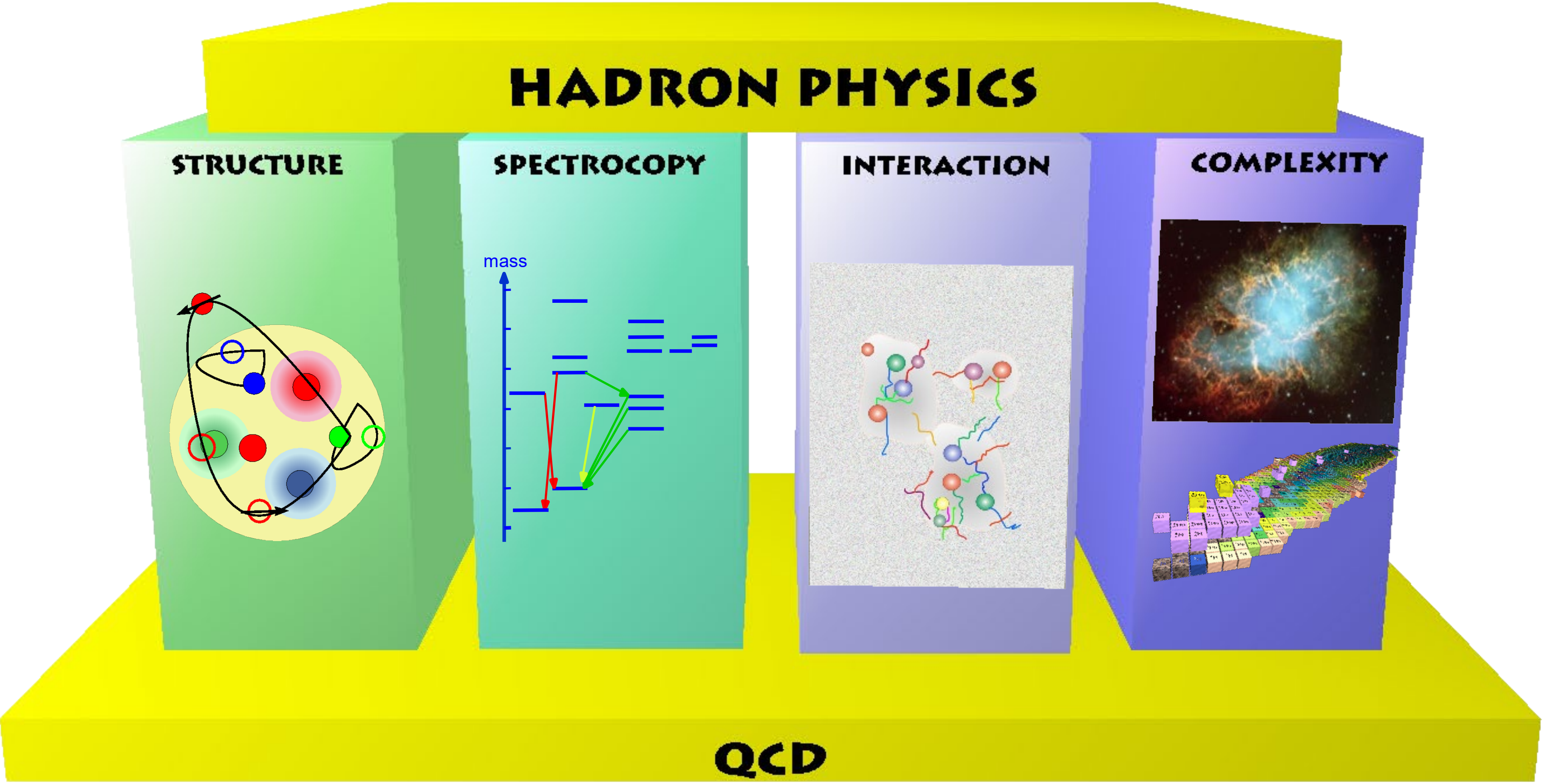
STRANGE HADRONS:
Bridge BETWEEN
QUARKS And StARS

- MOtivation
- HADRONS in COLD NUCLEI
  - EXOTIC HYPERNUCLEI
  - Double hypernuclei
  - ANTIBARYONS in nuclei
- conclusion

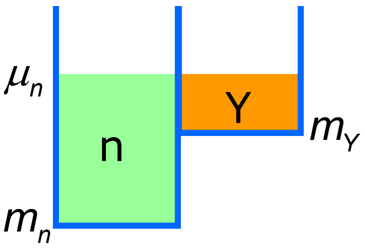
Bundesministerium
für Bildung
und Forschung

Pillars of Hadron Physics



What is the heart of a Neutronstar?

picture: Fridolin Weber



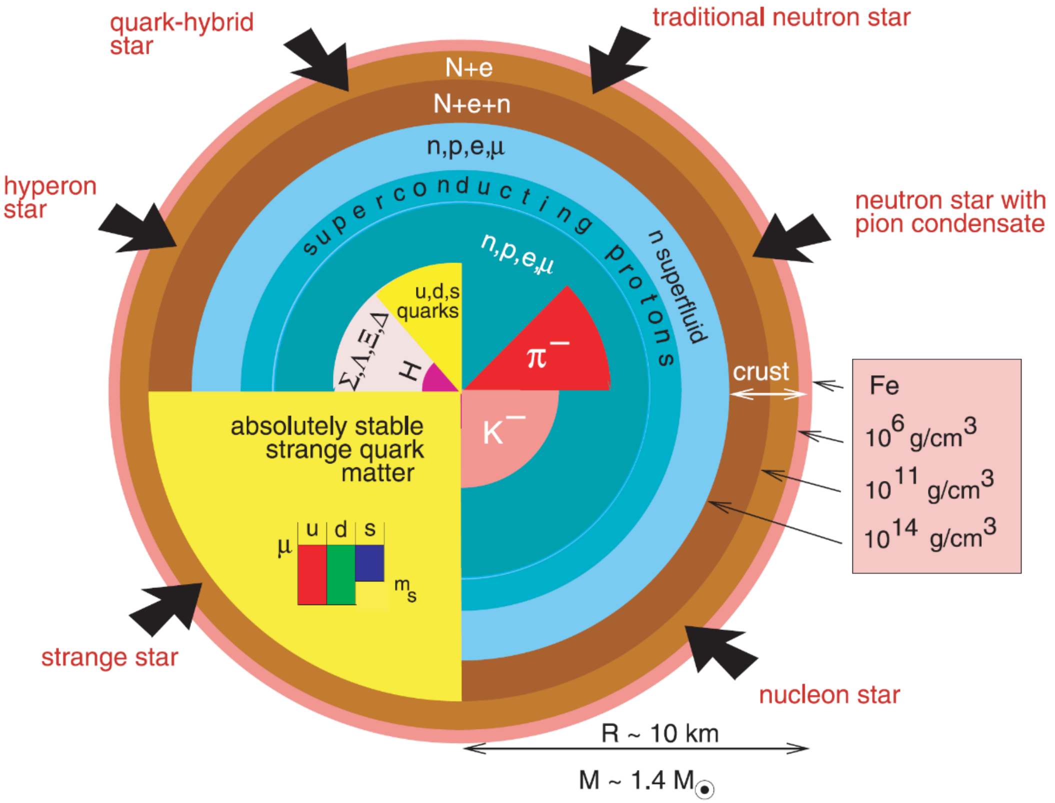
$$e^- + p \to \nu_e + \Sigma^-$$

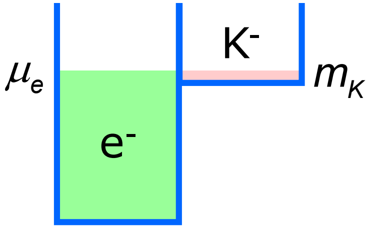
$$e^- + n \to \nu_e + \Lambda$$

$$p_F \ge \sqrt{m_\Lambda^2 - m_N^2} \approx 3fm^{-1}$$

$$\Rightarrow \rho > 2\rho_0$$

Cameron 1959,
Ambartsumyan &
Saakyan 1960





$$e^- \to K^- + \nu_e$$

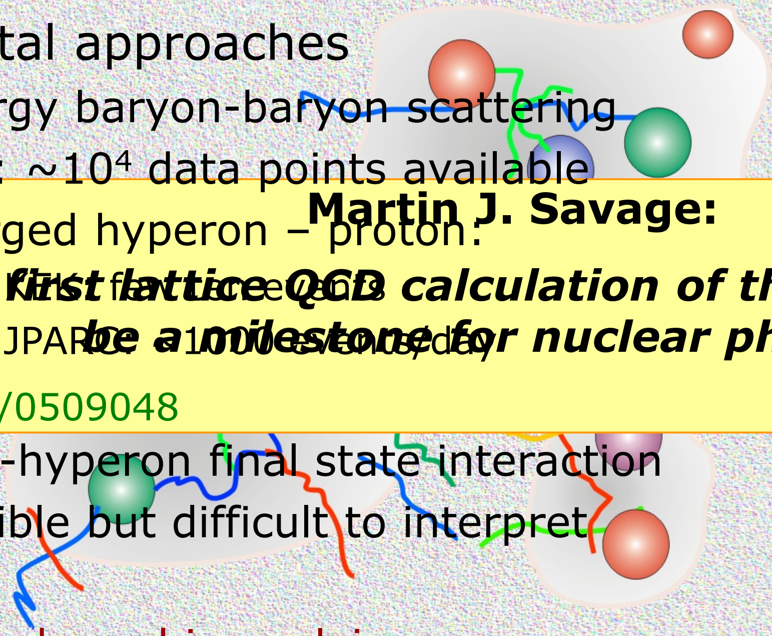
$$n \to p + K^-$$

Kaplan & Nelson 1986

- …even more speculations: supersymmetric baryons
  S. Balberg *et al*., The Astrophysical Journal, 548:L179–L182 (2001)b
- present data on neutron star masses do not (yet) exclude exotic cores
- simultaneous treatment of all possible ingredients (K,Y,q…) missing

Moderne Version of B-B Interaction

- Baryons and their mutual interactions is a complex, quantum-fieldtheoretical, non-perturbative many-body problem



- Experimental approaches
  - low energy baryon-baryon scattering
    - N-N: ~10^4 data points available
    - charged hyperon – proton:
      - KEK: few [illegible] events
      - JPARC: ~1000 events/day
  - hyperon-hyperon final state interaction
    - feasible but difficult to interpret
  - hyperons bound in nuclei
  - hyperon-antihyperon pair production in nuclei

Martin J. Savage:

"The first lattice QCD calculation of the deuteron will be a milestone for nuclear physics."

hep-lat/0509048

after H.R. Fiebig, hep-lat/0212037

exotic hypernuclei

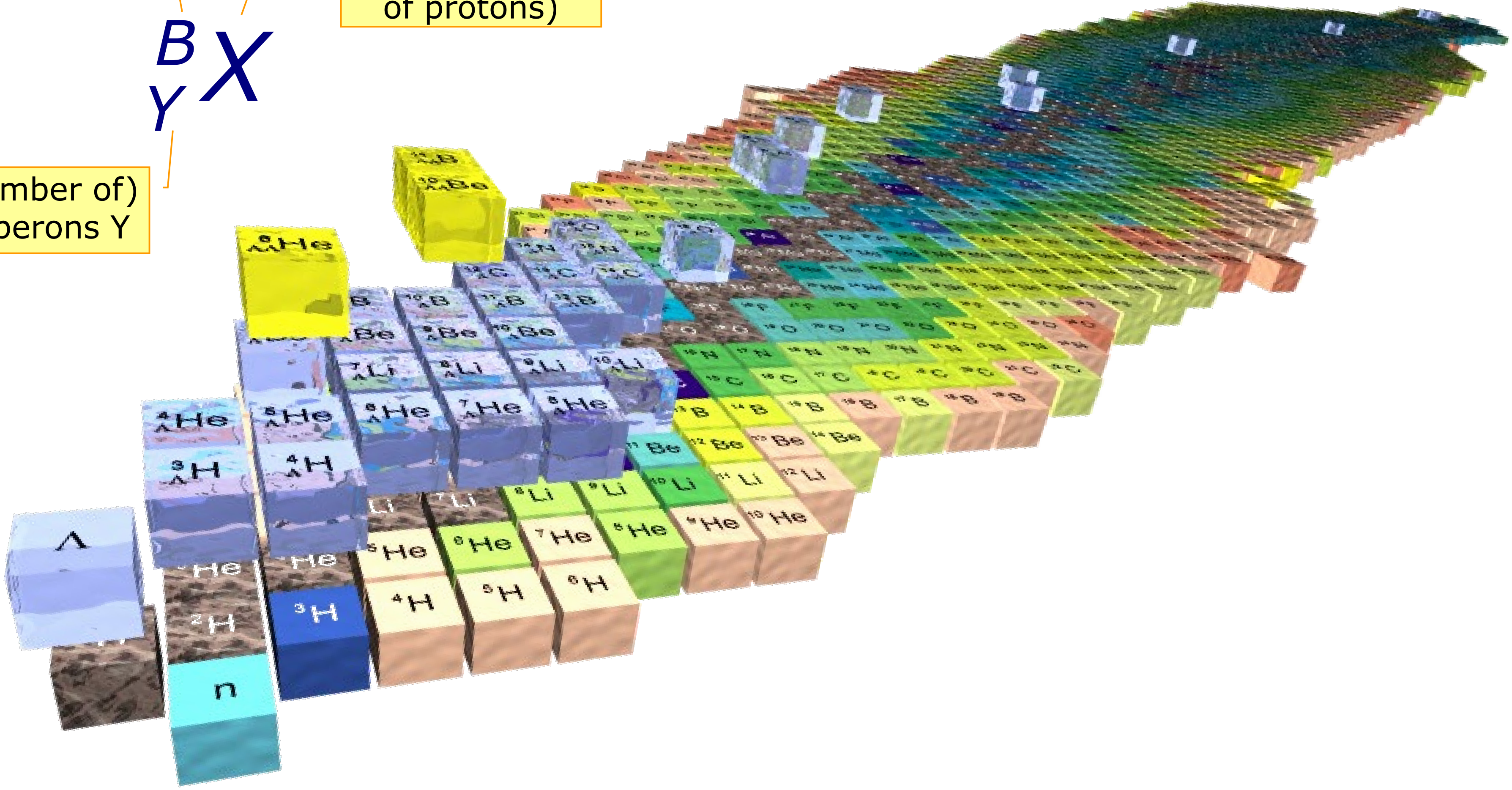
Baryon-baryon interaction

number of baryons N+Z+Y

element = total charge (not number of protons)

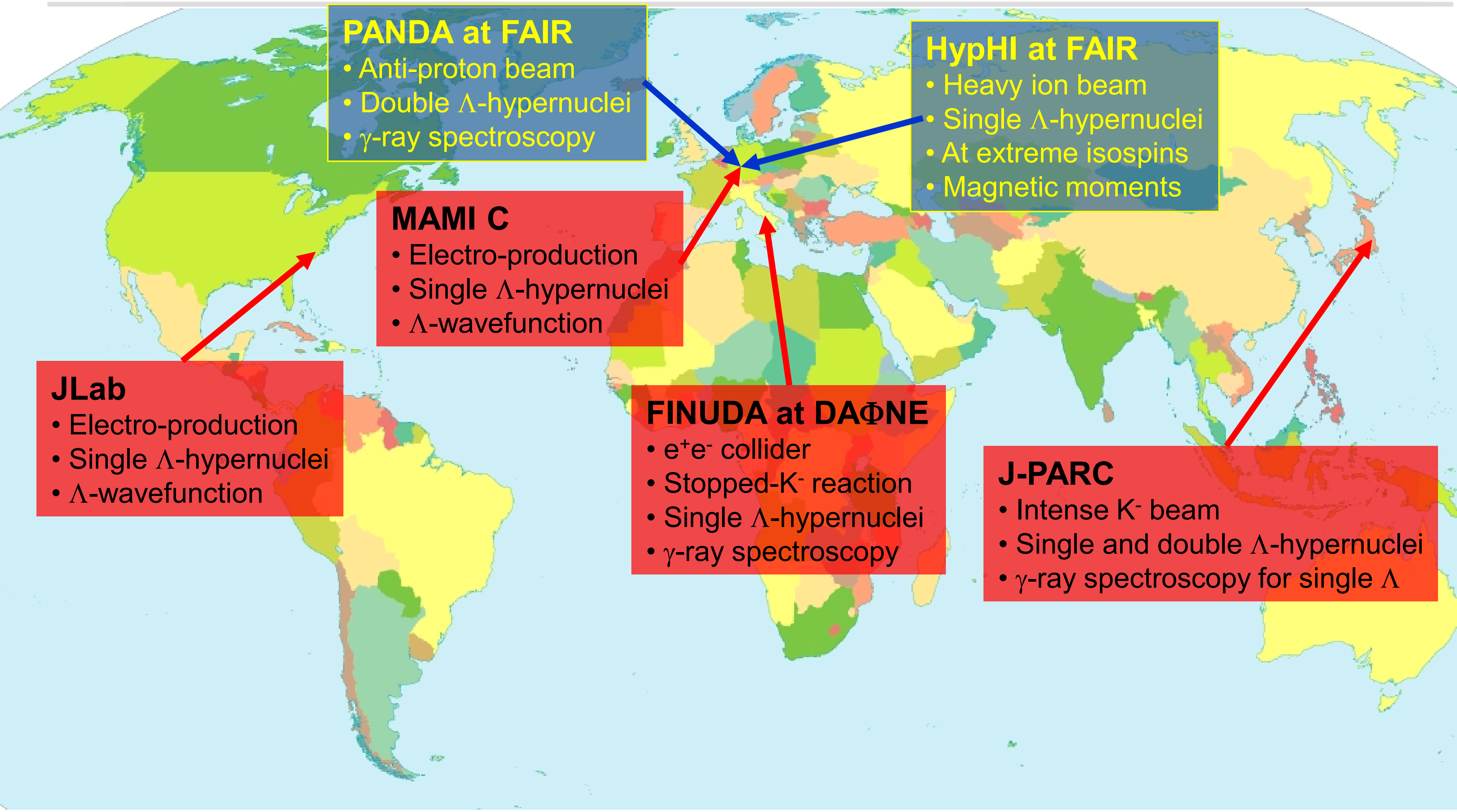
$${}^{B}_{Y}X$$

(number of) hyperons Y



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

International Hypernuclear Network



PANDA at FAIR
- Anti-proton beam
- Double Λ-hypernuclei
- γ-ray spectroscopy

HypHI at FAIR
- Heavy ion beam
- Single Λ-hypernuclei
- At extreme isospins
- Magnetic moments

