Production of Hypernuclei

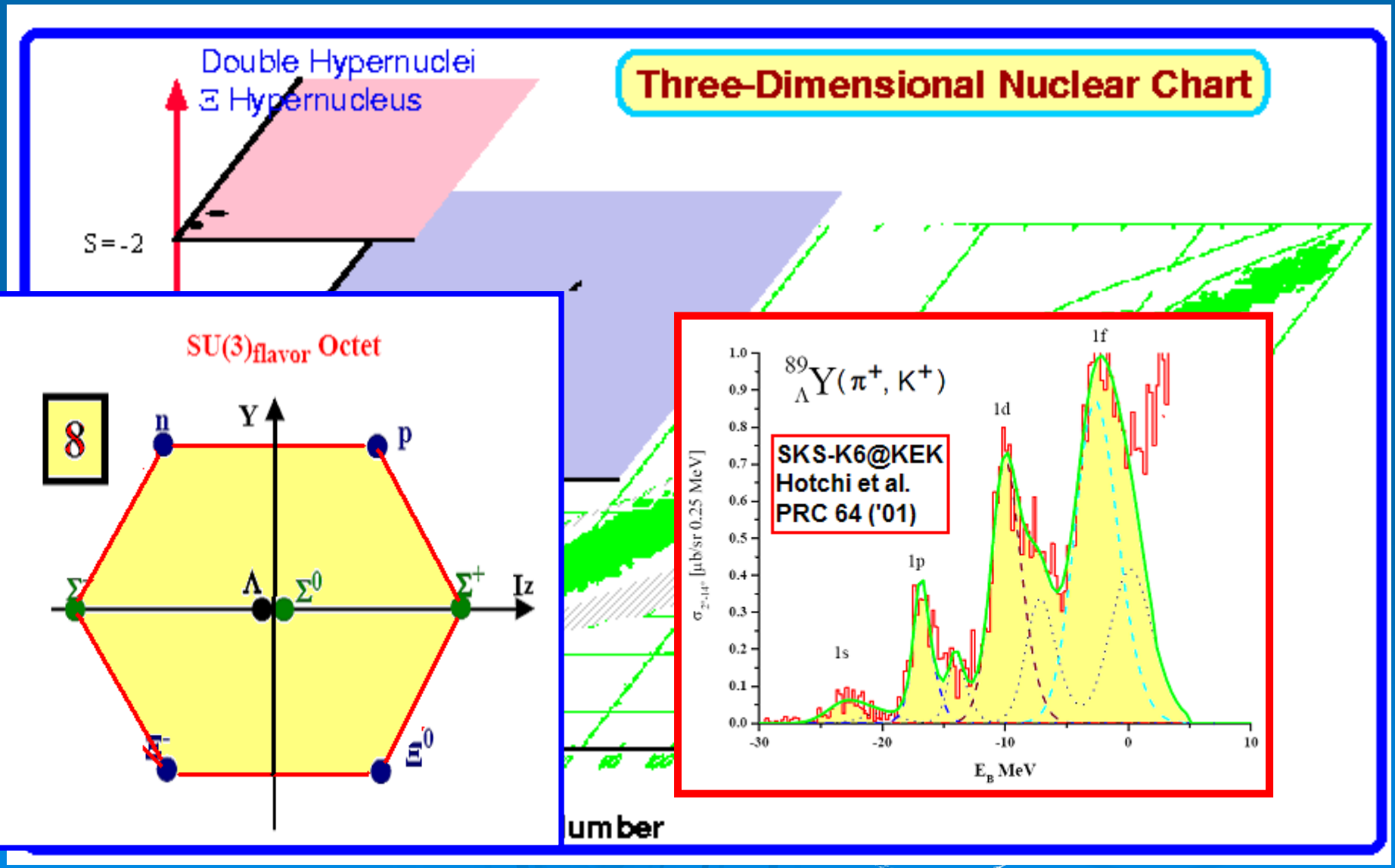
H. Lenske

Topics:

1. Introduction
2. Aspects of YN Interactions
3. Strangeness Production on the Nucleon
4. Strangeness Production by Resonance Excitation
5. Hadro-Production of Hypernuclei
6. Photo- and Electroproduction of Hypernuclei
7. Production of Hypernuclei in Relativistic Fragmentation Reactions
8. Outlook

I. Introduction

Strangeness and Hypernuclear Physics: From SU(2) Isospin to SU(3) Flavour Dynamics



Hypernuclear Physics and Reaction Studies:

- production mechanism of strangeness
- reaction dynamics
- YN and YY interactions
- dynamics of nuclear many-body systems with strangeness
- spectroscopy of hypernuclei
- which types of hypernuclei do exist?

