Challenges in Hypernuclear Physics of the 21st Century

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U Mainz

Nov. 2o11

Topics selected for this talk

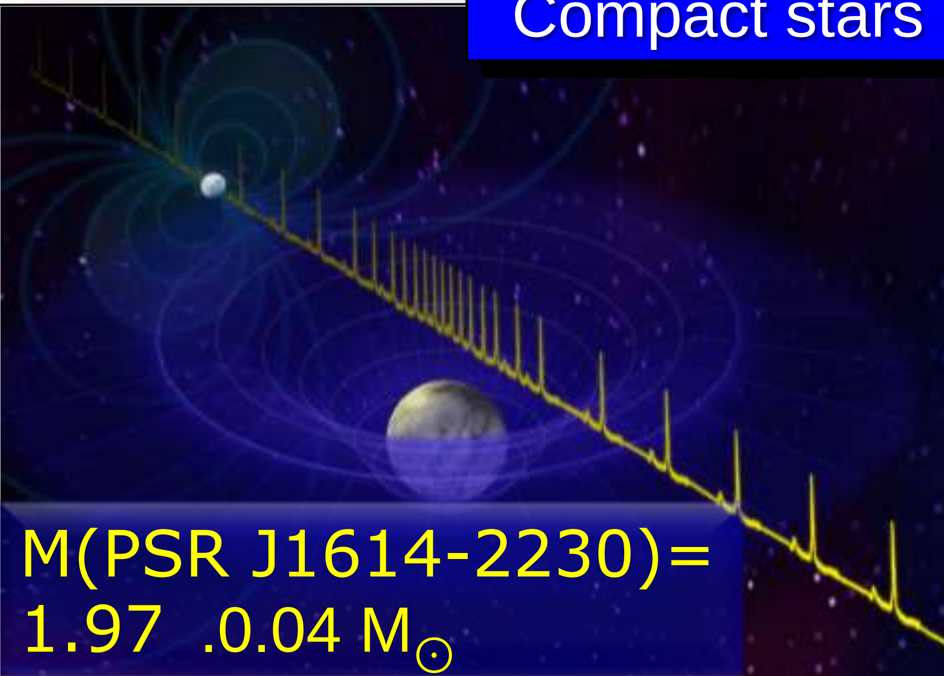
two current issues in strangeness physics

- strangeness in neutron stars
- charge symmetry breaking in nuclei

two experimental programs in strangeness physics

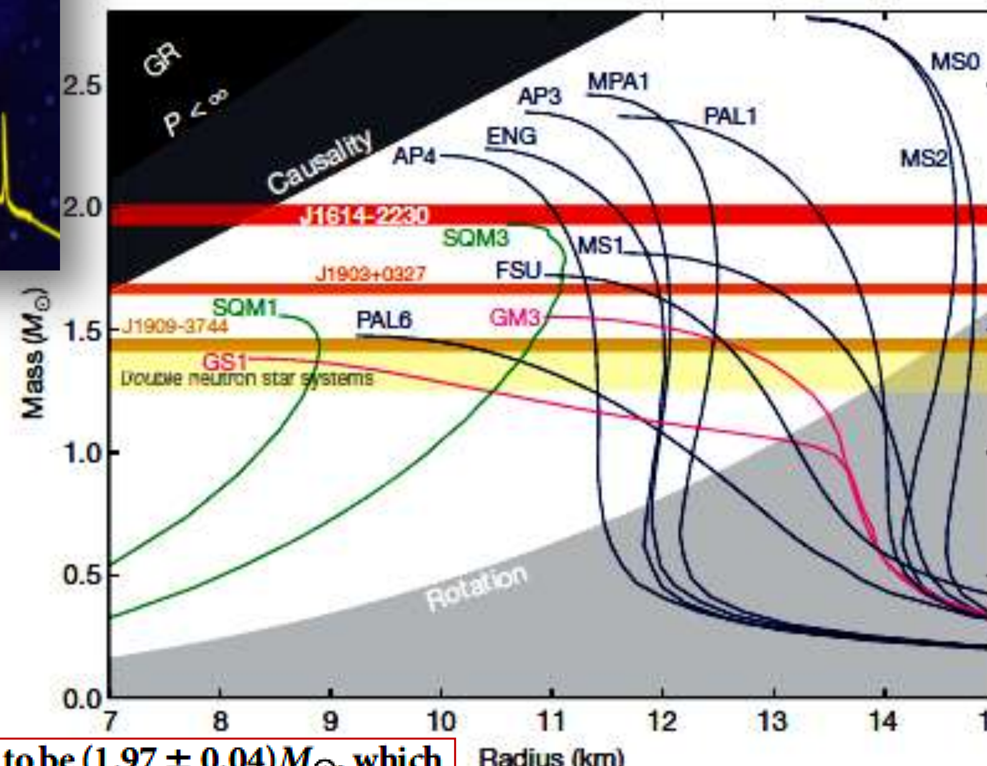
- hypernuclear electroproduction experiments at JLab & MAMI
- double strange hypernuclear experiments at PANDA

Compact stars & nuclear forces



[P. B. Demorest et al., *A two-solar-mass neutron star measured using Shapiro delay*, Nature 467, (2010) 1081]

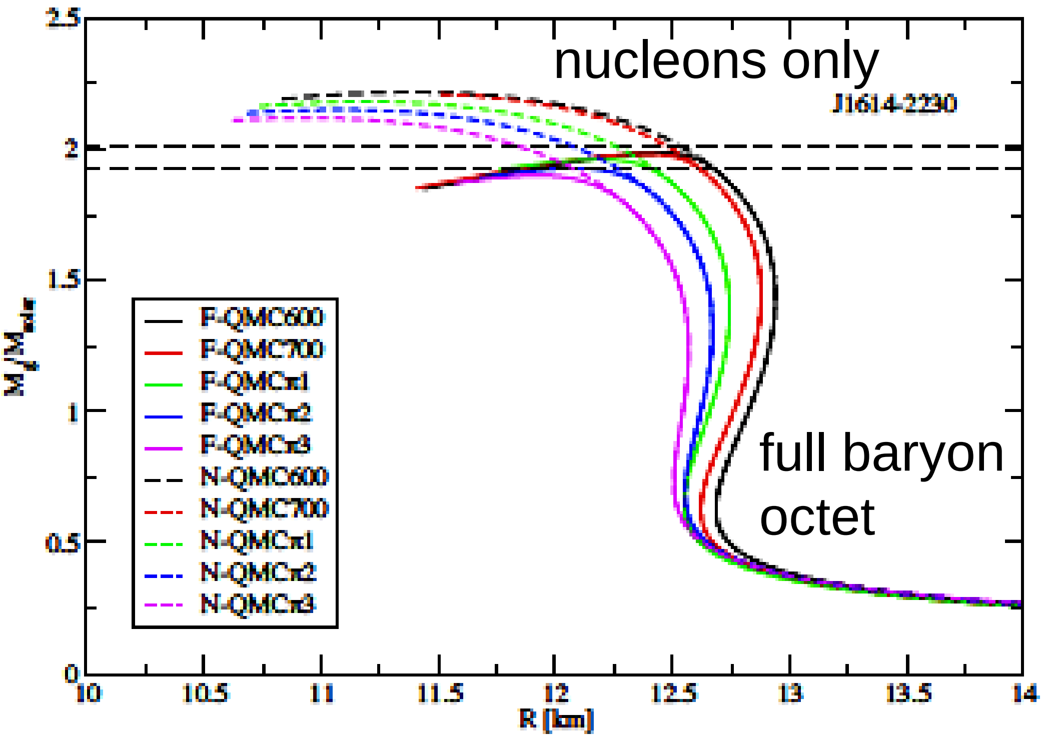
assumed *YN* & *YY* interaction
determines equation-of-state (EOS)
→ prediction of mass-radius relation



We calculate the pulsar mass to be $(1.97 \pm 0.04)M_\odot$, which rules out almost all currently proposed[2–5] hyperon or boson condensate equations of state ($M_\odot$, solar mass).

Quarks & nuclear forces

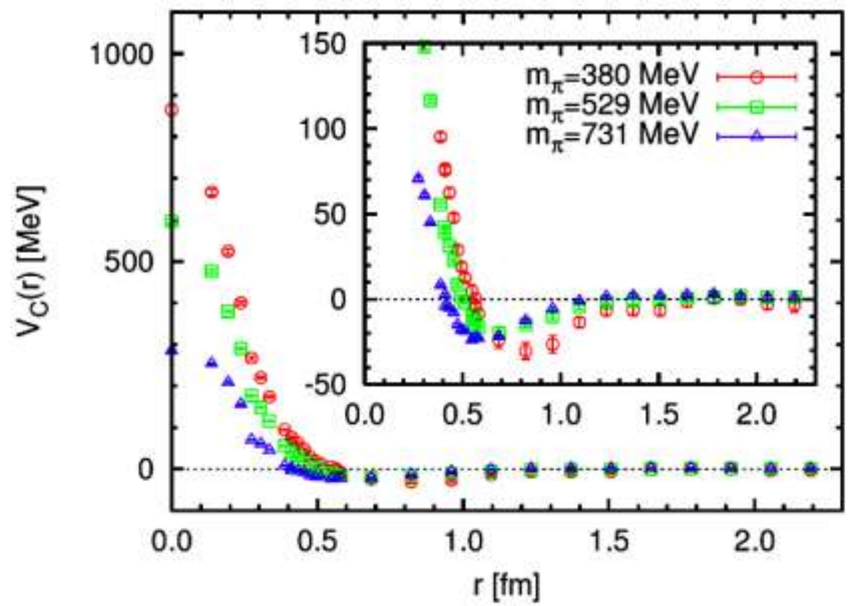
equation-of-state predicted within
quark-meson-coupling model:



[J.R Stone, P.A.M. Guichon and A.W. Thomas]

→ experimental evidences of the 2$M_\odot$ neutron star <u>does not</u> exclude hyperons in the EoS

Nuclear forces from Lattice QCD:



[S. Aoki, T. Hatsuda and N. Ishii, Prog. Theor. Phys. 123 (2010) 89]

Charge Symmetry Breaking

Protons and neutrons are the two isospin states of the nucleon

Protons and neutrons have different masses

Coulomb interaction would make p (uud) heavier than n (udd)

The mass difference between up and down quarks is the strong-interaction effect that breaks charge symmetry

u $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.5$ to 3.0 MeV [a] Charge $= \frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

$m_u/m_d = 0.3$ to 0.6

d $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 3$ to 7 MeV [a] Charge $= -\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

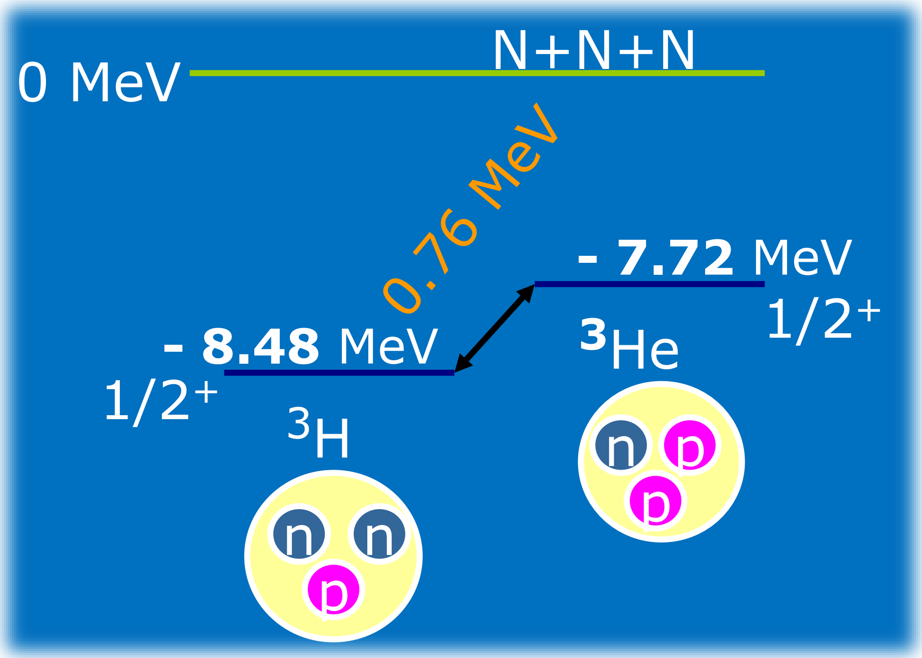
$m_s/m_d = 17$ to 22

$\overline{m} = (m_u + m_d)/2 = 2.5$ to 5.5 MeV

Strong CSB in S = 0 sector makes neutrons decay into protons and is therefore decisive for the structure of our universe

CSB in nuclei and hypernuclei

without ΛN charge symmetry breaking $\Rightarrow B_\Lambda$ of mirror nuclei identical



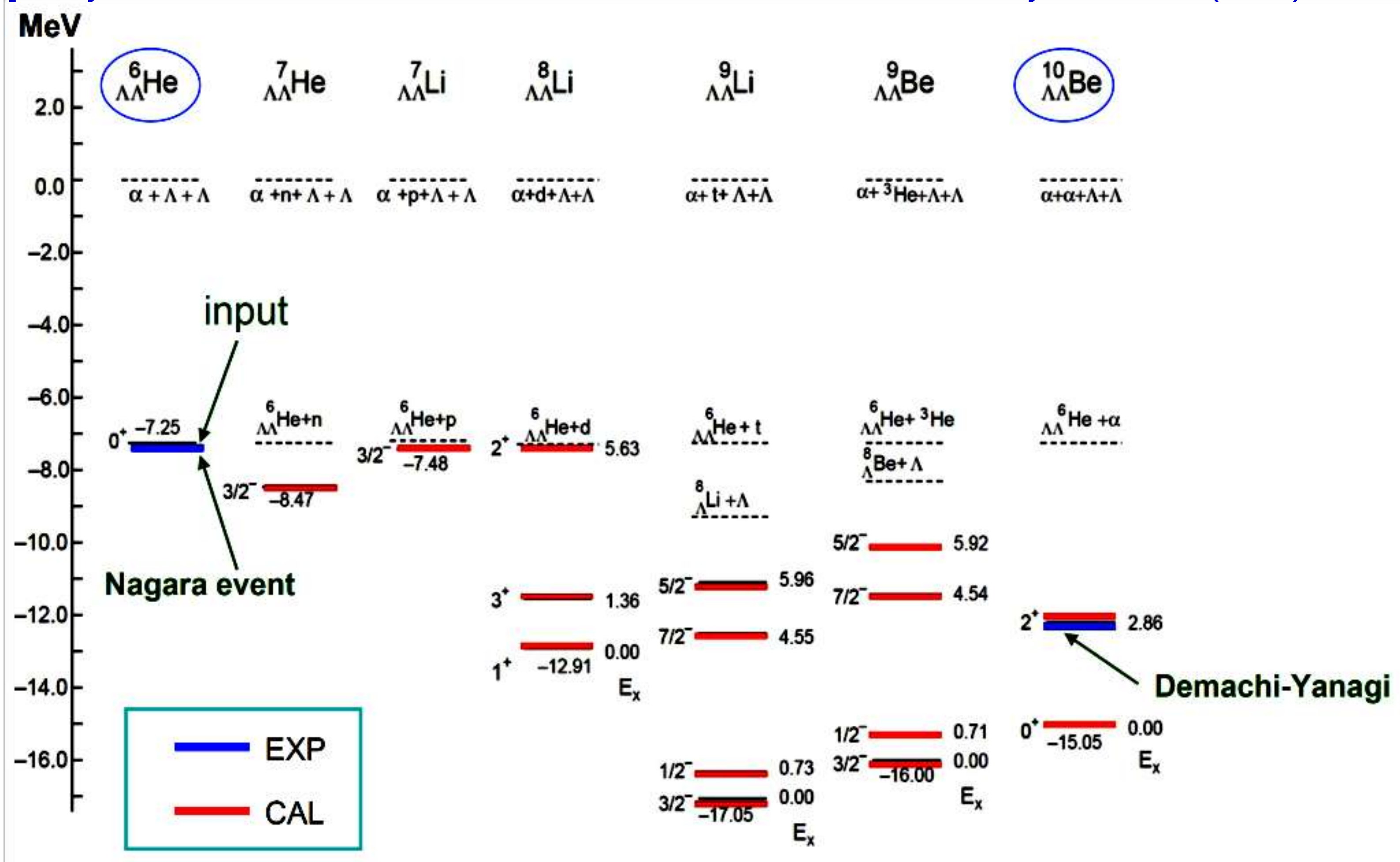
[Emiko Hiyama]

