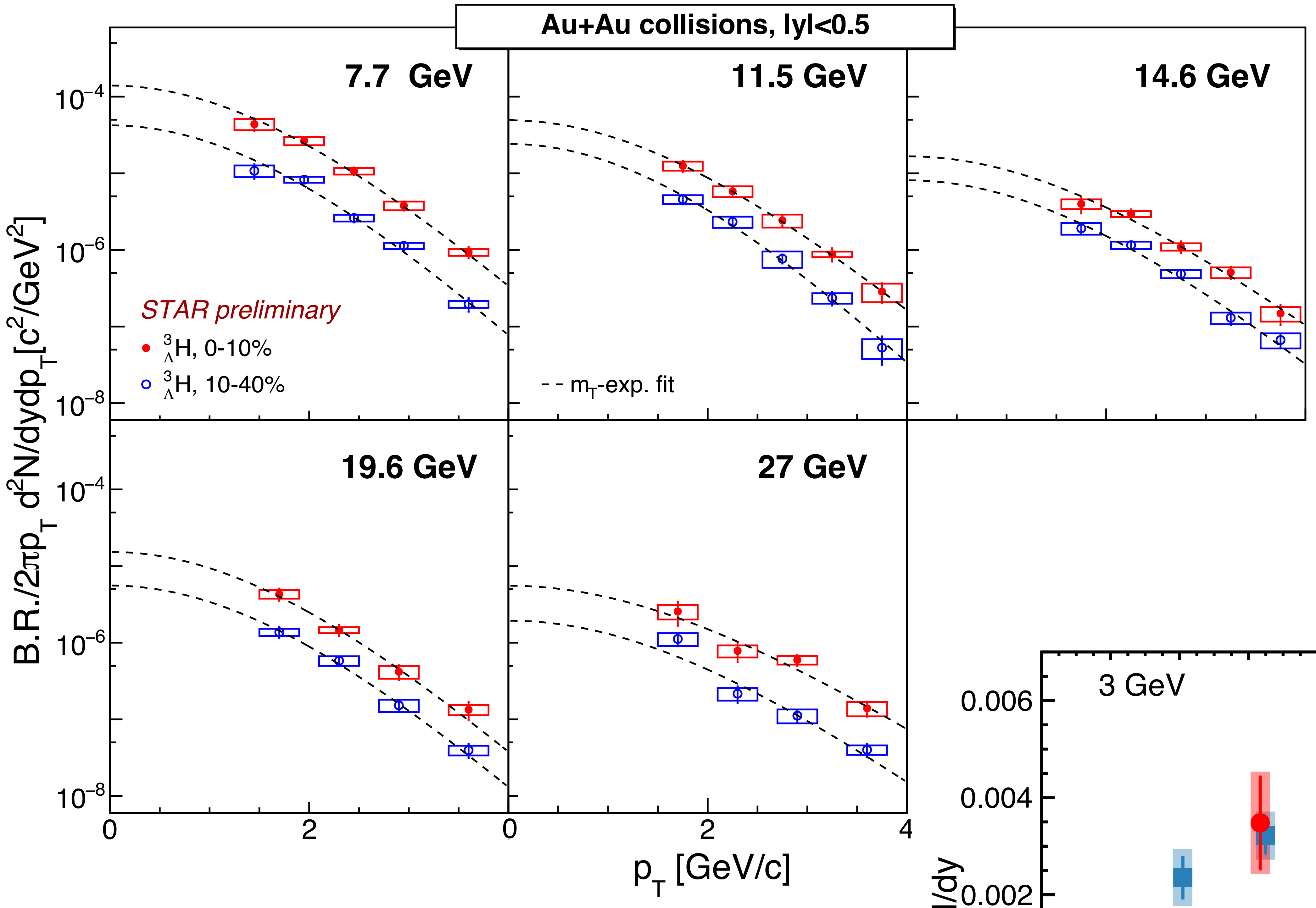




- Reconstruction channel: ${}^{3}_{\Lambda}\mathrm{H}\rightarrow{}^{3}\mathrm{He}+\pi^{-}$
- Particle identification from energy loss measurement using TPC
- KF particle package is used for signal reconstruction

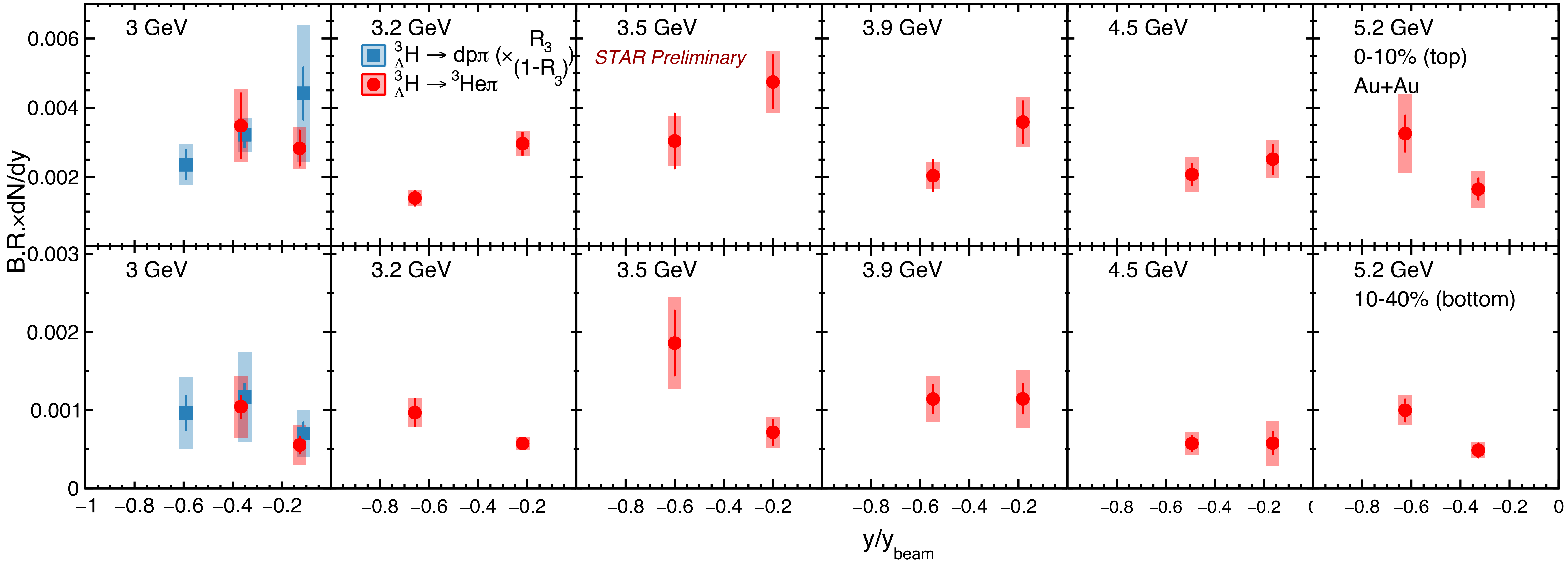
XY. Ju et al. Nucl.Sci.Tech. 34 (2023) 10, 158