Theory of Strong Interactions: QCD

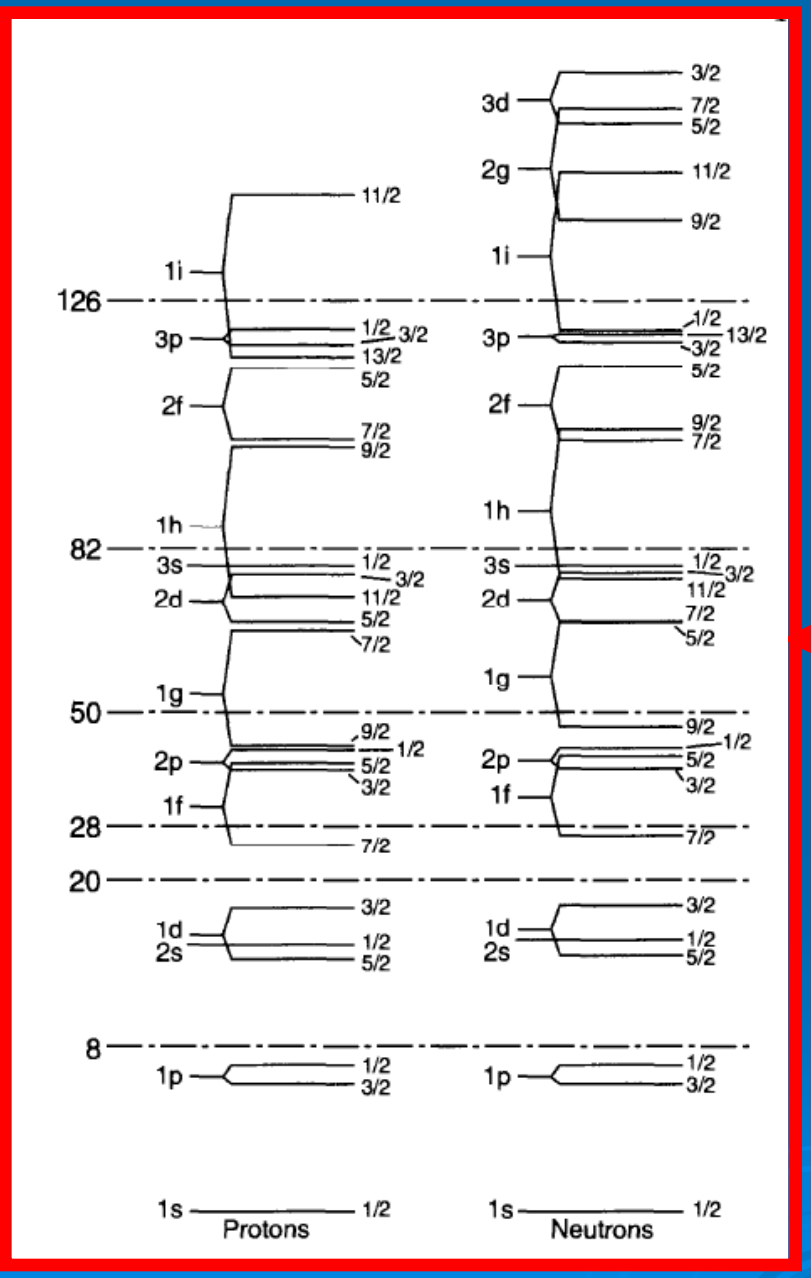
$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left(i\gamma^{\mu}D_{\mu} - m\right)q - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

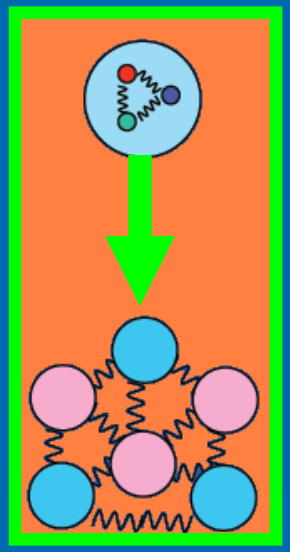
$$= \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q + g\bar{q}\gamma^{\mu}T_{a}qA^{a}_{\mu} - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

