Hypernucleus physics in STAR forward experiment

Jinhui Chen (陈金辉)

Institute of Modern Physics, Fudan University

Workshop on STAR Forward Tracking Detector Upgrade and Related Physics

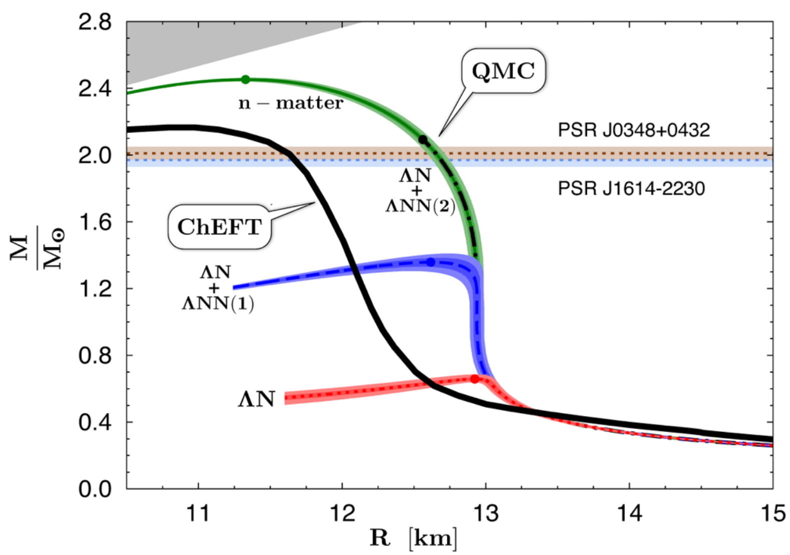
2019.5.7-8,Qingdao

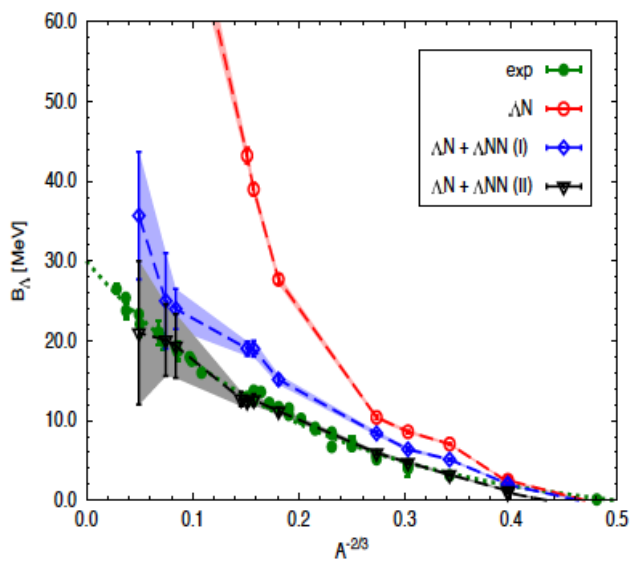
Hyperons in neutron stars

☑ 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 neutron stars ~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 add 0.3M to Mmax of NS
- Lonardoni: adding YNN stiffens EoS of NS, and increase the mass; solution to overbinding in s-shell hypernuclei?

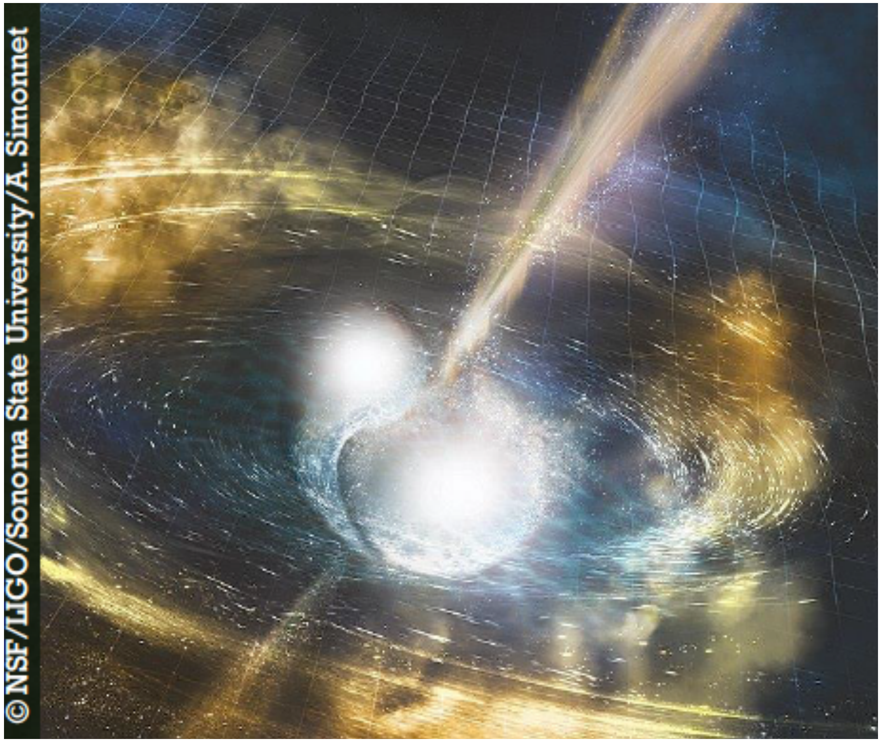
From hypernuclei to neutron stars

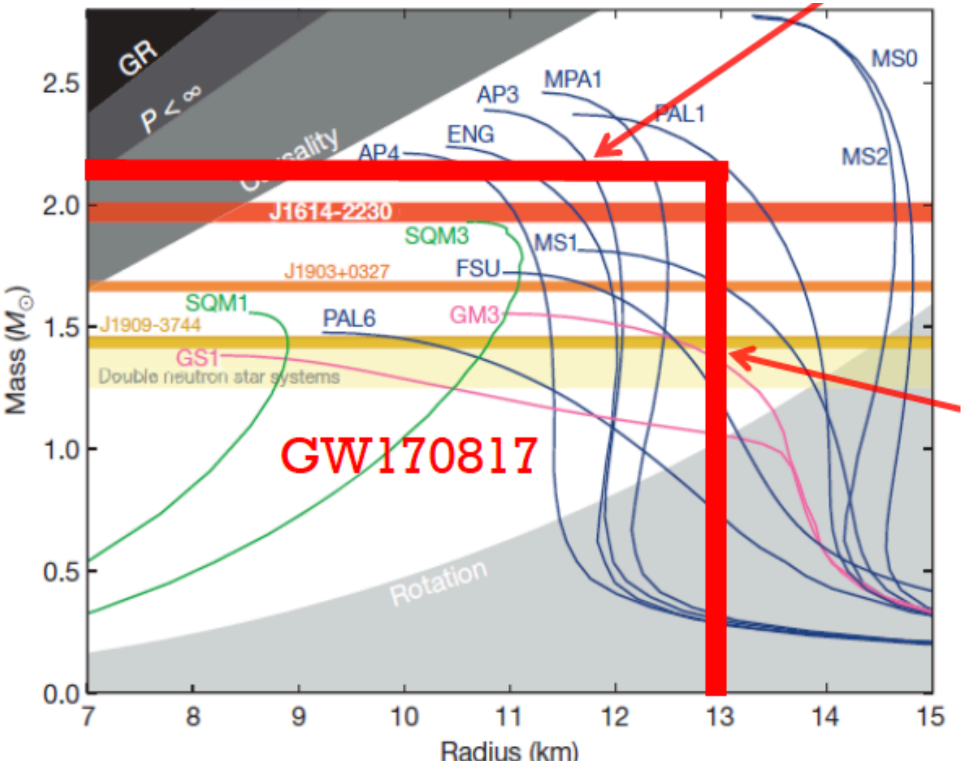
- ☑ GW from NS merger, provides new information on NS EoS, and new constrains on radius and mass

The LIGO and Virgo Col., Phys. Rev. Lett. 119, 161101 (2017); Phys. Rev. Lett. 121, 161101 (2018)

