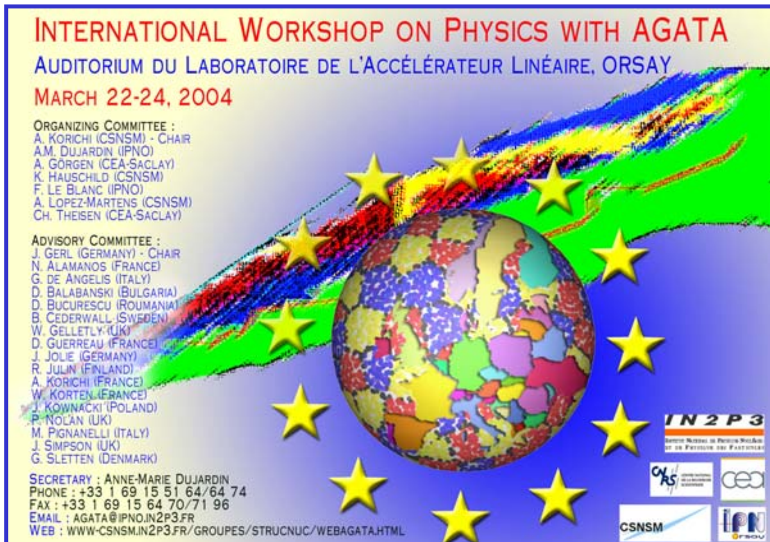
High resolution spectroscopy of hypernuclei with γ-ray detectors



- **multi-Λ hypernuclei**
- ***H*-particle**

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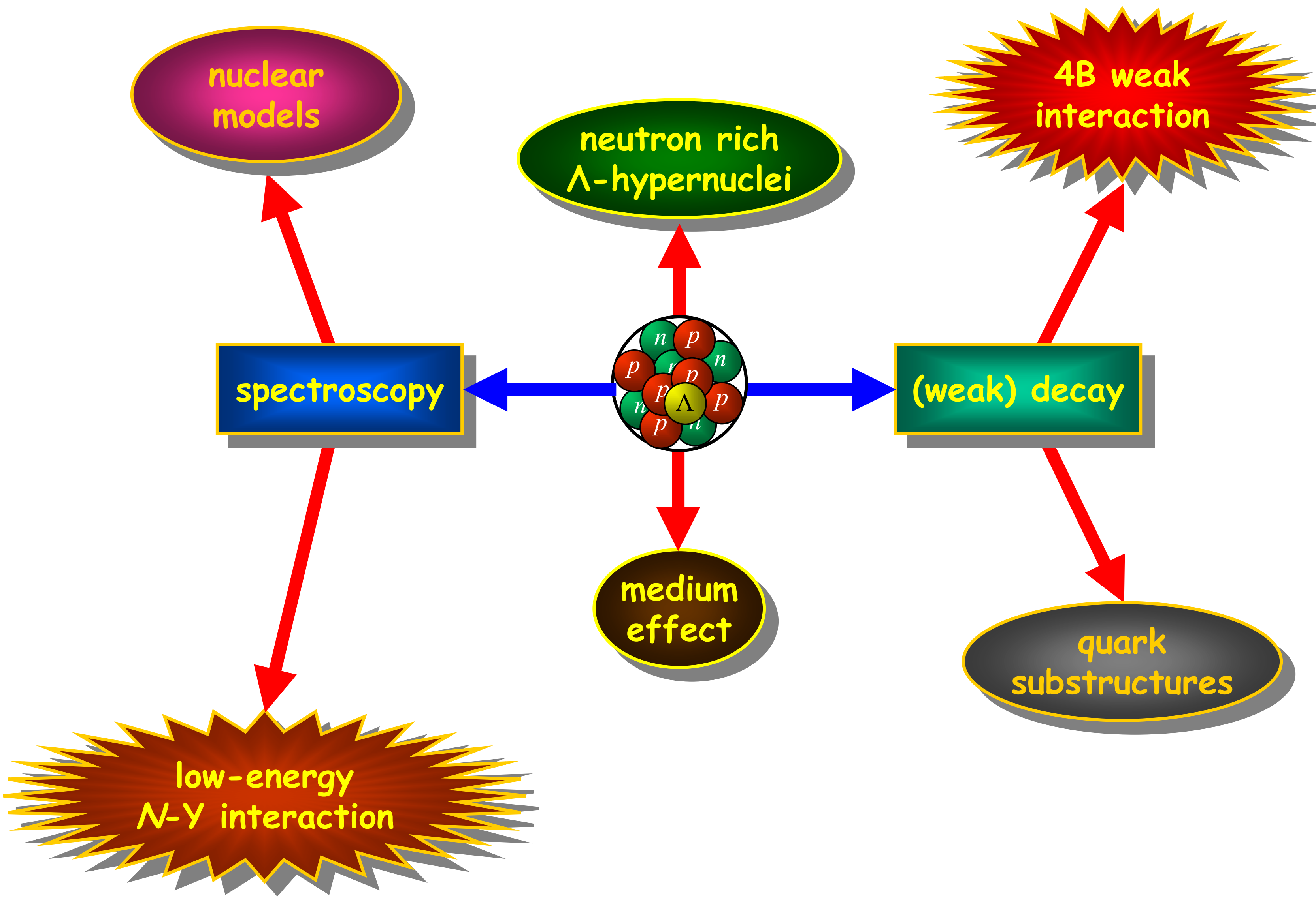
I.N.F.N. - Sezione di Torino