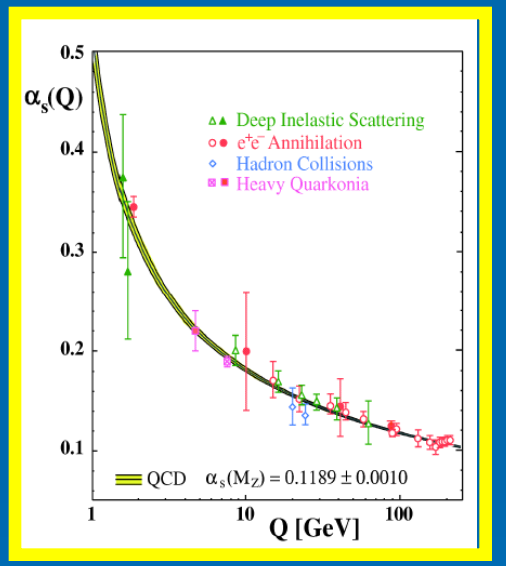
…and from asymptotic freedom…

to confinement…

to the nuclear shell model

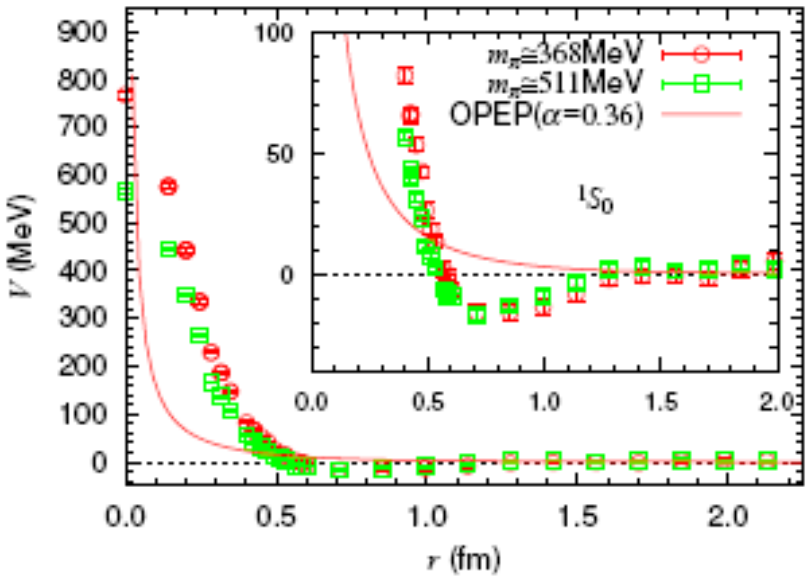




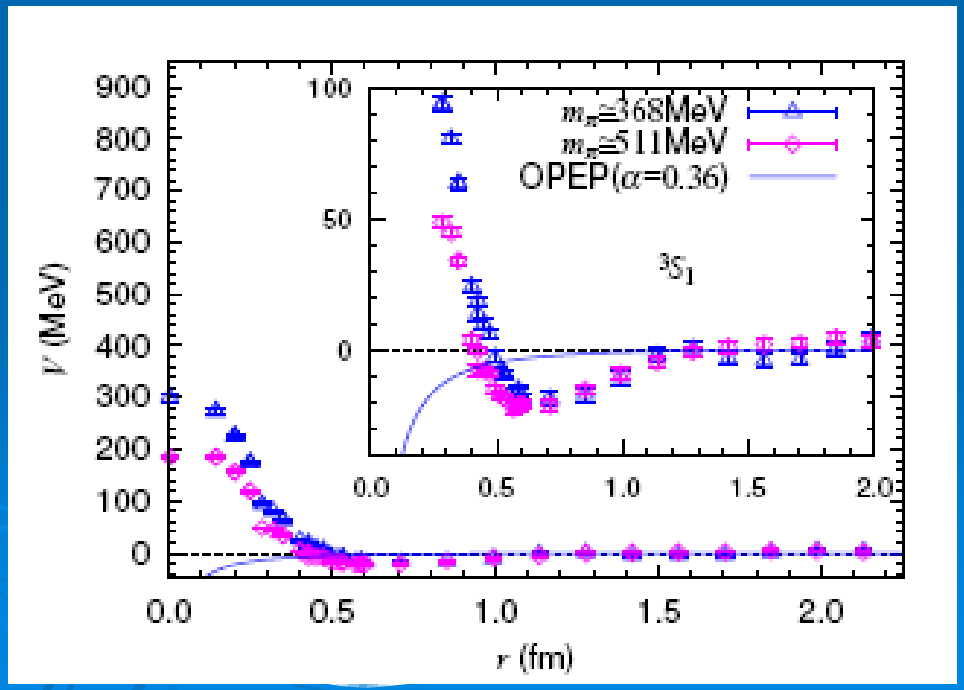


- Nucleus ~ cold, degenerate Fermi-Gas of Quasiparticles
- $U = U_0 + U_{so}\,\ell \cdot \sigma$

pΞ⁰ (S=-2) Potentials from LQCD „pn“like: n[udd]→Ξ⁰[uss]



$$V_C^\pi = -(1-2\alpha)\frac{g_{\pi NN}^2}{4\pi}\frac{(\vec{\tau}_N\cdot\vec{\tau}_\Xi)(\vec{\sigma}_N\cdot\vec{\sigma}_\Xi)}{3}\left(\frac{m_\pi}{2m_N}\right)^2\frac{e^{-m_\pi r}}{r},$$

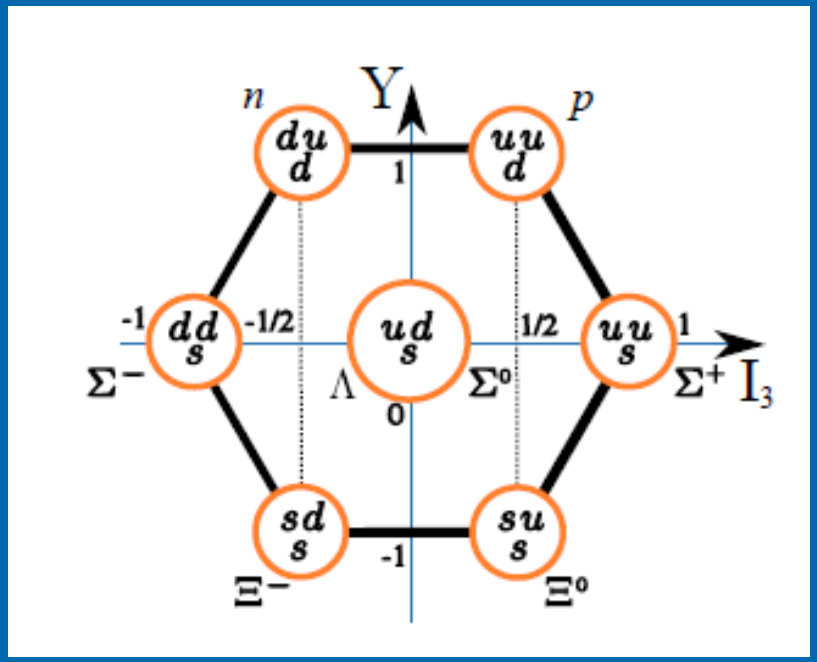


H. Nemura, N. Ishii, S. Aoki, T. Hatsuda
arXiv:0806.1094

(Valence) Quark Content of Octet and Decuplet Baryons

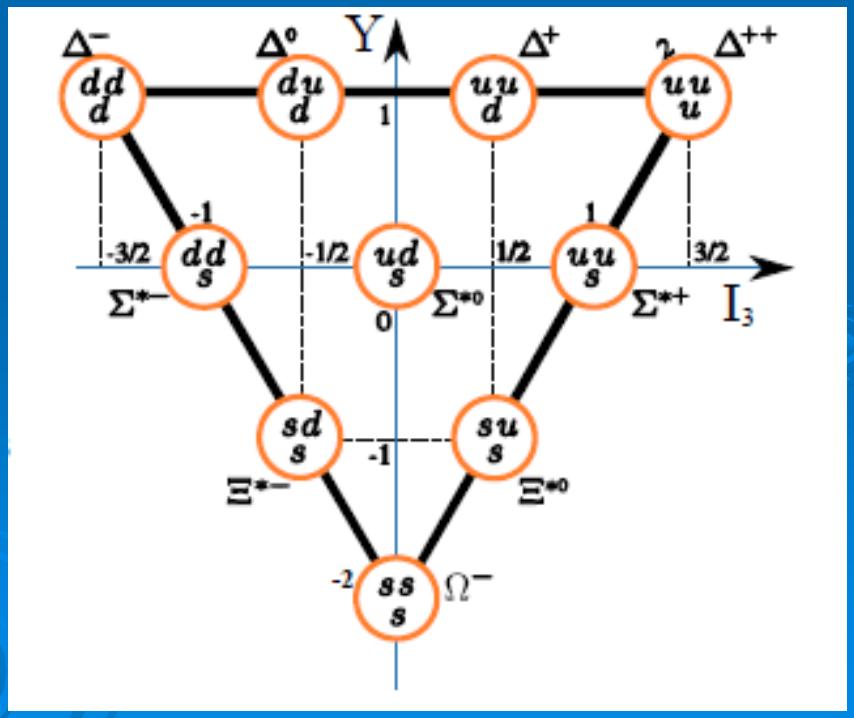
Octet: weak decay of hyperons

$$\tau_{1/2} \sim 10^{-8}...10^{-10}\, s >> \tau_{reac} \sim 10^{-22}\, s$$



Hypercharge Y and Strangeness S:

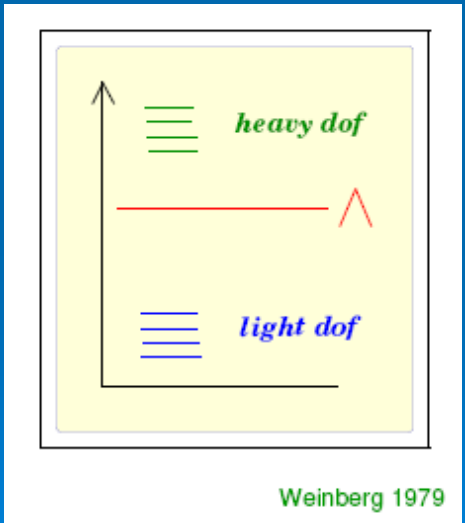
$$Y = S + B = 2(Q - I_3)$$



QCD and Low-Energy Nuclear Physics:

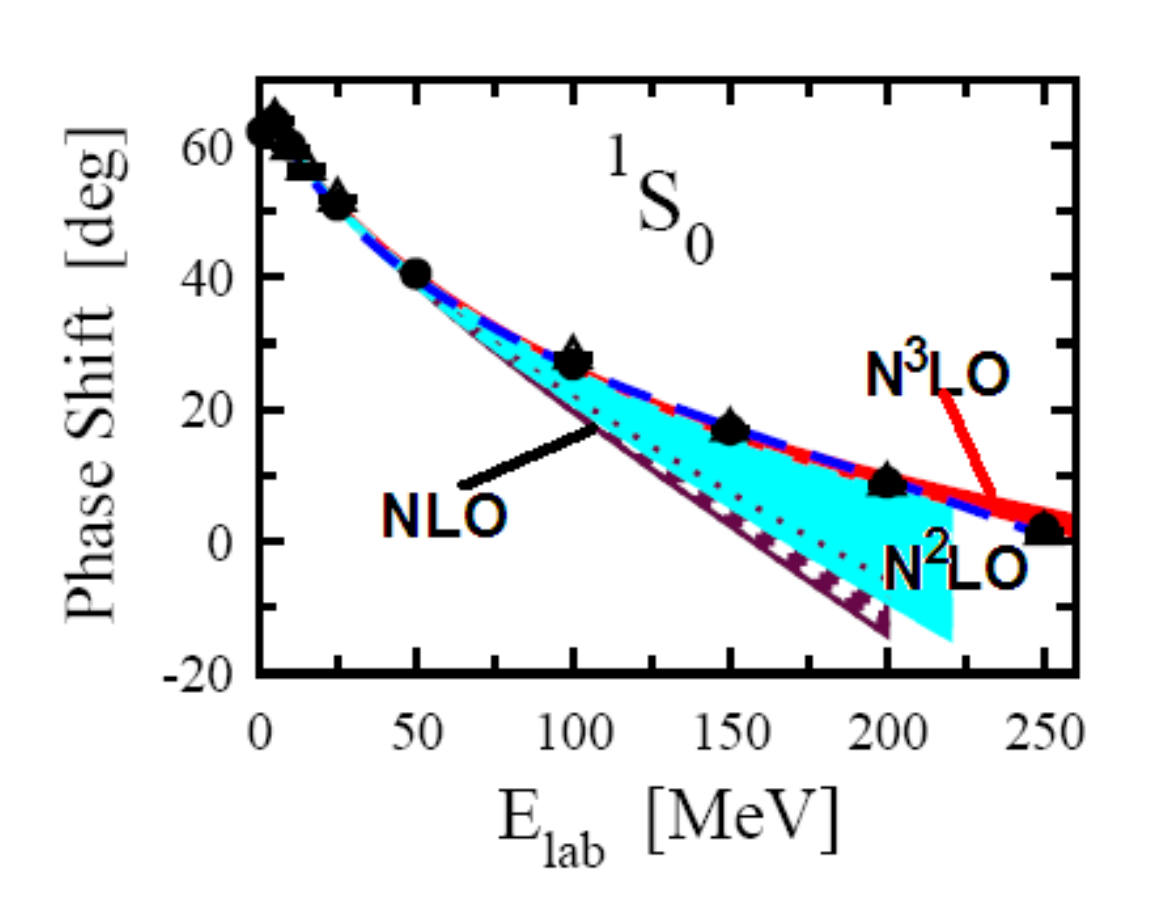
Weinberg Hypothesis (~1979):

- Nuclear Physics ≅ EFT of Pions and Nucleons
- Symmetries of the underlying fundamental theory of QCD
- Spontaneously broken chiral symmetry
- Low energy theorems
- Order-by-Order expansion in Q/Λ with Low Energy Constants (LEC)



$$\mathcal{L}_{\mathrm{QCD}} \rightarrow \mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi\mathrm{N}} + \mathcal{L}_{\mathrm{NN}} + \ldots$$

EFT NN-Phase shifts



$$\mathcal{L}_{QCD} \rightarrow \mathcal{L}_{EFT} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

