Hypernucleus physics from view point of heavy ion experiment

Jinhui Chen
Shanghai Institute of Applied Physics, CAS

The 1st Symposium on Intermediate-energy Heavy Ion Collisions, 4/8-11, Tsinghua Uni., Beijing, China

Why hypernuclei?

★ QCD theory development

- Micro-lab. with proton, neutron and hyperons;
- YN & YY interaction (strangeness sector of hadronic EOS)

★ Astrophysics

- Hyperons are important for cosmology, physics of neutron stars…

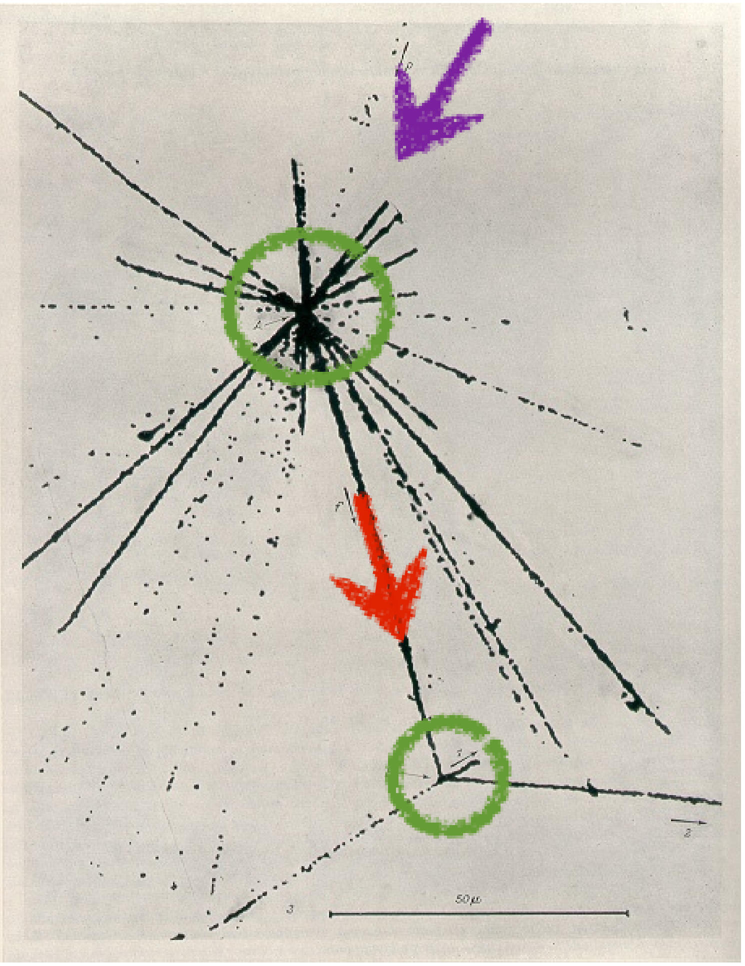
★ Nuclear Physics

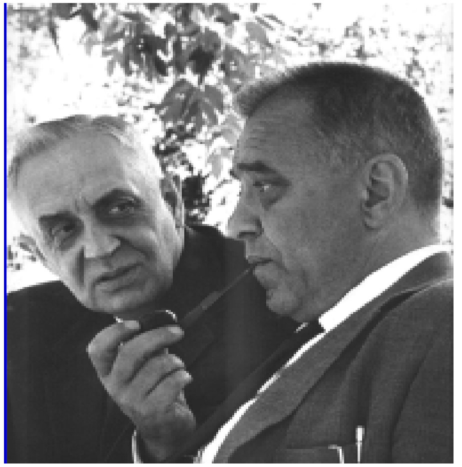
- Phenomenology: extension of nuclear charts into strangeness, exotic nuclei…
- Structure theory: nuclear dof for investigating interaction of baryons in nuclei (hyperons – w/o Pauli blocking)
- Reaction theory: new probe for fragmentation of nuclei, phase transition and EOS in hypermatter and finite hypernuclei

The first hypernucleus

★ The 1st hypernucleus was observed in a stack of photographic emulsions exposed to cosmic rays at about 26 km above the ground.

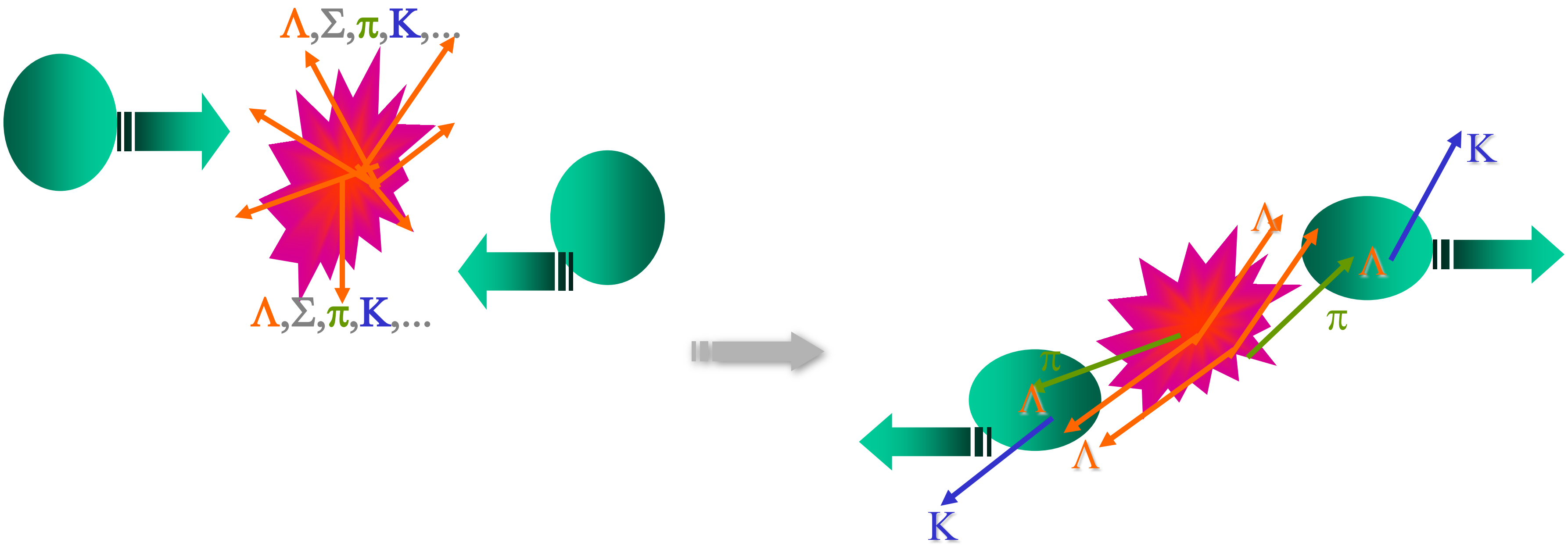
M. Danysz & J. Pniewski, Phil. Mag. **44**, 348 (1953)





- Incoming high energy proton from cosmic ray, colliding with a nucleus of the emulsion, breaks it in several fragments forming a star.
- All nuclear fragments stop in the emulsion after a short path
- From the 1st star, 21 tracks → $9\alpha + 11H + 1\ _{\Lambda}X$
- The fragment $_{\Lambda}X$ disintegrates later, makes the bottom star. Time takes~10^{-12} sec (typical for weak decay)
- This particular nuclear fragment, and the others obtained afterwards in similar conditions, were called hyperfragments or hypernuclei

Hypernuclei production in HI Collisions



★ Production of hypermatter in relativistic HI and hadron collisions

- Production of strange particles and hyperons by “participants”,
- Rescattering and absorption of hyperons by excited “spectators”

Hyperons in neutron stars

★ "Hyperon puzzle"

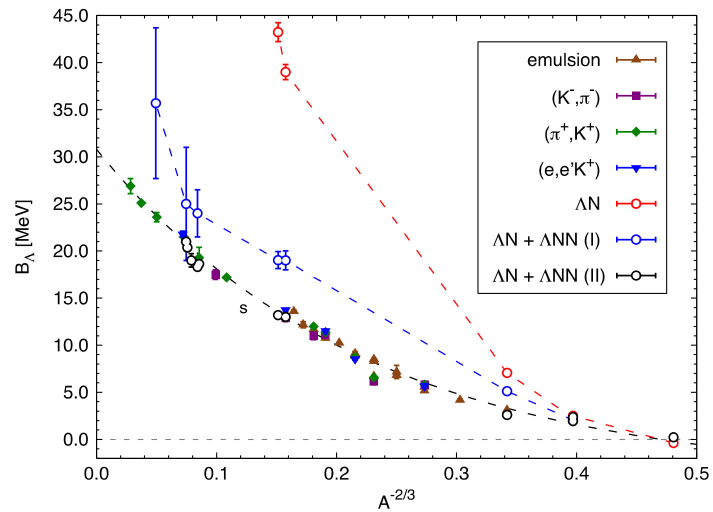
•Hyperons are predicted to exist inside neutron stars at densities exceeding 2-3ρ_0
•The inner core of NS is so dense, Pauli blocking prevents hyperons from decaying by limiting the phase space available to nucleons
•The presence of hyperon reduces the maximum mass of NS ~0.5-1.2M_0

•However, new observation for large mass of NS!

