HyperNIS-SRC Project

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Project leaders

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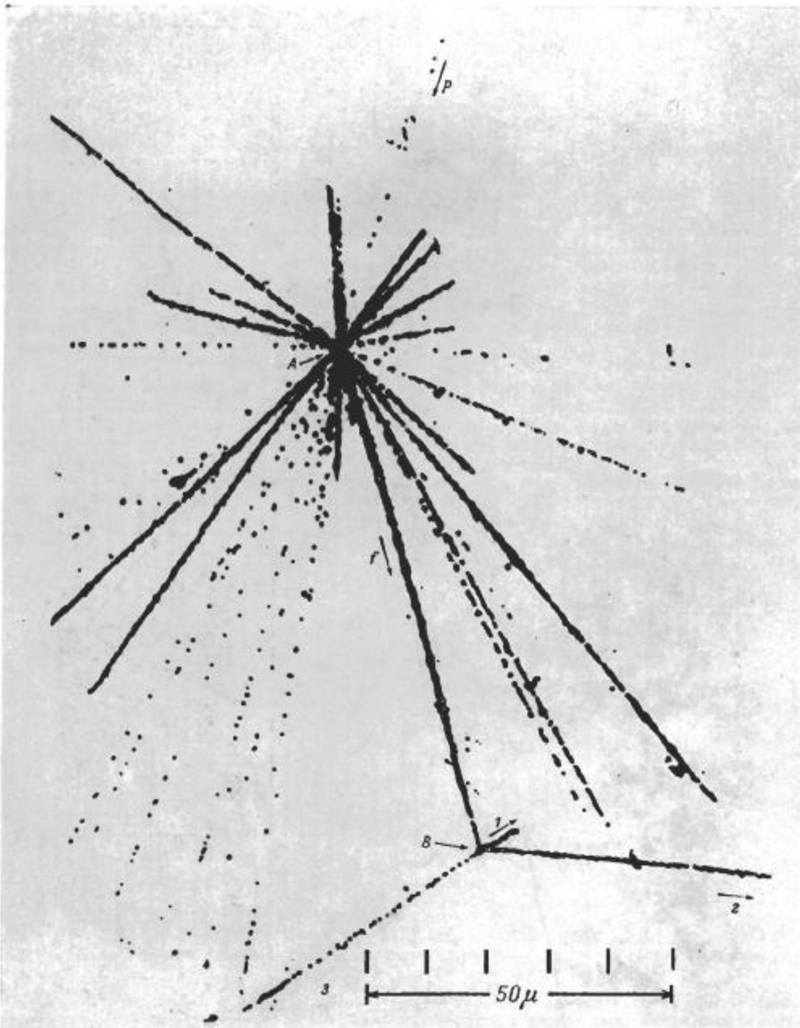
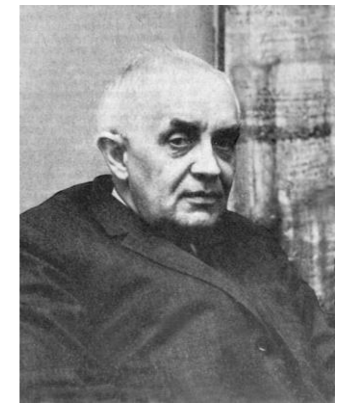
The first hypernucleus Warsaw September 1952 by Marian Danysz and Jerzy Pniewski



C.F.Powell, P.H. Fowler, D.H. Perkins
"*The study of elementary particles by the photographic method*", 1959

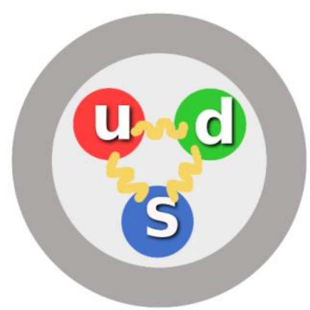
Marian Danysz



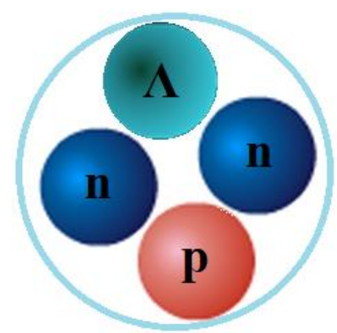
Jerzy Pniewski

Hyperon is any baryon containing one or more strange quarks

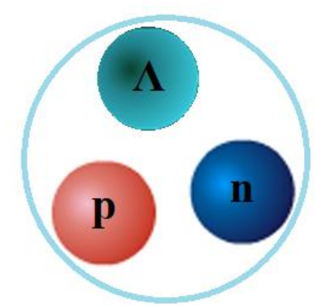
Hypernucleus is similar to a conventional atomic nucleus, but contains at least one hyperon in addition to the normal protons and neutrons



lambda baryon (Λ)



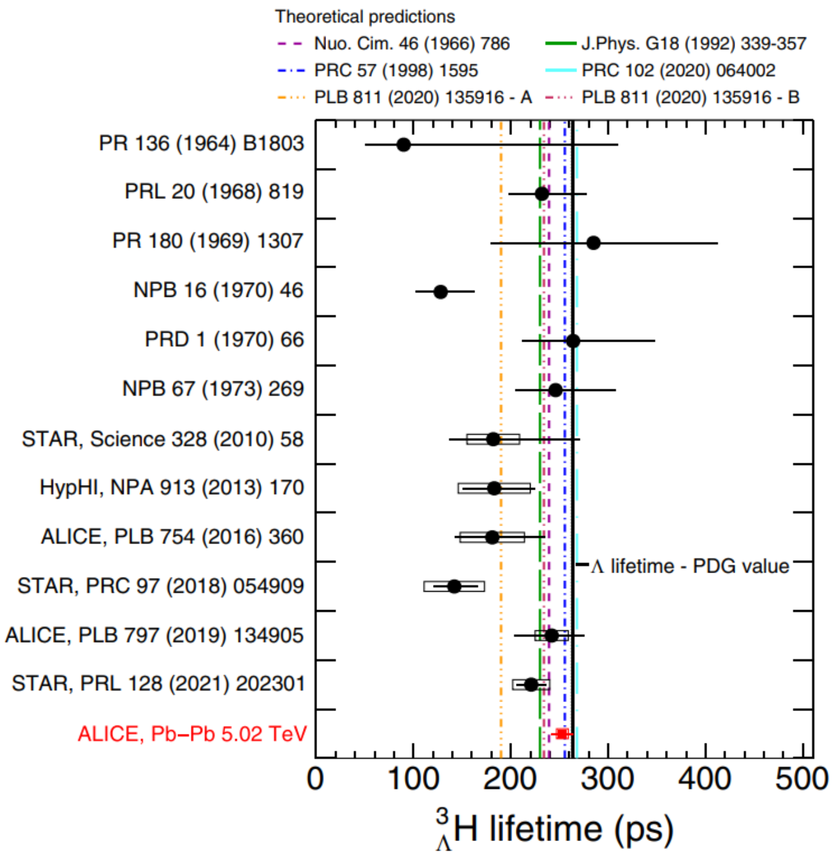
${}^{4}_{\Lambda}H$



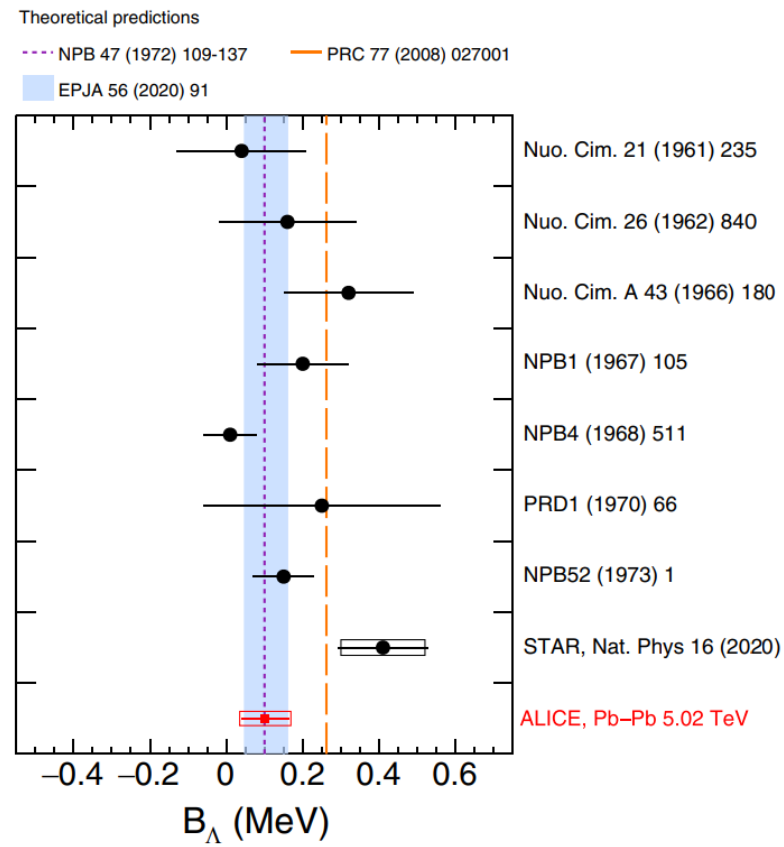
hypertriton ${}^{3}_{\Lambda}H$

Hypertriton World Data

Hypertriton Lifetime



Hypertriton B_Λ



ALICE data

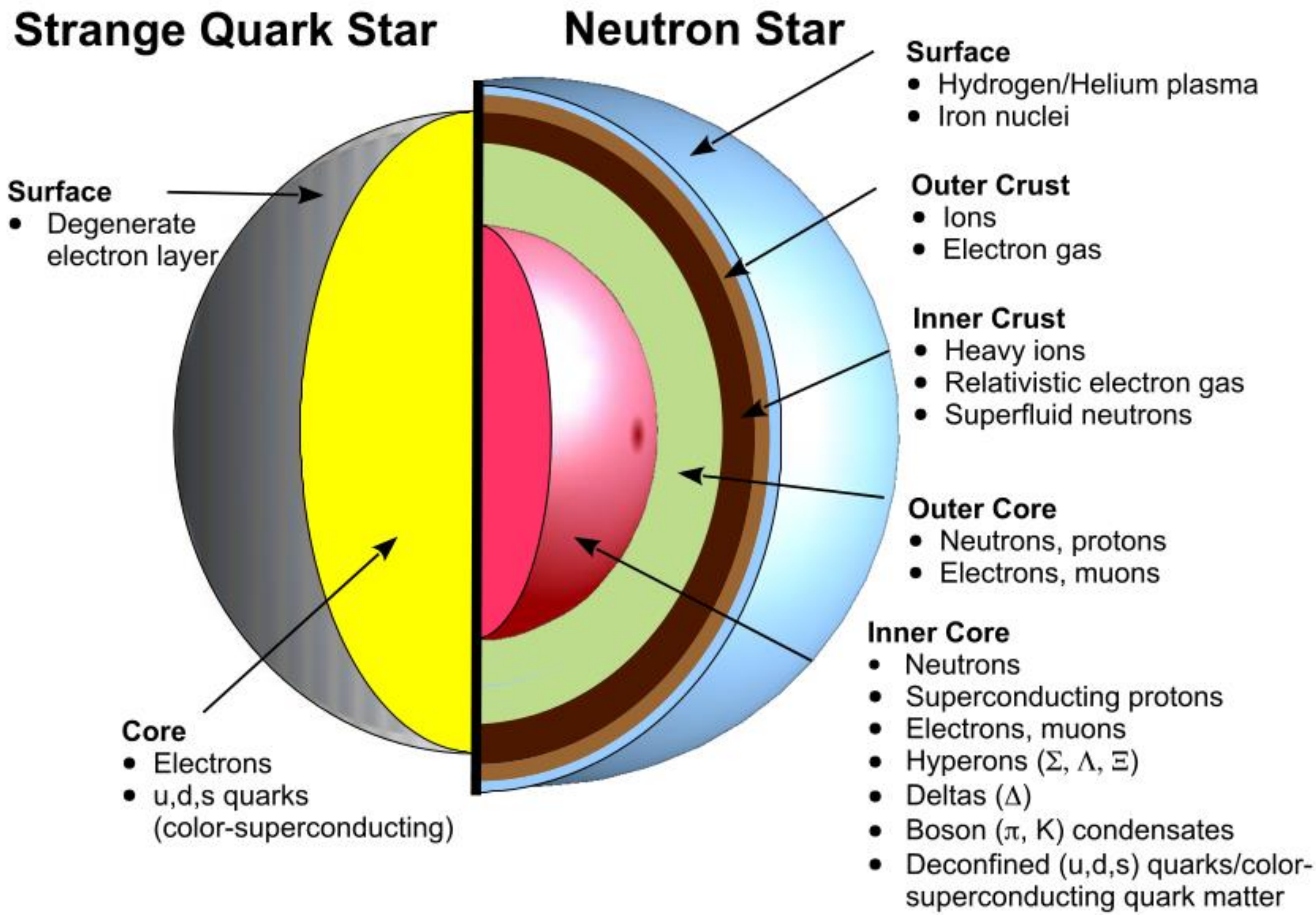
τ = [253 ± 11 (stat.) ± 6 (syst.)] ps **B_Λ = [72 ± 63 (stat.) ± 36 (syst.)] KeV**

STAR data

τ = [221 ± 15 (stat.) ± 19 (syst.)] ps **B_Λ = [410 ± 12] KeV**

(ALICE Collaboration) PHYSICAL REVIEW LETTERS 131, 102302 (2023)
DOI: 10.1103/PhysRevLett.131.102302

Hyperon Puzzle and Neutron Star



Modern Physics Letters A Vol. 29, No. 23 (2014) 1430022 (13 pages) c World Scientific Publishing Company DOI: 10.1142/S0217732314300225

Properties of high-density matter in neutron stars
Fridolin Weber et al. (2014)

How to get Hypernuclei?

- Target nucleus → hypernucleus at rest(?):

  1) Kaon beam (**Mihail Podgoretsky**) $K^- + A \rightarrow \pi^- + {}_{\Lambda}A$

  2) Stopped kaons (Frascati) $K^- + A \rightarrow \pi^- + {}_{\Lambda}A$

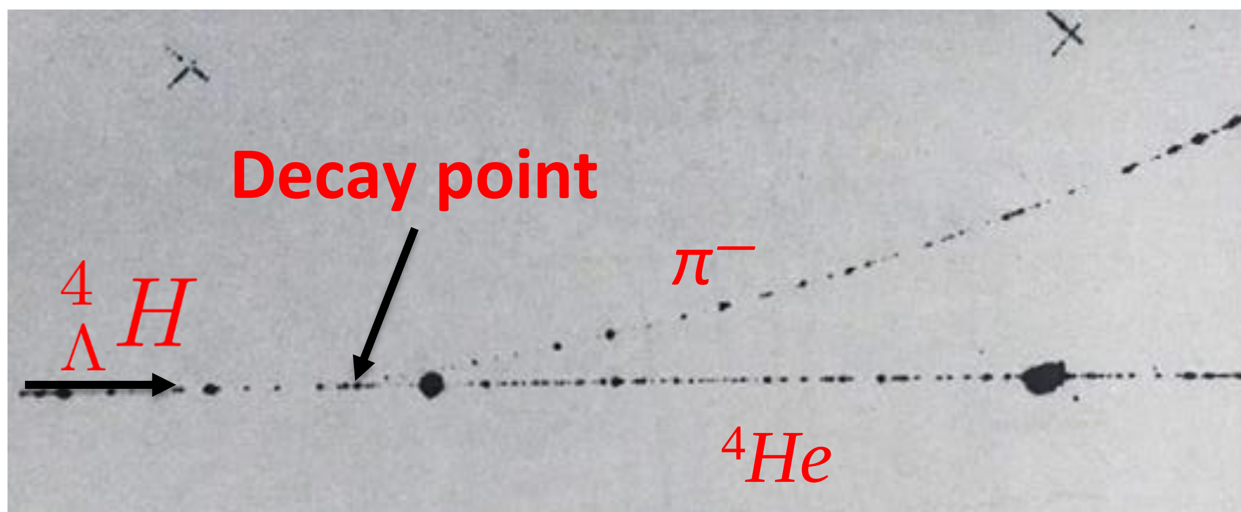
  3) Pion beam (J-Park) $\pi^+(\pi^-) + A \rightarrow K^+ + {}_{\Lambda}A$

  4) electron beam $e + A \rightarrow e + K + {}_{\Lambda}A$

- Beam nucleus or fragment → hypernucleus: **"Hypernuclear production in flight"**

  1) Method **elaborated at Dubna** $A + C \rightarrow {}_{\Lambda}A + X$

Typical image of hyper hydrogen decay in the **streamer chamber** selected by **special trigger**



Avramenko S.A. et al. Magnetic Spectrometr GIBS, P13-98-111, **Dubna, 1998**.

