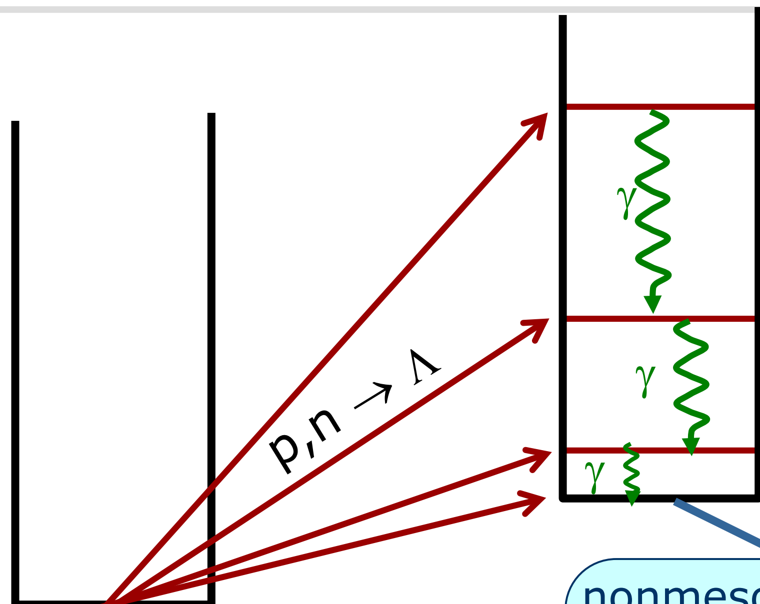
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Hypernuclei at MAMI-C and PANDA

- Introduction
- Hypernuclei at MAMI-C: KAOS
- The GSI project: PANDA
- Search for the $\Xi^{--}(1860)$ in WA89

Birth, life and death of a hypernucleus



electromagnetic decays

mesonic decays
$\Lambda \rightarrow p\pi^-$
$\Lambda \rightarrow n\pi^0$

nonmesonic weak decay
$\Lambda p \rightarrow np$
$\Lambda n \rightarrow nn$
$\Lambda\Lambda \rightarrow YN$

hadronic decay in emulsion

strangeness deposition
$e^+ + e^- \rightarrow \Phi \rightarrow K^+ + K^-$
$K^-_{stopped} + {}^A Z \rightarrow {}^A_\Lambda Z + \pi^-$
FINUDA

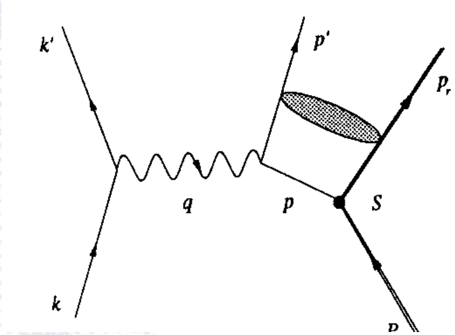
strangeness production
(π^+, K^+), (π^-, K^0)
BNL,KEK,(GSI)

strangeness exchange
(K^-, π^-) ,(K^-, π^0)
BNL,KEK,JPARC

electroproduction
$(e,e'K^+)$, (γ,K^+)
Jlab, MAMI-C

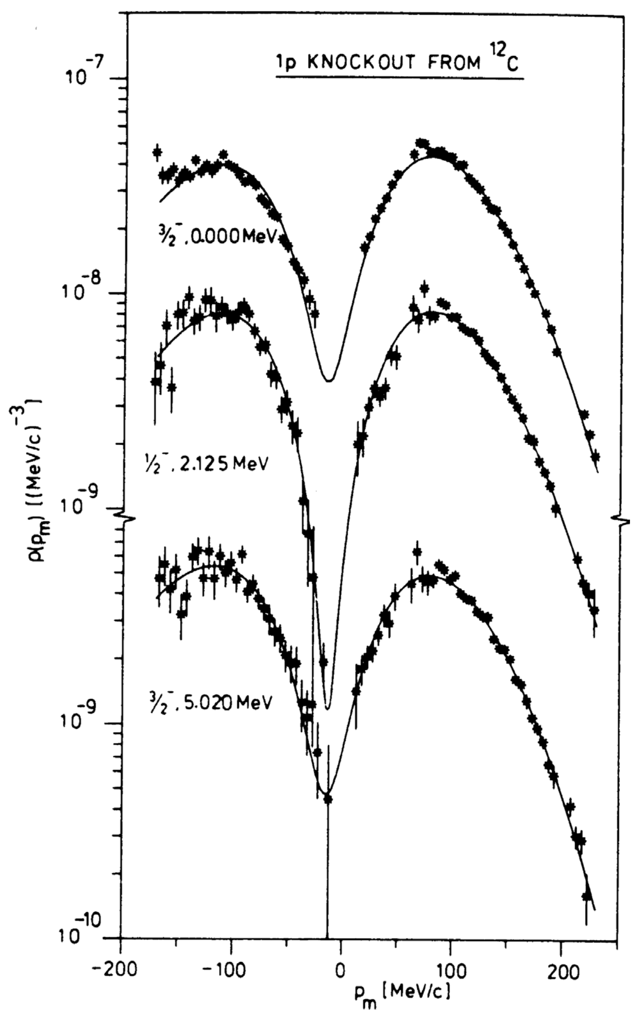
Reminder:momentum distributions

- semi inclusive measurements of one-nucleon knockout reactions provide information on the momentum distribution of the nucleon and hence on the nucleon wave function

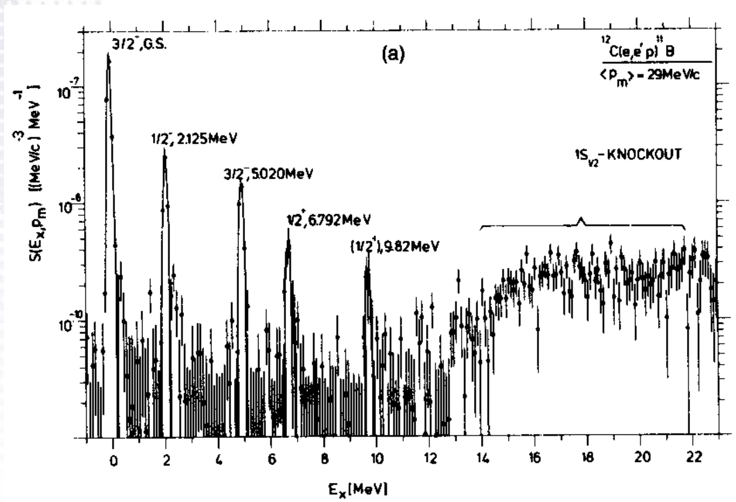


$$E_x = \omega - T_p - T_{A-1} - E_s$$

$$p_m = q - p'$$



- Example: $^{12}C(e,e'p)^{11}B$
  - Steenhoven et al., (1988)



Double Hypernuclei

- Multi-Hypernuclei are *terra incognita*, but they exist !

1963: Danysz *et al.* $_{\Lambda\Lambda}{}^{10}$Be

1966: Prowse $_{\Lambda\Lambda}{}^{6}$He

1991: KEK-E176 $_{\Lambda\Lambda}{}^{13}$B (or $_{\Lambda\Lambda}{}^{10}$Be)

2001: AGS-E906 $_{\Lambda\Lambda}{}^{4}$H (~15);

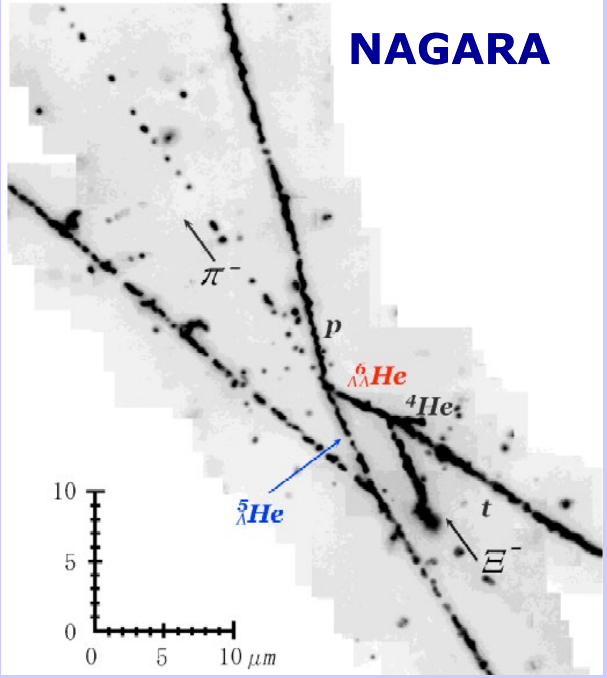
no binding energies

2001: KEK-E373 $_{\Lambda\Lambda}{}^{6}$He (Nagara)

" $_{\Lambda\Lambda}{}^{10}$Be (Demachi-Yanagi)

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

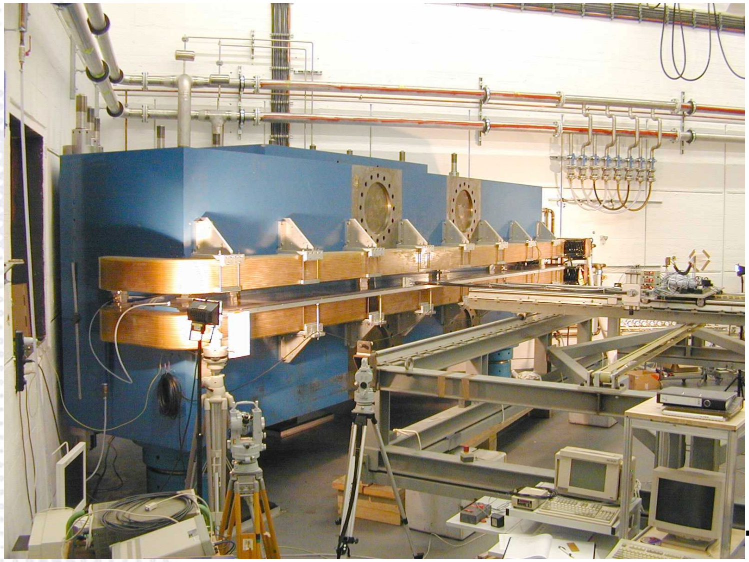
$$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

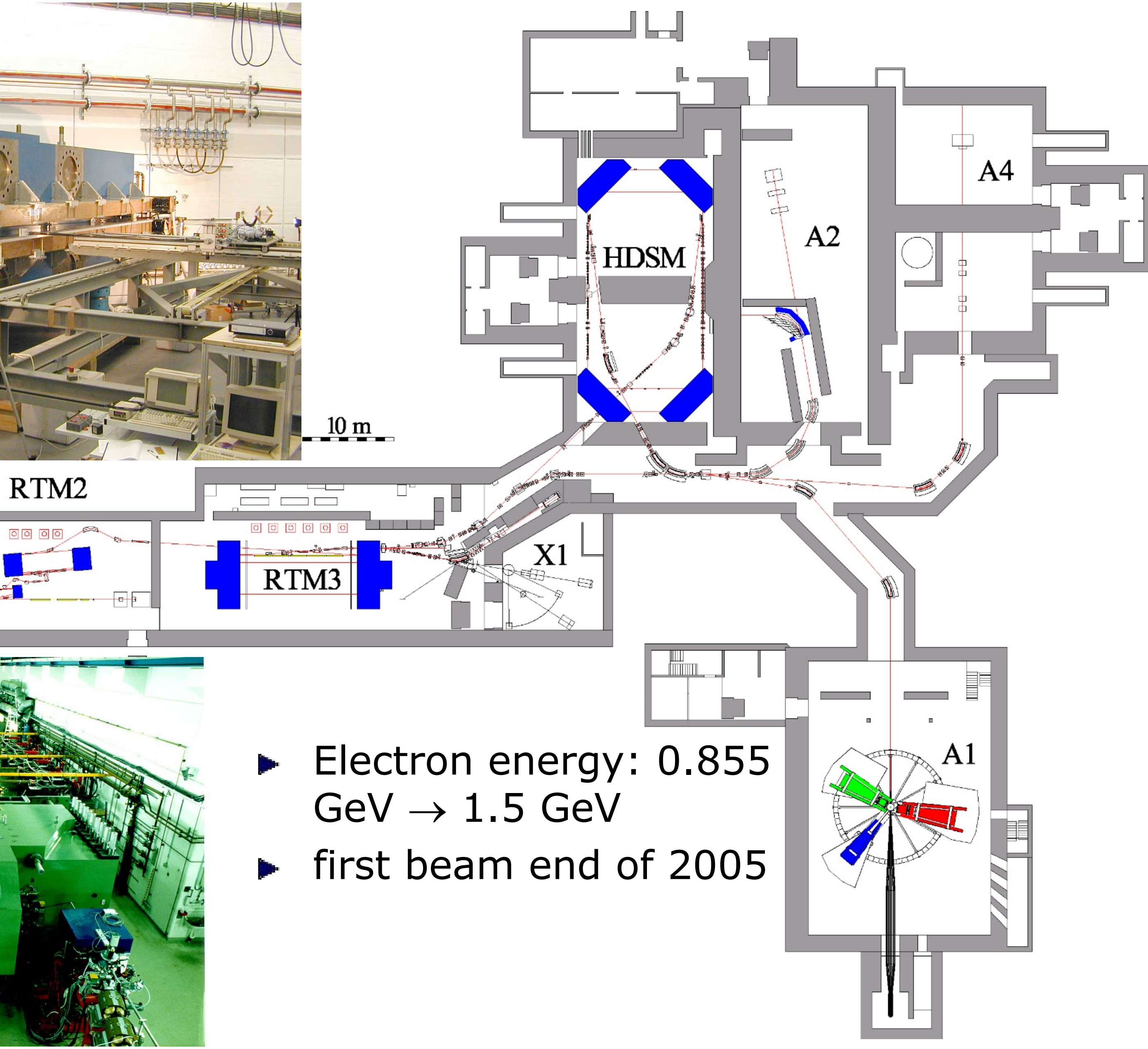


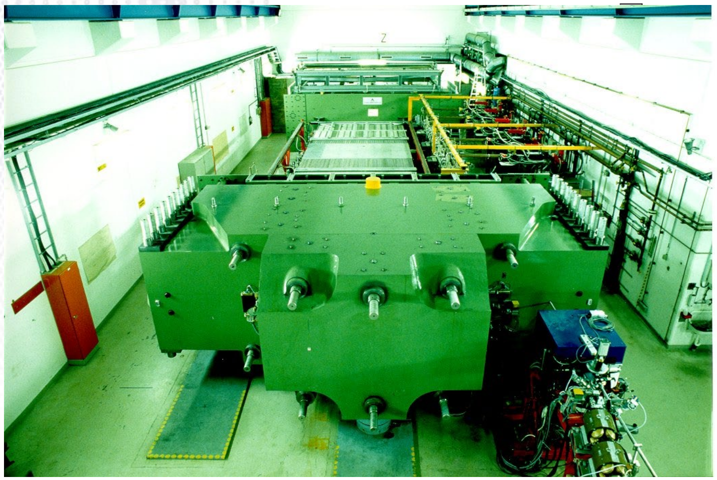
H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

