Weak Decays of Hypernuclei

- Weak decay modes
- Weak decay observables
- Theoretical approaches
- Connecting data with theory
- Prospects

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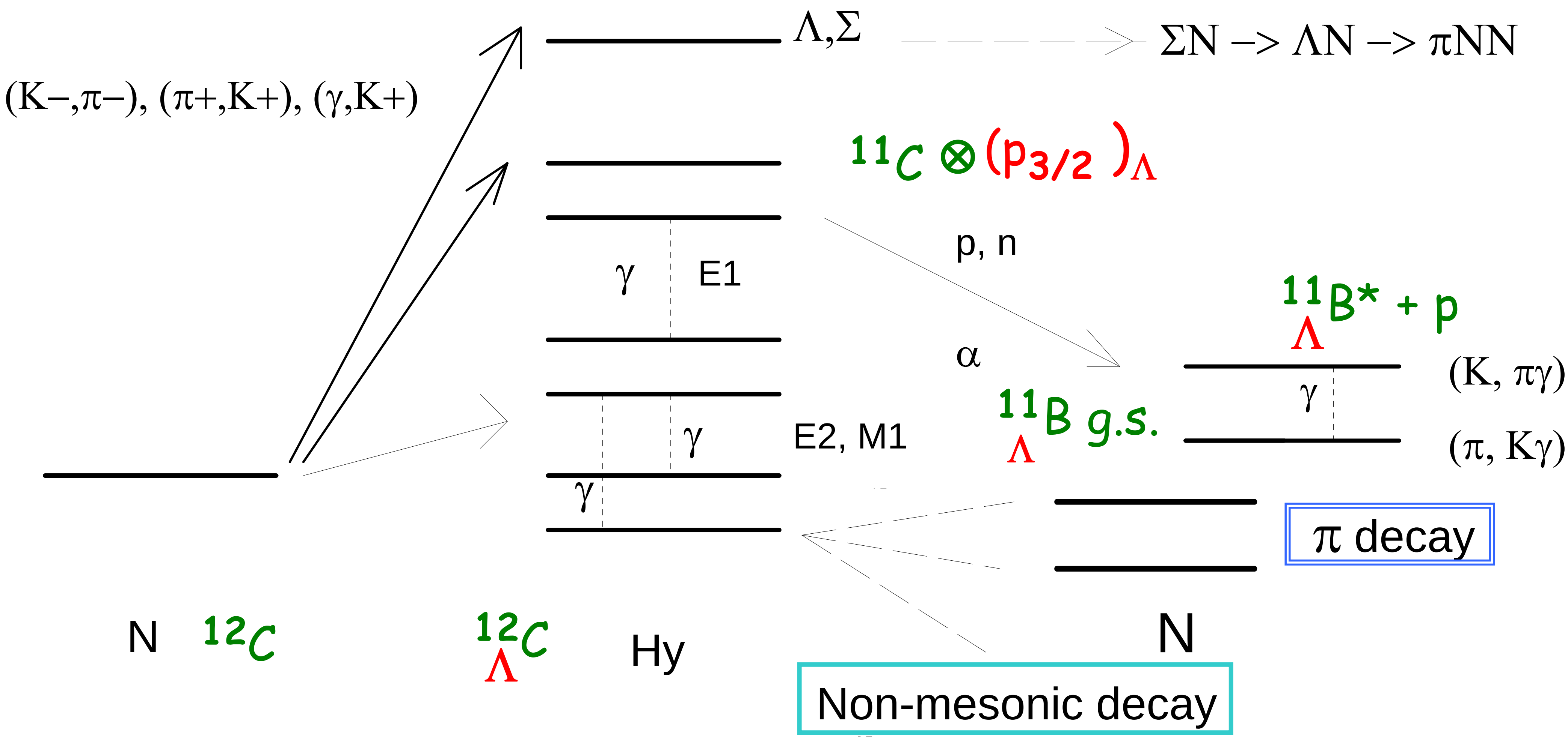
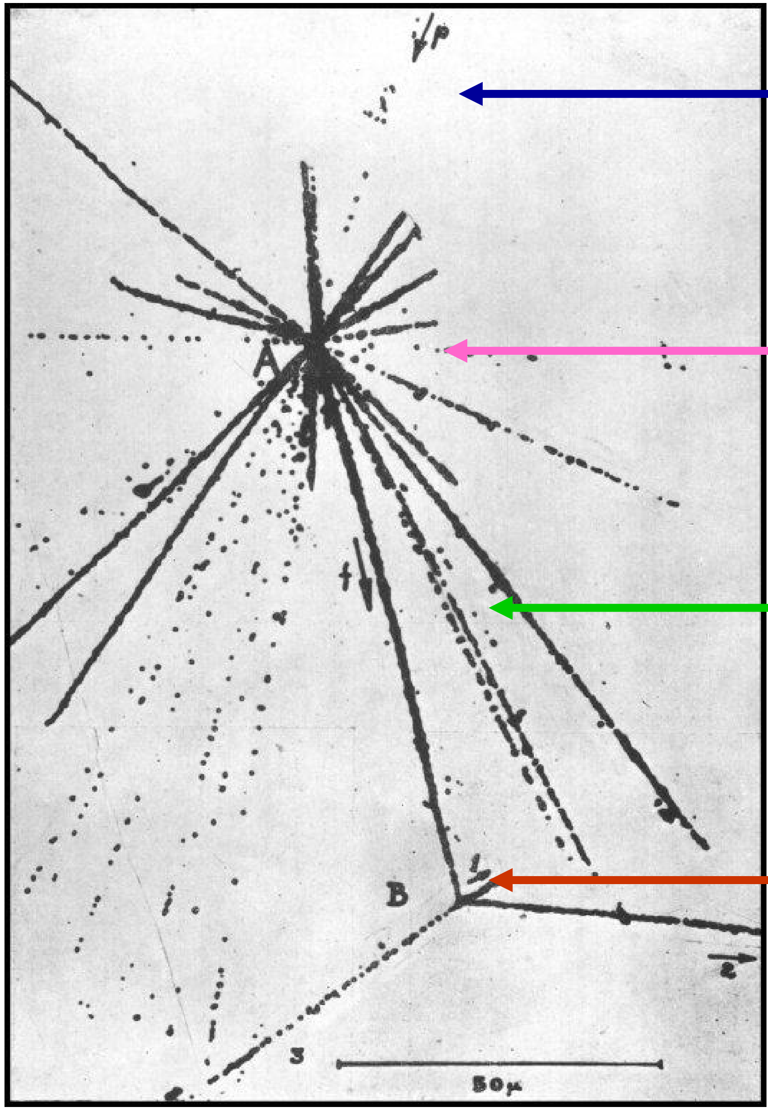
Weak decay modes (WDM)



Brookhaven, CERN, COSY, DAPHNE, KEK, TJNAF

First hypernuclear event observed in a nuclear emulsion

M. Danysz and J. Pniewski, Philos. Mag. 44 (1953) 348



Incoming high energy cosmic ray

Collision with the nucleus

Nuclear fragments that eventually stop in the emulsion

One fragment containing a hyperon disintegrates weakly

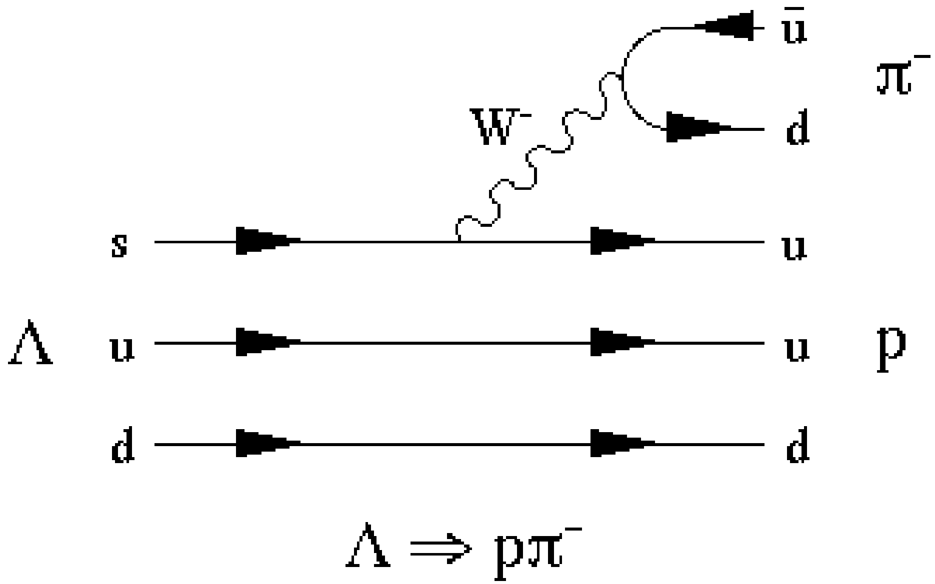
Λ decay in free space

Λ: Baryon with m_Λ = 1115.684 ± 0.006 MeV/c² q_Λ =0, $I(J)^P = 0(1/2)^+$

Semi-leptonic and weak radiative decay modes…

$$\Lambda \rightarrow \begin{cases} n\gamma & (\text{B.R.} = 1.75 \times 10^{-3}) \\ p\pi^-\gamma & (\text{B.R.} = 8.4 \times 10^{-4}) \\ pe^-\overline{\upsilon}_e & (\text{B.R.} = 8.32 \times 10^{-4}) \\ p\mu^-\overline{\upsilon}_\mu & (\text{B.R.} = 1.57 \times 10^{-4}) \end{cases}$$

Λ decay in free space



Orders of magnitude smaller than the mesonic decay mode $\Lambda \rightarrow \pi$ **N**

(B.R.=0.997)

