Measurement of hypernuclei radius

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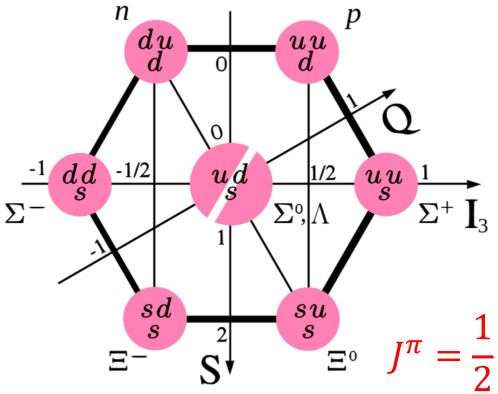
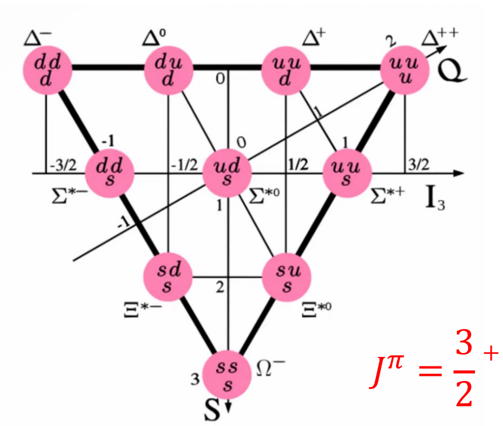
Outline

- ☐ Two puzzles: Hyperon puzzle and 3LH lifetime puzzle
- ☐ Hypernuclei production and decay, invariant-mass method
- ☐ Two-target method   S. Velardita, ... YLS, Eur. Phys. J. A, 59:139 (2023)
- ☐ HYDRA TPC in GLAD/R3B
- ☐ HYDRA design: field cage, amplification, gas system, laser system, electronics
- ☐ Perspectives

Hyperon puzzle

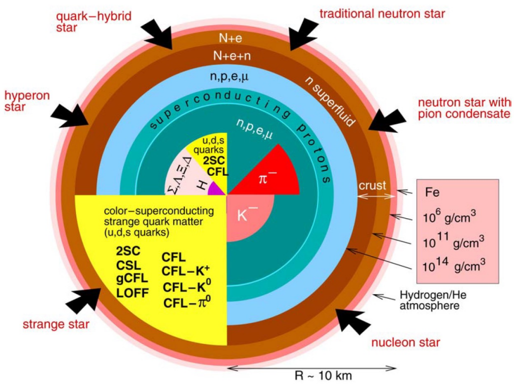


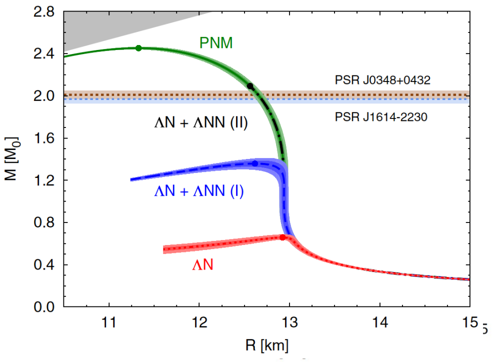
$J^\pi = \frac{1}{2}^+$



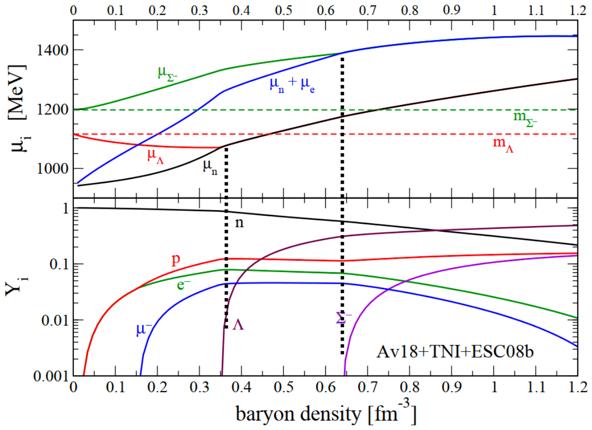
$J^\pi = \frac{3}{2}^+$

F. Weber, PPNP 54,193 (2005)





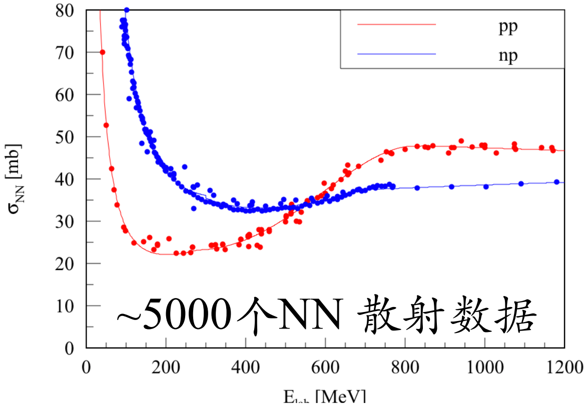
Diego Lonardoni *et al.*, PRL 114, 092301 (2015)



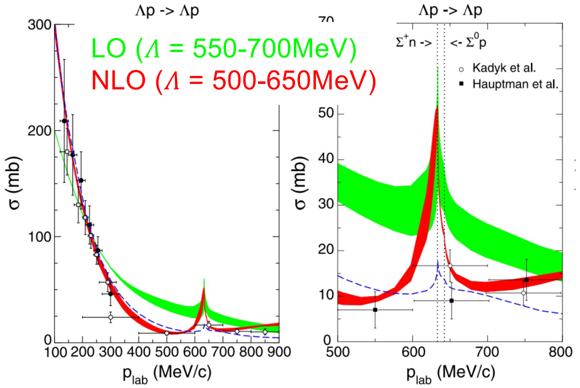
Ignazio BombacI JPS Conf. Proc. , 101002 (2017)

- ➢ 99% visible mass in the universe p&n
- ➢ Experimentally observed bayons (uds quarks) p, n, **Λ**, **Σ**, **Δ**, **Ξ**, **Ω** (hyperons)
- ➢ Existence hyperons in Neutron star?
- ➢ Need better constrain on YNN forces

Hyperon puzzle



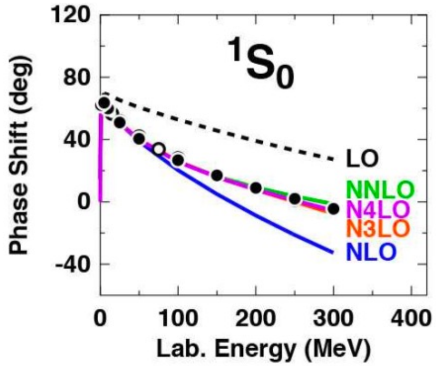
~5000个NN 散射数据



LO (Λ = 550-700MeV)
NLO (Λ = 500-650MeV)

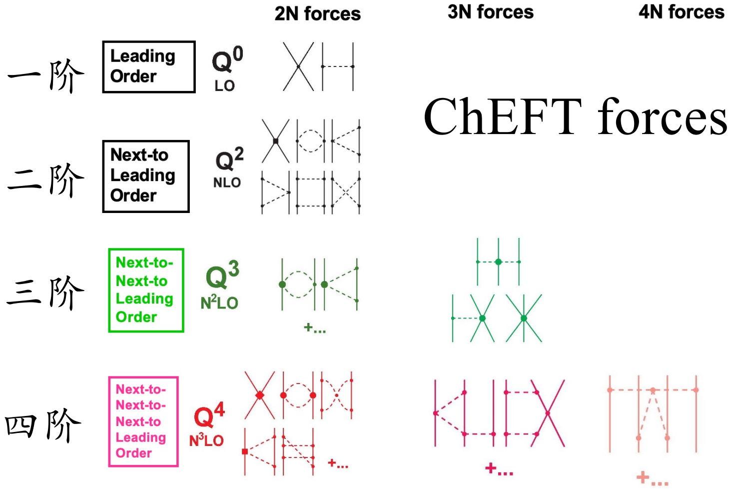
J. Haidenbauer *et al.* / Nuclear Physics A 915 (2013) 24–58.

Phaseshift analysis



D. Entem, et al., Front. Phys., 18 March 2020;
PRC 68, 041001(R) (2003).

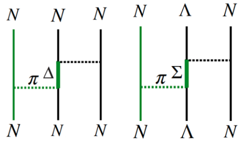
→2N forces up to N4LO(5阶)



ChEFT forces

3N appears from N2LO

- ☐ Baryon-Baryon scattering
- ✓ ~5000 NN scattering
- ✓ 70 YN scattering
- ✓ 1 YY scattering



→YN forces up to NLO(2阶)

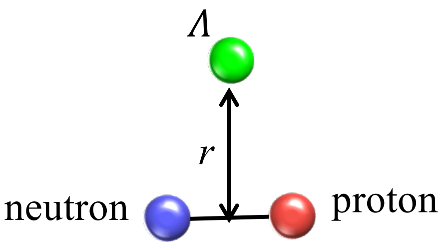
N: First excited state ~300 MeV
Λ: First excited state ~70 MeV