MAMI C
- Electro-production
- Single Λ-hypernuclei
- Λ-wavefunction

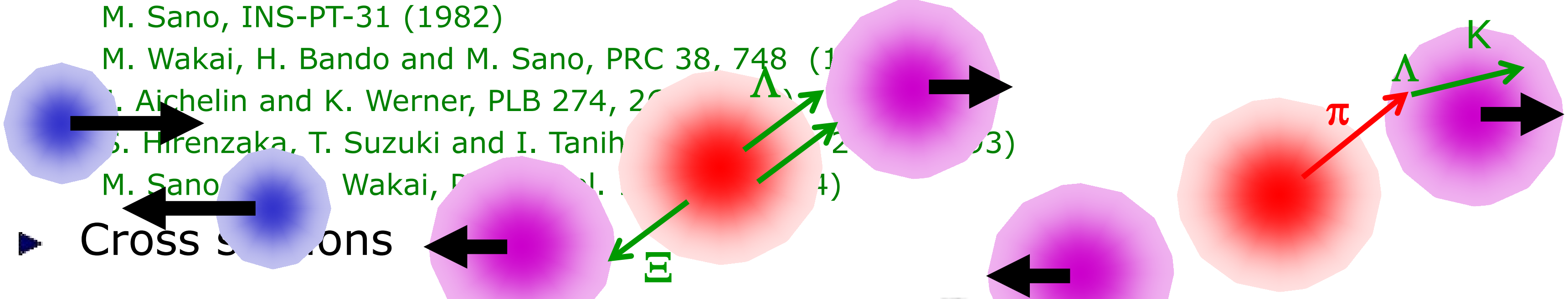
JLab
- Electro-production
- Single Λ-hypernuclei
- Λ-wavefunction

FINUDA at DAΦNE
- e^+e^- collider
- Stopped-K^- reaction
- Single Λ-hypernuclei
- γ-ray spectroscopy

J-PARC
- Intense K^- beam
- Single and double Λ-hypernuclei
- γ-ray spectroscopy for single Λ

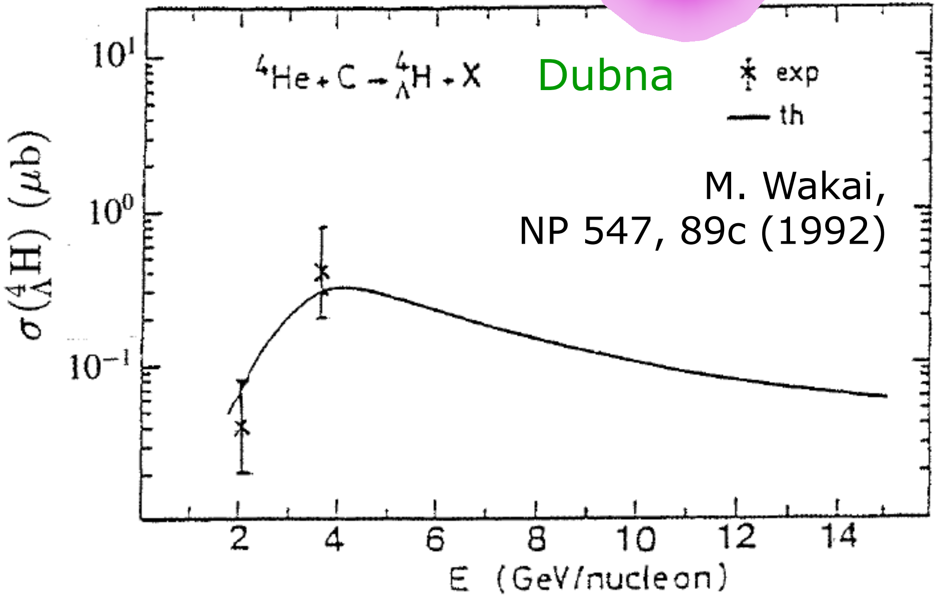
Relativistic Hypernuclei

- 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

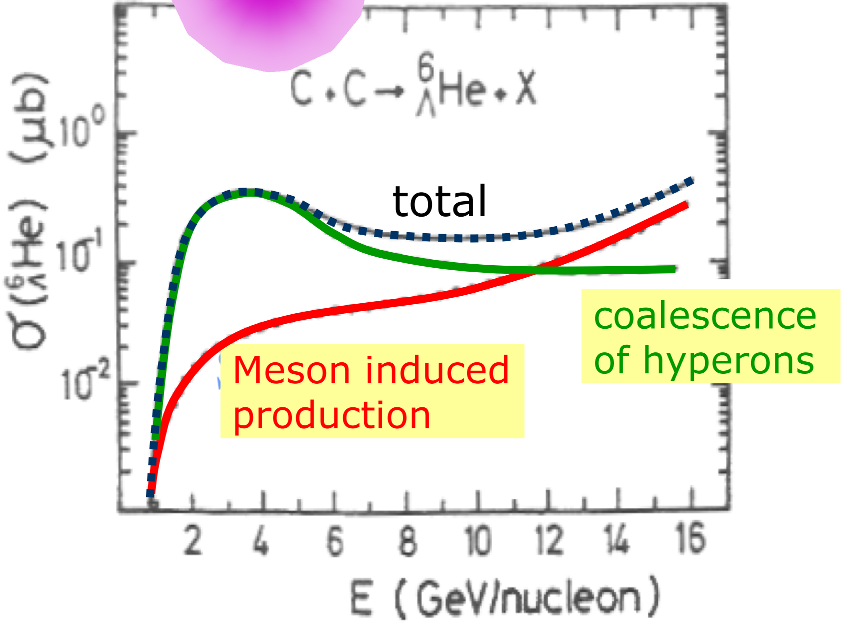


M. Sano, INS-PT-31 (1982)
M. Wakai, H. Bando and M. Sano, PRC 38, 748 (1
. Aichelin and K. Werner, PLB 274, 2
. Hirenzaka, T. Suzuki and I. Tanih 2 3)
M. Sano Wakai, l. 4)

- Cross s ons



M. Wakai,
NP 547, 89c (1992)

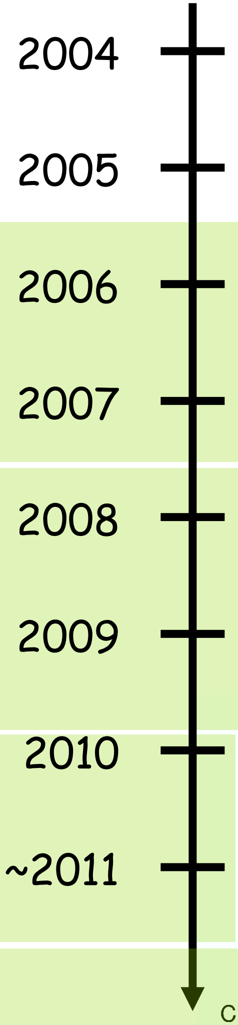


Meson induced production

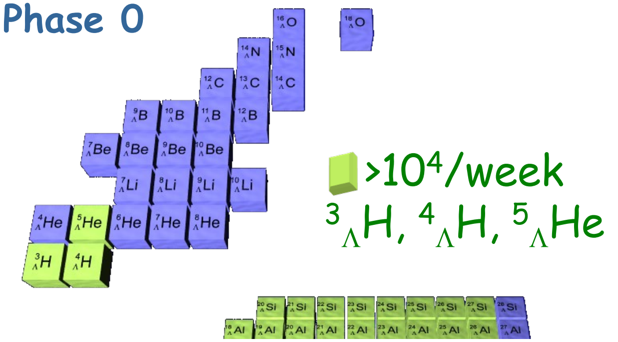
coalescence of hyperons

The HYPHI Project T. Saito

- HypHI project started
- LOI and progress report to the GSI PAC, Design study
- Design study, preparation for the phase 0 experiment
- Phase 0: experiment with ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{5}_{\Lambda}He$
- Design study for the setup for hypenuclear non-mesonic weak decay measurements
- Phase 1: Experiments for proton rich hypernuclei
- Phase2: Experiment for neutron rich hypernuclei at NuSTAR/FAIR
- Phase 3: Hypernuclear separator
  - Hypernuclear magnetic moments
  - Hypernuclear driplines

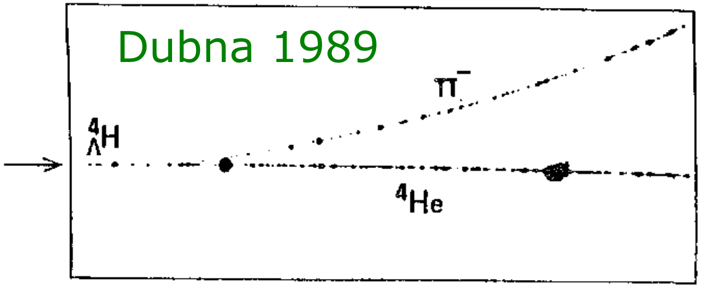


Phase 0

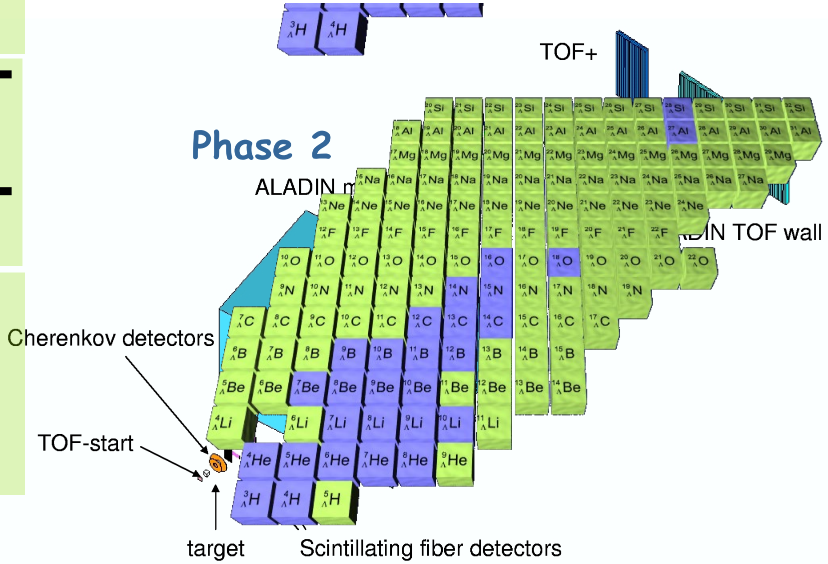


${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, ${}^{5}_{\Lambda}He$

Dubna 1989



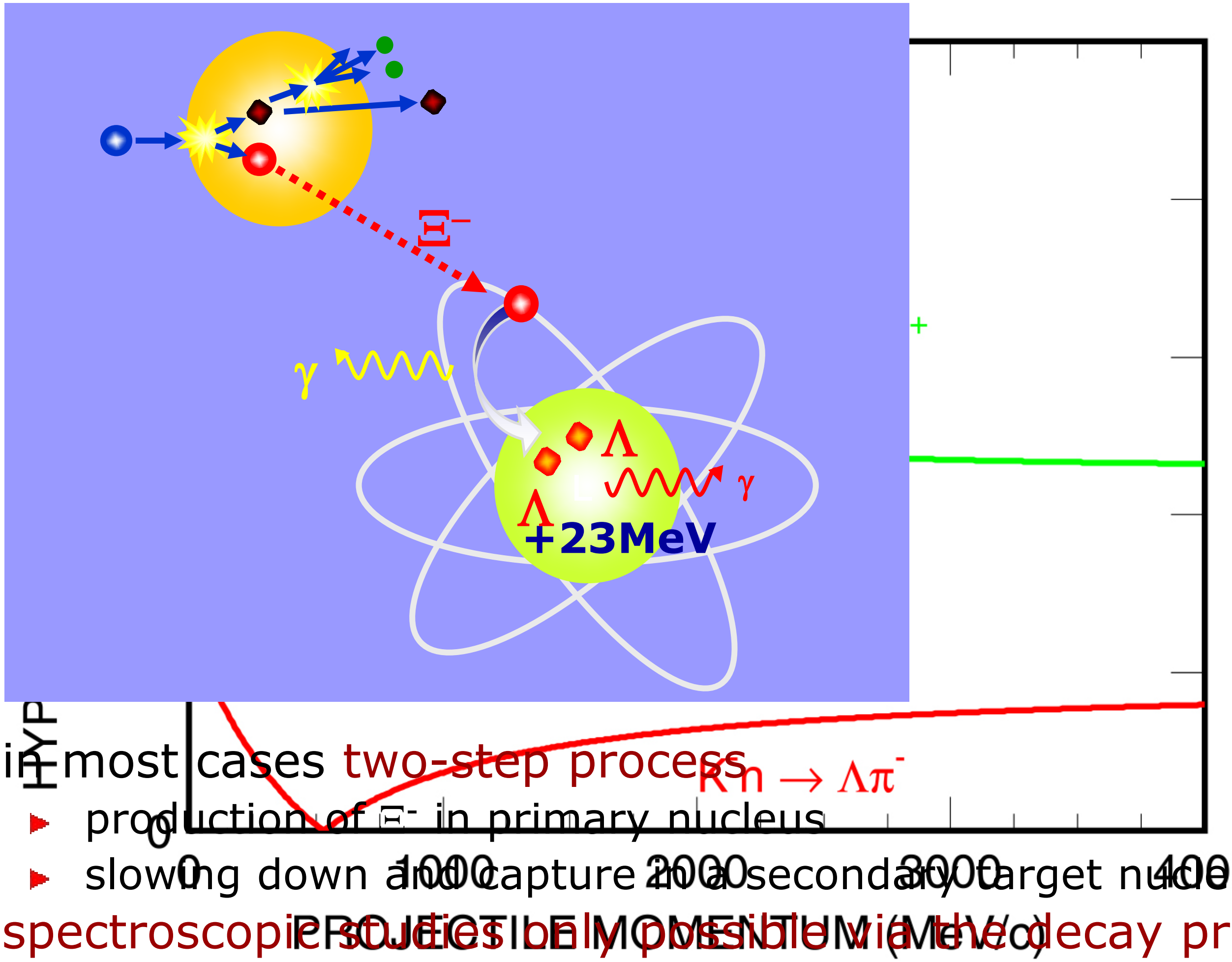
Phase 2



double hypernuclei

Production of $\Lambda\Lambda$–Hypernuclei

- simultaneous implantation of two Λ is not feasible
- 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

KEK-E373: the NAGARA event

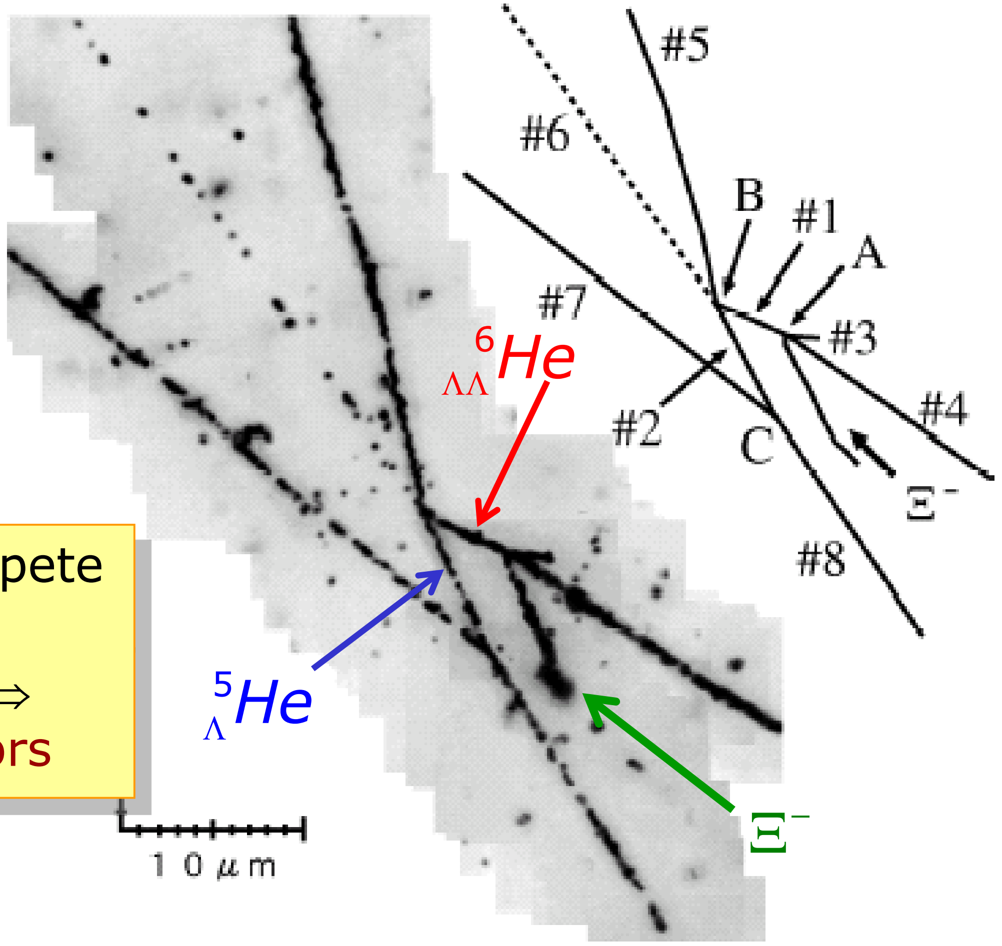
- H. Takahashi *et al*., PRL 87, 212502-1 (2001)
  - hybrid emulsion technique
  - cleanest event so far (also theoretically)

