Light Nuclei and Hypernuclei Production in Heavy-Ion Collisions

— *Recent Experiment Results and Future Prospects*

RHIC-BES online seminar

Yue-Hang Leung
University of Heidelberg

30th May, 2023

Outline

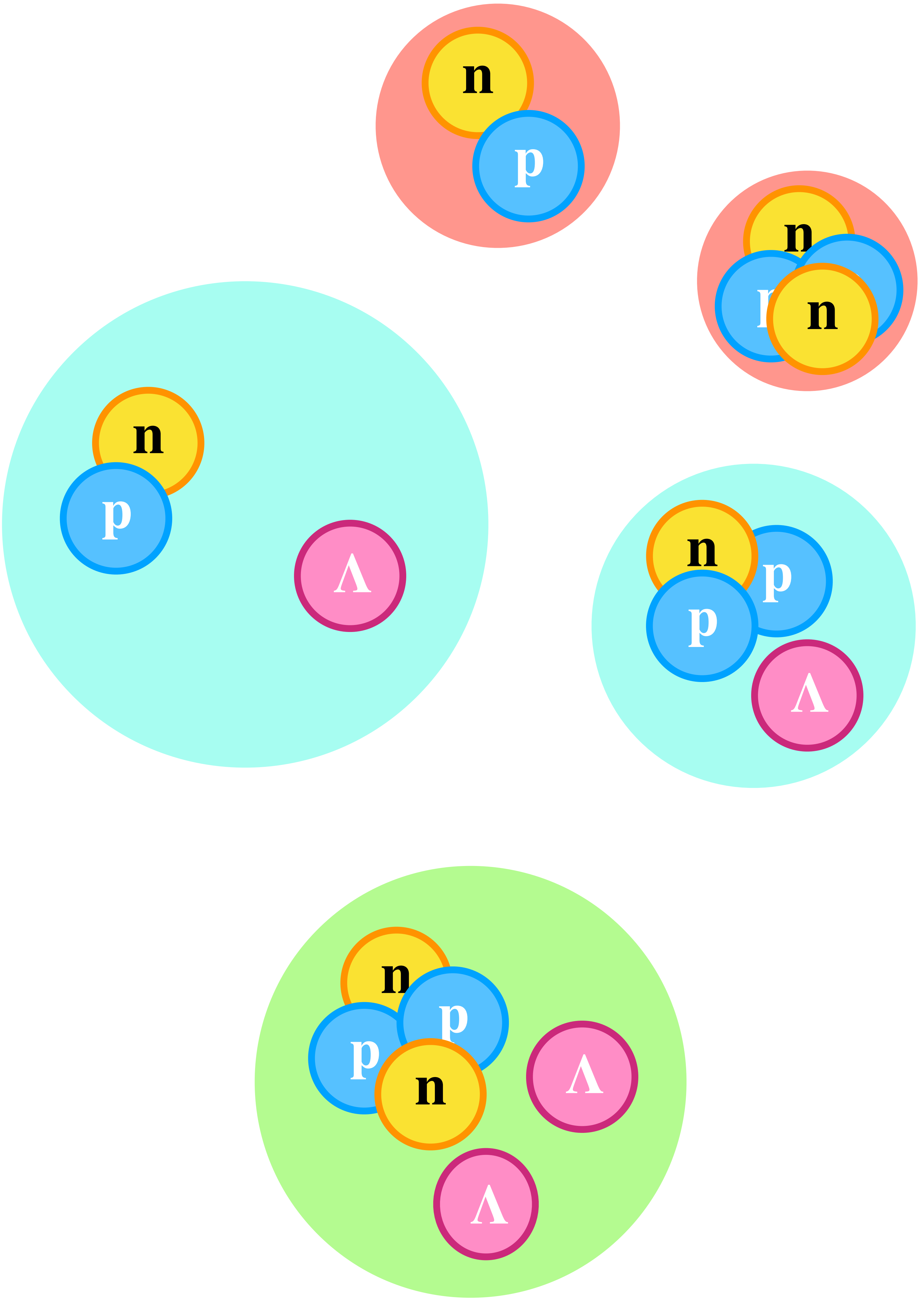
- **Introduction**
- **Experimental observables**
  - Production Yield
  - Aside: Hypernuclei Properties
  - Collective Flow
  - Femtoscopic Correlations
  - Cumulants
- **Summary**
- **Outlook**

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

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

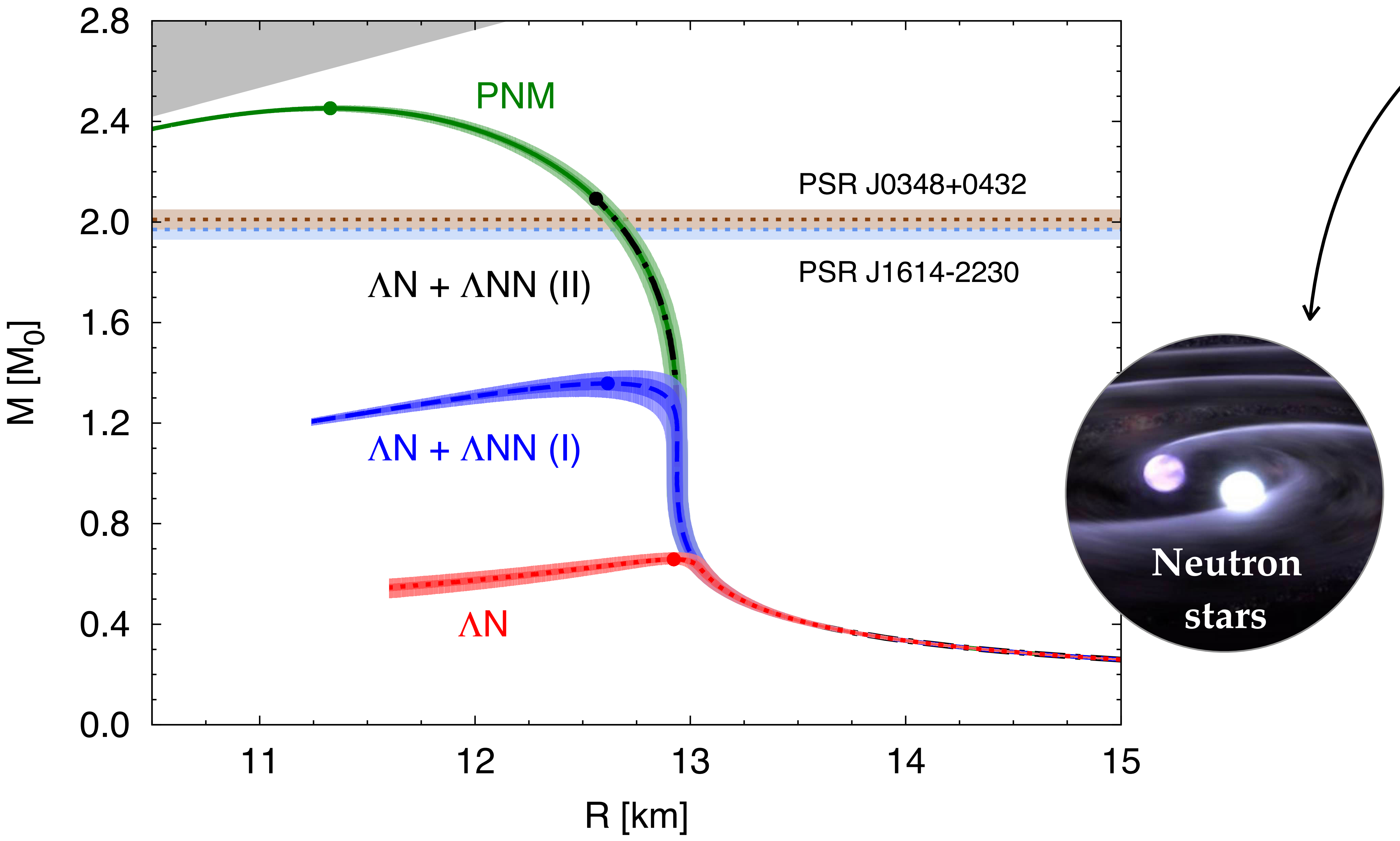
Sensitive to baryon-strangeness correlations

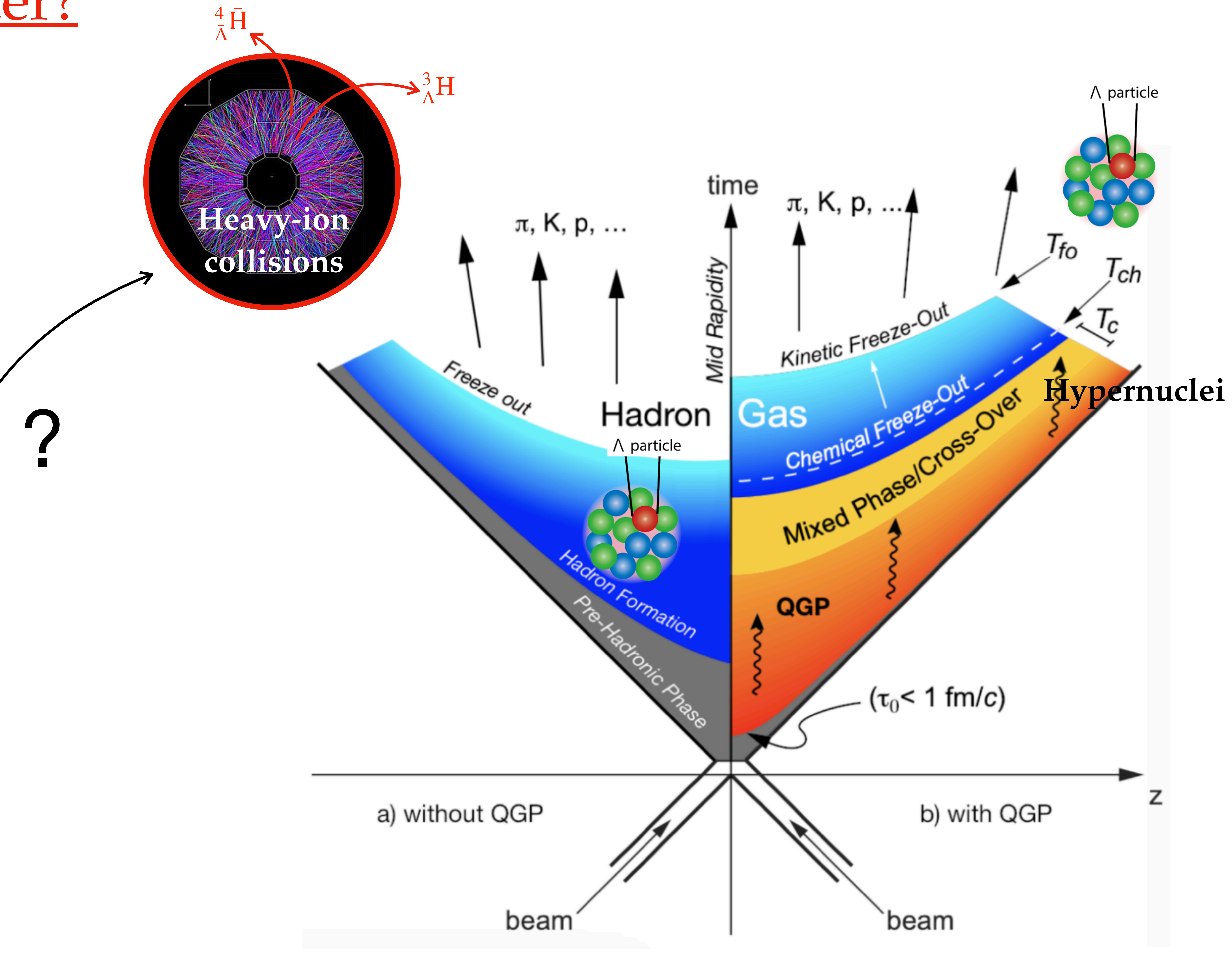
Phys. Lett. B 684 (2010) 224
Phys. Lett. B 781 (2018) 499

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





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

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

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)

