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STAR

Measurement of Hypertriton Production at RHIC

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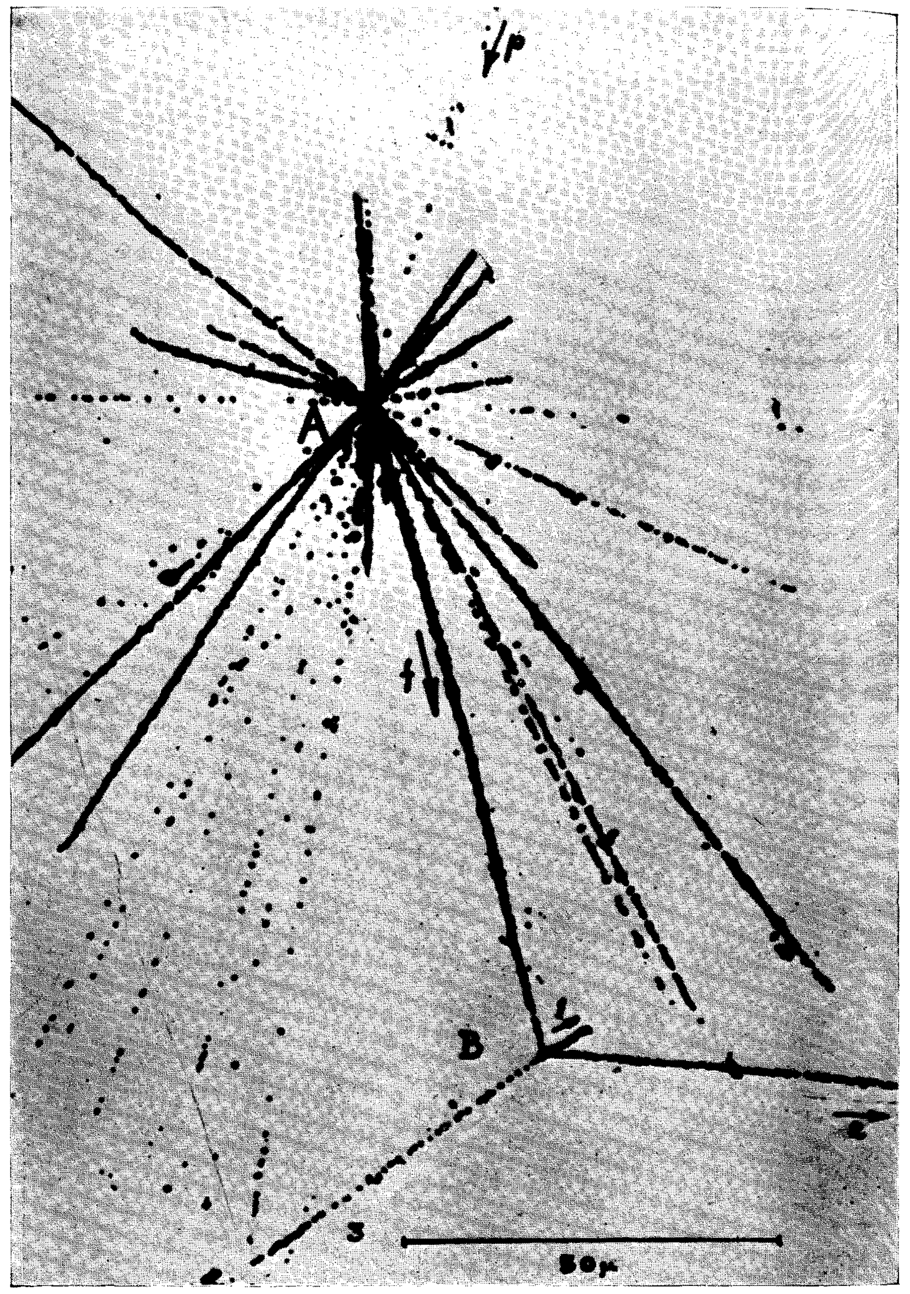
Introduction: hypernuclei

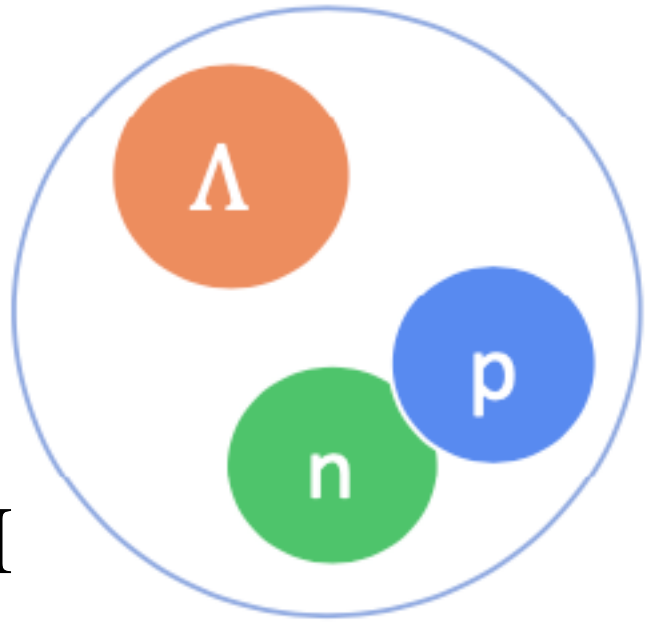
- Hypernuclei: bound nuclear systems of non-strange and strange baryons

— **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.