PWA-Data (Symbols): Nijmwegen/Virginia Tech

II. Aspects of YN Interactions

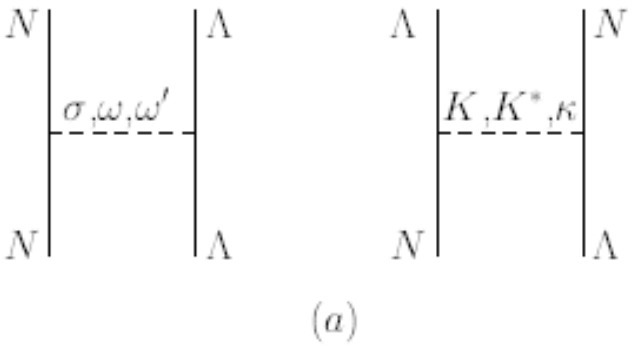
Some facts about YN interactions:

1. ΛN interaction is weaker than the nucleon-nucleon interaction,
2. ΛN spin-spin interaction is weak and therefore spin vector $p_N - h_N$ excitation is suppressed,
3. a Λ hyperon with zero isospin can excite only isoscalar $p_N - h_N$ modes of the core nucleus,
4. no exchange term with nucleons is required.

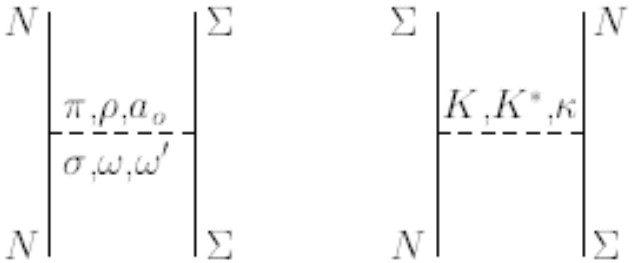
Non-relativistic empirical form of YN interactions:

$$V_{\Lambda N}(r) = V_0(r) + V_\sigma(r)\ \boldsymbol{s}_\Lambda\, \boldsymbol{s}_N + V_\Lambda(r)\ \boldsymbol{l}_{\Lambda N}\, \boldsymbol{s}_\Lambda + V_N(r) \boldsymbol{l}_{\Lambda N}\, \boldsymbol{s}_N + V_T(r)\, S_{12}$$

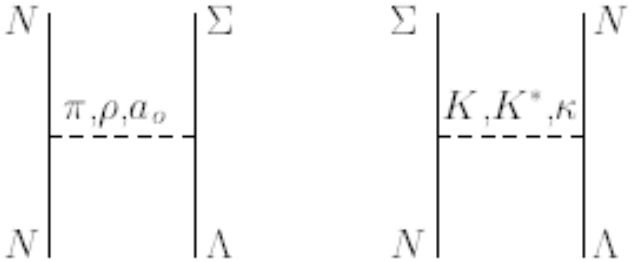
Meson-exchange picture for YN interactions



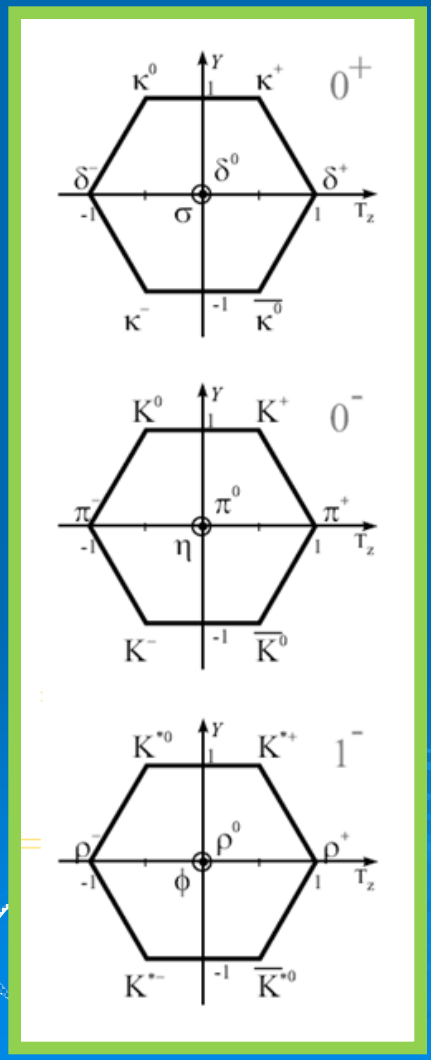
(a)



(b)



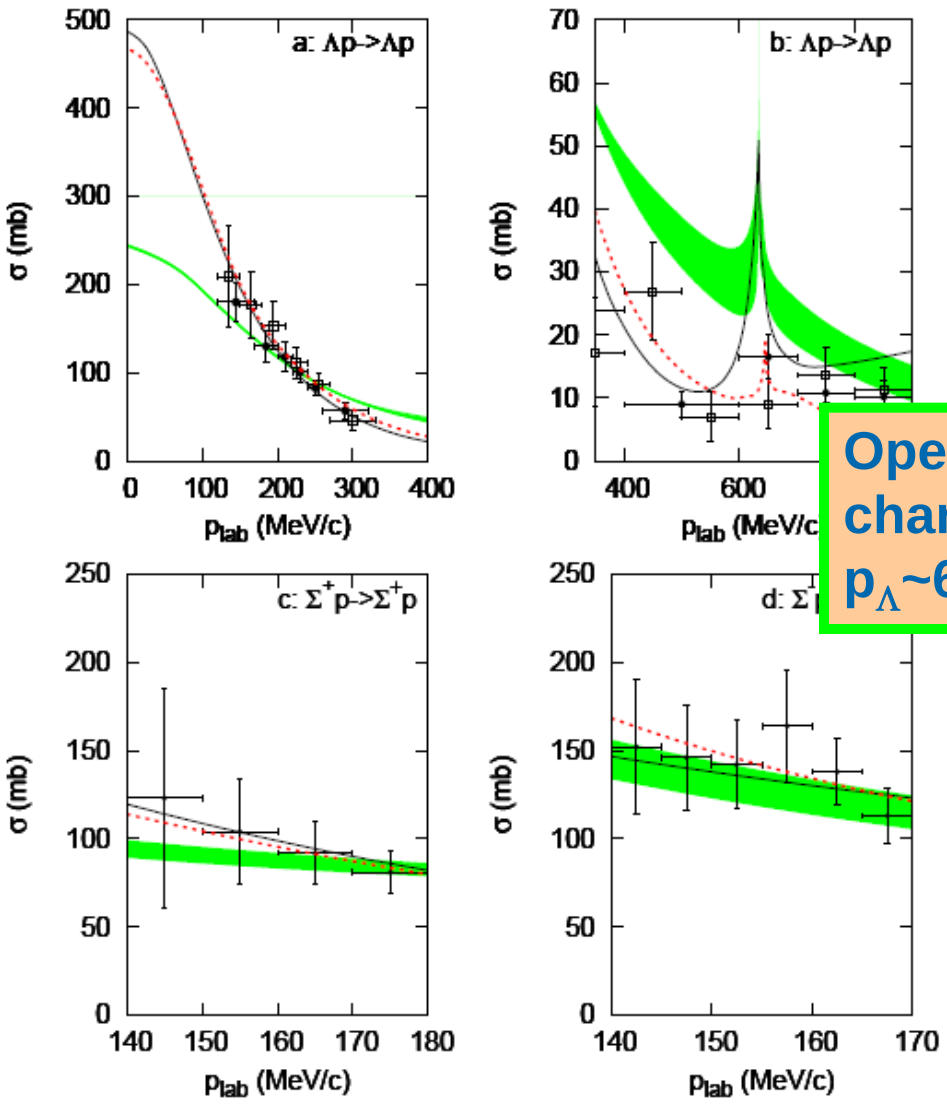
(c)