$1.97\ M_\odot$ $R_1 = 11.9^{+1.4}_{-1.4}$ km $R_2 = 11.9^{+1.4}_{-1.4}$ km

Rezzolla et al., Astro. J. Lett. 852 (2018) $M \leq 2.16\ M_\odot$



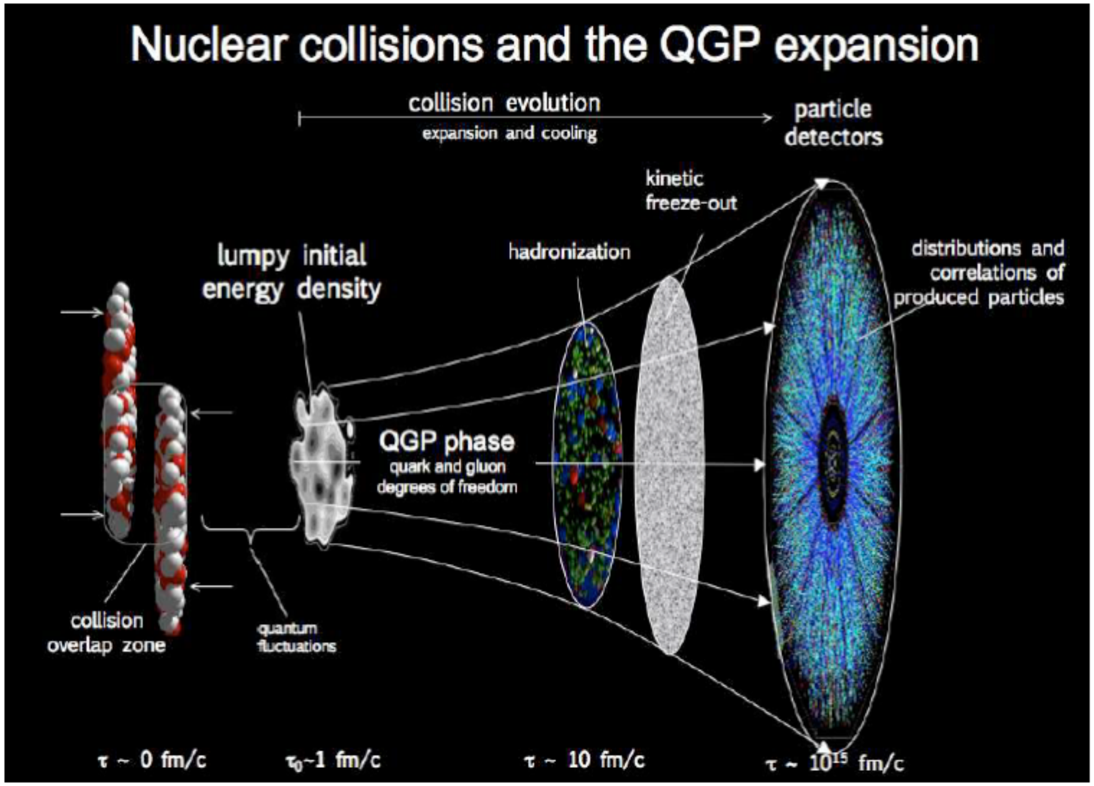


Raithel et al., Astro. J. Lett. 857 (2018) $R \leq 13\ km$

- ☑ Study on YNN interaction on-lab will provide constrains on EoS of NS

Lonardoni et al., Phys. Rev. Lett. 114 (2015); Wirth and Roth, Phys. Rev. Lett. 117 (2016)

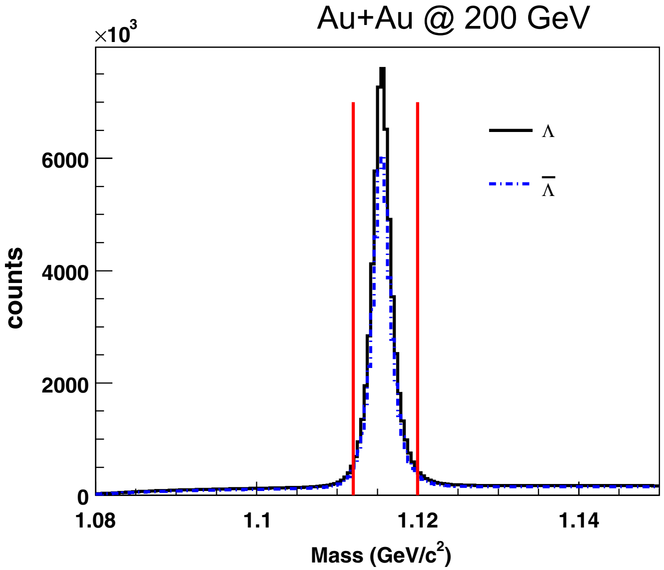
Heavy ion collider as a hyperon factory



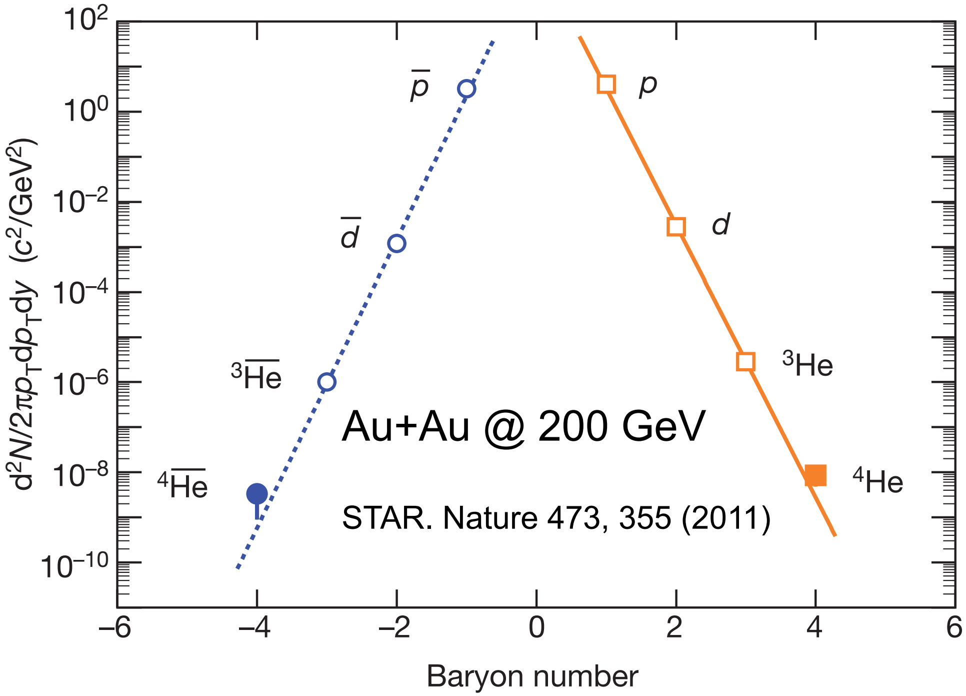
- ☑ RHIC, a QCD machine, small bang
- ☑ Hyperon rate is high, lab. for Y-N interaction
- ☑ Excellent secondary vertex reconstruction in STAR and ALICE

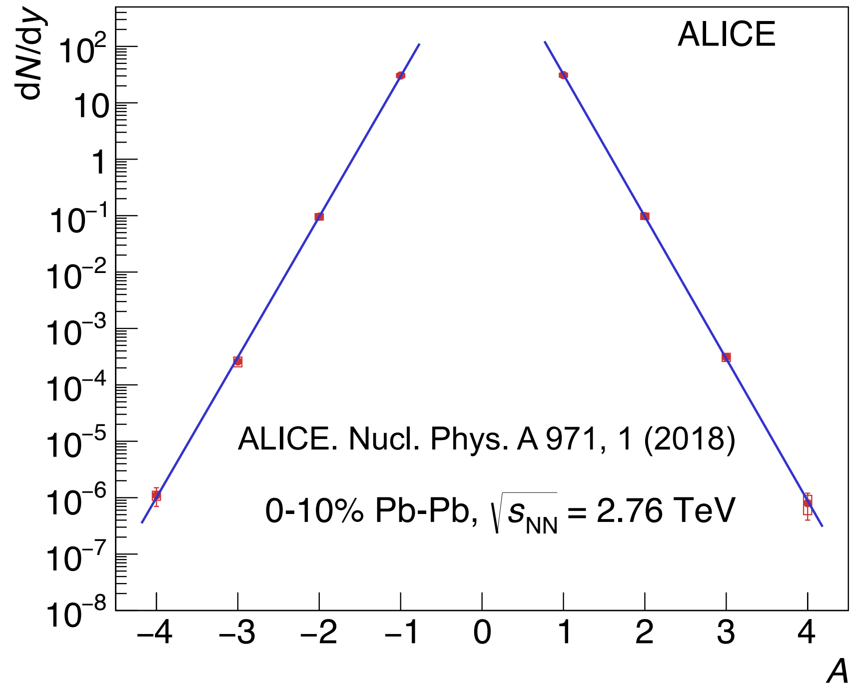
0-5% central collisions, Au+Au @ 200 GeV, Pb-Pb @ 2.76 TeV

$$\left.\frac{dN_Y}{dy}\right|_{y=0} \simeq \begin{cases} \mathbf{16.7}, & \mathbf{26}, & \Lambda\ \mathbf{(S=-1)} \\ \mathbf{2.2}, & \mathbf{3.3}, & \Xi\ \mathbf{(S=-2)} \\ \mathbf{0.3}, & \mathbf{0.6}, & \Omega\ \mathbf{(S=-3)} \end{cases}$$