${}^{4}_{\Lambda}H$	2.04 ± 0.04	${}^{4}_{\Lambda}He$	2.39 ± 0.03
${}^{6}_{\Lambda}He$	4.18 ± 0.10	${}^{6}_{\Lambda}Li$	3.92 ± 0.37
	4.42 ± 0.13		
${}^{7}_{\Lambda}He$	3.69 ± 0.90	${}^{7}_{\Lambda}Be$	5.16 ± 0.08
${}^{8}_{\Lambda}Li$	6.80 ± 0.03	${}^{8}_{\Lambda}Be$	6.84 ± 0.05
${}^{9}_{\Lambda}Li$	8.53 ± 0.15	${}^{9}_{\Lambda}B$	7.88 ± 0.15
${}^{10}_{\Lambda}Be$	9.11 ± 0.22	${}^{10}_{\Lambda}B$	8.89 ± 0.12
${}^{12}_{\Lambda}B$	11.37 ± 0.06	${}^{12}_{\Lambda}C$	10.76 ± 0.19
			11.38 ± 0.09
${}^{16}_{\Lambda}N$	13.76 ± 0.16	${}^{16}_{\Lambda}O$	12.42 ± 0.05
			13.28 ± 0.36
			13.40 ± 0.40

Coulomb interaction and modifications of nuclear structure due to Coulomb interaction may mask the effect of the strong CSB

Spectroscopy of ΛΛ-hypernuclei

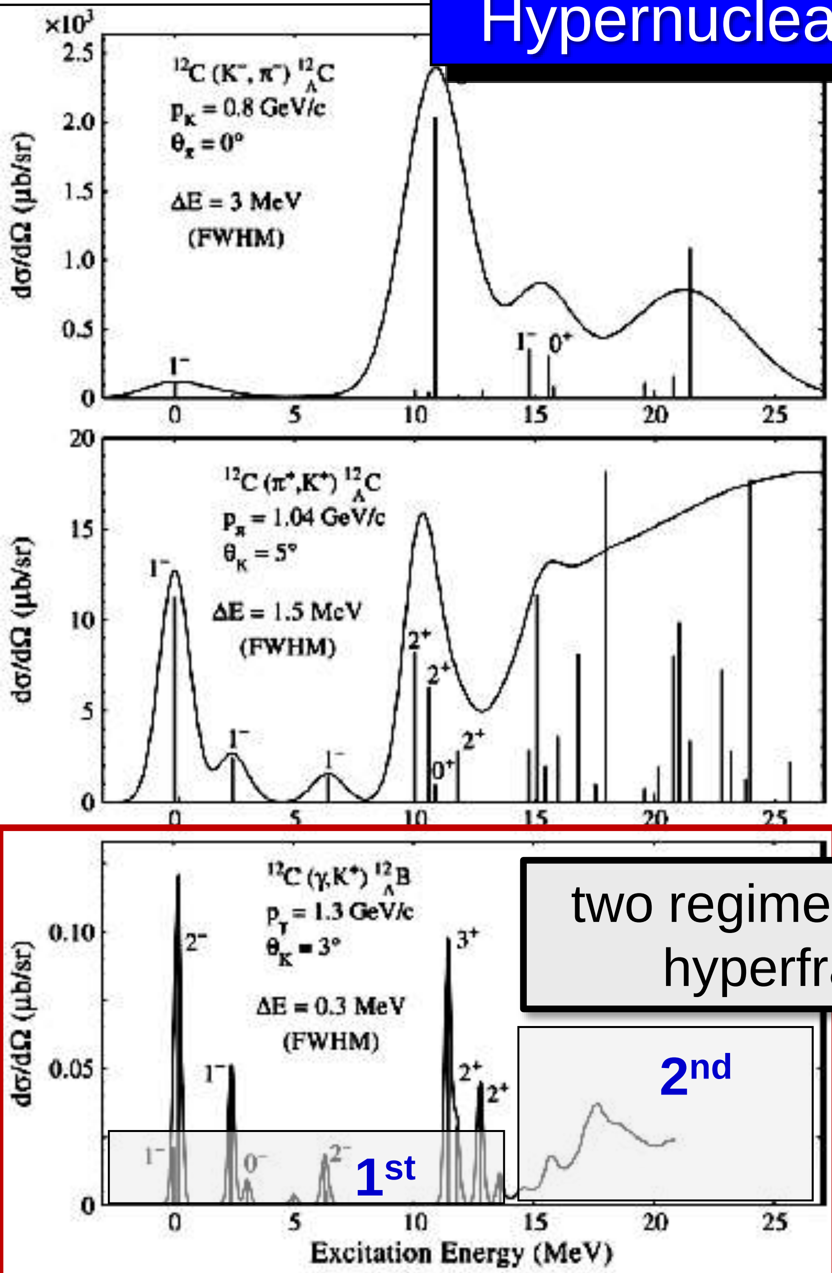
[E. Hiyama, M. Kamimura, T.Motoba, T. Yamada and Y. Yamamoto, Phys. Rev. 66 (2002) , 024007]



- many excited, particle stable states in double hypernuclei predicted
- level structure reflects levels of core nucleus

Electroproduction of hypernuclei and hyperfragments

Hypernuclear production methods



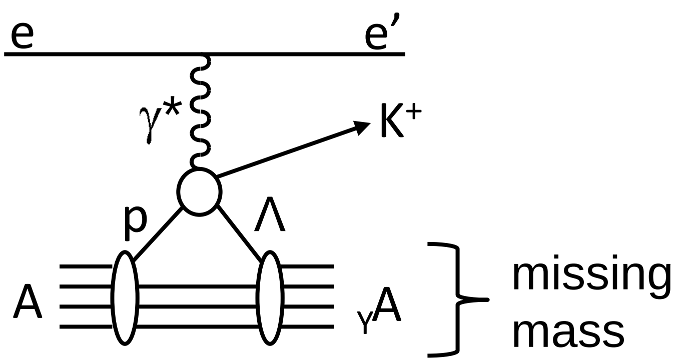
hypernuclear experiments with electron beams:

- the detection of unknown (core-excited) hypernuclear states
- the measurement of kaon angular distributions
- precise determination of binding energies

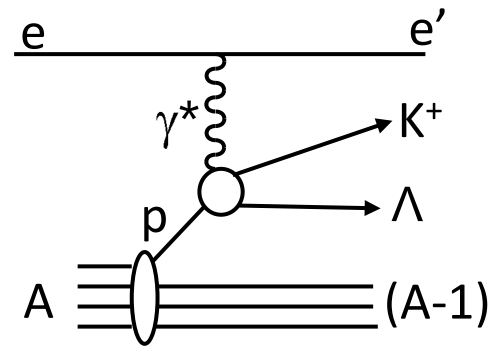
two regimes for hypernuclear and hyperfragment production

[O. Hashimoto and H. Tamura, *Prog. Part. Nucl. Phys. 57*, 564 (2006).]

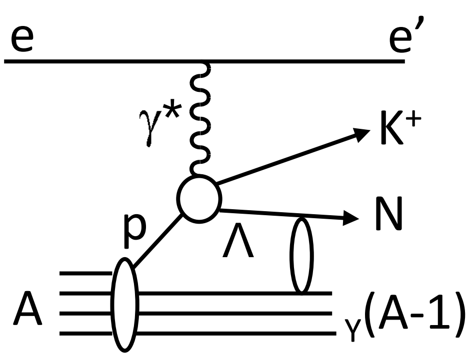
Electro-production of hypernuclei and hyperfragments

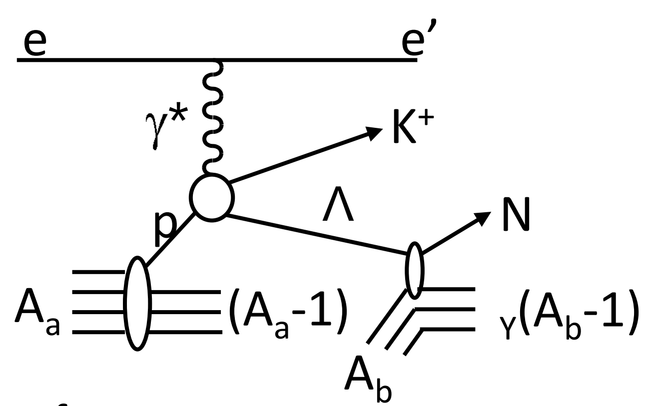


direct production of hypernuclei



quasi-free Λ production (continuum)

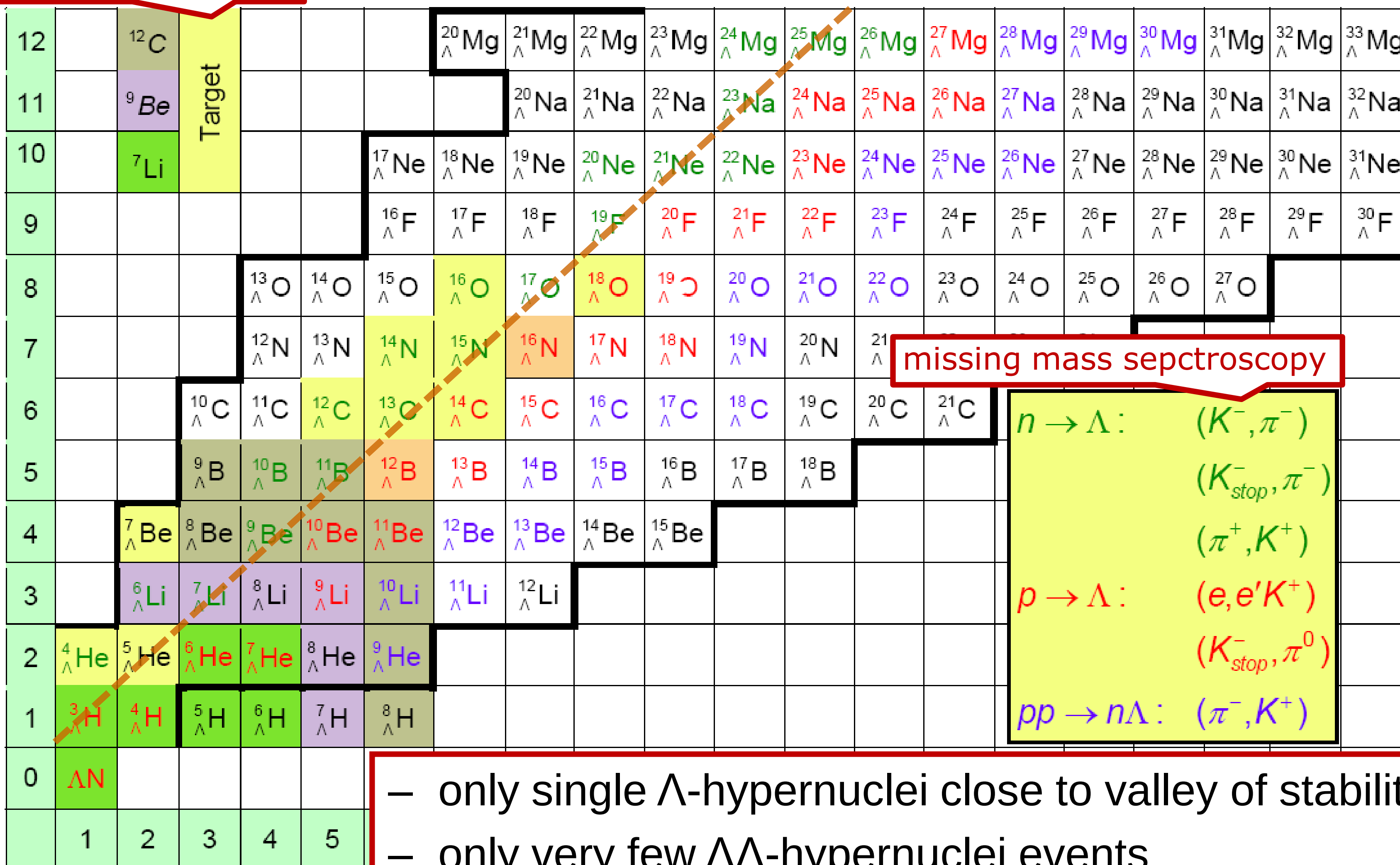




secondary production of hyperfragments (continuum)

[prepared by Liguang Tang]

Hypernuclear spectroscopy

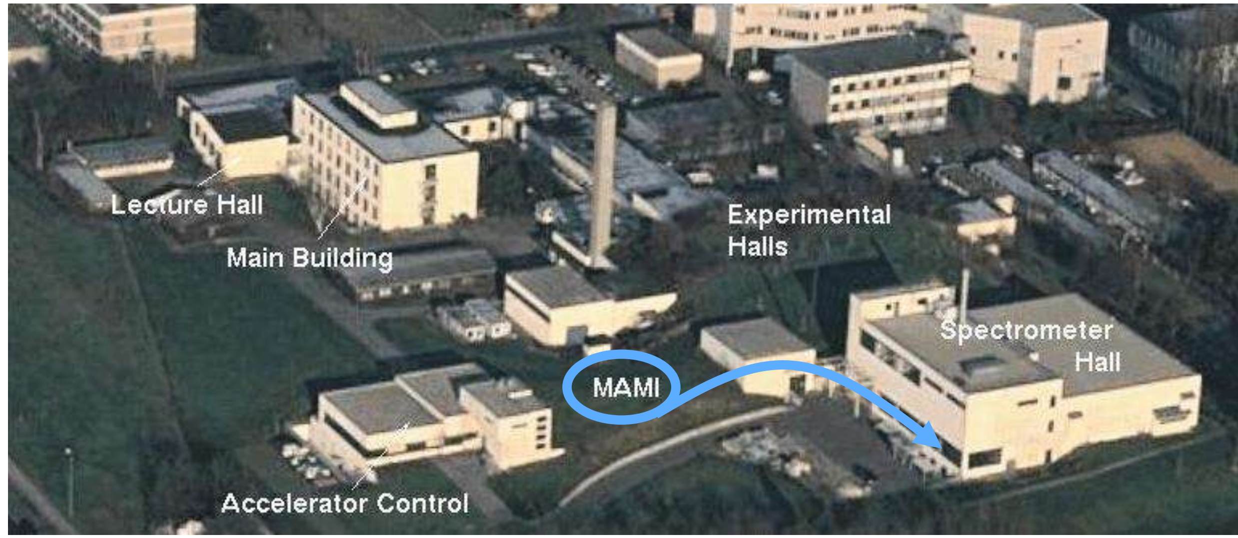


- only single Λ-hypernuclei close to valley of stability
- only very few ΛΛ-hypernuclei events

Electron beam facilities

Jefferson Lab, VA

MAMI, Germany



$$E_{CM} = \sqrt{2E_\gamma M_p + M_p^2} = M_\Lambda + M_{K^+} = 1,6\text{GeV}$$

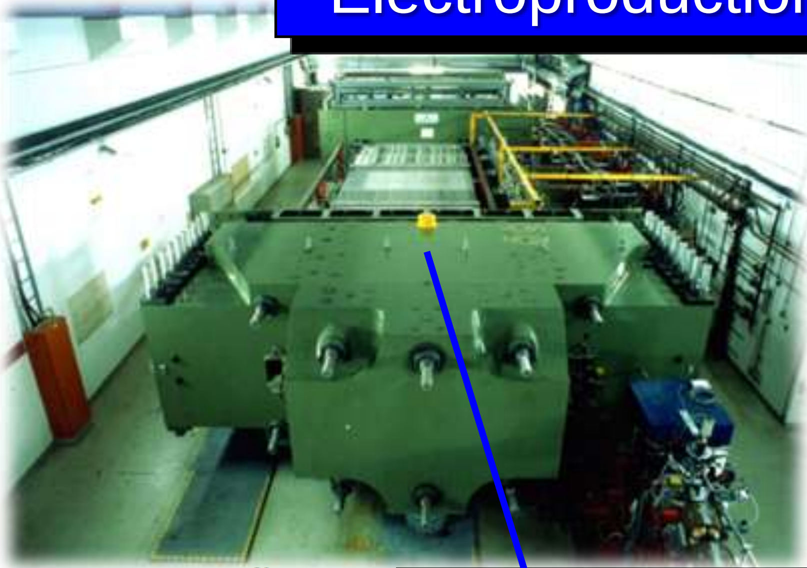
$$\Rightarrow \boxed{E_\gamma = 0,9\text{GeV}}$$