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

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

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

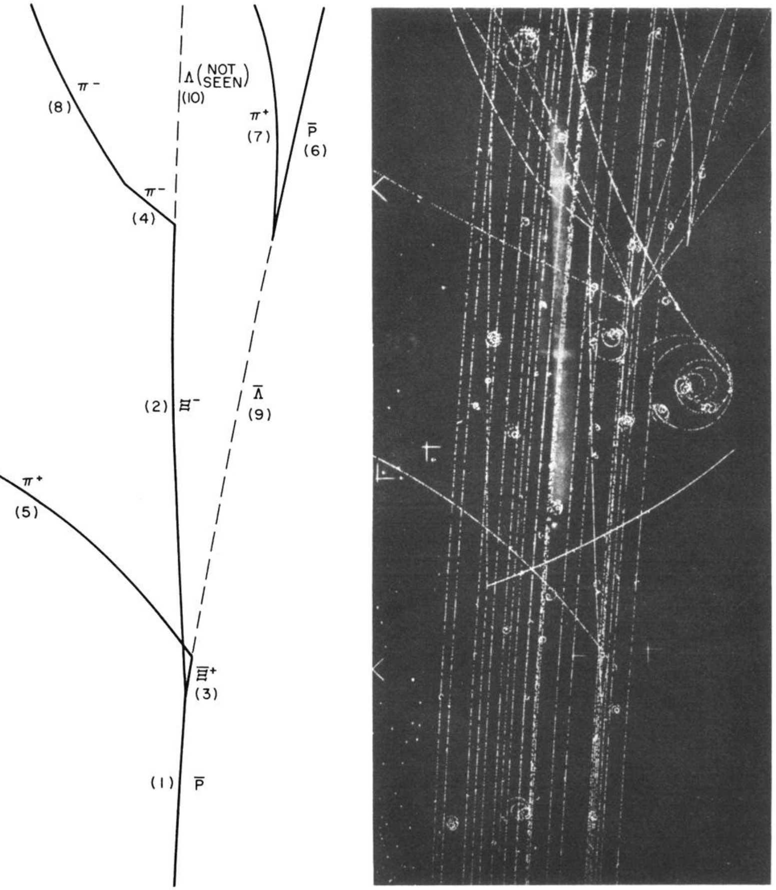
- no electronic detector can compete with emulsions
- structure with high resolution ⇒ γ-spectroscopy with Ge detectors

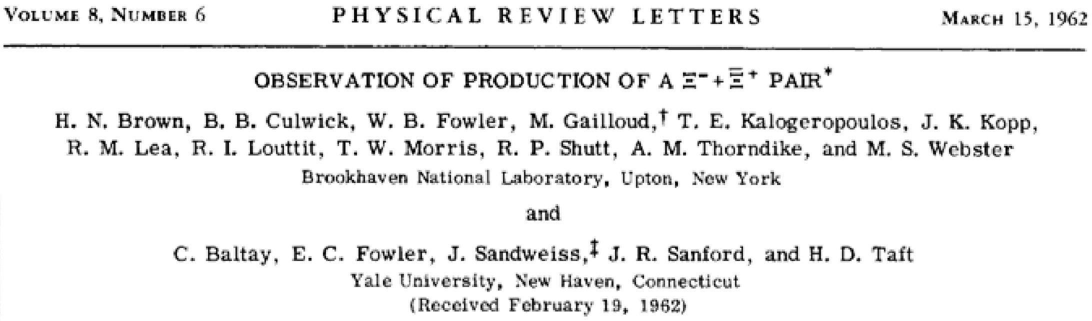


The Discovery of the anti-Xi

- discovered simultaneously at CERN and SLAC

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





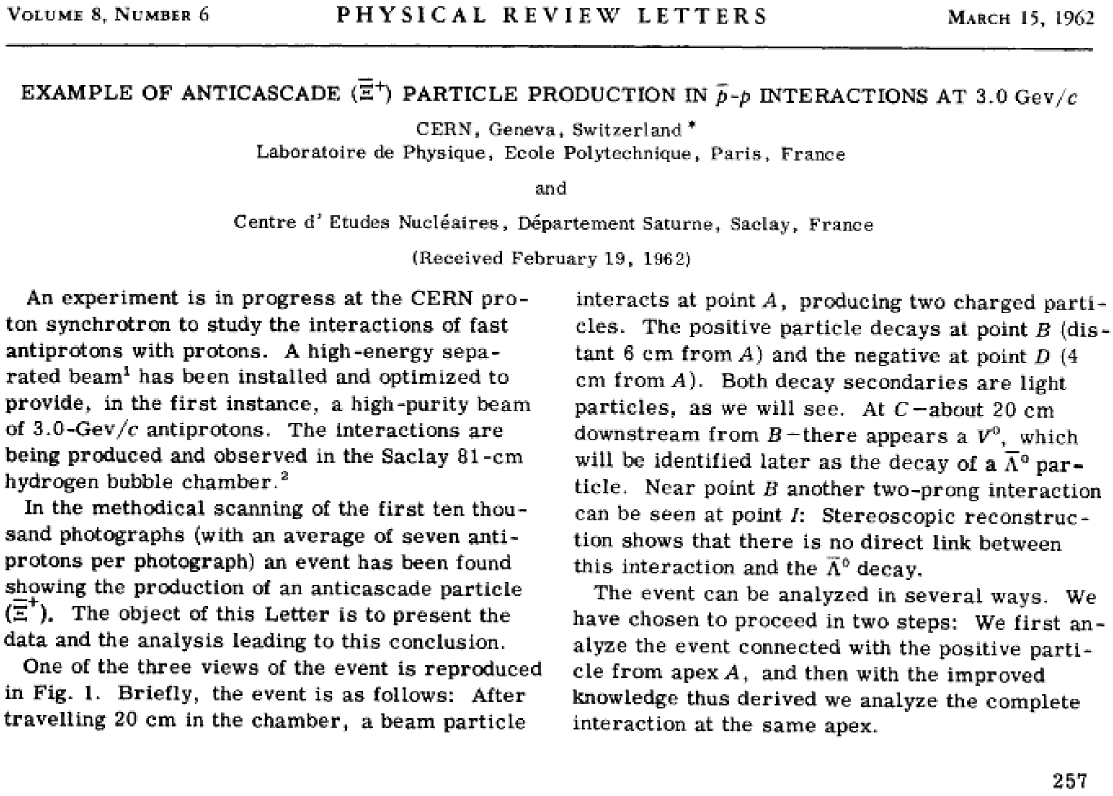
Volume 8, Number 6 PHYSICAL REVIEW LETTERS March 15, 1962

OBSERVATION OF PRODUCTION OF A $\Xi^- + \bar{\Xi}^+$ PAIR[*]

H. N. Brown, B. B. Culwick, W. B. Fowler, M. Gailloud,[†] T. E. Kalogeropoulos, J. K. Kopp,
R. M. Lea, R. I. Louttit, T. W. Morris, R. P. Shutt, A. M. Thorndike, and M. S. Webster
Brookhaven National Laboratory, Upton, New York

and

C. Baltay, E. C. Fowler, J. Sandweiss,[‡] J. R. Sanford, and H. D. Taft
Yale University, New Haven, Connecticut
(Received February 19, 1962)



Volume 8, Number 6 PHYSICAL REVIEW LETTERS March 15, 1962

EXAMPLE OF ANTICASCADE ($\bar{\Xi}^+$) PARTICLE PRODUCTION IN $\bar{p}$-p INTERACTIONS AT 3.0 Gev/c

CERN, Geneva, Switzerland[*]
Laboratoire de Physique, Ecole Polytechnique, Paris, France

and

Centre d' Etudes Nucléaires, Département Saturne, Saclay, France
(Received February 19, 1962)

An experiment is in progress at the CERN proton synchrotron to study the interactions of fast antiprotons with protons. A high-energy separated beam[1] has been installed and optimized to provide, in the first instance, a high-purity beam of 3.0-Gev/c antiprotons. The interactions are being produced and observed in the Saclay 81-cm hydrogen bubble chamber.[2]

In the methodical scanning of the first ten thousand photographs (with an average of seven antiprotons per photograph) an event has been found showing the production of an anticascade particle ($\bar{\Xi}^+$). The object of this Letter is to present the data and the analysis leading to this conclusion.

One of the three views of the event is reproduced in Fig. 1. Briefly, the event is as follows: After travelling 20 cm in the chamber, a beam particle interacts at point A, producing two charged particles. The positive particle decays at point B (distant 6 cm from A) and the negative at point D (4 cm from A). Both decay secondaries are light particles, as we will see. At C—about 20 cm downstream from B—there appears a V^0, which will be identified later as the decay of a $\bar{\Lambda}^0$ particle. Near point B another two-prong interaction can be seen at point I: Stereoscopic reconstruction shows that there is no direct link between this interaction and the $\bar{\Lambda}^0$ decay.

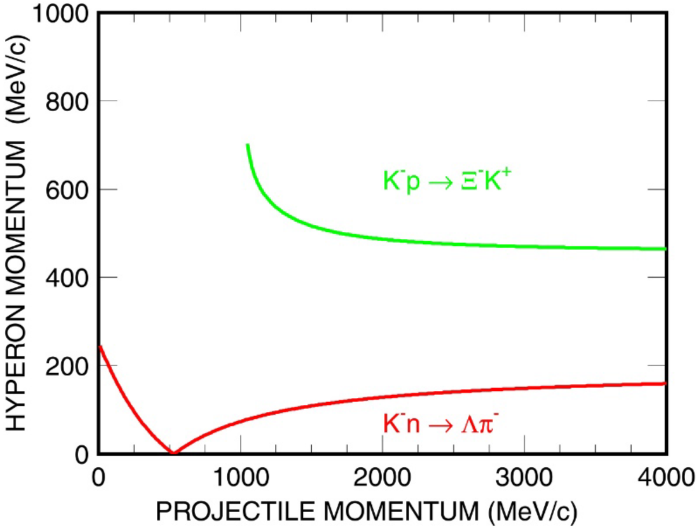
The event can be analyzed in several ways. We have chosen to proceed in two steps: We first analyze the event connected with the positive particle from apex A, and then with the improved knowledge thus derived we analyze the complete interaction at the same apex.

Production of Ξ^-

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

- Ξ- production
  - $p(K^-,K^+)\Xi^-$
    - 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
  - AGS-E885: 10^4 stopped Ξ

  $\Big\}$ per week(s)



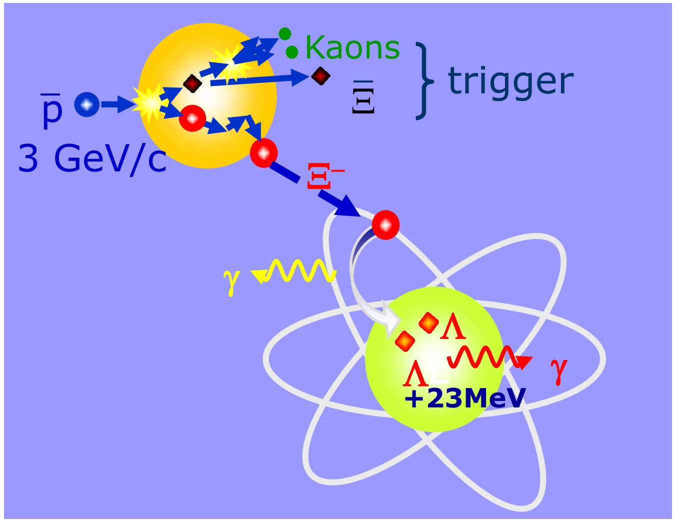
- antiproton storage ring HESR

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

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

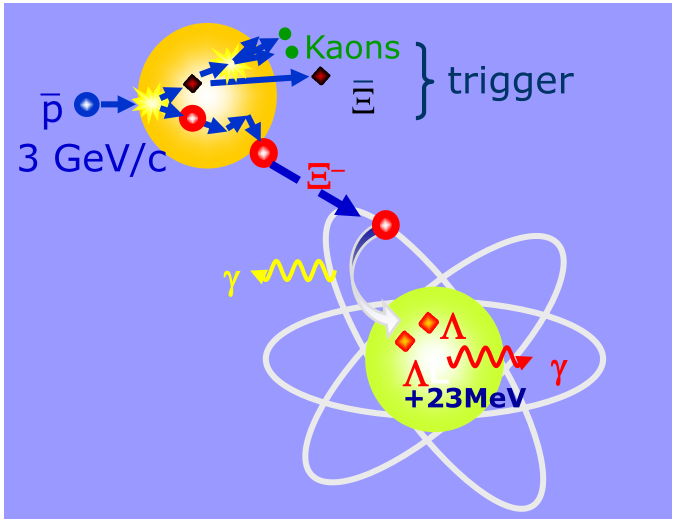
- few times 10^5 stopped Ξ per day

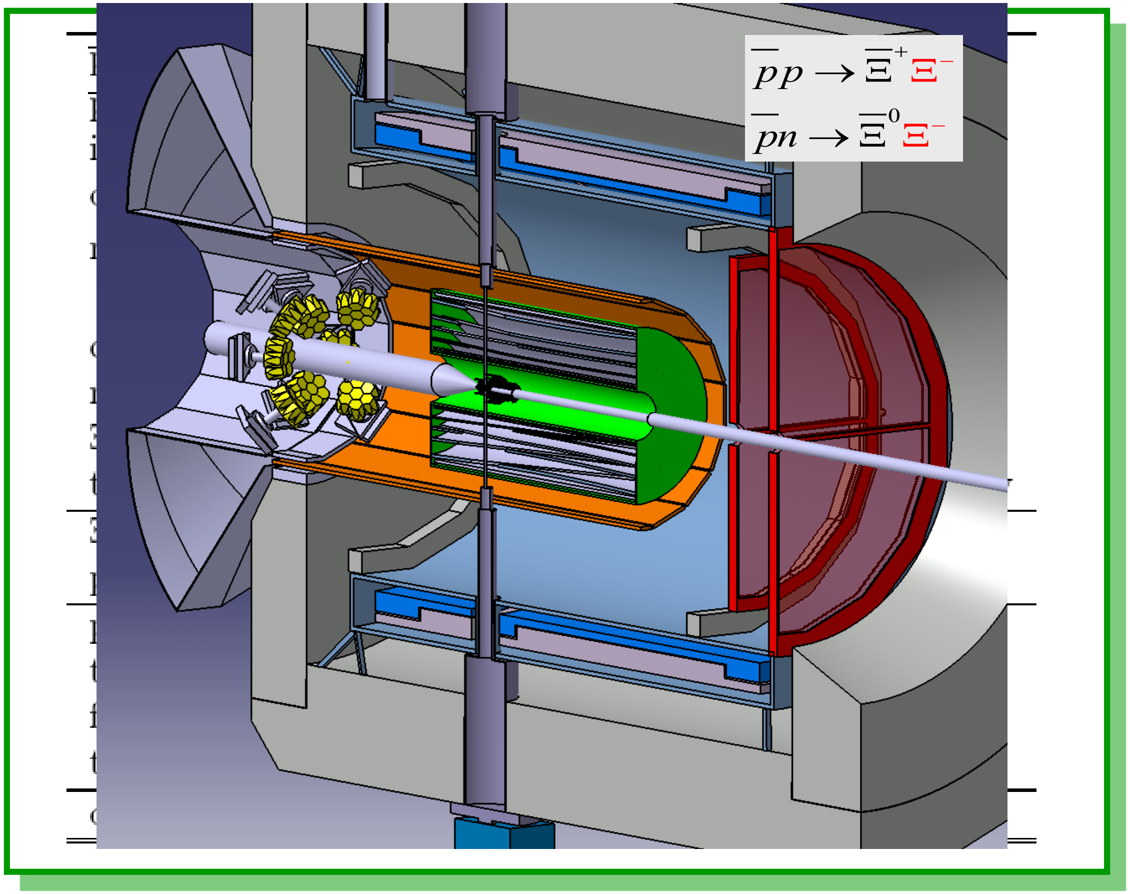
$\Rightarrow$ γ-spectroscopy feasible



PANDA setup

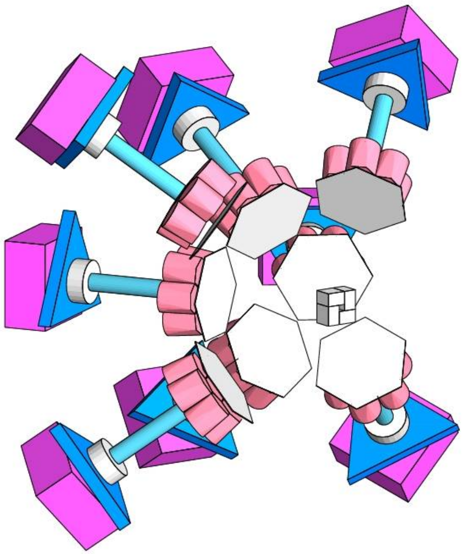
- θ_{lab}< 45°: Ξ-bar, K trigger (PANDA)
- θ_{lab}= 45°-90°: Ξ^--capture, hypernucleus formation
- θ_{lab}>90°: γ-detection (Euroball)
  - neutron background (4000n $cm^{-2}s^{-1}$)





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

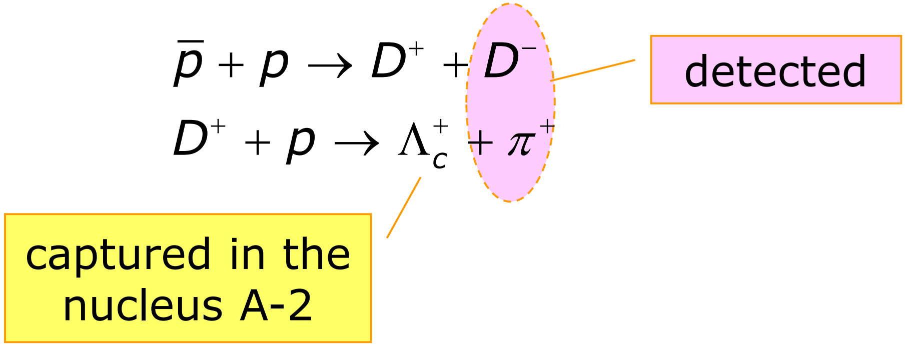
$$\bar{p}n \to \bar{\Xi}^0 \Xi^-$$



Can we do more?