$^{3}_{\Lambda}H$ rapidity and p_T spectra

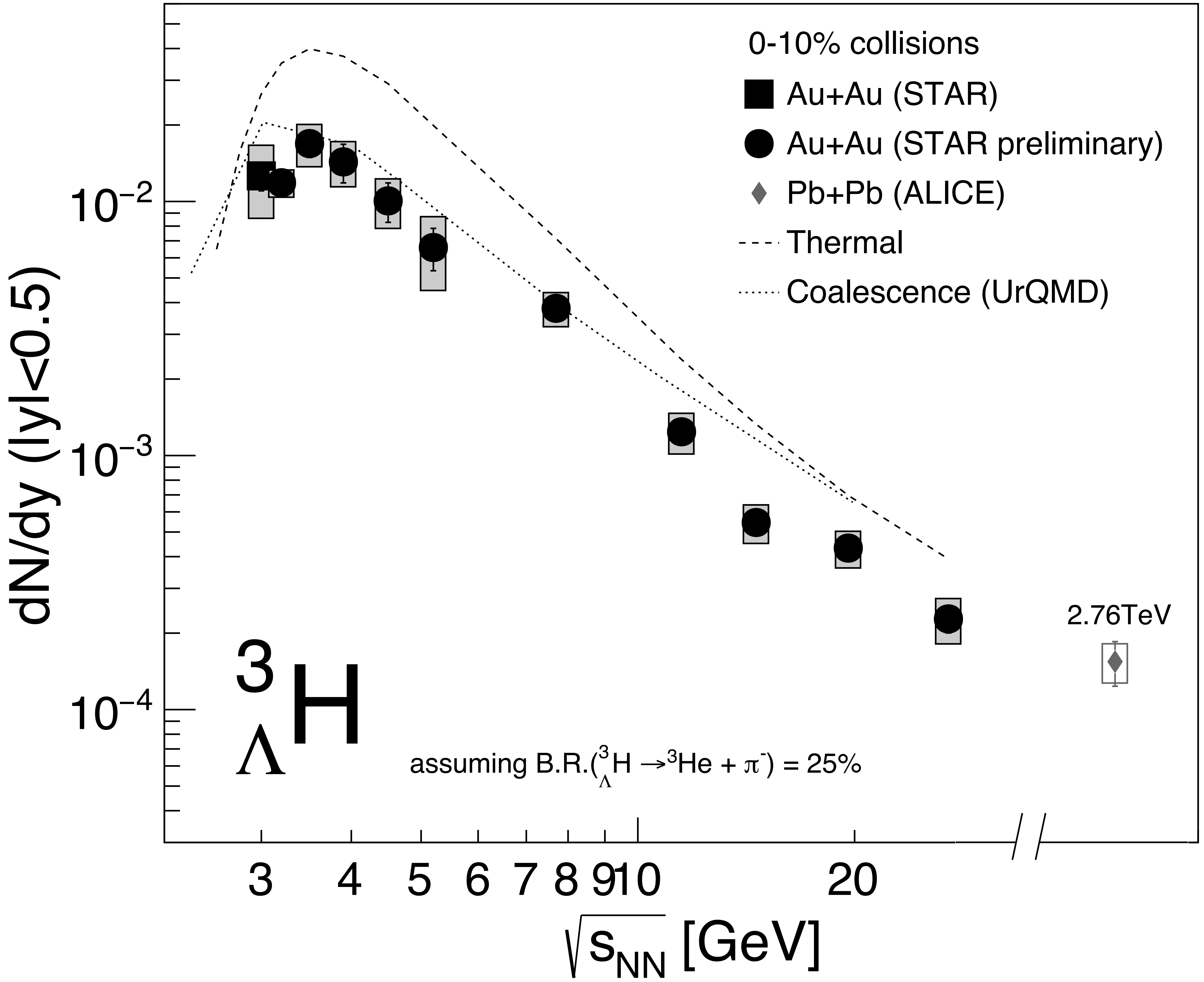


- Measurements cover 11 different energies

Collider: 7.7, 11.5, 14.6, 19.6, 27 GeV
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2 GeV



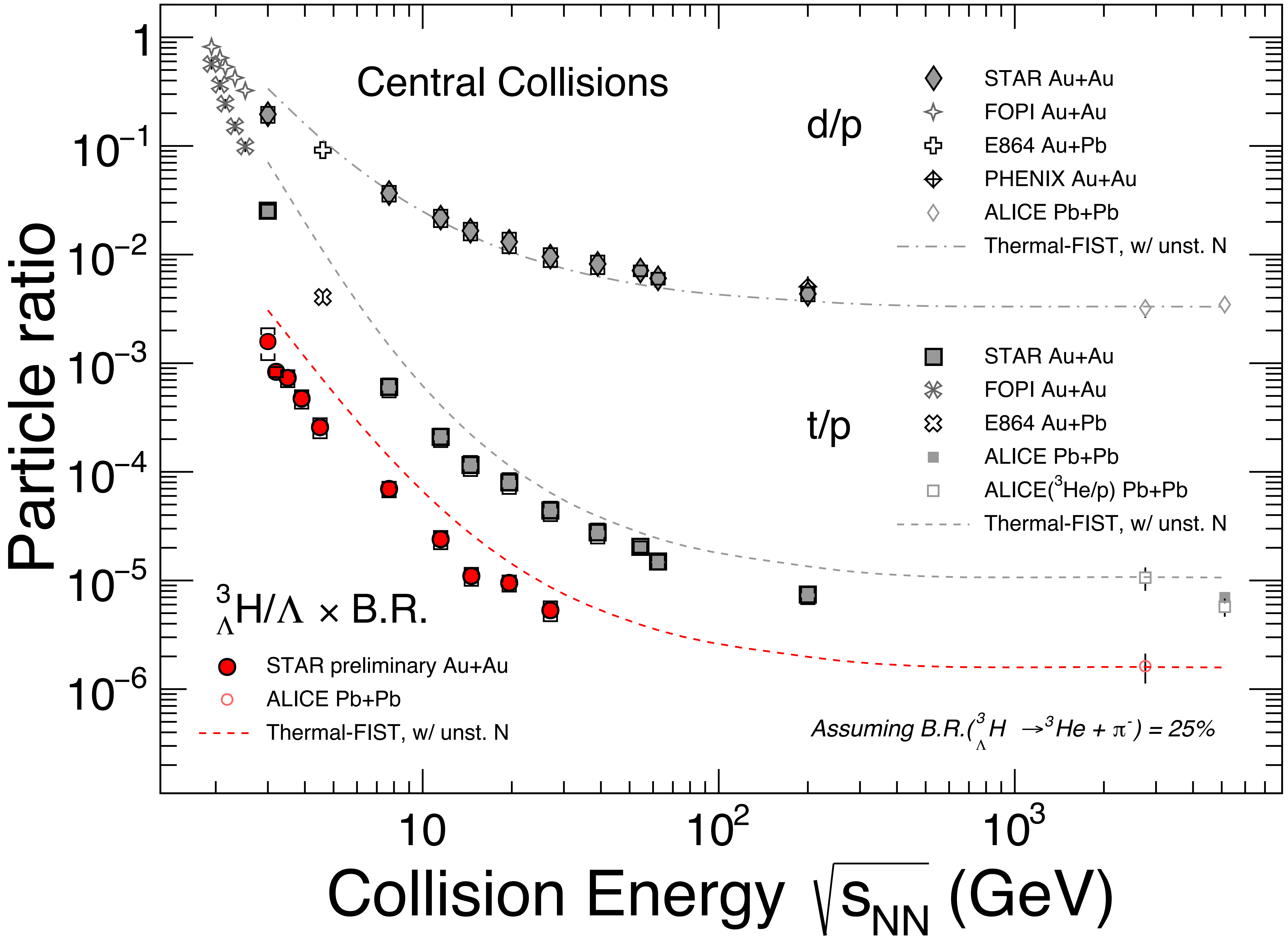
Energy dependence of ${}^{3}_{\Lambda}\mathrm{H}$ production



- Yields increase strongly from $\sqrt{s_{NN}}$ = 27 GeV to ~4 GeV
- Peak at 3-4 GeV
- **UrQMD + coalescence models** qualitatively describe the data
- **Thermal model** overestimates the data

STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
T. Reichert, et al, PRC 107 (2023) 014912