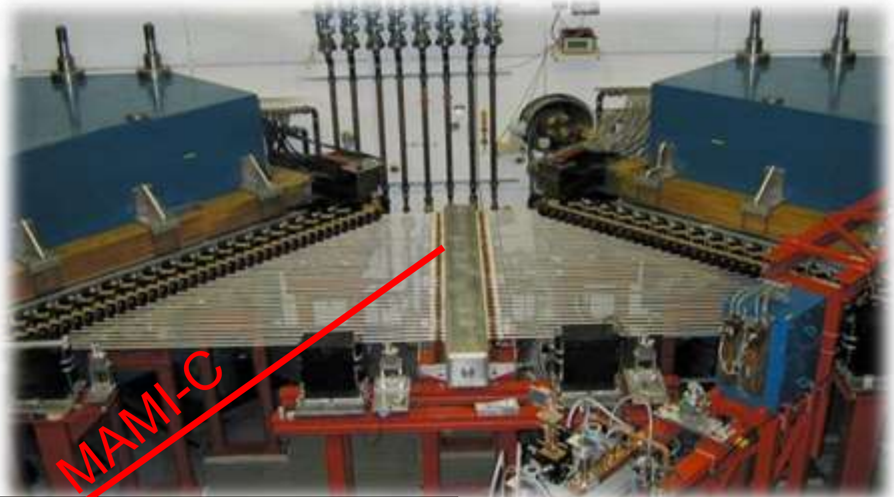
available electron machines:

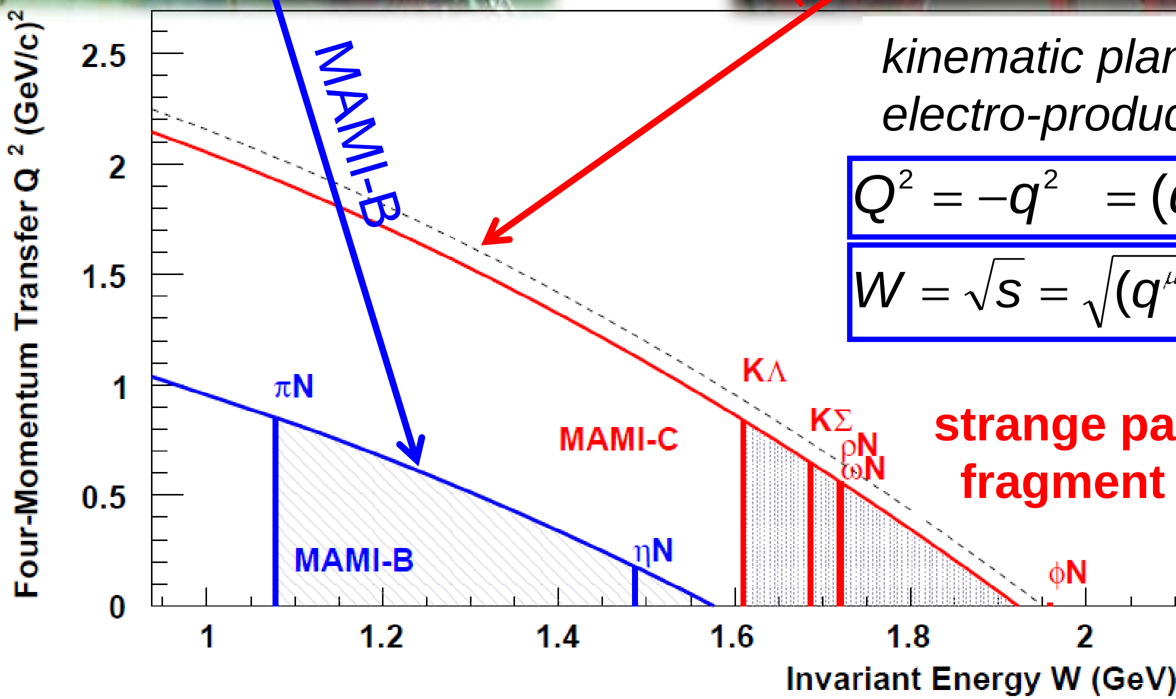
1. CEBAF at Jefferson Lab
2. MAMI-C in Mainz

	CEBAF	MAMI-C
beam energy	6.0 GeV	1.5-1.6 GeV
beam intensity	100 μA	100 μA 6 x 10^{14} electrons/s
beam size	~ 100 μm (rms)	~ 100 μm (rms)

Electroproduction off the nucleon with MAMI-C







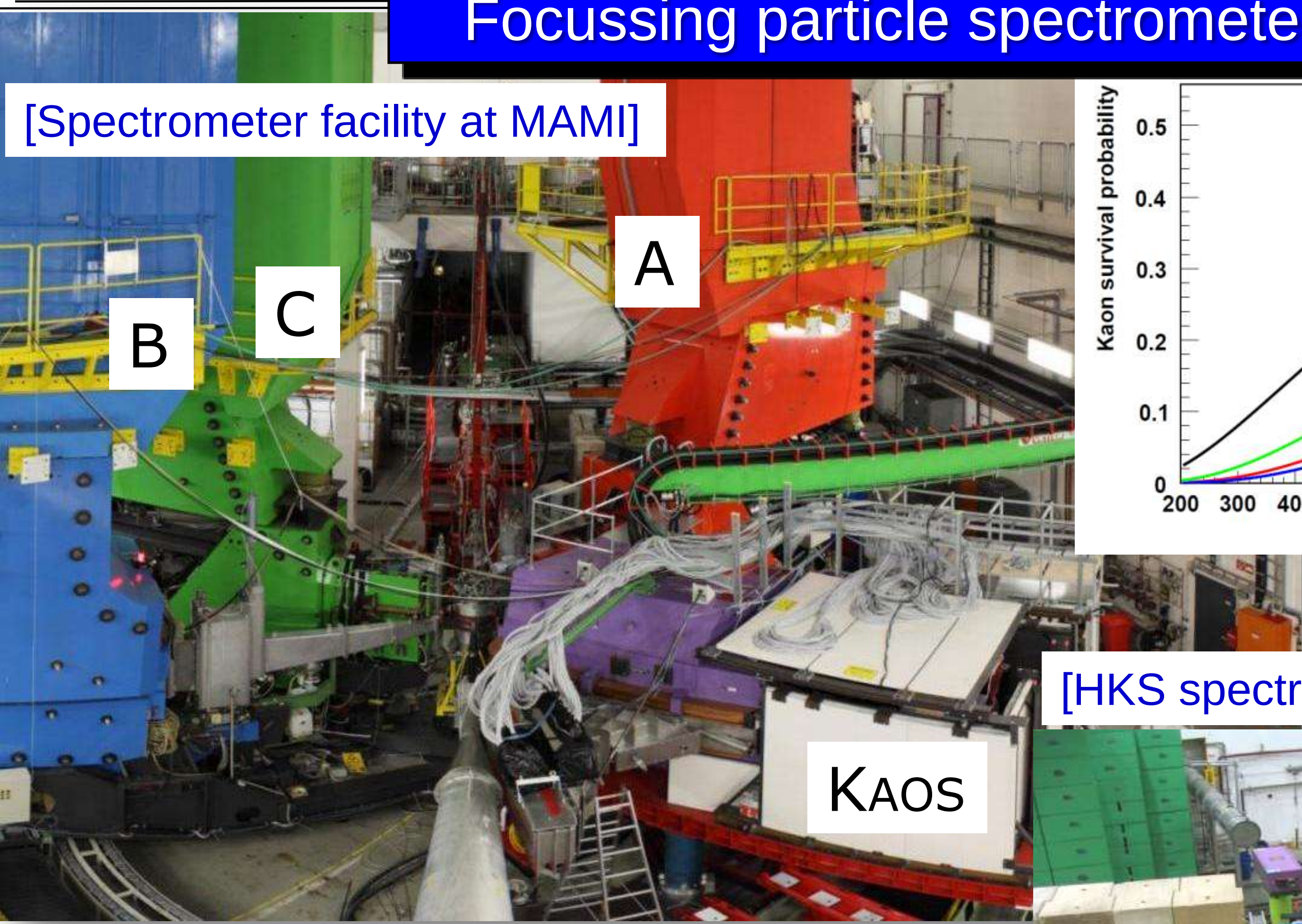
kinematic plane in electro-production:

$$Q^2 = -q^2 = (q^{\mu}_{e} - q^{\mu}_{e'})^2$$

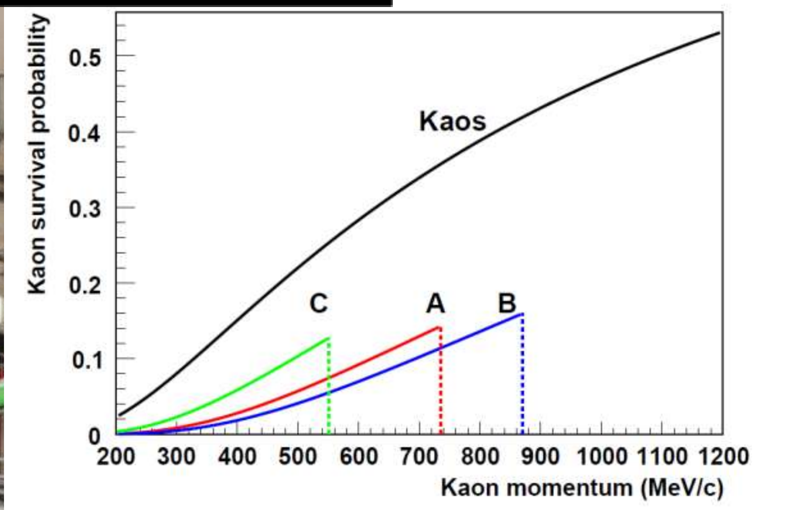
$$W = \sqrt{s} = \sqrt{(q^{\mu} + p^{\mu}_{target})^2}$$

strange particle and fragment production

Focussing particle spectrometers



[Spectrometer facility at MAMI]



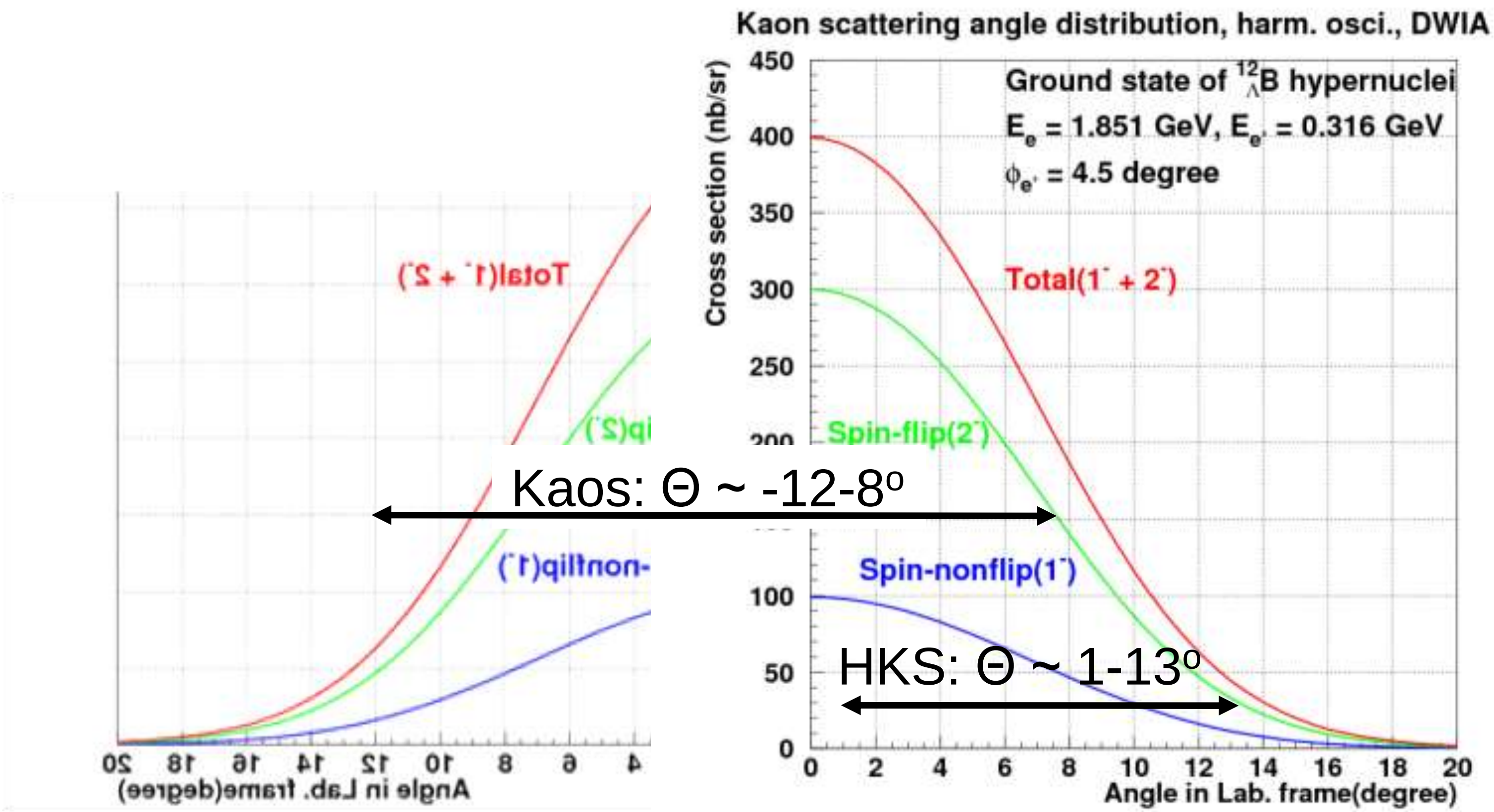
[HKS spectrometer at Jefferson Lab]

Magnetic focusing spectrometers:

- 3 high resolution $\Delta p/p \sim 10^{-4}$ spectrometers
- one short orbit spectrometer (KAOS , since 2008)

Angular dependence of Λ-hypernuclei production

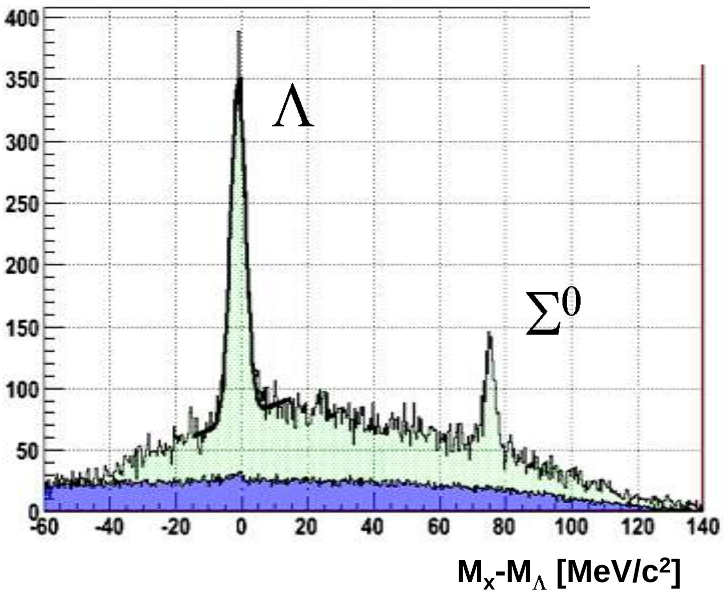
- kaon detection at forward angles: $\Theta_K < 10^o$
- large kaon angle acceptance



Missing mass spectroscopy

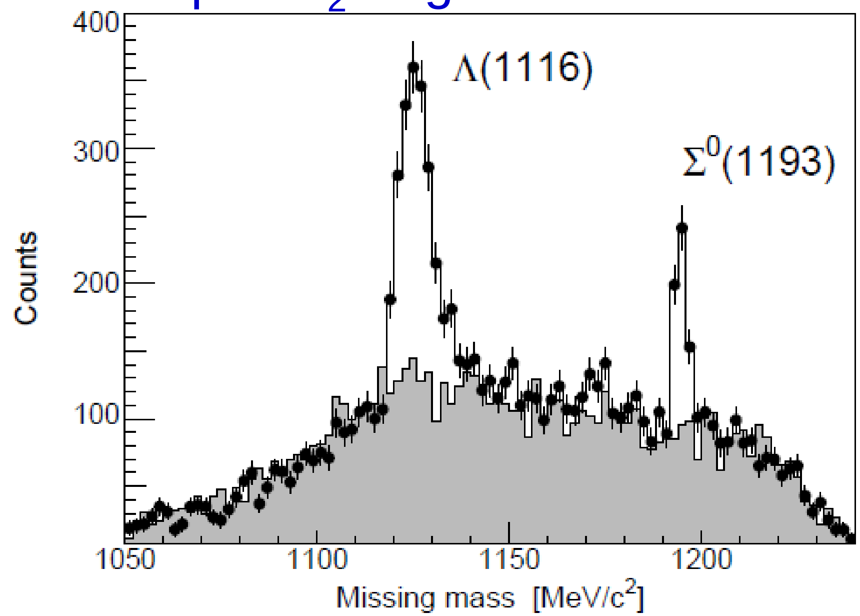
$$E_X = E_e - E_{e'} + M_{targ} - E_K = \omega + M_{targ} - E_K,$$
$$\vec{P}_X = \vec{q} - \vec{p}_K,$$