(Hyper-)nuclei production in HIC





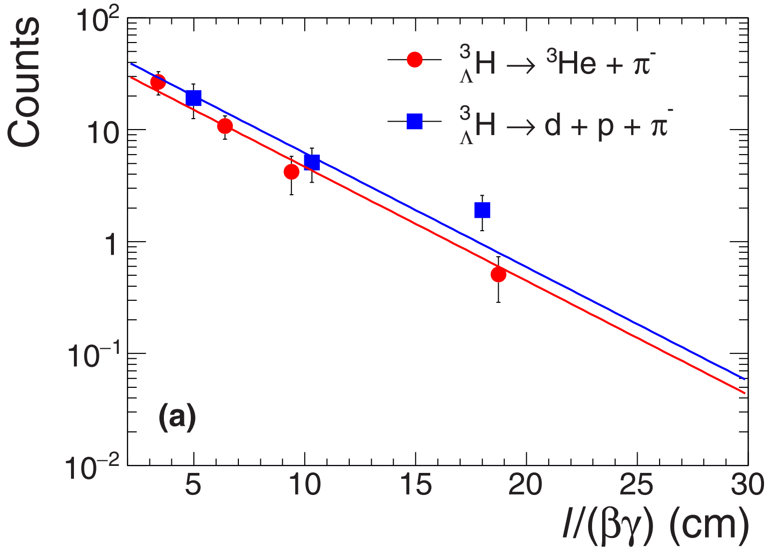
STAR. Science 328, 58 (2010)

Particle type	Ratio
${}^3_{\bar{\Lambda}}\overline{H}/{}^3_{\Lambda}H$	$0.49 \pm 0.18 \pm 0.07$
${}^3\overline{He}/{}^3He$	$0.45 \pm 0.02 \pm 0.04$
${}^3_{\bar{\Lambda}}\overline{H}/{}^3\overline{He}$	$0.89 \pm 0.28 \pm 0.13$
${}^3_{\Lambda}H/{}^3He$	$0.82 \pm 0.16 \pm 0.12$

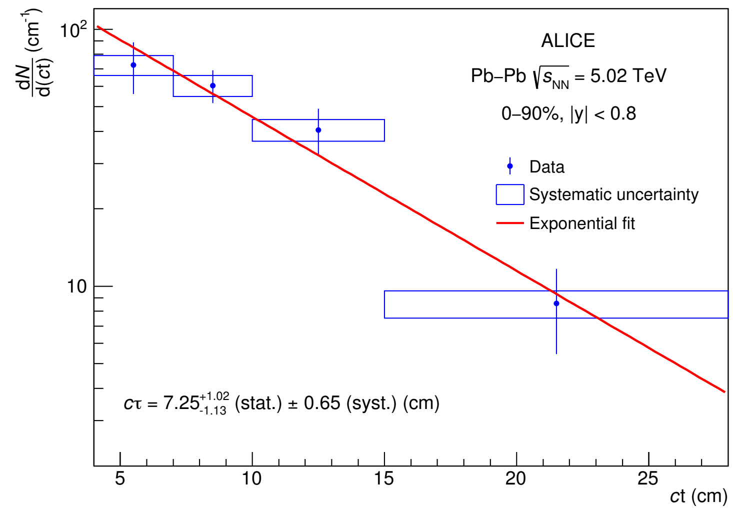
☑ The production reduction factor is up to 10^3 at RHIC and 300 at LHC, limited to A<4 system

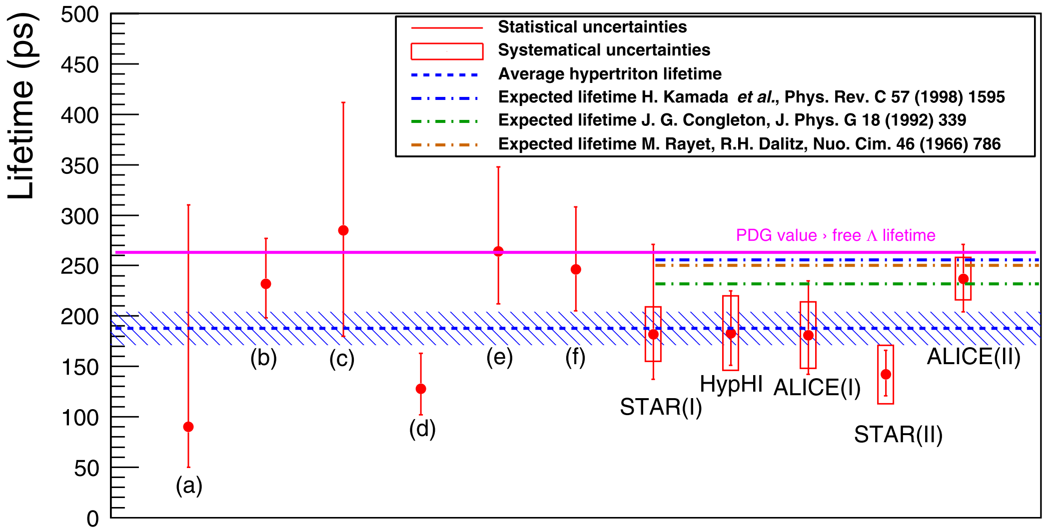
Recent results on lifetime measurement

STAR Phys. Rev. C 97 (2018)



ALICE runII





"Toward resolving the hyper triton lifetime puzzle"
Phys. Lett. B 791 (2019)

- ☑ A new evaluation by Gal with early popular theoretical framework, suggest 10% shorter than the free Lambda's, including pion FSI attraction effect give another 10% shorter than the free Lambda's

Binding energy: an answer to Dalitz's question?

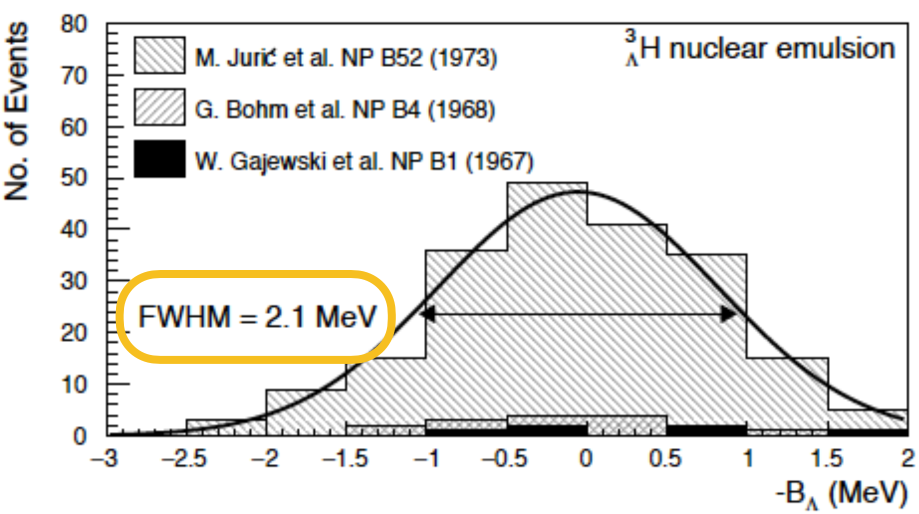
☑ The early data suffers from large statistical uncertainty!