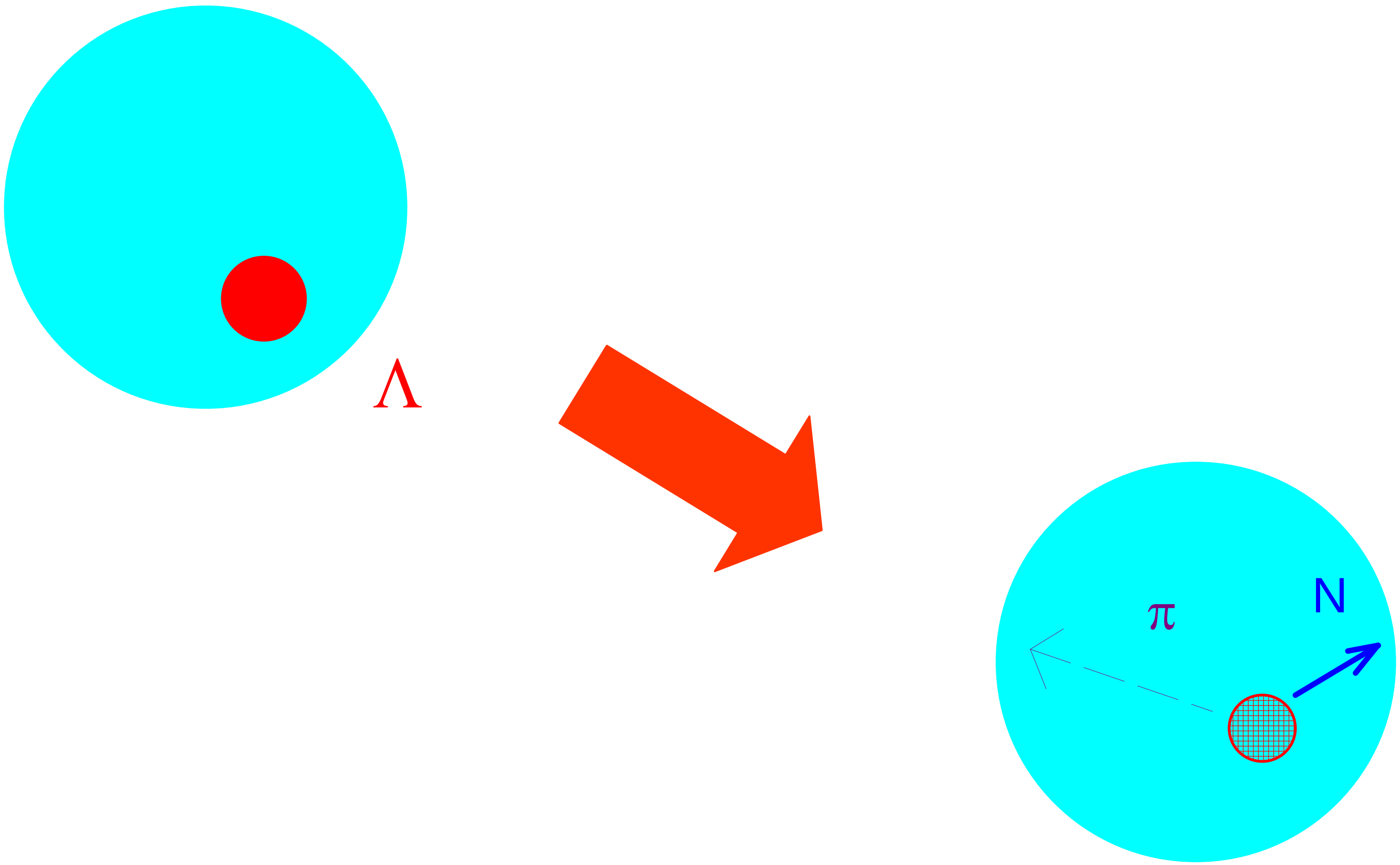
$(\Lambda \rightarrow \pi^- \mathbf{p}) \div (\Lambda \rightarrow \pi^0 \mathbf{n}) \approx$ **64 ÷ 36**

$\tau_\Lambda \equiv \hbar/\Gamma_\Lambda = 2.632 \times 10^{-10}$ sec.

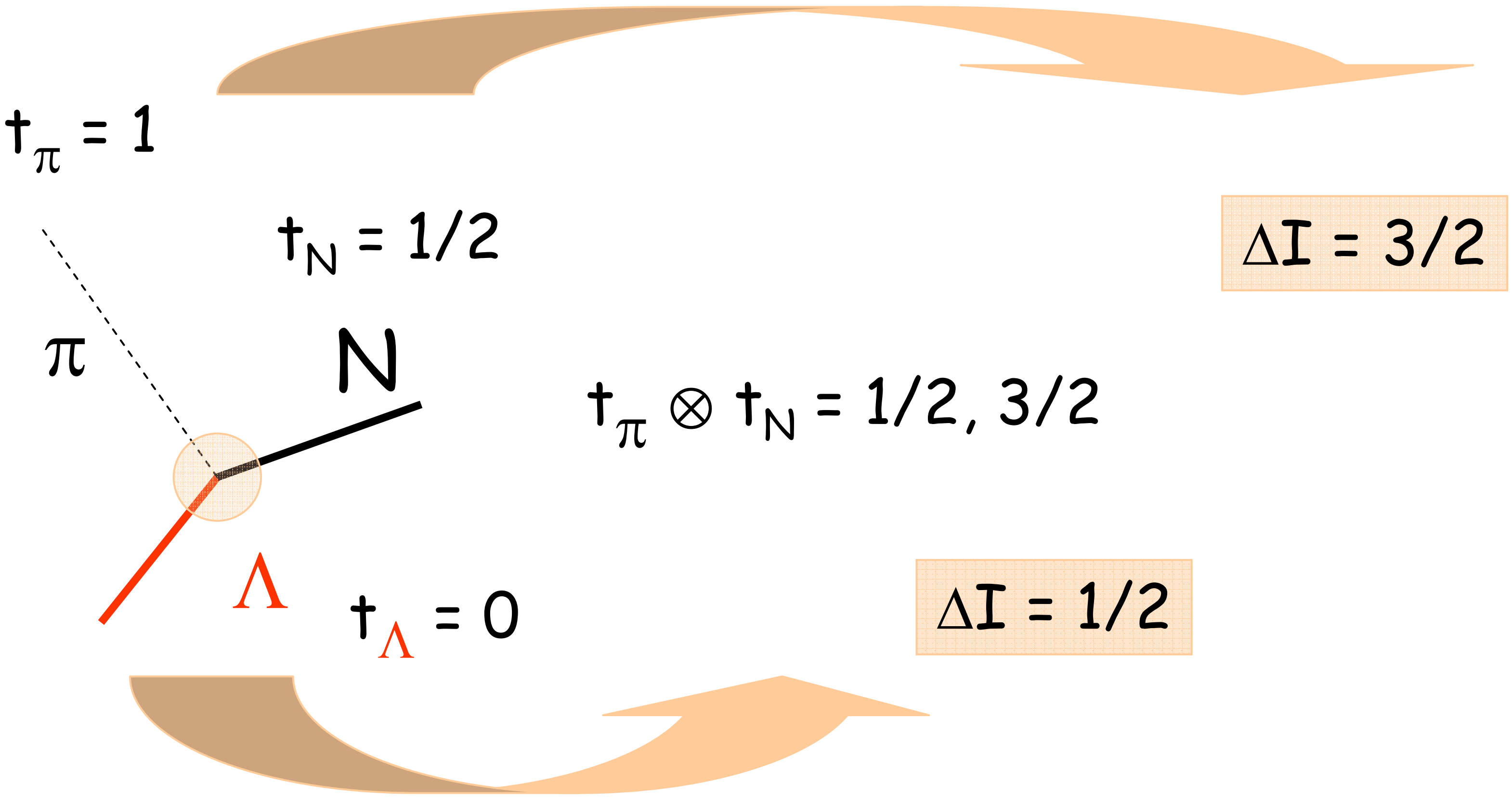
Does not conserve parity, strangeness, isospin

Λ decay in the medium

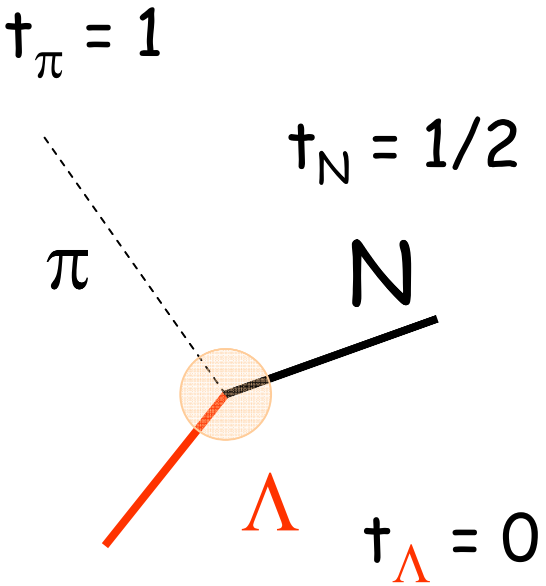
$$\Lambda \to \pi N$$



Mesonic decay



Mesonic decay



$$\begin{cases} |\pi^- p\rangle = \sqrt{\frac{1}{3}}\left|\frac{3}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{2}{3}}\left|\frac{1}{2},-\frac{1}{2}\right\rangle \\ |\pi^0 n\rangle = \sqrt{\frac{2}{3}}\left|\frac{3}{2},-\frac{1}{2}\right\rangle + \sqrt{\frac{1}{3}}\left|\frac{1}{2},-\frac{1}{2}\right\rangle \end{cases}$$

$$\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}} \approx \frac{|\langle\pi^- p|T_{1/2,-1/2}|\Lambda\rangle|^2}{|\langle\pi^0 n|T_{1/2,-1/2}|\Lambda\rangle|^2} = \left|\frac{\sqrt{2/3}}{\sqrt{1/3}}\right|^2 = 2 \qquad \text{for } \Delta I = 1/2,$$

$$\frac{\Gamma^{\text{free}}_{\Lambda\to\pi^- p}}{\Gamma^{\text{free}}_{\Lambda\to\pi^0 n}} \approx \frac{|\langle\pi^- p|T_{3/2,-1/2}|\Lambda\rangle|^2}{|\langle\pi^0 n|T_{3/2,-1/2}|\Lambda\rangle|^2} = \left|\frac{\sqrt{1/3}}{\sqrt{2/3}}\right|^2 = \frac{1}{2} \qquad \text{for } \Delta I = 3/2.$$

Experimentally $\left\{\frac{\Gamma^{free}_{\Lambda\to\pi^- p}}{\Gamma^{free}_{\Lambda\to\pi^0 n}}\right\}^{Exp} \approx 1.78$