2. (e,e'K) at MAMI-C

MAMI-C



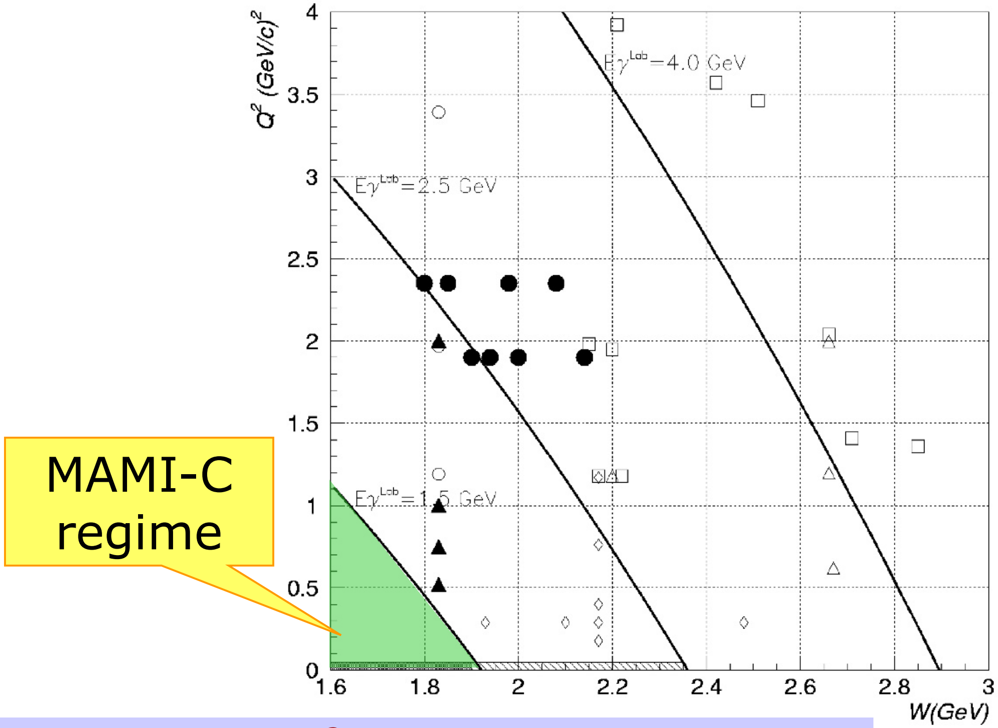




- Electron energy: 0.855 GeV $\rightarrow$ 1.5 GeV
- first beam end of 2005

Existing data and experiments

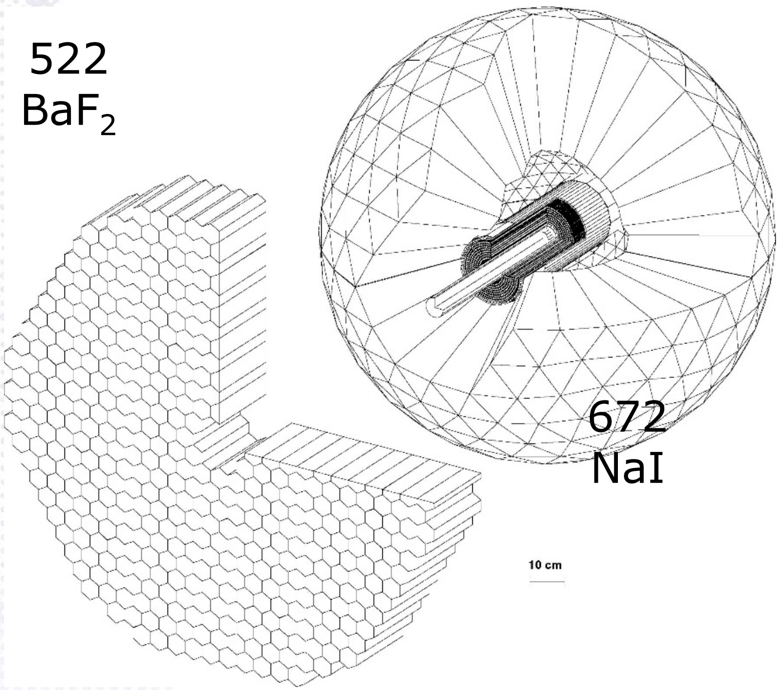
- photoproduction
  - 1970: Cornell, CalTech, Bonn, DESY, Orsay
  - 2000: SAPHIR (Bonn), GRAAL (Grenoble), CLAS (Jlab, Hall B)
- electroproduction
  - 1970: Cornell, DESY, CEA
  - 2000: E93-018 (Jlab, Hall C), E98-108 (Jlab, Hall A)



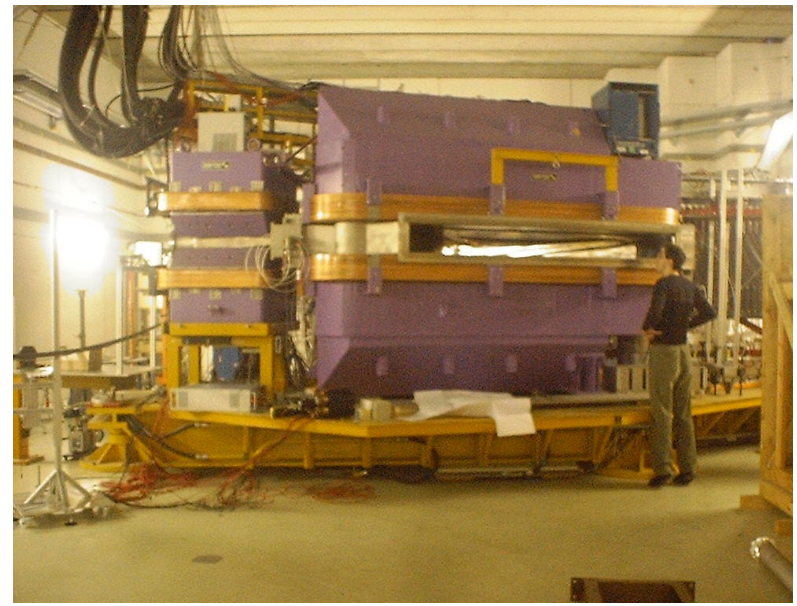
- for $Q^2<0.5$ (GeV/c)^2 only few precise data

New Experimental Opportunities

- Crystal ball +TAPS (A2)
  - real photons
  - calorimetry of neutral and charged particles



- KAOS (A1)
  - virtual photons
  - high resolution spectroscopy of charged particles



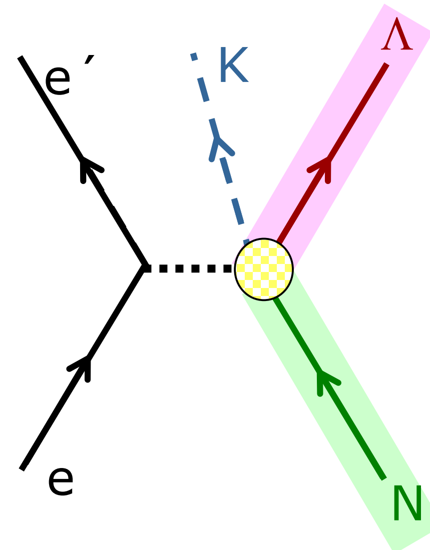
(→ Volker Kochs talk)

Hypernucleus production

- cross section for $A(e,e'K^+)_\Lambda B$ in e.g. relativistic impulse approximation

$$d\sigma \propto (2\pi)^4 \delta^4(p_e + p_A - p_{e'} - p_B - p_K)$$
$$\times \frac{d^3\vec{p}_{e'} m_e}{(2\pi)^3 E_{e'}} \cdot \frac{d^3\vec{p}_K}{(2\pi)^3 E_K} \cdot \frac{d^3\vec{p}_B (2m_p)(2m_e)}{(2\pi)^3 \sqrt{(p_e \cdot p_A)^2 - p_e^2 p_A^2}}$$
$$\times \underbrace{\sum_{M_i, M_f} \left| \sum_{\alpha,\alpha'} \langle J_f M_f T_f N_f | C^\dagger_{\alpha'} C_\alpha | J_i M_i T_i N_i \rangle \cdot \langle \alpha' | t | \alpha \rangle \right|^2}$$

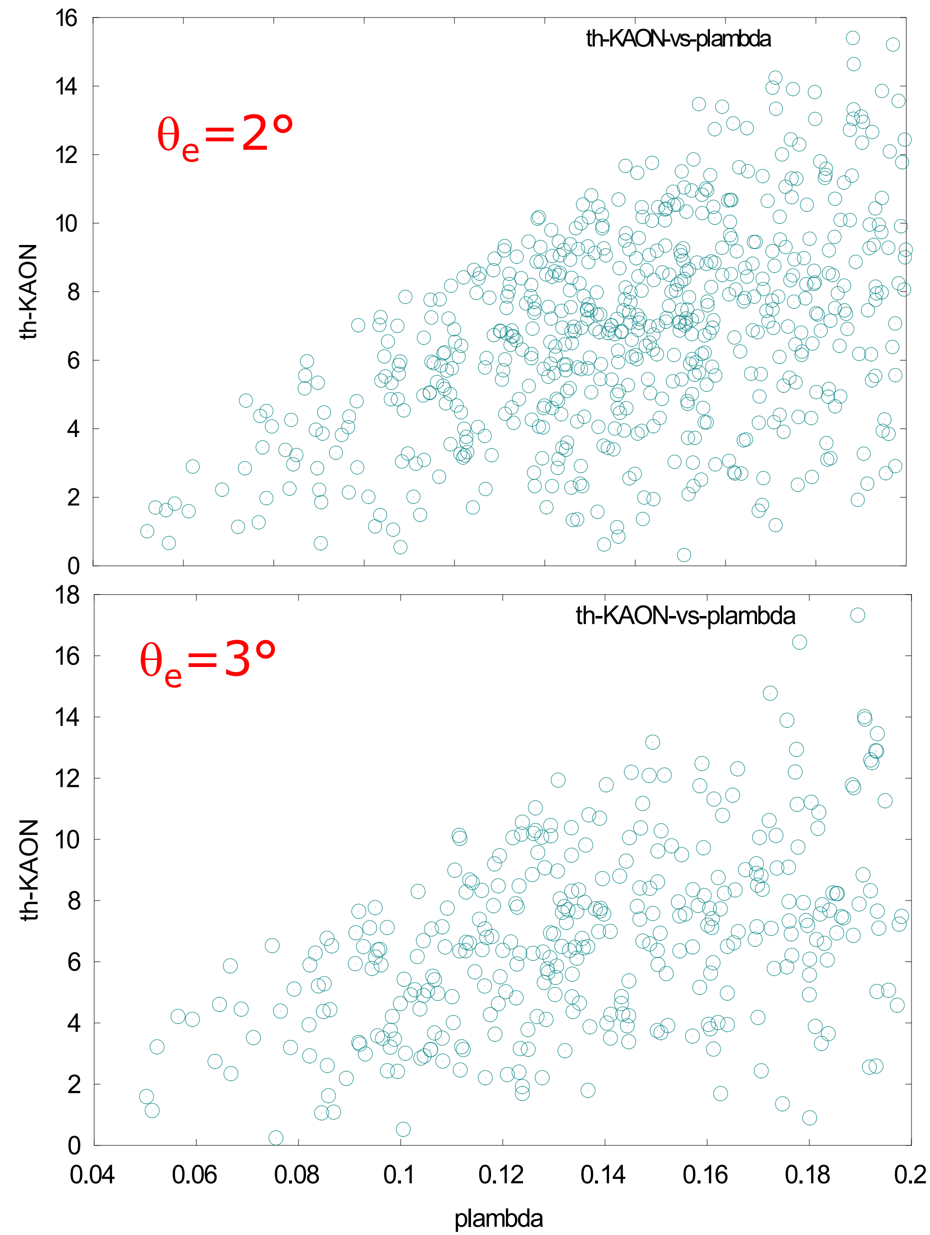
matrix elements × elementary operator for $p(\gamma,K^+)\Lambda$



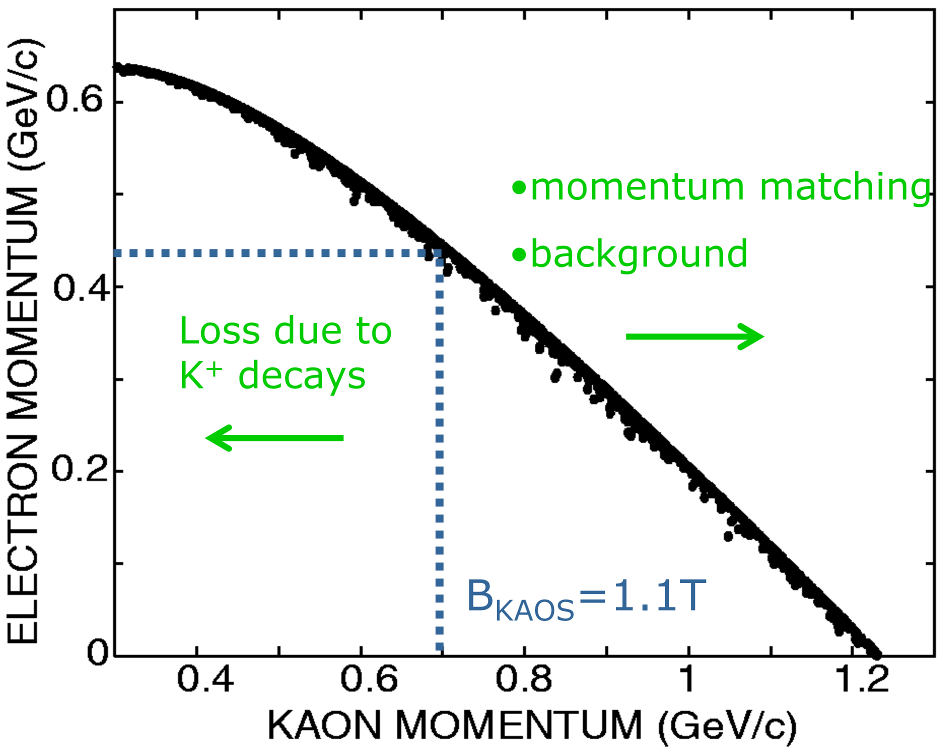
- key ingredient to the elementary operator $p(\gamma,K^+)\Lambda$
  - nucleon wave function and spectroscopic factor (e.g. from (e,e´p))
  - K^+ optical potential (e.g. from K^+ elastic scattering)
  - Λ wave function
- we can map out the Λ wave function by varying the kaon angle

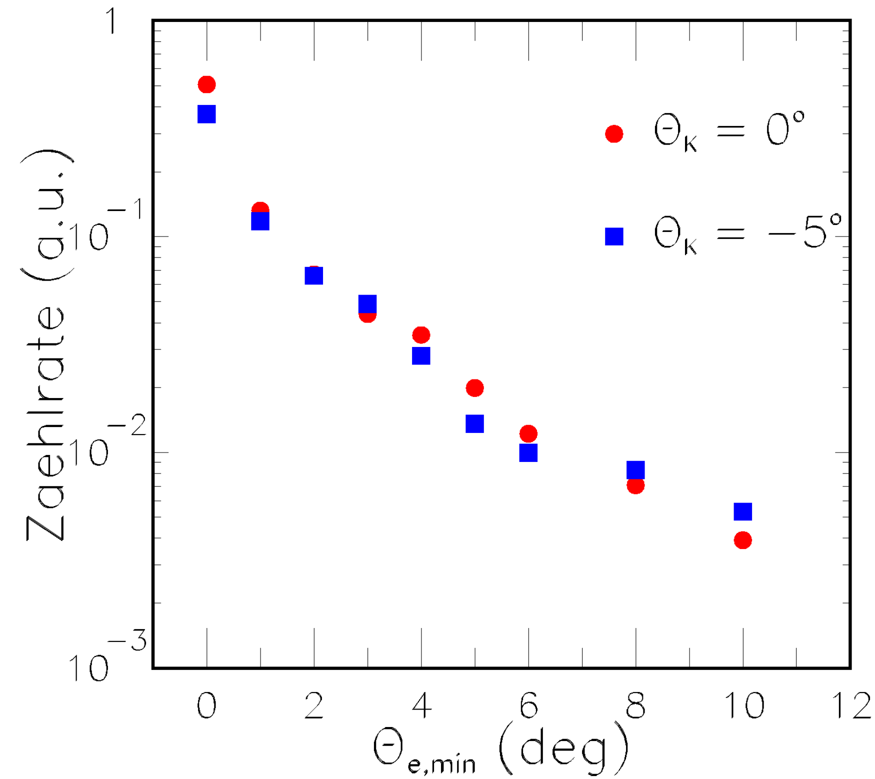
Kinematics

- qualitative example
  - $\langle p_{K+} \rangle = 0.8$ GeV/c
  - $\langle p_e \rangle = 0.4$ GeV/c
  - $\langle \theta_{K+} \rangle = 6.8°$
  - averaged over all kaon momenta