P. Demorest et al., Nature 467 (2010) 1081; Antoniadis et al., Science 340 (2013) 448

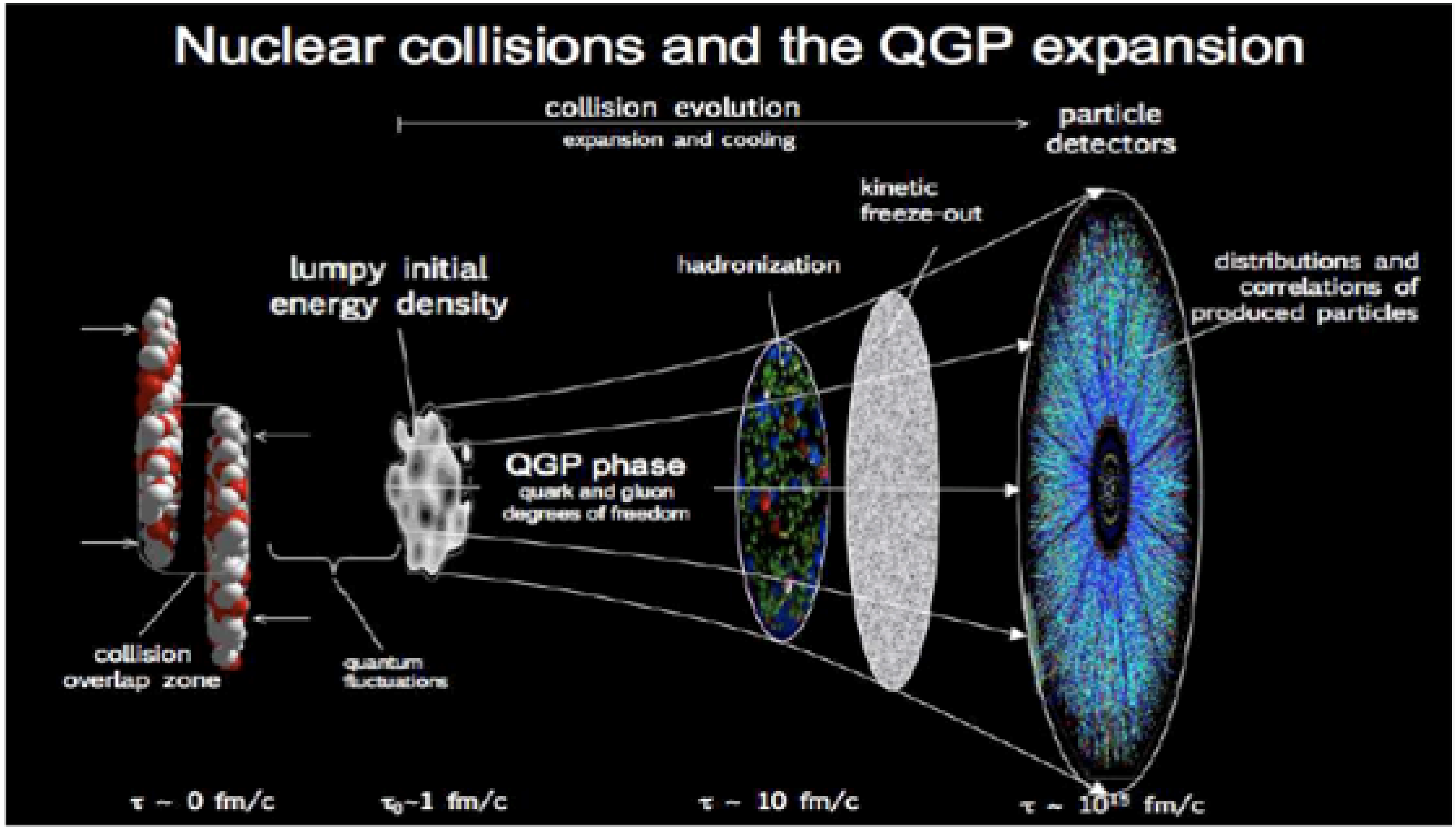
✓ Rijken and Schulze: Inclusion of YY interactions increase mass of NS

✓ Lonardoni et al., repulsive ΛNN interactions increase the mass of NS



"Stronger constrains on Y-N force are necessary in order to properly access the role of hyperons in NS"

Heavy-ion collision as a hyperon factory



★ Dozens of hyperons production in central heavy-ion collisions at RHIC and LHC

★ Excellent secondary vertex reconstruction with STAR and ALICE

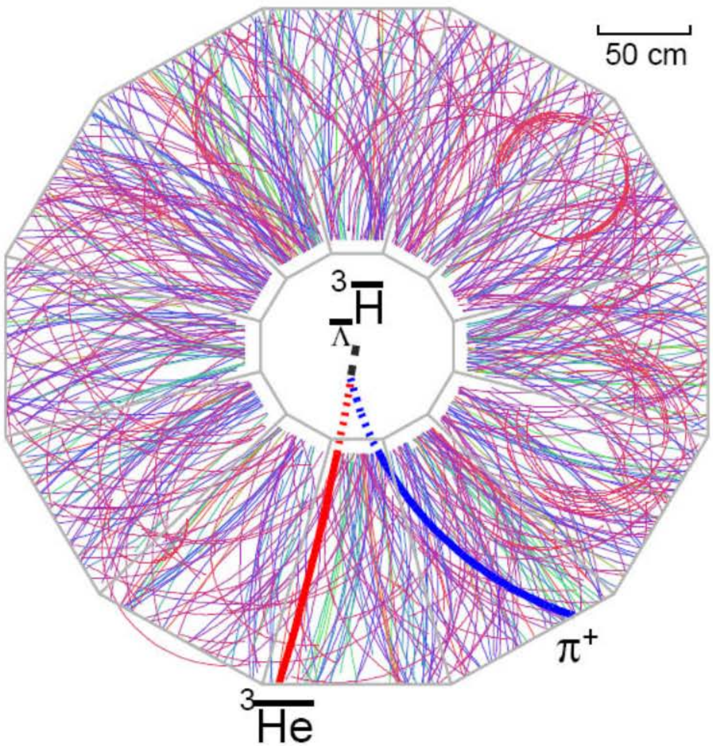
SINAP

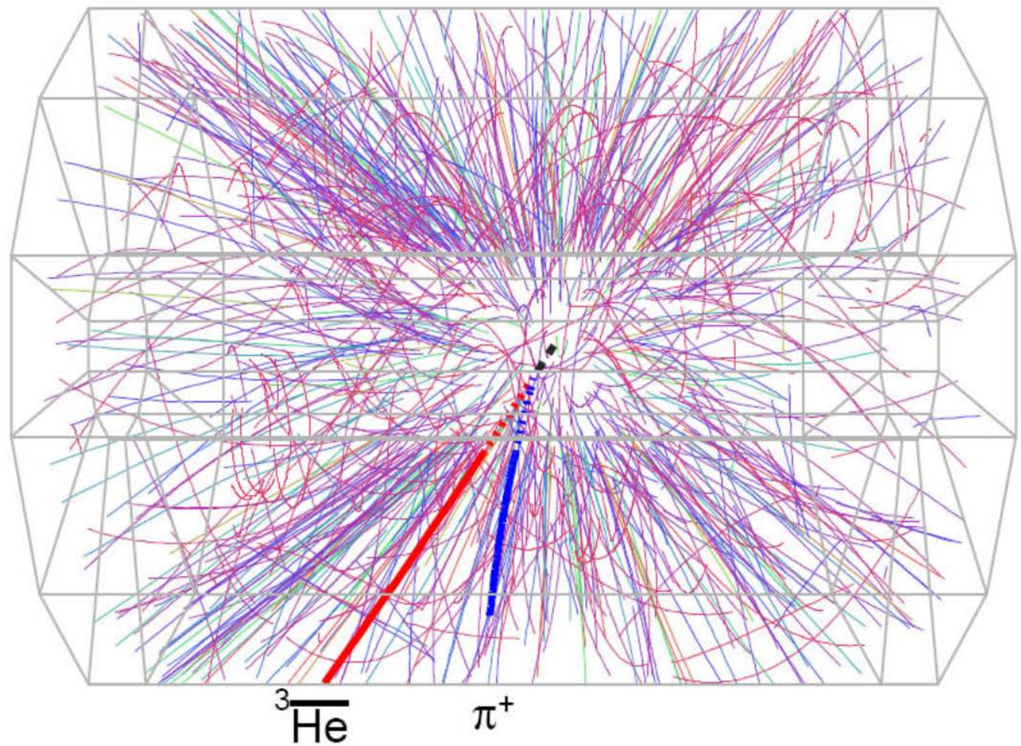
Event display

${}^{3}_{\Lambda}H(n+p+\Lambda)$

${}^{3}_{\bar{\Lambda}}\overline{H}(\bar{n}+\bar{p}+\bar{\Lambda})$

STAR Collaboration, Science 328 (2010) 58





★ A beautiful event in the STAR TPC that includes the production and decay of a antihypertriton candidate. (Data taken from Run4 Au+Au 200GeV MB collision)

The mesonic decay of hypertriton

Kamada et al., PRC 57, 1595(1998)

TABLE I. Partial and total mesonic and nonmesonic decay rates and corresponding lifetimes.