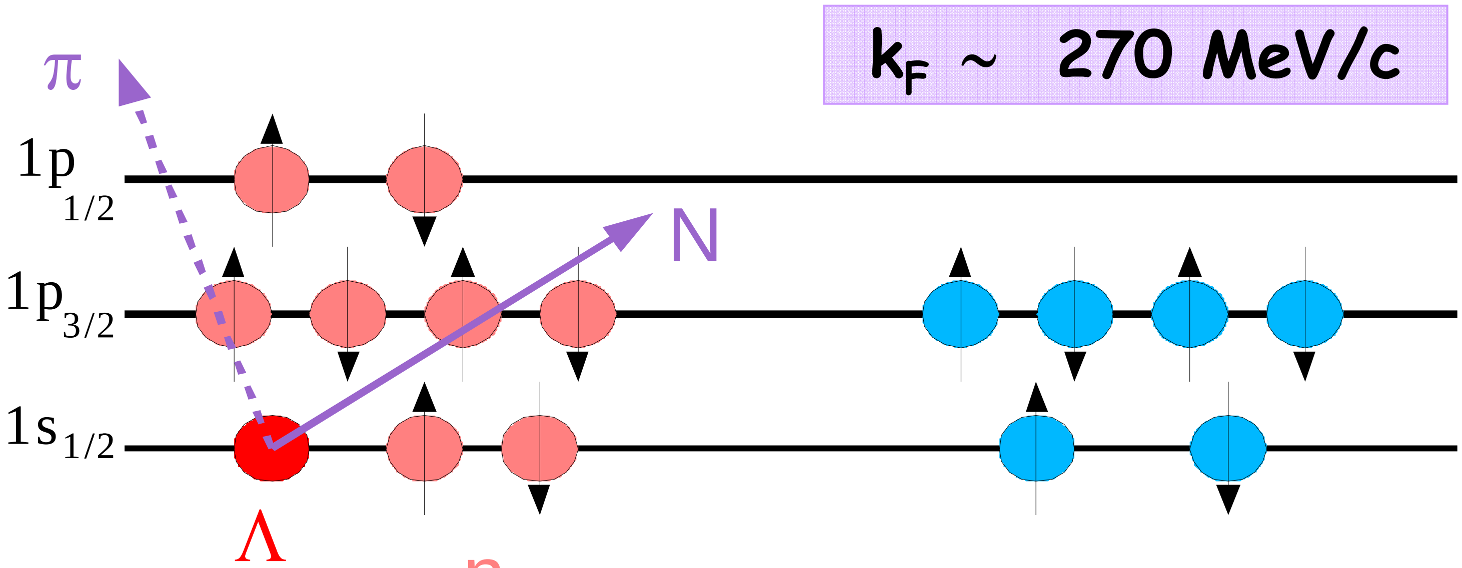
$\Rightarrow \Delta I = \frac{1}{2}$ rule

WDM: Mesonic decay
What happens in the medium?

Q-value $\cong m_\Lambda - m_N - m_\pi \cong$ 35 MeV $\Longrightarrow p_N \sim$ 100 MeV/c

$B_\Lambda - B_N$ = -27 + 8 MeV $\Longrightarrow \downarrow Q \Longrightarrow \downarrow p$

$\Longrightarrow$ **Pauli Blocked in the medium!!**



2 (2j+1)

WDM: Mesonic decay

- Strictly forbidden in normal infinite nuclear matter.
- In finite nuclei it can happen due to:
  - Hyperon momentum distribution
  - Pion distortion

Inside the medium

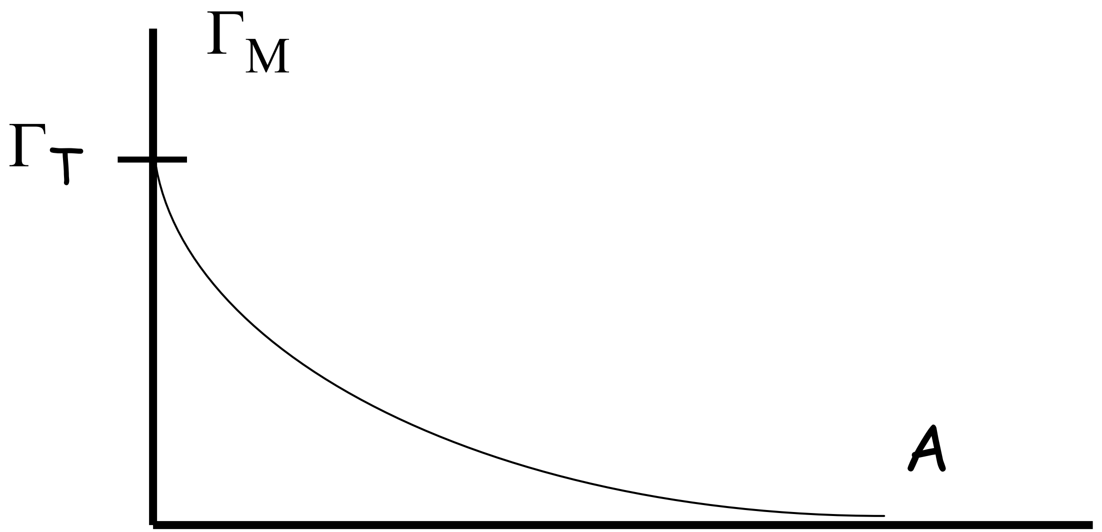
$$E_\pi \leq \sqrt{(q^2+m_\pi^2)} \rightarrow \quad E_\Lambda = E_N + \sqrt{(q^2+m_\pi^2)} + U_\pi$$

  - *" The pion distortion induces high-momentum components in the pion wave-function and, by momentum conservation, the nucleon acquires also higher momentum, hence having more chances to overcome the Fermi momentum"*

  - Smaller local Fermi momentum at the nuclear surface

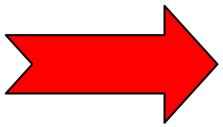
Nieves, Oset (1993) Motoba, Itonaga (1994)

- Nevertheless, at the end, what one gets is that it decreases as the mass number increases...



- More reduction:

Small efect $\rightarrow$ Absortion of the final pion in the medium

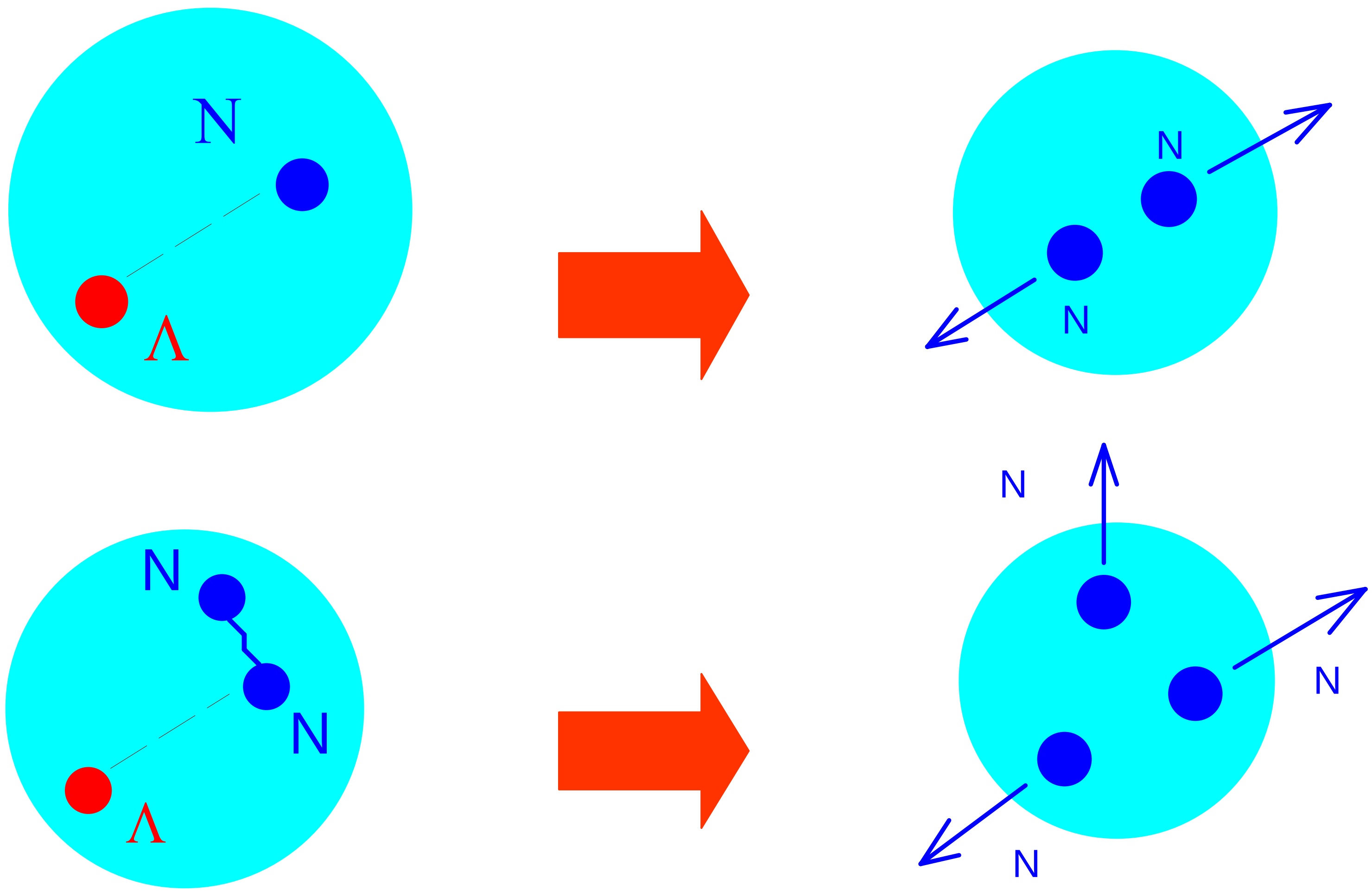


The Λ decay is observed as non-mesonic

Final state with 3 nucleons: Λ NN $\rightarrow$ NNN

WDM: Non-mesonic decay

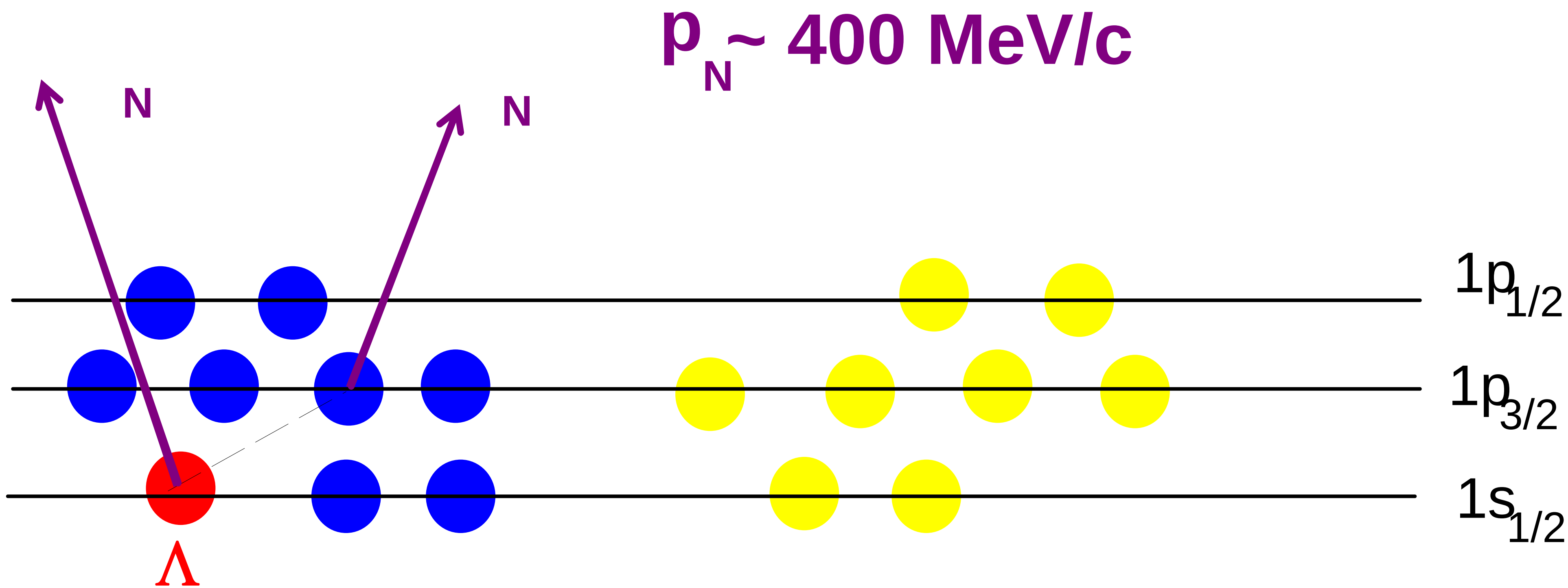
$\Lambda N \rightarrow nN, \quad \Lambda NN \rightarrow nNN$



WDM: Non-mesonic decay

$\Lambda N \rightarrow nN, \quad \Lambda NN \rightarrow nNN$

Dominant mode for A~5 or larger



(Limited kinematical region)

What do we learn from those decays?

- The non-mesonic channel, with Q $\sim$ 175 MeV ($= m_\Lambda - m_N$), produces highly energetic nucleons which become quite insensitive to nuclear structure details

  $\Rightarrow$ Study of the weak BB interaction

- Use the $|\Delta S|=1$ as a signature of the weak hyperon-nucleon interaction
  - In contrast with the weak $|\Delta S| = 0$ NN $\rightarrow$NN, the $|\Delta S| = 1$ ΛN $\rightarrow$NN process allows us to study the weak interaction, since the Parity-Conserving amplitude is not masked by the strong interaction (which constitutes a much more stronger PC signal).

Non-mesonic decay mode

$$(\Lambda\ N \to NN)$$

There are not stable hyperon beams

$\Rightarrow$ Study of bound strange systems

Complications:

- account for nuclear structure
- medium effects (propagation of final particles through the medium, etc.)

Decay observables. Hypernuclear lifetimes.

- Hypernuclear lifetimes – Decay rates

$$\Gamma = \Gamma_M + \Gamma_{NM} + \Gamma_{2N}$$
$$= \Gamma_{\pi^0} + \Gamma_{\pi^-} + \Gamma_n + \Gamma_p + \Gamma_{np}$$

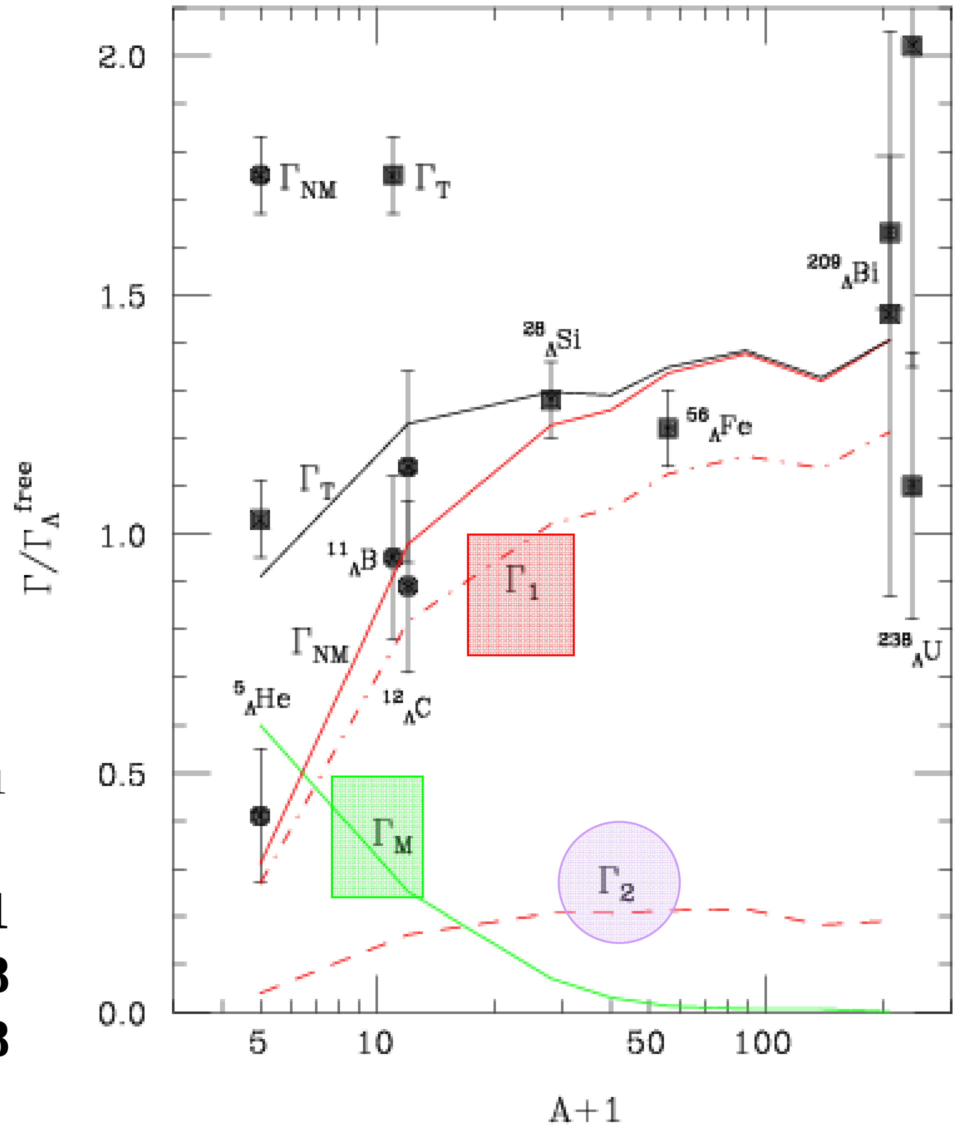
$\Lambda N N \rightarrow NNN$
p_N~340 MeV

$\Lambda N \rightarrow NN$
p_N~420 MeV

$\Lambda \rightarrow N\pi$
p_N~100 MeV

$$\Gamma \sim \Gamma_\Lambda^{free}$$
$$\Gamma_\Lambda^{free} = 3.8 \times 10^9 \, s^{-1}$$

BNL, 91
KEK, 95, 98
Jülich, 93, 97, 98



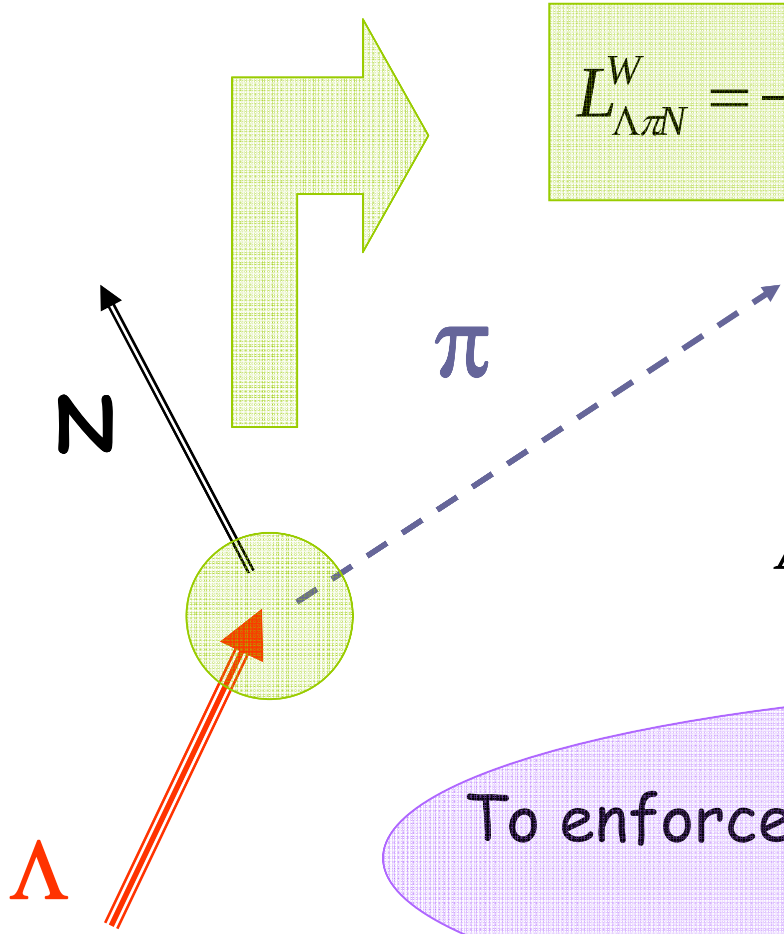
(Γ is well reproduced by theoretical models for a wide range of hypernuclear masses)

Finite nucleus calculation of the decay rates

- Polarization Propagator Method (PPM):
  - Relies on a many-body description of the hyperon self-energy in nuclear matter.
  - The calculation is then implemented in finite nuclei through the Local Density Aproximation (LDA).