Kinematics $e + {}^{A}Z \rightarrow e' + K^{+} + {}^{A}_{\Lambda}(Z-1)$

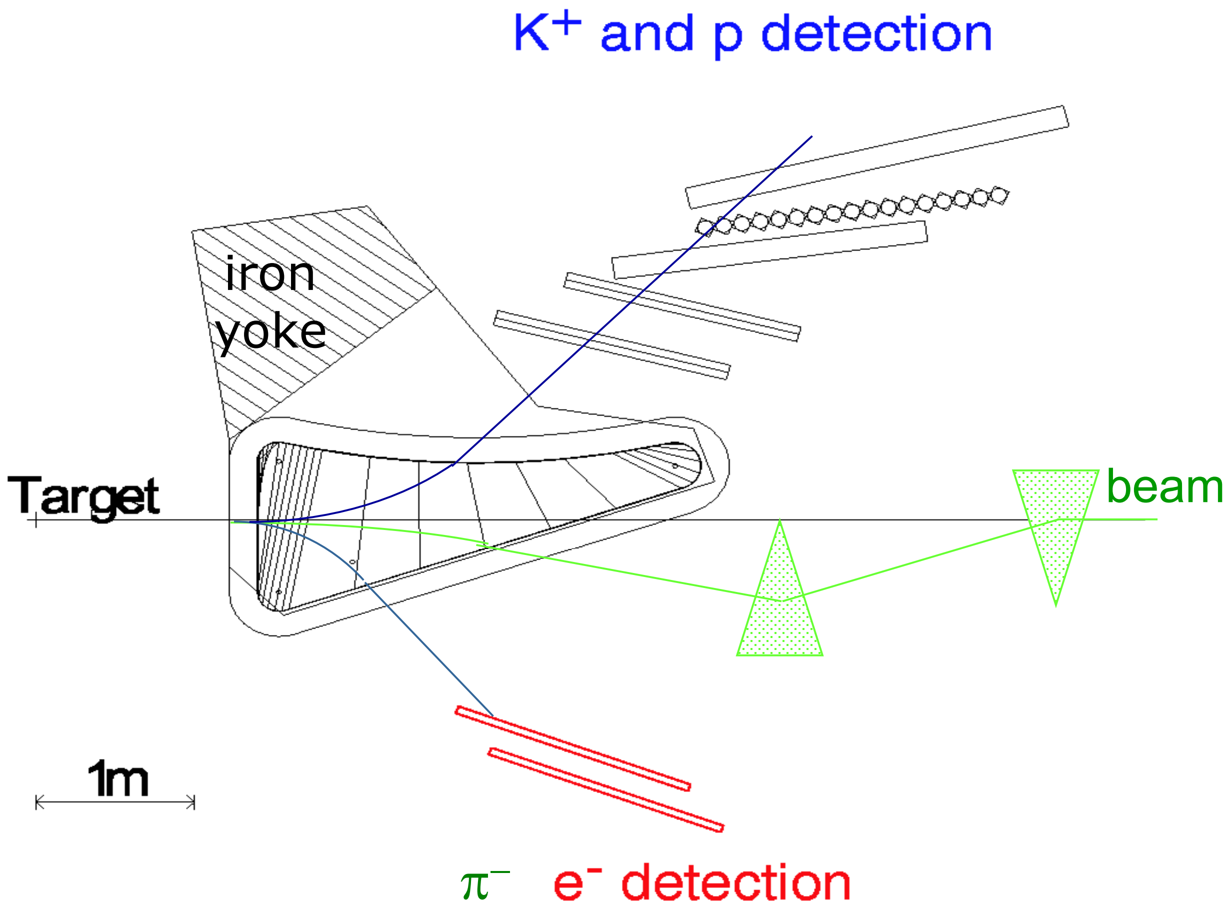




- strong correlation between kaon and scattered electron momentum
  - large momentum acceptance for both particles
- both particles are produced at small angle
  - forward double spectrometer

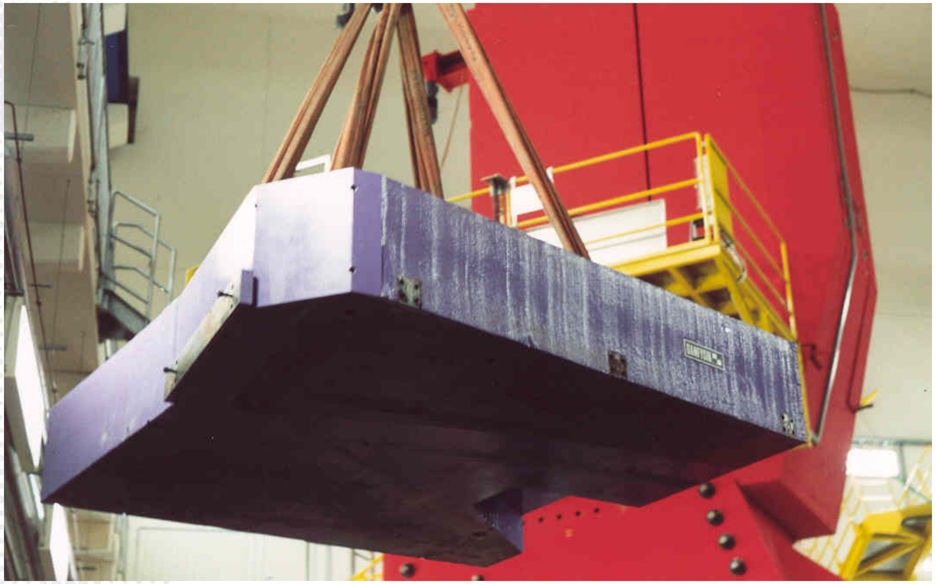
KAOS at 0°

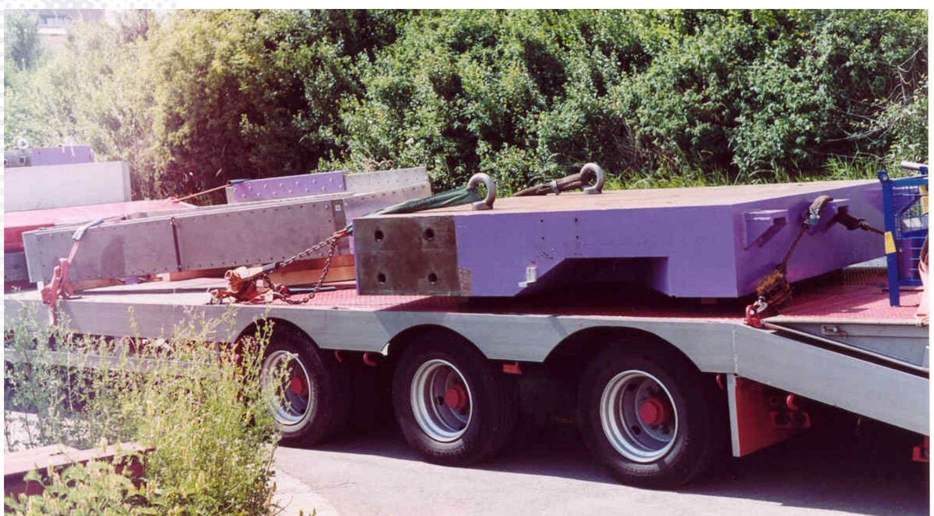
- large count rate
- chicane for primary beam

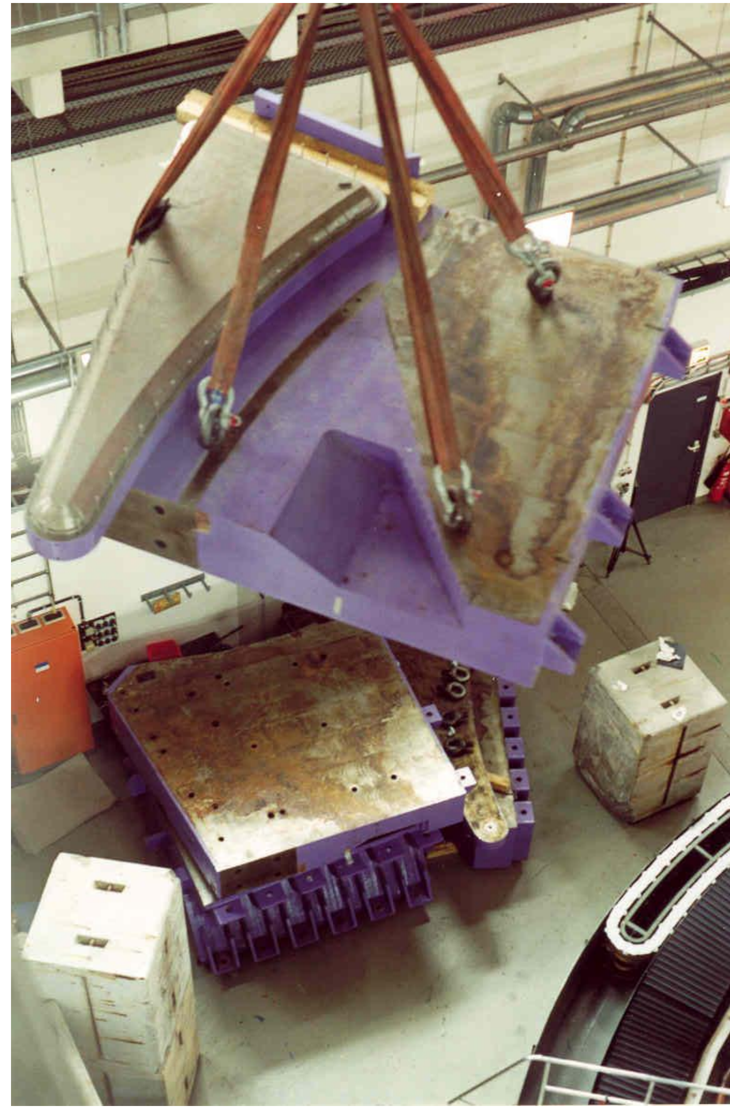


KaoS@MAMI

- arrival of KaoS at Mainz on 11 June 2003

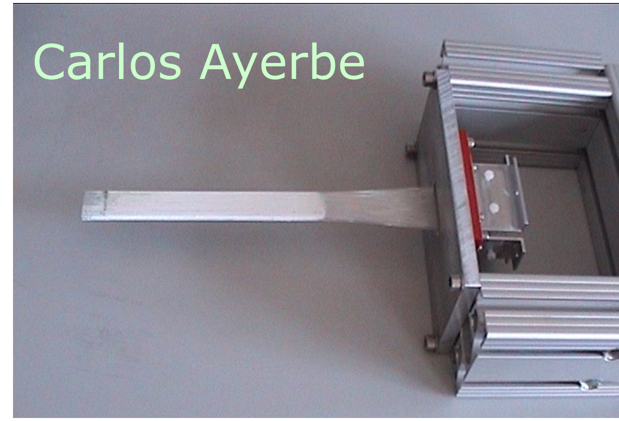


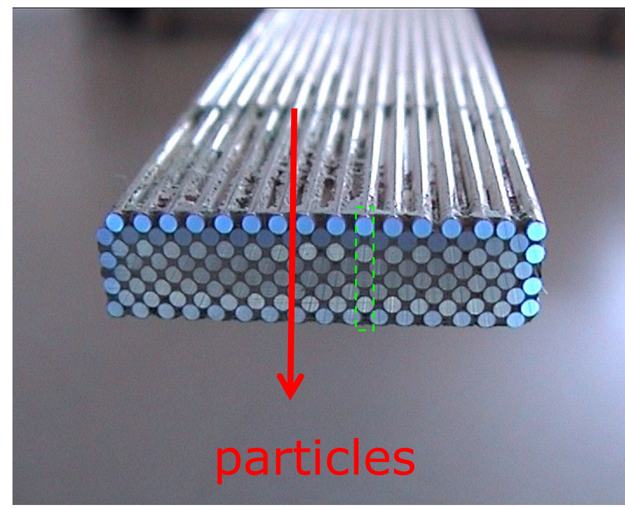




Fiberdetectors for KAOS

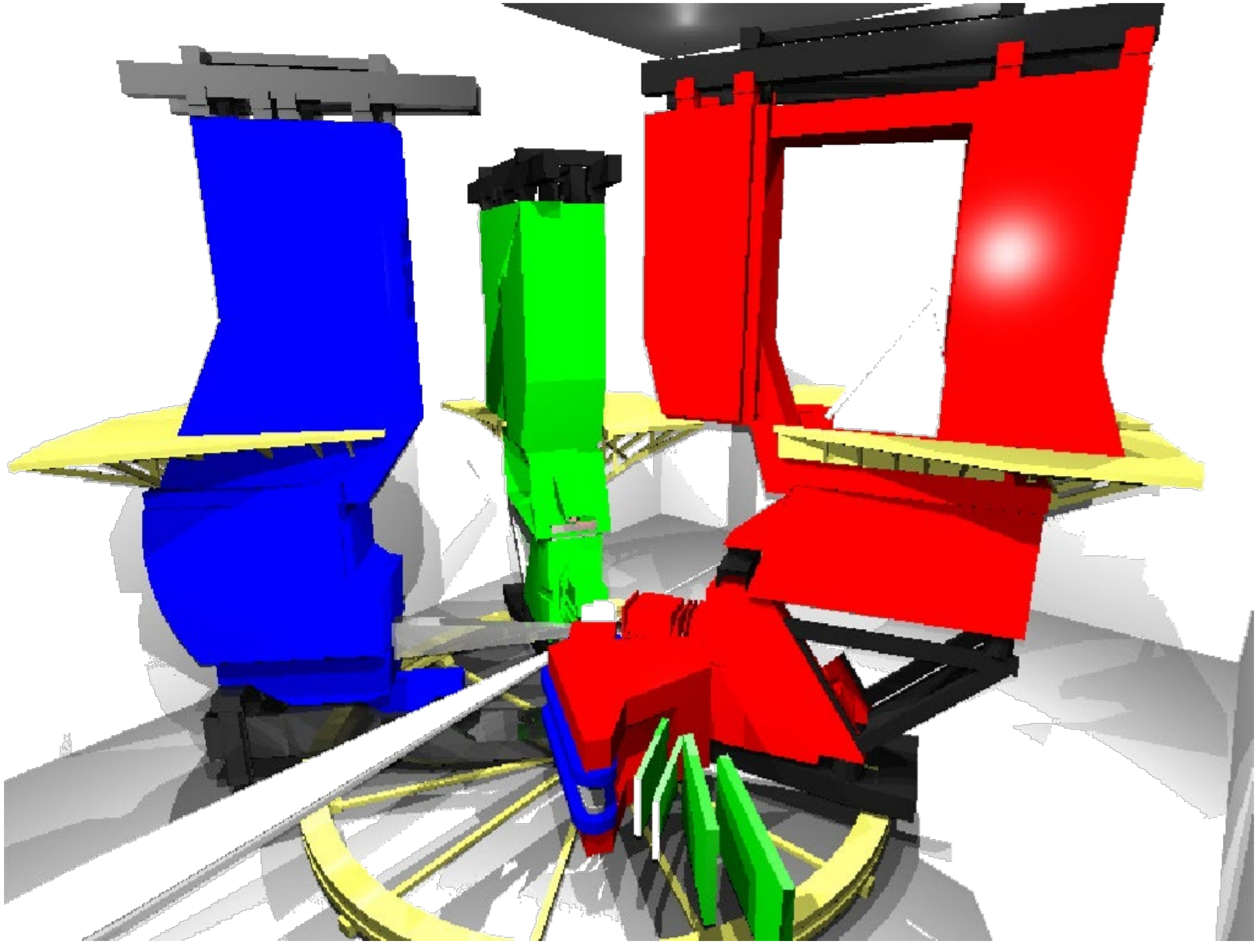
- requirements
  - high count rate capability
  - good position resolution (150 mm)
  - timing information (needed for trigger)
- realization
  - 0.83 mm fiber diameter
  - 4 fibers=1 PMT channel
  - 4000 channels
  - multi-anode phototube (32 ch/tube)
  - 32-ch discriminator based on double threshold discriminator chip GSI-3
- funded by HBFG