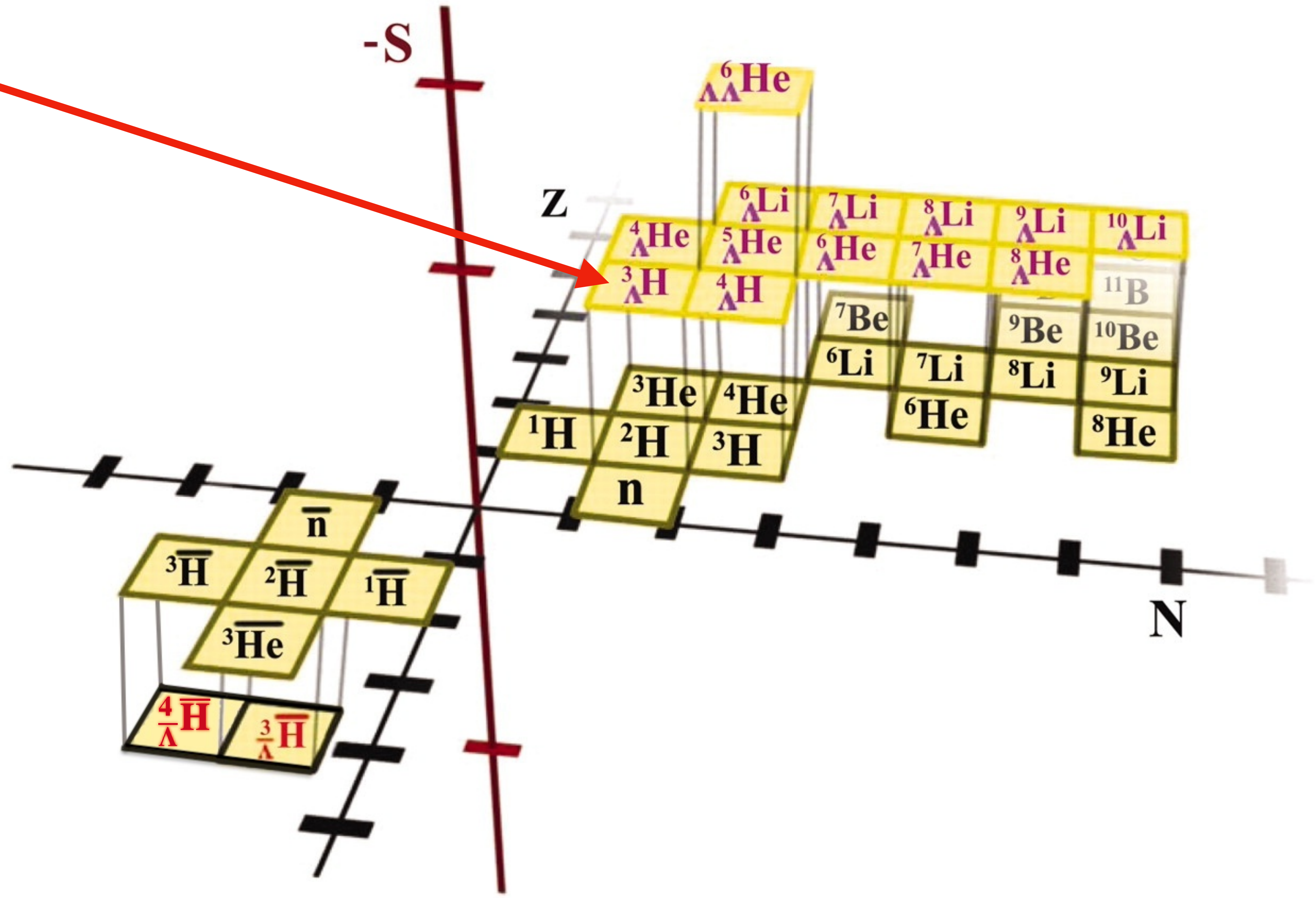


$^{3}_{\Lambda}\mathrm{H}$

lightest hypernucleus

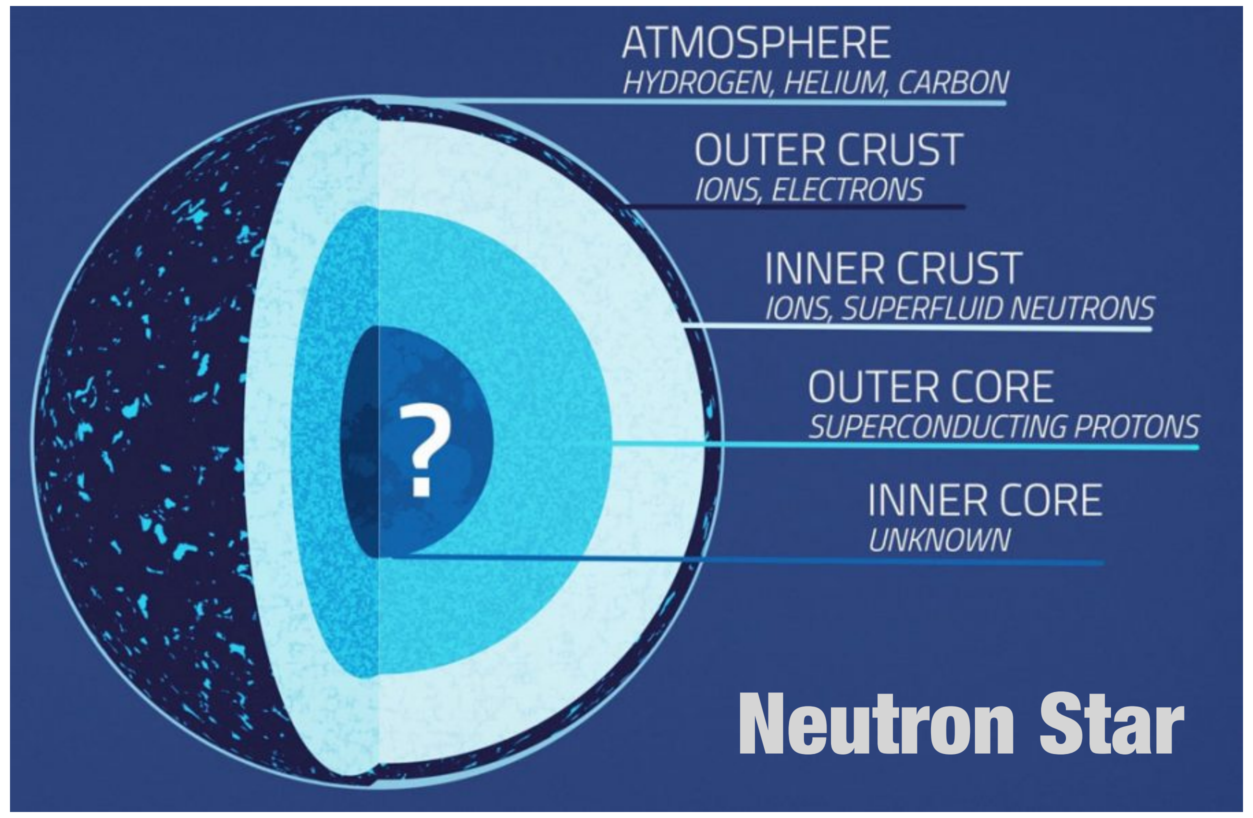
$B_{\Lambda} \sim 0.15\mathrm{MeV}$

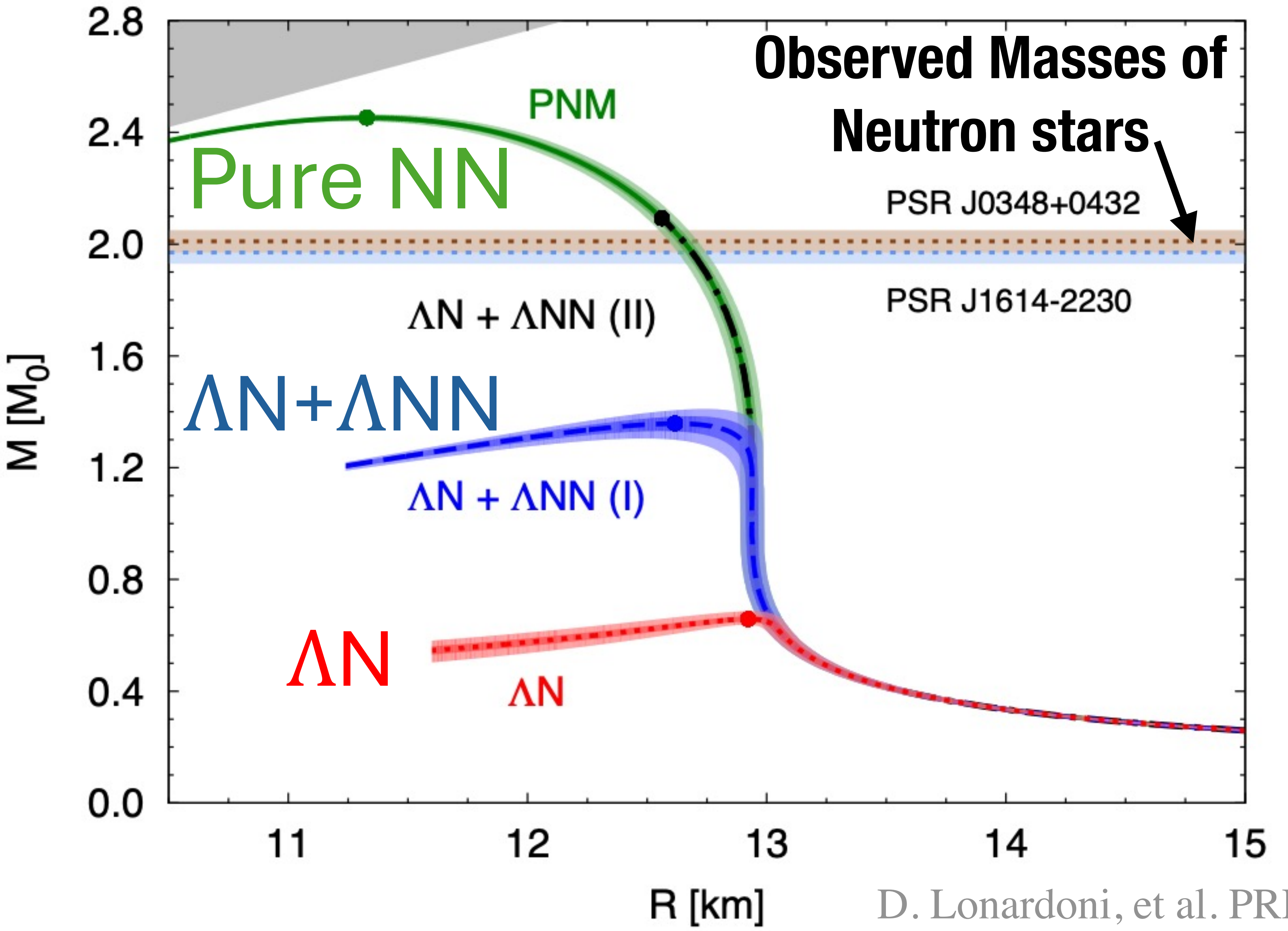
RMS radius $5 \sim 10\ \mathrm{fm}$



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





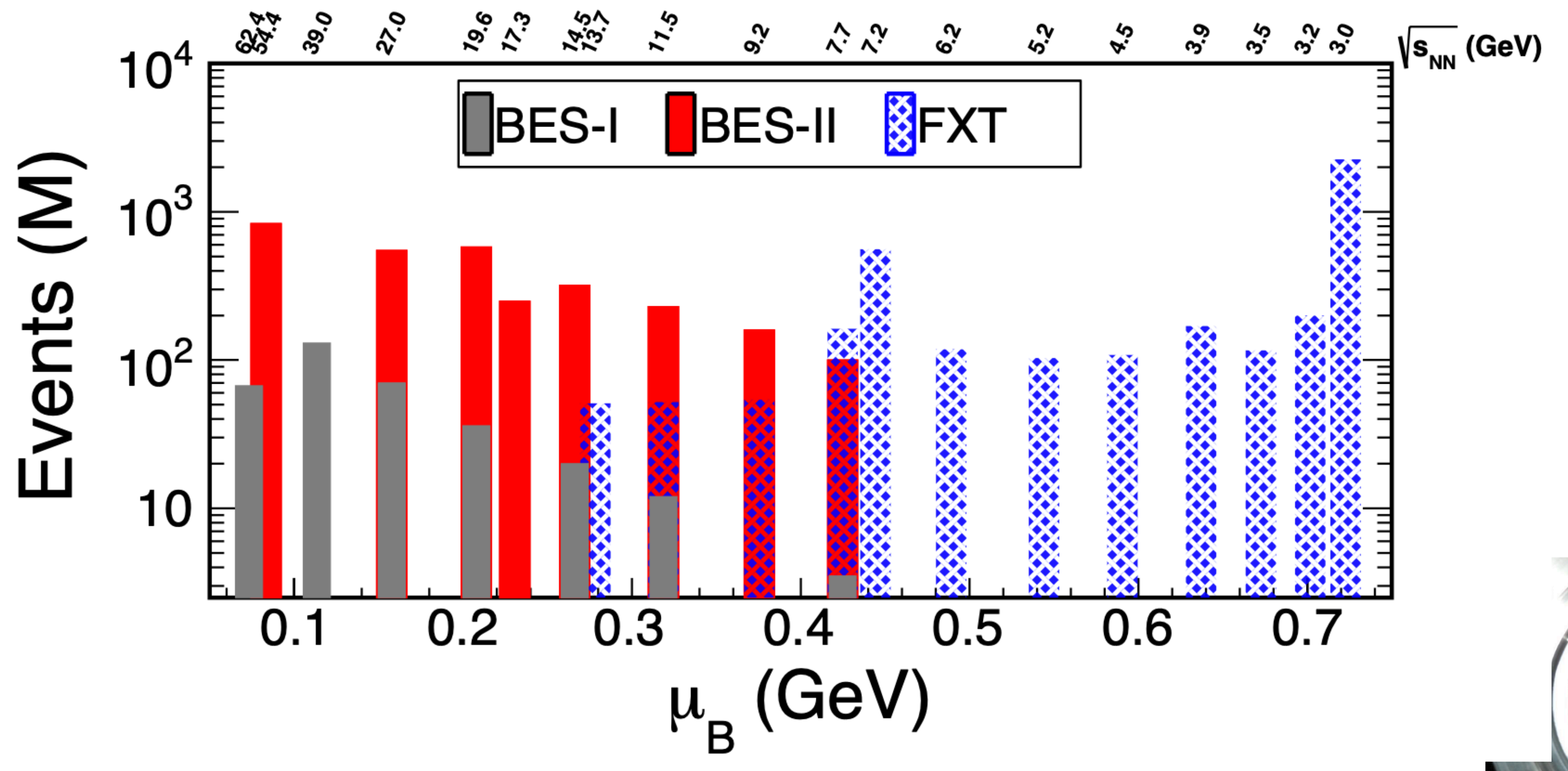
D. Lonardoni, et al. PRL 114, 092301 (2015)

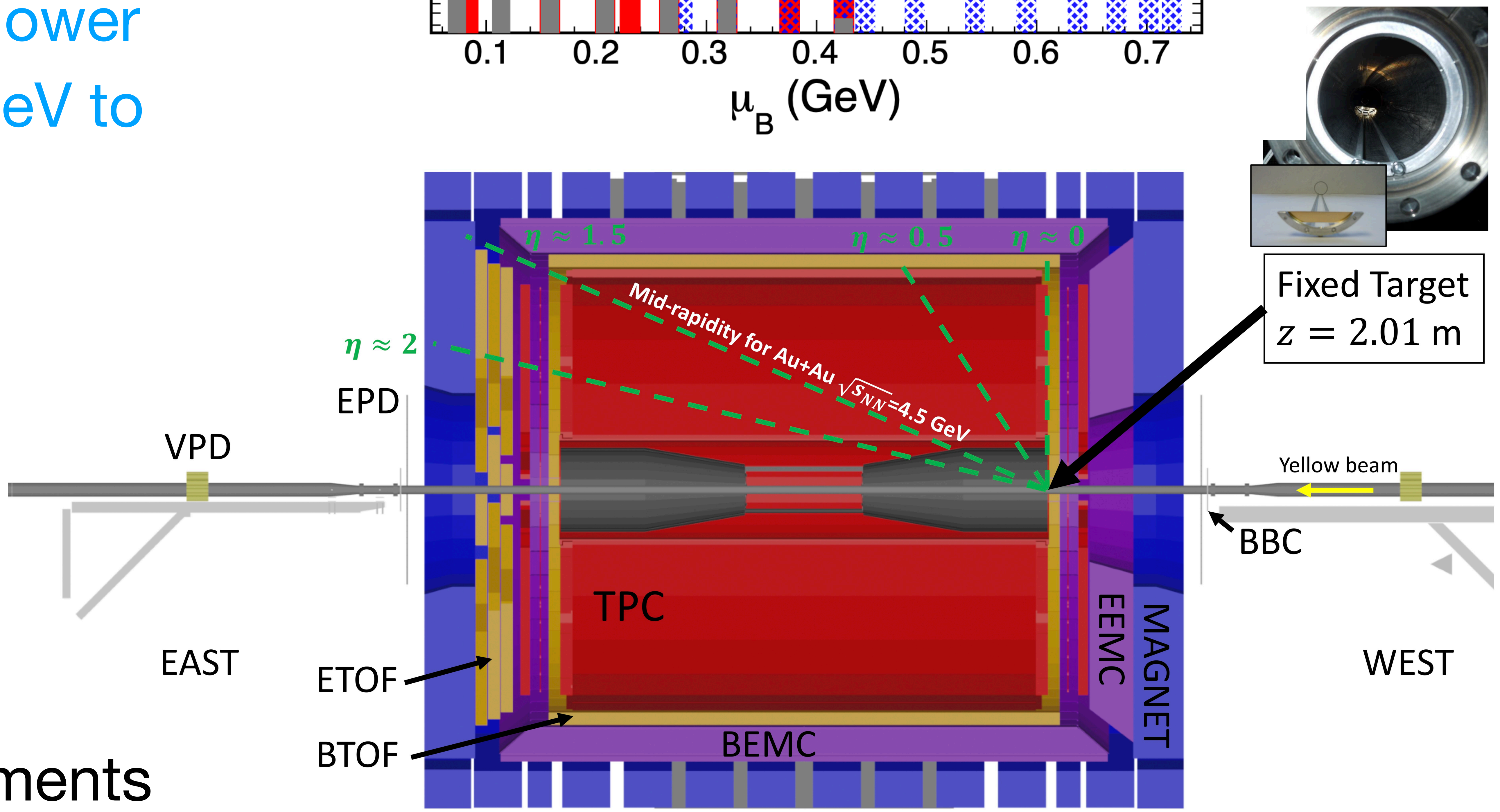
- **Hyperon puzzle**: do hyperons exist in the dense inner core of neutron stars?
  - Lack of experimental data of YN, YY, YNN interactions to constrain theoretical models of the dense matter equation of state (EoS)

Introduction: RHIC BES-II

- RHIC Beam Energy Scan phase II (BES-II):
  - Specific focus on low $\sqrt{s_{NN}}$
    - 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

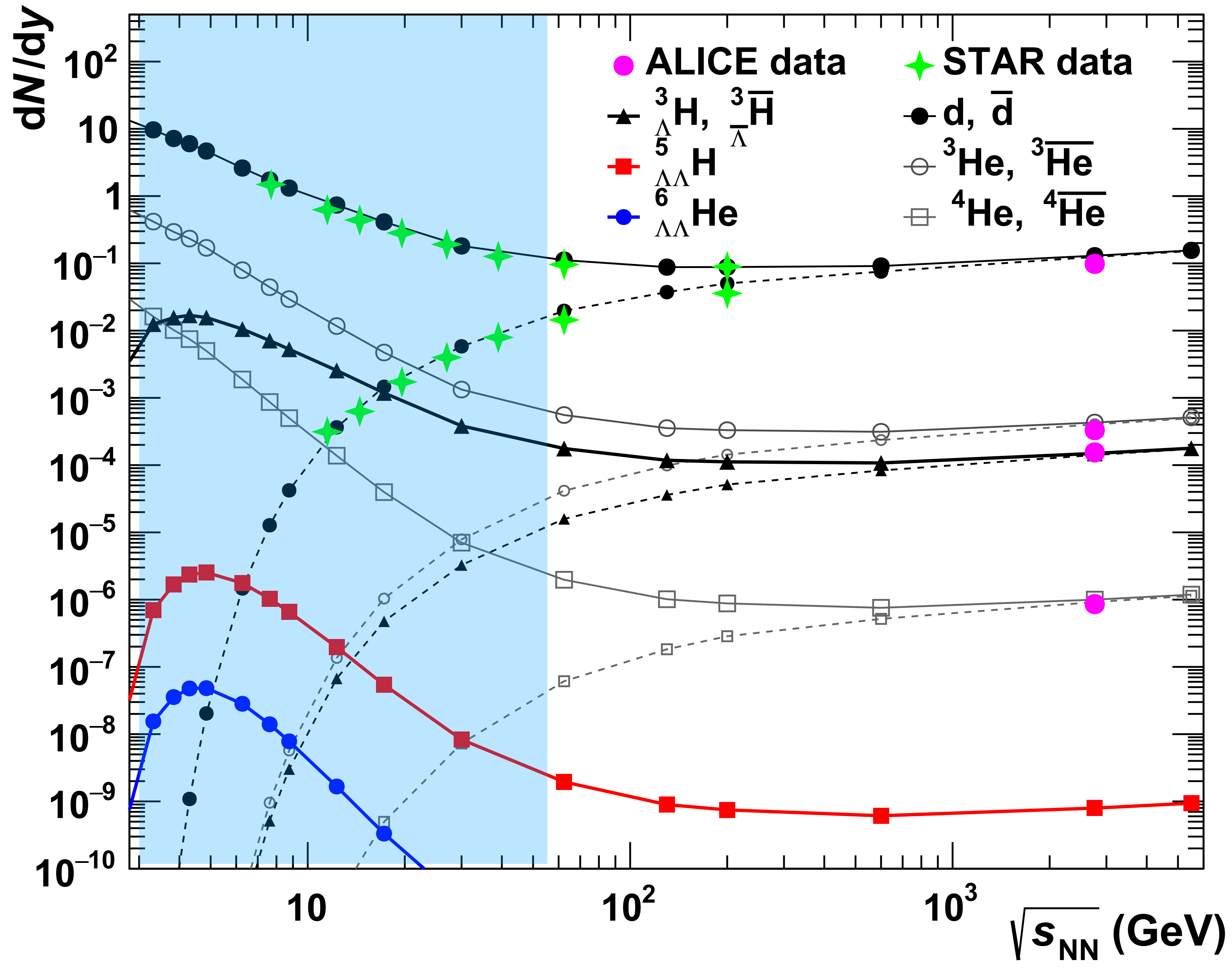




Introduction: hypernuclei in HI collisions

Production mechanism of hypernuclei is still not well understood.