Goals of the Experiment (First Step)

Measurements for light hypernuclei (hydrogen, helium)

- ❑ Lifetime
- ❑ mass value
- ❑ production cross section
- ❑ search and study of extremely neutron rich hypernuclei

$$^{7}\mathrm{Li} + C \rightarrow {}^{6}_{\Lambda}\mathrm{H} + \mathrm{p} + \ldots \rightarrow {}^{6}\mathrm{He} + \pi^{-} + \ldots$$

also to be registered

$$^{7}\mathrm{Li} + C \rightarrow {}^{4}_{\Lambda}\mathrm{H} + \mathrm{d} + \ldots \rightarrow {}^{4}\mathrm{He} + \pi^{-} + \ldots$$

$$^{7}\mathrm{Li} + C \rightarrow {}^{3}_{\Lambda}\mathrm{H} + \mathrm{t} + \ldots \rightarrow {}^{3}\mathrm{He} + \pi^{-} + \ldots$$

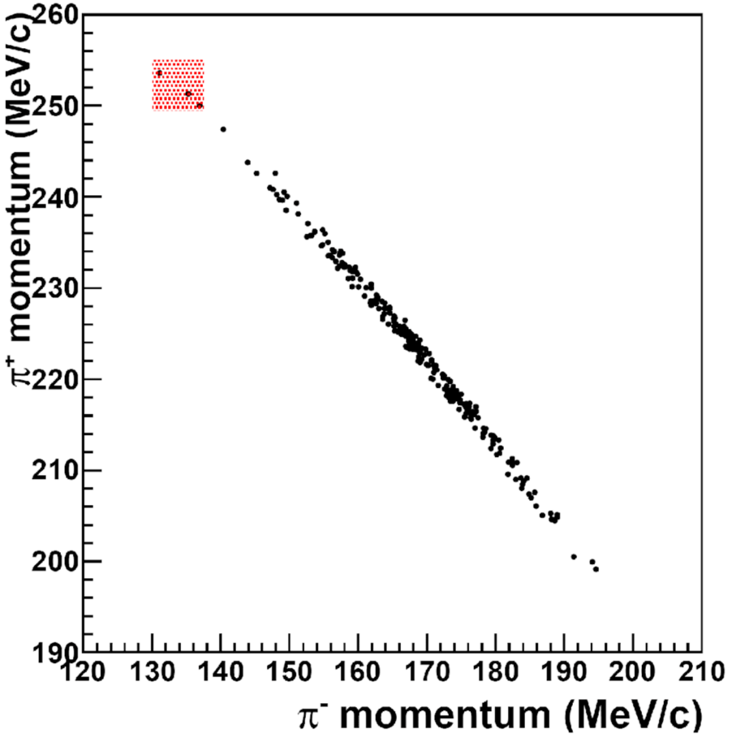
World Experimental State

Frascati points

Three candidate events of hypernuclei were observed by FINUDA collaboration

ArXiv:1112.4529v1 [nucl-ex] 19 DEC 2011

$$K^- + {}^6\mathrm{Li} \rightarrow \pi^+ + {}^6_\Lambda\mathrm{H} \rightarrow \pi^+ + \pi^- + {}^6\mathrm{He}$$



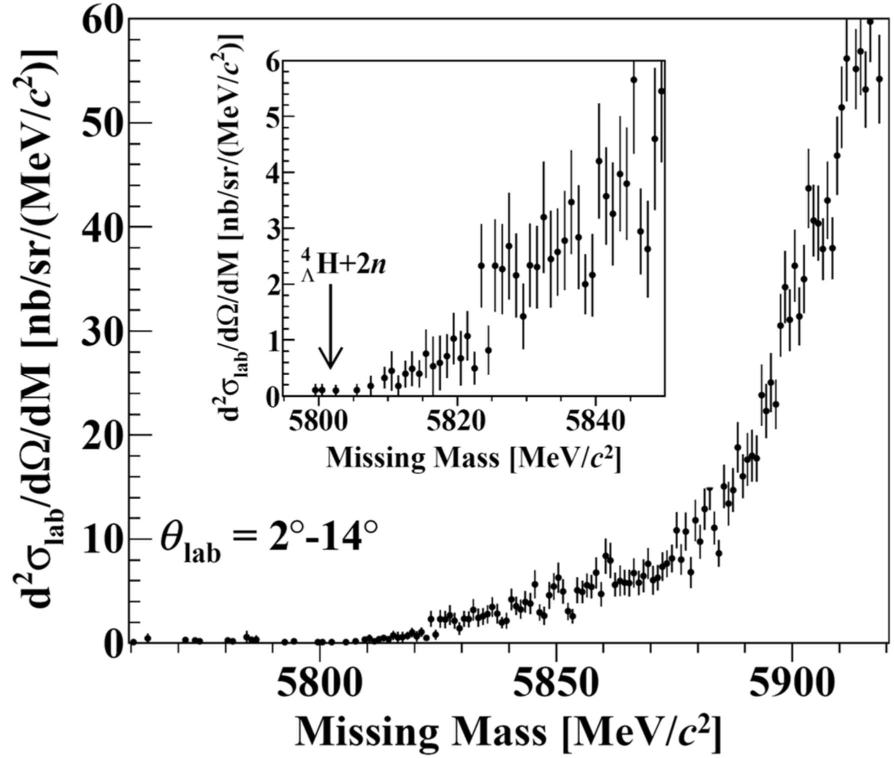
low statistic

J-PARC E10-experiment

$$\pi^- + {}^6\mathrm{Li} \rightarrow K^+ + {}^6_\Lambda\mathrm{H}$$

As Gal predicted, the background is too big to indicate hypernucleus signals

ArXiv:1310.6104v2 [nucl-ex] 6 Feb 2014

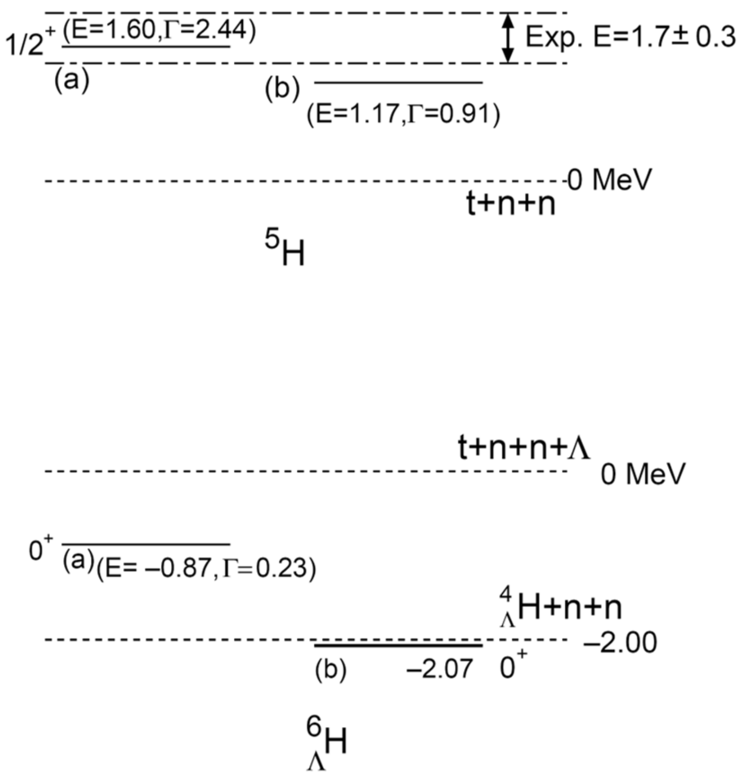


no peak found

Theoretical discrepancies

Four-body Structure of $^{6}_{\Lambda}H$ Neutron-rich Hypernucleus

E. Hiyama, S. Ohnishi, M. Kamimura, and Y. Yamamoto



does not exist

ArXiv:1304.0317v1 [nucl-th] 1 Apr 2013

$^{4}_{\Lambda}H + n + n$ model of $^{6}_{\Lambda}H$

B.F.Gibson, I.R.Afnan, Nuclear Physics A(2013)

The $^{6}_{\Lambda}$H binding energy with different Model A α–n interaction channels excluded.

Channel excluded	B.E.($^{6}_{\Lambda}$H) (MeV)
None	0.756
$S_{1/2}$	1.056
$P_{1/2}$	0.593
$P_{3/2}$	No bound state

exists

http://dx.doi.org/10.101016/j.nuclphysa.2013.02.017

Goals of the Experiment (Next Steps)

$$^{12}\mathrm{C} + \mathrm{Al} \rightarrow {}^{9}\mathrm{Li} + \mathrm{C} \rightarrow {}^{8}_{\Lambda}\mathrm{H} + \mathrm{p} \rightarrow {}^{8}\mathrm{He} + \pi^{-} + \mathrm{p}$$

$$^{6}\mathrm{Li} + \mathrm{C} \rightarrow {}^{6}_{\Lambda}\mathrm{He} + \ldots \rightarrow {}^{6}\mathrm{Li} + \pi^{-} + \ldots$$

the neutron separation energy, $B_n = 0.17 \pm 0.10$ MeV

Unprecedented possibility to determine partial width of nonmesonic decays and matrix elements of ΛN interactions

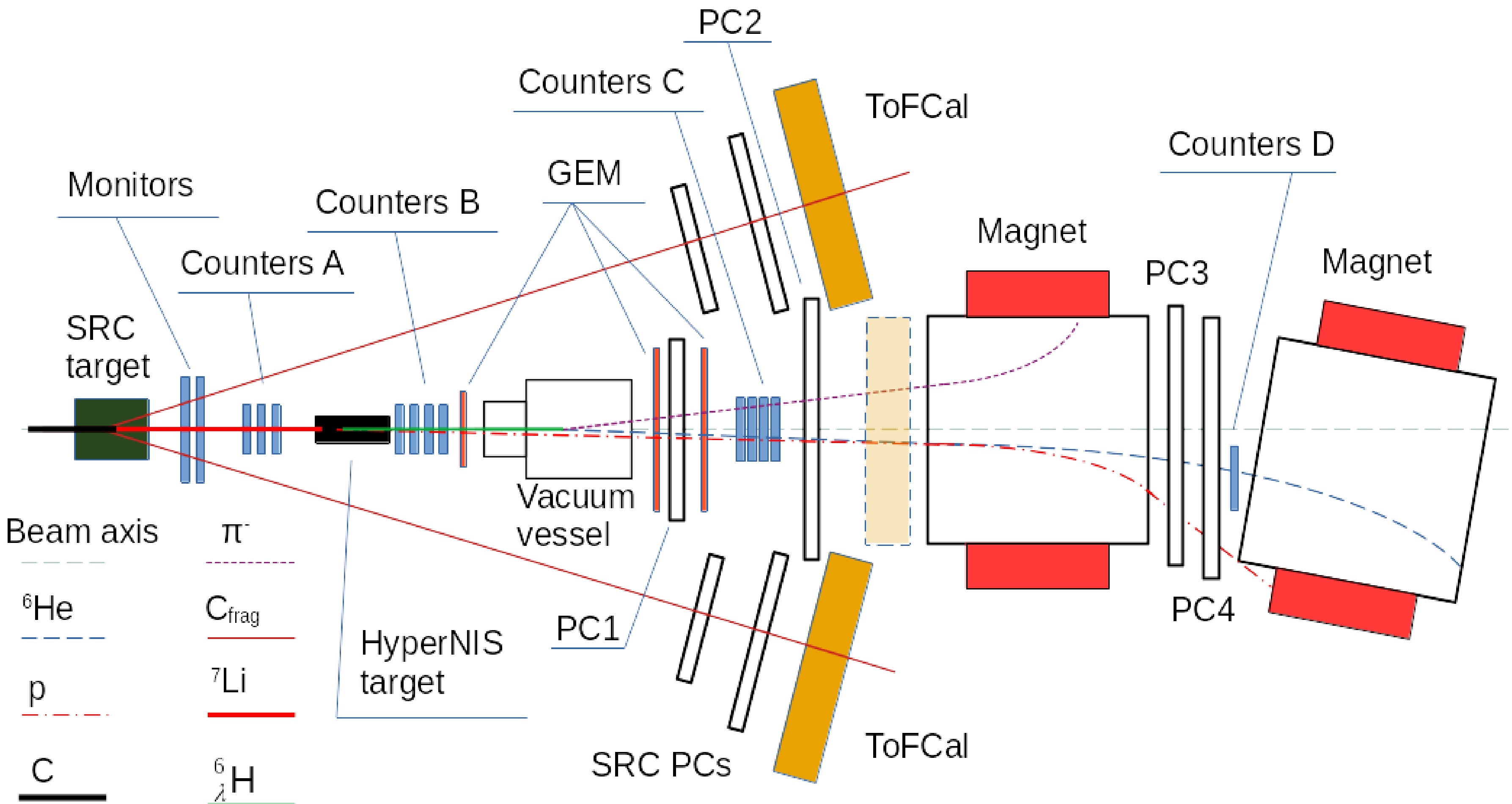
$$\Gamma^{n\,(p)}_{\alpha\alpha\,i}({}^{10}_{\Lambda}Be) \quad \Gamma^{n\,(p)}_{\alpha\alpha\,i}({}^{10}_{\Lambda}B)$$

$$\mathrm{C} + \mathrm{C} \rightarrow {}^{10}_{\Lambda}\mathrm{B} + \mathrm{X} \rightarrow {}^{10}_{\Lambda}\mathrm{B} \rightarrow n + p + {}^{8}\mathrm{Be} \rightarrow \alpha + \alpha$$