KAOS @ A1

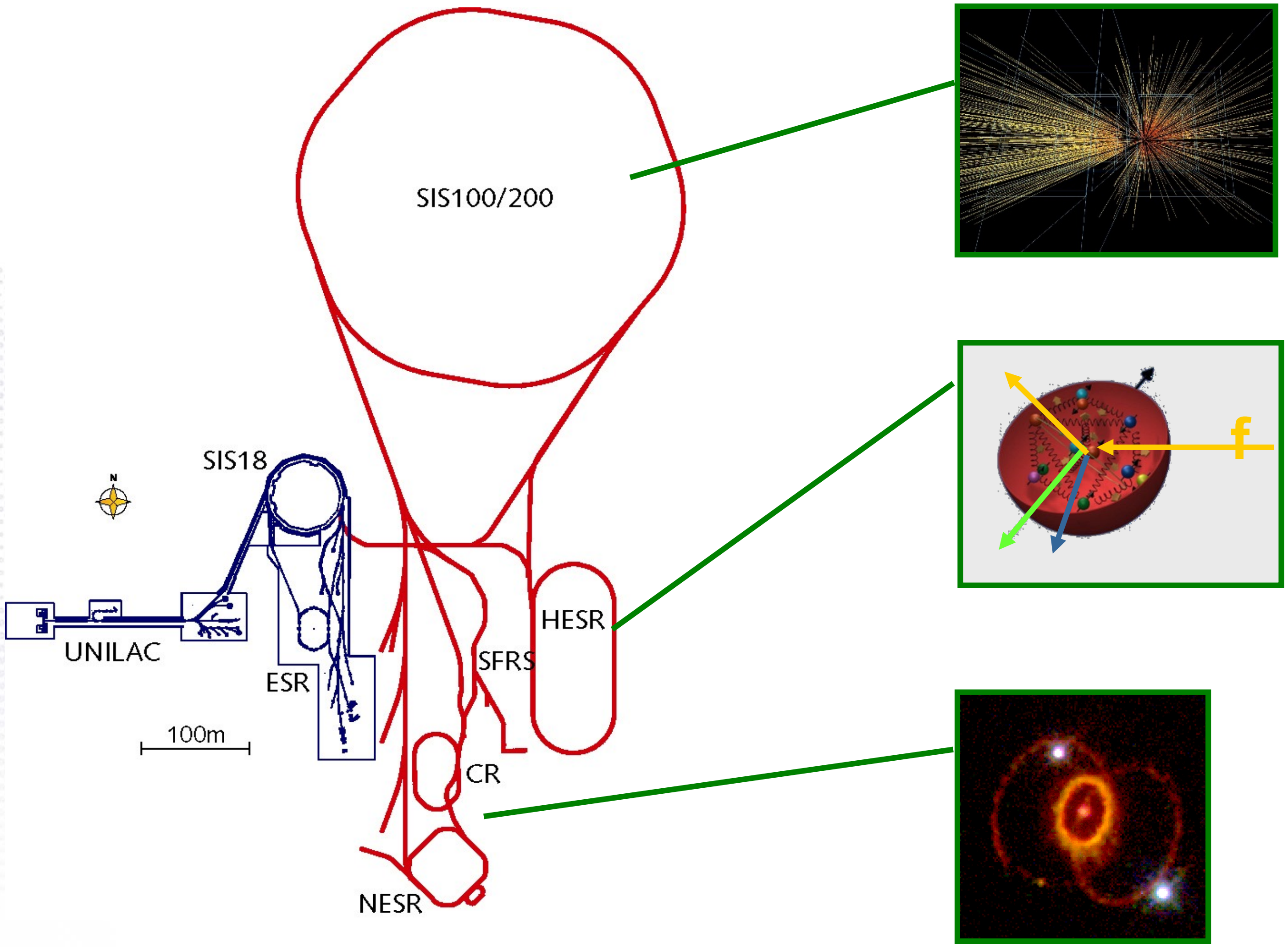
- planing for setting up KaoS is ongoing
  - electrical power, water cooling...
  - parking position, vertical and horizontal moving
  - at 0°: chicane for beam dump (background!)
  - trigger
  - ...



3. The GSI Future Project

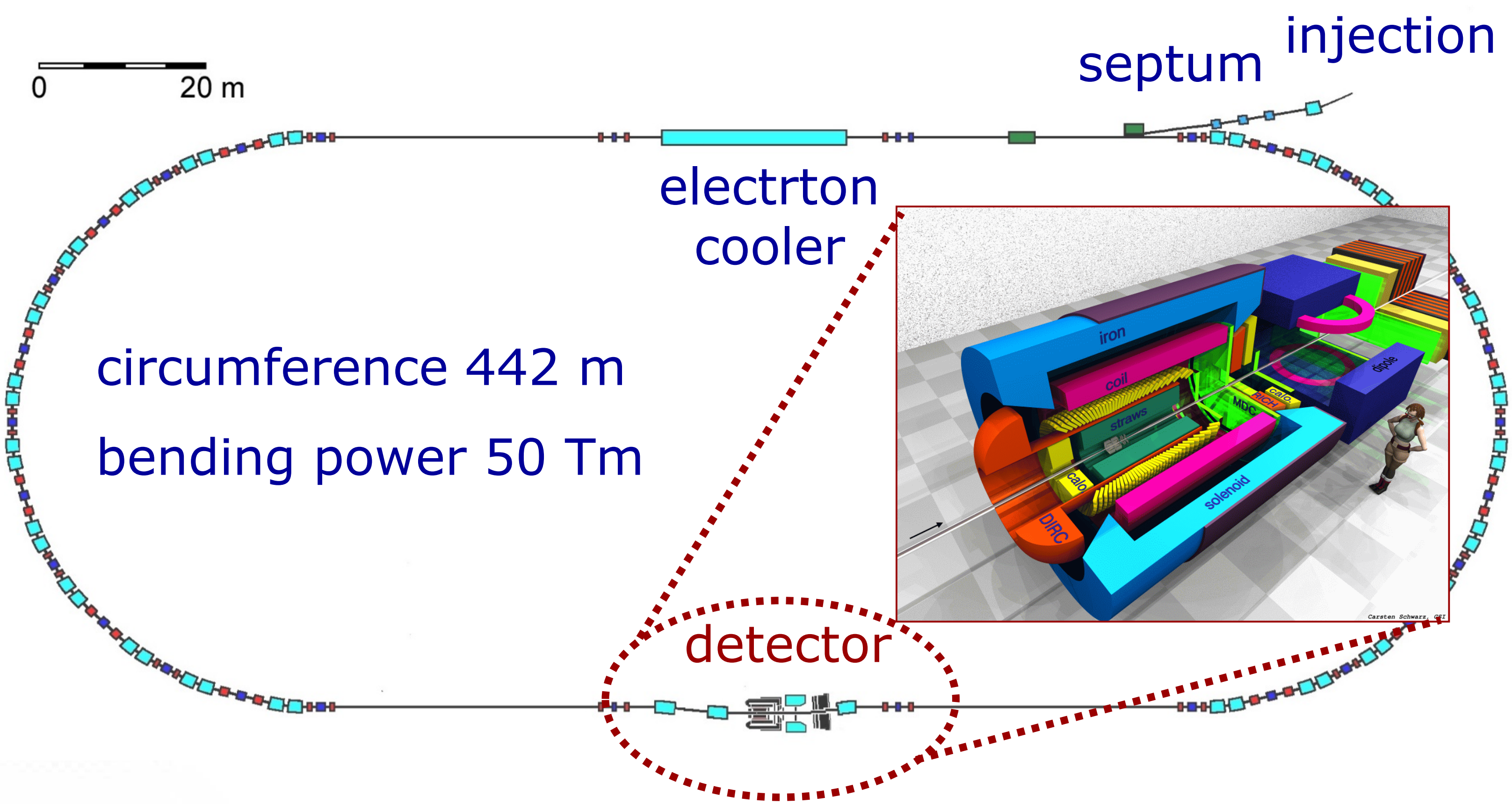
The GSI Future Project

- origin of *confinement* ?
- hierarchy of quark masses ?
- atomic nucleus and nuclear matter as quark-gluon systems ?



Antiproton Storage Ring

- Antiproto momentum 1.5 – 15 GeV/c
- Luminosity $2 \cdot 10^{32}\ cm^{-2}s^{-1}$
- beam diameter 10-100μm
- $\Delta p/p = 10^{-4} ... 3 \cdot 10^{-5}$



The PANDA Project

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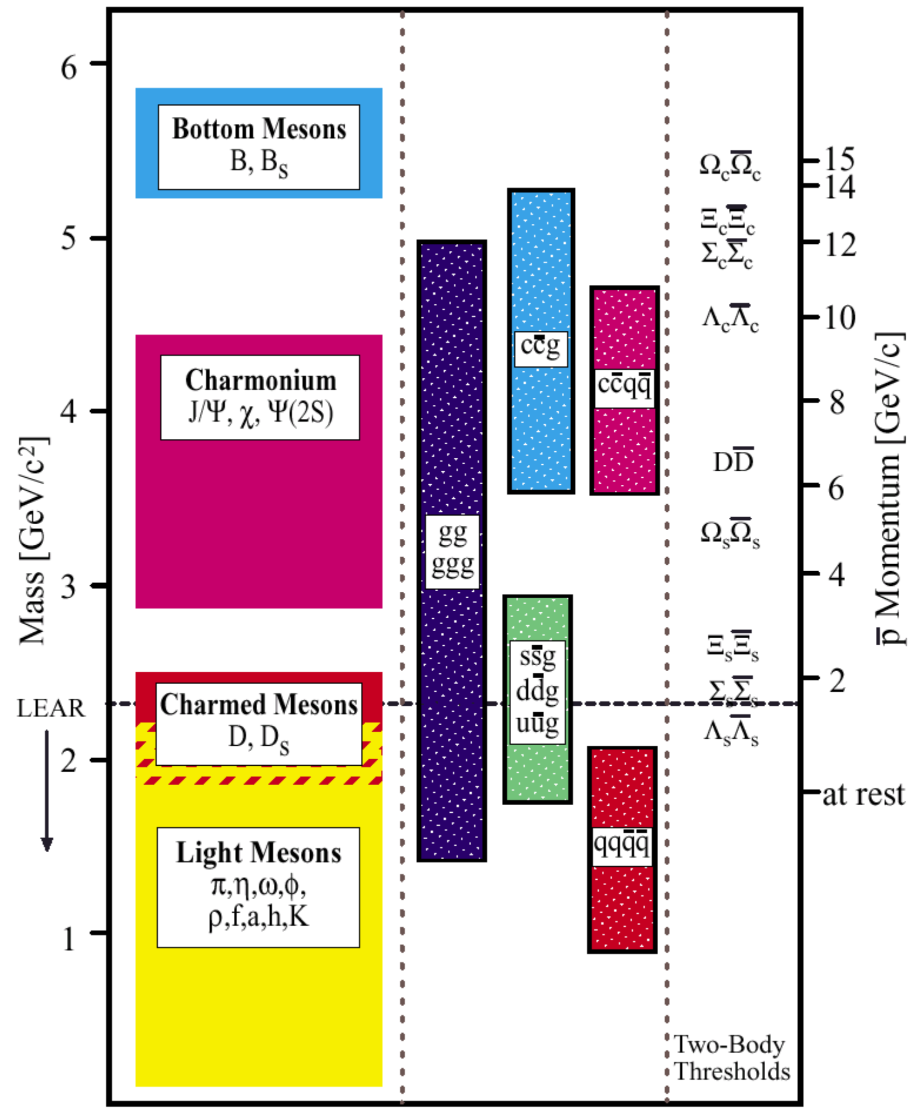
- Anti-proton storage ring HESR
  - internal target
- Physics program
  - quark-quark interaction
    ⇒ charmonium spectroskopy
  - gluonische degress of freedom
    ⇒ glueballs, hybrids
  - hadrons in nuclear matter
    ⇒ mesons in nuclei
    ⇒ Hyperkerne
- Far future
  - CP violation?
  - inverse DVCS ?



Double hypernuclei: what is known?

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

Hyperkern	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)		
${}^{6}_{\Lambda\Lambda}He$	10.9 ± 0.5	4.7 ± 0.6	Prowse	(1966)
${}^{6}_{\Lambda\Lambda}He$	$7.25 \pm 0.19^{+0.18}_{-0.11}$	$1.01 \pm 0.20^{+0.18}_{-0.11}$	KEK-E373	(2001)
${}^{10}_{\Lambda\Lambda}Be$	17.7 ± 0.4	4.3 ± 0.4	Danysz	(1963)
${}^{10}_{\Lambda\Lambda}Be$	8.5 ± 0.7	-4.9 ± 0.7	KEK-E176	(1991)
${}^{13}_{\Lambda\Lambda}B$	27.6 ± 0.7	4.8 ± 0.7	KEK-E176	(1991)
${}^{10}_{\Lambda\Lambda}Be$	$12.33^{+0.35}_{-0.21}$		KEK-E373	(2001, unpublished)

same event

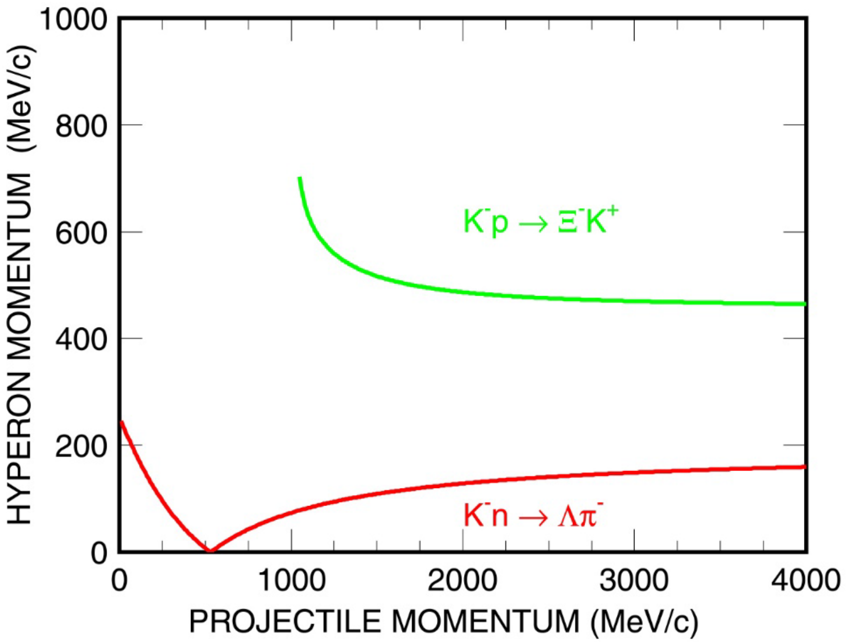
- Interpreting $\Delta B_{\Lambda\Lambda}$ as $\Lambda\Lambda$ bond energy one has to consider e.g.
  - dynamical change of the core nucleus
  - ΛN spin-spin interaction for non-zero spin of core
  - excited states possible …
- if $\Lambda\Lambda$- or intermediate Λ-nuclei are produced in excited states
  - Q-value difficult to determine (particularly for heavy nuclei)
  - nuclear fragments difficult to identify with usual emulsion technique
- new concept required $\Rightarrow$ γ-spectroscopy!

