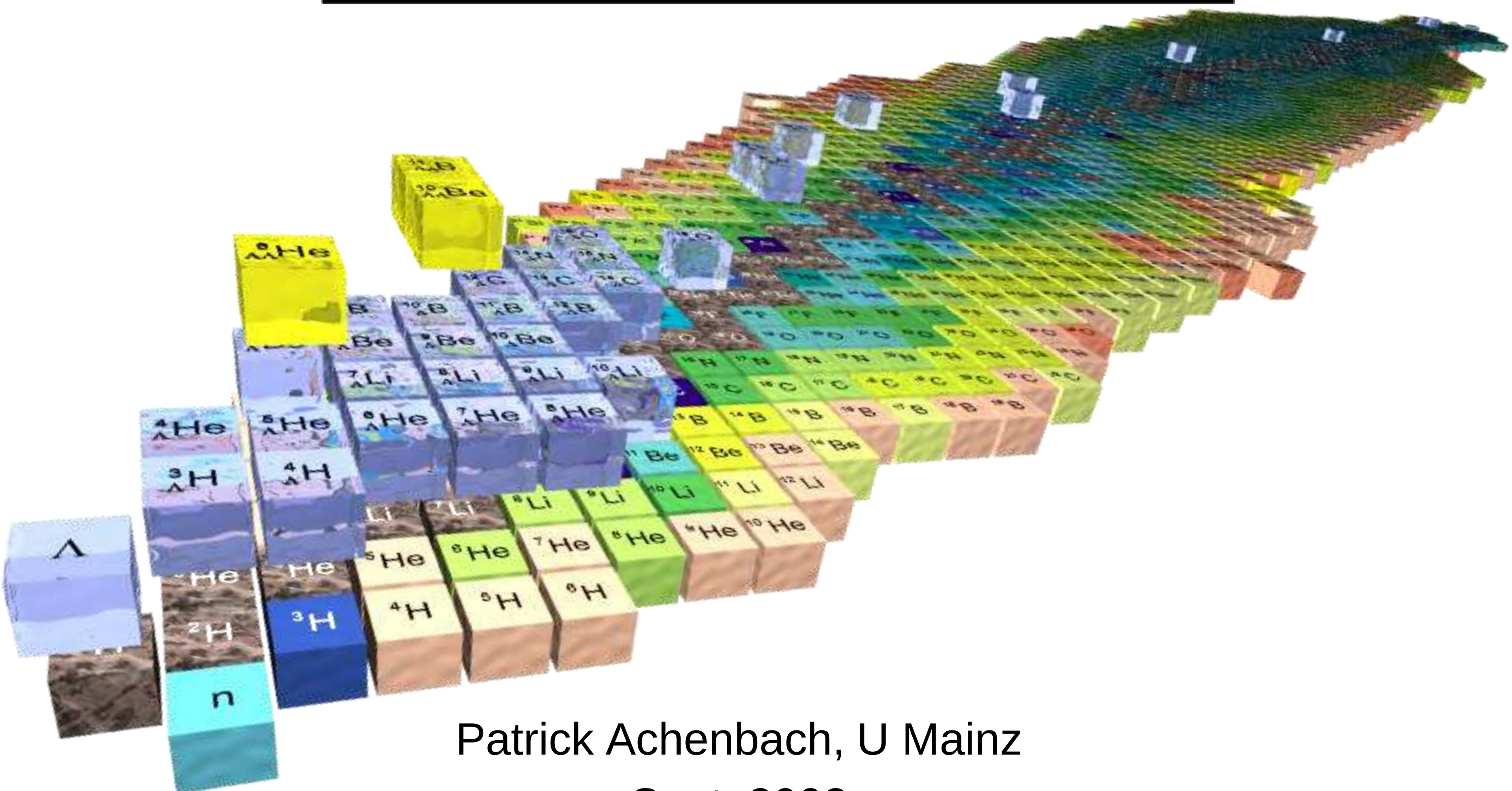
Physics of Hypernuclei
as seen by an experimenter



Patrick Achenbach, U Mainz

Sept. 2008

Outline of the talk

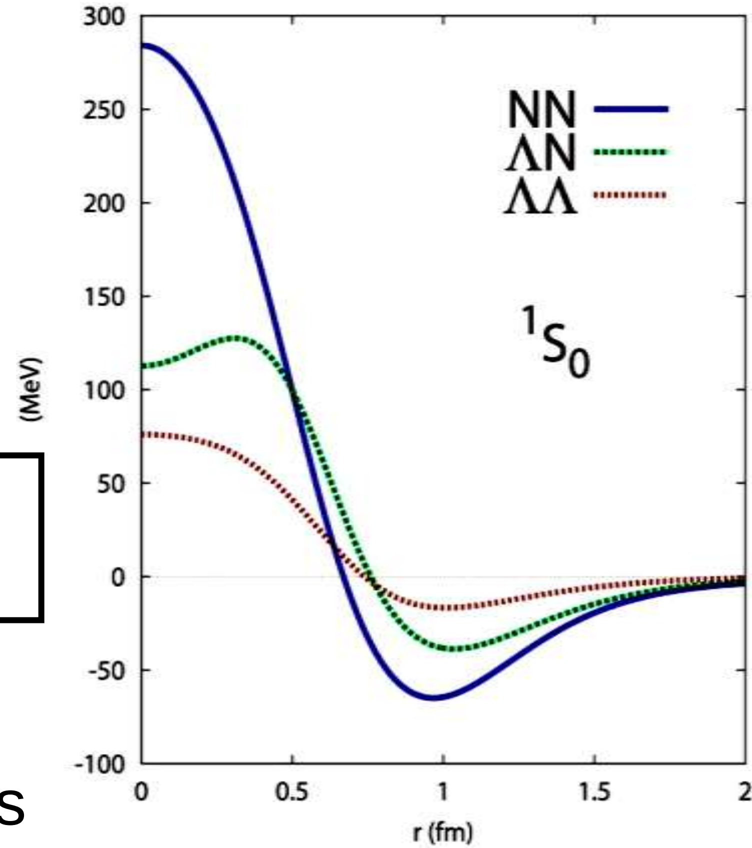
- interaction with strangeness
  - the hyperon-nucleon interaction
- hypernuclear formation in electroproduction
  - the KAOS spectrometer at the accelerator MAMI-C
- hypernuclear spectroscopy with stable heavy ion beams and rare isotope beams
  - the HypHI experiment at GSI/FAIR
- hypernuclear physics with anti-protons
  - the Panda experiment at FAIR
- summary of present activities

The hyperon-nucleon interaction

- Y-N and Y-Y scattering:
  - no hyperon target available:
    τ (hyperon) ~ 10^{-10} s
  - very high energy hyperon beams:
    CERN WA89 and SELEX
  - low energy hyperons on nuclei:
    very poor hyperon beam profile

→ **impossible to deduce precise Y-N data**

→ **impossible to deduce any Y-Y data**



[Fujiwara et al., nucl-th/0607013]

- hypernuclei: nuclei with strange quarks
  - nuclear bound system with hyperon (Y)
  - a “laboratory” to study baryon-baryon interactions with strange quarks

The hypernuclear landscape

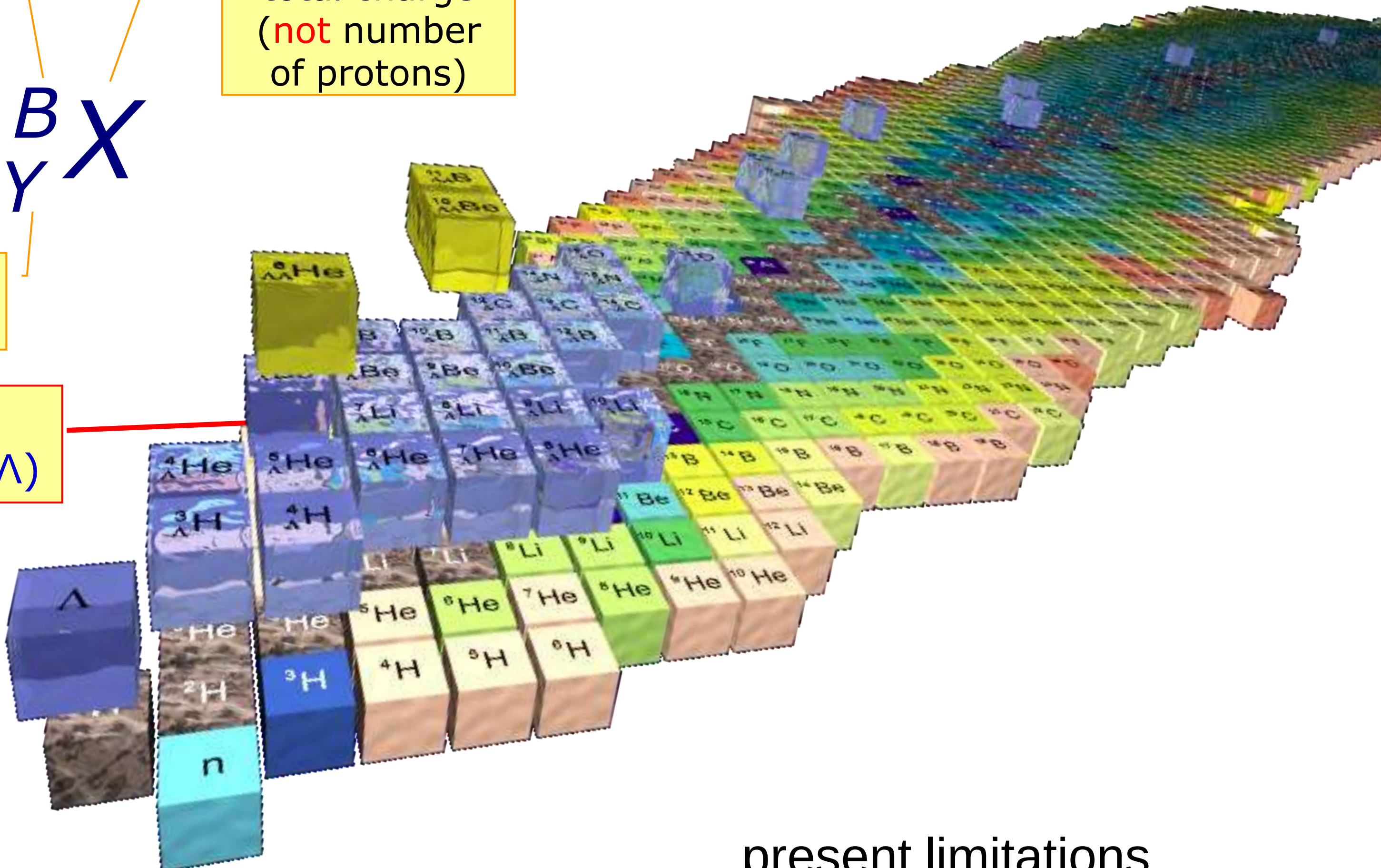
number of baryons $N+Z+Y$

element = total charge (not number of protons)

$^{B}_{Y}X$

number of hyperons Y

Example:
$^{7}_{\Lambda}$Li (^{6}Li + Λ)

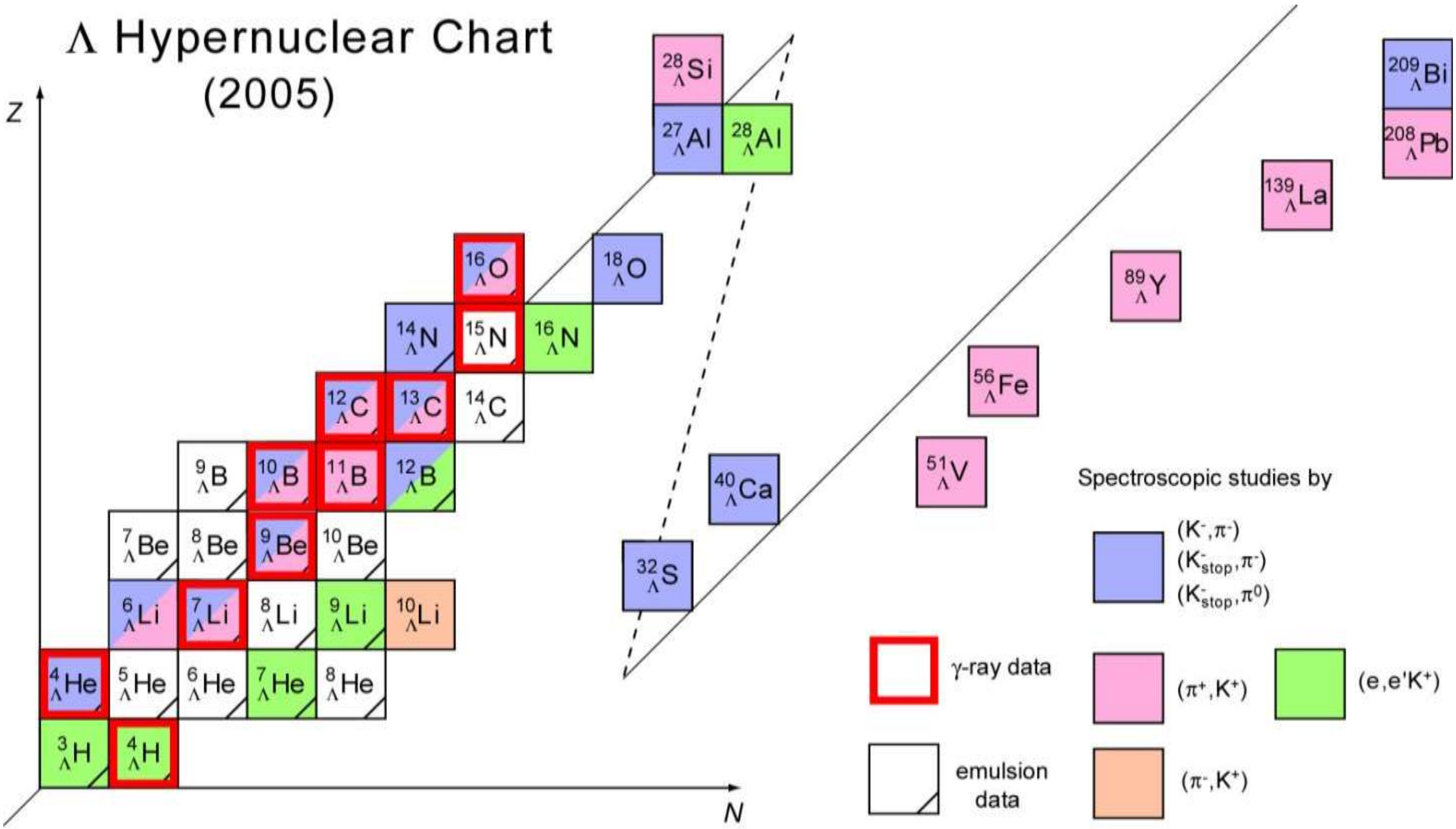


increasing strangeness

present limitations

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

Spectroscopy of single Λ-hypernuclei



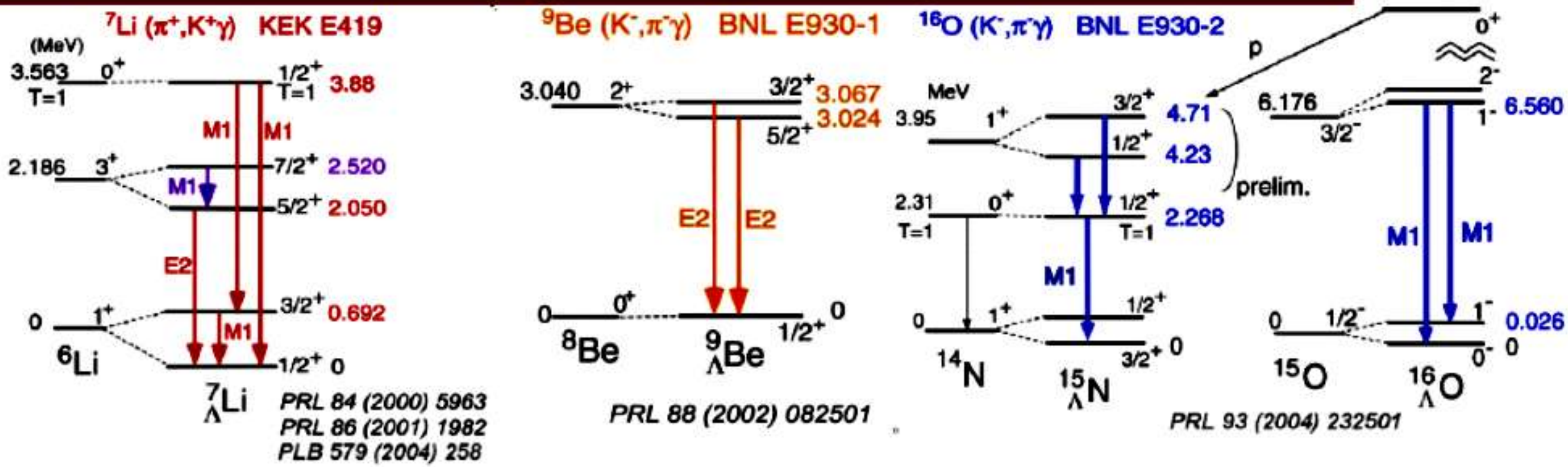
[Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564]

Observed γ-transitions in single Λ-hypernuclei

many excited, particle stable states in single hypernuclei observed
γ-spectroscopy of these states is used to study effective ΛN potential

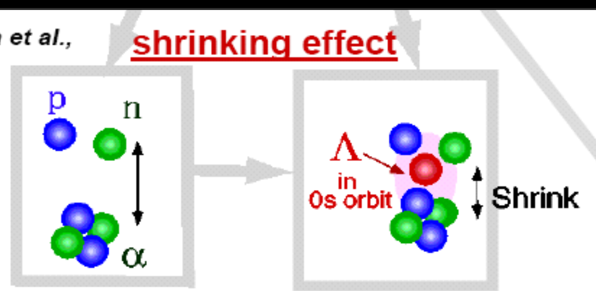
$$V_{\Lambda N}^{eff} = V_0 + \Delta(\vec{s}_\Lambda \cdot \vec{s}_N) + S_N(\vec{l}_{\Lambda N} \cdot \vec{s}_N) + S_\Lambda(\vec{l}_{\Lambda N} \cdot \vec{s}_\Lambda) + T(s_{12})$$

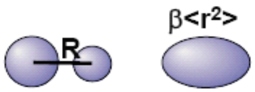
$^7_\Lambda$Li $(3/2^+,1/2^+)$	$^7_\Lambda$Li $(5/2^+,1/2^+)$	$^9_\Lambda$Be $(3/2^+,5/2^+)$	$^{16}_\Lambda$O $(1^-,0^-)$
Δ = 0.4 MeV	S_N = - 0.4 MeV	S_Λ = - 0.01 MeV	T = 0.03 MeV



Strangeness impurity effects

Predicted by Motoba et al., Prog.Theor.Phys. 70 (1983) 189.





B(E2) ∝|<f| e r² Y₂ |i>|²
∝R⁴ or (β<r²>)²

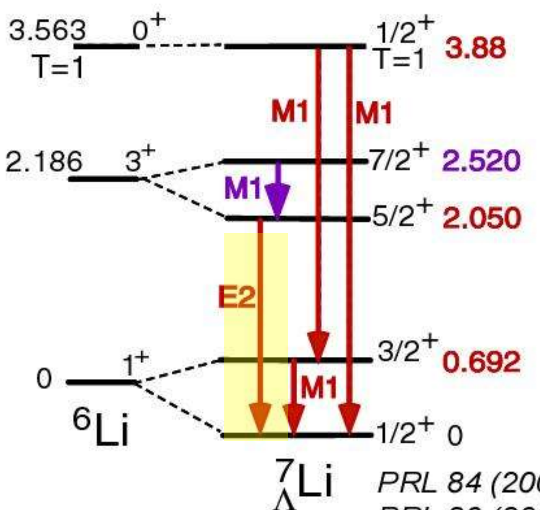
B(E2) [e² fm⁴]

