BARYONS AND ANTIBARYONS IN COLD NUCLEI

- INTRODUCTION
- EXOTIC SINGLE HYPERNUCLEI
- DOUBLE HYPERNUCLEI
- CONCLUSION

INTRODUCTION

Nomenclature

- a hypernucleus is specified by
  - the number of neutrons N
  - the number of protons Z
  - the number of hyperons Y

number of baryons N+Z+Y

(number of) hyperons Y

$${}^{B}_{Y}X$$

element = total charge (not number of protons)

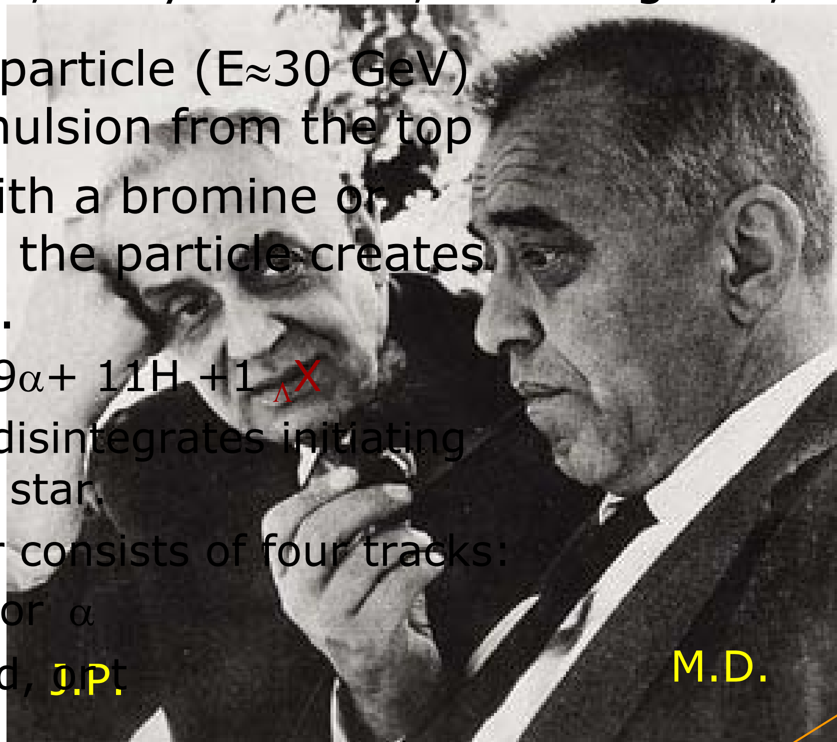
- since we have more than one hyperon (Λ, Ξ^-, Σ^{-+0}) one usually writes explicitely the symbols of one (or more) hyperon
- examples:

$${}^{10}_{\Lambda\Lambda}Be \rightarrow \begin{cases} Be & \rightarrow \text{4 protons} \\ \Lambda\Lambda & \rightarrow \text{2 lambdas} \\ 10 & \rightarrow \text{10-4-2=4 neutrons} \end{cases}$$

$${}^{4}_{\Sigma}He \rightarrow \begin{cases} 1p + 2n + 1\Sigma^{+} \\ 2p + 1n + 1\Sigma^{0} \\ 3p + 0n + 1\Sigma^{-} \end{cases} \quad \text{indistinguishable}$$

How it began

- Marian Danysz, Jerzy Pniewski *et al.;* Bull. Acad. Pol. Sci.**1**, 42 (1953)
- Marian Danysz, Jerzy Pniewski, Phil. Mag. **44**, 348 (1953)

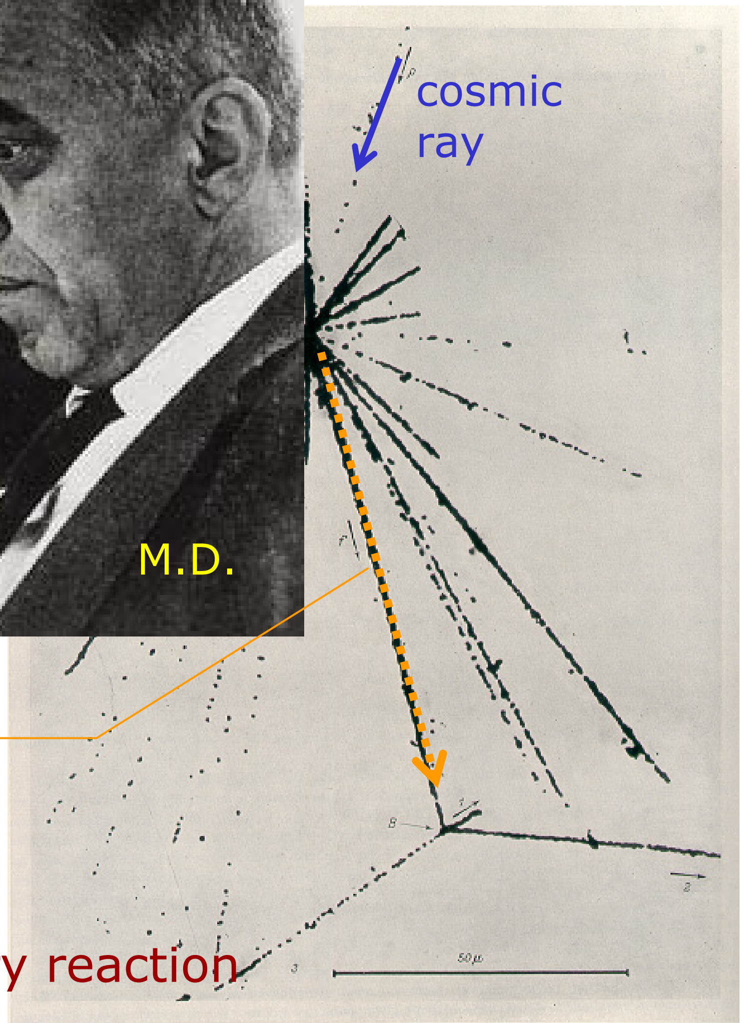


- A cosmic ray particle (E≈30 GeV) enters the emulsion from the top
- Interacting with a bromine or silver nucleus the particle creates an upper star.
  - 21 tracks: 9α+ 11H +1 $_\Lambda X$
  - Finally, $_\Lambda X$ disintegrates initiating the bottom star.
  - second star consists of four tracks:
    - 2 p,d,t or α
    - 1 π, p, d, or t
    - 1 recoil
  - energy release >140MeV

$$t > \frac{s}{c} \sim \frac{80\mu m}{300000 km/s} \approx 2.6 \cdot 10^{-13} s$$

$$\tau(\Lambda) = 2.6 \cdot 10^{-10} s$$

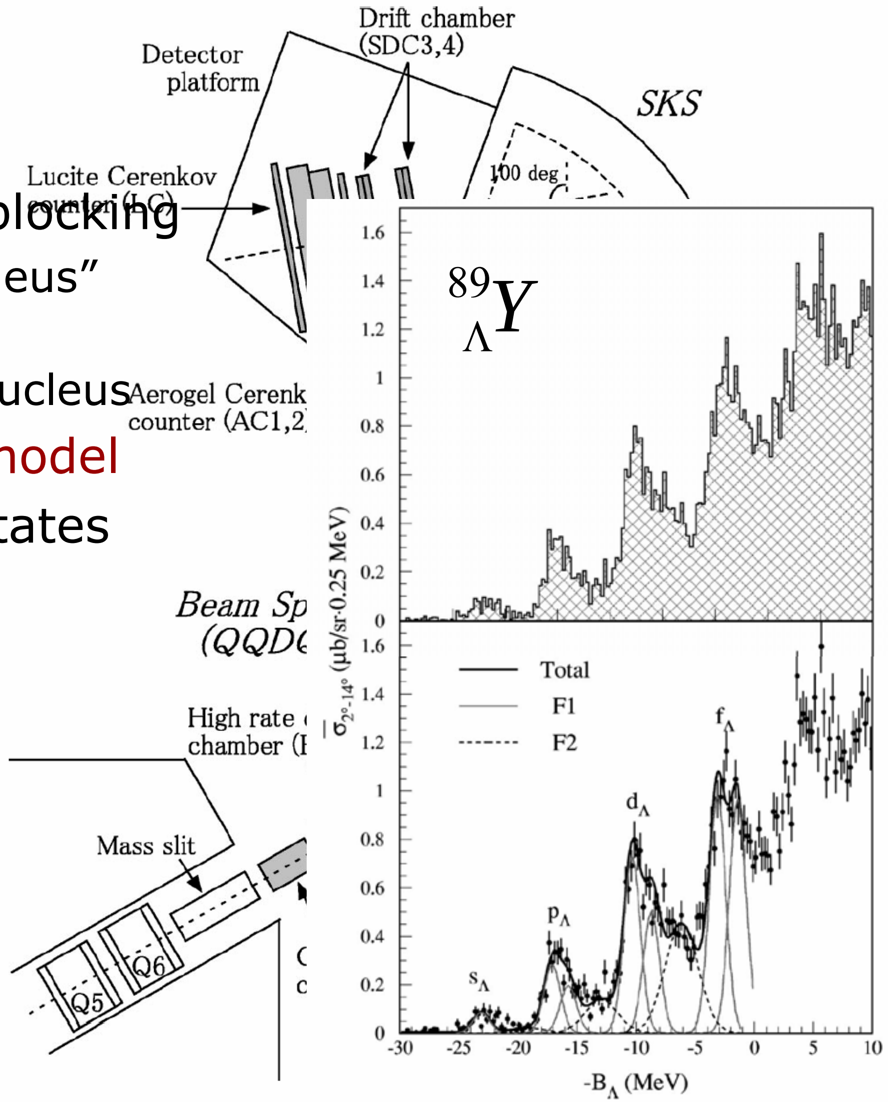
$\Rightarrow$ typical for weak decay



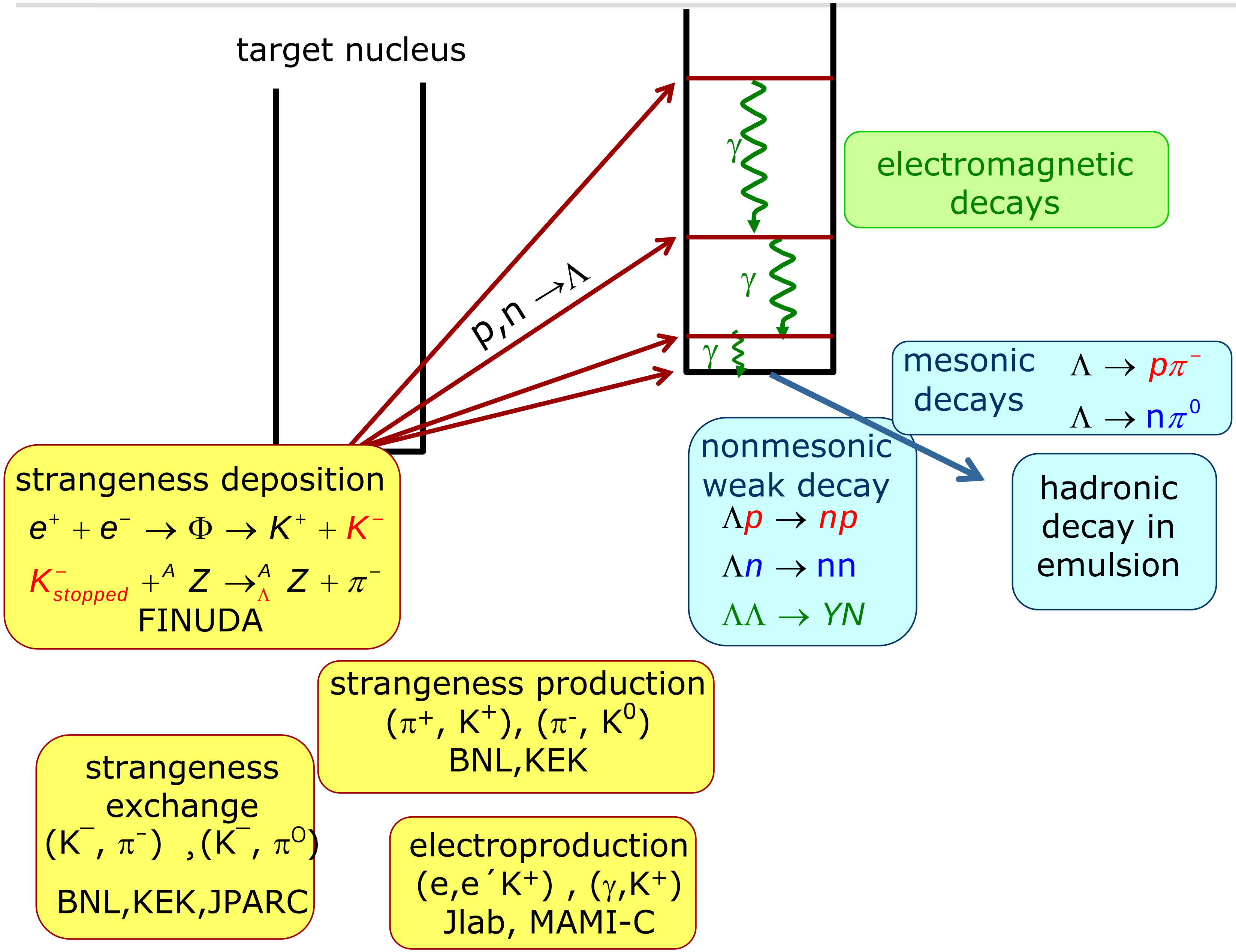
- many associated particles in primary reaction

Single Particle States in Nuclei

- H. Hotchi *et al.*, PRC 64, 044302 (2001)
- KEK, Superconduction Kaon Spectromter (SKS)
- P_π=1.05GeV/c, $p_K \approx$0.72GeV/c
- Hyperons are free from Pauli blocking
  - can stay at the "center of nucleus" (especially for Λ)
  - is a good probe for depth of nucleus
- confirmation of nuclear shell model
- deeply bound single particle states
- small spin-orbit interaction

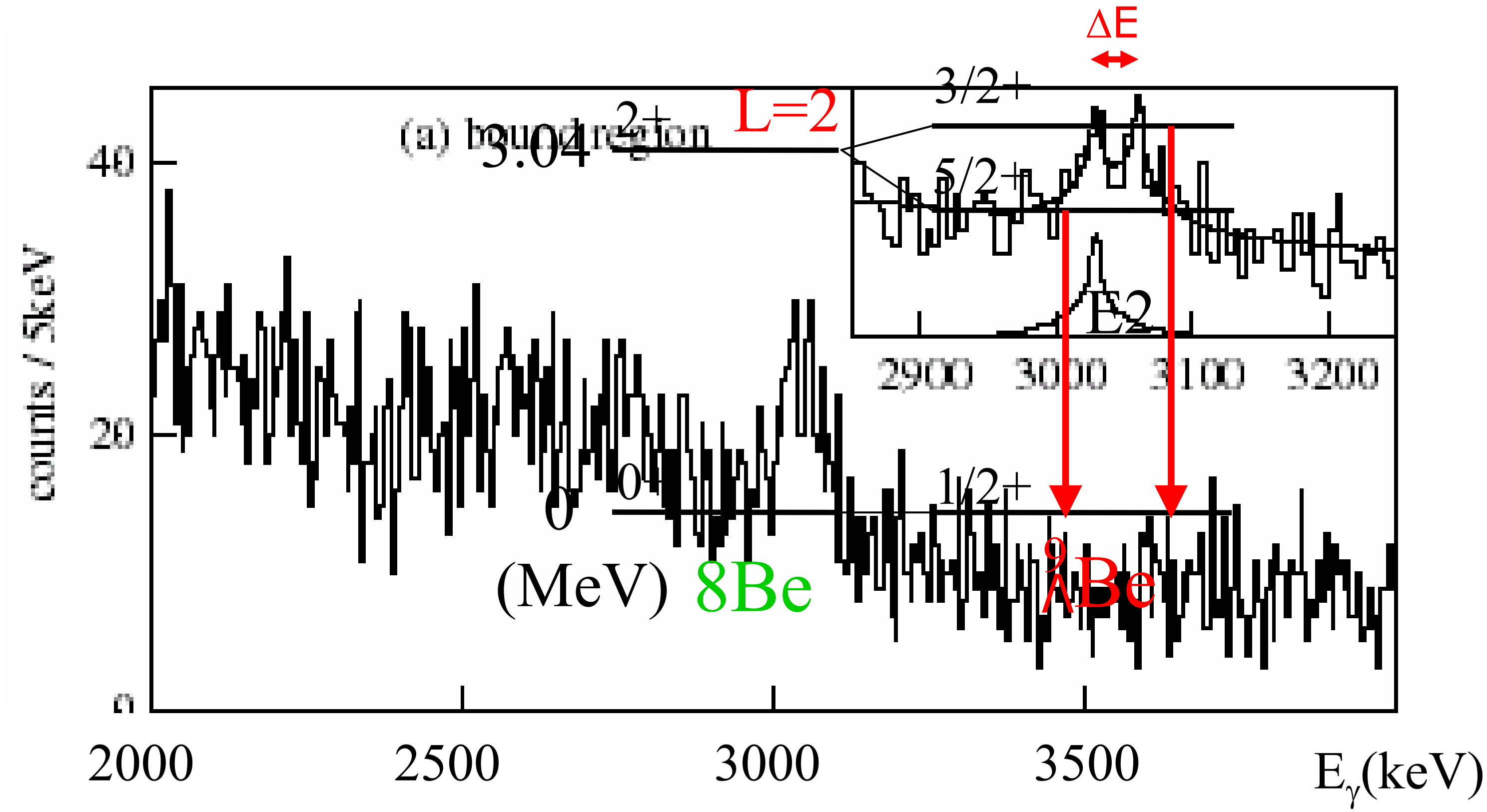


Birth, life and death of a hypernucleus



Spin-Orbit Force

- BNL AGS E930; H. Akikawa et al., PRL88(2002)082501
- γ ray from ${}^{9}_{\Lambda}Be$ created by ^{9}Be(K^{-},π^{-}) reaction
- ΔE(5/2^{+},3/2^{+}) $\Rightarrow$ ΛN spin-orbit force, LS
  (core structure: 2α rotating with L=2)