➢ More YN scattering data is calling for

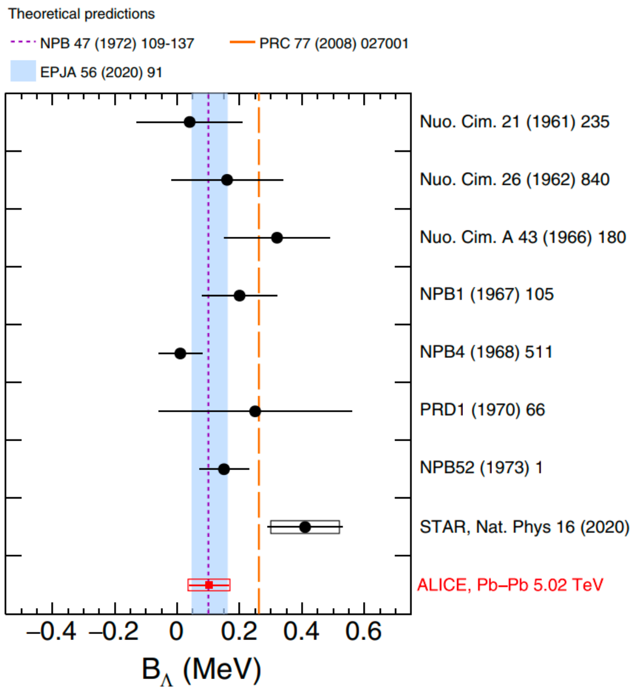
3LH lifetime puzzle

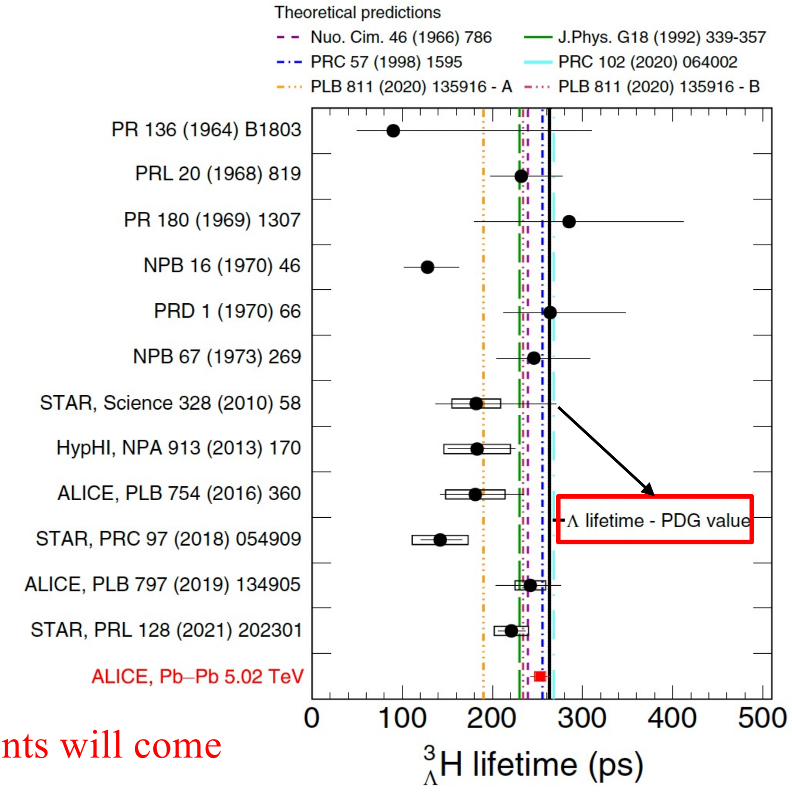
❑ Lightest hypernuclei 3LH

❑ $B_{\Lambda} = \sim 100$ keV vs $B_d = 2.2$ MeV



3LH: $d + \Lambda$





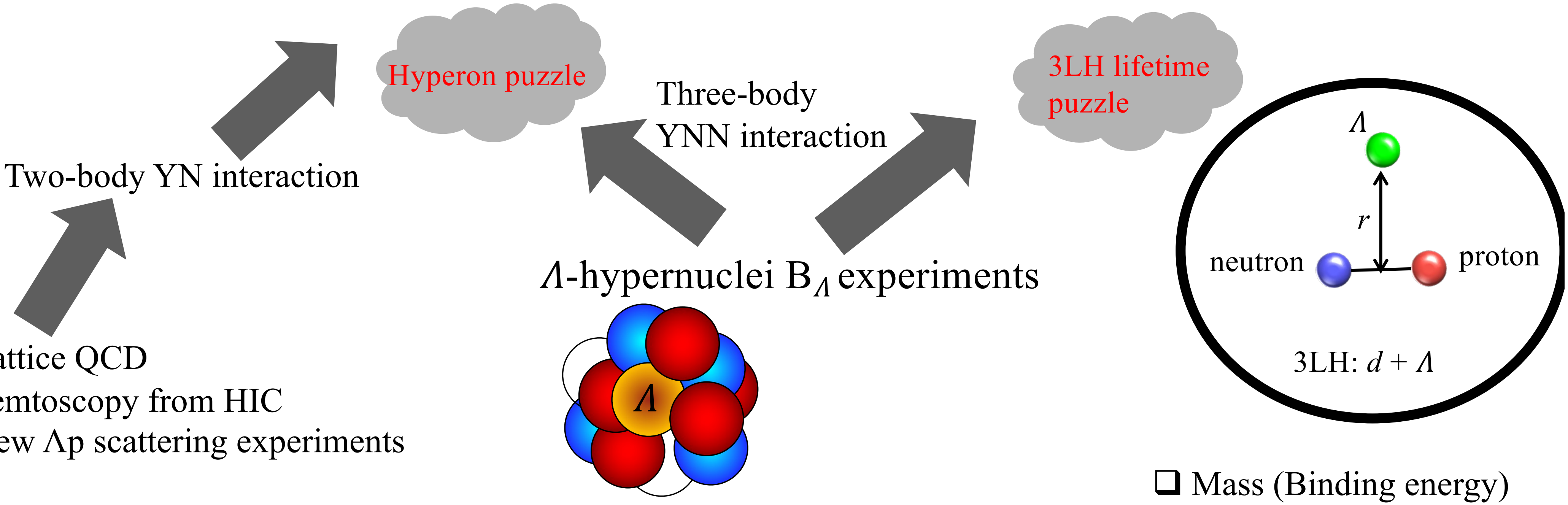
➢ More high-precision B_{Λ} experiments will come

$B_{\Lambda} = [102 \pm 63(\mathrm{stat}) \pm 67(\mathrm{syst})]$ keV

ALICE Collaboration, PRL 131, 102302 (2023)

$\tau = [253 \pm 11(\mathrm{stat}) \pm 6(\mathrm{syst})]$ ps

Measurment of 3LH radius?

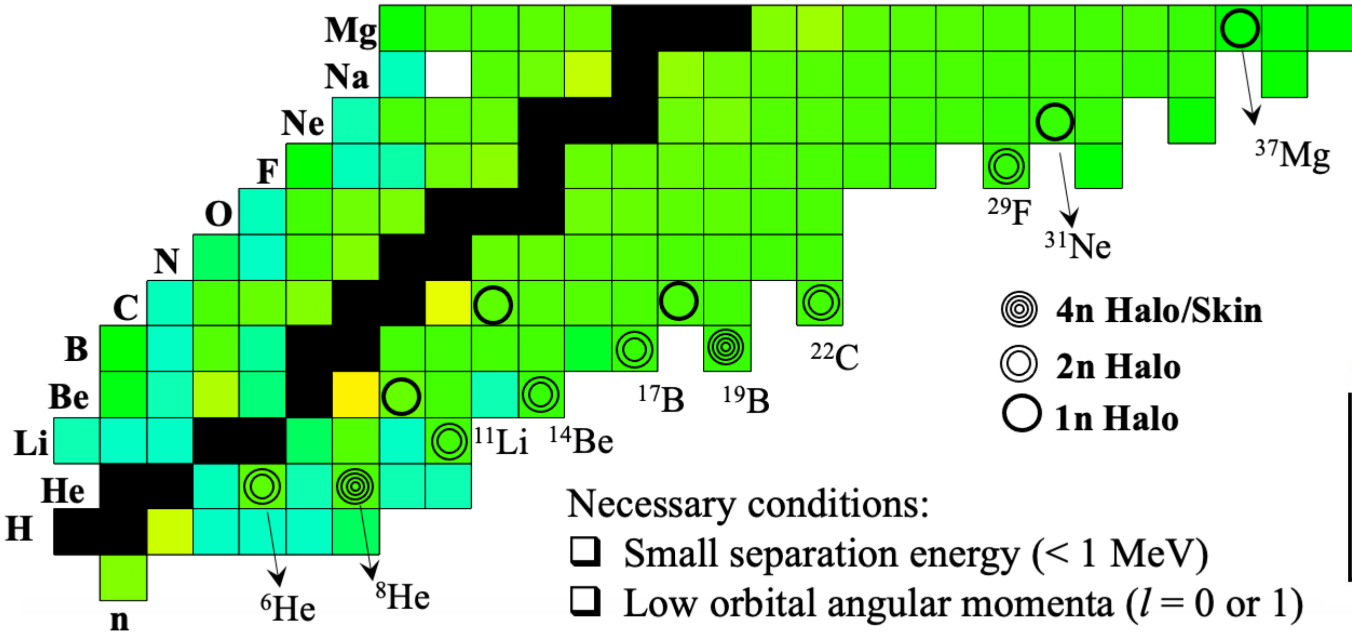


- Lattice QCD
- Femtoscopy from HIC
- New Λp scattering experiments

☐ Mass (Binding energy)
☐ Lifetime (Decay width)
☐ Charge radius ?
☐ Matter radius ?

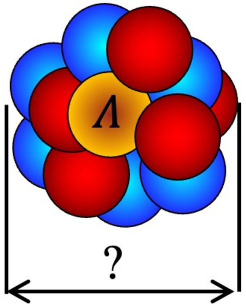
☐ Additional constrain on ΛN and ΛNN interactions
☐ Additional constrain on B_Λ

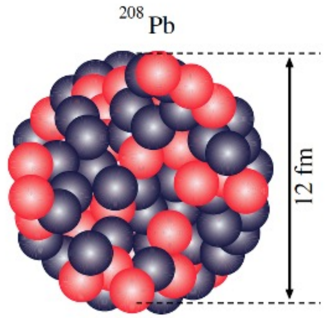
Halo nuclei

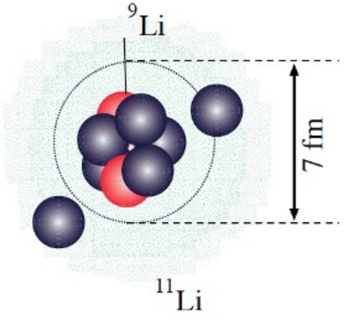


Necessary conditions:
- ❑ Small separation energy (< 1 MeV)
- ❑ Low orbital angular momenta ($l = 0$ or 1)

I. Tanihata *et al.*, Phys. Rev. Lett. 55, 2676 (1985).
I. Tanihata *et al.*, Phys. Lett. B206, 592 (1988).







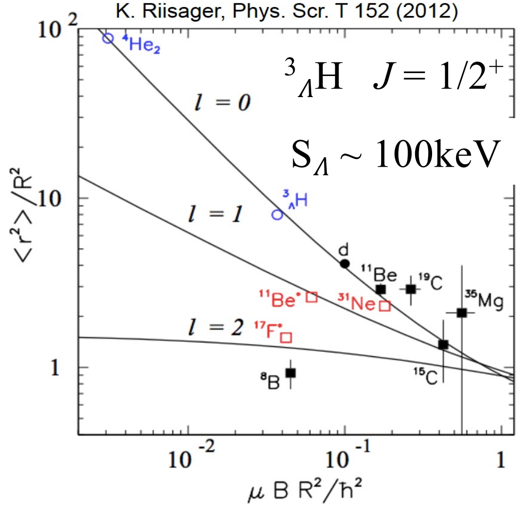
- ❑ Constrain NN interaction at low density, clustering...
- ❑ Challenge *ab initio* nuclear theories
- ❑ Halo also exist in hypernuclei?