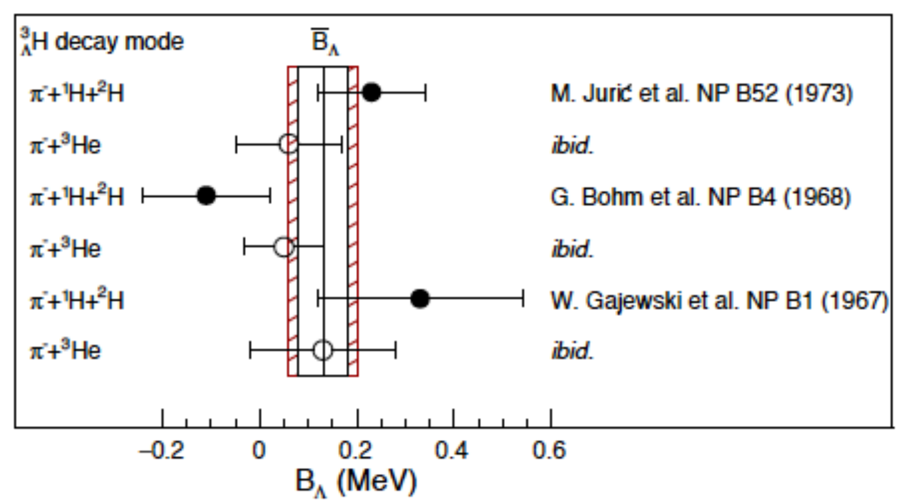
	$B_\Lambda \pm \Delta B_\Lambda$ (MeV)		δB_Λ (MeV)
	Bohm et al.[a]	This work	
$^{3}_{\Lambda}$H	0.01 ± 0.07	0.15 ± 0.08	0.14 ± 0.11

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

$$B_\Lambda = 0.13 \pm 0.05\,\text{MeV}$$

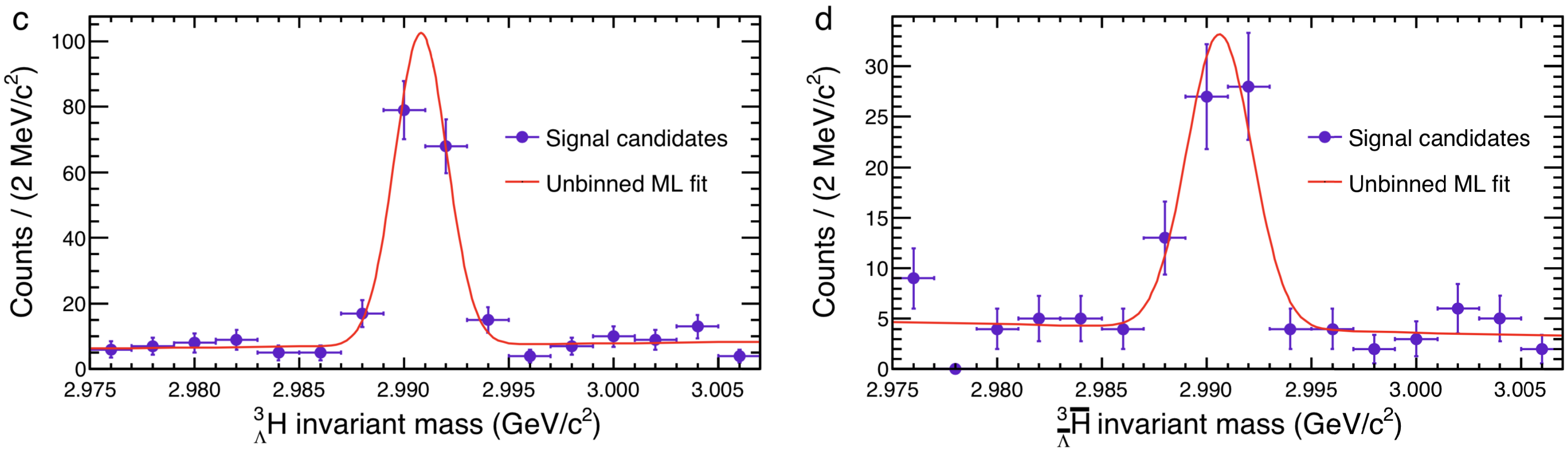
P. Achenbach, PoS (Hadron 2017) 207



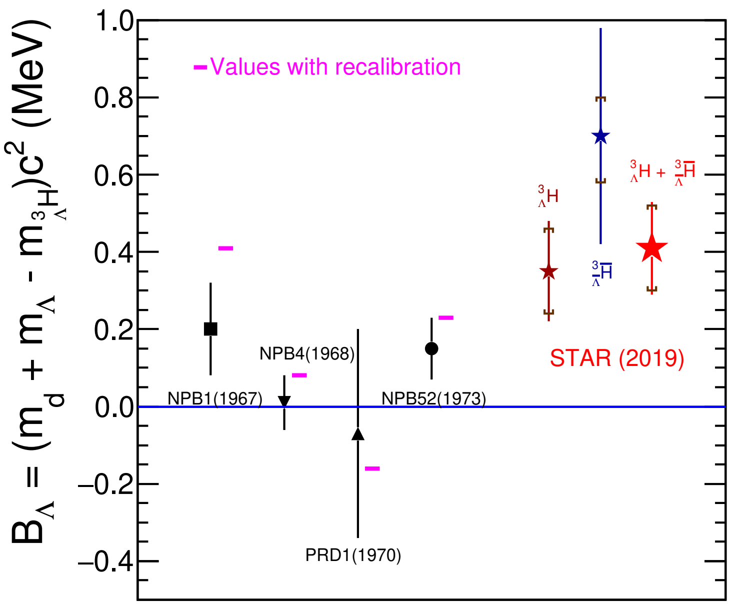


"I feel that we are far from seeing the end of this road. A good deal of theoretical work on this 3-body system would still be well justified." R.H. Dalitz Nucl. Phys. A 754, 14 (2005)

Our measurements with modern technology



STAR Col. arXiv 1904.10520



- High precision vertex detector in STAR: a precise mass measurements
- STAR data differs from zero and larger than the prior measurements from 1973
- Strong Y-N interaction in hypernucleus system

Recent data on QCD phase diagram study

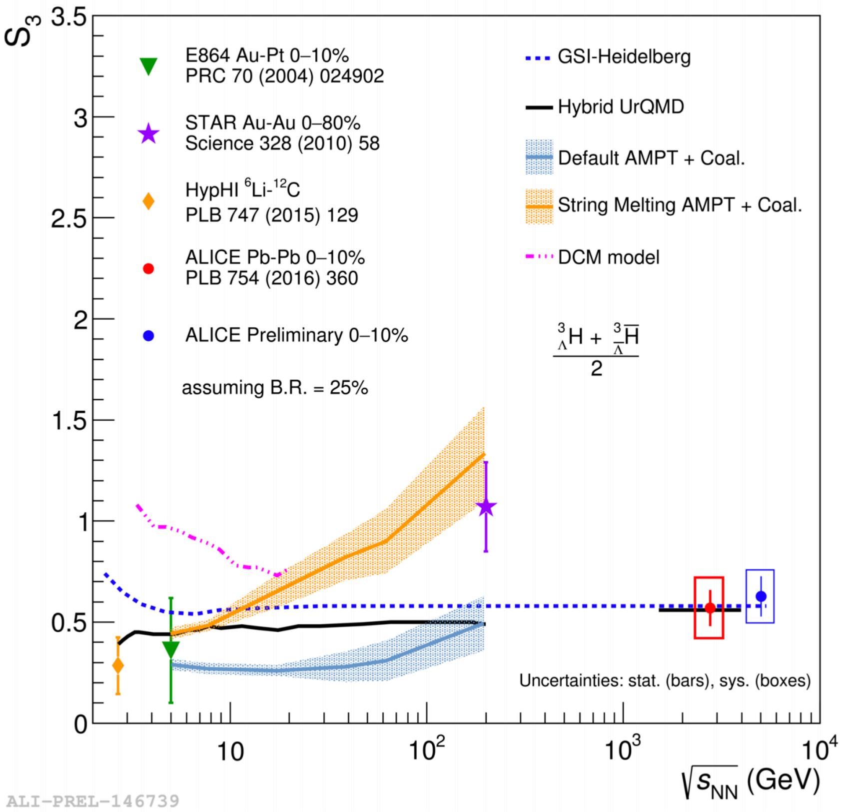
(Hyper)nuclei production and density fluctuation