Hypernuclei formation process in violent relativistic heavy-ion (HI) collisions can be studied through measurements related to **spectra and collective flow.**

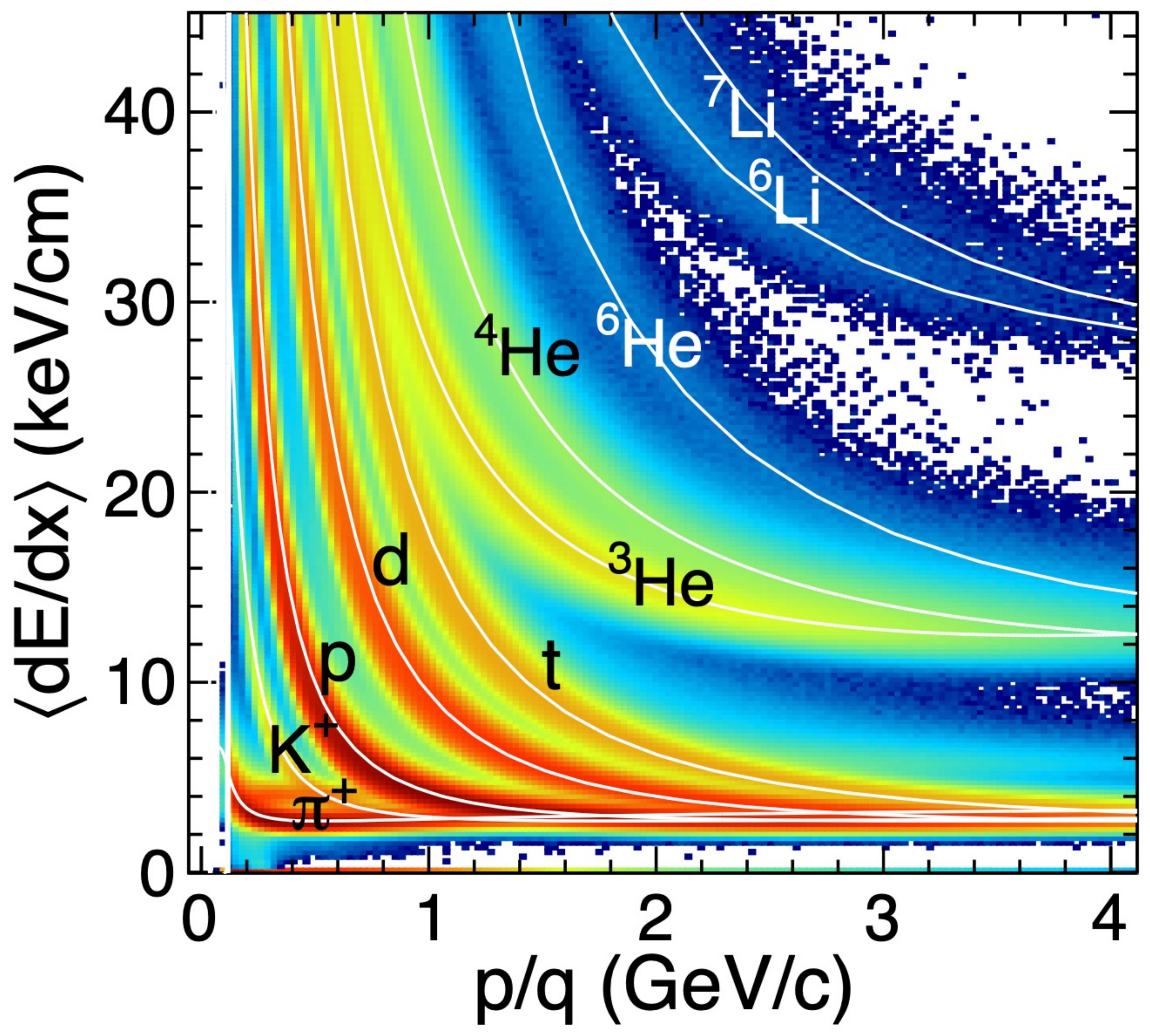


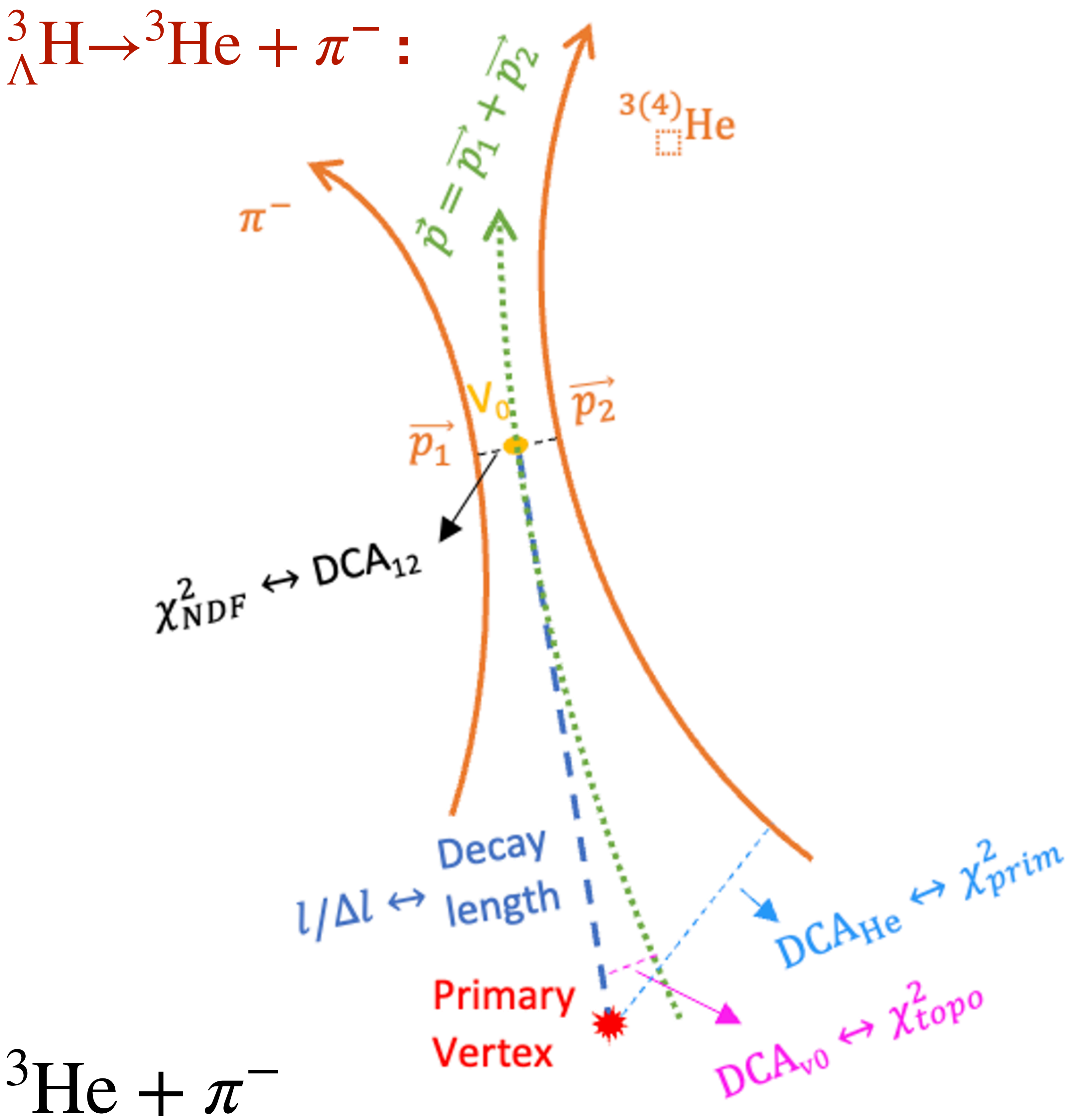
B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207

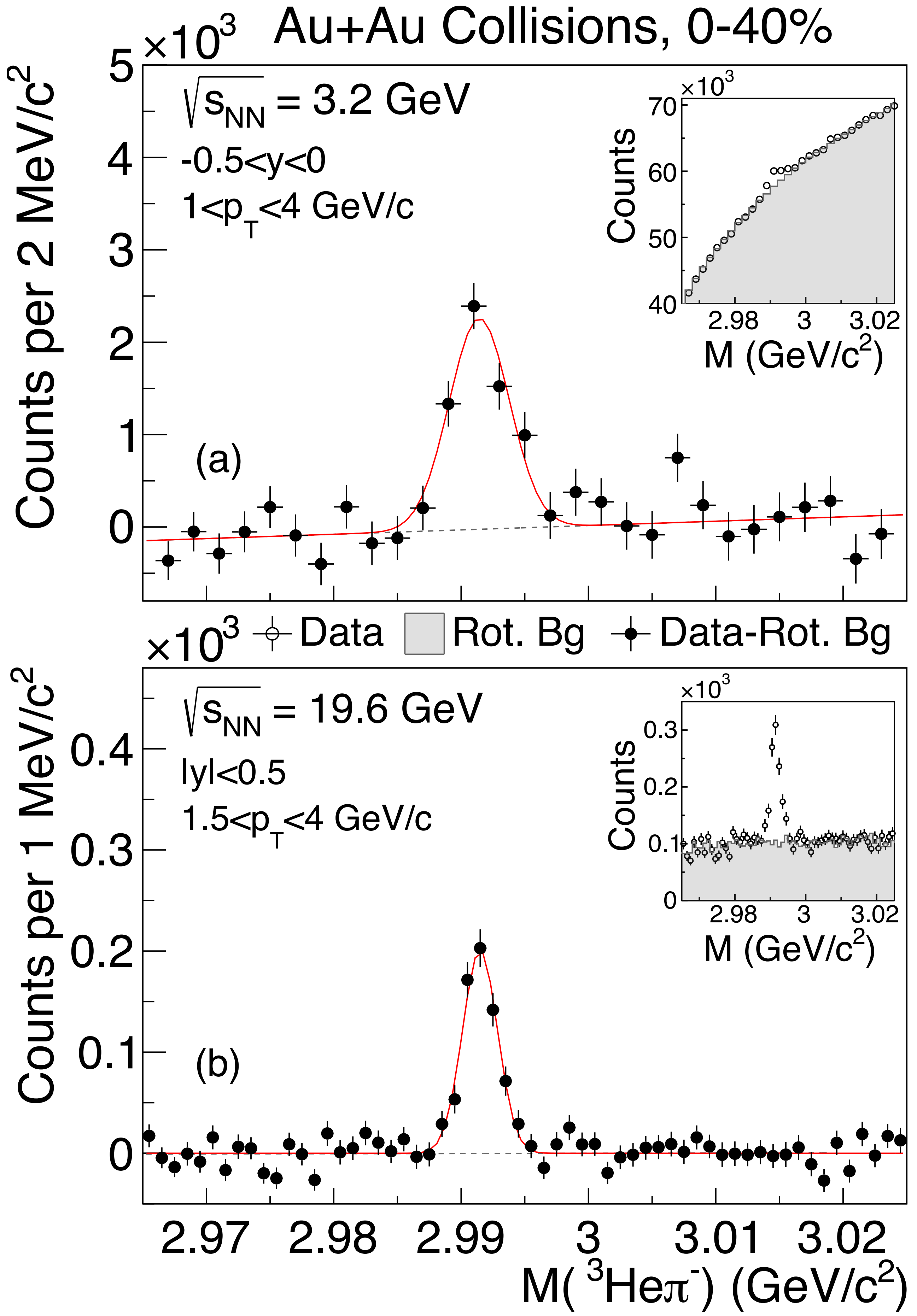
- Hypernuclei measurements are scarce in HI collision experiments
- At **low beam energies**, hypernuclei production is expected to be **enhanced** due to high baryon density

RHIC BES-II offers great opportunity for hypernuclei measurements.

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



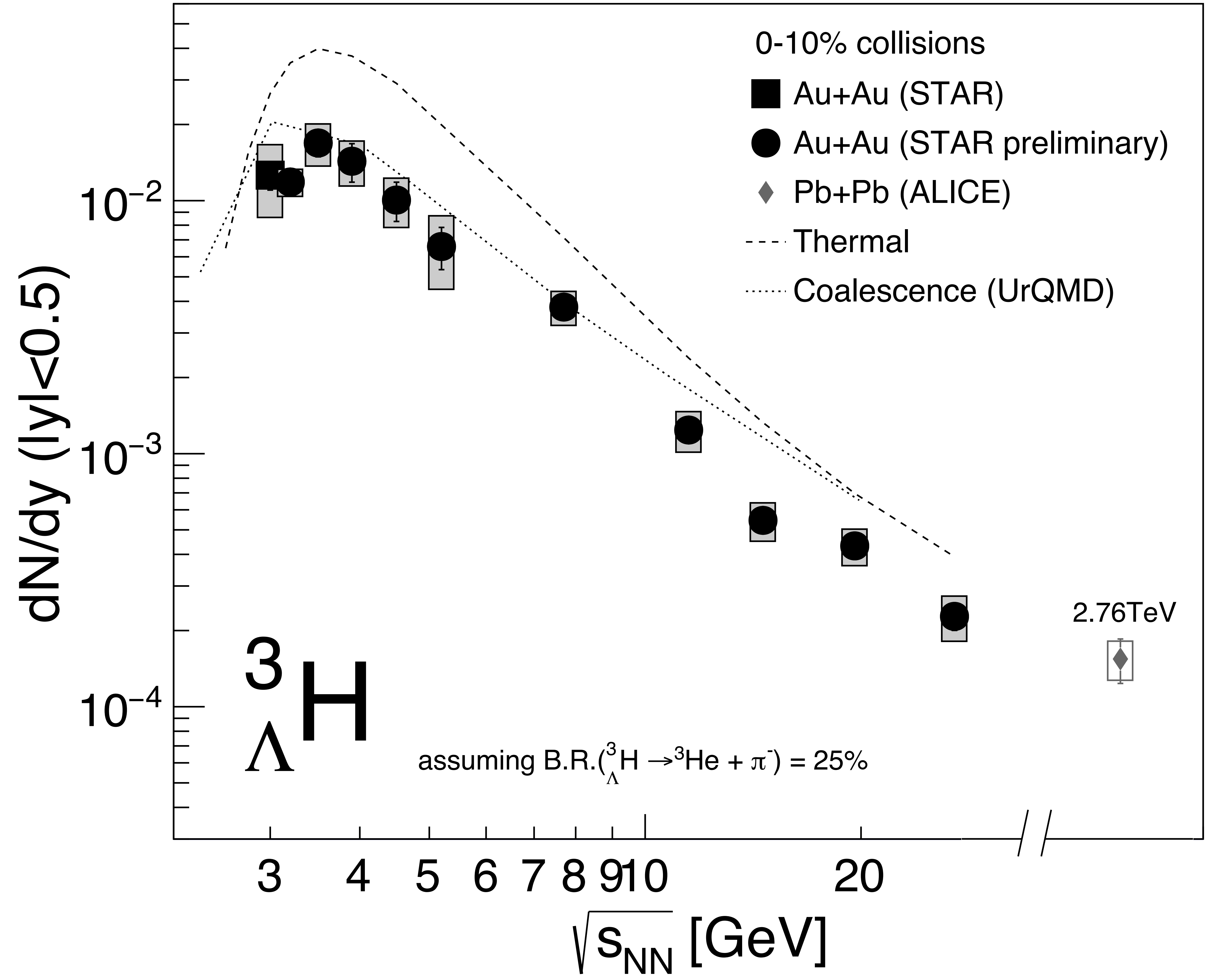




- Reconstruction channel: ${}^{3}_{\Lambda}\mathrm{H}\rightarrow{}^{3}\mathrm{He}+\pi^{-}$
- Particle identification from energy loss measurement using TPC
- KF particle package is used for signal reconstruction
- Backgrounds reconstructed by ${}^{3}\mathrm{He}$ rotation