CH$_2$ target



E05-115 (2oo9) preliminary

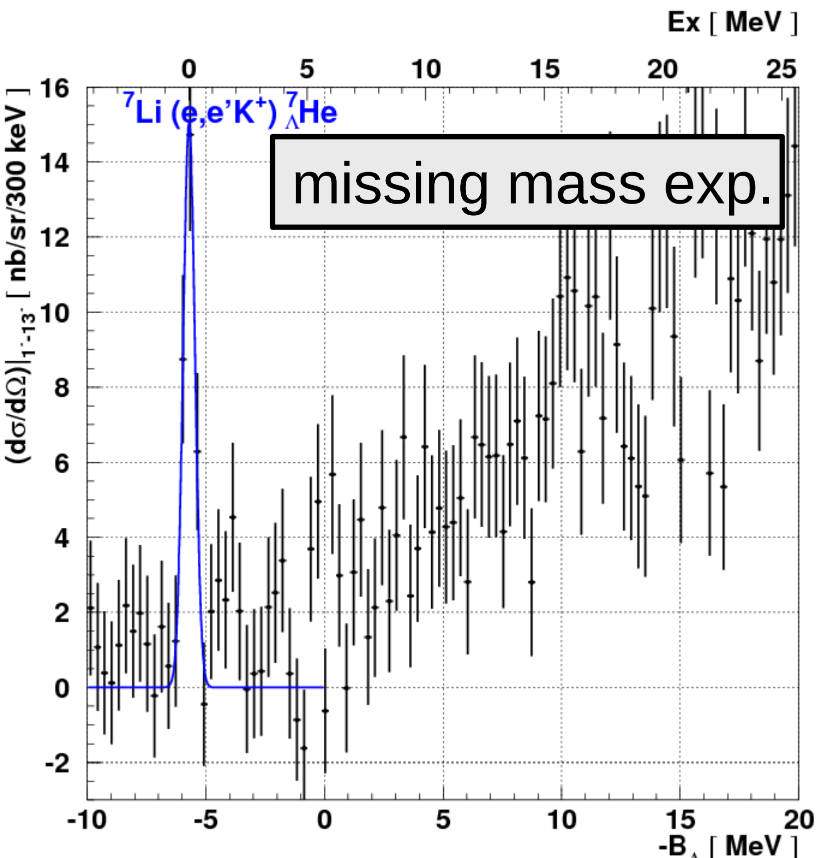
liquid H$_2$ target



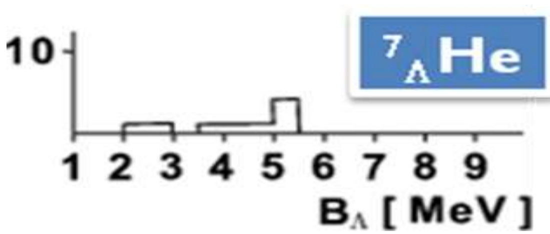
KAOS 2oo9 beam-time

$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$

first reliable observation of $^{7}_{\Lambda}He$ with good statistics



missing mass exp.



emulsion exp.

[M. Juric et al., Nucl. Phys. B 52 (1973) 1]

1. Present E01-011 Result (Preliminary)

ID	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]
#1	-5.68 ± 0.03 (*stat.*) ± 0.22 (*sys.*)	26 ± 3 (*stat.*) ± 10 (*sys.*)

2. Theoretical calculations

Cross section : Sotona *et. al.*

$-B_{\Lambda}$: Hiyama *et. al.*

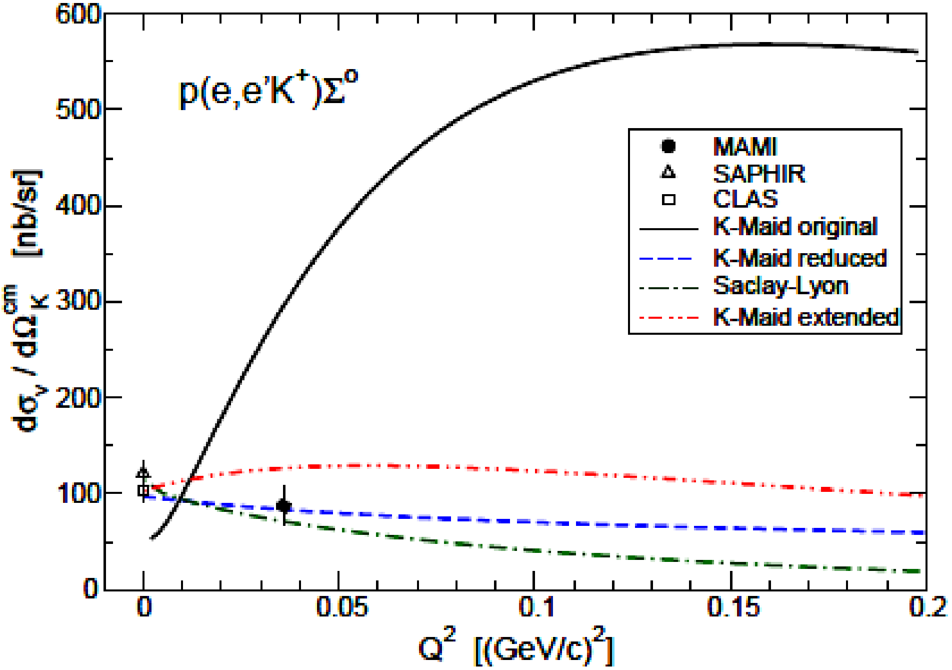
($1.3 < E_{\gamma} < 1.6$ GeV, $1 < \theta_{K} < 13$ deg.)

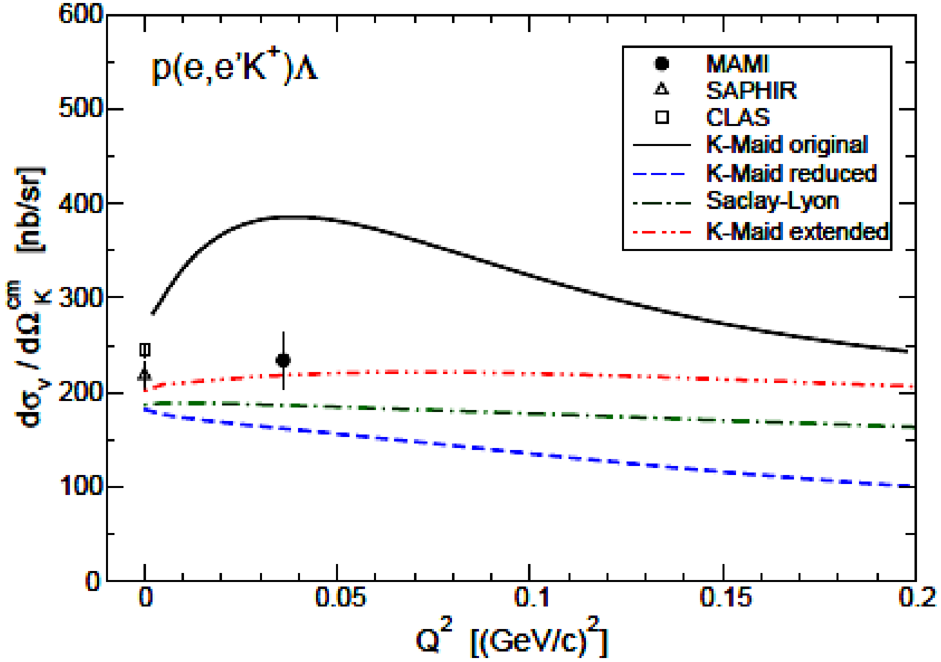
J^{π}	$-B_{\Lambda}$ [MeV]	Cross section [nb/sr]		
		SLA	C4	KMAID
$1/2^{+}$	-5.36	13.2	16.2	9.7

[prepared by Osamu Hashimoto]

Results for the elementary process

[P. Achenbach *et al*. (A1 Collaboration), arXiv:1104.4245]



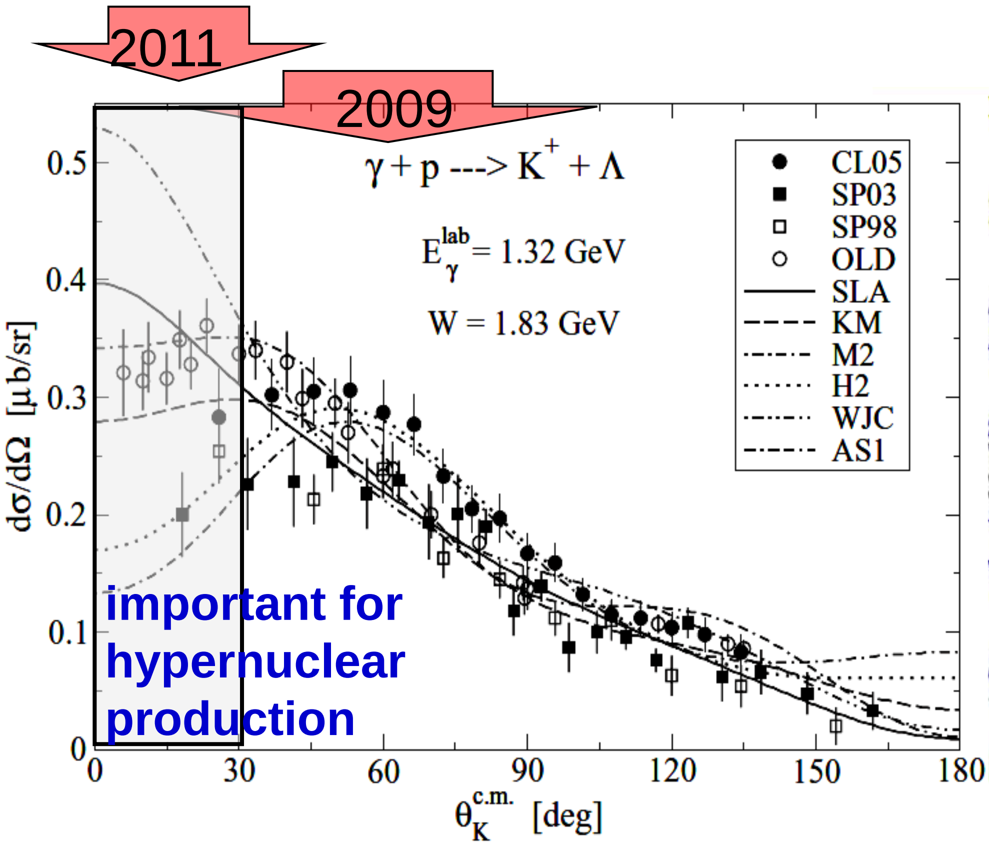


- first time measurement of cross-section at low Q^2
- only small differences to photoproduction data observed
- original K-Maid model excluded with high significance

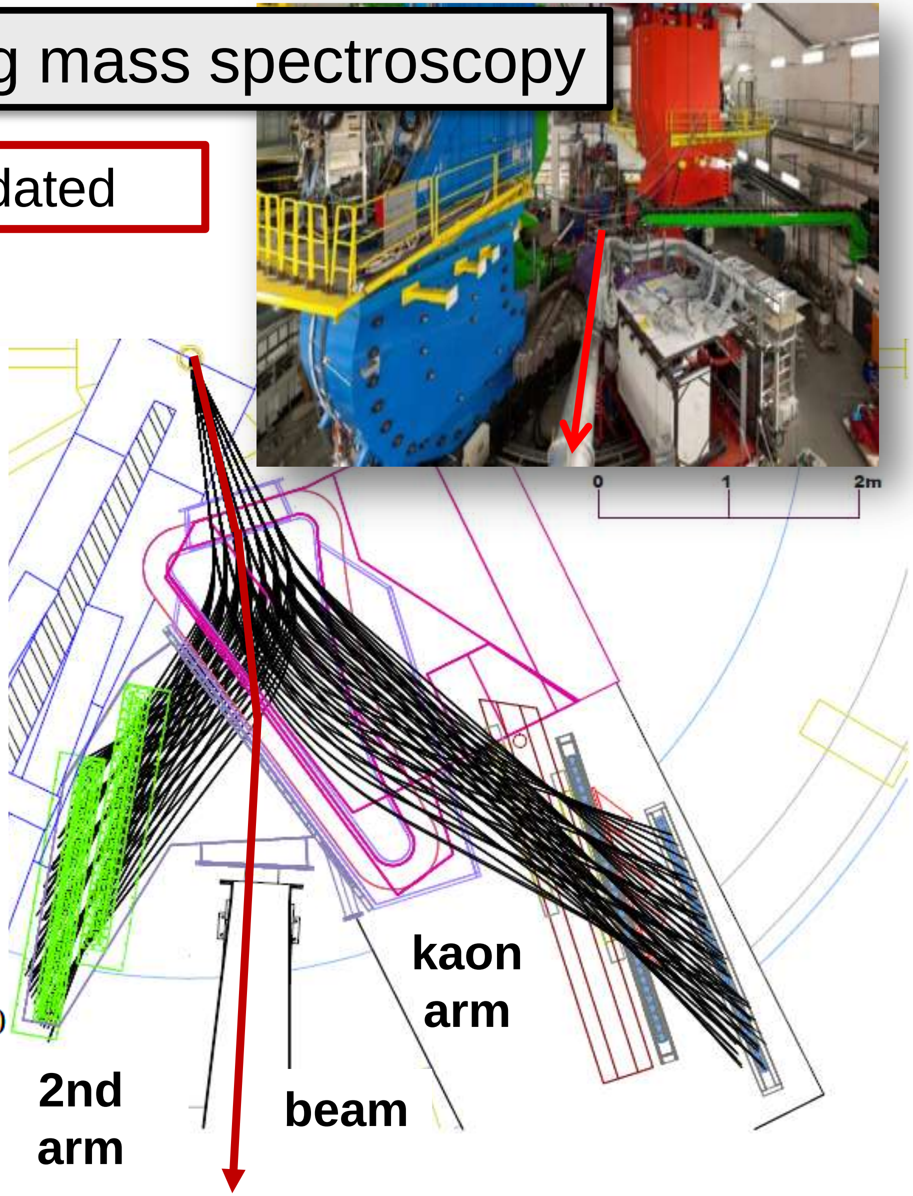
Detection of hypernuclei

First approach: missing mass spectroscopy

status: experimental setup is consolidated

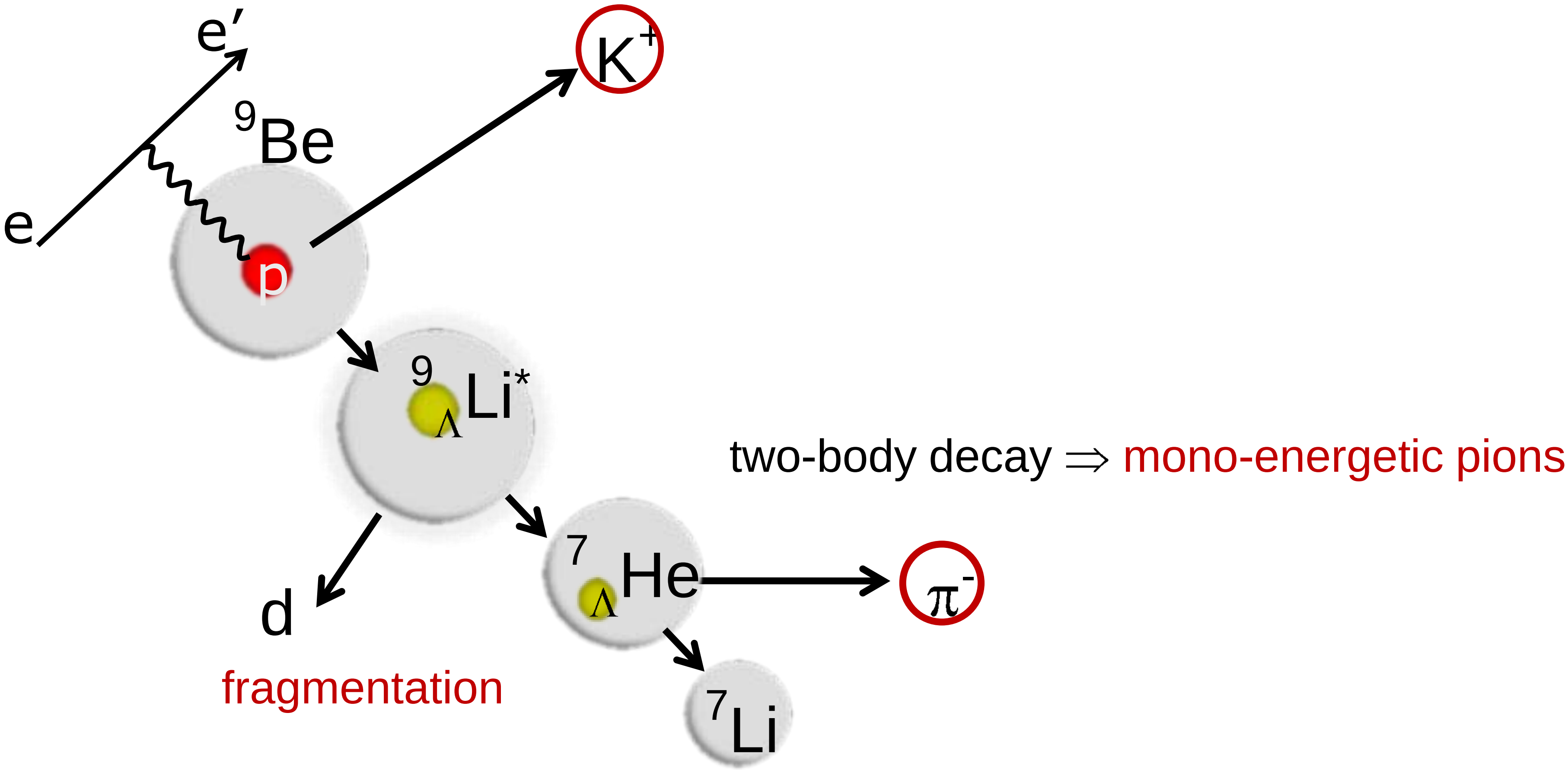


From: [T. Mart and A. Sulaksono, *Phys. Rev. C 74,* 055203 (2006).]