OBE and χEFT NY-Cross Sections:

Results by the Jülich Group: E. Epelbaum et al.

- χEFT (LO)
- Jülich 04
- Nijmwegen SC97



Opening of the ΣN channel at p_Λ~650MeV/c

Scaling of (In-Medium) Hyperon Interactions

Naïve Quark Model Scaling:

$g_{m\Lambda} = 2/3\ g_{mN}$ …

or SU(3)/SU(6) relations…

but…

$$K_{\Lambda N} = \frac{1}{1 - z V_{NN} G Q_F}\, z V_{NN} = R K_{NN}$$

$$R_m = \frac{g_{mNY}}{g_{mNN}}\left(1 + \chi_m(k_F, \Delta M)(1 - z_m)\ldots\right)$$

…characterizing interactions by their strength: s-wave Effective Range Expansion

$$\frac{\tan(\delta)}{q_s} = -\frac{2\mu}{(\hbar c)^2 4\pi} K(q_s, q_s)$$

$$\frac{1}{\mu} = \frac{1}{M_1} + \frac{1}{M_2}$$

$$\frac{q_s}{\tan(\delta)} = -\frac{1}{a} + \frac{1}{2} q_s^2 r + \ldots$$

- scattering length a
- effective range r

…scaling for free space NΛ Interactions?

$$a_s^{N\Lambda} = -1.8^{+2.3}_{-4.2}\,\mathrm{fm}$$
$$a_t^{N\Lambda} = -1.8^{+1.1}_{-0.8}\,\mathrm{fm}$$

$$a_s^{np} = -23.751\,fm$$
$$a_t^{np} = +5.423\,fm$$

$$K_{N\Lambda} = K_{00} + K_{10}\vec{\sigma}_N \bullet \vec{\sigma}_\Lambda + \ldots$$

$$a_s^{N\Lambda} \sim K_s = K_{00} - 3K_{10} \sim K_\sigma + K_\omega - 3K_\eta$$
$$a_t^{N\Lambda} \sim K_t = K_{00} + K_{10} \sim K_\sigma + K_\omega + K_\eta$$

→**Scaling Factors $R_m = K_{mN\Lambda}/K_{mNN} \sim 1/40 \ldots 1/4$**

$(m = \sigma, \omega, \eta)$

IV. Strangeness Production on the Nucleon

The Giessen Model: Coupled Channels Approach to Meson Production on the Nucleon below 2GeV