Halo- Hyperhalo in hypernuclei

- ☐ Halo/skin candidates in hypernuclei $^{3}{}_{\Lambda}$H, $^{6}{}_{\Lambda}$He and $^{7}{}_{\Lambda}$Be
- ☐ No data exist about their radii

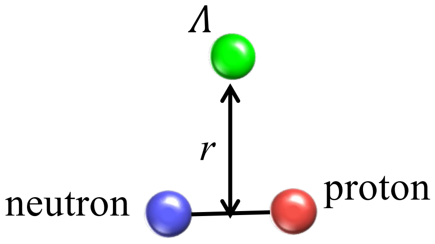
$^{3}{}_{\Lambda}$H: $d + \Lambda$

K. Riisager, Phys. Scr. T 152 (2012)



$^{3}{}_{\Lambda}$H $J = 1/2^{+}$

S$_{\Lambda}$ ~ 100keV



3LH → $d + \Lambda$

- ☐ Radial wave function u(r) = $R(r)/r$:

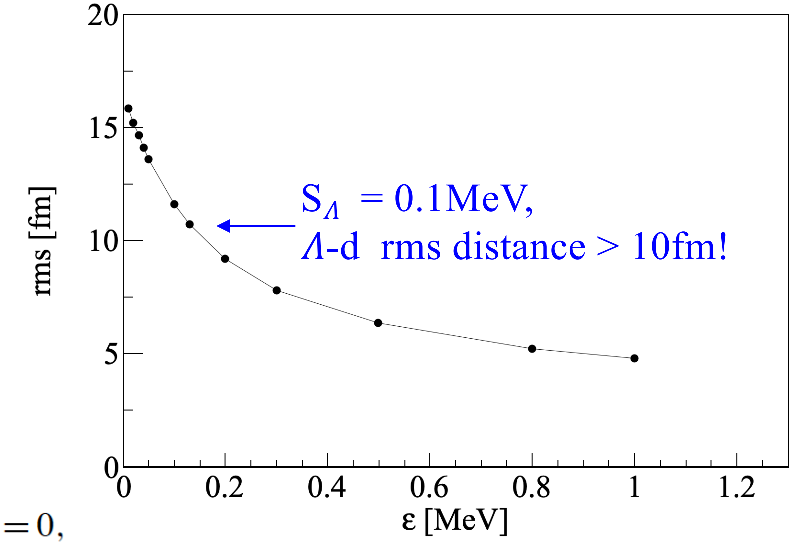
$$\frac{d^2R(r)}{dr^2} + \frac{2\mu}{\hbar^2}\left[E - U(r) - \frac{l(l+1)\hbar^2}{2\mu r^2}\right]R(r) = 0,$$

$$U(r) = -V_0 f(r)$$

- ☐ s-wave, $l = 0$

$$f(r) = [1 + \exp(\tfrac{r-R}{a})]^{-1}$$

Three-body model by E. Hiyama *et al*., PRC 53 (1996)

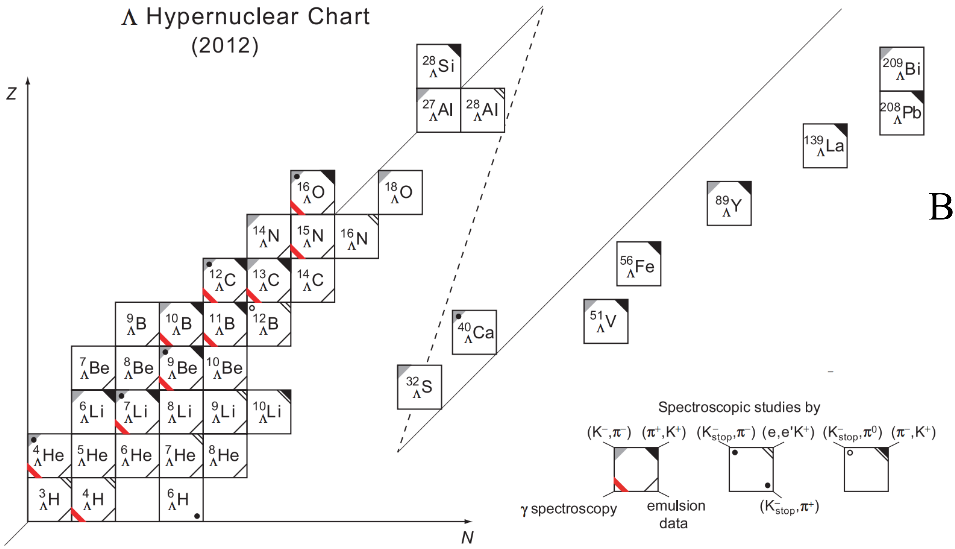


S$_{\Lambda}$ = 0.1MeV,
Λ-d rms distance > 10fm!

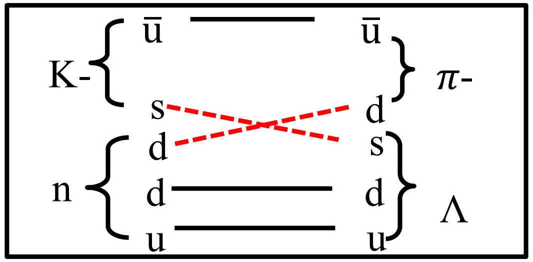
→How do we measure the radius of 3LH?

Hypernuclei production and decay

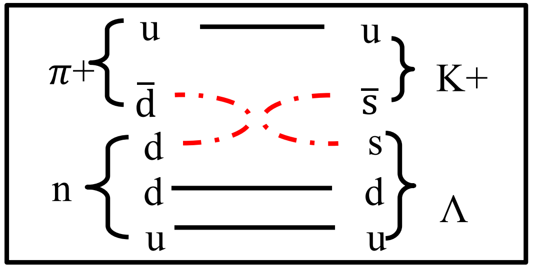
Hypernuclei chart



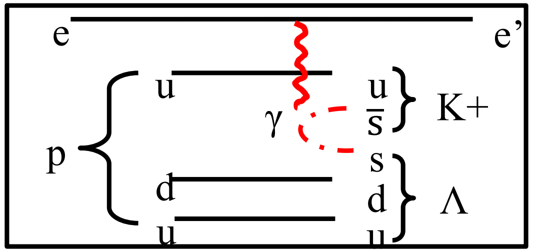
❑ K/π/e⁻ beam + fixed target. Missing mass method



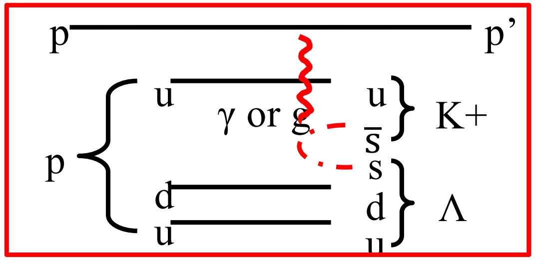
BNL, KEK, INFN(FINUDA) (K-, π-)



BNL, KEK (π+, K+)



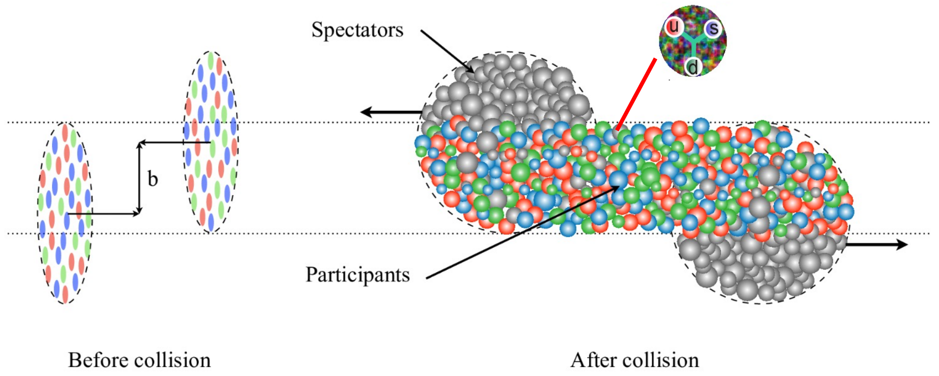
Jlab (e, e'K+)

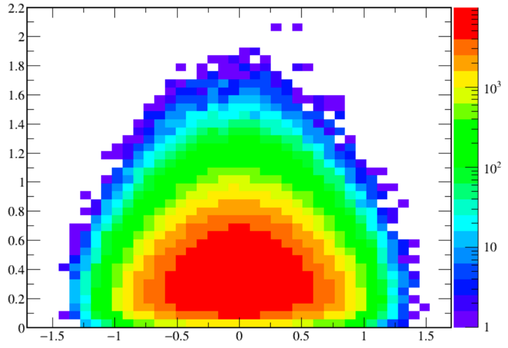


CERN (ALICE)、BNL(STAR)
GSI(HypHI)
Heavy-ion beam induced reactions

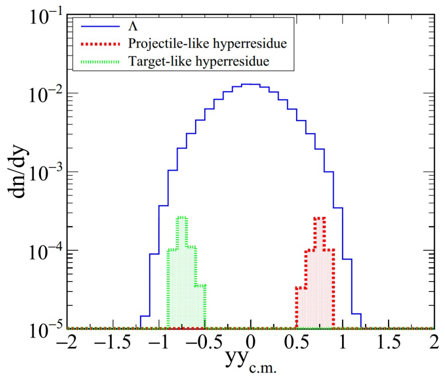
❑ Heavy ion beam collisions → Invariant mass method

Hypernuclei production from Heavy-ion collisions





P_t vs Rapidity



YLS et al., PRC 98, 024903 (2018)

Strong interaction

- ☐ NN → N + Λ + K^+ (>=1.58GeV/nucleon)
- ☐ πN→ Λ + K^+ (>=0.76GeV/nucleon)

- ☐ Λ has a broad phasespace distribution
- ☐ Mid-rapidity region: ALICE/STAR
- ✓ $|y| < 0.5$
- ✓ Light hypernuclei
- ☐ Projectile-rapidity region: HypHI@GSI
- ✓ y~1
- ✓ Projectile-like (light&heavy) hypernuclei

The simplest hypernuclei: 3LH

Mesonic decay:

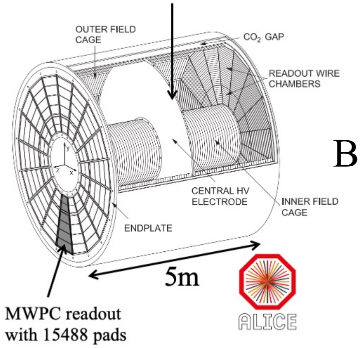
～20%	${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^{-}$	${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{H} + \pi^{0}$
～40%	${}^{3}_{\Lambda}\mathrm{H} \to {}^{2}\mathrm{H} + p + \pi^{-}$	${}^{3}_{\Lambda}\mathrm{H} \to {}^{2}\mathrm{H} + n + \pi^{0}$
	${}^{3}_{\Lambda}\mathrm{H} \to p + p + n + \pi^{-}$	${}^{3}_{\Lambda}\mathrm{H} \to n + n + p + \pi^{0}.$

Non-mesonic decay < 2%:

$${}^{3}_{\Lambda}\mathrm{H} \to {}^{2}\mathrm{H} + n$$

$${}^{3}_{\Lambda}\mathrm{H} \to n + n + p.$$

-100kV



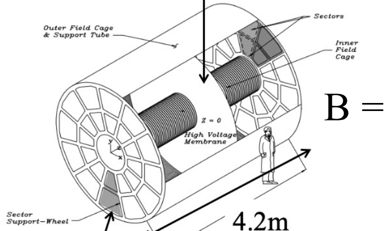
B = 0.5T

MWPC readout
with 15488 pads

Pb-Pb@$\sqrt{SNN}$ = 5TeV

PRL 131, 102302 (2023)

-28kV



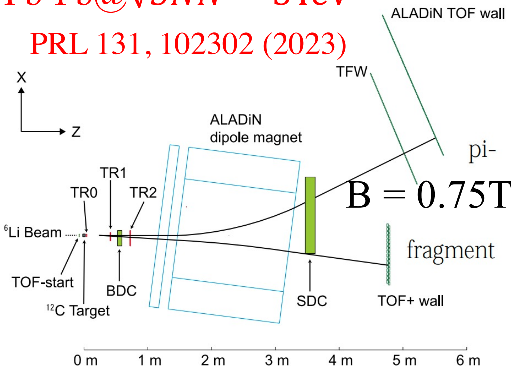
B = 0.5T

MWPC readout
with 5692 pads

STAR

Au-Au@$\sqrt{SNN}$ = 200GeV

Nature Physics 16, 409–412 (2020)



