Hypernuclei production in heavy-ion collisions

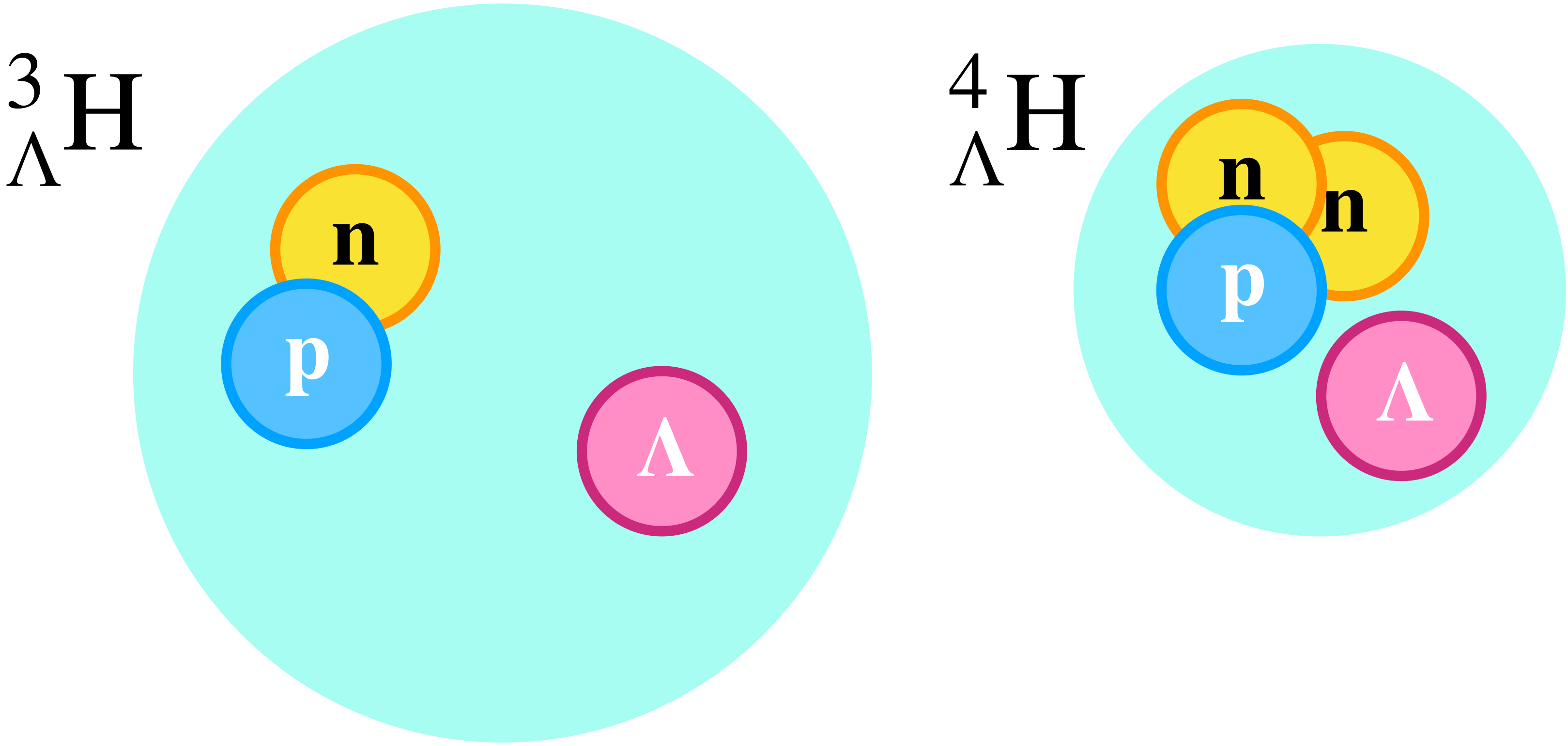
Yue-Hang Leung

Relativistic Nuclear Collisions Program (RNC)

NSD staff meeting Jul 13, 2021

- **Introduction**
- **Experimental apparatus**
- ($^{3}_{\Lambda}H, ^{4}_{\Lambda}H$) **lifetime**
- ($^{3}_{\Lambda}H, ^{4}_{\Lambda}H$) **production in heavy-ion collisions**
- **Outlook**

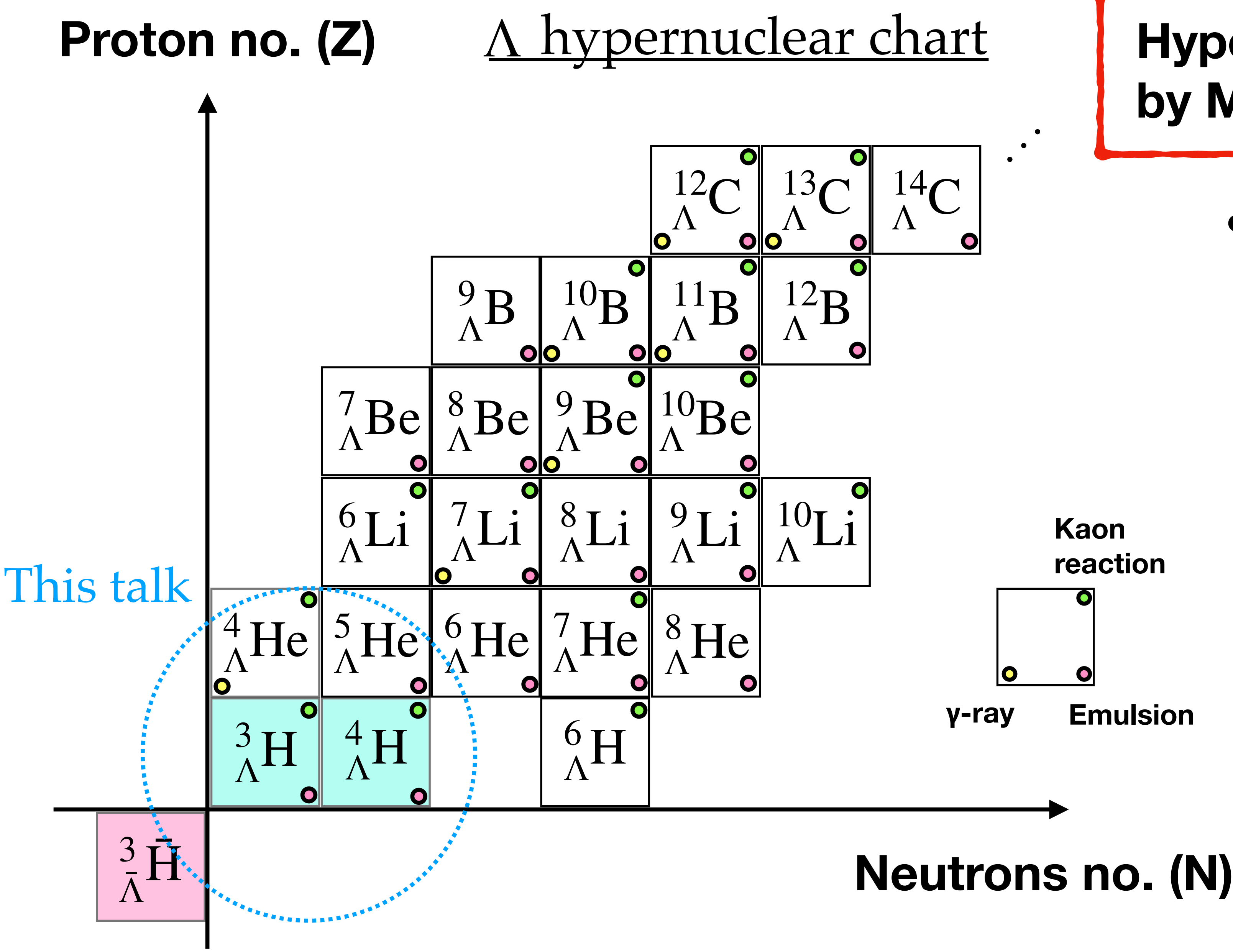
Hypernuclei



<u>Hypernuclei</u> are nuclei containing at least one hyperon

- provide access to the hyperon–nucleon (Y-N) interaction
  - <u>strangeness</u> in high density nuclear matter
    - EOS of neutron star
    - Hadronic phase of a heavy ion collision

Why heavy ion for hypernuclei?



Hypernuclei first discovered in 1952 by Marian Danysz and Jerzy Pniewski

- Traditionally, emulsion, γ ray or strangeness exchange reactions used to study properties of hypernuclei
- E864 collaboration: first measurement of hypernuclei in HI collisions (2004)

PRC70 (2004) 024902

- First observation of anti-hypernuclei by STAR (2009) STAR, Science 328 (2010) 58

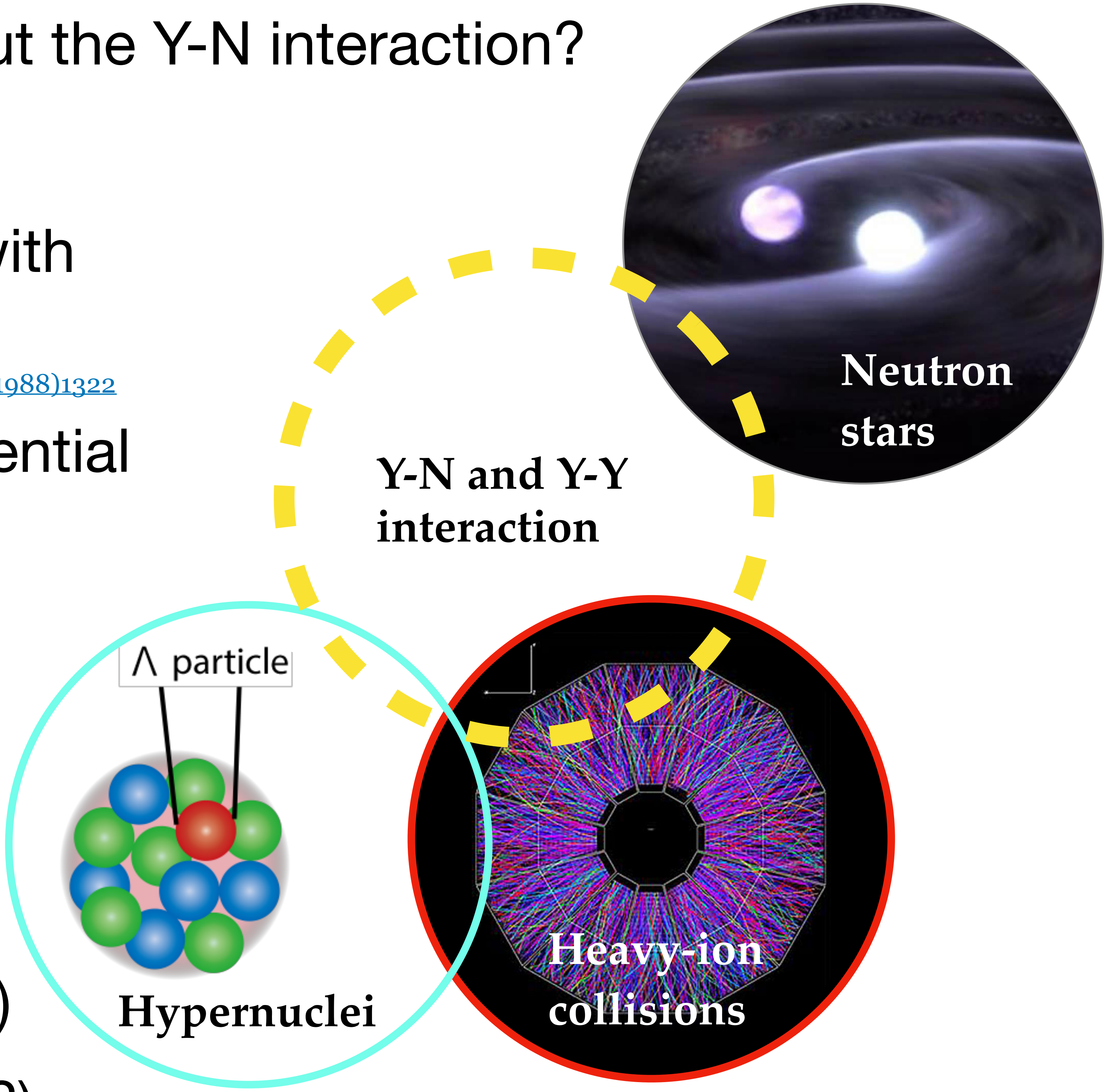
- HIC vs traditional techniques:

- **Precise analysis of light/anti hypernuclei structure → Y-N interaction**
- **Production mechanisms → Y-N interaction + properties of the matter formed**
- **Search for exotic hypernuclei**