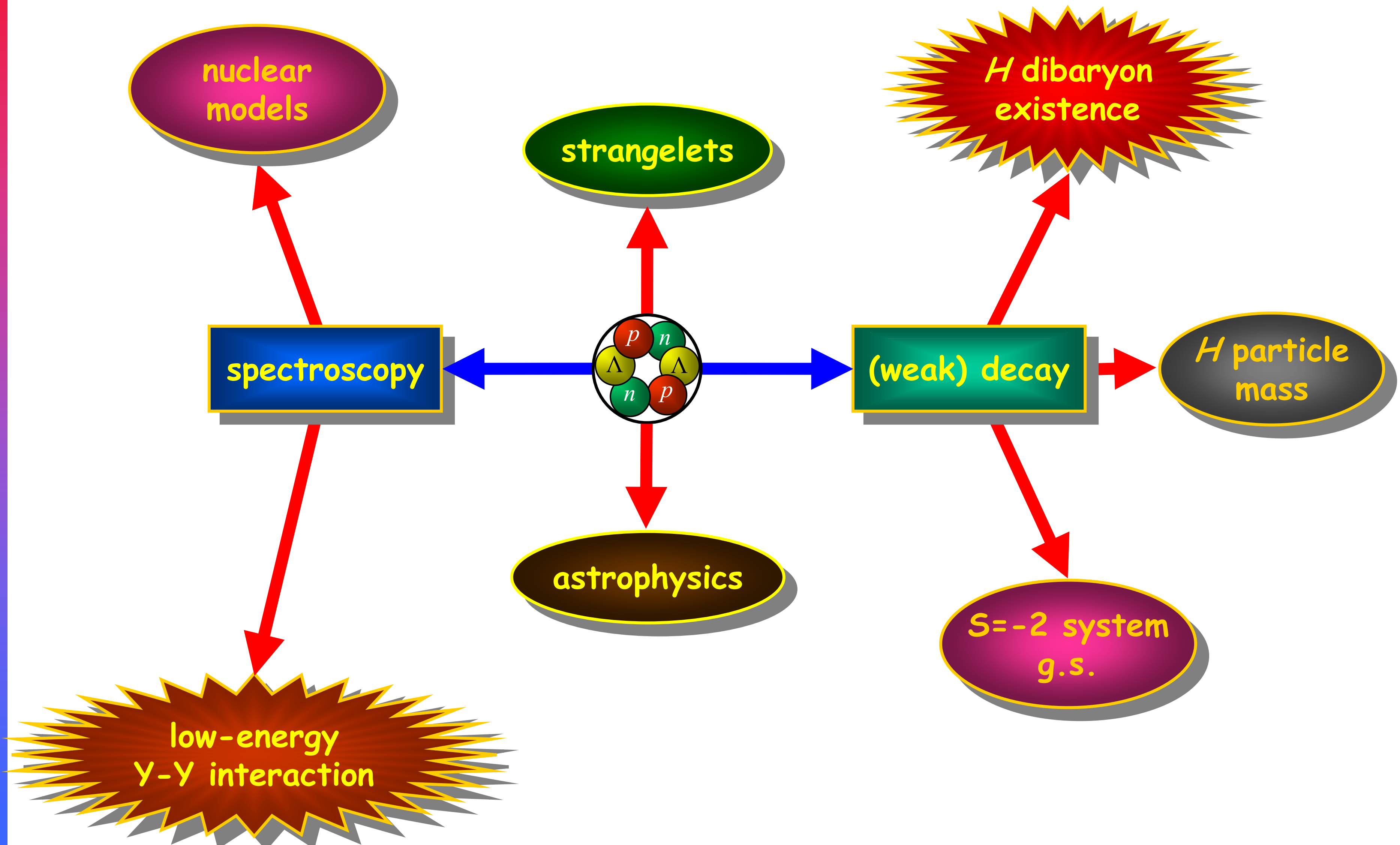
Contents

- Discovery potential of the strangeness nuclear physics
- Need of sub-MeV resolution apparatuses
  - γ-ray spectroscopy
- Ideas for new experimental apparatuses
  - FINUDA2 @ LNF/DAΦNE2
  - PANDA @ GSI/HESR

Physics output (S=-1)



Physics output (S=-2)



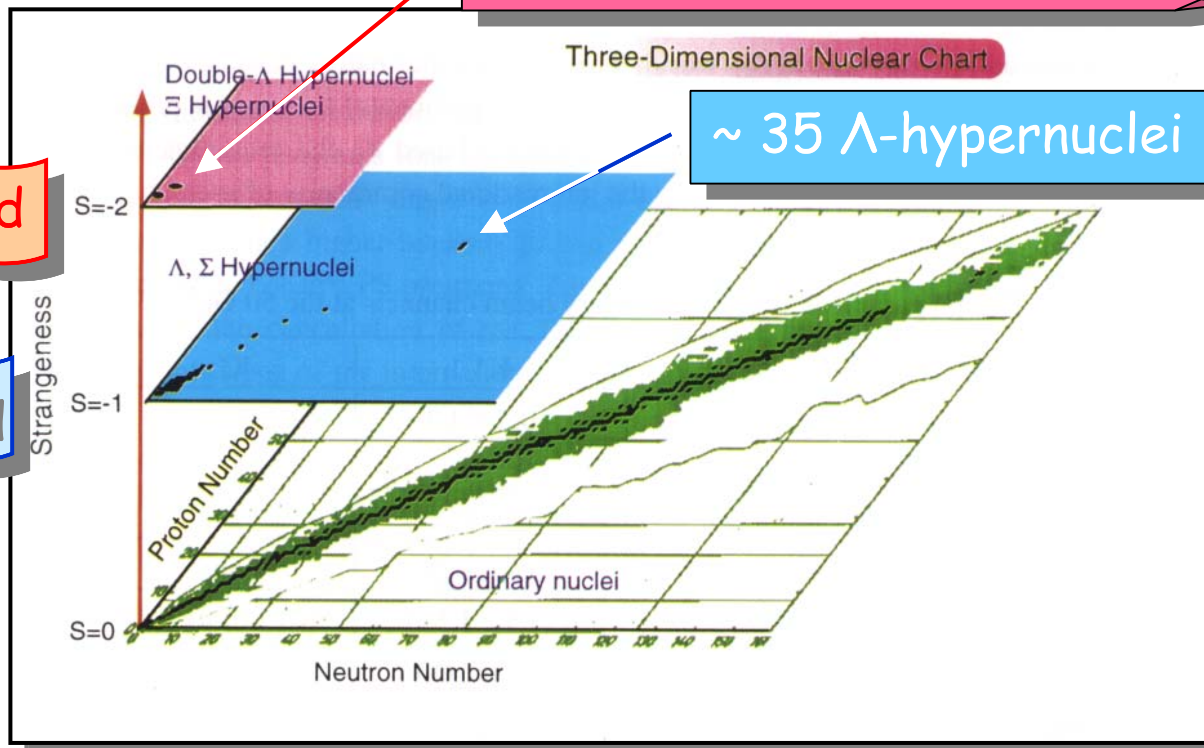
The status of the art

4 ΛΛ-hypernuclei identified (?)

~ 35 Λ-hypernuclei identified

41 years old

51 years old



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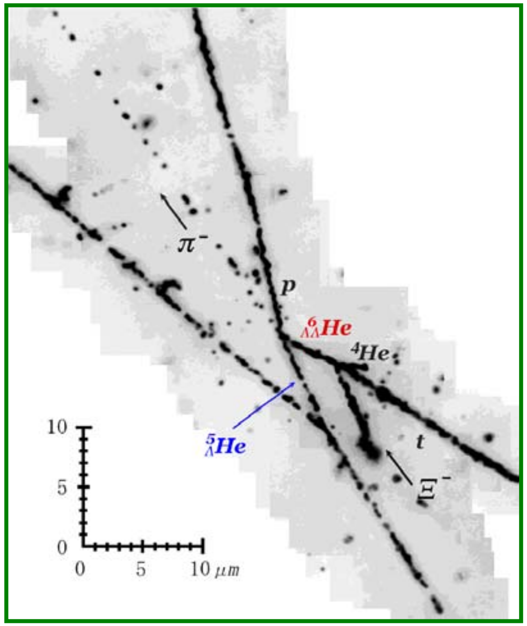
Observed ΛΛ-hypernuclei

- 1963: Danysz et al. $^{10}_{\Lambda\Lambda}Be$ (emulsion)
- 1966: Prowse $^{6}_{\Lambda\Lambda}He$ (emulsion, Dalitz criticises the interpretation)
- 1991: KEK-E176 $^{13}_{\Lambda\Lambda}B$ (or $^{10}_{\Lambda\Lambda}Be$, emulsion counter hybrid experiment)
- 2001: BNL-E906 $^{4}_{\Lambda\Lambda}H$
- 2001: KEK-E373 $^{6}_{\Lambda\Lambda}He$
- 2001: KEK-E373 $^{10}_{\Lambda\Lambda}Be$

$$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$$

$$\hookrightarrow \quad {}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$$



Progress in detection technique

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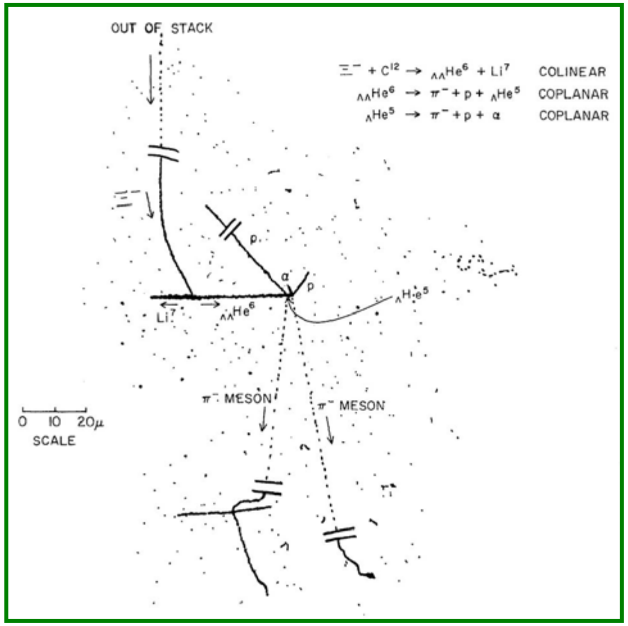
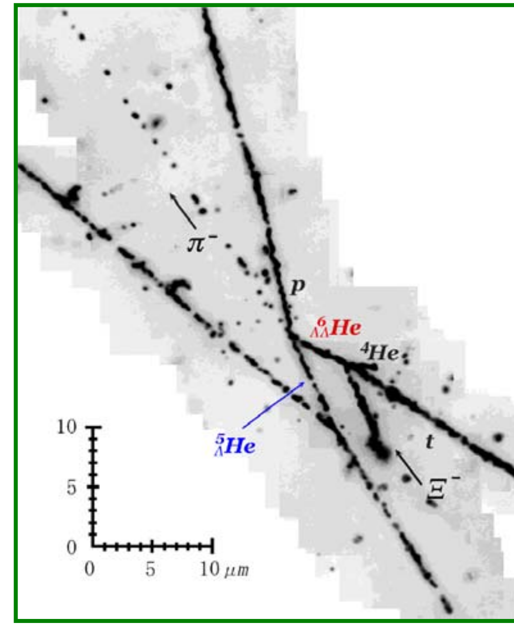
1966: Prowse