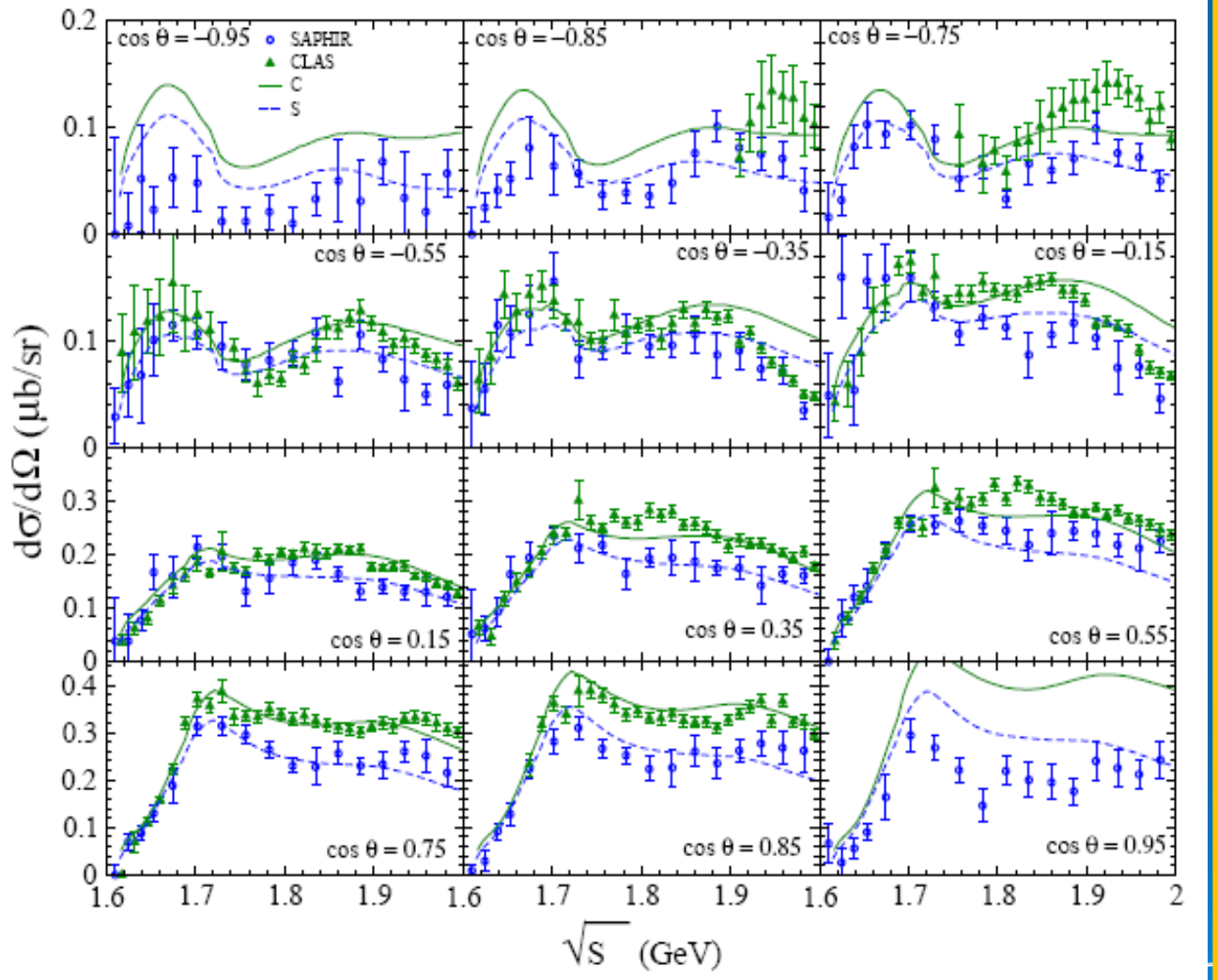
$$T_{ab}(q,q') = V_{ab}(q,q') + \sum_c \int \frac{d^3k}{(2\pi)^3} V_{ac}(q,k) G_{cc}(k,q_s) T_{cb}(k,q')$$

$$\pi N \to K\Lambda$$

+

$\gamma N \to \gamma N$	$\pi N \to \pi N$
$\gamma N \to \pi N$	$\pi N \to 2\pi N$
$\gamma N \to \eta N$	$\pi N \to \eta N$
$\gamma N \to \omega N$	$\pi N \to \omega N$
$\gamma N \to K\Sigma$	$\pi N \to K\Sigma$

γp → KΛ Results from the Giessen Model

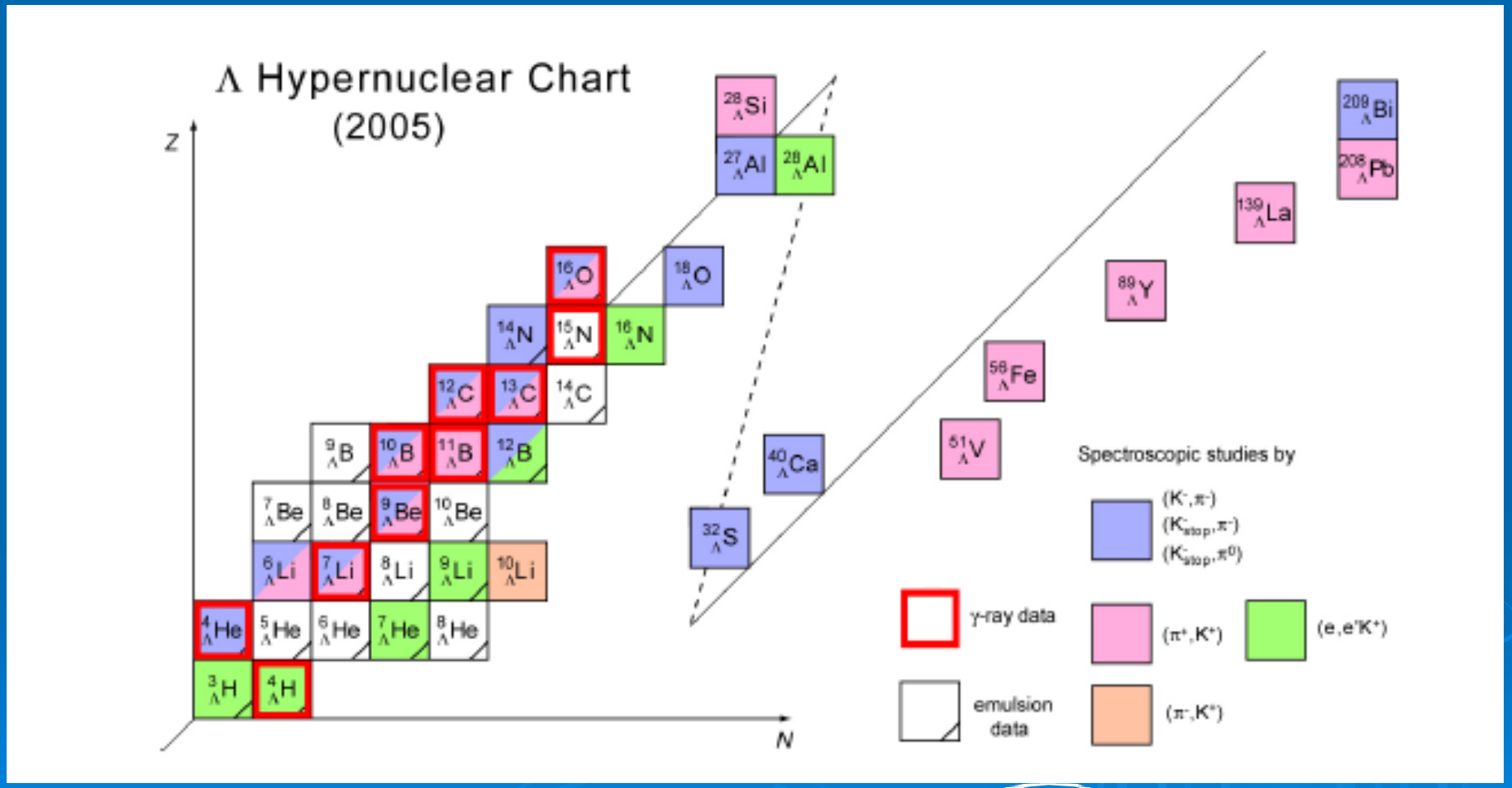


- separate fits to SAPHIR and CLAS data
- constraints from other hadronic and γ channels