- triple hypernuclei via $p\bar{p} \to \Omega\bar{\Omega}$ $\quad \Omega pn \to \Lambda\Lambda\Lambda + 203MeV$?
  - lower cross section
  - large momenta $\Rightarrow$ lower stopping probability
  - large Q-value $\Rightarrow$ low probability for triple Λ nuclei
  - γ-spectroscopy most likely not practical at the beginning

- Λ_c hypernuclei
  - production via primary + secondary target not possible because of short lifetime of $\tau_{\Lambda c}$ =0.2ps which exceeds stopping time
  - direkt production via pp $\to \Lambda_c\Lambda_c$bar or $\pi^- p \to \Lambda_c D^-$ difficult because of high momenta involved (very low sticking probability)
  - does a two-step process *within one nucleus* work?



$$\bar{p} + p \to D^+ + D^-$$
$$D^+ + p \to \Lambda_c^+ + \pi^+$$

detected

captured in the nucleus A-2

  - determination of the Λ_c hypernucleus mass via missing mass
    - needs good knowledge of beam momentum (10^{-4})
    - excellent momentum resolution for π^+ and D^- (resp. decay products)
  - expected rate ~0.01 day^{-1} (??? rescattering → $1 day^{-1}$???)

antibaryons in nuclei

G-Parity and N$\bar{\text{N}}$ Potential

- strong interaction conserves isospin and C-parity
- *G*=charge conjugation + 180° rotation around 2nd axis in isospin
  - Lee und Yang 1956, L. Michel 1952 „Isoparity"
  - G-parity of particle-antiparticle multipletts

$$G\left|f\bar{f}\right\rangle = (-1)^I C\left|f\bar{f}\right\rangle = (-1)^{I+L+S}\left|f\bar{f}\right\rangle$$

$$G\left|\pi^{\pm 0}\right\rangle = (-1)^1 C\left|\pi^{\pm 0}\right\rangle = -\left|\pi^{\pm 0}\right\rangle$$

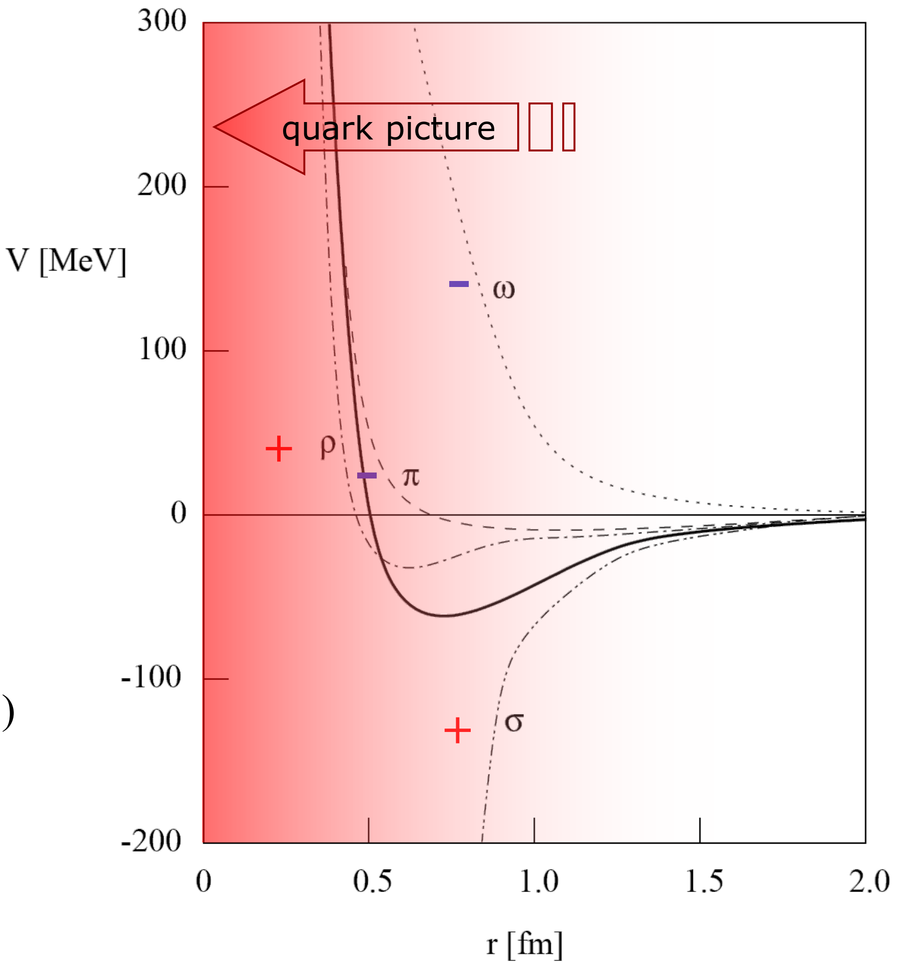
$$G\left|\rho\right\rangle = (-1)^1 C\left|\rho\right\rangle = +\left|\rho\right\rangle$$

$$G\left|\omega\right\rangle = (-1)^0 C\left|\omega\right\rangle = -\left|\omega\right\rangle$$

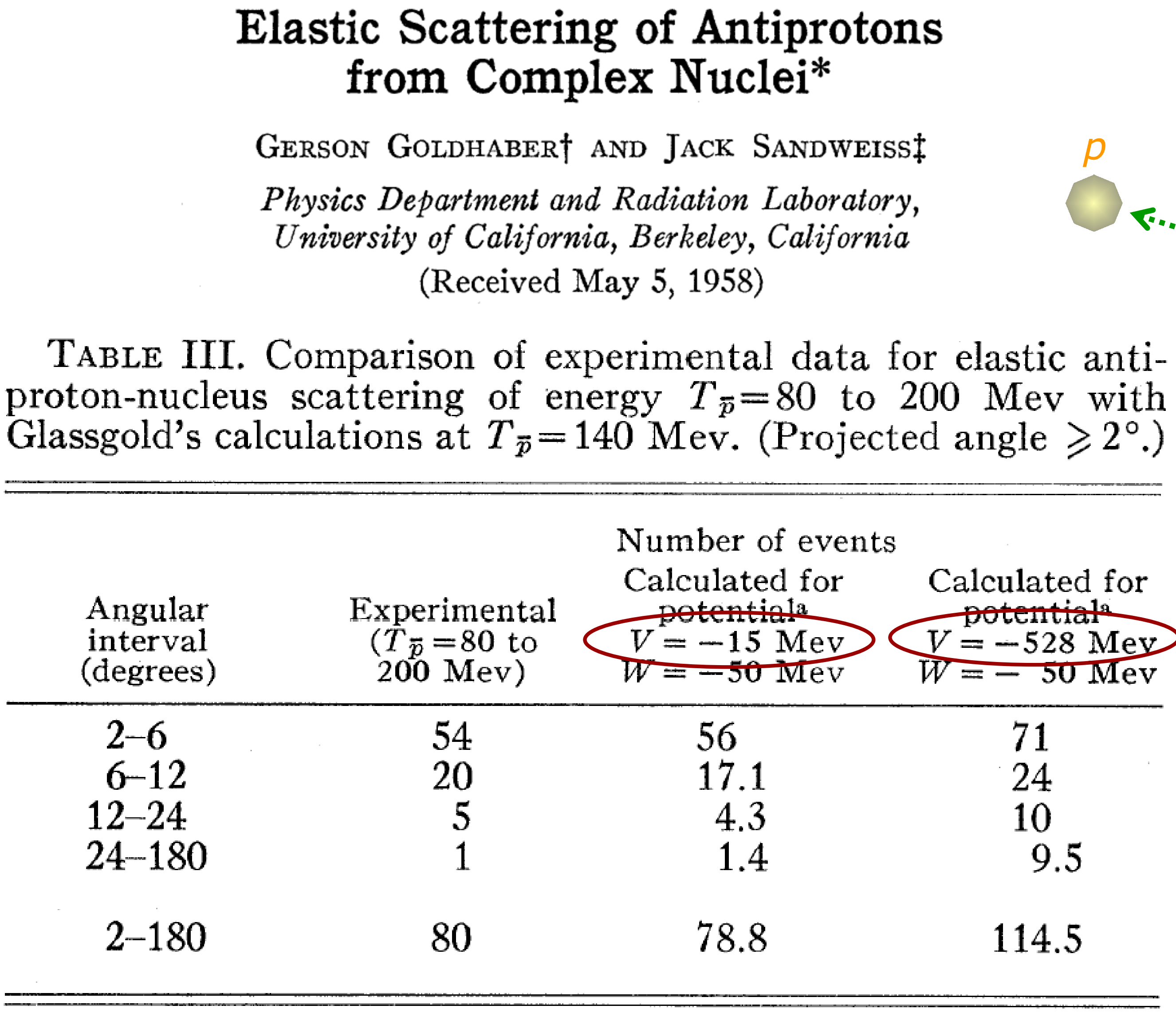
$$G\left|\sigma\right\rangle = (-1)^0 C\left|\sigma\right\rangle = +\left|\sigma\right\rangle$$

- Hans-Peter Dürr and Edward Teller, Phys. Rev. **101**, 494 (1956)
  - sign change in coupling constant

$$V(NN)(r) = \sum_M V_M(r) \rightarrow V(N\bar{N})(r) = \sum_M G_M V_M(r)$$



Elastic Antiproton-Nucleus Scattering



Elastic Scattering of Antiprotons from Complex Nuclei*

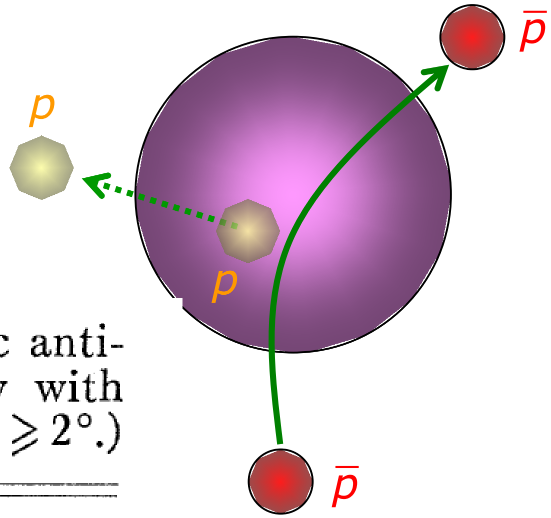
Gerson Goldhaber† and Jack Sandweiss‡

Physics Department and Radiation Laboratory,
University of California, Berkeley, California

(Received May 5, 1958)

Table III. Comparison of experimental data for elastic antiproton-nucleus scattering of energy $T_{\bar{p}}=80$ to 200 Mev with Glassgold's calculations at $T_{\bar{p}}=140$ Mev. (Projected angle $\gtrsim 2°$.)

		Number of events	
Angular interval (degrees)	Experimental ($T_{\bar{p}}=80$ to 200 Mev)	Calculated for potential[a] $V=-15$ Mev $W=-50$ Mev	Calculated for potential[a] $V=-528$ Mev $W=-\ 50$ Mev
2–6	54	56	71
6–12	20	17.1	24
12–24	5	4.3	10
24–180	1	1.4	9.5
2–180	80	78.8	114.5

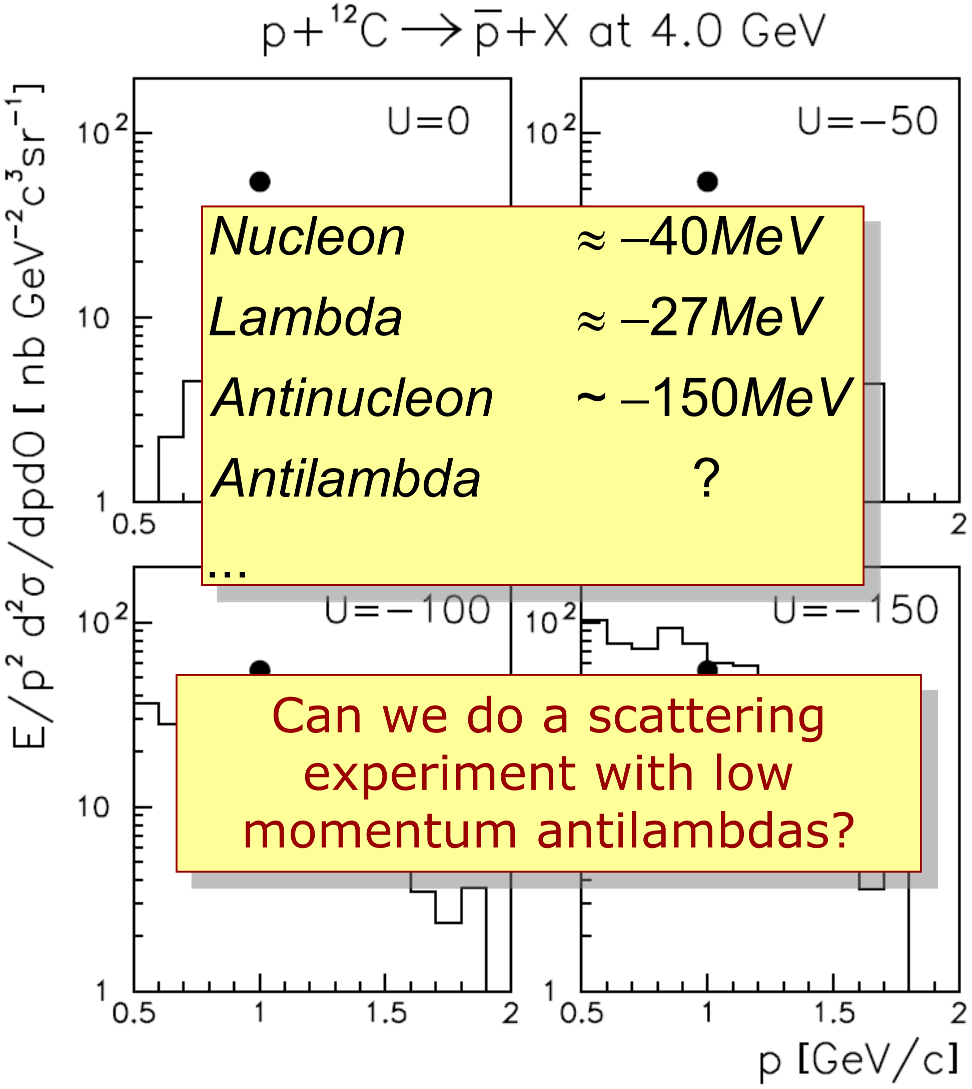


Antiprotonproduction in HI Collisions

- see e.g.

  A. Sibirtsev, W. Cassing *et al*., Nucl. Phys. A **632**, 131 (1998)

  C. Spieles *et al*., Phys. Rev. C **53**, 2011-2013 (1996)

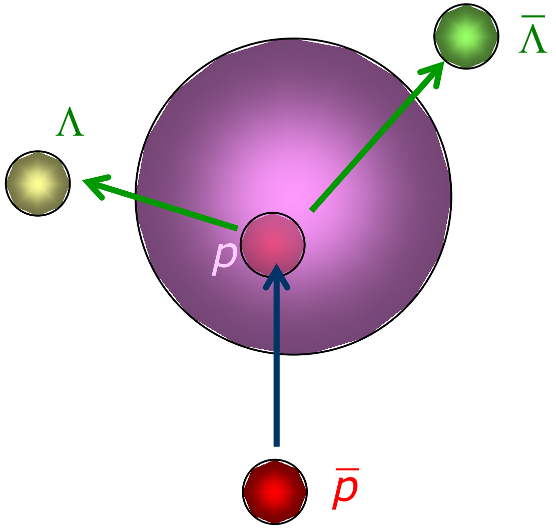


Nucleon	$\approx -40 MeV$
Lambda	$\approx -27 MeV$
Antinucleon	$\sim -150 MeV$
Antilambda	?
...	

Can we do a scattering experiment with low momentum antilambdas?