Nucl. Phys. A 1005 (2021) 121754

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

Multi-fragmentation

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

Phys.Rev.C 76 (2007) 024909

Roadmap

Production yields

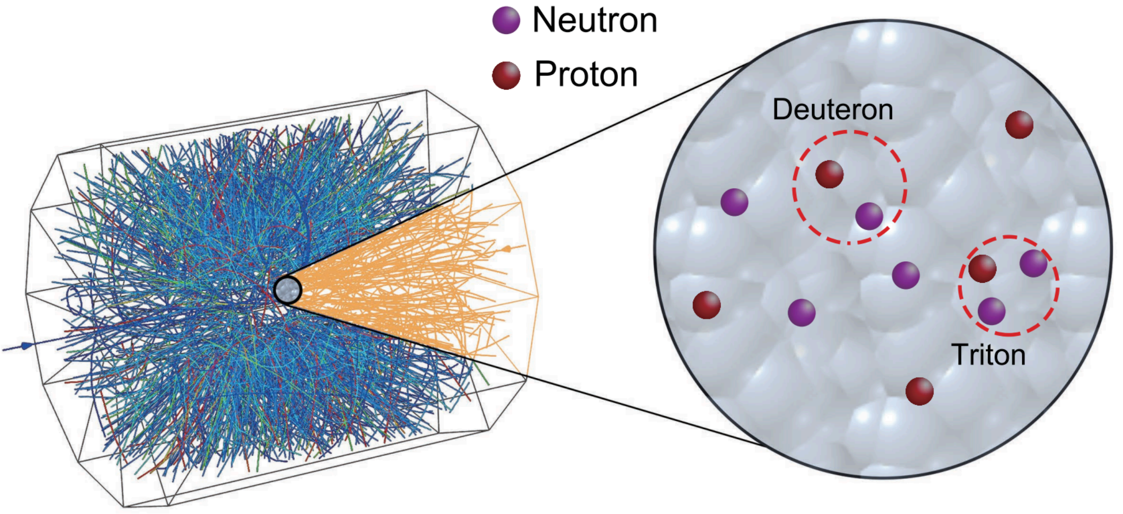
Collective flow

Hypernuclei properties

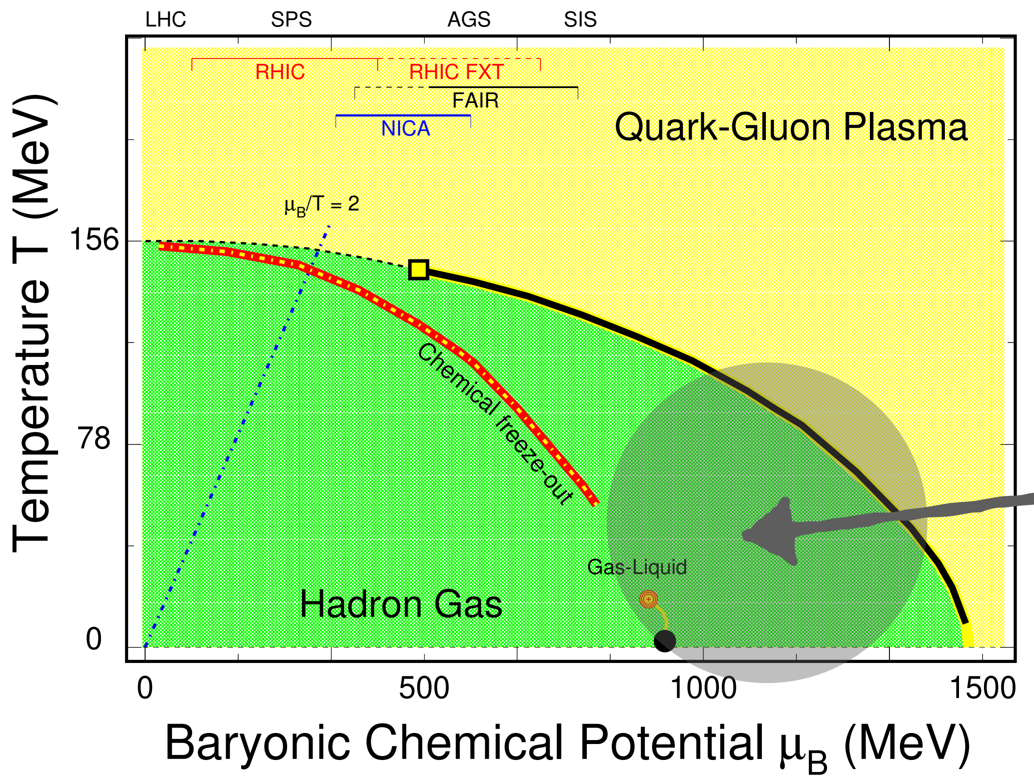
Binding energy

Lifetime

Production mechanisms



QCD phase diagram



EoS at high μ_B

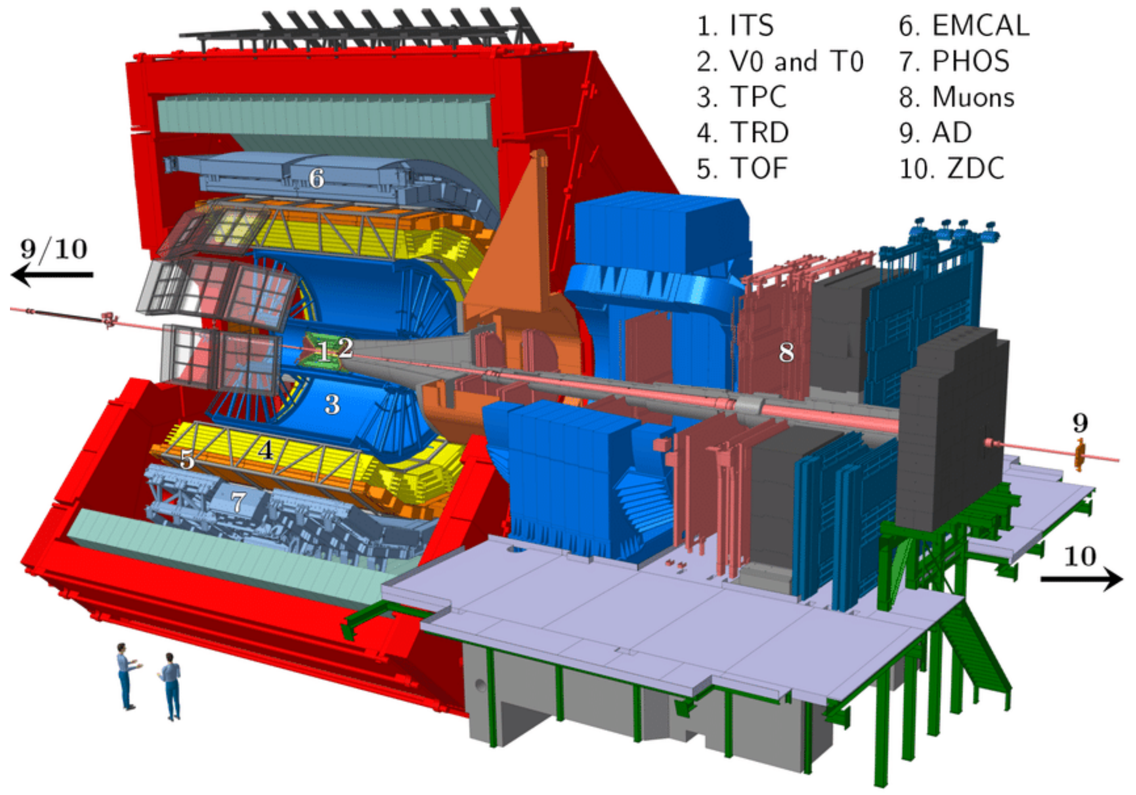
Femtoscopic correlations

Cumulants

Figure credit: Yige Huang

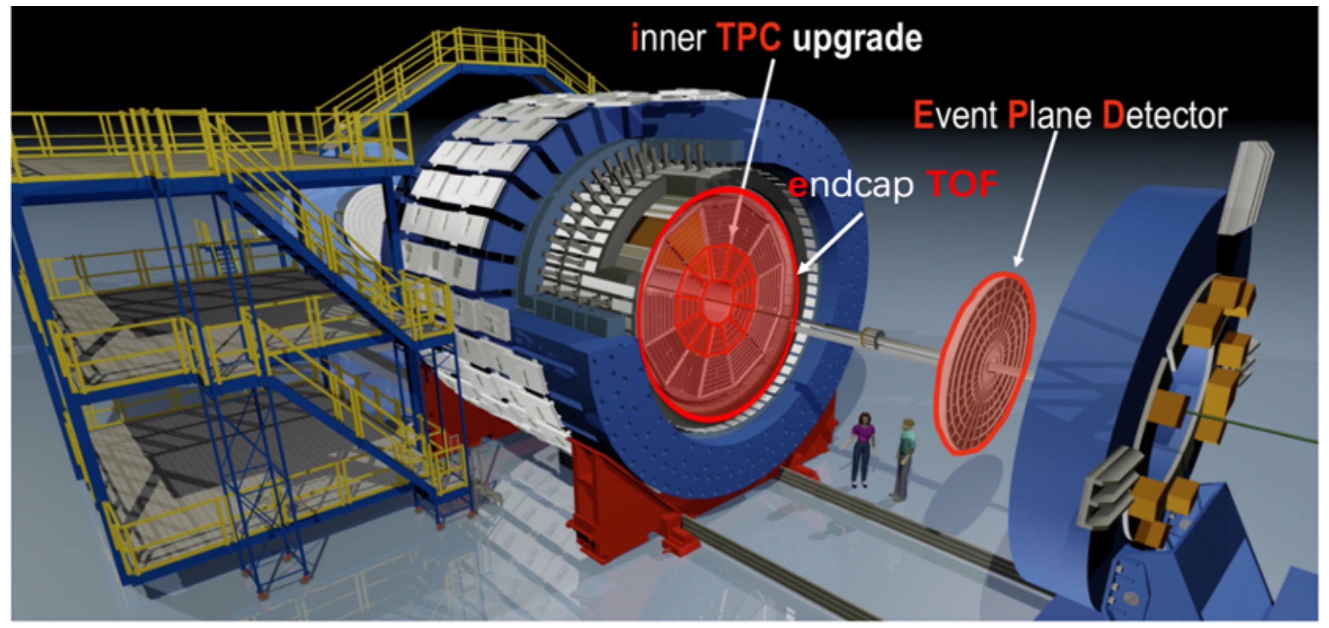
Experimental Facilities

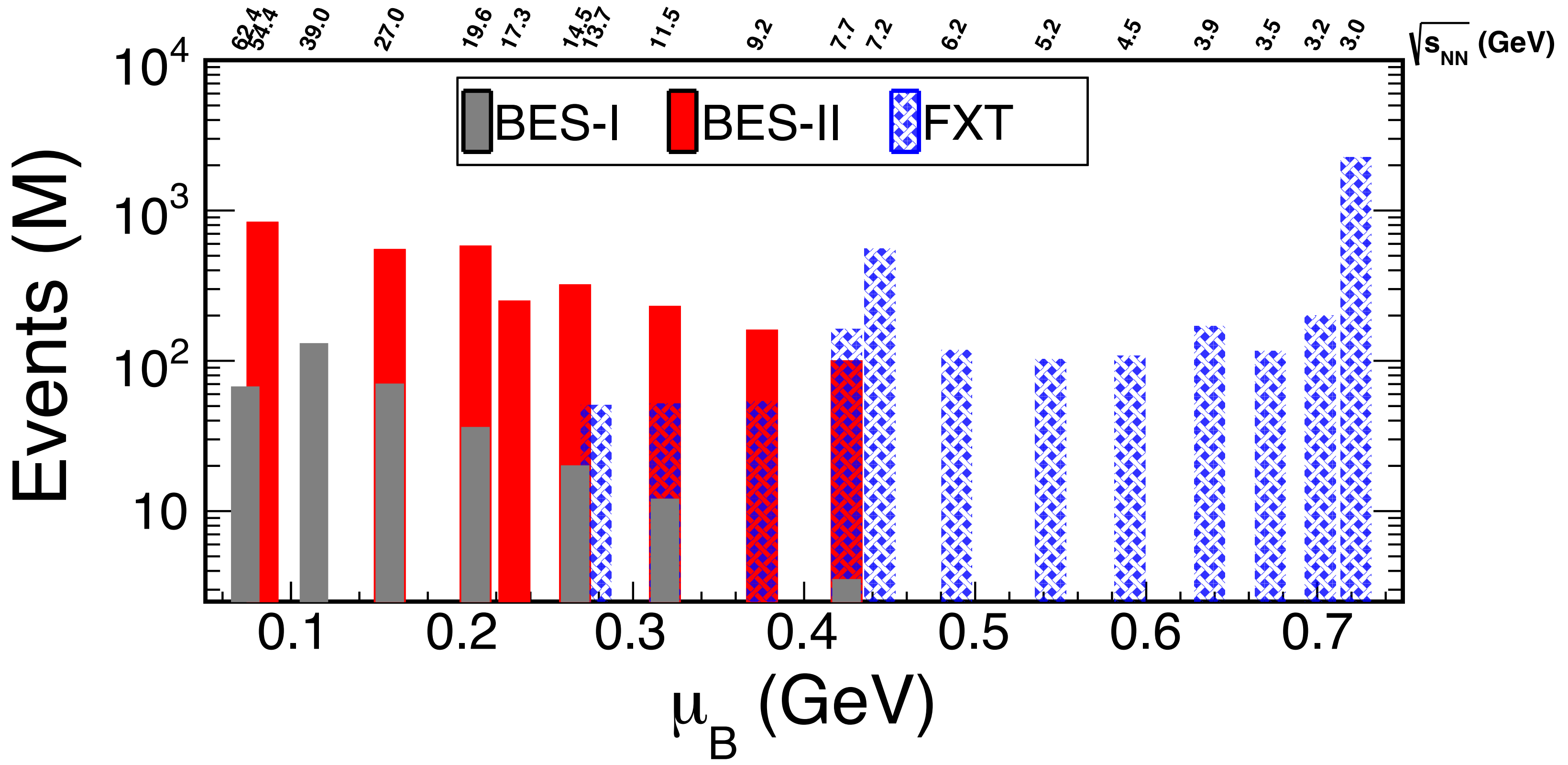
ALICE LHC, Switzerland



- Pb+Pb, p+p, p+Pb, …
- $\sqrt{s_{NN}}$ = 2.76 - 5.02 TeV (Pb+Pb)

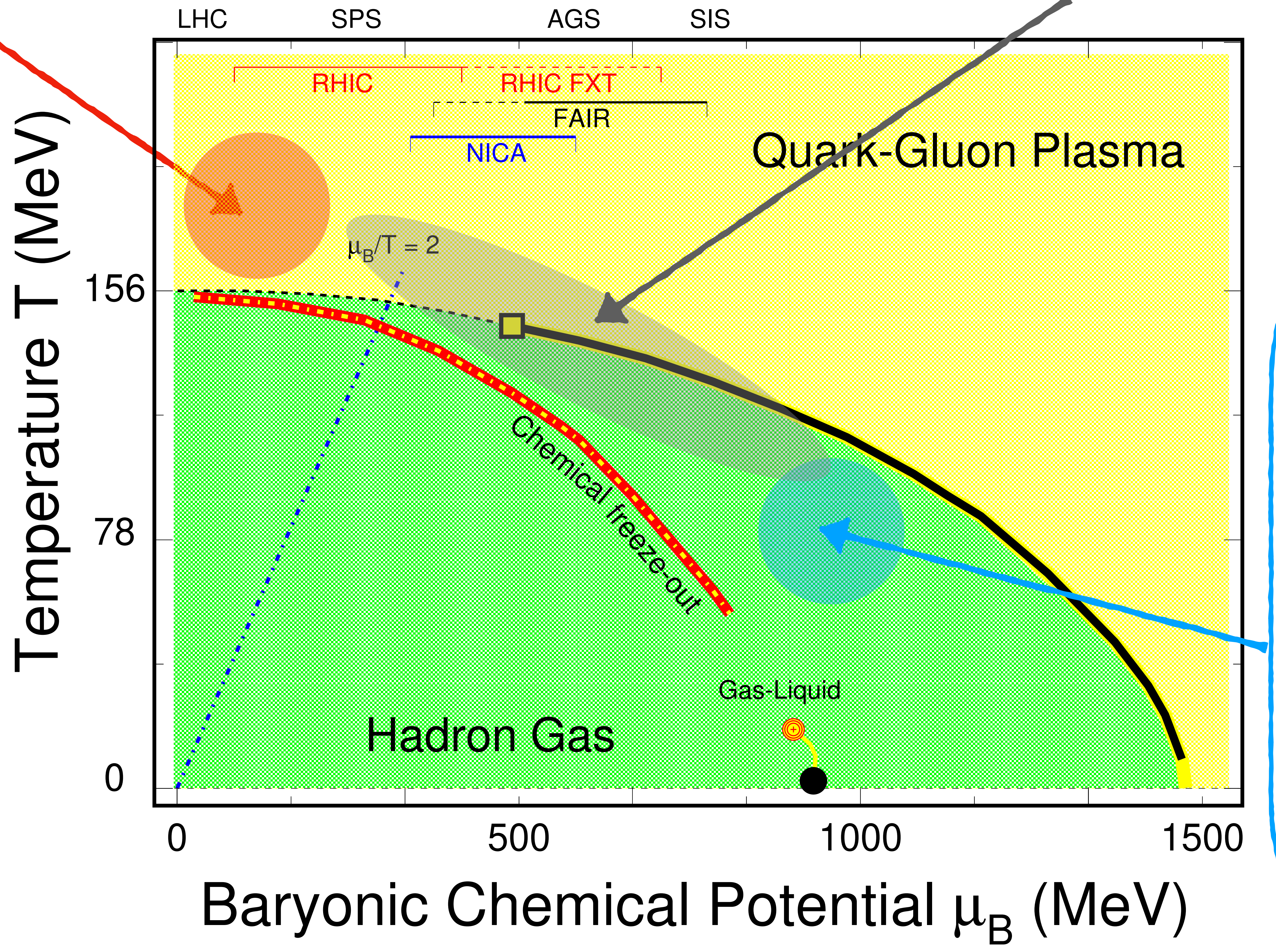
STAR RHIC, US



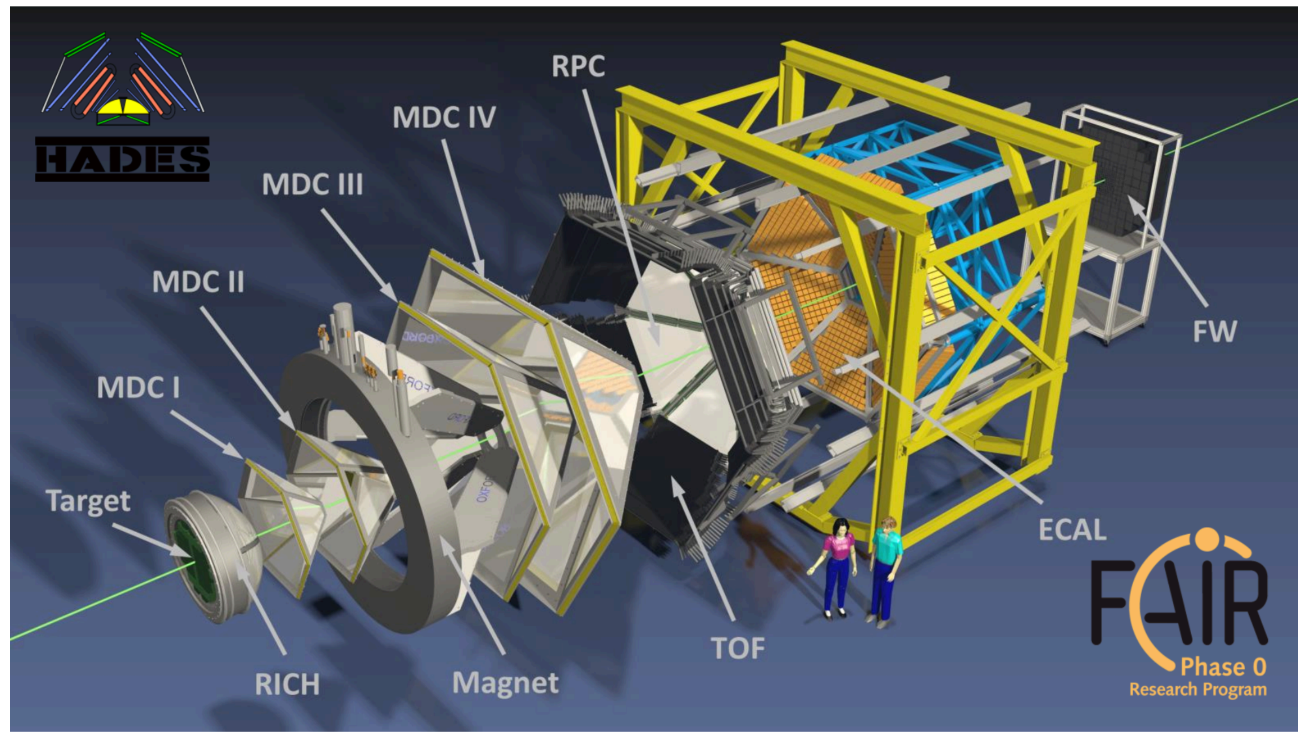


- Au+Au, p+p, p+Au, …
- $\sqrt{s_{NN}}$ = 3-200 GeV (Au+Au)

μ_B = 750 - 20 MeV



HADES SIS18, GSI, Germany



- Au+Au, Ag+Ag, …
- $\sqrt{s_{NN}}$ = 2.55 GeV (Ag+Ag)

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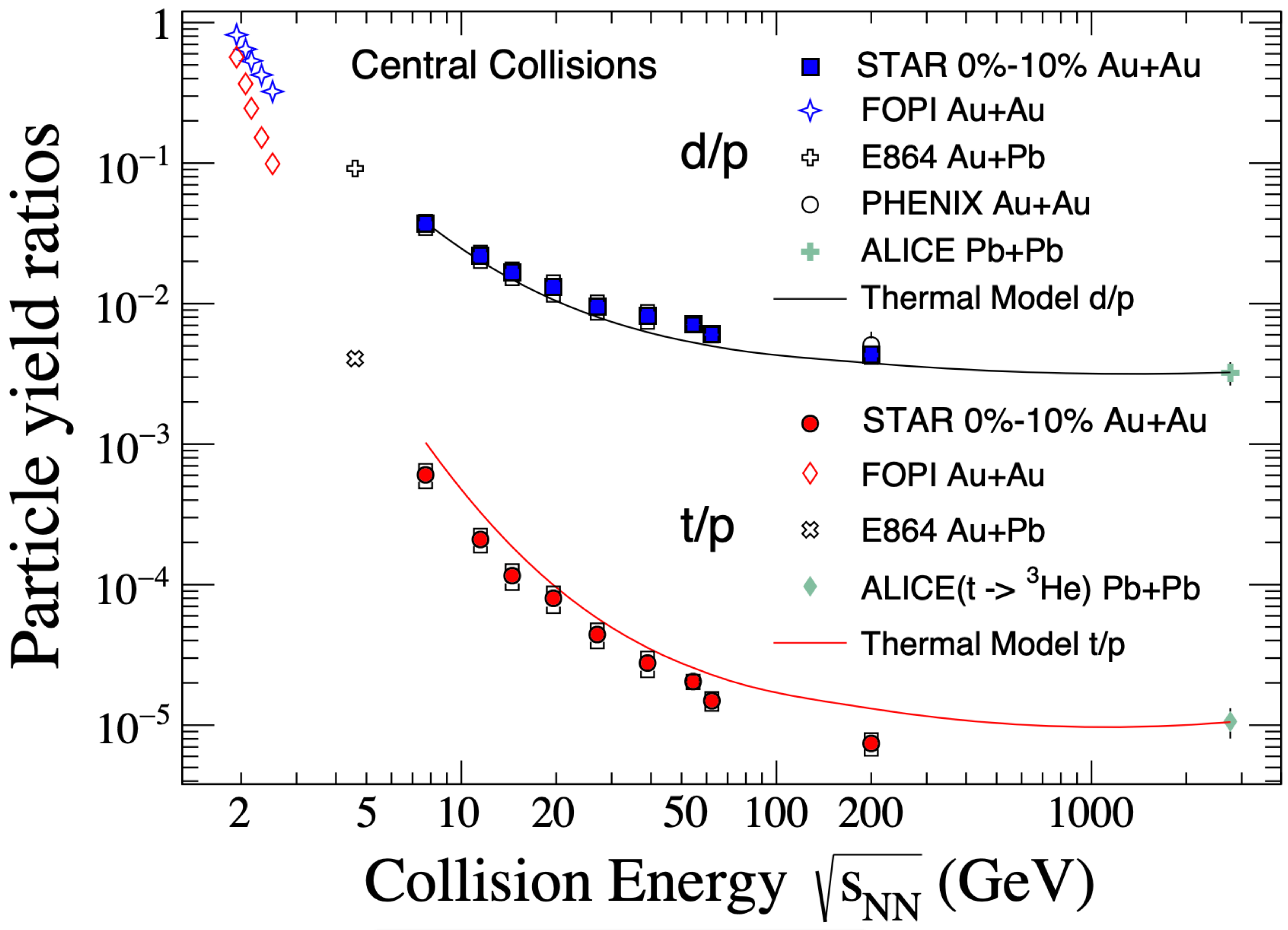
Light Nuclei Ratios in Central Collisions