The hyperon-nucleon (Y-N) interaction

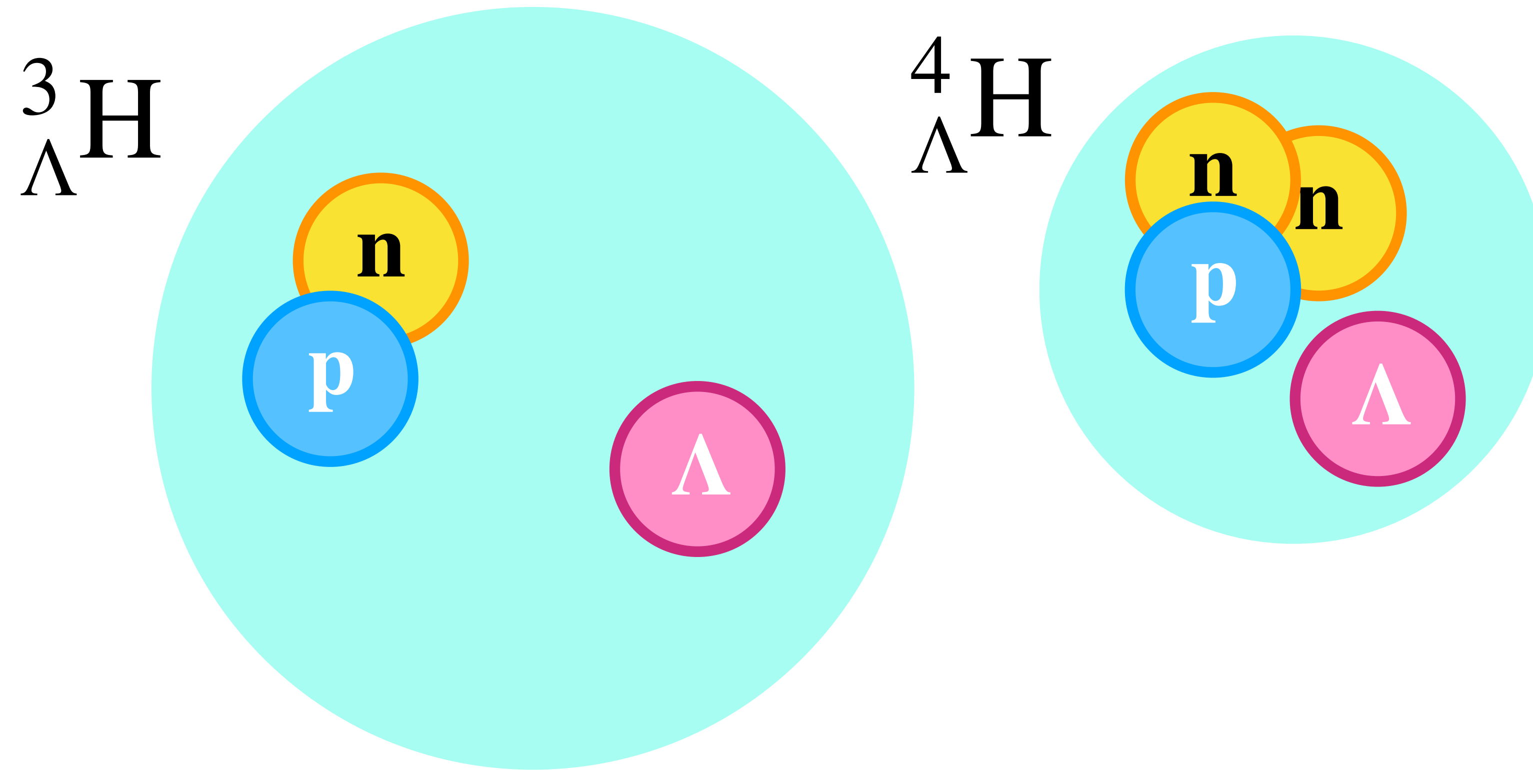
- What have we learnt about the Y-N interaction?
- Λ-N (40+ Λ-hypernuclei)
  - Attractive Λ potential with depth ≈ 30 MeV

    T. Motoba et al, PRC38(1988)1322
  - About 2/3 nucleon potential
  - **Precise measurements of B_Λ, τ, and decay B.R. can give tighter constraints**
- Ξ-N, Σ-N (few Ξ/Σ hypernuclei)
- Λ-Λ, (few Λ-Λ hypernuclei)
  - Λ-Λ weakly attractive (?)



Light hypernuclei $({}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H})$

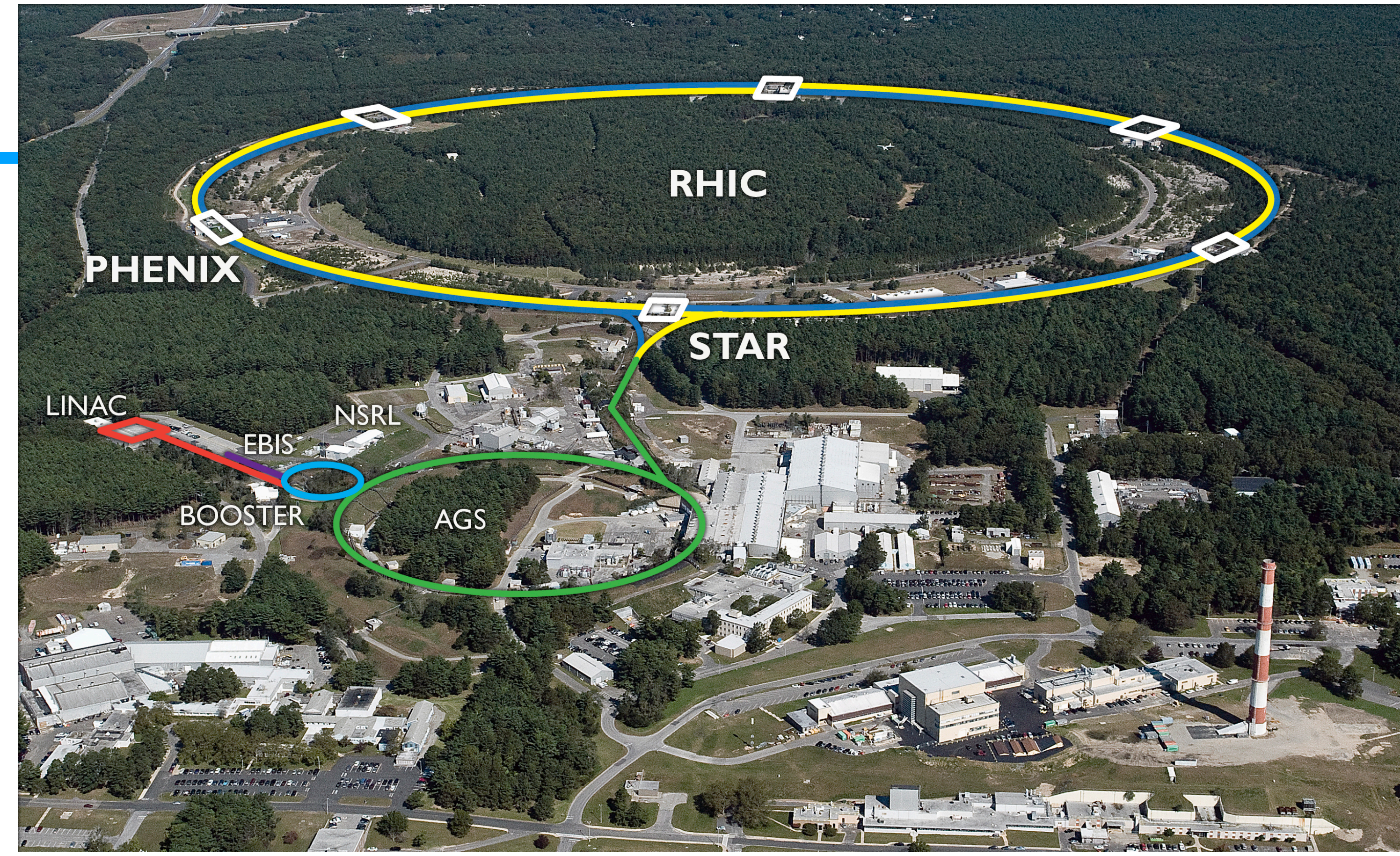
- Binding energy (B_Λ)
  - ${}^{3}_{\Lambda}\mathrm{H}$: ~0.2 MeV
  - ${}^{4}_{\Lambda}\mathrm{H}$: ~2.2 MeV
- **Loosely bound objects**



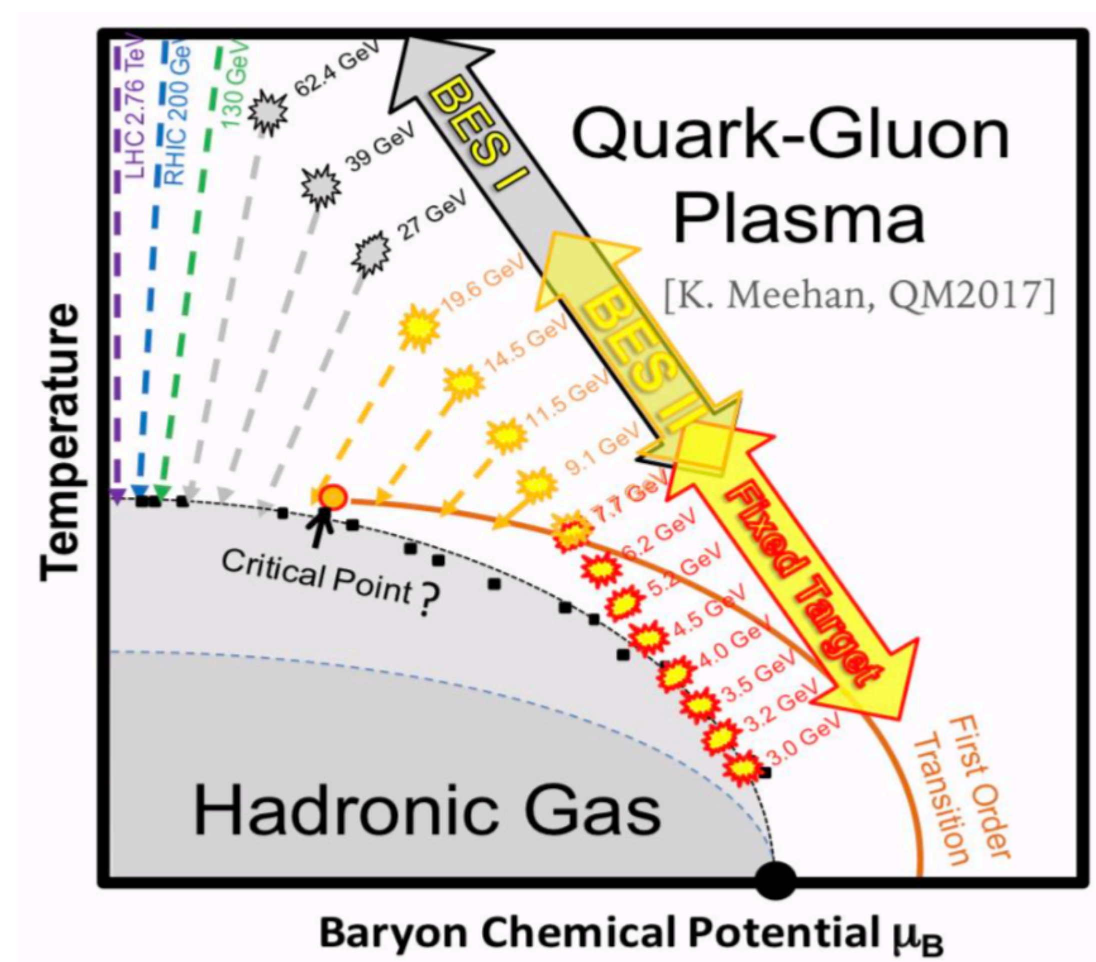
- ${}^{3}_{\Lambda}\mathrm{H}$ lifetime
  - Weak binding -> small overlap between Λ and d wavefunction
  - Expect ${}^{3}_{\Lambda}\mathrm{H}$ lifetime very close to Λ lifetime
- Production yield in HI collisions ("Ice in the Fire")
  - Weak binding -> Strong influence on yield calculations in a coalescence approach
  - Fragile objects, may be destroyed immediately after formation

RHIC and BES-II

- The Relativistic Heavy Ion Collider (RHIC)
  - Au ions collide at relativistic speeds



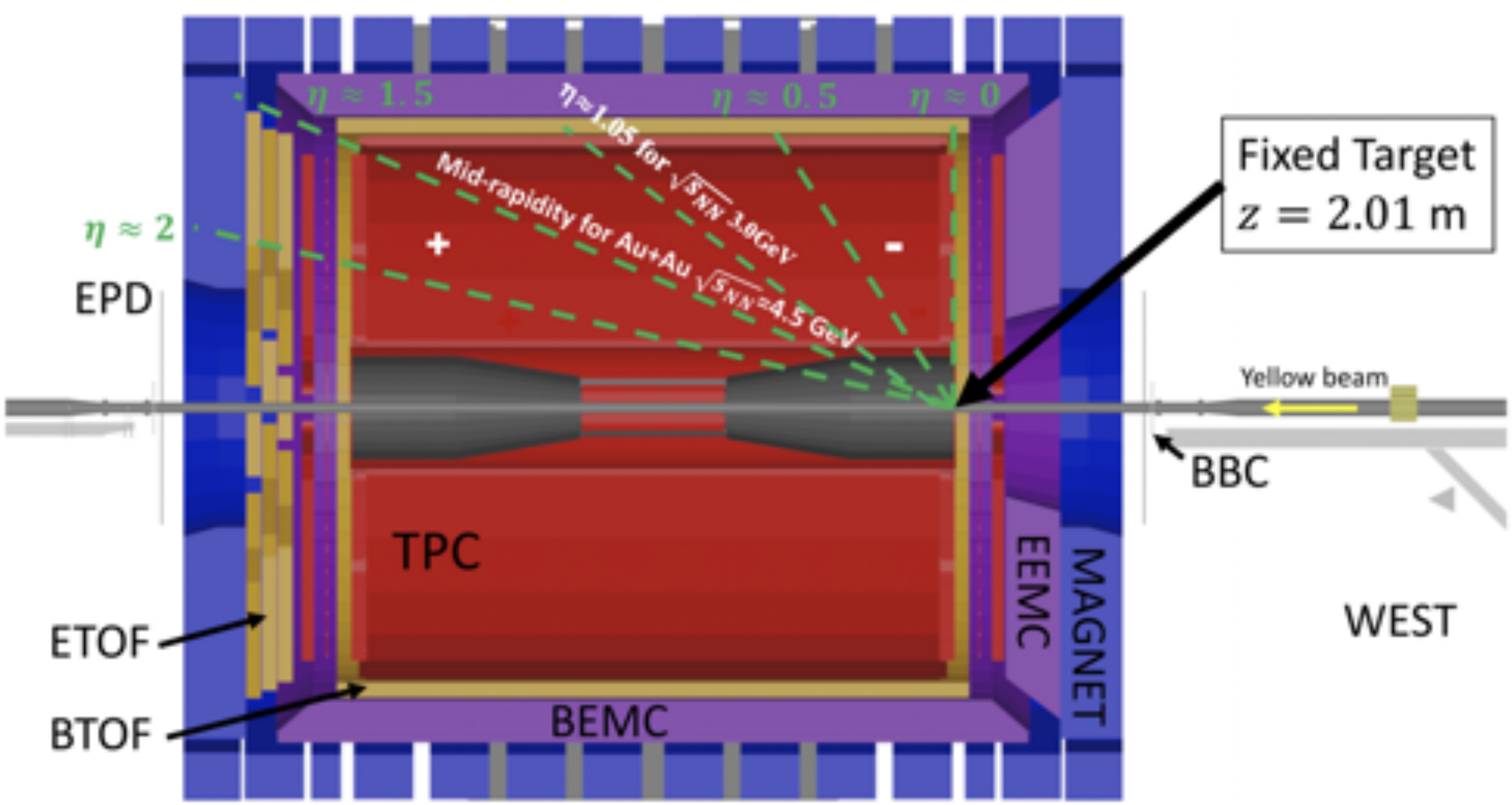
- Beam energy scan (BES) II program
  - Probes onset of deconfinement, search for critical point etc.
- Fixed target Au+Au collisions
  - $\sqrt{s_{NN}} = 3 - 13.7$ GeV
  - **High baryon density matter**