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

- $p + \bar{p} \rightarrow \Lambda + \bar{\Lambda}$ close to threshold within complex nuclei
- Question: is the momentum of the Λ and anti-Λ equal?
- If yes, Λ and anti-Λ that leave the nucleus will have different asymptotic momenta
  - the momentum difference is sensitive to the potential difference



- experimental complications
  - Fermi motion
  - leading effect
  - exclusiveness

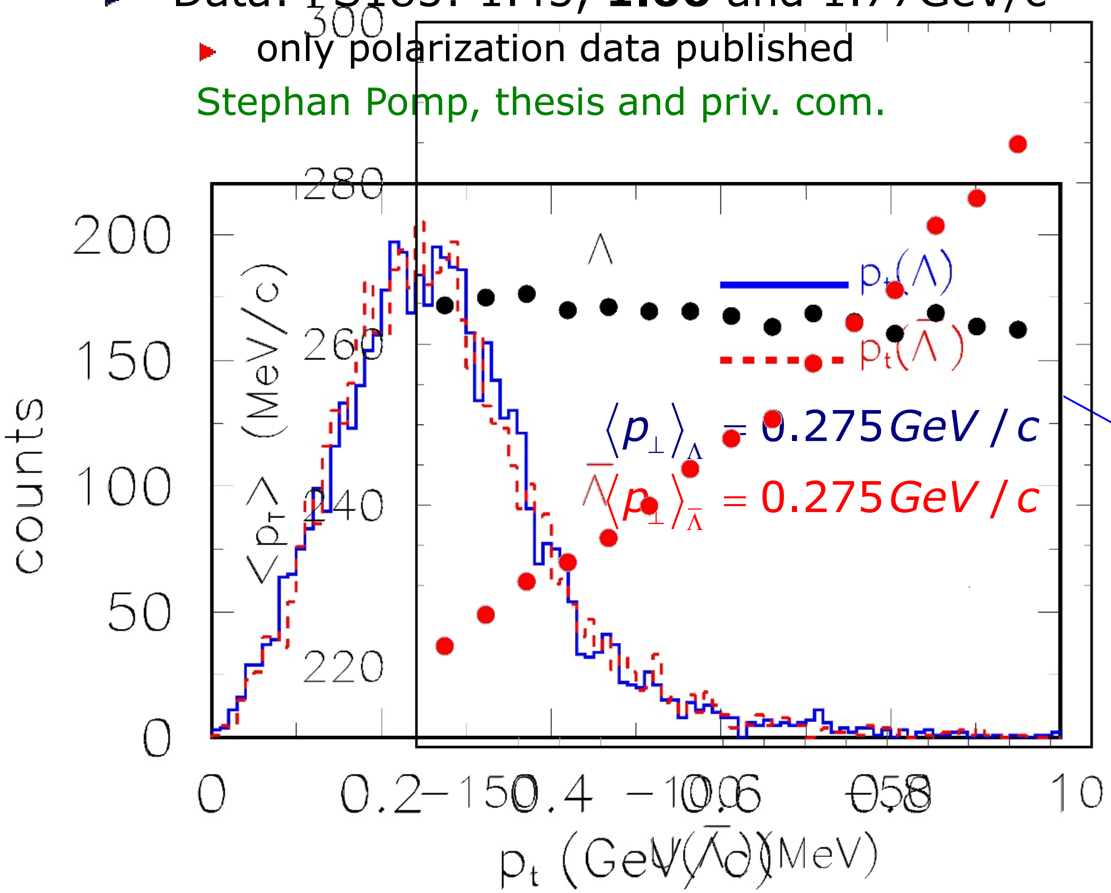
$\Rightarrow$ need to look at average *transverse* momentum close to threshold of *coincident* $\Lambda\bar{\Lambda}$ pairs

Pair production in Nuclei: $\bar{p}\,^{12}C \to \bar{\Lambda}\Lambda X$

- Simulations: Antiproton momentum: 1.66 GeV
  - Λ potential: -28MeV
  - Fermi motion ($1s_{1/2}$ and $1p_{3/2}$ single-particle wf)
  - angular distribution (leading effect)
  - absorption (still crude)

- Data: PS185: 1.45, **1.66** and 1.77GeV/c
  - only polarization data published

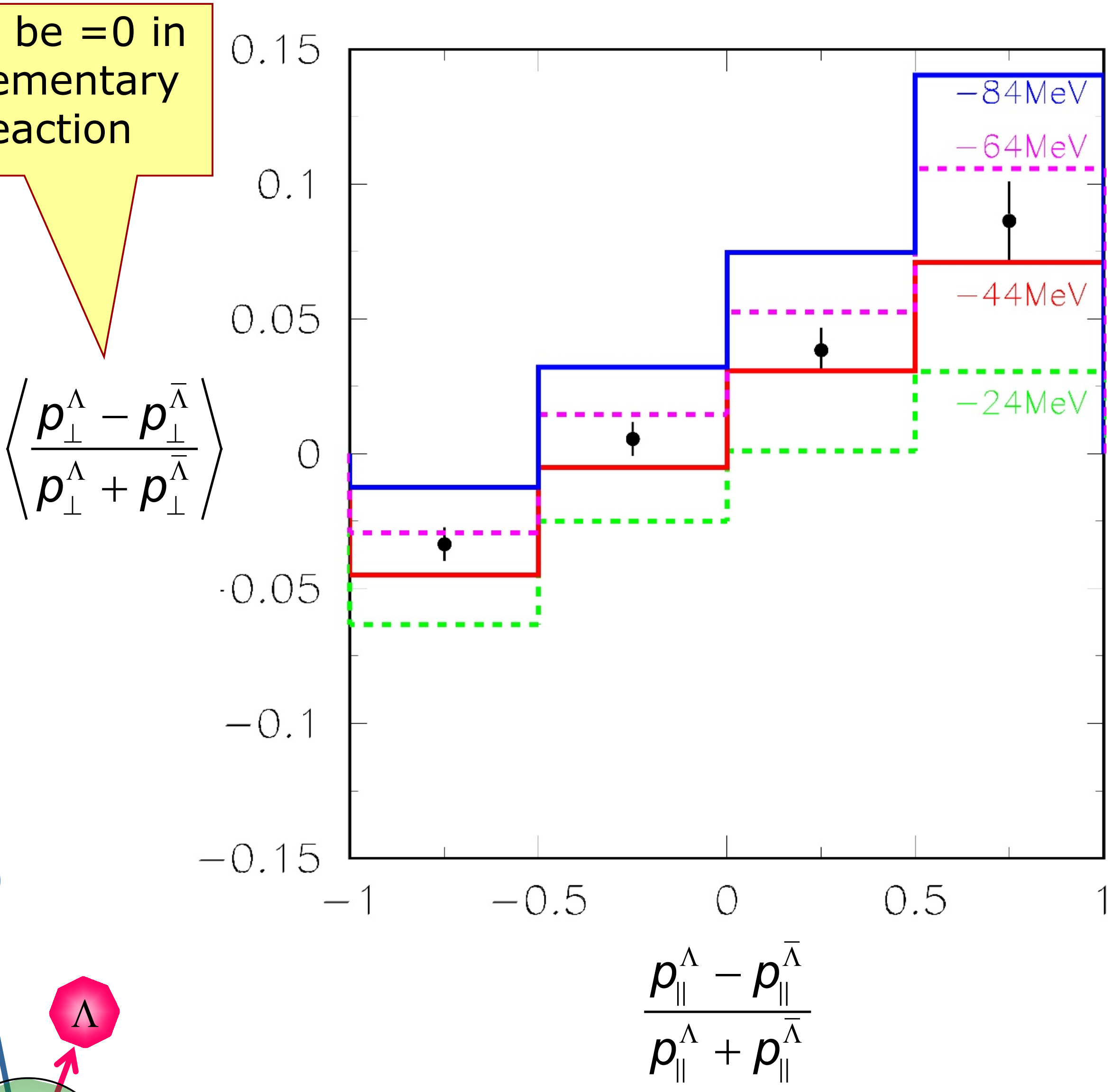
Stephan Pomp, thesis and priv. com.

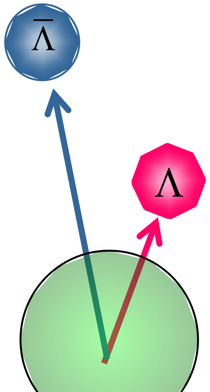


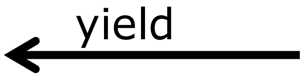
$\bar{\Lambda}$ have larger momenta ⇒ less influenced by potential or Fermi motion

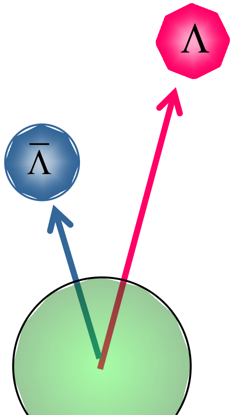
A Closer Look…

this has to be =0 in case of elementary $p\bar{p} \to \Lambda\bar{\Lambda}$ reaction



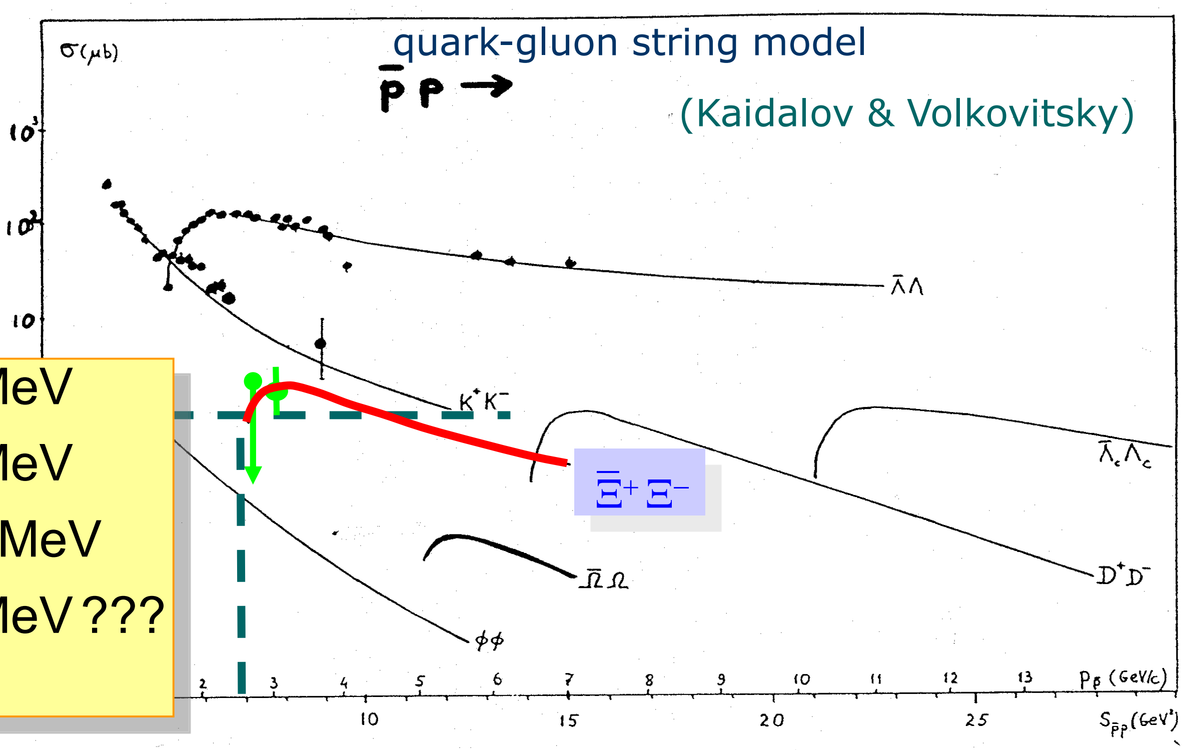






Outlook

- the (exclusive) production of B-$\bar{\mathrm{B}}$ pairs in nuclei by antiproton beams may offer the possibility to study the behaviour of antibaryons in nuclei



quark-gluon string model

(Kaidalov & Volkovitsky)

Nucleon	≈ -40MeV
Lambda	≈ -27MeV
Antinucleon	~ -150MeV
Antilambda	~ -50MeV ???

…

- Open tasks
  - momentum dependent absorption
  - momentum dependent rescattering
  - formation time
  - …and probably many more

conclusion

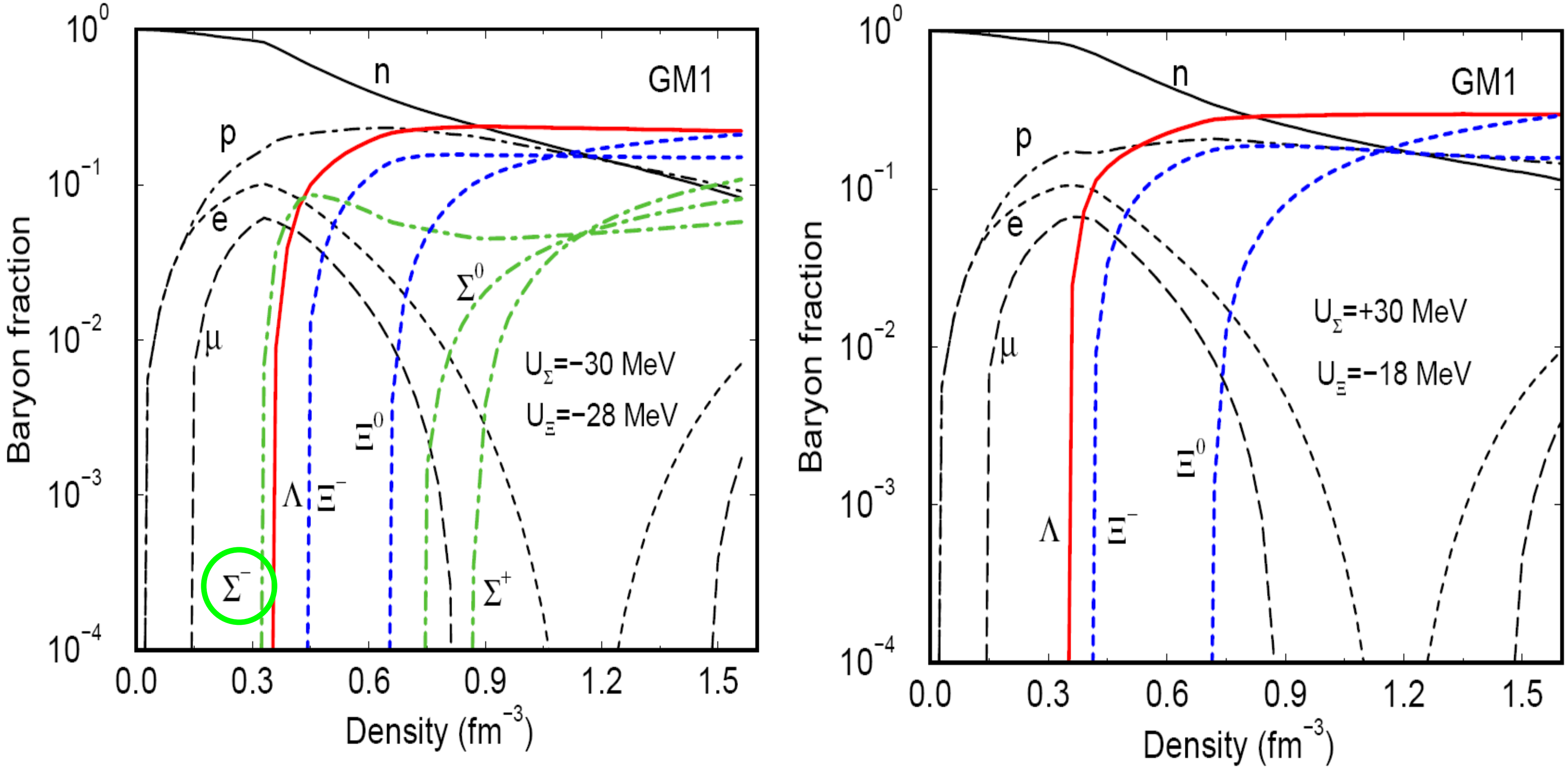
Conclusion

- Antiproton collisions with nuclei offer many opprtunities to study strange baryons in cold nuclei
  - baryon-baryon interaction
  - properties of (anti-)baryons in nuclei
  - spectroscopy of baryonic atoms
  - weak decay
  - …

- These studies are made possible by a unique combination of experimental facilities at FAIR
  - hypernuclei spectrometer ⊕ secondary relativistic HI beams
  - γ-spectroscopy with Ge detectors ⊕ antiproton beams