Detection of hypernuclei

Second approach: decay-pion spectroscopy



status: first experiments have been performed in Mainz

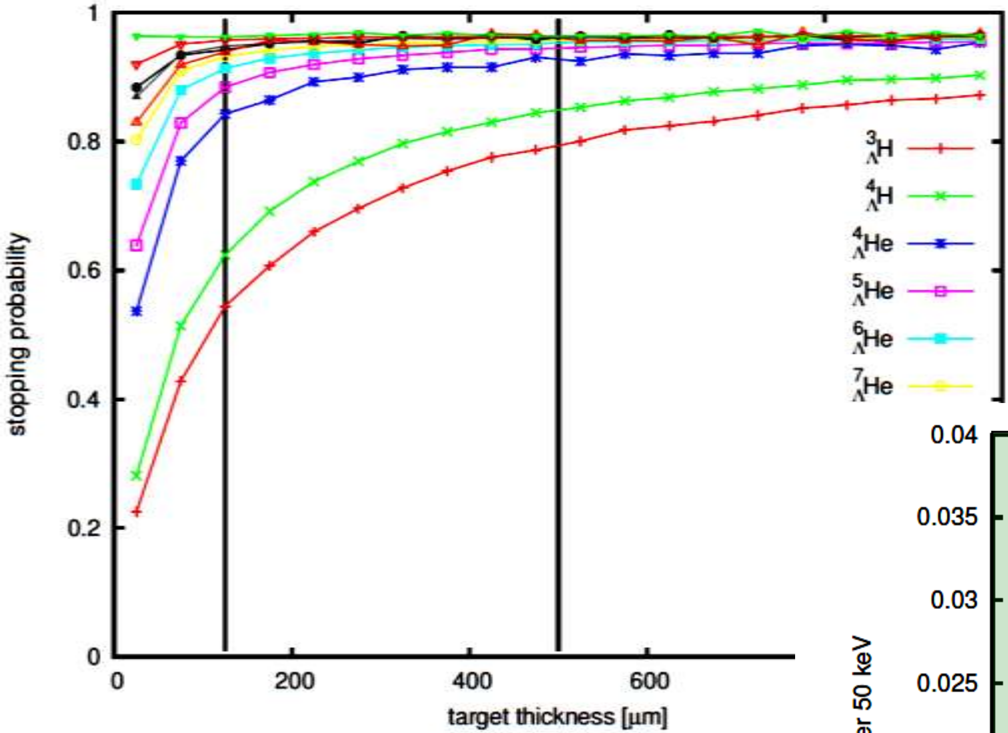
Hypernuclei from a ^{9}Be target

Two-body decays of 12 different hypernuclei

break-up mode	*Q* value (MeV)	π^- decay	p_π (MeV/*c*)
$^{9}_{\Lambda}$Li	-	^{9}Be + π^-	121.18
p + $^{8}_{\Lambda}$He	-13.817	^{8}Li + π^-	116.40
n + $^{8}_{\Lambda}$Li	-3.756	^{8}Be + π^-	124.12
2p + $^{7}_{\Lambda}$H	-40.328 (B_Λ=6.1)	^{7}He + π^-	135.17
d + $^{7}_{\Lambda}$He	-12.568	^{7}Li + π^-	114.61
2n + $^{7}_{\Lambda}$Li	-12.218	^{7}Be + π^-	108.02
^{3}He + $^{6}_{\Lambda}$H	-29.608 (B_Λ=5.1)	^{6}He + π^-	133.47
^{3}H + $^{6}_{\Lambda}$He	-9.745	^{6}Li + π^-	108.39
3n + $^{6}_{\Lambda}$Li	-18.957	^{6}Be + π^-	100.58
α + $^{5}_{\Lambda}$H	-11.749 (B_Λ=4.1)	^{5}He + π^-	133.42
n + α + $^{4}_{\Lambda}$H	-12.005	^{4}He + π^-	132.95
^{6}He + $^{3}_{\Lambda}$H	-18.183	^{3}He + π^-	114.29

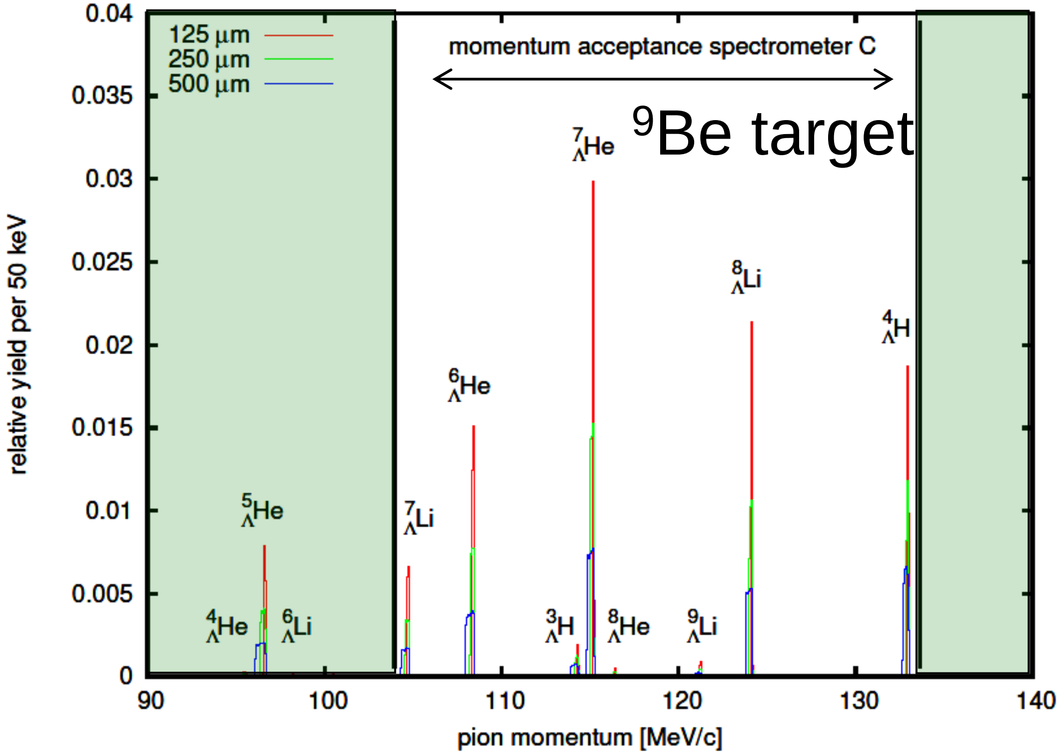
[from Liguang Tang]

Stopping and decay in Be

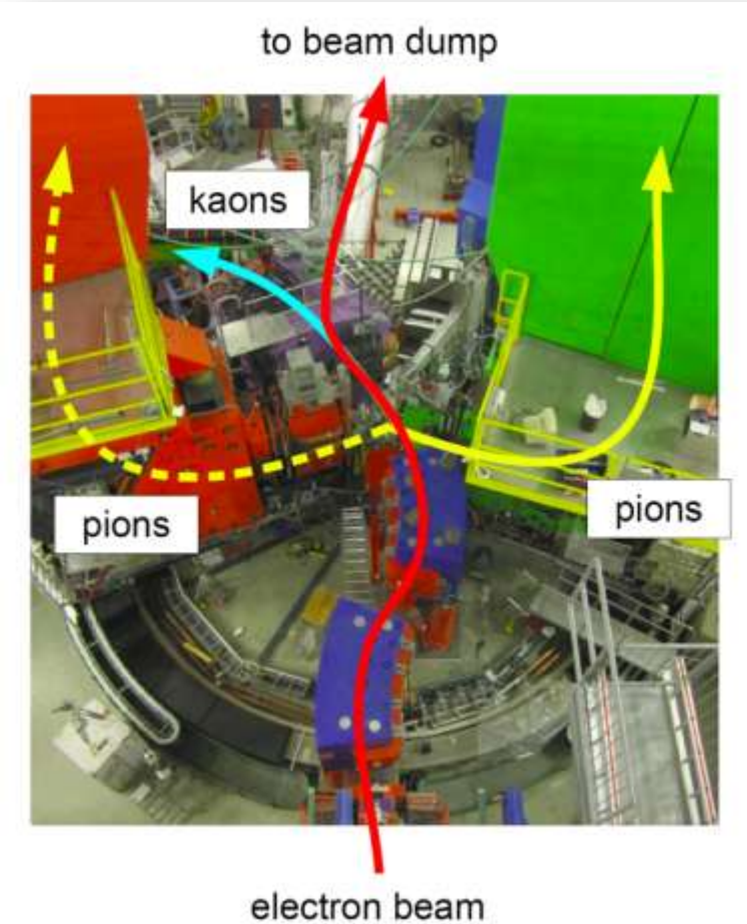


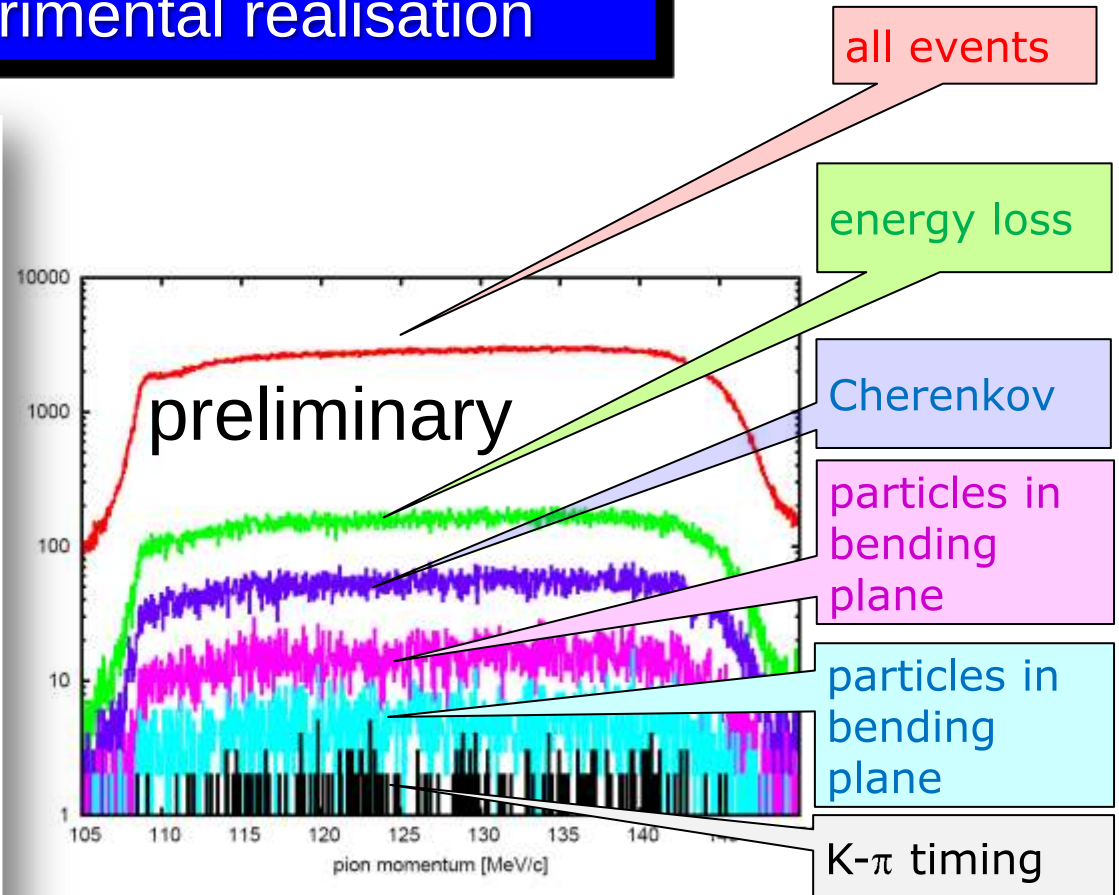
predicted pion spectrum:

various light hypernuclei accessible



Experimental realisation

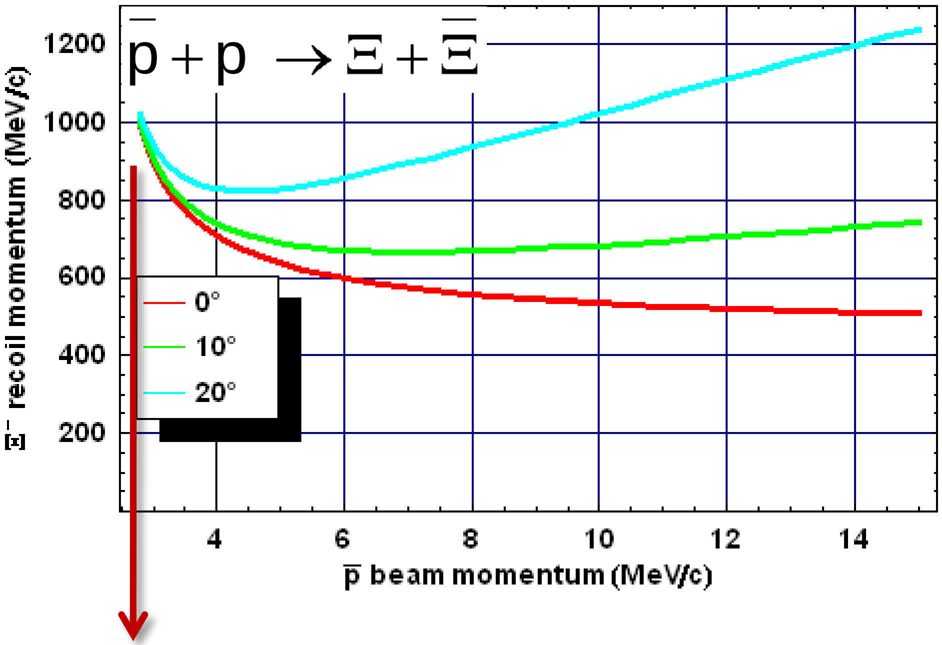




- 1500 MeV beam energy
- zero-degree kaon tagging by Kaos
- decay-pion detection with Spectrometer A & C ($\delta p/p < 10^{-4}$)

Double strange hypernuclear experiments

Formation of double hypernuclei from Xi particles



1. dE(Ξ^-)/dx → stop + capture

2. hyperatom + atomic decay

3. capture in nucleus ($_{\Xi^-}Z$)

4. conversion: $\Xi^- + p \rightarrow \Lambda\Lambda$

5. hypernuclei ($_{\Lambda\Lambda}Z^*$ or $_{\Lambda}Z^* + _{\Lambda}Z'^*$)

Xi hyperons may produce:

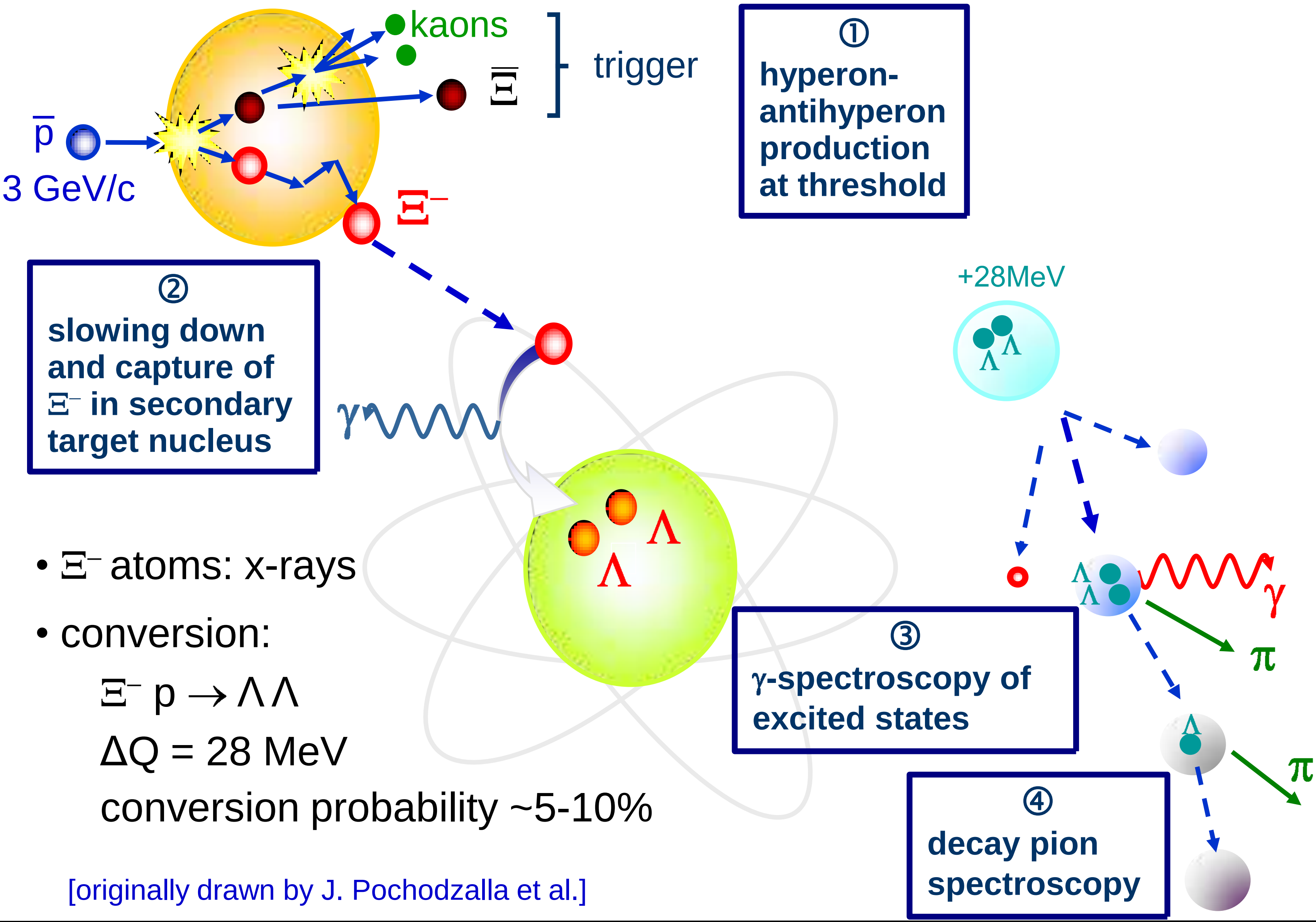
- single hypernuclei: $_{\Lambda}Z$ ($_{\Sigma}Z$)
- twin hypernuclei: $_{\Lambda}Z + _{\Lambda}Z'$
- doubly strange hypernuclei: $_{\Xi^-}Z$
- double hypernuclei: $_{\Lambda\Lambda}Z$
- H particle in a nucleus(?): ΛΛ

strangeness production tagged by anti-hyperon or decay products

→ forward detector for trigger and particle ID

→ PANDA at FAIR

Production mechanism and detection strategy at PANDA



- Ξ^- atoms: x-rays
- conversion:

  $\Xi^- p \rightarrow \Lambda\Lambda$

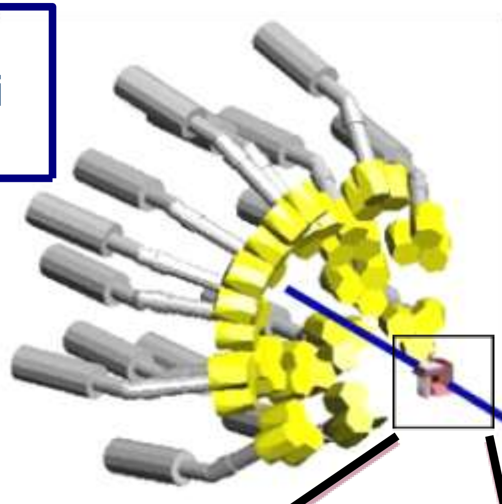
  $\Delta Q = 28$ MeV

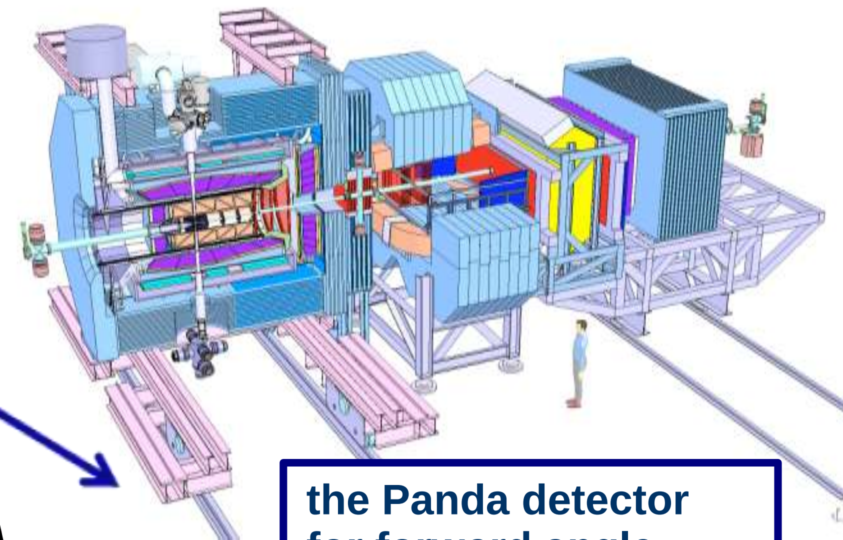
  conversion probability ~5-10%

[originally drawn by J. Pochodzalla et al.]

Instrumentation for hypernuclear physics at PANDA

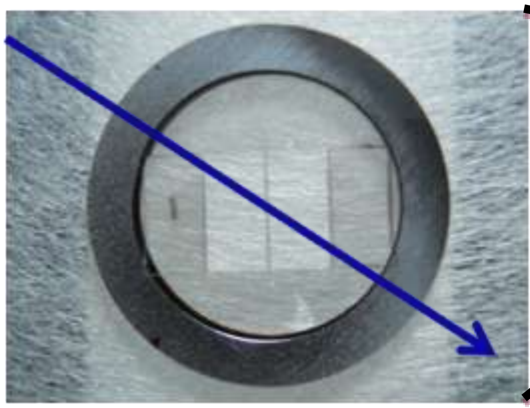
Germanium detector array for hypernuclei spectroscopy

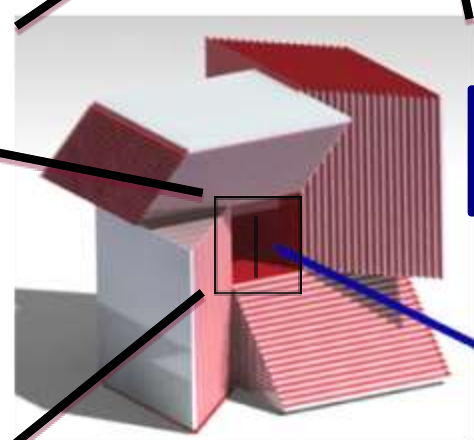




the Panda detector for forward angle particle identification

primary diamond target for Ξ production





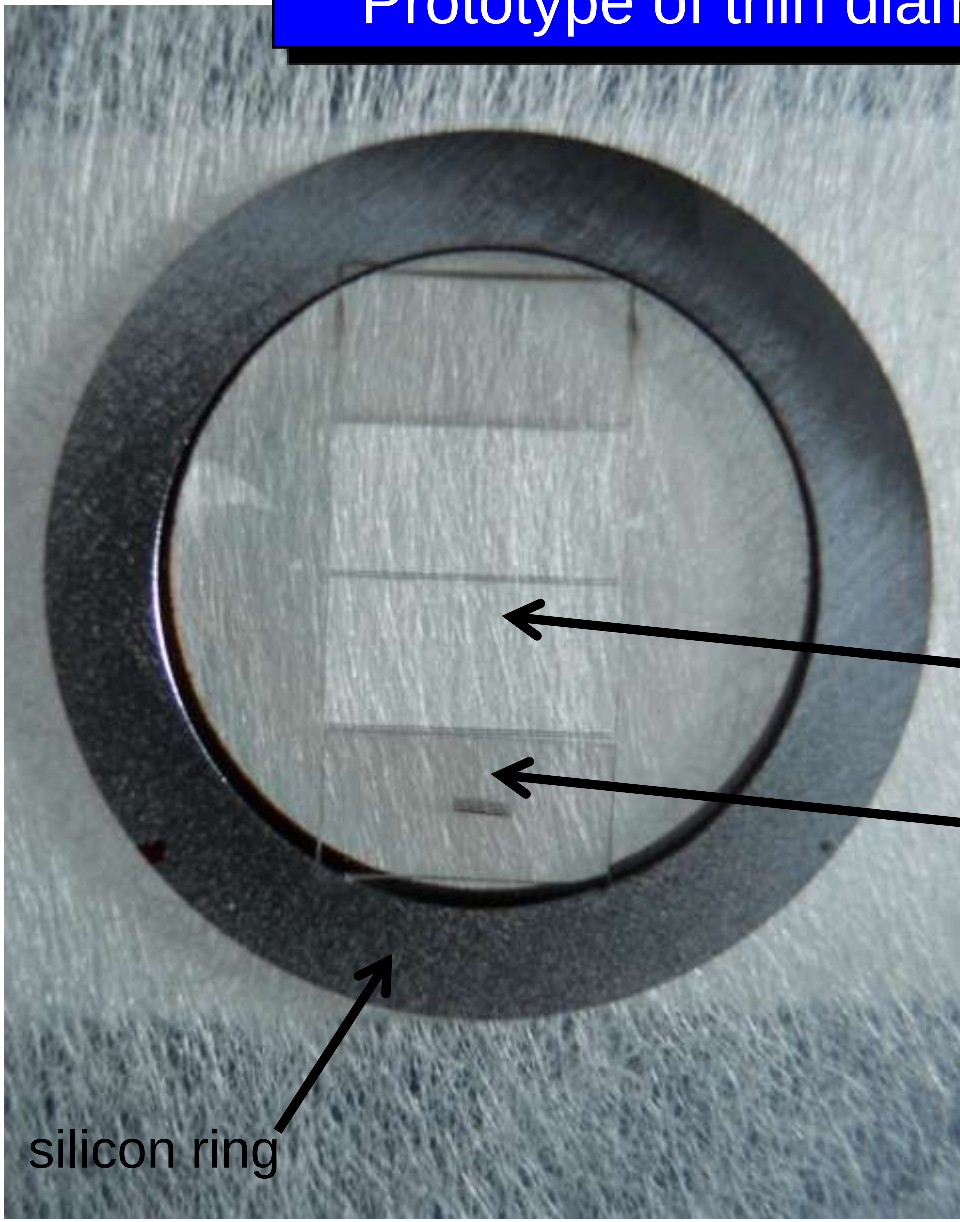
secondary target for hypernuclei formation

[Figures from PANDA Meeting 6 Sept. 11]

Open issues being studied by the Panda Hypernuclear Groups

1. design and fabrication of the primary target
2. design and development of the secondary target
3. design and operation of the HPGe γ-array
4. electromechanical cooling of HPGe crystals
5. integration into the PANDA target spectrometer
6. simulation of the expected performance

Prototype of thin diamond target



diamond wire

diamond membrane

- silicon ring inner Ø =11 mm
- diamond thickness = 3 μm
- diamond wire width = 99.9 μm

[Shown by F. Iazzi, PANDA Meeting 6 Sept. 11]

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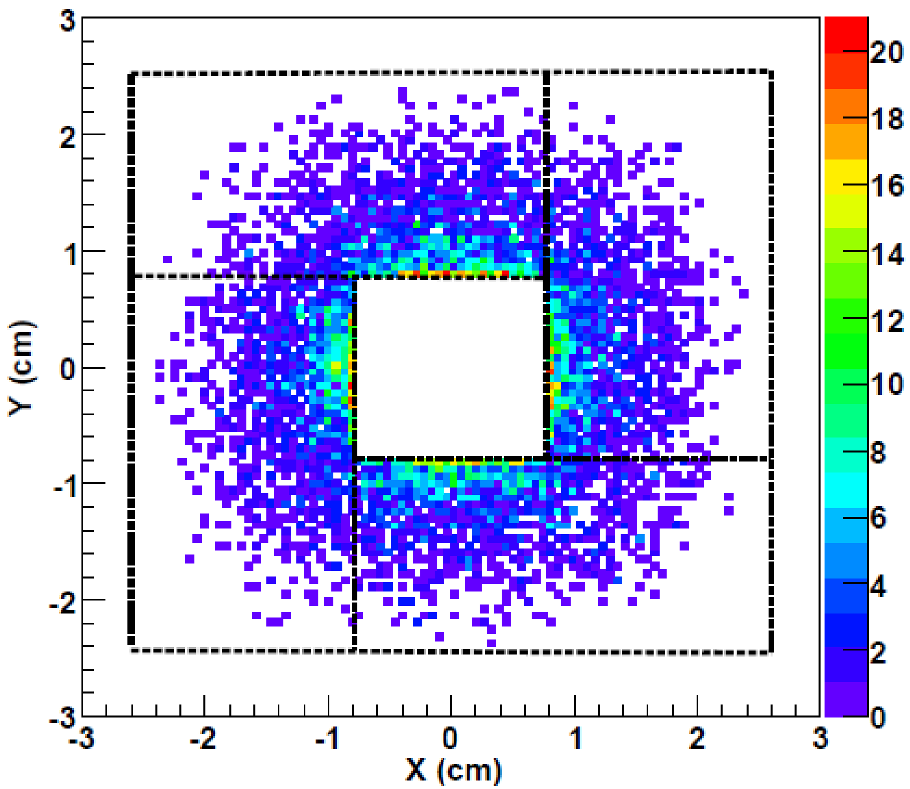
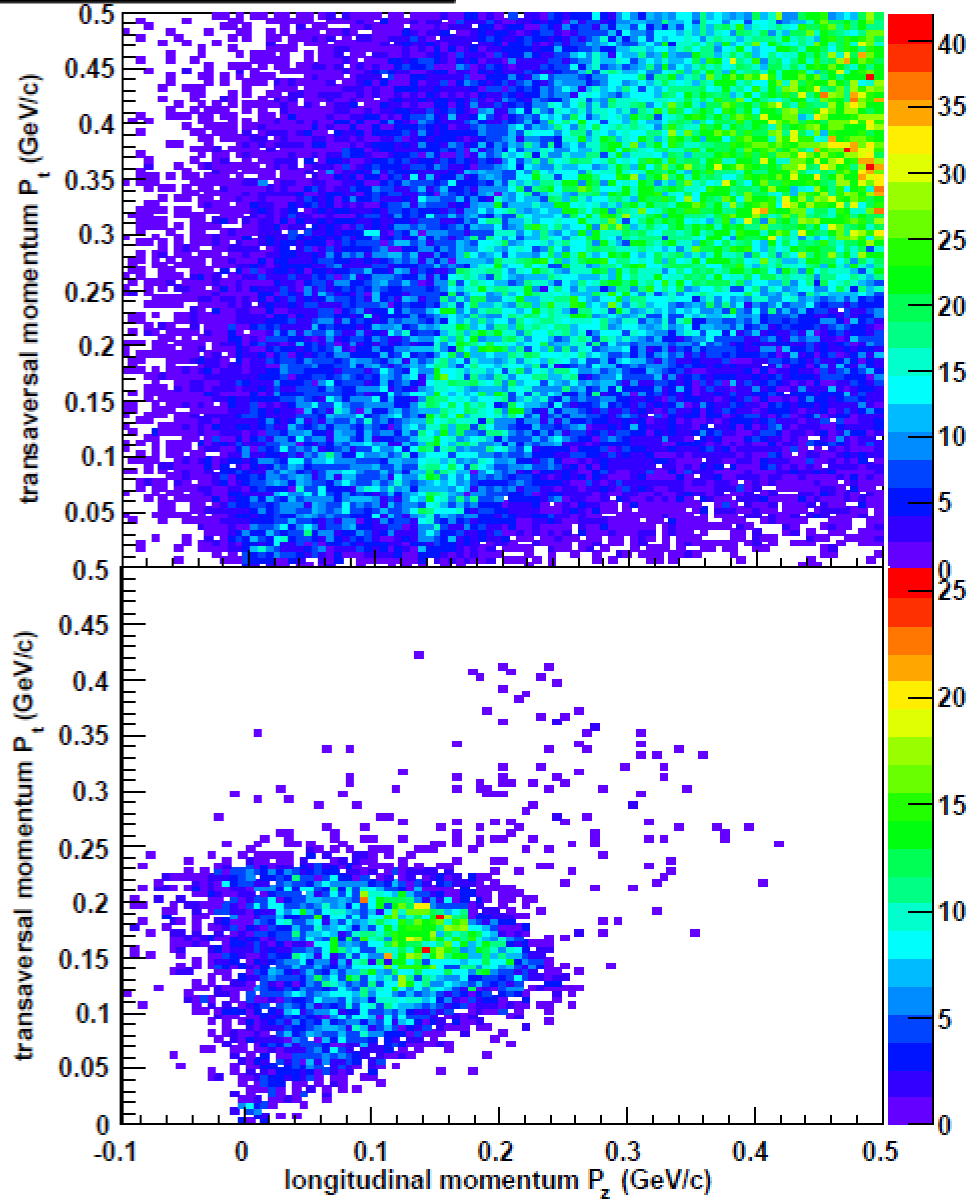
Stopping of the Xi particles