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

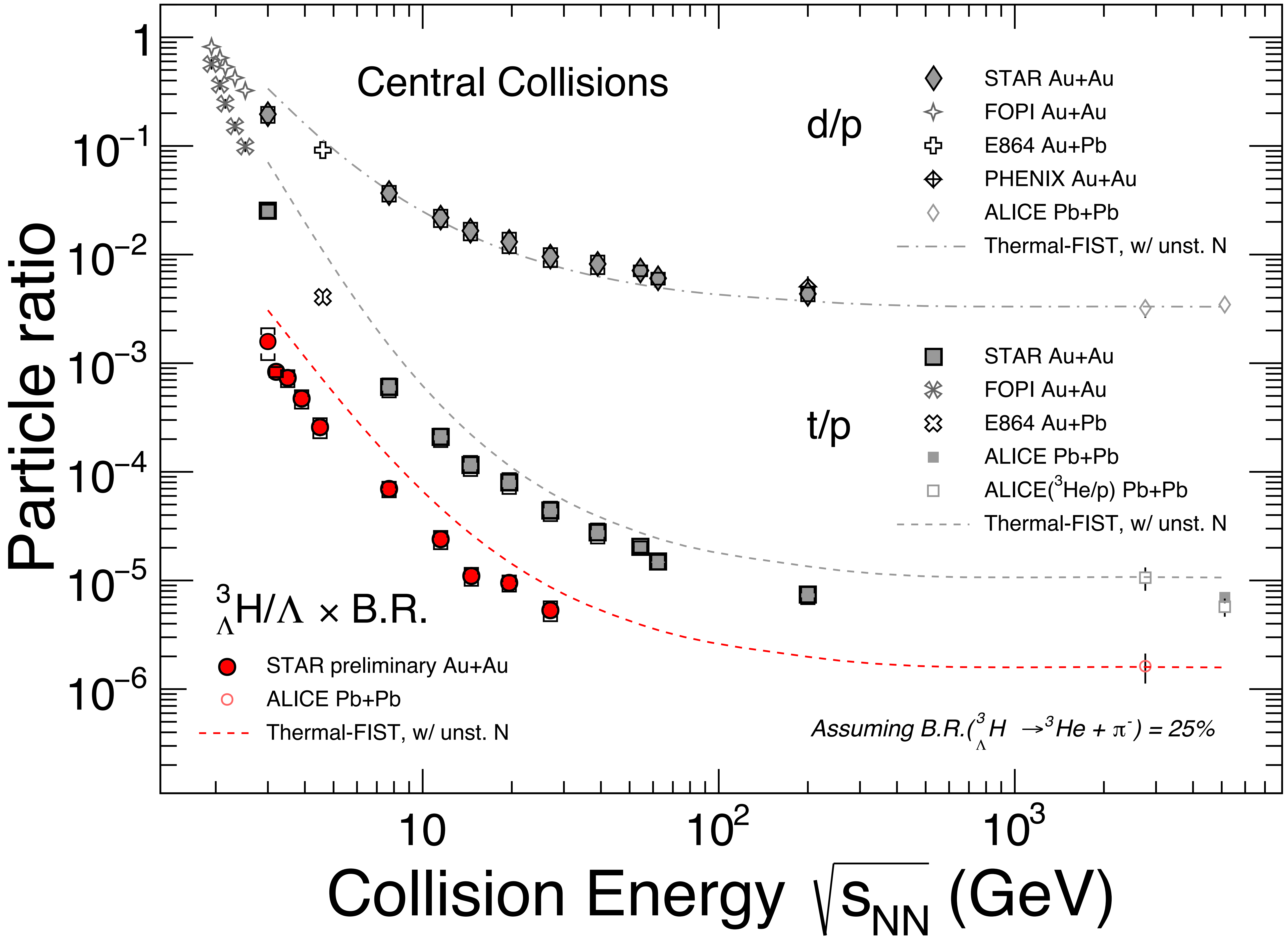
Energy dependence of ${}^{3}_{\Lambda}\mathrm{H}$ production



- Yields increase strongly from $\sqrt{s_{NN}}$ = 27 GeV to ~4 GeV
- Peak at 3-4 GeV
- **UrQMD + coalescence model** describe data from 3-10 GeV
- **Thermal model** overestimates data by ~ 2 times

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

Nuclei-to-hadron ratios



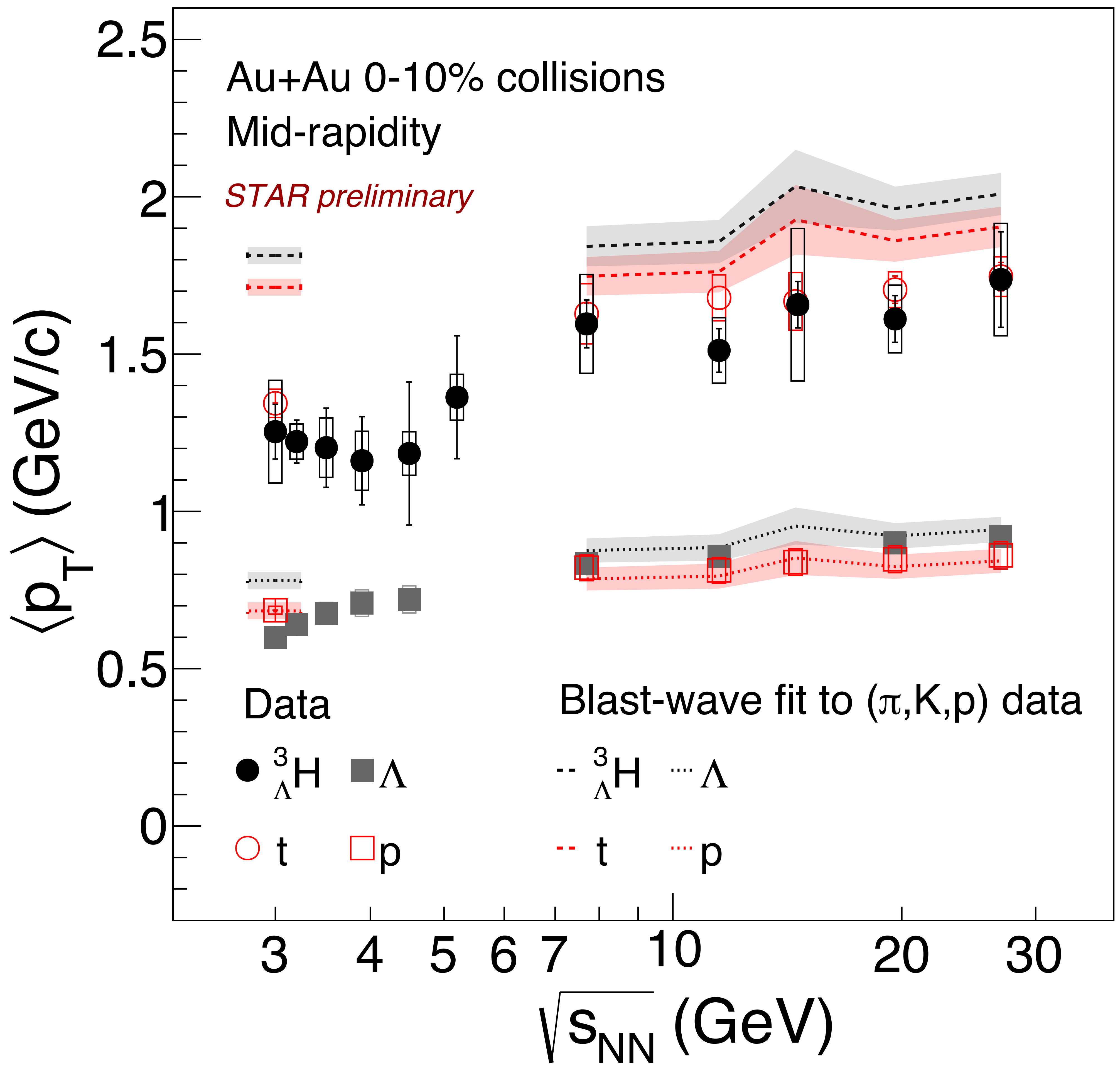
STAR, PRL 130 (2023) 202301
STAR, arXiv: 2311.11020
T. Reichert, et al, PRC 107 (2023) 014912

- **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

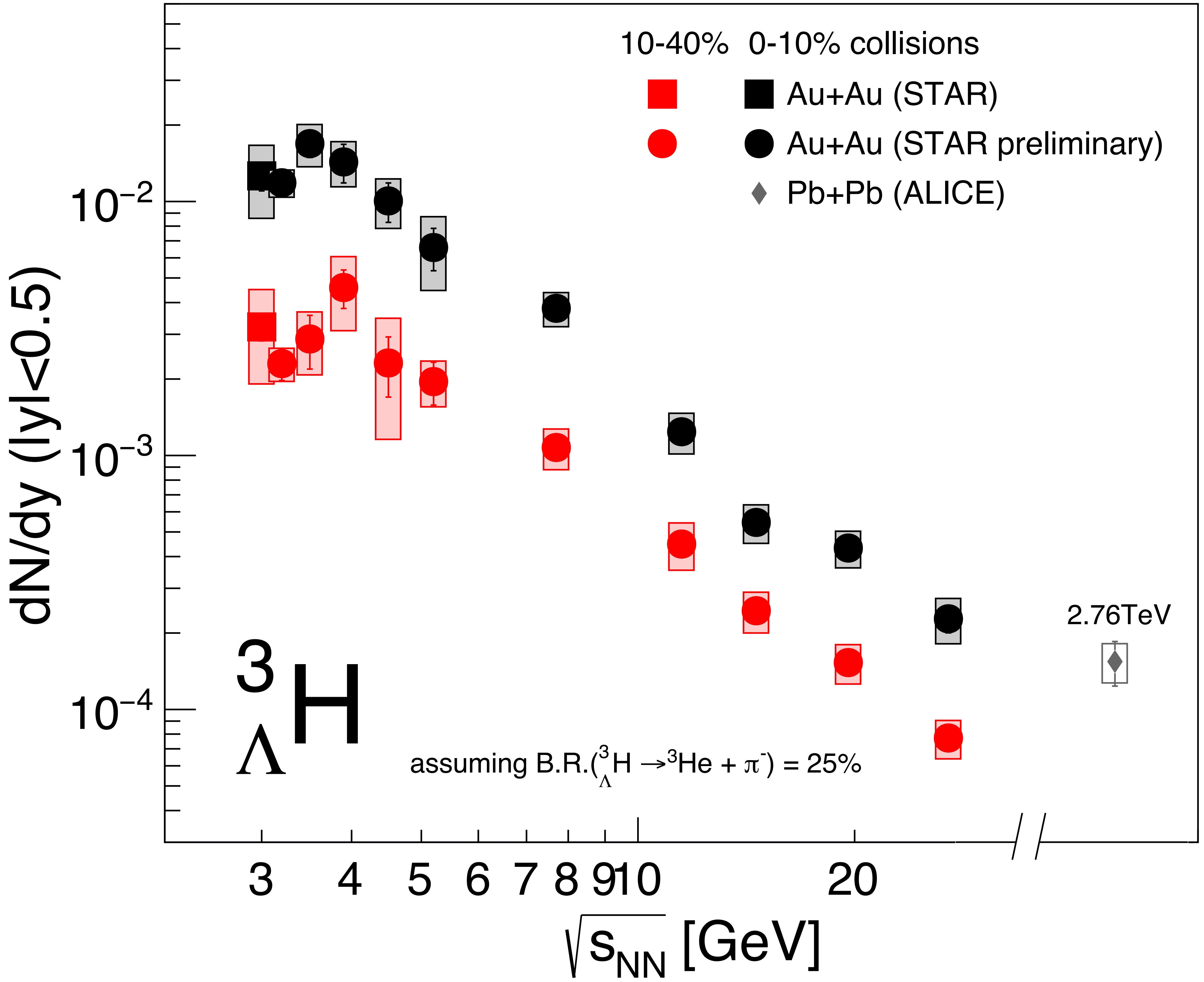
Energy dependence of ${}^{3}_{\Lambda}\mathrm{H}\ \langle p_T \rangle$



- ${}^{3}_{\Lambda}\mathrm{H}$ 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 **kinetic freeze-out parameters from measured light hadrons** (π, K, p)