Baryon stars

- Input: Baryons in chemical Equilibrium, conservation laws, interaction



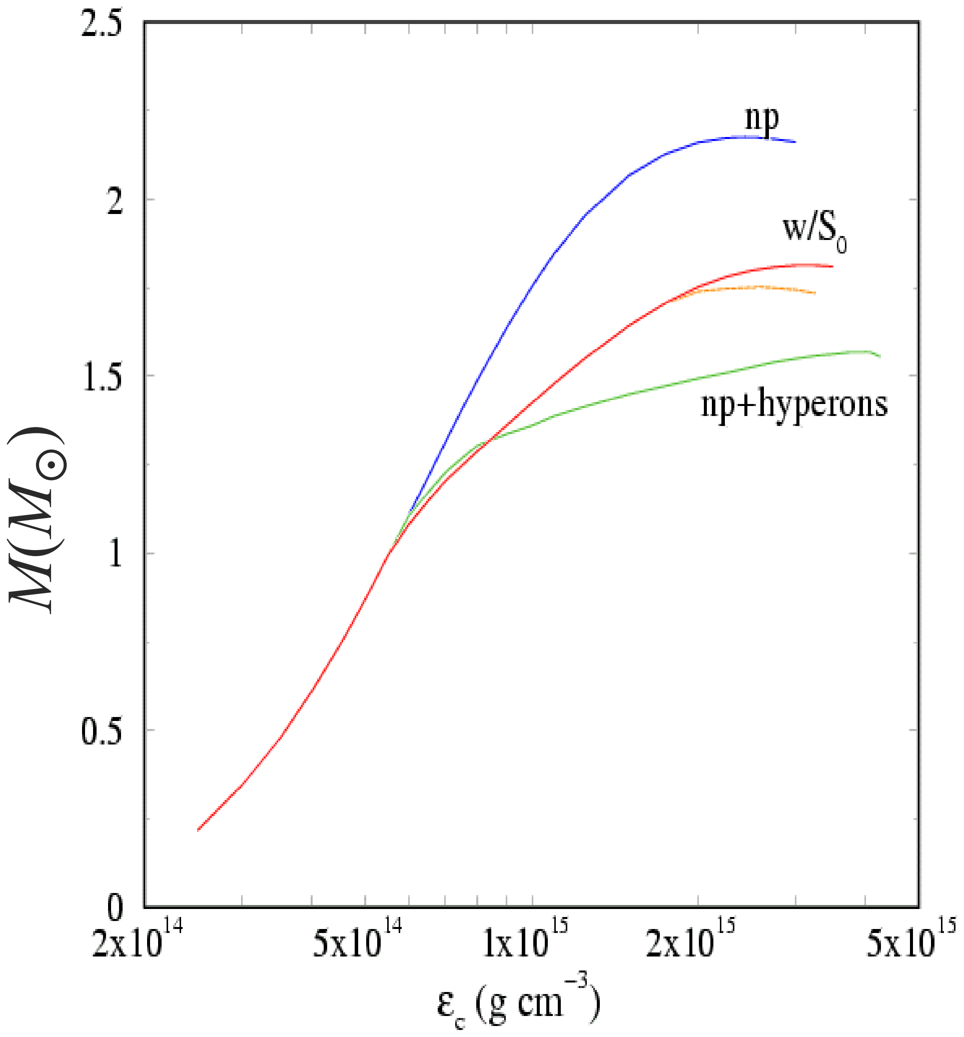
N. K. Glendenning, Phys. Rev. C **64**, 025801 (2001)

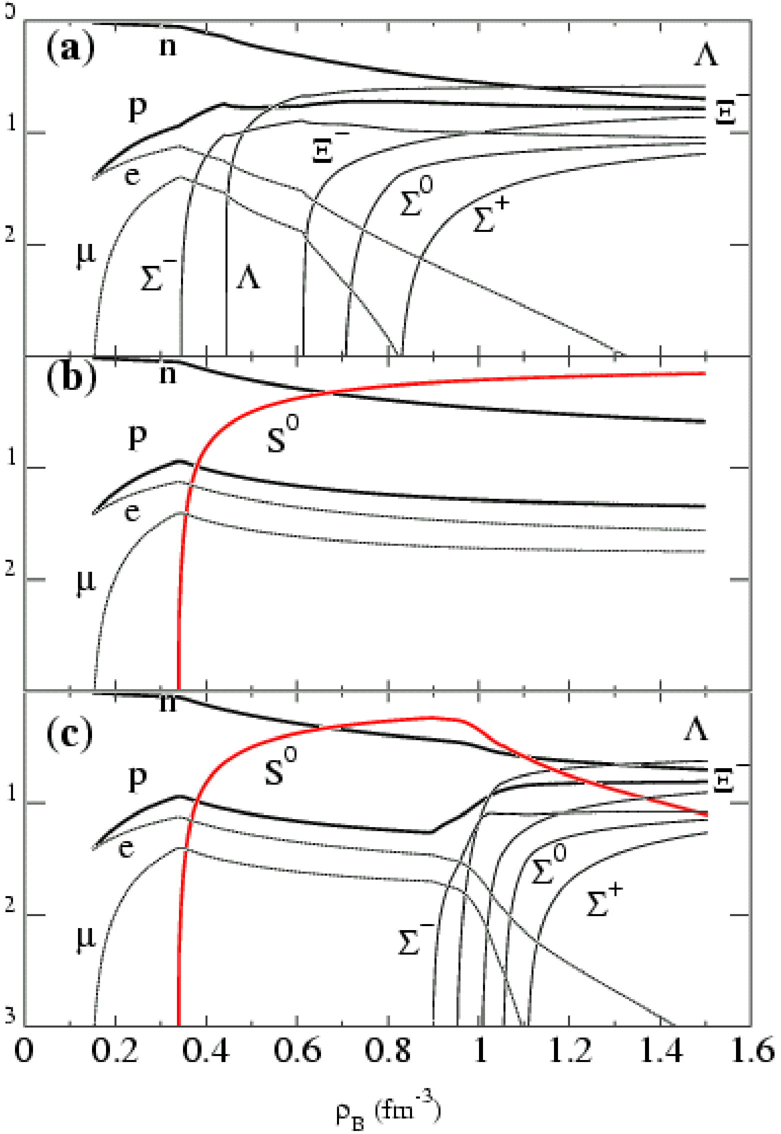
  - beyond $2\rho_0$ hyperons may play a significant role in neutron stars
  - in the core hyperons may even be more abundant than neutrons

- needed: BB interaction at high density= at small distances

Supersymmetric Particles

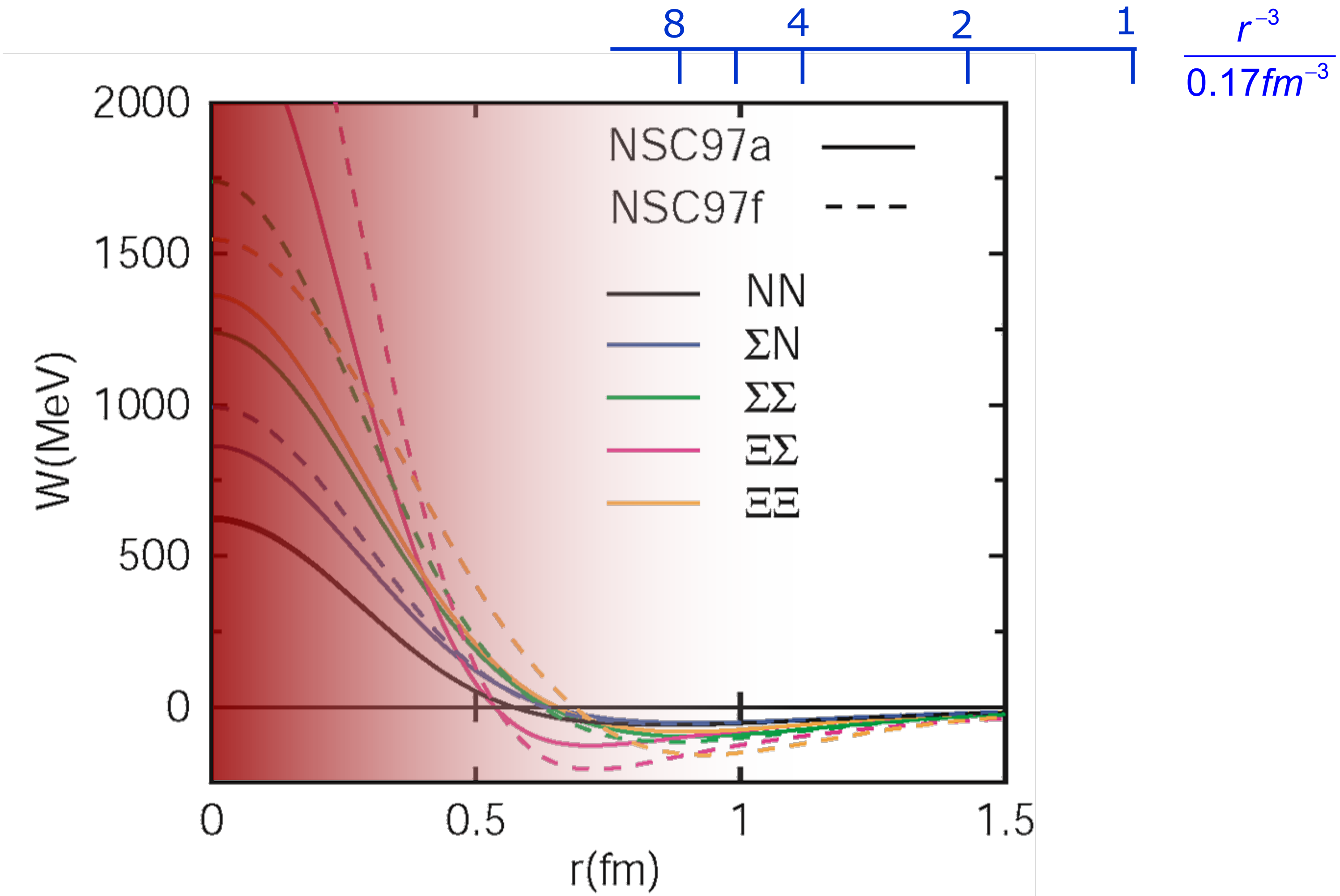
- The Astrophysical Journal, 548:L179–L182, 2001
- Shmuel Balberg, Glennys R. Farrar, and Tsvi Piran





Baryon-Baryon „Potential"

- Baryon-Stars ⇔ BB interaction at high density= at small distances



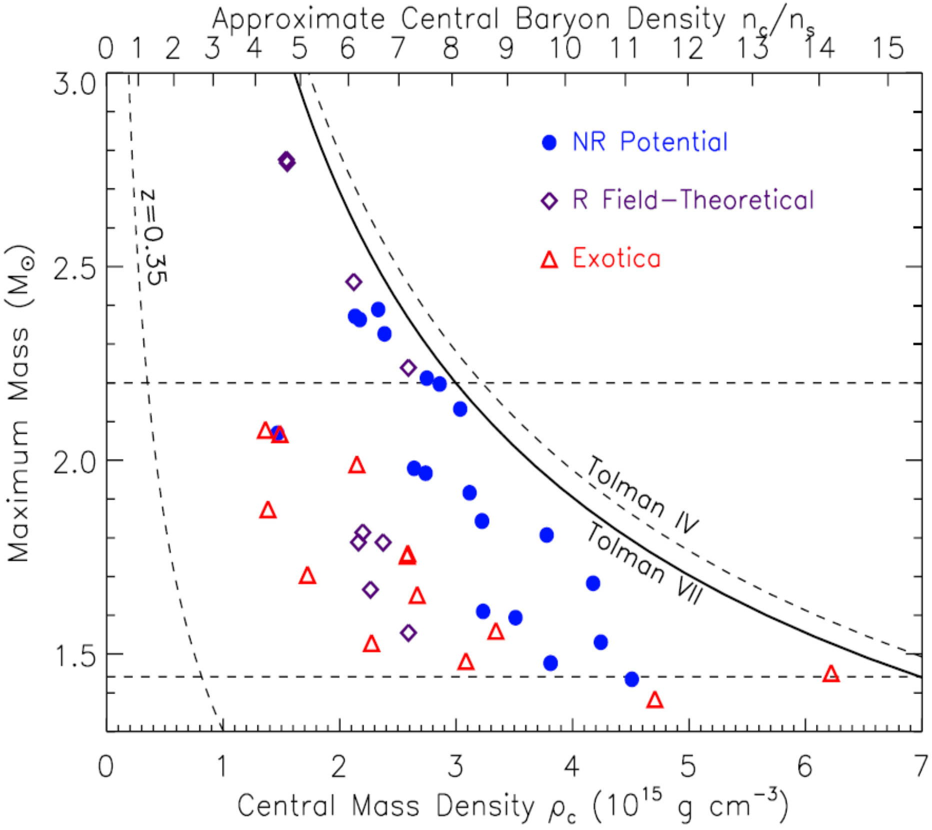
- Nijmegen OBE Potential fitted to ΛN Daten + SU(3) Symmetrie

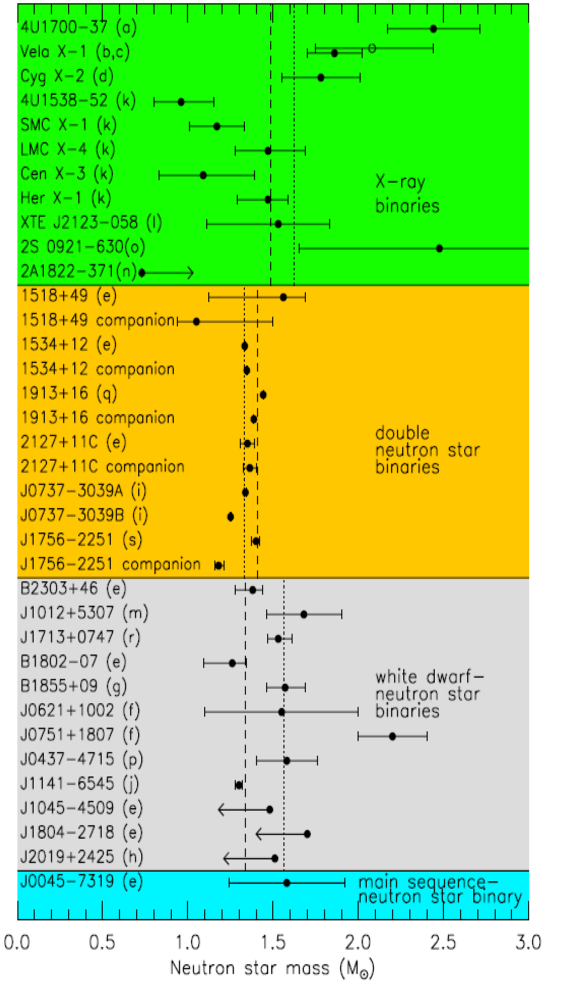
Th.A. Rijken, V.G.J. Stoks, Y. Yamamoto, Phys. Rev. C 59, 21 (1999)

Observable Consequence

- Main consequence of hyperons and other exotica in neutron stars: softer EOS $\Rightarrow$ lower mass and smaller central density

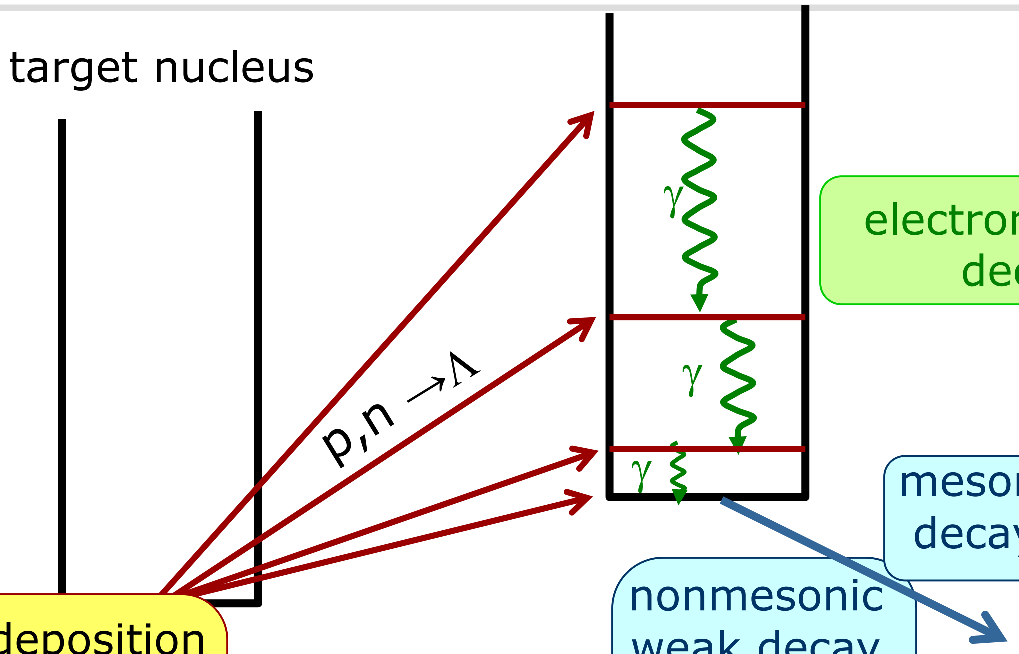
James M. Lattimer and Madappa Prakash
Phys. Rev. Lett. **94**, 111101 (2005)





- present data on neutron star masses do not exclude exotic cores
- simultaneous treatment of all possible ingredients (K,Y,q…) missing

Birth, life and death of a hypernucleus



strangeness deposition

$e^+ + e^- \to \Phi \to K^+ + K^-$

$K^-_{stopped} + {}^A Z \to {}^A_\Lambda Z + \pi^-$

FINUDA

electromagnetic decays

mesonic decays

$\Lambda \to p\pi^-$

$\Lambda \to n\pi^0$

nonmesonic weak decay

$\Lambda p \to np$

$\Lambda n \to nn$

$\Lambda\Lambda \to YN$

hadronic decay in emulsion

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

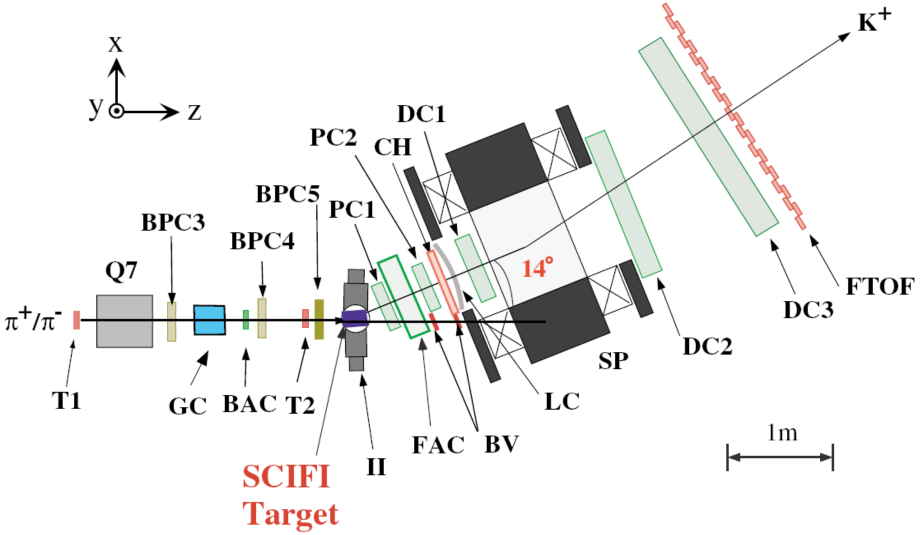
strangeness exchange
(K^-, π^-) , (K^-, π^0)