Nuclei-to-hadron ratios



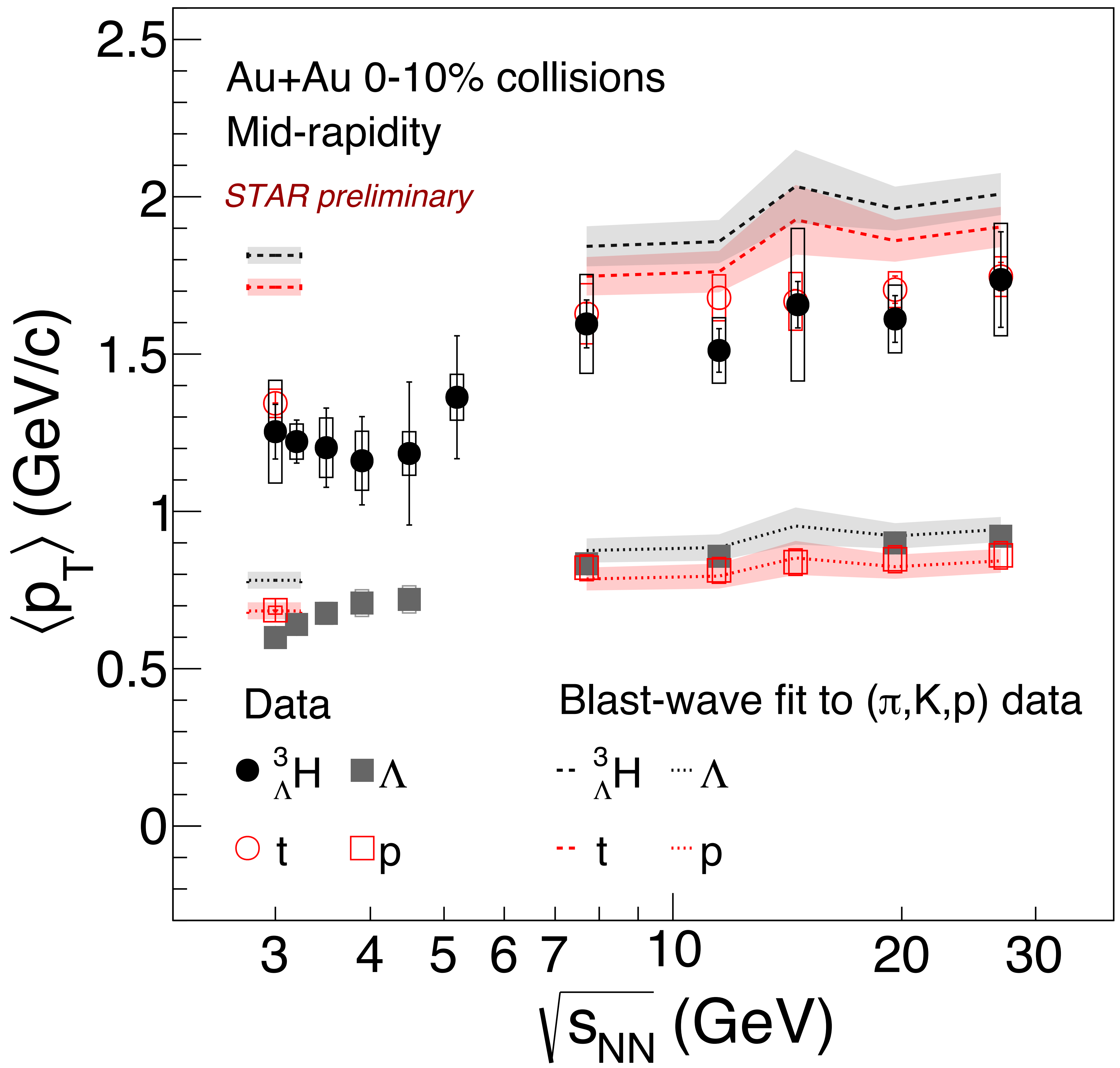
STAR, PRL 130 (2023) 202301
STAR, arXiv: 2311.11020
T. Reichert, et al, PRC 107 (2023) 014912

- **Thermal model:**
  - Light/hypernuclei **chemical freeze-out** happens at same time with hadrons

- d/p consistent with thermal model
- $^3_\Lambda$H/Λ, as well as t/p, overestimated by thermal model by a factor of ~2

Suggest $^3_\Lambda$H and t yields are not in equilibrium and fixed at chemical freeze-out simultaneously with other hadrons

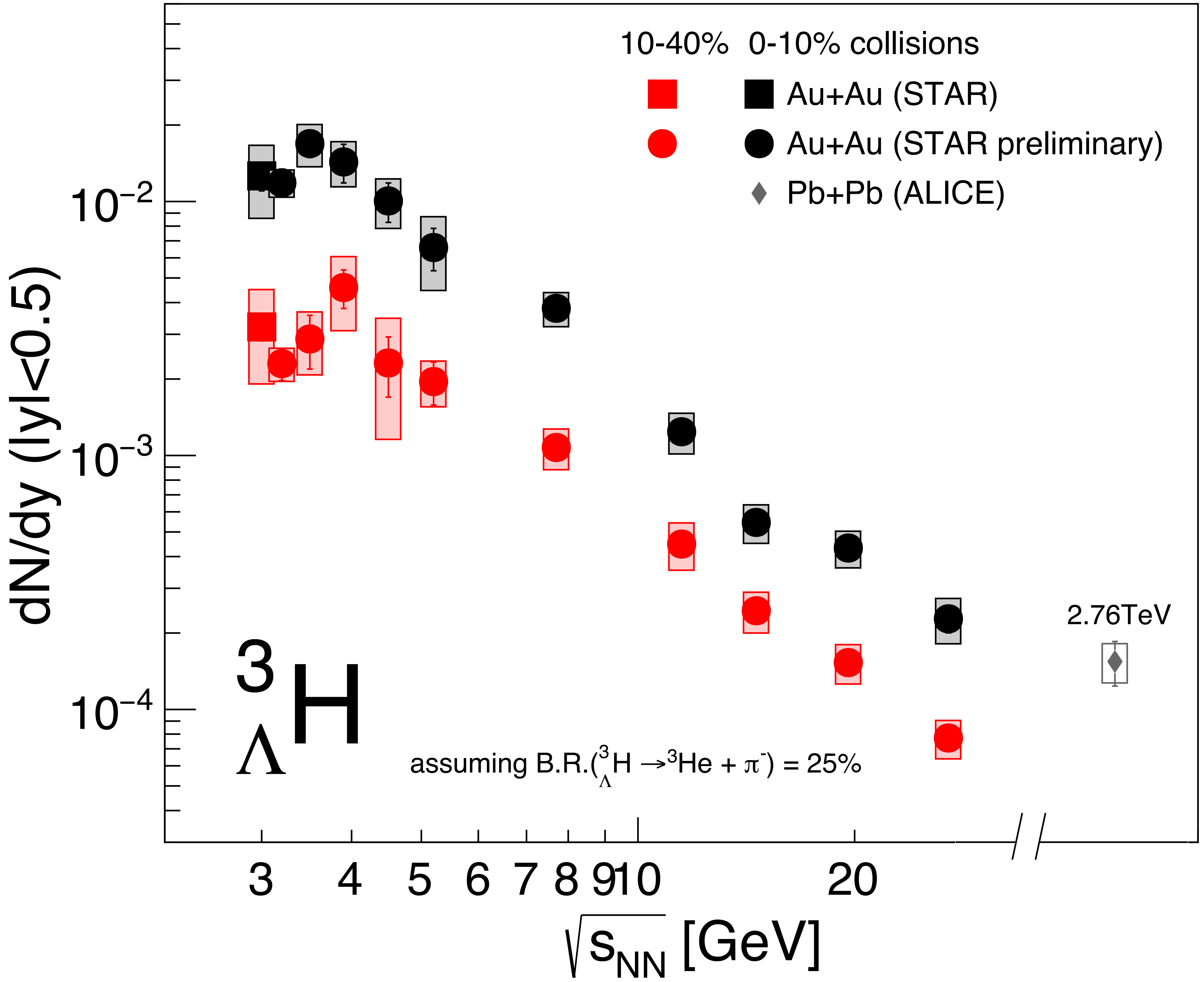
Energy dependence of ${}^{3}_{\Lambda}\mathrm{H}\ \langle p_T \rangle$



- ${}^{3}_{\Lambda}\mathrm{H}$ and t $\langle p_T \rangle < \langle p_T \rangle^{BW}$ at 3 GeV
- Hint of ${}^{3}_{\Lambda}\mathrm{H}$ and t $\langle p_T \rangle < \langle p_T \rangle^{BW}$ at $\sqrt{s_{NN}} > 7.7$ GeV
  - Blast-wave fit using measured **kinetic freeze-out parameters from light hadrons** (π, K, p)

${}^{3}_{\Lambda}\mathrm{H}$ and t might do not follow same collective expansion as light hadrons.