- |ΔE| = 31$\pm$3 keV
- surprisingly small spin-orbit force (~ 1/100 of NN case)

Traditional Approach to Nuclear Structure

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- Structureless protons and neutrons : interact through 2-, 3- and 4-body forces (usually non-relativistic)
- NN force has origin in Yukawa’s meson-exchange model (simple Heisenberg uncertainty principle)
- Add observed form factors (e.g. electromagnetic) by hand….
  i.e. un-modified in-medium
- Saturation of nuclear matter a result of phenomenological “hard core” of NN force (ω-meson exchange repulsive)

ΛN Spin dependent interaction

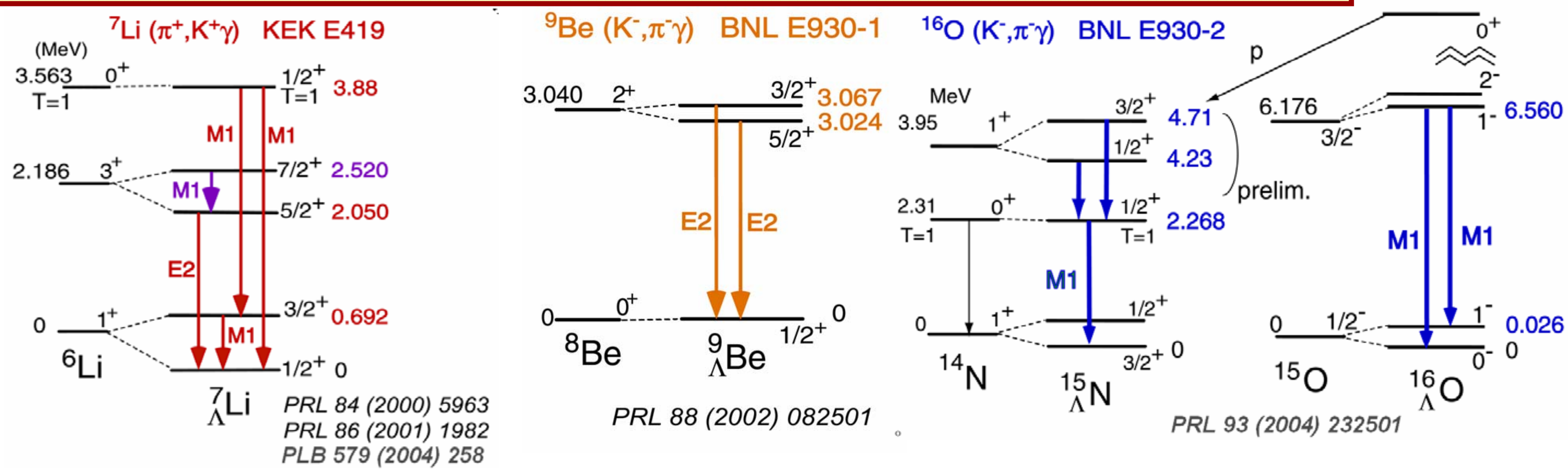
- Phenomenological two-body ΛN effective interaction
  - Dalitz and A. Gal, Ann. Phys. 116, 167 (1978)
  - D.J. Millener *et al.*, Phys. Rev. C31, 499 (1985)
  - V.N. Fetisov *et al.*, Z. Phys. A 339, 399 (1991)
- Consider Λ in 0s orbit interacting with p-shell core

  ⇒ 4 radial integrals

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

$^7_\Lambda$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**



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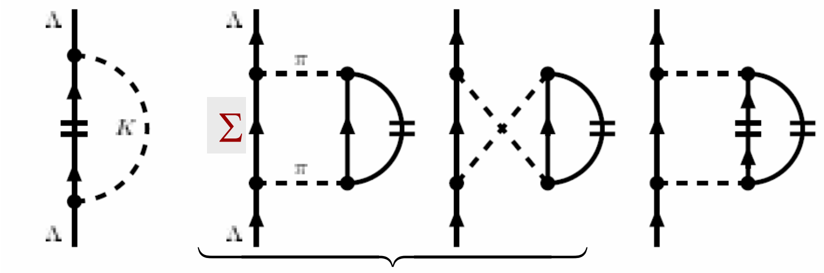
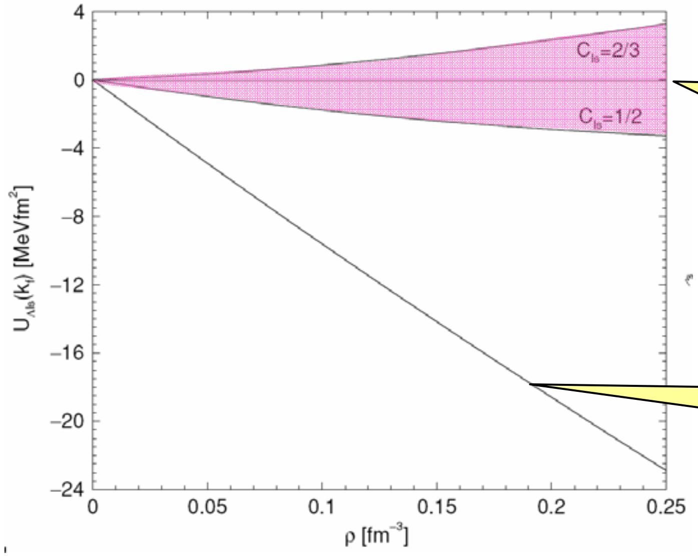
- Modern version is Effective Field Theory…..

Example: spin-orbit interaction

- Many attempts to understand small spin-orbit interaction
  - one-boson exchange ΛN potentials overestimate spin-orbit splitting
  - many different approaches – often introducing additional parameters
- more recent: in-medium effective field theory, e.g.
  - N. Kaiser and W. Weise, PRC 71, 105203 (2005)



$$U_\Lambda(\rho_0) = (+4.17 \quad -39.77 \quad +7.46)\,\text{MeV} = -28.15\,\text{MeV}$$

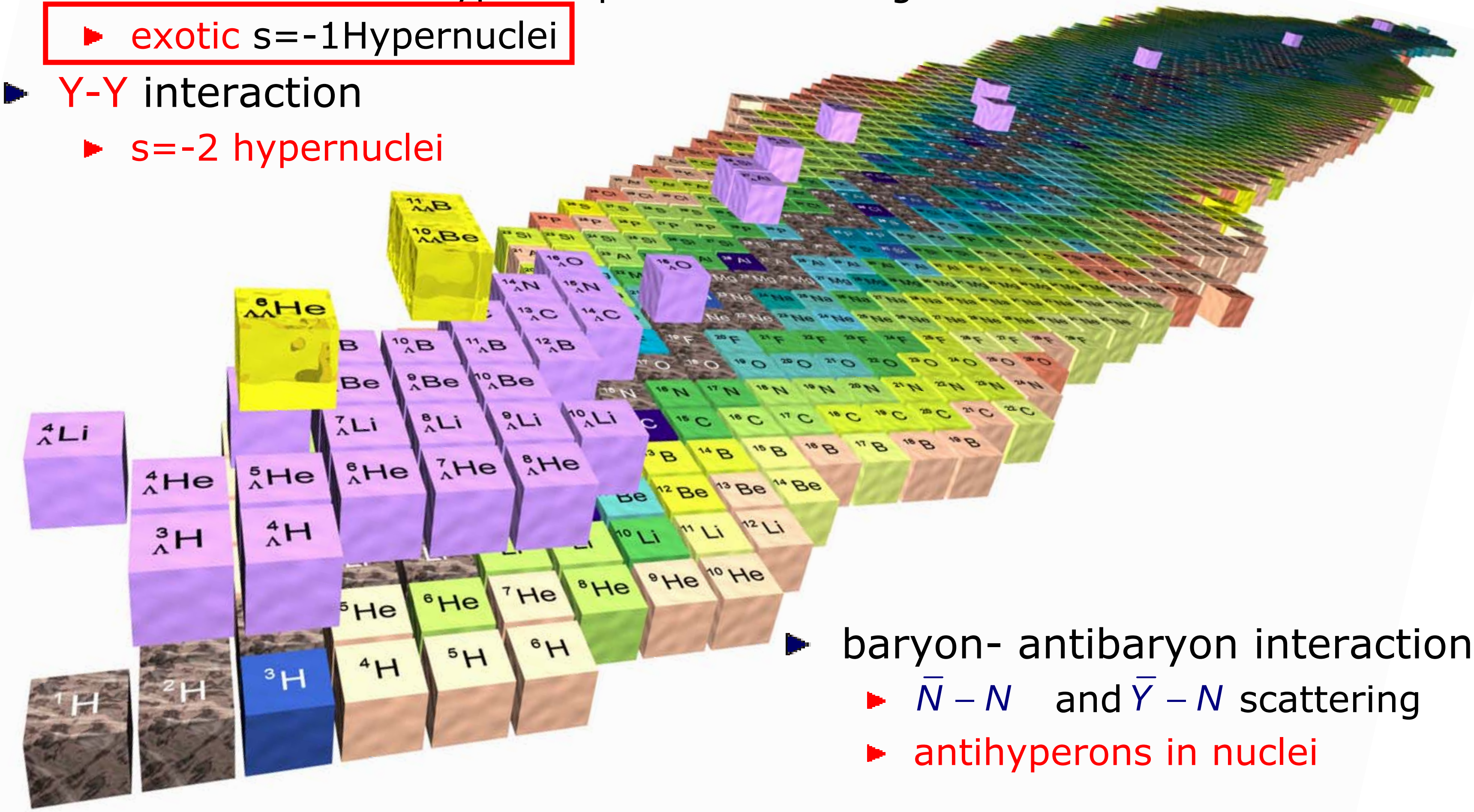


long- range 2π +short-range contribution

long- range 2π contribution only

Baryon-baryon interaction

- N-N interaction
  - N-N scattering
  - ordinary nuclei
- Y-N interaction
  - low momentum hyperon-proton scattering
  - exotic s=-1Hypernuclei
- Y-Y interaction
  - s=-2 hypernuclei



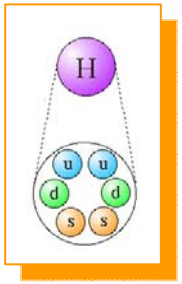
- baryon- antibaryon interaction
  - $\bar{N}-N$ and $\bar{Y}-N$ scattering
  - antihyperons in nuclei

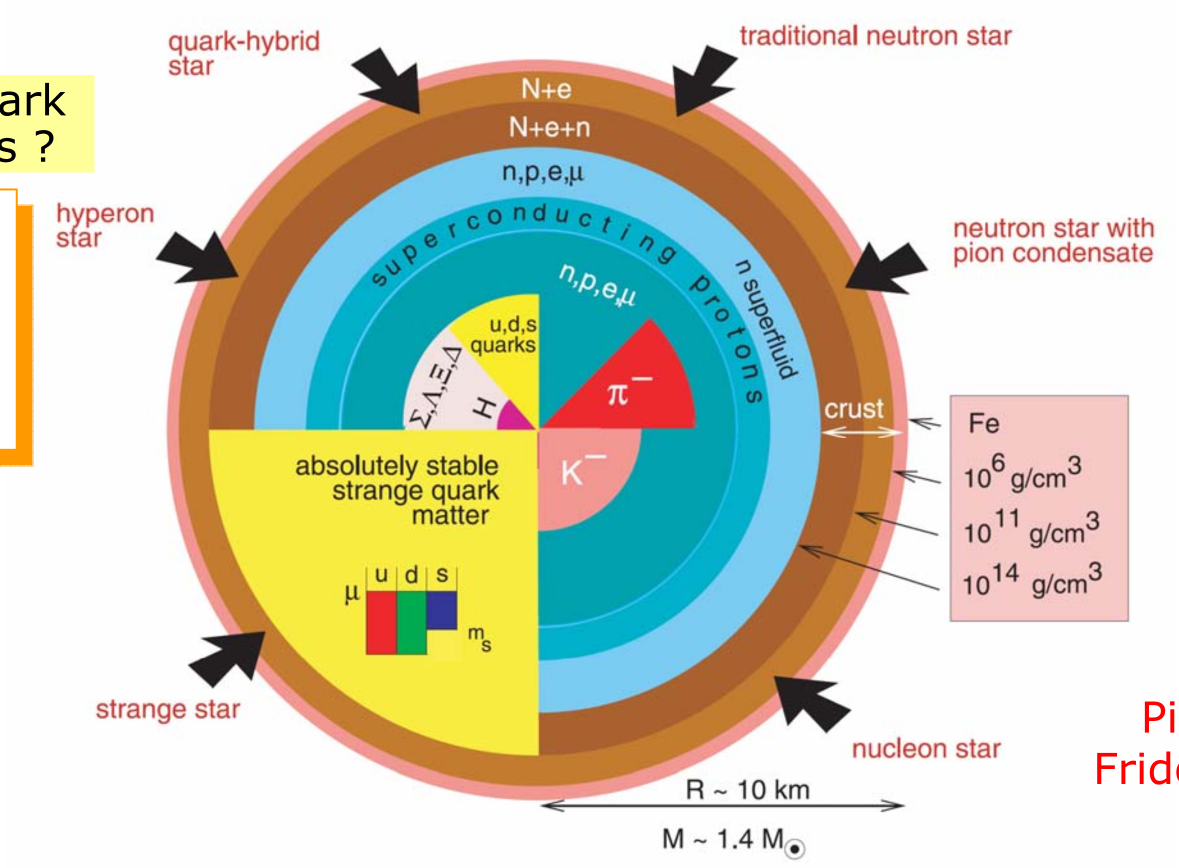
EXOTIC (SINGLE) HYPERNUCLEI

Exotic Hypernuclei

- „Neutronstars":
  - at about $2\rho_0$ hyperons may play a role in neutron stars
  - consequence: softer EOS $\Rightarrow$ lower mass and smaller radii

exotic quark structures ?