$10.9 \pm 0.9 \longrightarrow 3.6 \pm 0.5 \pm ^{0.5}_{0.4}$

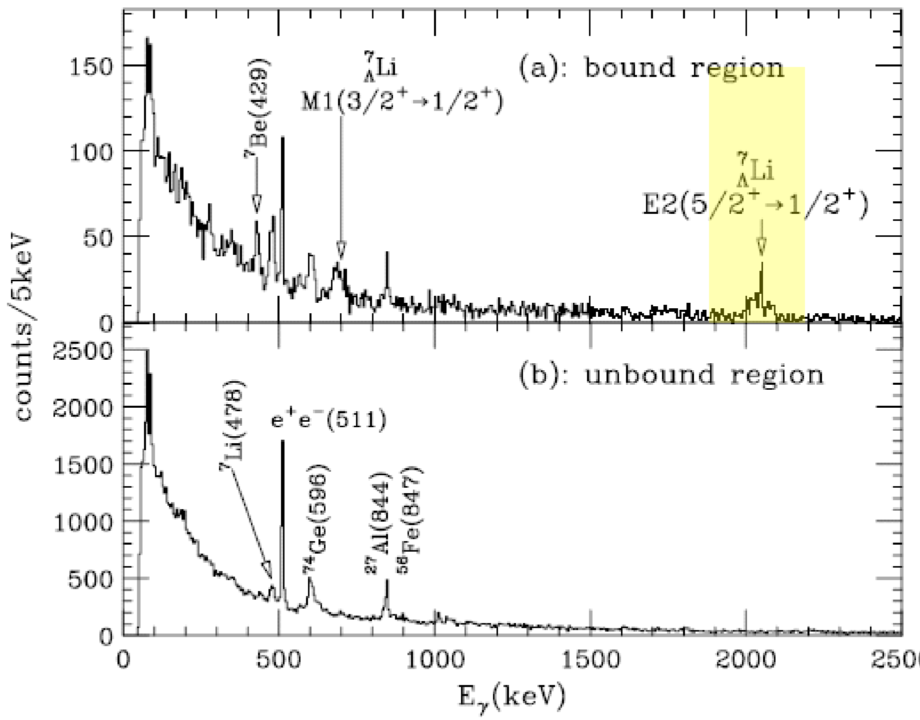
⇒ 19±4% shrinkage by Λ

Tanida et al., PRL 86(2001) 1982

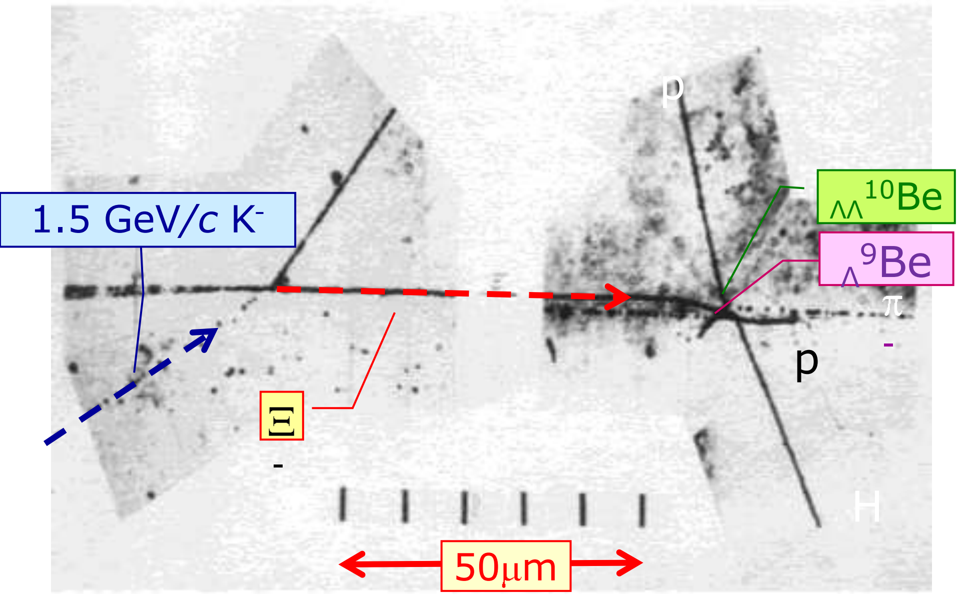
^{7}Li (π^+,$K^+\gamma$) KEK E419

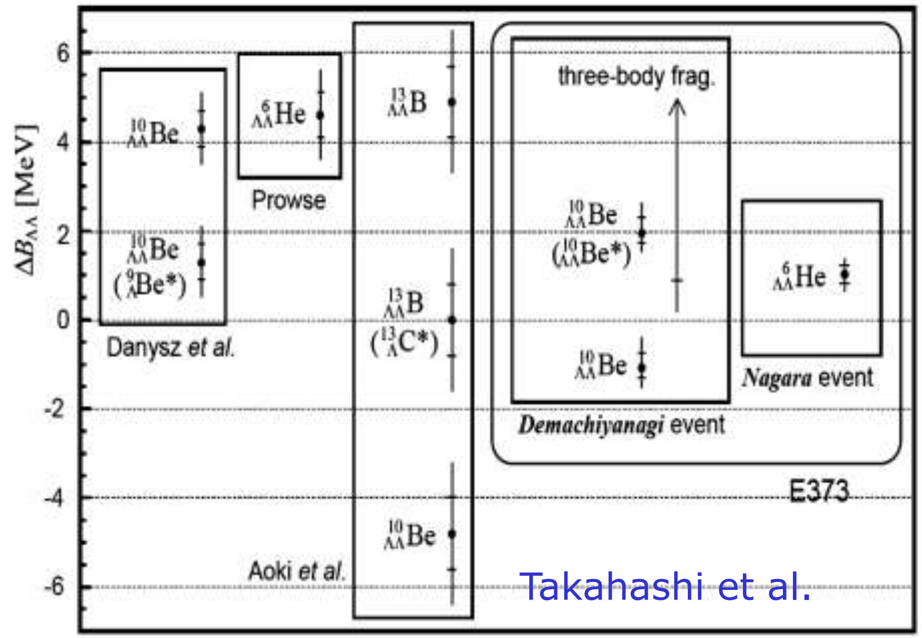


PRL 84 (2000) 59
PRL 86 (2001) 19
PLB 579 (2004) 2
PRC 73 (2006) 01



Hyperon-hyperon interaction





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

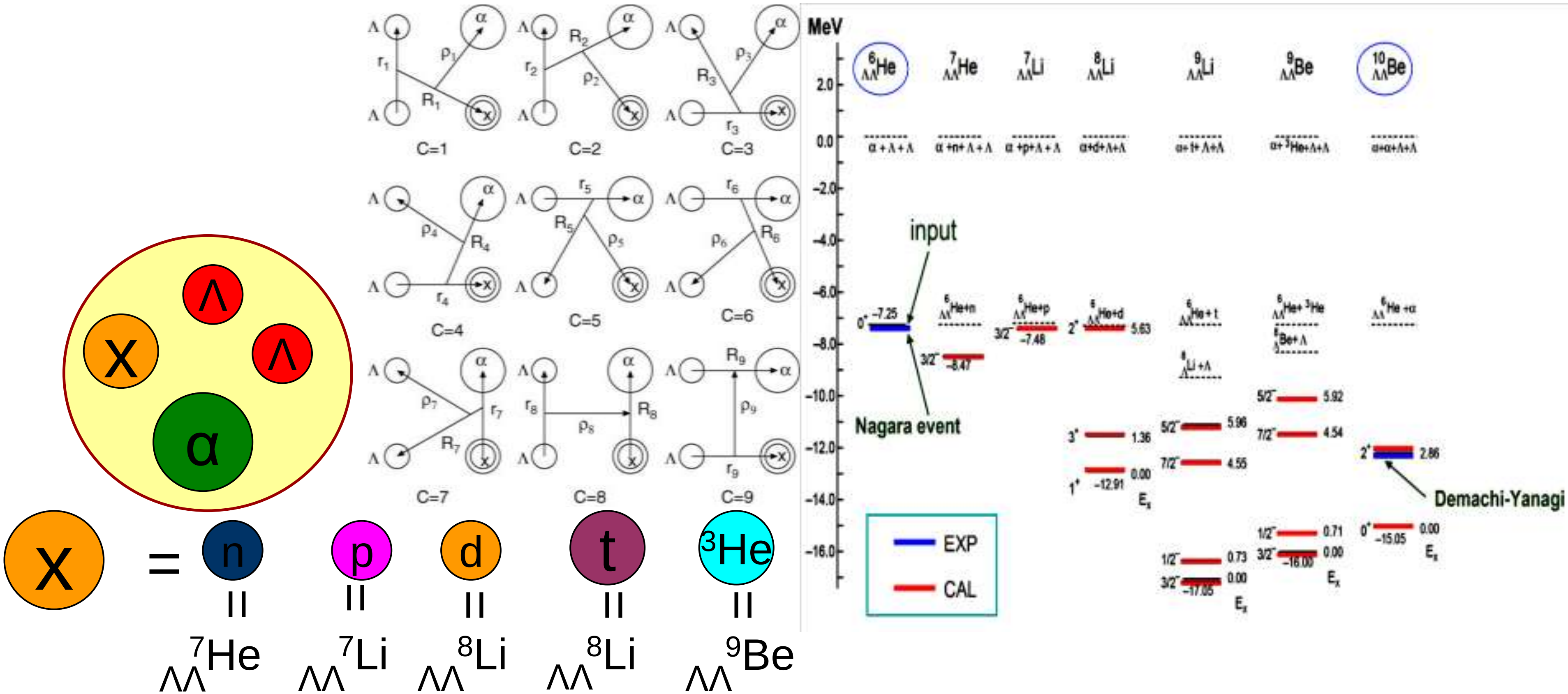
$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

1963: Danysz *et al.* $^{10}{}_{\Lambda\Lambda}$Be
1966: Prowse $^{6}{}_{\Lambda\Lambda}$He
1991: KEK-E176 $^{13}{}_{\Lambda\Lambda}$B
2001: KEK-E373 $^{6}{}_{\Lambda\Lambda}$He
2001: AGS-E906 $^{4}{}_{\Lambda\Lambda}$H ? (~15)

Spectroscopy of ΛΛ-hypernuclei

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

4-body cluster model for light nuclei:

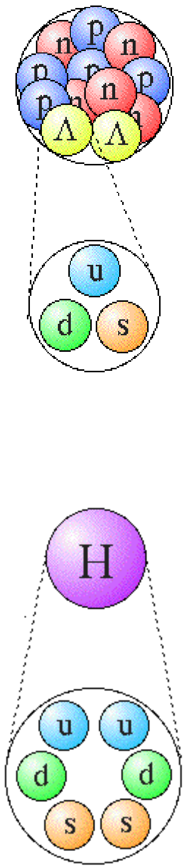


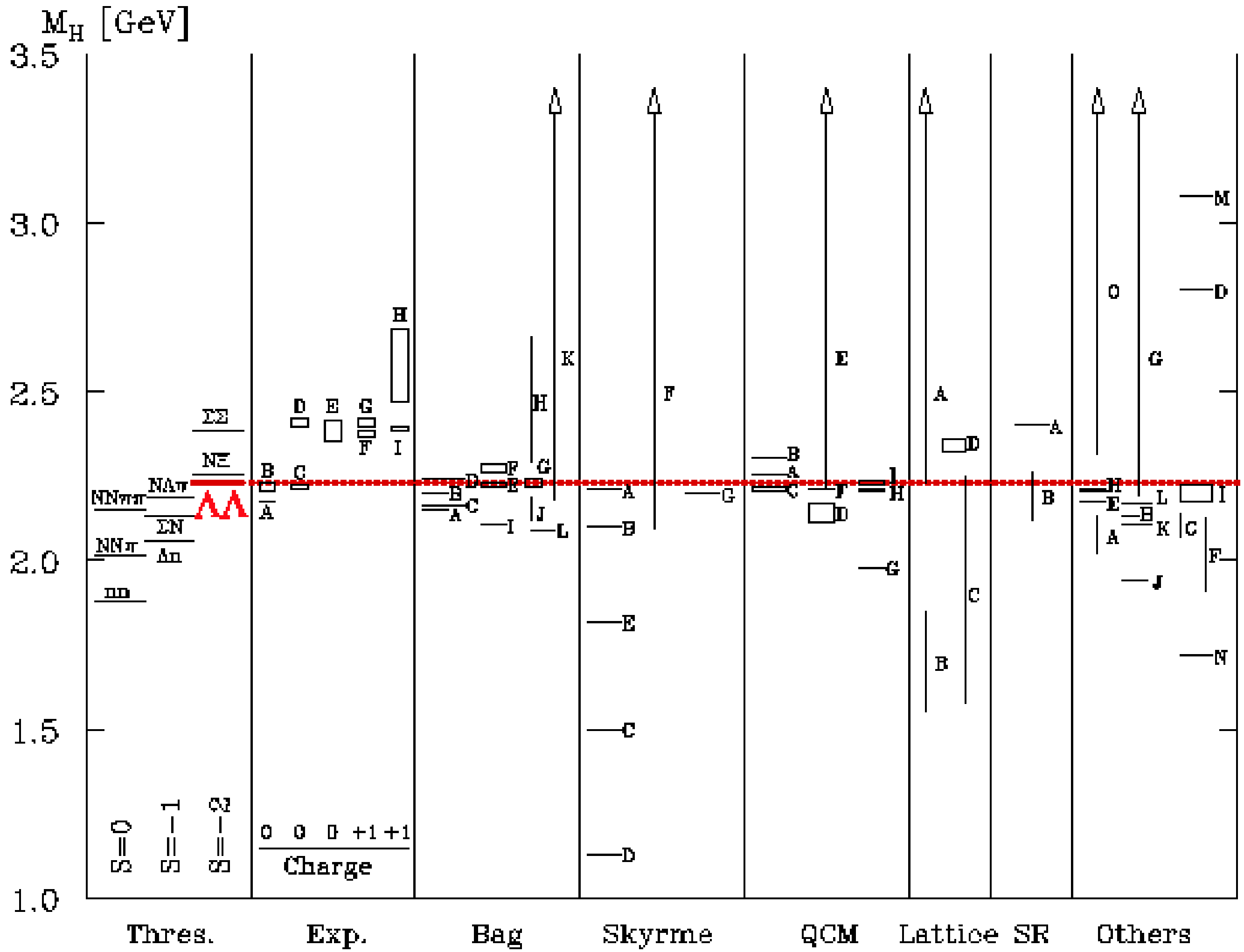
many excited, particle stable states in double hypernuclei predicted
γ-spectroscopy of these states is mandatory to study ΛΛ interaction

ΛΛ-nuclei as gateway to H-particles

H-particle predicted as ΛΛ bound state

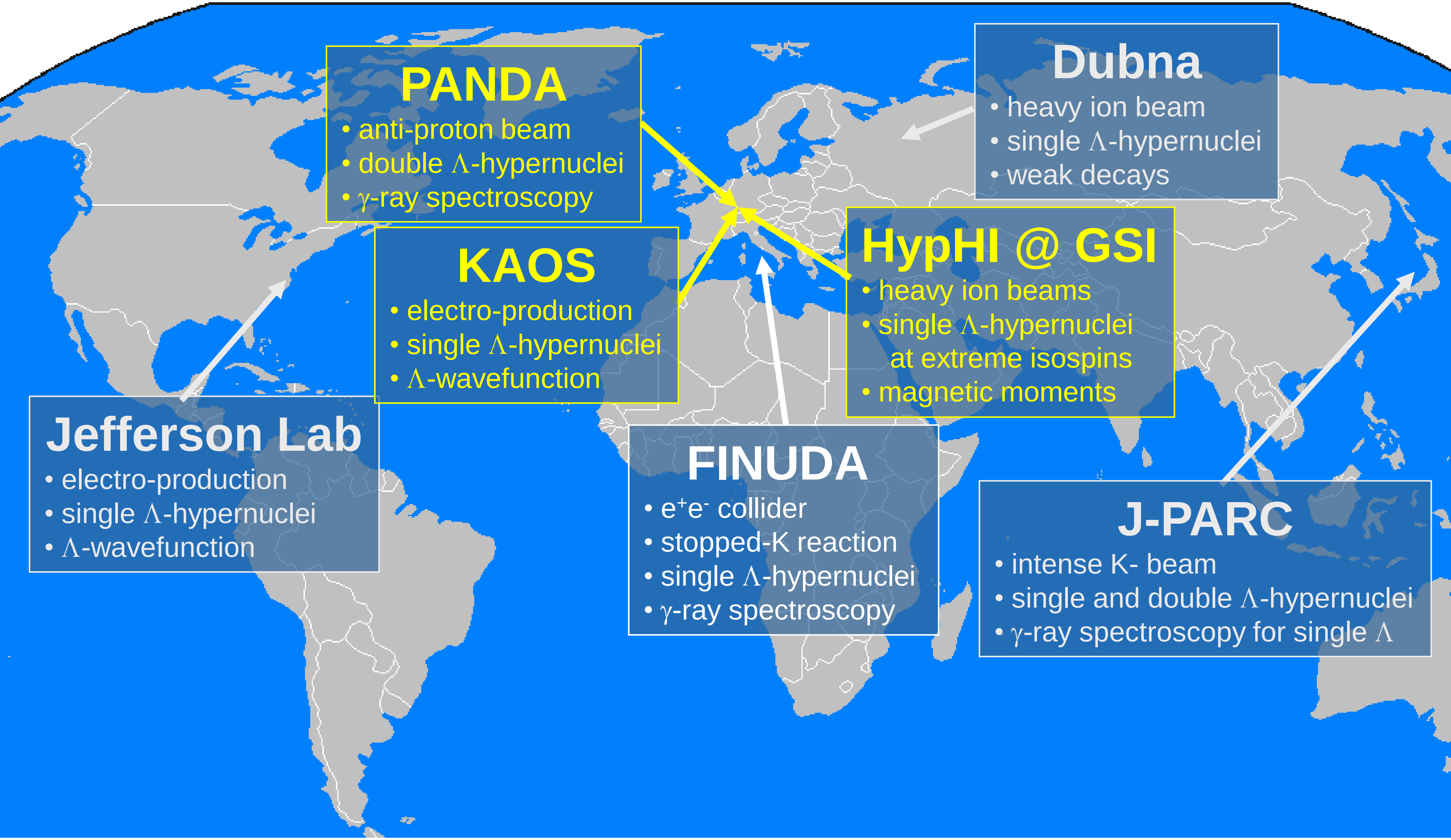
[R.L. Jaffe (1977)]





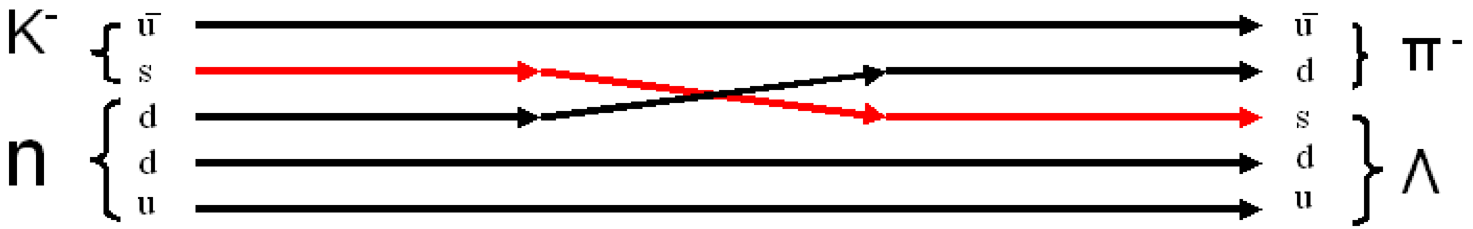
[T. Sakai, K. Shimizu, K. Yazaki
Prog.Theor.Phys.Suppl. 137 (2000) 121-145]

International hypernuclear network

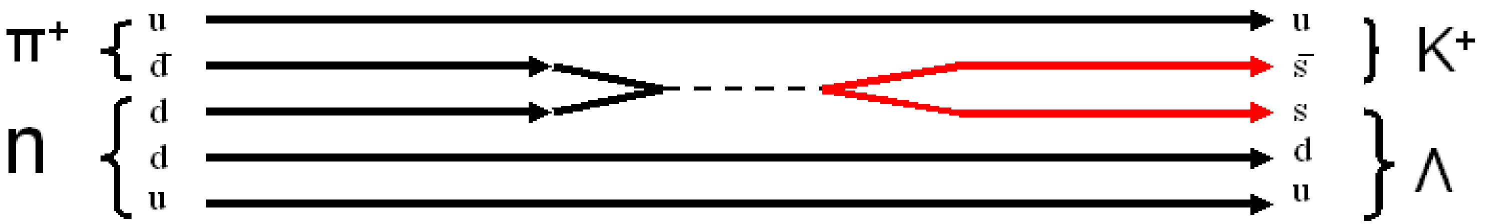


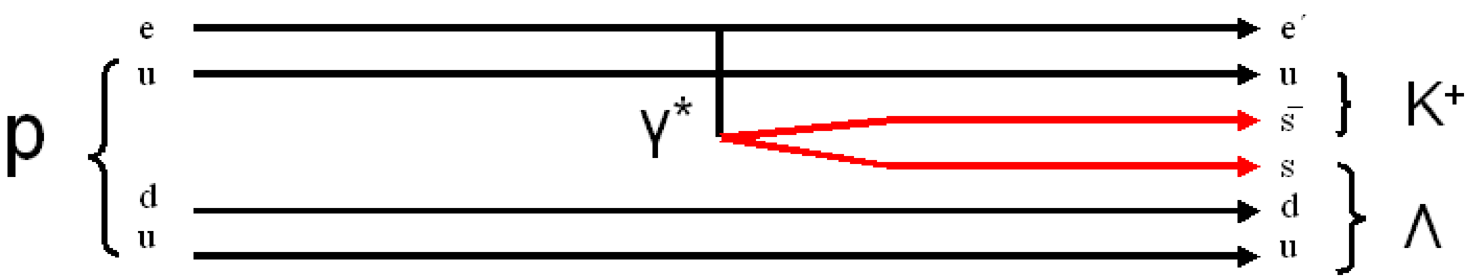
Strangeness reactions

exchange of strangeness

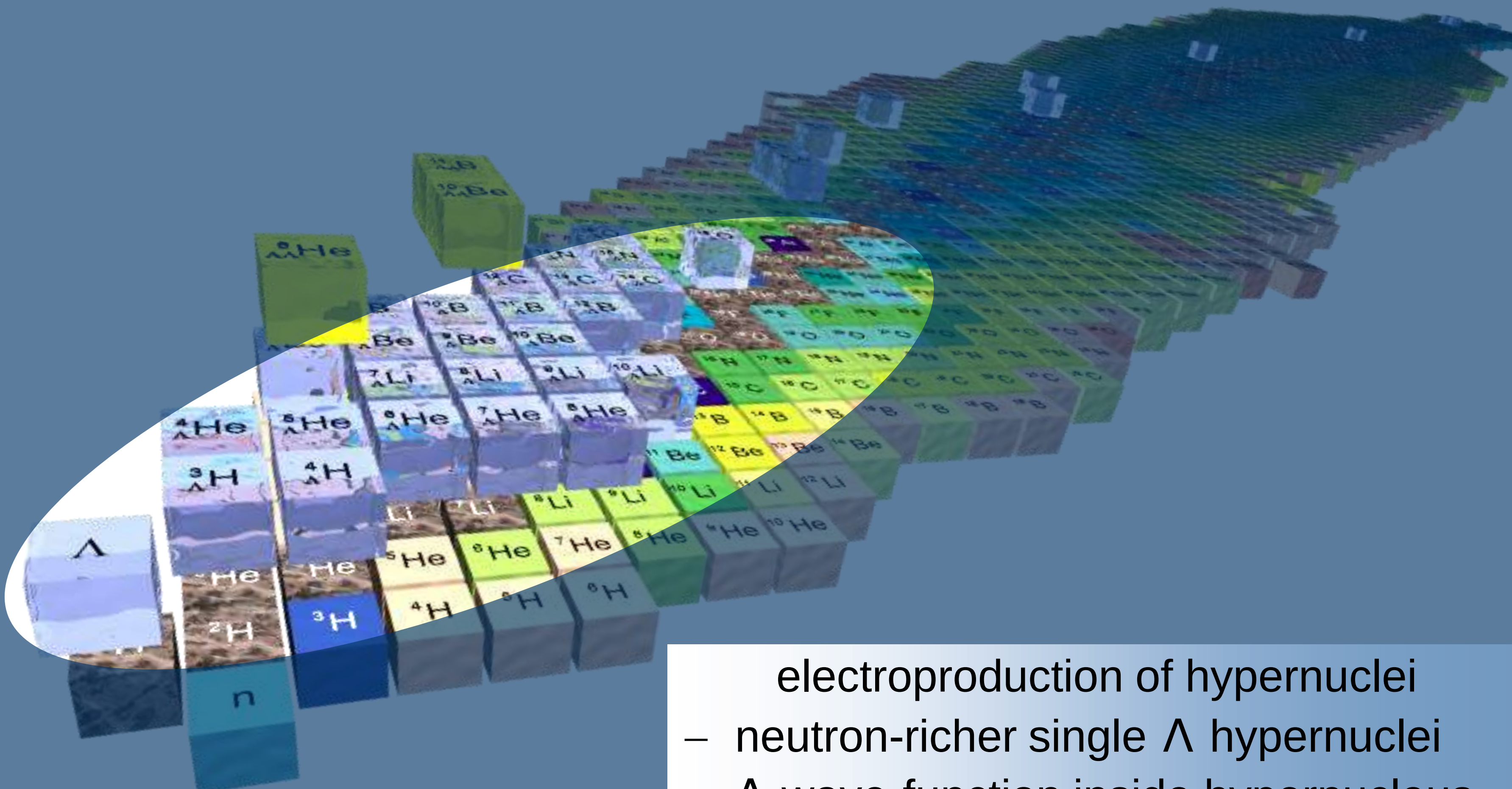


production of open strangeness





Strangeness electroproduction



electroproduction of hypernuclei

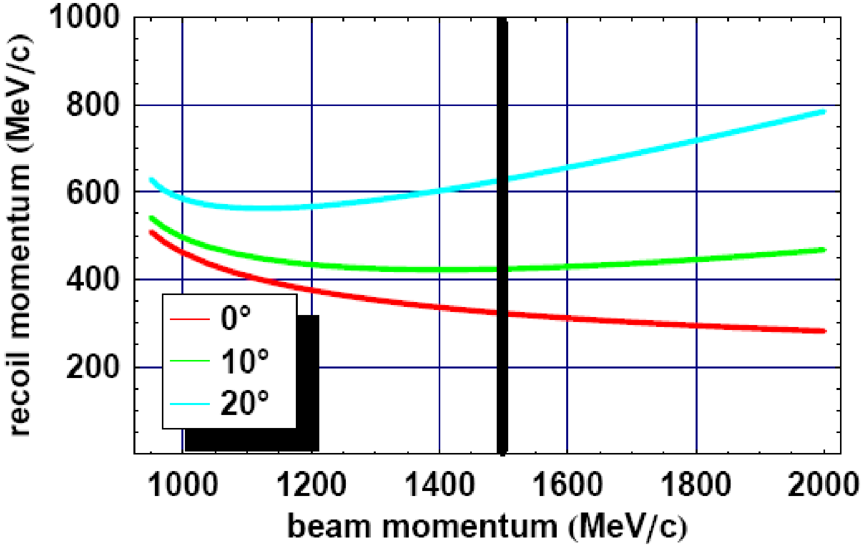
- neutron-richer single Λ hypernuclei
- Λ wave-function inside hypernucleus
- large momentum transfer components