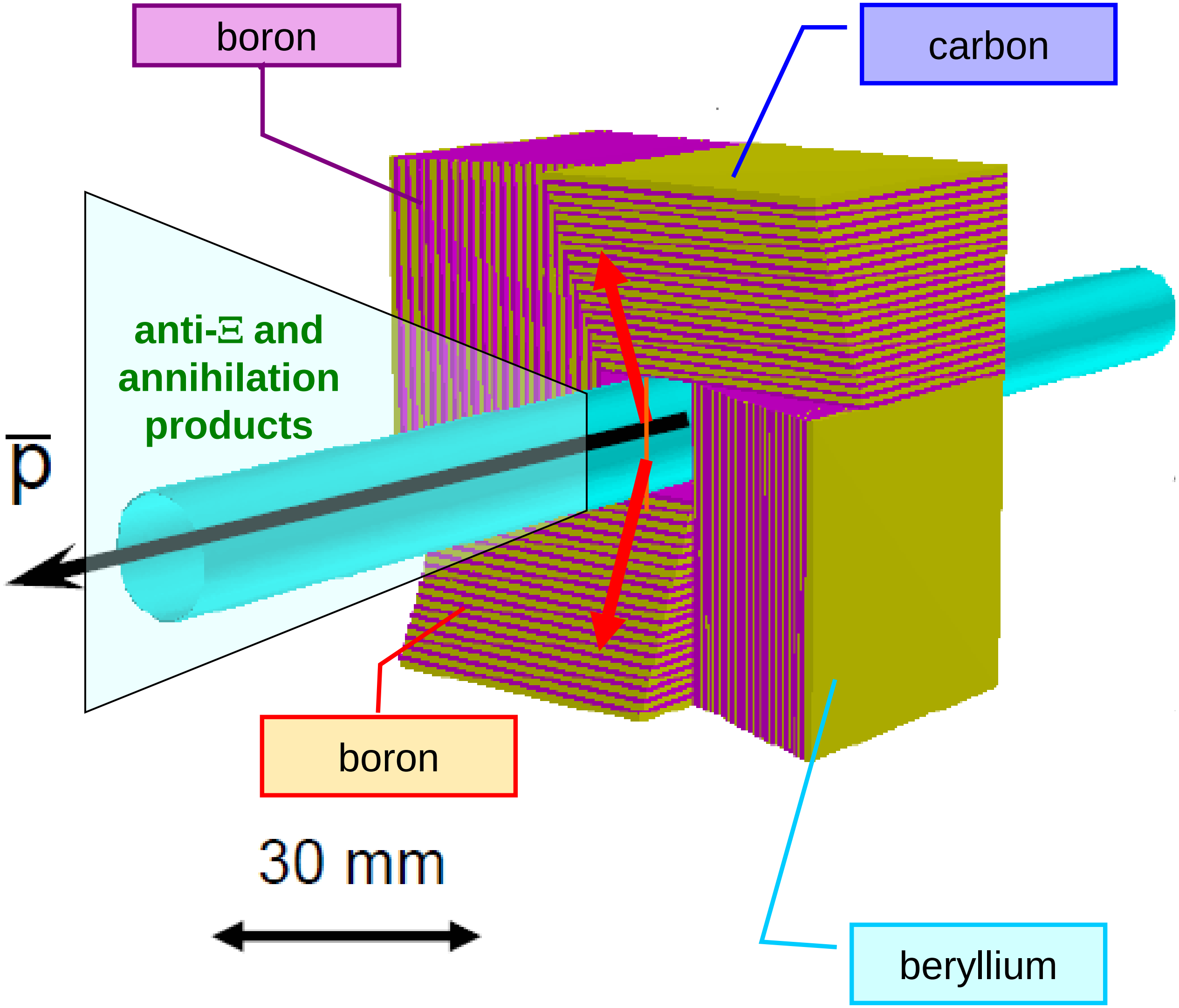




target geometry adjusted to stopping time and lifetime of Ξ-

[PANDA Physics Performance Report, 2009,p.142-3. Simulations by A. Sanchez Lorente]

The secondary target design



four separated sections:

– some layers of double sided silicon strip detectors (300 µm thick) in each block

– some layers of absorbers (1 mm thick) different for each block (Be, B and C)

[PANDA Physics Performance Report, 2009, p. 21]

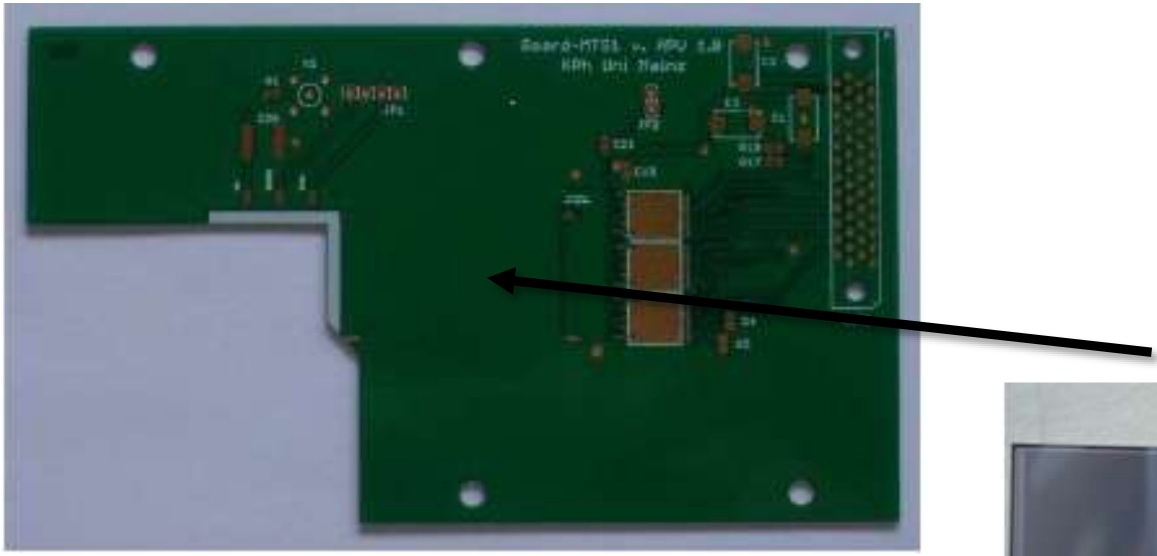
Prototype developments for the secondary target

frontend electronics:

minimization of mass on detecting volume:

ultra-thin Al-Polyimide readout cables

[J.M. Heuser et al., HadronPhysics2/JRA-ULISI]



[S. Bleser, U Mainz]

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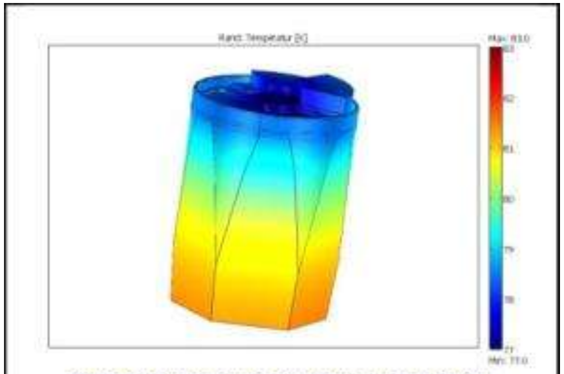
Towards a prototype of HPGe Cluster Array

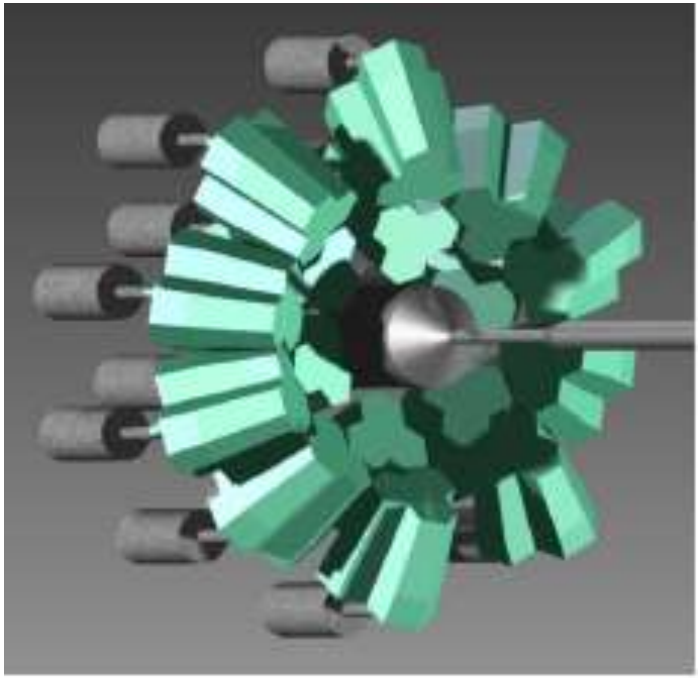
simulation of different crystal multiplicities

operation of double or triple cluster detectors



Surface temperature distribution of a single Ge-detector: the heat losses are 2.5 W for an aluminum capsule surface emissivity of 0.14.

[M. Steinen, U Mainz, I. Kojouharov, GSI]



[M. Steinen, U MainzI]

high rate environment:
radiation damages & pile-up effects

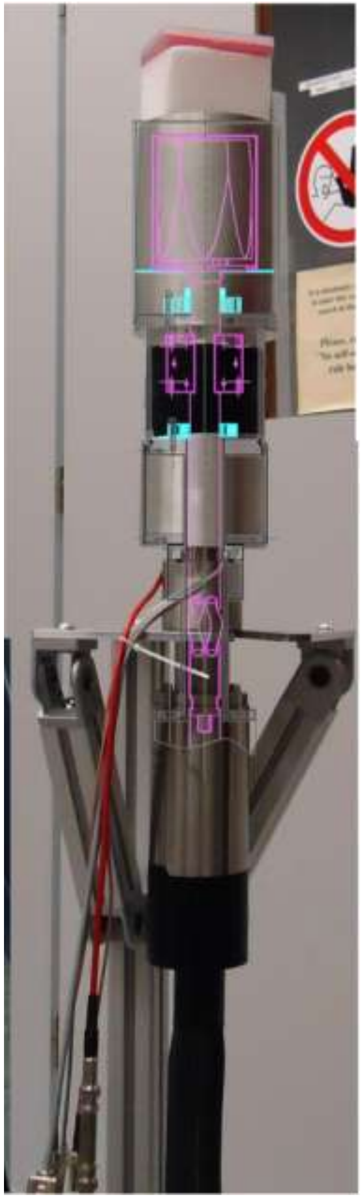
magnetic field environment:
loss and recovery of energy resolution

[A. Sanchez Lorente et al., NIM A 573 (2007) 410.]

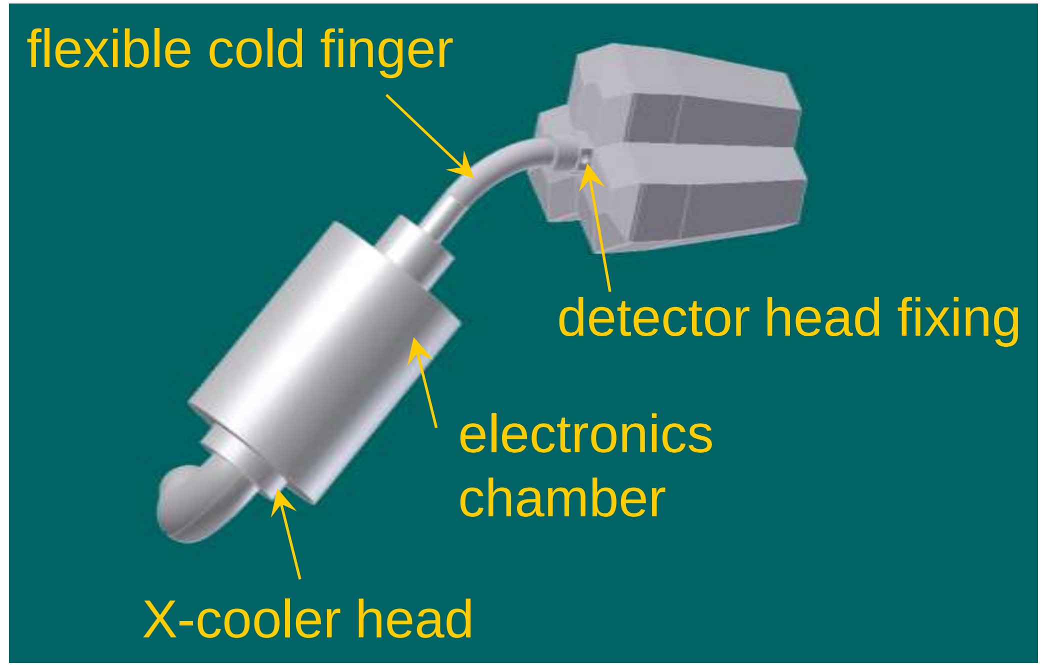
Open issues being studied by the Panda Hypernuclear Groups

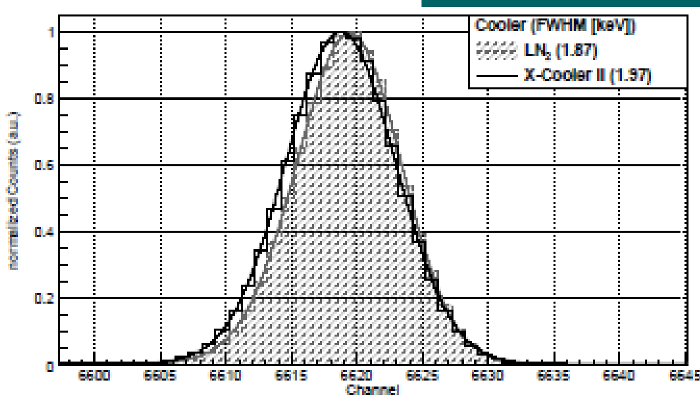
1. design and fabrication of the primary target
2. design and development of the secondary target
3. design and operation of the HPGe γ-array
4. electromechanical cooling of HPGe crystals
5. integration into the PANDA target spectrometer
6. simulation of the expected performance

Towards a prototype of HPGe Cluster Array



HPGe encapsulated crystal
attached to electromechanical cooler





[M. Steinen, U Mainz, I. Kojouharov, GSI]