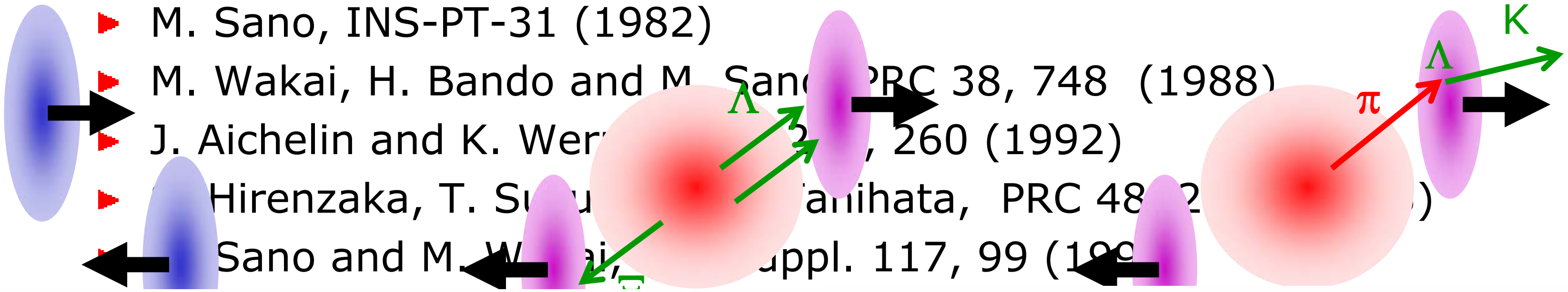


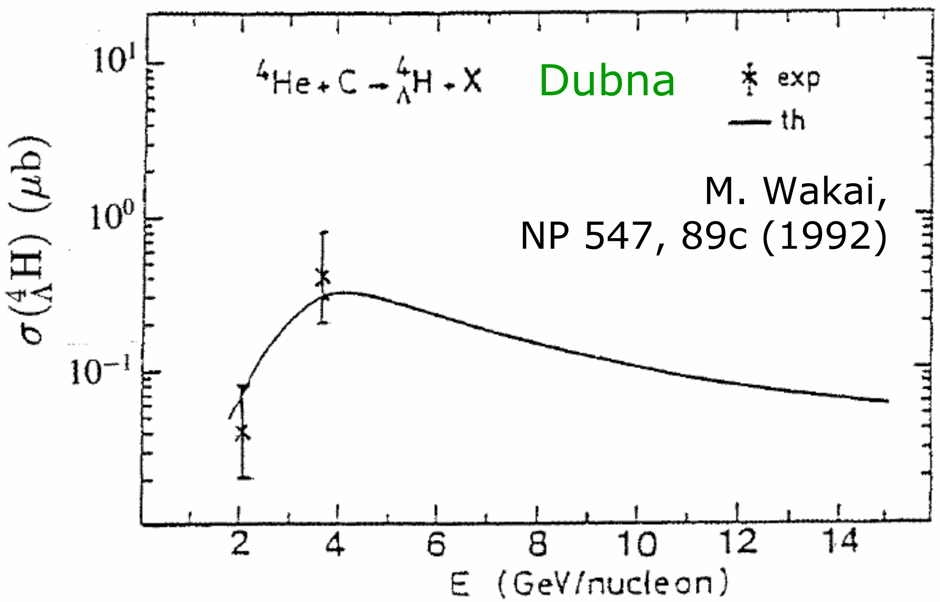
Picture from Fridolin Weber

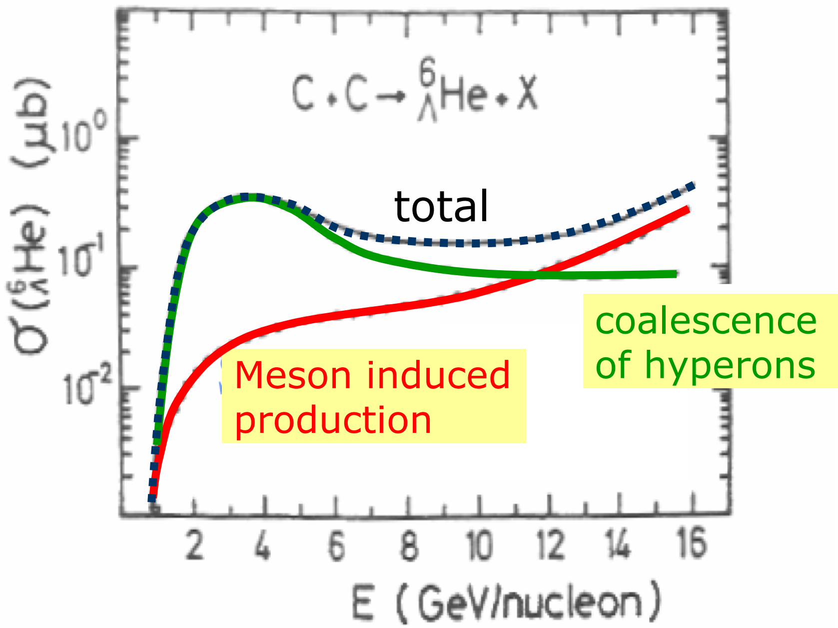
- Isospin dependence of Y-N and Y-Y interaction?
  $\Rightarrow$ Information on hyperons in neutron rich matter/nuclei needed

Relativistic Hypernuclei

- 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
- Many predictions based on coalescence model
  - M. Sano, INS-PT-31 (1982)
  - M. Wakai, H. Bando and M. Sano, PRC 38, 748 (1988)
  - J. Aichelin and K. Wer… 260 (1992)
  - …Hirenzaka, T. Su… …anihata, PRC 48…
  - …Sano and M. W…ai, … …uppl. 117, 99 (19…







Magnetic moment

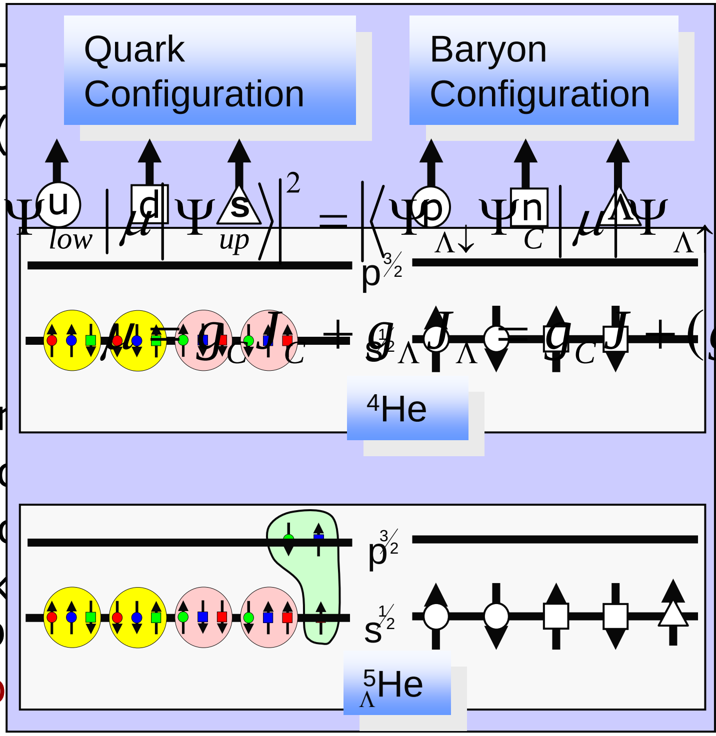
- Baryons do not „melt" in nuclei: quark effects are small
- EMC-effect: Whether there is any change in nucleon properties in nuclei remains controversial.
  - If mass and size of a baryons changes inside nuclei, also it's magnetic moment might change
  - Magnetic moment may be a sensitive probe of hyperon properties in nuclear matter
  - If so, why? Meson current, $\Lambda\Sigma$ mixing, partial deconfinement…?
- Experiment
  - B(M1) (

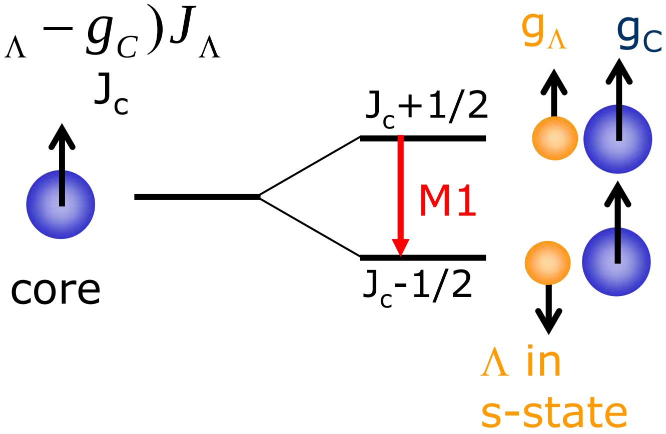
$$B(M1) \propto \left|\left\langle \Psi_{low} \left| \mu \right| \Psi_{up} \right\rangle\right|^2 = \left|\left\langle \Psi_{\Lambda\downarrow}\Psi_C \left| \mu \right| \Psi_{\Lambda\uparrow}\Psi_C \right\rangle\right|^2 \propto (g_\Lambda - g_C)^2$$

$$\mu = g_C J_C + g_\Lambda J_\Lambda = g_C J + (g_\Lambda - g_C) J_\Lambda$$

    - M1 tr
  - Spin prec
    - Λ dec
    - Work doub

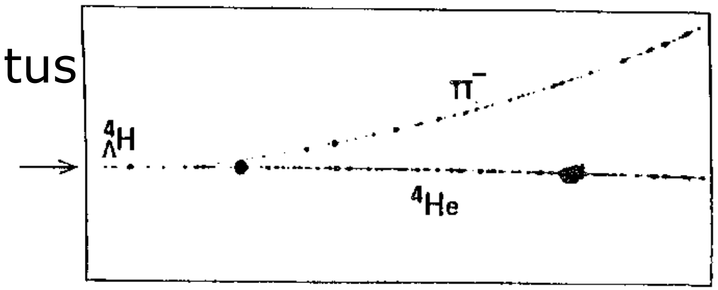
g$_\Lambda$ do



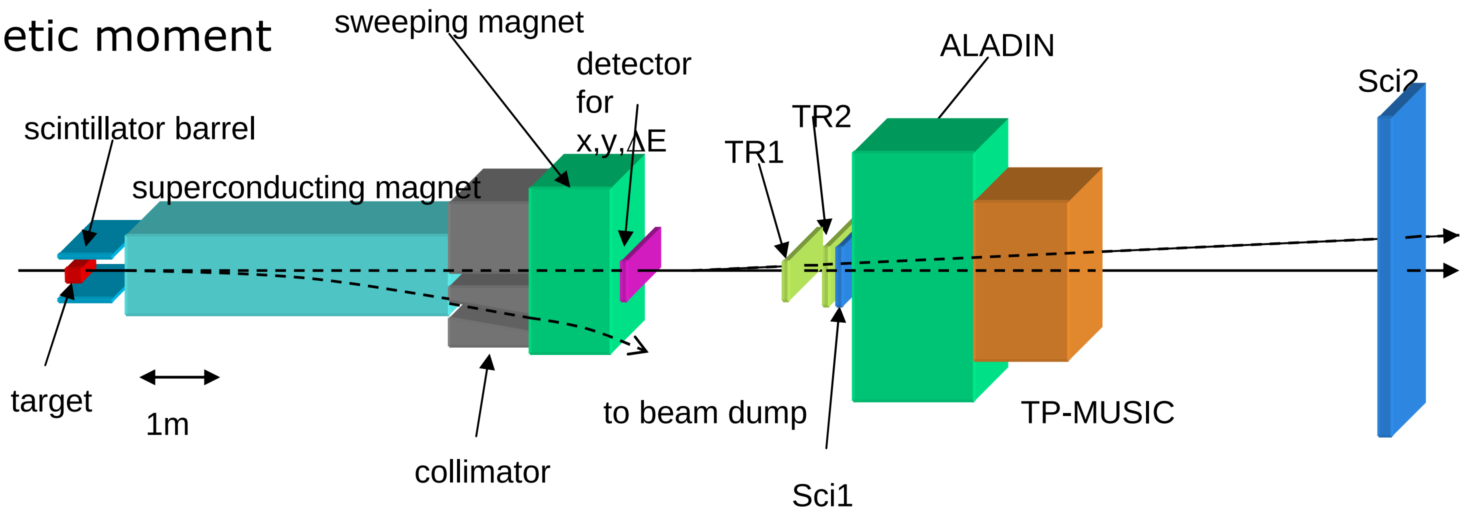


HypHI Project

- Hypernuclear Spectroscopy with Stable Heavy-Ion beams and RI-beams at GSI
  - spokesperson: T. Saito
  - GSI PAC in February 2005
  - GSI scientific council in May 2005
- Phase 0: SIS beam and existing apparatus
  - ⇒ verification of 1989 Dubna data



- Phase 1: SIS+FRS
  - ⇒ proton rich hypernuclei
- Phase 2: FAIR+R3B@NUSTAR
  - ⇒ neutron-rich hypernculei
- Phase 3: FAIR+Hypernuclei Separator
  - ⇒ magnetic moment