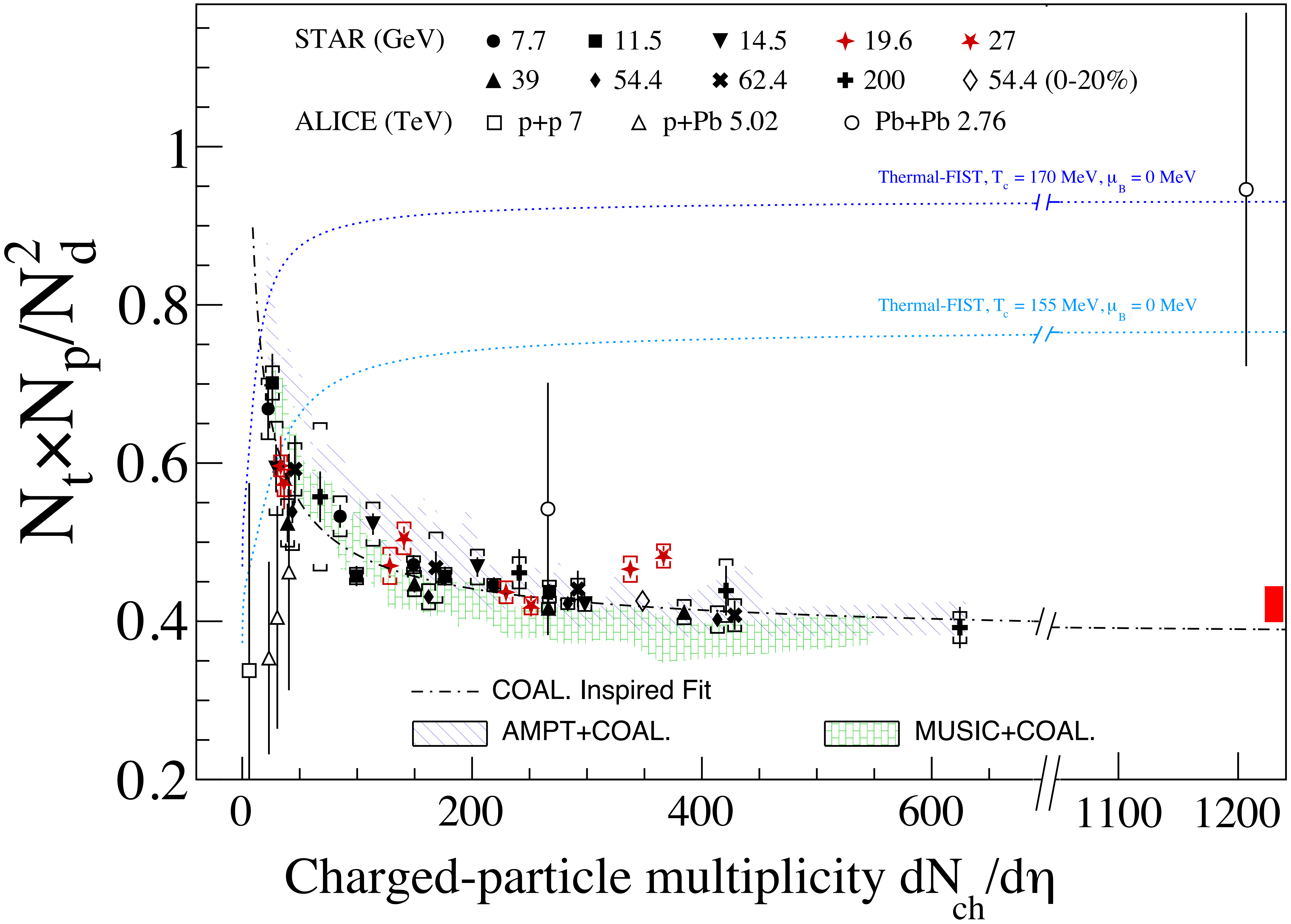
STAR, Phys. Rev. Lett. 130 (2023) 202301

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

Effects from hadronic re-scattering?

arXiv:2207.12532

Nuclear Compound Yield Ratio



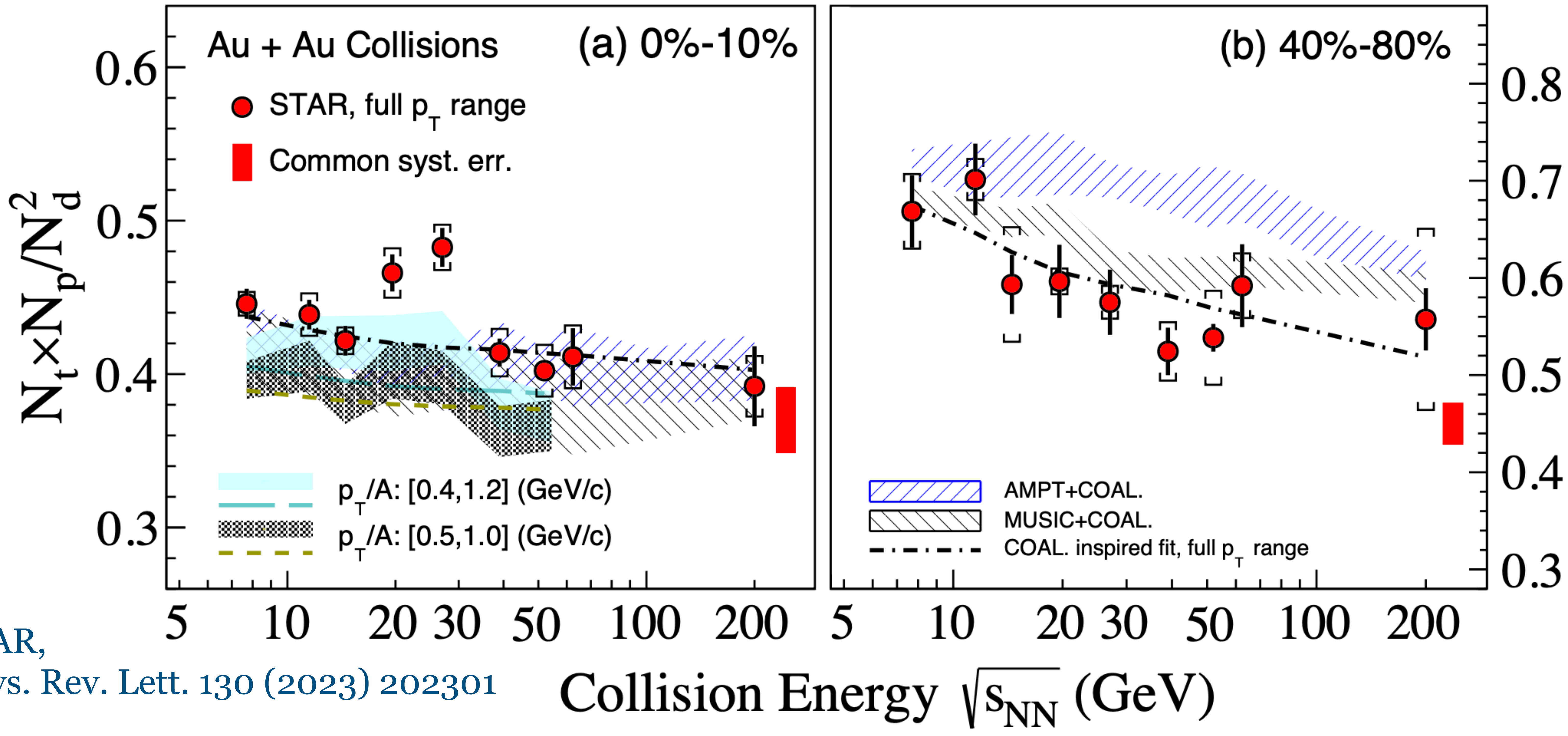
STAR, Phys. Rev. Lett. 130 (2023) 202301

THERMAL-fist: Comput. Phys. Commun. 244, 295 (2019)

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

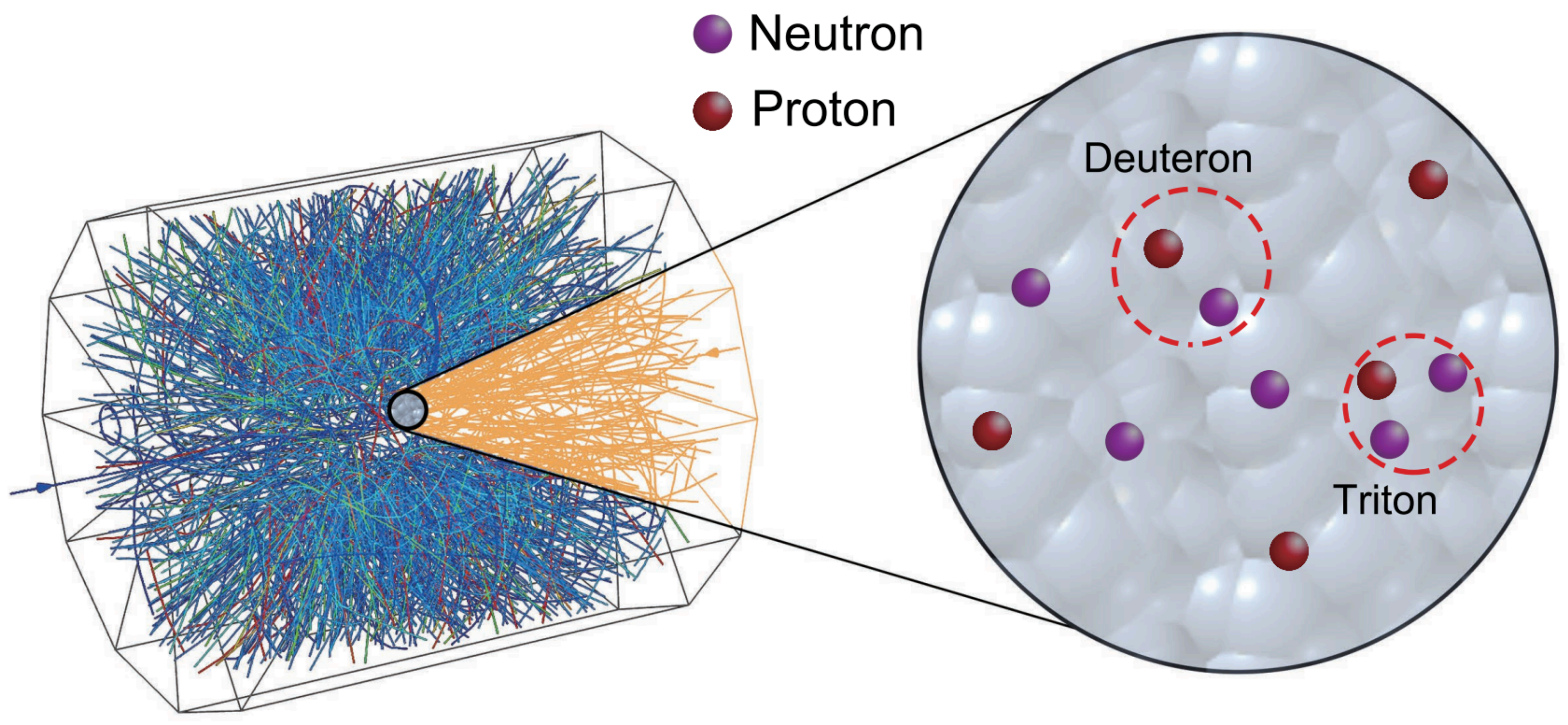
Data favors coalescence prescription

Energy Dependence of Nuclear Compound Yield Ratio



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

Figure credit: Yige Huang

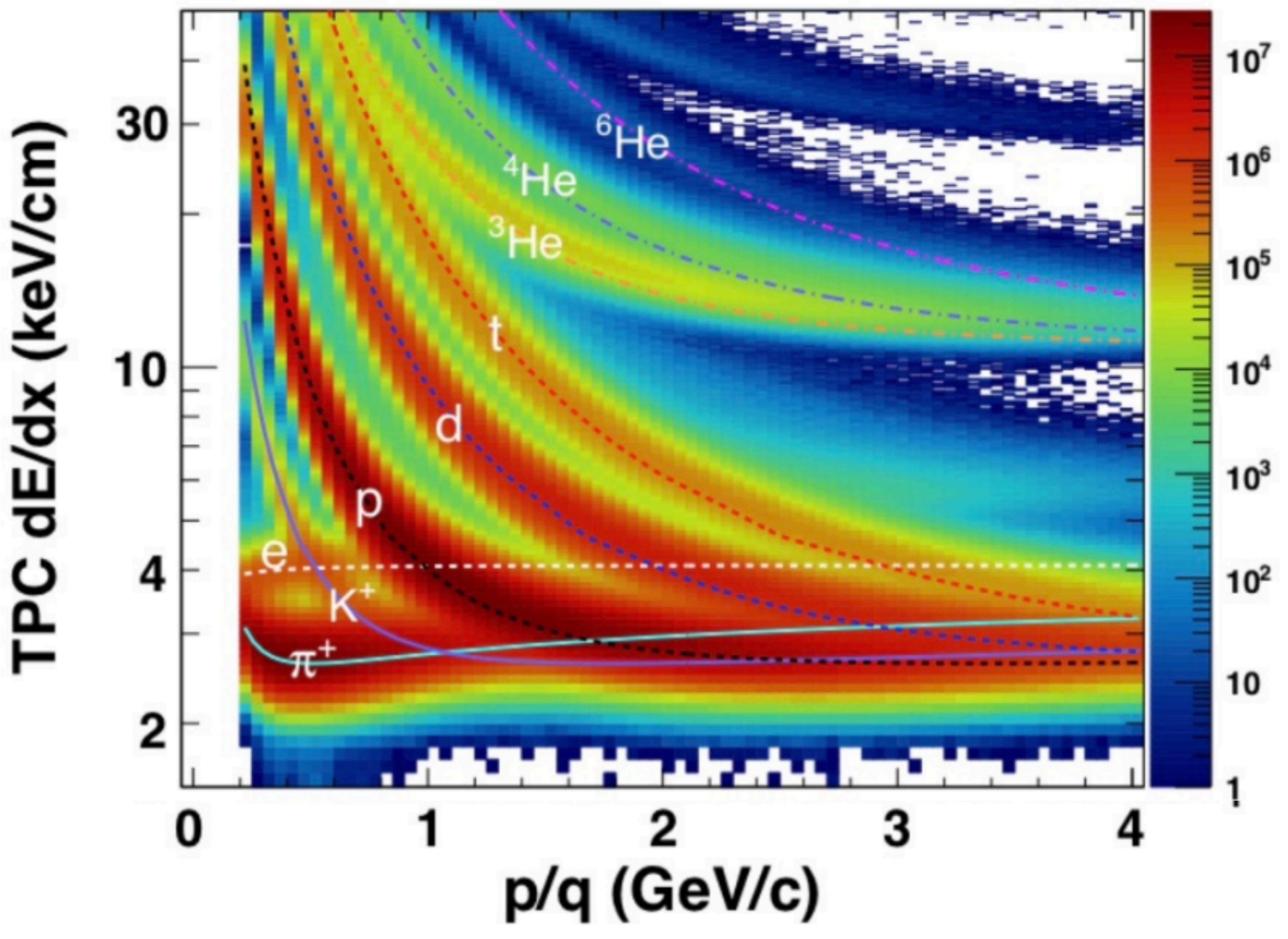


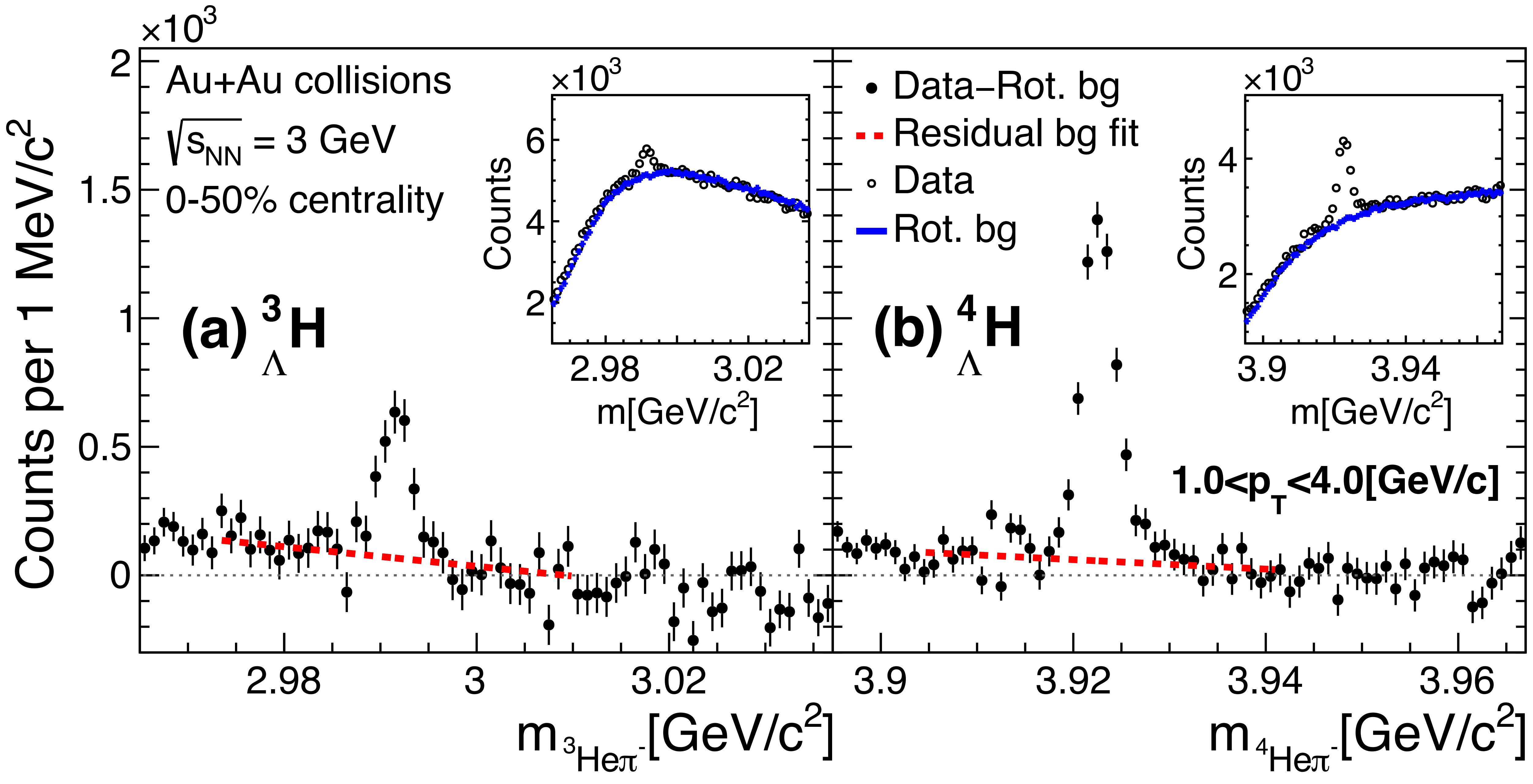
$$\frac{t \times p}{d^2} = g(1 + \Delta n)$$