Channel	Γ [sec^{-1}]	Γ/Γ_Λ	$\tau=\Gamma^{-1}$ [sec]
$^3He + \pi^-$ and $^3H + \pi^0$	0.146×10^{10}	0.384	0.684×10^{-9}
$d+p+\pi^-$ and $d+n+\pi^0$	0.235×10^{10}	0.619	0.425×10^{-9}
$p+p+n+\pi^-$ and $p+n+n+\pi^0$	0.368×10^{8}	0.0097	0.271×10^{-7}
All mesonic channels	0.385×10^{10}	1.01	0.260×10^{-9}
$d+n$	0.67×10^{7}	0.0018	0.15×10^{-6}
$p+n+n$	0.57×10^{8}	0.015	0.18×10^{-7}
All nonmesonic channels	0.64×10^{8}	0.017	0.16×10^{-7}
All channels	0.391×10^{10}	1.03	2.56×10^{-10}
Expt. [6]			$2.64\ +0.92\ -0.54 \times 10^{-10}$
Expt. (averaged) [11]			$2.44\ +0.26\ -0.22 \times 10^{-10}$

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

- Though the mesonic decays are Pauli blocked in heavier hypernuclei, they are the dominant channels in hypertriton.

- In experiment, the 2-body helium3 channel and the 3-body deuteron channel are more easy to access.

Focus on the hypertriton lifetime (1)

- The lifetime measurements are interest especially in view of the short values from early experiments :

The 1st measurements is $(0.95^{+0.19}_{-0.15})*10^{-10}$s from helium bubble chamber, by Block et al., presented in the proceeding of Conference on Hyperfragments at St, Cergue, 1963, p.62

Results from AGS nuclear-emulsion experiments: $(0.9^{+2.2}_{-0.4})*10^{-10}$s,
Phys. Rev.136 (1964) B1803,
from Bevatron and AGS: Phys. Rev.139 (1965) B401
2-body (3 in flight, 4 at rest) $(0.8^{+1.9}_{-0.3})*10^{-10}$s
2-body combined with 3-body (5 in flight, 18 at rest) $(3.4^{+8.2}_{-1.4})*10^{-10}$s

- Nuclear-emulsion with maximum likelihood procedure, Nucl. Phys. B 16 (1970) 46, $(1.28^{+0.35}_{-0.26})*10^{-10}$s,

Focus on the hypertriton lifetime (2)

★ But NEW measurements gave different values:

Helium bubble chamber from Argonne ZGS:

$(2.32^{+0.45}_{-0.34})*10^{-10}$s, PRL 20(1968)819
$(2.64^{+0.84}_{-0.52})*10^{-10}$s, PRD 1(1970)66
$(2.46^{+0.62}_{-0.41})*10^{-10}$s, NPB 67(1973)269

Nuclear-emulsion from Bevatron:

2-body is $(2.00^{+1.10}_{-0.64})*10^{-10}$s and 3-body $(3.84^{+2.40}_{-1.32})*10^{-10}$s,
and a combined of $(2.74^{+1.10}_{-0.72})*10^{-10}$s

PRLv20(1968)1383

★ How about the theoretical understanding of these experimental results?

Focus on the hypertriton lifetime (3)

- The hypertriton being a loosely-bound nuclear system, its mean lifetime should not be significantly different from that of the free Lambda

  Theoretical calculations from Dalitz et al., initially gave a short value and updated later on a larger value close to the free Lambda's
  Phys. Lett. 1 (1962) 58 and Nuovo Cimento A 46,786 (1986)

  The calculations based on modern 3-body interaction force, the total lifetime is predicted to be $2.56*10^{-10}$s, Phys. Rev. C 57 (1998) 1595

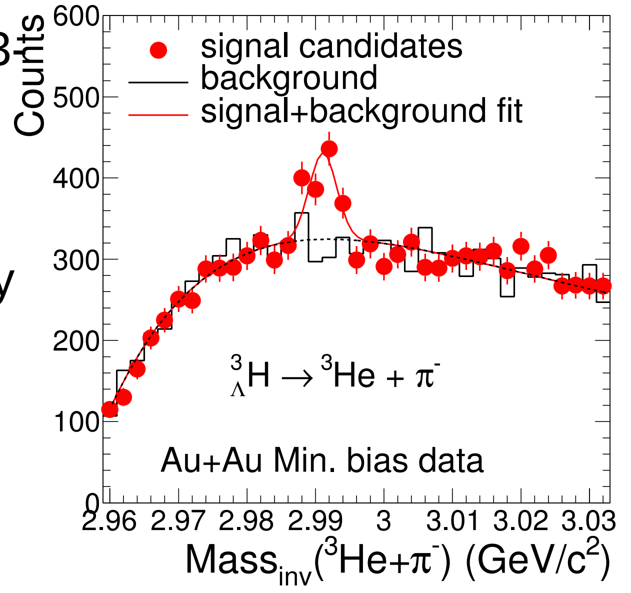
- The hypertriton lifetime data are not sufficiently accurate to distinguish between model, more precise measurements are needed.

Results from RHIC-STAR Col.

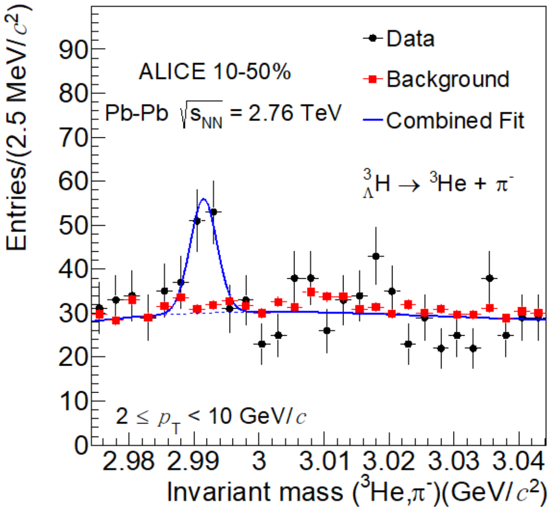
- Inv. Mass with 2 and 3 body analysis

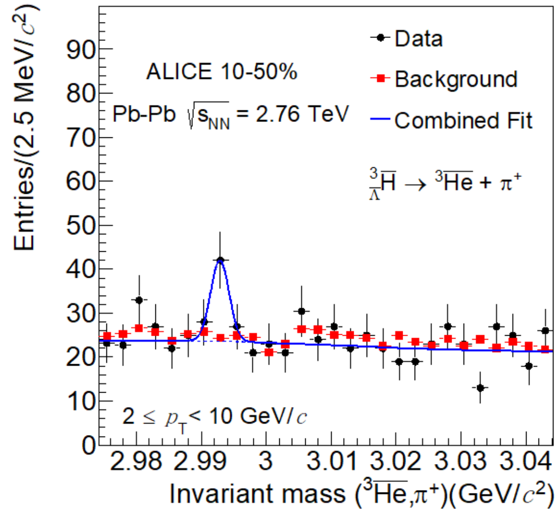
- Lifetime is significantly shorter than free lambda