DOUBLE HYPERNUCLEI

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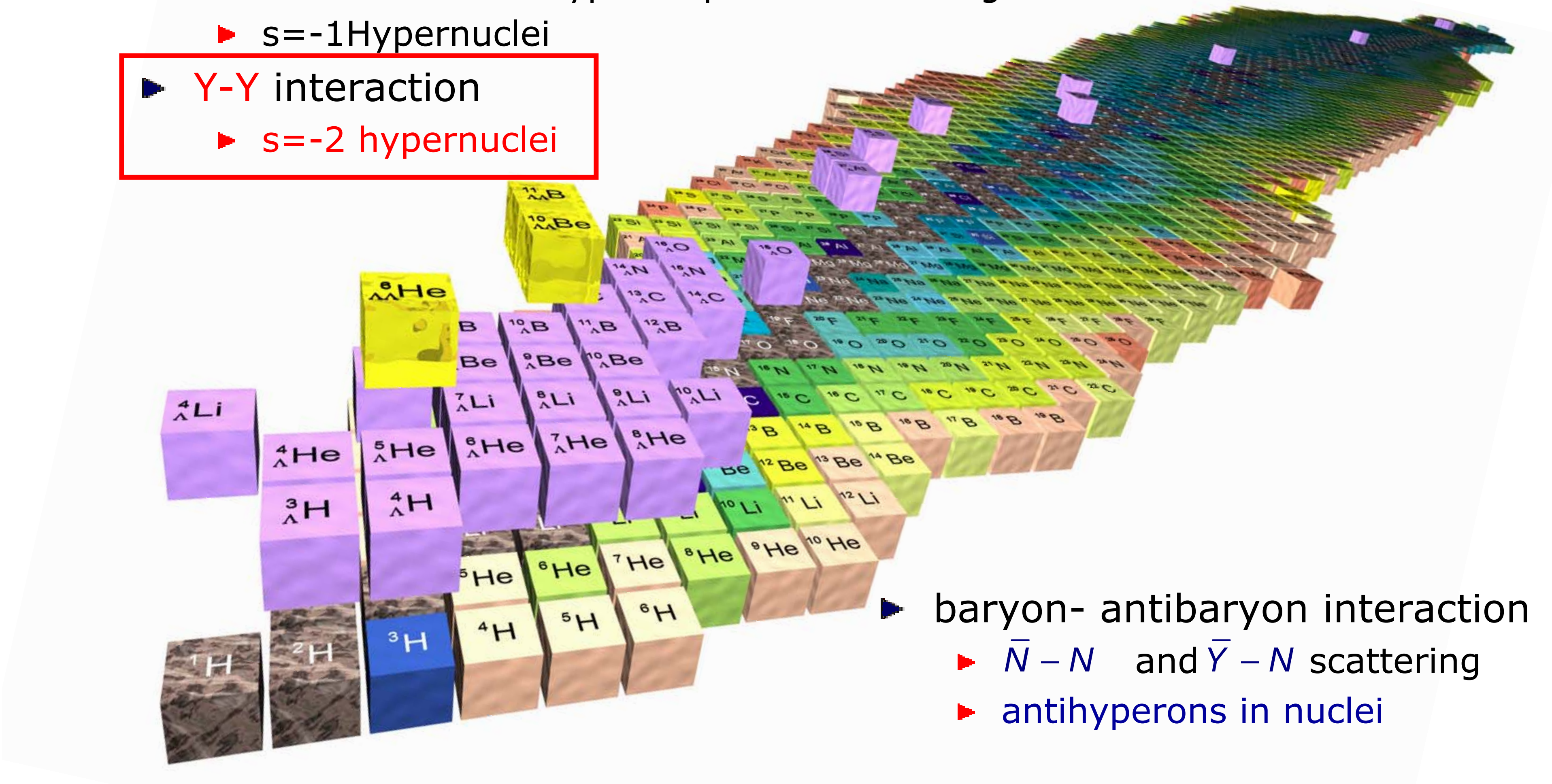
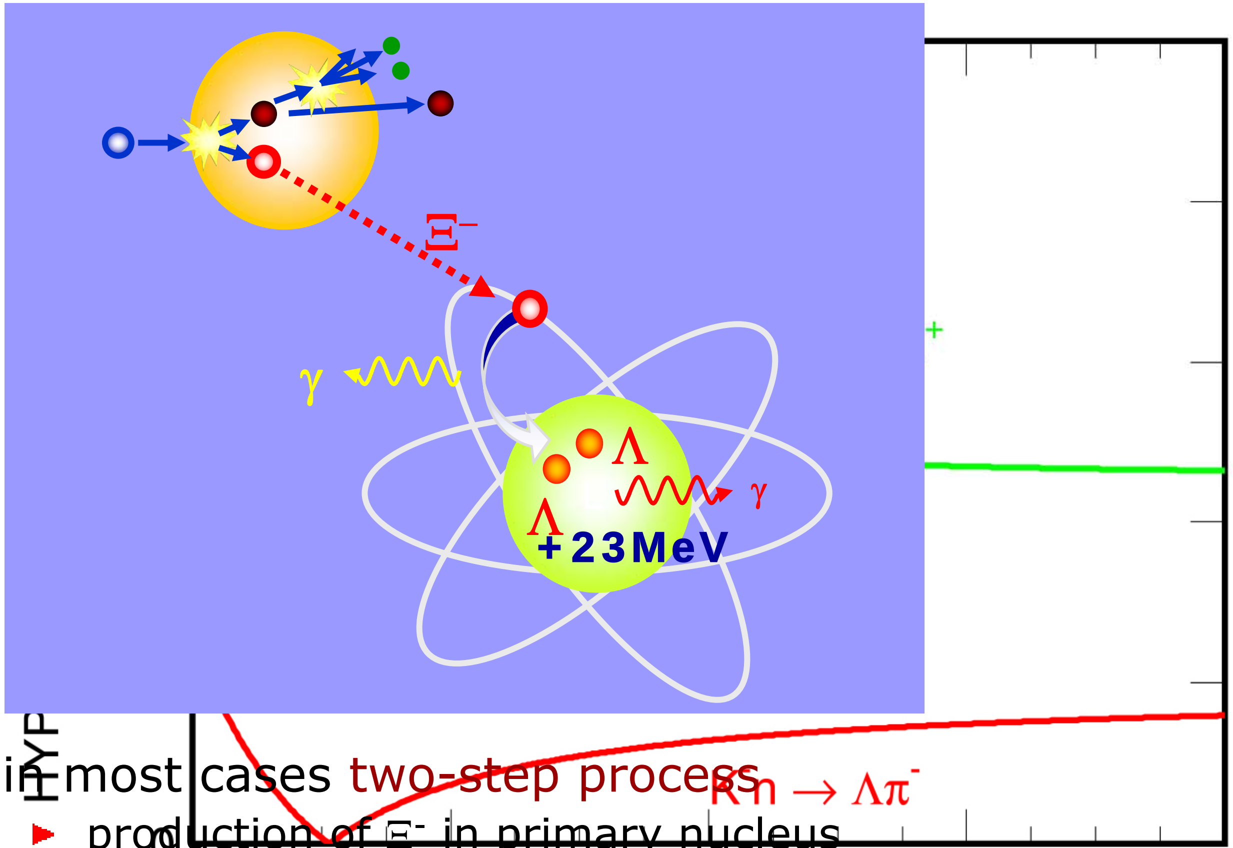


- baryon- antibaryon interaction
  - $\bar{N}-N$ and $\bar{Y}-N$ scattering
  - antihyperons in nuclei

Production of ΛΛ–Hypernuclei

- simultaneous implantation of two Λ is not feasible (→ RHIC?)
- reaction with lowest Q-value: $\Xi^- p \rightarrow \Lambda\Lambda$: 26MeV
- direct implantation of a Ξ^- via a two-body reaction difficult because of large momentum transfer



- in most cases two-step process
  - production of Ξ^- in primary nucleus
  - slowing down and capture in a secondary target nucleus
- spectroscopic studies only possible via the decay products

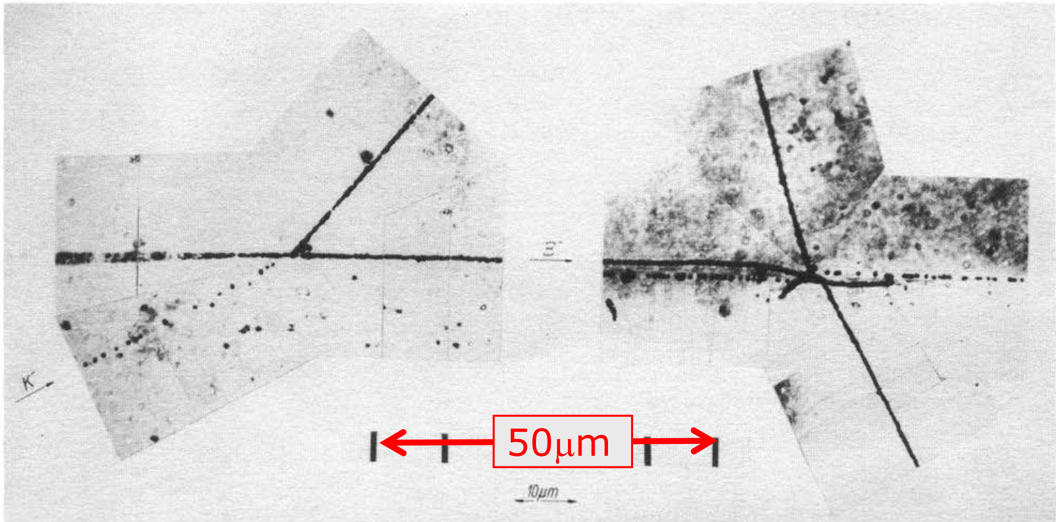
The first ΛΛ event

- 1.3-1.5 GeV/c K^-+Emulsion; 31000 K^-
- carefully reanalyzed
  - ≈1963 by P.H. Fowler, V.M. Mayes and E.R.Fletcher
  - Dalitz *et al.*, Proc. R. Soc. Lond. A426, 1 (1989)

VOLUME 11, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1963

OBSERVATION OF A DOUBLE HYPERFRAGMENT

M. Danysz, K. Garbowska, J. Pniewski, T. Pniewski, and J. Zakrzewski
Institute of Experimental Physics, University of Warsaw, Warsaw, Poland
and Institute for Nuclear Research, Warsaw, Poland



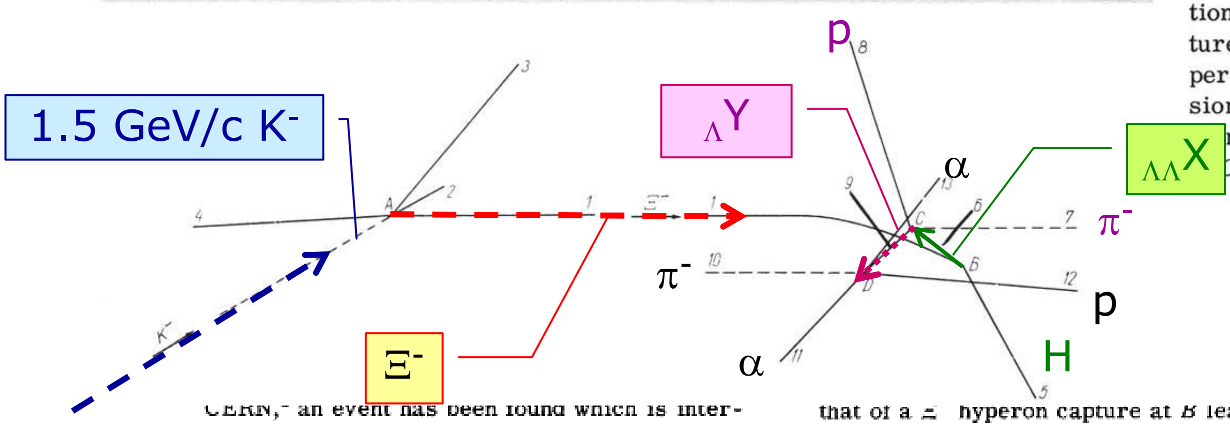


FIG. 1. A photomicrograph and a schematic drawing of the production of a Ξ^- hyperon in a 1.5-GeV/c K^--meson interaction at A followed by capture at rest of the Ξ^- hyperon at B with the emission of a double hyperfragment decaying in cascade C and D.

CERN, an event has been found which is inter-

that of a Ξ^- hyperon capture at B leading to the

What can we do

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- we can only study the decay of double hypernuclei
- groundstate decay of the hypernucleus initiated by the decay of the hyperon(s)
- goal: mass of decaying system

  $\Rightarrow$ need detection of nearly all decay products (p,n,d,t,a,γ,…)

  but: usually we can only detect charged decay products

  $\Rightarrow$ only light nuclei which decay exclusively in charged particles

  still: low kinetic energies (few MeV per nucleon, few μm range)

  $\Rightarrow$ need sub-μm resolution

  $\Rightarrow$ emulsion
- interesting: $\Lambda\Lambda$-interaction in nuclear medium $\Rightarrow$ heavy nuclei
  - $\Lambda\Lambda$-hypernuclei and intermediate Λ-nuclei are produced in excited states
    - Q-value difficult to determine
    - nuclear fragments difficult to identify (neutrons!) with emulsion technique
  - non-mesonic weak decay dominates
    - non-mesonic: mesonic $\approx$ 5

$$\Lambda + n \rightarrow n + n + 176\,\text{MeV}$$

$$\Lambda + p \rightarrow n + p + 176\,\text{MeV}$$

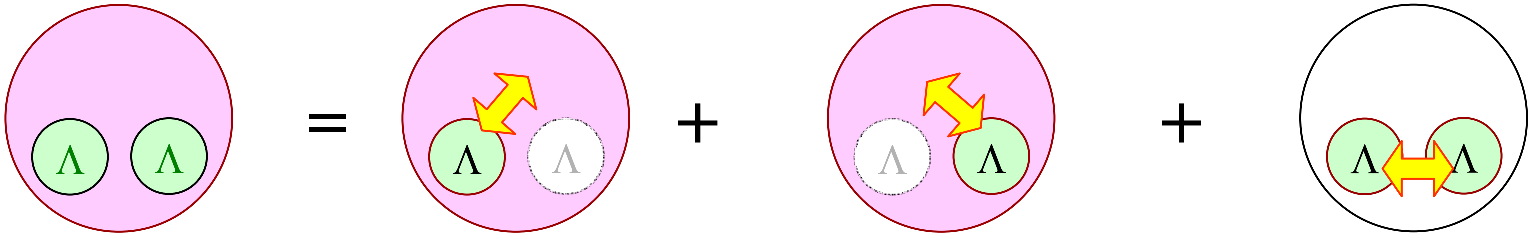
- new approach
  - high resolution spectroscopy of γ-rays from particle stable, excited states

    $\Rightarrow$ need of high statistics

    $\Rightarrow$ fully electronic detectors

First approach to the ΛΛ interaction

- We are mainly interested in the additinal binding energy *between* the two Λs



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

- in the case of the Danysz-event one obtains

$$B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) + B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (17.7 \pm 0.4)\,\mathrm{MeV}$$

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda}({}^{A}_{\Lambda\Lambda}Z) - B_{\Lambda}({}^{A-1}_{\Lambda}Z) = (4.3 \pm 0.4)\,\mathrm{MeV}$$

- positive ⇒ attractive interaction
- this is the net ΛΛ binding provided that
  - the core is not distorted by adding one Λ after the other
  - the core spin is zero
  - no γ-unstable excited states are produced

note:

$\Delta B_{\Lambda\Lambda}$ is proportional to the kinetic energy of the produced pions

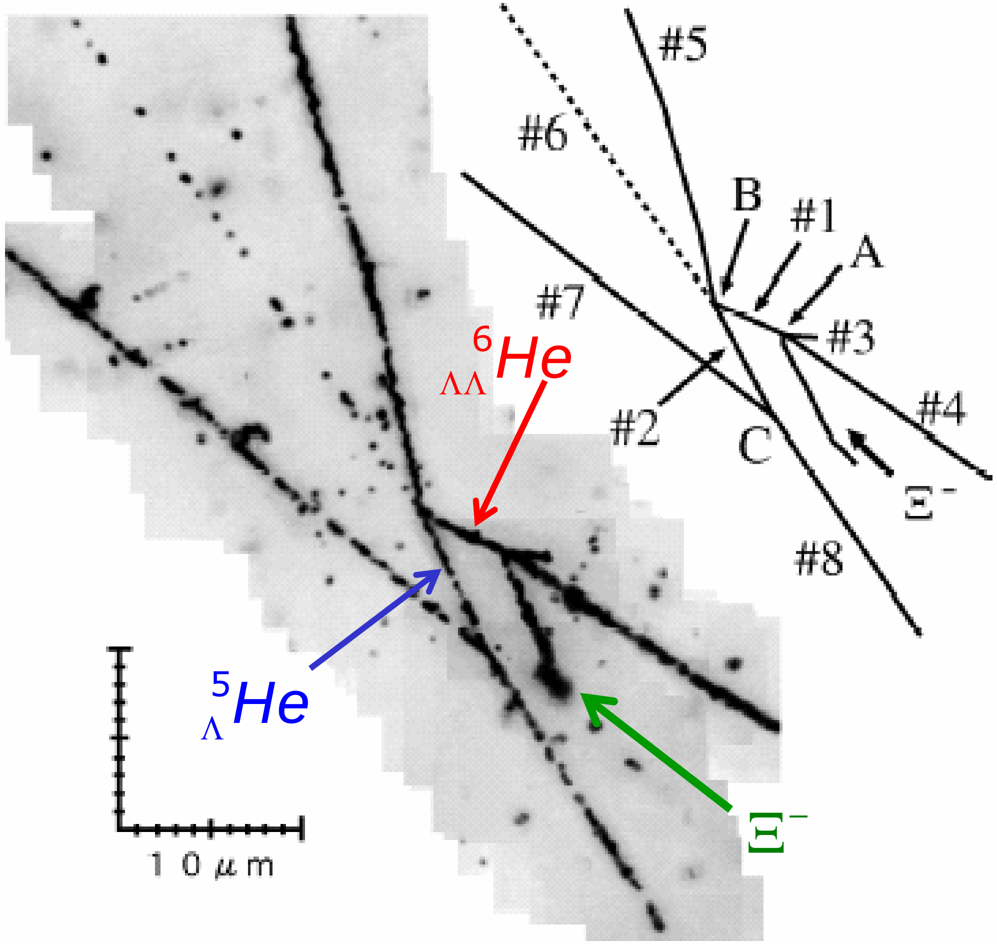
KEK-E373: the NAGARA event

- H. Takahashi *et al.*, PRL 87, 212502-1 (2001)
  - hybrid emulsion technique
  - cleanest event so far (also theoretically)