L. Majling and Yu. Batusov, Nucl. Phys. A 691 , 185c (2001).

Scheme of Experimental Setup

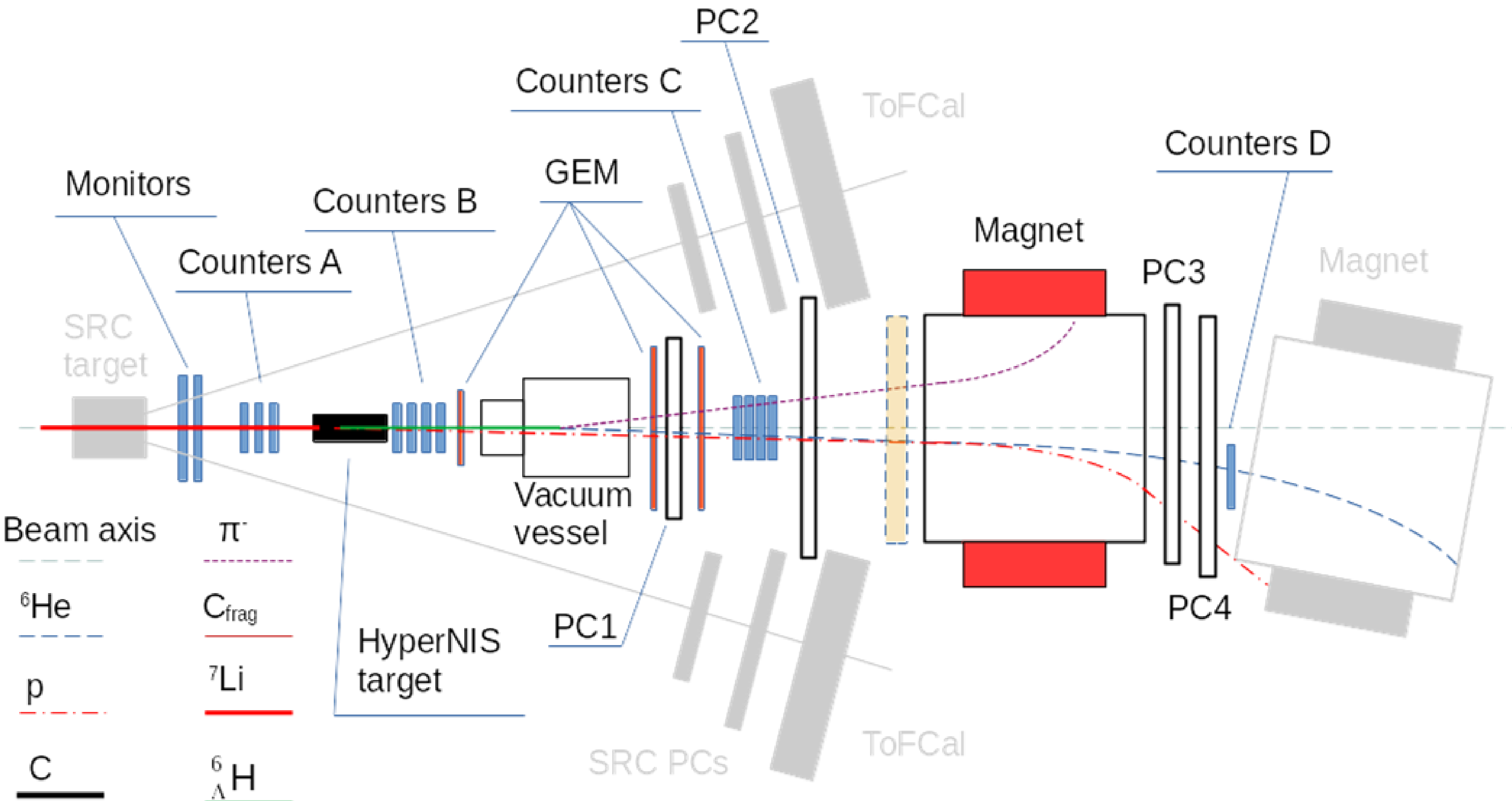
$$^{7}Li + C \rightarrow {}^{6}_{\Lambda}H + p_{frag} + X \rightarrow {}^{6}He + \pi^{-} + p_{frag} + X$$



- Target (carbon 12x3x3 cm, 20.4 g/cm^2);
- A,C — groups of scintillation counters;
- B – group of Cerenkov counters;
- PC1–PC4 — proportional chambers;
- TOF detectors.
- Magnets

Scheme of Experimental Setup

$$^7Li + C \to {}^6_\Lambda H + p_{frag} + X \to {}^6He + \pi^- + p_{frag} + X$$



- ❑ Target (carbon 12x3x3 cm, 20.4 g/cm^2);
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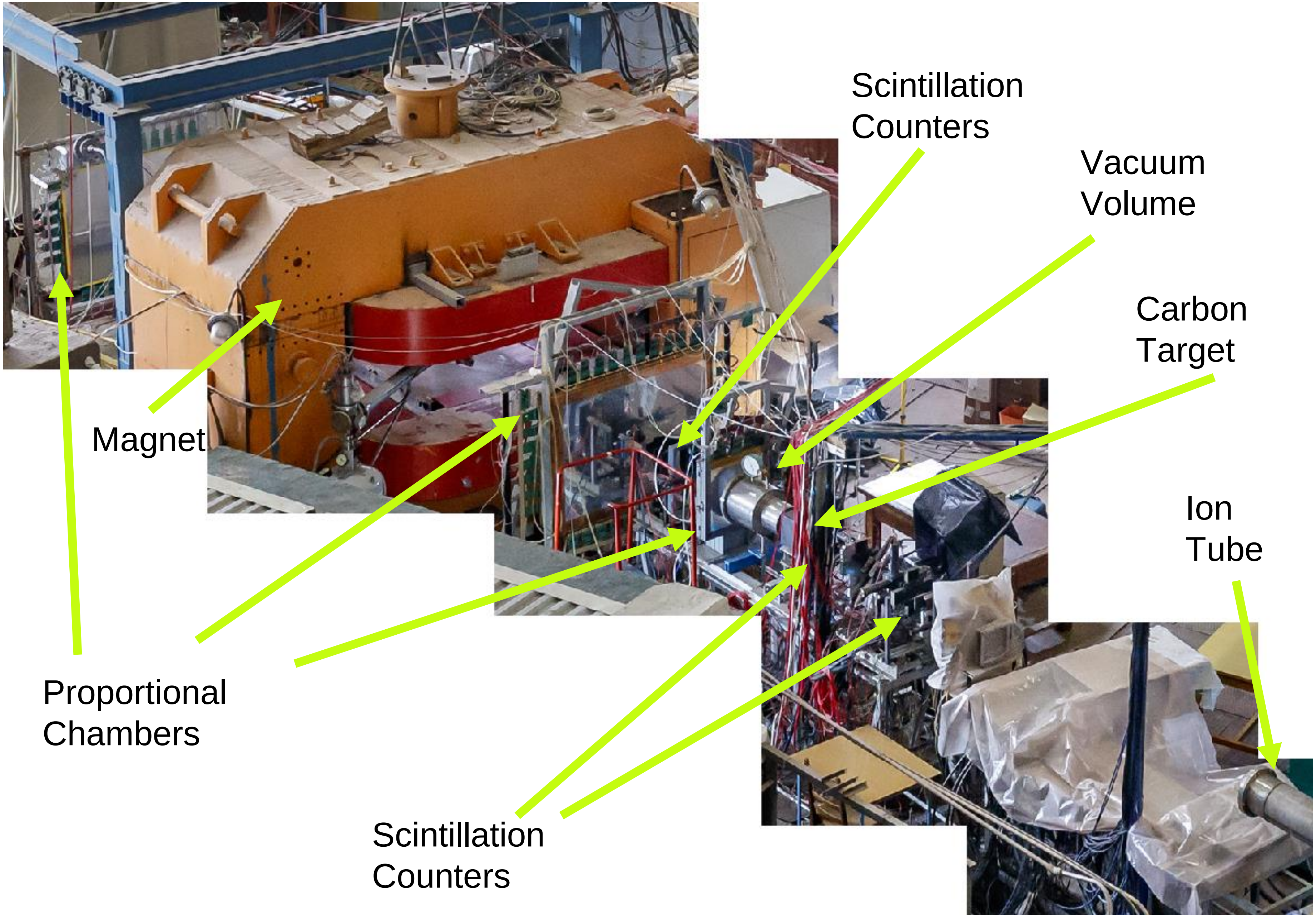
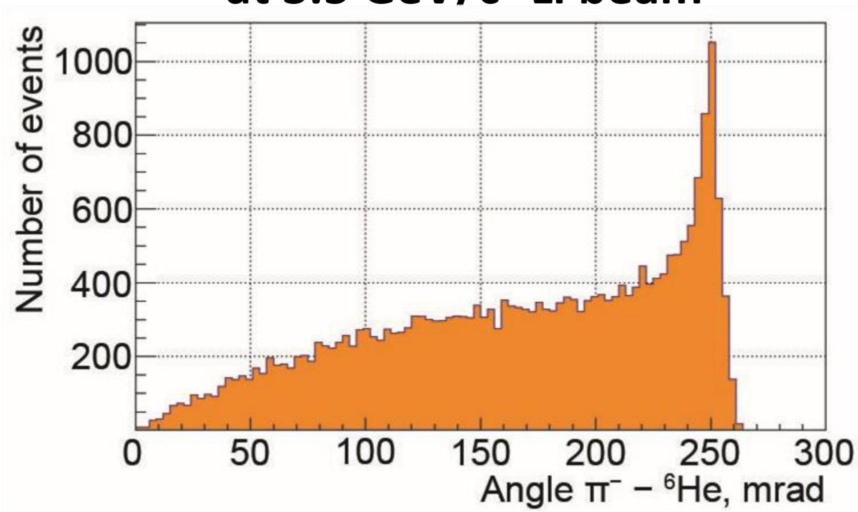
- ❑ B – group of Cerenkov counters;
- ❑ PC1–PC4 — proportional chambers;
- ❑ TOF detectors.
- ❑ Magnets

View of HyperNIS Spectrometer

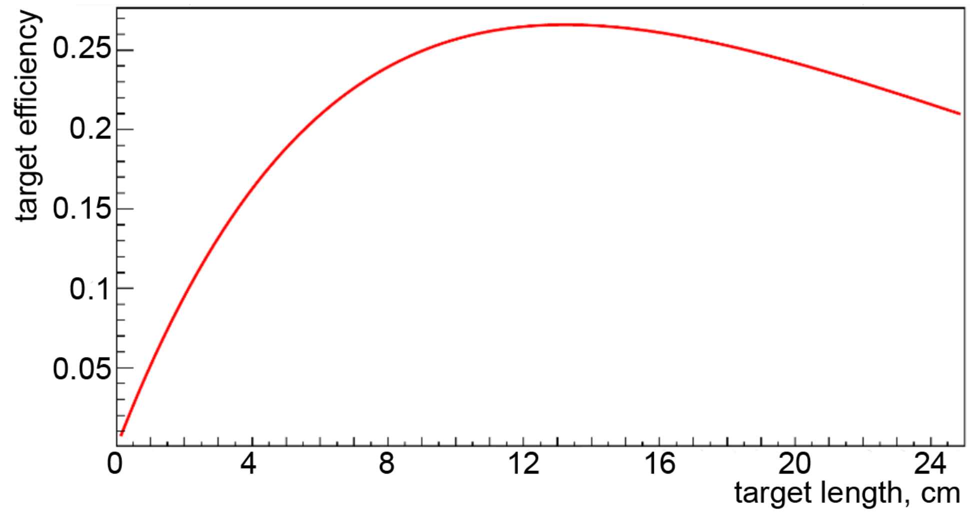


Simulation Results

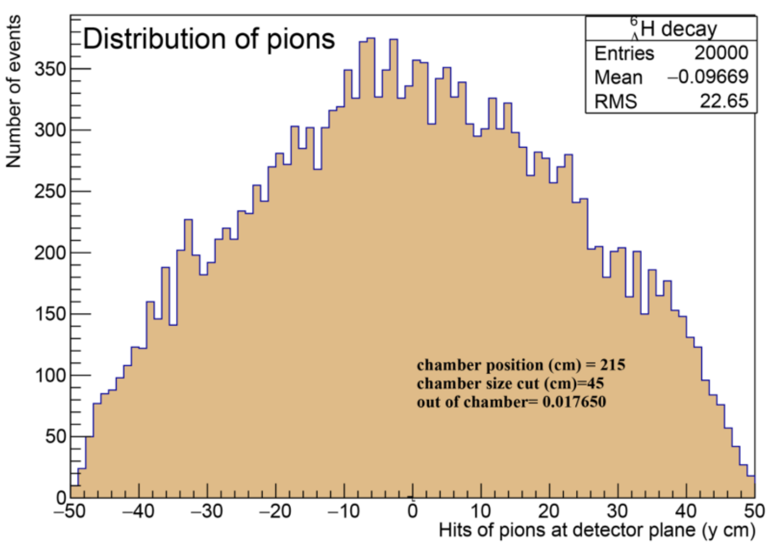
$^{6}He - \pi^{-}$ separation angle at 3.5 GeV/c ^{7}Li beam

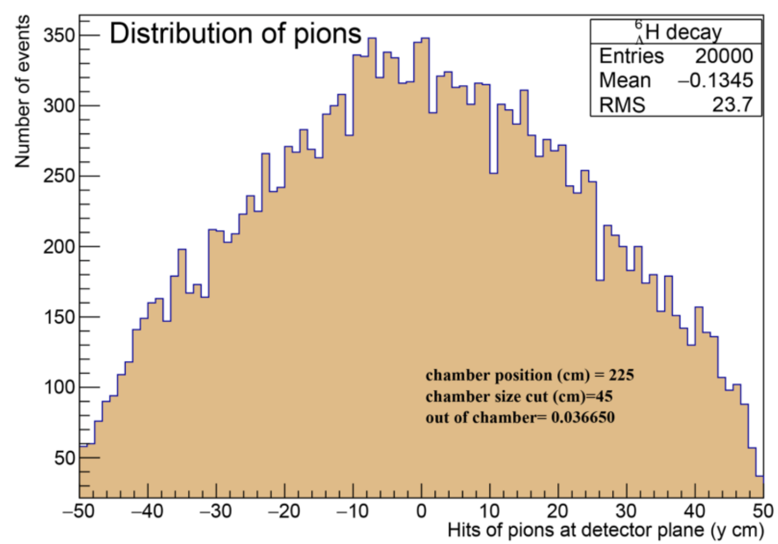


Target efficiency max value at 12 cm of length

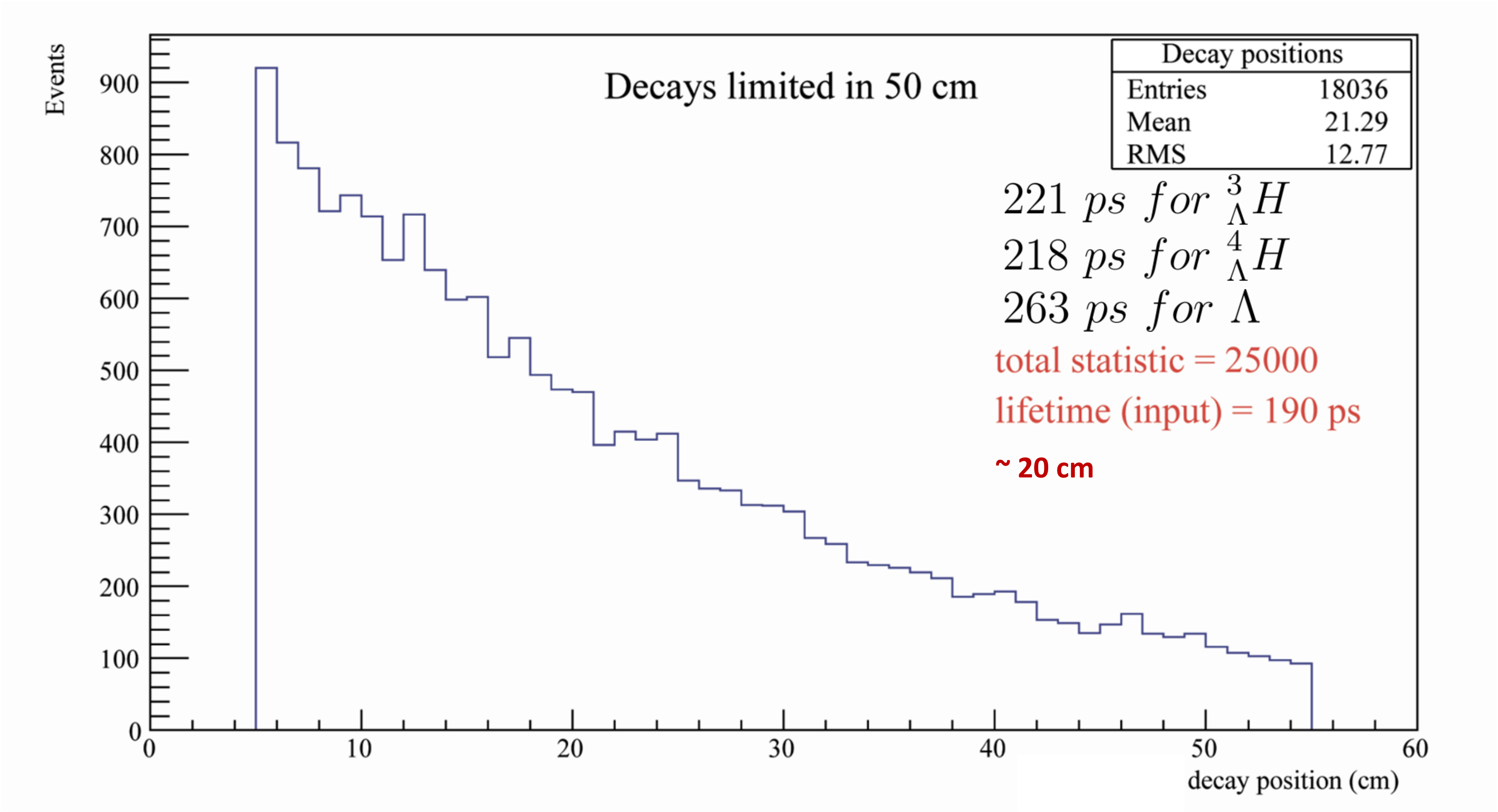


Pion hits at the last chamber located at 215 cm and 225 cm distances from target





Simulation Results



Expected decay points inside of 50 cm distance. Since 25000 events have been analyzed and about 18000 hypernuclei decay inside of 50 cm distance, it is 70% of the statistics if the first point is in 5 cm distance from the target.