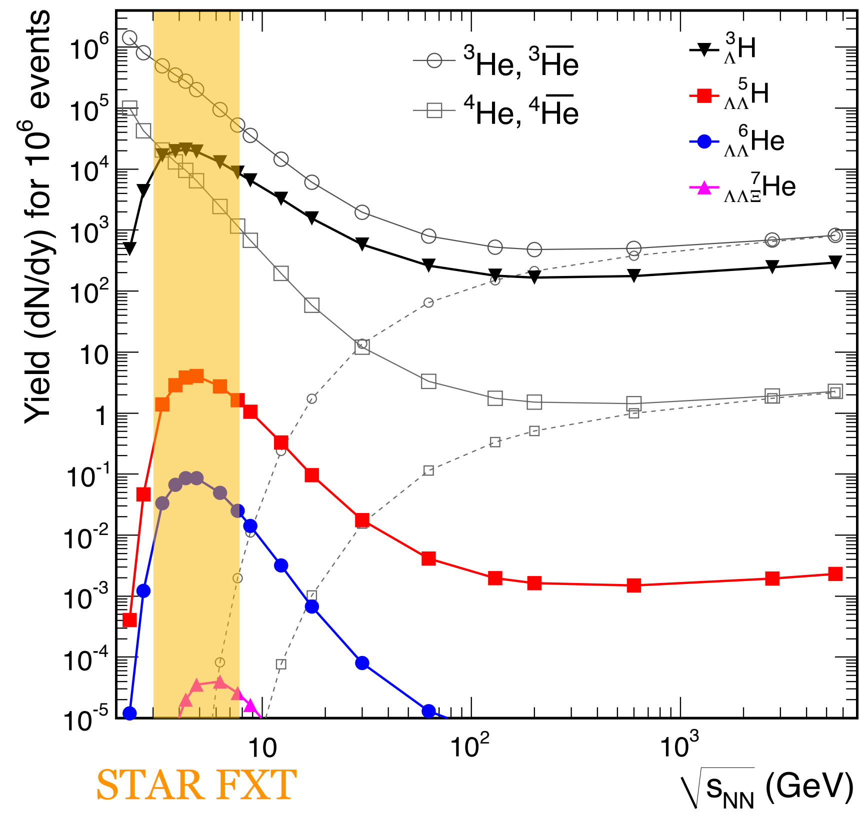


STAR Fixed-Target (FXT) mode

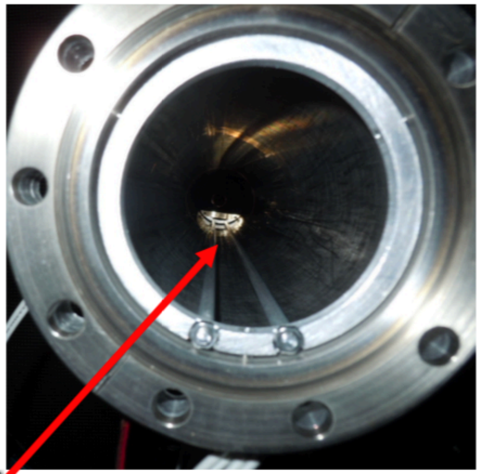
- High light hypernuclei yield expected at lower beam energies
  - STAR BES-II -> great opportunity to study hypernuclei production

STAR Fixed-target Experiment Setup





PLB 697 (2011)203 (Thermal Model)

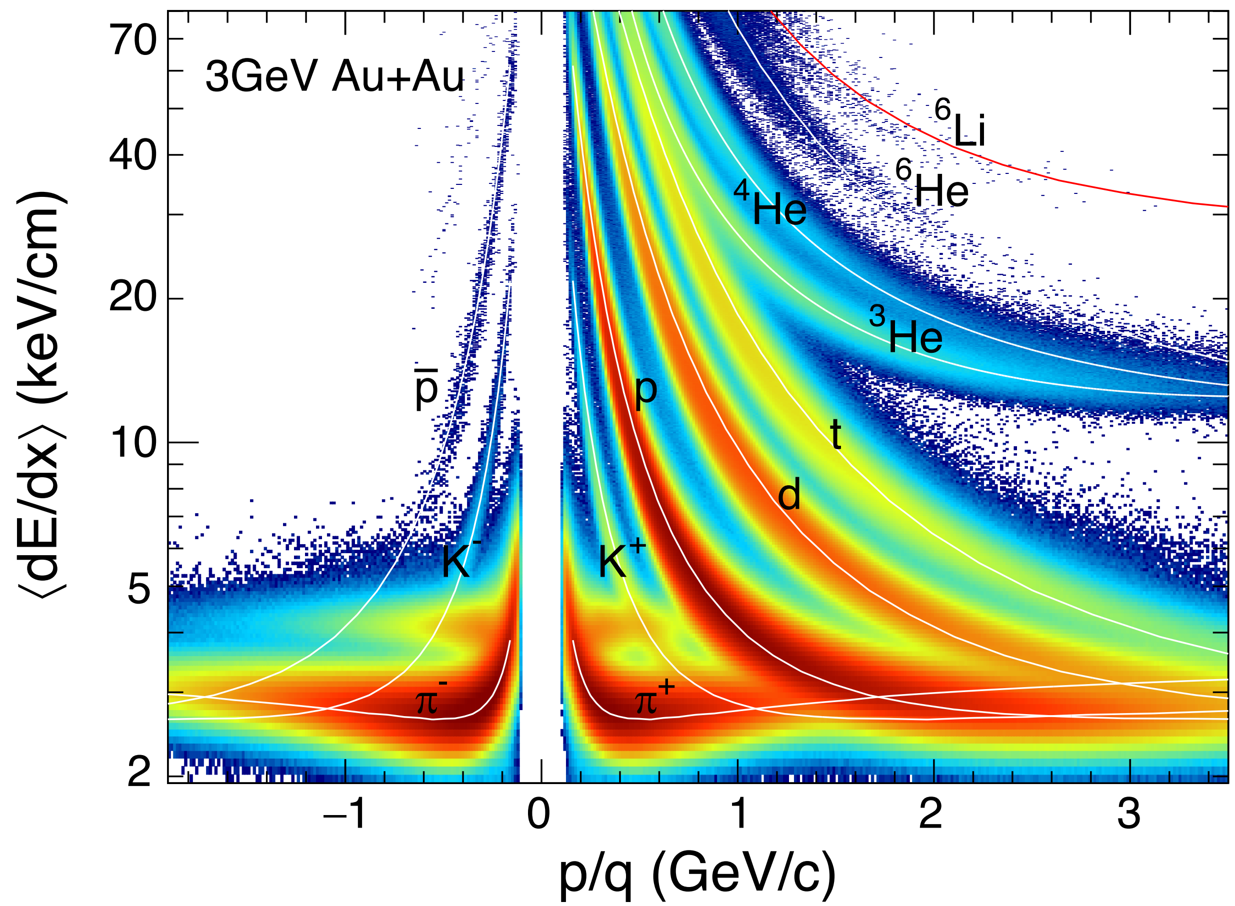


Beam pipe

Au-Target =0.25mm thickness
1% interaction probability

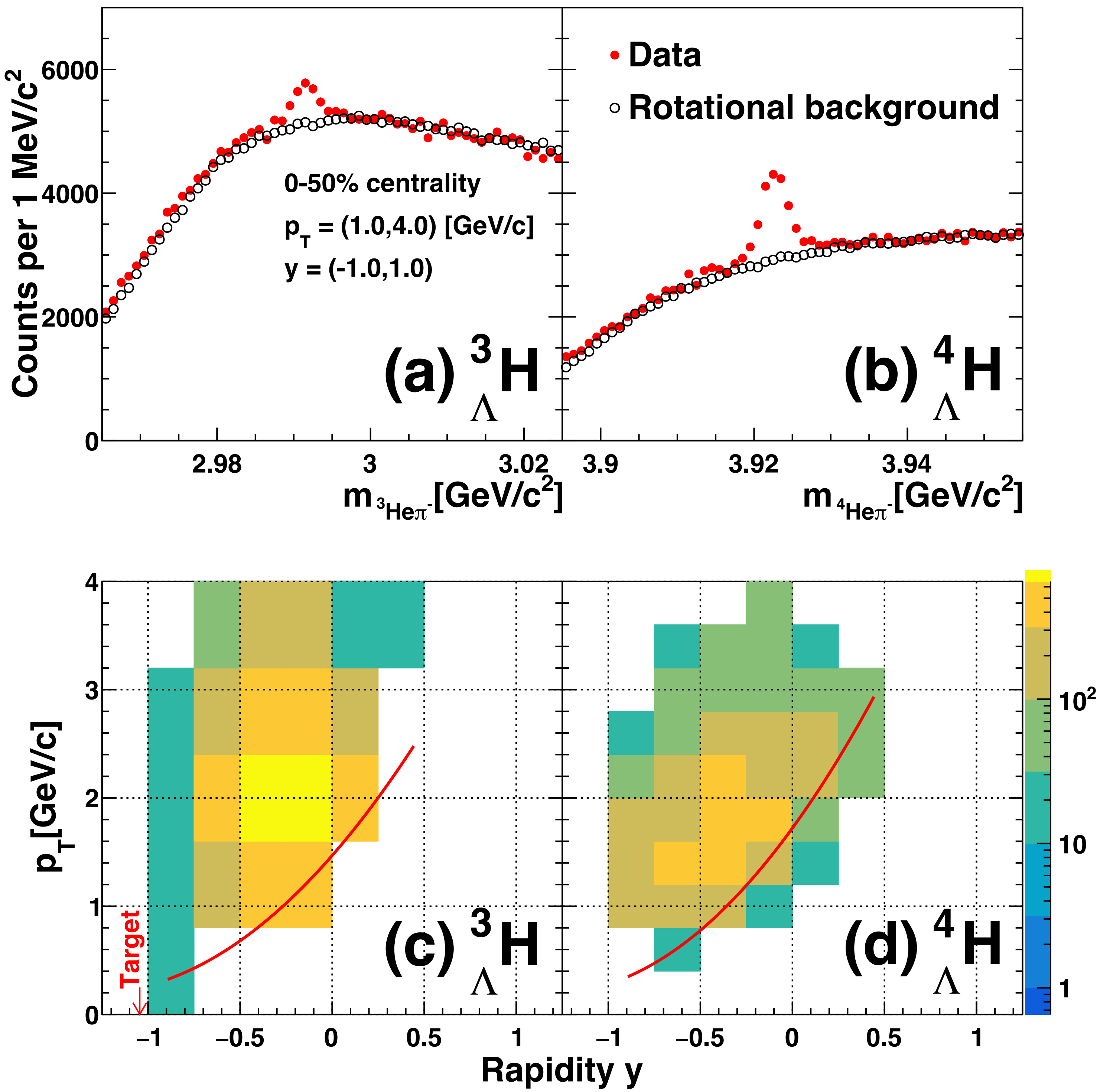
- 250M events at $\sqrt{s_{NN}} = 3$ GeV with STAR FXT mode in 2018

Particle identification



- Main detector used for the analysis is Time Projection Chamber (TPC)
    - Track reconstruction
    - Provides high quality dE/dx measurement for particle identification

Hypernuclei reconstruction and acceptance



- Hypernuclei reconstructed via weak decays
  - inv. mass method
- Decay channels

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi \quad (B.R. \approx 25\%)$$

PRC57(1998)1595

~2900 candidates

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi \quad (B.R. \approx 50\%)$$

~6300 candidates

NPA585(1995) 365c

NPA639(1998) 251c

- Good mid-rapidity coverage at 3 GeV

**KFParticle package used for reconstruction*

*M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR", thesis, urn:nbn:de:hebis:30:3-414288