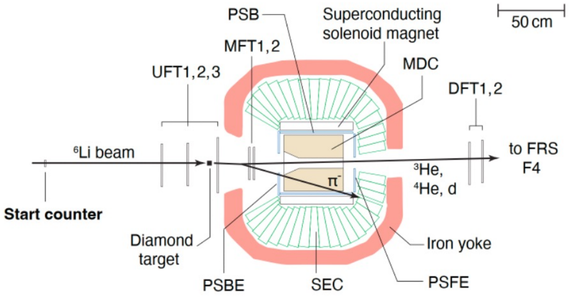
pi-

B = 0.75T

fragment

HypHI phase0 ^{6}Li+^{12}C@2GeV/nucleon

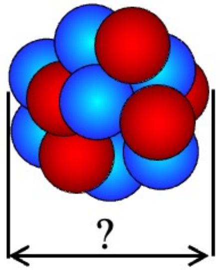
NPA 913 (2013) 170–184



WASA-FRS

B ~1.0 T

Transmission method



Interaction cross section:
proton and/or neutron removal

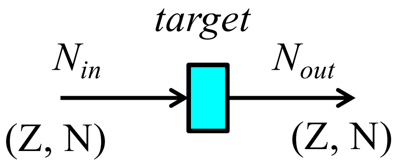
- ☐ $N_{out} = N_{in}*\mathrm{Exp}(-\sigma_{I}*N_t)$
- ☐ $\boldsymbol{\gamma} = N_{out}/N_{in.}$ $(\boldsymbol{\gamma} < 1)$
- ➢ $\sigma_I = (1/N_t)\log(1/\boldsymbol{\gamma})$

- ☐ Consider reaction loss on non-target material
- ☐ $\boldsymbol{\gamma}_0$ is the ratio of empty target run
- ➢ $(\boldsymbol{\gamma} < \boldsymbol{\gamma}_0)$
- ➢ $\sigma_I = (1/N_t)\log(\boldsymbol{\gamma}_0/\boldsymbol{\gamma})$

⊕

Model the link Raidus with $\boldsymbol{\sigma}_I$, eg:

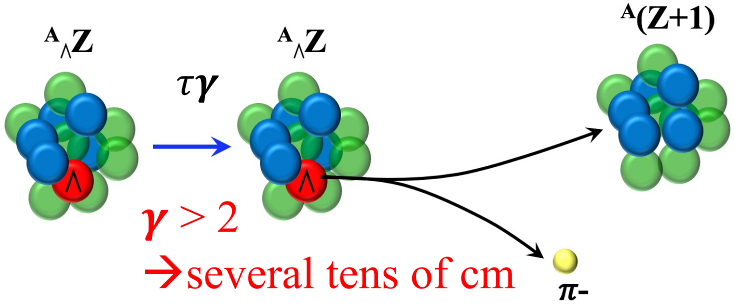
$\sigma_I(p, t) = \boldsymbol{\pi}[R_I(p) + R_I(t)]^2$
$\rightarrow R_I(p) = \mathrm{sqrt}(\sigma_I/\boldsymbol{\pi}) - R_I(t)$
$R_I(^{12}C) = 2.61\mathrm{fm}$



N_t

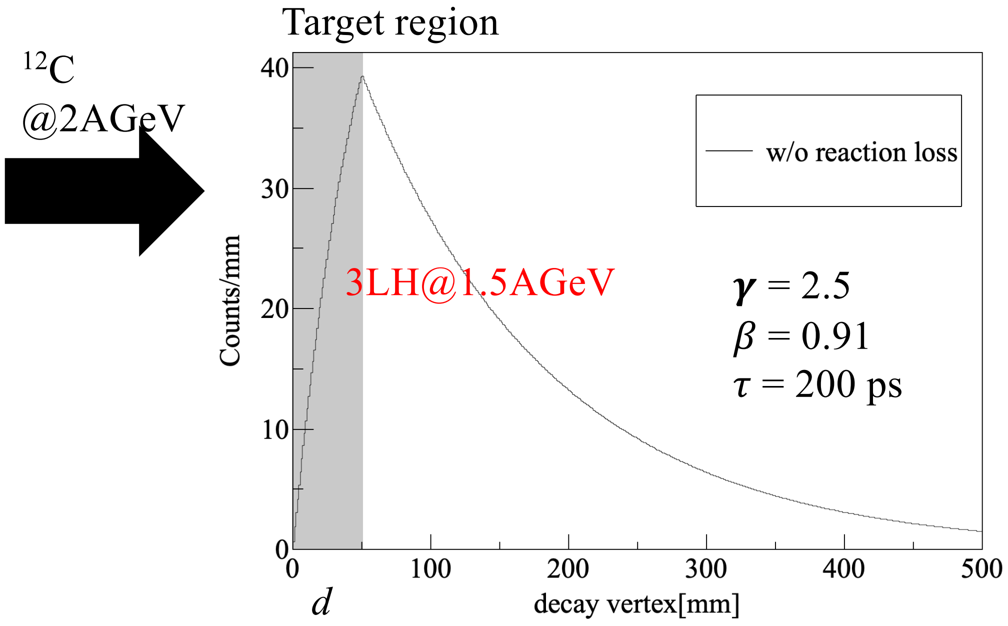
"Transmission method"

→Applicicable to hypernuclei ?
Difficulty: short lifetime (~200ps)
no hypernuclei beam ☹



$\boldsymbol{\gamma} > 2$
→several tens of cm

Two-target method



N_0: Beam number

n: target density

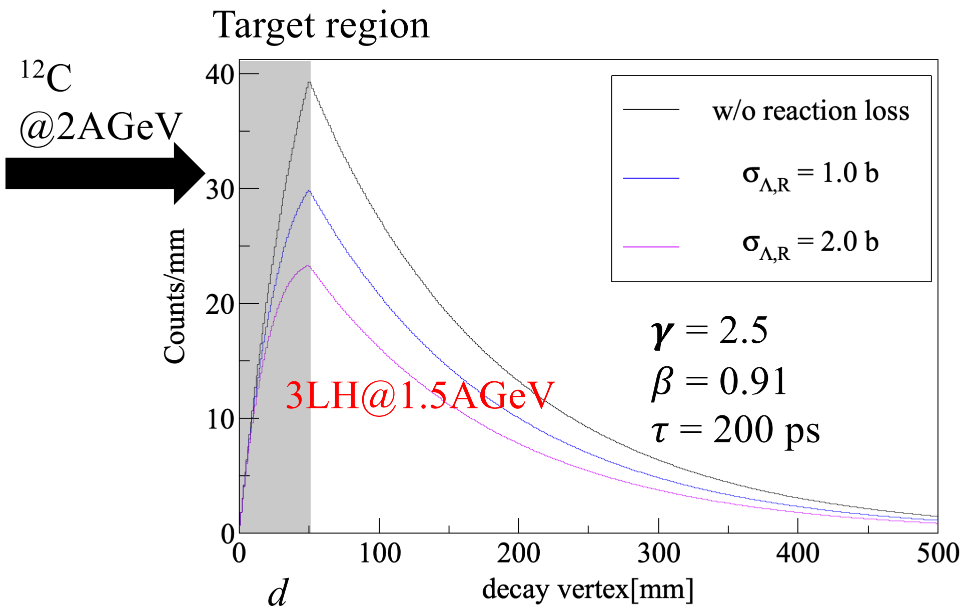
σ_Λ : hypernuclei production cross section

σ_R : Beam reaction cross section

τ: hypernuclei lifetime

$$N_\Lambda(z) = \frac{n\sigma_\Lambda N_0}{\frac{1}{\gamma\beta c\tau} - n\sigma_R}\left(e^{-n\sigma_R z} - e^{-(\frac{1}{\gamma\beta c\tau})z}\right)$$

Two-target method



N_0: Beam number
n: target density
σ_{Λ} : hypernuclei production cross section
σ_R : Beam reaction cross section
$\sigma_{\Lambda, R}$: hypernuclei reaction cross section
τ: hypernuclei lifetime

Two unknowns
→ Two measurements
with different target thickness

$$N_{\Lambda}(z) = \frac{n\sigma_{\Lambda}N_0}{\frac{1}{\gamma\beta c\tau} + n\sigma_{\Lambda R} - n\sigma_R}\left(e^{-n\sigma_R z} - e^{-\left(\frac{1}{\gamma\beta c\tau} + n\sigma_{\Lambda R}\right)z}\right)$$

S. Velardita, ... YLS, Eur. Phys. J. A, 59:139 (2023)

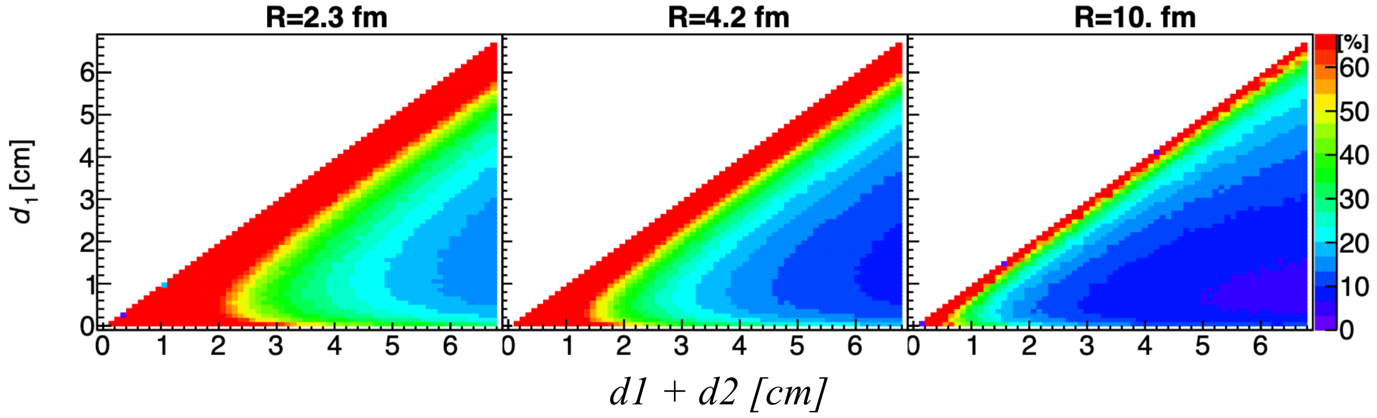
Two-target method

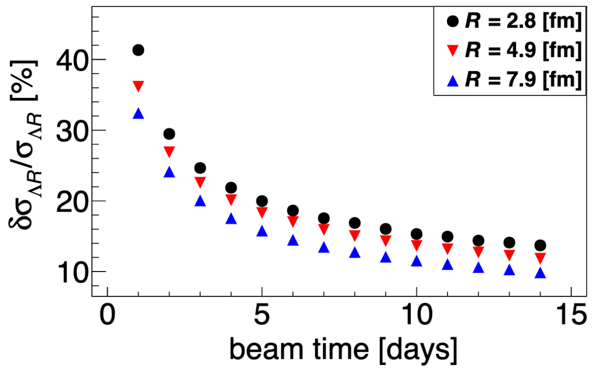
- ❑ Two measurements with target thickness d1 and d2