Advantages of the "HyperNIS" experiment

- The main tasks of the project cannot be solved in the near future in any other experiments.
- The experimental method is developed and tested at VBLHEP.
- Unique approach allows using of hypernuclear **beams**.
- New FEE for PC and other apparatus upgrades improve the spectrometer performance.
- Collaboration with SRC experiment increase the beam usage efficiency.

Risks

- Some equipment has logistical troubles to come to Russia.
- Due to Nuclotron beams have not been available for years, tests in beams are very much needed before the run especially for FEE.

Necessary Run Time

The study of hypernucleus ${}^{6}_{\Lambda}\mathrm{H}$:

Optimal statistics for the goal:
500 detected events.

Nuclotron beam:
Spill > 5 sec
Intensity – 200-300 $*10^3$ sec^{-1}

Expected 300 ${}^{4}_{\Lambda}\mathrm{H}$ per day

If binding energy of ${}^{6}_{\Lambda}\mathrm{H}$ is very low production cross section can be lower than for ${}^{4}_{\Lambda}\mathrm{H}$ by factor of 3-4

Optimal first physical run time length: 200 hours

Measured and estimated cross sections of hypernucleus production.

Beam	Hyper-nuclei	Energy, AGeV	Cross sec., μb Theory	Cross sec., μb Exp.
${}^{3}\mathrm{He}$	${}^{3}_{\Lambda}\mathrm{H}$	5.14	0.03	$0.05^{+0.05}_{-0.02}$
${}^{4}\mathrm{He}$	${}^{3}_{\Lambda}\mathrm{H}$	3.7	0.06	< 0.1
	${}^{4}_{\Lambda}\mathrm{H}$	2.2	0.08	< 0.08
		3.7	0.29	$0.4^{+0.4}_{-0.2}$
${}^{6}\mathrm{Li}$	${}^{3}_{\Lambda}\mathrm{H}$	3.7	0.09	$0.2^{+0.3}_{-0.15}$
	${}^{4}_{\Lambda}\mathrm{H}$	3.7	0.2	$0.3^{+0.3}_{-0.15}$
${}^{7}\mathrm{Li}$	${}^{7}_{\Lambda}\mathrm{Li}$	3.0	0.11	< 1
	${}^{6}_{\Lambda}\mathrm{He}$	3.0	0.25	< 0.5

H. Bandō et al., Nucl. Phys. A 501, 900 (1989)

S. A. Avramenko et al., JINR Communication P1-91-206, Dubna (1991)

FTE of the project

Category of personnel	Full name	Division	Amount of FTE
research scientists	Aksinenko V.D.	VBLHEP	1
	Atovullaev T.	VBLHEP	1
	Averyanov A.V.	VBLHEP	0.9
	Fechtchenko A.A.	VBLHEP	0.7
	Gertsenberger S.V.	VBLHEP	0.1
	Korotkova A.M.	VBLHEP	0.9
	Krivenkov D.O.	VBLHEP	0.7
	Lukstins J.	VBLHEP	0.5
	Nepochatykh S.M.	VBLHEP	1
	Patsyuk M.A.	VBLHEP	1
	Khvorostukhin A.S	VBLHEP	1
	Strokovsky E.A.	VBLHEP	0.8
	Tereschenko V.V.	DLNP	0.2
engineers	Atovullaeva A.	VBLHEP	1
	Okhrimenko O.V.	VBLHEP	1
	Parfenova N.G.	VBLHEP	0.5
	Plyashkevich S.N.	VBLHEP	1
	Salamatin A.V.	VBLHEP	1
	Bochkova A.G.	VBLHEP	0.5
Total:			**14.8**

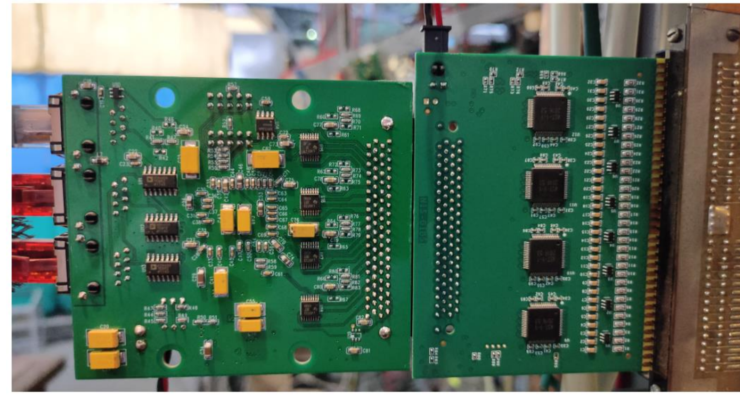
Cost estimate for the HyperNIS only

Expenditures, resources, funding sources	Cost (thousands of US dollars)/ Resource requirements	Cost/Resources, distribution by years				
		1st year	2nd year	3rd year	4th year	5th year
International cooperation	75	15	15	15	15	15
Materials	125	25	25	25	25	25
Equipment, Third-party company services						
Commissioning						
R&D contracts with other research organizations						
Software purchasing	10	2	2	2	2	2
Design/construction						
Service costs						
Resources						
- the amount of FTE,		15	15	15	15	15
- accelerator/installation,		360	360	360	360	360
- reactor,…						

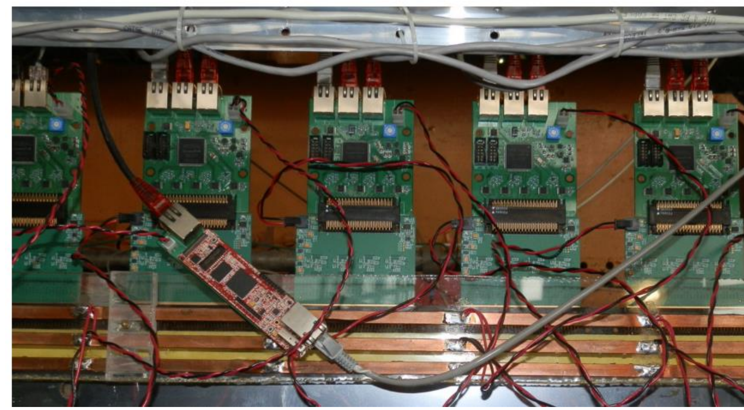
Thank you for attention

Back up slides

Last years results



- R&D and production of new front-end electronics for proportional chambers. 200 analog signal cards (32 inputs in each card) were produced in Minsk. The digital part of the FEE cards was designed and tested in JINR.



- New HV power supply system for proportional chambers is tested and ready to operate

Summary

The HyperNIS spectrometer is almost ready for hypernuclear experiments. Li and C beams are necessary!

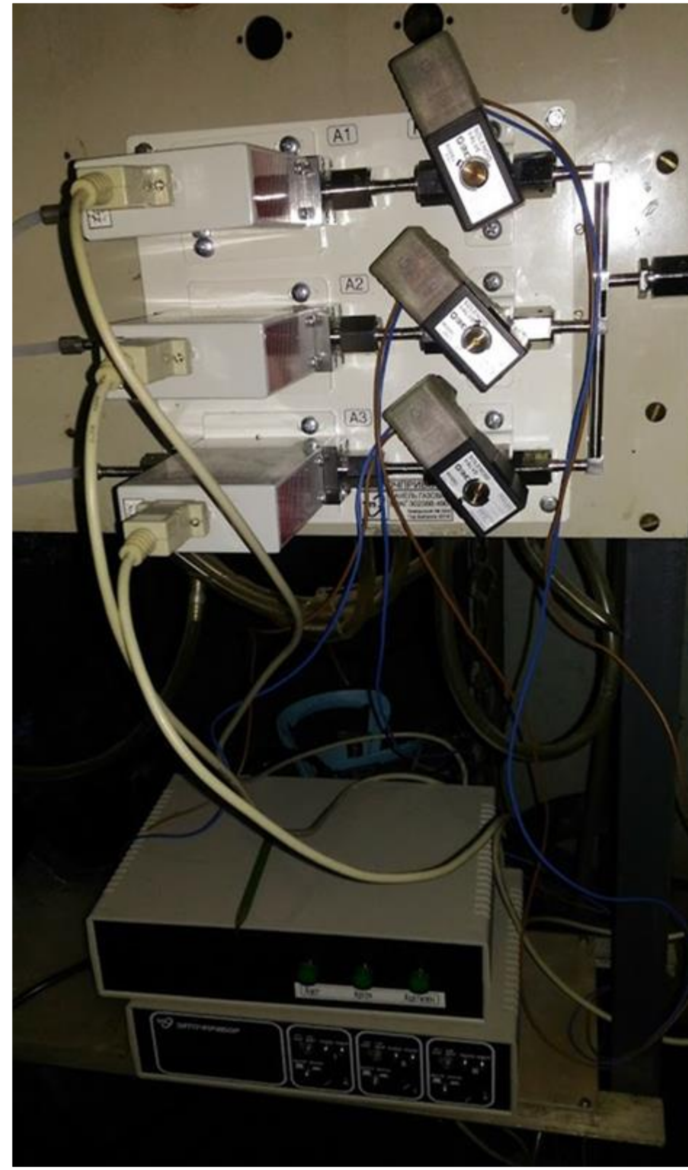
It is planned to test all new spectrometer systems on the Nuclotron beams at the end of the year.

The very first experiments are devoted to $^{6}_{\Lambda}\mathrm{H}$ and $^{8}_{\Lambda}\mathrm{H}$ problem – do they exist?

HyperNIS research programme is adequate for the method elaborated in Dubna – chosen tasks are interesting and necessary for hypernuclear physics, hard to be solved at particle beams.

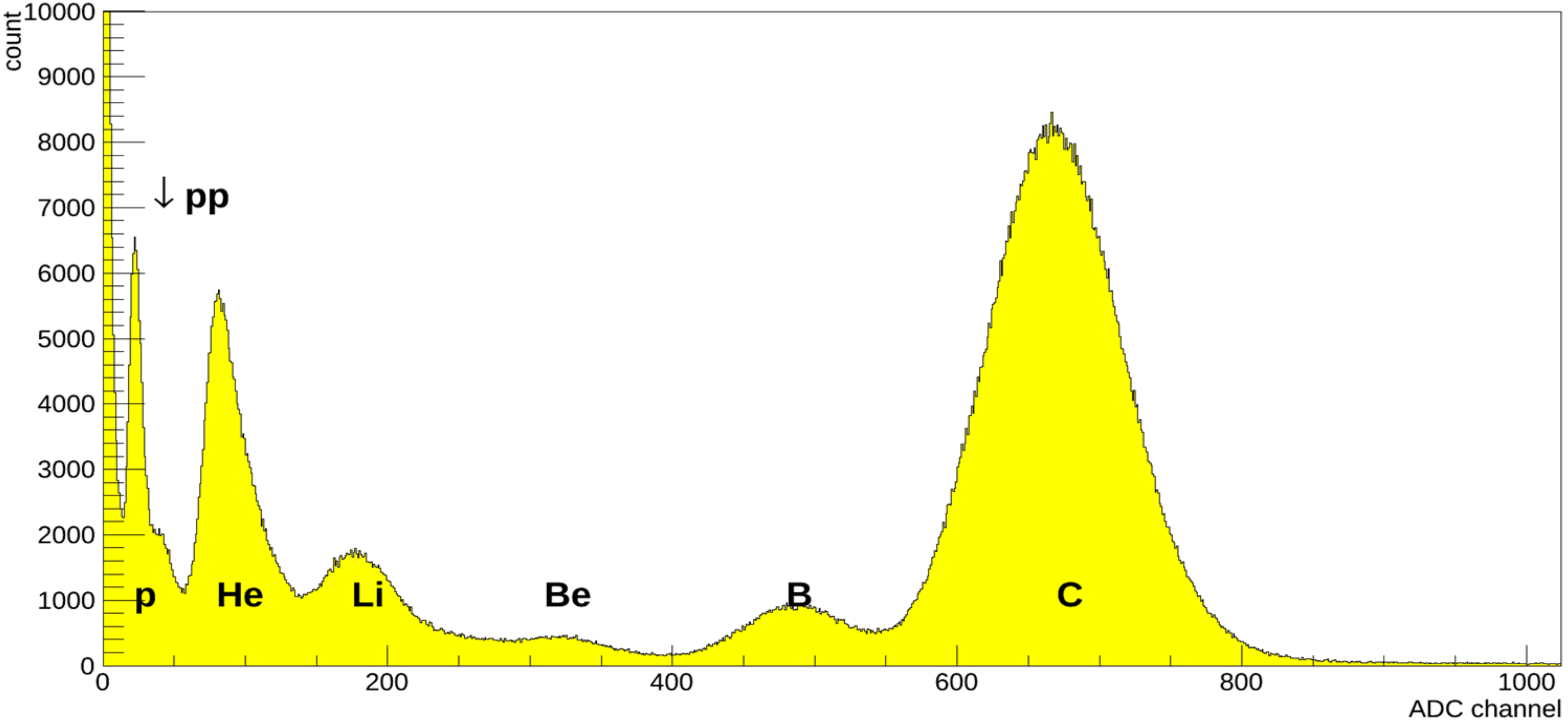
Last years results

- A new electronic gas supply system for the proportional chambers is prepared.
- Test of 10x10 cm GEM chamber is in progress now. Two 40x40 cm GEM chambers were purchased and the production was completed but they have not been delivered to Dubna yet due to the logistical difficulties.
- MC simulations were updated according to the modern conditions for the experiment.