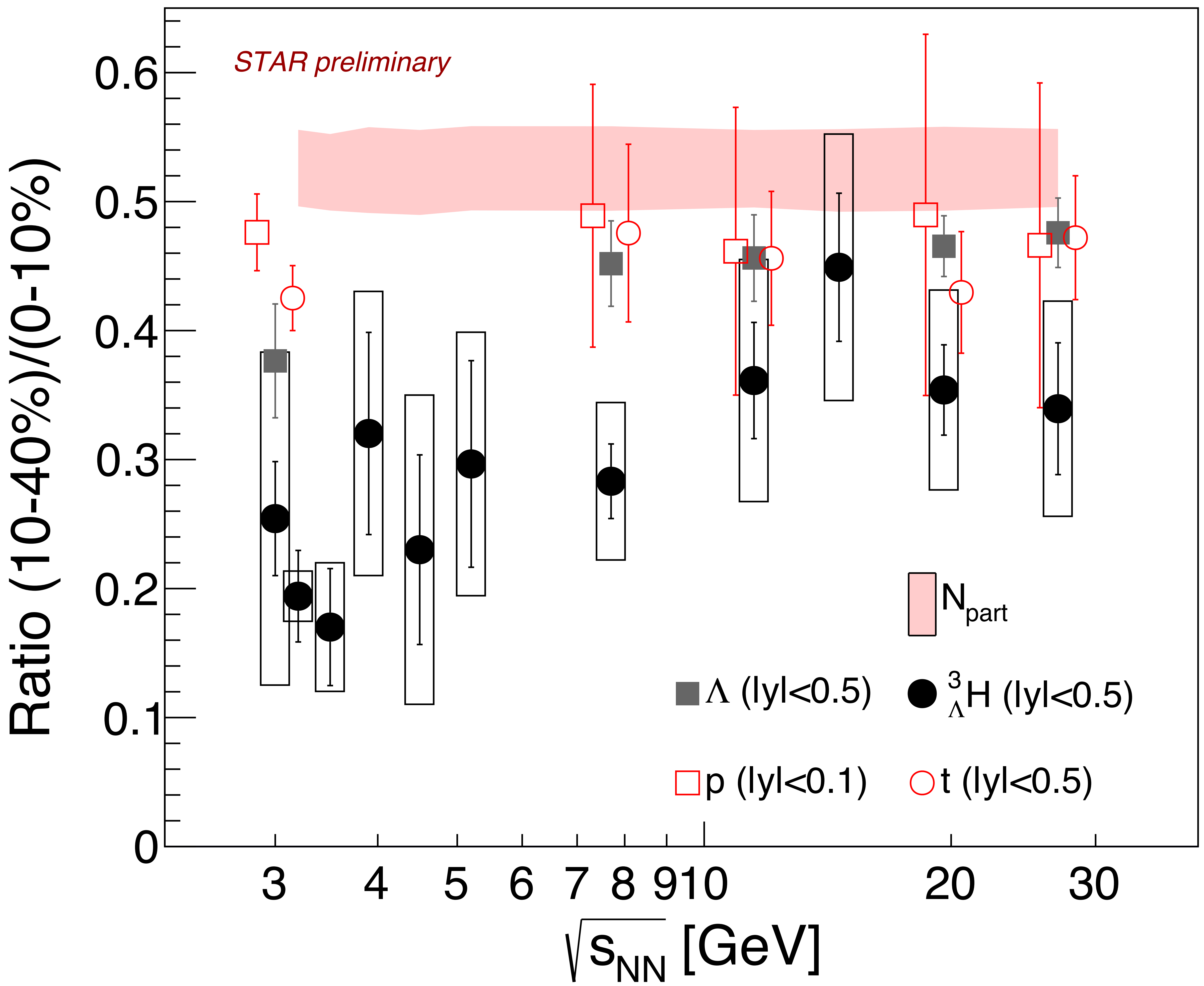
Centrality dependence of $^{3}_{\Lambda}\mathrm{H}$ production



- Similar trend in central (0-10%) and mid-central (10-40%) collisions

STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360

Centrality dependence of ${}^{3}_{\Lambda}\mathrm{H}$ production

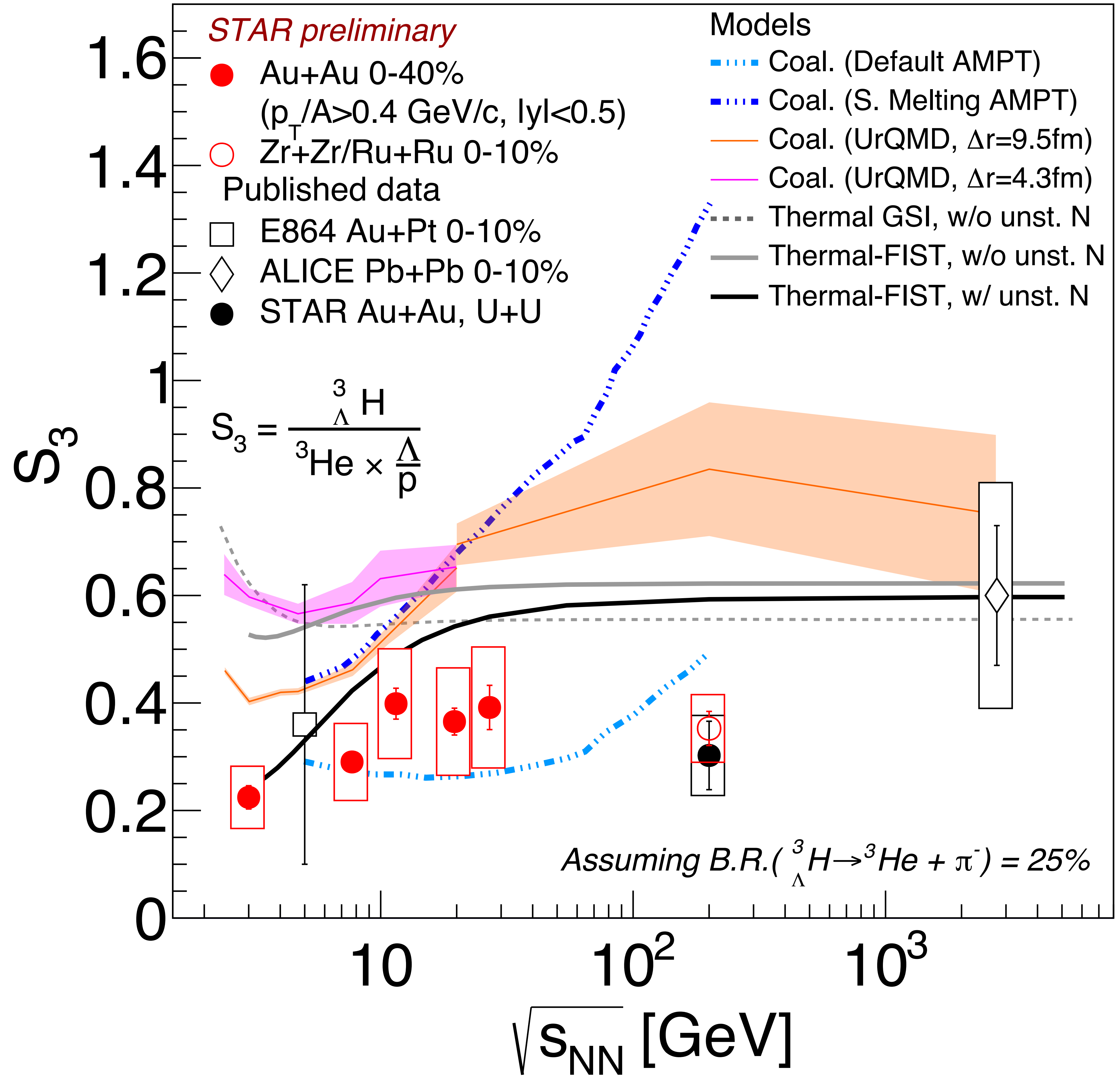


- Suppression of mid-central/central ${}^{3}_{\Lambda}\mathrm{H}$ yield ratio w.r.t N_{part}, seems more apparent below $\sqrt{s_{NN}}$ = 7.7 GeV
- ${}^{3}_{\Lambda}\mathrm{H}$ yield ratio tends to increase more steeply than proton, Λ, triton at low energies

Suppression of ${}^{3}_{\Lambda}\mathrm{H}$ production in more peripheral collisions at low energies

Related to the created system size?

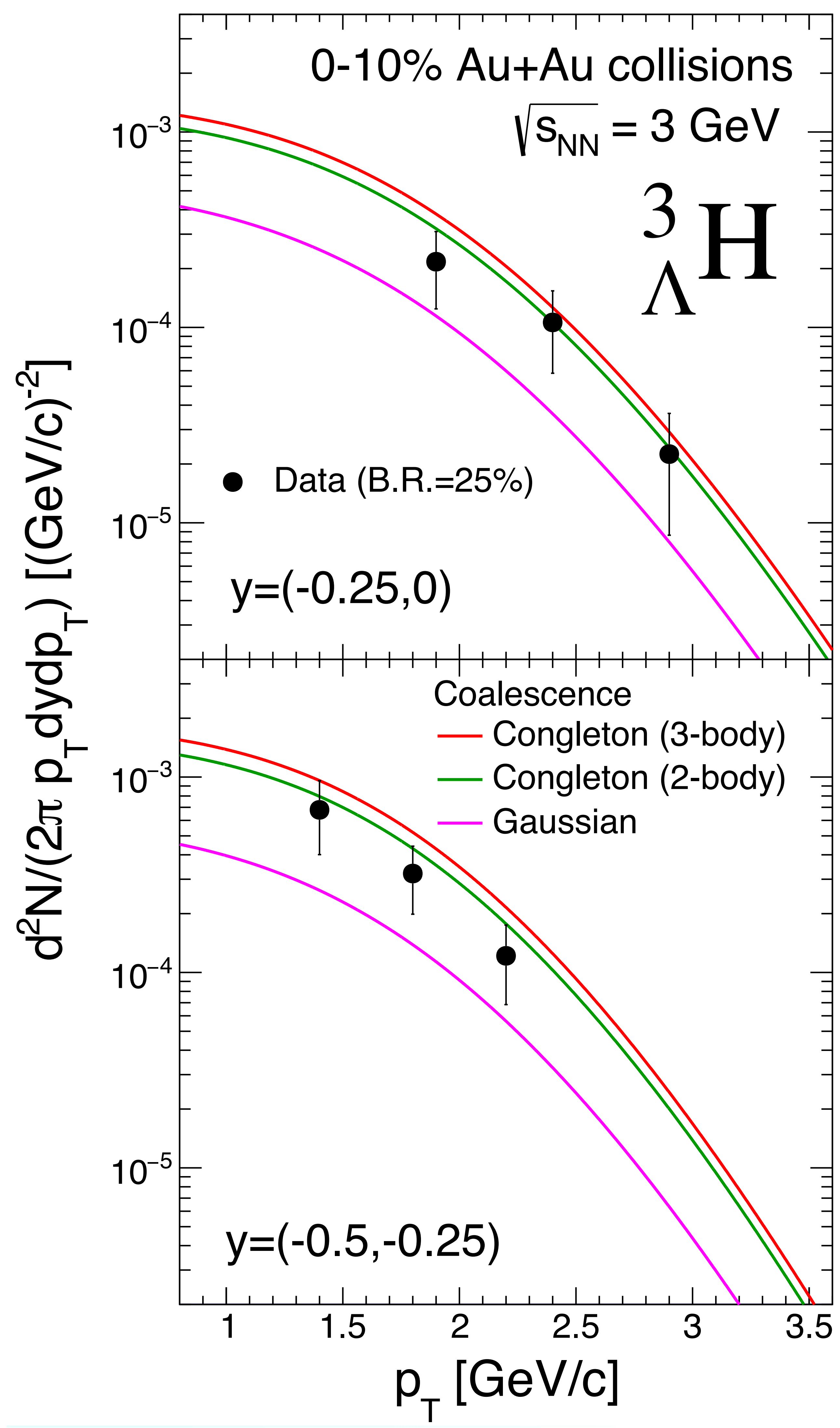
Energy dependence of strangeness population factor S_3