Production of $\Lambda\Lambda$–Hypernuclei

- Ξ^- conversion in 2 Λ

$$\Xi^- + p \to \Lambda + \Lambda + 28.5\text{MeV}$$

- Ξ- production
  - p(K$^-$,K$^+$)Ξ^-
    - needs K$^-$ beam (c·τ=3.7cm)
    - recoil momentum >460 MeV/c
  - KEK-E176: 10^2 stopped Ξ
  - E373: 10^3 stopped Ξ
  - AGS-E885: 10^4 stopped Ξ

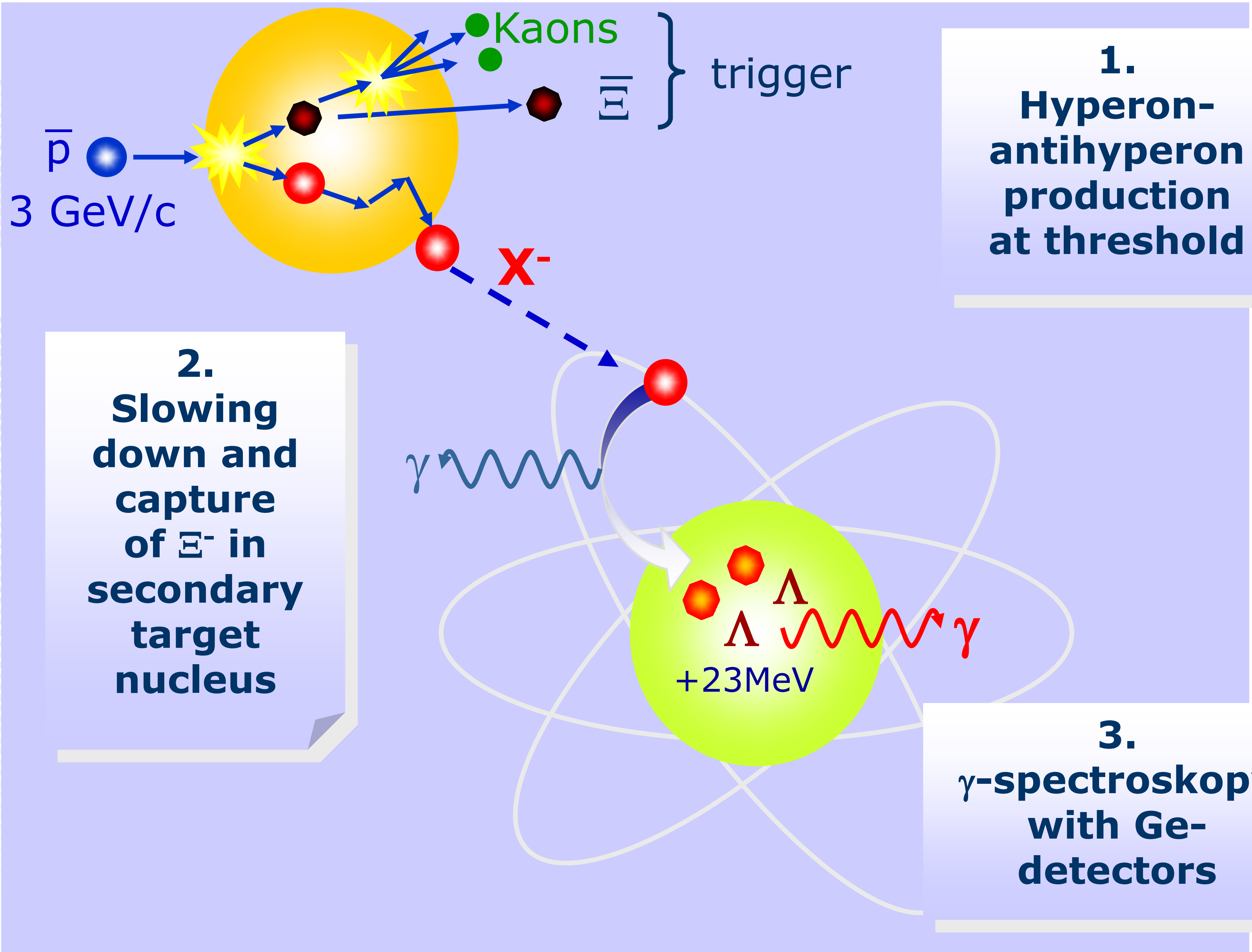


- at HESR

$$p + \bar{p} \to \Xi^- + \bar{\Xi}^+$$
$$p + \bar{p} \to \Omega^- + \bar{\Omega}^+$$

  - few times 10^5 stopped Ξ per day
  - γ-spectroscopy possible

Production of Double Hypernuclei



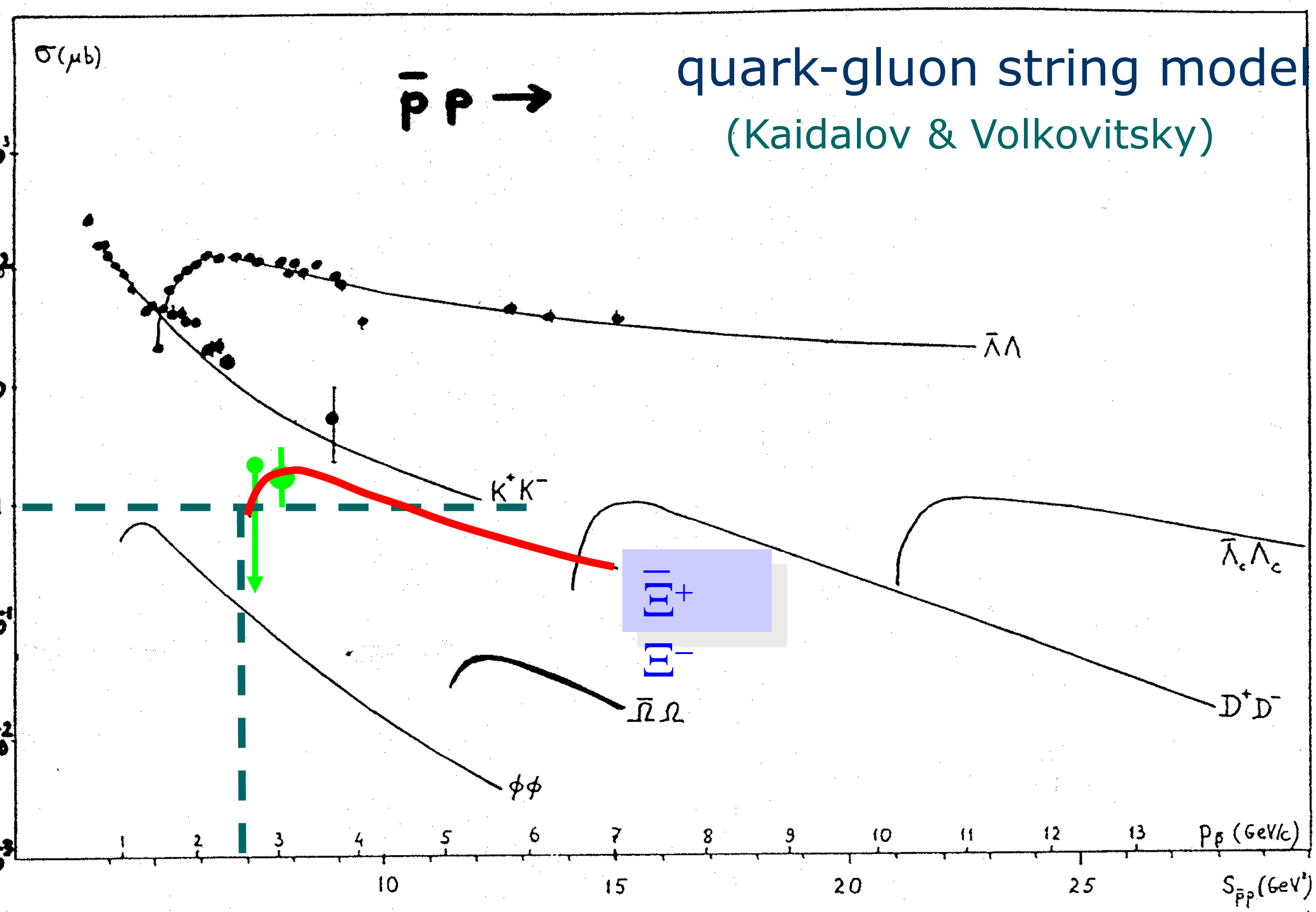
1. Hyperon-antihyperon production at threshold

2. Slowing down and capture of Ξ- in secondary target nucleus

3. γ-spectroskopy with Ge-detectors

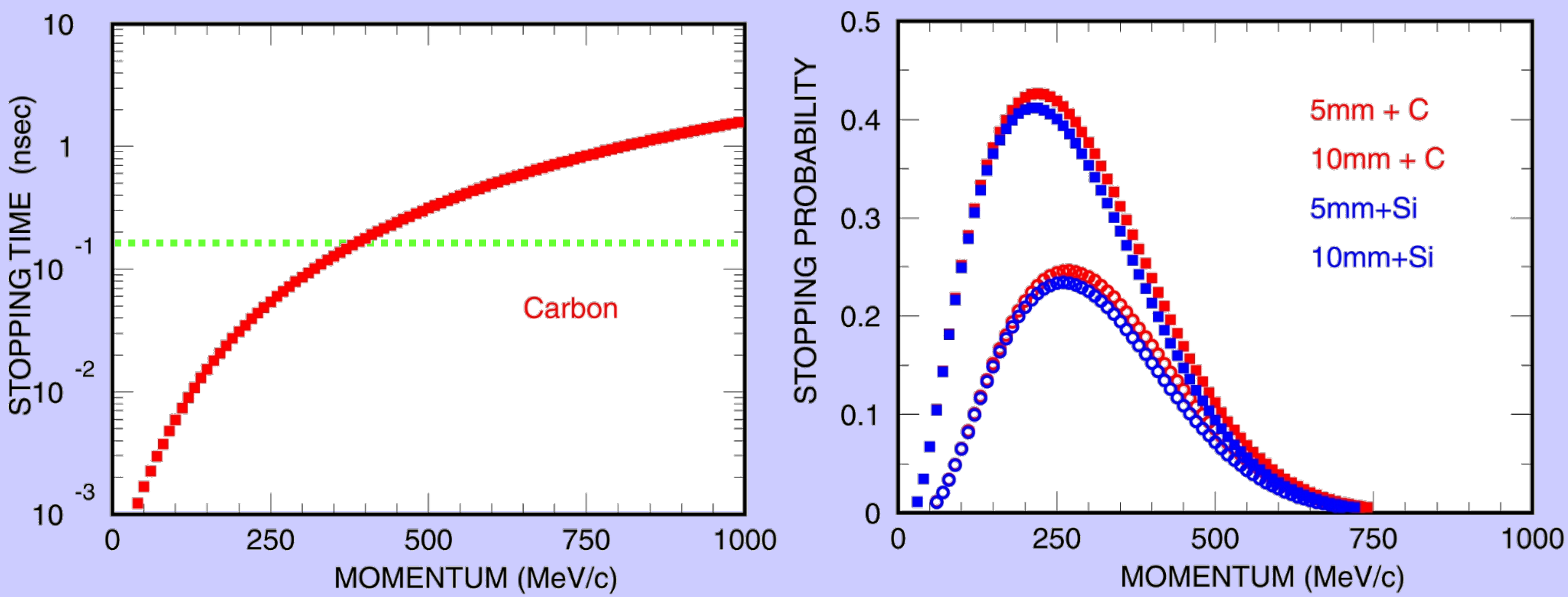
General Idea

- Use $p\bar{p}$ Interaction to produce a hyperon "beam" ($t \sim 10^{-10}$ s) which is tagged by the antihyperon or its decay products



Ξ^- properties

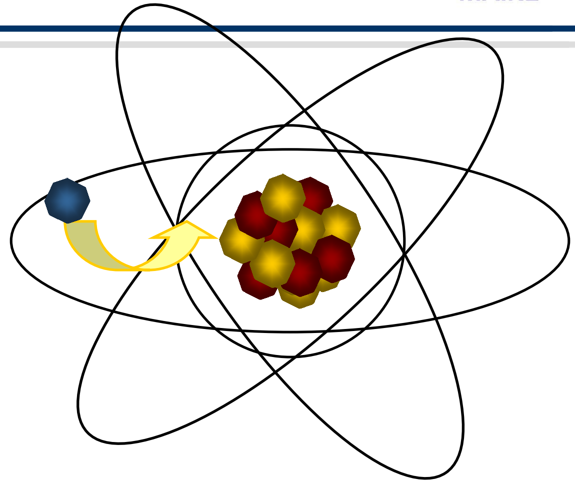
- Ξ^- mean lifetime 0.164 ns

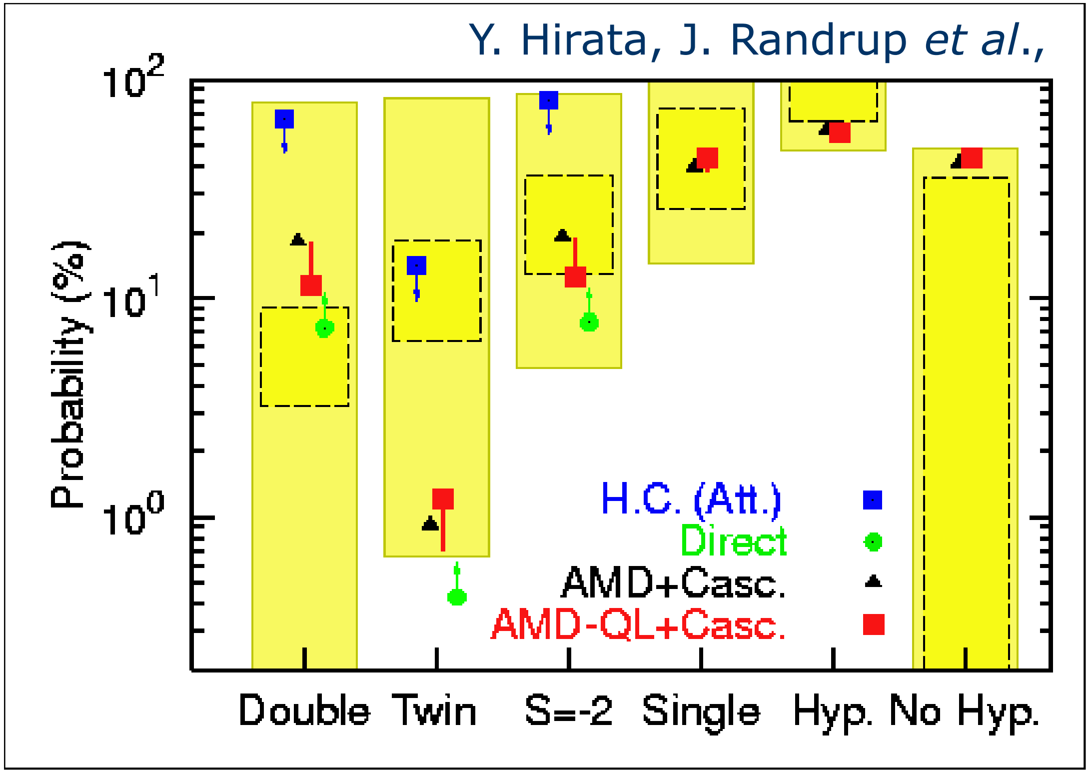


- minimal distance production ⇒capture
- initial momentum 100-500 MeV/c ⇒ range ~ few g/cm^2

Ξ⁻ capture

- Ξ⁻-atoms: x-rays
- conversion
  - **Ξ^-(dss)** p**(uud)** $\Rightarrow$ **Λ(uds) Λ(uds)**
  - ΔQ = 28 MeV
- Conversion probability approximatly 5-10%





Expected Count Rate

- Ingredients (golden events: Ξ^+ trigger)
  - luminosity $2 \cdot 10^{32}$ cm^{-2}s^{-1}
  - $\Xi^+\Xi^-$ cross section 2mb for pp Þ 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^- Þ 3000 / day