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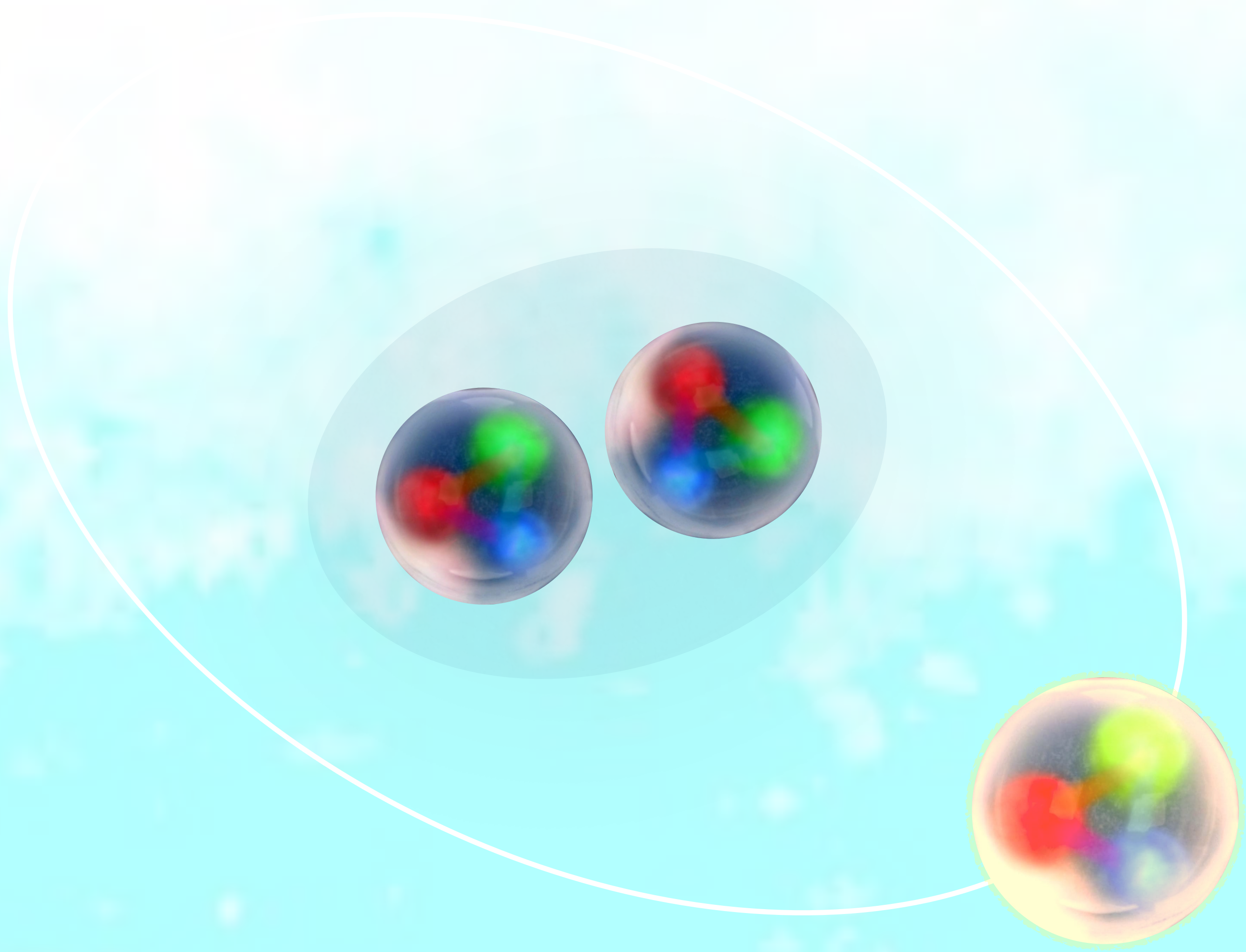
- Experimental apparatus
- **Lifetime**
- Production in heavy-ion collisions
- Outlook

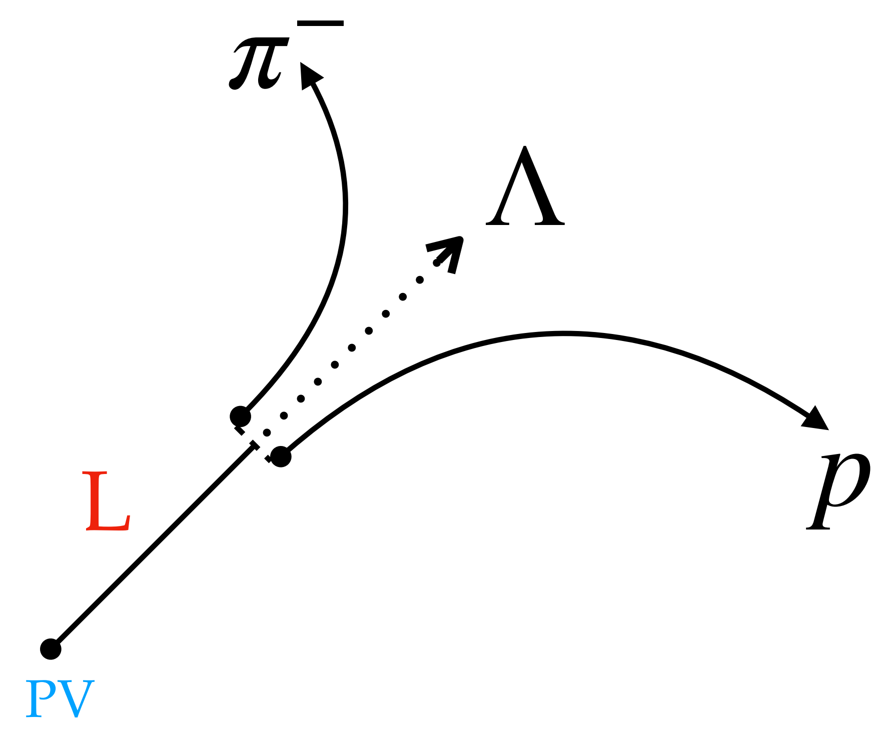


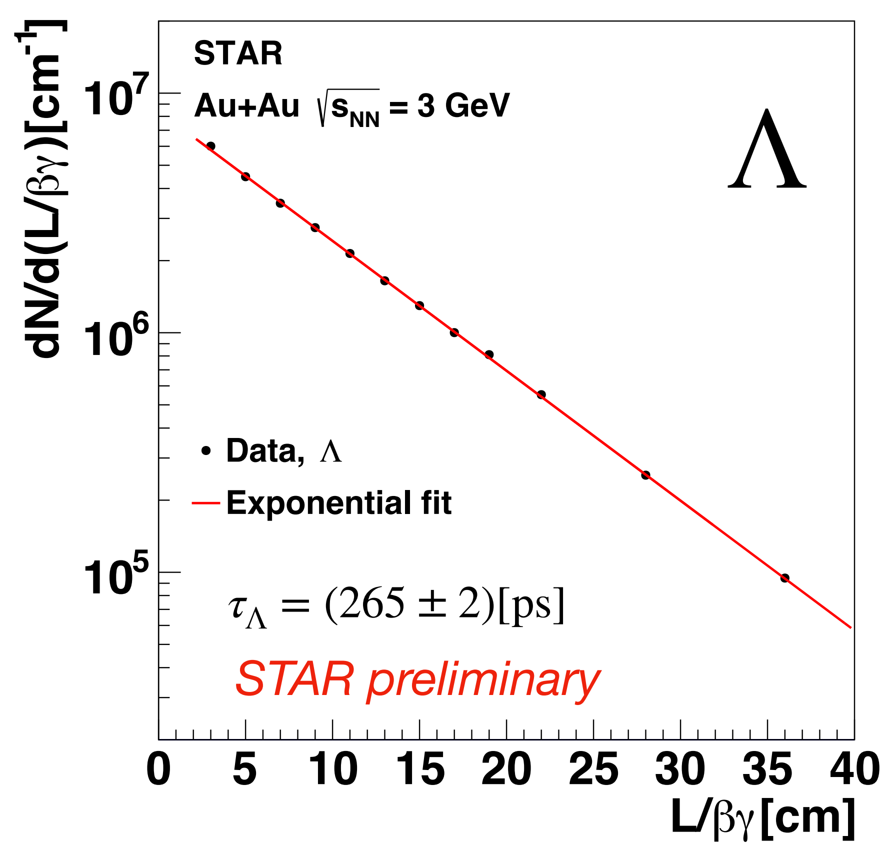
Outline of lifetime analysis

- Momentum and spatial coordinates of daughter tracks from TPC
- Reconstruction of mother particle
  - Momentum, decay length (L)
- Measure the yield as a function of $L/\beta\gamma$

$$N(t) = N_0 e^{-t/\tau} = N_0 e^{-L/\beta\gamma c\tau}$$

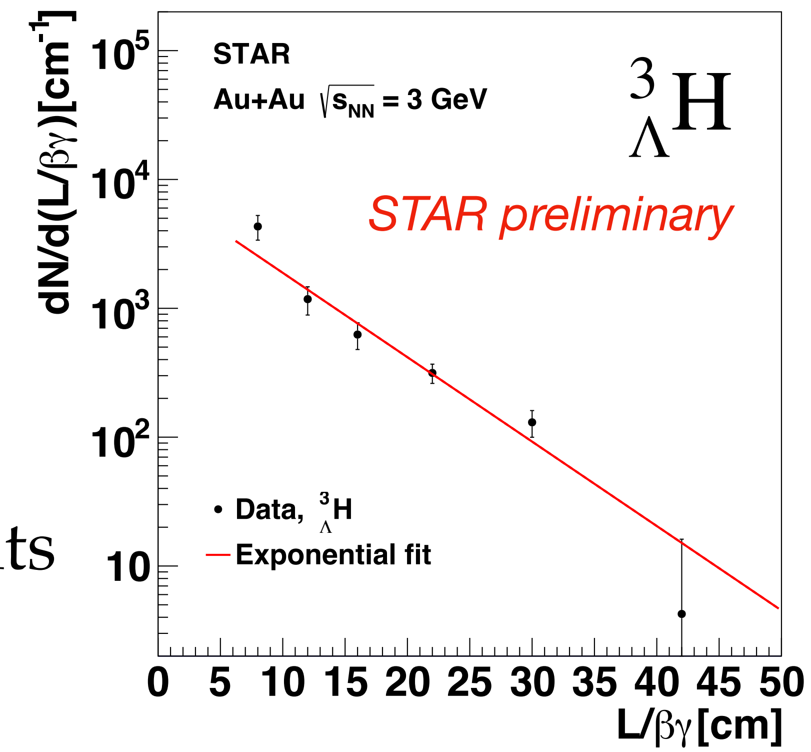
  - Efficiency corrections from GEANT sim.
- Extract lifetime by exponential fit
- Measured Λ lifetime consistent with Particle Data Group value