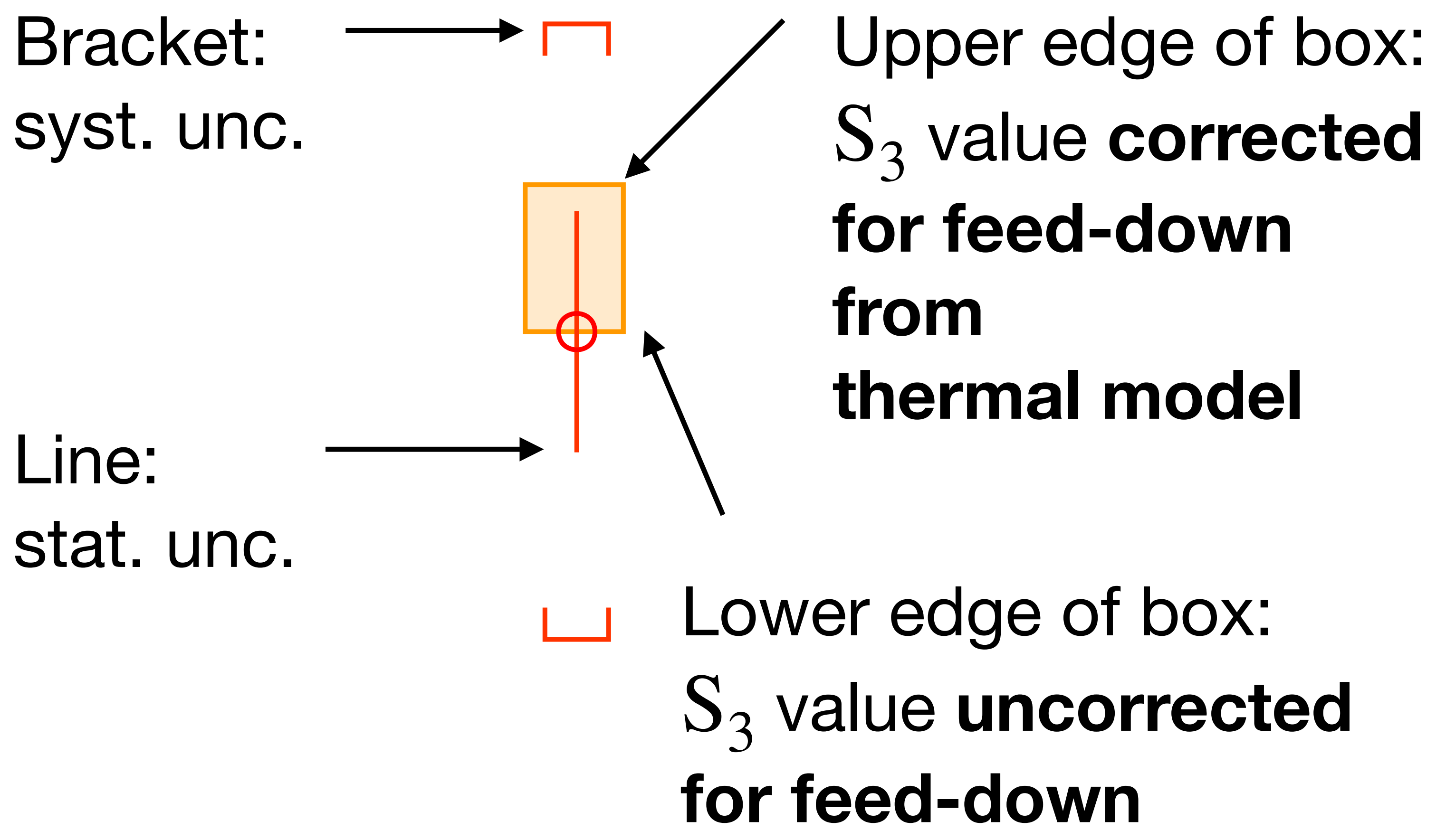


- A prominent enhancement of S_3 was proposed as a probe for deconfinement S. Zhang et al. PLB 684 (2010) 224–227
- Data shows a mild increasing trend from $\sqrt{s_{NN}}$ = 3.0 GeV to 2.76 TeV
- For coalescence(UrQMD) models, the energy dependence is sensitive to the **source radius** (Δr). Data favor larger radius.
  - Due to the **difficulty in forming** $^3_\Lambda H$ of **large radius in small systems**
- Thermal-FIST, which includes **feed-down from unstable nuclei** to stable p, ^3He, describes the S_3 data better
  - Possible feed-down should be accounted

STAR, arXiv: 2310.12674
ALICE, PLB 754 (2016) 360
E864, PRC 70 (2004) 024902
A. Andronic et al, PLB 697 (2011) 203 (Thermal (GSI))
S. Zhang, PLB 684 (2010) 224 (Coal.+AMPT)
T. Reichert, et al, PRC 107 (2023) 014912 (UrQMD, Thermal-FIST)