2001: KEK-E373



$$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{7}Li$$

$$\hookrightarrow \; {}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

$$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$$

$$\hookrightarrow \; {}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

emulsion based experiments provide one of the most powerful techniques to measure masses and binding energies, but they are not suitable for systematic studies which require large statistics

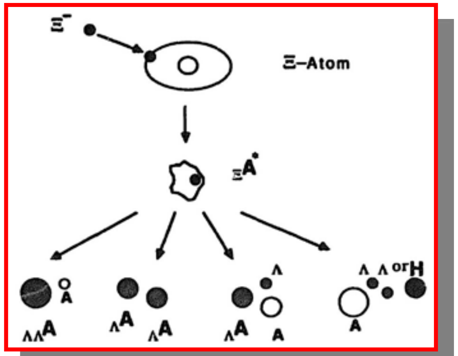
ΛΛ-hypernucleus production

Ξ^- atomic capture reaction at rest
is one of the most effective way to look for double Λ-hypernuclei

- compound double Λ state:

$$\Xi^- + {}^{A}Z \rightarrow {}^{(A-1)}(Z-1) \oplus \Lambda \oplus \Lambda$$

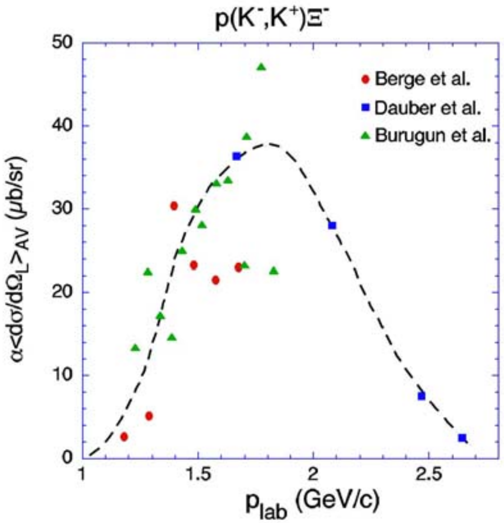
$$\Xi^- + p \rightarrow \Lambda + \Lambda + 28\ \mathrm{MeV}$$



- quasi deuteron model:

$$\Xi^- + {}^{A}Z \rightarrow {}^{A}_{\Lambda\Lambda}(Z-1) + n$$ ← high energy

$$\Xi^- + \text{“d”} \rightarrow \text{“}\Lambda\Lambda\text{”} + n$$ ← high energy



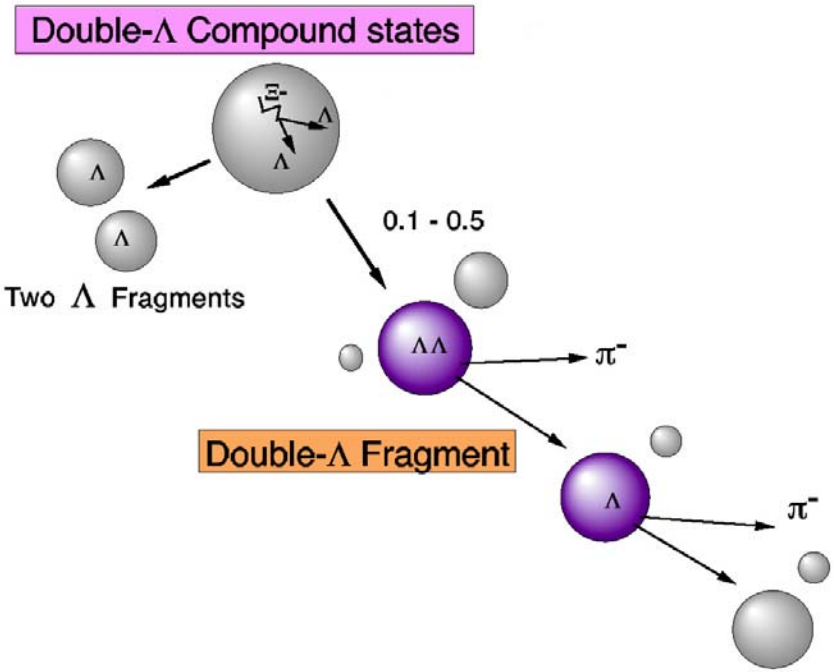
$$K^- + p \rightarrow \Xi^- + K^+$$ q.f.

$$K^- + {}^{A}Z \rightarrow {}^{A}_{\Xi}(Z-1) + K^+$$

K⁻ beams:

@	BNL	1.88 GeV/c
@	KEK	1.66 GeV/c
@	Jparc	1.80 GeV/c

How to identify a ΛΛ-hypernucleus



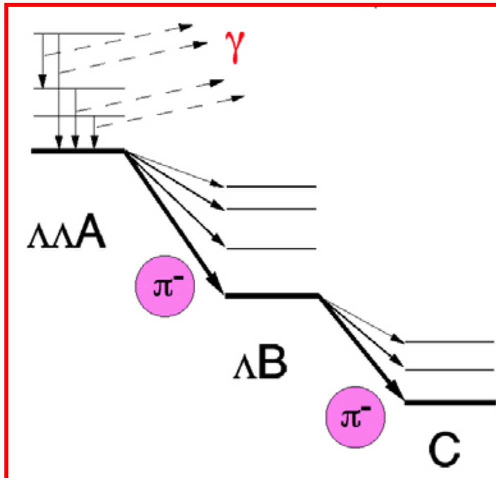
limited target choice

(at least for the pilot runs)

^{6}Li, ^{7}Li, ^{9}Be, ^{12}C

sequential pionic decay

$${}^{A}_{\Lambda\Lambda}Z \rightarrow {}^{A'}_{\Lambda}Z' \rightarrow {}^{A''}Z''$$