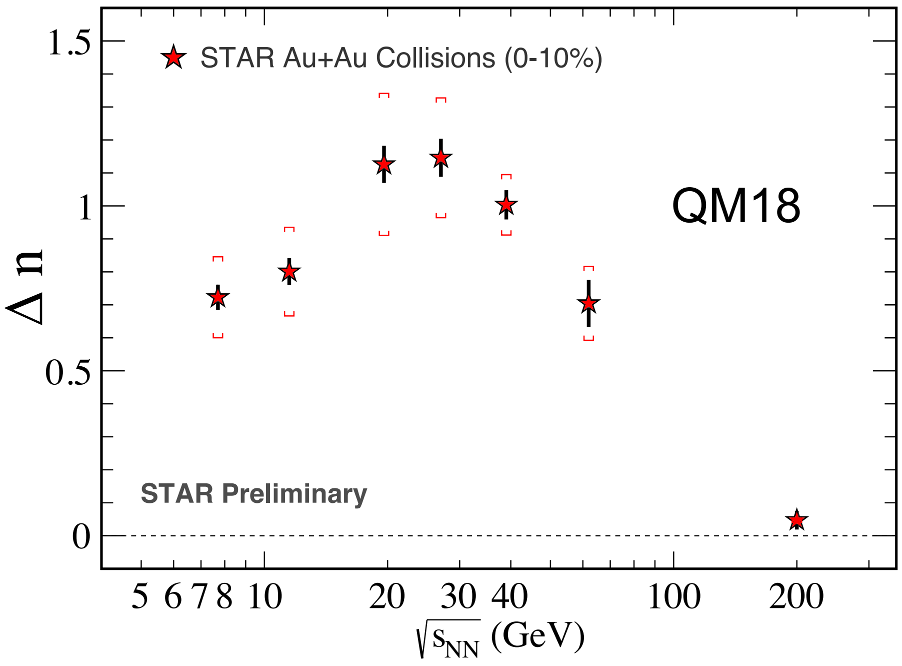
$$S_3 = {}^{3}_{\Lambda}H / ({}^{3}He \times \Lambda / p)$$

$$\Delta n = \langle(\delta n)^2\rangle / \langle n \rangle^2$$

$$N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)$$

g=0.29.

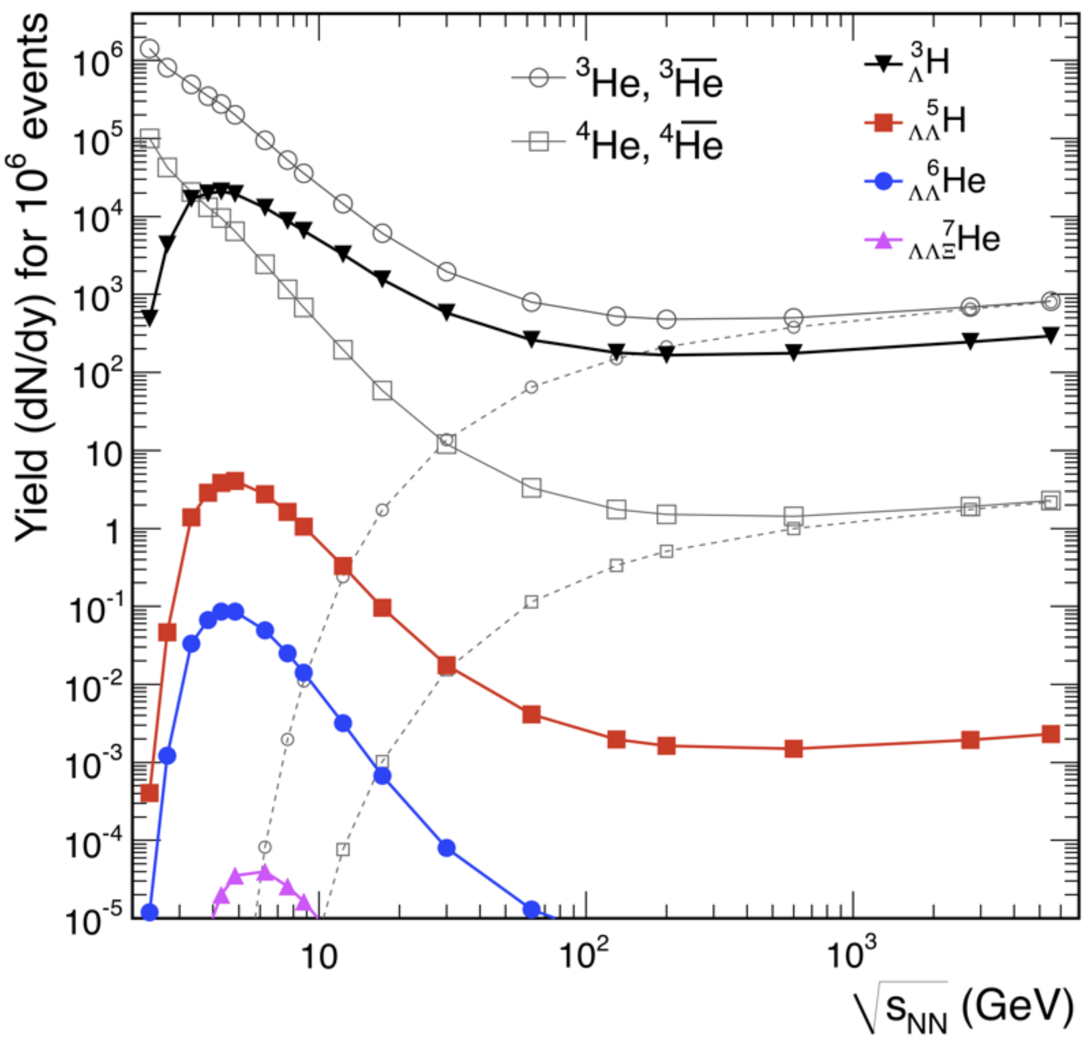




(Hyper)nuclei production at forward upgrade

- ☑ Rich hyperon and hypernuclei production rate at lower energies
- ☑ Better lifetime and binding energy measurements and will improved the understanding on Y-N interaction
- ☑ The baryon number desntidy fluctuation and baryon-strangeness correlations accessible probe to the QCD phase transition