- Direct finite nucleus calculation ≡ Wave Function Method (WFM):
  - Use of shell model nuclear and hypernuclear wave functions (at hadronic and quark level).
  - Use of pion wave functions generated by pion-nucleus potentials (mesonic decay).

Mesonic decay. Propagator Method



$$L^{W}_{\Lambda\pi N} = -\mathrm{i}\, G m_\pi^2\, \overline{\psi}_N \left(A + B\gamma_5\right) \vec{\tau}\cdot\vec{\phi}_\pi\, \psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix} + h.c.$$

$$G m_\pi^2 = 2.21\times 10^{-7}$$

(P.V)

$$A = 1.05$$

(PC)

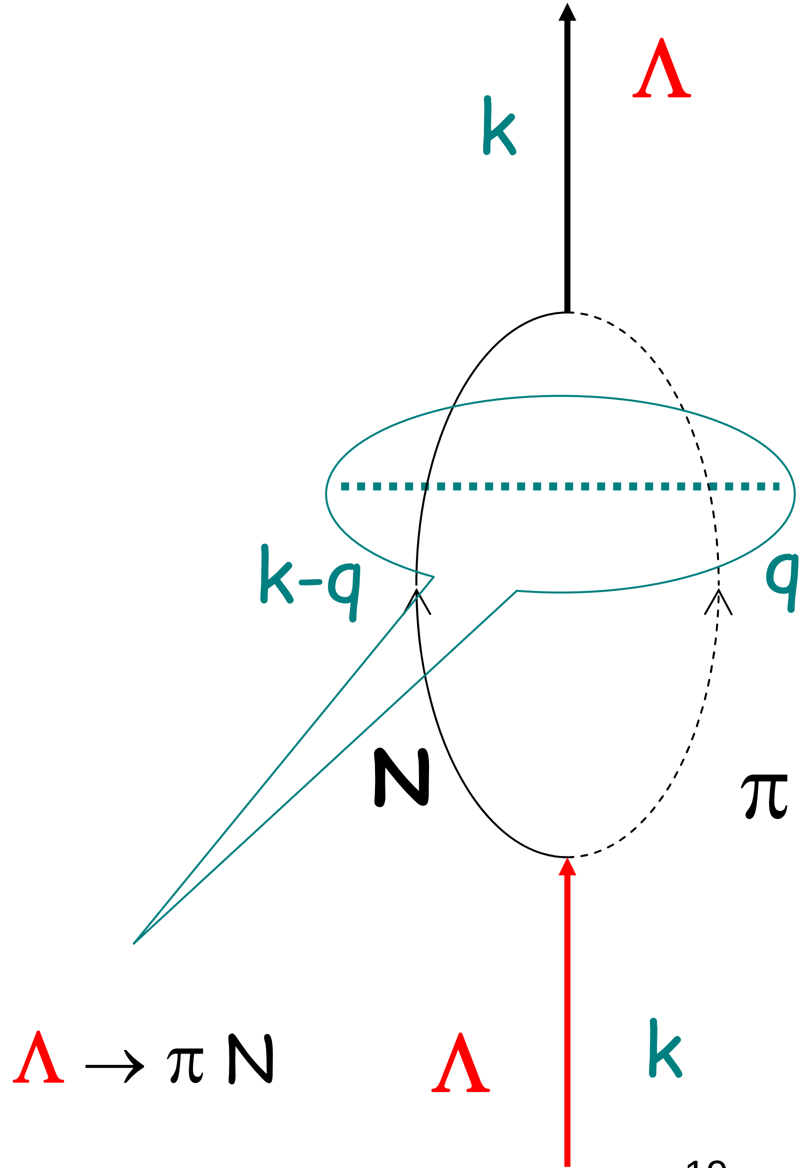
$$B = -7.15$$

To enforce the ΔI=1/2 rule: |Λ⟩ = |1/2 -1/2⟩ (isospurion)

Mesonic decay. Propagator Method

Λ width $\rightarrow \Gamma = -2\,\mathrm{Im}\,\Sigma$

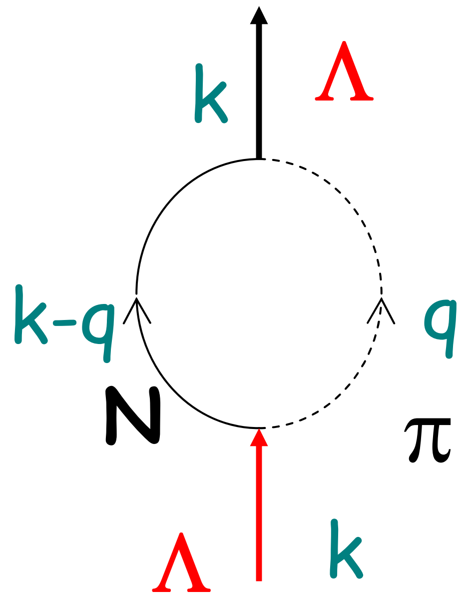
Λ free self-energy



Mesonic decay. Propagator Method

Λ width $\rightarrow \Gamma = -2\,\mathrm{Im}\,\Sigma$

Λ free self-energy



Feynman rules + non relativistic reduction

$$-\mathrm{i}\,\Sigma(k) = 3\left(Gm_\pi^2\right)^2 \int \frac{d^4q}{(2\pi)^4}\, G(k-q)\, D(q) \left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

$$G(k) = \frac{1}{k^0 - E(\vec{k}) + \mathrm{i}\varepsilon}$$

$$D(q) = \frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^{\,2} + \mathrm{i}\varepsilon}$$

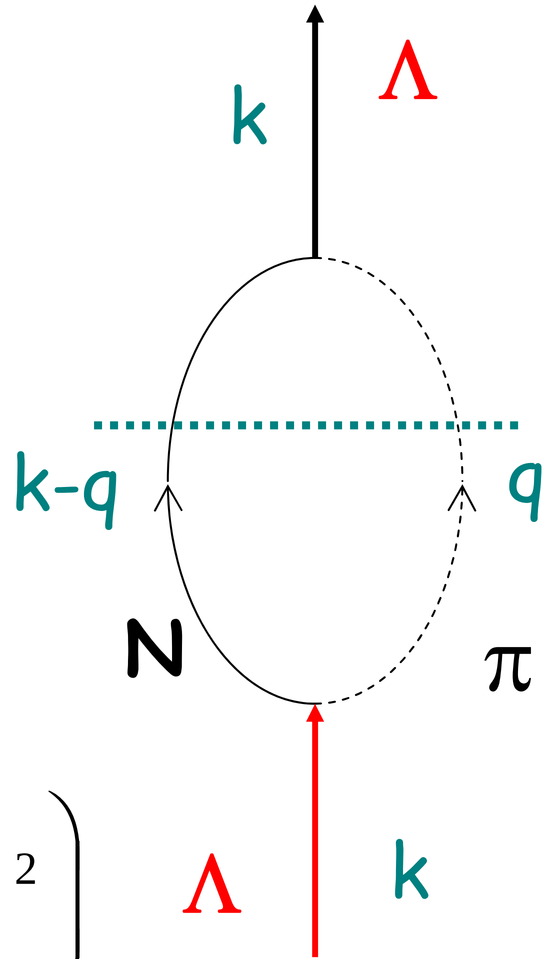
$\Lambda \rightarrow \pi\,N$

$$S = A$$
$$P = \frac{m_\pi B}{2m_N}$$

Free nucleon and pion propagators

Mesonic decay. Propagator Method

Free Λ width:



$$\Gamma_{\Lambda}^{\text{free}} = 3\left(G m_{\pi}^{2}\right)^{2} \int \frac{d^{3}\vec{q}}{(2\pi)^{3} 2\omega(\vec{q})}$$

$$\times 2\pi\, \delta\left[E_{\Lambda} - \omega(\vec{q}) - E_{N}(\vec{k} - \vec{q})\right]\left(S^{2} + \frac{P^{2}}{m_{\pi}^{2}}\vec{q}^{\,2}\right)$$

Oset, Fernández de Córdoba, Salcedo, Brockmann (1990)

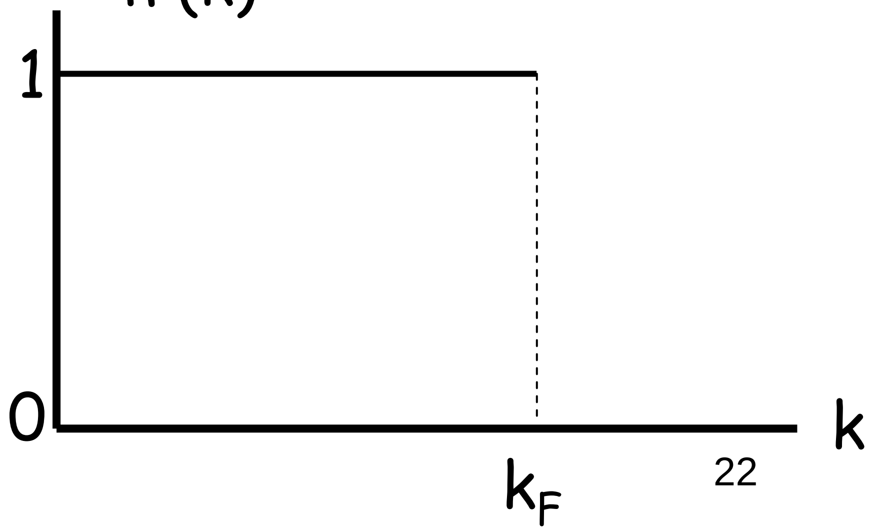
Mesonic decay in the medium. Propagator Method

- Fermi sea of nucleons:

$$G(p) = \frac{1 - n(\vec{p})}{p^0 - E(\vec{p}) - V_N + i\varepsilon} + \frac{n(\vec{p})}{p^0 - E(\vec{p}) - V_N - i\varepsilon}$$