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

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

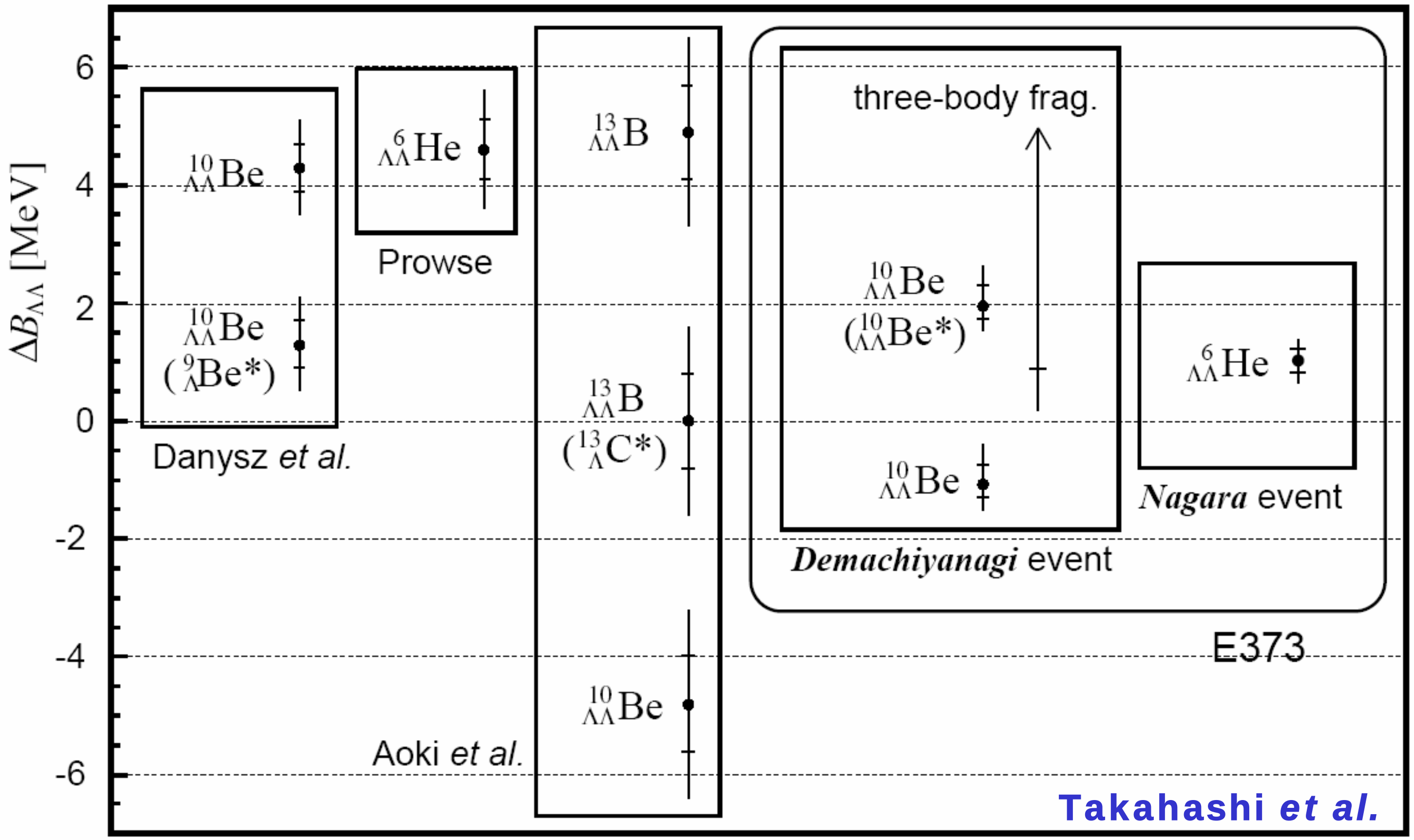
$$\Rightarrow \Delta B_{\Lambda\Lambda} = +1.01 \pm 0.2^{+0.18}_{-0.11} \mathrm{MeV}$$



  - inconsistent with Prowse event
- one additional event
  - Demachiyanagi-event:

$${}^{10}_{\Lambda\Lambda}Be$$

Summary

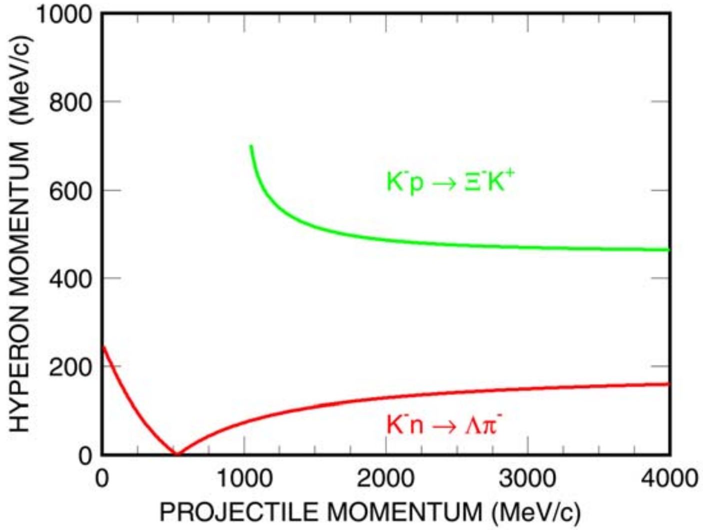


- Interpreting $\Delta B_{\Lambda\Lambda}$ as $\Lambda\Lambda$ bond energy one has to consider e.g.
  - dynamical change of the core nucleus
  - ΛN spin-spin interaction for non-zero spin of core
  - $\Lambda\Lambda$–ΞN-$\Sigma\Sigma$ coupling
  - excited states possible, but have not been clearly identified so far

Production of Ξ^-

- Ξ^- conversion in 2 Λ: $\Xi^- + p \rightarrow \Lambda + \Lambda + 28.5\text{MeV}$

- Ξ- production
  - p(K$^-$,K$^+$)Ξ^-
    - needs K$^-$ beam ($c\cdot\tau$=3.7cm)
    - recoil momentum >460 MeV/c
  - KEK-E176: 10^2 stopped Ξ
  - KEK- E373: 10^3 stopped Ξ } per week(s)
  - AGS-E885: 10^4 stopped Ξ

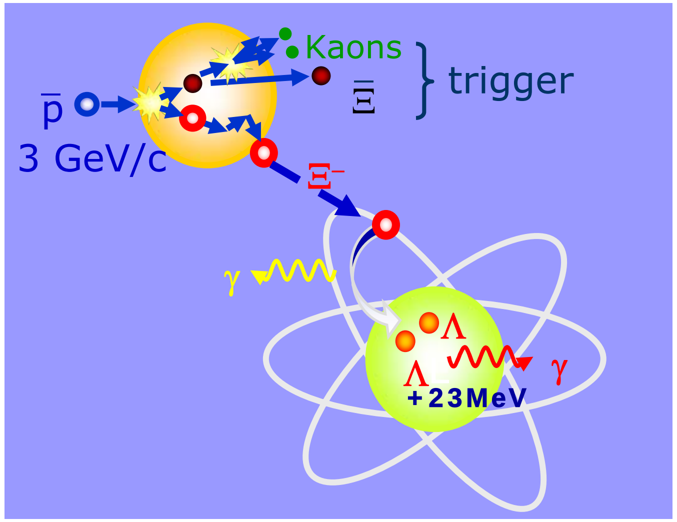


- antiproton storage ring HESR

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

- few times 10^5 stopped Ξ per day

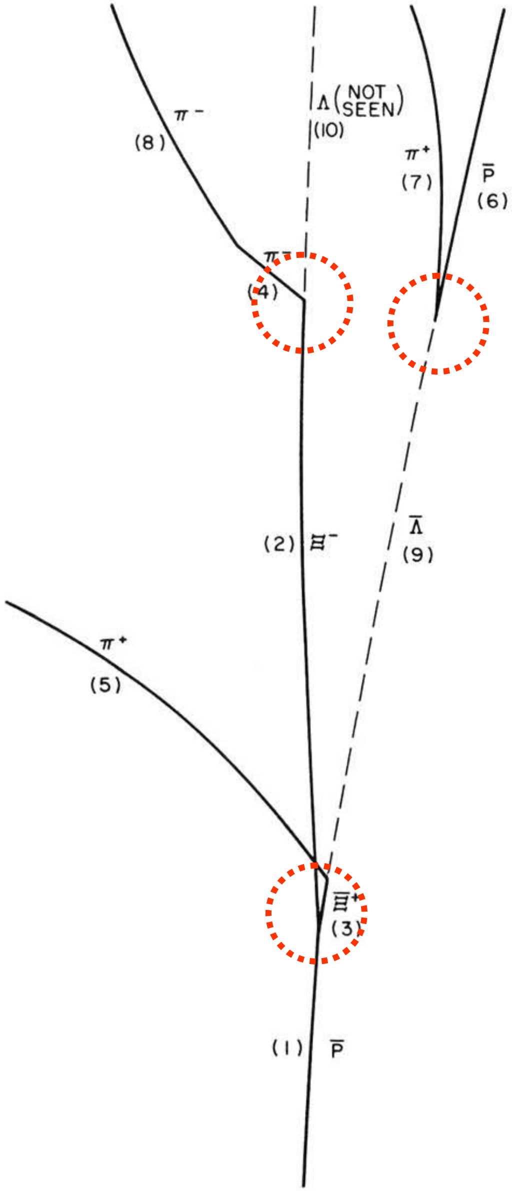
$\Rightarrow$ γ-spectroscopy feasible

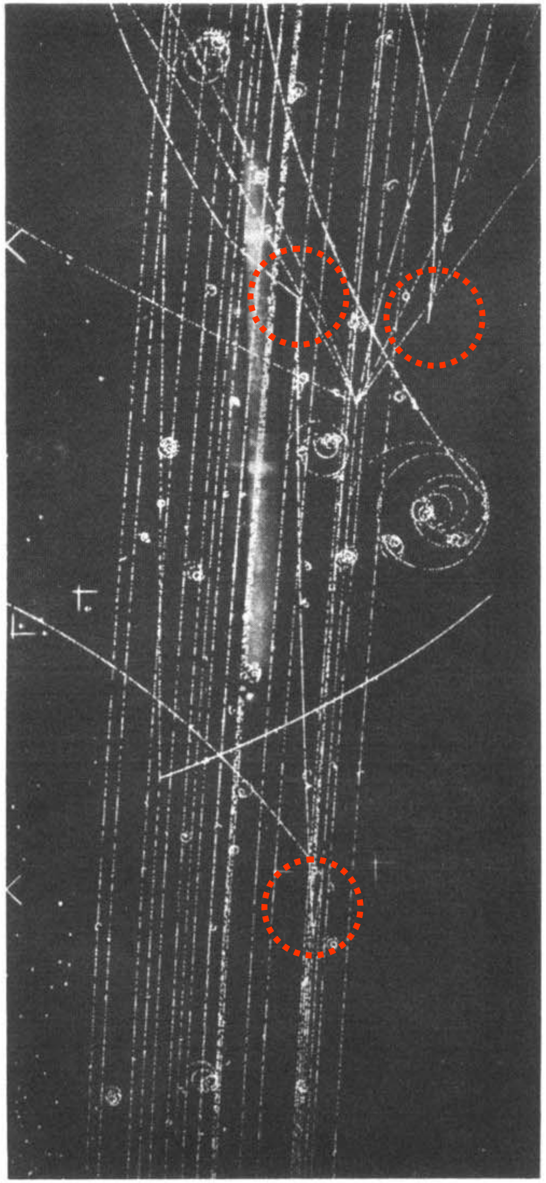


The Discovery of the anti-Xi

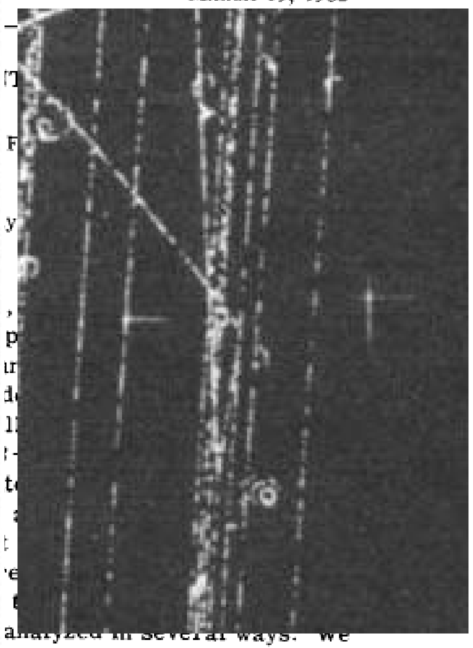
- discovered simulataniously at CERN and SLAC

FIG. 1. A print of the event $\bar{p}+p\rightarrow\Xi^-+\bar{\Xi}^+$ as photographed in the BNL 20-in. liquid hydrogen bubble chamber is shown. The sketch of the event as shown is labelled according to the most likely mass interpretation for each observed track. The numbers on each track are those used in Table I.



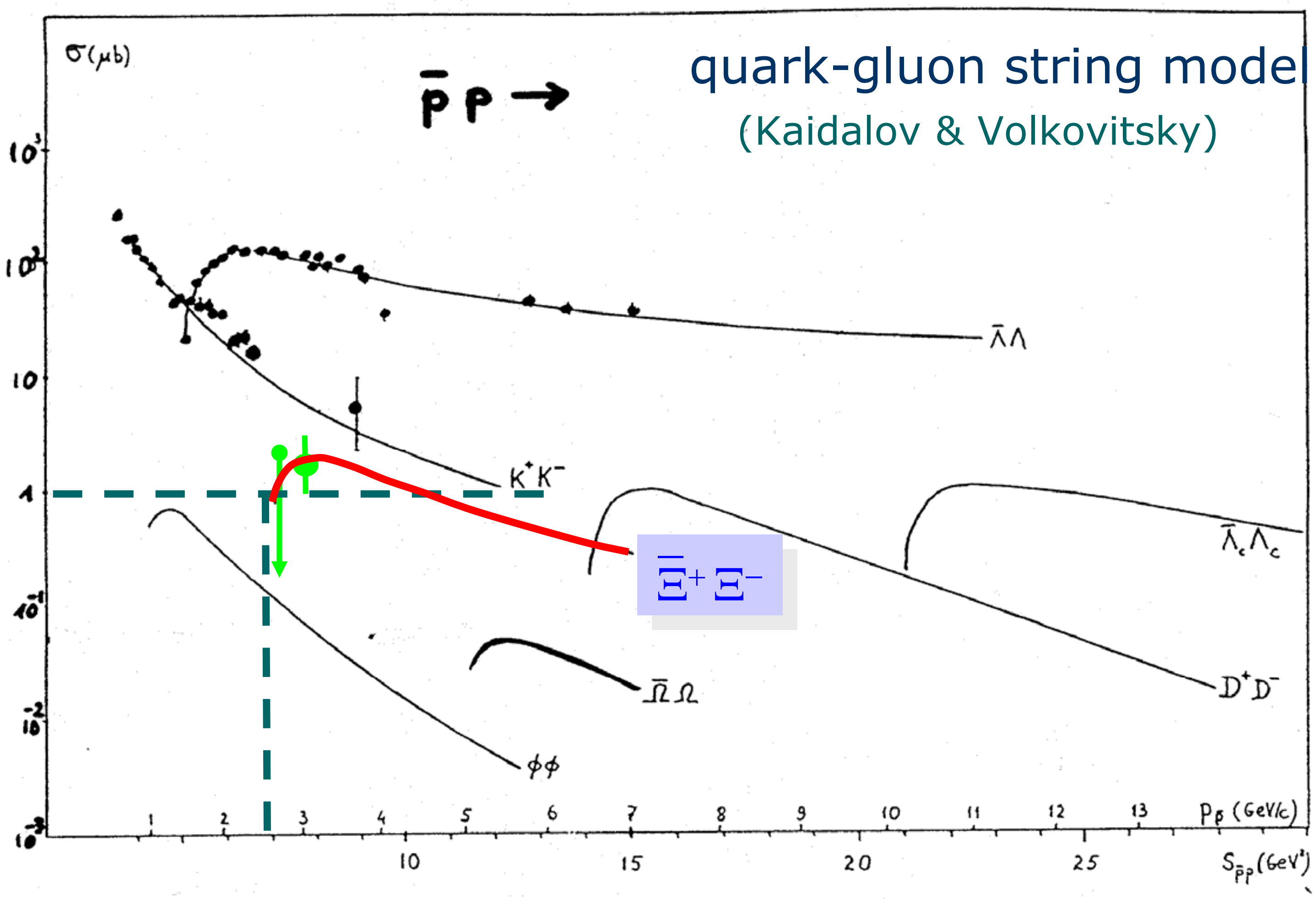


MARCH 15, 1962



General Idea

- Use $p\bar{p}$ Interaction to produce a hyperon "beam" (t~10^{-10} s) which is tagged by the antihyperon or its decay products
  - Ξ-pair threshold 2.62 GeV/c
  - Ξ-pair+pion threshold 3GeV/c