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

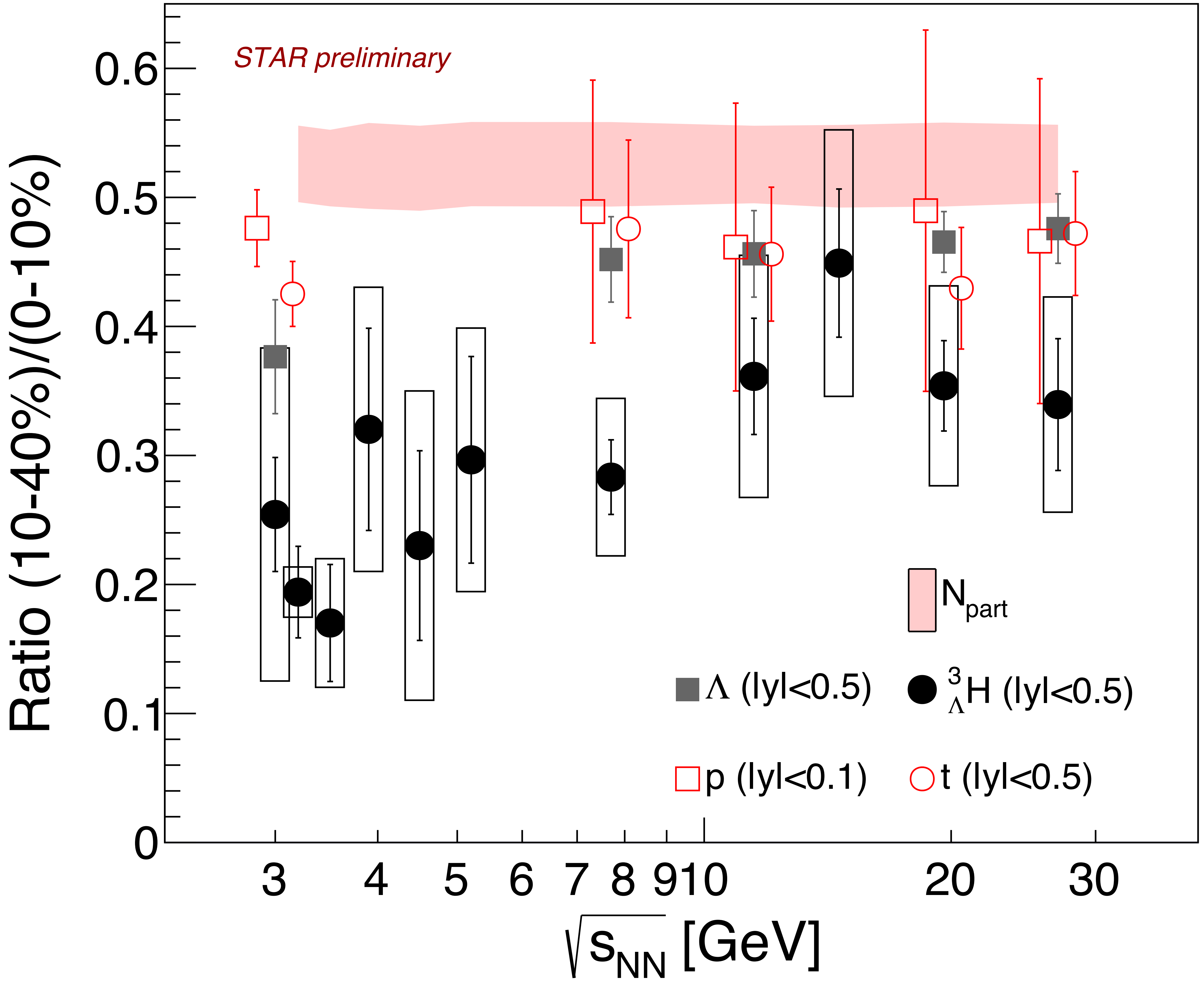
Centrality dependence of ${}^{3}_{\Lambda}\mathrm{H}$ production



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

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

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

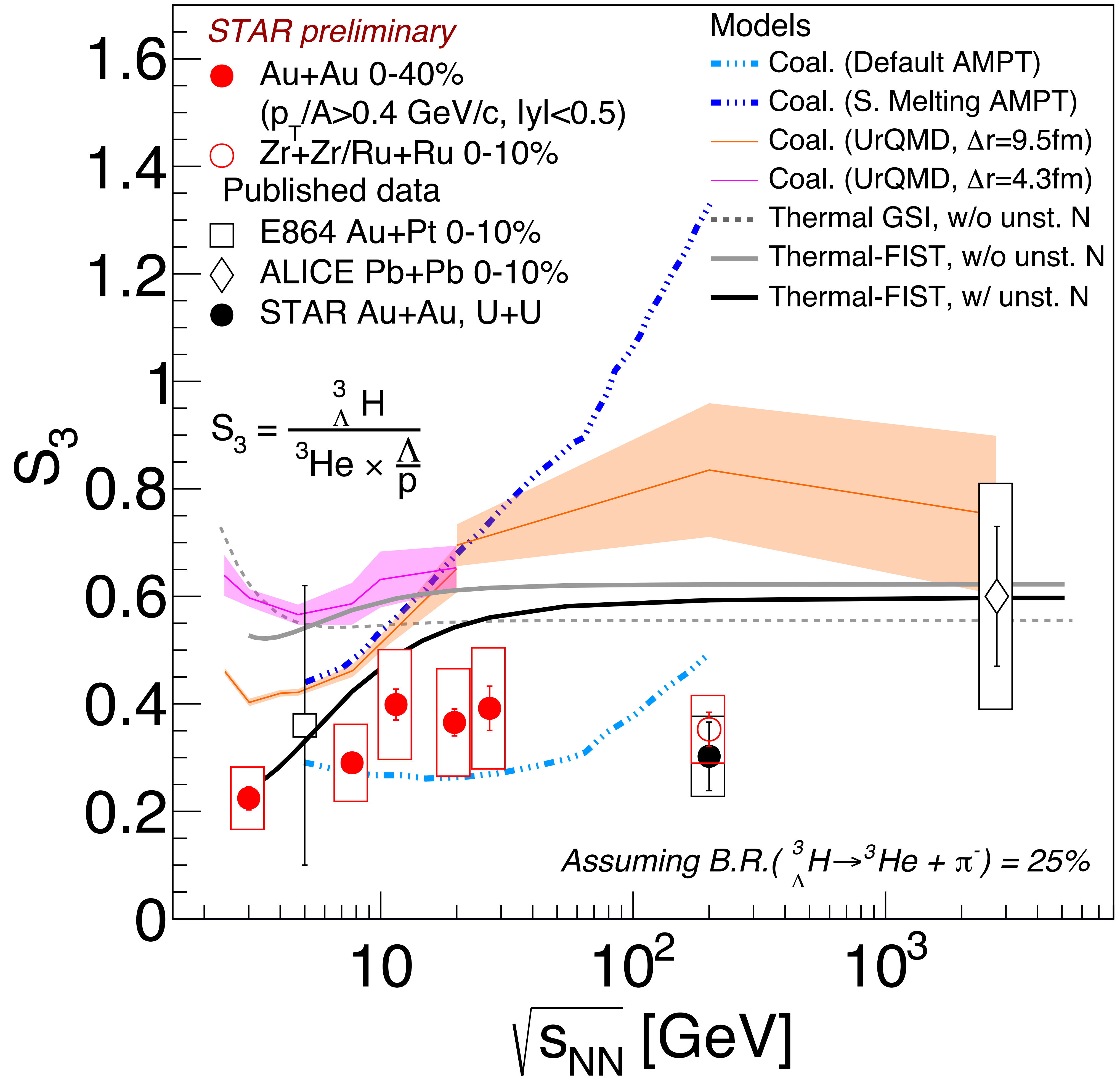


- Suppression of mid-central/central ${}^{3}_{\Lambda}\mathrm{H}$ yield ratio w.r.t $\mathrm{N_{part}}$, seems more apparent below $\sqrt{s_{NN}}$ = 7.7 GeV
- ${}^{3}_{\Lambda}\mathrm{H}$ yield ratio tends to increase more steeply than proton, Λ, triton at low energies

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



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 (Coal.+UrQMD, Thermal-FIST)

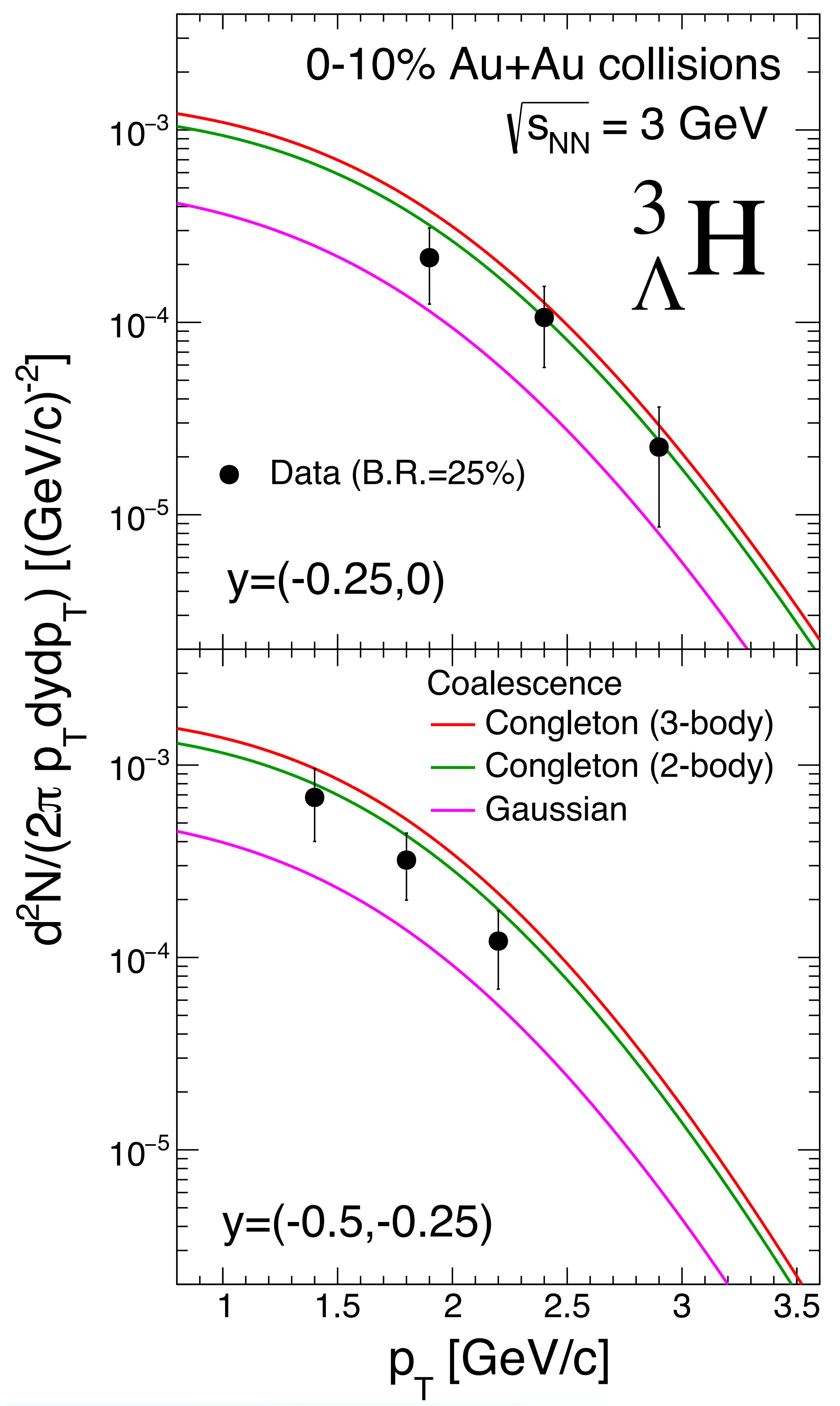
Increasing trend of S_3 proposed as a signal of deconfinement

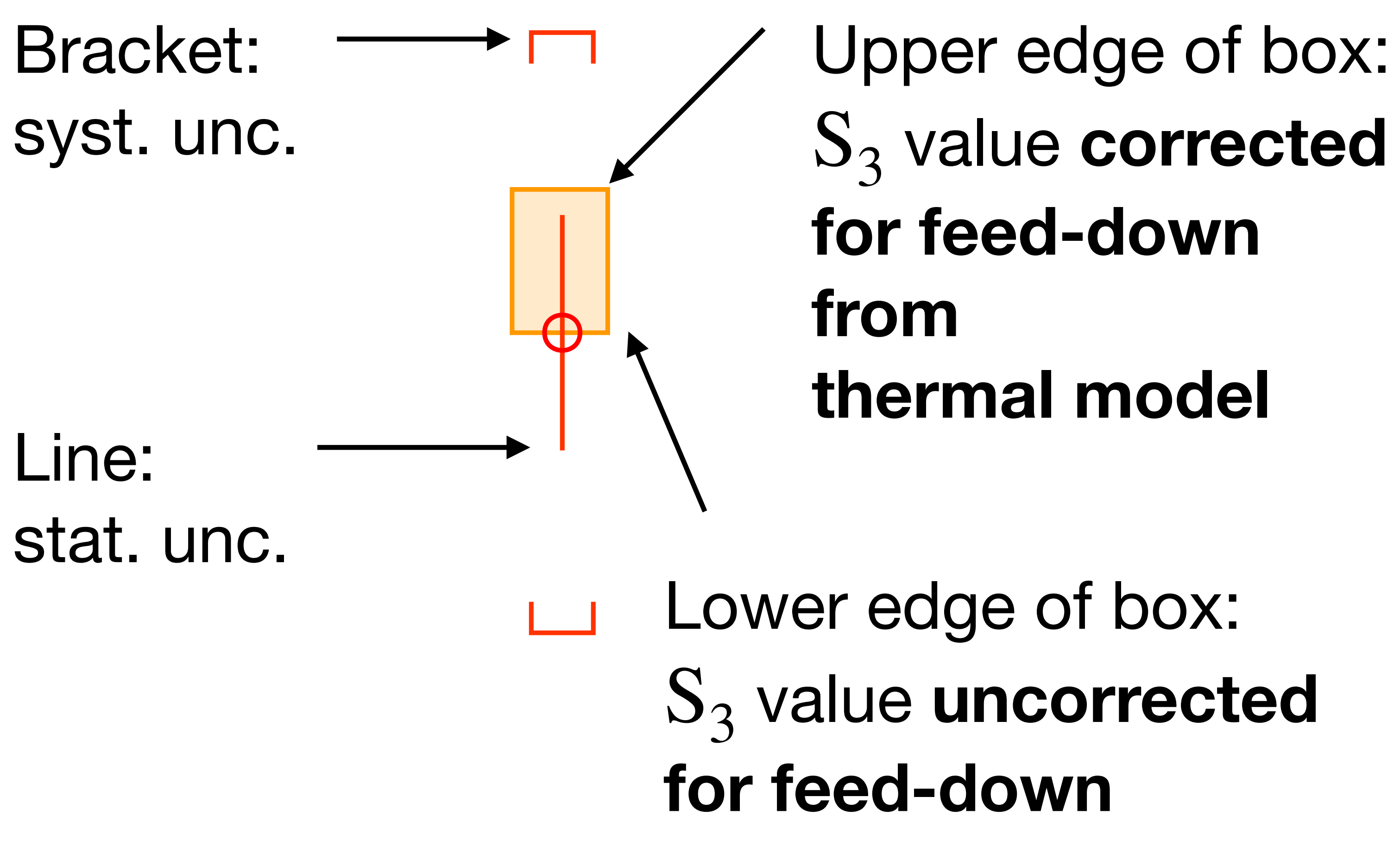
S. Zhang et al. PLB 684 (2010) 224–227

- Data shows a mild increasing trend
- UrQMD + coalescence also suggest increasing trend
  - Suppression of $^3_\Lambda H$ due to large size
- Thermal-FIST also suggest increasing trend
  - Suggest **feed-down from unstable nuclei** to stable nuclei