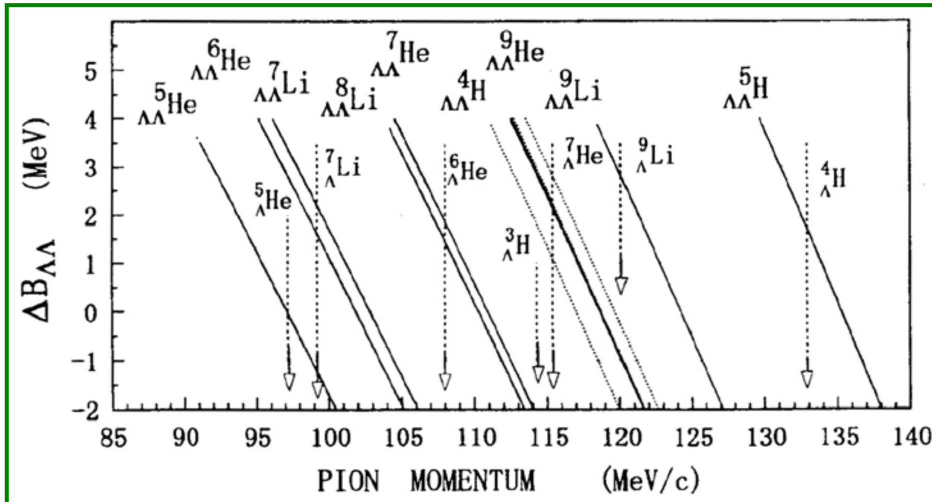
main background

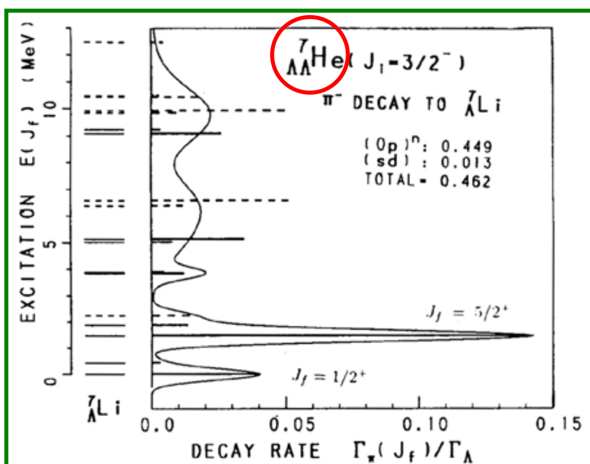
$$\Xi^{-} \rightarrow \Lambda + \pi^{-}$$

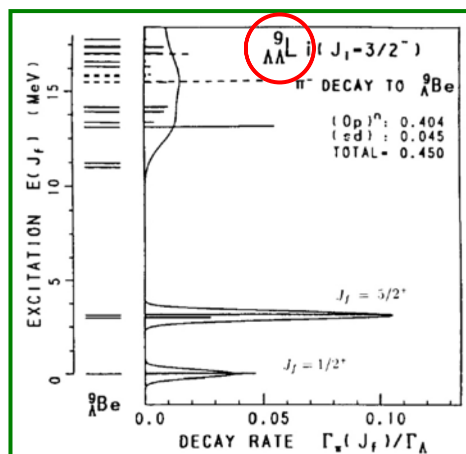
$$\Lambda \rightarrow p + \pi^{-}$$

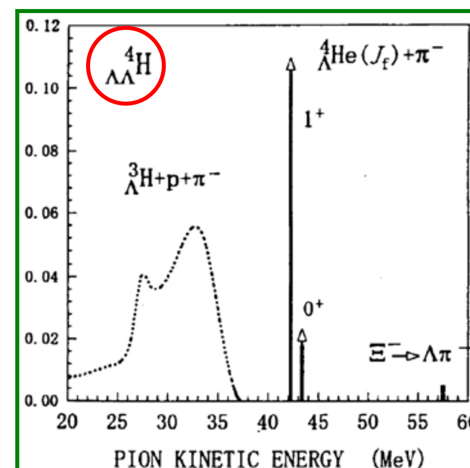
critical!

Expected π⁻ momentum spectrum









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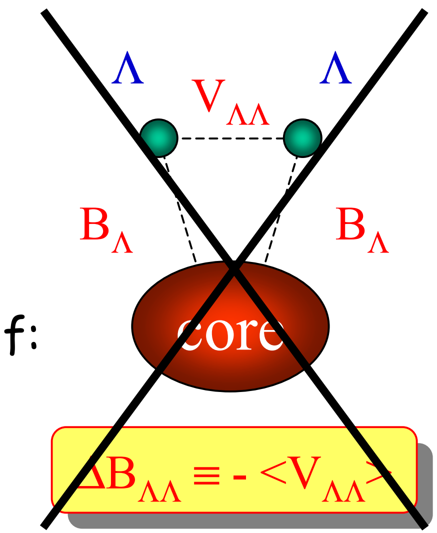
The status of the art

Hypernucleus	$B_{\Lambda\Lambda}$ [MeV]	$\Delta B_{\Lambda\Lambda}$ [MeV]
$^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4
$^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6
same event! $^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7
same event! $^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7 !
$^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$
$^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$	

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$



one can not to interpret $\Delta B_{\Lambda\Lambda}$ as ΛΛ binding energy because of:

- dynamical change of the core nucleus
- ΛΛ spin-spin interaction for non-zero spin of core
- possible excited states

if ΛΛ- or intermediate Λ-hypernuclei are produced in excited states:

- Q-value is difficult to extract (especially for heavy nuclei)
- nuclear fragments are difficult to identify with usual emulsion technique

new concept required! → γ-spectroscopy

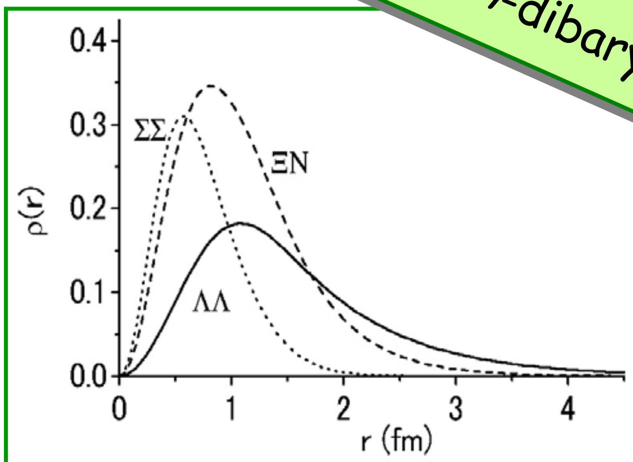
Open questions

decay properties:

- ? total decay rate
- ? lifetime measurements
- ? non-mesonic weak decay modes
- ? influence of the *H*-like structure