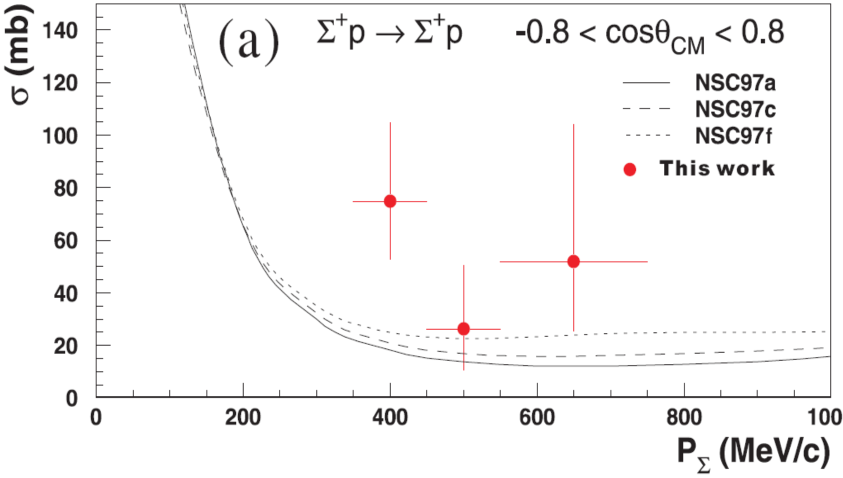
BNL,KEK,JPARC

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

Exp. Approaches to Y-N interactions

- low energy baryon-baryon scattering
  - N-N: ~10^4 data points available
  - charged hyperon – proton: scattering in a scintillator target
    - Σ^-p: KEK-PS E289 (π^-,K^+) ⇒ 30 events
    - Σ^+p: KEK-PS 251 & KEK-PS E289 (π^+,K^+) ⇒ 31 events each
    - Ξ^- p: (K^-,K^+) ⇒ 1 candidate

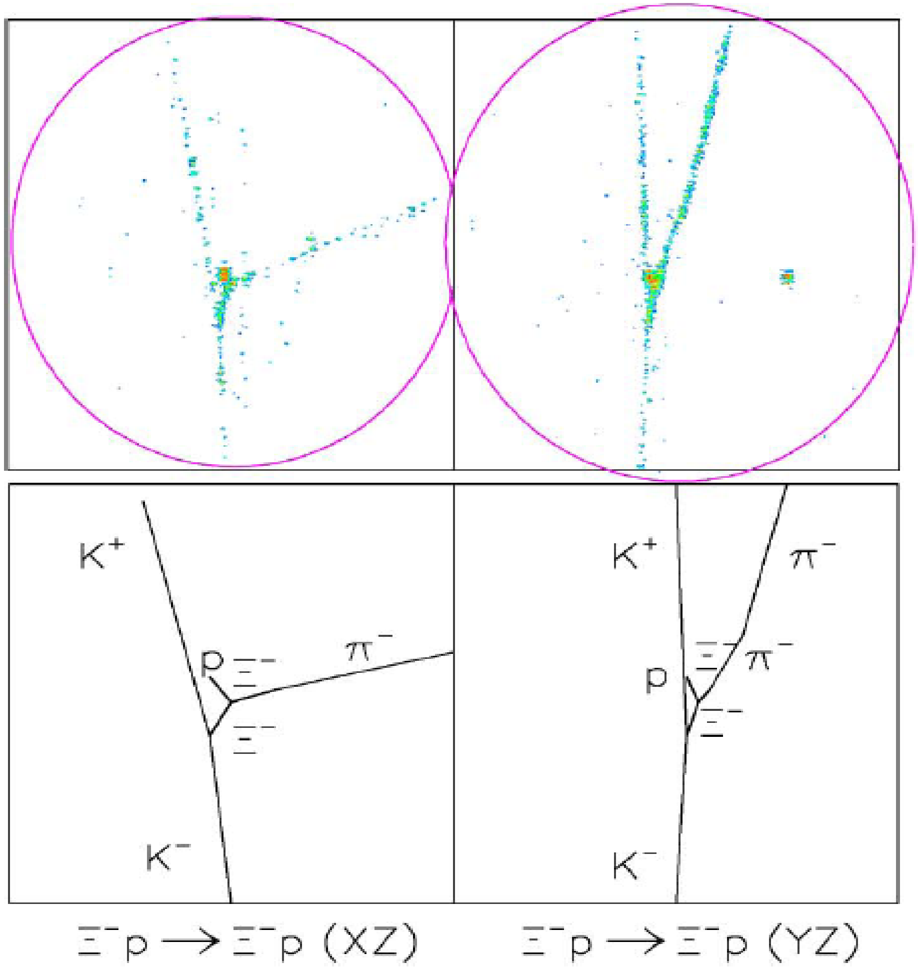




-
  -
    - JPARC: ~1000 events/day
- hyperon-hyperon final state interaction
  - feasible but difficult to interpret
- hyperons bound in nuclei
- hyperon-antihyperon pair production in nuclei

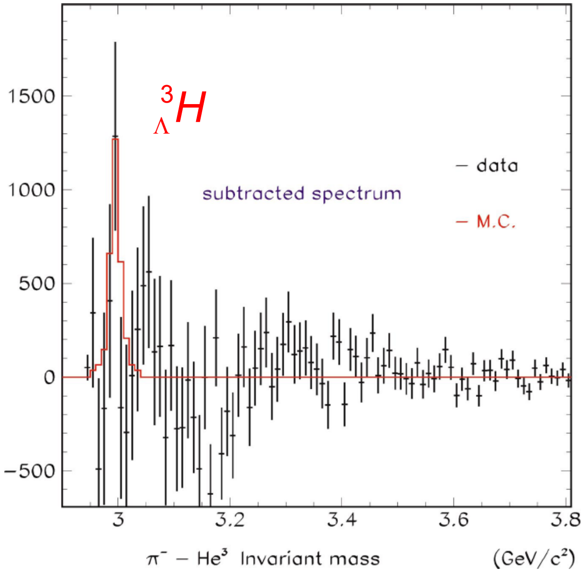
Ξ^- scattering

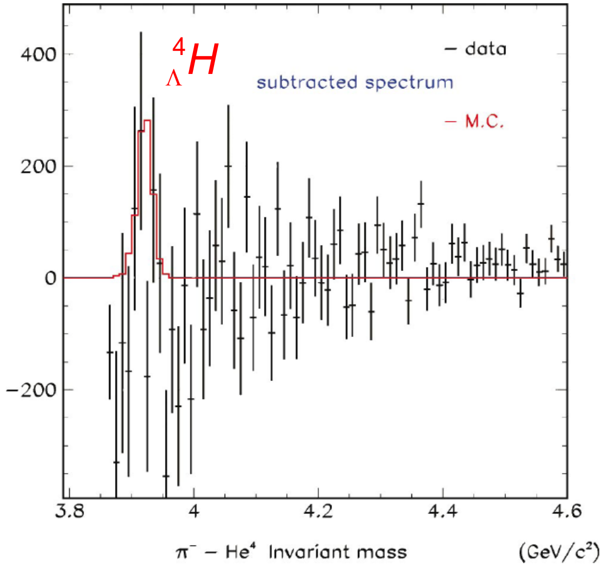
- Ahn et al.

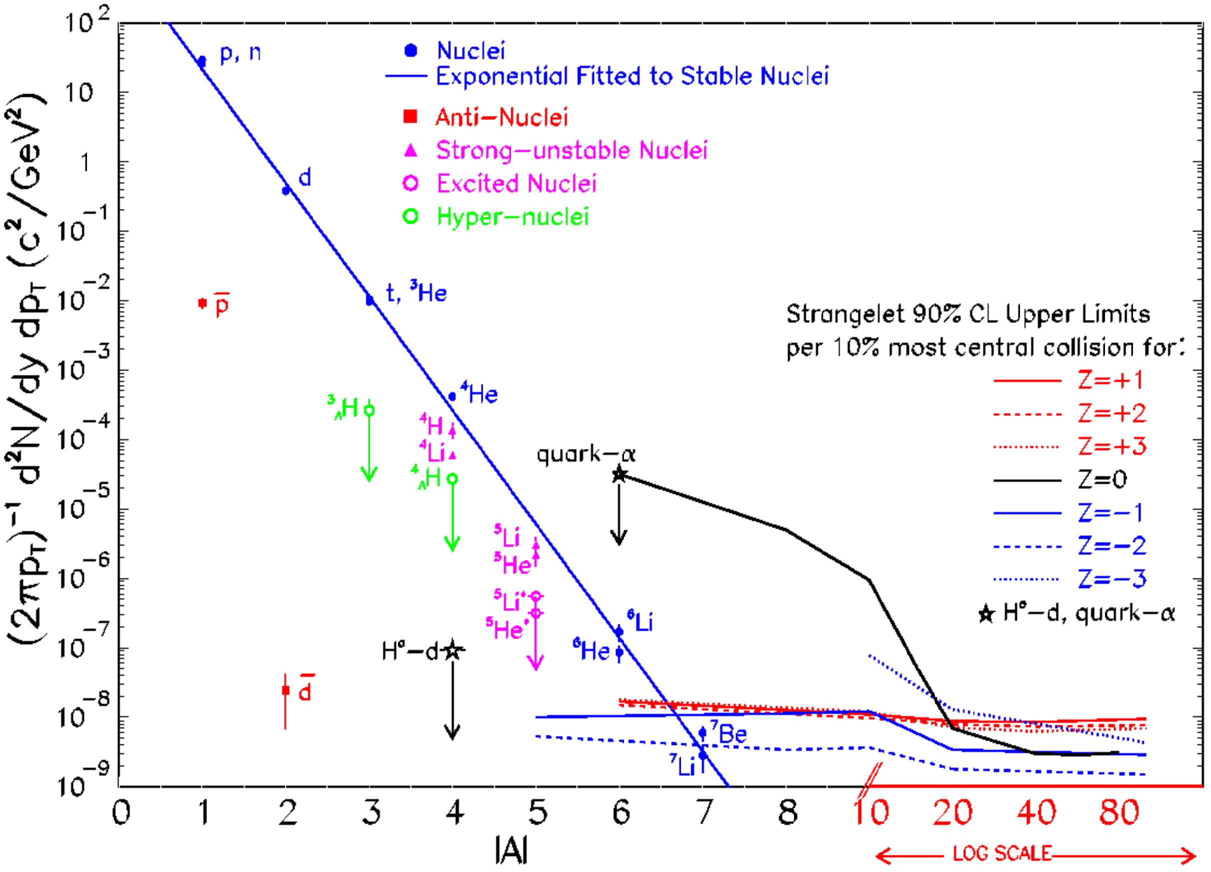


Summary of E864

- Phys. Rev. C **70**, 024902 (2004)



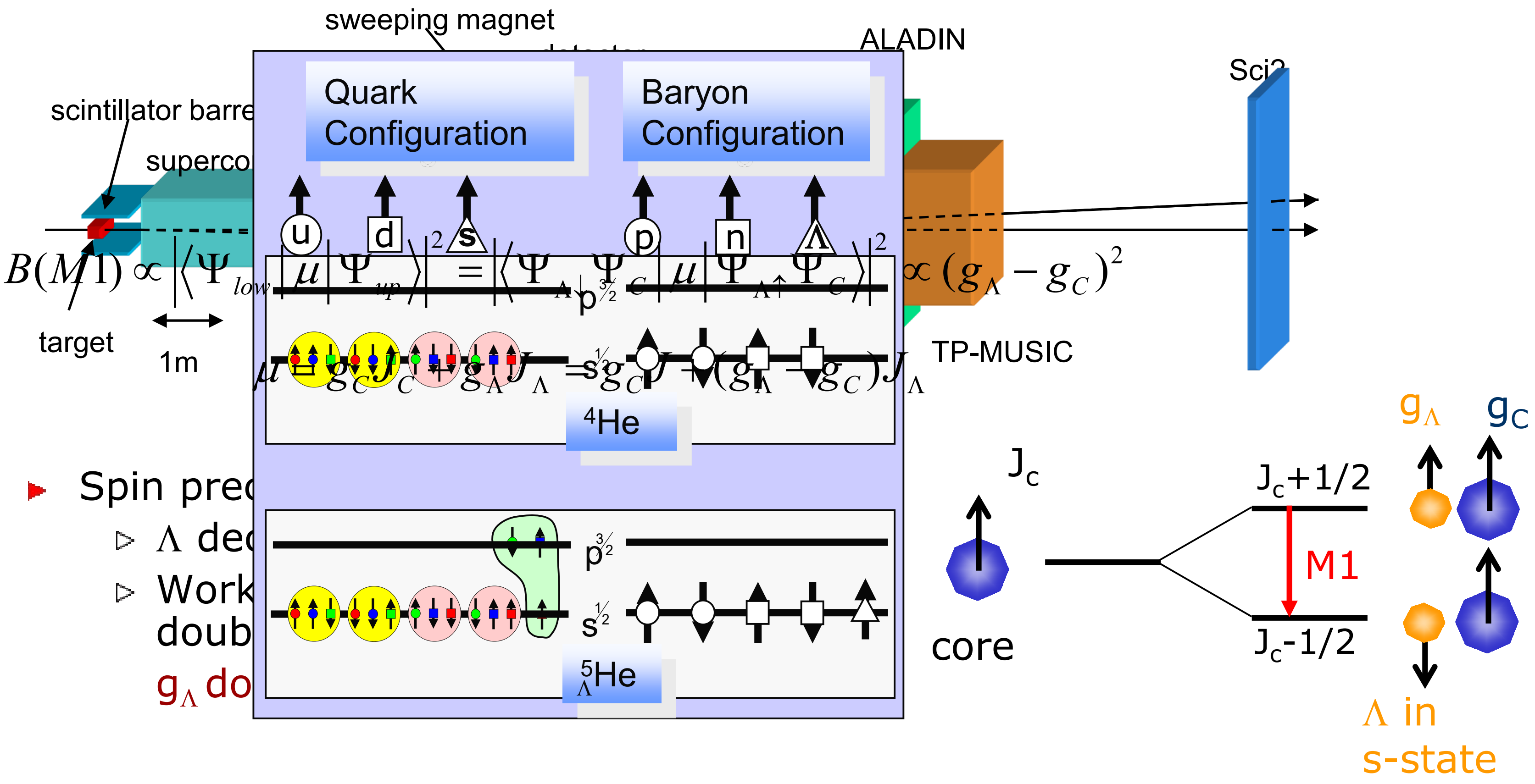




- Limits compatible with coalescence taking low biding energy and large size of hyperncului into acount

Magnetic moment of Λ in nuclei

- 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
  - If so, why? Meson current, ΛΣ mixing, partial deconfinement…?