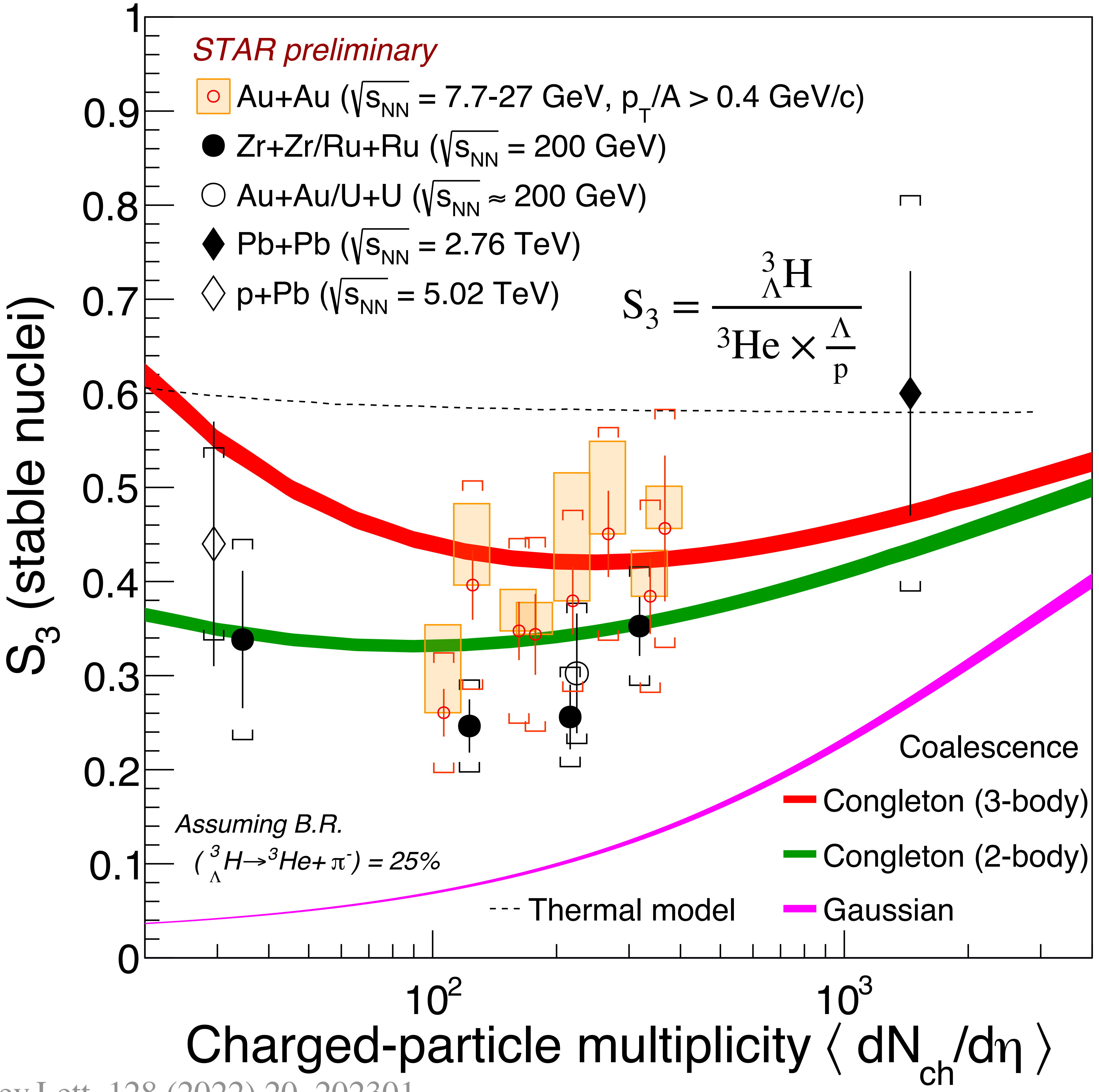
V. Vovchenko, PLB 809 (2020) 135746

Multiplicity dependence of S_3





- Coalescence using Gaussian wave function for $^{3}_{\Lambda}$H underestimate data
- Coalescence using Congleton wave function or $^{3}_{\Lambda}$H describe the data across wide range of energies

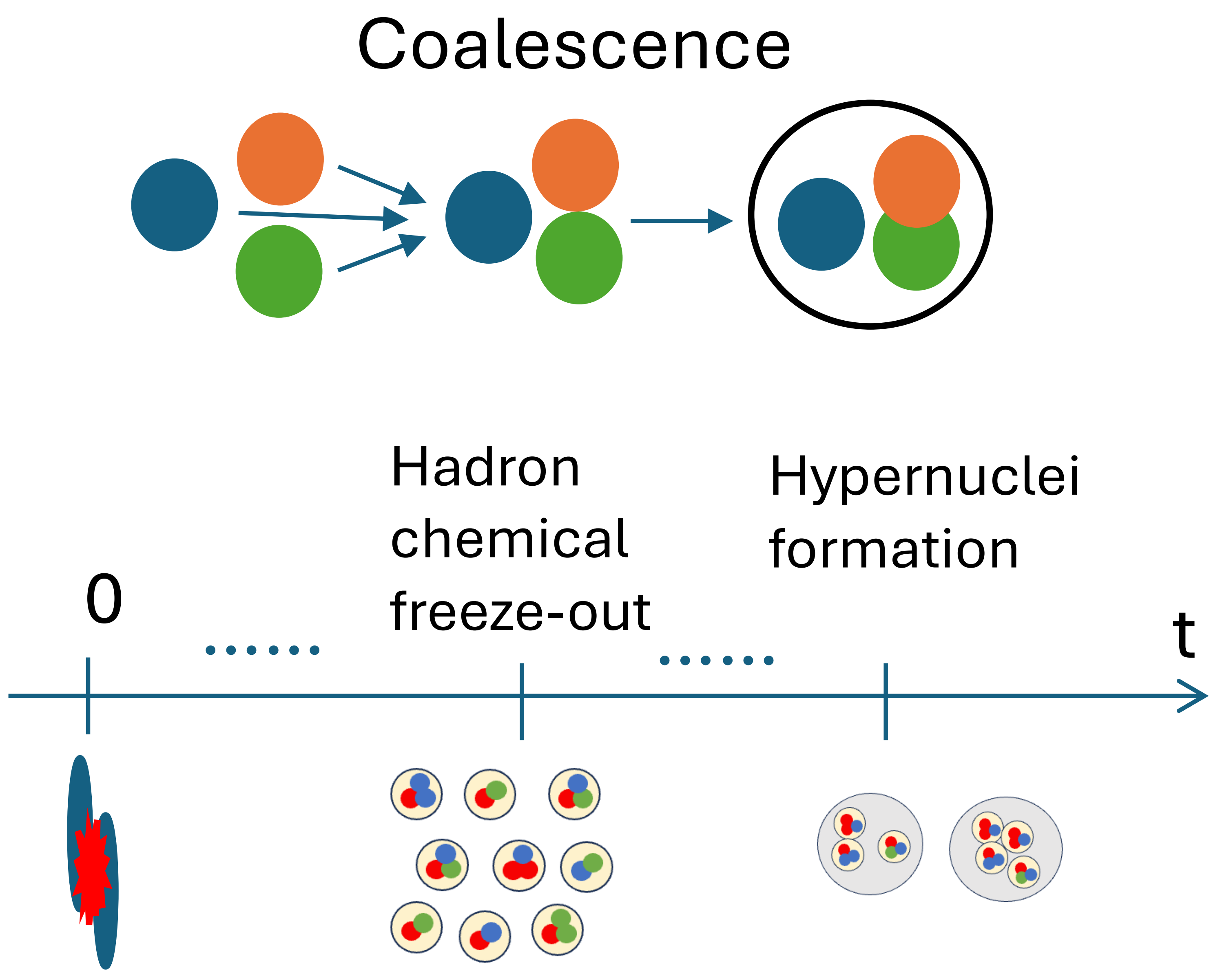


STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
ALICE, PRL 128(2022)252003
ALICE, PLB 754 (2016) 360
V. Vovchenko, PLB 785(2018)171 (Thermal)
Y-H. Leung, arXiv: 2510.06758 (Coalescence)