$\delta\sigma_{\Lambda\mathrm{R}}/\sigma_{\Lambda\mathrm{R}}$ with $\sigma_{\Lambda} = 1.8\mathrm{ub}$, $\sigma_{\mathrm{R}} = 888 \pm 19\mathrm{mb}$, $\tau = 216 \pm 19$ ps, $\delta N_{\Lambda} = \mathrm{sqrt}(N_{\Lambda})$

- ❑ 8 days beam time, uncertainty ~15%:

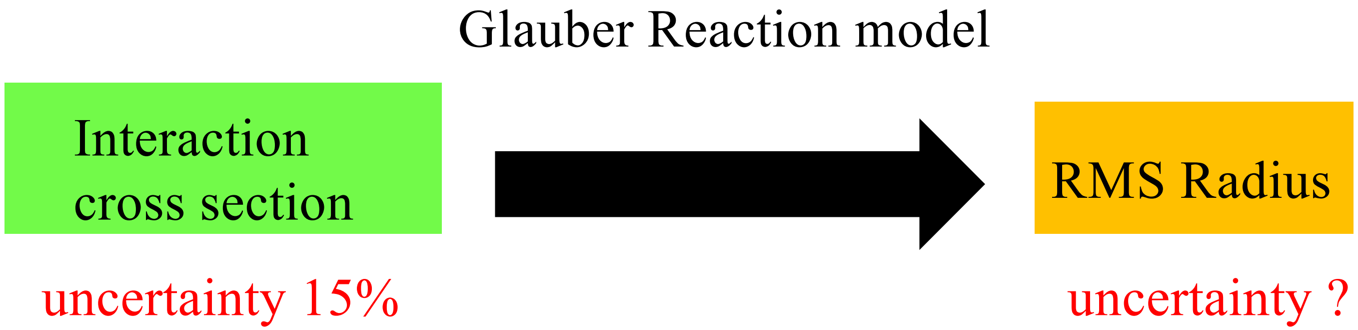
Thin target (d1 = 1cm) for the 1st measurement
Thick target (d2 = 5cm) for the 2nd measurement





S. Velardita, ... YLS, Eur. Phys. J. A, 59:139 (2023)

Two-target method



Glauber Reaction model

Interaction cross section

uncertainty 15%

RMS Radius

uncertainty ?

Glauber model

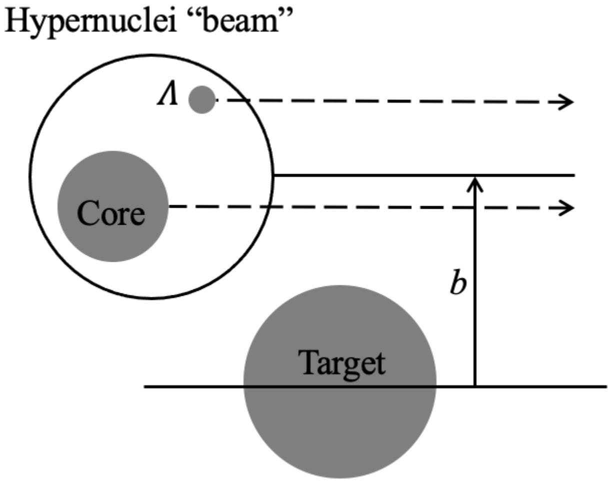
$$\sigma_{\mathrm{reac}}(\mathrm{P}+\mathrm{T}) = \int \mathrm{d}\boldsymbol{b}\left(1-\left|\mathrm{e}^{\mathrm{i}\chi_{\mathrm{PT}}(\boldsymbol{b})}\right|^2\right) \quad \text{with} \quad \mathrm{e}^{\mathrm{i}\chi_{\mathrm{PT}}(\boldsymbol{b})} \to \left\langle \varphi_0 \middle| \mathrm{e}^{\mathrm{i}\chi_{\mathrm{CT}}(\boldsymbol{b}_{\mathrm{C}})+\mathrm{i}\chi_{\mathrm{NT}}(\boldsymbol{b}_{\mathrm{C}}+\boldsymbol{s})} \middle| \varphi_0 \right\rangle$$

$$\mathrm{i}\chi_{\mathrm{CT}}(\boldsymbol{b}) = -\int \mathrm{d}\boldsymbol{r} \int \mathrm{d}\boldsymbol{r}'\, \rho_{\mathrm{C}}(\boldsymbol{r})\rho_{\mathrm{T}}(\boldsymbol{r}')\Gamma(\boldsymbol{b}+\boldsymbol{s}-\boldsymbol{s}')$$

→ NN interaction, density of the core and target

$$\mathrm{i}\chi_{\mathrm{NT}}(\boldsymbol{b}) = -\int \mathrm{d}\boldsymbol{r}\, \rho_{\mathrm{T}}(\boldsymbol{r})\Gamma(\boldsymbol{b}-\boldsymbol{s}).$$

→ ΛN interaction, density of target



χ: phase shift function
Γ: profile function

$$\Gamma(\boldsymbol{b}) = \frac{1-\mathrm{i}\alpha}{4\pi\beta}\sigma_{\mathrm{NN}}\mathrm{e}^{-\boldsymbol{b}^2/2\beta} \quad \text{(finite range)},$$

$$\Gamma(\boldsymbol{b}) = \frac{1-\mathrm{i}\alpha}{2}\sigma_{\mathrm{NN}}\delta(\boldsymbol{b}) \quad \text{(zero range)}.$$

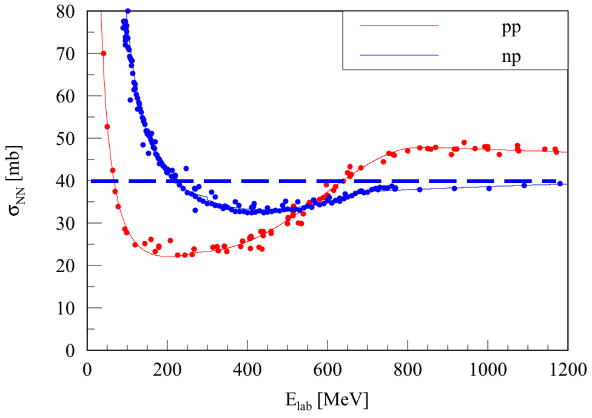
B. Abu-Ibrahim *et al.*, CPC 151 (2003) 369–386

Glauber model

❑ ΛN total cross section

	$\sigma(\Lambda p)$ [mb]	$\sigma(\Lambda n)$ [mb]
1– 5 GeV/c	35	---
6 – 21 GeV/c	34.6(4)	34.0(8)

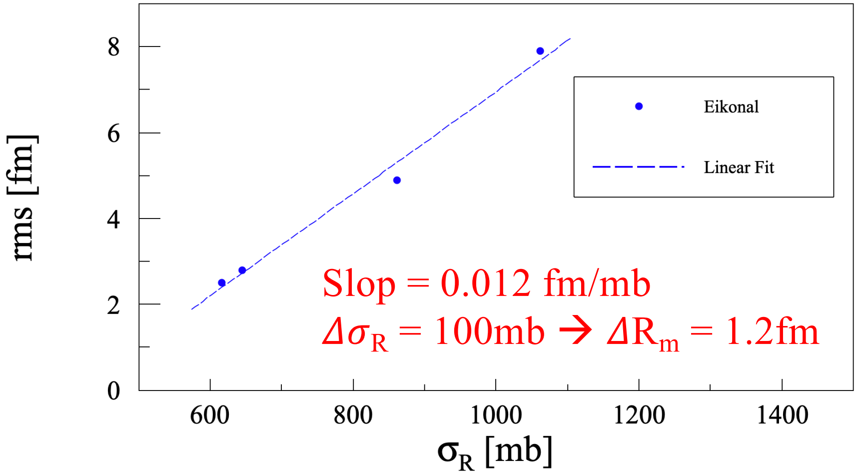
S. Gjesdal et al. Phys. Lett. B, 40:152–156, (1972)
D. Bassano et al. Phys. Rev., 160:1239–1244, (1967)



❑ Density distribution from pionless EFT

[1] F. Hildenbrand and H.-W. Hammer, PRC 100, 034002 (2019)

Separation energy [keV]	RMS [fm] pionless EFT [1]	Cross section [mb] Glauber Model
500	2.5	616
410	2.8	645
130	4.9	861
50	7.9	1062



Slop = 0.012 fm/mb
$\Delta\sigma_R$ = 100mb → ΔR_m = 1.2fm

Uncertainty estimation

3LH + ^{12}C at 1.5GeV/nucleon

Separation energy [keV]	**RMS [fm]** [1]	σ_R**[mb]** Glauber Model	$\Delta\sigma_R$ **15%** [mb]	Δ**RMS** [fm]	ΔRMS/RMS
500	2.5	616	92	1.1	44%
410	2.8	645	97	1.2	43%
130	4.9	861	129	1.5	31%
50	7.9	1062	159	1.9	24%

[1] pionless EFT, F. Hildenbrand and H.-W. Hammer, PRC 100, 034002 (2019)

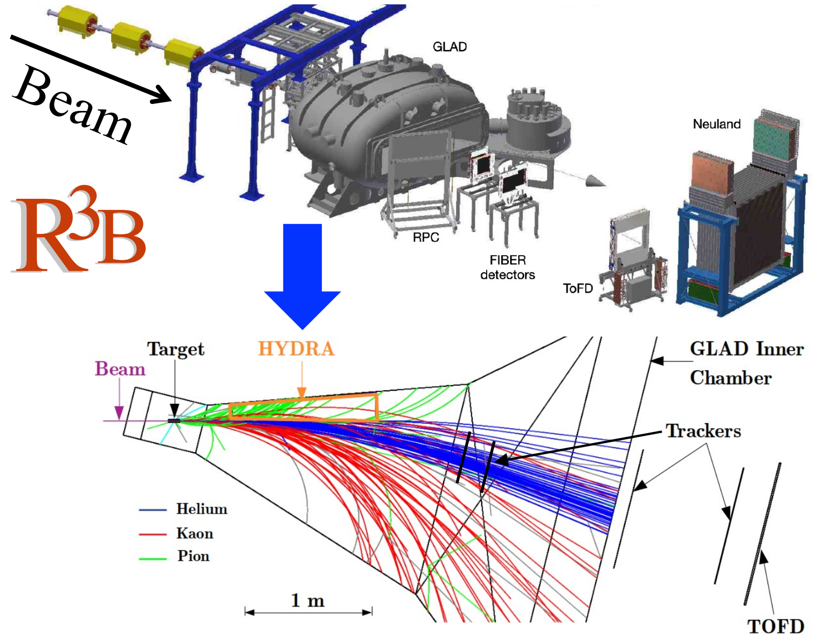
HYDRA (Hypernuclei Decay R^{3}B Apparatus)