Kinematic differences to meson induced reactions

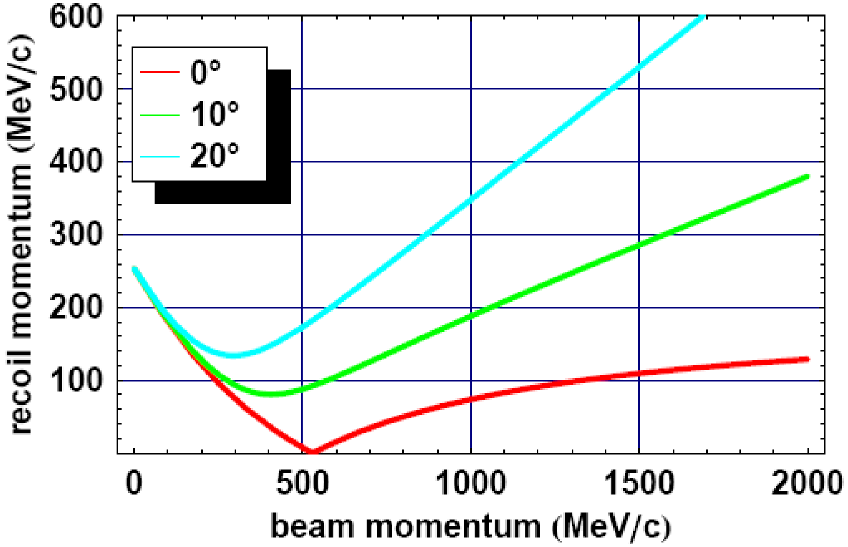
- typical momentum transfers: $\approx 300 - 600$ MeV/c
- minimum momentum transfer for $\theta_K = 0°$
- energy and momentum transfer independent:

$$Q^2 = -q_\mu q^\mu = \omega^2 - \vec{q}^{\,2}$$

- momentum transfer $\longrightarrow 0$ for "magic momentum"
- minimum momentum transfer for $\theta_\pi = 0°$
- momentum distributions cannot be measured



[strangeness electroproduction $(e, e'K^+)$]

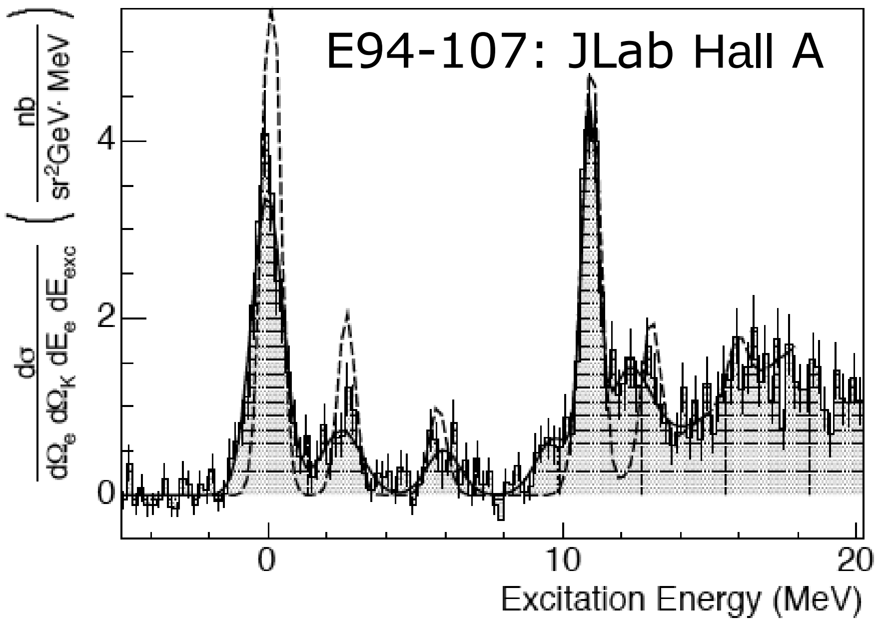


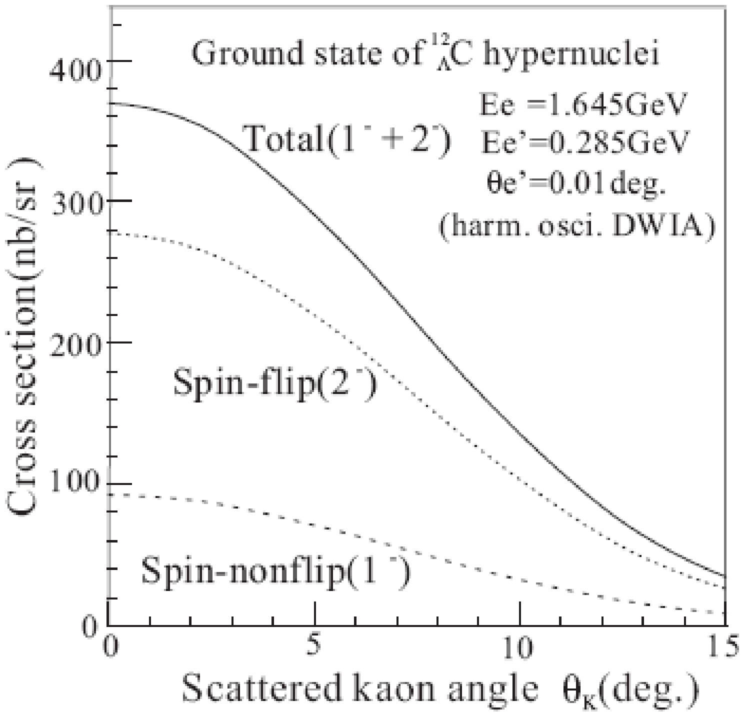
[strangeness exchange (K^-, π^-)]

hypernuclei: spectrometry of mesons at forward angles

Extracting hypernuclear structure information

- cross sections calculated with harmonic oscillator potential and DWIA
- typical K^+ angular distributions peaked at 0°, falling rapidly:





ΔE~650 keV; Core excited states
Theoretical interpretation and publication in progress

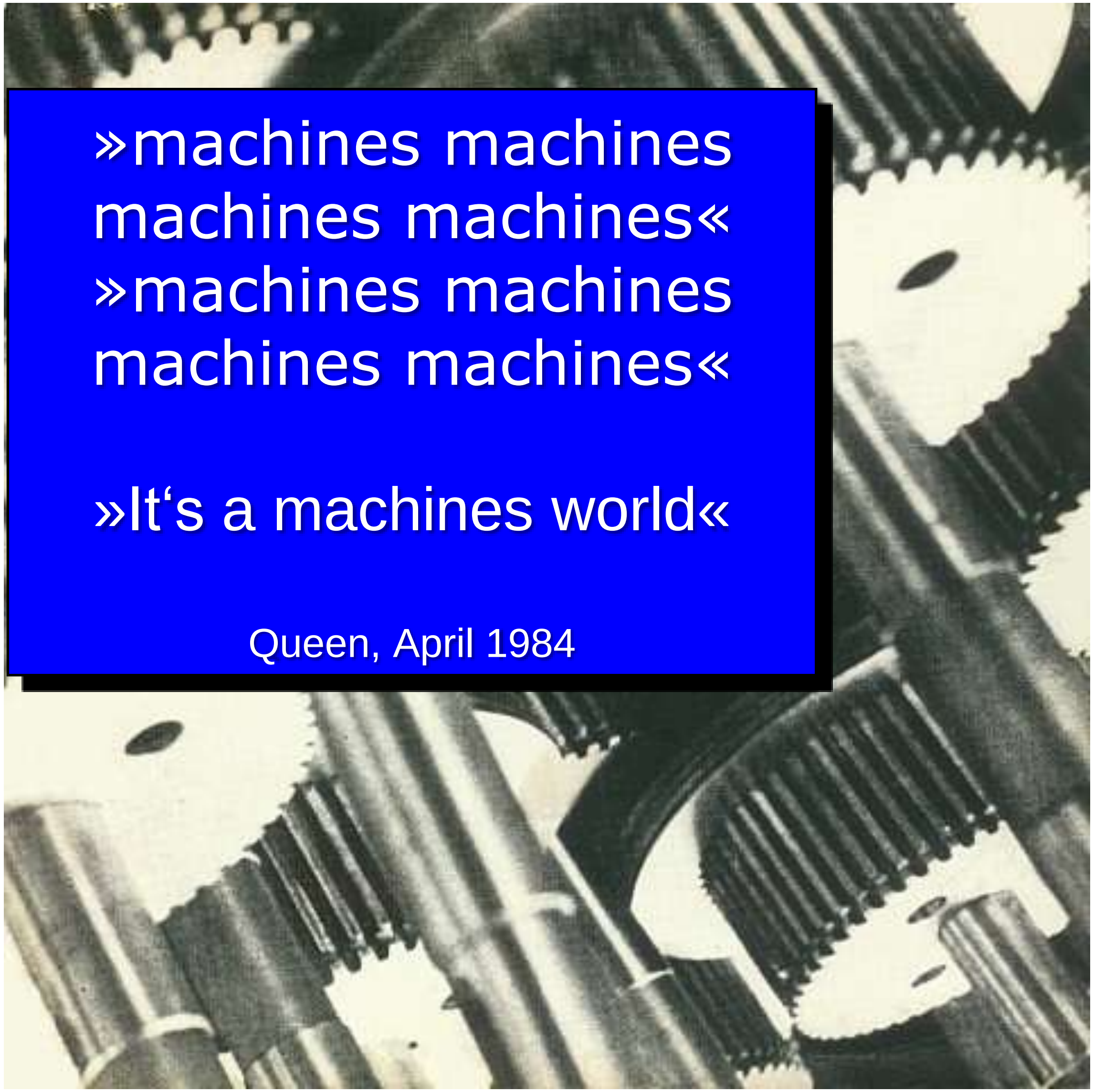
[J. Reinhold (FIU), DNP Town Meeting, Dec. 2007]

[M. Sotona and S. Furullani, Prog. Theor. Phys. Suppl. **117**, 151 (1994)]

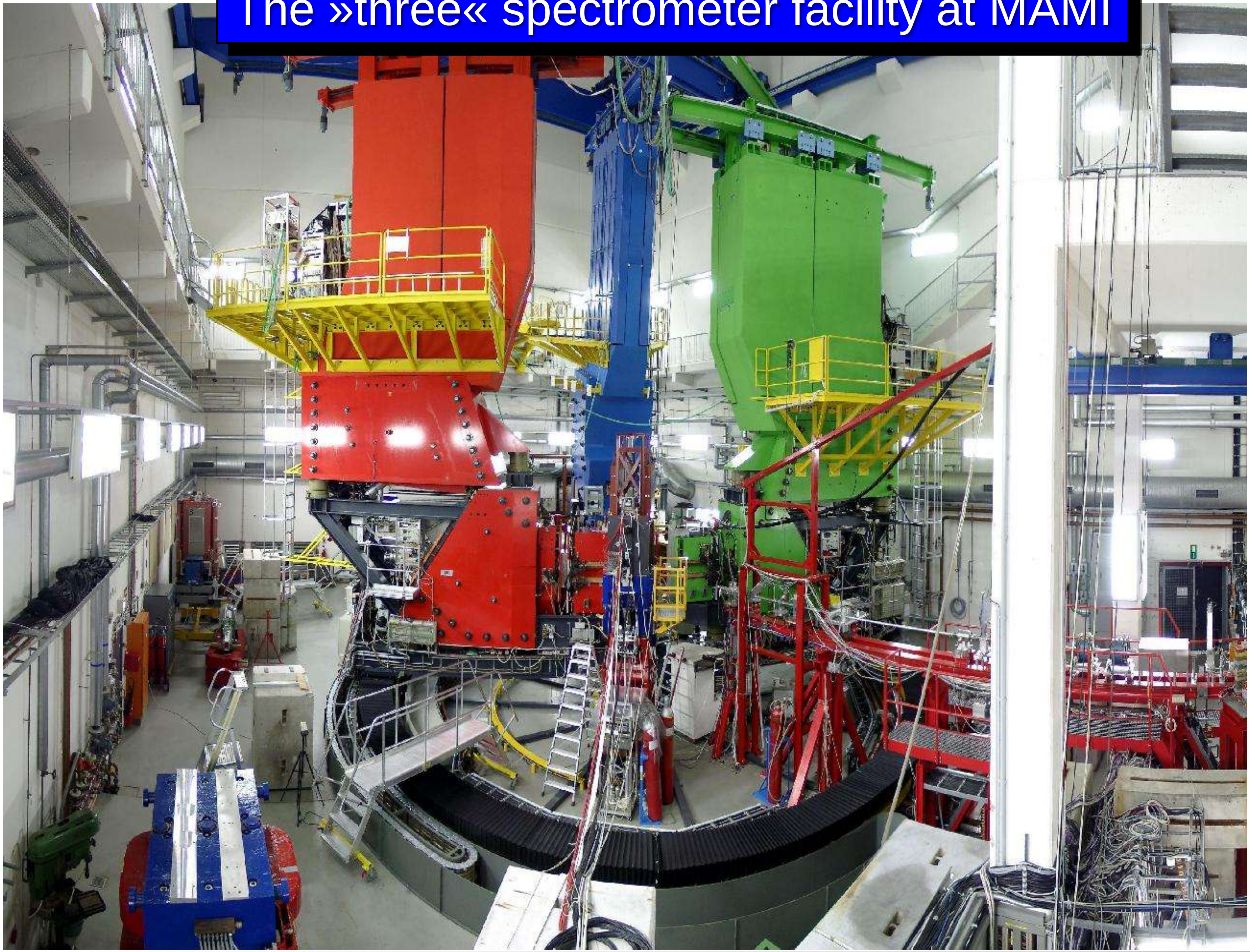
»machines machines
machines machines«
»machines machines
machines machines«

»It's a machines world«

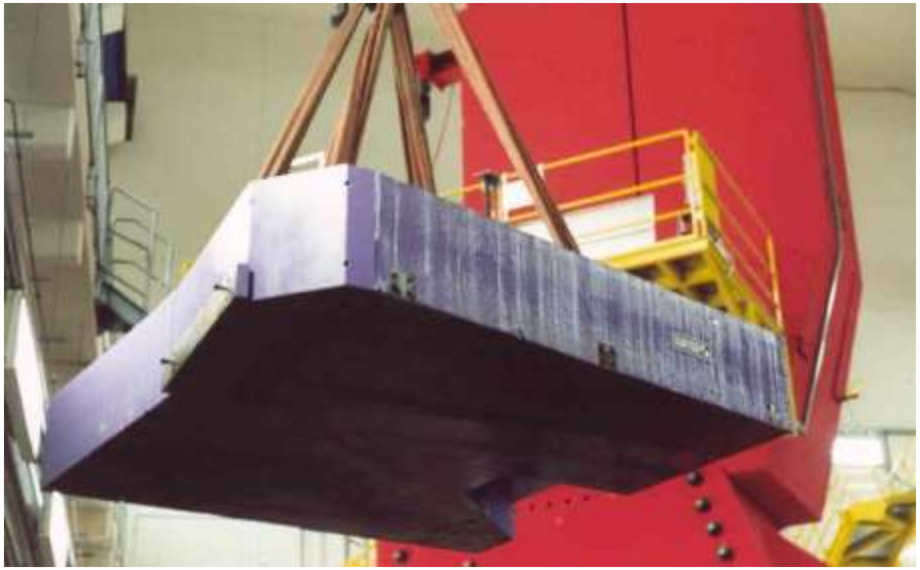
Queen, April 1984

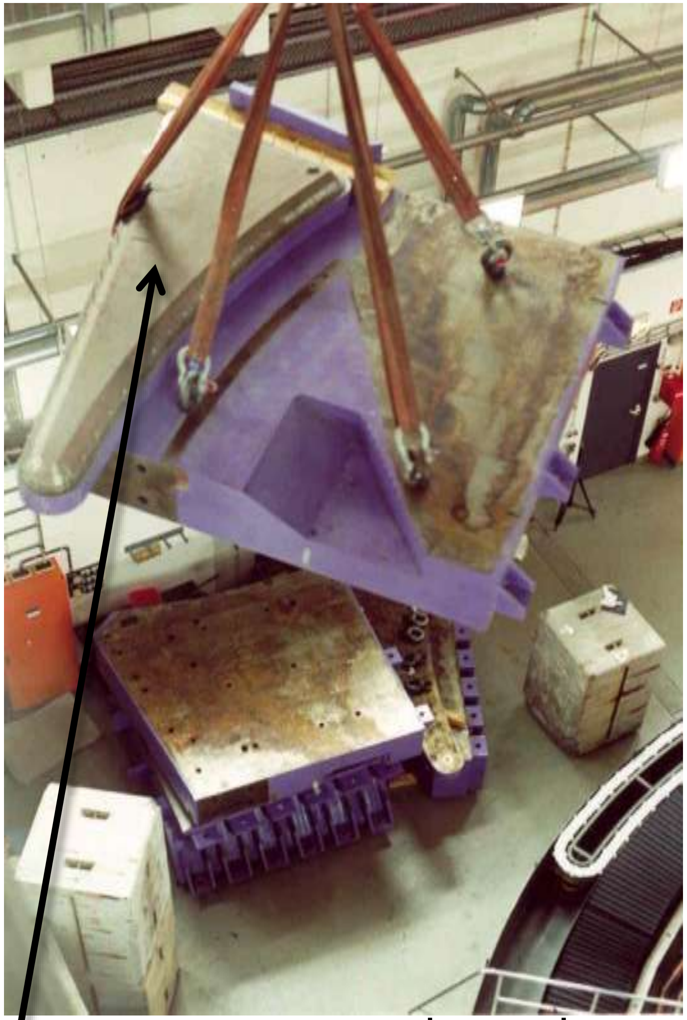


The »three« spectrometer facility at MAMI



Transport of KAOS to Mainz in June 2003

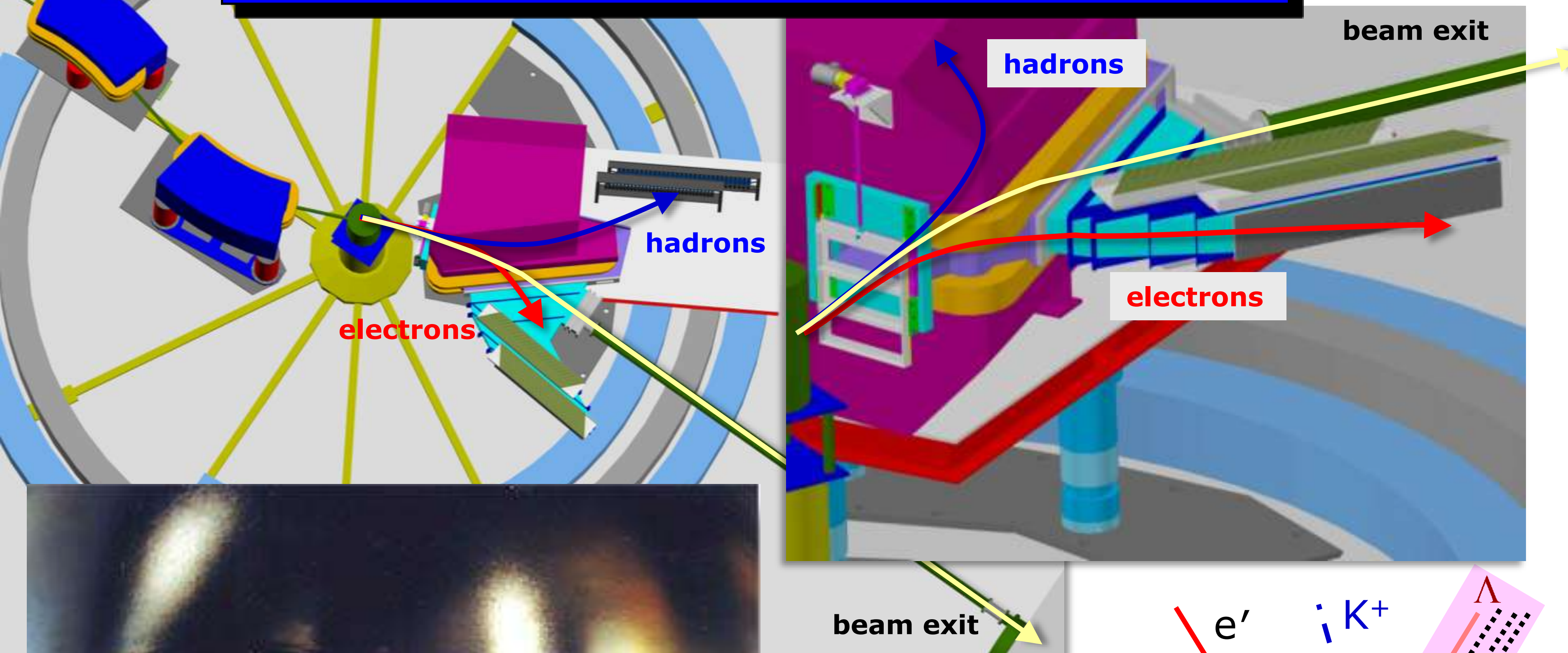


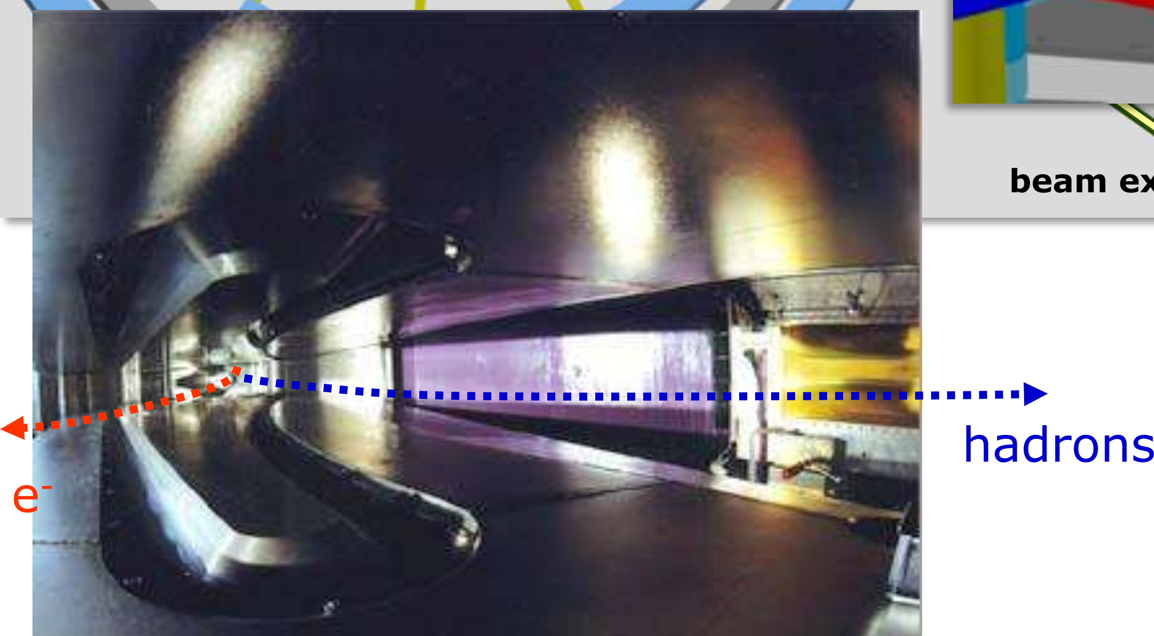


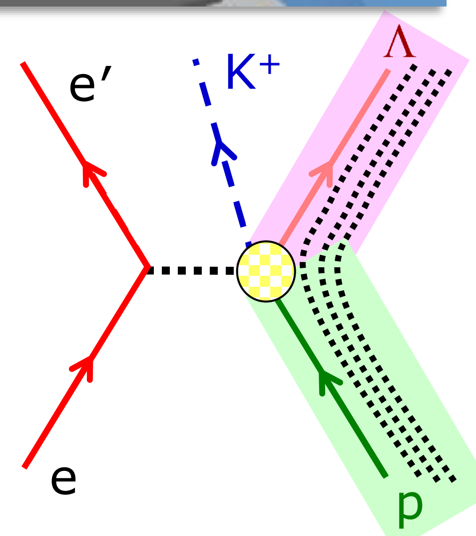
compact, open yoke and
extended pole face