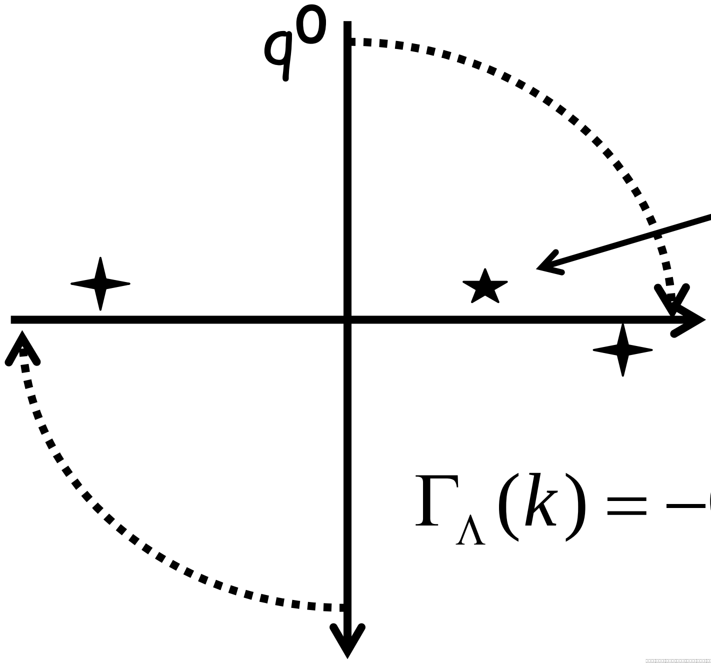
$$D(q) = \frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^{\,2} + \Pi\left(q^0, \vec{q}\right)}$$

pion self-energy



Λ self-energy

Mesonic decay in the medium. Propagator Method



$$k^0 - E(\vec{k} - \vec{q}) - V_N$$

Pauli blocking factor

$$\Gamma_\Lambda(k) = -6\left(G m_\pi^2\right)^2 \int \frac{d^3\vec{q}}{(2\pi)^3}$$

$$\times \left[1 - n\left(\vec{k} - \vec{q}\right)\right] \theta\left(k^0 - E\left(\vec{k} - \vec{q}\right) - V_N\right) \left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

$$\times \operatorname{Im} \left. \frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^2 - \Pi\left(q^0, q\right)} \right|_{q^0 = k^0 - E\left(\vec{k} - \vec{q}\right) - V_N}$$

Oset, Salcedo (1985)

Mesonic decay in the medium. Propagator Method

$\Lambda \rightarrow \pi N$

k=0 $\Rightarrow$ q $\cong$ 100 MeV/c < k_F = 270 MeV/c ↪ 1-n(k-q)=0

Nuclear medium: Λ wf overlaps the nuclear surface (smaller k_F)

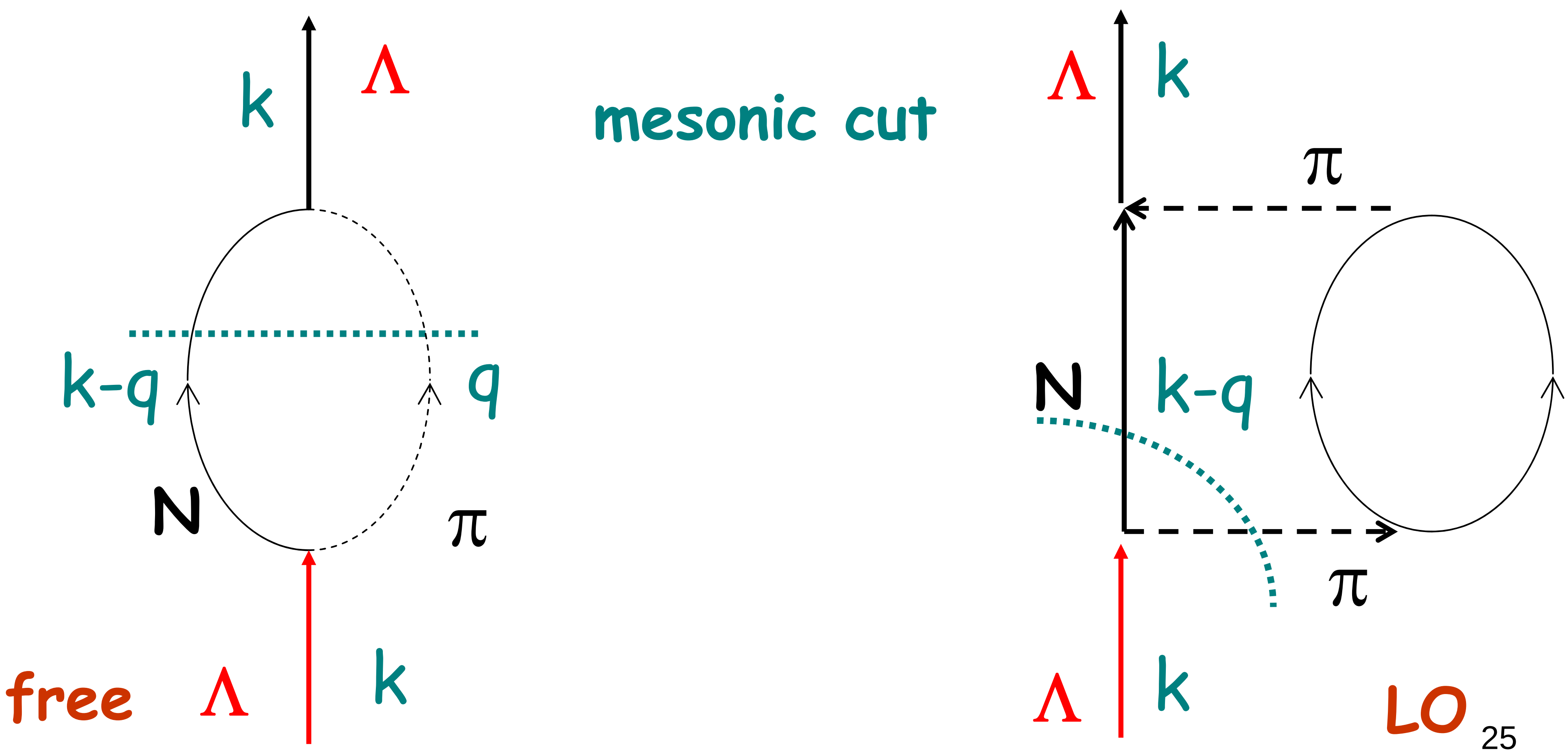
$$\Gamma_\Lambda(k) = -6\left(Gm_\pi^2\right)^2 \int \frac{d^3\vec{q}}{(2\pi)^3}$$

$$\times\left[1-n\left(\vec{k}-\vec{q}\right)\right]\theta\left(k^0 - E\left(\vec{k}-\vec{q}\right)-V_N\right)\left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

$$\times \operatorname{Im} \left.\frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^2 - \Pi\left(q^0, q\right)}\right|_{q^0 = k^0 - E\left(\vec{k}-\vec{q}\right) - V_N}$$

Mesonic decay in the medium. Propagator Method

Diagrammatically…



Mesonic decay in the medium. Propagator Method

$$\Gamma_{\Lambda}^{\mathrm{mes}} = 3\left(G m_{\pi}^{2}\right)^{2} \int \frac{d^{3}\vec{q}}{(2\pi)^{3}} \frac{1}{\left[2\tilde{\omega}(\vec{q}) - \frac{\partial \Pi}{\partial \tilde{\omega}}\right]}$$

$$\times 2\pi\, \delta\left[E_{\Lambda} - \tilde{\omega}(\vec{q}) - E_{N}(\vec{k} - \vec{q}) - V_{N}\right]\left(S^{2} + \frac{P^{2}}{m_{\pi}^{2}} \vec{q}^{\,2}\right)$$

nucleon potential

renormalized pion energy

Oset, Fernández de Córdoba, Salcedo, Brockmann (1990)

Mesonic decay in the medium. Propagator Method

$$\Gamma_\Lambda^{\text{mes}} = 3\left(G m_\pi^2\right)^2 \int \frac{d^3\vec{q}}{(2\pi)^3} \frac{1}{\left[2\tilde{\omega}(\vec{q}) - \frac{\partial \Pi}{\partial \tilde{\omega}}\right]}$$

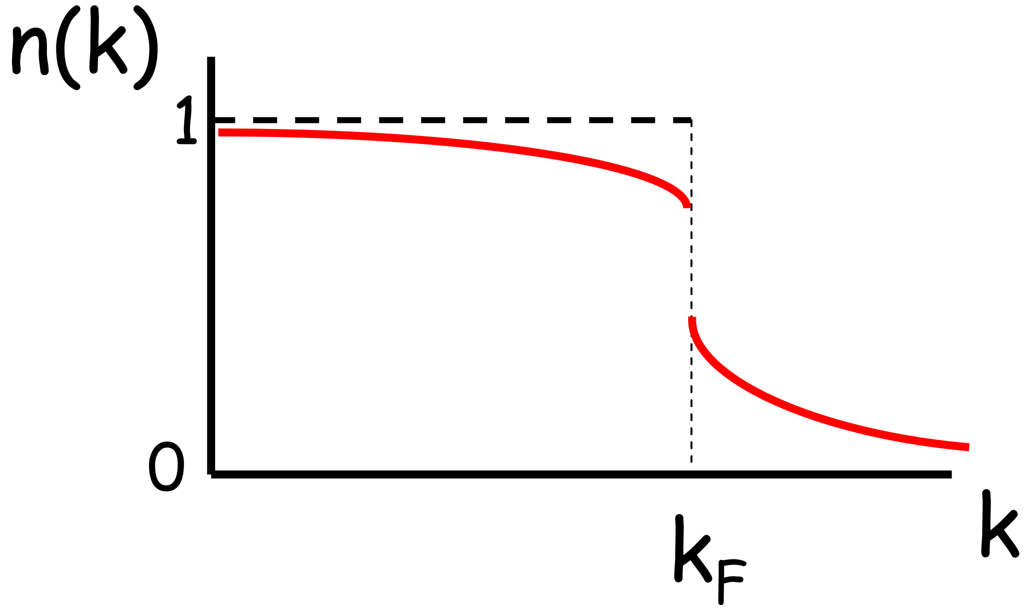
$$\times 2\pi\, \delta\left[E_\Lambda - \tilde{\omega}(\vec{q}) - E_N(\vec{k} - \vec{q}) - V_N\right]\left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

The attractive character of the pion-self energy leads to a large pion momentum for the same pion energy and thus, to a larger momentum for the nucleon due to momentum conservation, increasing the mesonic width.

Oset, Fernández de Córdoba, Salcedo, Brockmann (1990)

Mesonic decay. Propagator Method and the occupation number

nucleon occupation number
for an interacting Fermi sea



Leads to an overestimation of the width by 3 orders of magnitude for heavy nuclei !!!