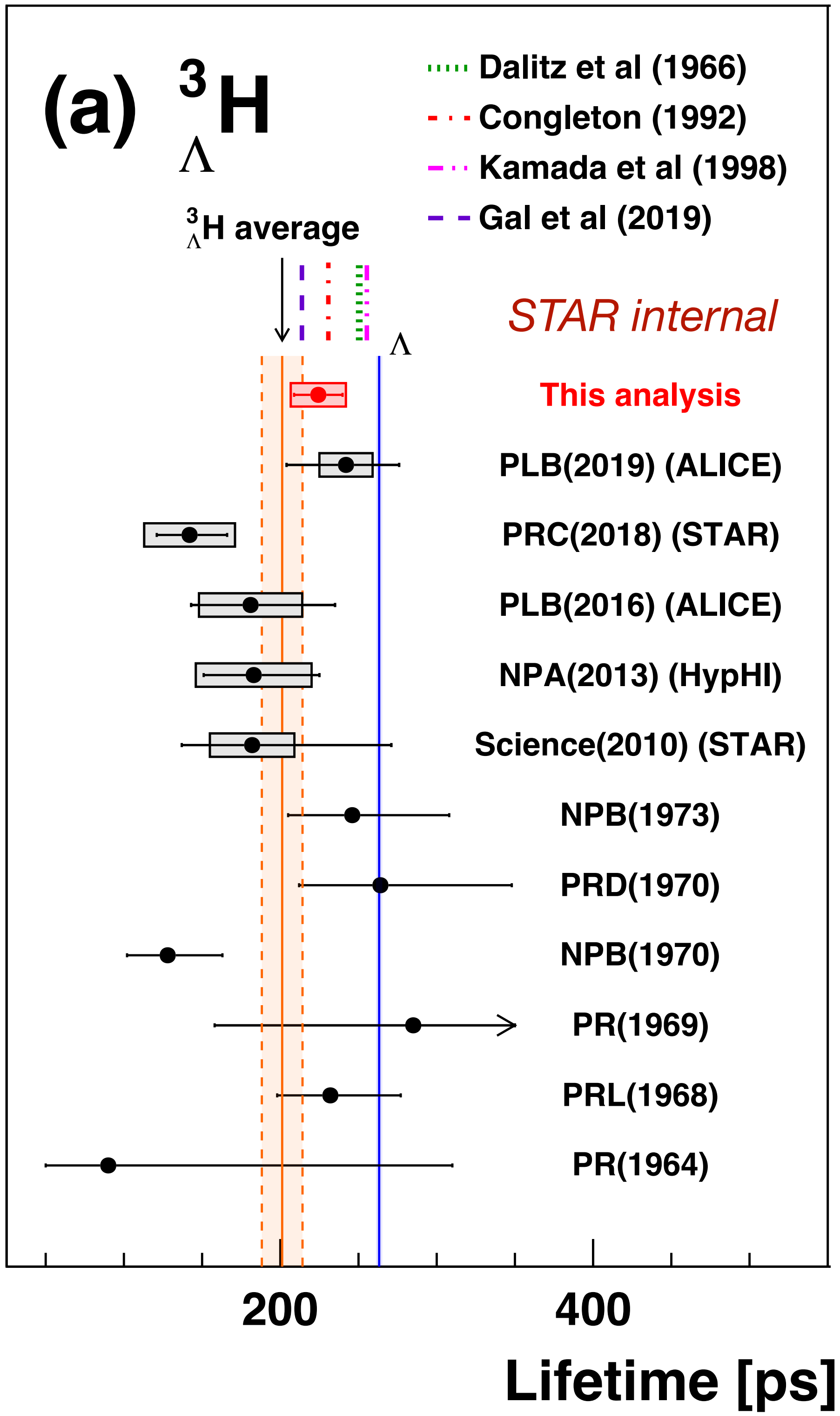


Hypertriton lifetime

- Precise measurement of ${}^{3}_{\Lambda}\mathrm{H}$ lifetime



  - Consistent with previous measurements

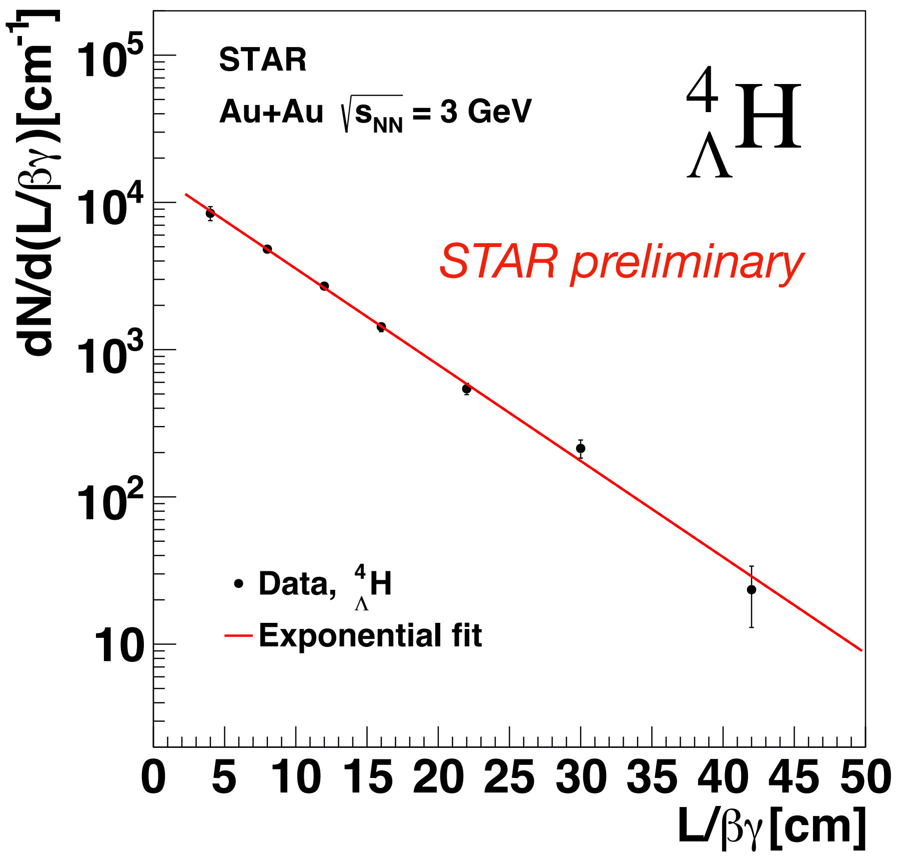


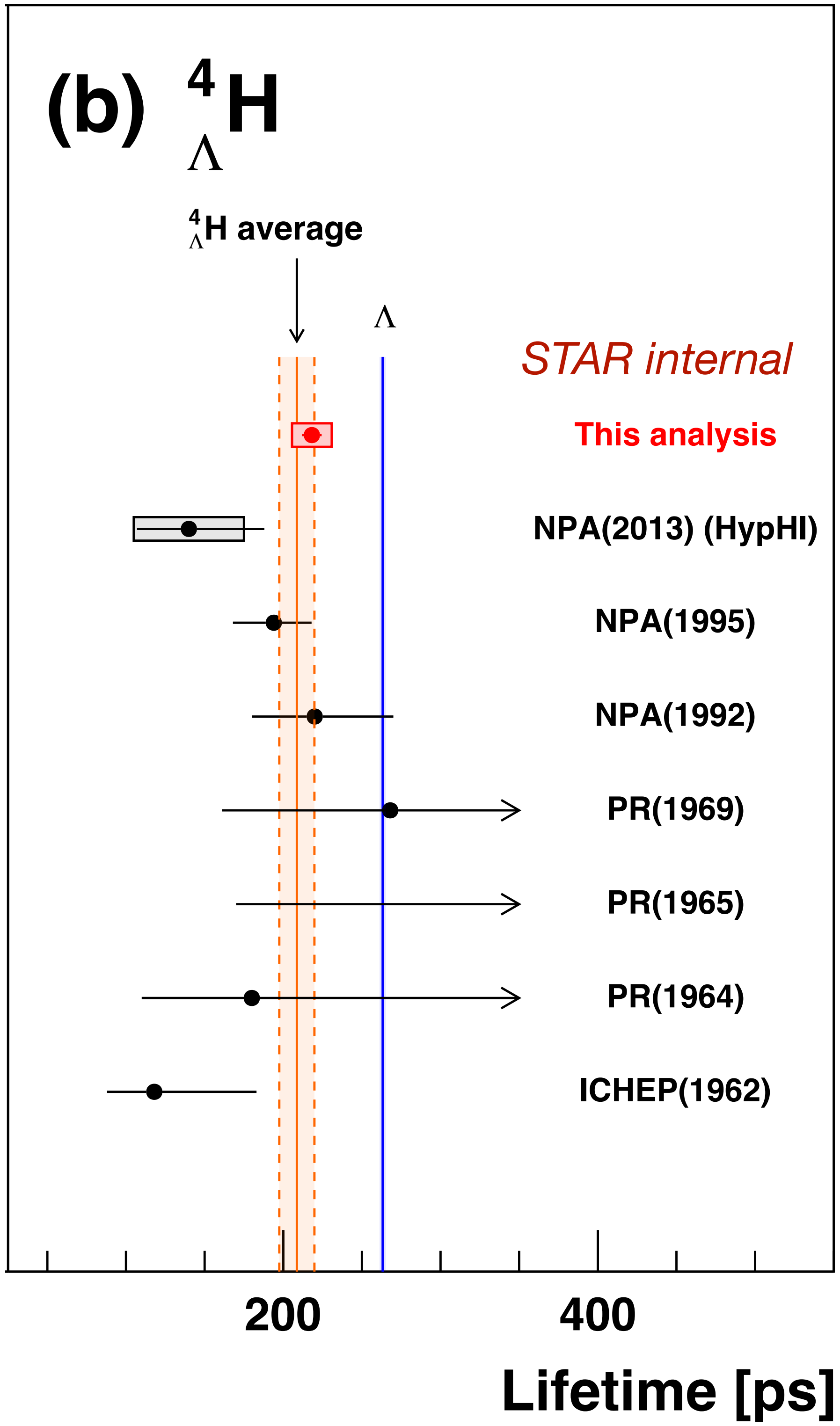
- Updated world average (76±5)% of free Λ lifetime τ_{Λ}

- Theory expects lifetime of hypertriton close to the lambda lifetime
  - Recent calculations including pion FSI interactions: $\tau({}^{3}_{\Lambda}\mathrm{H}) = (81 \pm 2)\,\%\,\tau_{\Lambda}$

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

- Most precise measurement of ${}^{4}_{\Lambda}H$ lifetime





- **Give tighter constraints to models**
- **Further our understanding in structure of hypernuclei and Y-N interaction**

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- Experimental apparatus
- Lifetime
- **Production in heavy-ion collisions**
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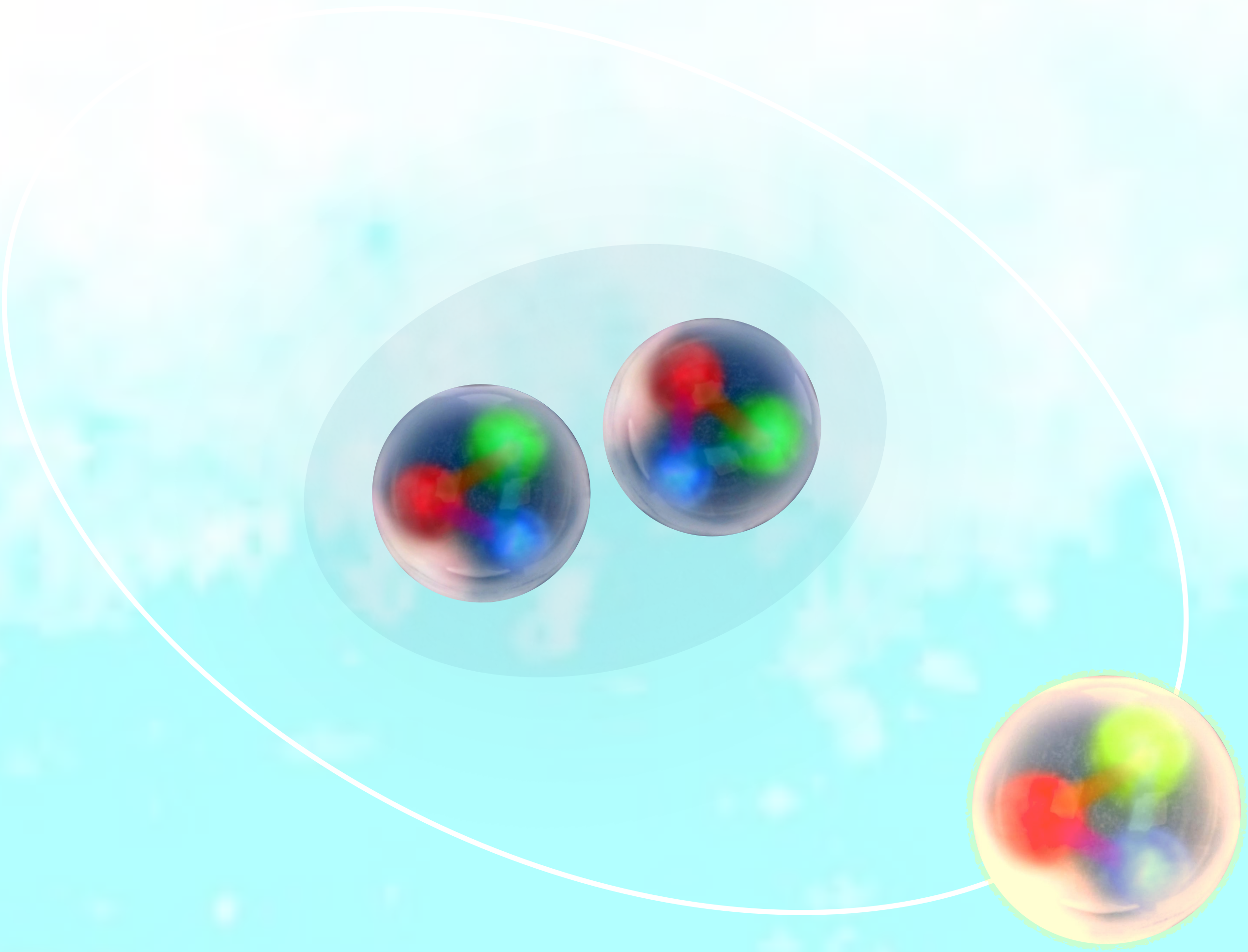
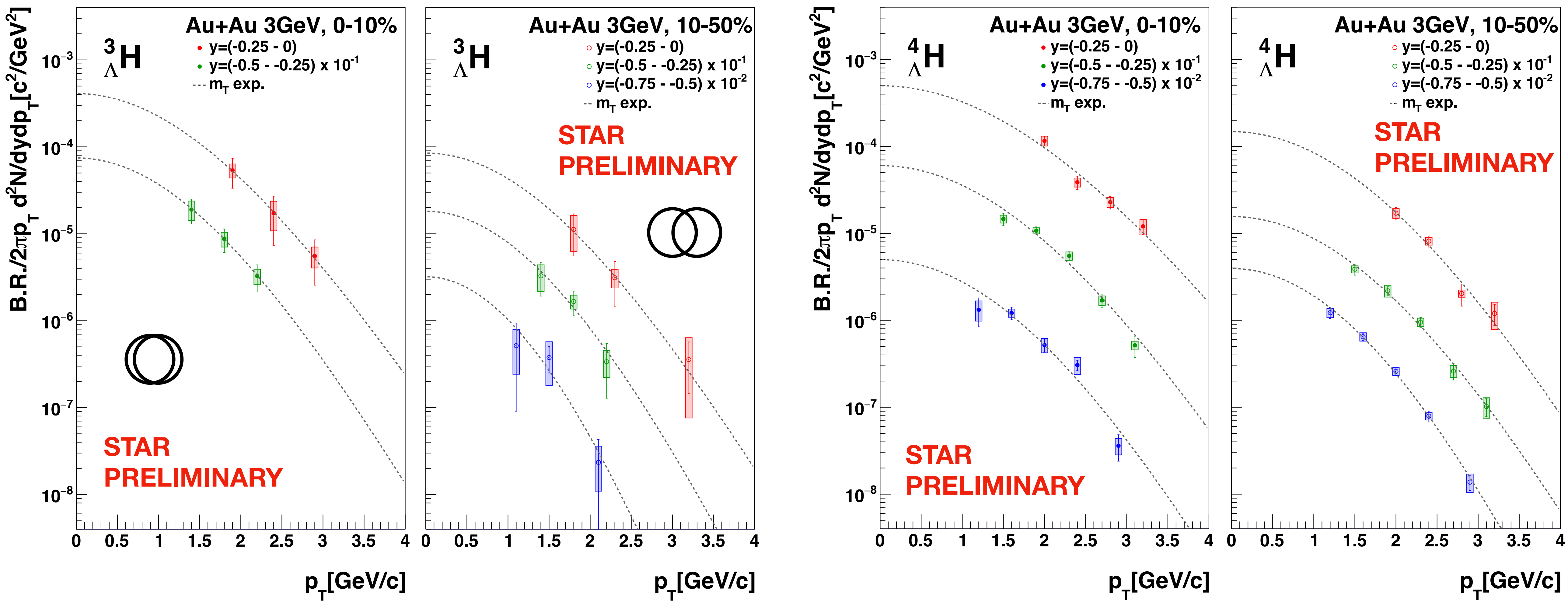
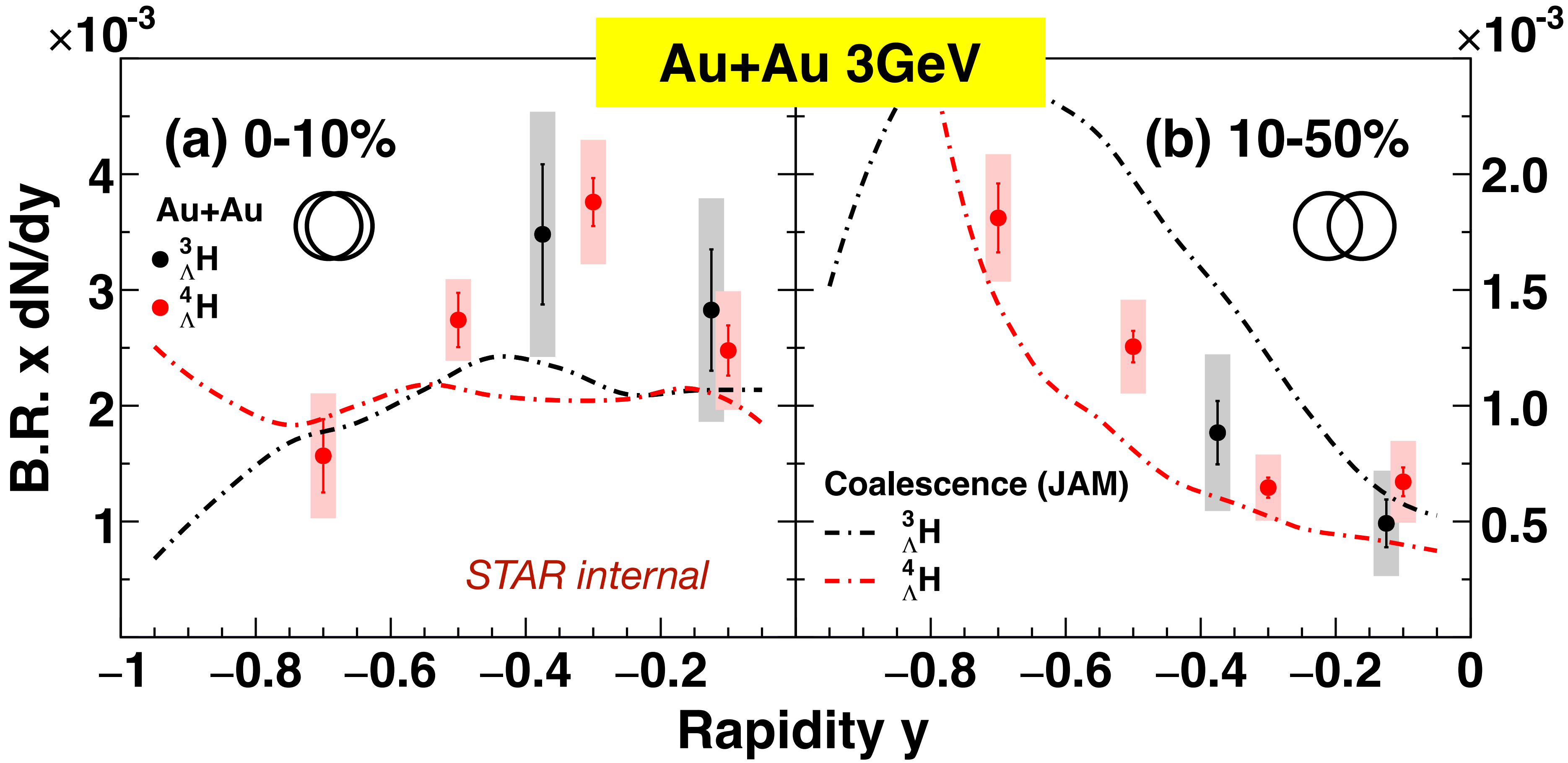