STAR Col. arXiv:1710.00436

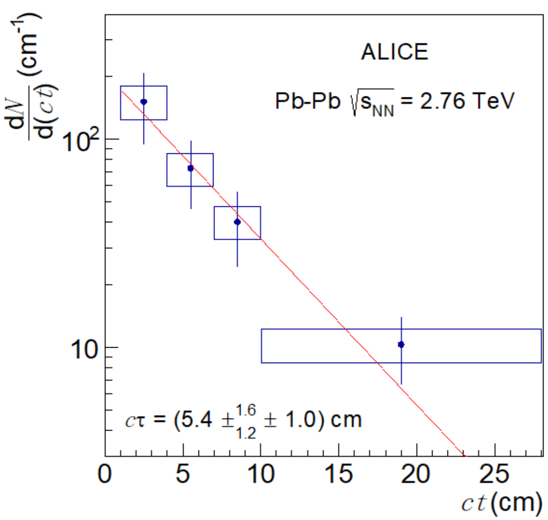


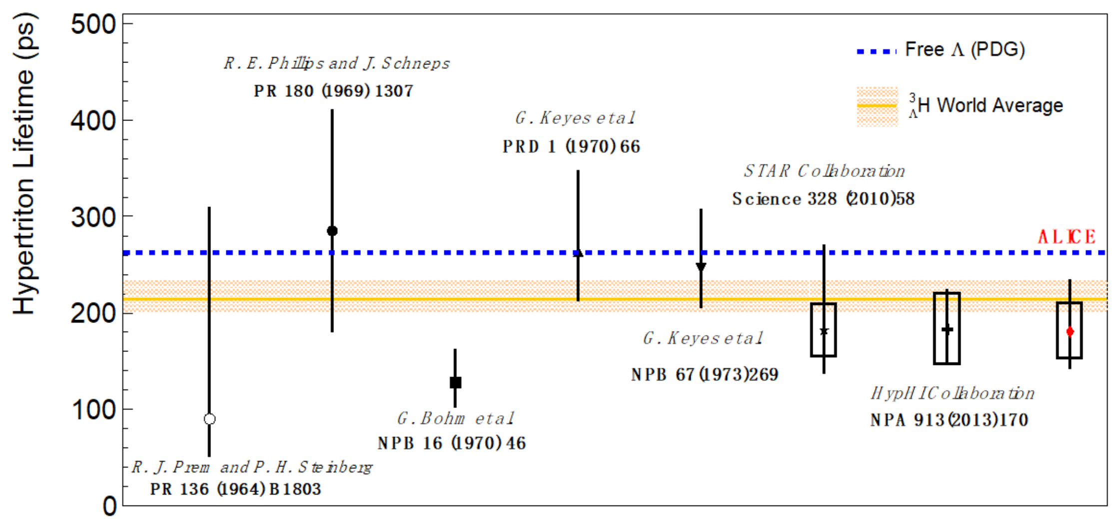
Measurement from LHC-ALICE



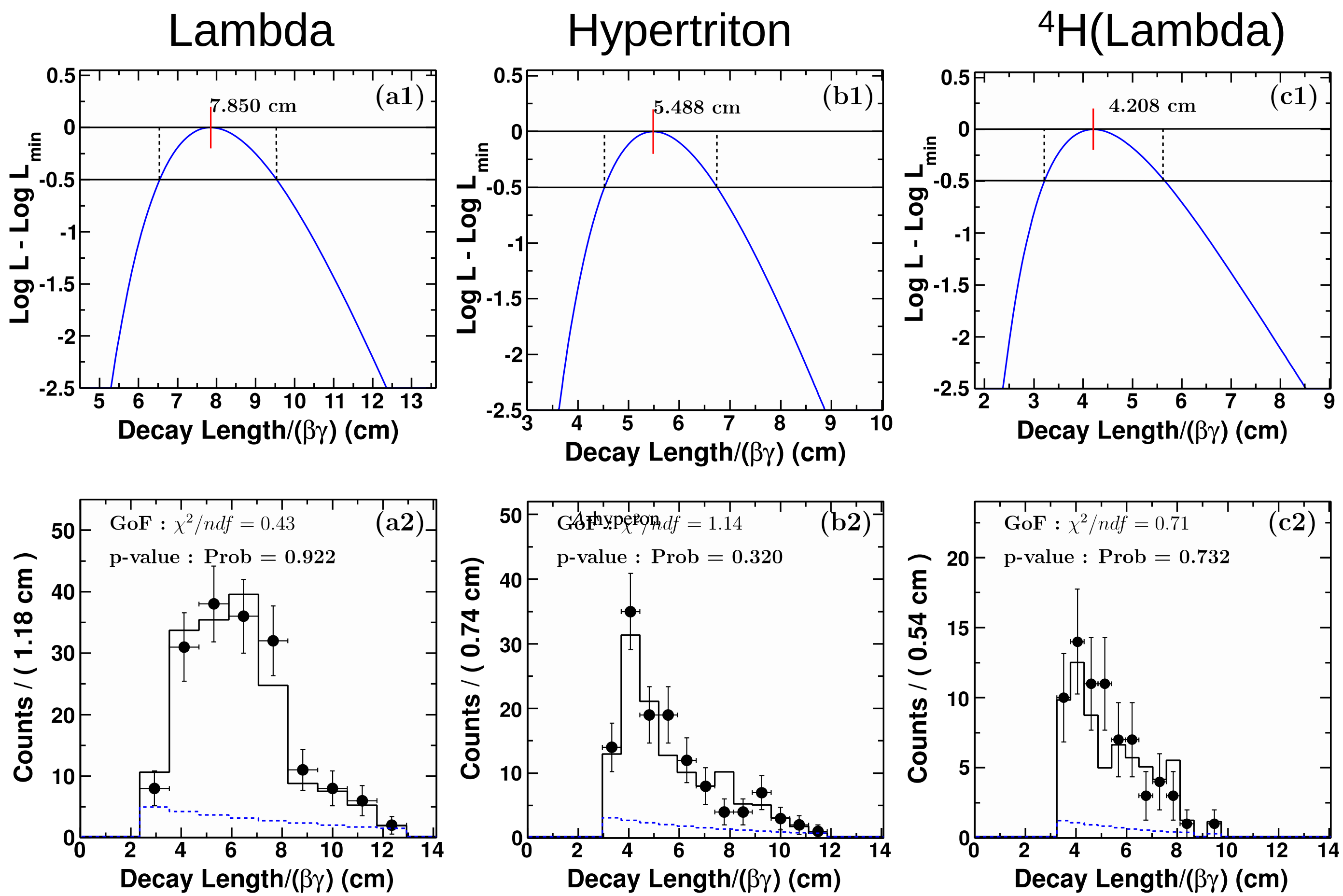


ALICE Collaboration
PLB 754, 360 (2016)





Measurement from HpyHI project

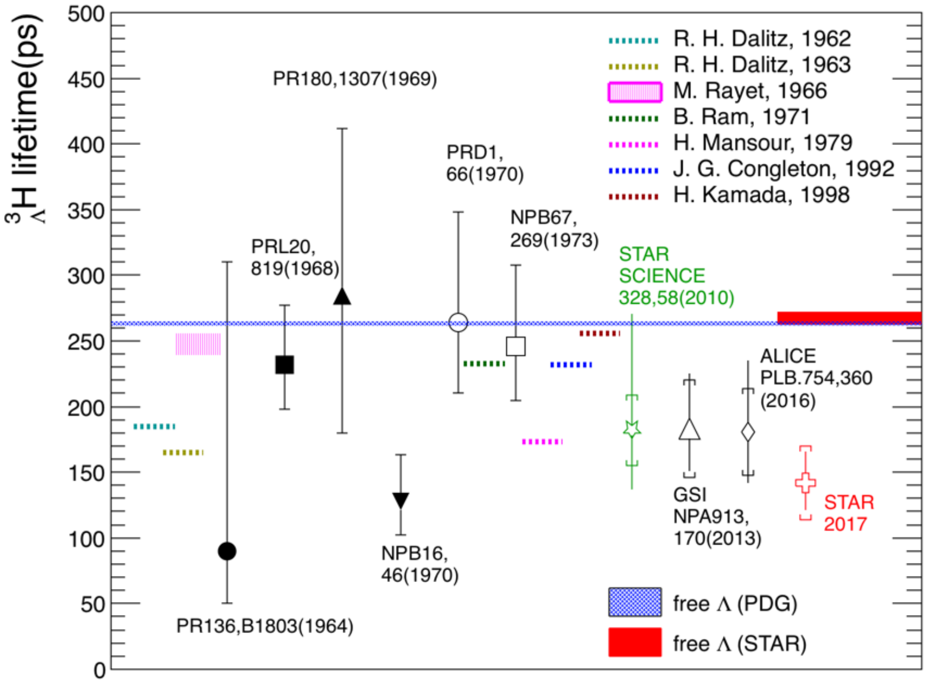


★ Hypernuclear spectroscopy at GSI: ^{6}Li projectiles on ^{12}C target at 2 A GeV presents the hypertriton lifetime measurement from 2-body channel:

Nucl. Phys. A 913(2013)170

$$\tau = 183 \pm^{42}_{32} \pm 37\, ps$$

How to understand the data?

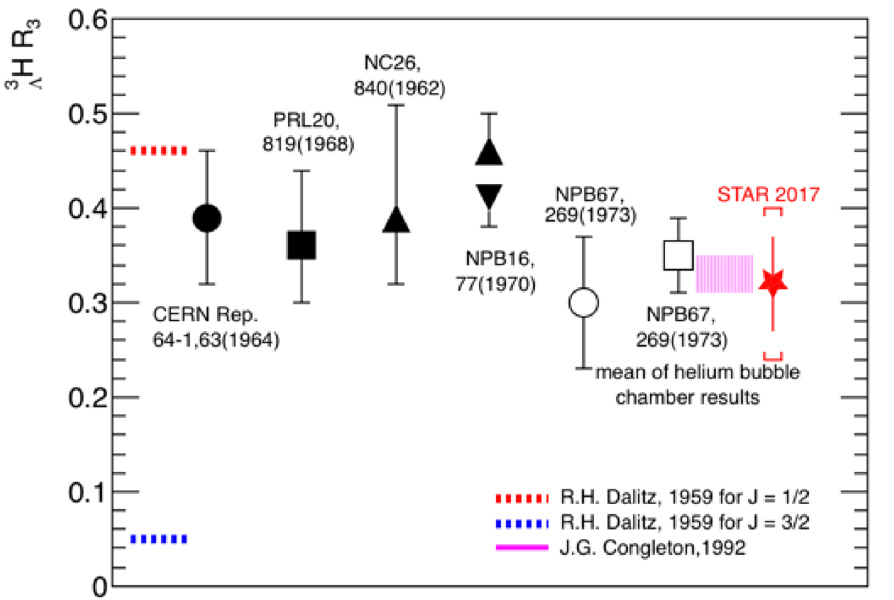


In 2016, Rev. OF. Mod. Phys. 2016 Jul-Sep.