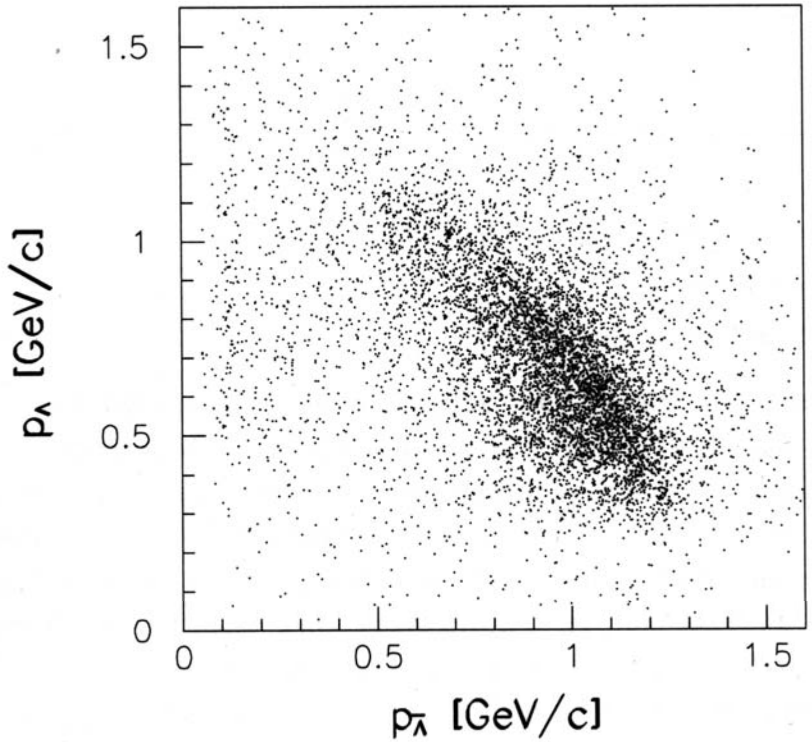


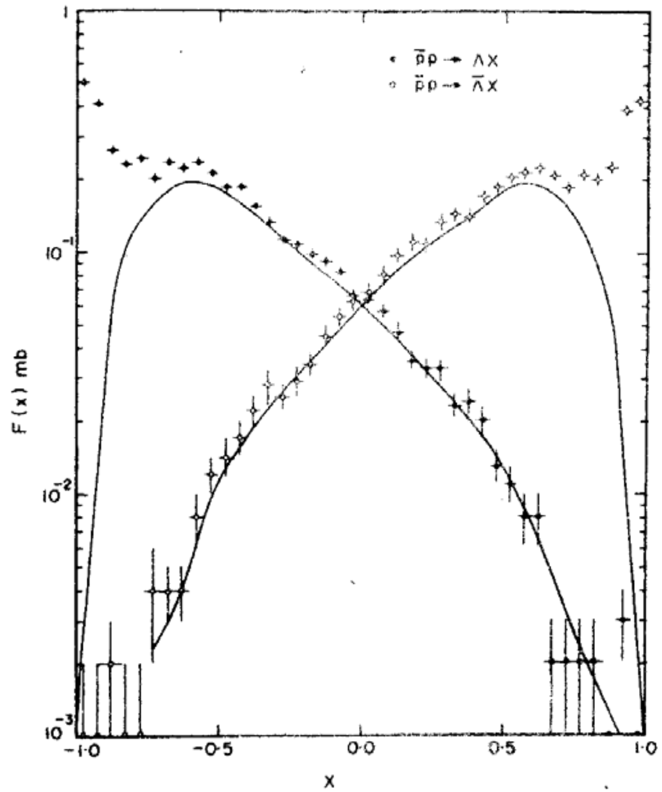
Leading effect

- present calculations assume isotropic decay!
  - count rate will be actually higher

$1.662 GeV/c\ \bar{p}\,^{12}C \rightarrow \bar{\Lambda}\Lambda X$

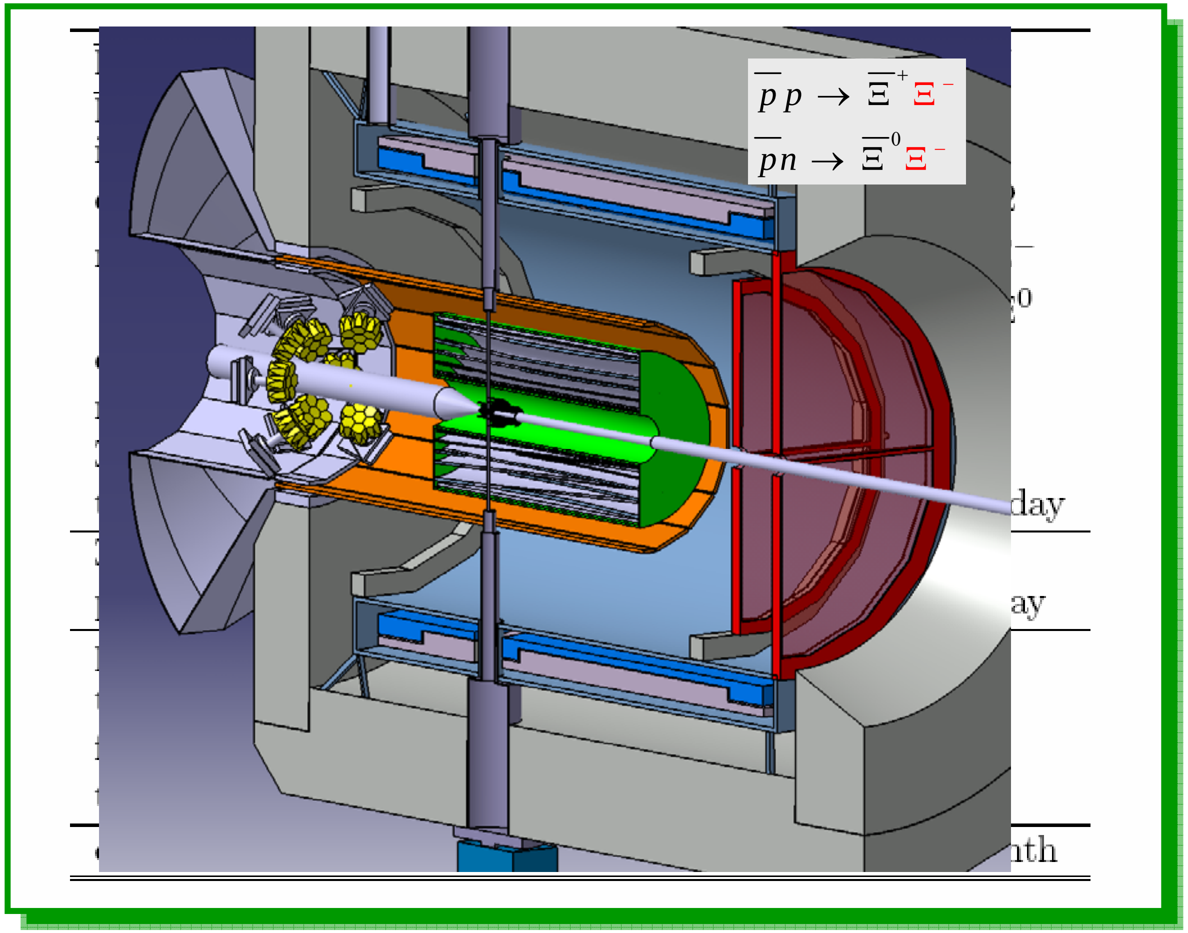
(PS188@LEAR Stephan Pomp, thesis 1999)

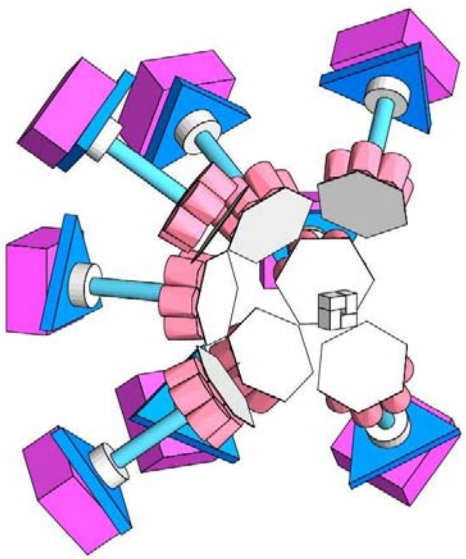




PANDA setup

- $\theta_{lab} < 45°$: Ξ-bar, K trigger (PANDA)
- $\theta_{lab} = 45°\text{-}90°$: Ξ-capture, hypernucleus formation
- $\theta_{lab} > 90°$: γ-detection Euroball at backward angles
  - neutron background (4000n $cm^{-2}s^{-1}$)





ANTI-HYPERONS IN NUCLEI

Baryon-baryon interaction

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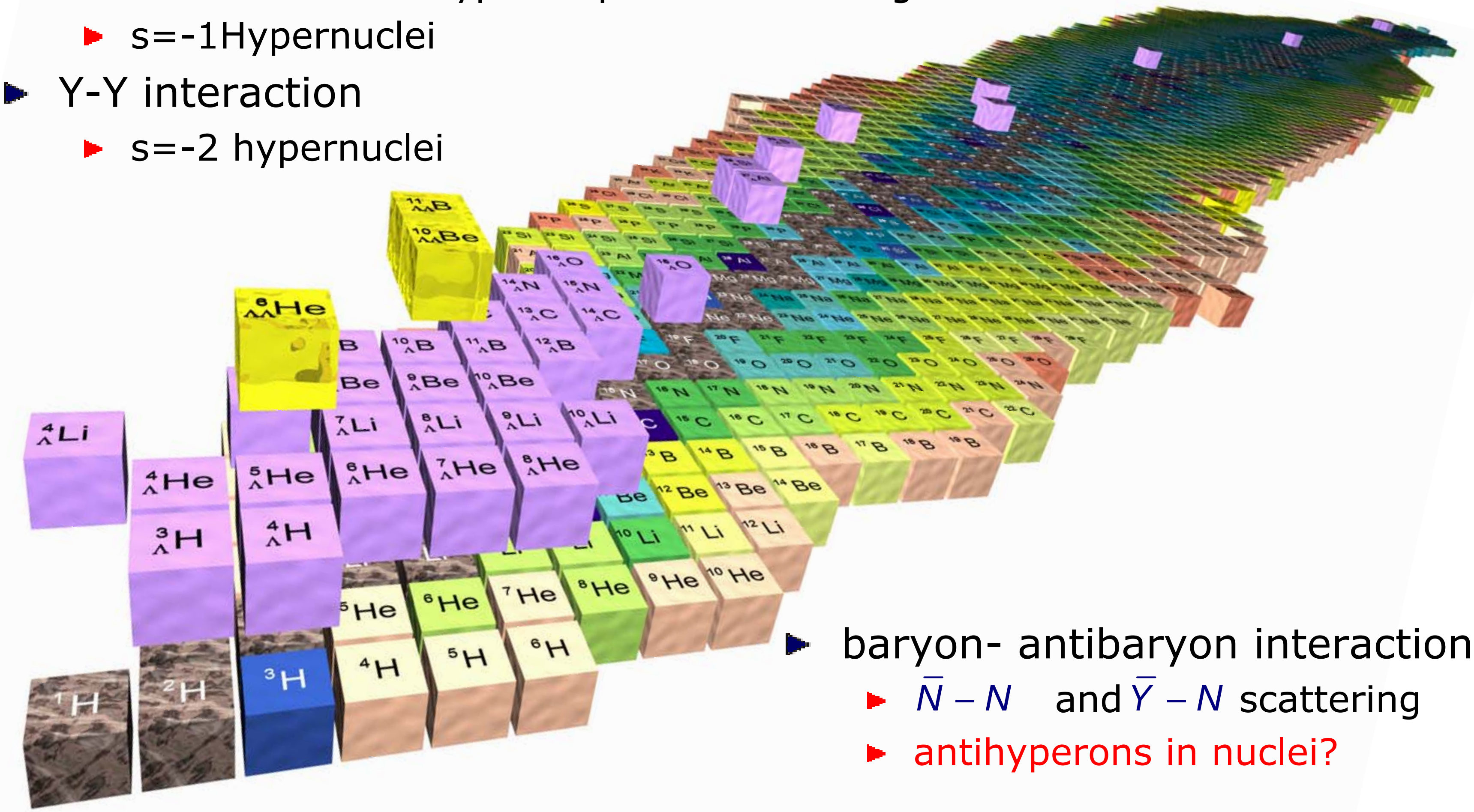
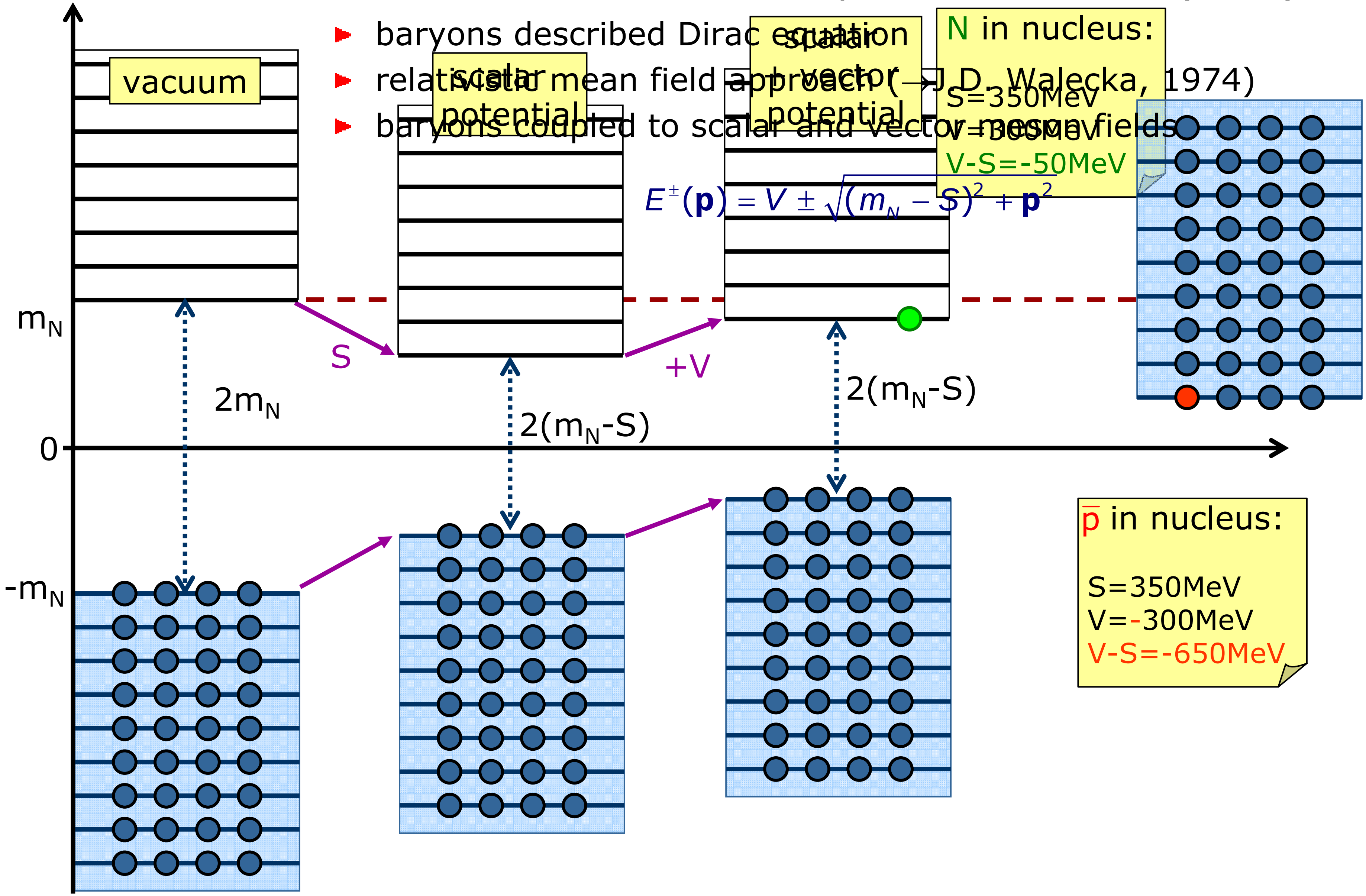
- N-N interaction
  - N-N scattering
  - ordinary nuclei
- Y-N interaction
  - low momentum hyperon-proton scattering
  - s=-1Hypernuclei
- Y-Y interaction
  - s=-2 hypernuclei



- baryon- antibaryon interaction
  - $\bar{N}-N$ and $\bar{Y}-N$ scattering
  - antihyperons in nuclei?