  - Ξ^- to $\Lambda\Lambda$–nucleus conversion probability $p_{\Lambda\Lambda} \approx 0.05$
  - total $\Lambda\Lambda$ hyper nucleus production Þ 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
- ~ several 100/day with *KK* trigger

high resolution γ-spectroscopy of double hypernuclei will be feasible

Competition

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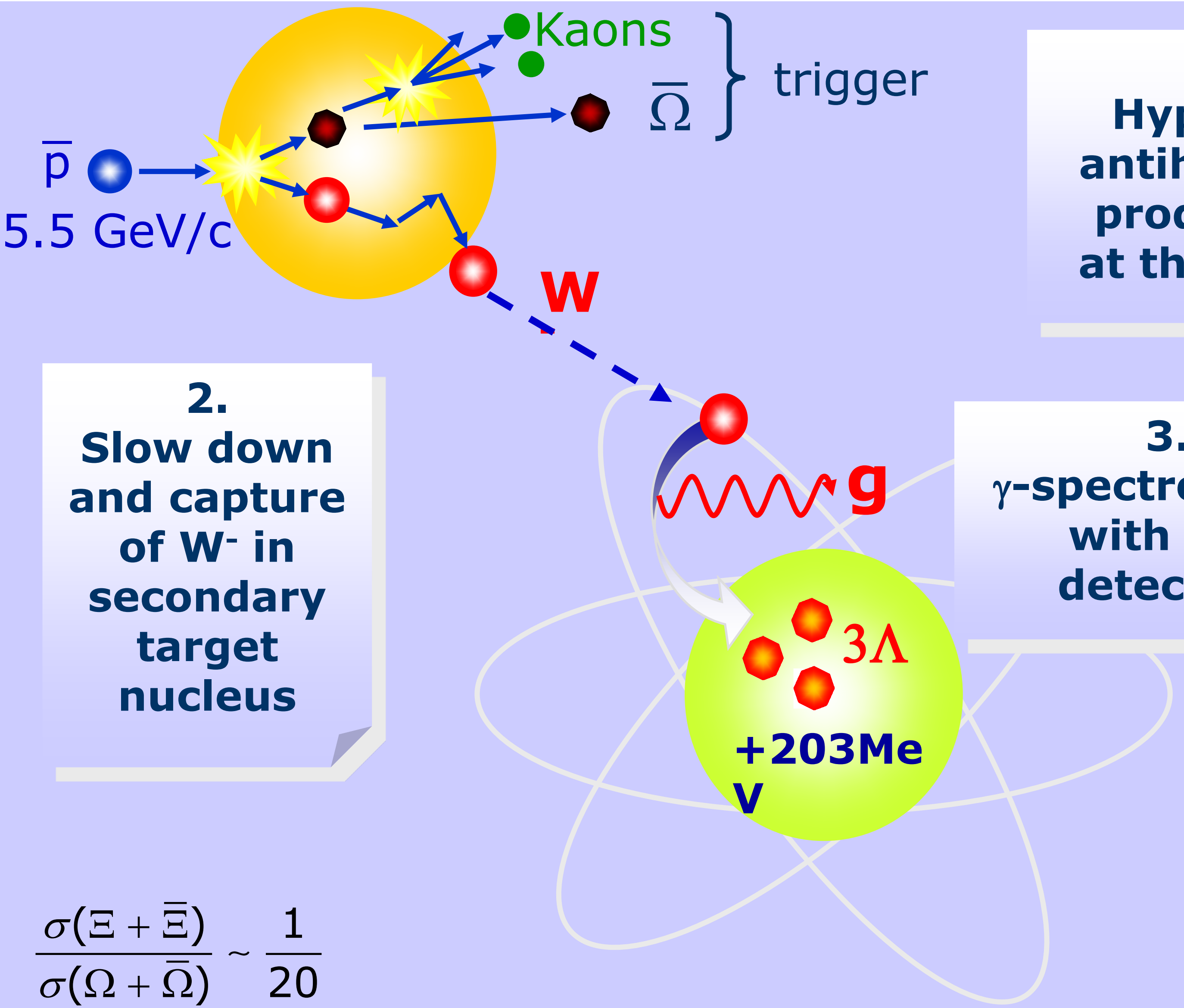
experiment	*reaction*	*device*	*beam/ target*	*status*
BNL-AGS E885	$(\Xi^-, {}^{12}C) \rightarrow {}^{12}_{\Lambda\Lambda}B + n$	neutron detector arrays	K^- beam, diamond target	20000 stopped Ξ^-
BNL-AGS E906	2π decays	Cylindrical Detector System	K^- beam line	few tens 2π decays of ${}^{4}_{\Lambda\Lambda}H$
KEK-PS E373	$(K^-,K^+)\Xi$	emulsion	(K^-,K^+)	several hundreds stopped Ξ^-
facility	*reaction*	*device*	*beam/ target*	*Captured Ξ^- per day*
JHF	$(K^-,K^+)\Xi$	spectrometer, $\Delta\Omega$ =30 msr	$8 \cdot 10^6$/sec 5 cm ^{12}C	<7000
cold anti-protons	$p\bar{p} \rightarrow K^*\bar{K}^*$ $\bar{K}^*N \rightarrow X\,K$	vertex detector	10^6 stopped $\bar{p}$ per sec	2000
GSI-HESR	$p\bar{p} \rightarrow \Xi\bar{\Xi}$	vertex detector + γ-spectrometer	$L=2 \cdot 10^{32}$, thin target, production vertex $\neq$ decay vertex	3000 „golden events" ~ 100000 KK trigger (numbers incl.trigger)

Production of Ω-Atoms



1.
Hyperon-antihyperon production at threshold

2.
Slow down and capture of W⁻ in secondary target nucleus

3.
γ-spectroskopy with Ge-detectors

$$\frac{\sigma(\Xi + \bar{\Xi})}{\sigma(\Omega + \bar{\Omega})} \sim \frac{1}{20}$$

Fundamental Properties of Baryons

- Contributions to *intrinsic* quadrupole moment of baryons
  - One-gluon exchange
  - Meson exchange

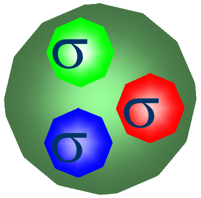
$$Q_i = \int d^3 r \, \rho(r)(3z^2 - r^2)$$

- J=1/2 baryons have no *spectroskopic* quadrupole moment

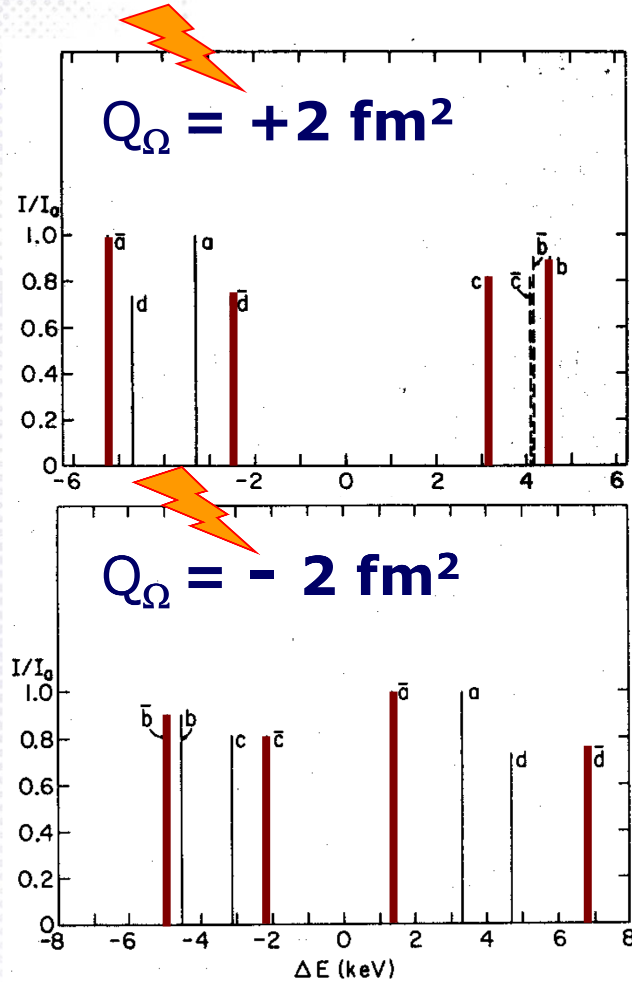
$$Q_s \propto (3J_z^2 - J(J+1)) \xrightarrow[J_z=1/2]{J=1/2} 0$$

- Ω^- Baryon:
  - J=3/2
  - long mean lifetime $0.82 \cdot 10^{-10}$ s
  - only one-gluon contributions to quadrupole moment

  (A.J. Buchmann Z. Naturforsch. **52** (1997) 877-940)



A very strange Atom



R.M. Sternheimer, M. Goldhaber
PRA 8, 2207 (1973)

M.M. Giannini, M.I. Krivoruchenko
Phys. Lett. B 291, 329 (1992)

- Ω atoms by $\Omega\bar{\Omega}$ produktion
- hyperfine splitting in Ω-atom
  $\Rightarrow$ electric quadrupole moment of Ω

spin-orbit	$\Delta E_{ls} \sim (aZ)^4\, l \cdot m_\Omega$
quadrupole	$\Delta E_\Theta \sim (aZ)^4 Q m^3_\Omega$

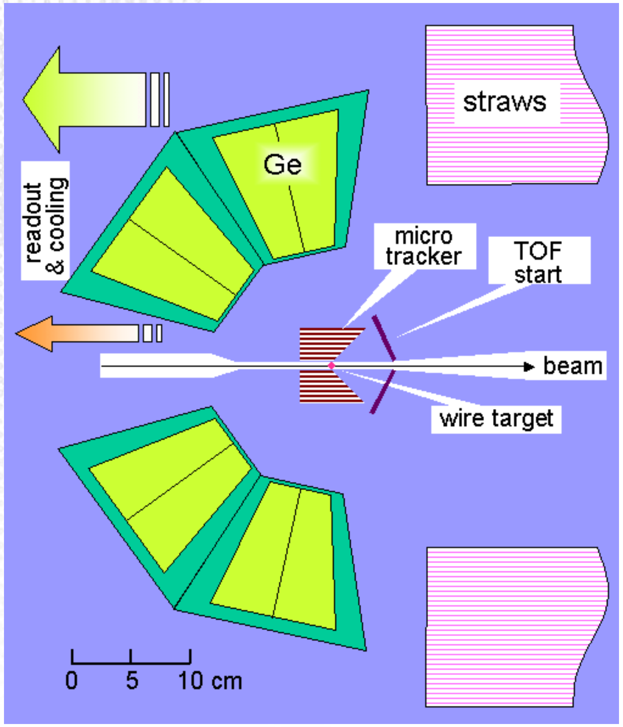
- prediction Q_Ω = (0 - 3.1) 10^{-2} fm²
- E(n=11, l=10 $\rightarrow$ n=10, l=9) ~ 520 keV
  - calibration with 511keV line!
- ΔE_Θ ~ few tenth of keV for Pb

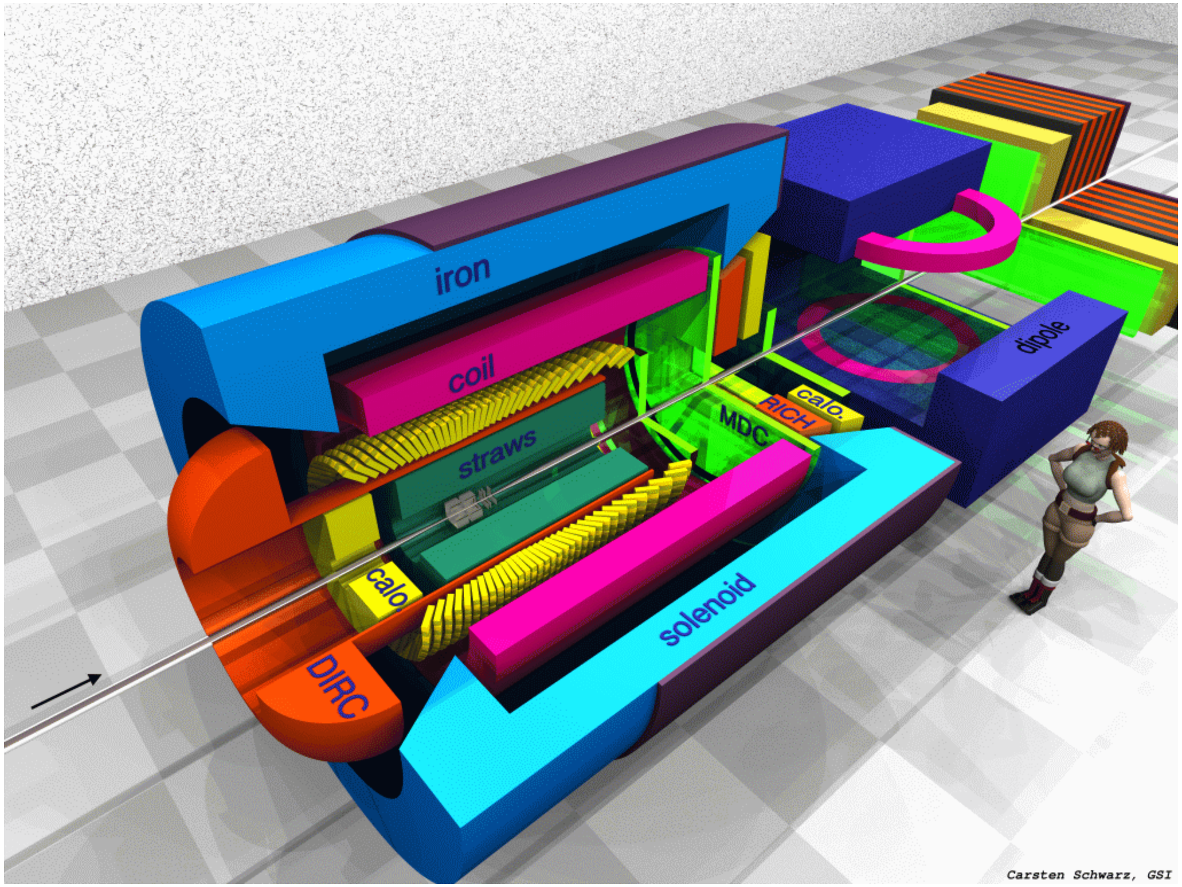
close to 511keV

with high resolution γ-spectroscopy difficult
but feasible if statistics sufficient

The PANDA Detector

- hermetic (4π)
- high rate
- PID (γ, e, μ, π, K, p)
- trigger (e, μ, K, D, Λ)
- compact (€)
- modular





- Solid state-micro-tracker
  - thickness ~ 3 cm
- High rate germanium detector

4. $\Xi(1860)$ search in WA89

NA49: Ξ⁻⁻ Pentaquark

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Observation of an Exotic S = −2, Q = −2 Baryon Resonance in Proton-Proton Collisions at the CERN SPS