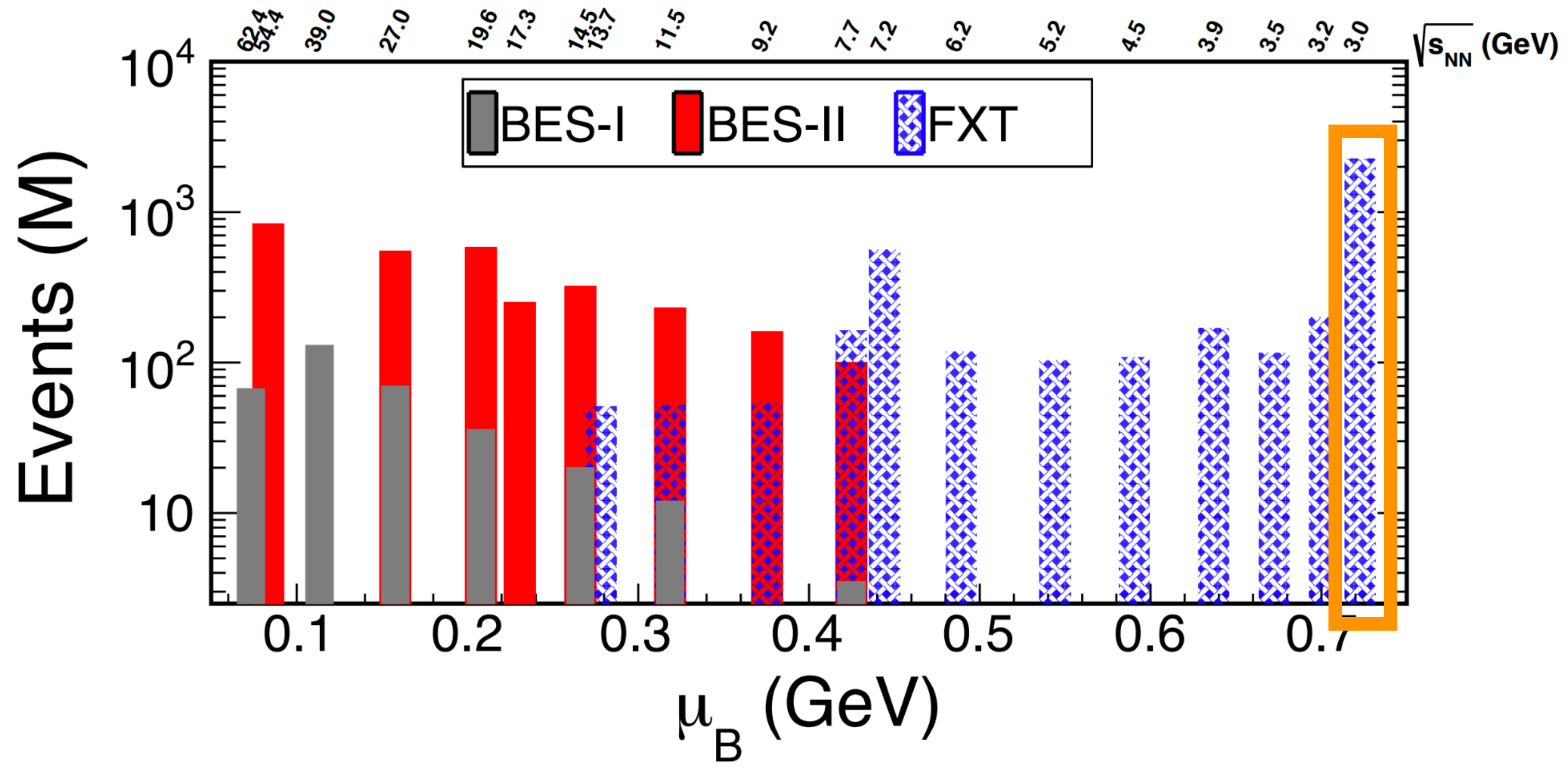
Summary

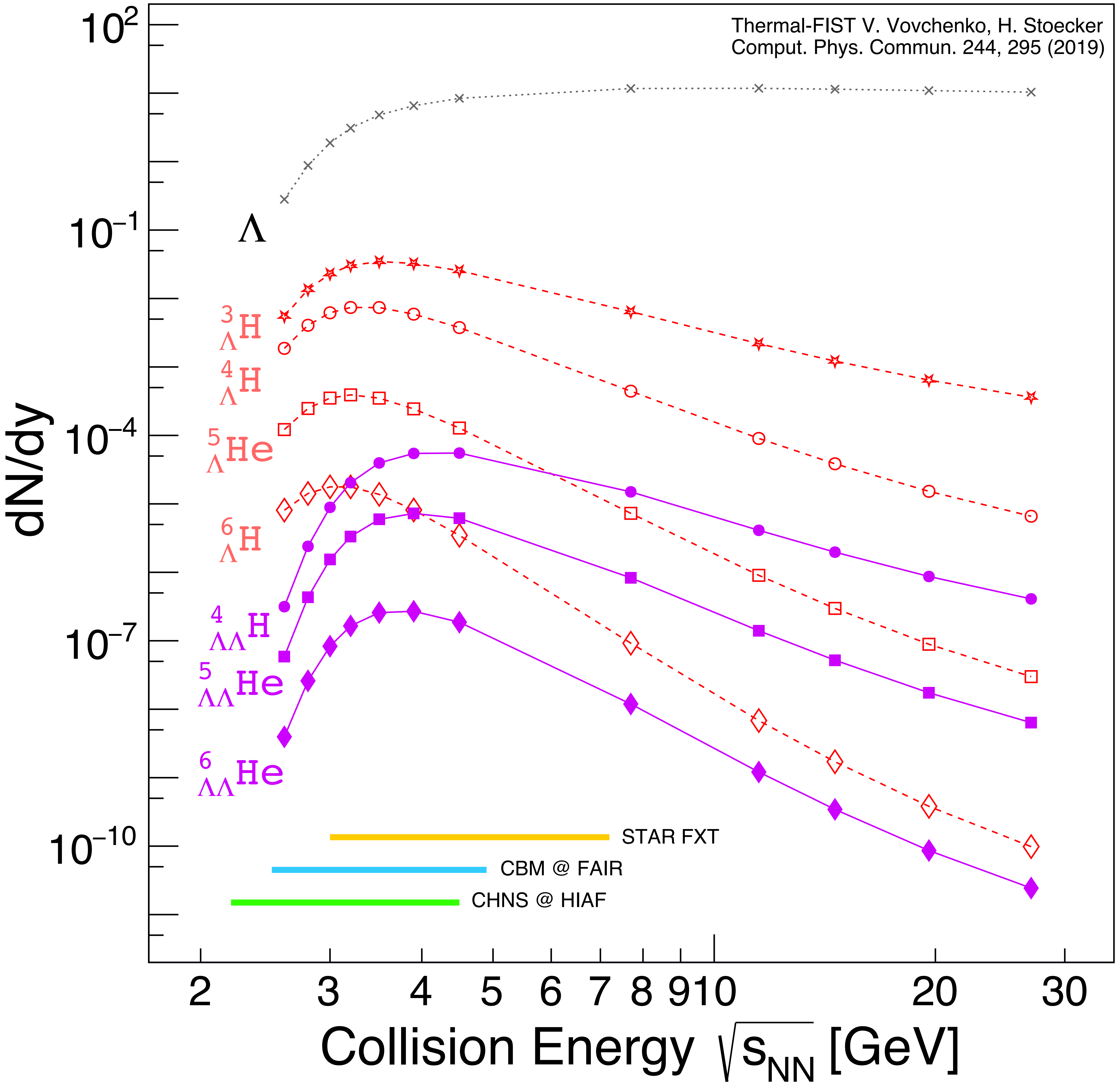
- Experimental results of ${}^{3}_{\Lambda}\mathrm{H}$ production in:
  - 3.0 – 27 GeV Au+Au collisions
  - 200 GeV Zr+Zr/Ru+Ru collisions

- **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

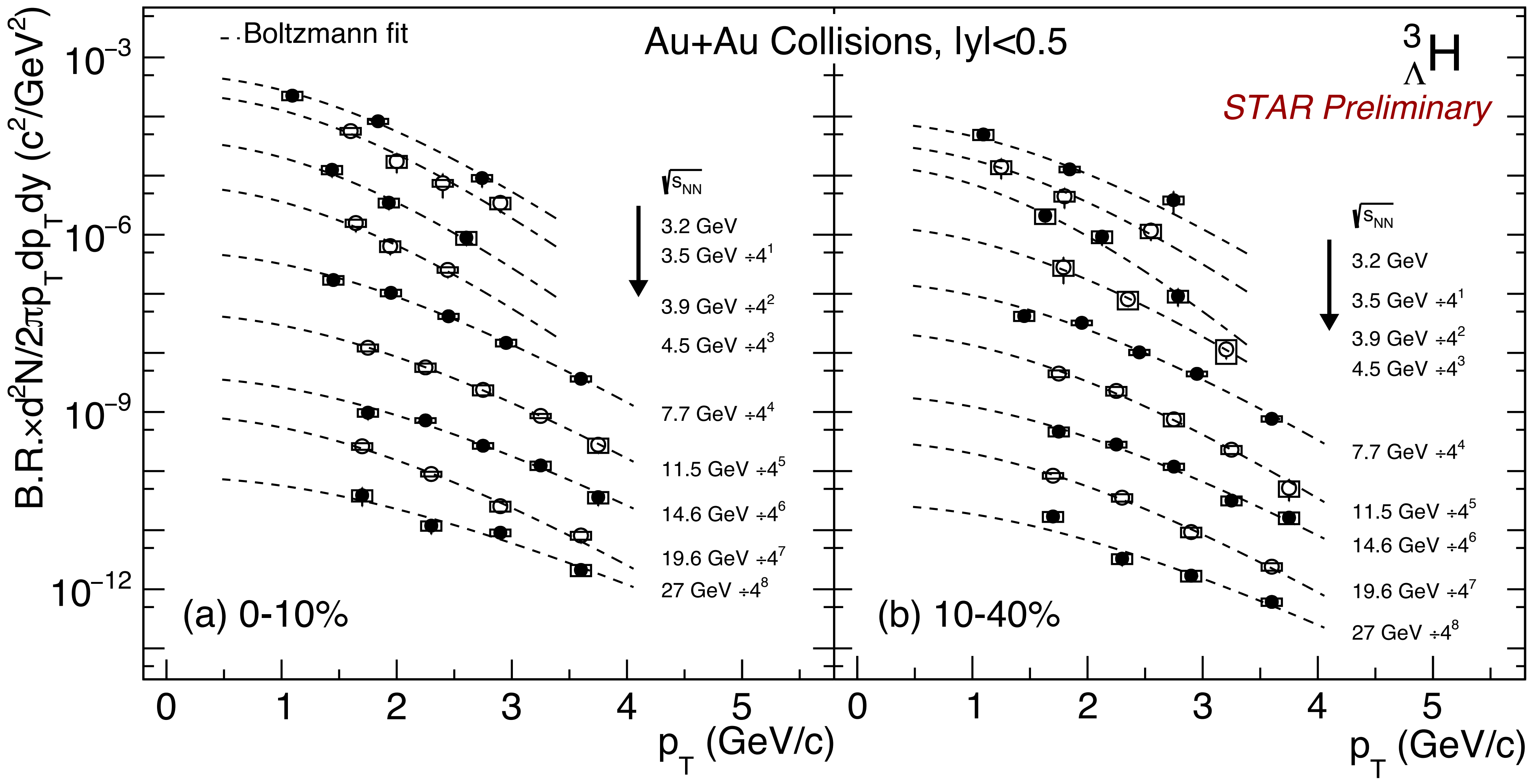




- RHIC-STAR: huge datasets at RHIC top and lowest energies
  - Run 21, Au+Au 3 GeV, ~2 billion events
  - Run 18, Isobar 200 GeV, ~6 billion events
  - Run 23-25, Au+Au 200 GeV, ~18 billion events
- Opportunities for heavier (anti-)hypernuclei