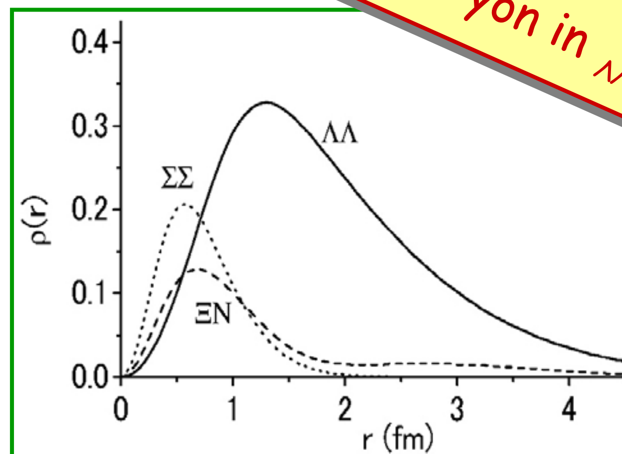
S = - 2 systems and H-dibaryon states

free *H*-dibaryon



$B_{\Lambda\Lambda}$ = 12.2 MeV

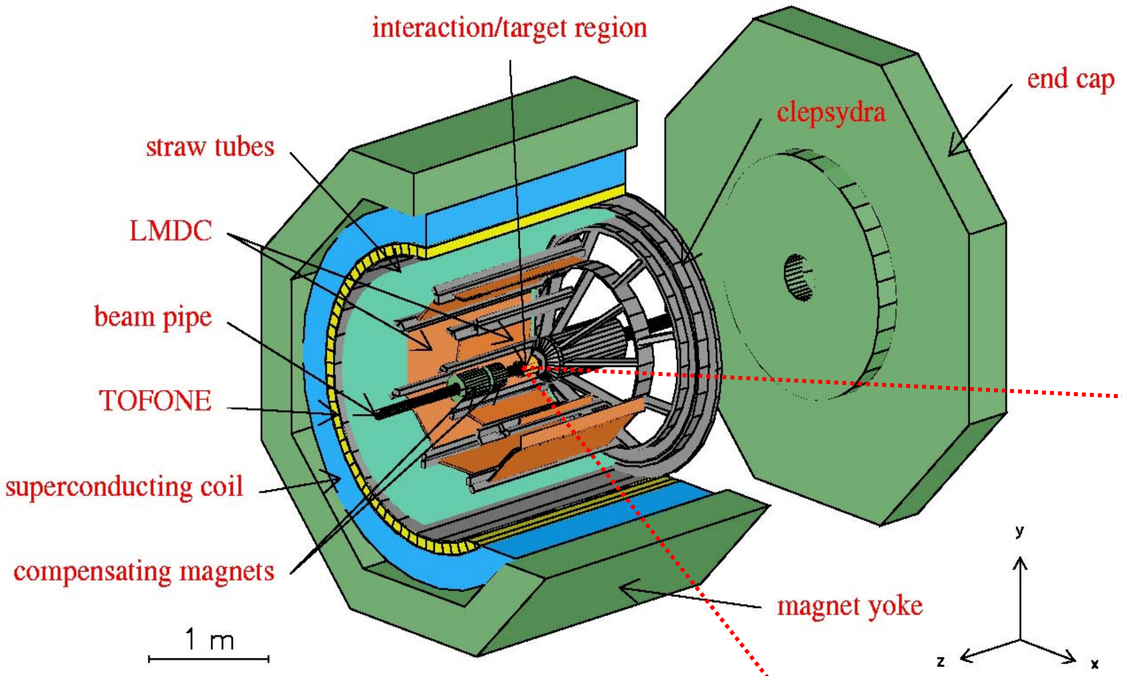
H-dibaryon in $^{10}_{\Lambda\Lambda}Be$



$B_{\Lambda\Lambda}$ = 24 MeV

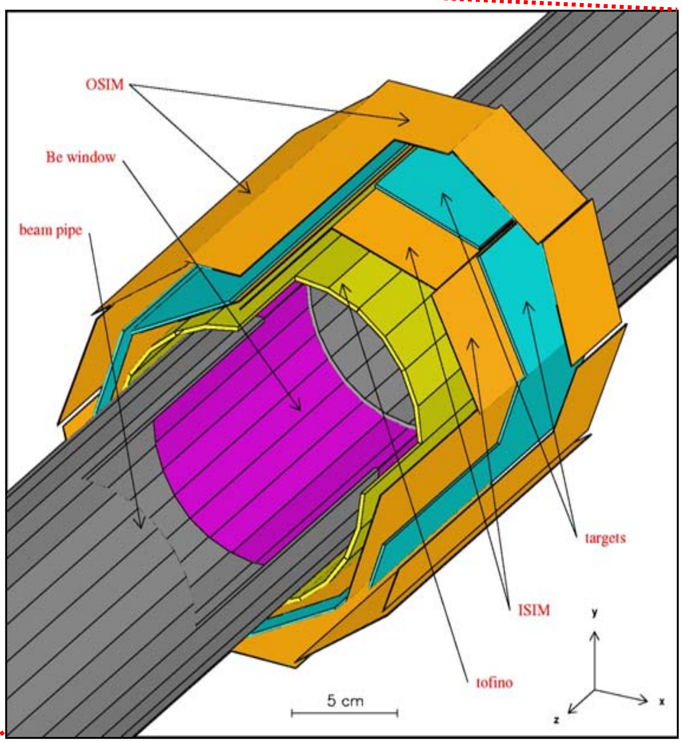
H particle formation can be revealed by a modification of the energy levels of ΛΛ-hypernuclei

FINUDA1 @ DAΦNE1



$$e^- + e^+ \rightarrow \phi \rightarrow K^- K^+$$

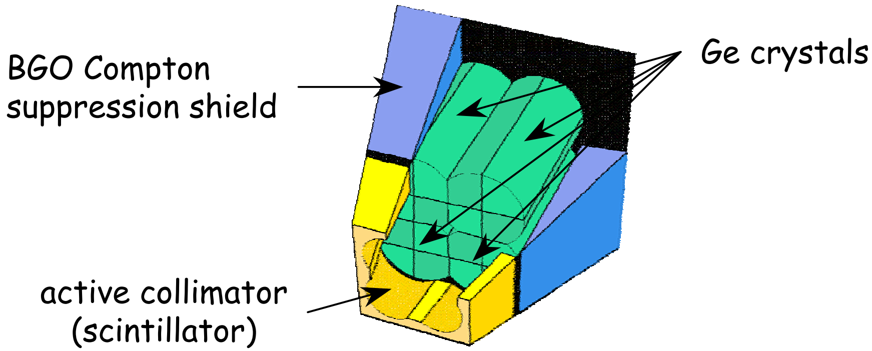
$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^-$$



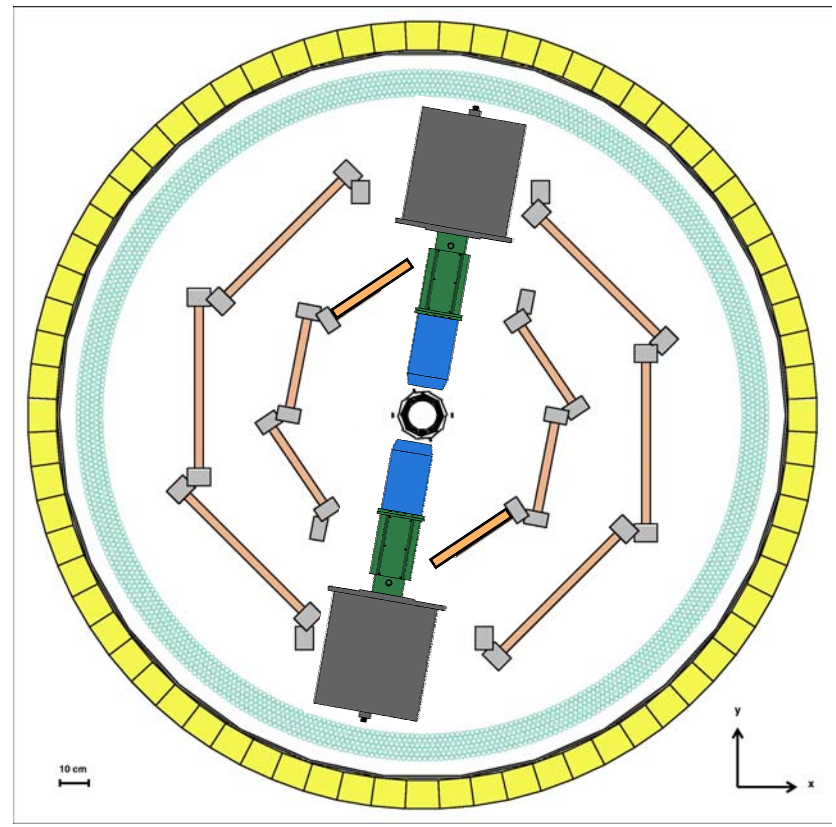
$\mathcal{L} = 7 \times 10^{31}\ cm^{-2} s^{-1}$

FINUDA2 @ DAΦNE2

The Segmented Clover Detector



$\mathcal{L} \approx 10^{34} cm^{-2} s^{-1}$



Geometrical acceptance reduced to 72%

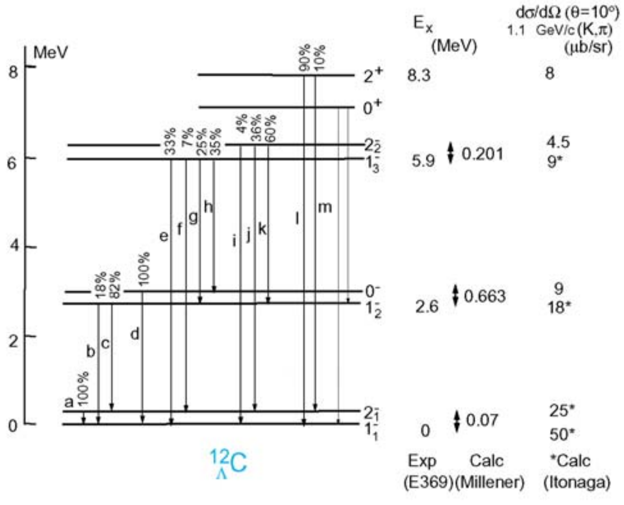
Expected rates

@ $\mathscr{L}$ = 10^{34} cm^{-2} s^{-1} FINUDA can observe ~ 1.6×10^4 ev/h from YN g.s.