⇒ use as double spectrometer

Two-arm spectrometer operation of KAOS



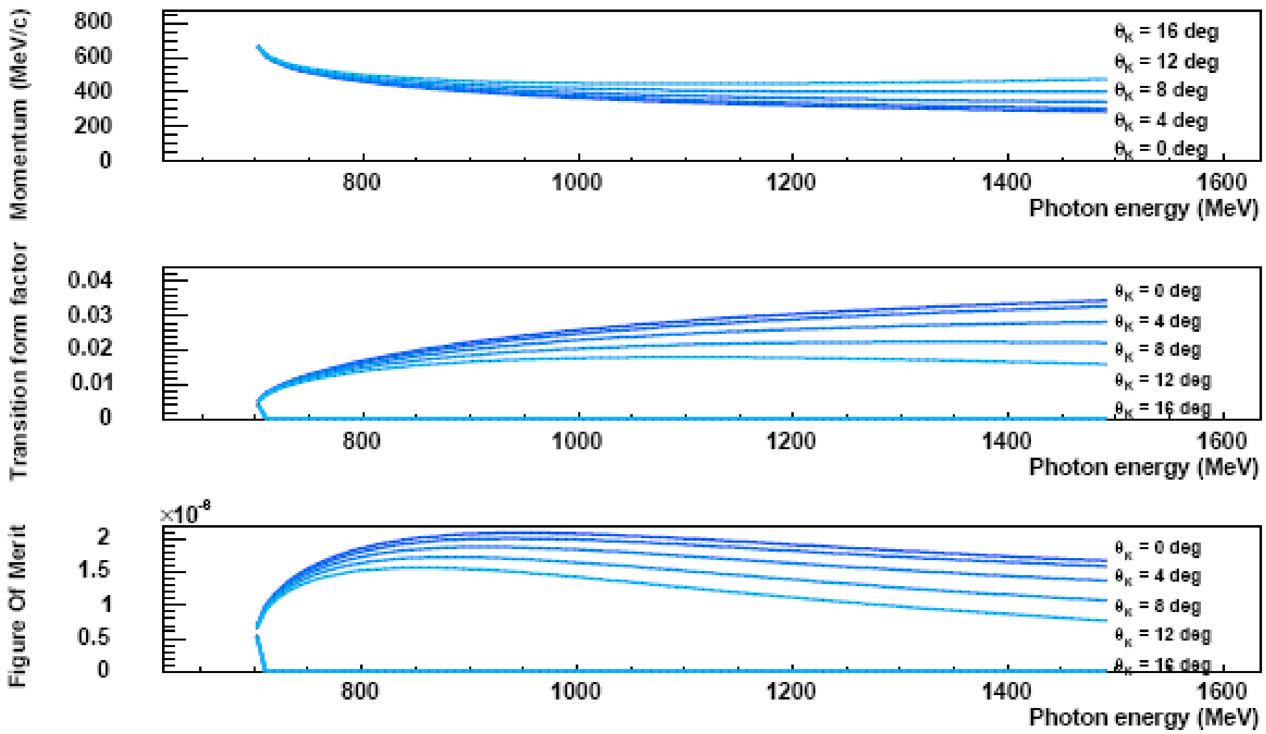




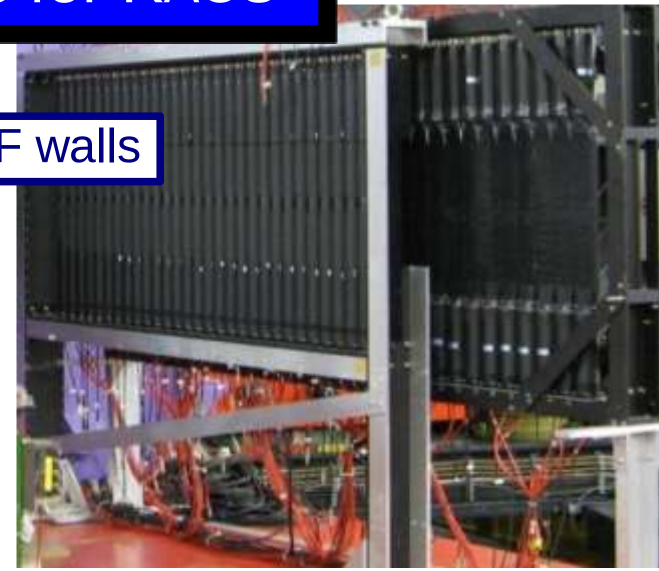
Kinematical optimisation of the formation rate

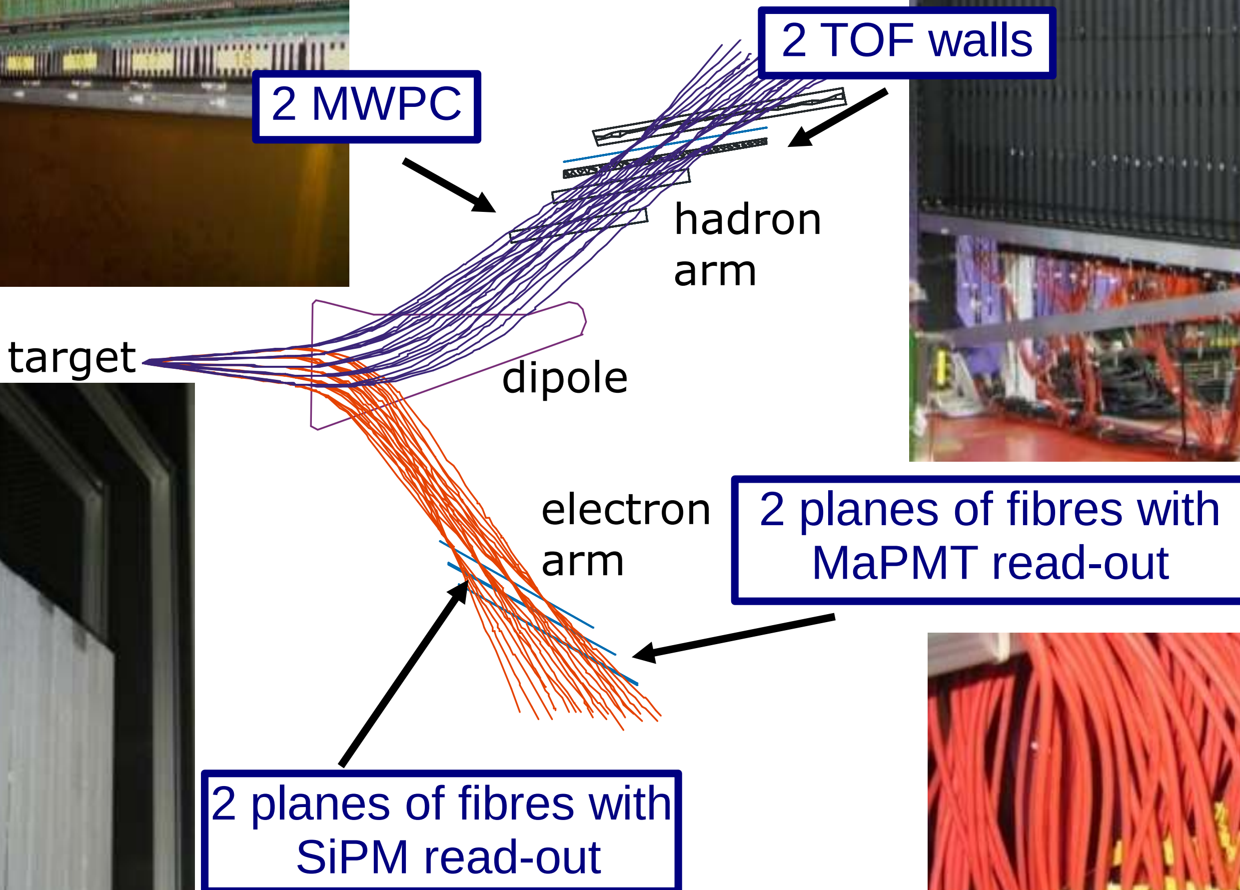
$$\text{FOM} = S_\Lambda \times \Gamma \quad \text{with} \quad \Gamma = \frac{\alpha}{2\pi^2}\frac{E'}{E}\frac{k_\gamma}{Q^2}\frac{1}{1-\epsilon}$$

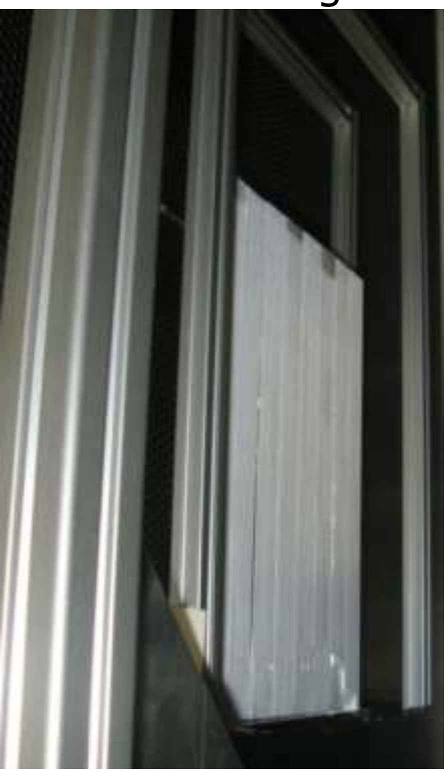
[$Q^2 = 0.01\,\text{GeV}^2/c^2$, $W = 11.995\,\text{GeV}$, $E = 1.50\,\text{GeV}$, $E' = 0.650\,\text{GeV}$, $\theta_e = 5.8°$, $p_K = 0.446\,\text{GeV}/c$, $p_Y = 0.423\,\text{GeV}/c$, and $\theta_K = 5.5°$]

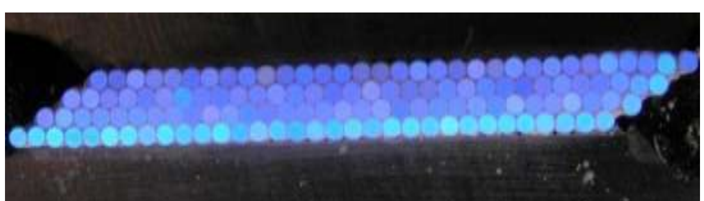


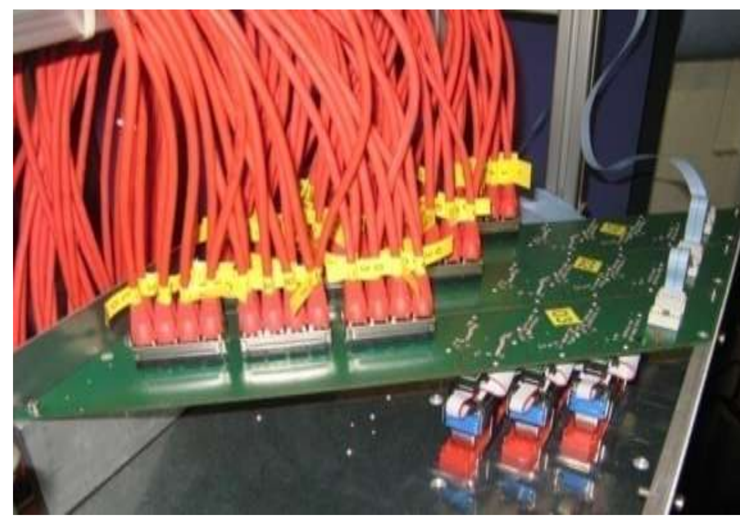
The detector packages for KAOS



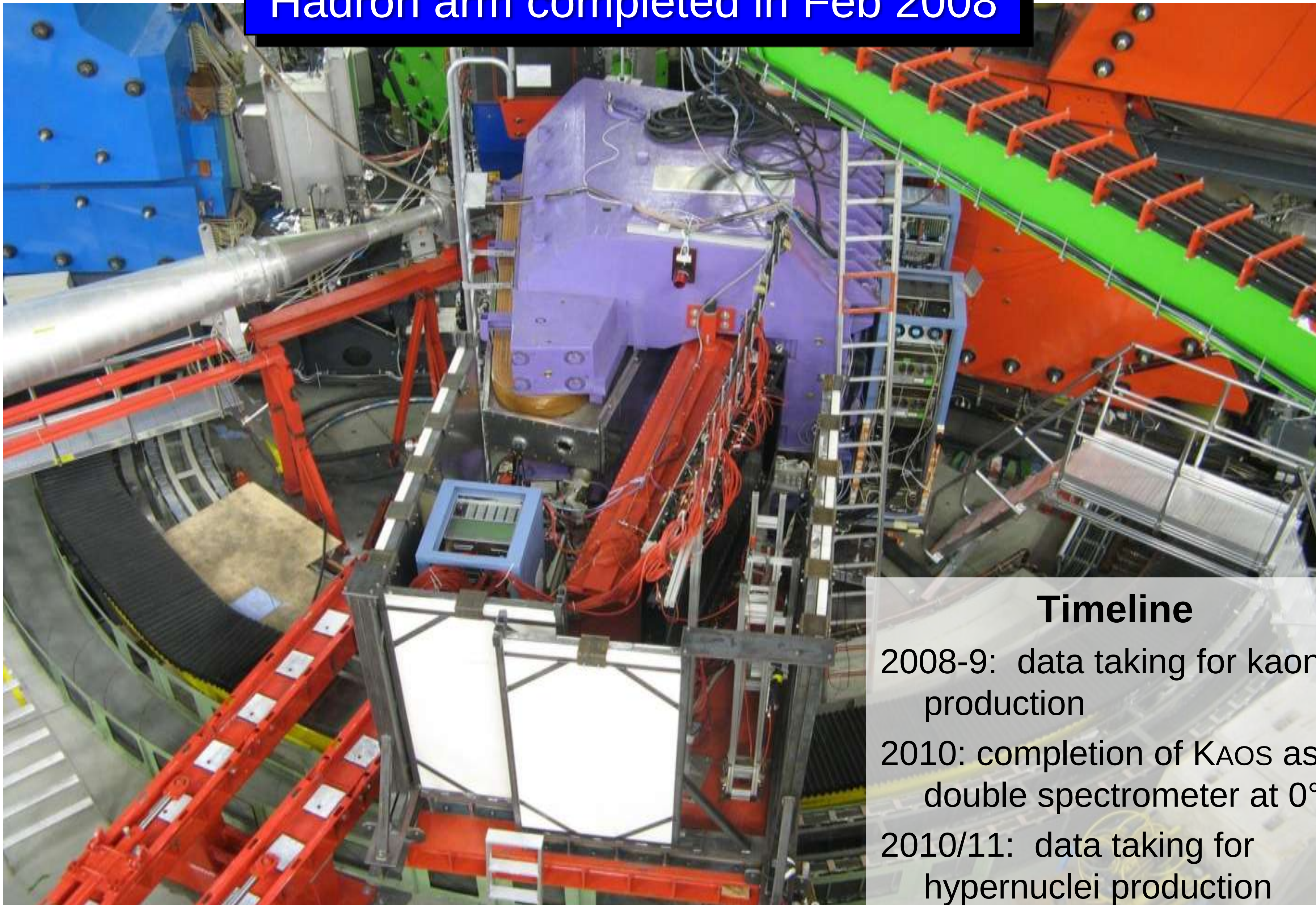








Hadron arm completed in Feb 2008



Timeline

2008-9: data taking for kaon production

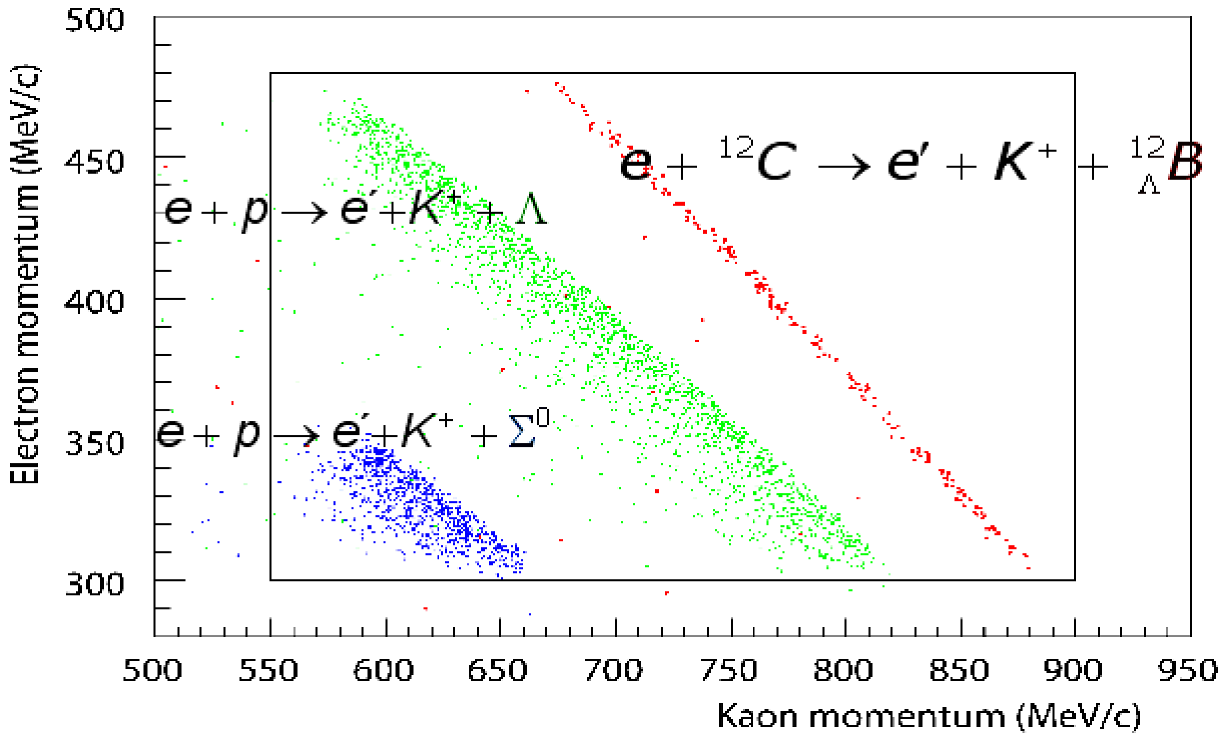
2010: completion of KAOS as double spectrometer at 0°

2010/11: data taking for hypernuclei production

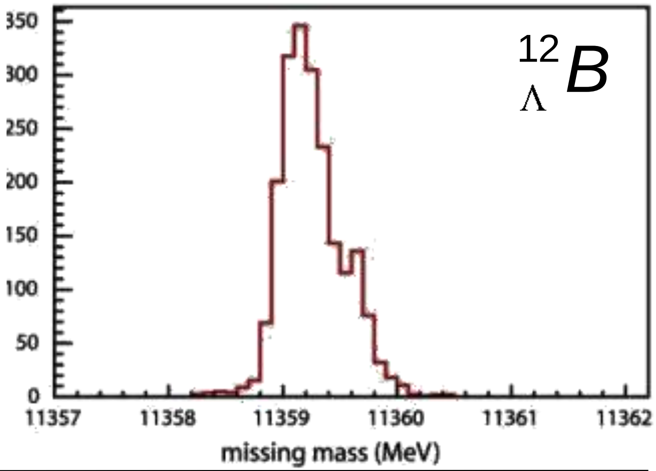
Challenges and prospects

special features of electro-production at MAMI-C (and JeffersonLab)

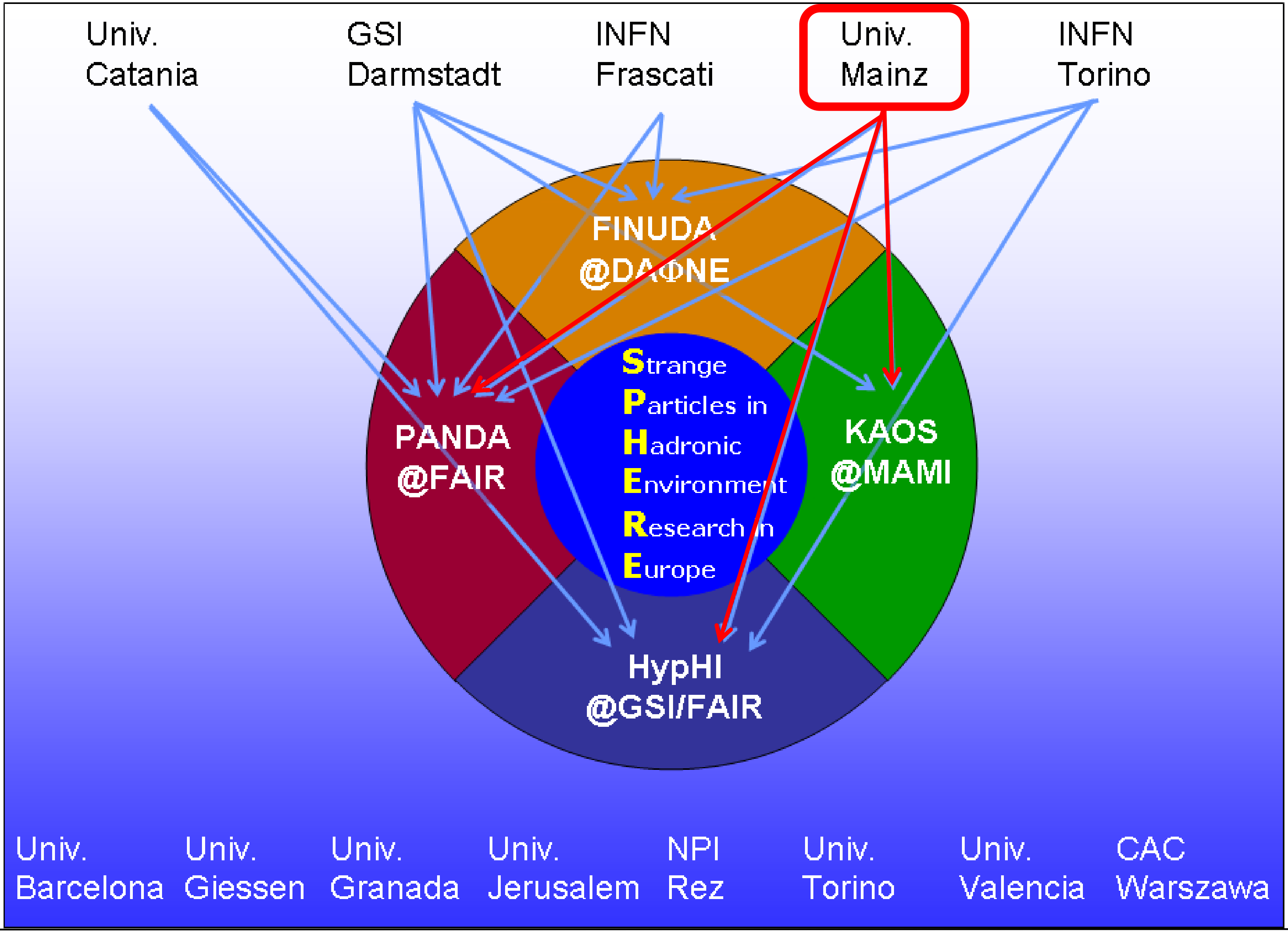
- better resolution compared to (π^+,K^+) or (K^-, π^-)
- access to new isotopes of hypernuclei (converting p into Λ)
- measurements at different kaon angles map out
  different parts of the Λ momentum distribution
- unique with KAOS: double spectroscopy in a single spectrometer