Amplitudes of Scintillation Counters

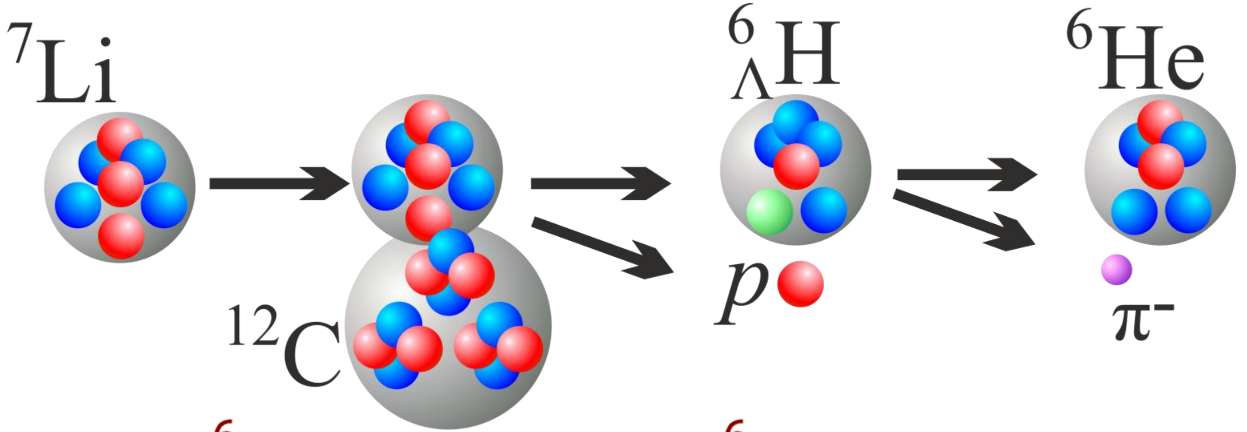
Amplitude spectrum of signals from a counter of the trigger system, obtained with the carbon (^{12}C) beam. Background suppression above factor at least 10^4 can be obtained with 4 counters in coincidence.



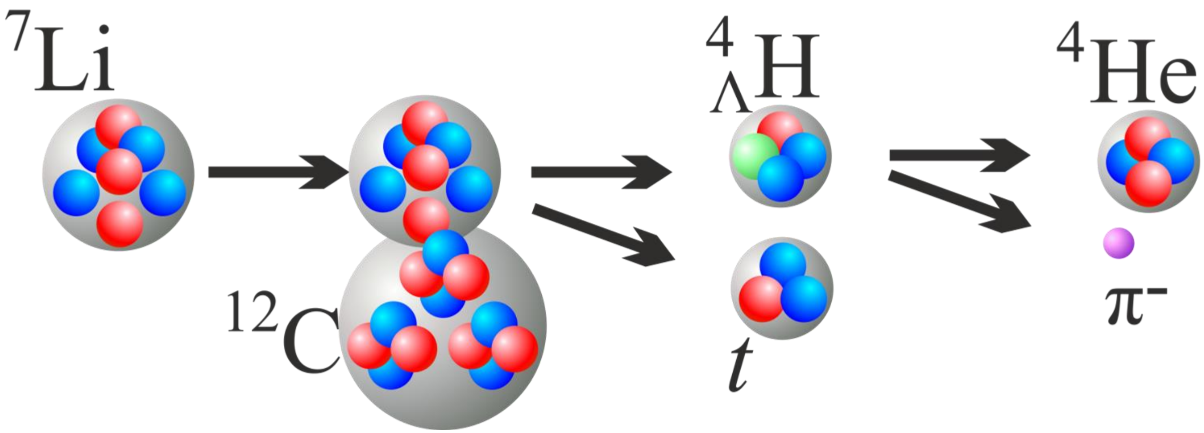
New Equipment Which is Already Installed

Block of 4 Cerenkov counters with subsequent quartz 4 mm radiators. High density graphite (1.7 g/cm^3) target is placed close to radiators.

Hypernuclei Production Reaction at NUCLOTRON



$$^{7}Li + C \rightarrow {}^{6}_{\Lambda}H + p_{frag} + X \rightarrow {}^{6}He + \pi^{-} + p_{frag} + X$$



$$^{7}Li + C \rightarrow {}^{4}_{\Lambda}H + t_{frag} + X \rightarrow {}^{4}He + \pi^{-} + t_{frag} + X$$

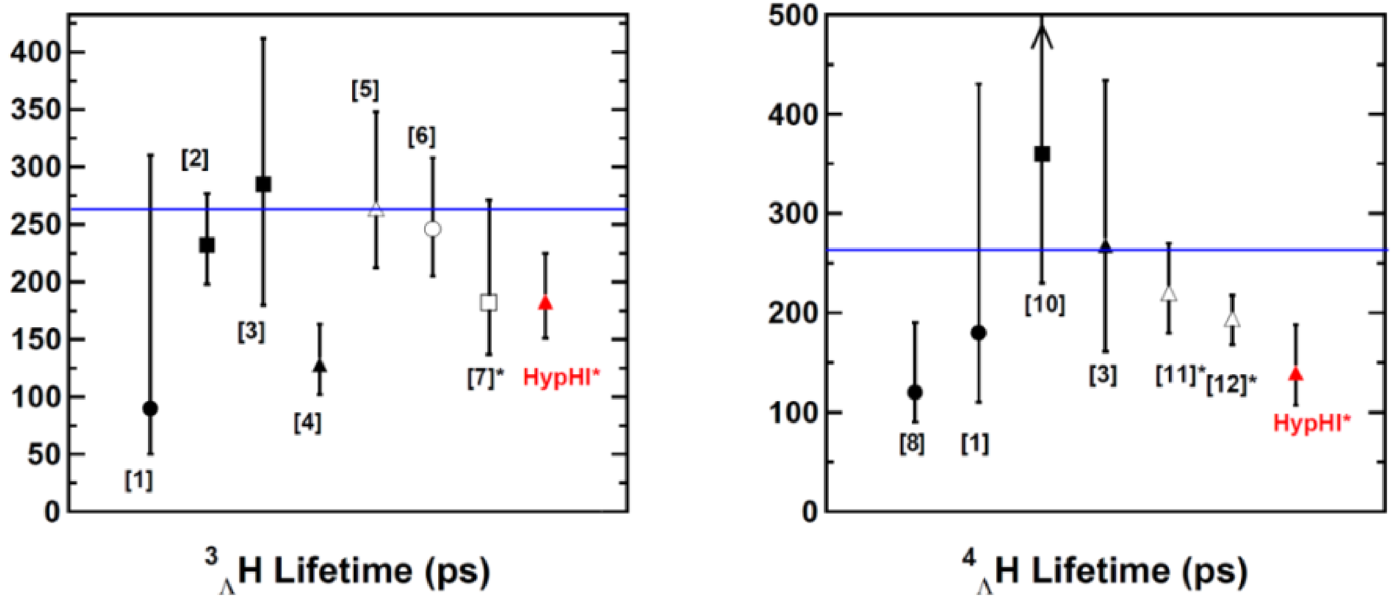
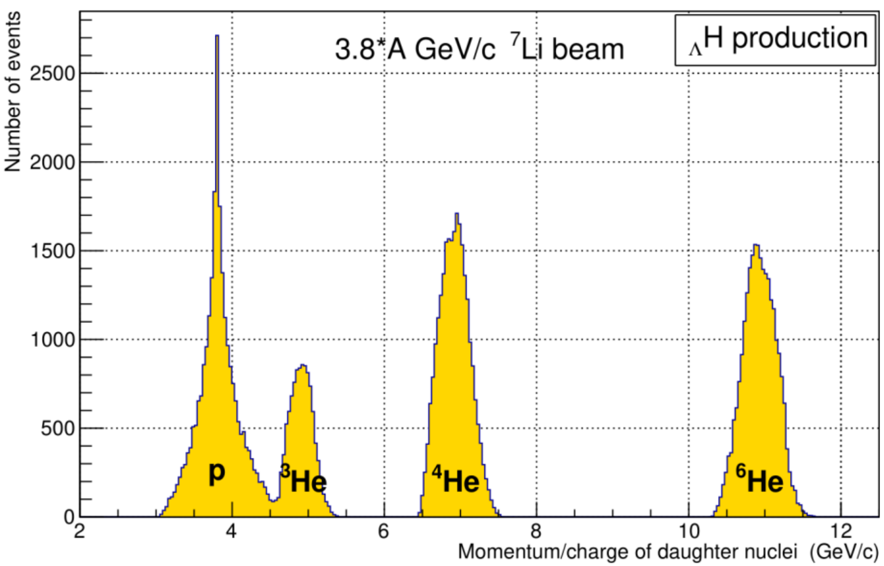


Figure 13: World data comparison of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ lifetimes presented by Rappold in Proceedings [13] where references are listed. It should be said that ${}^{4}_{\Lambda}H$ lifetime value noted as [11] is result of our previous experiment [15]. Values deduced in the HypHI experiment are indicated by HypHI. The horizontal line at 263.2 ps shows the known lifetime of the Λ hyperon. References to counter experiments are marked by an asterisk.

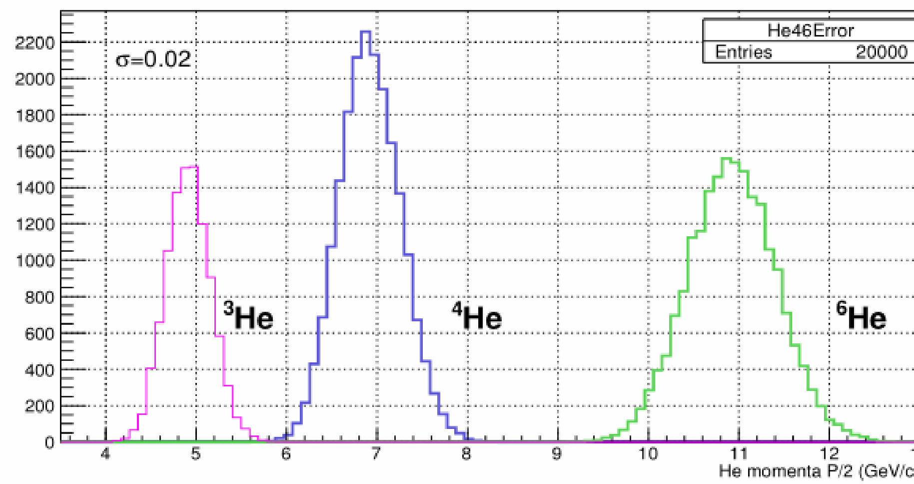
Separation of Daughter Nuclei of ${}^{6}_{\Lambda}H\ {}^{4}_{\Lambda}H\ {}^{3}_{\Lambda}H$

$$^{7}Li + C \rightarrow {}^{6}_{\Lambda}H + p_{frag} + X \rightarrow {}^{6}He + \pi^{-} + p_{frag} + X$$

$$^{7}Li + C \rightarrow {}^{4}_{\Lambda}H + t_{frag} + X \rightarrow {}^{4}He + \pi^{-} + t_{frag} + X$$

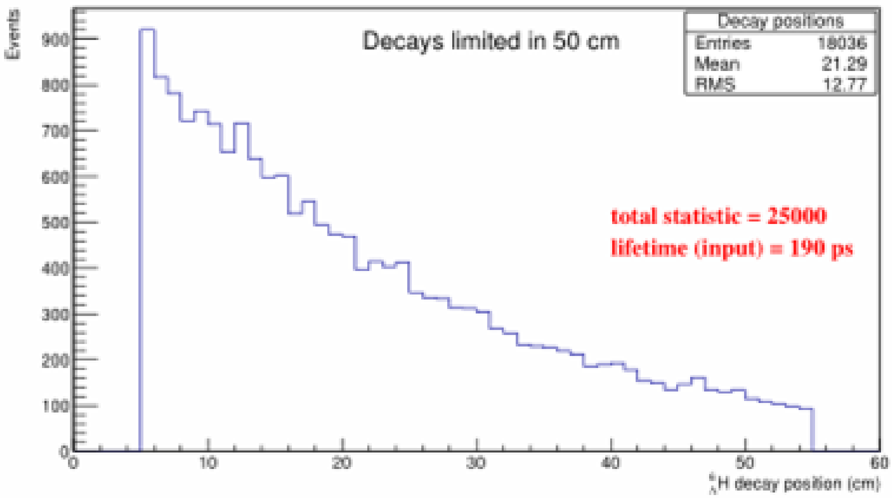


Expected distribution of He (hydrogen hypernuclei daughter nuclei) momenta values divided by their charge



Expected distribution of He (hydrogen hypernuclei daughter nuclei) momenta values divided by their charge
in case of 2% momenta error distribution

Simulation Results



Expected decay points inside of 50 cm distance. Since 25000 events have been analyzed and about 18000 hypernuclei decay inside of 50 cm distance, it is 70% of the statistics if the first point is in 5 cm distance from the target.

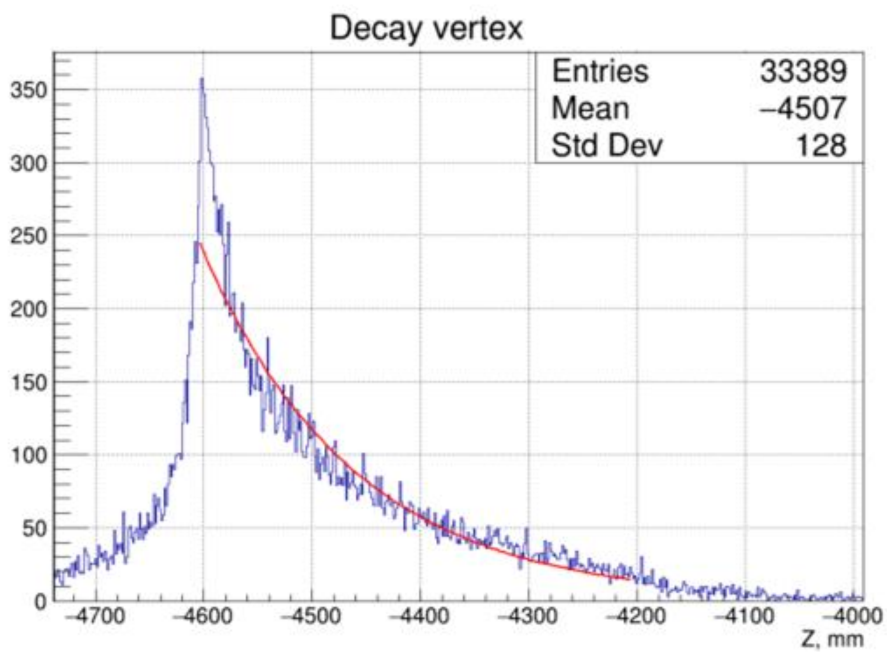


Figure 15: Properly reconstructed decay points allow one to measure lifetime of hypernucleus. Z=-4600mm is beginning of fiducial decay volume.