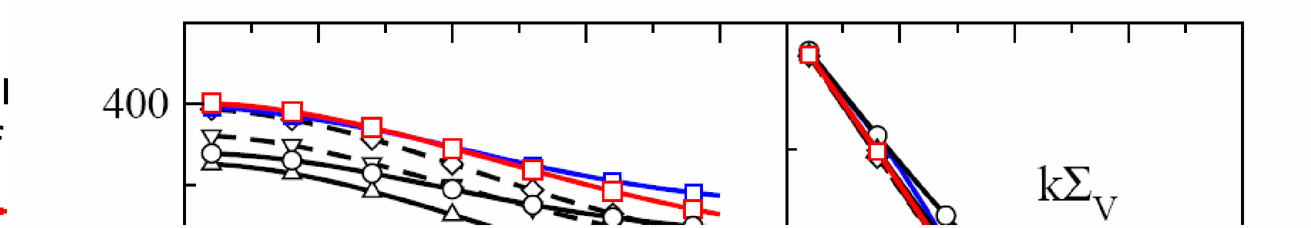
Antibaryons in nuclei

- Hans-Peter Dürr and Edward Teller, Phys. Rev. **101**, 494 (1956)
  - baryons described Dirac equation
  - relativistic mean field approach (→J.D. Walecka, 1974)
  - baryons coupled to scalar and vector meson fields



Why do antihyperons in matter matter?

- Relativistic mean field calculations, relativistic many-body calculations (DBHF) and QCD in-medium sum rules yield comparable fields S and V
  - Oliver Plohl, Tübingen



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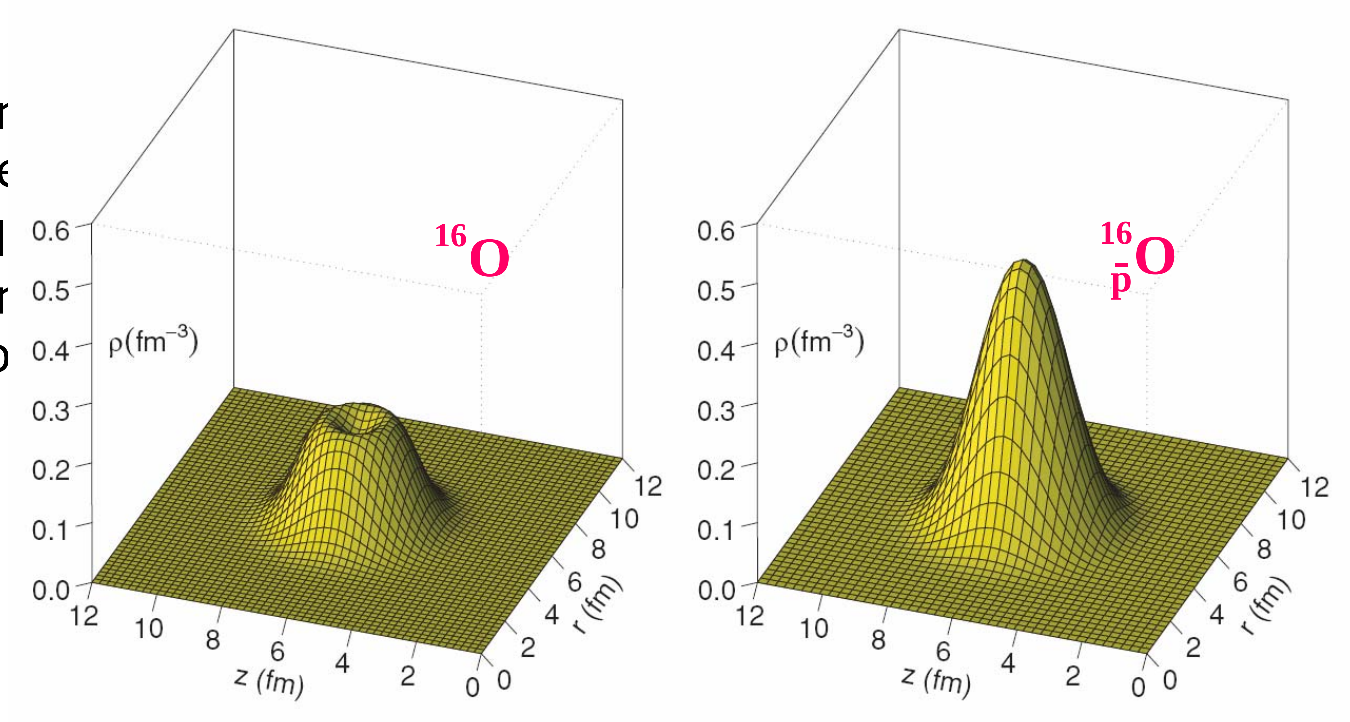

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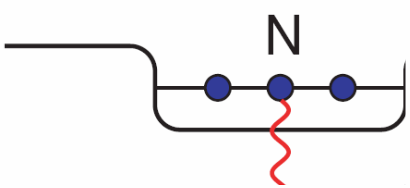
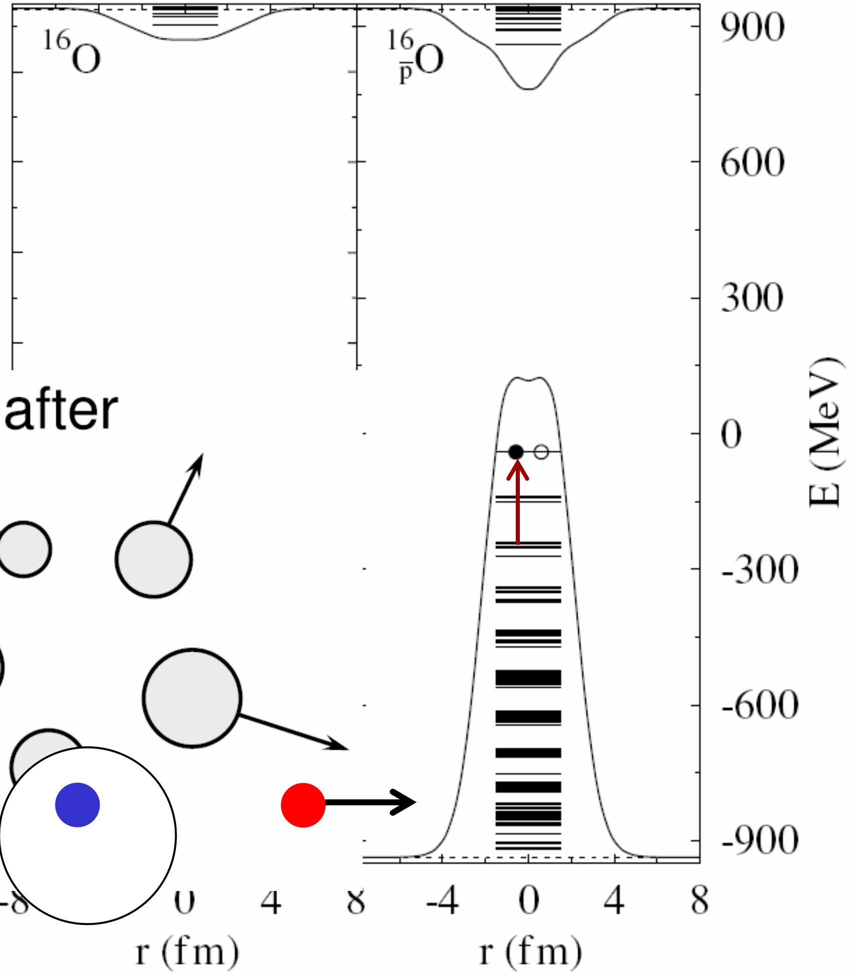
Antihyperons stopped in Nuclei

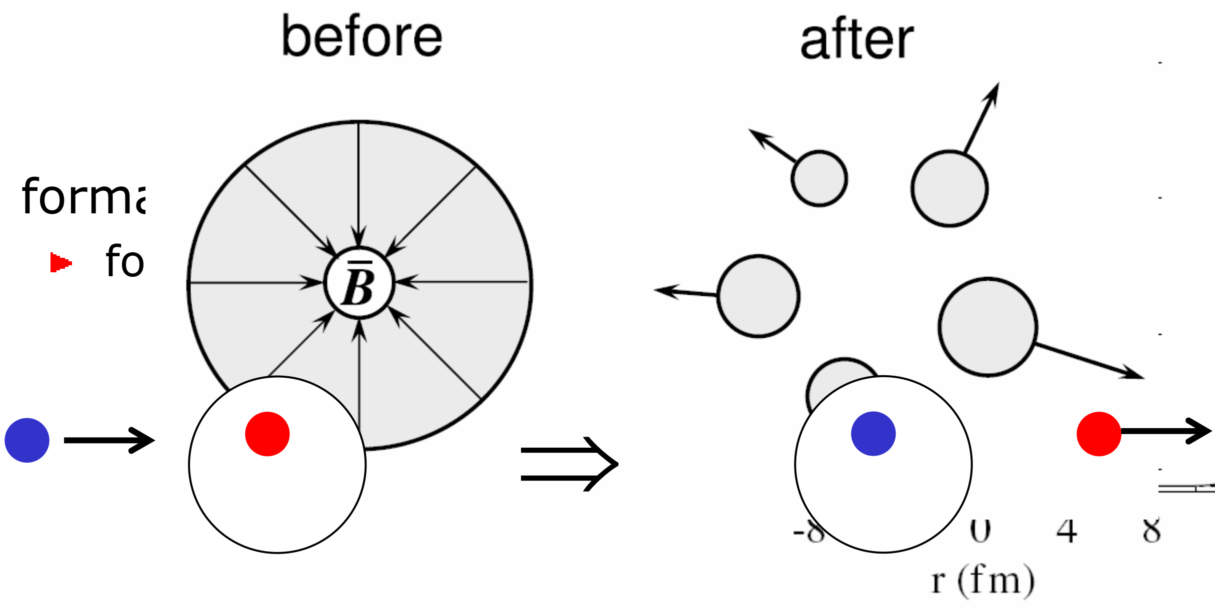
- antibaryons stopped in nuclei

$$\bar{p} + \mathrm{A} \rightarrow {}_{\bar{B}}\mathrm{A} + X$$

  - I.N. Mishustin *et al.*, Phys. Rev. C 71, 035201 (2005)
  - suggested observables
    - "Super-transitions" from Fe (mono-energetic mesons)
    - Transitions between levels of each
    - Explosio after an
    - formatic







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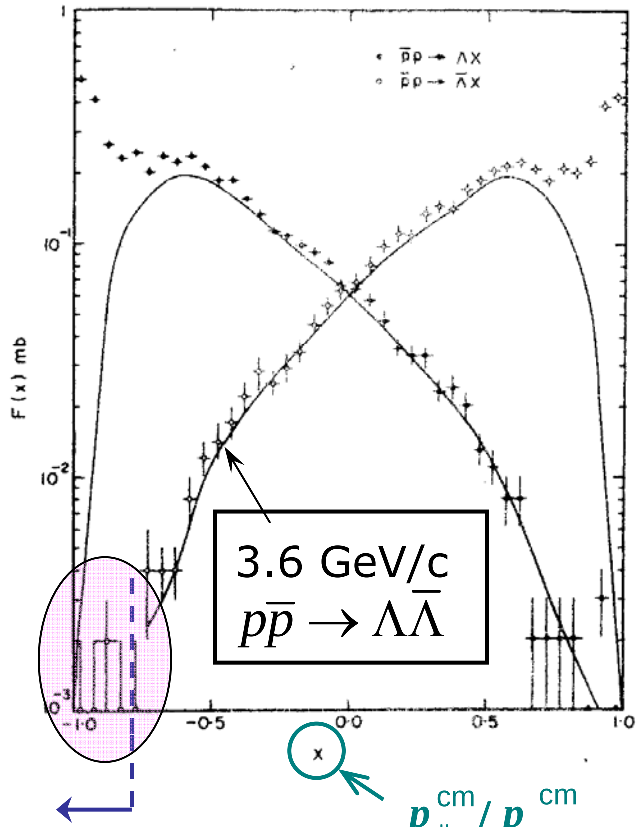
Difficulties

- cross section?
  - for antiprotons o.k.
  - for Λ's unclear
- no direct observation of the antibaryon
  - no smoking gun
  - background?
- both methods work possibly for antiproton and antilambda nuclei but not for anti-Ξ or heavier antihyperons

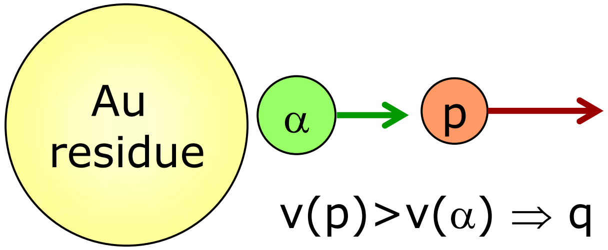


$$p_{\parallel}^{lab} \leq \Delta p \;\; = 400\, MeV/c$$

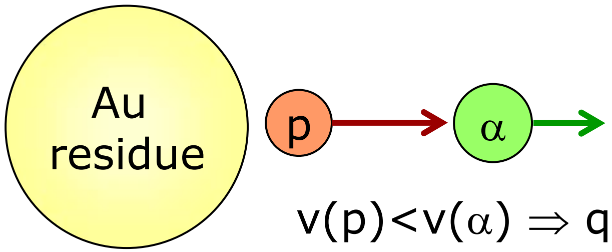
(from I. Mishustin (2005))

Decay of a resonance in a Coulomb field

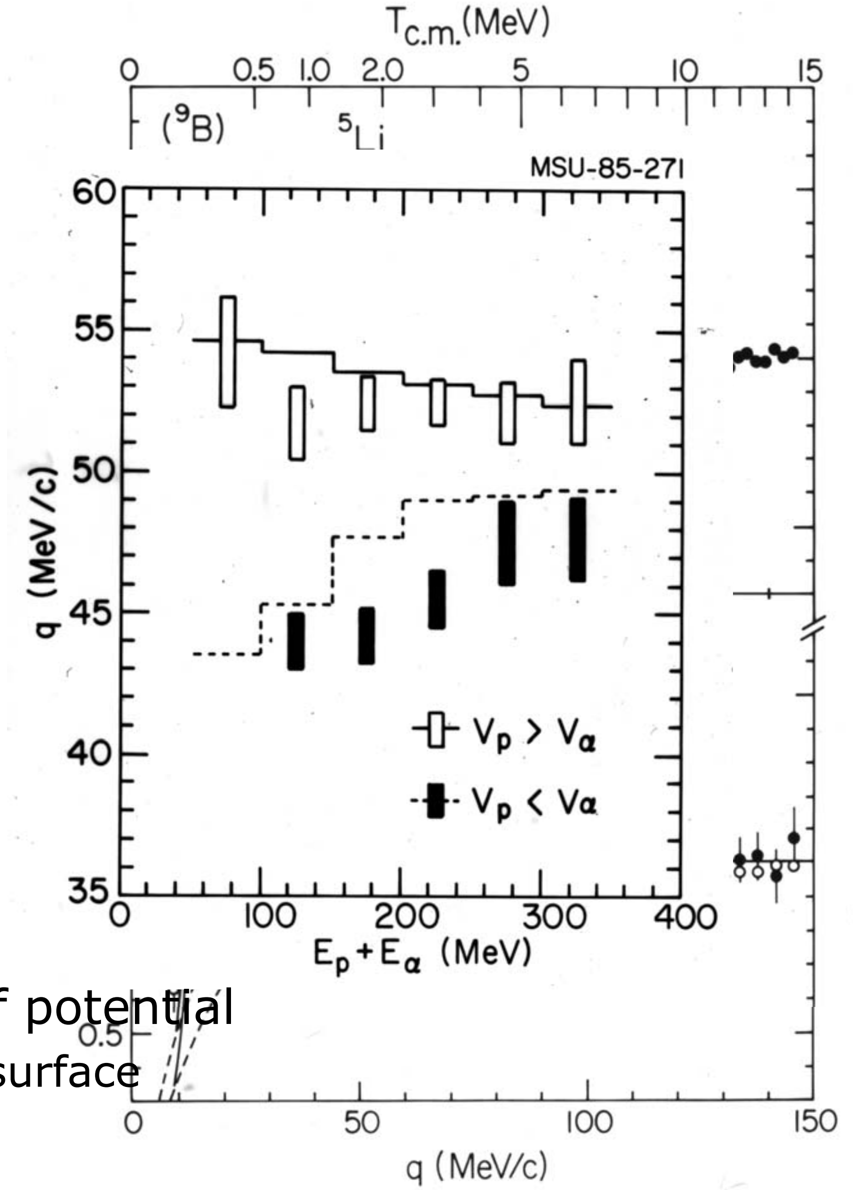
- Phys. Lett. 161B, 256 (1985)
- meanlife of ^{5}Lig.s. ≈130fm/c
- Coulomb boost
  - a=F/m~Z/A
    ⇒ a(p) ≈ 2a(α)



v(p)>v(α) ⇒ q gets larger



v(p)<v(α) ⇒ q gets smaller

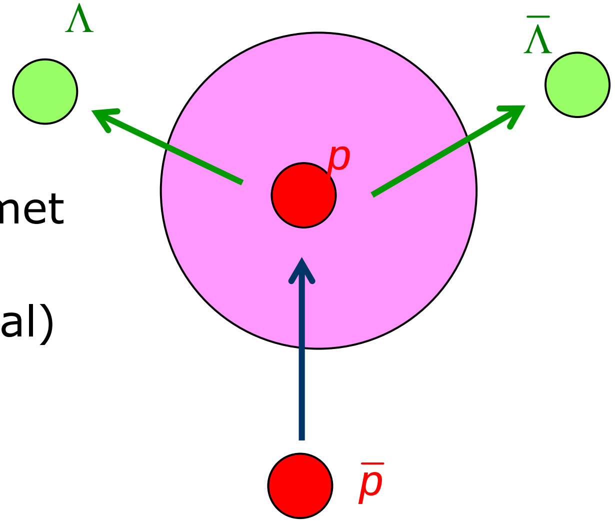


- different boost is a measure of potential
  - here: emission point close to surface

Can we measure the potential for $\overline{Y}$?