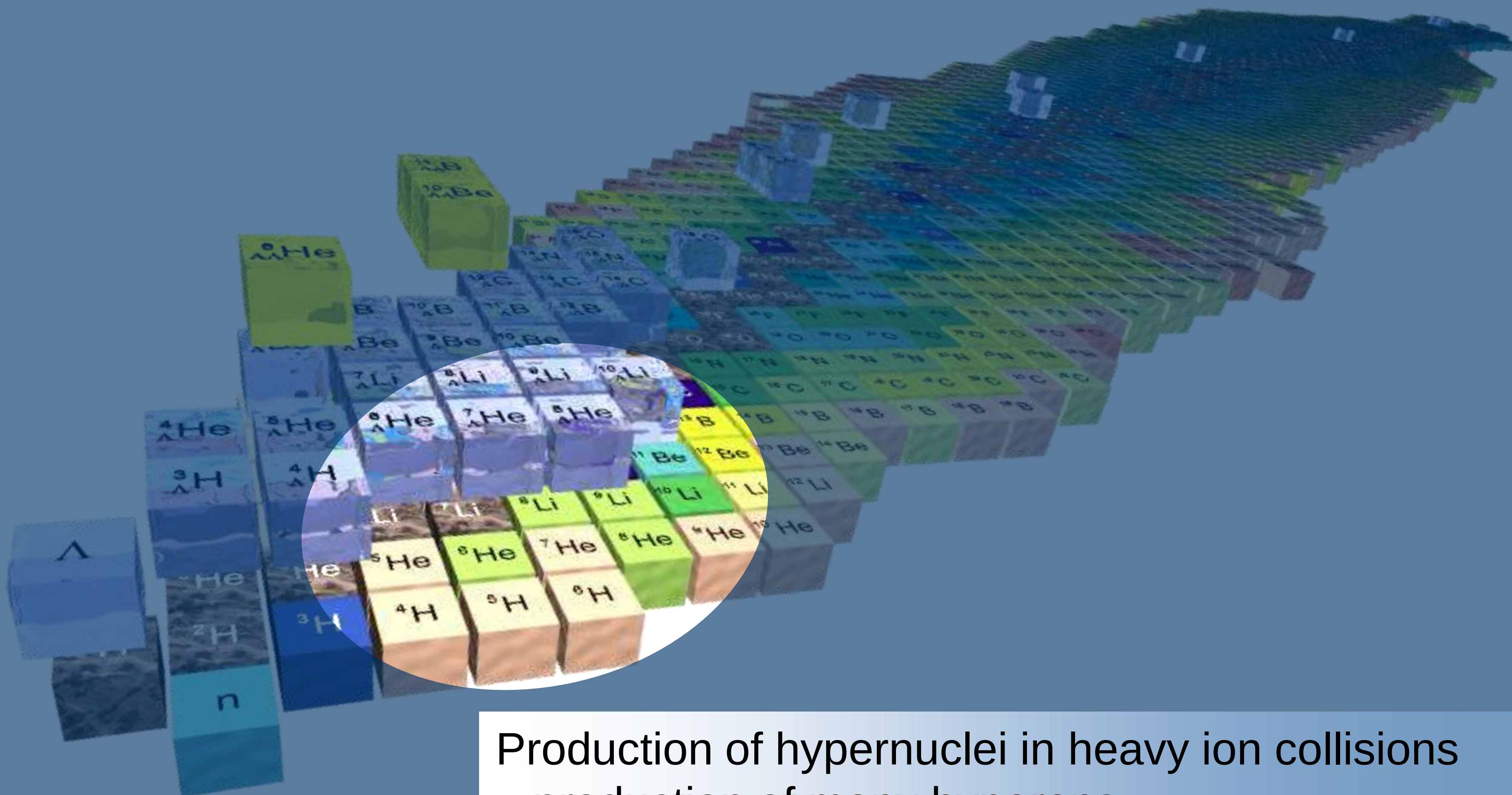
expected mass resolution:
σ_m = 275 keV



Networking Activity SPHERE (EU FP7 *HadronPhysics2*)

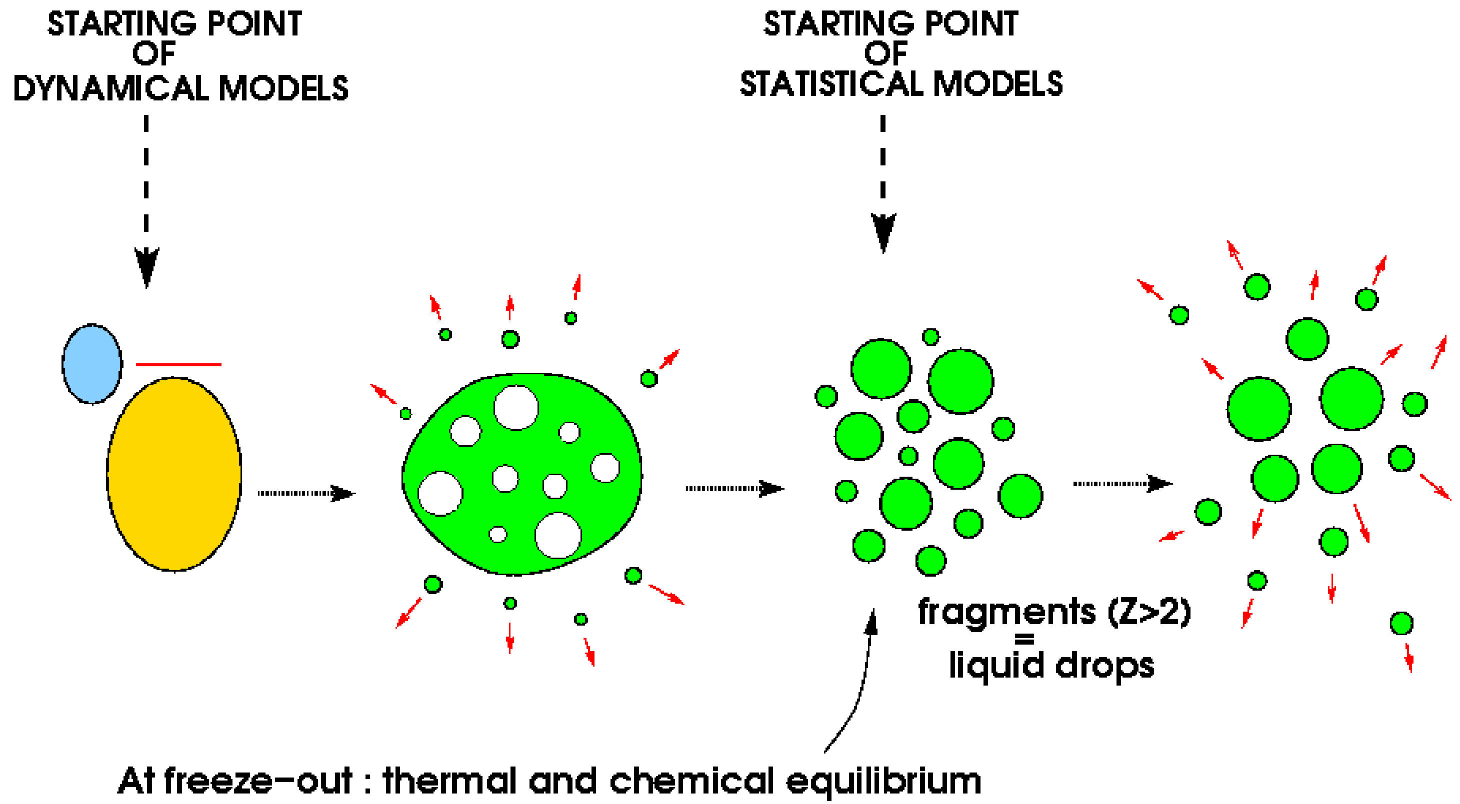


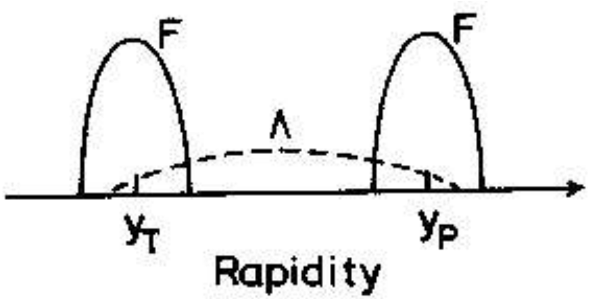
HypHI @ GSI/FAIR



Production of hypernuclei in heavy ion collisions
– production of many hyperons
– multiple coalescence of hyperons with fragments
– (π,K), (K, π) and (K^-,K^+) reactions on fragments

HypHI @ GSI/FAIR





Production of hypernuclei in relativistic heavy ion collisions

–production of many hyperons

–multiple coalescence of hyperons with fragments

–(π,K), (K, π) and (K^-,K^+) reactions on fragments

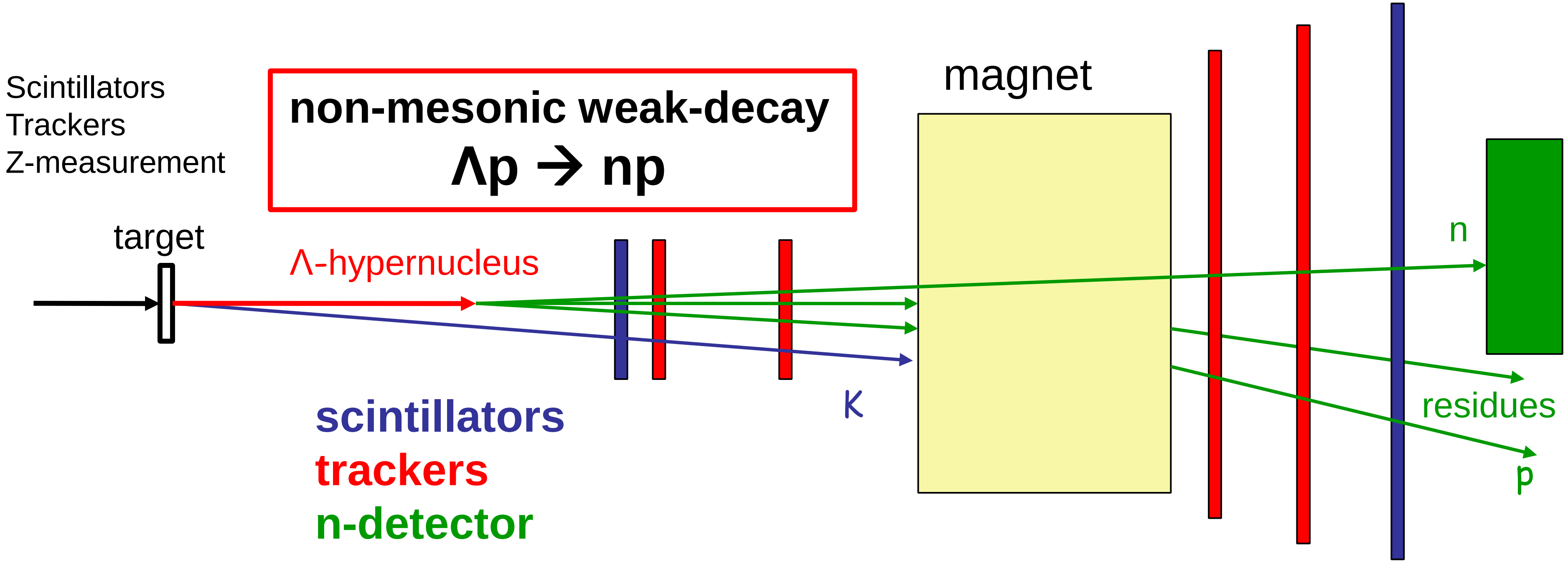
Concept of the HypHI experiment

Produced hypernucleus at similar velocity as projectiles

large Lorentz factor: $\gamma > 3$: life-time 200 ps → ~600 ps

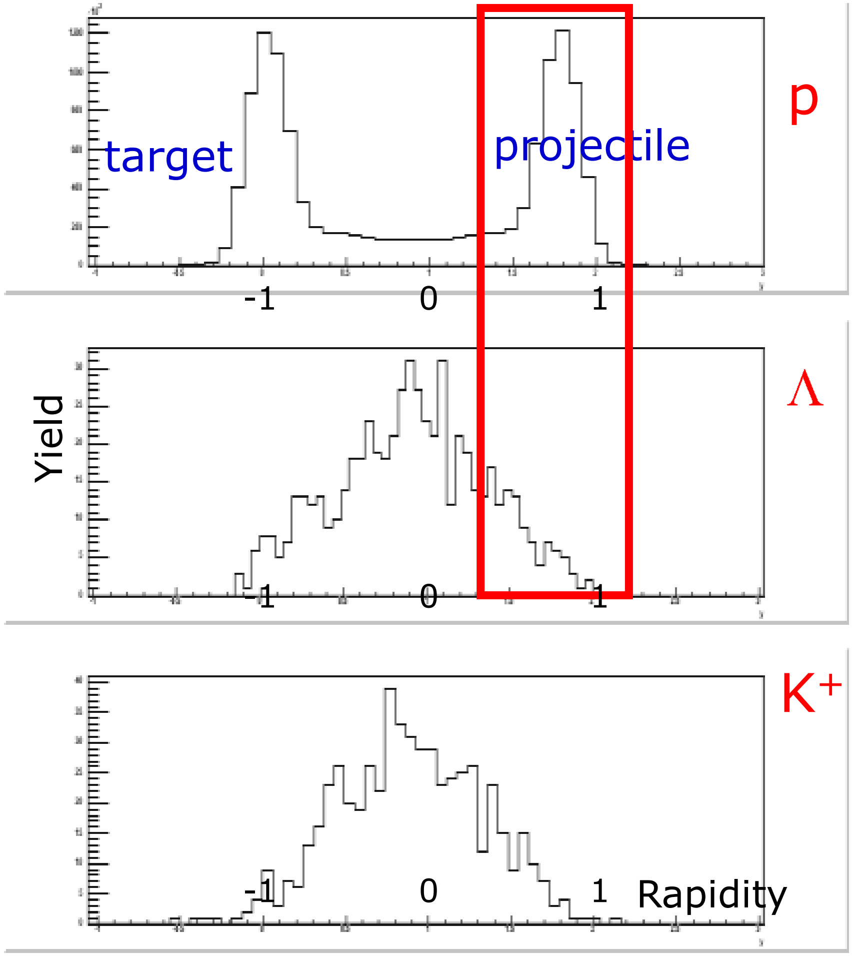
hypernuclear decay in flight

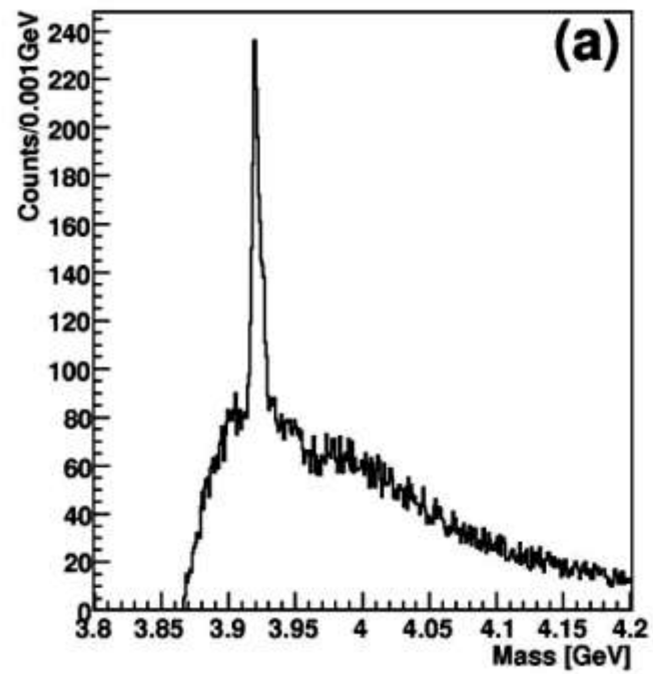
Example : $^{12}C + {}^{12}C \rightarrow {}^{A}_{\Lambda}Z + K^{+,0} + X$



Monte Carlo simulations

	Expected cross section [μb]	Reconstructed events /week
${}^{3}_{\Lambda}$H	0.1	2.8×10^3
${}^{4}_{\Lambda}$H	0.1	2.6×10^3
${}^{5}_{\Lambda}$He	0.5	6.5×10^3





Scintillating fibre detectors

- fibre diameter: 0.83 mm
- HAMAMATSU H7260KS
- X and Y tracking with resolution of ~ 0.5 mm
- discriminator cards (1400 ch) from Kaos
- energy readout by CAEN QDC for TR0
- time readout by VUPROM 2

HypHI phases

Design study, preparation for the phase 0 experiment

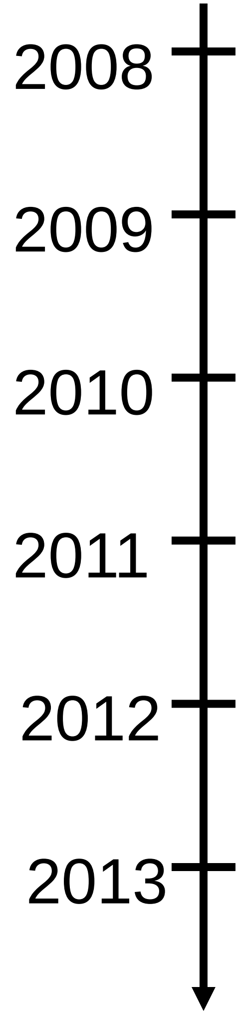
Phase 0: experiment with ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H and ${}^{5}_{\Lambda}$He

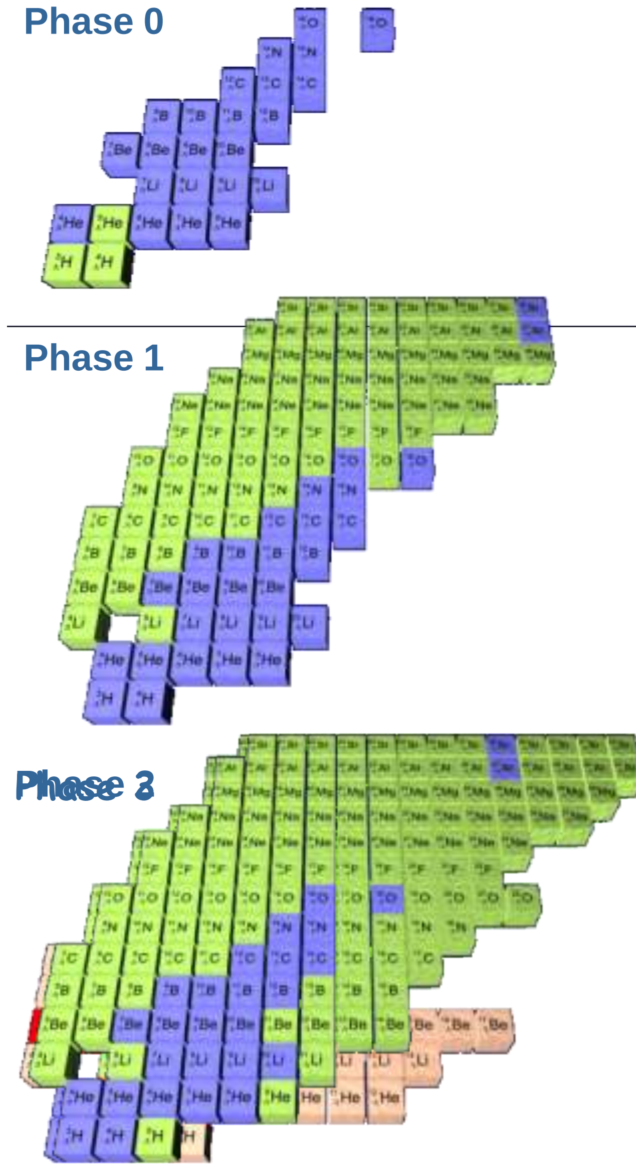
Phase 1: Experiments with proton rich hypernuclei

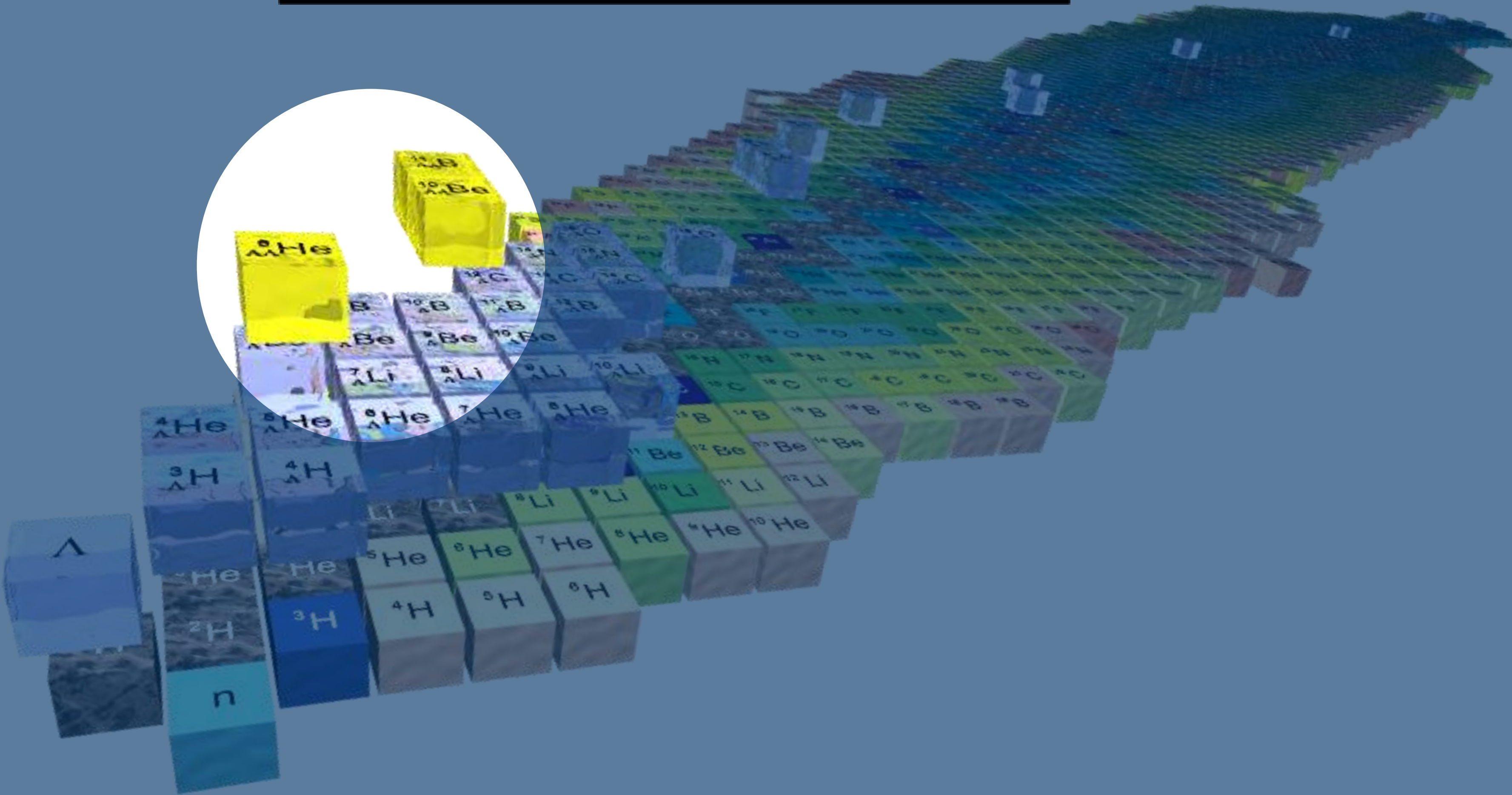
Phase 2: Experiment with neutron rich hypernuclei at NuSTAR/FAIR