"The discrepancy between the lifetimes measured in HIC and the lifetime prescribed by theory is disturbing, posing a major problem for the understanding of hypertriton, the lightest and hardly bound hypernucleus. More work is necessary to understand the HI lifetime results."

- Strong Y-N interaction in the hypernucleus system?
- The discrepancy may be in the B_Λ?
- Spin assignment : favor ½

STAR Col. arXiv:1710.00436



We can do more on the B_Λ

★ The early data suffers from large statistical uncertainty!

If charge symmetry holds for the ΛN interaction, the ${}^4_\Lambda$H and ${}^4_\Lambda$He hyp
members of an isotopic spin doublet, should have equal binding energies c
contributions from the distortions of the core nuclei and the Coulomb eff
been taken into account. Definite deviations from this prediction indicati
B_Λ value for ${}^4_\Lambda$He have been reported first by Raymund [14] and confirm

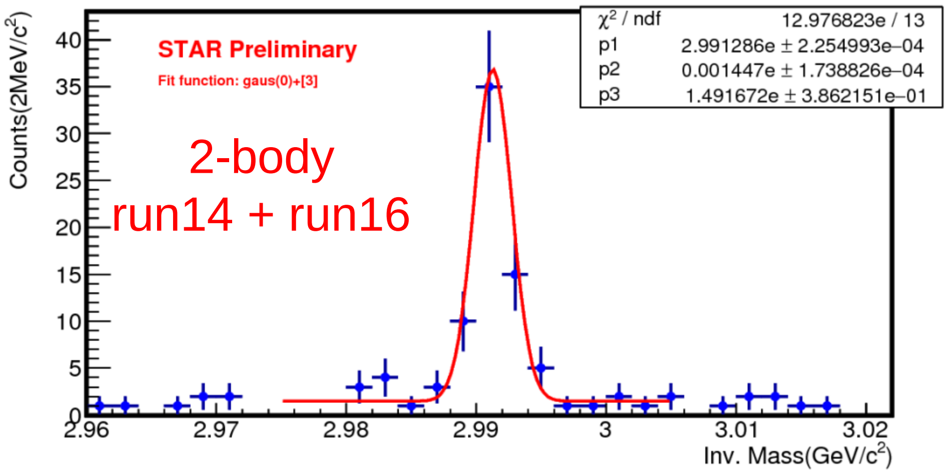
a) G. Bohm et al., Nucl. Phys. B4 (1968) 511
b) This work : M. Juric, G. Bohm et al., Nucl. Phys. B52 (1973) 1

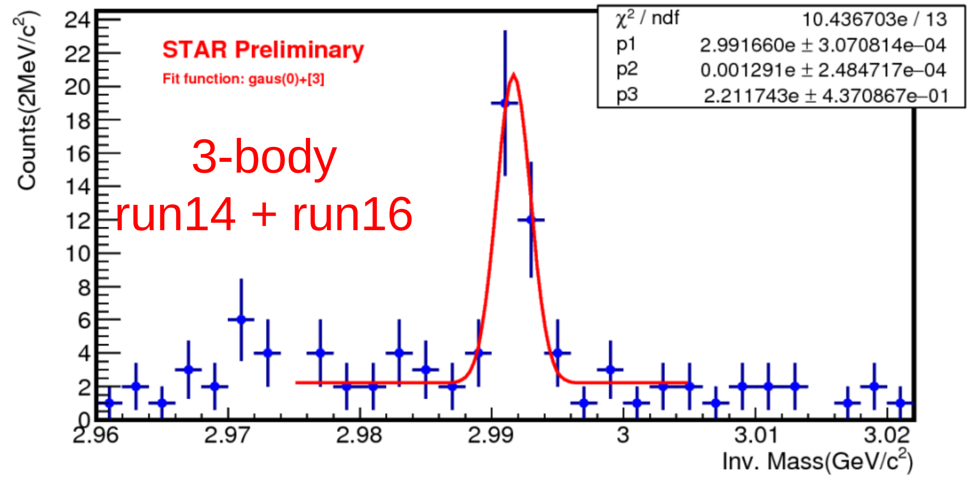
for the deuteron mass. The two-body decay events give $B_\Lambda = 0.25 \pm 0.31$ MeV, while the combined decays give $B_\Lambda = -0.07 \pm 0.27$ MeV. These results should be compared to the two emulsion measurements 0.06 ± 0.06 [20] and 0.24 ± 0.12 MeV.[21]

G. Keyes et al., PRD 1 (1970) 66

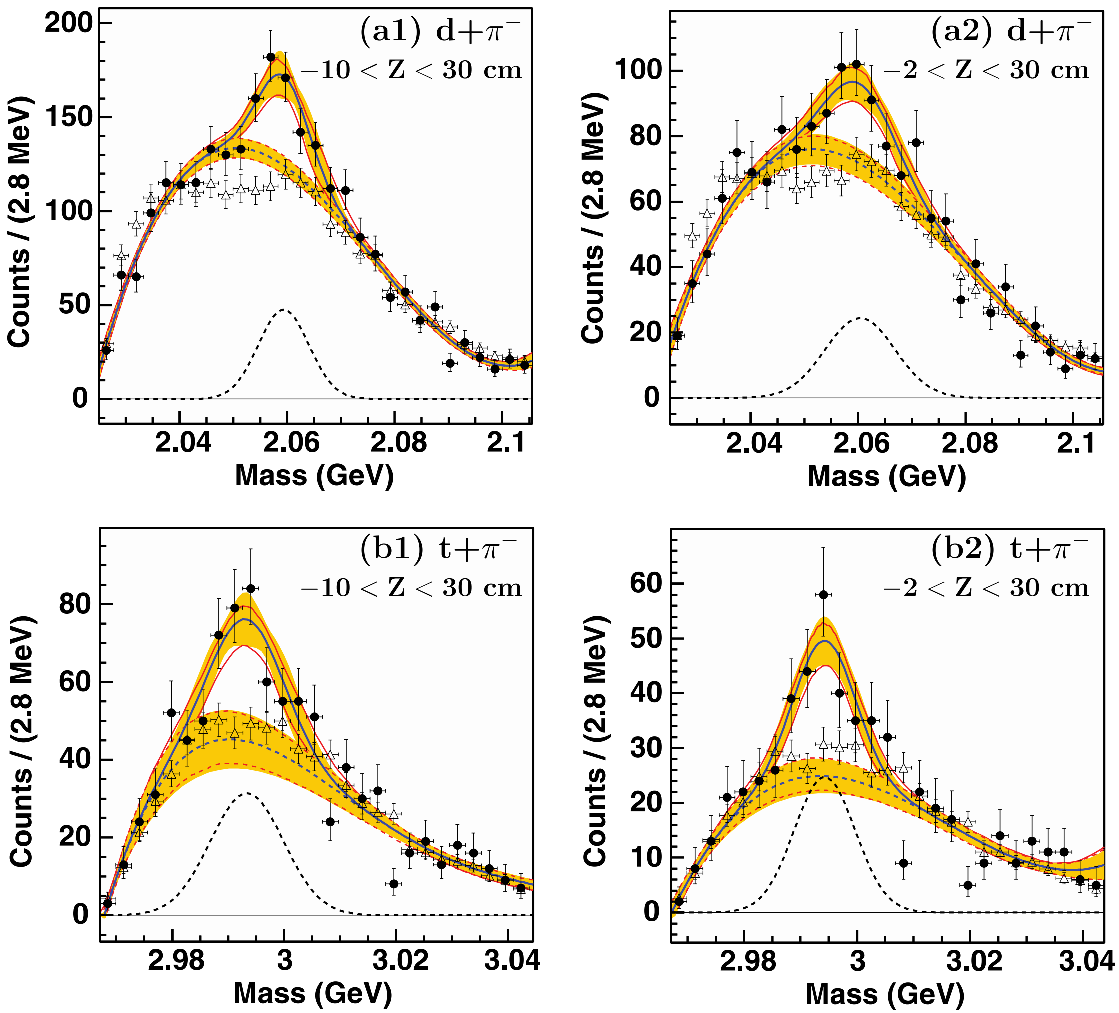
Dalitz, Nucl. Phys. A 754 (2005) 14c, "I feel that we are far from seeing the end of this road. A good deal of theoretical work on this 3-body system would still be well justified."

★ With micro-vertex detector in STAR, hypertriton is background free. Systematic uncertainty under control!





(nnΛ) signal in HI reaction?



HypHI exp. observed a signal in the invariant mass distribution of d+pi and t+pi channel.