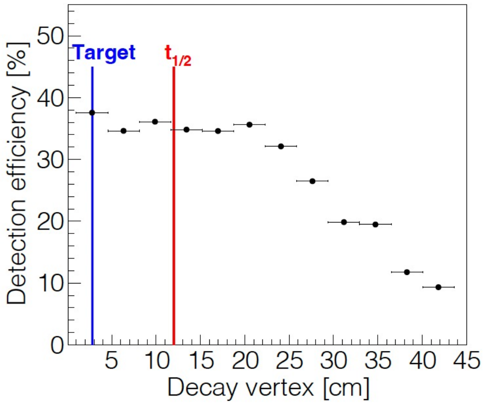
Invariant mass method

- ❑ R^{3}B spectrometer to measure heavy fragments
- ❑ A TPC in GLAD(2T) to measure π-

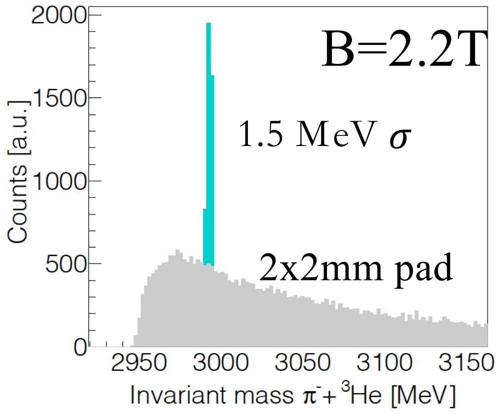
Uniquness:

- ❑ High beam intensity (avoid beam at 0deg)
- ❑ Neutron-rich hypernuclei production with neutron rich secondary beam



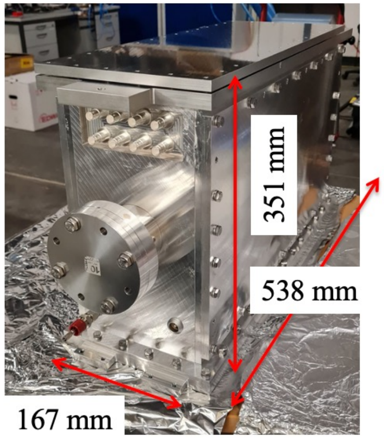


π detection eff～30%

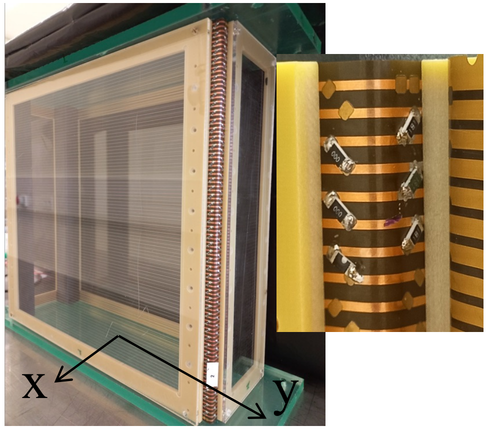


ALICE/STAR: 0.5T
HypHI: ~1T

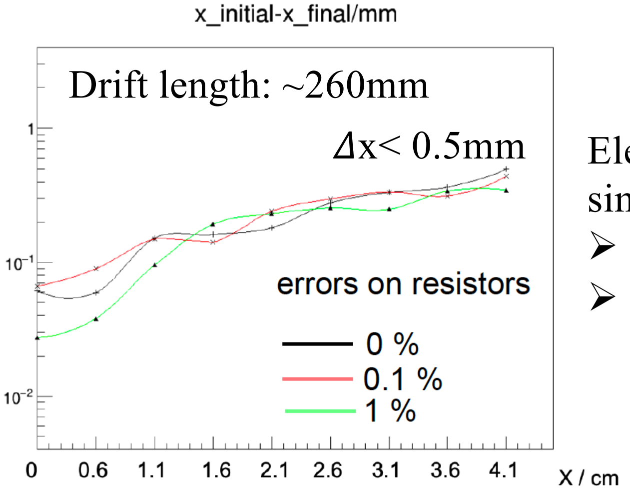
HYDRA Prototype



- TPC chamber



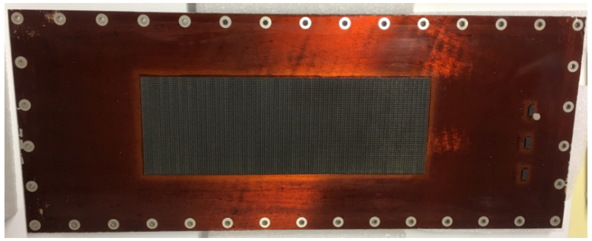
- Double layered wire field cage
- 256x256x88mm
- Wire gap 3mm
- 1 MΩ resistor chain



Electron drfit (GARFIELD simulation)

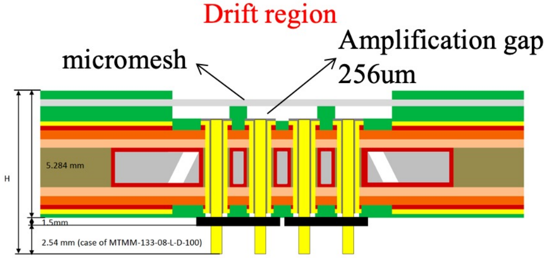
- 250 V / cm
- 96% Ar + 2% iC4H10 + 2% CF4

Liancheng Ji @ TUDa



- Anode pad plane

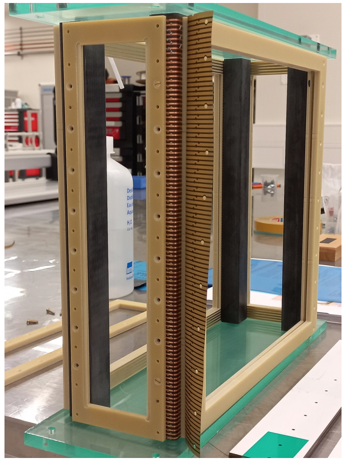
Metal-core pad plane
6-mm Al (<50um);
Pitch 2 mm
5632 pads (2 *2 mm^2)

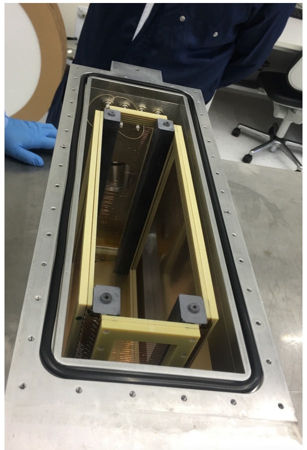


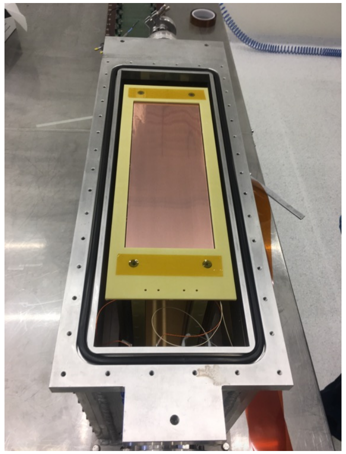
J. Giovinazzo *et al.*, NIMA 892 (2018) 114–121

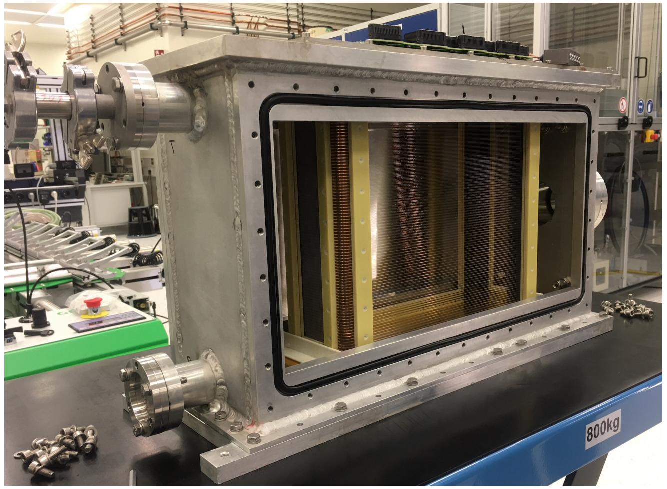
In collaboration with:
S. Ota from CNS (Field cage design)
H. Joerg from GSI (Field cage contruction)
J. Pibernat from CENBG (Pad plane design)
Rui De Oliveira from CERN (pad plane construction)

HYDRA Prototype



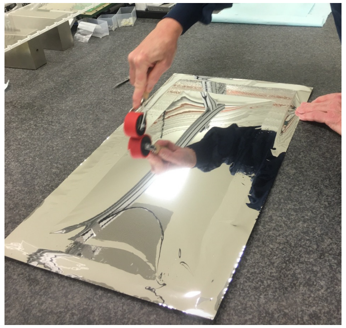


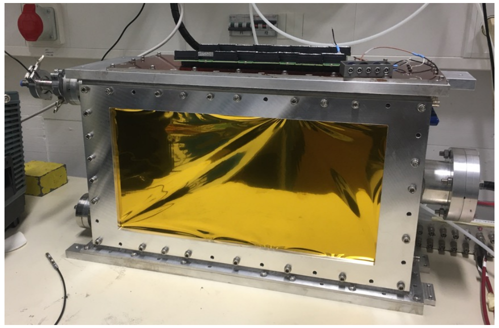




Assembly@GSI clean room

1） Field cage pilars and wired PCBs
2） Field cage in the chamber
3） GEM installation (GEM+MM to reduce IBF)
4） Anode pad plane
5） Kapton window

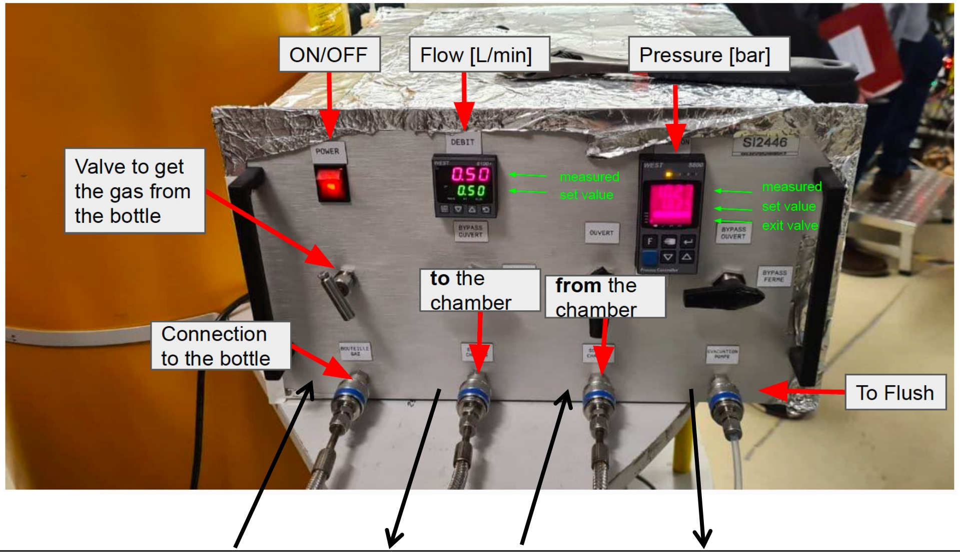




Gas controller

BROOKS SLA5800
mass flow and pressure controller

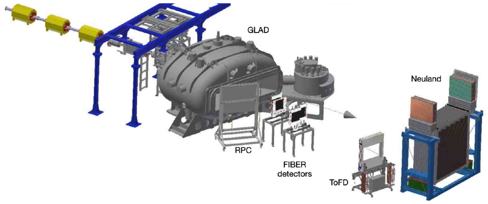
- ☐ Pre mixed 96% Ar + 2% iC4H10 + 2% CF4
- ☐ Based on R3B/MUSICgas system (CEA/T. Julien)
- ☐ Gas flow and pressure regulator
- ☐ ~1.01bar