Phase 3: Hypernuclear separator

- hypernuclear magnetic moments
- hypernuclear driplines





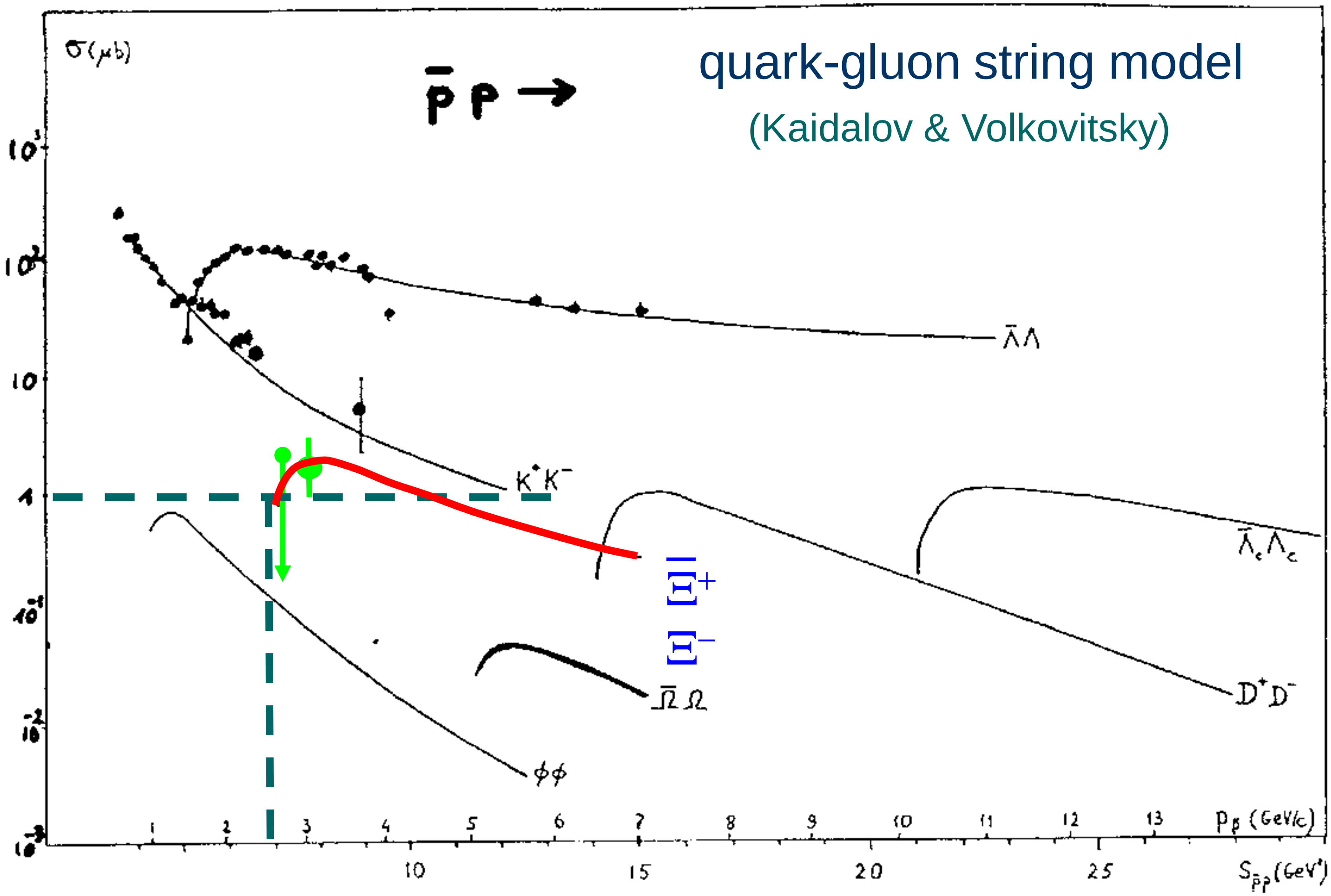


anti-proton beam induced hypernuclei production:

- high resolution γ-spectroscopy of double ΛΛ hypernuclei
- weak decays

General Idea

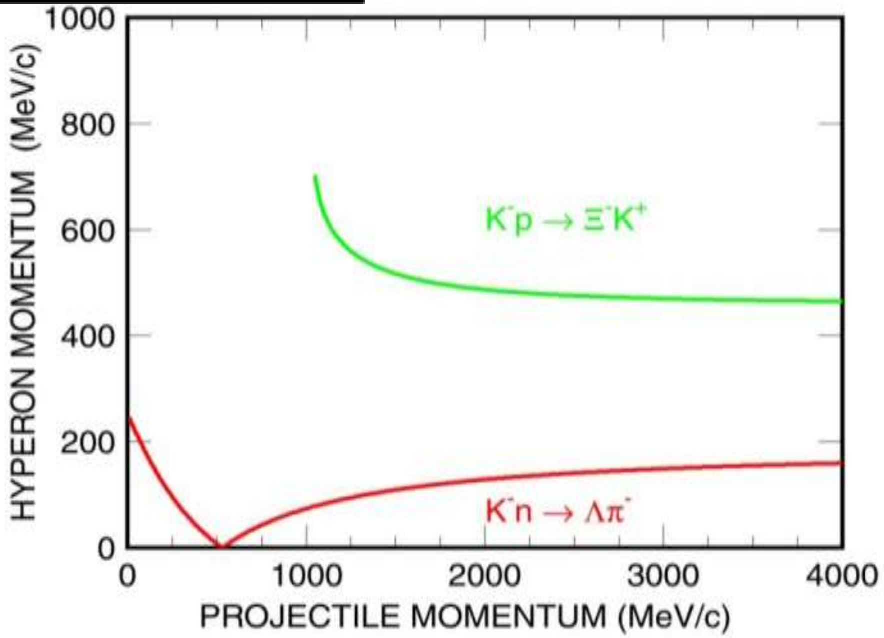
Use p$\bar{p}$ Interaction to produce a hyperons which are tagged by the anti-hyperon or its decay products



Double hypernuclei with kaons

Indirect reaction (quasi-free in nucleus):

$K^- + p \rightarrow K^+ + \Xi^-$



p(K^-) ≈ 1.8 (1.66) GeV/*c* → p(K^+, Ξ^-) ≈ 1.3, 0.5 (1.15, 0.5) GeV/*c* (forward)

Direct reactions:

$K^- + {}^AZ \rightarrow p(K^-,K^+)\Xi^- \rightarrow$ *rescattering in nucleus* $\rightarrow K^+ + {}^A_{\Xi}(Z-1)$

$\sigma(\theta=0) \approx 3.5\ \mu b/sr$ (Dover & Gal)
p(K^-) ≈ 1.8 (1.66) GeV/*c* → p(K^+) ≈ 1.39 (1.24) GeV/*c* (forward)

$K^- + {}^AZ \rightarrow$ *through* $\pi^0 + {}^A_{\Lambda}(Z-1) \rightarrow K^+ + {}^A_{\Lambda\Lambda}(Z-2)$

$\sigma(\theta) \approx 10$ nb/sr (May)
p(K^-) ≈ 1.8(1.66) GeV/*c* → p(K^+) ≈ 1.42 (1.28) GeV/*c* (forward)

Double hypernuclei with antiprotons

Indirect reaction:

$\bar{p}$ (3 GeV/c) + N → $\bar{\Xi}$ + Ξ^-

(PANDA)

Two-step process in one nucleus:

$\bar{p}$ *(low p)* + N → K* + $\bar{K}$ *

K* + N′ → $\bar{K}$ + Ξ^- *(≈ at rest)*

(FLAIR)

Recoilless production:

$\bar{p}$ (>15 GeV/c) + N → $\bar{\Xi}$ + Ξ^-

Formation of double hypernuclei from Xi hyperons

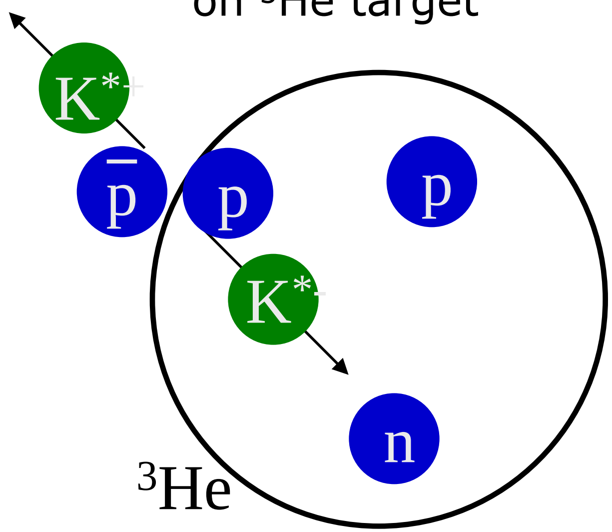
1. $dE(\Xi^-)/dx$ → stop + capture
2. hyperatom + atomic decay
3. capture in nucleus $({}^{A'}_{\Xi}Z')$
4. conversion: $\Xi^- + p \rightarrow \Lambda\Lambda + 28MeV$
5. double hypernucleus $({}^{A'}_{\Lambda\Lambda}Z')$

Production mechanism at FLAIR

[original idea K. Kilian 1987]

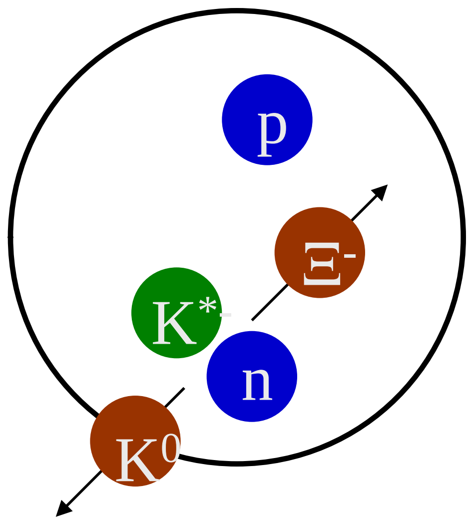
step 1: $\bar{p}$ (p n p) → K^{*-} K^{*+}

large $\bar{p}$ stopping rate on ^{3}He target



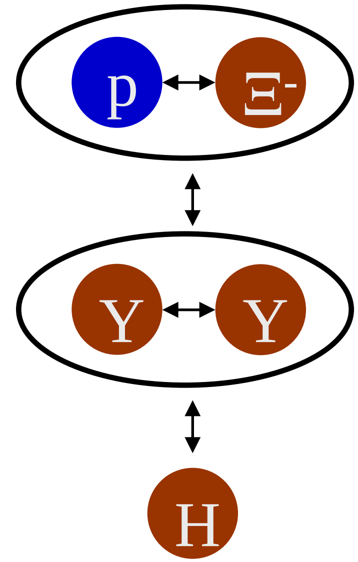
step 2: K^{*-} (n p) → Ξ^{-} K^{0}

very low recoil on Ξ^{-}
(recoil free kinematics)

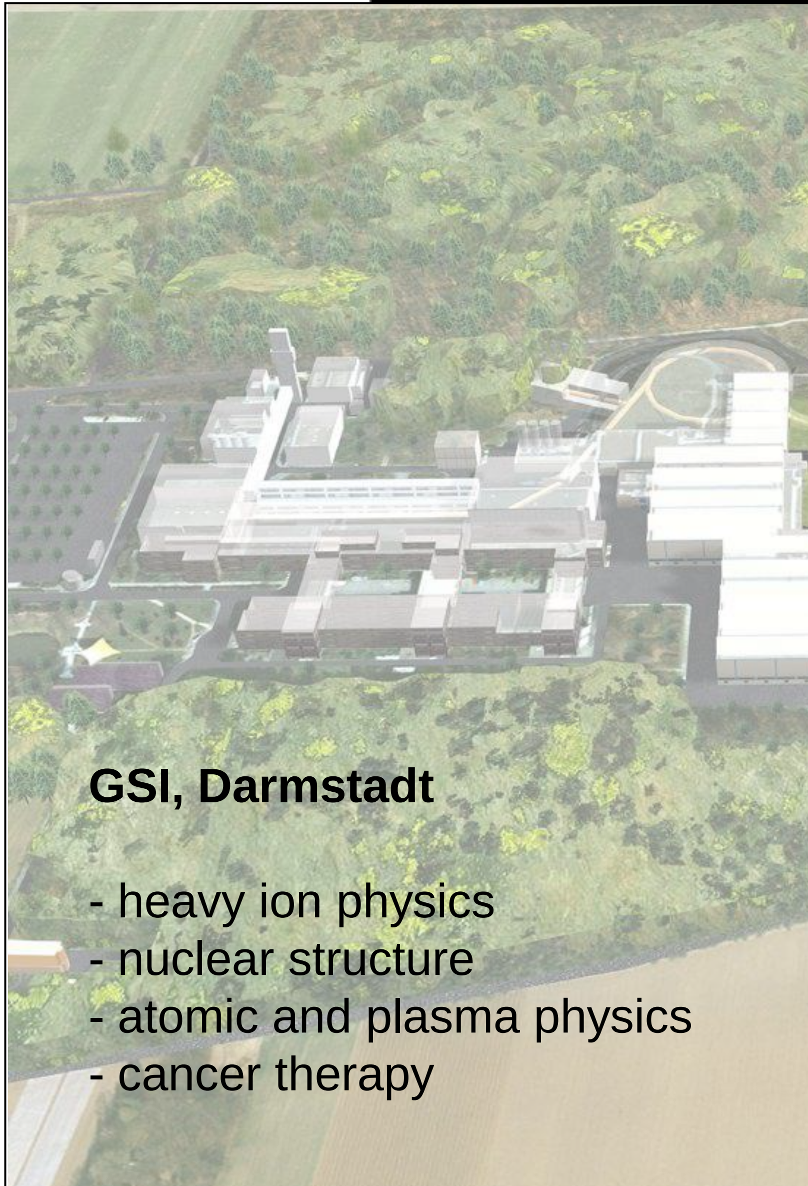


S= -2 state

low relative energy

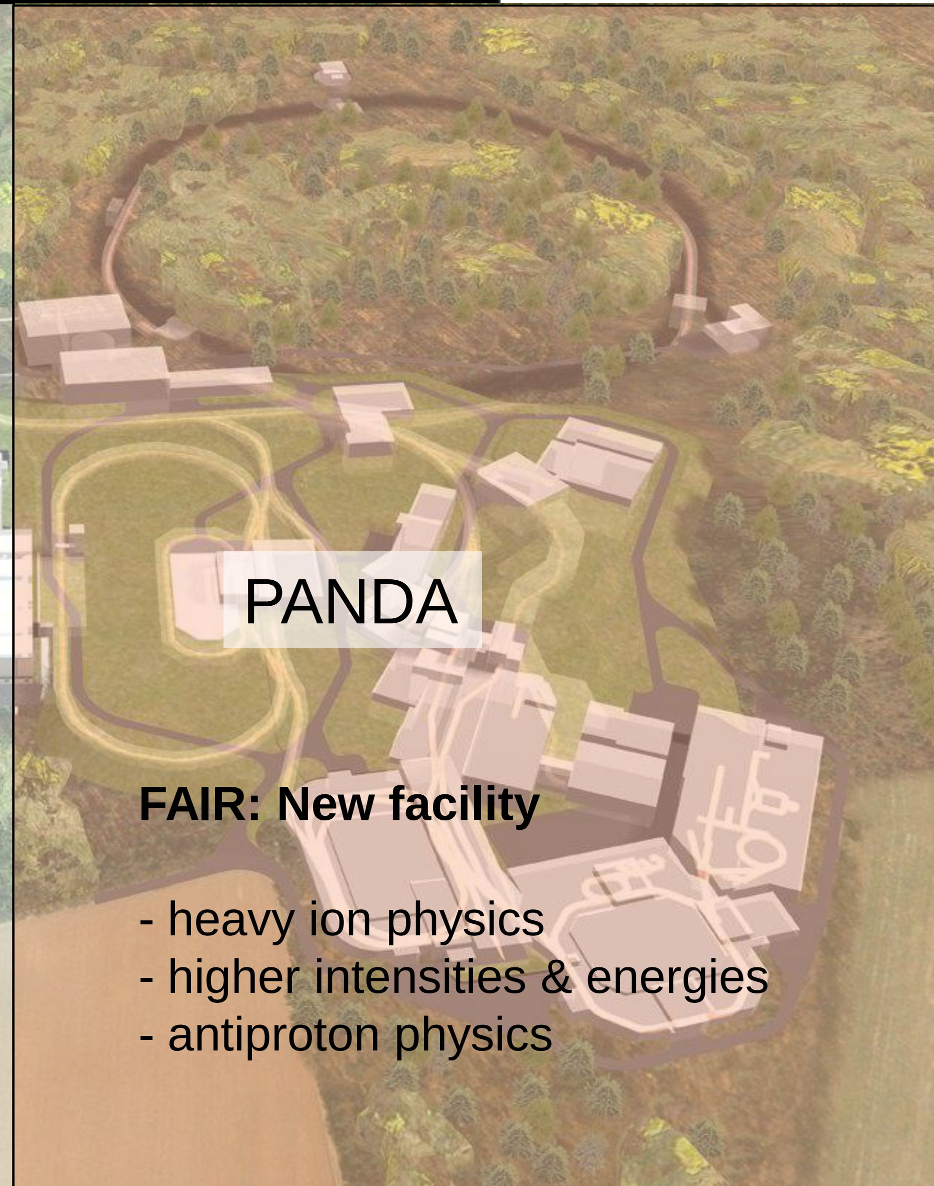


GSI and FAIR facilities



GSI, Darmstadt

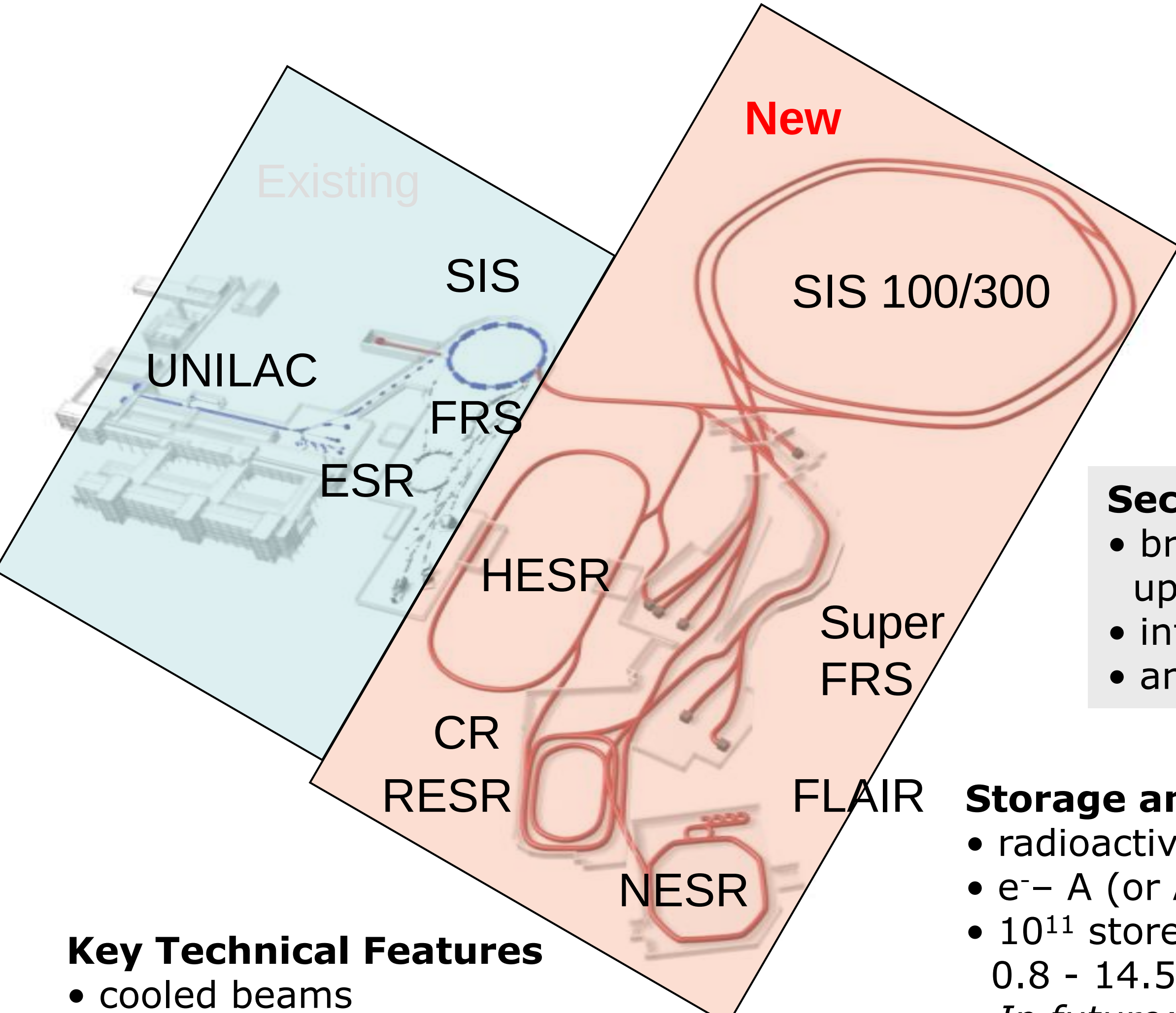
- heavy ion physics
- nuclear structure
- atomic and plasma physics
- cancer therapy



FAIR: New facility

- heavy ion physics
- higher intensities & energies
- antiproton physics

FAIR facilities



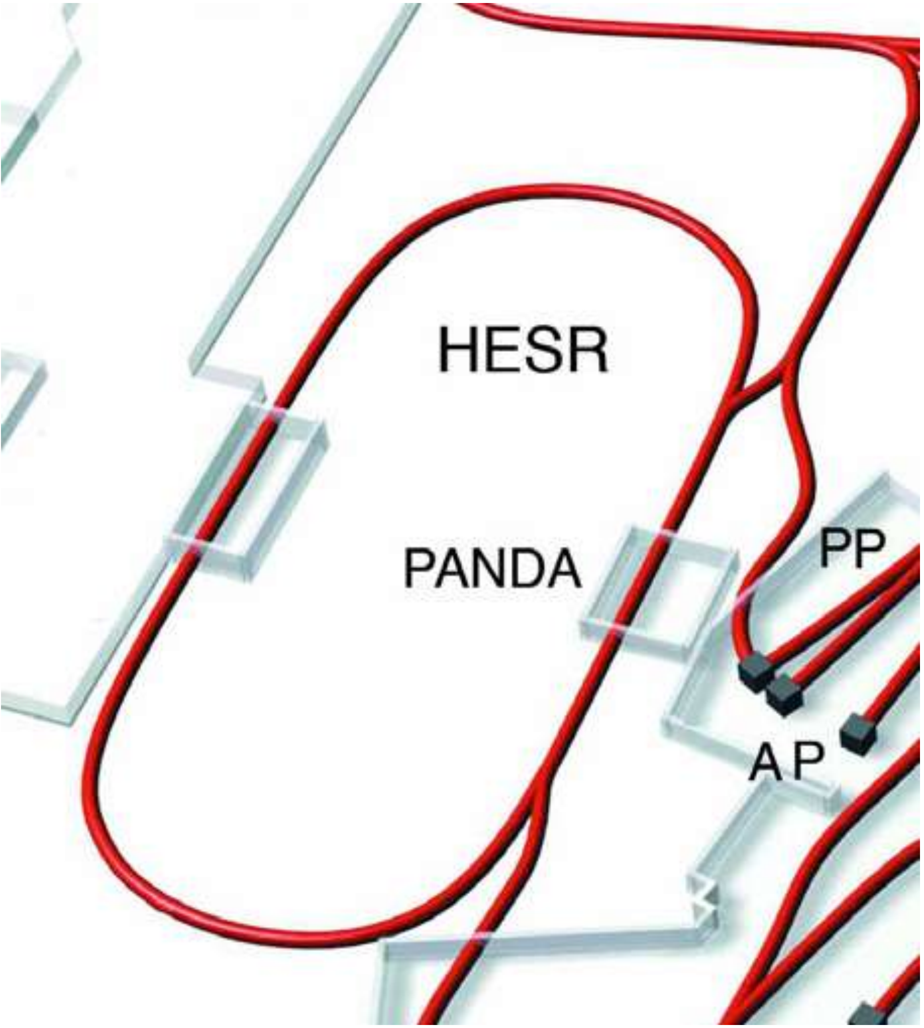
Primary Beams
- **238U^{28+}** : 10^{12}/s @ 1.5-2 AGeV;
- **238U^{92+}**: 10^{10}/s @ up to 35 AGeV
- **Protons** : 2 x10^{13}/s @ 30 GeV; up to 90 GeV
- 100-1000 times present intensity

Secondary Beams
- broad range of radioactive beams up to 1.5 - 2 AGeV
- intensity up to 10 000x over present
- antiprotons 0 - 15 GeV

Storage and Cooler Rings
- radioactive beams
- e^-– A (or Antiproton-A) collider
- 10^{11} stored and cooled antiprotons 0.8 - 14.5 GeV/c
- *In future:* polarized antiprotons (?)