- machine duty cycle: 75%
- spectrometer acceptance: 72%
- Ge acceptance: ~ 30%
- ε_{Ge}: ~ 30%

~ 1.87×10^4 ev/d

~ 1.87×10^4 ev/d



Expected Yield (5 days)

single				γγ coincidnece with a		with c		with d	
a	112000	h	1700	c	1900	a	1900	h	55
b	2600	i	64	f	50	g	39		
c	12000	j	580	g	150	k	50		
d	7500	k	1400	j	94				
e	1100	l	2000	k	170				
f	240	m	230	m	31				
g	1300								

MC data

5 day data taking

~ 9.33×10^4 ev

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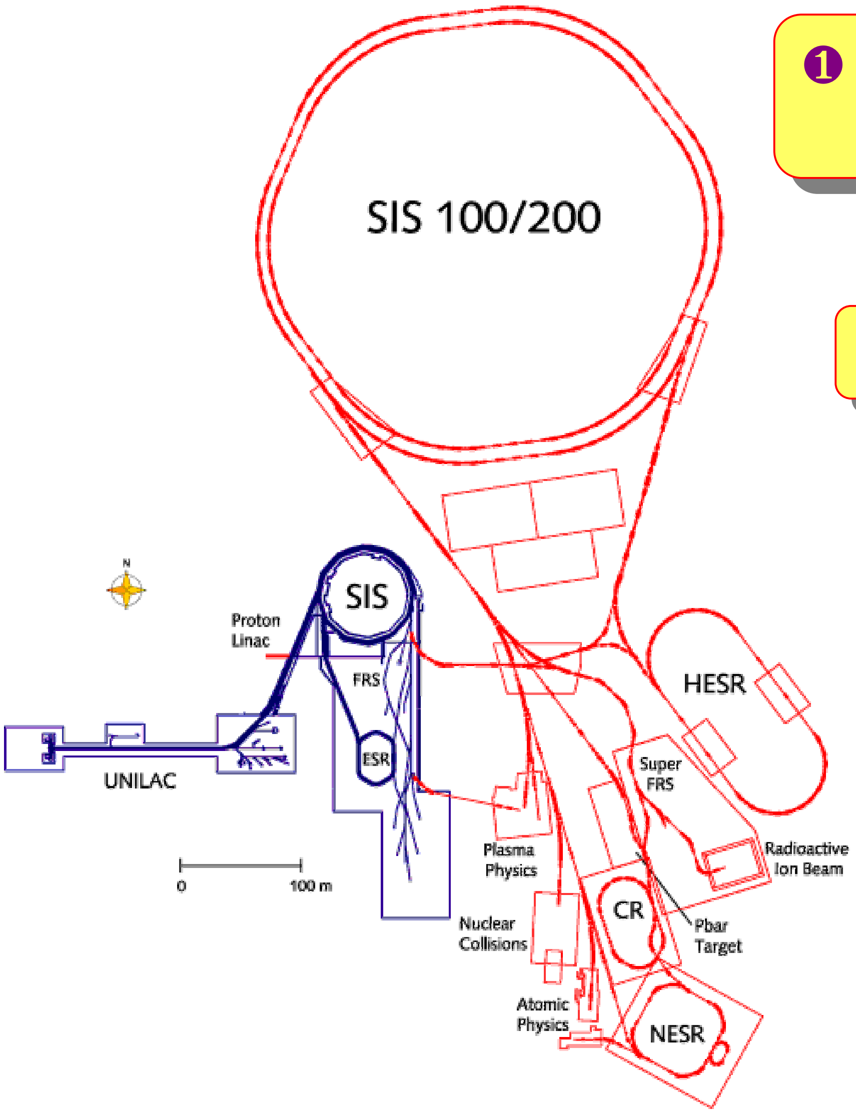
The GSI future upgrade



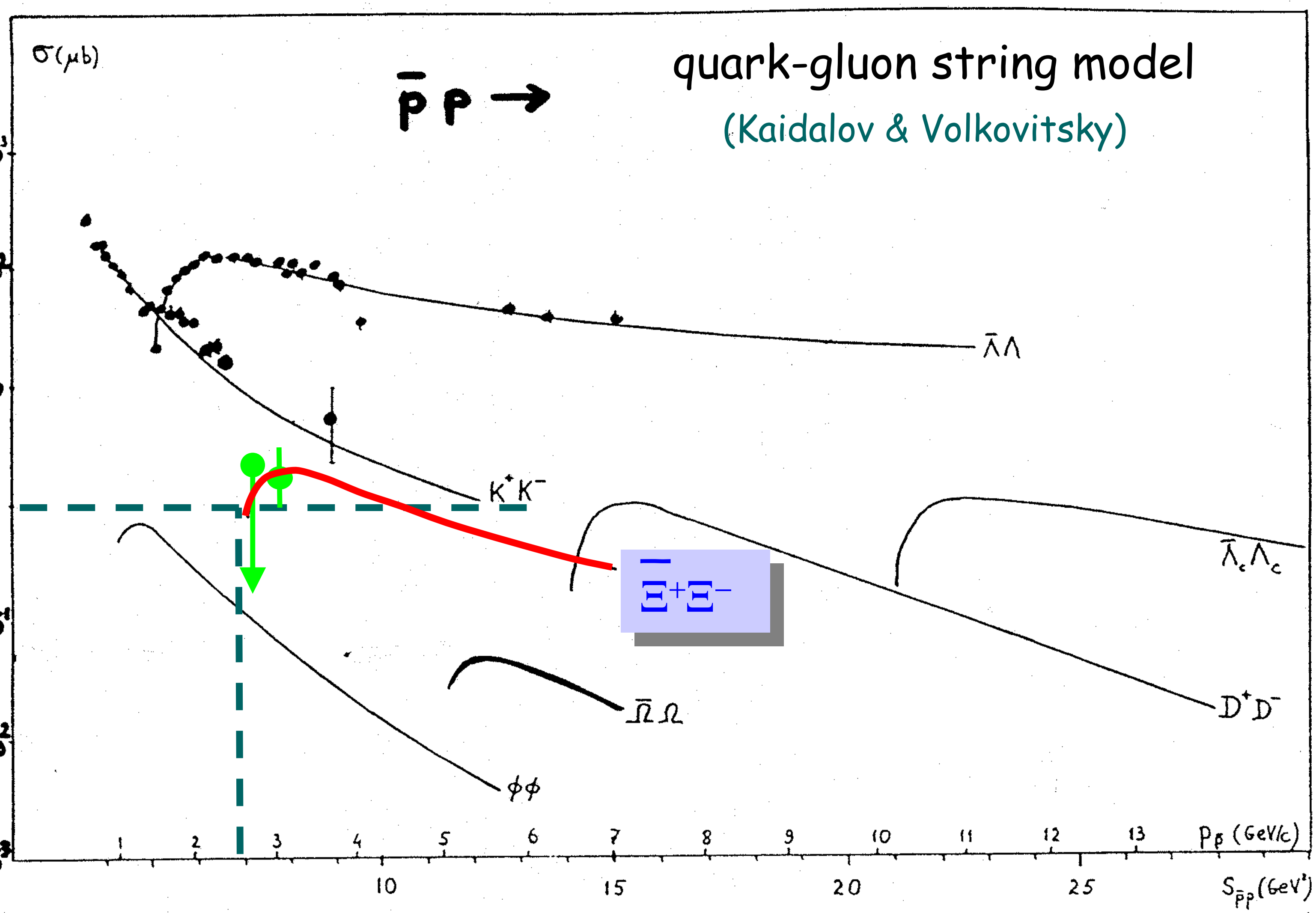
❶ higher beam intensity (100 ×)
☛ fast cycling synchrotrons