A.Andronic et al., PLB 697 (2011) 203



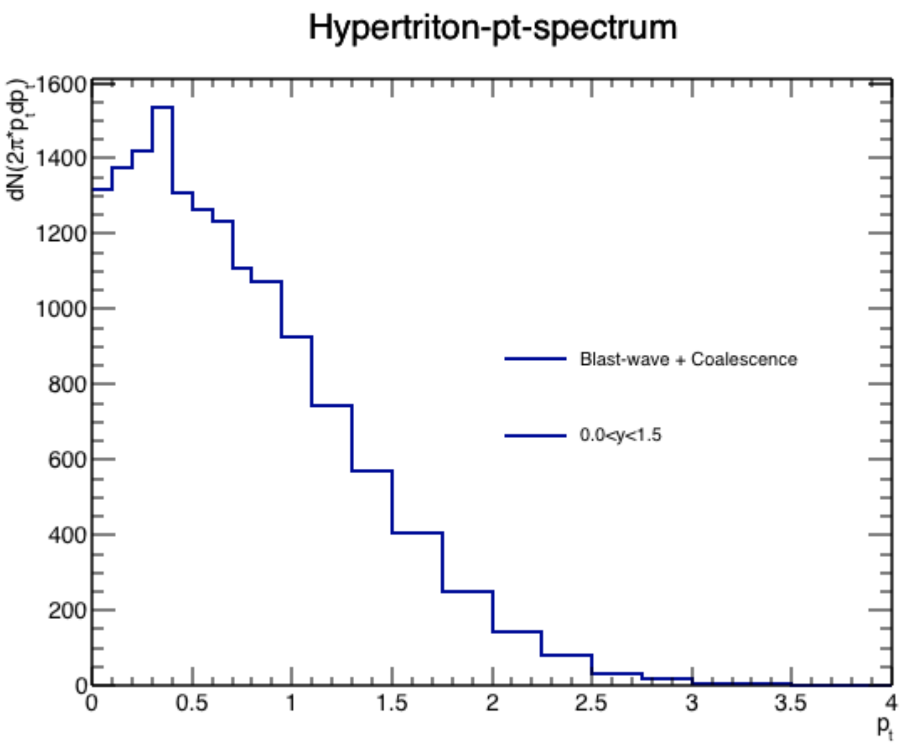
Rate estimated at 11.5 GeV

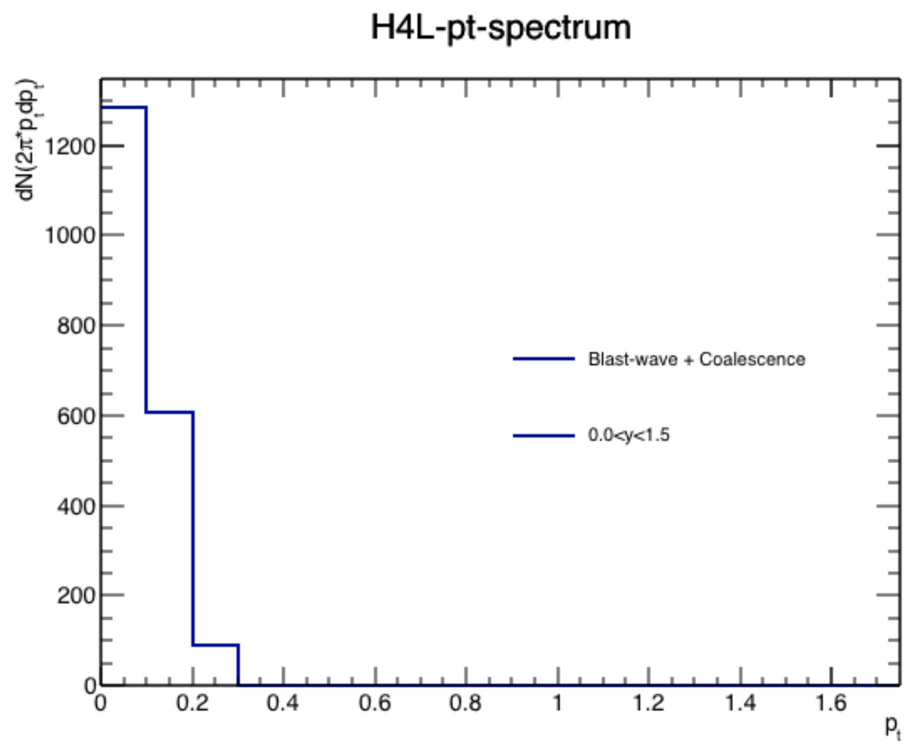
☑ Blast wave + nucleon coalescence

Phys. Lett. B 754 (2016)

- 17M events produced 13903 hypertriton in rapidity window (0,1.5), assuming eff. 20%, BR to helium3 and pion 25%, the count is 695

- But the difficulty is on A=4 hypernuclei, only 146 signal obtained without eff. or BR factor in

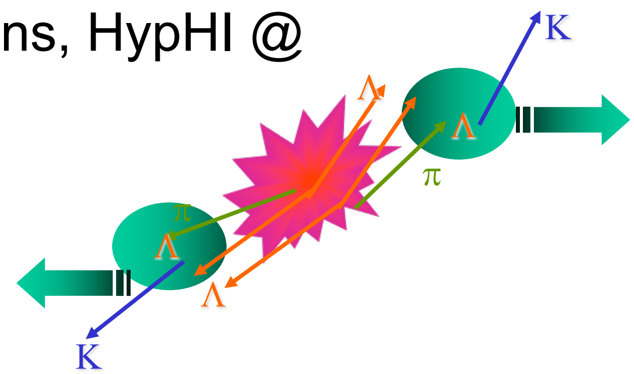


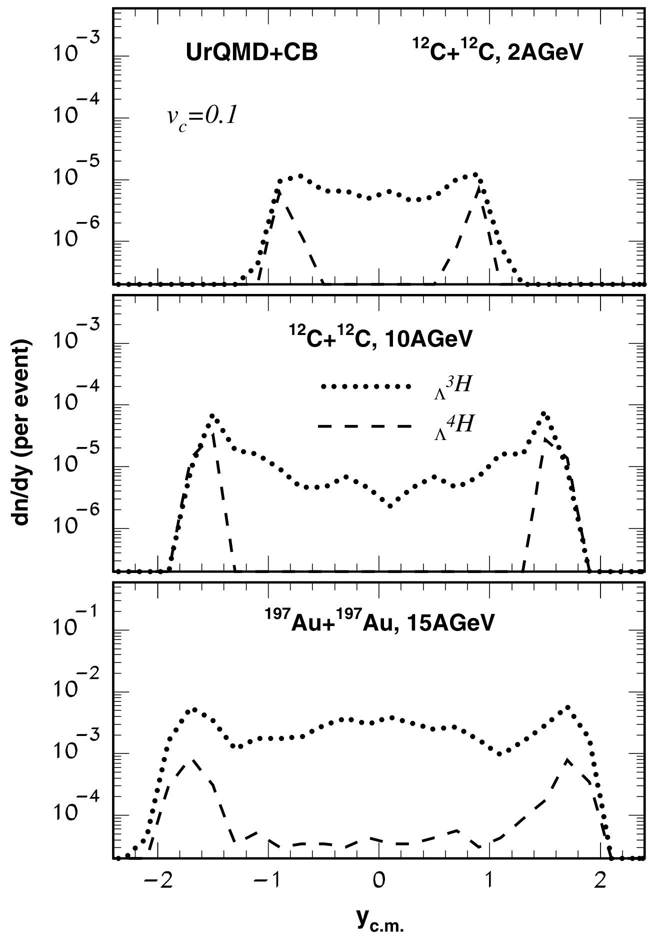


Estimates with different production mechanism

- ☑ Production in central and peripheral HIC are quite different: re-scattering and absorption of hyperons by excited spectators in peripheral collisions

Producing light hypernuclei in peripheral collisions, HypHI @ GSI





- ☑ Calculations based on UrQMD+CB are strongly depend on the coalescence parameter

Botvina et al., Phys. Lett. B 742 (2015) 7

$$|\vec{v}_i - \vec{v}_{cm}| < v_c$$

$$\vec{v}_{cm} = \frac{1}{E_A} \sum_{i=1}^{A} \vec{p}_i$$

Proposal from other exp. (1)