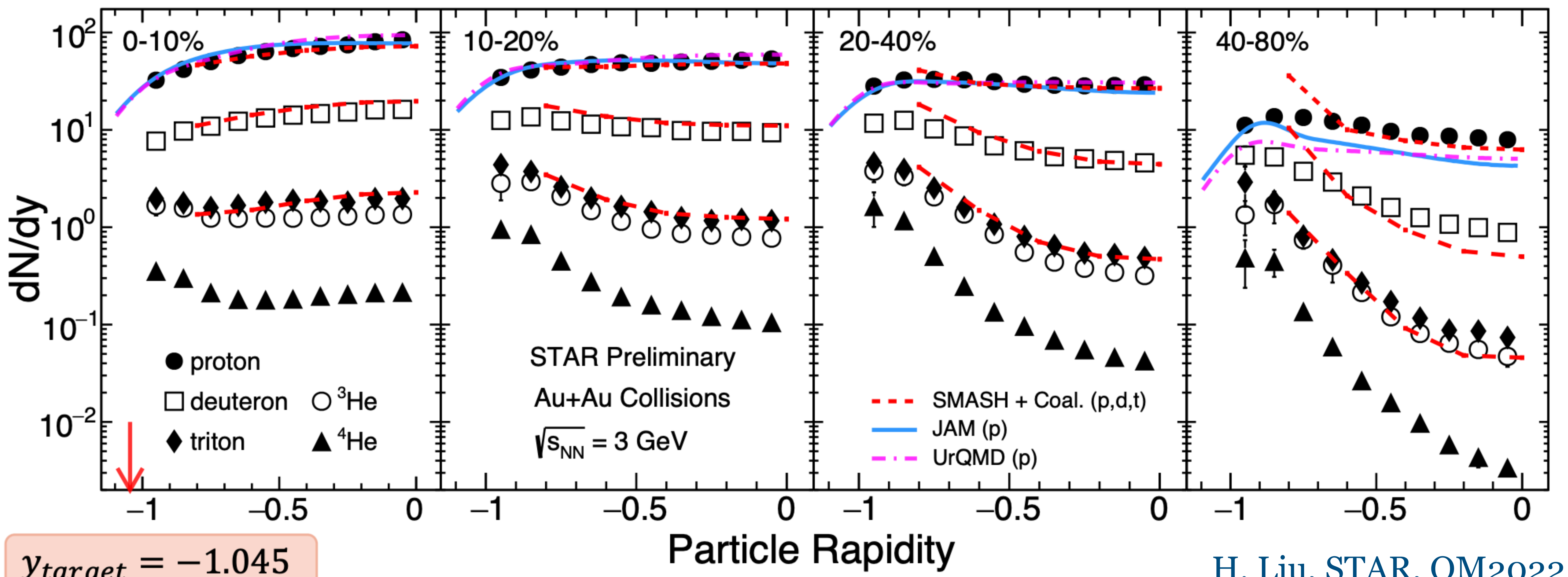
Phys. Lett. B 781 (2018) 499

- 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

Fixed Target Au+Au Collisions at 3 GeV in STAR BES-II







$y_{target} = -1.045$

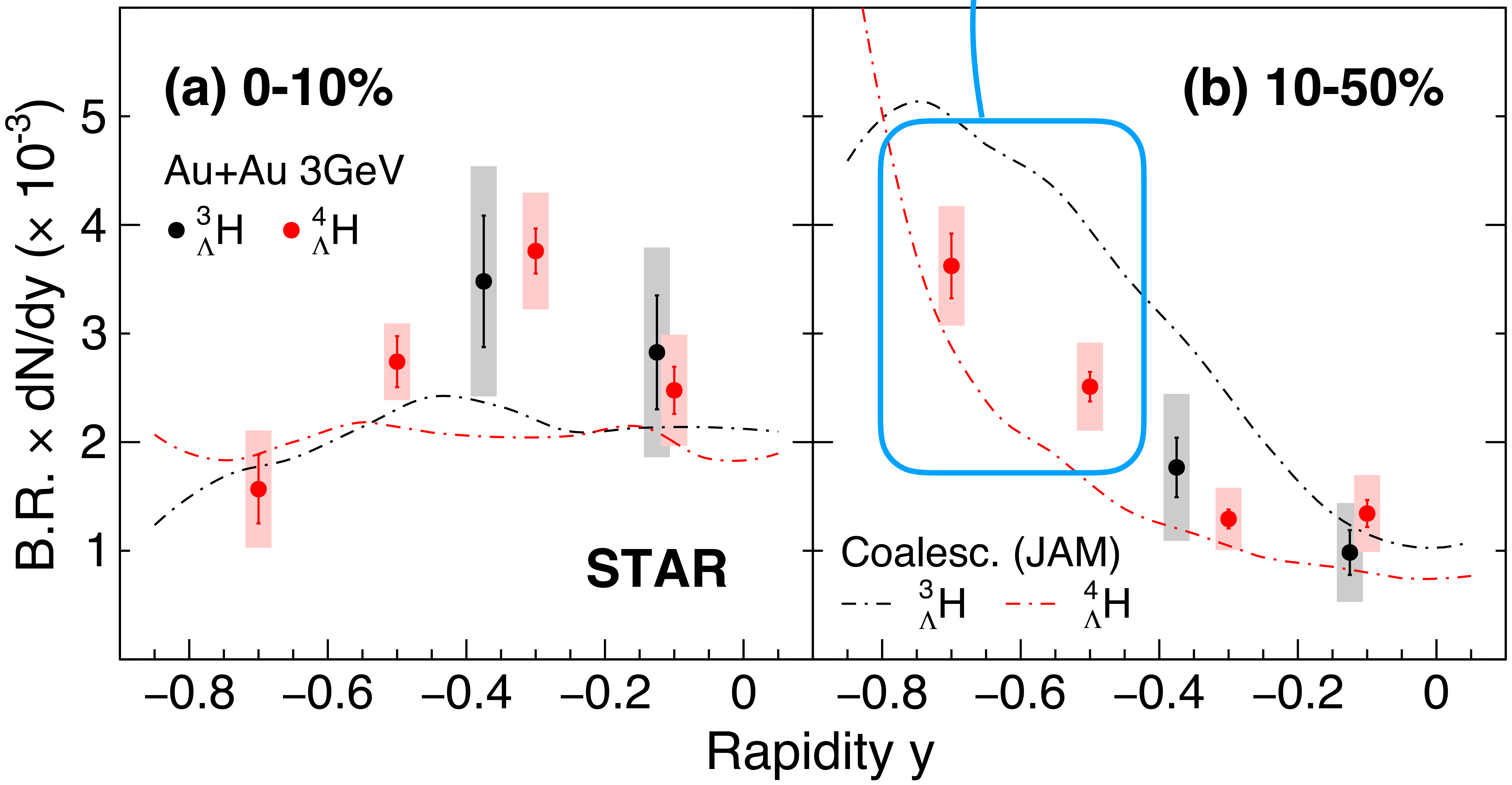
- 260M 3 GeV Au+Au events collected in 2018
- Nuclei up to A=6, hypernuclei up to A=4
- Good mid-rapidity coverage for most particles

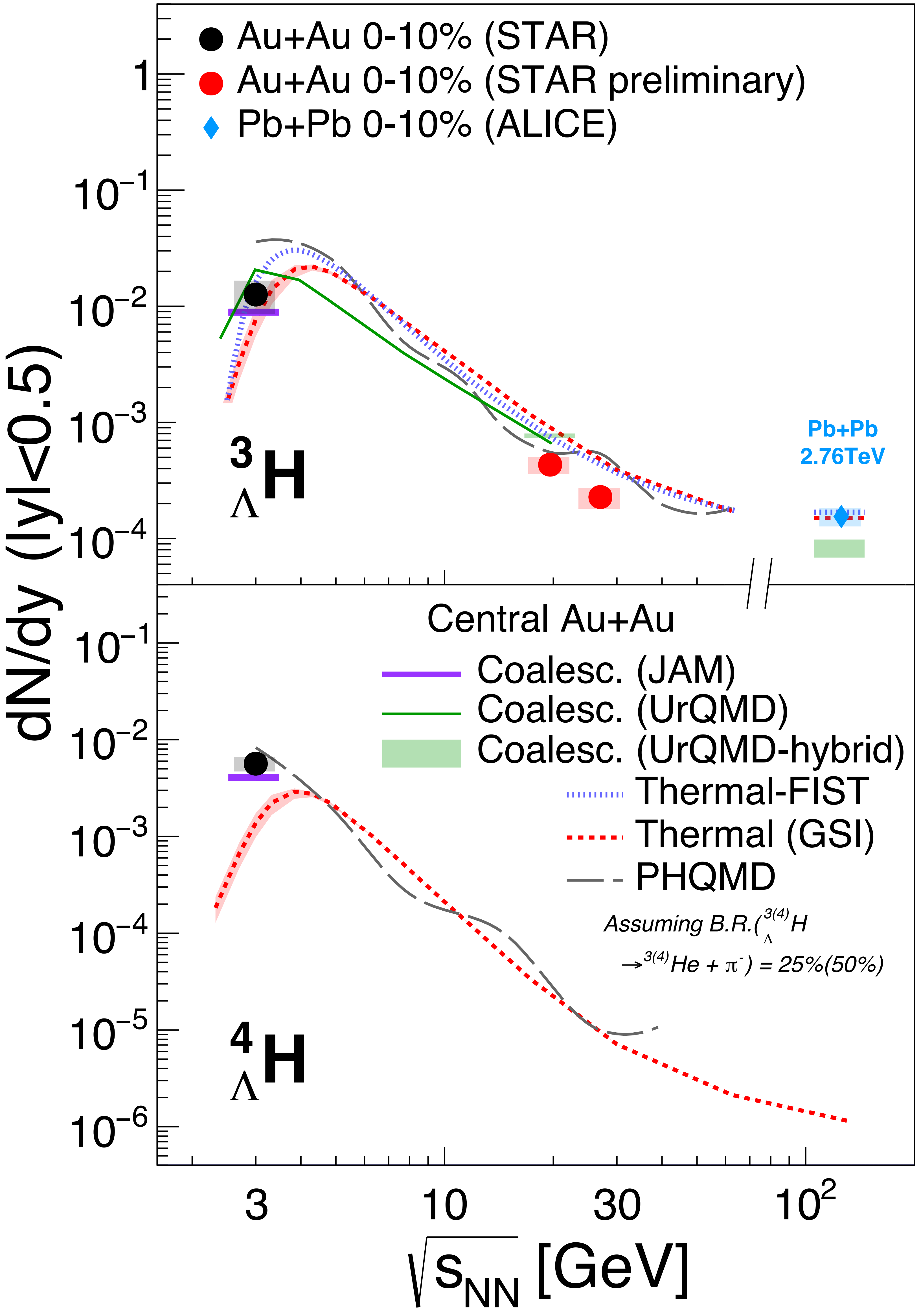
H. Liu, STAR, QM2022

Hypernuclei production yields

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

Fragmentation from strange "spectator" matter?





- Different trends in rapidity in different centrality regions for $^{4}_{\Lambda}H$

Strangeness Population Factors S_3 and S_4 at 3 GeV

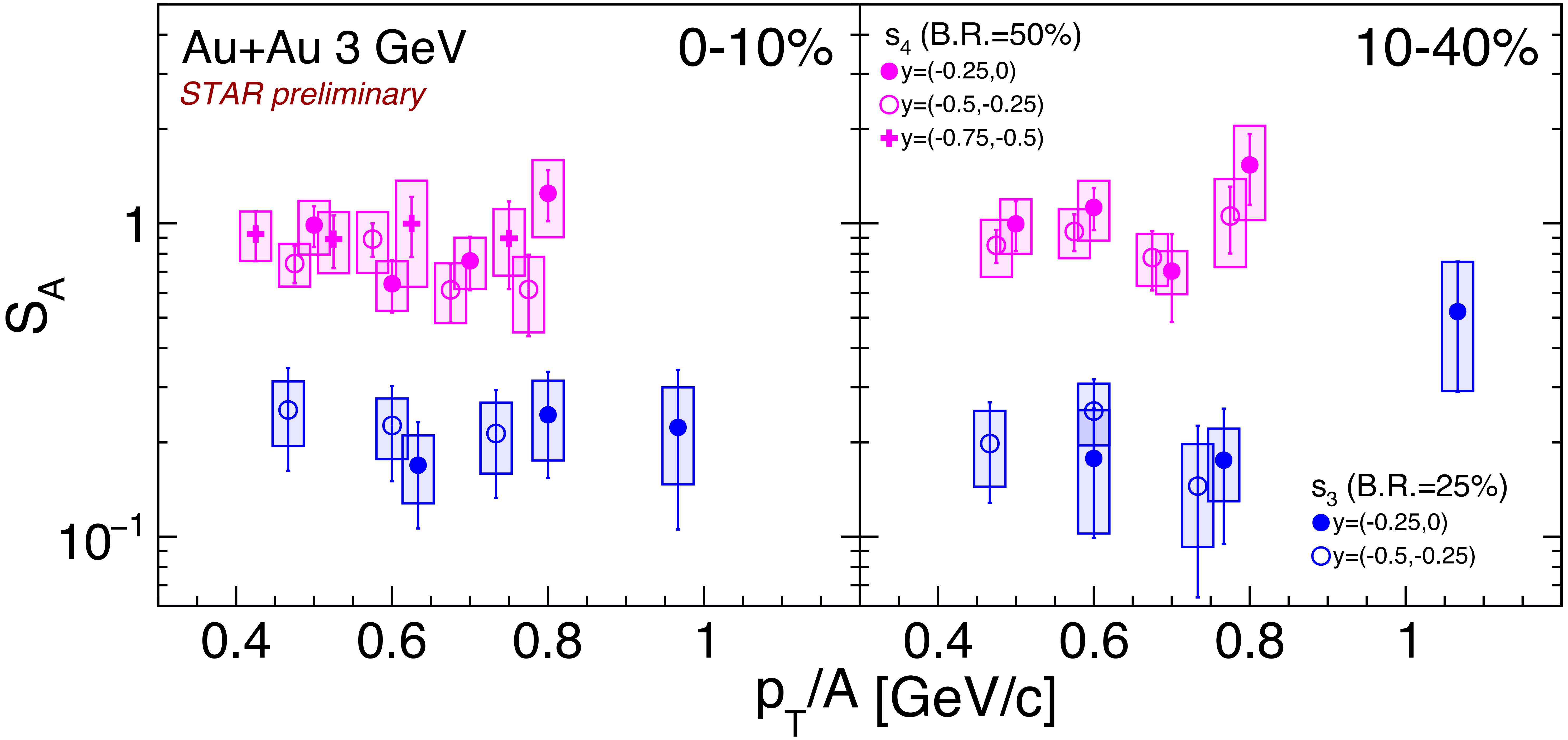
S. Zhang et al, PLB 684(2010)224

- Strangeness population factor:

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

- Ratio of coalescence parameters B_A:

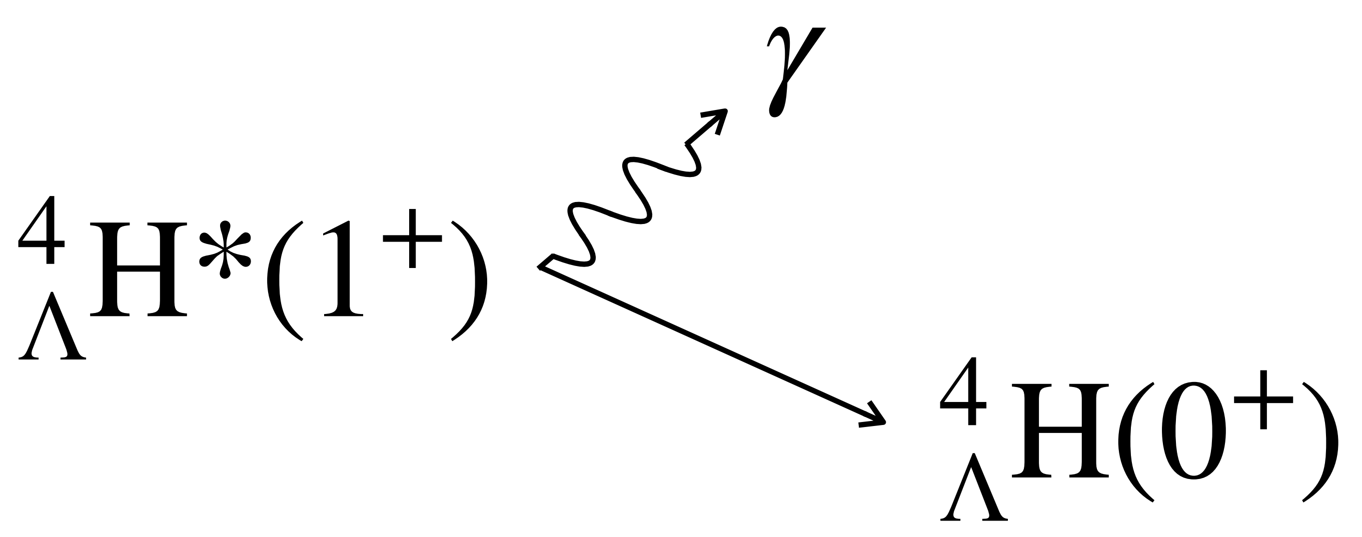
$$S_A(\mathrm{p_T}/\mathrm{A}) = \frac{{}^{A}_{\Lambda}\mathrm{H}(\mathrm{p_T})}{{}^{A}\mathrm{He}(\mathrm{p_T}) \times \frac{\Lambda}{\mathrm{p}}(\mathrm{p_T}/\mathrm{A})} = \frac{\mathrm{B_A}({}^{A}_{\Lambda}\mathrm{H})(\mathrm{p_T}/\mathrm{A})}{\mathrm{B_A}({}^{A}\mathrm{He})(\mathrm{p_T}/\mathrm{A})}$$



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

Mechanics behind formation for hypernuclei and nuclei are similar

- $S_4 \approx 4\ S_3$



Supports creation of excited hypernuclei

Strangeness population factor as a Probe for Medium Properties?