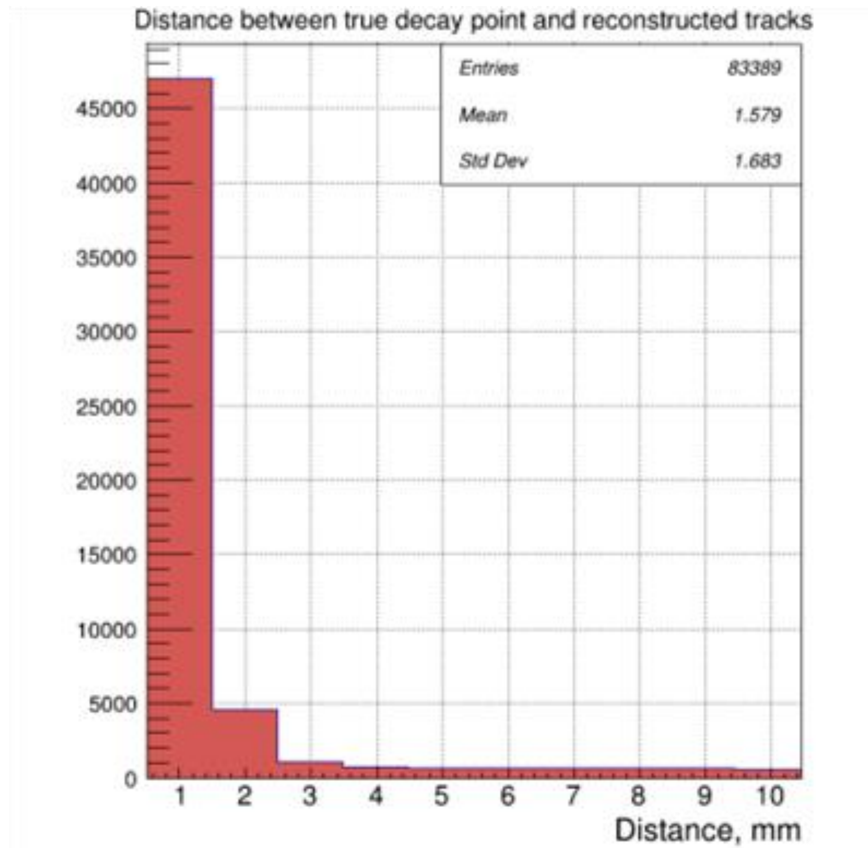
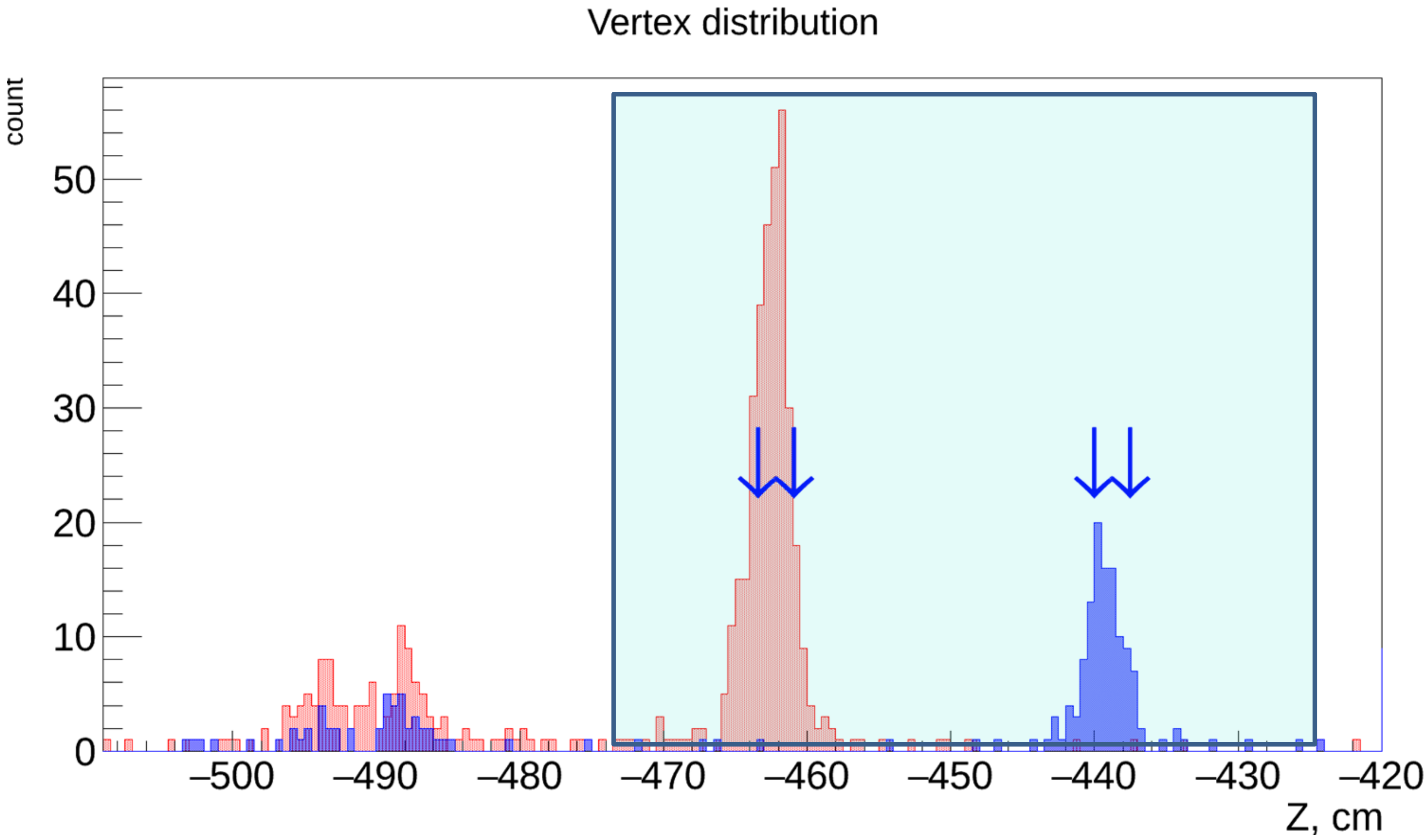


Figure 16: Decay points can be localized into two mm.

Vertex Reconstruction Procedure

Two different positions of an Al target (red and blue) reconstructed with two track vertex reconstruction procedure. Arrows shows target width.
Position of two trigger counters are also seen.



Goals of the Experiment (Future Steps)

2. **Binding energy** of loosely bound hypernuclei ${}^{6}_{\Lambda}He$ to be obtained by measuring the Coulomb dissociation cross sections in different targets ($\sigma_{Coulomb}$ increases at low binding energy values!)

$$\sigma_{Coulomb} \sim Z^{1.92} \quad \sigma_{Nucl} \sim A^{0.6}$$

V.L.Lyuboshitz

3. **Matrix elements of the weak ΛN interaction** (study of non-mesonic decay of hypernuclei ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B partial widths of nonmesonic weak decay via intermediate chain ^{8}Be$\rightarrow \alpha + \alpha$)

L.Majling

A.Sakaguchi* at Sendai Conference:

"The level structure of ${}^{6}_{\Lambda}\mathrm{H}$ still has ambiguities only with the FINUDA result, and complementary measurements are necessary. The production mechanism by the DCX (double charge exchange) reaction and the structure of the neutron-rich hypernuclei are not well understood, yet. More detailed analysis of the already obtained experimental data and further experimental studies of other neutron-rich hypernuclei are necessary."

* **Proc. 12th Int. Conf. on Hypernuclear and Strange Particle Physiscs (HYP2015) JPS Conf. Proc. 17, 011007 (2017), https://doi.org/10.7566/JPSCP.17.011007.**

$$^{7}\mathrm{Li} + \mathrm{C} \rightarrow {}^{6}_{\Lambda}\mathrm{H} + \mathrm{p} + \mathrm{X} \rightarrow {}^{6}\mathrm{He} + \pi^{-} + \mathrm{p} + \mathrm{X}$$

Probability of fragmentation of ^{7}Li is much higher than DCX (Dubna experiment)

NONMESONIC DECAYS OF HYPERNUCLEI

Unprecedented possibility to determine
partial widths of nonmesonic weak decay
$\Gamma^n_{\alpha\alpha i}({}^{10}_{\Lambda}\mathrm{Be})$ and $\Gamma^p_{\alpha\alpha i}({}^{10}_{\Lambda}\mathrm{B})$

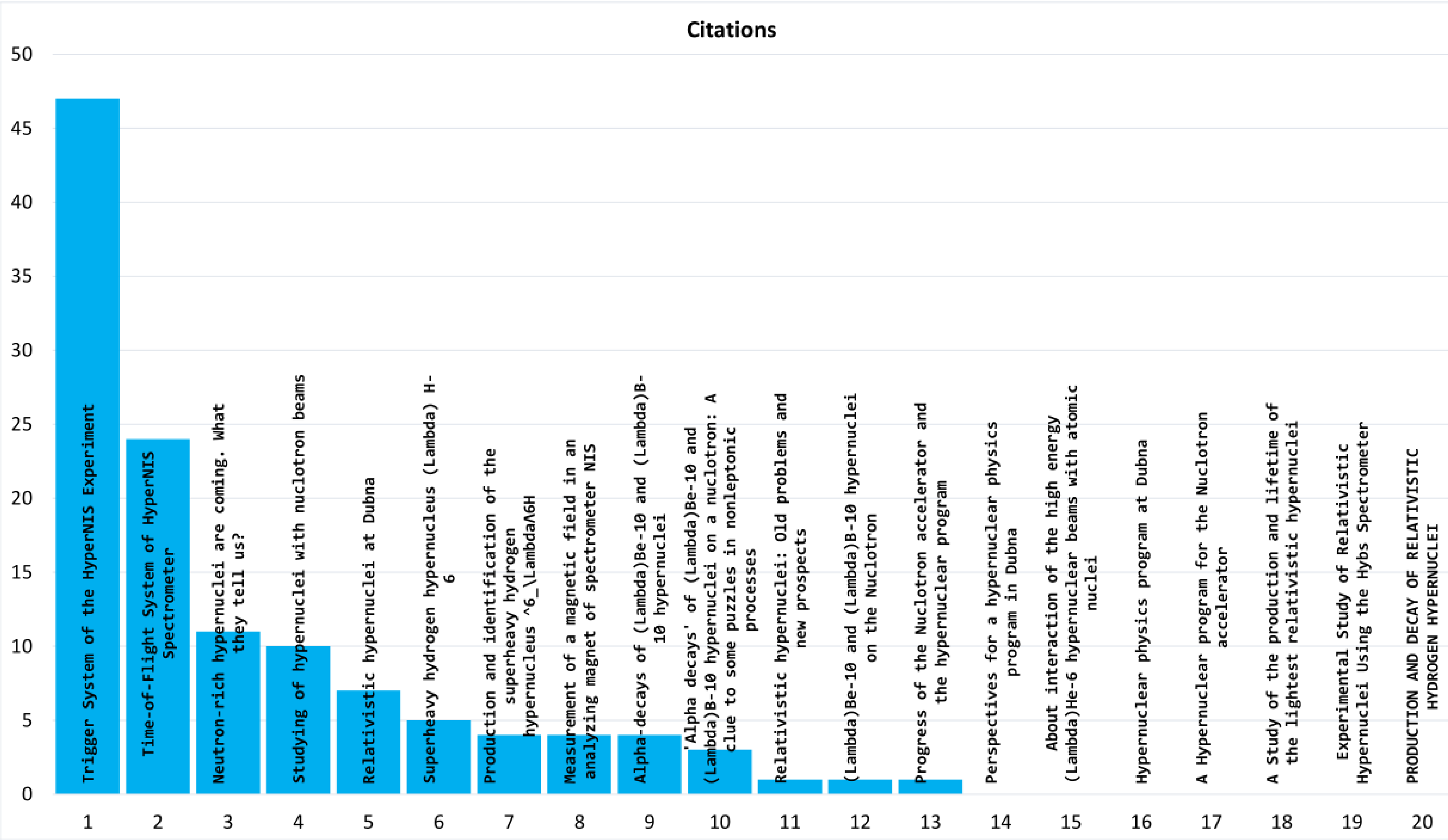
Their study offers a unique possibility to determine
matrix elements of the weak ΛN interaction
(for p-shell hypernuclei at least).

One should register the chain of decays

$$\mathrm{C{+}C} \to {}^{10}_{\Lambda}\mathrm{B{+}X} \to {}^{10}_{\Lambda}\mathrm{B} \to n+p+\,{}^{8}\mathrm{Be}$$
$$^{8}\mathrm{Be} \to \alpha+\alpha$$