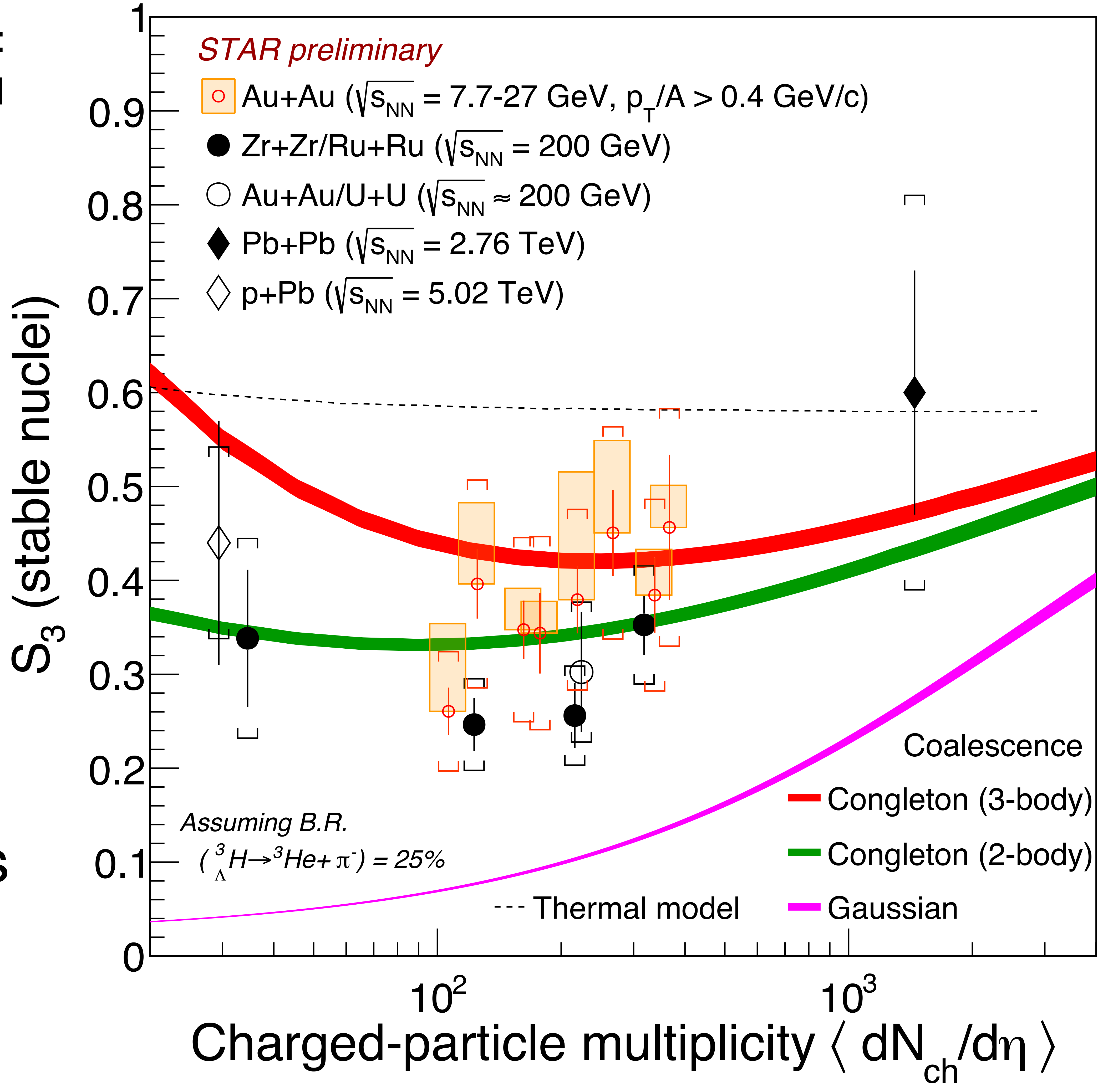
Multiplicity dependence of S_3





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

- Coalescence quantitatively reproduces the data across wide range of energies

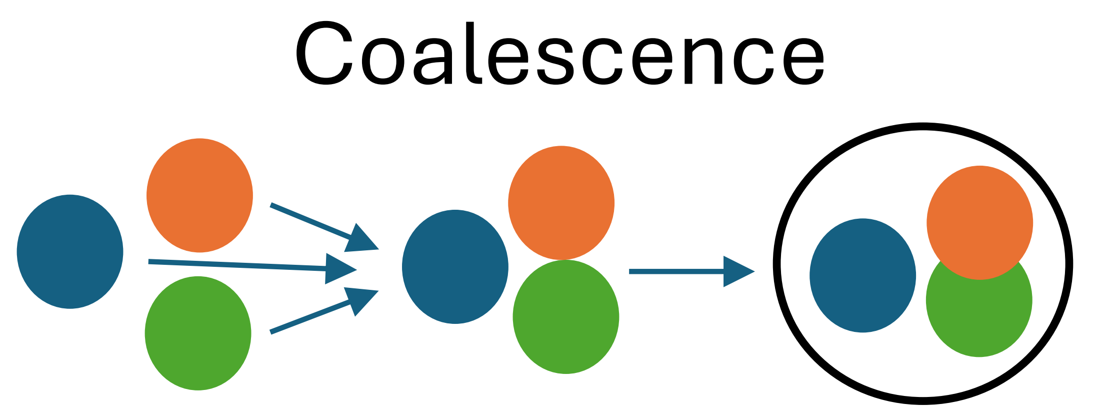


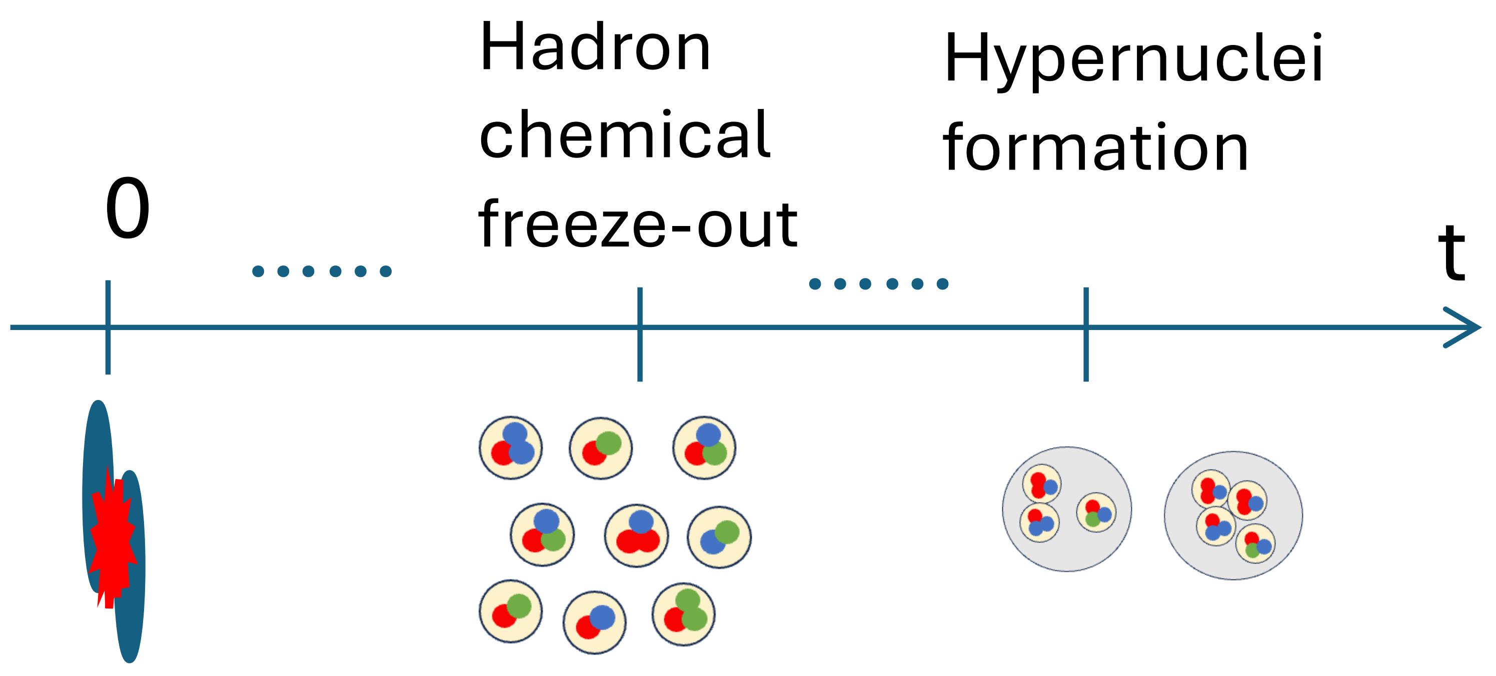
STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
ALICE, PRL 128(2022)252003
ALICE, PLB 754 (2016) 360
V. Vovchenko, PLB 785(2018)171 (Thermal)
Y-H. Leung, arXiv: 2510.06758 (Coalescence)