Key Technical Features
- cooled beams
- rapidly cycling superconducting magnets
- parallel operation

High Energy Storage Ring



H E S R Performance

Racetrack shaped ring: 574 m length

Luminosity/Intensity:

- Pbar production rate: $2x10^7$ /s
- High luminosity mode: L = $2x10^{32}$ $cm^{-2}s^{-1}$
- High resolution mode: L = $2x10^{31}$ $cm^{-2}s^{-1}$ (for target thickness $4x10^{15}$ $atoms/cm^2$)

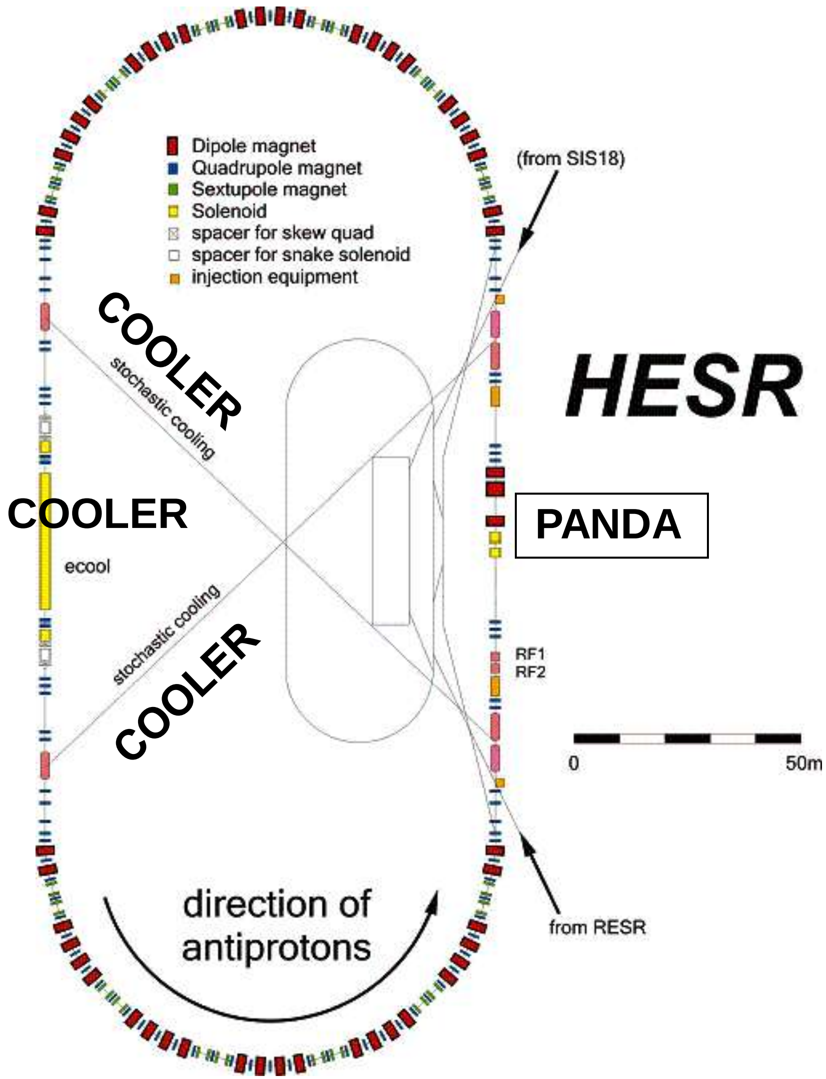
Momentum range:

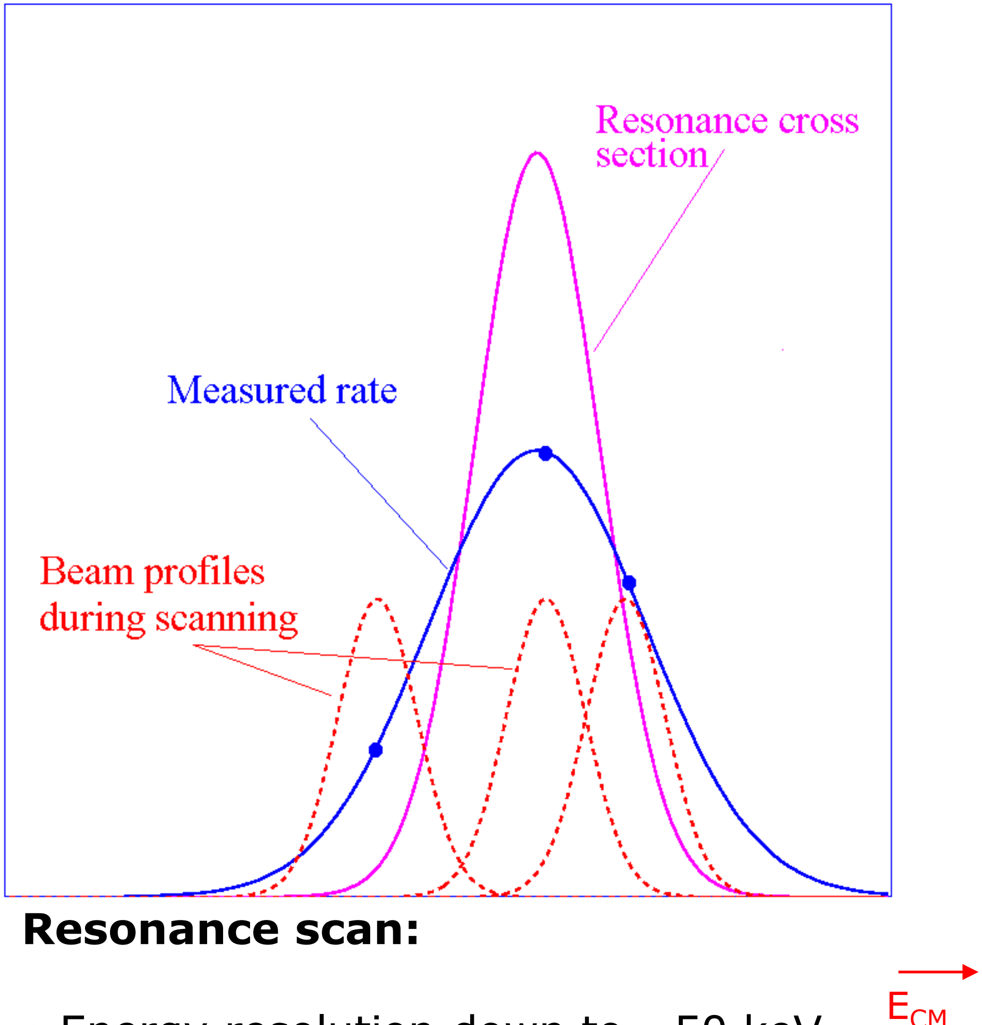
- 1.5 – 15 GeV/c (0.831- 14.1 GeV)
- Revolution frequency: $5x10^5$ Hz

Momentum resolution:

- High luminosity mode: $\Delta p/p=10^{-4}$ (stochastic cooling above 3.8 GeV/c)
- High resolution mode: $\Delta p/p=10^{-5}$ (electron cooling)

Beam cooling in HESR

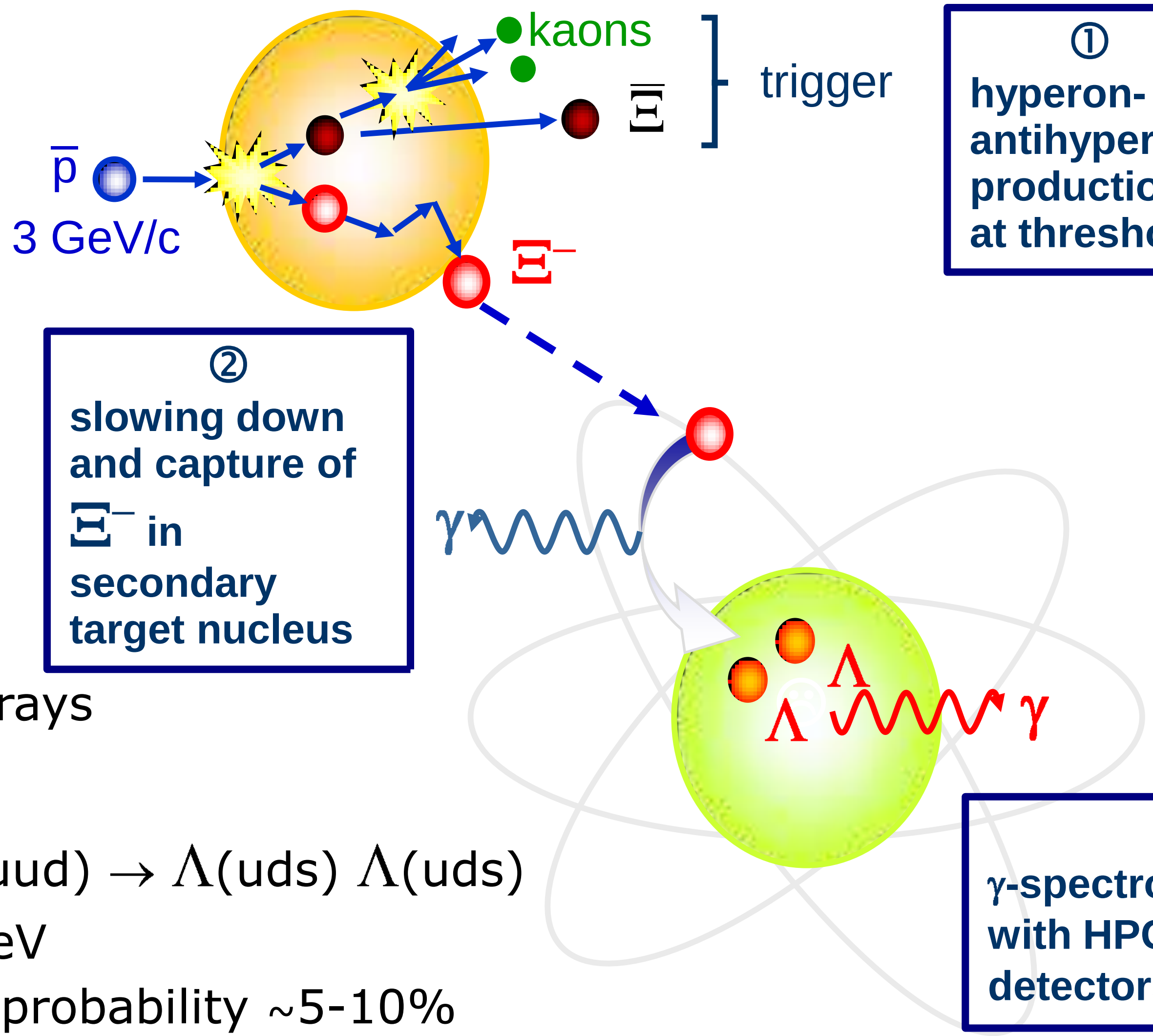




Resonance scan:

- Energy resolution down to ~50 keV
- Tune E_{CM} to probe resonance
- Get precise mass and width

Production mechanism at PANDA



① hyperon-antihyperon production at threshold

② slowing down and capture of Ξ^- in secondary target nucleus

③ γ-spectroscopy with HPGe detectors

- Ξ^- atoms: x-rays
- conversion:

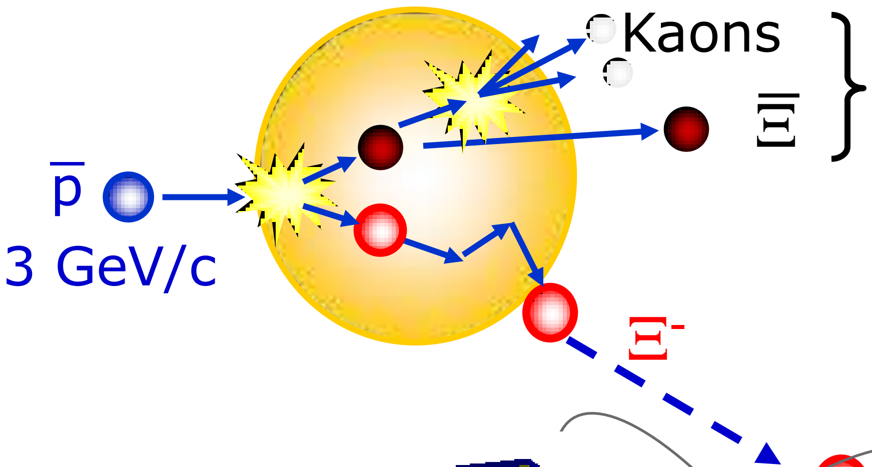
  Ξ^-(dss) p(uud) → Λ(uds) Λ(uds)

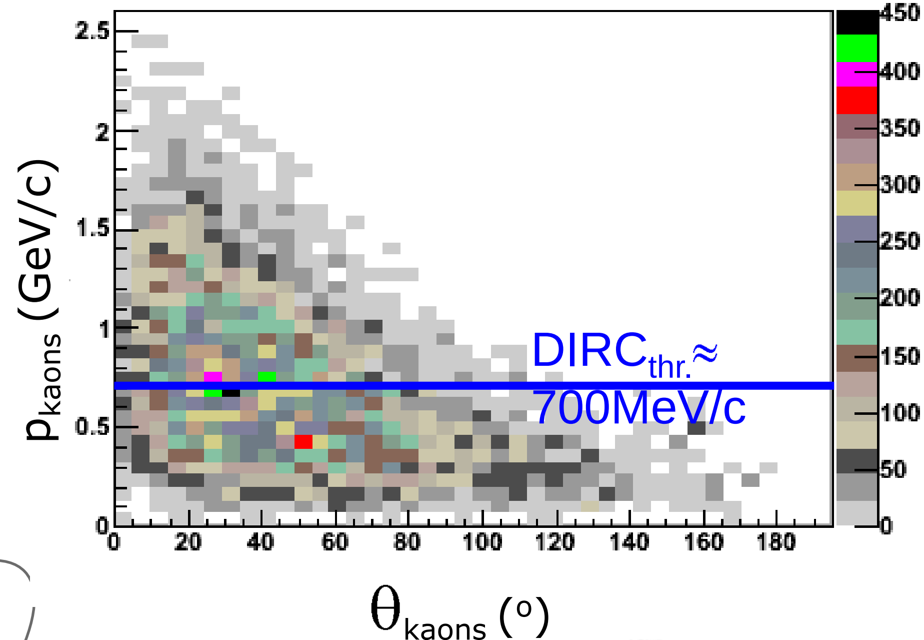
  ΔQ = 28 MeV

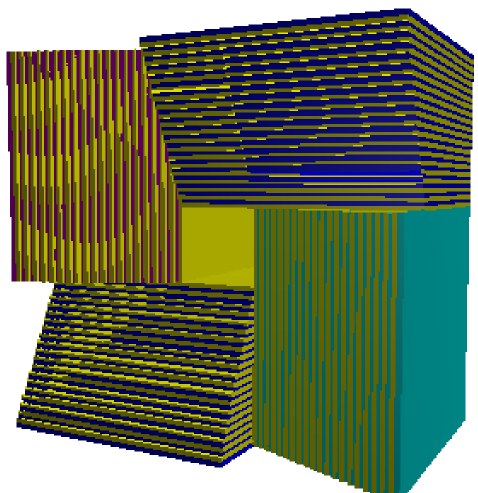
  conversion probability ~5-10%

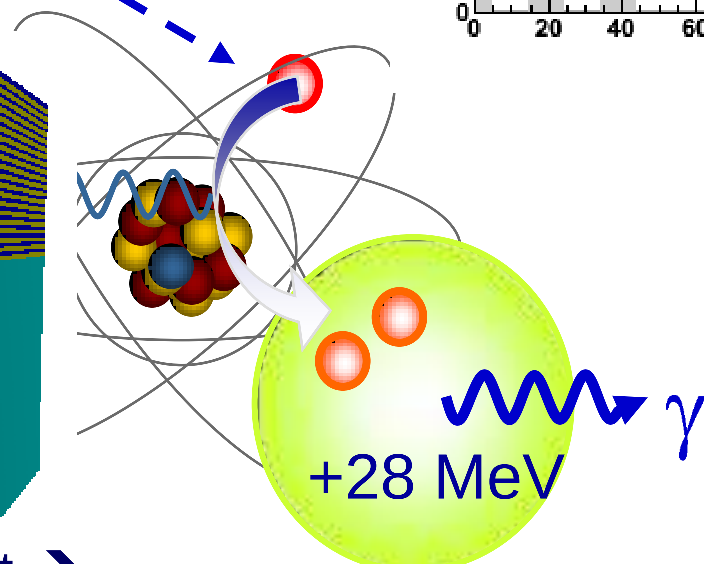
[Y. Hirate et al., Nucl. Phys. **A639**, 389c (1998),
Y. Hirate et al., Prog. Theor. Phys. **102**, 89 (1999)]