- 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

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

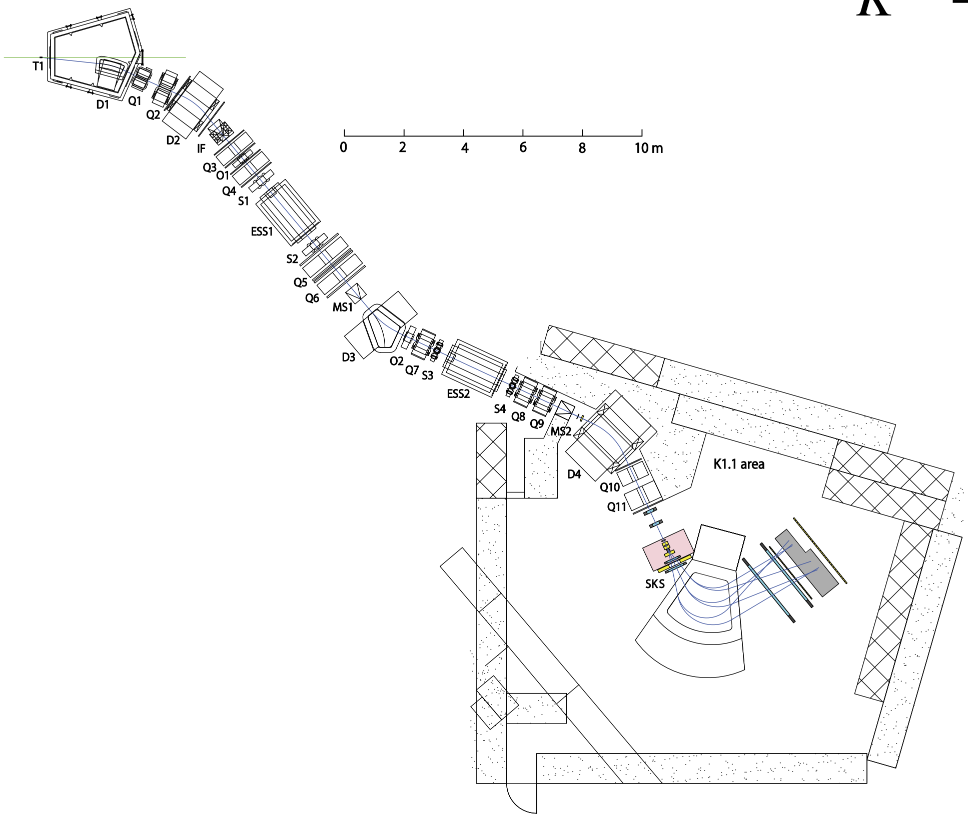
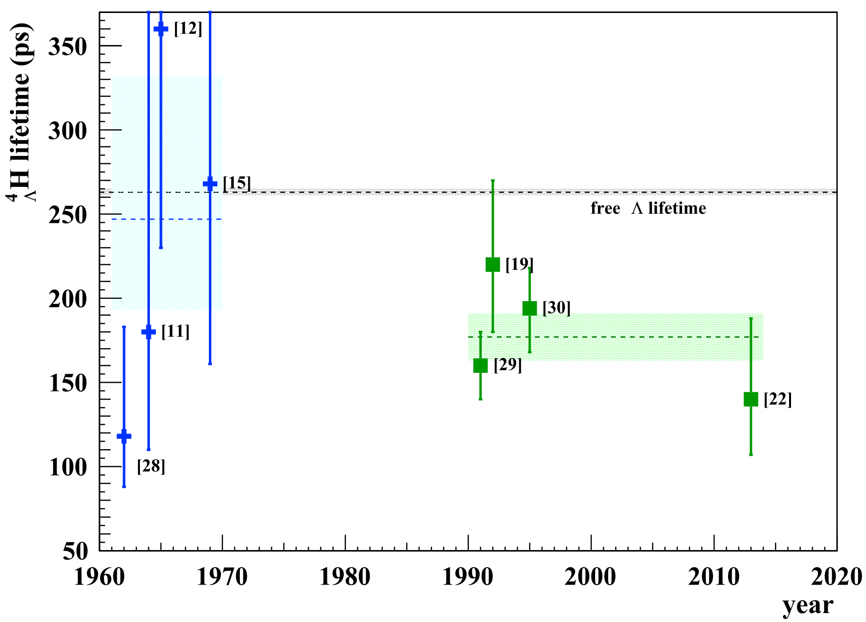
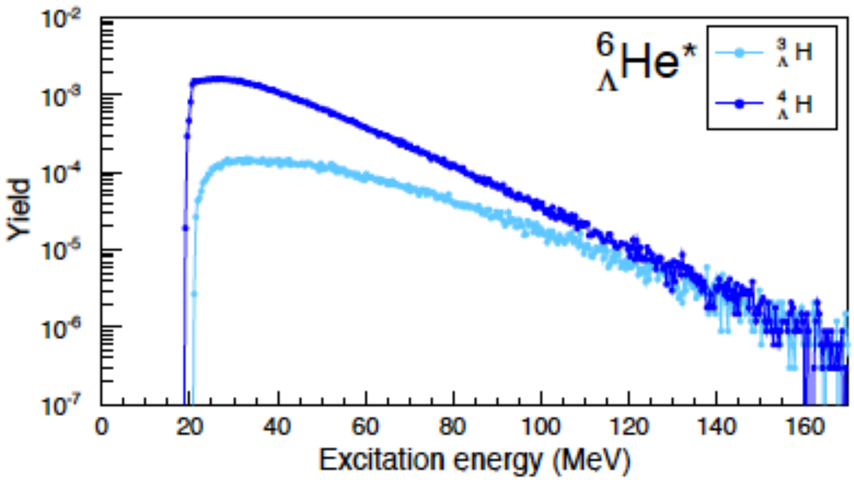


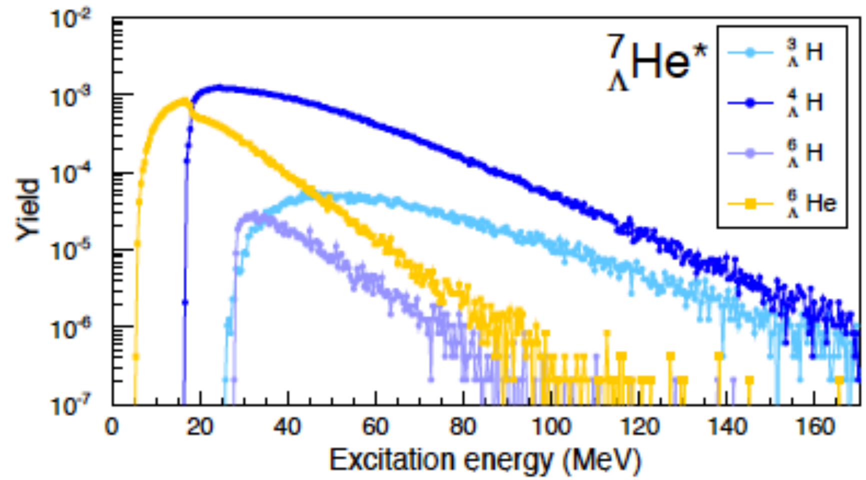
Fig. 4. Layout of the J-PARC K1.1 beam line and K1.1 experimental area. From [46].



Proposal from other exp. (2)

Achenbach and Pochodzalla (2017)





- ☑ Proposal to use the high-precision technique of decay-pion spectroscopy at the Mainz Microtron (MAMI) to the accurate determination of the binding energy measurement
- ☑ Statistical decay calculations suggest that lithium is the optical target material to observe hypertriton decays under relative clean conditions with only few other light hyperfragments being produced

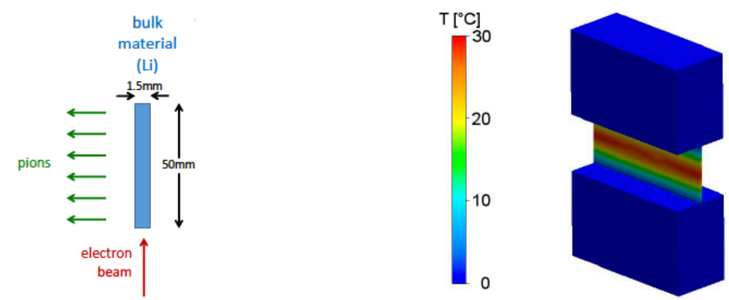
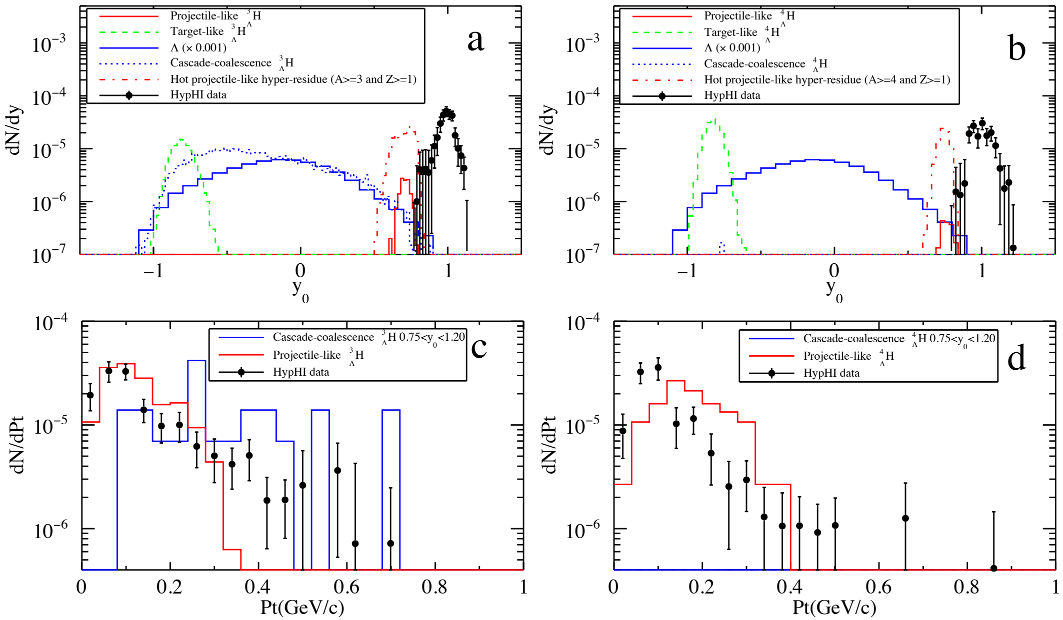


Figure 3: Left: Schematic view of a possible Li target and detection geometry to be employed in the hypertriton measurement (view from top; not to scale). Right: Expected temperature distribution in a 1 mm thick block of Li inside a cooling frame, while an electron beam of 5 μA current, vertically wobbled by $\Delta y = \pm 2$ mm, is entering the target.