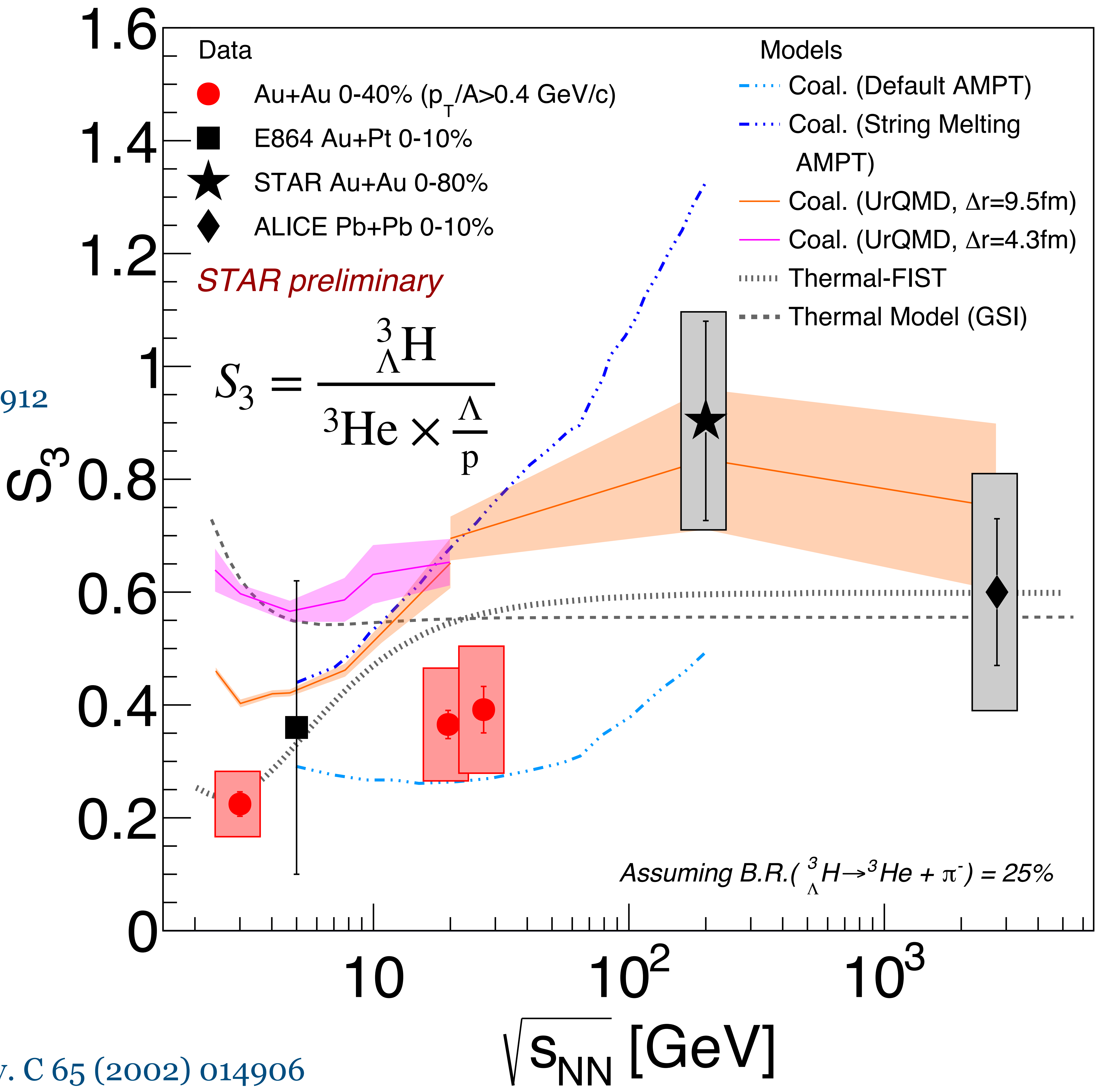
Increasing trend of S_3 originally proposed as a signature of onset of deconfinement

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
- Thermal-FIST also suggest increasing trend
  - Unstable nuclei breakup enhance ${}^{3}\mathrm{He}$ yields? Phys. Lett. B 809 (2020) 135746

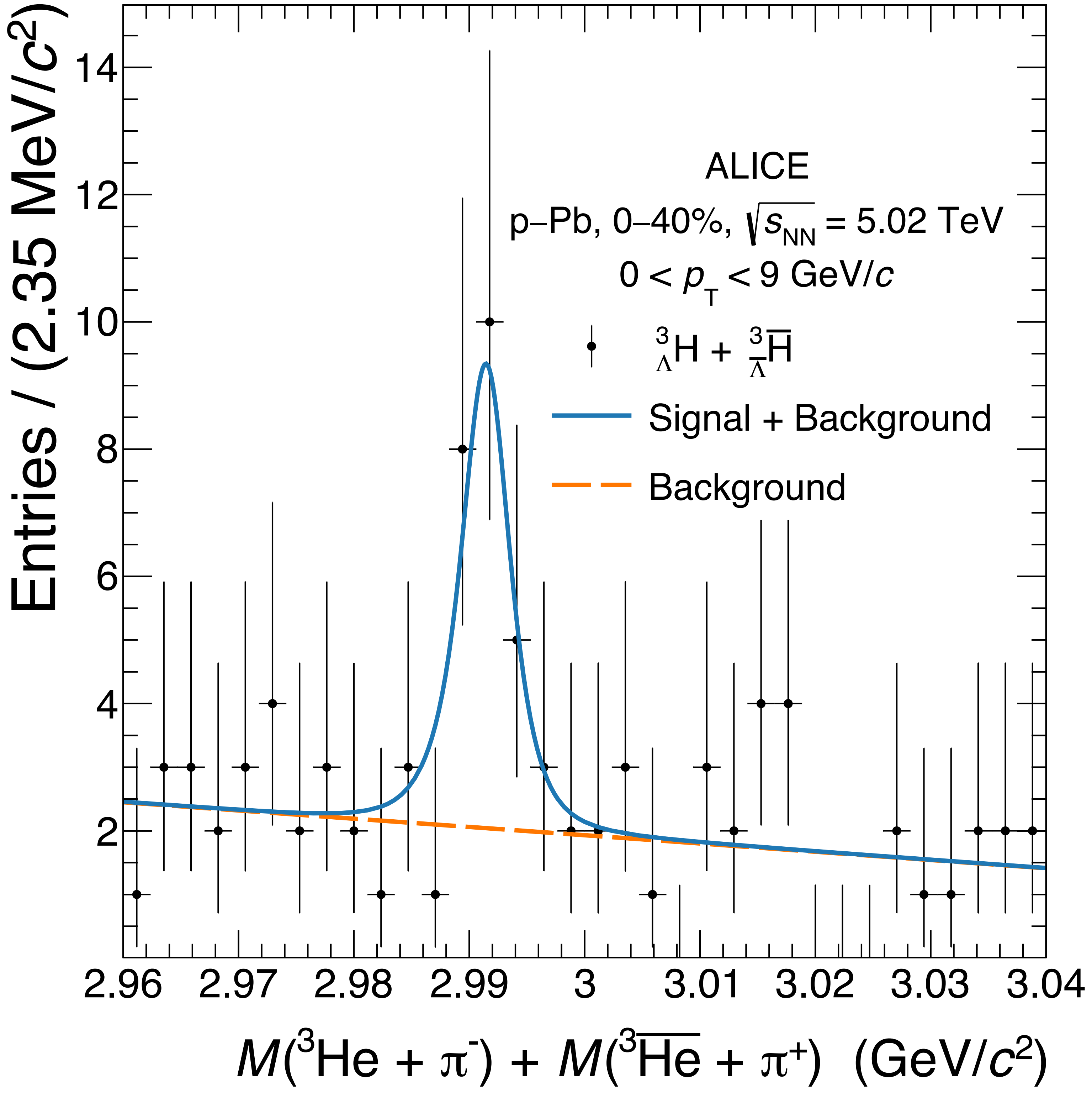
    $$e.g.\ {}^{4}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + p$$

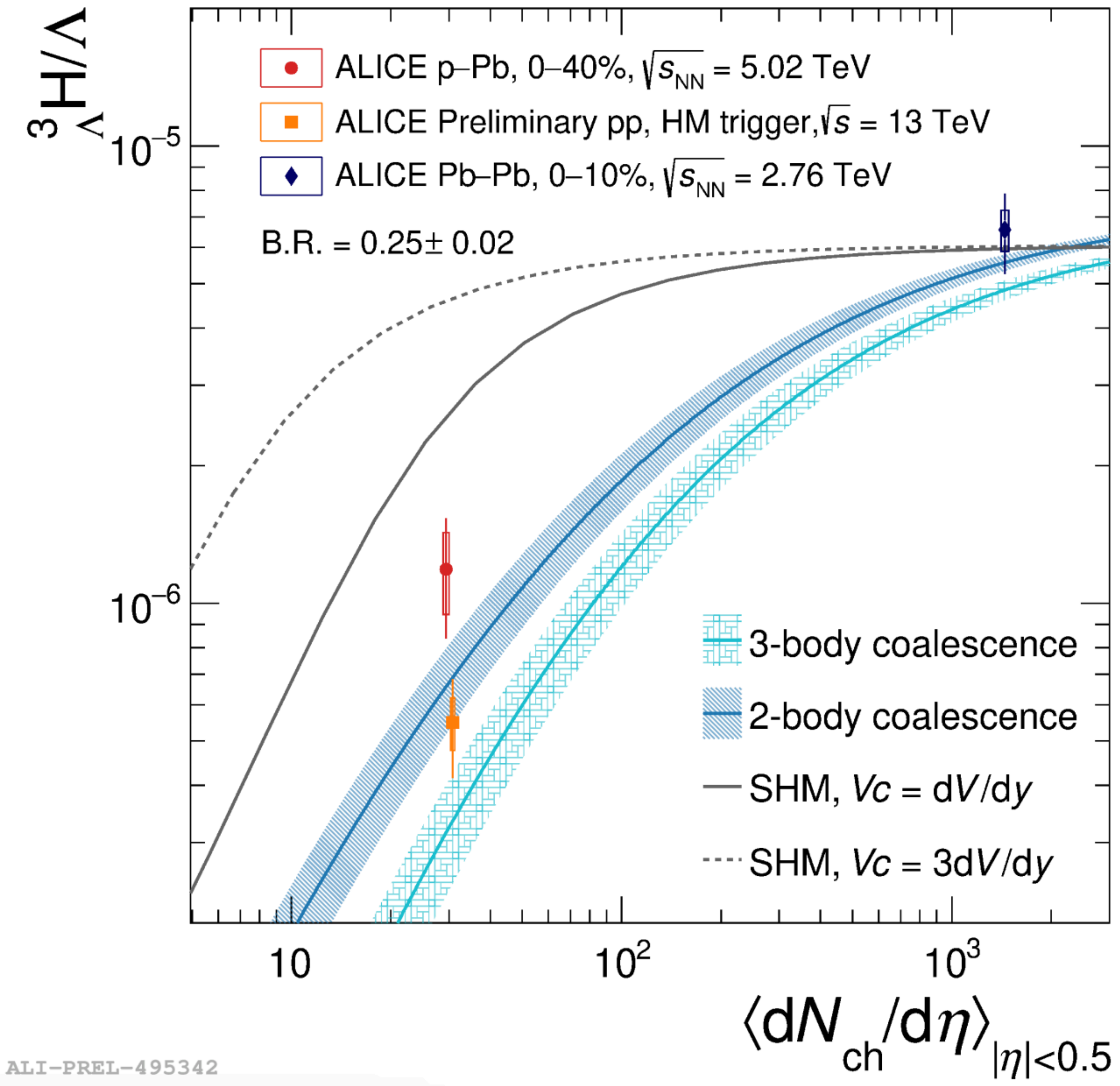
  - Measurements from AGS suggest suppression of ${}^{4}\mathrm{Li}$ production E864, Phys. Rev. C 65 (2002) 014906



Hypertriton Production in Small Systems

Small systems ⟶ stronger distinguishing power b/w thermal and coalescence models





- $^3_\Lambda$H have been observed in p+p and p+Pb collisions

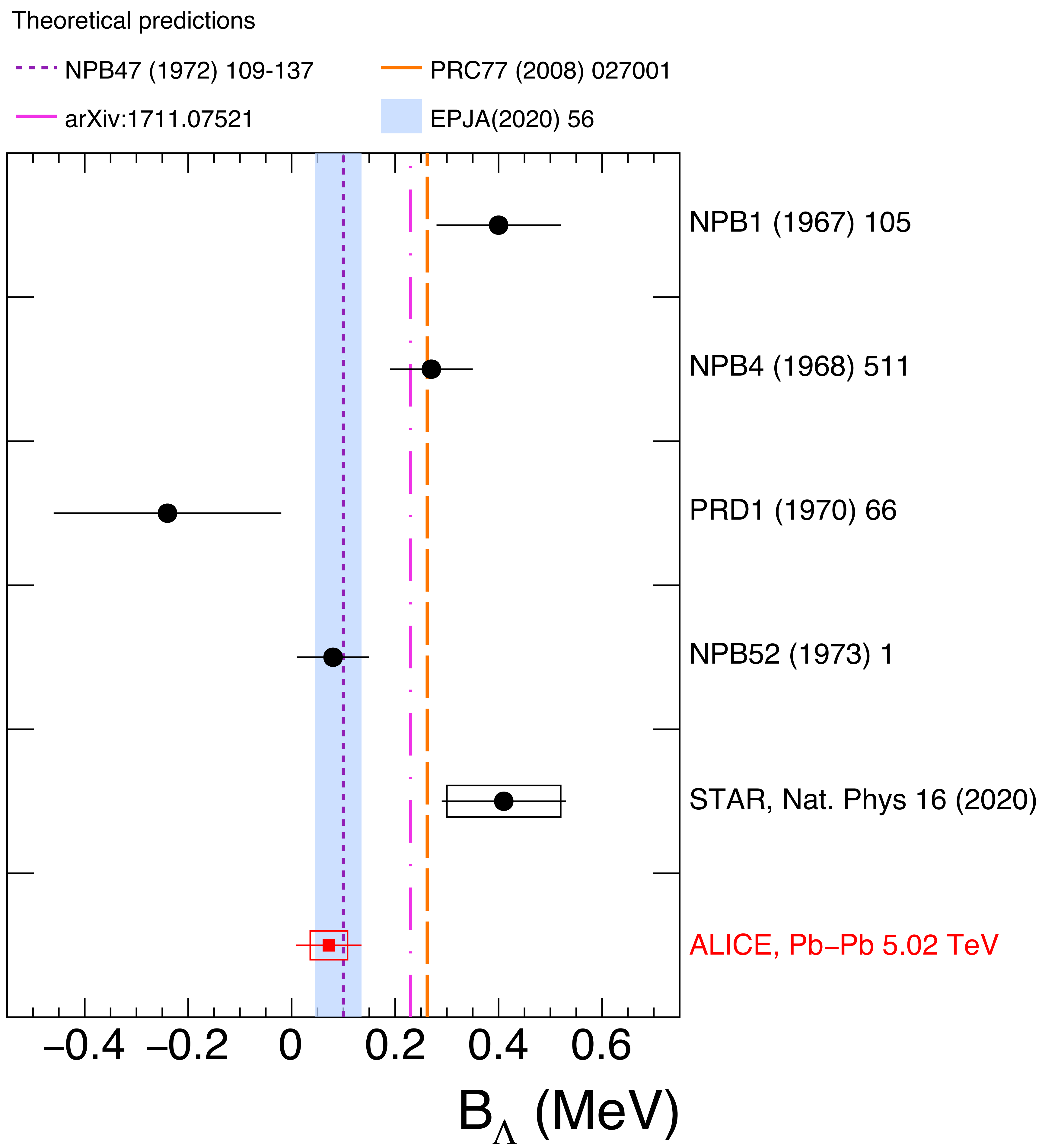
Yield ratio described by 2-body coalescence, in tension with thermal model

ALICE, Phys. Rev. Lett. 128 (2022) 252003

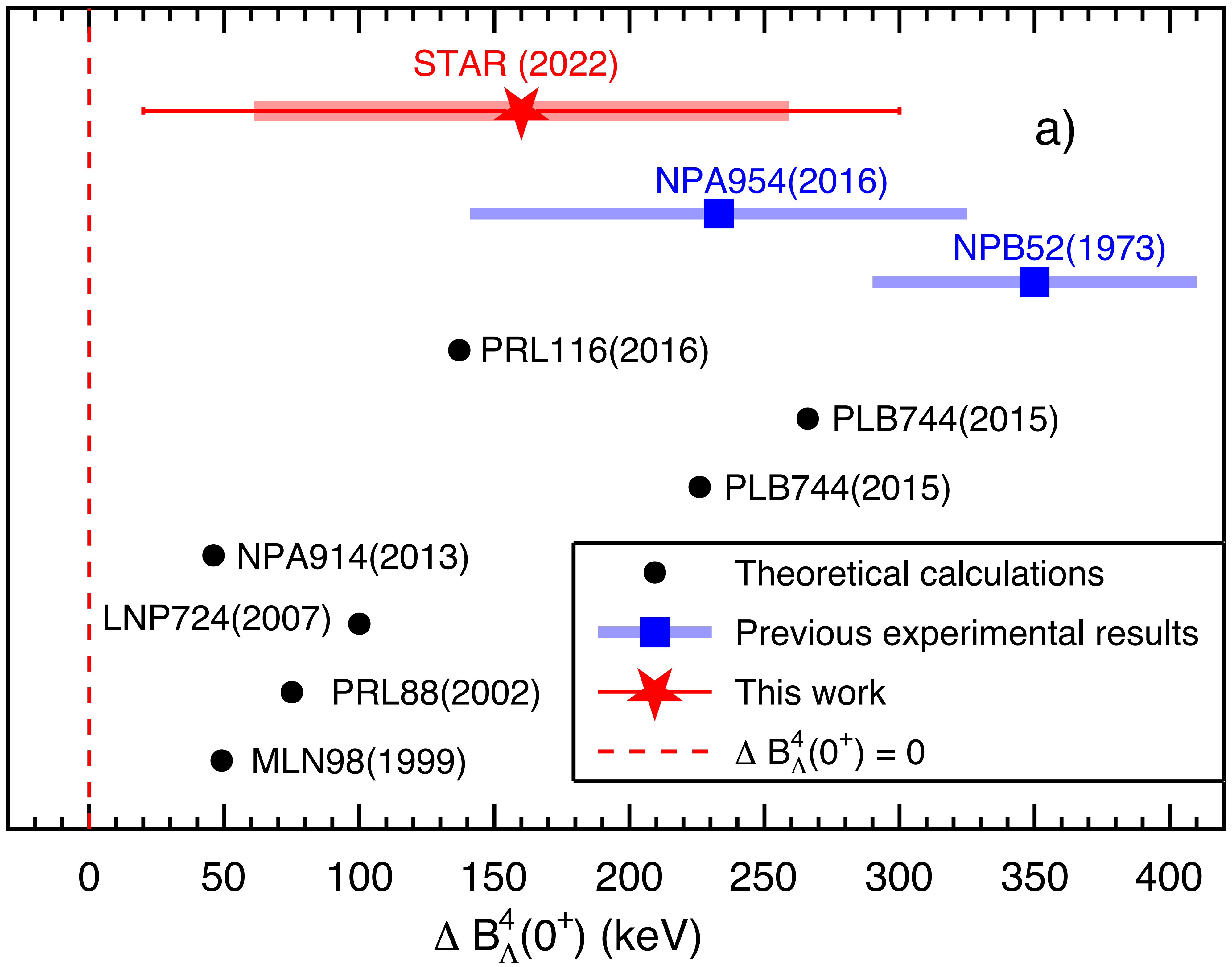
Aside: Hypernuclei Binding Energy

STAR Phys. Lett. B 834 (2022) 137449

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



${}^{4}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{He}$ binding energies