❷ higher beam energy (15 ×)

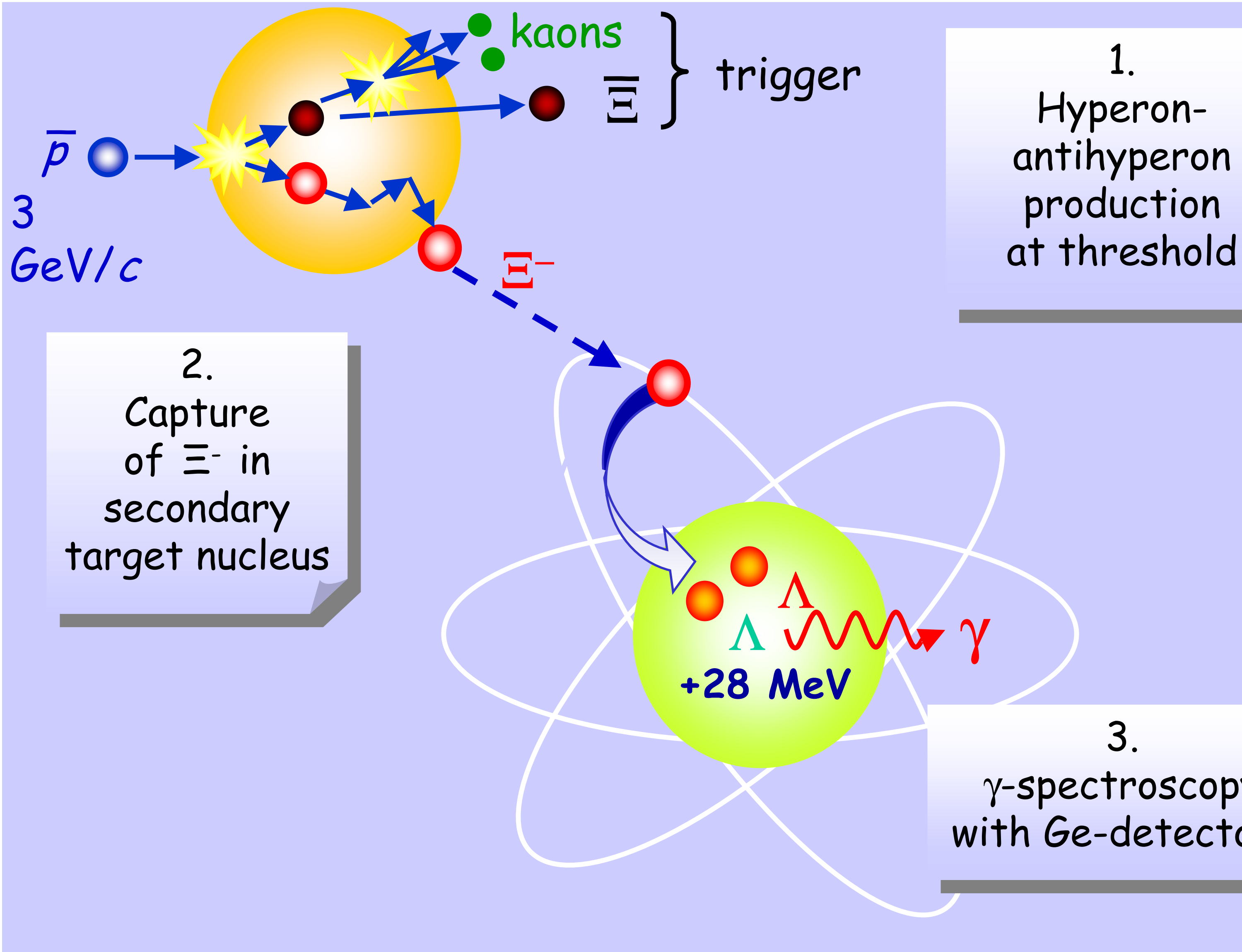
❸ higher beam quality
☛ stochastic and electron cooling
☛ bunch compression (50 ns)

❹ high parallelism in operation

General idea



ΛΛ-hypernucleus production @ GSI



1.
Hyperon-antihyperon production at threshold

2.
Capture of Ξ^- in secondary target nucleus

3.
γ-spectroscopy with Ge-detectors

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Expected rates

$\sigma_{\bar{p}p}(\Xi\bar{\Xi}) = 2 \ \mu b \ @ \ 3 \ \mathrm{GeV}/c$

$\sigma_{\bar{p}A}(\Xi\bar{\Xi}) = A^{2/3} \cdot \sigma_{\bar{p}p}(\Xi\bar{\Xi})$

by using, e.g., a ^{12}C wire target:

@ $\mathscr{L} = 10^{32}\ cm^{-2}\ s^{-1}$ HESR will produce $\Xi^-\bar{\Xi}$ pairs @ ~ 7×10^2 Hz

- joint $\Xi^-\bar{\Xi}$ escape probability: 5×10^{-4}
  (trigger on $\bar{\Xi}$ + p_{Ξ^-} = 100 – 500 MeV/c)
- $\bar{\Xi}$ reconstruction efficiency: ~ 50%
- Ξ^- stopping and capture probability: ~ 20%