- $p + \bar{p} \rightarrow \Lambda + \bar{\Lambda}$ close to threshold in complex nuclei
- Question: is the momentum of the Λ and anti-Λ on the average equal?
- possible answer:
  - at the point of creation inside the nucleus momentum conservation is met
  - but: Λ and anti-Λ have different effective mass (= different scalar potential)
  - if Λ and anti-Λ leave the nucleus they will have different asymptotic momenta
  - the momentum difference is sensitive to the potential difference

is this correct?



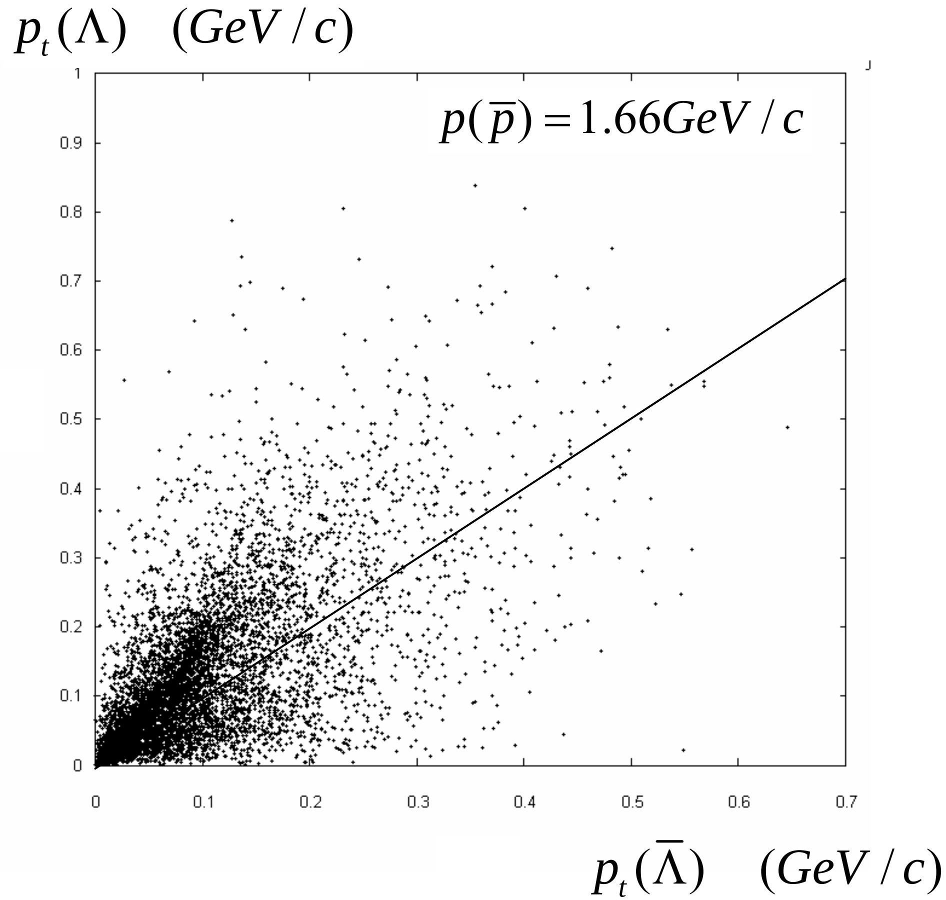
- experimental details
  - need to average over Fermi motion
  - use light nucleus to reduce rescattering
  - leading effect $\Rightarrow$ need to look at (average) transverse momentum

Simple MC: pbar-C

$$E_H(\vec{p}) = V + \sqrt{(m_H - S)^2 + \vec{p}^2}$$

- proton: S=350MeV
  V=300MeV (V-S=-50MeV)
- antiproton: S=350MeV V=-300MeV (V-S=-650MeV)
- C target
- Λ potential=2/3 of nucleons
- Fermi motion
- leading effect

momentum	$p_t(\Lambda)$	$p_t(\Lambda$bar)
1.45GeV/c	0.125	0.095
1.66GeV/c	0.130	0.101



- can be extended to every hadron-antihadron production ($\Lambda_c\Lambda_c$…)

Are there any data?

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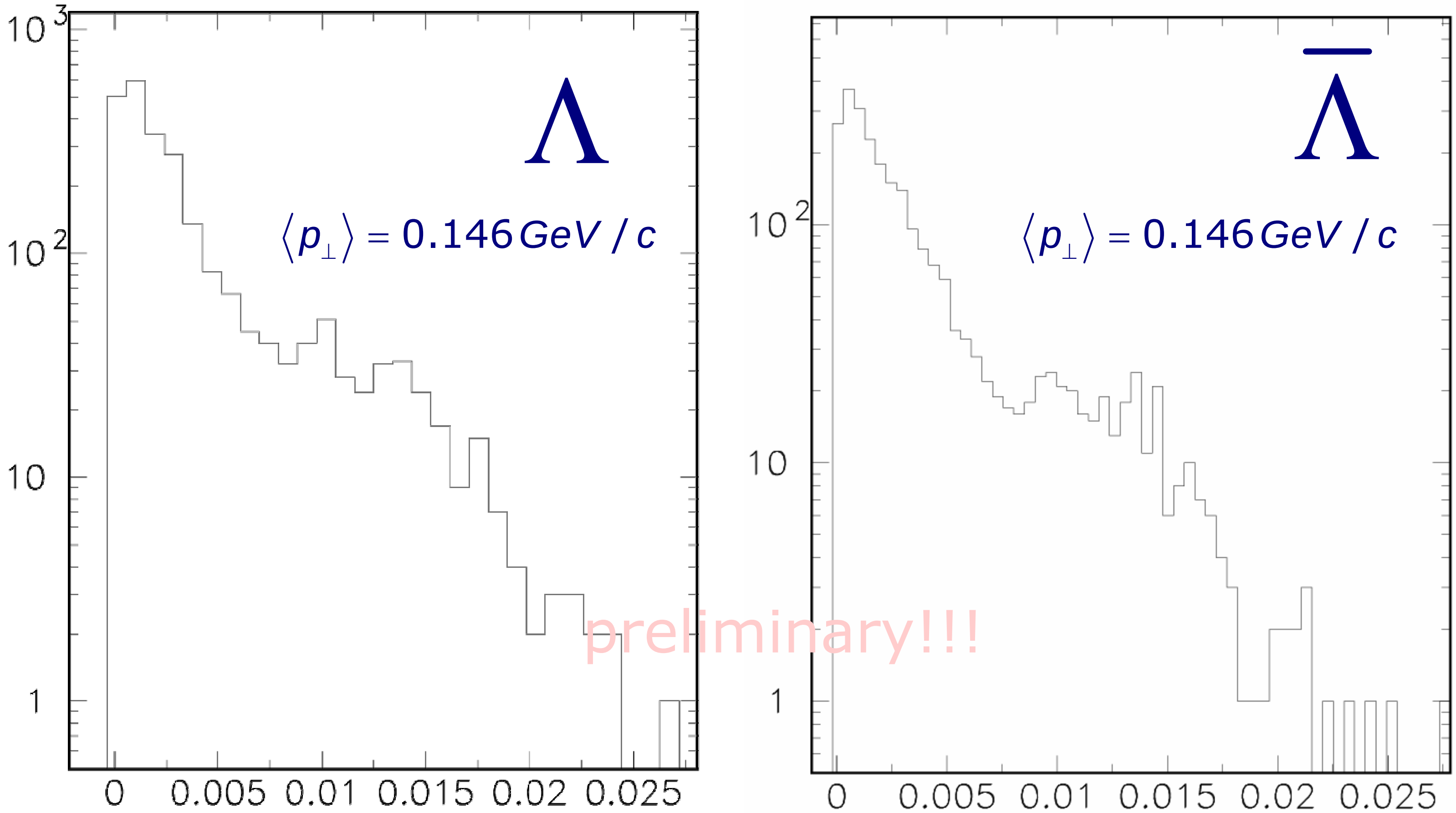
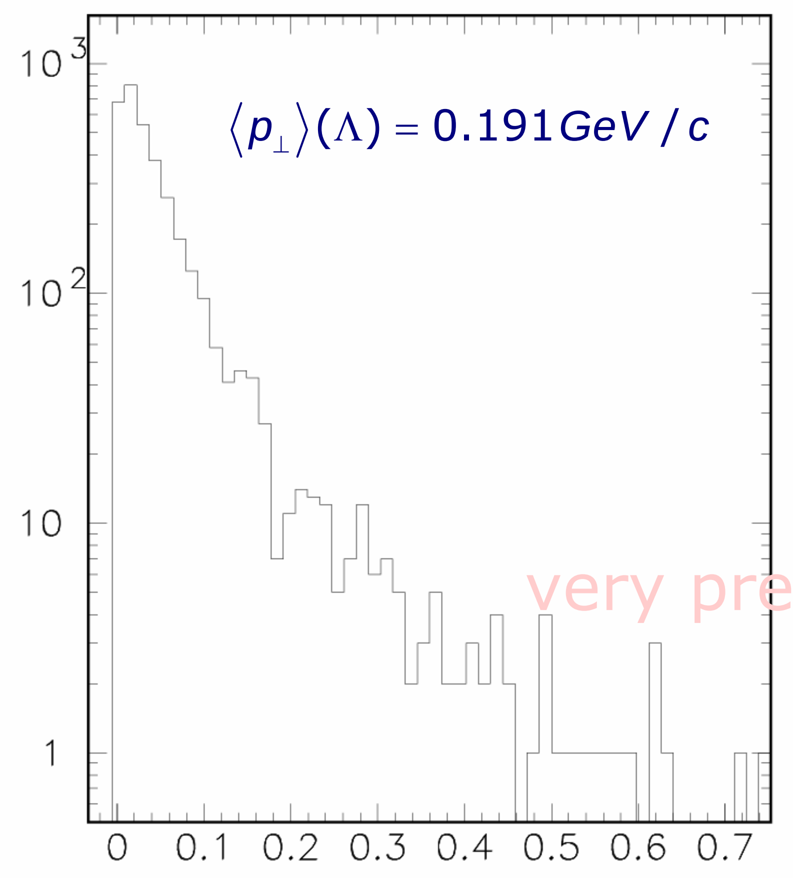
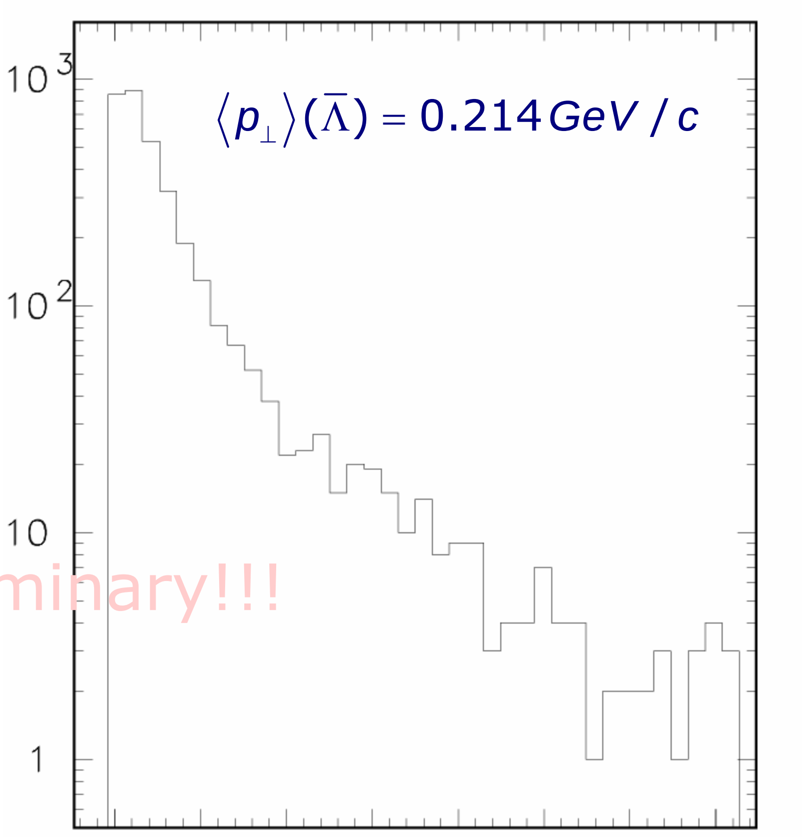
- perhaps
- PS185: 1.45, 1.66 and 1.77GeV/c $\bar{p}\,^{12}C \to \bar{\Lambda}\Lambda X$
- Stephan Pomp, thesis
- only polarization data published
  - p_{miss}<250MeV/c



Non Quasi Free Events

- PS185: 1.45GeV/c
  - p_{miss}>250 MeV/c





very preliminary!!!

p_{miss}	$p_t(\Lambda)$	$p_t(\Lambda$bar)
no cut	0.125	0.095
>0.25GeV/c	0.317	0.153

- different momentum dependent a
- cuts…???

Some open questions

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- different absorption of hyperon and antihyperon
- rescattering
  - influence of nuclear mass $\Rightarrow$ use light nucleus to reduce rescattering
  - but: coherence length of Λ antiΛ pair: t~ħ/E_F~5fm/c $\Rightarrow$ need large nucleus
- use Λ and anti-Λ polarization to enhance anti-$\Lambda\Lambda$ pairs which did not encounter a rescattering on their way out
- if method is successful: can be extended to any hadron-antihadron production (even $\Lambda_c\bar{\Lambda}_c$...)

CONCLUSION

Conclusion

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- Hypernuclei offer a wide range of unique opportunities to study strong QCD in a multi-body environment

observable	**n-rich**	**stable**	**p-rich**
groundstate mass, energy levels			
Λ momentum distribution			
lifetime			
g-factors (M1, spinrotation)			
γ-decays			
weak decays			
$\Lambda\Lambda$-nuclei			
K-nuclei			
antibaryon-nuclei			

- Many new experimental opportunities in the future

(π,K), (K,π) → JPARC
(K^-,K^+) → JPARC
K_{stop} → FINUDA
(e,e') → MAMIC, CEBAF
HI → HypHi, JPARC
pbar-p → PANDA

- New production schemes seem to be very promising