Summary

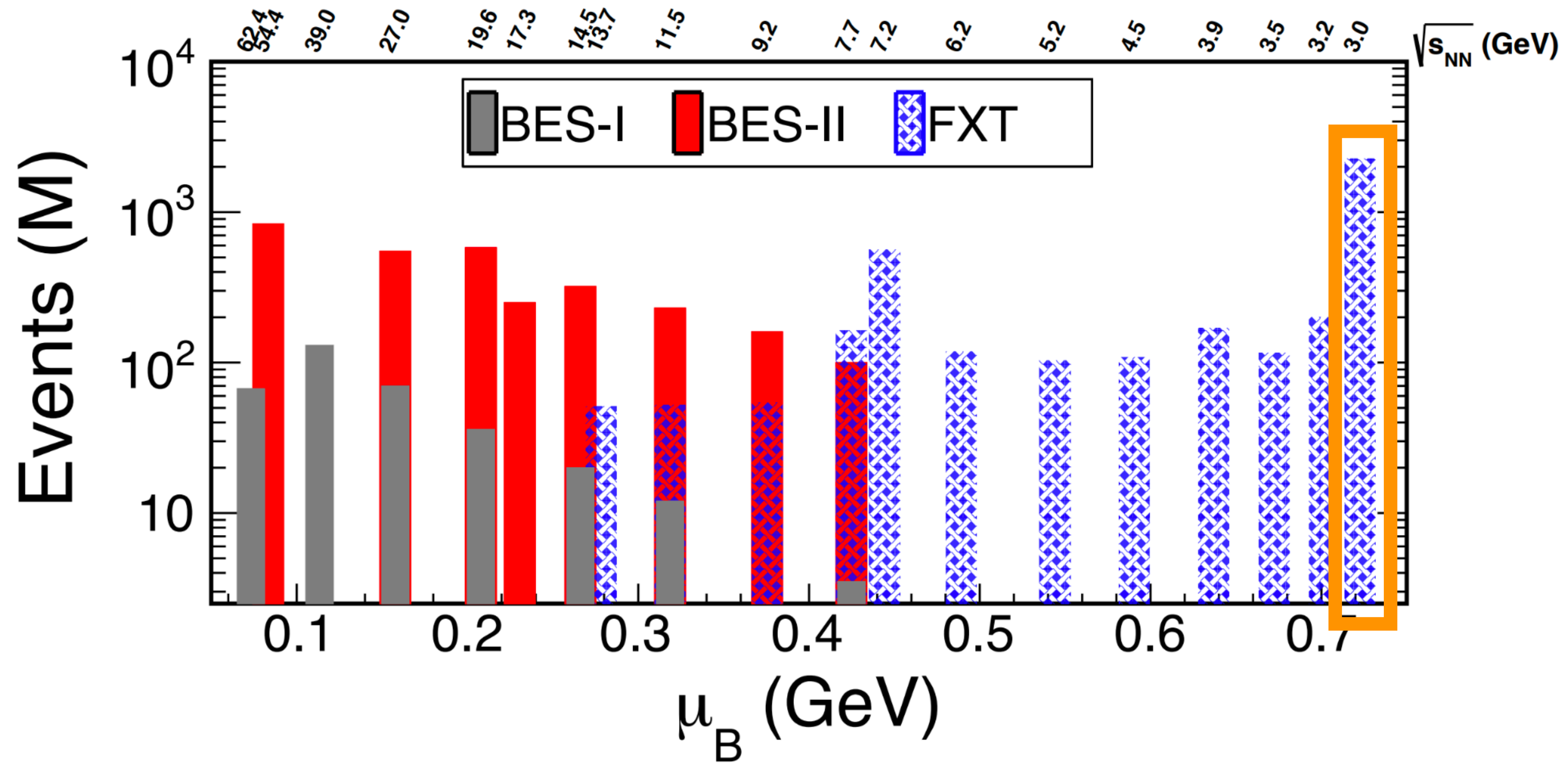
- Experimental results of ${}^{3}_{\Lambda}\mathrm{H}$ production in:
  - 3.0 – 27 GeV Au+Au collisions
  - 200 GeV Zr+Zr/Ru+Ru collisions

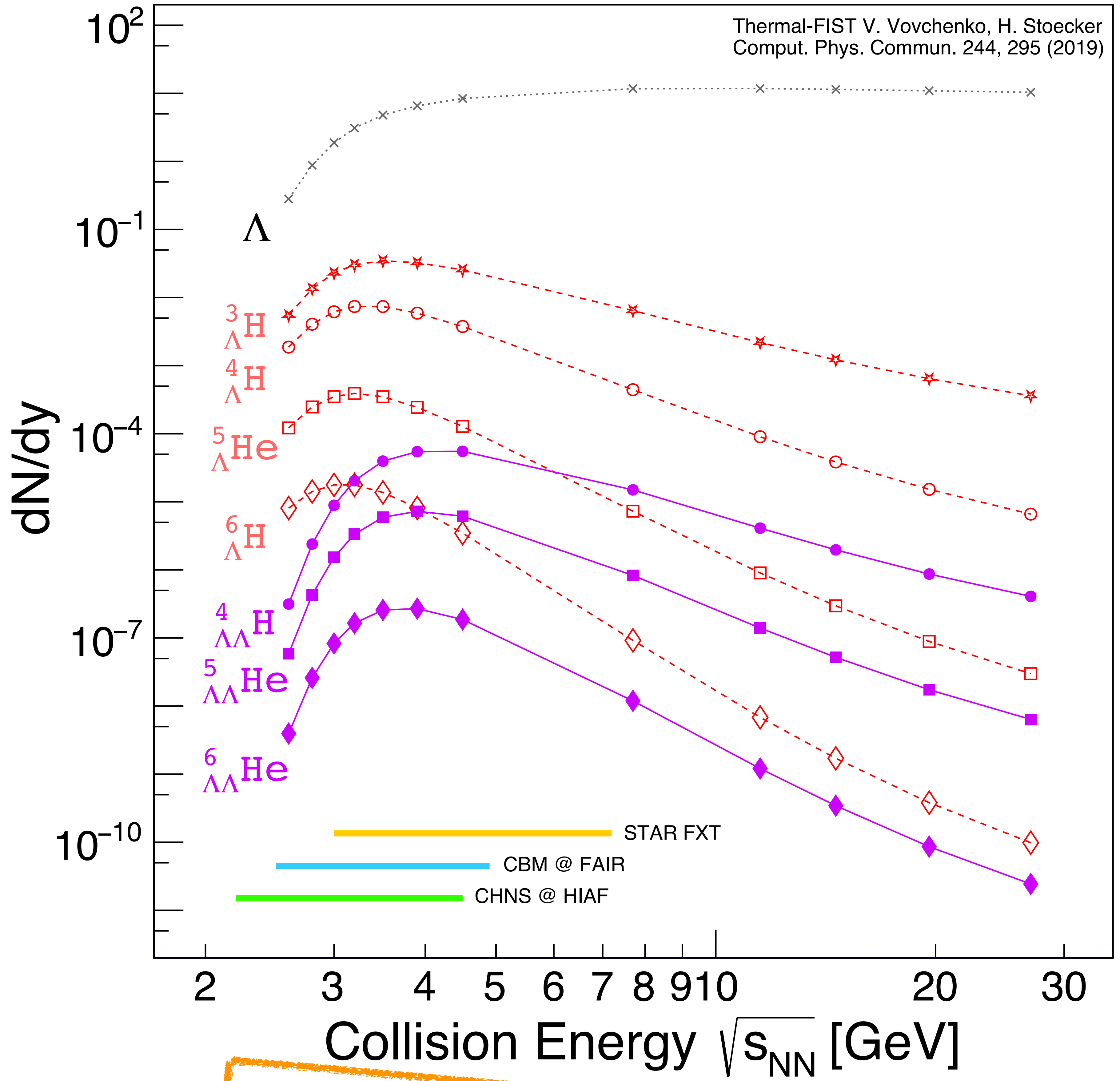
- **Experimental data support coalescence is a dominate mechanism of ${}^{3}_{\Lambda}\mathrm{H}$ formation at mid-rapidity in heavy-ion collisions at RHIC.**
- **${}^{3}_{\Lambda}\mathrm{H}$ are likely not in thermal equilibrium at hadron chemical freeze-out.**