PRC 88,041001R(2013)

Data from HIRES Col. Excluded the (Lp) candidates

PLB 687, 31(2010)

PRD 84, 032002(2011)

A possible interpretation might be the two- and three-body decays of an unknown bound state of 2 neutrons associated with a Lambda:

via ${}^{3}_{\Lambda}n \to t + \pi^-$ and ${}^{3}_{\Lambda}n \to t^* + \pi^- \to d + n + \pi^-$,

Sensitivity to QCD Phase Transition

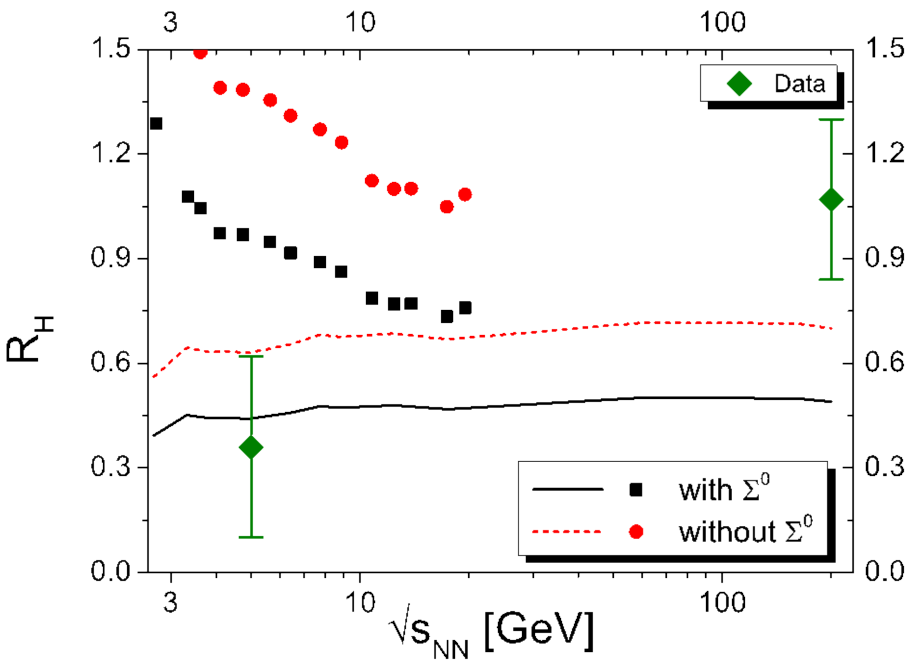
- Hypertriton is a local baryon-strangeness correlation system

$$S_3 = {}^{3}_{\Lambda}H / ({}^{3}He \times \Lambda / p)$$

- Strangeness Population Factor

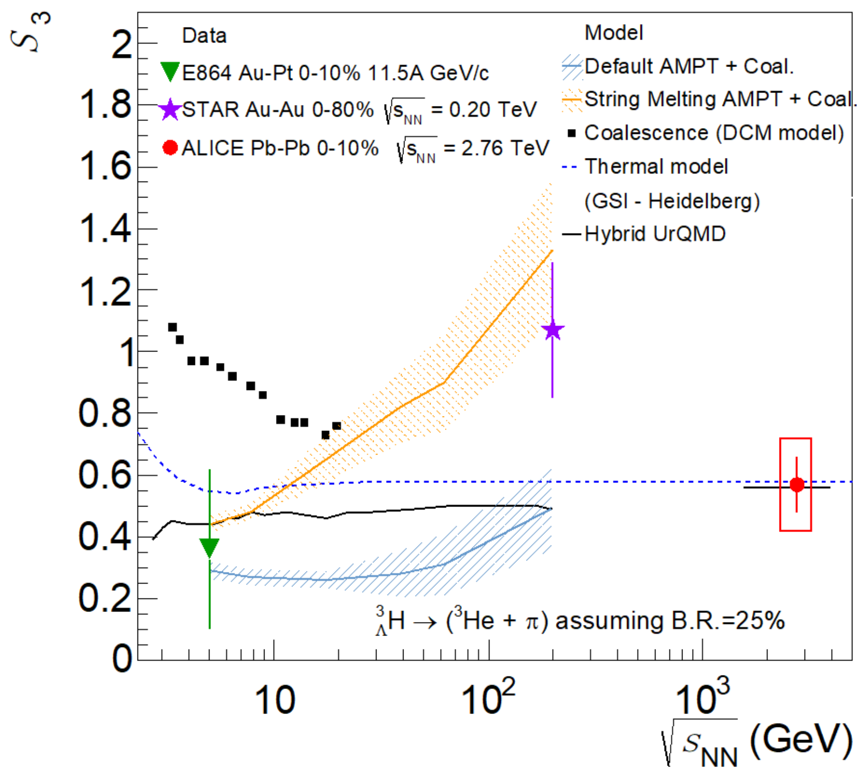
S.Zhang et al., PLB 684 (2010) 224
J. Steinheimer et al.,PLB 714 (2012) 85
...

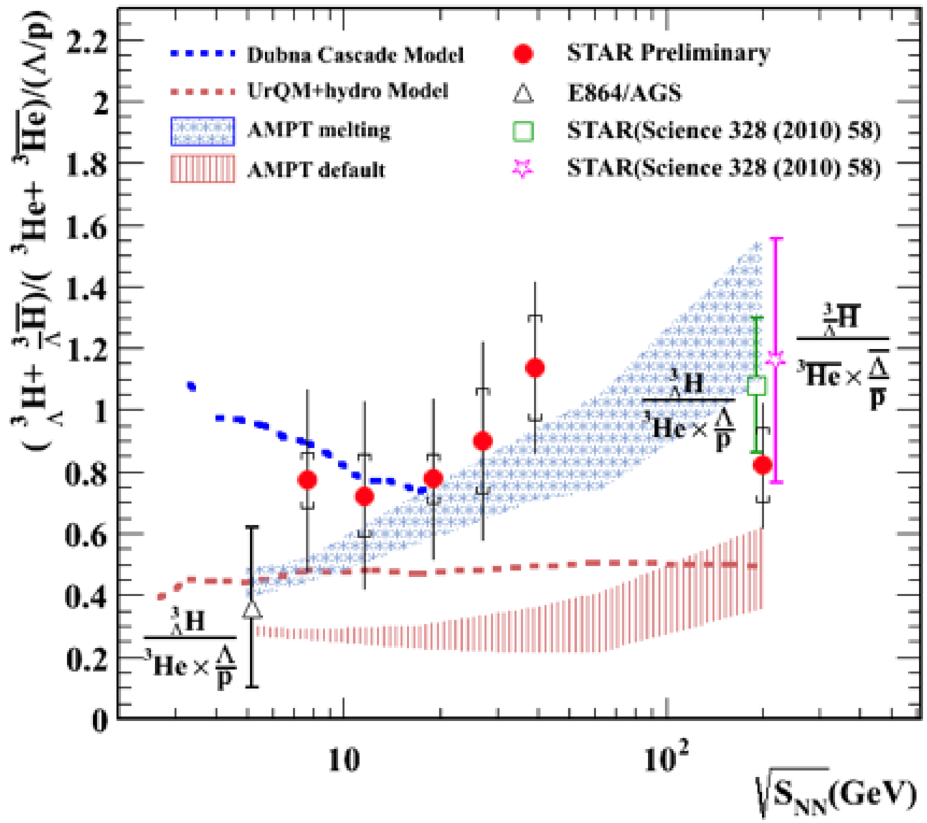
- It is predicted that the beam energy dependence of S_3 would behave differently in pure hadron gas and QGP



Beam energy dependence of S_3

ALICE Collaboration PLB 754, 360 (2016)





★ LHC energy seems to close to thermal model prediction

★ STAR BES data indicates an increasing trend with the increase of energy

Concluding remarks

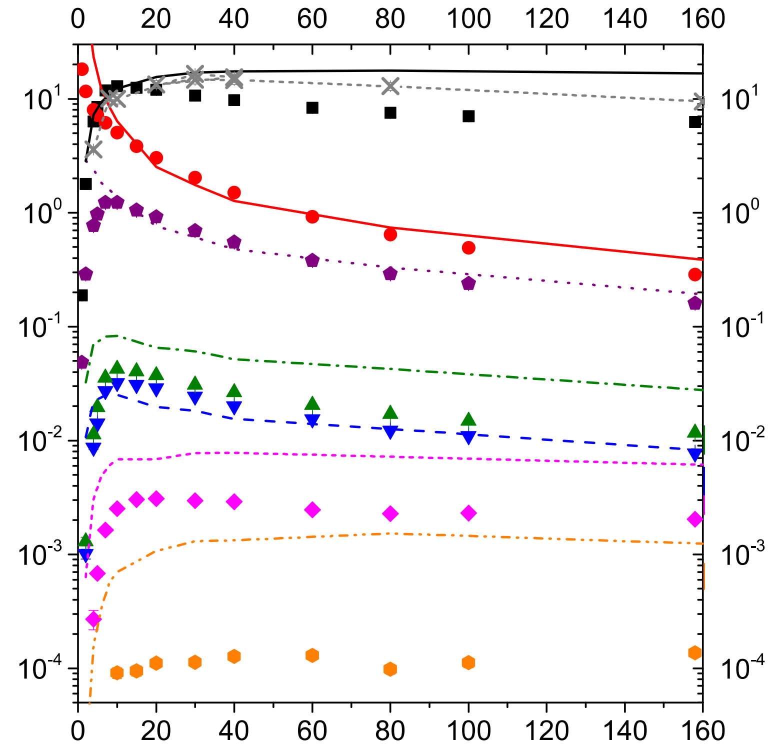
- ★ Hypernuclei is a control tool to study Y-N interaction in lab.
- ★ Measurements of hypertriton lifetime have be interesting project in the field. Independent exp. present different results.
- ★ Several theoretical interpretations have achieved in the field and tent to conclude a value close to the free Lambda's
- ★ New and precise measurements (>600 signals) in heavy-ion collisions have been released.The discrepancy among different exp. is still there, the hypertriton lifetime is still a puzzle. Future direction may be related to the binding energy of light hypernuclei system