$({}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H)$ Transverse momenta spectra



- Using a similar methodology, we can measure the p_T spectra in different rapidity and centrality intervals
- Estimate the p_T integrated yield by extrapolating to the unmeasured region

$({}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H)$ rapidity distributions



- **First measurement of rapidity distributions of hypernuclei in HI collisions**

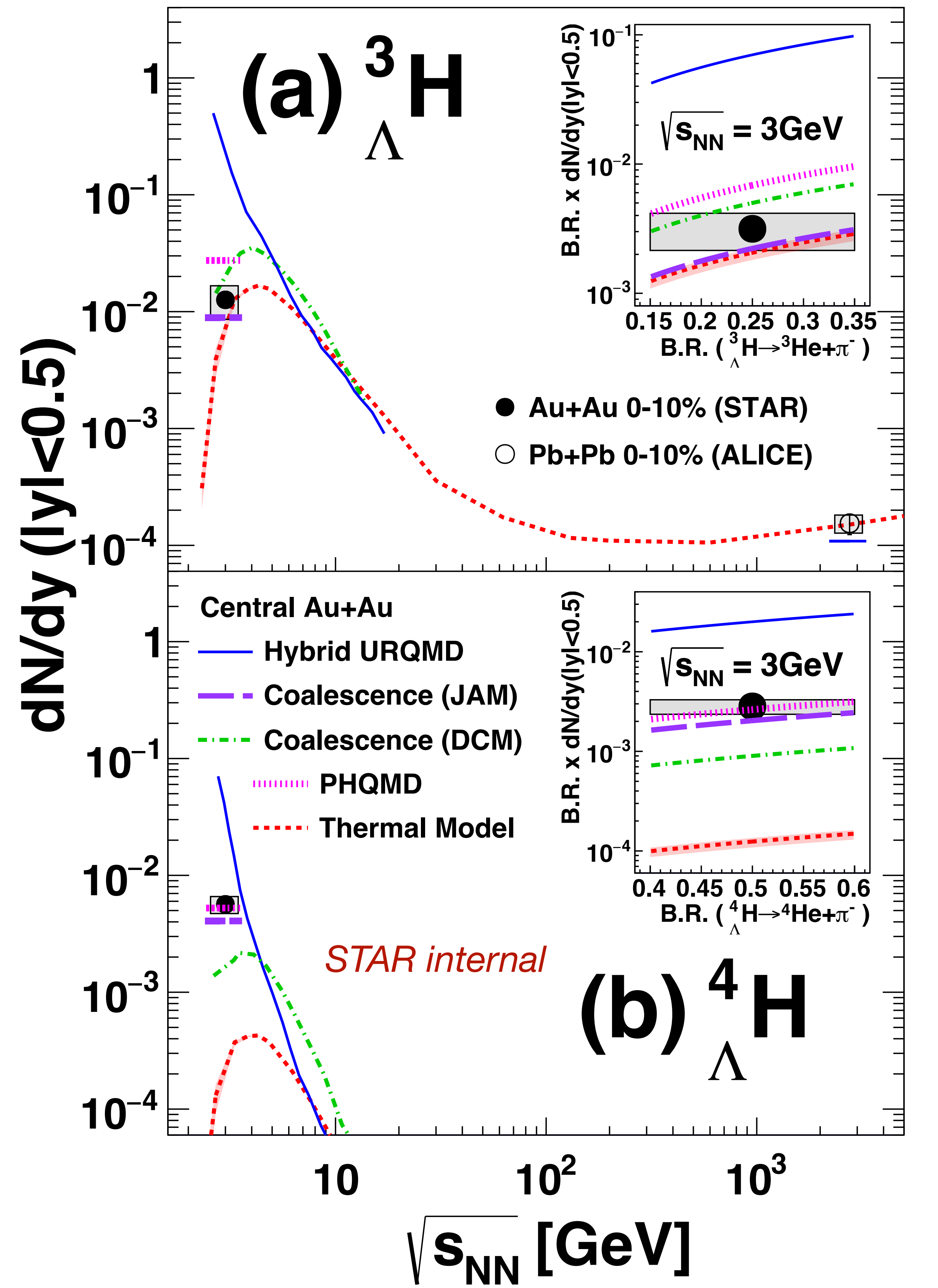
- Coalescence model:
  - Composite particles formation from constituents
  - condition: proximity of constituents in momentum and coordinate space

Coalescence models with tuned coalescence parameters qualitatively describe data

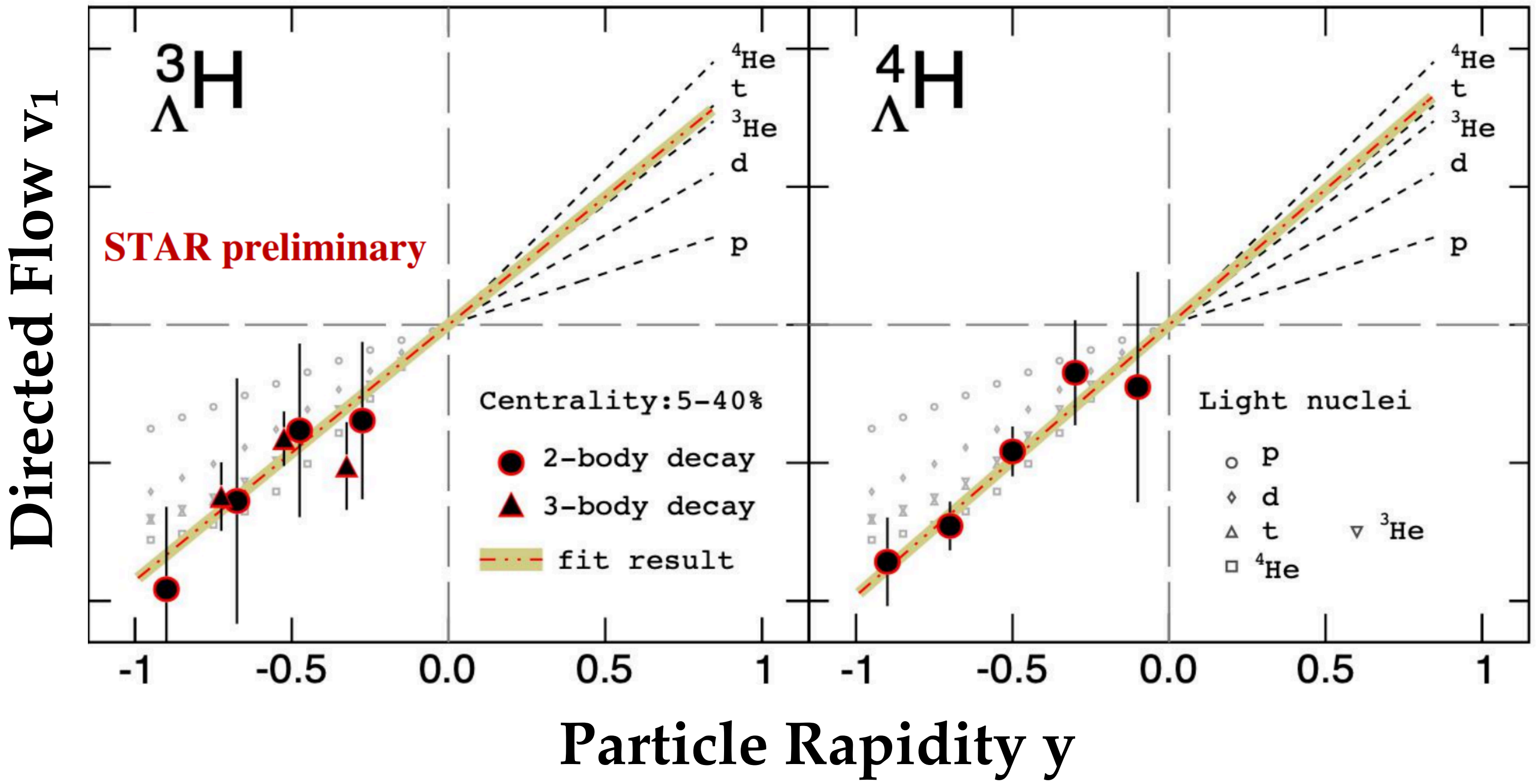
Energy dependence of hypernuclei production

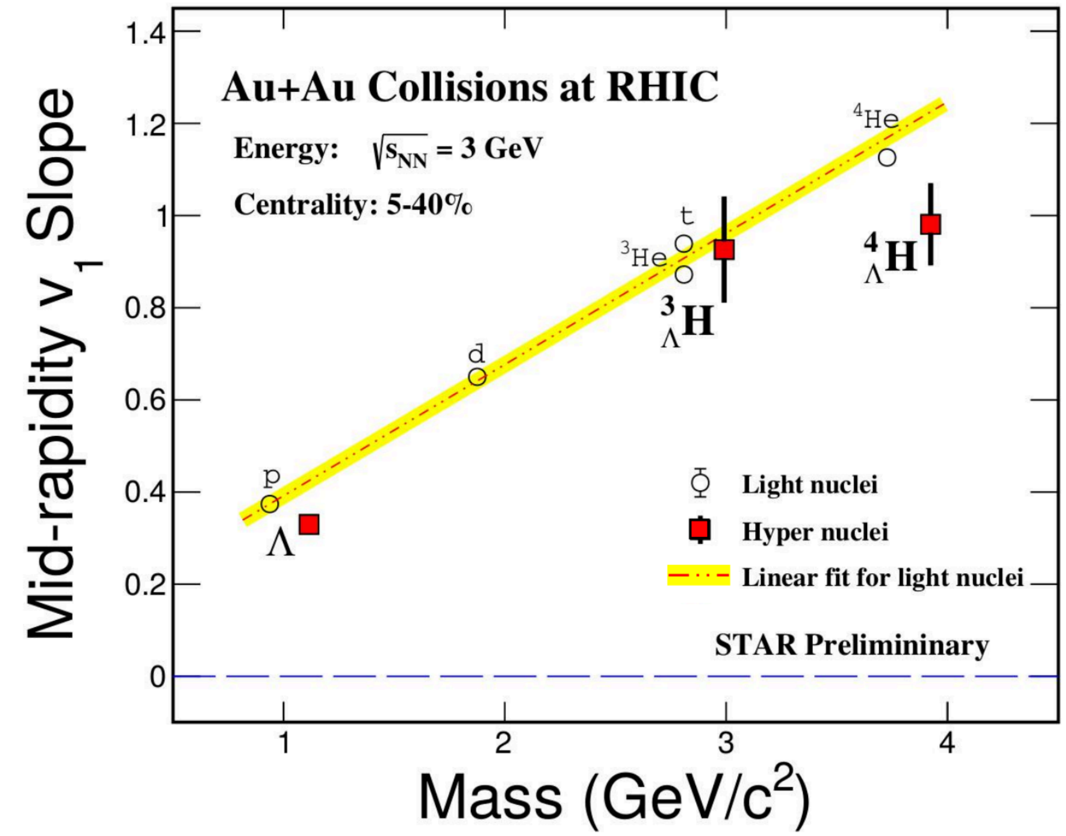
- **Thermal model:**
  - Assumes hadro-chemical equilibrium
  - Describes ${}^{3}_{\Lambda}\mathrm{H}$ yield over few orders of magnitude of $\sqrt{s_{\mathrm{NN}}}$
  - Underestimates ${}^{4}_{\Lambda}\mathrm{H}$ at 3 GeV
- **Coalescence models:**
  - Different coalescence parameters needed to simultaneously describe ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$
- **More recent calculations (PHQMD)** utilizes a dynamical description of hypernuclei formation

Provides input for theoretical developments in the formation of loosely bound objects in HI collisions



Hypernuclei directed flow v_1, Au+Au 3 GeV





Chenlu Hu (STAR), SQM2021

- **First observation of hypernuclei collectivity v_1 in HI collisions**
- **v_1 slope follow baryon number scaling in 5-40% 3 GeV Au+Au collisions**