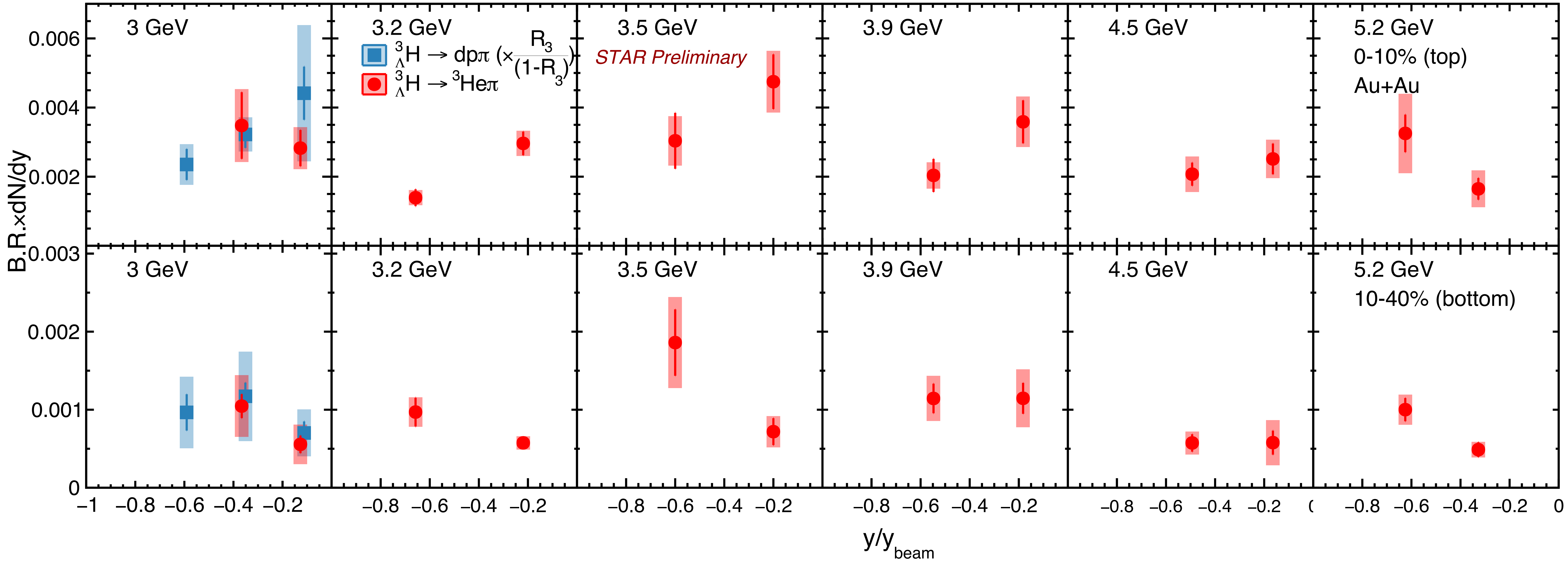
backups

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

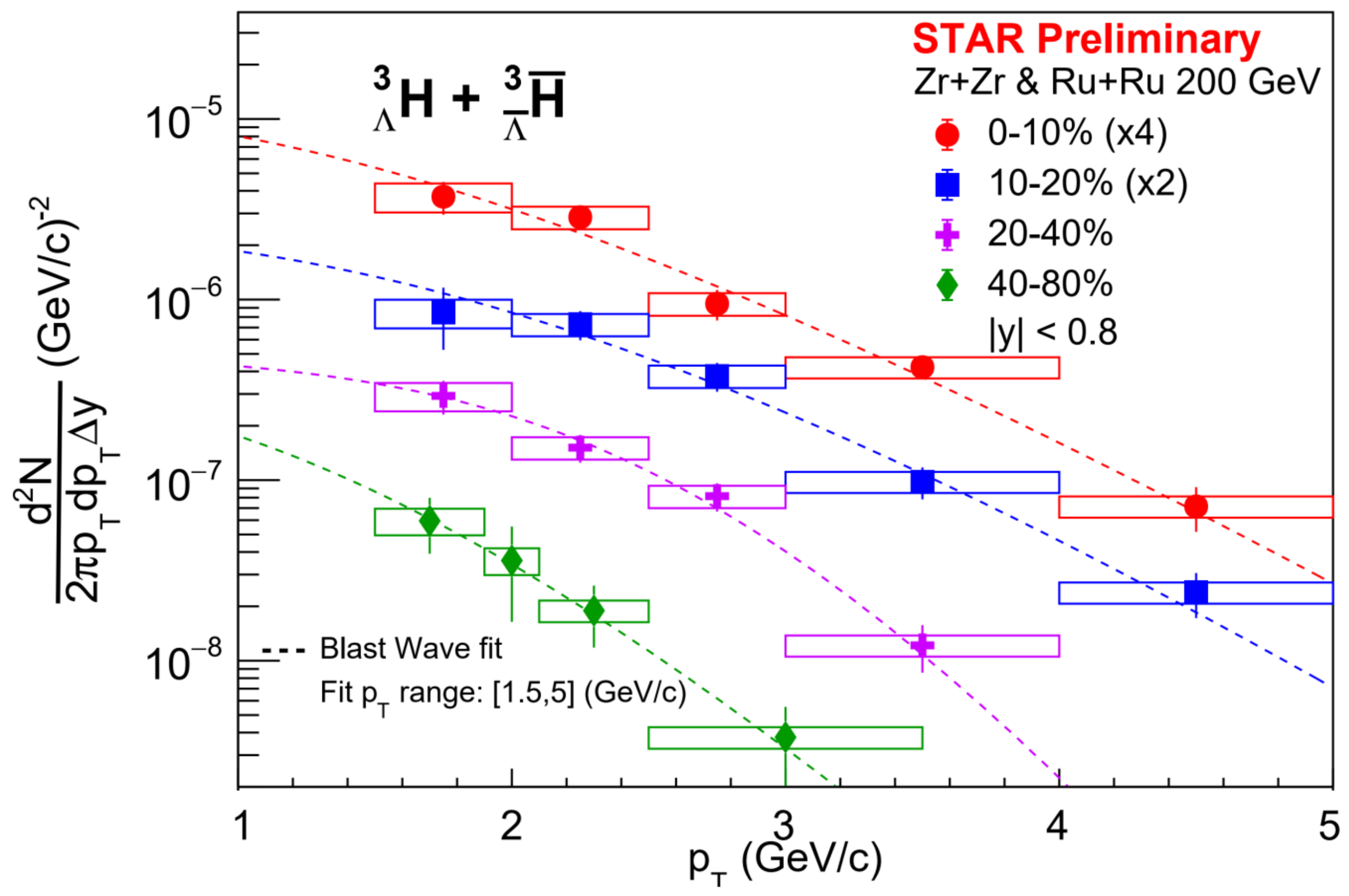


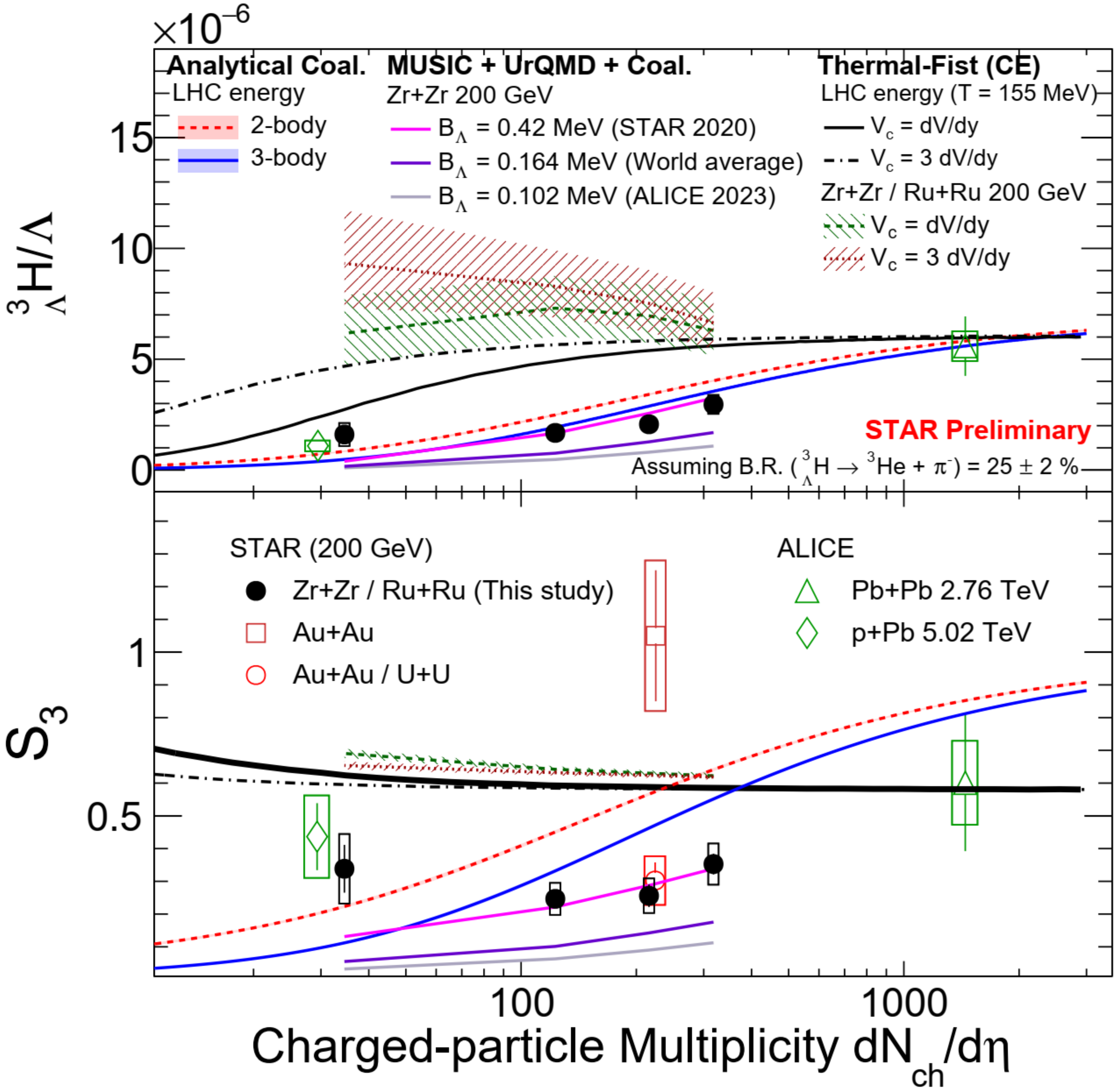
- Measurements cover:

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

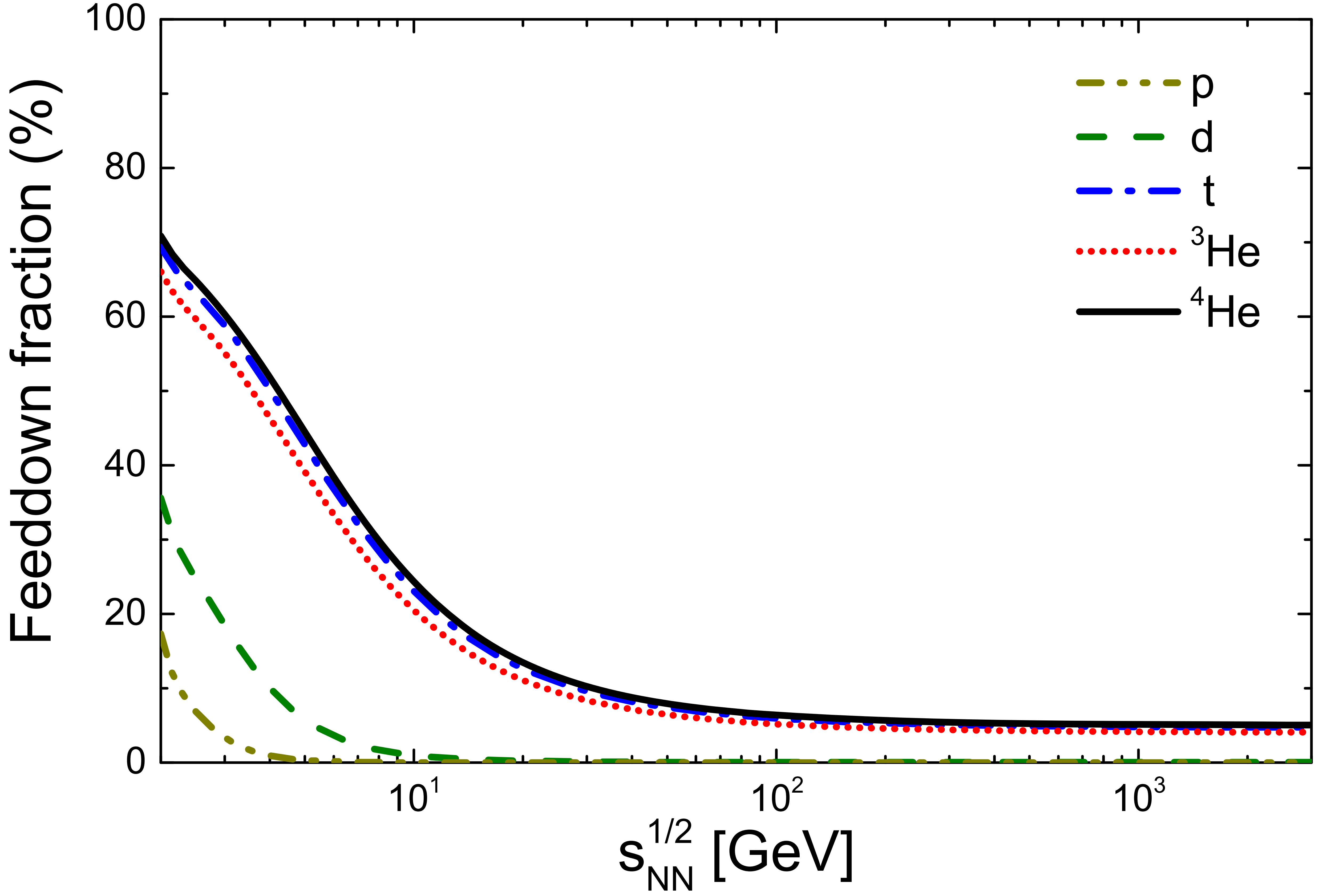


$^{3}_{\Lambda}H$ production in isobar 200 GeV

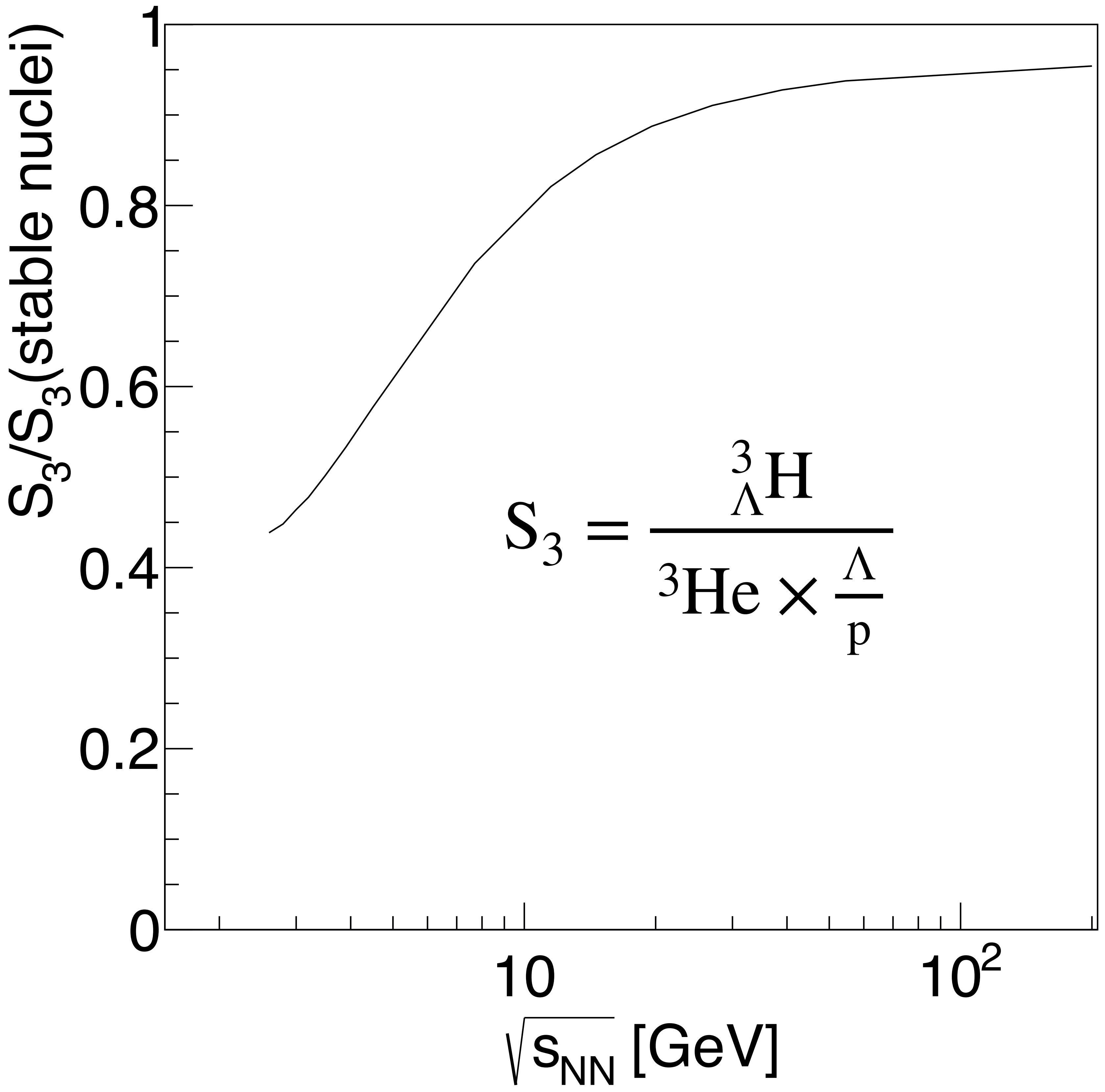




Feed-down from unstable nuclei



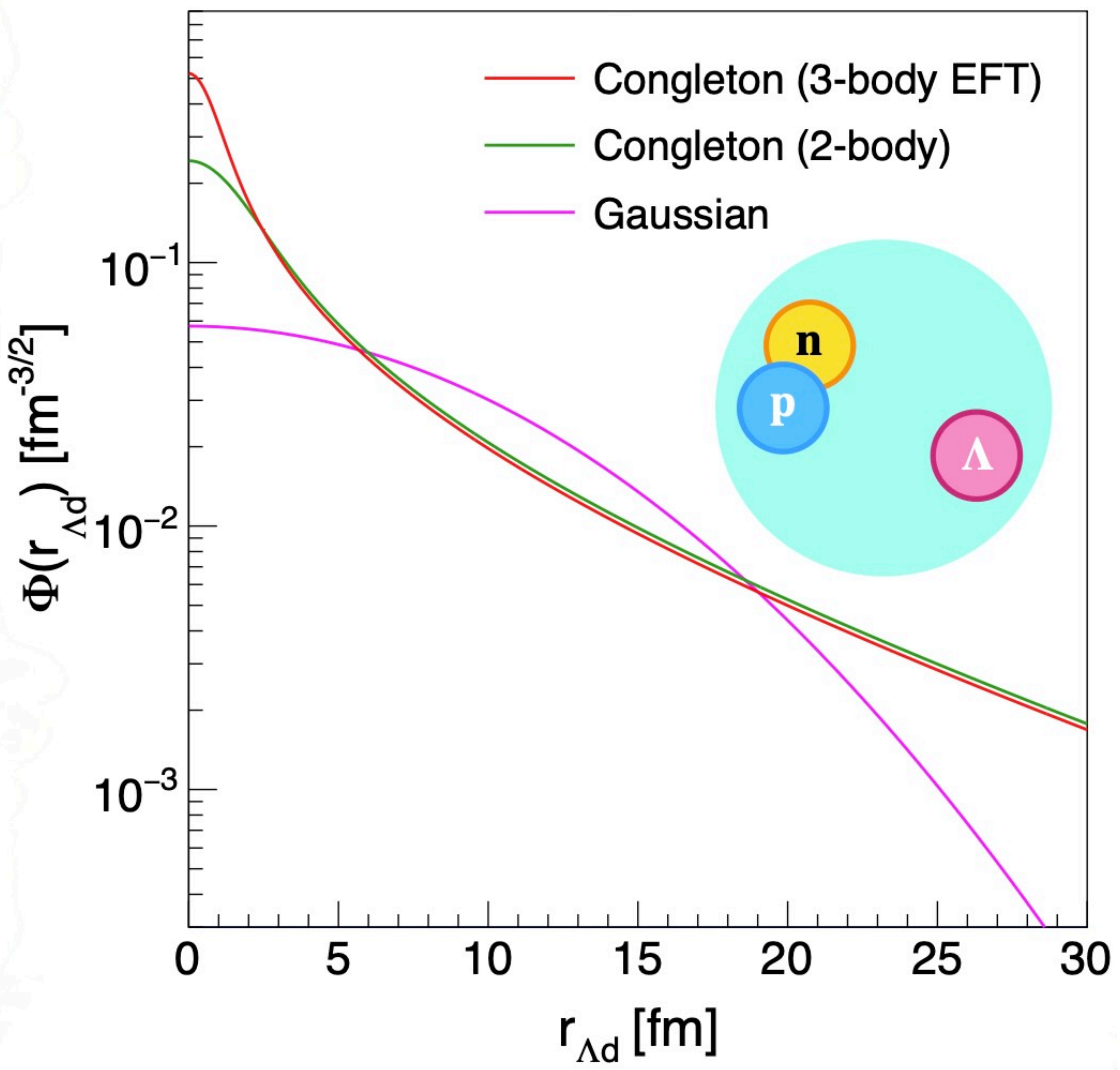
V. Vovchenko, PLB 809 (2020) 135746



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

- 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

Nuclei wave functions



Y-H. Leung, arXiv: 2510.06758 (Coalescence)

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

- Extracted source size at 0-10% Au+Au 200GeV ~ 4.5 fm
- At $r_{\Lambda d} < 4.5$ fm, wave functions with larger probability density will yield higher production rates.