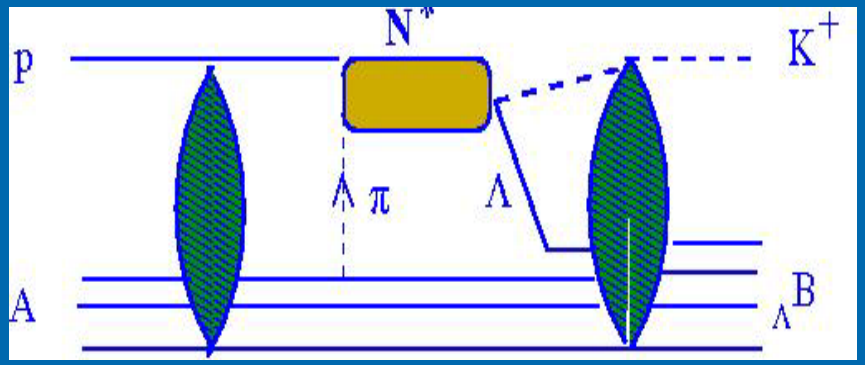
V. Shyklar, H.L., U. Mosel, nucl-th/0505010/PRC 72:015210 (2005)

IV. Production of Hypernuclei: The Giessen Resonance Model

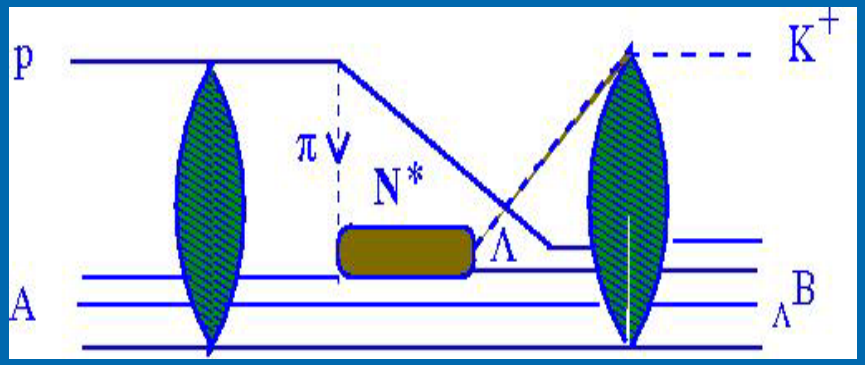
4.1 Known Λ-Hypernuclei and Spectroscopic Studies



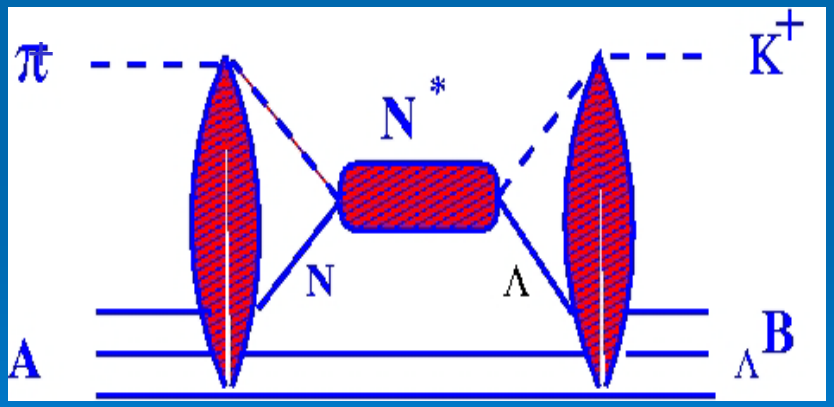
4.2 Dynamics of strangeness production: The Giessen Resonance Model



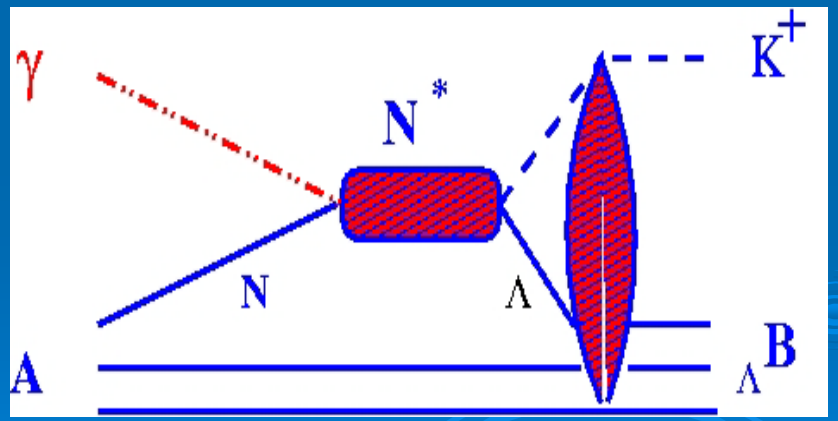
Target emission $A\,(p,K^+)_\Lambda B$



Projectile emission $A\,(p,K^+)_\Lambda B$



$A\,(\pi^+,K^+)_\Lambda B^*$



$A\,(\gamma,K^+)_\Lambda B'$

N*(1650), N*(1710), N*(1720) resonances (PDG).

…we need:

- dynamics of the particles used as probes
- description of the production dynamics
- dynamics of the hyperon in nuclear matter