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

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

- Spin prec
  - Λ dec
  - Work doub

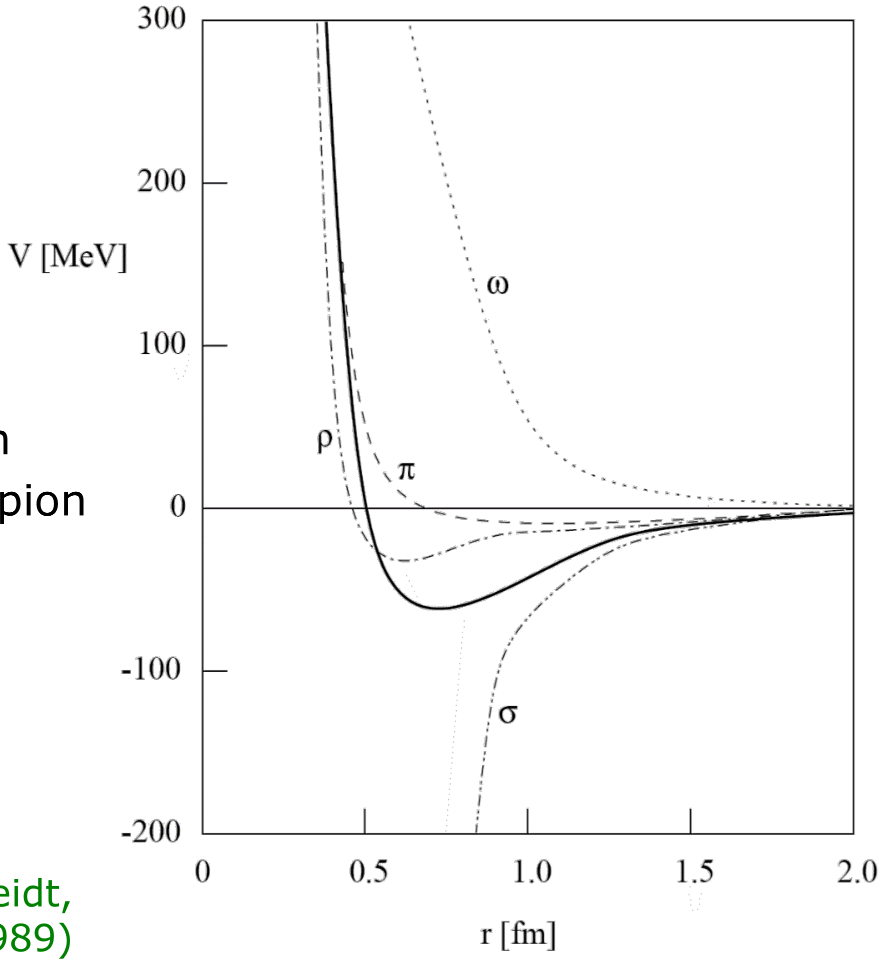
g_Λ do

Traditional View of the N-N Interaction

- Experimental observation
  - short range (r<0.5fm) repulsion
  - intermediate (r≈1fm) strong attraction
  - long range (r>1.5fm) attraction
- Boson exchange model
  - Yukawa (1935)
  - Klein-Gordon equation

$$\left(\partial^2 + m^2\right)\varphi(x) = g\bar{\psi}\psi$$

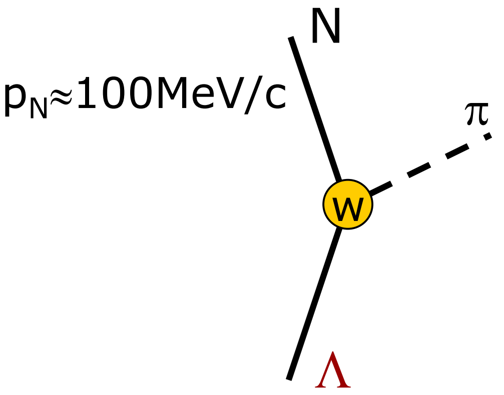
  - range of N-N interaction R≈2fm
  - $R=\hbar c/mc^2 \Rightarrow m\approx 100\text{MeV}/c^2 \Rightarrow$ pion



after R. Machleidt,
Adv. Nucl. Phys. **19**, 189 (1989)

Weak Decay of Λ Hypernuclei

free Λ decay



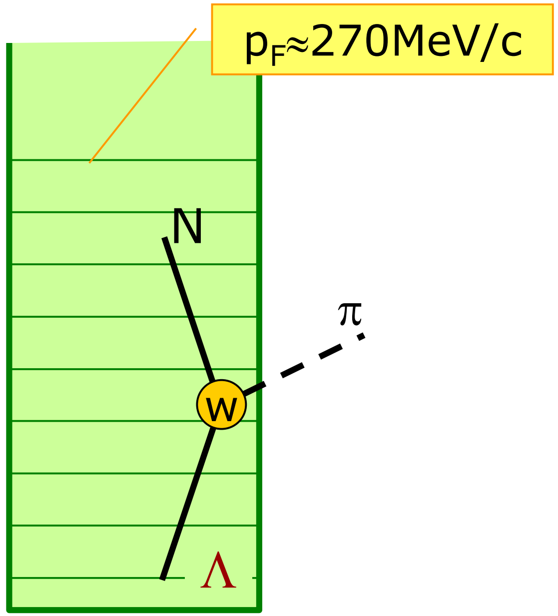
$$\Lambda \to p\pi^- + 38\text{MeV} \quad (64\%)$$

$$\Lambda \to n\pi^0 + 41\text{MeV} \quad (36\%)$$

$$\tau_\Lambda = 263ps$$

ΔI=1/2 rule

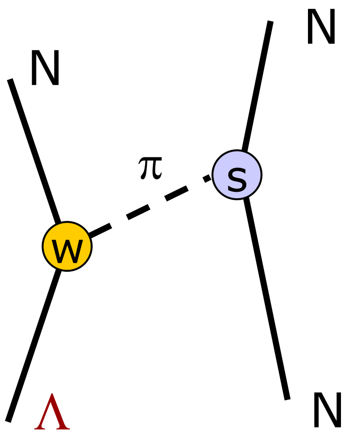
mesonic decay of hypernuclei



p_F≈270MeV/c

suppresed by Pauli blocking

non-mesonic decay of hypernuclei



$$\Lambda p \to np + 176\text{MeV}$$

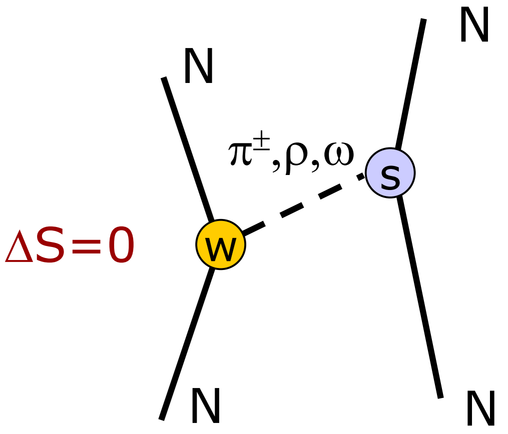
$$\Lambda n \to nn + 176\text{MeV}$$

dominant in all but the lightest hypernuclei

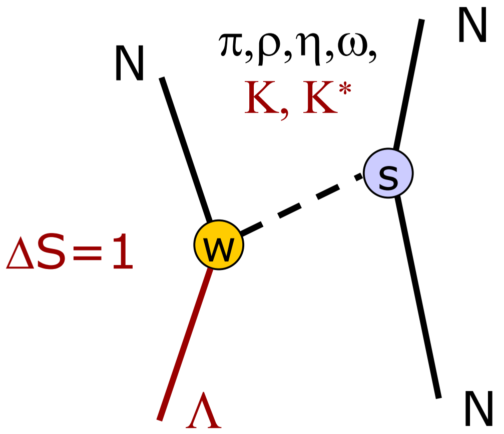
Weak baryon-baryon interaction (1)

- non-mesonic weak decay of hypernuclei explore the baryon-baryon weak interaction

N-N scattering



$\Lambda N \to N\,N$



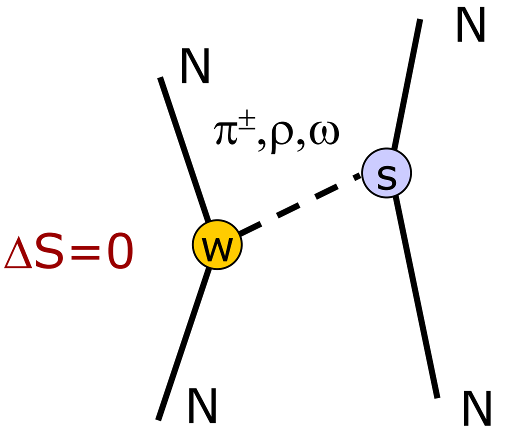
- only parity violating part of weak interaction
- parity-conserving part masked by strong interaction

- parity violating *and* parity-conserving part of weak, strangeness changing, interaction
- q~400 MeV/c

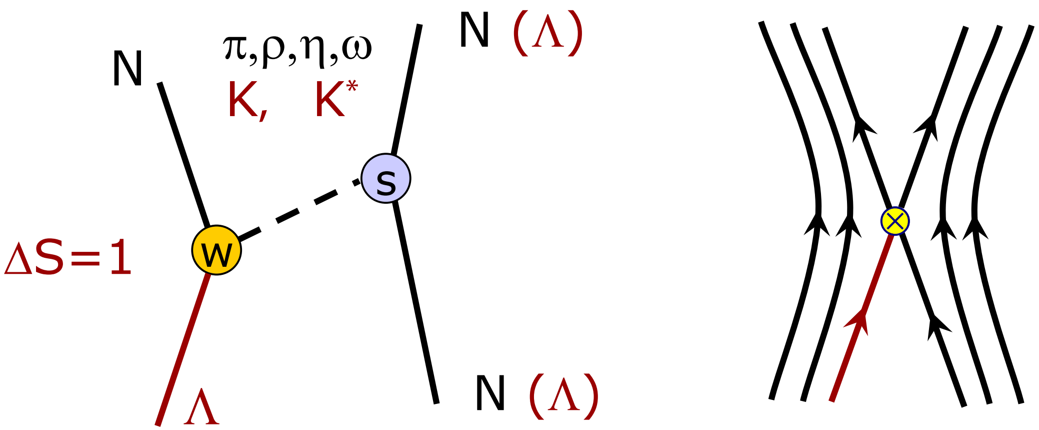
  ⇒ probes short distances

Weak decay in double Hypernuclei

N-N scattering



ΛN→N N and ΛΛ→Y N



- only parity violating part of weak interaction
- parity-conserving part masked by strong interaction

- parity violating *and* parity-conserving part of weak, strangeness changing interaction
- meson vs. direct quark process

- Interesting theoretical developments:
  - Effective Field Theories in S=-1 sector

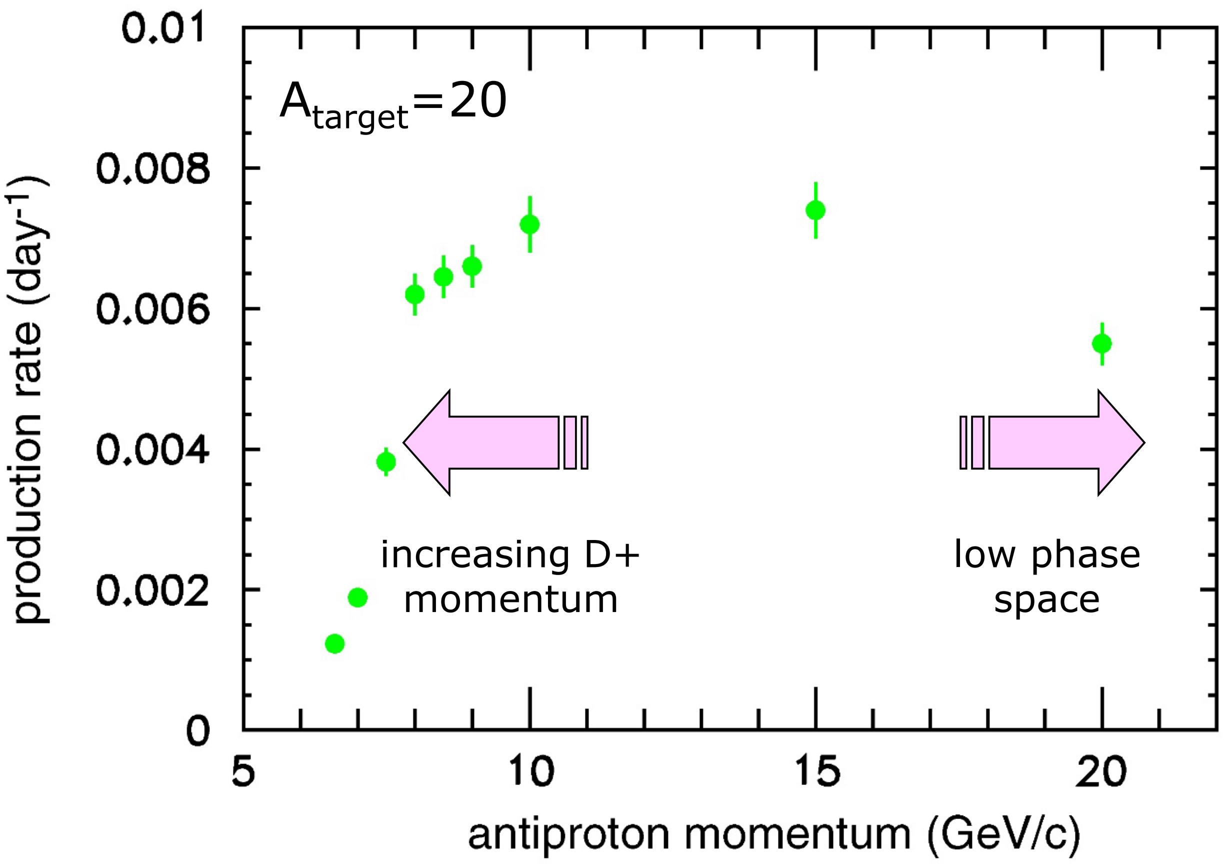
    A. Parreno, C. Bennhold and B.R. Holstein, nucl-th/0308074 & 0308056

weak decay studies need the detection of the decay pion or nucleon

S.R. Beane et al., nucl-th/0311027

Rate

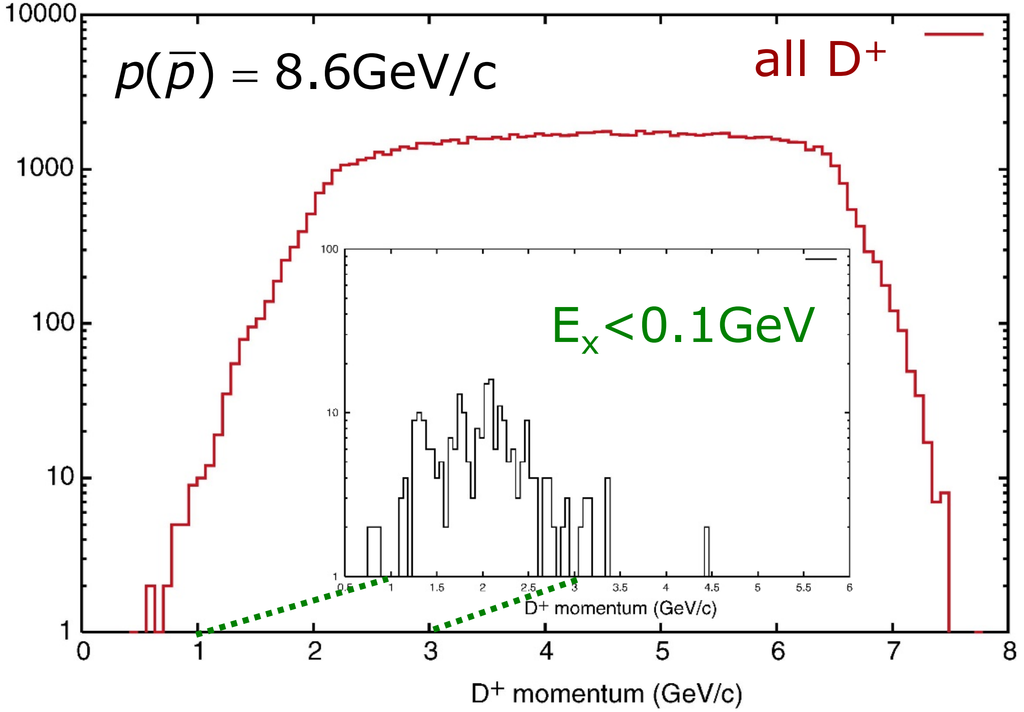
- with increasing antiproton momentum decreasing *minimum* D^+ momentum
- smaller phase space at larger antiproton momenta



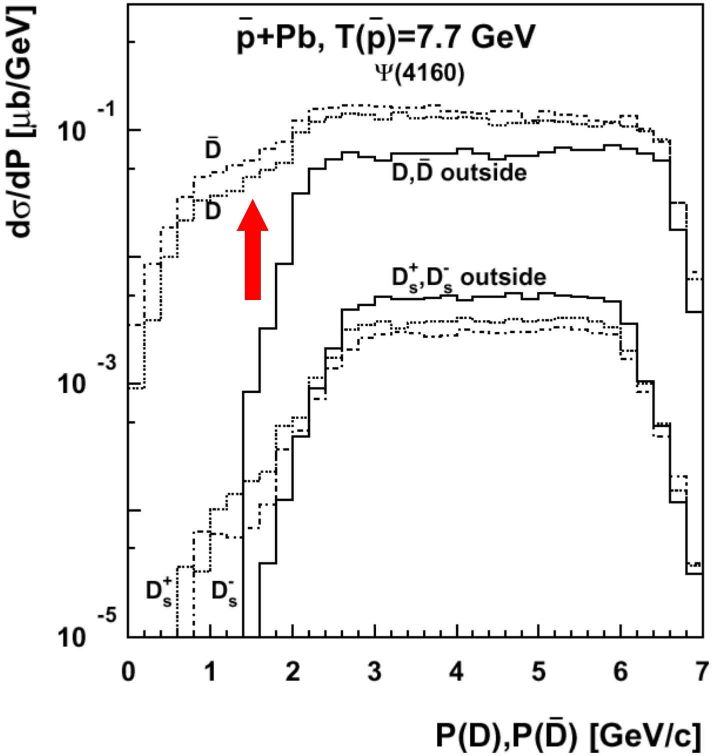
- production rate ~0.01 day^{-1}....*hopeless!?*

Is there still a happy end possible?

- relevant for Λ_c production are D^+ momenta < 1-2 GeV/c



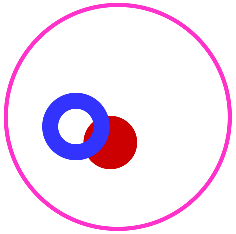
- significant broadening by rescattering
  - Ye.S. Golubeva *et al.*, Eur. Phys. J. A14, 255 (2002)
  - increase of yield by order(s) of magnitude may be possible



Chiral Symmetry (John Cramer)

Question 1: The up and down "current" quarks have masses of 5 to 10 MeV. The π^- (a down + anti-up combination) has a mass of ~140 MeV.
Where does the observed mass come from?

Answer 1: The quarks are more massive in vacuum due to "dressing". Also the pair is tightly bound by the color force into a particle so small that quantum-uncertainty *zitterbewegung* gives both quarks large average momenta. Part of the π^- mass comes from the *kinetic energy* of the constituent quarks .



Question 2: ***What happens*** when a pion is placed in a hot, dense medium?

Answer 2: Two things happen:

1. The binding is reduced and the pion system expands because of external color forces, reducing the *zitterbewegung* and the pion mass.
2. The quarks that were "dressed" in vacuum become "undressed" in medium, causing up, down, and strange quarks to become more similar and closer to massless particles, an effect called "chiral symmetry restoration". In many theoretical scenarios, chiral symmetry restoration and the quark-gluon plasma phase usually go together.

Question 3: ***How can a pion regain its mass*** when it goes from medium to vacuum?

Answer 3: It must do work against an *average attractive force*, losing kinetic energy while gaining mass. In effect, it must climb out of a potential well that may be 140 MeV deep.