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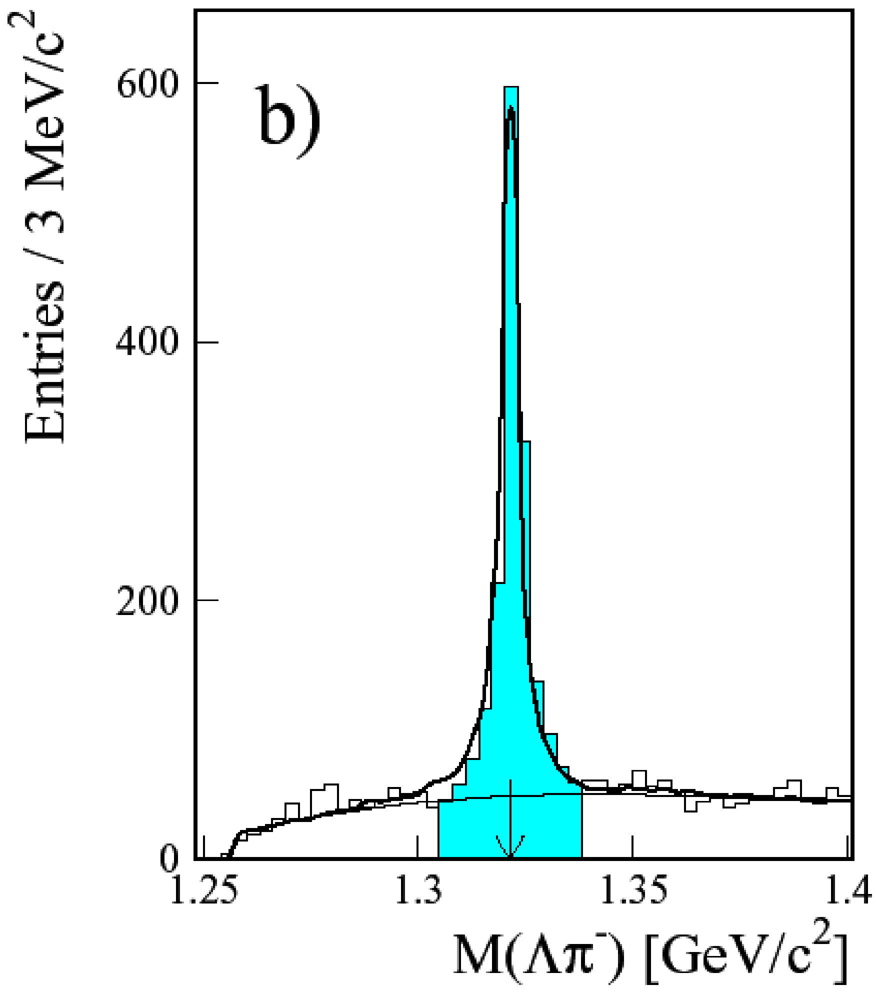
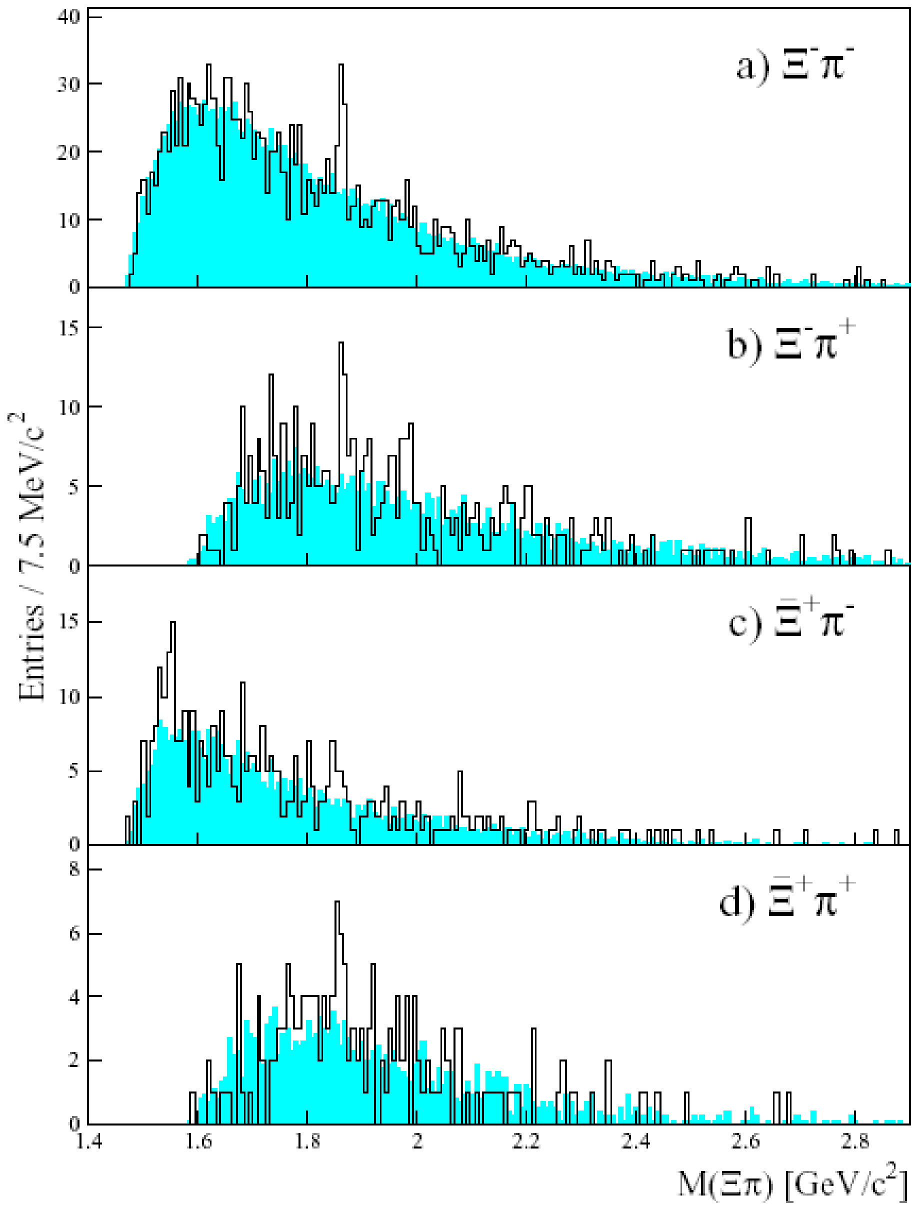
Ξ^- in NA49

- distance between primary and secondary vertex 12cm
- additional cuts on track impact position and angle
- 1640 Ξ^- events
- 551 anti-Ξ^+ events



- Ξ^- combined with primary π^-
- $\theta(\pi-,\Xi^-)>4.4°$
- $p(\pi+)>3GeV/c$
- ...several additional cuts



The WA89 Experiment

- Σ^- and π- beam of 340 GeV/c, n-beam of 260 GeV/c
- 1993, 1994 data taking
- $4 \cdot 10^8$ interactions

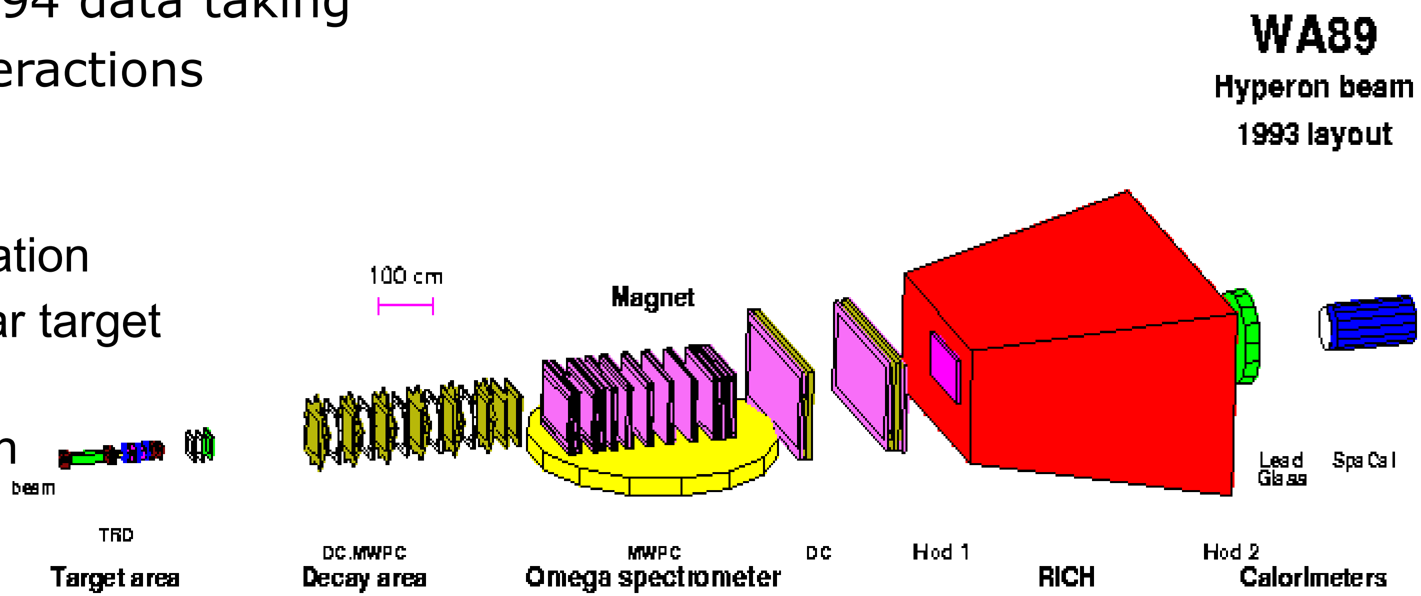
TRD: beam identification

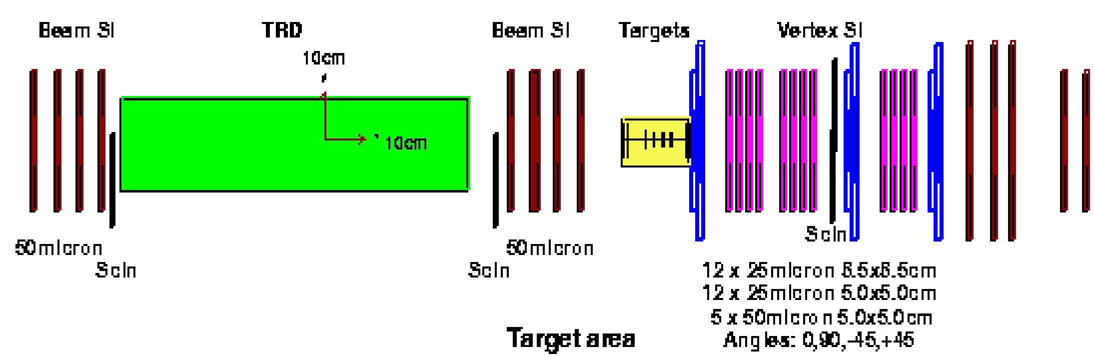
Si-µ-strip vertex near target

MWPC: tracking

RICH: π/K separation

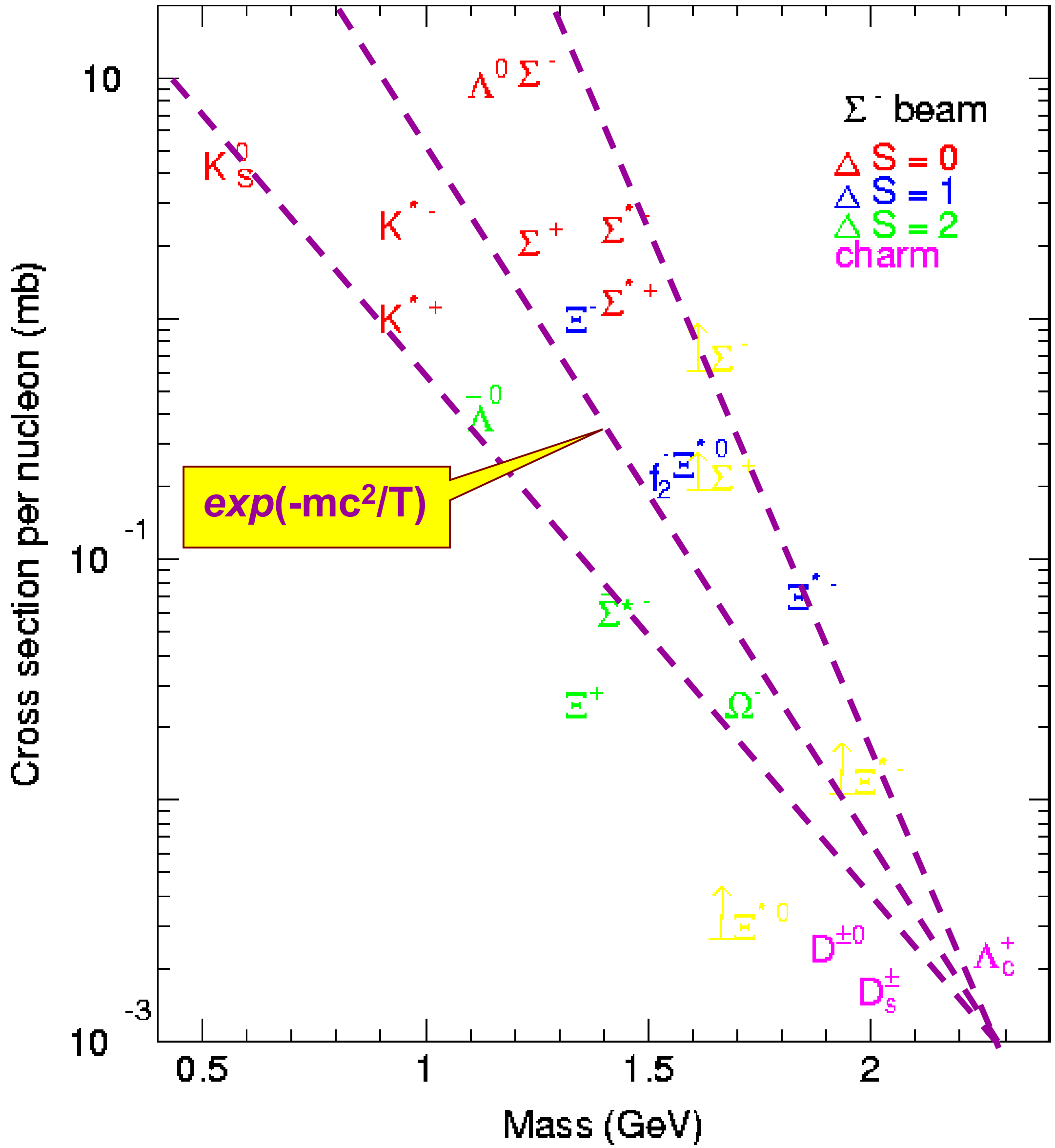
Calorimeter: e,γ, n





Cross sections

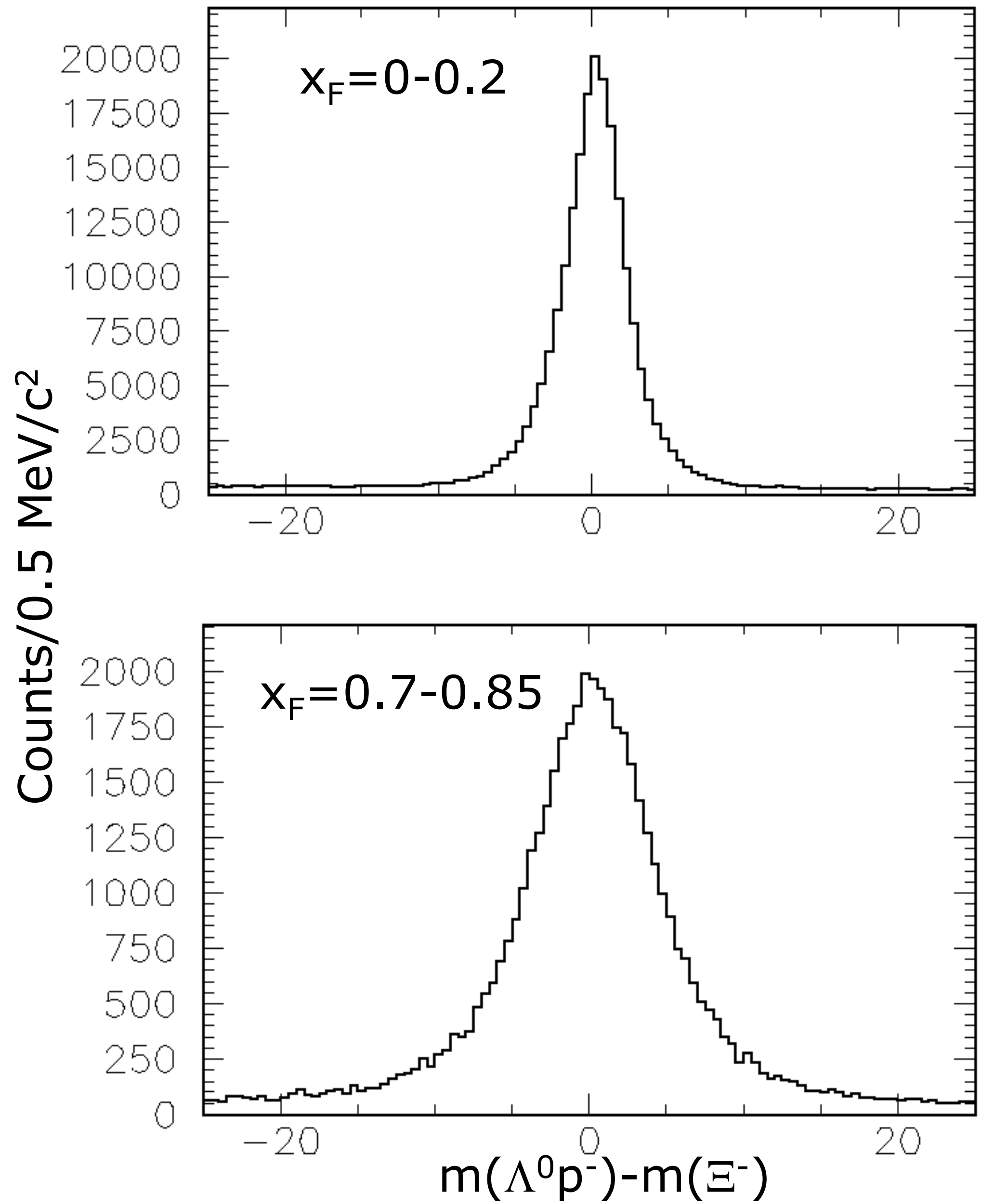
- more than 20 different strange hadrons are analyzed under identical conditions
- typical statistical distribution with slope ~ 150 MeV