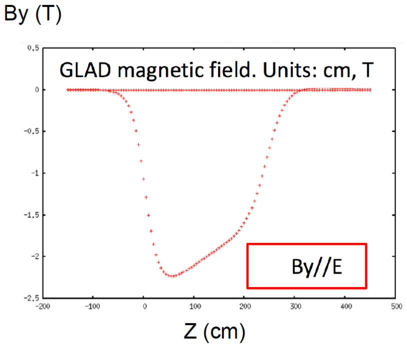


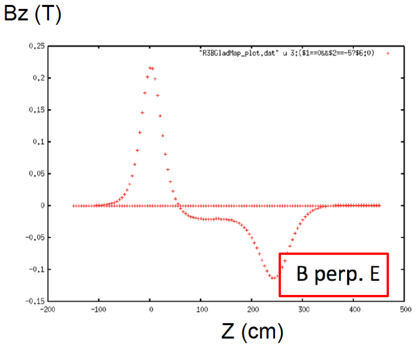
Gas mixture	Proportion	Drift velocity [cm/μs]	Transversal diffusion [μm/ √cm]	Longitudinal diffusion [μm/ √cm]
Ar-CF4-iC4H10	95/1/4	5.5	110	250
	96/2/2	7	90	225
Ar-C3F8-iC4H10	96/1/3	6	105	250
Ar-Xe-iC4H10	92/6/2	5.5	110	250
Ar-C3F8	98/2	7.5	80	225
Ar-C2F6-iC4H10	95/1/4	5.5	105	250
Ar-CF4-CO2	97/1/2	5	125	275
Ar-iC4H10	95/5	4.25	140	275
Ar-neoC5H12	95/5	4.75	130	275

@E=250V/cm and B=2T

Laser calibration system



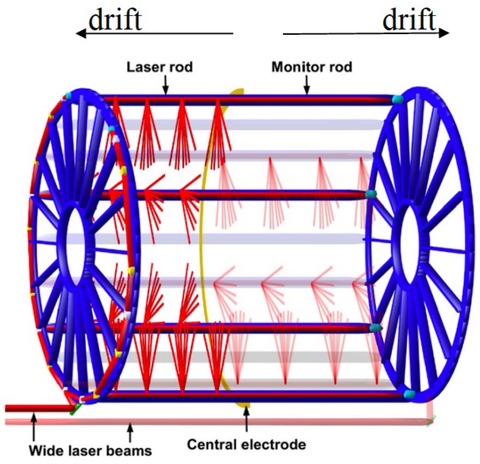




- ☐ Non-uniform B filed
  - ➢ Pion trajectory distoration
  - ➢ Drift electron trajectory distoration

Reference track for calibration

- ☐ Technique used in ALICE/STAR TPC
- ☐ Drift velocity calibration
- ☐ TPC stability
- ☐ Trajectory distoration due to E/B field non-uniformity



Laser system for ALICE TPC
NIMA 622 (2010) 316–367

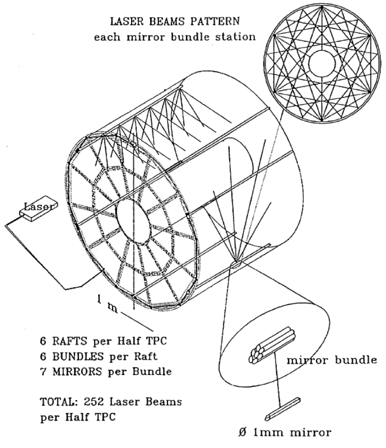
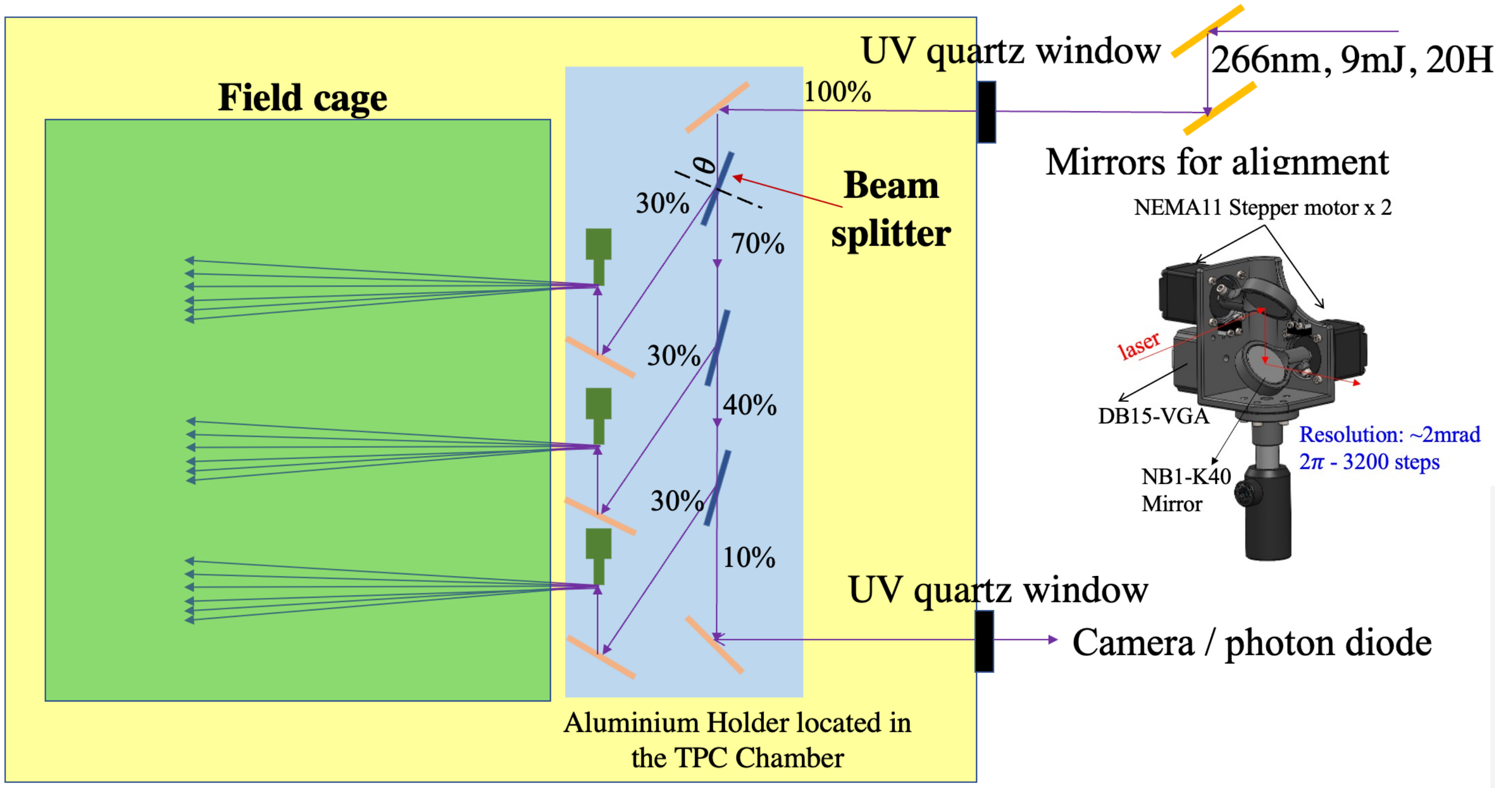


Fig. 1. Conceptual design of the laser system.

Laser system for STAR TPC
NIMA 478 (2002) 163–165

Laser calibration system



Viron Nd:YAG laser

Thorlabs VPCH42/NB1

UV converter + CMOS camera

❑ All coated for reflection or tranparency of 266 nm laser

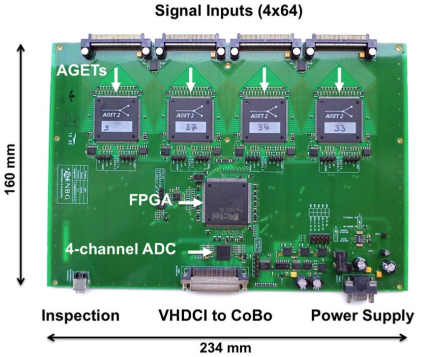
Reacout electronics

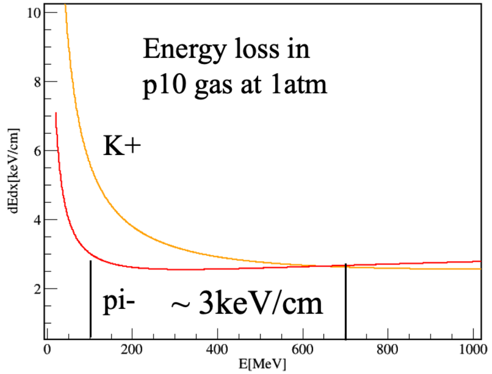
- ☐ Energy loss of pion in gas ~ 3keV/cm→ ~ 20e/pad
- ☐ x 5000 gain → 16fC/channel

TPC test (with laser)   Experiment

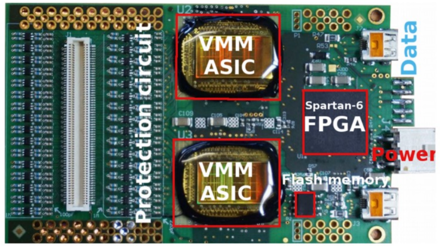
	Phase 1 prototype	phase 2 of prototype, HYDRA
	GET/AGET	SRS/VMM
Channels/chip	64 (256 per AsAd)	64 (128 per Hybrid)
max channel support	1024 with zCoBo (WU)	no limit (16k/crate)
Input range	10pC /1pC / 120 fC	2pC – 60fC (8 values)
Charge gain	0.2 / 2 / 16 mv/fC	0.5 -16 mv/fC
shaping time	50ns – 1us (16 values)	25 – 200 ns
Time resolution	1 ns	1 ns
ENC	850 e- at 30pF	300e- at 30pF
output	waveform	time/amplitude
readout rate	1 kHz	4 MHit/ch, 12 MHit/FEC
ADC bit	12 bit	8bit for time, 10bit for peak
Triggered	yes	optional