Future direction (1)

★ STAR BES-II at 2019 and 2020

- detector upgrades
- low energy electron cooling
- rich hyperon production

Collision Energies	Proposed Event	BES-I Event
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36



J. Steinheimer et al., Phys. Lett. B 714 (2012) 85

Future direction (2)

Proposed (π^-,K^0) reaction on nuclear targets for precise determination of the lifetime of the hydrogen hyperisotopes and other neutron-rich Λ-hypernuclei at J-PARK

M. Agnello et al., NPA 954 (2016) 176

$$K^- + {}^{3,4}\text{He} \rightarrow \pi^0 + {}^{3,4}_{\Lambda}\text{H}$$
$$\hookrightarrow \gamma\gamma$$

$$\pi^- + {}^{3,4}\text{He} \rightarrow K^0 + {}^{3,4}_{\Lambda}\text{H}$$
$$\hookrightarrow \pi^+\pi^-$$

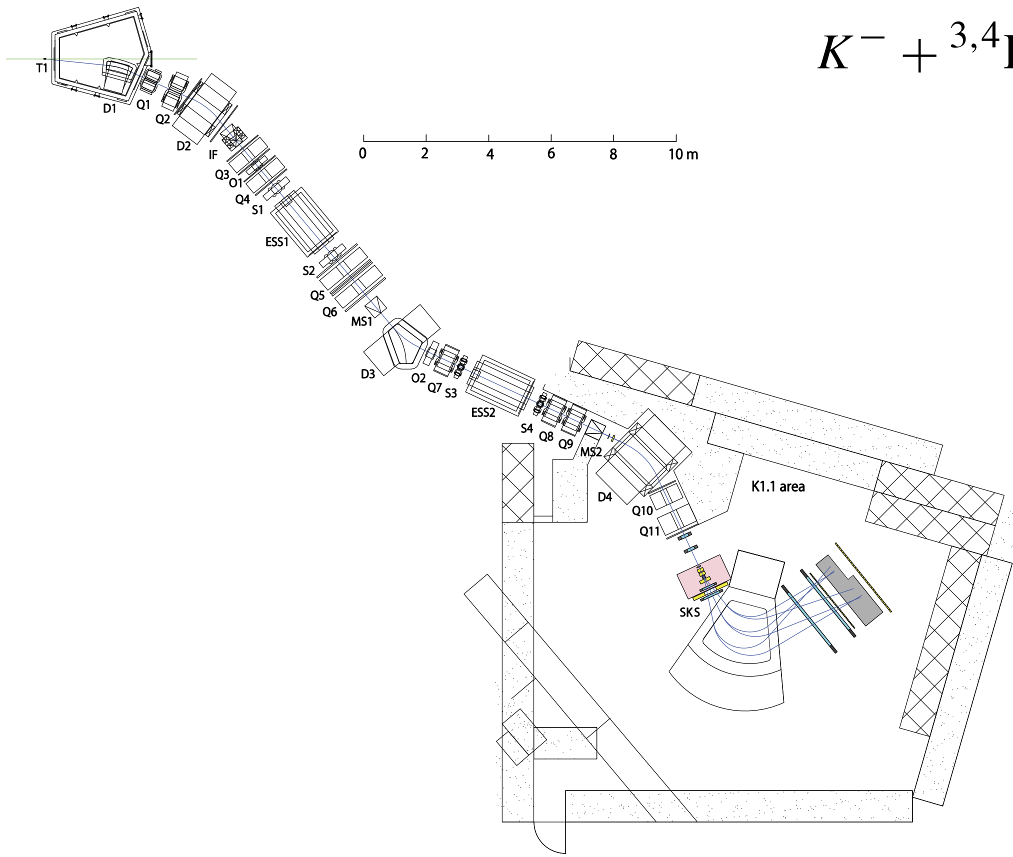
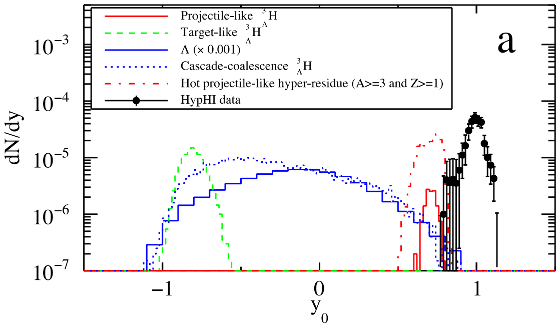


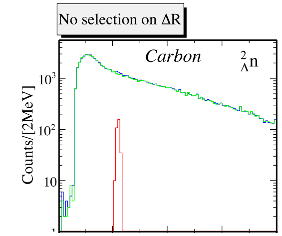
Fig. 4. Layout of the J-PARC K1.1 beam line and K1.1 experimental area. From [46].

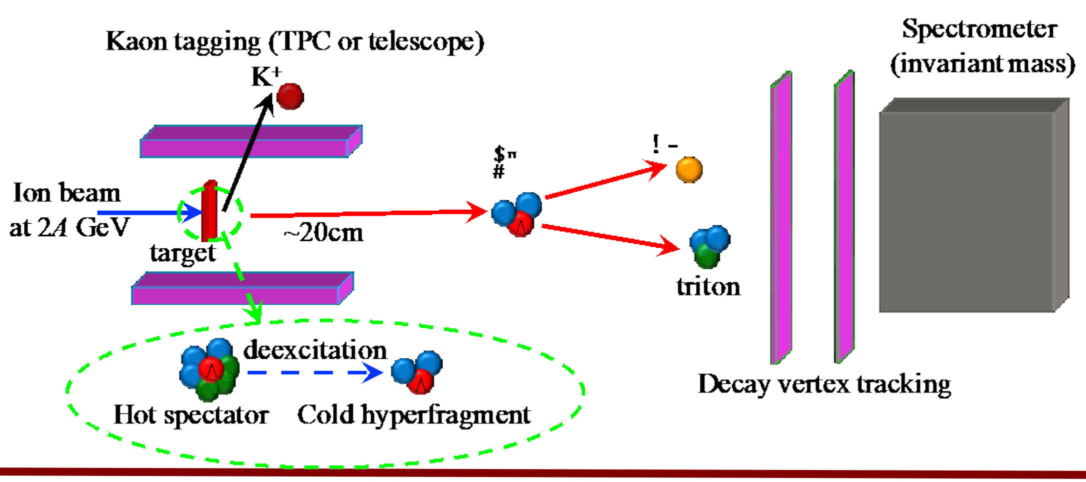
Future direction (3)



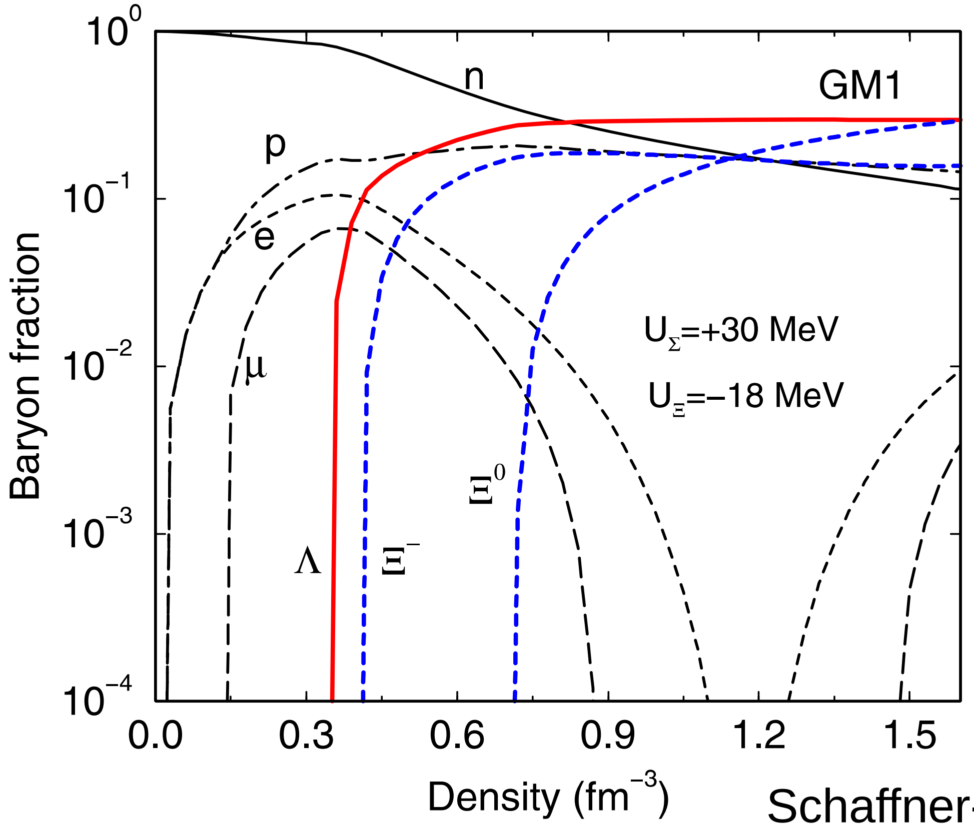
★ Light hypernuclei production in peripheral ion collisions