Results consistent with hypernuclei production from coalescence of hyperons and nucleons at mid-rapidity

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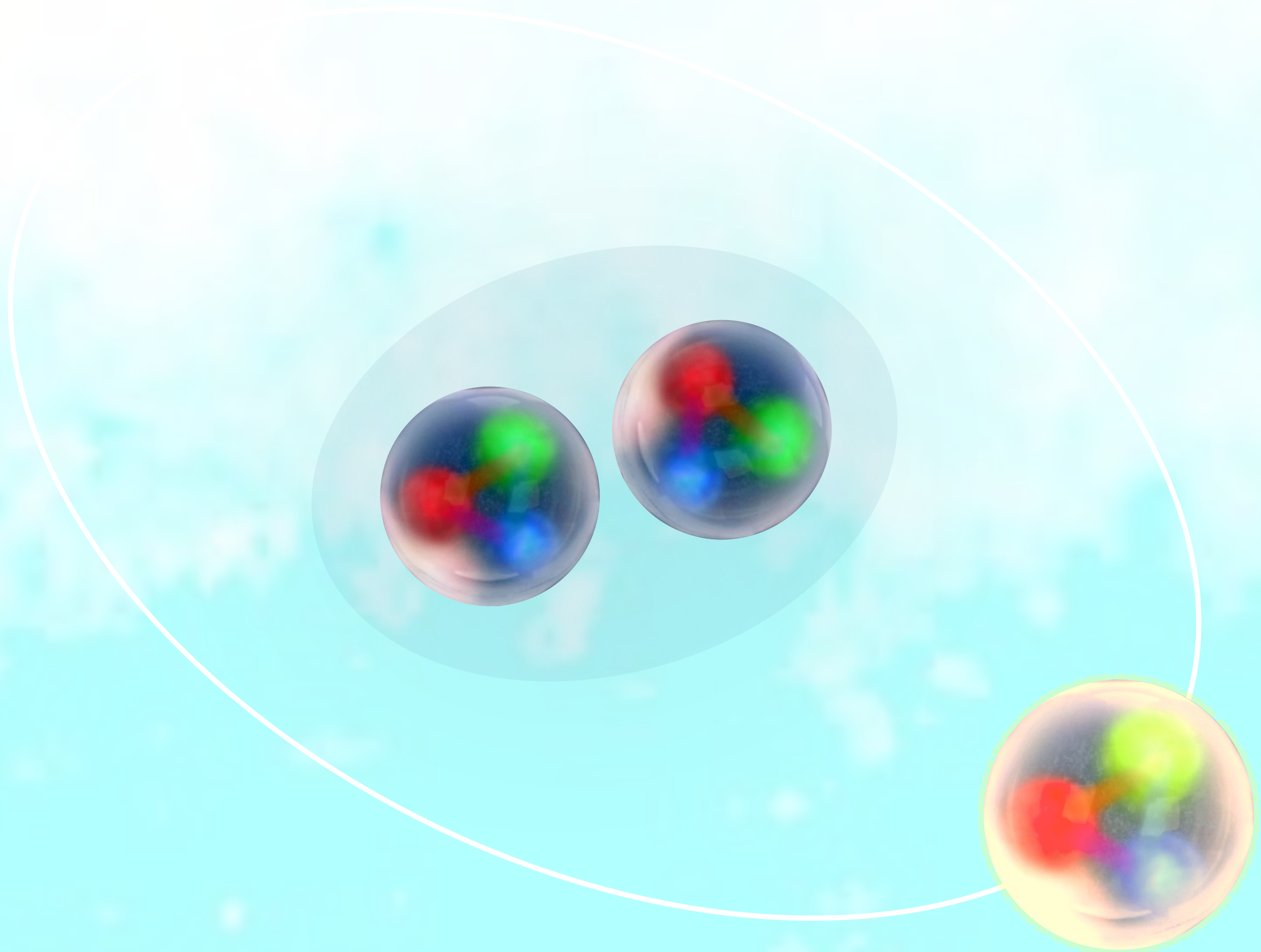


Outlook

STAR detector upgrade

- iTPC + eTOF installed in 2019
- Improve low pT reach / rapidity coverage

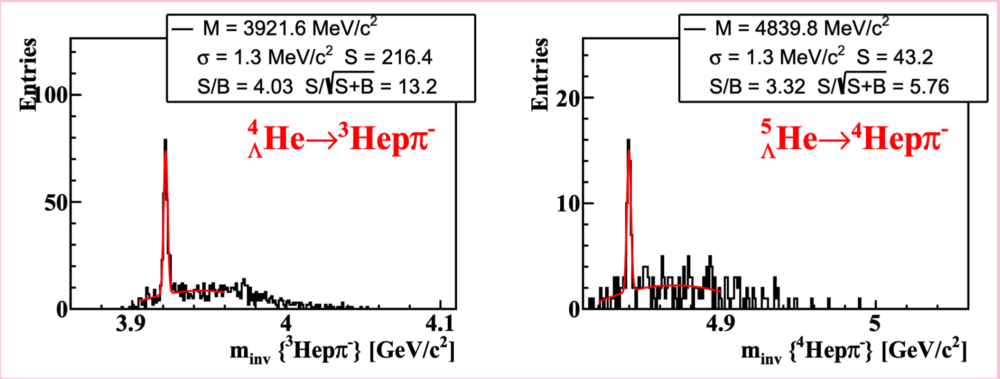
Data from BES

Year	$\sqrt{s_{NN}}$ [GeV]	# of Good Events
2017	54.4	1350 M
2018	27	1550 M
	7.2	155 M
	3.0	258 M
2019	19.6	582 M
	14.6	324 M
	7.7	50.6 M
	3.9	52.7 M
	3.2	200 M
2020	11.5	235 M
	9.2	58 M
	7.7	112 M
	6.2	118 M
	5.2	103 M
	4.8	235 M
	4.5	108 M
	3.9	117 M
	3.5	116 M
2021	7.7	100 M
	9.2	50 M
	11.5	50 M
	13.7	50 M
	17.3	250 M
	3.0	2 B

Physics observables

- Production Yield
  - Centrality/rapidity dependence
  - Energy dependence
  - Branching ratio
- Lifetime
- Collectivity (v_1, v_2)
- Binding energy
- ${}^{3}_{\Lambda}H$ polarization

Heavier hypernuclei



M. Zyzak et al

- ${}^{4}_{\Lambda}He$, ${}^{5}_{\Lambda}He$ etc.
- ΛΛ hypernuclei (?)

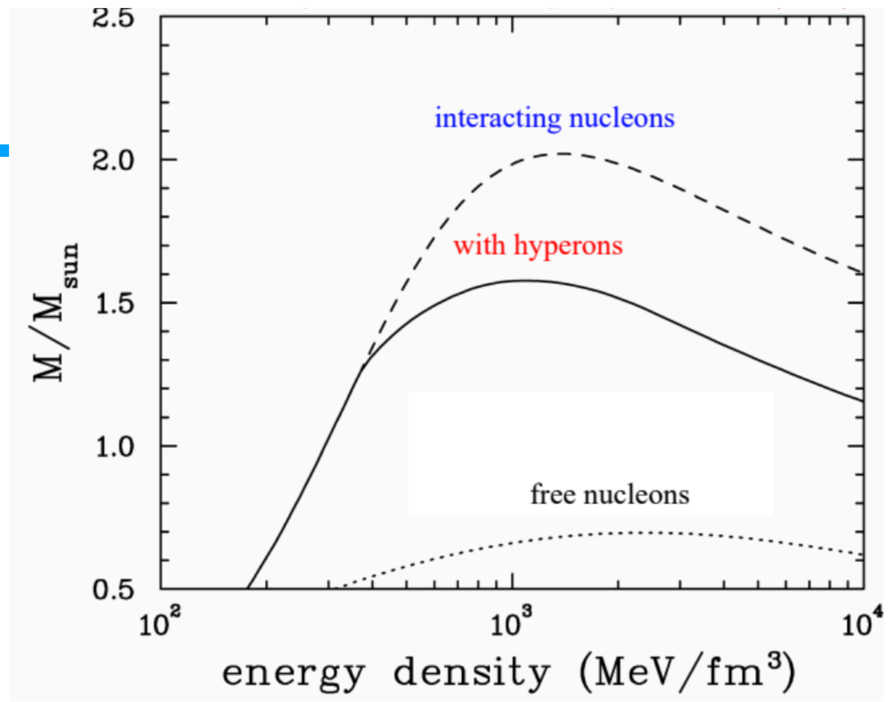
Relations to astrophysics

- Hyperons believed to be present in neutrons stars
    - Added degree of freedom -> Softening of the EOS
- Neutron stars with mass = 2 x M_{sun} have been observed → **The hyperon puzzle**

A full understanding of the EOS requires knowledge in Λ-N and Λ-Λ interactions

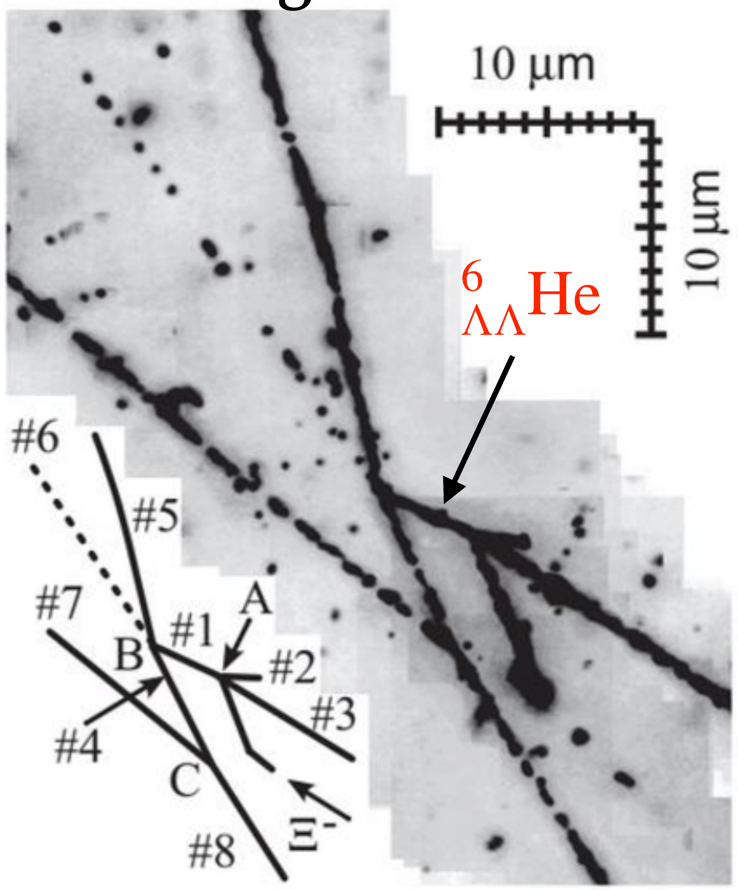
- Single-Λ hypernuclei → Λ-N potential
    - Attractive Λ potential with depth ~30 MeV
- Double-Λ hypernuclei → Λ-Λ potential
    - Not well understood

${}^{6}_{\Lambda\Lambda}He$, ${}^{10}_{\Lambda\Lambda}Be$, ${}^{11}_{\Lambda\Lambda}Be$	Double-Λ hypernuclei discovered



Kapusta and Gale, Finite Temperature Field Theory

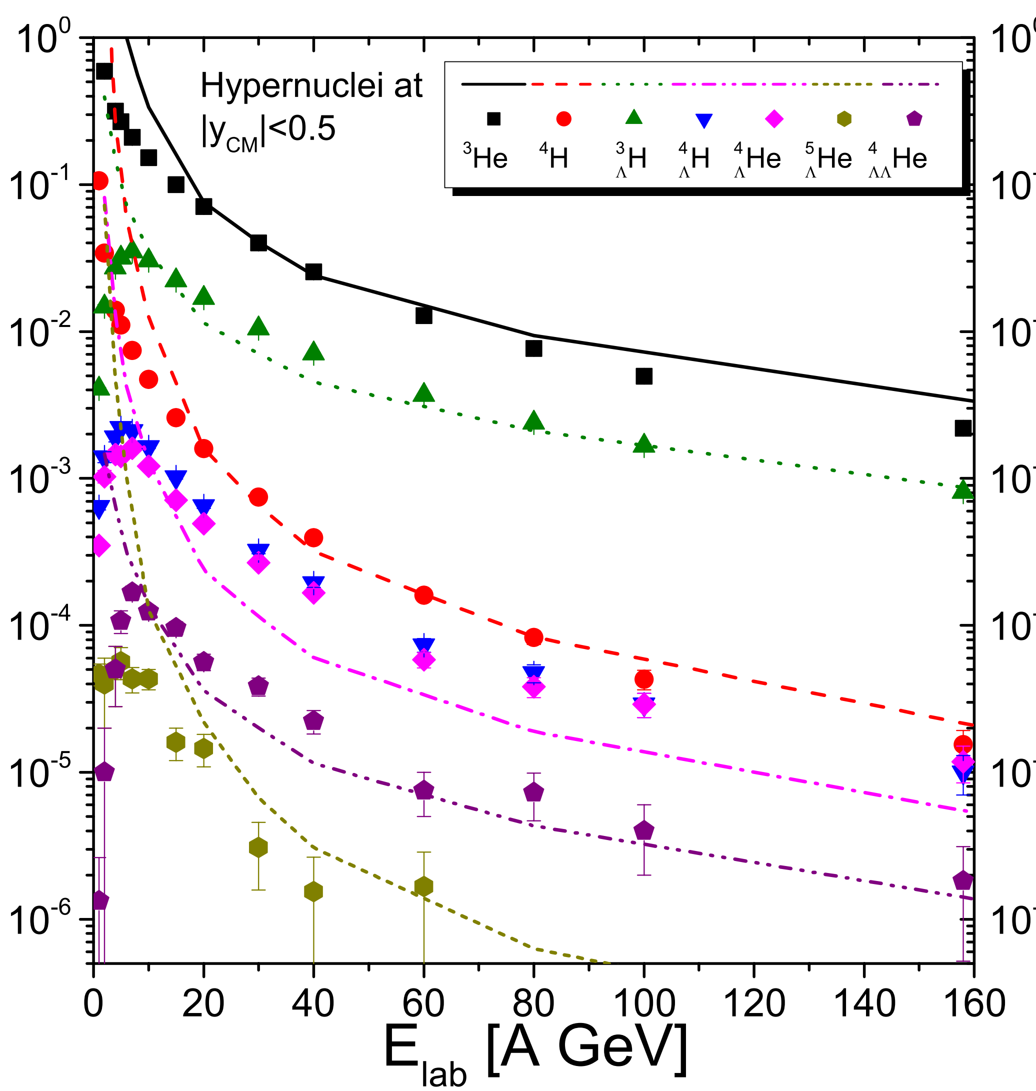
"Nagara" event



H. Takahashi et al., Phys. Rev. Lett. 87, 212502 (2001)
J.K. Ahn et al., Phys. Rev. C 88, 014003 (2013)

STAR search for S=2 hypernuclei

- High baryon density at low beam energies provides an opportunity to create S=2 hypernuclei
- Modest production rate predicted by coalescence models