emitting α's within a very small angle

The *h*-index



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Trigger System of the HyperNIS Experiment
Time-of-Flight System of HyperNIS Spectrometer
Neutron-rich hypernuclei are coming. What they tell us?
Studying of hypernuclei with nuclotron beams
Relativistic hypernuclei at Dubna
Superheavy hydrogen hypernucleus (Lambda) H-6
Production and identification of the superheavy hydrogen hypernucleus ^6_\LambdaΛ6H
Measurement of a magnetic field in an analyzing magnet of spectrometer NIS
Alpha-decays of (Lambda)Be-10 and (Lambda)B-10 hypernuclei
'Alpha decays' of (Lambda)Be-10 and (Lambda)B-10 hypernuclei on a nuclotron: A clue to some puzzles in nonleptonic processes
Relativistic hypernuclei: Old problems and new prospects
(Lambda)Be-10 and (Lambda)B-10 hypernuclei on the Nuclotron
Progress of the Nuclotron accelerator and the hypernuclear program
Perspectives for a hypernuclear physics program in Dubna
About interaction of the high energy (Lambda)He-6 hypernuclear beams with atomic nuclei
Hypernuclear physics program at Dubna
A Hypernuclear program for the Nuclotron accelerator
A Study of the production and lifetime of the lightest relativistic hypernuclei
Experimental Study of Relativistic Hypernuclei Using the Hybs Spectrometer
PRODUCTION AND DECAY OF RELATIVISTIC HYDROGEN HYPERNUCLEI
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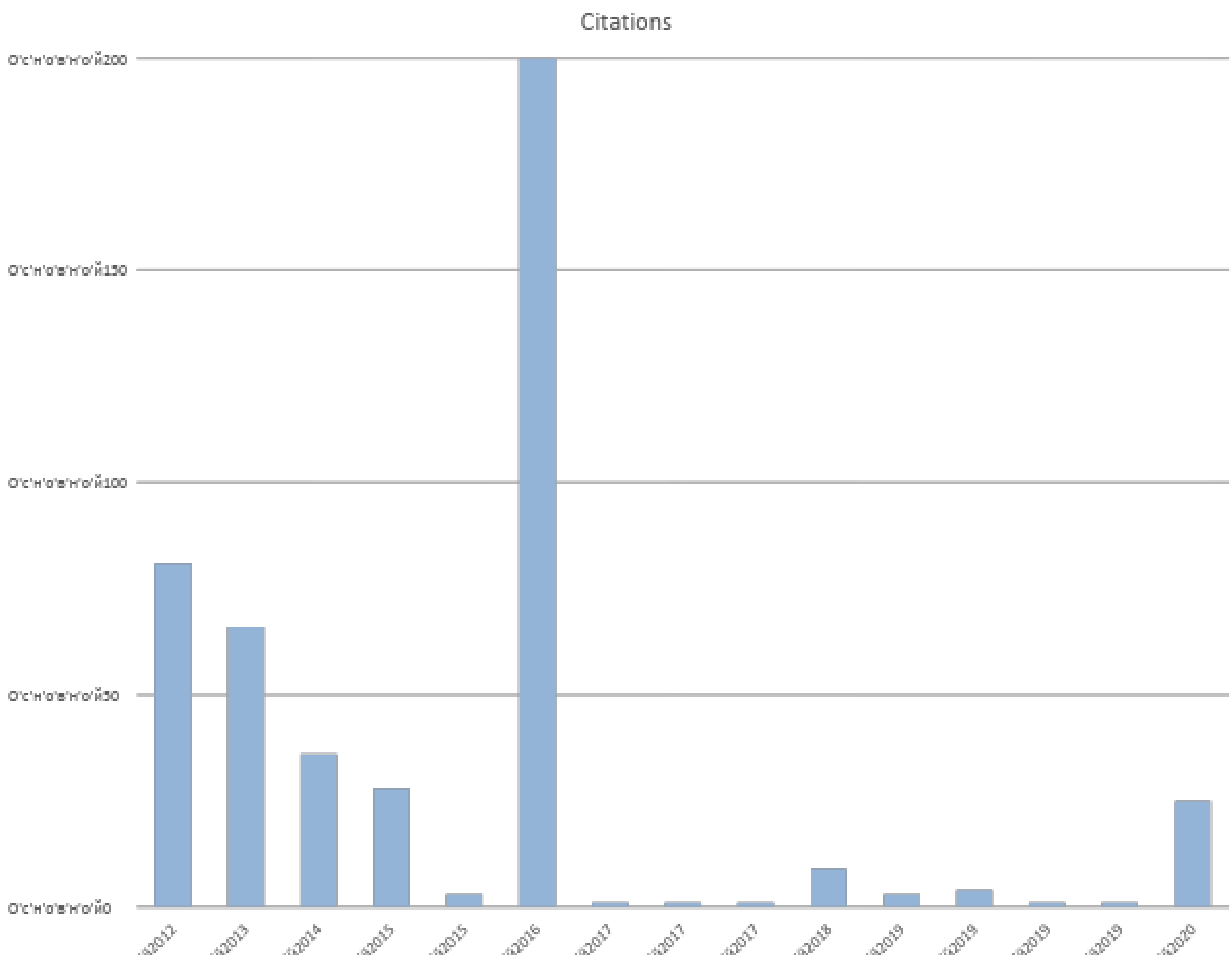
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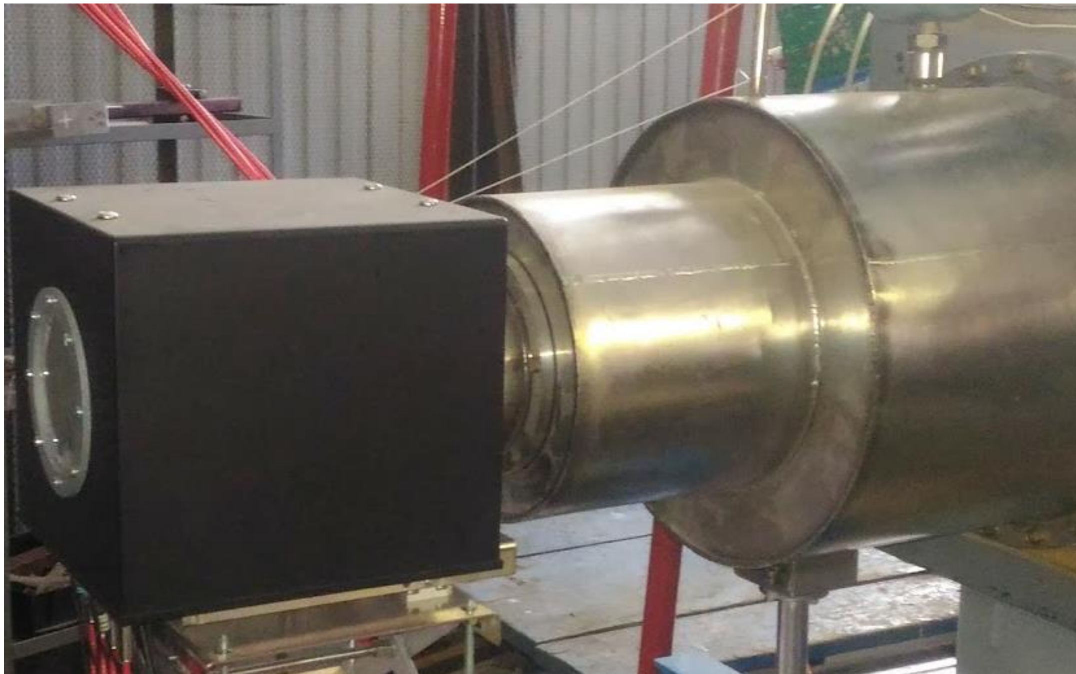
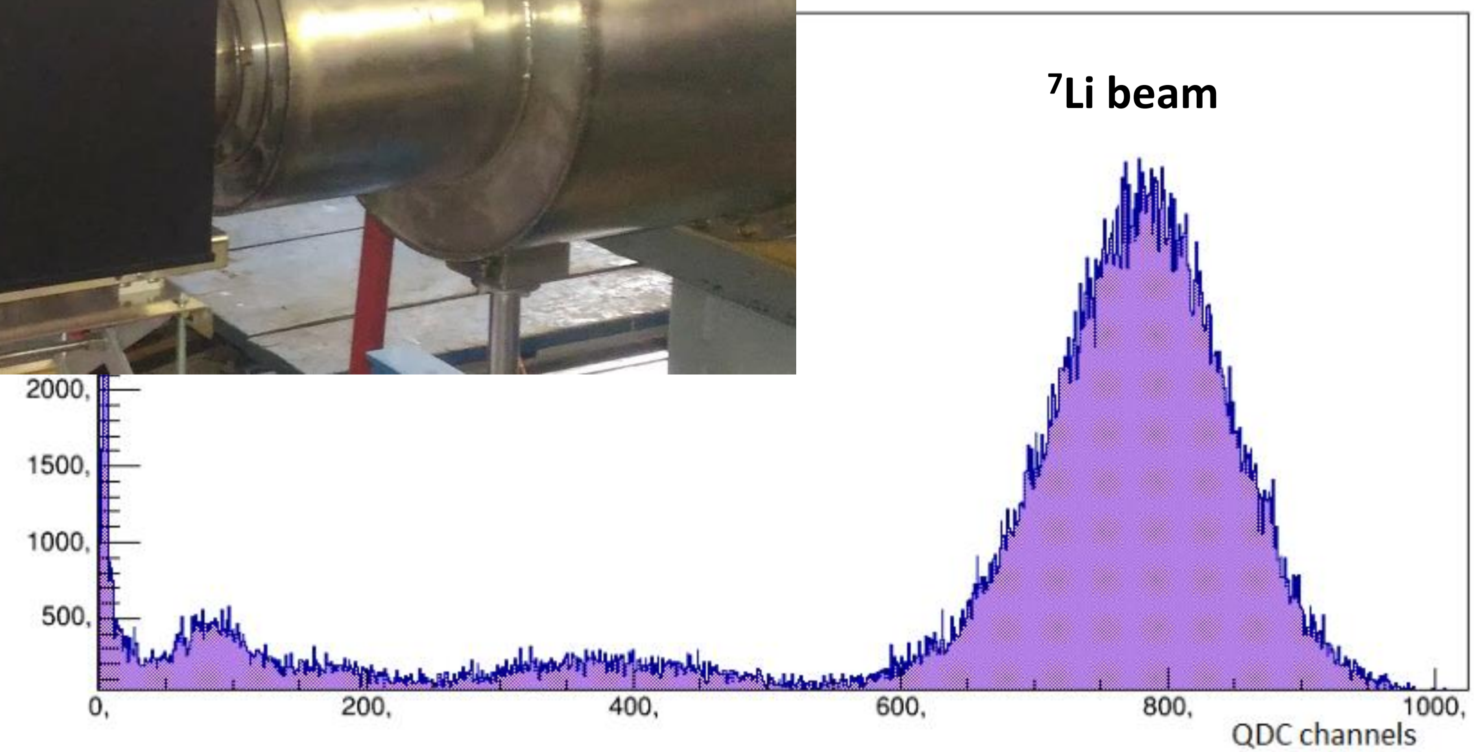
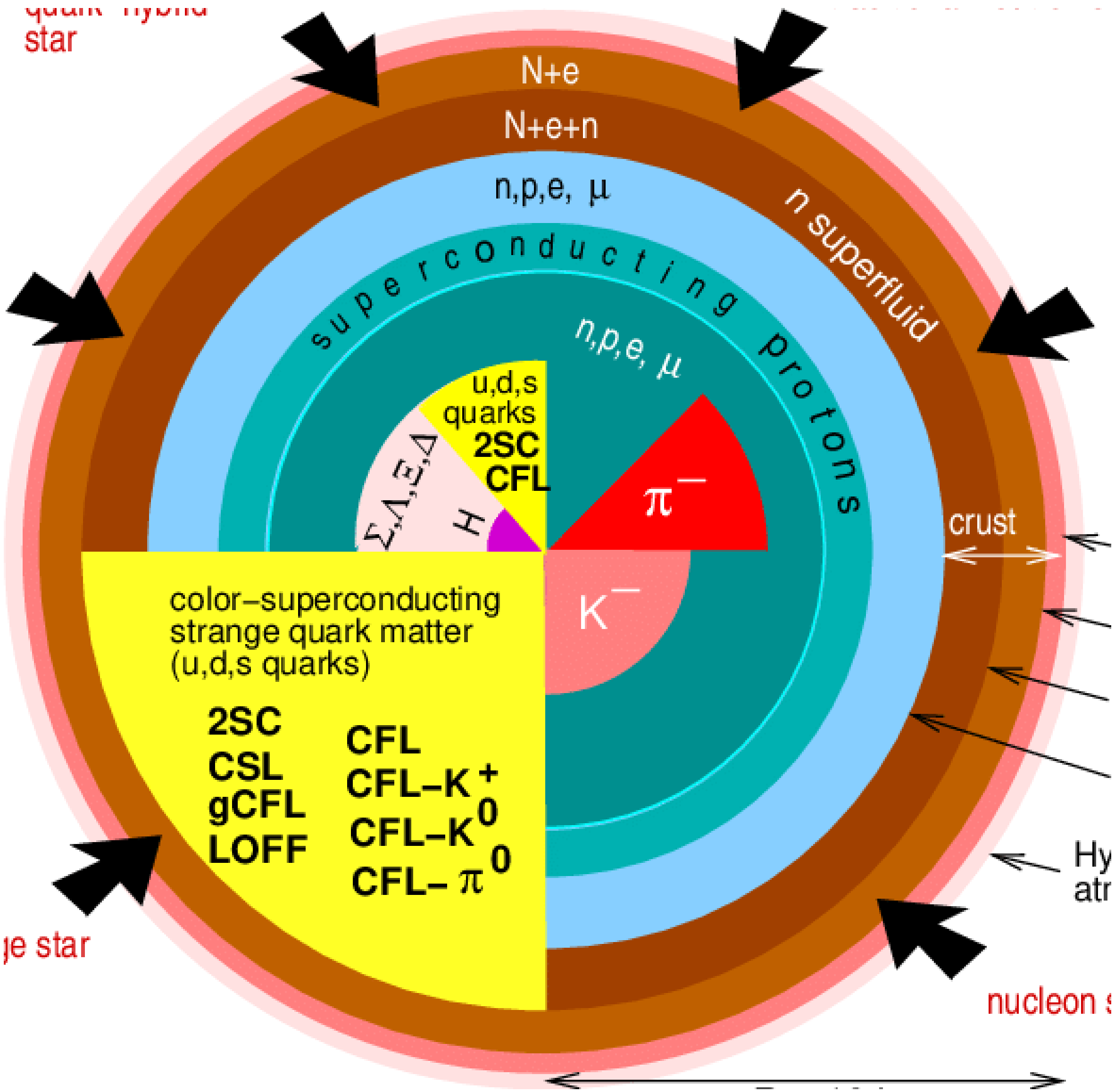
Amplitude resolution of Cerenkov counter

Block of Cerenkov counters installed near the vacuum vessel







star
N+e
N+e+n
n,p,e, μ
n superfluid
superconducting protons
n,p,e, μ
u,d,s
quarks
2SC
CFL
Σ,Λ,Ξ,Δ
H
π⁻
crust
K⁻
color−superconducting
strange quark matter
(u,d,s quarks)
2SC
CSL
gCFL
LOFF
CFL
CFL−K+
CFL−K0
CFL−π0
nucleon

Neutron-rich Hypernuclei

Hypernuclei with a large neutron excess have been theoretically predicted (L. Majling, *NPA 585 (1995) 211c*).

The Pauli principle does not apply to the Λ inside the nucleus + *extra* binding energy (Λ "*glue-like*" role) a larger number of neutrons can be bound with respect to ordinary nuclei.

Neutron-rich hypernuclei and neutron stars.

Stefano Gandolfi and Diego Lonardoni, **The EOS of neutron matter and the effect of Λ hyperons to neutron star structure,** Proc. 12th Int. Conf. on Hypernuclear and Strange Particle Physics (HYP2015) JPS Conf. Proc. 17.101001 (2017)

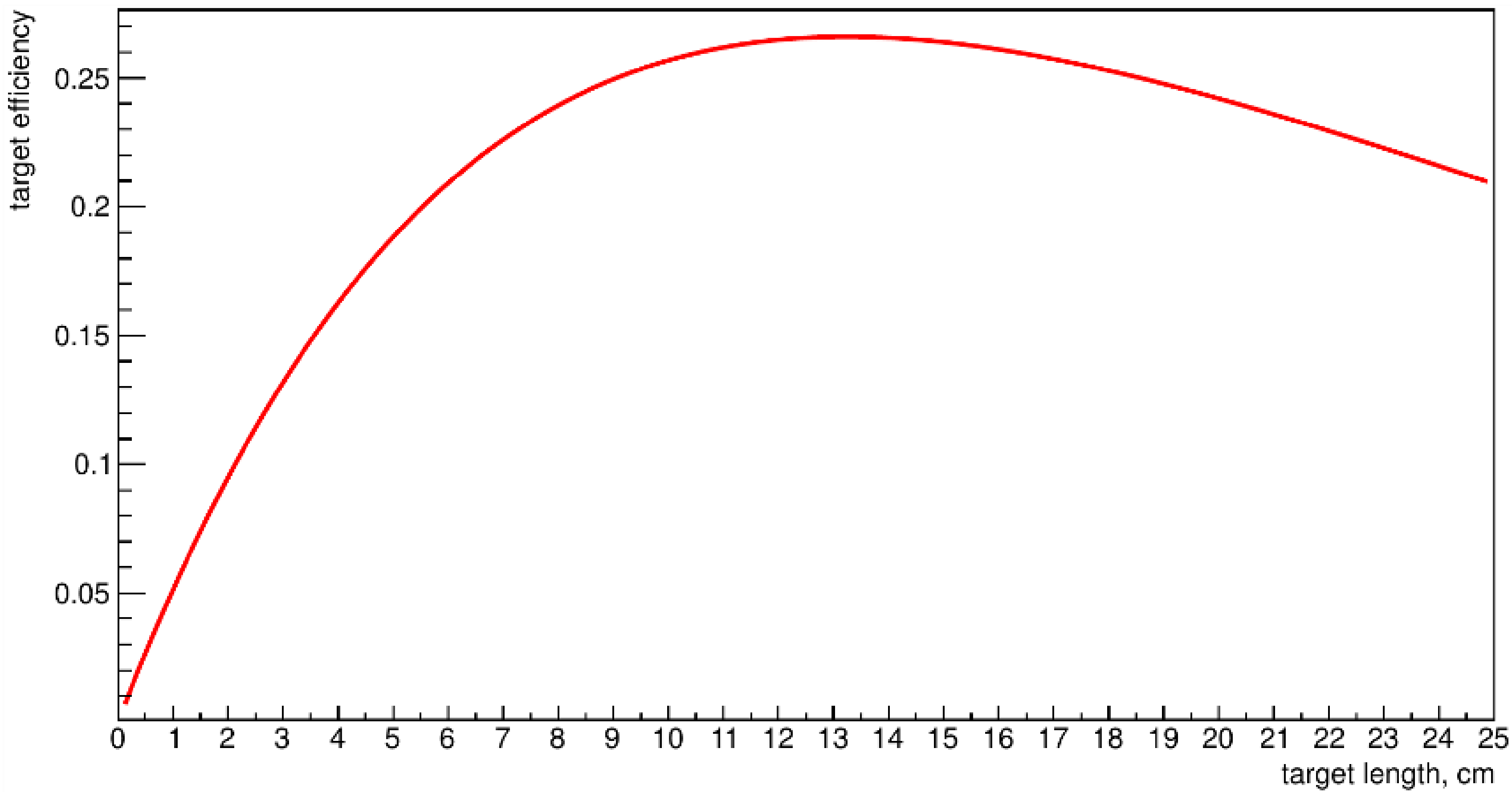
Ignazio Bombaci, **The Hyperon Puzzle in Neutron Stars**, Proc. 12th Int. Conf. on Hypernuclear and Strange Particle Physics (HYP2015) JPS Conf. Proc. 17.101002 (2017)

Do hypernuclei ${}^{6}_{\Lambda}H$ and ${}^{8}_{\Lambda}H$ exist?!

Why lifetime of hypernuclei is lower than of Λ?

Theory and experiment!