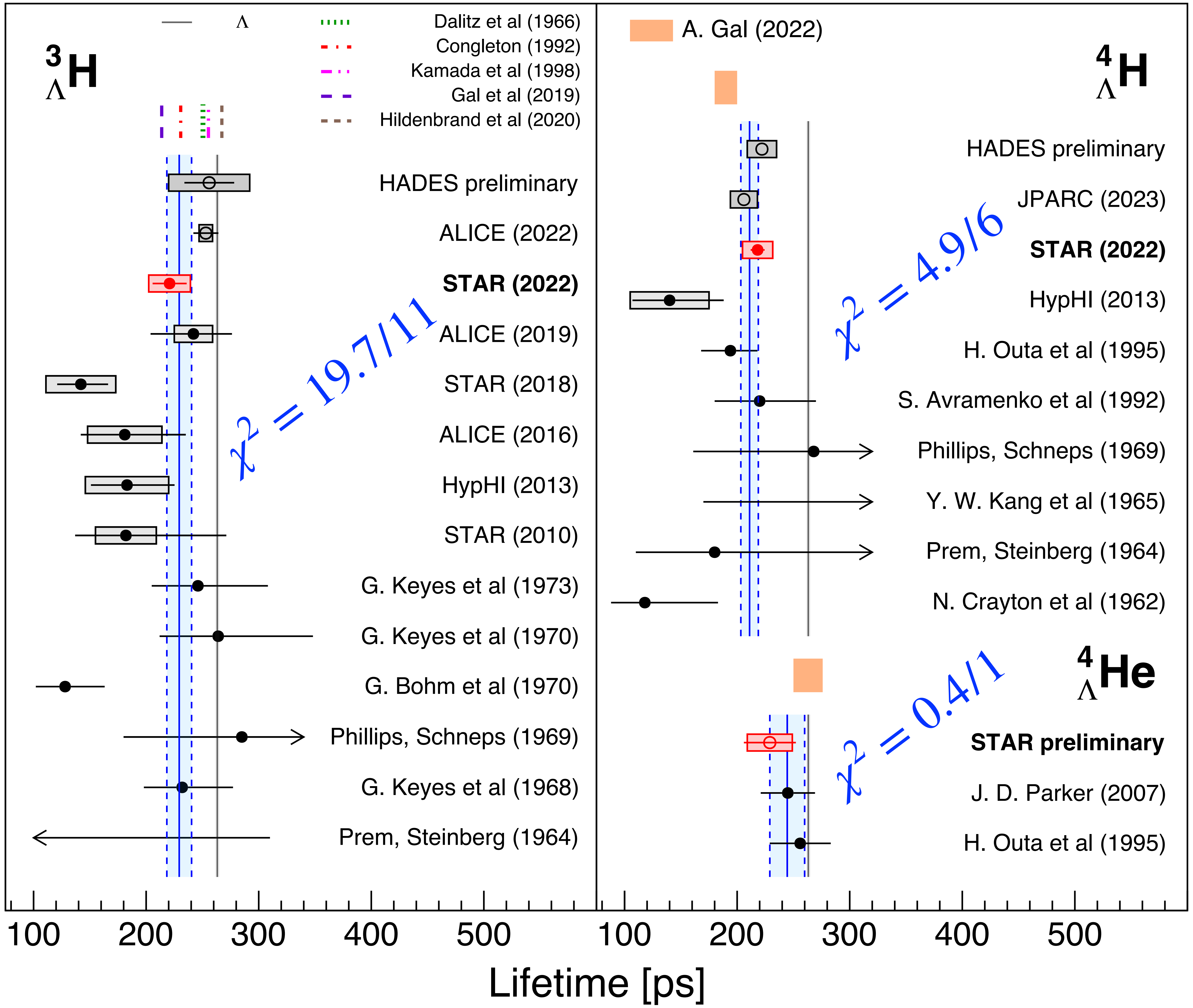
- Binding energy difference b/w mirror hypernuclei
- Avenue to investigate isospin dependence of YN interaction

Hypernuclei binding energies provide more direct constraints to the YN interaction

- ALICE reported the most precise measurement of B_Λ

ALICE, arXiv:2209.07360v2

Aside: Hypernuclei Lifetime



STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
ALICE, arXiv:2209.07360v2
HADES, S. Spies QM2022
JPARC, arXiv: 2302.07443

$^3_\Lambda$H

- Global avg. $= (87 \pm 4)\ \%\ \tau_\Lambda$, slightly shorter than τ_Λ
- Consistent with recent theoretical calculations including pion FSI

A. Gal et al, PLB791(2019)48

$^4_\Lambda$H, $^4_\Lambda$He

- Application of isospin rule* to A=4 hypernuclei suggests lifetime of $^4_\Lambda$H to be shorter than $^4_\Lambda$He

$$\frac{\tau_{avg}(^4_\Lambda\mathrm{H})}{\tau_{avg}(^4_\Lambda\mathrm{He})} = 0.86 \pm 0.06$$ consistent with theoretical estimations: 0.74 ± 0.04

A. Gal (2021), arXiv:2108.10179

Light hypernuclei serves as cornerstones of our understanding of the YN interaction

$$* \quad \frac{\Gamma(^4_\Lambda\mathrm{He} \to {}^4\mathrm{He} + \pi^0)}{\Gamma(^4_\Lambda\mathrm{H} \to {}^4\mathrm{He} + \pi^-)} = \frac{\Gamma(\Lambda \to n + \pi^0)}{\Gamma(\Lambda \to p + \pi^-)} \approx \frac{1}{2}$$

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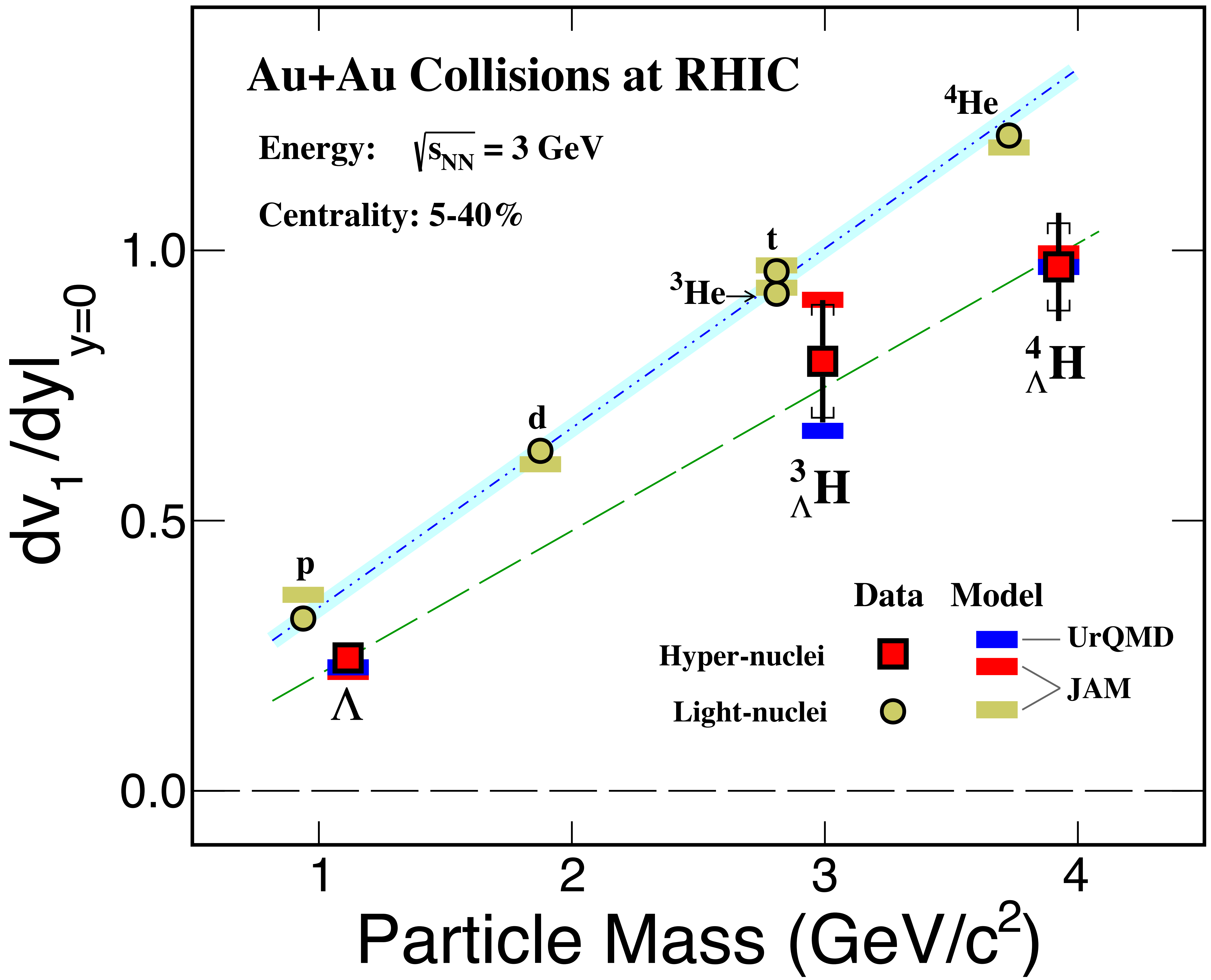
Nuclei and Hypernuclei Directed Flow

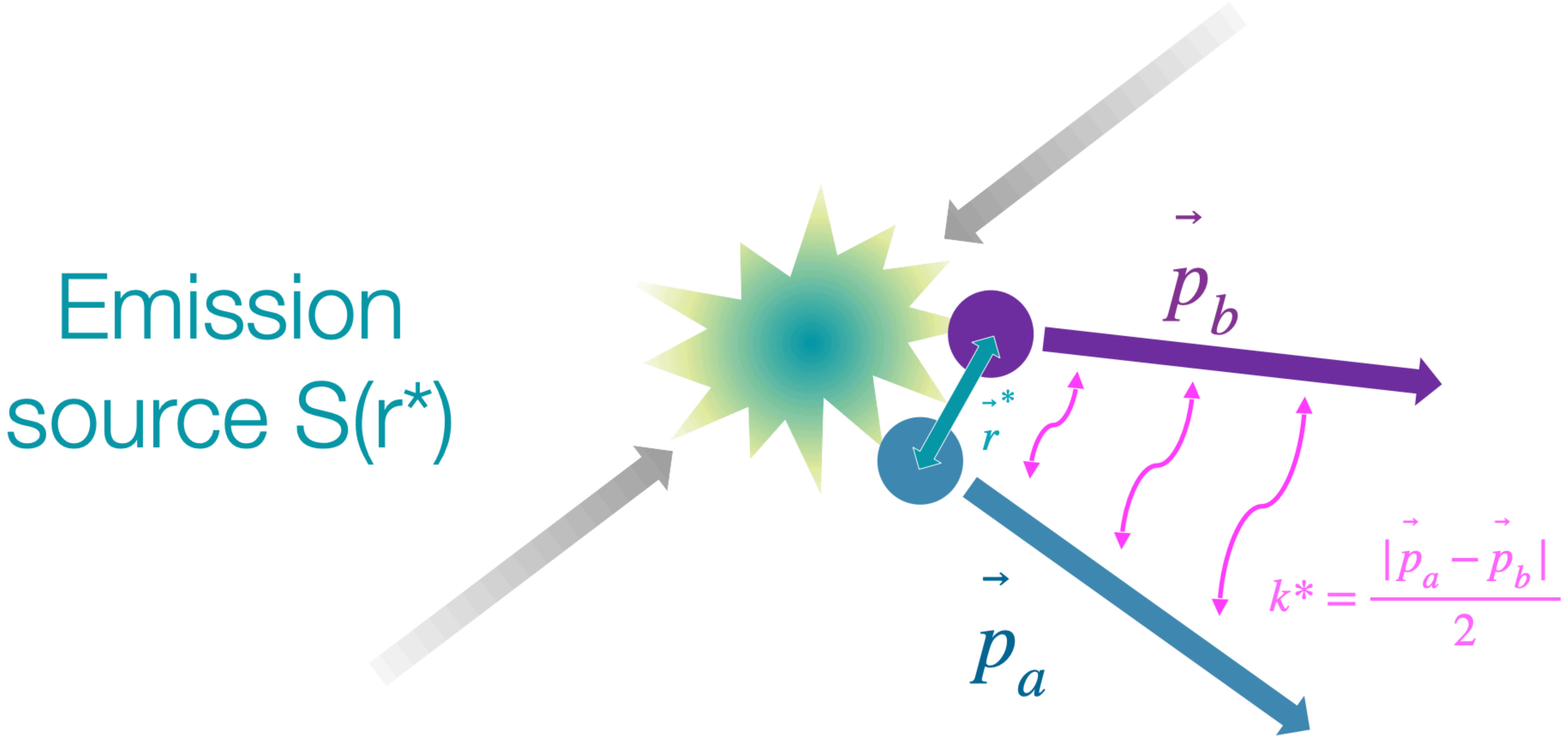


STAR, Phys. Rev. Lett. 130 (2023) 212301

- v_1 slope of light nuclei follow mass number scaling at 3 GeV
- First observation of hypernuclei collectivity v_1 in HI collisions
- Hypernuclei v_1 slope also follows mass number scaling, consistent with coalescence models

Results qualitatively consistent with (hyper)nuclei production from coalescence

p-d correlations (p+p 13 TeV)



$$C(k^*) = \int \boxed{S(r)}\,|\boxed{\Psi(\vec{k}^*, \vec{r})}|^2 d^3r = \mathrm{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

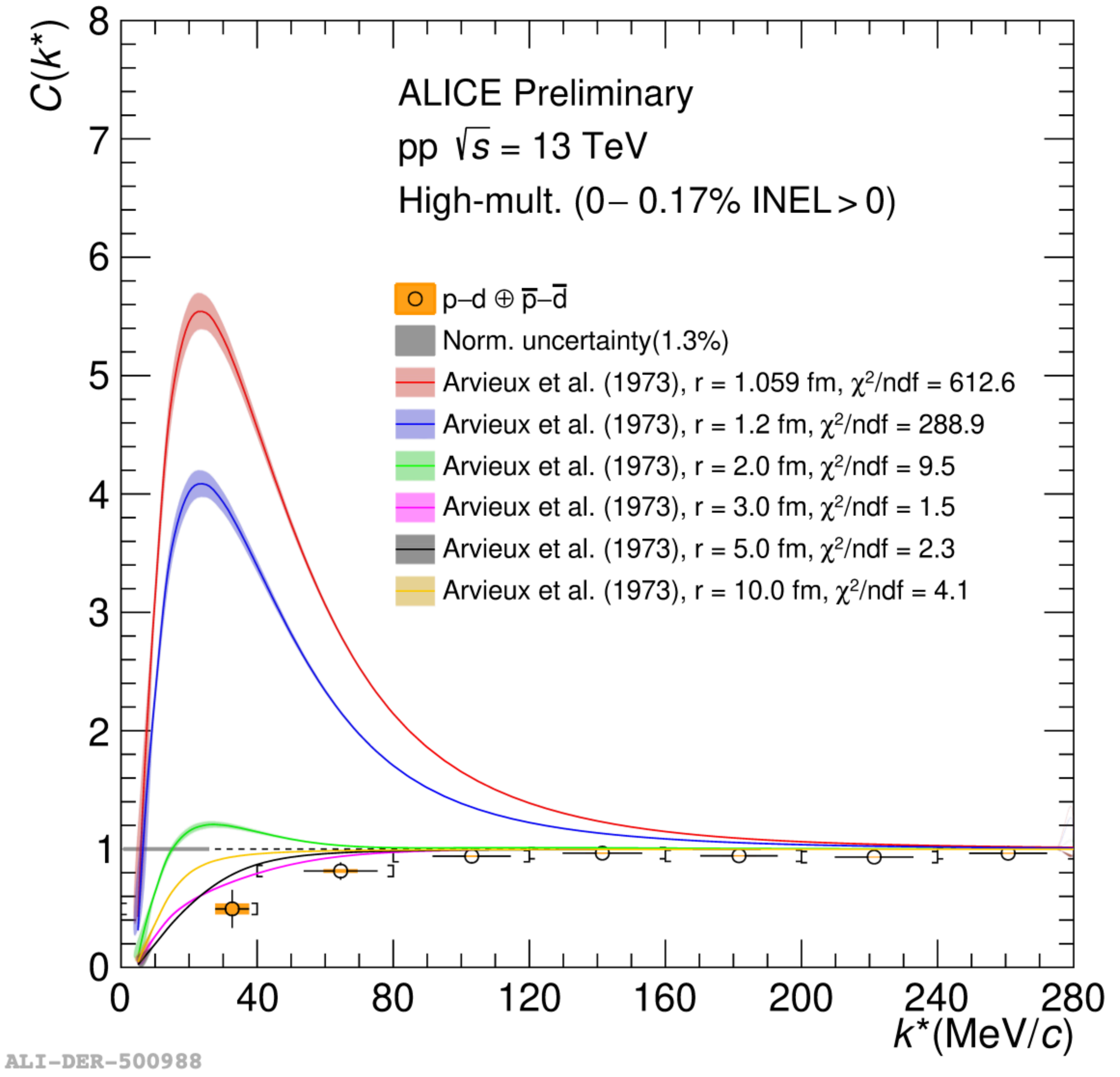
Emission source — *2-particle wavefunction*

↓ *Radii of p-d emission*

↓ *Interacting potential b/w p-d (3-body forces?)*

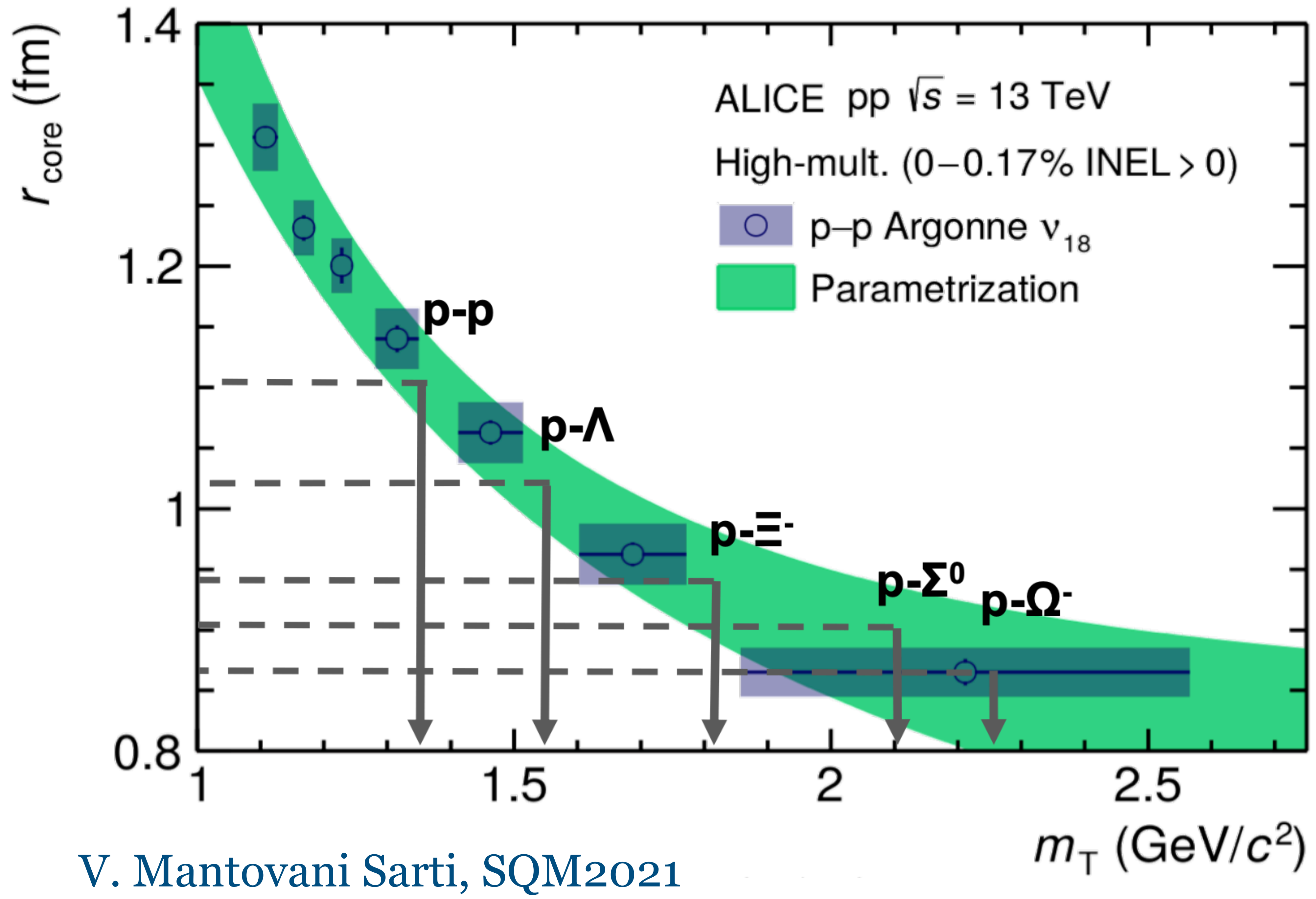
- Depletion at low k* observed

B. Singh, ALICE, QM2022
J. Arvieux et al., Nucl. Phys. A 221 (1973) 253-268



p-d correlations (p+p 13 TeV)