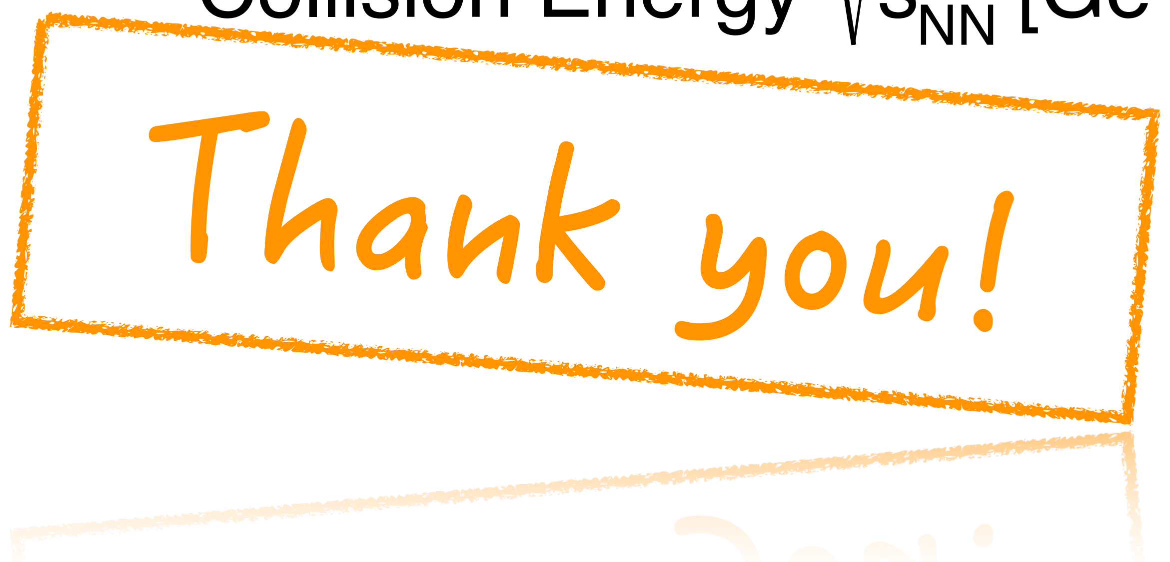


Outlook



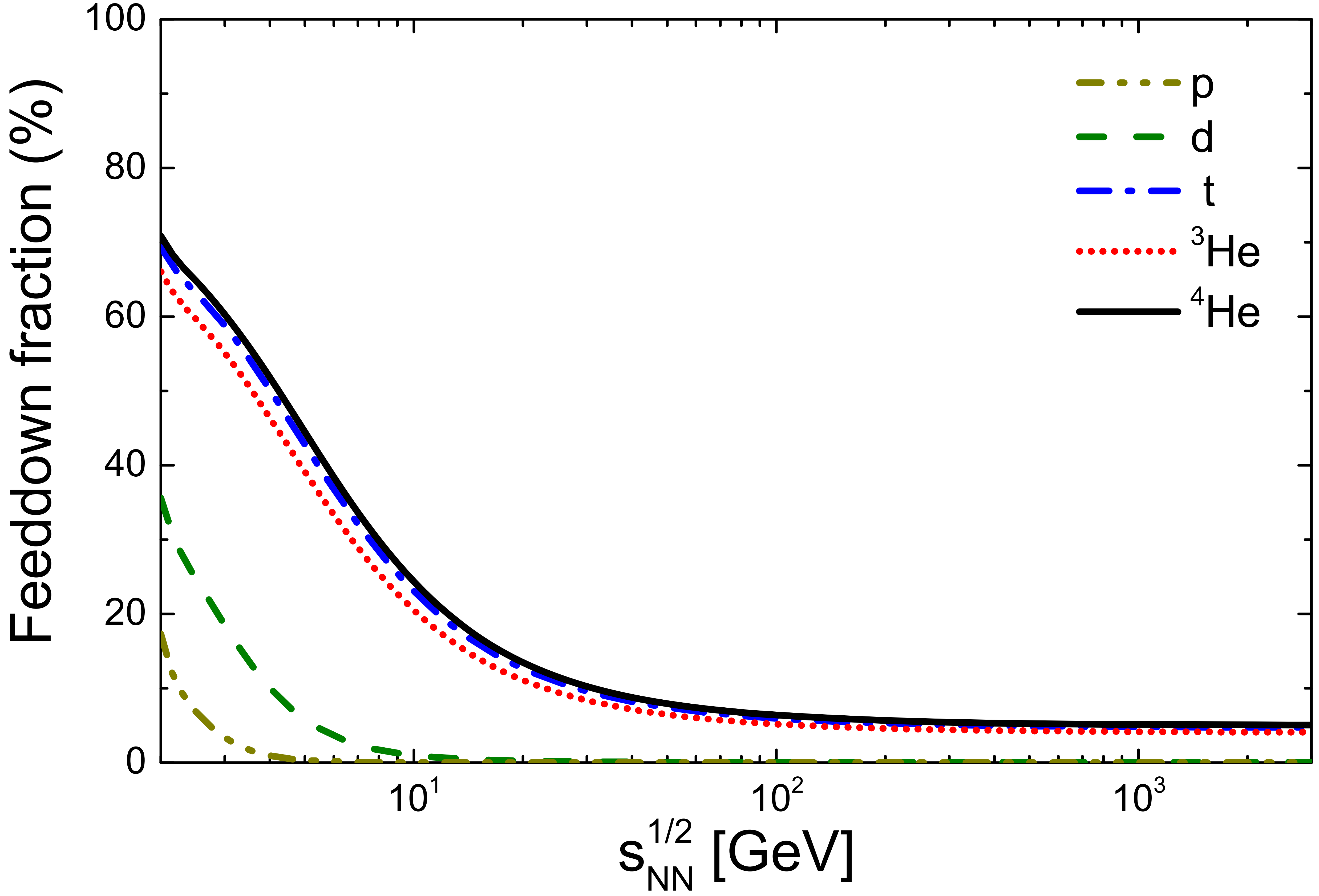


- RHIC-STAR
  - huge datasets give opportunities for heavier hypernuclei at FXT energies and anti-hypernuclei measurements at RHIC top energy
    - Run 21, Au+Au 3 GeV, ~2 billion events
    - Run 18, Isobar 200 GeV, ~6 billion events
    - Run 23-25, Au+Au 200 GeV, ~18 billion events

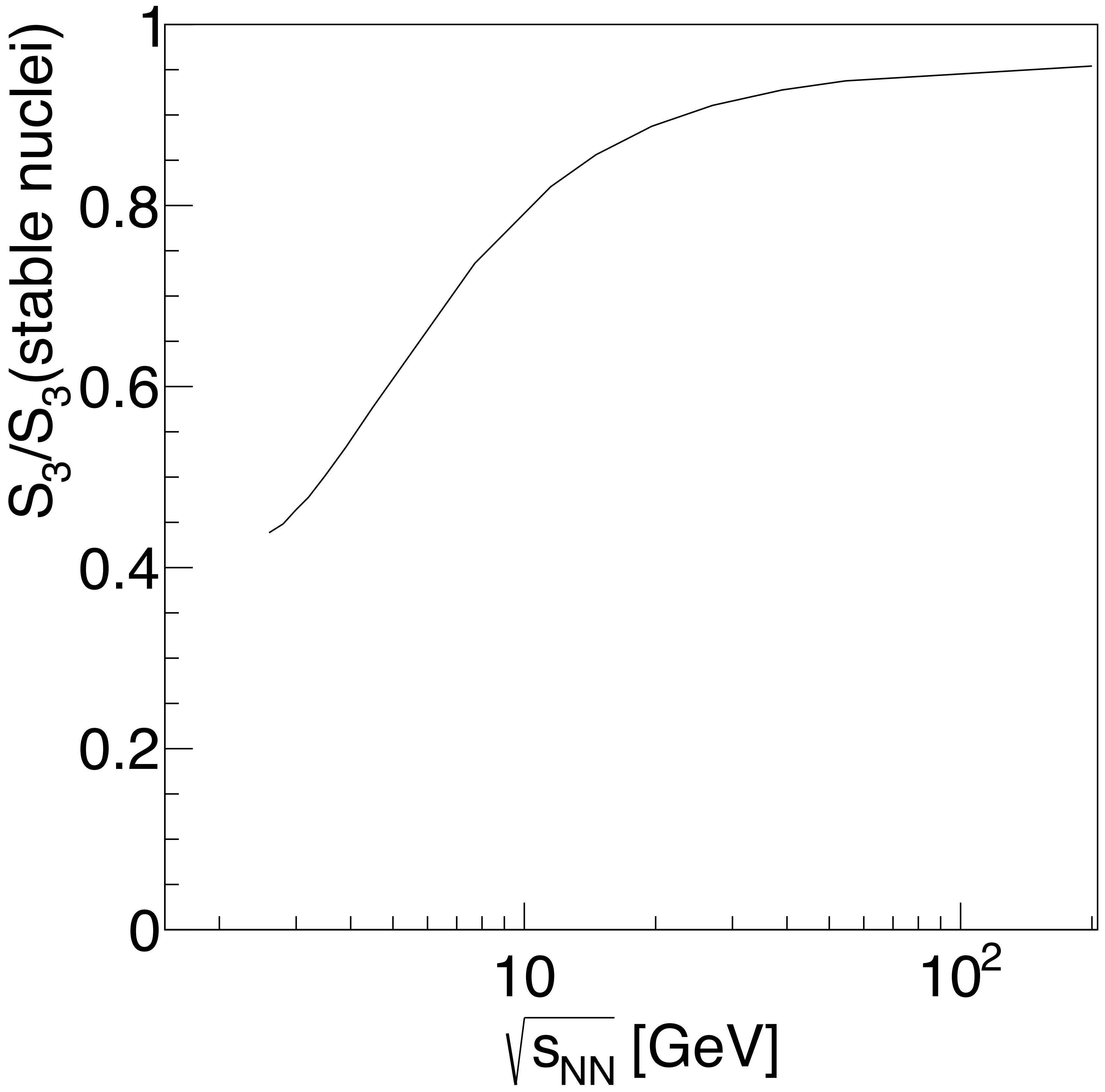


backups

Feed-down from unstable nuclei



V. Vovchenko, PLB 809 (2020) 135746



- Feed down fraction estimated by Thermal-Fist
  - From unstable nuclei (4H, 4He, 4Li, 5H, 5He, 5Li) to the stable lower mass nuclei(p, d, t, He3, He4)
- Feed-down correction of S_3 from unstable nuclei estimated using Thermal-FIST