- ☐ GET/AGET



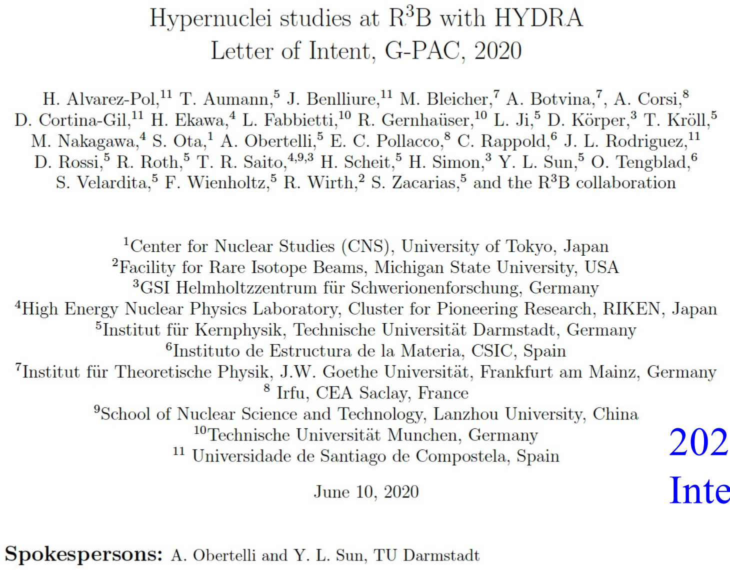


- ☐ SRS/VMM3a (RD51 collaboration)



- ☐ gain~5000
- ☐ laser: 8 fC/channel
- ☐ π: 16 fC/channel
- ☐ GET system 1024 ch multiplexing readout
- ☐ SRS system 5632 ch 88 VMM3a chips

HYDRA Collaboration



Hypernuclei studies at R^{3}B with HYDRA
Letter of Intent, G-PAC, 2020

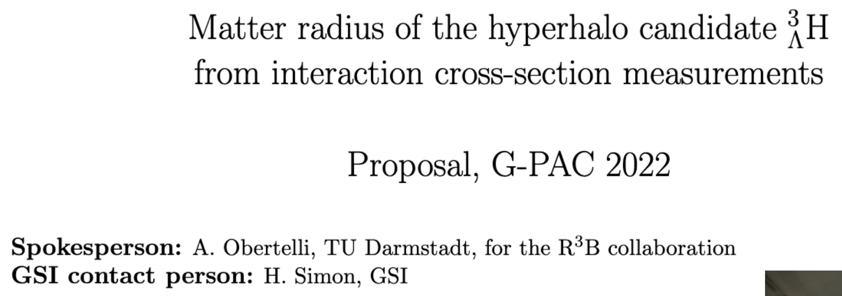
H. Alvarez-Pol,[11] T. Aumann,[5] J. Benlliure,[11] M. Bleicher,[7] A. Botvina,[7], A. Corsi,[8] D. Cortina-Gil,[11] H. Ekawa,[4] L. Fabbietti,[10] R. Gernhaüser,[10] L. Ji,[5] D. Körper,[3] T. Kröll,[5] M. Nakagawa,[4] S. Ota,[1] A. Obertelli,[5] E. C. Pollacco,[8] C. Rappold,[6] J. L. Rodriguez,[11] D. Rossi,[5] R. Roth,[5] T. R. Saito,[4,9,3] H. Scheit,[5] H. Simon,[3] Y. L. Sun,[5] O. Tengblad,[6] S. Velardita,[5] F. Wienholtz,[5] R. Wirth,[2] S. Zacarias,[5] and the R^{3}B collaboration

[1]Center for Nuclear Studies (CNS), University of Tokyo, Japan
[2]Facility for Rare Isotope Beams, Michigan State University, USA
[3]GSI Helmholtzzentrum für Schwerionenforschung, Germany
[4]High Energy Nuclear Physics Laboratory, Cluster for Pioneering Research, RIKEN, Japan
[5]Institut für Kernphysik, Technische Universität Darmstadt, Germany
[6]Instituto de Estructura de la Materia, CSIC, Spain
[7]Institut für Theoretische Physik, J.W. Goethe Universität, Frankfurt am Mainz, Germany
[8] Irfu, CEA Saclay, France
[9]School of Nuclear Science and Technology, Lanzhou University, China
[10]Technische Universität Munchen, Germany
[11] Universidade de Santiago de Compostela, Spain

June 10, 2020

Spokespersons: A. Obertelli and Y. L. Sun, TU Darmstadt

LOI submitted in 2020
31 collaborators from 11 institutes



Matter radius of the hyperhalo candidate $^{3}_{\Lambda}$H
from interaction cross-section measurements

Proposal, G-PAC 2022

Spokesperson: A. Obertelli, TU Darmstadt, for the R^{3}B collaboration
GSI contact person: H. Simon, GSI

Proposal submitted for G-PAC 2022

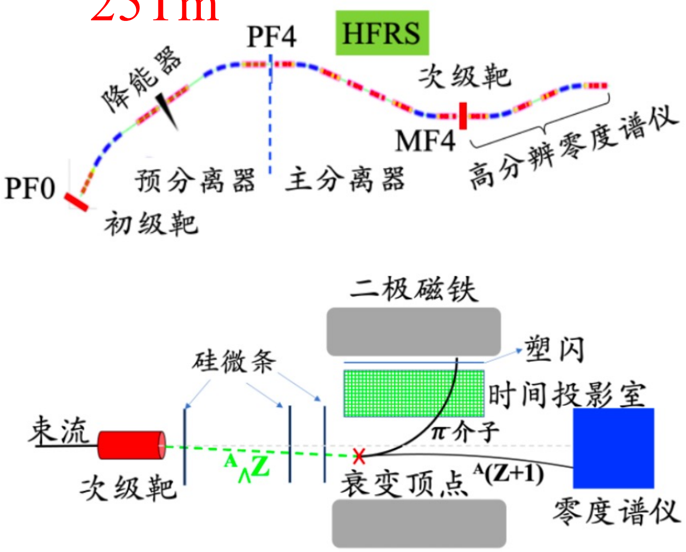
2022-10-21, Ranked as A, 34 shifts (11days) granted!
Interaction cross section of 3LH+C

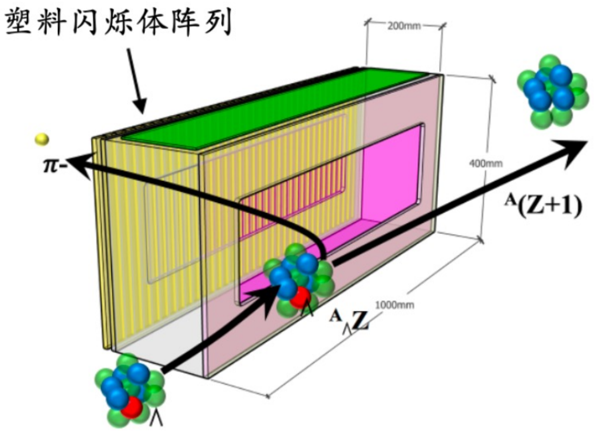
Laser test in GLAD: 2023-Nov.
Experiment expected: 2025 Feb.

Laser test in GLAD

Perspectives: Hypernuclei study based on HFRS@HIAF

25Tm



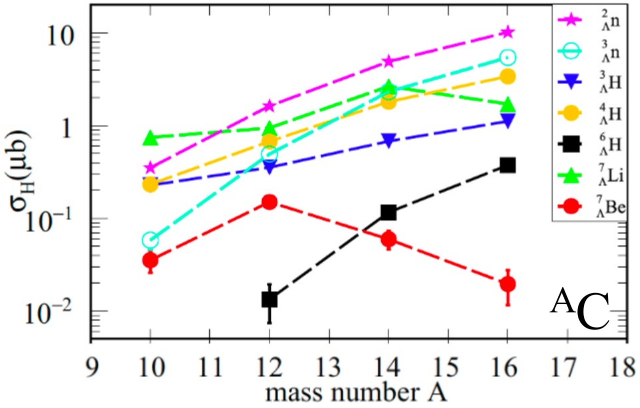


$^{A}_{\Lambda}Z \rightarrow \pi^- + {}^{A}(Z+1)$

25Tm, world highest energy secondary beam line

^{12}C 2.9AGeV

^{16}C 2.0AGeV

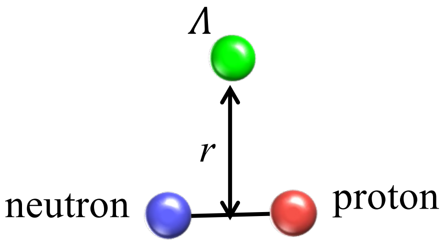


YLS et al., PRC 98, 024903 (2018)

- Possibility to study the production of neutron-rich hypernuclei with neutron-rich beams

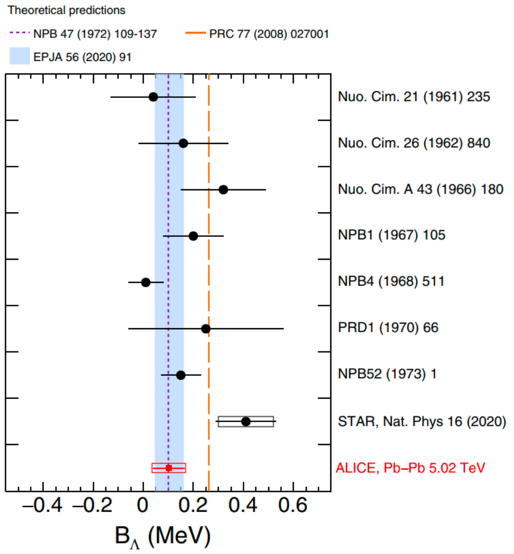
Perspectives: Coulomb breakup of 3LH ?

- ☐ E > 1.6 GeV/u
- ☐ Lightest hypernuclei 3LH
- ☐ B_Λ = ~ 100 keV vs 400keV

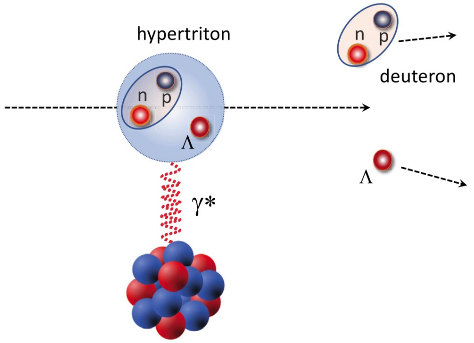


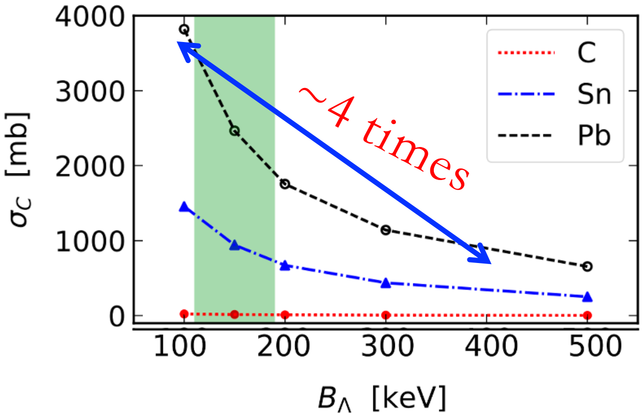
3LH: $d + \Lambda$

Lifetime or B_Λ puzzle



ALICE Collaboration, PRL 131, 102302 (2023)





C.A. Bertulani, PLB 837,137639 (2023)

Thank you for your attention!