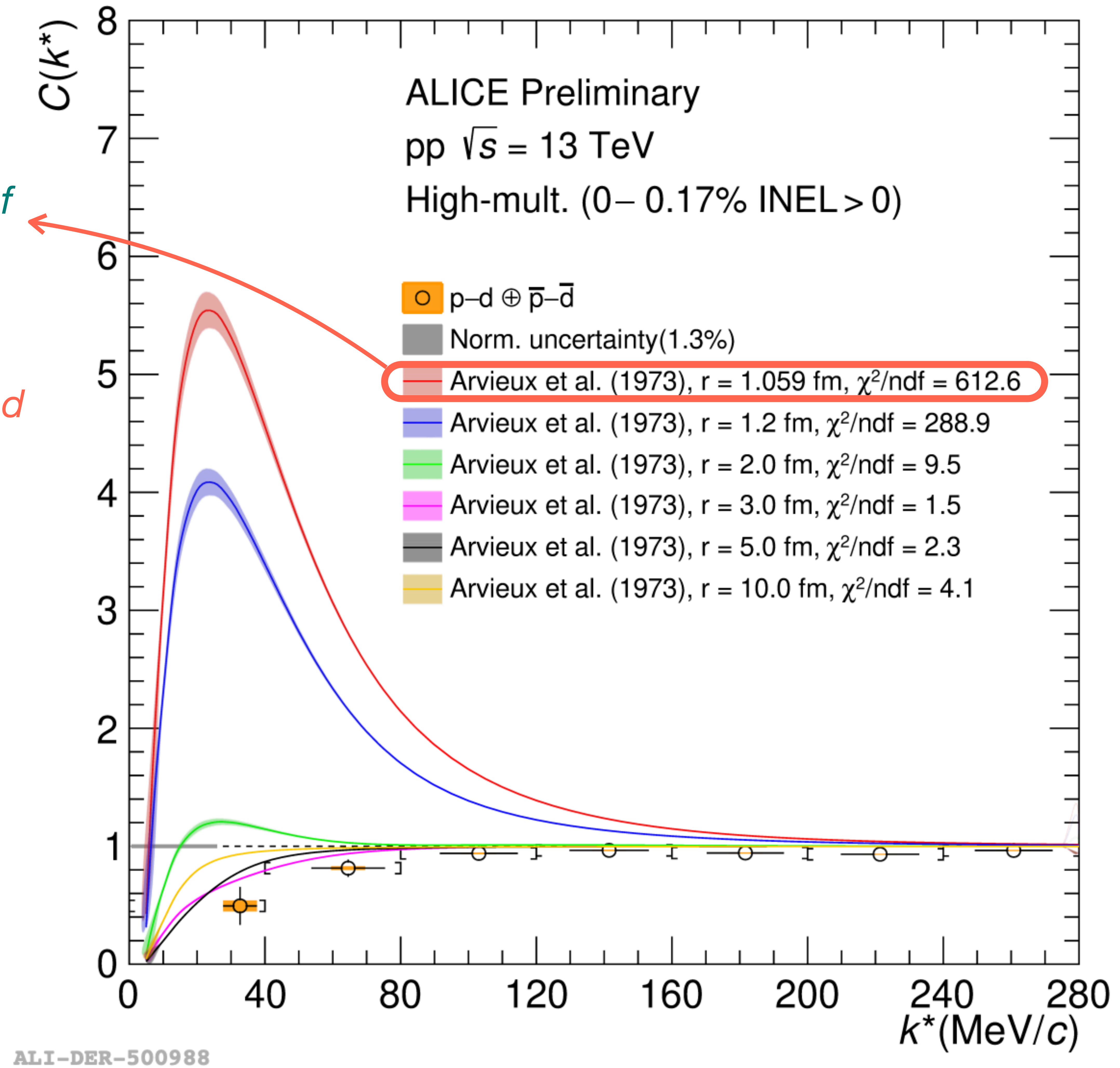
B. Singh, ALICE, QM2022
J. Arvieux et al., Nucl. Phys. A 221 (1973) 253-268



V. Mantovani Sarti, SQM2021

Assumptions:

1. *Common source of for all particles, scales with m_T*
2. *Point-like particle models constrained to p-d scattering measurements*



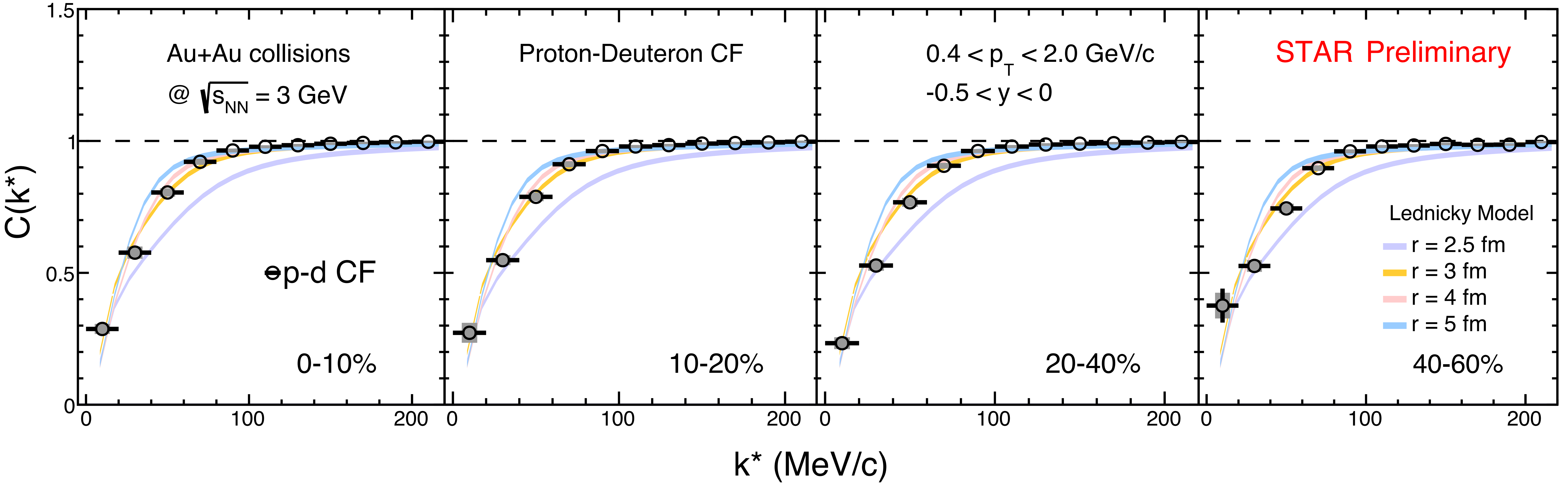
ALI-DER-500988

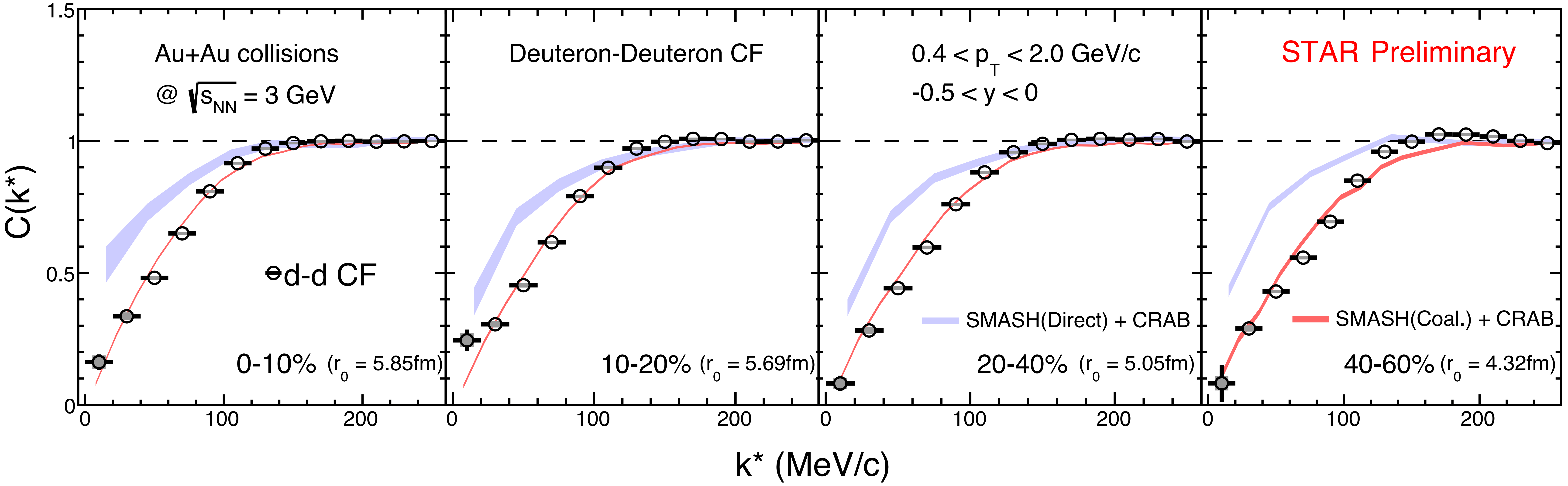
- Depletion at low k* observed
- At large r~3.0fm, model best agrees with data

Late formation of deuterons?

p-d, d-d correlations (Au+Au 3 GeV)

K. Mi, STAR, QM2022





- p-d correlation function shows depletion at low k*
- d-d correlation function compared with calculations from 2 scenarios:
  1. SMASH + CRAB
  2. SMASH + coalescence + CRAB

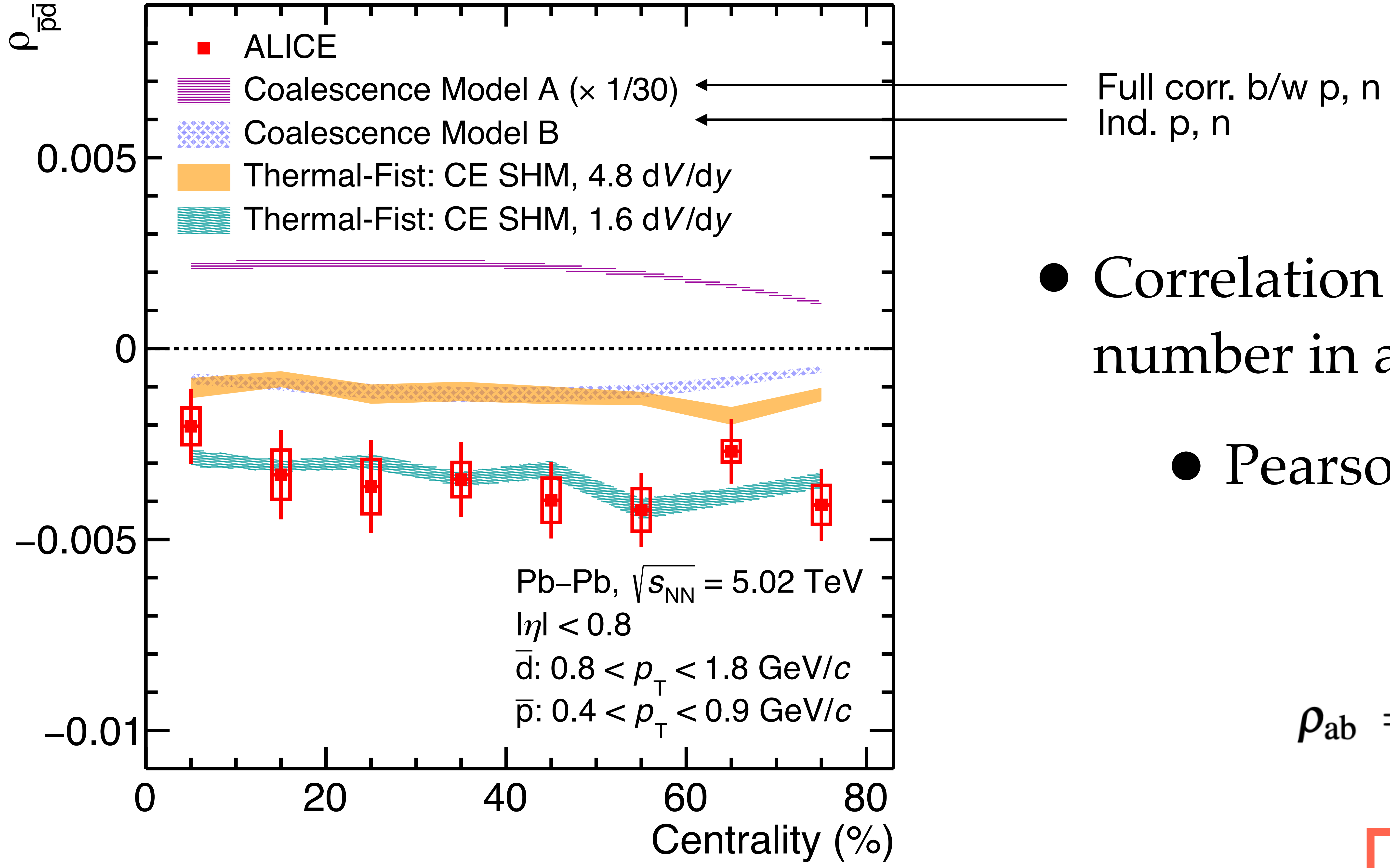
Deuteron data better described by model including coalescence

- High baryon density at 3 GeV enable p-d, d-d studies with high statistical precision

Proton-deuteron number correlations (Pb+Pb 5.02 TeV)

Phys. Rev. C 93 5, (2016) 054906
ALICE, arXiv:2204.10166

Correlations b/w proton and deuteron production
- *Distinguishing power b/w coalescence and thermal models*



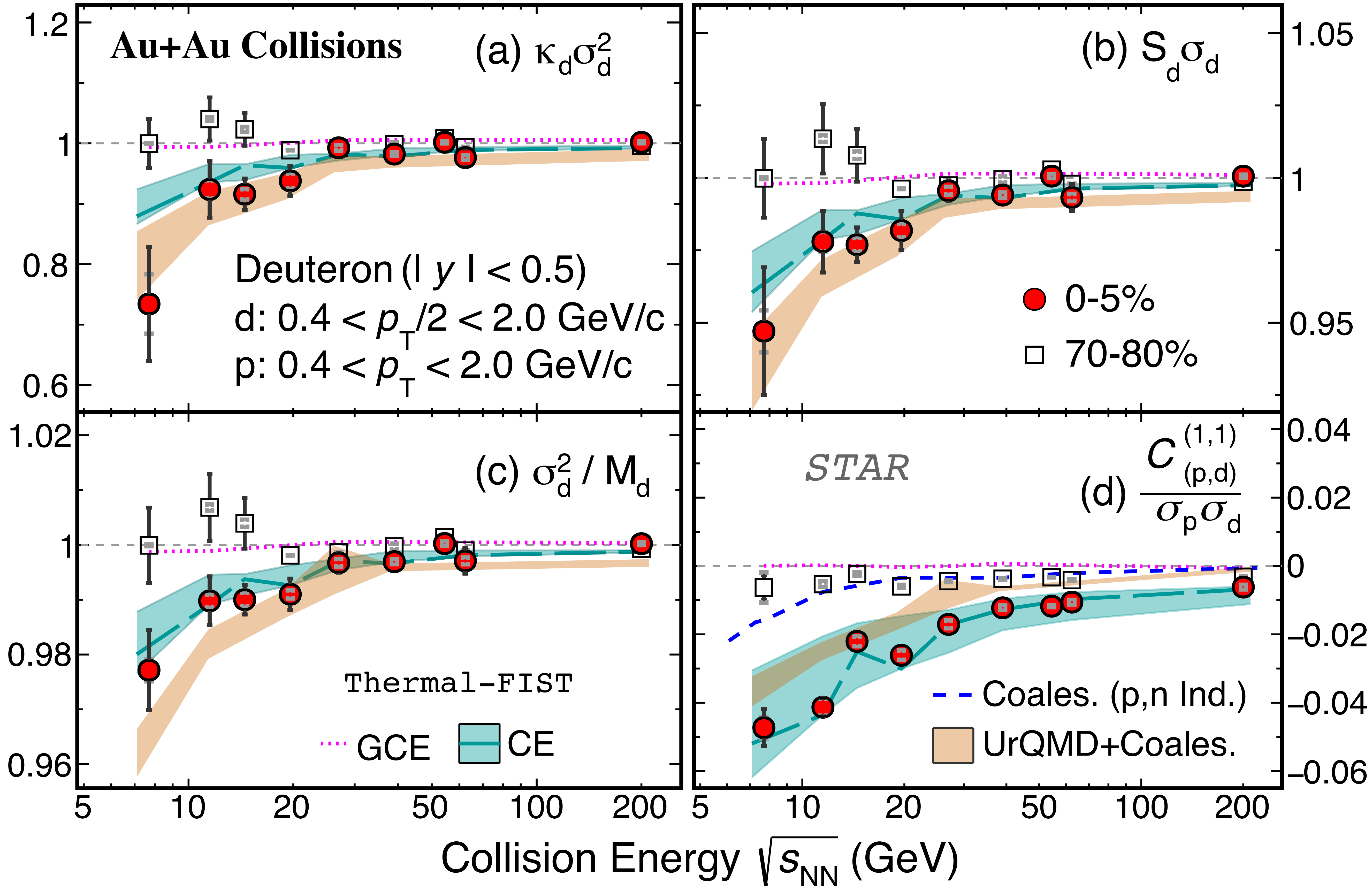
- Correlation between the proton and deuteron number in a single event
  - Pearson correlation coefficient (ρ_{ab})

$$\kappa_1 = \langle n \rangle,$$
$$\kappa_m = \langle (n - \langle n \rangle)^m \rangle,$$
$$\rho_{ab} = \langle (n_a - \langle n_a \rangle)(n_b - \langle n_b \rangle) \rangle / \sqrt{\kappa_{2a}\kappa_{2b}},$$

Proton and deuteron production are anti-correlated

- Thermal model reproduces the data well, while coalescence models seem to fail

Collision Energy Dependence of Deuteron Cumulants and proton-deuteron number correlations



STAR, arXiv:2304.10993

- Suppression of cumulant ratios at low energies
- Canonical ensemble is mandatory to describe cumulant ratios below 20 GeV

- -ve $\frac{C^{(1,1)}_{(p,d)}}{\sigma_p\sigma_d}$ from 7.7 GeV to 5.02 TeV

Importance of baryon number conservation in baryon-nucleus correlations

- Simple coalescence model which neglects phase space info. fail to describe data