Target length



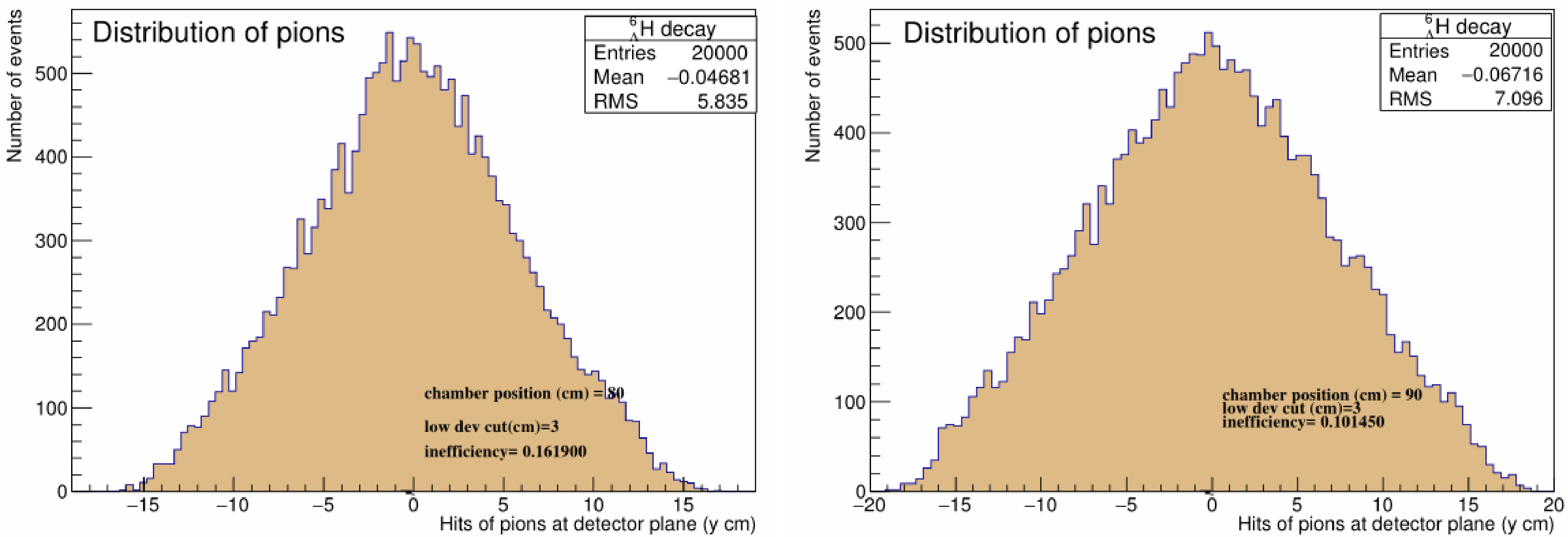


Figure 11: Distribution of pion hits on the proportional chamber situated at 80 cm (left) and 90 cm distance from the beam entrance point of the target. There are no pions outside the chamber. Arbitrary large cut of 3 cm distance between He and pion is chosen as a limit of inefficiency, the cut should be checked experimentally.

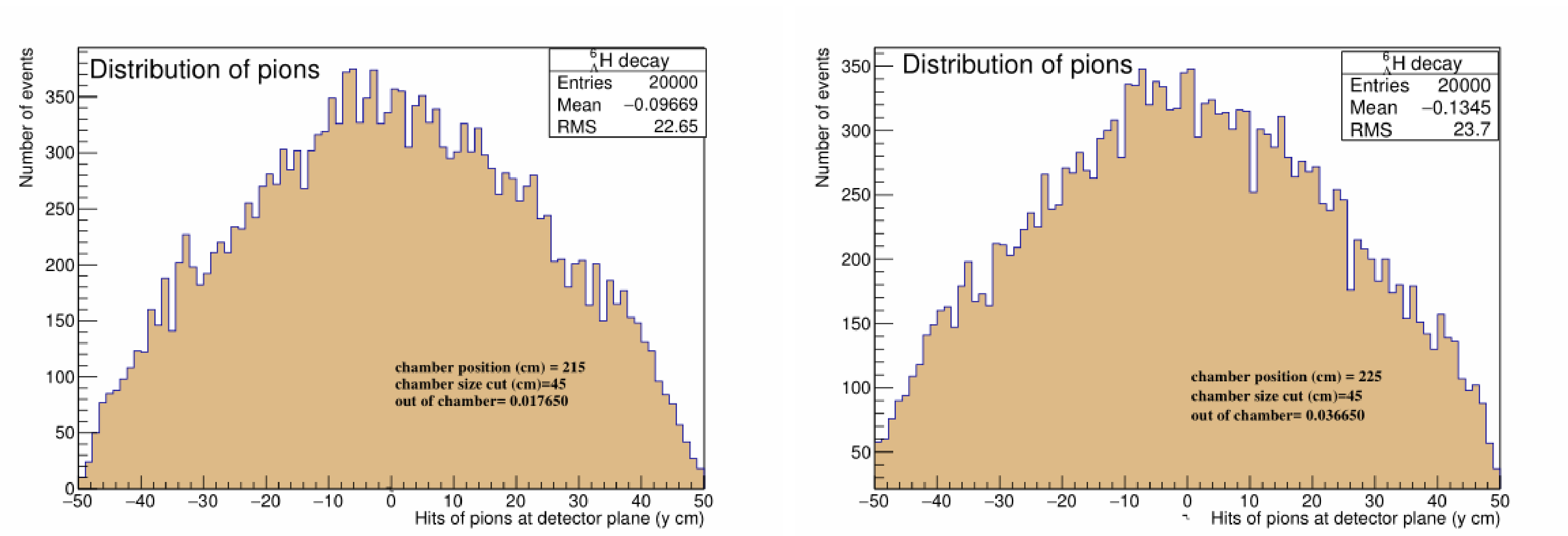


Figure 12: Pion hits at the last chamber to register pions. Geometrical efficiency depends on 10 cm shift of the target position in few percent loss. For the experiment distance of 215 cm is chosen.

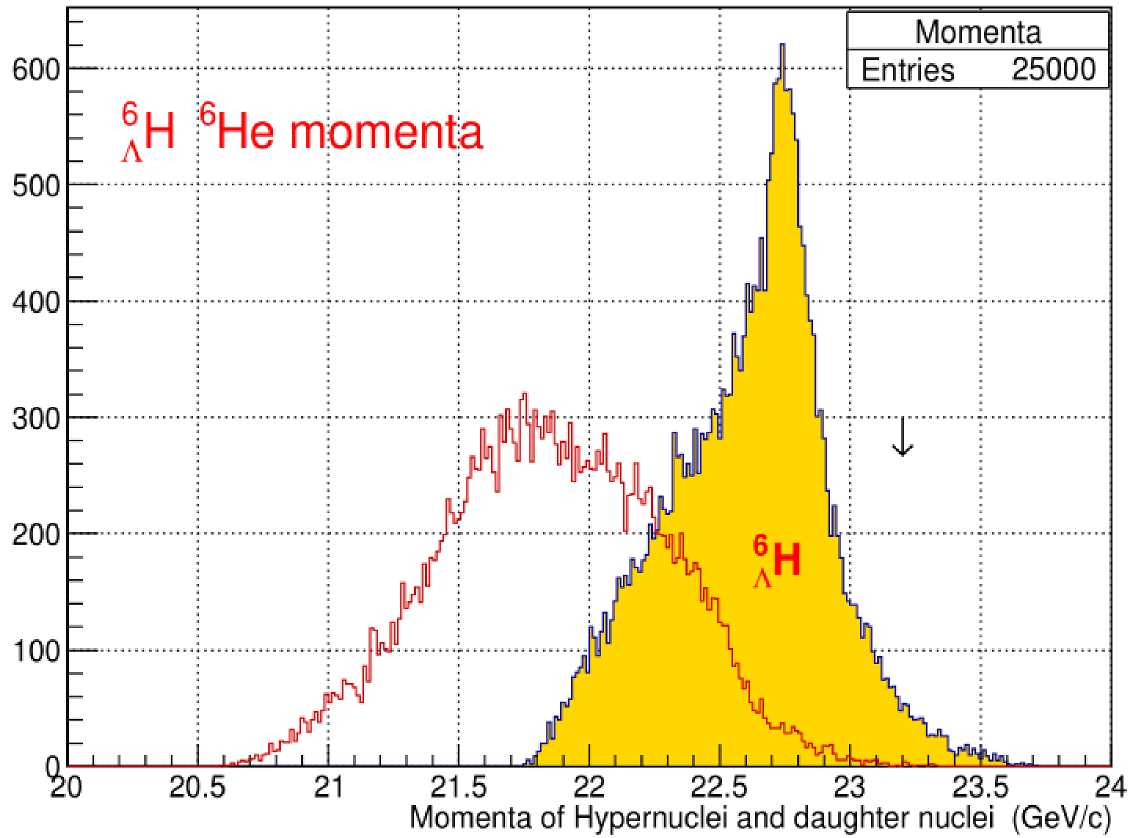
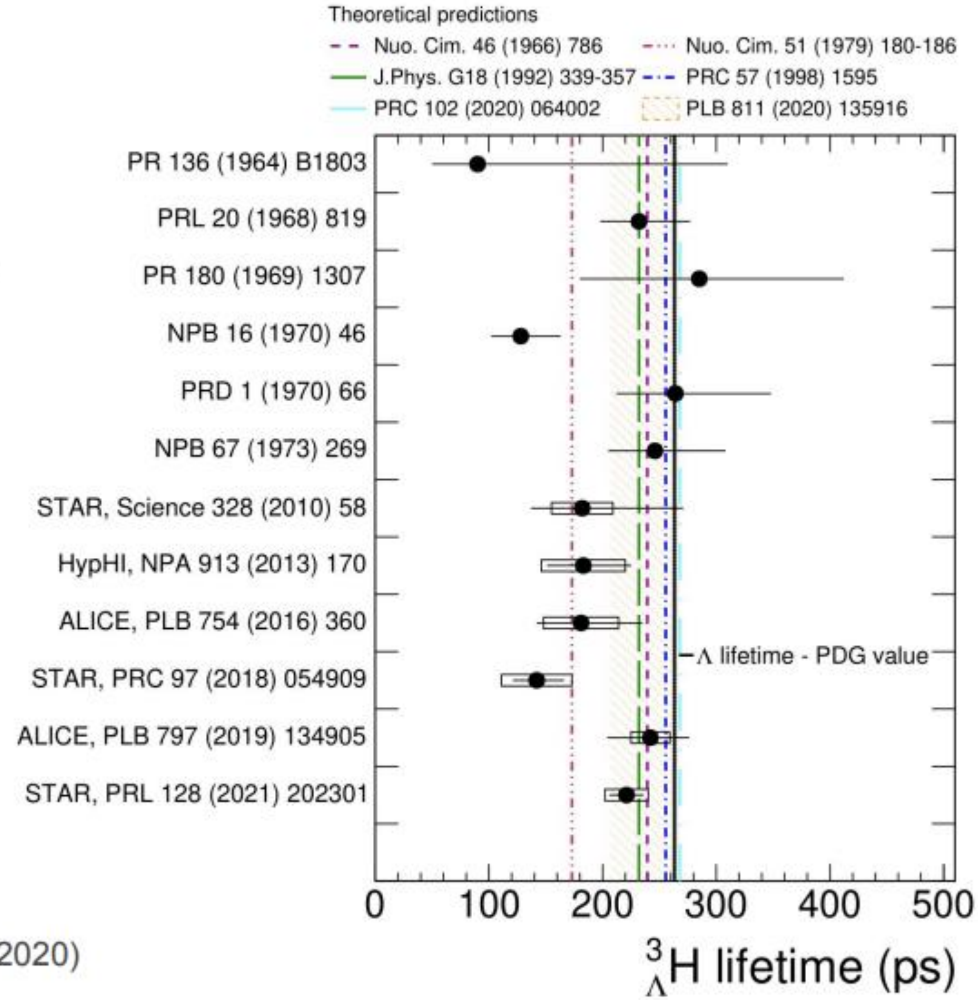


Figure 14: Expected distribution of $^{6}_{\Lambda}H$ hypernuclei and daughter He momenta. Arrow shows beam momentum (23.2 GeV/c). Due to Fermi motion and beam fragmentation momenta of few hypernuclei is higher than mean momentum value for 6 nucleons (^{7}Li beam).

Hypertriton structure: lifetime

- Lifetime of the $^{3}_{\Lambda}H$
  - ➢ A low B_{Λ} should imply a lifetime close to the free Λ hyperon one
  - ➢ Many measurements performed, all with uncertainties > 10%
    - $<\tau> = 219 \pm 13$ ps

- Large theoretical uncertainties
  - ➢ connection between τ and B_{Λ} not well constrained even in state-of-the-art EFT models[1, 2]



[1] Hildenbrand F. et al., *Physical Review C*, vol. 102, no. 6 (2020)
[2] Pérez-Obiol A., *Physics Letters B*, vol. 811 (2020)

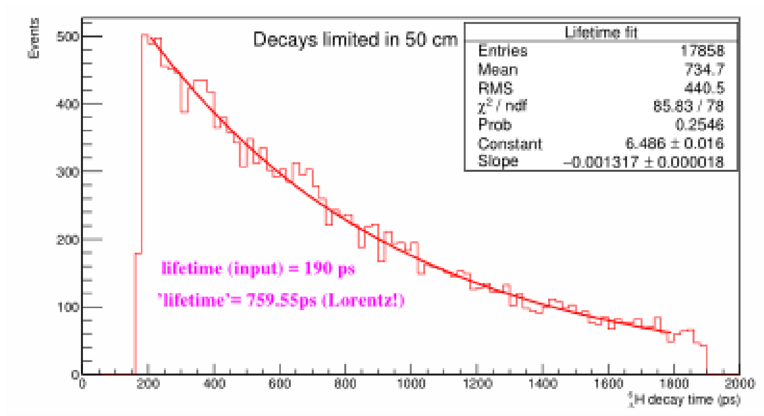


Figure 8: Expected decay time distribution inside of 50 cm distance. Due to Lorentz factor distribution is exponent with 760 ps decay parameter.

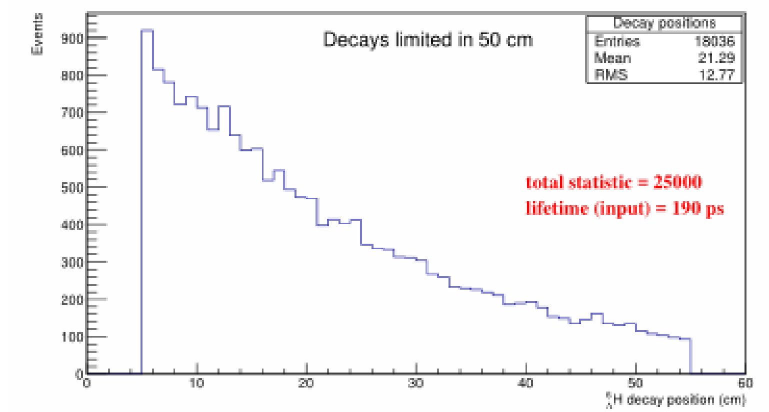


Figure 9: Expected decay points inside of 50 cm distance. Since 25000 events analyzed and 18036 hypernuclei decay inside of 50 cm distance it is 70% of the statistics if the first point is in 5 cm distance from the target.

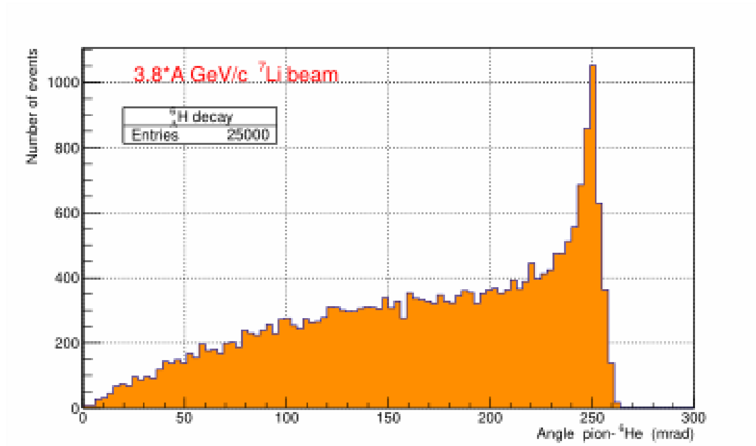


Figure 10: Calculated pion helium separation angle distribution.