Fernández de Córdoba, Oset (1991)

Mesonic decay. Propagator Method and the occupation number

nucleon propagator for an interacting Fermi sea:

$$G\left(k^0,k\right)=\int_{-\infty}^{\mu} d\omega\,\frac{S_h(\omega,k)}{k^0-\omega-\mathrm{i}\varepsilon}+\int_{\mu}^{\infty} d\omega\,\frac{S_p(\omega,k)}{k^0-\omega+\mathrm{i}\varepsilon}$$

chemical potential

Fernández de Córdoba, Oset (1991):

negligible consequences on the mesonic width for light-medium hypernuclei

Mesonic decay in the medium. Propagator Method + LDA

Finite nuclei

→ Local Density Approximation

$$k_F(\vec{r}) = \left\{\frac{3}{2}\pi^2 \rho(\vec{r})\right\}^{\frac{1}{3}}$$

$$\rho_A(\vec{r}) = \frac{\rho_0}{\left\{1 + \exp\left[\frac{r - R(A)}{a}\right]\right\}}$$

with $R(A) = 1.12\, A^{\frac{1}{3}} - 0.86\, A^{-\frac{1}{3}}$, and $a = 0.52$ fm

$$\varepsilon_F(\vec{r}) + V_N(\vec{r}) \equiv \frac{k_F^2(\vec{r})}{2\, m_N} + V_N(\vec{r}) = 0$$

Mesonic decay in the medium. Propagator Method + LDA

Finite nuclei

→ Local Density Approximation

$$\Gamma_{\Lambda}(\vec{k}) = \int d^3r \, |\psi_{\Lambda}(\vec{r})|^2 \, \Gamma\left(\vec{k}, \rho(\vec{r})\right)$$

... plus average over momentum distribution of the Λ wf.

$$\Gamma = \int d^3k \, \left|\tilde{\psi}_{\Lambda}\left(\vec{k}\right)\right|^2 \Gamma_{\Lambda}(\vec{k})$$

Mesonic decay. Finite nucleus (WFM)

Oset, Salcedo (1986) Itonaga, Motoba, Bando, (1988)

In free space…

$$\Gamma_\alpha^{\text{free}} = c_\alpha \left(G m_\pi^2\right)^2 \int \frac{d\vec{q}}{(2\pi)^3 2\omega(\vec{q})} 2\pi\, \delta\left[m_\Lambda - \omega(\vec{q}) - E_N\right] \left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

$c_\alpha = 1$ for Γ_{π^0}

$c_\alpha = 2$ for $\Gamma_{\pi-}$

$\Delta I = 1/2$ rule

$$S = A$$

$$P = \frac{m_\pi B}{2 m_N}$$

$$\Gamma_\alpha^{\text{free}} = c_\alpha \left(G m_\pi^2\right)^2 \frac{1}{2\pi} \frac{m_N q_{c.m.}}{m_\Lambda} \left(S^2 + \frac{P^2}{m_\pi^2} q_{c.m.}^2\right)$$

… Reproduces the free decay rates

Mesonic decay. Finite nucleus (WFM)

Oset, Salcedo (1986) Itonaga, Motoba, Bando, (1988)

In the finite nucleus…

$$\Gamma_\alpha = c_\alpha \left(G m_\pi^2\right)^2 \sum_{N \notin F} \int \frac{d\vec{q}}{(2\pi)^3 2\omega(\vec{q})} 2\pi\, \delta\left[E_\Lambda - \omega(\vec{q}) - E_N\right]$$

$$\times \left\{ S^2 \left| \int d\vec{r}\, \phi_\Lambda(\vec{r})\, \phi_\pi(\vec{q},\vec{r})\, \phi_N^*(\vec{r}) \right|^2 + \frac{P^2}{m_\pi^2} \left| \int d\vec{r}\, \phi_\Lambda(\vec{r})\, \vec{\nabla} \phi_\pi(\vec{q},\vec{r})\, \phi_N^*(\vec{r}) \right|^2 \right\}$$

Outgoing wave ⟷ Klein-Gordon Equation:

$$\left\{ \vec{\nabla}^2 - m_\pi^2 - 2\omega V_{\text{opt}}(\vec{r}) + \left[\omega - V_C(\vec{r})\right]^2 \right\} \phi_\pi(\vec{q},\vec{r}) = 0$$

Strong sensitivity of the WMD to the pion-nucleus optical potential !!

Mesonic decay

$^{5}_{\Lambda}He$

Ref.	$\Gamma_M/\Gamma_\Lambda^{free}$	Model
Oset–Salcedo 1985	0.65	PPM
Oset–Salcedo–Usmani 1986	0.54	PPM
Itonaga–Motoba–Bandō 1988	$0.331 \div 0.472$	WFM
Motoba *et al.* 1991	0.608	WFM + Quark Model
Motoba 1992	0.61	WFM
Straub *et al.* 1993	0.670	WFM + Quark Model
Kumagai–Fuse *et al.* 1995	0.60	WFM
Exp BNL 1991	$0.59^{+0.44}_{-0.31}$	
Exp KEK 2004	0.541 ± 0.019	

Mesonic decay

$^{12}_{\Lambda}C$

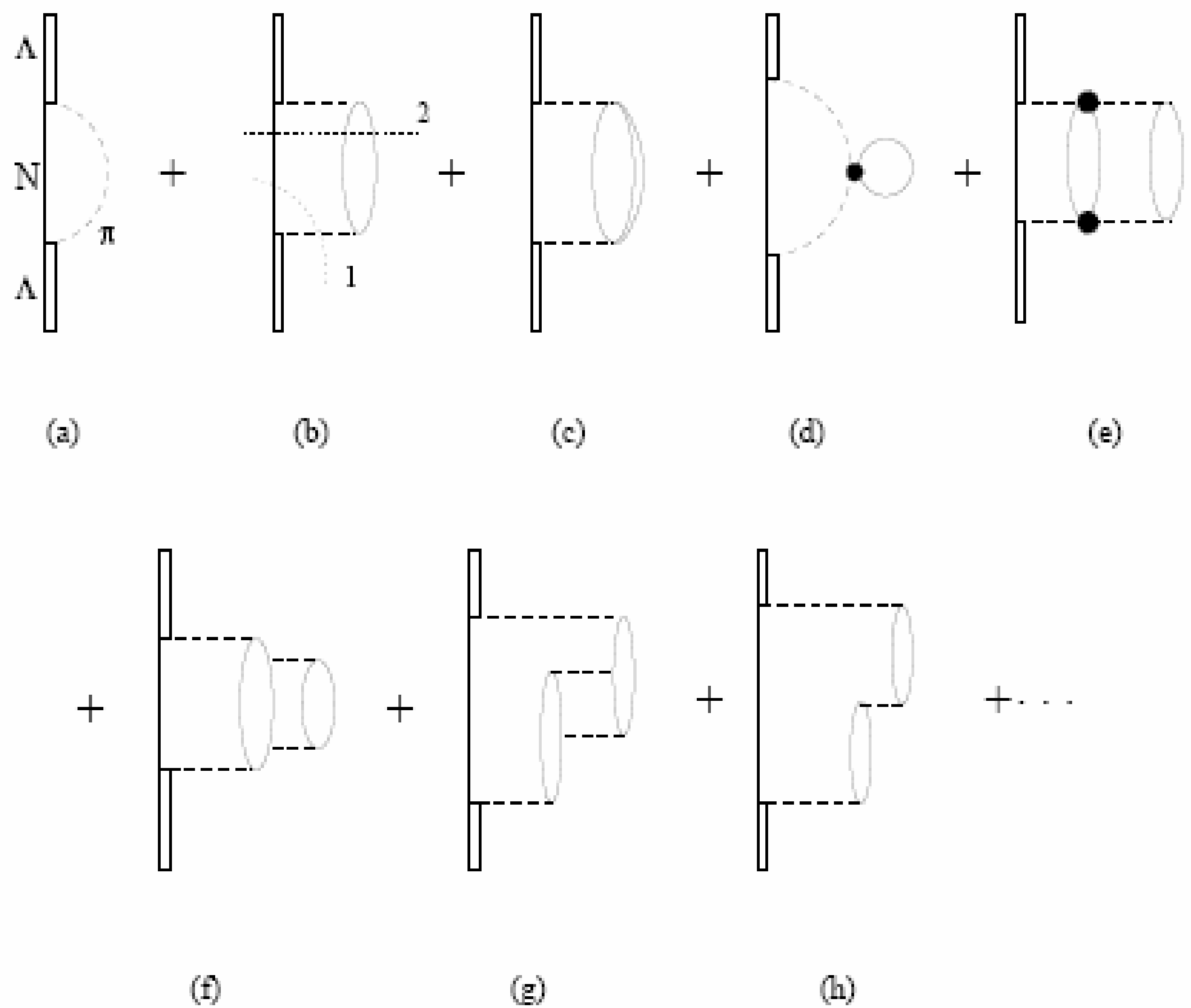
Ref.	$\Gamma_M/\Gamma_\Lambda^{\text{free}}$	Model
Oset–Salcedo 1985	0.41	PPM
Itonaga–Motoba–Bandō 1988	$0.233 \div 0.303$	WFM
Ericson–Bandō 1990	0.229	WFM
Nieves–Oset 1993	0.245	WFM
Itonaga–Motoba 1994	0.228	WFM
Ramos *et al.* 1995	0.31	PPM
Zhou–Piekarewicz 1999	0.112	Relativistic PPM
Albertus *et al.* 2003	0.25	WFM
Exp BNL 1991	0.11 ± 0.27	
Exp KEK 1995	0.36 ± 0.13	
Exp KEK 2004	0.313 ± 0.070	
Exp KEK 2004	0.288 ± 0.017	

Non-mesonic decay. PPM and LDA

Evaluate the Λ self energy inside the nuclear medium:

Homogeneous system (nuclear matter)
Random Phase Approximation (RPA)