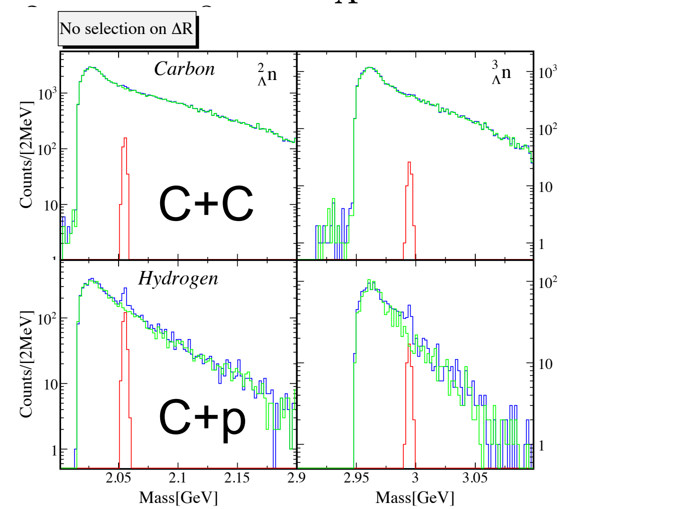
Proposal from other exp. (3)



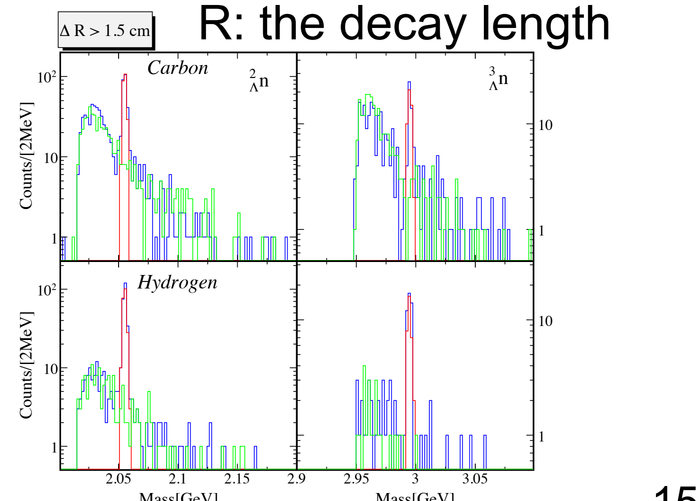
Phys. Rev. C 98,024903 (2018)

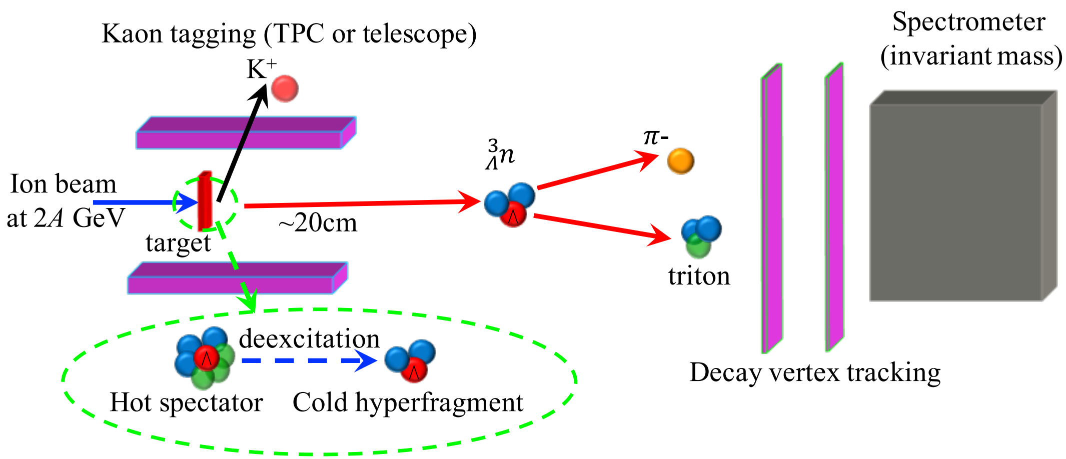
☑ Light hypernuclei production with light-ion beams and targets

$$^{2}_{\Lambda}n \to \pi^{-} + d,\quad ^{3}_{\Lambda}n \to \pi^{-} + t.$$

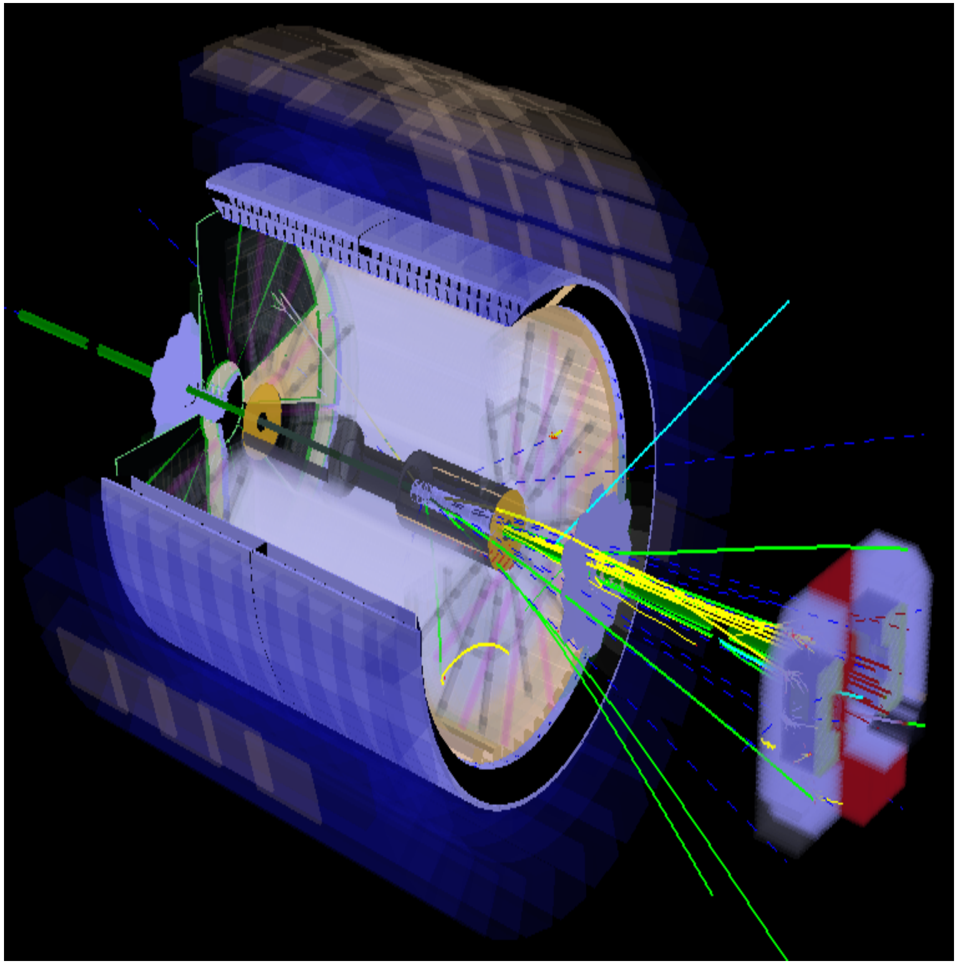


R: the decay length





Summary



It is promising to carry out a beautiful measurements on light (hyper)nuclei production at STAR forward experiment.

Thank you!