→ ~ 3×10^3 captured Ξ^- /d

- $\Xi^- p \to \Lambda\Lambda$ conversion probability: 5%

→ ~ 150 ΛΛ-hypernuclei /d

- γ-ray emission/event: 50%
- γ-ray Ge photopeak efficiency: 10%

→ ~ 7 "golden events" /d

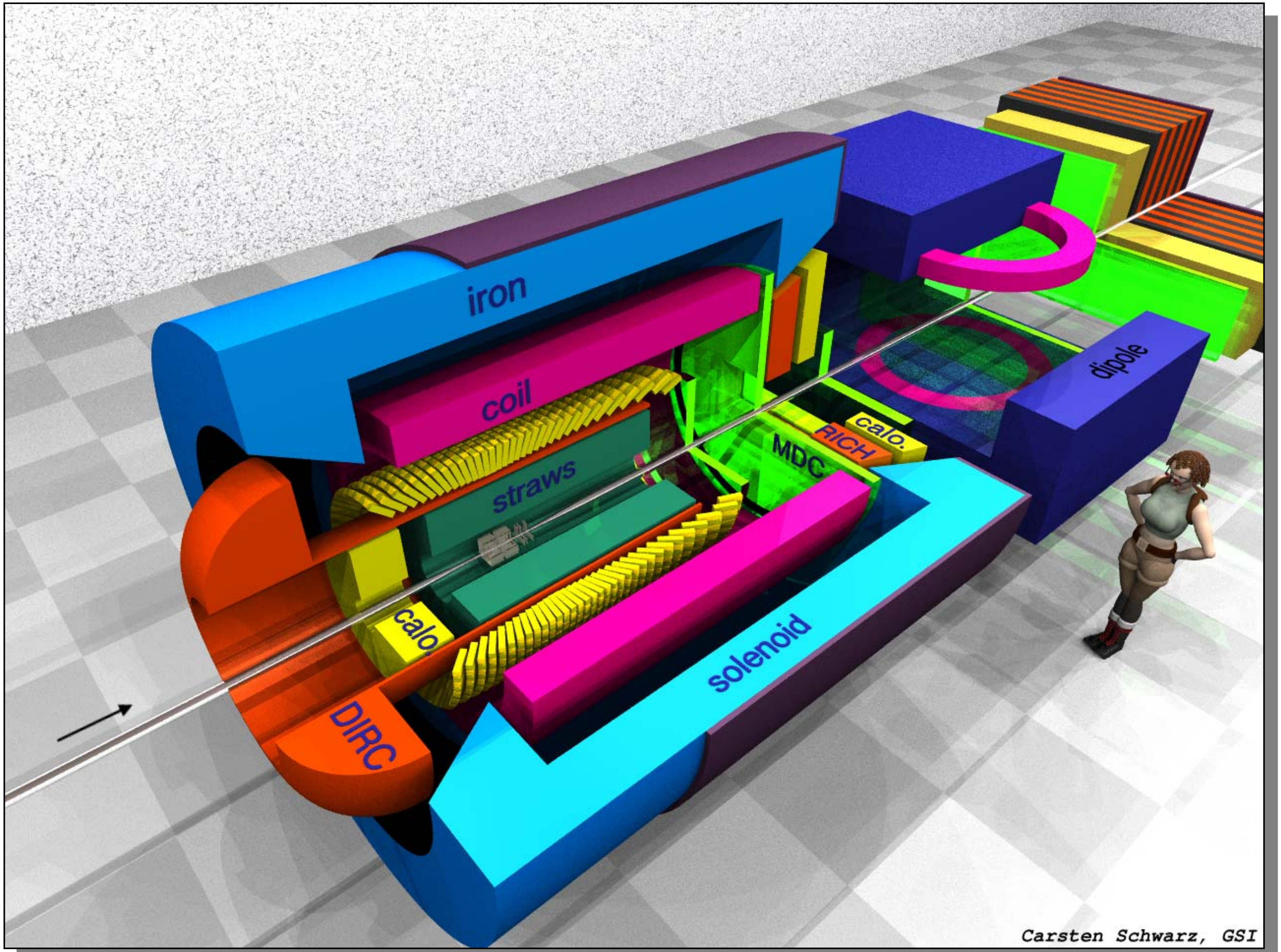
- K^+K^+ trigger

→ ~ 700 events /d

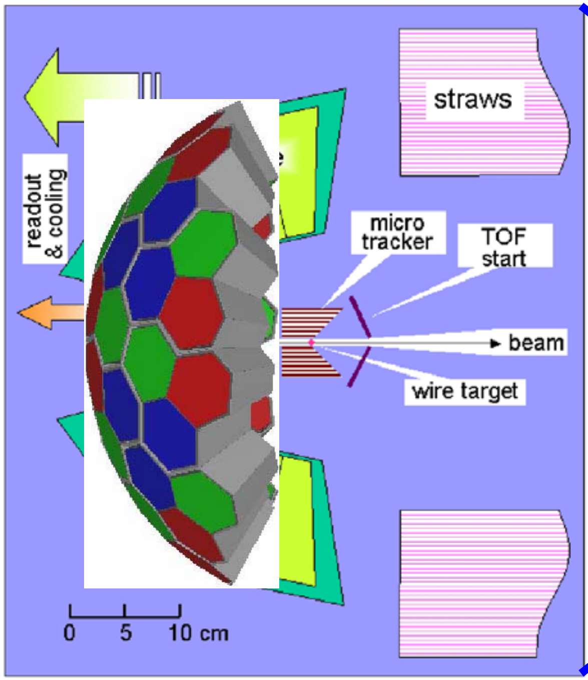
Competition

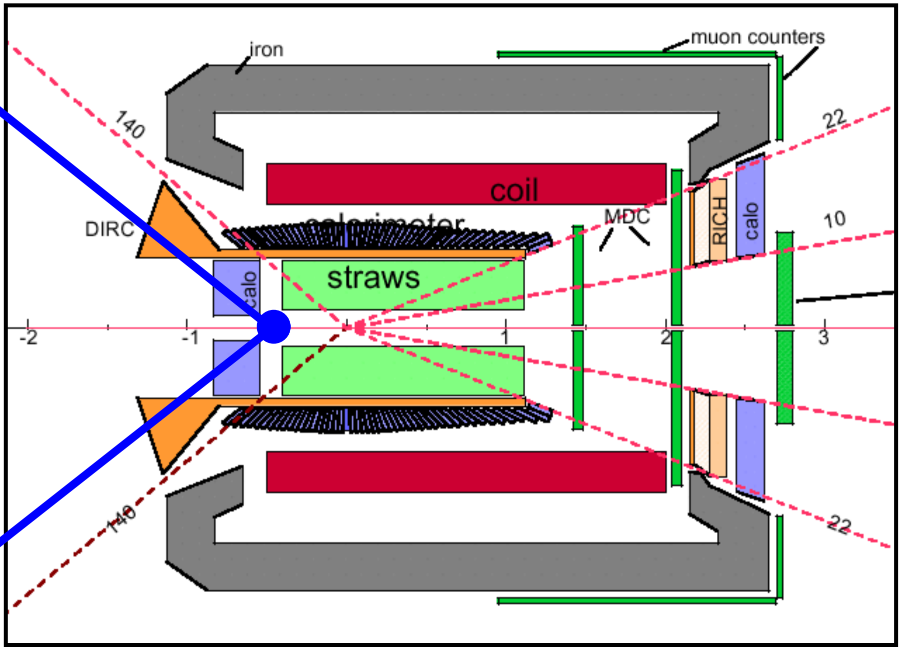
experiment	*reaction*	*device*	*beam/ target*	*status*
BNL-AGS E885	$(\Xi^-, {}^{12}C) \rightarrow {}_{\Lambda\Lambda}{}^{12}B + n$	neutron detector arrays	K^- beam, diamond target	20000 stopped Ξ^-
BNL-AGS E906	2π decays	Cylindrical Detector System	K^- beam line	few tens 2π decays of ${}_{\Lambda\Lambda}{}^{4}H$
KEK-PS E373	$(K^-,K^+)\ \Xi$	emulsion	(K^-,K^+)	several hundreds stopped Ξ^-
facility	*reaction*	*device*	*beam / target*	*Captured* Ξ^- */ day*
JPARC	$(K^-,K^+)\ \Xi$	spectrometer, $\Delta\Omega$ = 30 msr	$8 \cdot 10^6$/s 5 cm ${}^{12}C$	< 7000
cold anti-protons	$p\,\bar{p} \rightarrow K^* \bar{K}^*$ $K^* N \rightarrow \Xi\ K$	vertex detector	10^6 stopped $\bar{p}$/s	2000
GSI-HESR	$p\,\bar{p} \rightarrow \Xi\bar{\Xi}$	vertex detector + γ-spectrometer	$\mathcal{L} = 2 \cdot 10^{32}$, thin target, production vertex $\neq$ decay vertex	~ 3000 ~ 300000 KK trigger (incl. trigger)

The PANDA detector



Ge array for hypernuclei detection





- solid state micro-tracker (diamond or silicon)
  - compact: thickness ~ 3 cm
  - high rate capability
  - high resolution
- capillar (2D) or pixel (3D) detector
- position sensitive Ge detector (VEGA or AGATA like)
  - high rate capability

Technological challenges

- ✔ high photopeak efficiency ($\varepsilon_{ph} \geq 0.3$)
- ✔ good angular resolution in order to increase the Doppler correction capability (up to $v/c \approx 0.5$)

- ☞ high event rate capability
- ☞ fast background rejection
- ☞ operation into high magnetic fields

Technological challenges

- operation in presence of huge hadronic background
  - developing of readout schemes and tracking algorithms to perform high resolution γ-spectroscopy **notwithstanding** high particle fluxes
    - detector response characterization
    - detailed background studies
  - feasibility study for a fast reset circuit based on feedback from charged particle veto detector surrounding the Ge detectors
- operation into high magnetic field
  - developing of new techniques and procedures to make Ge detectors nearly insensitive to the perturbation

Summary

- ✓ The fifty-year-old field of strangeness nuclear physics is still alive and has a great discovery potential

- ✓ Ge γ-ray detectors are ideal tools to complement "traditional" magnetic spectrometer

- ☛ By exploiting the potentialities of the new GSI and Jparc facilities, a large number of ΛΛ-hypernuclei will be produced, allowing a significative step forward in multi-strange system knowledge

- 2013 will be the 50th anniversary of ΛΛ-hypernucleus discovery: we could successfully celebrate it with a long series of fundamental questions solved