arXiv: 1712.04658



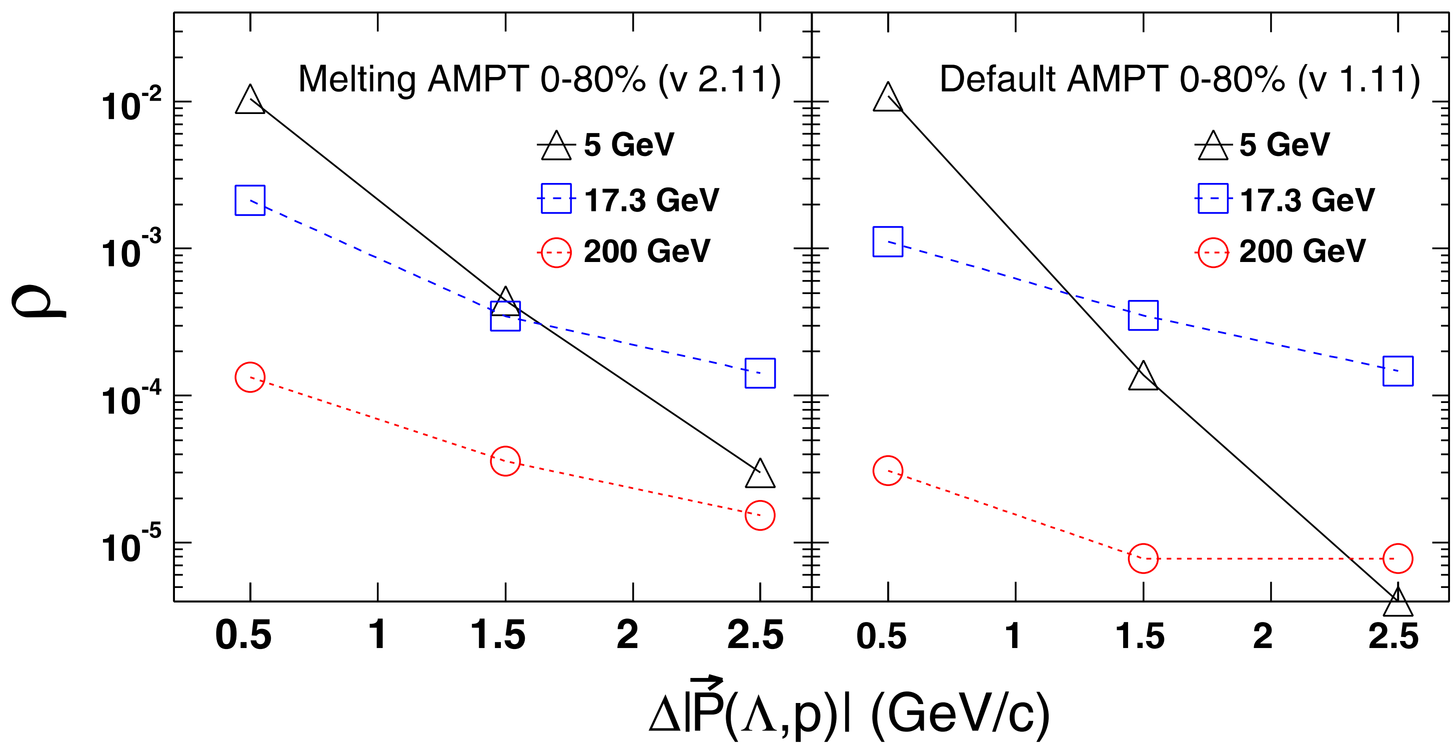


Backup slides



Schaffner-Bielich, 2008

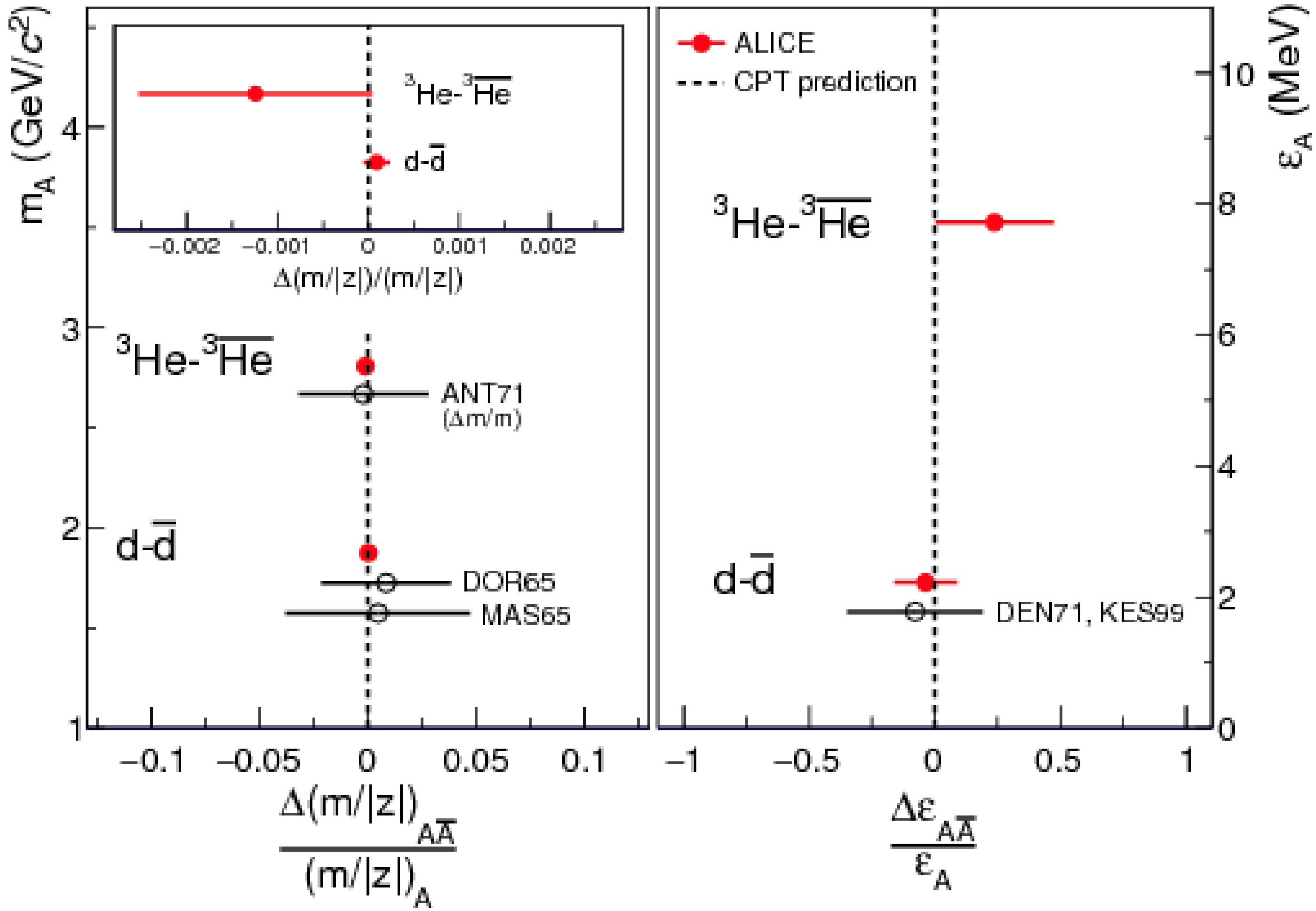
Neutron-star matter fractions of baryons and leptons, calculated as a function of density.



Melting AMPT 0-80% (v 2.11)
Default AMPT 0-80% (v 1.11)
5 GeV
17.3 GeV
200 GeV
ρ
10^-2
10^-3
10^-4
10^-5
0.5
1
1.5
2
2.5
Δ|P⃗(Λ,p)| (GeV/c)

Probing CPT invariant in nuclear force

ALICE Collaboration Nature Physics, 11 (2015) 811



★ Mass-over charge ratio difference confirms CPT invariance to an unprecedented precision in the sector of light nuclei