J. Steinheimer et al, PLB714(2012),85

Possible decay channels	
$^{4}_{\Lambda\Lambda}H$	$^{4}_{\Lambda}He + \pi^- \rightarrow {}^{3}He + p + \pi^- + \pi^-$
	$^{3}_{\Lambda}H + p + \pi^- \rightarrow {}^{3}He + p + \pi^- + \pi^-$
$^{5}_{\Lambda\Lambda}H$	$^{5}_{\Lambda}He + \pi^- \rightarrow {}^{4}He + p + \pi^- + \pi^-$
$^{6}_{\Lambda\Lambda}He$	$^{5}_{\Lambda}He + p + \pi^- \rightarrow {}^{4}He + p + \pi^- + p + \pi^-$
$^{4}_{\Xi}H$	$d + \Lambda + \Lambda \rightarrow d + p + \pi^- + p + \pi^-$

PRL124(2020)9,092501

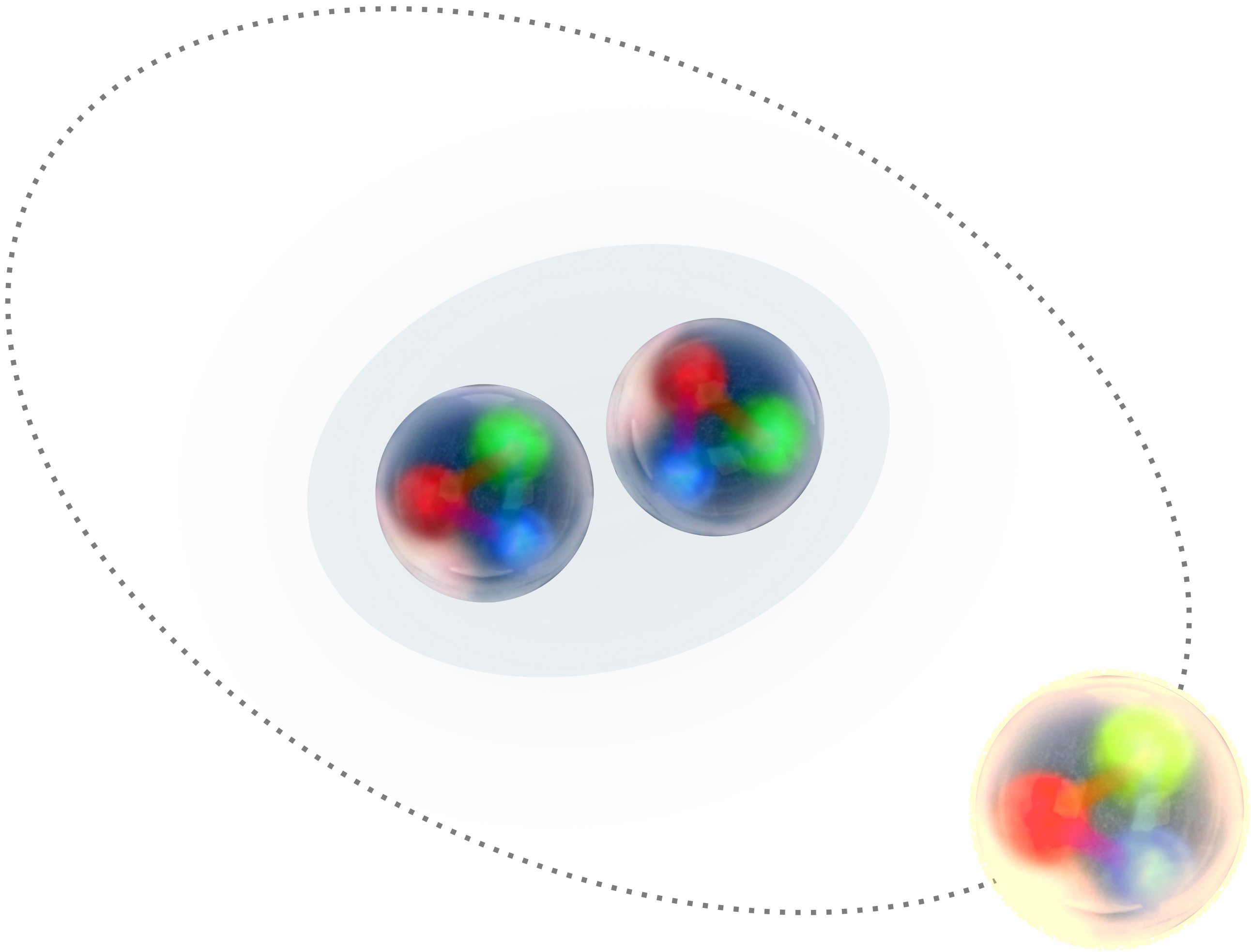
A discovery of these bound states will have a high impact on understanding of YY interactions

Summary

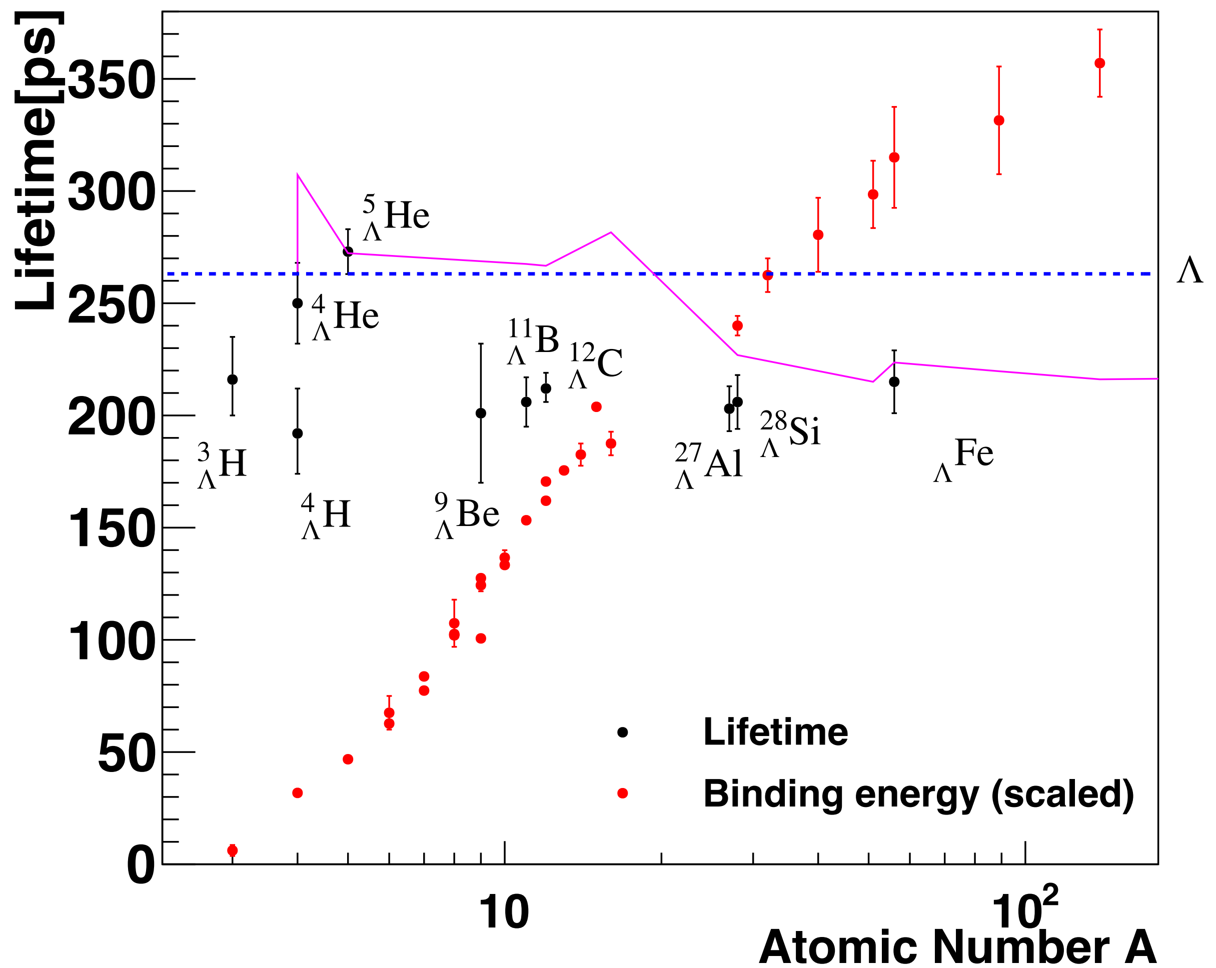
- Presented lifetime, yield and flow measurements of $({}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H})$ in Au+Au 3 GeV collisions using STAR detector
- Precise lifetime measurements give stronger constraints to models and further our understanding in the Y-N interaction
- Yield and flow measurements qualitatively consistent with coalescence prescription
  - New measurements gives insight to production mechanism of such loosely bound objects in HI collisions
- High statistics data taken allow for a search for S=2 hypernuclei
  - Binding energy of such hypernuclei help us understand Y-Y interaction -> implications to astrophysics / HI physics

Thank you for your attention!

Backup slides follow



Introduction: Hypernuclei lifetime



Riv.Nuovo Cim. 38 (2015) 9, 387-448

- Hypernuclei lifetime is quite stable from light– to medium–A hypernuclei
- Almost constant above A = 20, at ∼210 ps, which corresponds to ~80% of the free Λ lifetime.

Systematic uncertainties on the lifetime

- **(1) Analysis cuts**
  - **Imperfect description of topological variables between MC and data**
- **(2) Input MC p_T/rapidity/lifetime**
  - **Imperfect knowledge in the real kinematic distributions of hypernuclei**
- **(3) Single track efficiency**
  - **Mismatch of single track efficiency between simulations and data**
- **(4) Signal extraction**
  - **Uncertainties related to the background subtraction technique**

syst. uncertainty	$^{3}_{\Lambda}\mathrm{H}$	$^{4}_{\Lambda}\mathrm{H}$
Analysis cuts	5.5%	5.1%
Input MC	3.1%	1.8%
Tracking efficiency	5.0%	2.4%
Signal extraction	1.5%	0.7%
Extrapolation	N/A	N/A
Detector material	< 1%	< 1%
Total	8.2%	6.0%

Table: Syst. uncertainty for $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ lifetime

Systematic uncertainties

- **Additional sources of sys. unc.:**
- **Extrapolation**
  - **Different functions for extrapolation to estimate uncertainty**
    - **m_T exponential, blast wave, Boltzmann, etc.**
- **Target material**
  - **Took into account possible Coulomb dissociation when traversing target material**

    Physics of Atomic Nuclei, 2007, Vol. 70, No. 9, pp. 1617–1622
  - **Survival probability >95% in kinematic regions analyzed**

**Target thickness = 0.25mm*

syst. uncertainty	${}^{3}_{\Lambda}H$	${}^{4}_{\Lambda}H$
Analysis cuts	15.1%	6.9%
Input MC	8.8%	3.8%
Tracking efficiency	14.1%	5.2%
Signal extraction	14.3%	7.7%
Extrapolation	13.6%	10.9%
Detector material	4.0%	2.0%
Total	31.9%	16.6%

Table: Syst. uncertainty for ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ dN/dy at |y|<0.5 in Au+Au 0-10%.

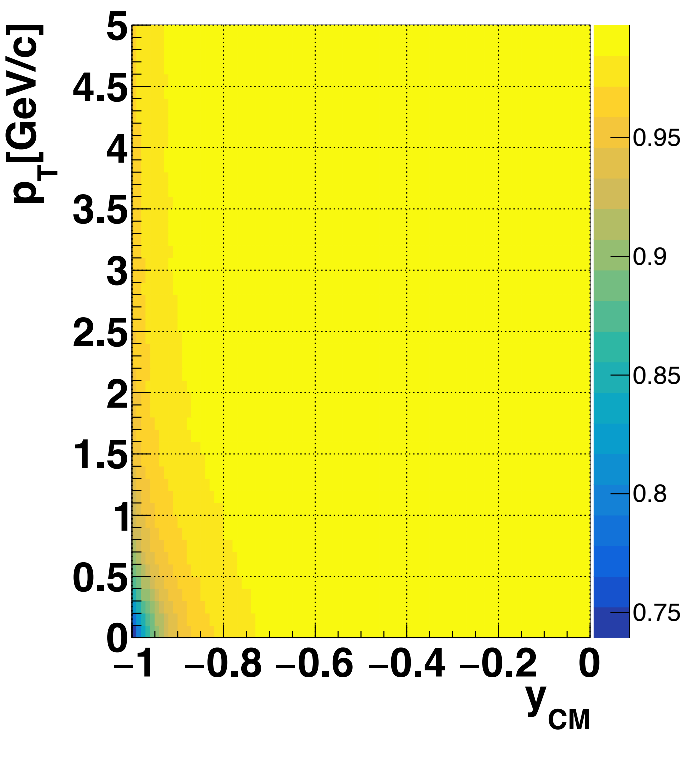


Fig: Survival prob. for ${}^{3}_{\Lambda}H$ estimated from MC study