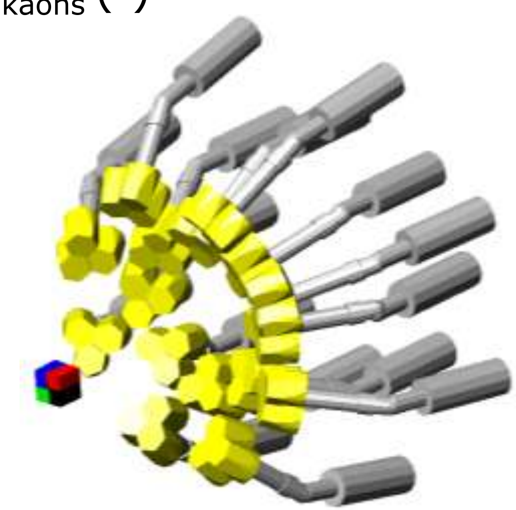
Detection and triggering







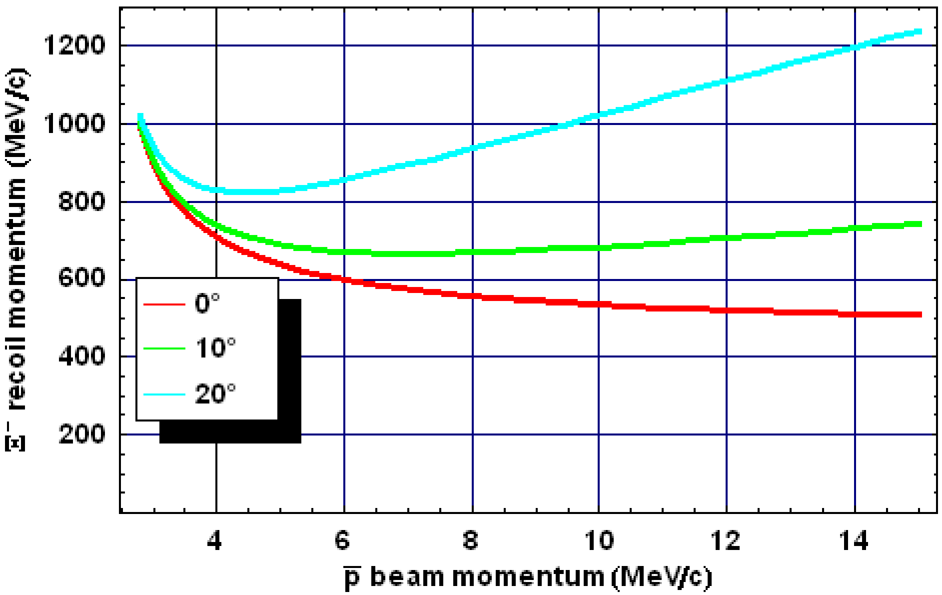


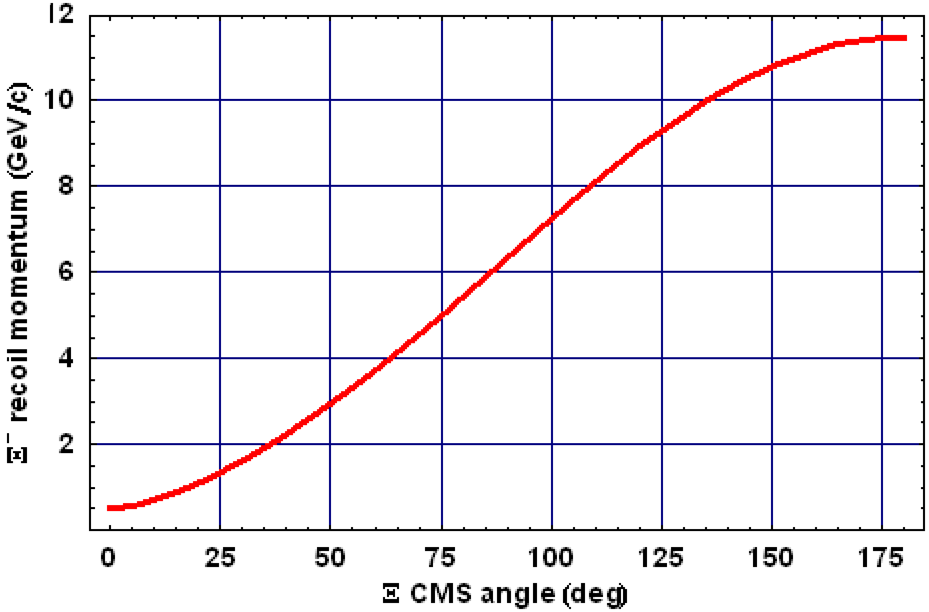


Active secondary target ➔ radiation hard material

EU FP6 HadronPhysics project

Recoil momentum in hyperon production

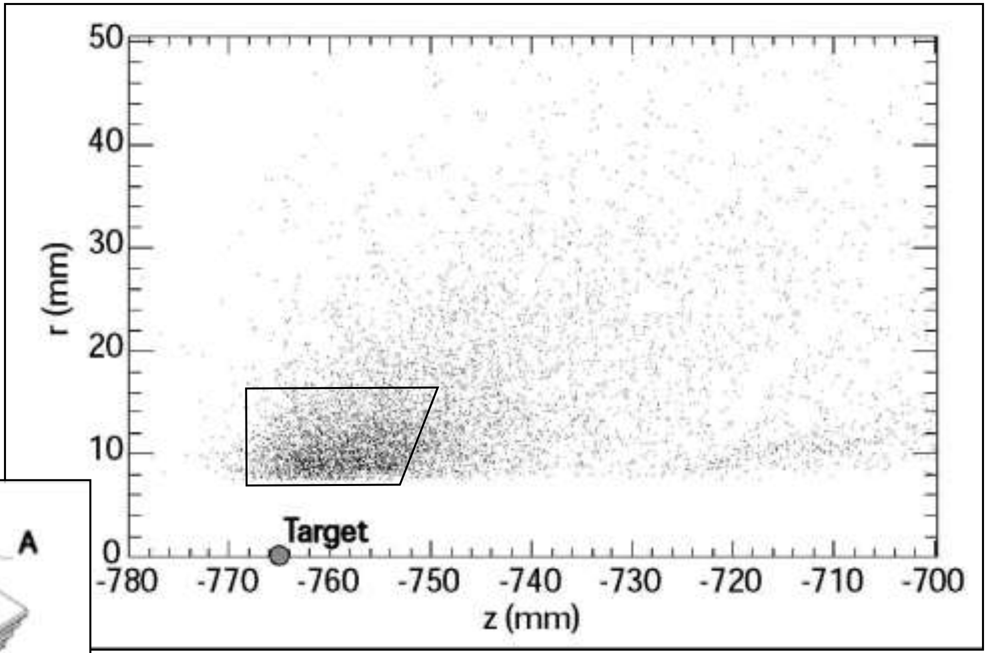




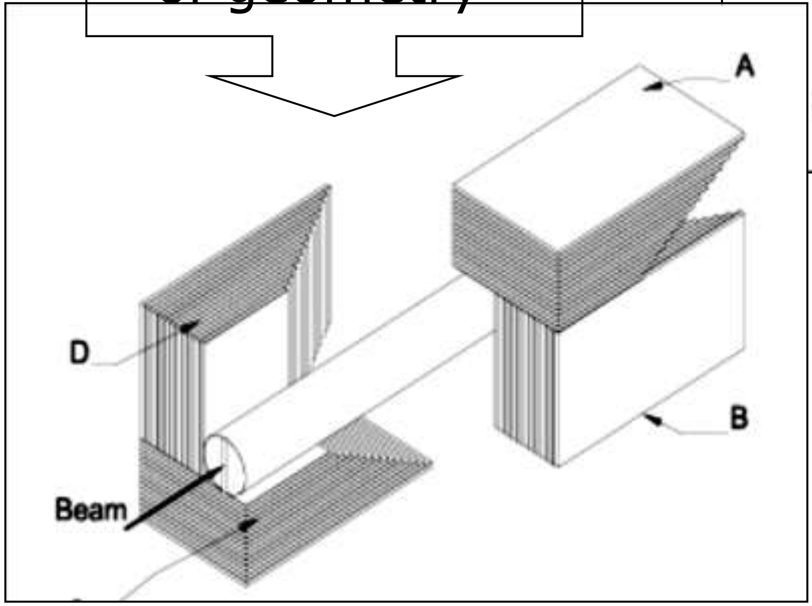
Application to target design

First step:

stop Ξ^- particles in nuclear targets



optimization of geometry

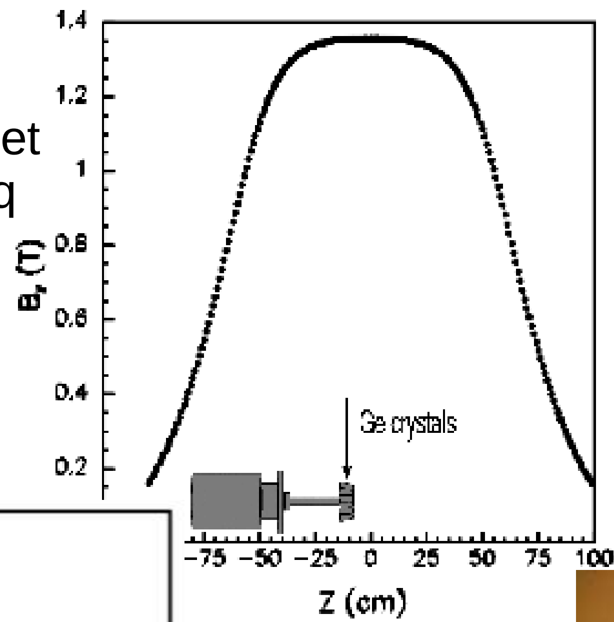


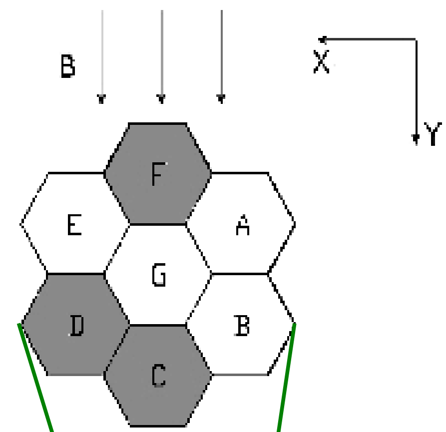
stopping points concentrated between 40° and 90° in a radial thickness of 20 mm

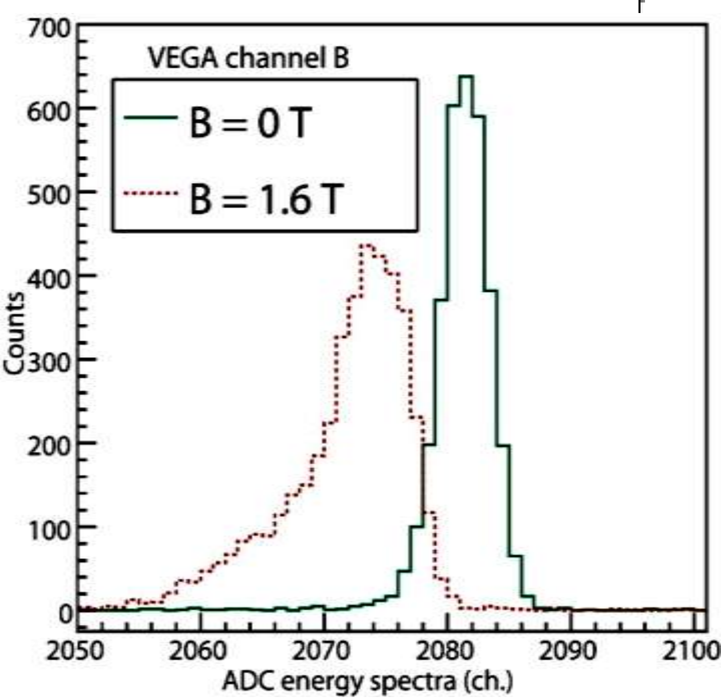
Preparatory experiment in 2004-5

experimental set-up:

- ALADiN dipole magnet
- Co source of 370 kBq
- VEGA clover and
- Euroball cluster



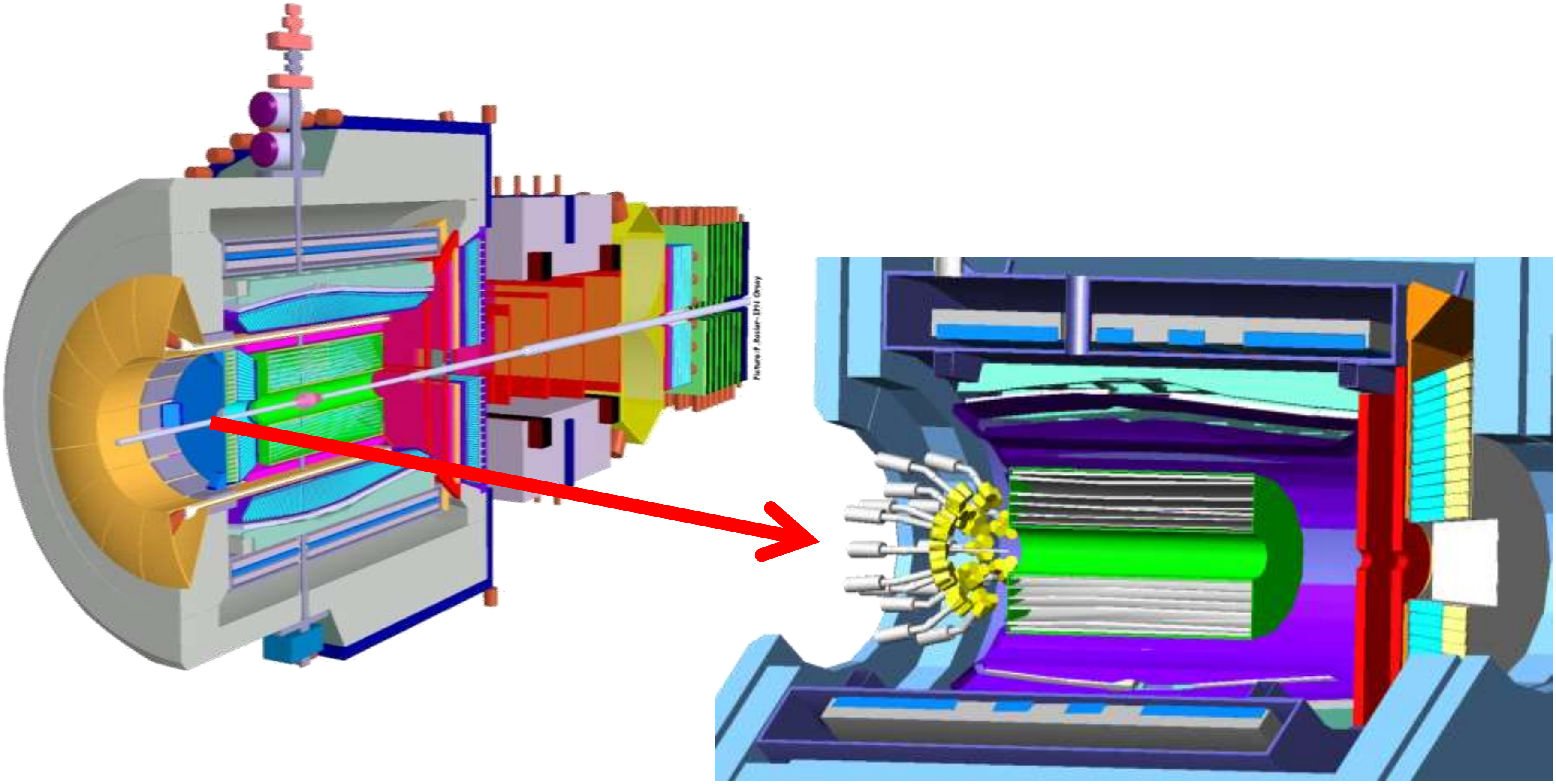




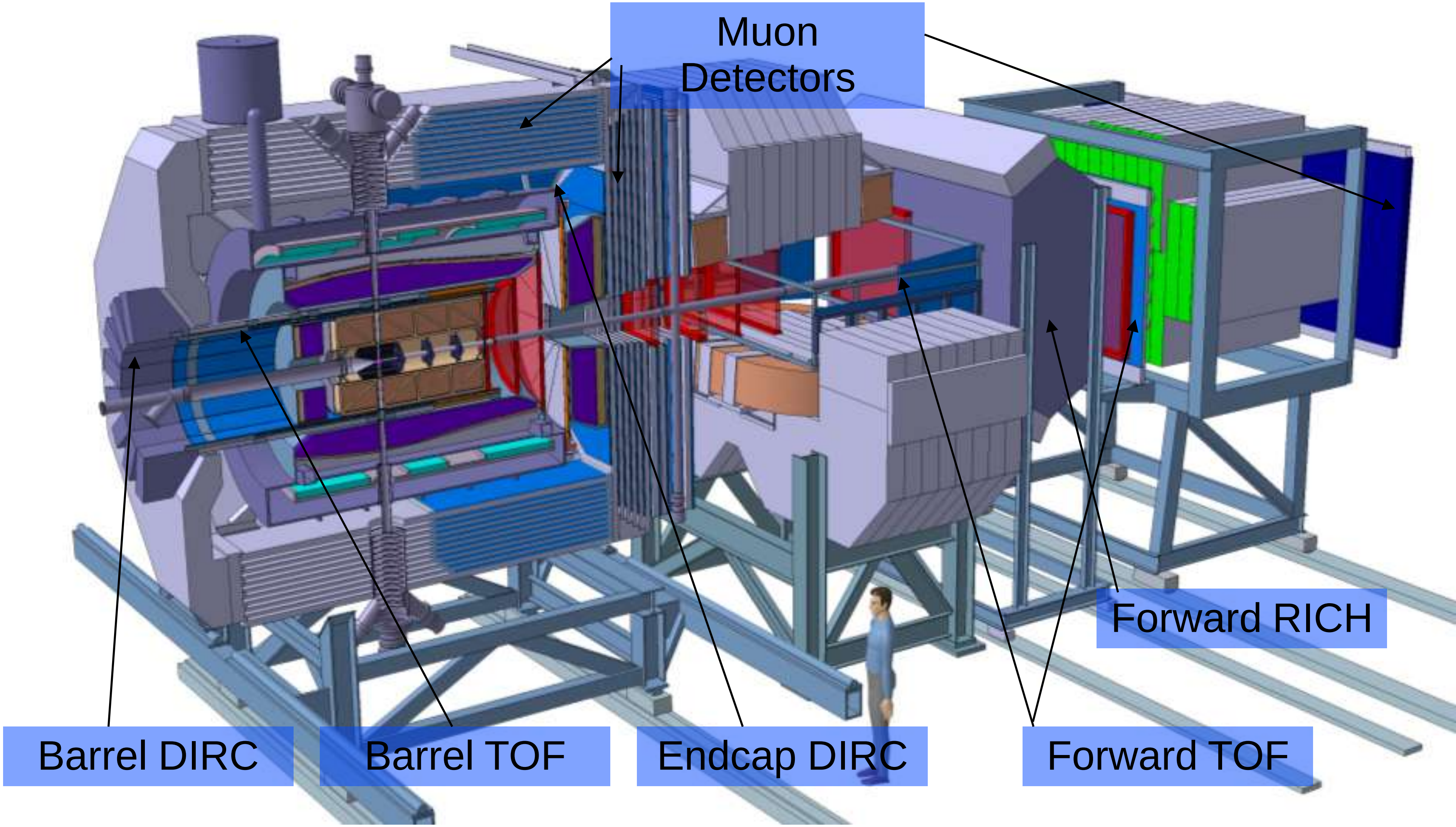
supported by a 6th European Framework HadronPhysics I3 Joint Research Activity

Hypernuclear set-up at PANDA

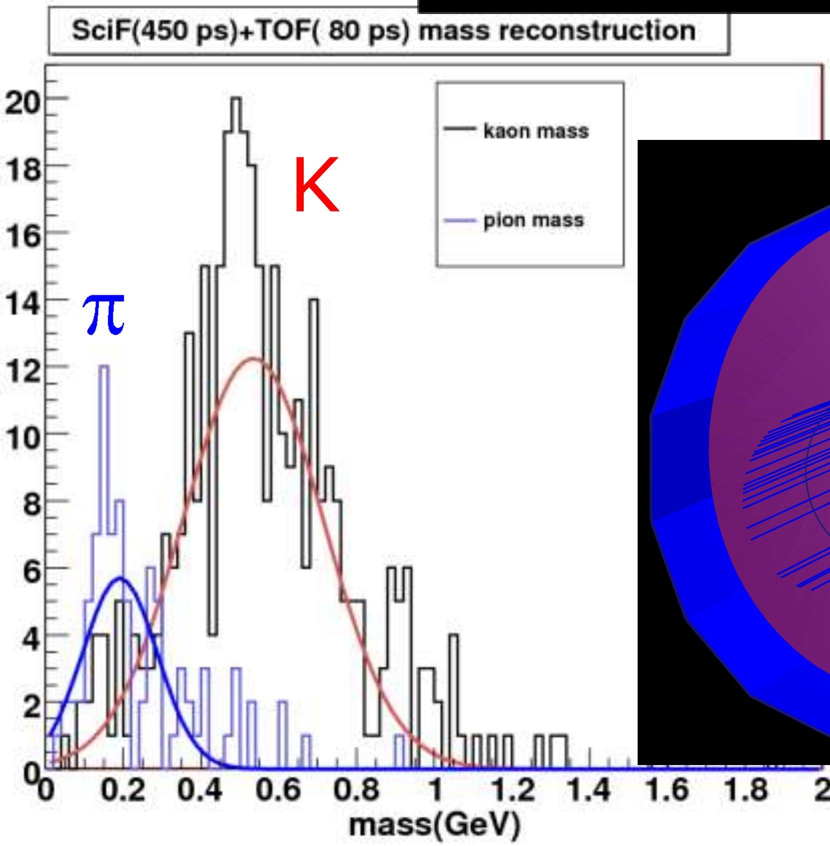
- θ_{lab}< 45°: Ξ-bar, K trigger and PID in PANDA spectrometer
- θ_{lab}= 45°-90°: Ξ-capture and hypernuclei formation
- θ_{lab}>90°: γ-detection with HPGe at backward angles

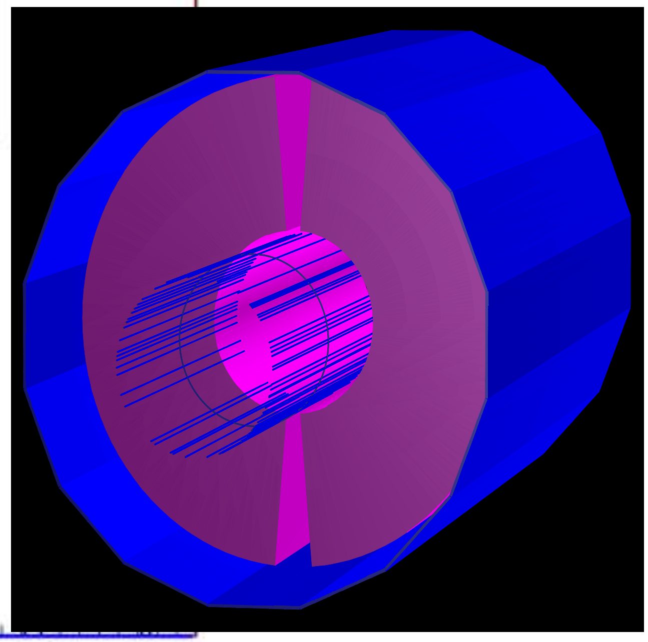


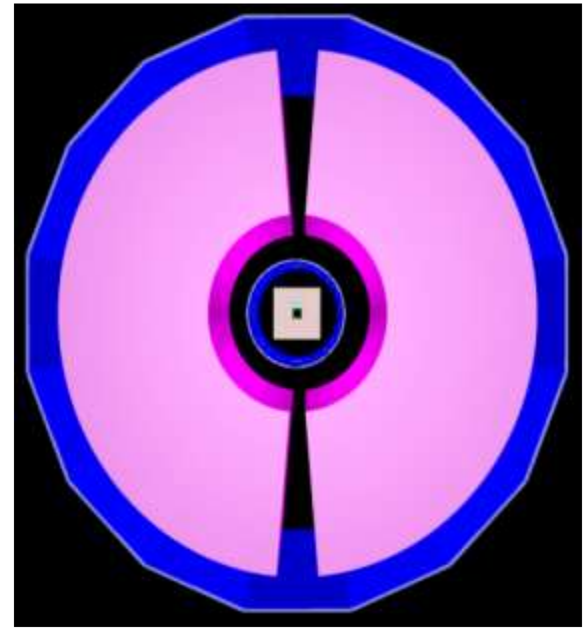
The PANDA PID detectors



TOF for low momentum kaons







- Scintillating fibers (START)

~2000 fibers placed in two rings ⊕ readout with SiPM

- TOF barrel (STOP)

time resolution ~ 80 ps with 16 slabs

[simulations by A. Sanchez, U Mainz]

Comparison of experiments

experiment	*reaction*	*device*	*beam/ target*	*status*
BNL-AGS E885	$(\Xi^-,{}^{12}C) \rightarrow {}^{12}_{\Lambda\Lambda}B + n$	neutron detector arrays	K^- beam, diamond target	20,000 stopped Ξ^-
BNL-AGS E906	2π decays	cylindrical detector system	K^- beam	few tens 2π decays of ${}^4_{\Lambda\Lambda}H$
KEK-PS E373	$(K^-,K^+)\Xi$	emulsion	(K^-,K^+)	several hundred stopped Ξ^-
facility	*reaction*	*device*	*beam/ target*	*captured Ξ^- per day*
JHF	$(K^-,K^+)\Xi$	spectrometer, $\Delta\Omega$ =30 msr	$8\cdot10^6$/sec 5 cm ^{12}C	< 7,000 expected
cold anti-protons	$p\bar{p} \rightarrow K^*\bar{K}^*$ $\bar{K}^*N \rightarrow \Xi K$	vertex detector	10^6 stopped $\bar{p}$ per sec	2,000 expected
PANDA	$p\bar{p} \rightarrow \Xi\bar{\Xi}$	vertex detector + γ–array	$L=2\cdot10^{32}$, thin target, production & decay target	3,000 „golden events“ expected ~ 300,000 KK trigger expected

Estimated count rates

"Golden events":

luminosity $2 \cdot 10^{32}$ cm^{-2}s^{-1}

$\Xi^+\Xi^-$ cross section 2mb for pp	$\Rightarrow$	700 Hz
p(100-500 MeV/c)		$p_{500} \approx 0.0005$
Ξ^+ reconstruction probability		0.5
stopping and capture probability		$p_{CAP} \approx 0.20$
total captured Ξ^-	$\Rightarrow$	3000 / day
Ξ^- to $\Lambda\Lambda$–nucleus conversion probability		$p_{\Lambda\Lambda} \approx 0.05$
total $\Lambda\Lambda$ hypernucleus production	$\Rightarrow$	4500 / month
gamma emission/event,		$p_\gamma \approx 0.5$
γ-ray peak efficiency		$p_{GE} \approx 0.1$

~ 7/day „golden“ γ-ray events with Ξ^+ trigger

~ 700/day with *KK* trigger

Summary

Hypernuclei offer a bridge between traditional nuclear and hadron physics to explore fundamental questions:

- how do nucleons and nuclei form out of quarks?
- can nuclear structure be derived *quantitatively* from QCD?
- what are the properties of strange baryons in nuclei?