1.83 keV FHM
@ ^{60}Co 1332 keV line
6 μs shaping time

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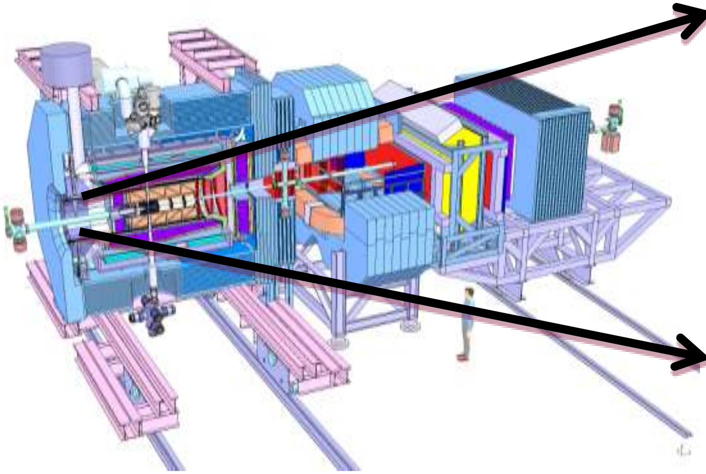
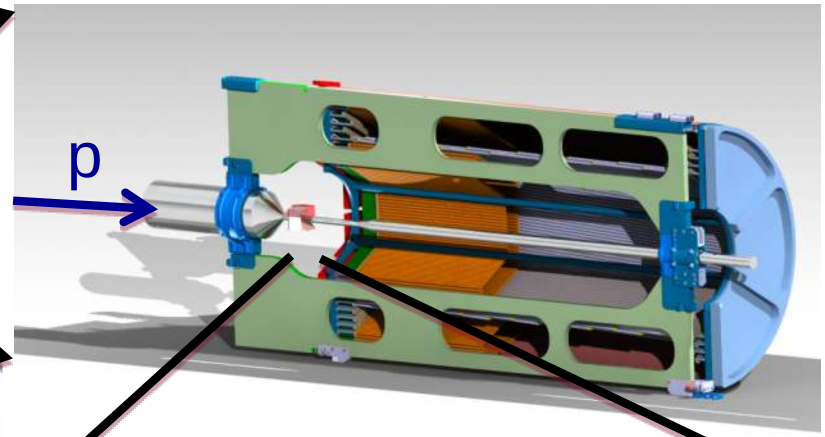
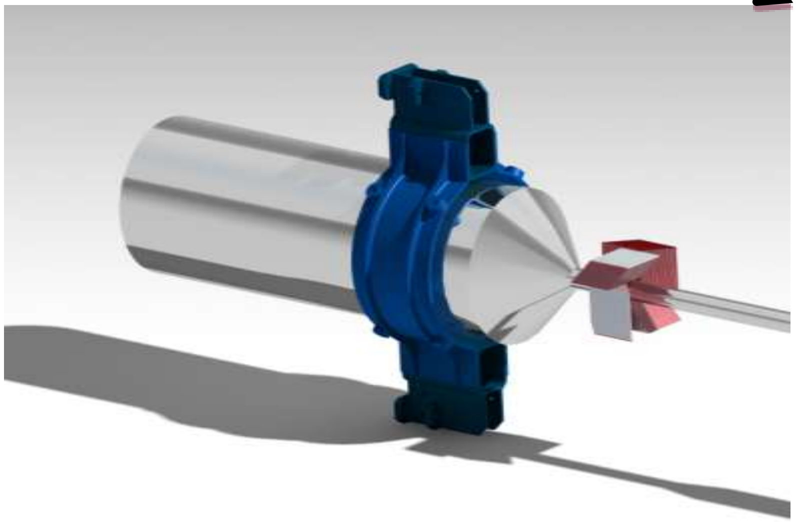
Target integration into the spectrometer







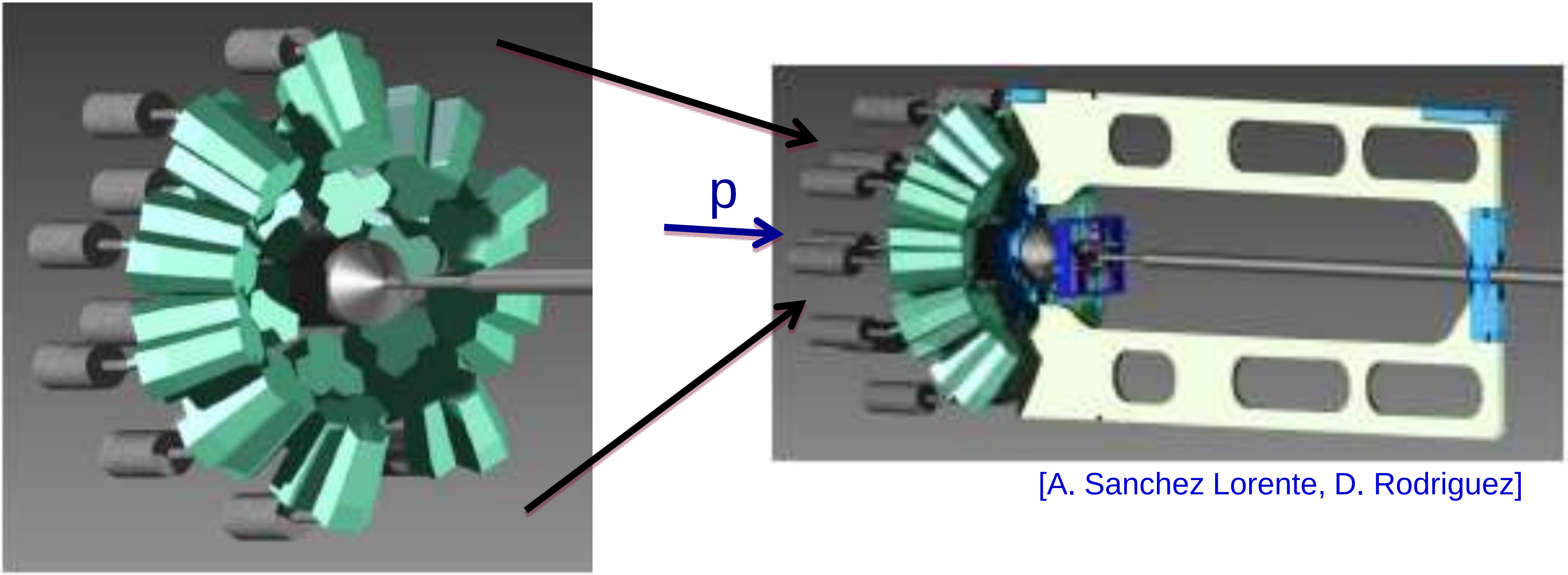
dedicated beam pipe going from 150 mm to 20 mm diameter

backward end cap calorimeter and MVD will not be used

modular structure

[A. Sanchez Lorente, D. Rodriguez, Shown at PANDA Meeting 6 Sept. 11]

HPGe array integration into the spectrometer



[A. Sanchez Lorente, D. Rodriguez]

- $\theta_{lab} < 45°$: Ξ-bar, K trigger and PID in PANDA spectrometer
- $\theta_{lab} = 45°\text{-}90°$: Ξ-capture and hypernuclei formation
- $\theta_{lab} > 90°$: γ-detection with HPGe at backward angles
  integration of electromechanical coolers for HPGe

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Statistical decay model for excited hypernuclei

example: $\Xi^- + {}^{12}C \Rightarrow {}^{A+Z+H}{}_{\Xi}Z \Rightarrow {}^{13}{}_{\Lambda\Lambda}B^*$

Population of excited, particle-stable states in double hypernuclei?

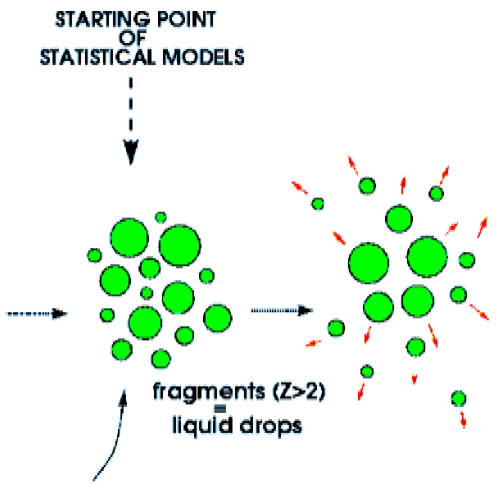
conversion width $\Xi + p \Rightarrow \Lambda\Lambda$ about Γ = 1MeV

precise Ξ^- binding energy not yet known (0.6 – 4 MeV)

typical excitation energy ~ a few MeV/nucleon

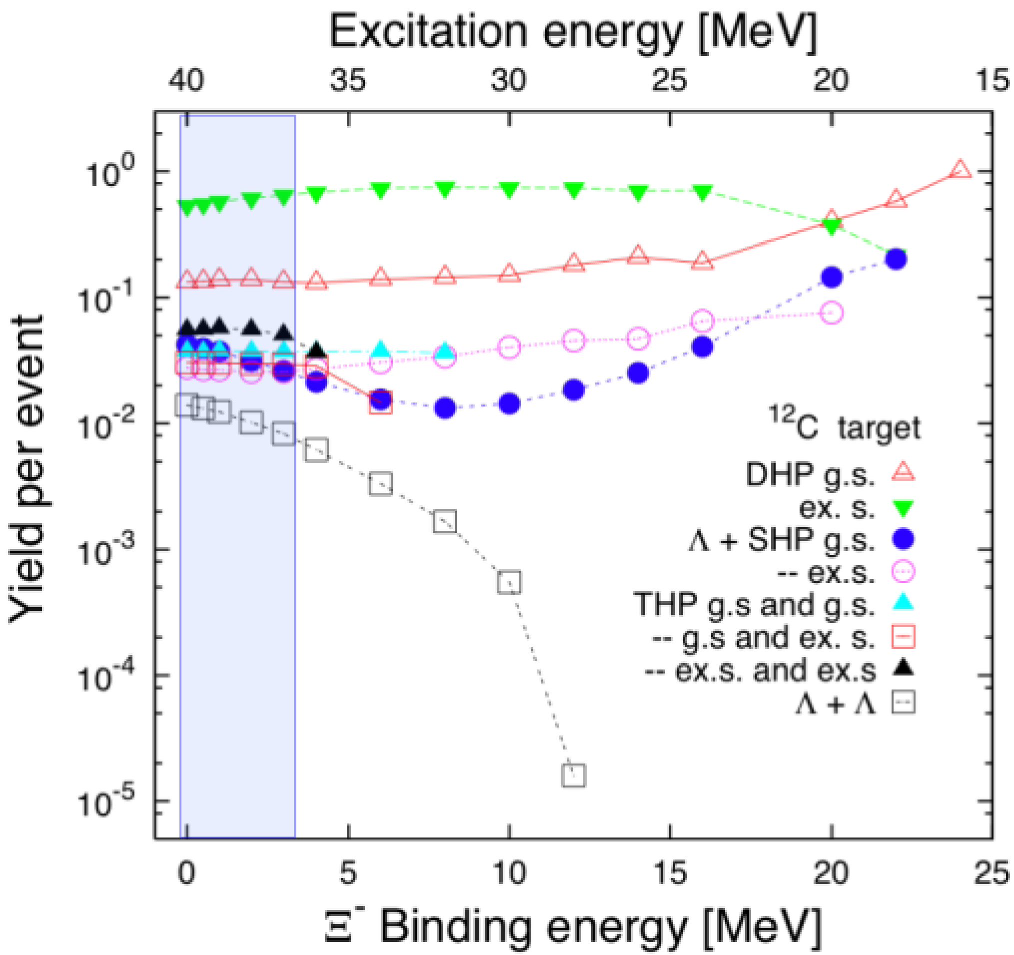
fragmentation of excited projectile remnants
are well understood in that regime

de-excitation of light nuclei via Fermi break-up process



[A. Sanchez Lorente, A. Botvina et J.Pochodzalla, PLB 697 (2011) 222- 228)]

Population of excited double hypernuclear states



$\Xi^- + {}^{12}C \Rightarrow {}^{13}{}_{\Lambda\Lambda}B^*$

▼ △ : double hypernuclei

● ○ : single hypernuclei

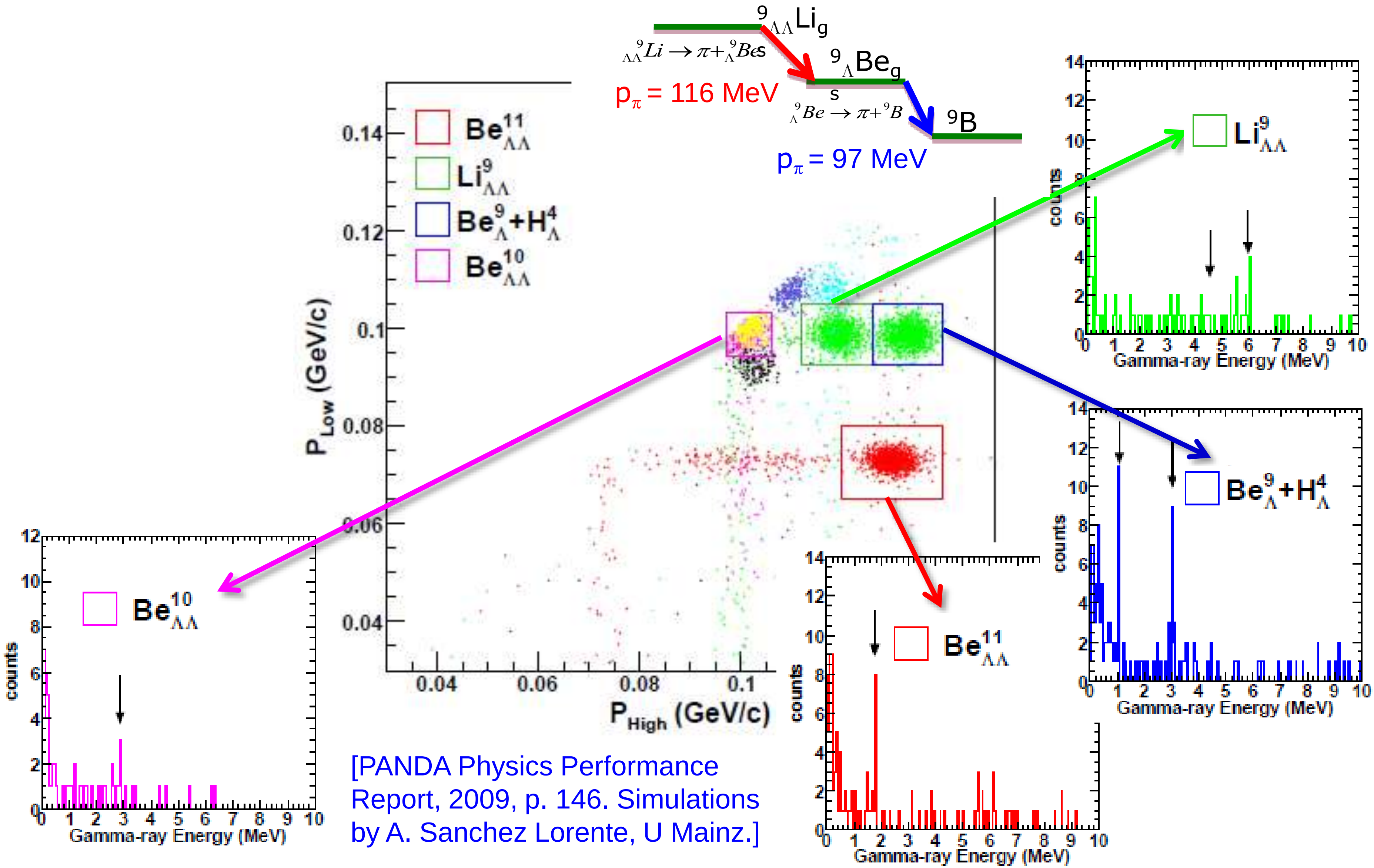
▲ ▲ □ : twin hypernuclei

□ : ΛΛ

⇒ production of excited states of double hypernuclei is significant

[A. Sanchez Lorente, A. Botvina et J.Pochodzalla, PLB 697 (2011) 222- 228]

Background suppression by decay pion correlation



[PANDA Physics Performance Report, 2009, p. 146. Simulations by A. Sanchez Lorente, U Mainz.]

Summary

- Hypersystems provide a link between nuclear physics and QCD to study basic properties of strongly interacting systems
- many experimental challenges to realize hypernuclear physics
- the *only* European experiments in current hypernuclear physics:

charged particle spectroscopy of single hypernuclei at MAMI

γ-spectroscopy of double hypernuclei at PANDA