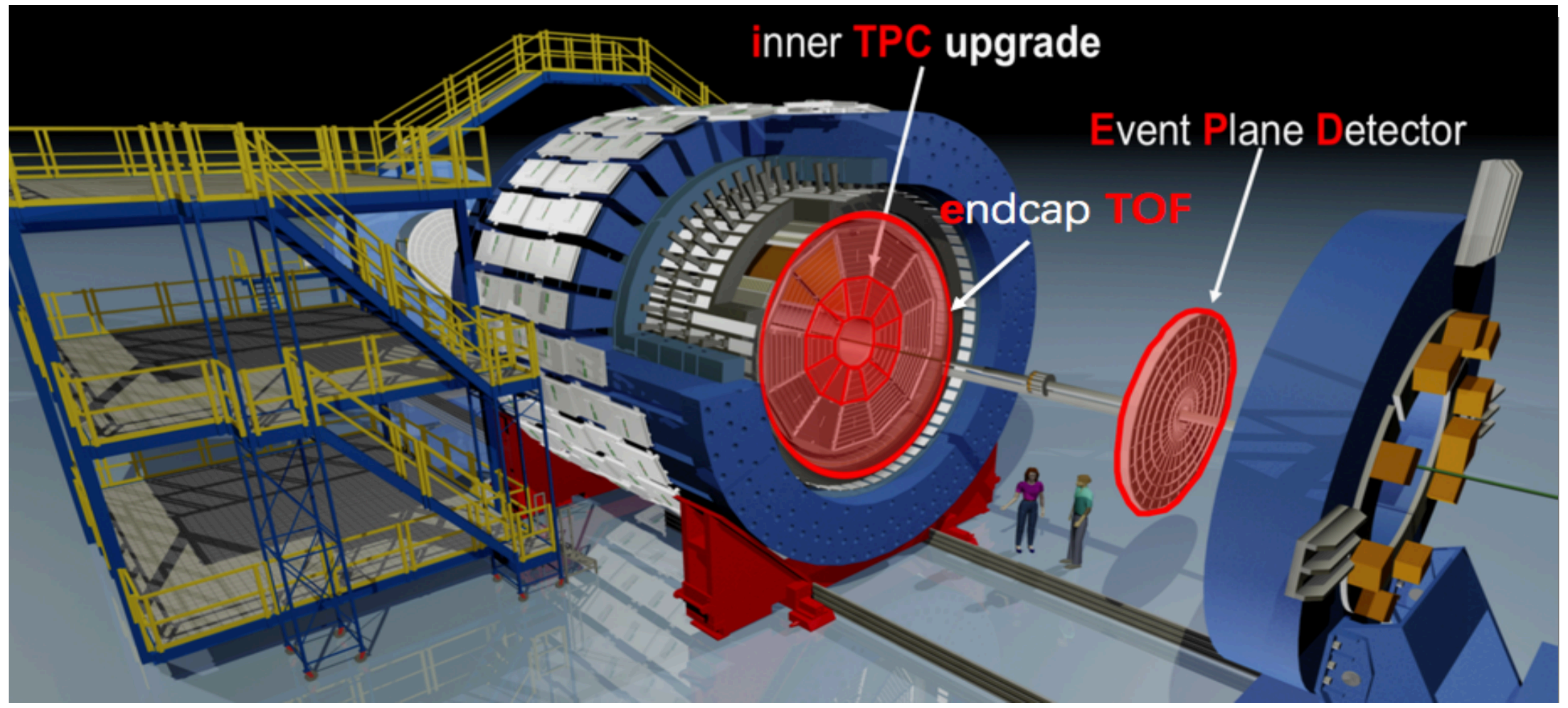
Phys. Rev. C 93 5, (2016) 054906

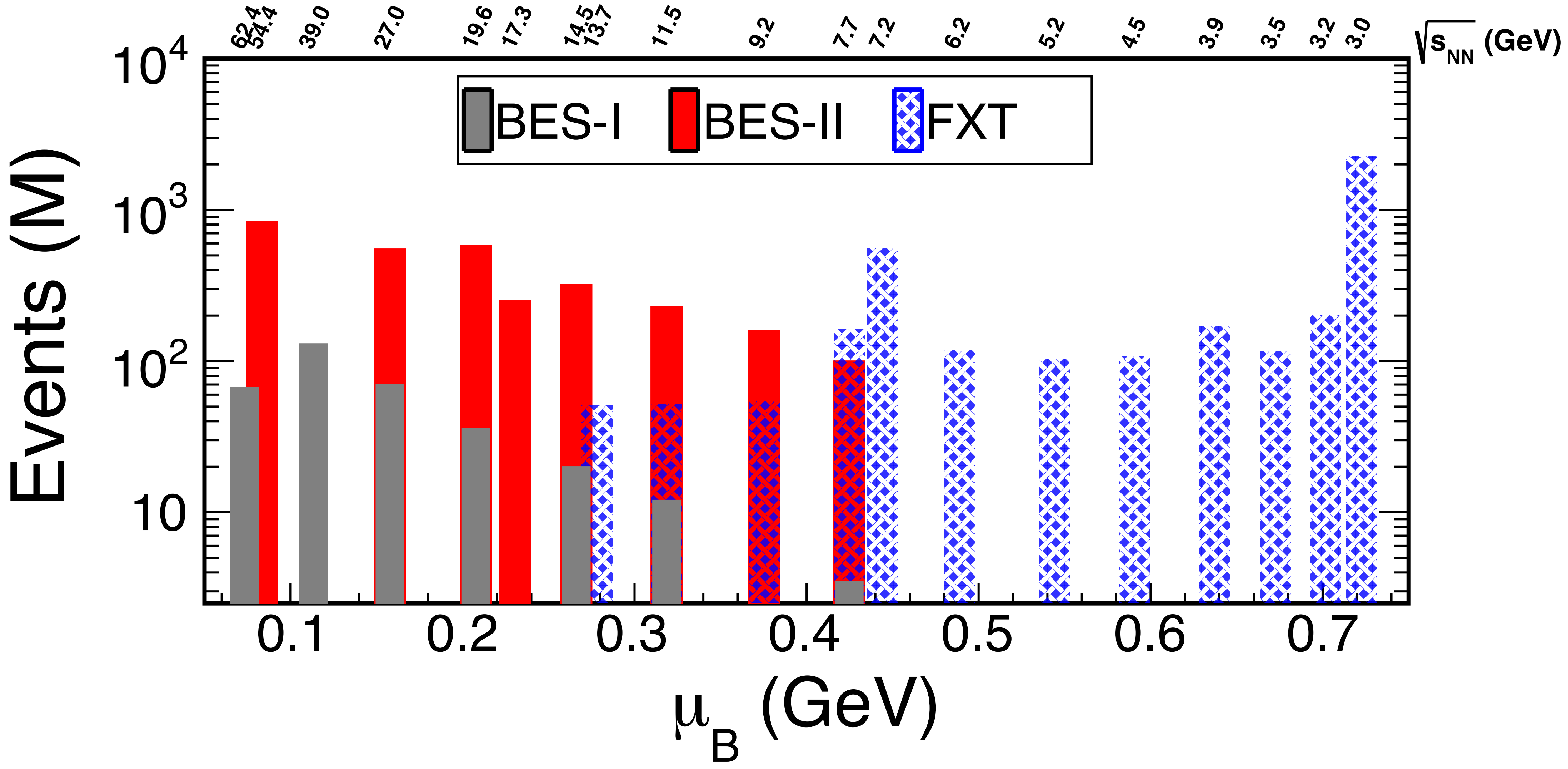
- UrQMD + coal. provides reasonable reasonable description of data

Summary

- Coalescence model can generally describe a wide range of light nuclei observables; details of the model (including transport) may require more scrutiny
- Thermal model compatible with deuteron observables, but is in tension with triton and hypertriton yields
- Discussed the prospects of light nuclei and hypernuclei measurements on improving our understanding of the QCD phase diagram and YN interaction
    - Stay tuned for more results from STAR BES-II!

Higher precision, larger acceptance, higher mass numbers, more differential measurements, etc..

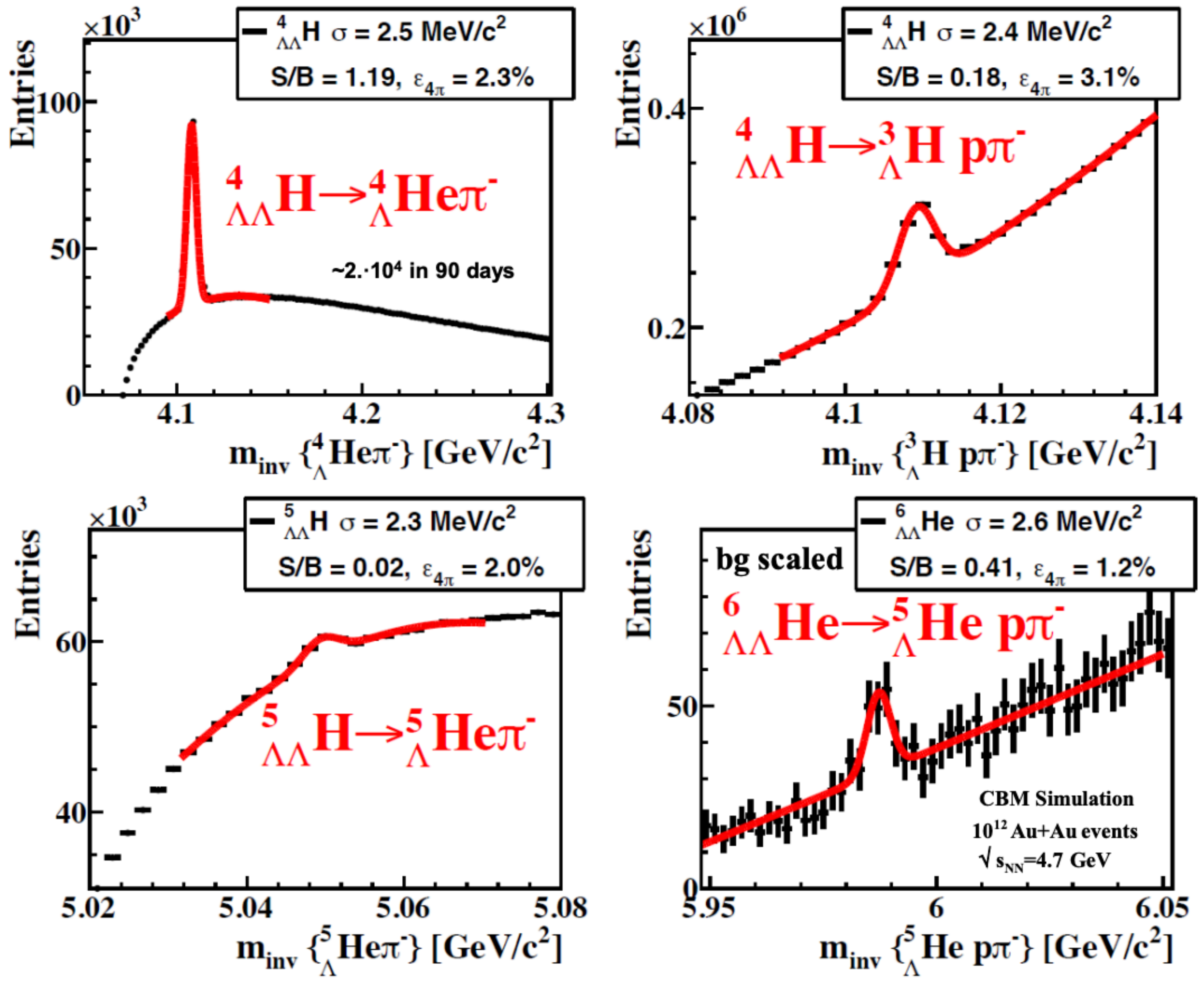




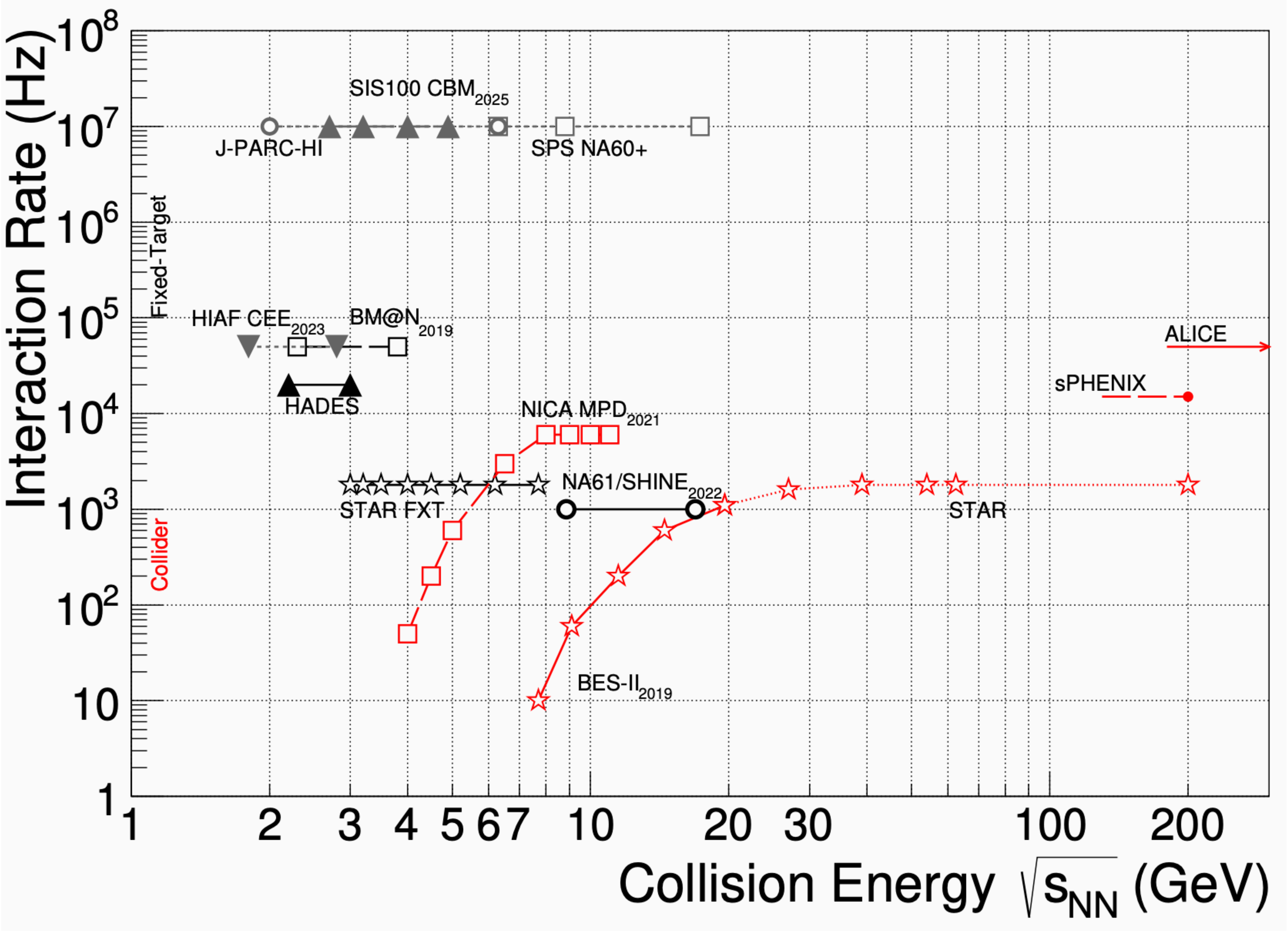
Outlook: Future Facilities

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

Interaction rates up to 10MHz!!



I. Vassiliev, CBM simulation



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

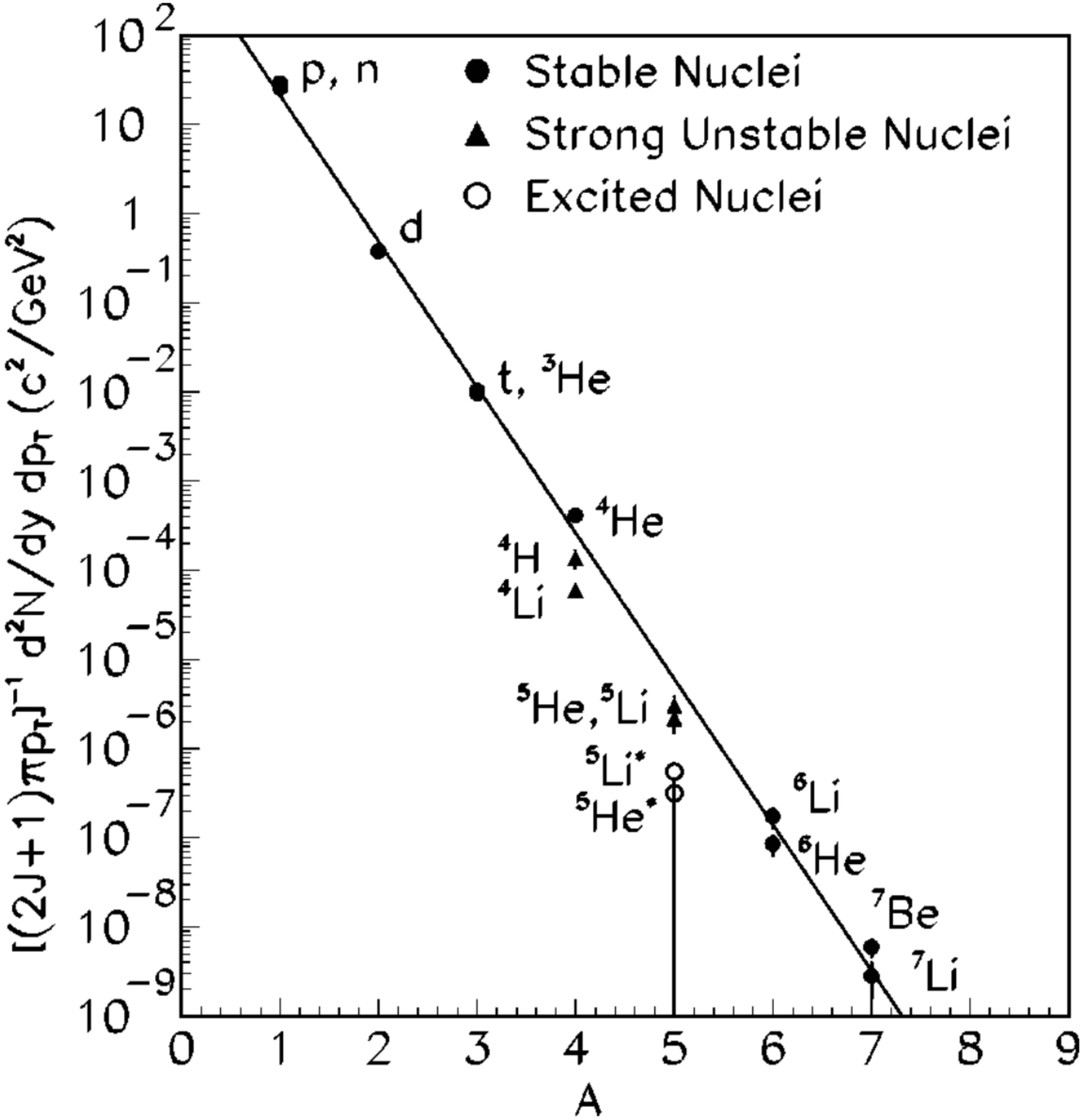
NA60+ LoI: arXiv:2212.14452

ΛΛ interaction: essential input to solve the hyperon puzzle

Thank you for listening!

Backup slides follow

Measurements of Unstable Nuclei from AGS



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

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