Ξ^- Mass Spectrum

- Ξ^- Þ $\Lambda^0 \pi^-$

  ↪ $p\, \pi^-$

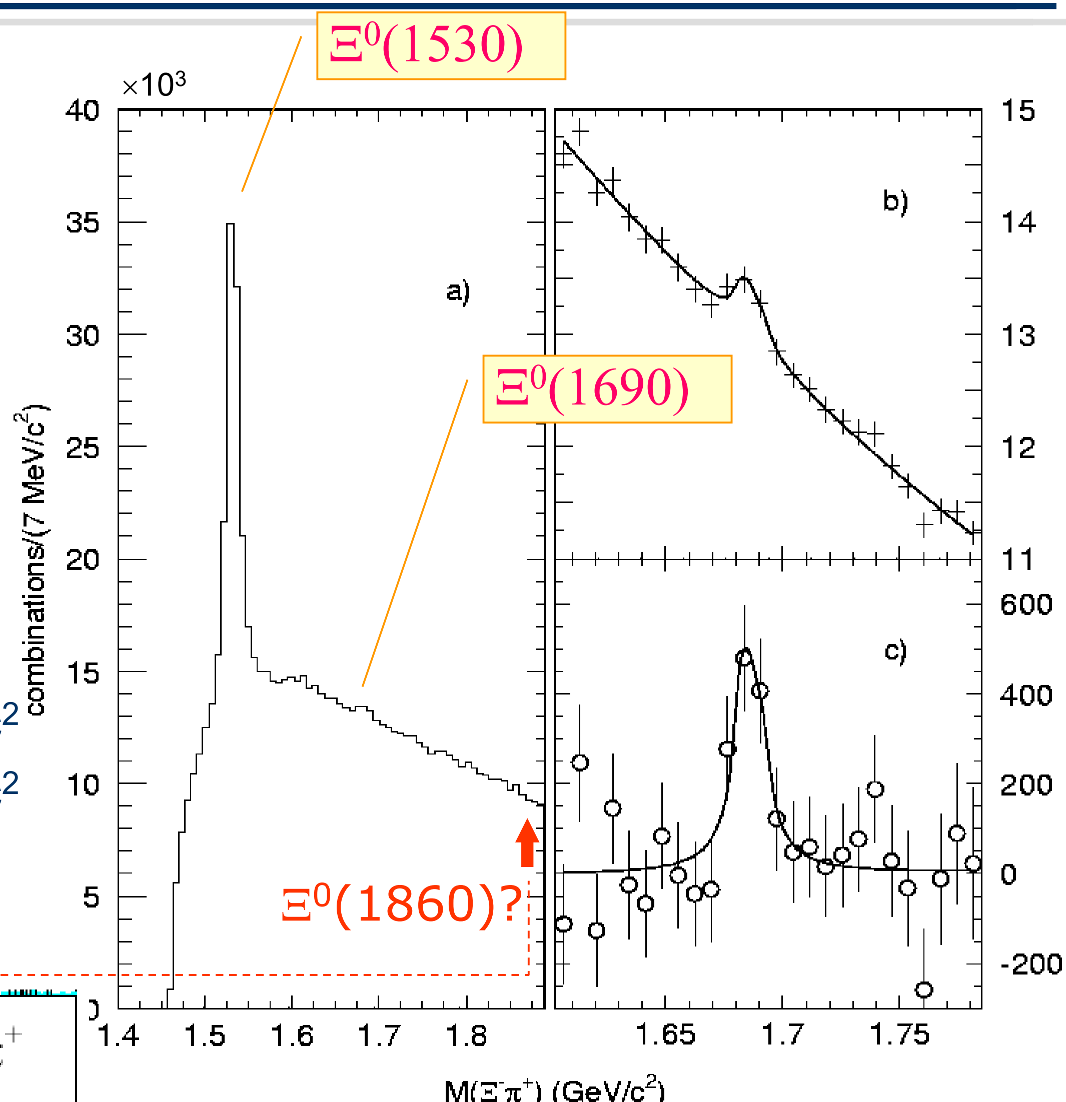


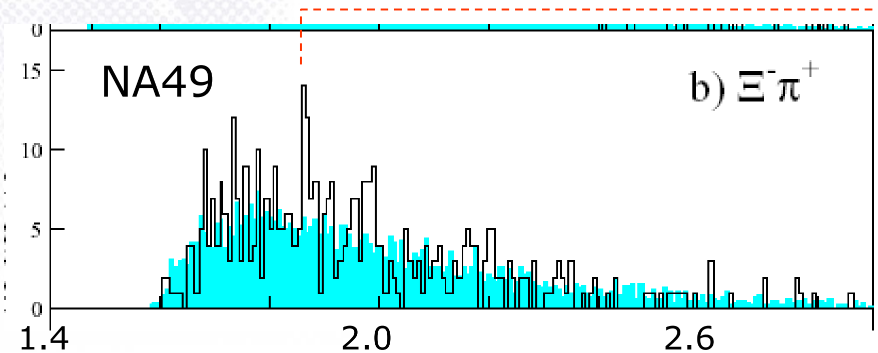
$\Xi^{*0}(1690) \rightarrow \Xi^-\pi^+$

- $\Xi^{*0}(1690) \rightarrow \Xi^- \pi^+$
  - $\hookrightarrow \Lambda^0 \pi^-$
    - $\hookrightarrow p\, \pi^-$

- $M(\Xi^{*0}) = 1685 \pm 4$ MeV/c²
- $\Gamma = 10 \pm 6$ MeV/c²
- $\sigma \cdot BR = 6.8 \pm 0.2 \mu b$
- $M(\Xi^{*-}) - M(\Xi^{*0}) =$
  - $\Delta(\Xi_{1690}) = 6 \pm 5$ MeV/c²
  - $\Delta(\Xi_{1530}) = 6.4 \pm 0.6$ MeV/c²
  - $\Delta(\Xi_{1320}) = 3.2 \pm 0.6$ MeV/c²

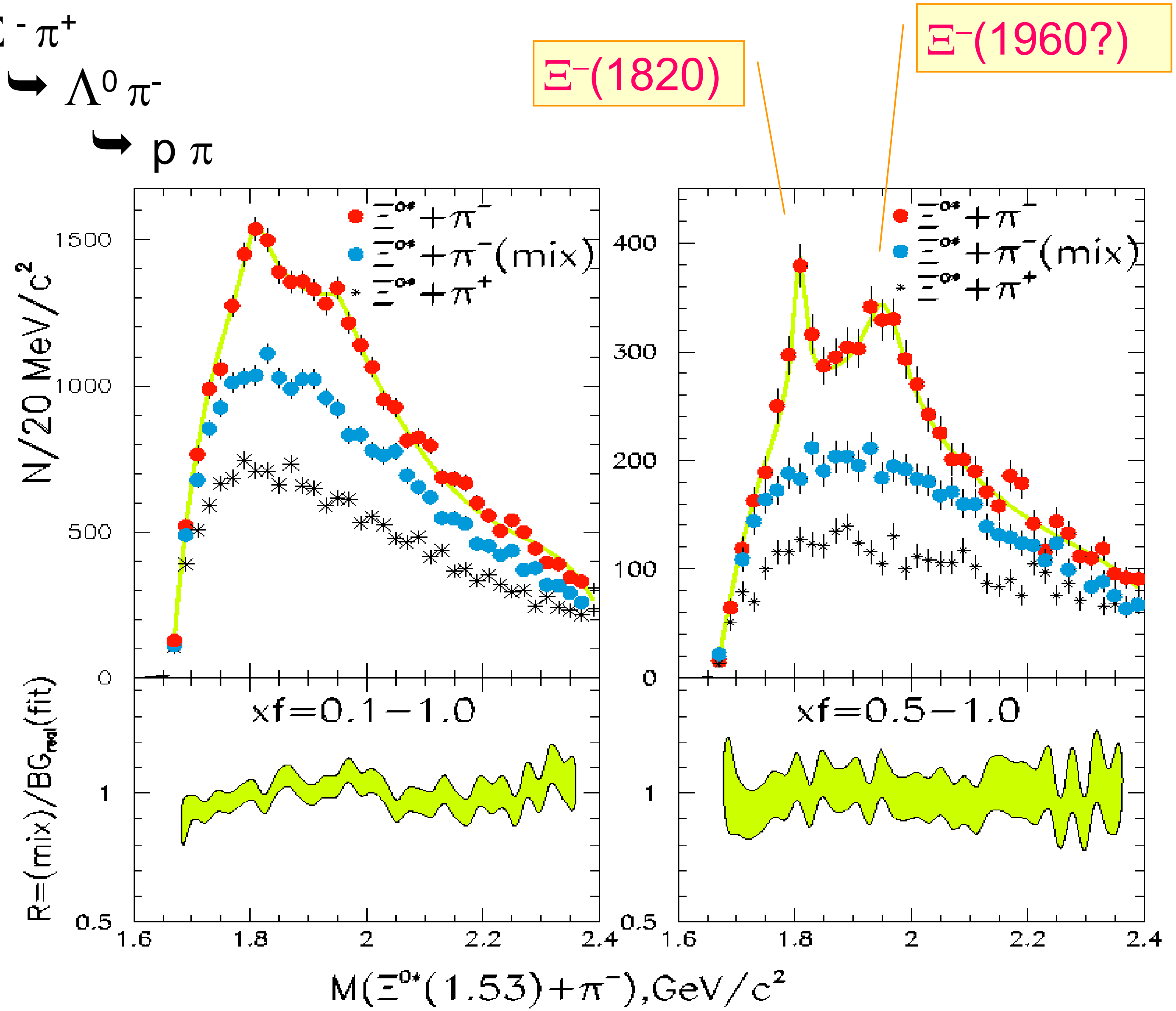
Euro. Phys. J. C **5**, 621 (1998)



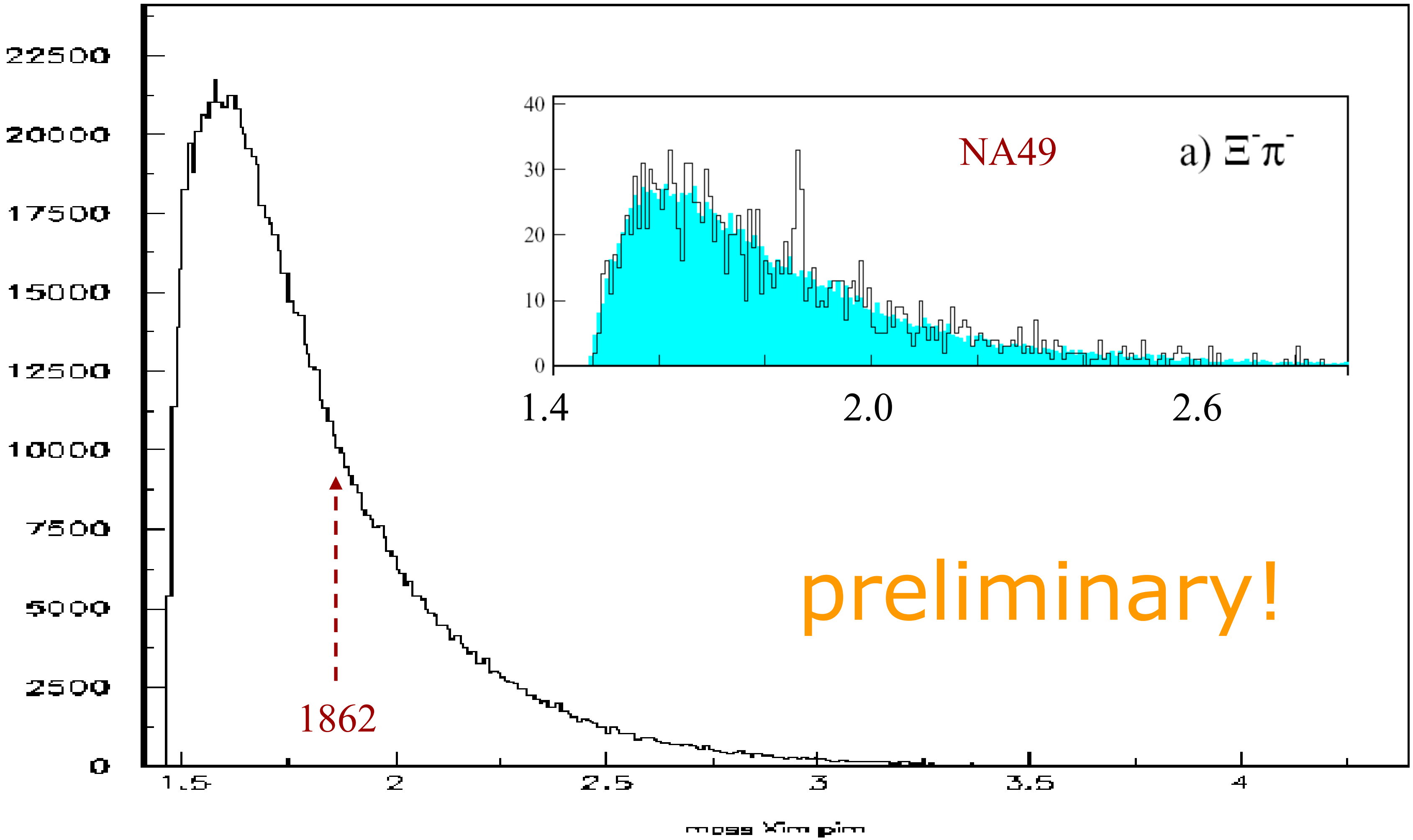


$\Xi^*(1820)$ and $\Xi^*(1960)$ Production

- Ξ^{*-} Þ $\Xi^{*0}(1530)\ \pi^-$ Eur. Phys. J. C11, 271 (1999)
  - ➥ $\Xi^-\pi^+$
    - ➥ $\Lambda^0\ \pi^-$
      - ➥ p π



$\Xi^- \pi^-$



- further cuts on p_t, x_F, θ_{cm}
- additional (justified) cuts?
- ...more to come

Summary

- Hypernuclear Physics is getting mature after 50 years

- MAMI-C is on track

- PANDA and HESR will enable high statistics double hypernuclear physics
  - many questions to answer, many problems to solve
  - comments, suggestions, help... are very welcome

See you all

in Mainz

2006