Non-mesonic decay. PPM and LDA



Polarization Propagator method and Local Density Approximation

$$\Gamma_\Lambda = -2\,\mathrm{Im}\,\Sigma_\Lambda$$

Non-relativistic limit

$$\Sigma_\Lambda(k) = 3\mathrm{i}\left(G m_\pi^2\right)^2 \int \frac{d^4 q}{(2\pi)^4} \left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2} \right) F_\pi^2(q)\, G_N(k-q)\, G_\pi(q)$$

$$G_N(p) = \frac{\theta\left(|\vec{p}| - k_F\right)}{p_0 - E_N(\vec{p}) - V_N + \mathrm{i}\varepsilon} + \frac{\theta\left(k_F - |\vec{p}|\right)}{p_0 - E_N(\vec{p}) - V_N - \mathrm{i}\varepsilon}$$

$$G_\pi(q) = \frac{1}{q_0^2 - \vec{q}^{\,2} - m_\pi^2 - \Sigma_\pi^*(q)}$$

One-nucleon induced decay rate. Finite nucleus calculation

$$\Gamma_{\rm nm} = \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} \sum_{\substack{M_i\ \{R\} \\ \{1\}\{2\}}} (2\pi)\,\delta(M_H - E_R - E_1 - E_2) \frac{1}{2J+1} \left|M_{\rm fi}\right|^2$$

$$M_{\rm fi} \approx \left\langle \vec{k}_1 m_1 \vec{k}_2 m_2 ; \Psi_{R'}^{A-2} \middle| \hat{O}_{\Lambda N \to NN} \middle| {}^{A}_{\Lambda}Z \right\rangle$$

Hypernuclear structure: $\left| {}^{A}_{\Lambda}Z \right\rangle \to \left| \Lambda N \right\rangle \otimes \left| \Psi_R^{A-2} \right\rangle$

Weak coupling scheme for the Λ :

$$\left| {}^{A}_{\Lambda}Z \right\rangle_{T_I T_{3I}}^{J_I M_I} = \left| \alpha_\Lambda \right\rangle \otimes \left| A-1 \right\rangle$$

$$= \sum_{m_\Lambda M_C} \left\langle j_\Lambda m_\Lambda J_C M_C \middle| J_I M_I \right\rangle \left| (n_\Lambda l_\Lambda s_\Lambda)\, j_\Lambda m_\Lambda \right\rangle \left| J_C M_C T_I T_{3I} \right\rangle$$

Nonmesonic decay rate
Finite nucleus calculation

Technique of the coefficients of fractional parentage:

$$\Psi_{\rm as}^{J_C T_C \alpha}(1\ldots N) = \sum_{\substack{J_{R_0} T_{R_0} \\ \alpha_0 j_N}} \left\langle J_C T_C \alpha \{ \middle| J_{R_0} T_{R_0} \alpha_0, j_N \right\rangle \times \left[\Psi_{\rm as}^{J_{R_0} T_{R_0} \alpha_0}(1\ldots N-1) \otimes \phi^{j_N}(N) \right]^{J_C T_C}$$

Core wave function:

$$\left| J_C M_C T_I T_{3I} \right\rangle = \sum_{J_R T_R j_N} \left\langle J_C T_I \{ \middle| J_R T_R, j_N t_N \right\rangle \left[\left| J_R T_R \right\rangle \times \left| (n_N l_N s_N) j_N, t_N \right\rangle \right]^{J_C M_C}_{T_I T_{3I}}$$

$$= \sum_{J_R T_R j_N} \left\langle J_C T_I \{ \middle| J_R T_R, j_N t_N \right\rangle$$

$$\times \sum_{M_R m_N} \sum_{T_{3_R} t_{3_i}} \left\langle J_R M_R j_N m_N \middle| J_C M_C \right\rangle \left\langle T_R T_{3_R} t_N t_{3_i} \middle| T_I T_{3I} \right\rangle \times \left| J_R M_R \right\rangle \left| T_R T_{3_R} \right\rangle \left| (n_N l_N s_N) j_N m_N \right\rangle \left| t_N t_{3_i} \right\rangle$$

Nonmesonic decay rate
Finite nucleus calculation

$$\Gamma_i^{\mathrm{nm}} = \int \frac{d^3P}{(2\pi)^3} \int \frac{d^3k}{(2\pi)^3} (2\pi)\,\delta\left(M_H - E_R - E_1 - E_2\right)$$

$$\times \sum_{S M_S} \sum_{J_R M_R} \sum_{T_R M_{T_R}} \frac{1}{2J+1} \sum_{M_I} \left| \left\langle T_R M_{T_R} \frac{1}{2} t_{3_i} \middle| T_I M_{T_I} \right\rangle \right|^2$$

$$\times \left| \sum_{T T_3} \left\langle T M_T \middle| \frac{1}{2} t_1 \frac{1}{2} t_2 \right\rangle \sum_{m_\Lambda M_C} \left\langle j_\Lambda m_\Lambda J_C M_C \middle| J_I M_I \right\rangle \times \sum_{j_N} \sqrt{S\left(J_C T_I ; J_R T_R , j_N t_{3_i}\right)} \right.$$

$$\times \sum_{M_R m_N} \left\langle J_R M_R\, j_N m_N \middle| J_C M_C \right\rangle \sum_{m_{l_N} m_{s_N}} \left\langle j_N m_N \middle| l_N m_{l_N} s_N m_{s_N} \right\rangle \sum_{m_{l_\Lambda} m_{s_\Lambda}} \left\langle j_\Lambda m_\Lambda \middle| l_\Lambda m_{l_\Lambda} s_\Lambda m_{s_\Lambda} \right\rangle$$

$$\times \sum_{S_0 M_{S_0}} \left\langle S_0 M_{S_0} \middle| \frac{1}{2} m_{s_\Lambda} \frac{1}{2} m_{s_N} \right\rangle \sum_{T_0 M_{T_0}} \left\langle T_0 M_{T_0} \middle| \frac{1}{2} - \frac{1}{2} \frac{1}{2} t_{3_i} \right\rangle$$

$$\left. \times\, t_{\Lambda N \to NN} \left(S, M_S, T, M_T, S_0, M_{S_0}, T_0, M_{T_0}, l_\Lambda, l_N, \vec{P}, \vec{k}\right) \right|^2$$

n,p

Nonmesonic decay rate
Finite nucleus calculation

H.O. wf's

$$t^{N_r L_r \; N_R L_R}_{\Lambda N \to NN} = \frac{1}{\sqrt{2}} \int d^3R \int d^3r \, e^{-i \vec{P}\vec{R}}$$

$$\times \Psi^{*}_{\vec{k}}(\vec{r}) \, \chi^{+S}_{M_S} \chi^{+T}_{M_T} \, V(\vec{r}) \, \Phi^{\mathrm{CM}}_{N_R L_R}\left(\frac{\vec{R}}{b/\sqrt{2}}\right) \Phi^{\mathrm{rel}}_{N_r L_r}\left(\frac{\vec{r}}{\sqrt{2}b}\right) \chi^{S_0}_{M_{S_0}} \chi^{T_0}_{M_{T_0}}$$

$$t^{N_r L_r \; N_R L_R}_{\Lambda N \to NN} = (2\pi)^{3/2} \; \Phi^{\mathrm{CM}}_{N_R L_R}\left(\vec{P}\frac{b}{\sqrt{2}}\right) t_{\mathrm{rel}}$$

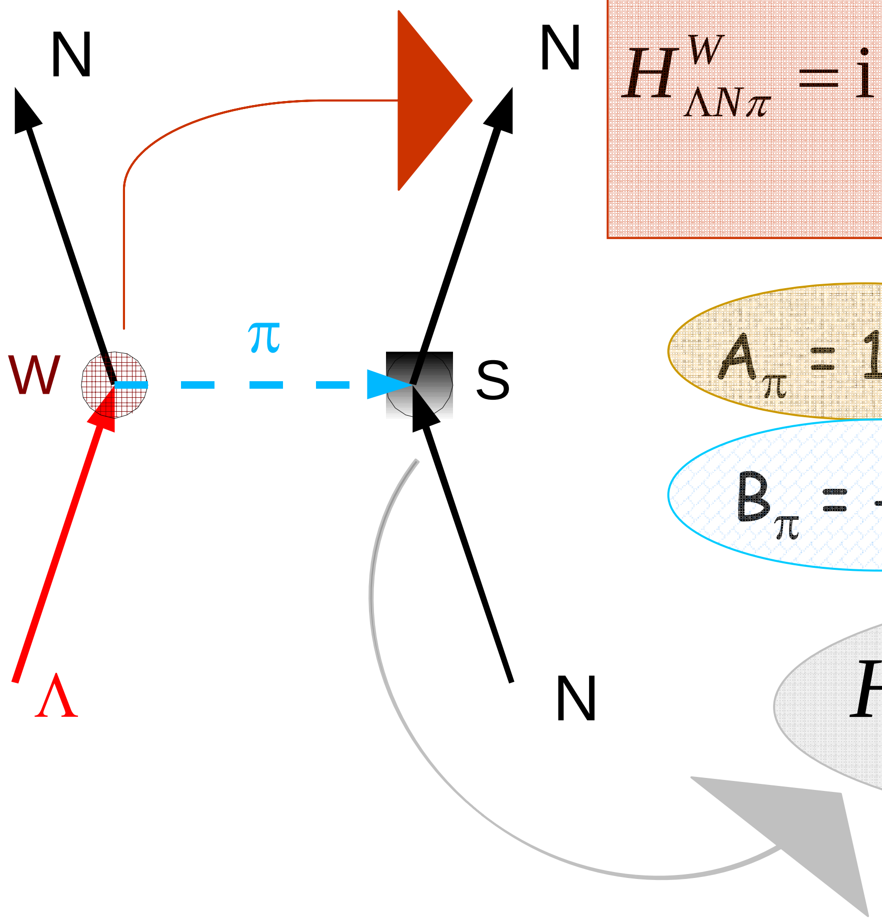
$$t_{\mathrm{rel}} = \frac{1}{\sqrt{2}} \int d^3r \;\; \Psi^{*}_{\vec{k}}(\vec{r}) \, \chi^{+S}_{M_S} \chi^{+T}_{M_T} \, V(\vec{r}) \, \Phi^{\mathrm{rel}}_{N_r L_r}\left(\frac{\vec{r}}{\sqrt{2}b}\right) \chi^{S_0}_{M_{S_0}} \chi^{T_0}_{M_{T_0}}$$

?

Nonmesonic decay rate
Finite nucleus calculation

In a meson exchange picture, the largest contribution comes from the One-Pion-Exchange mechanism.

M. Ruderman, R. Karplus, 1956 M.M.Block, R.H. Dalitz, 1963



$$H^{W}_{\Lambda N\pi} = \mathrm{i}\, G_F m_\pi^2\, \overline{\psi}_N \left(A_\pi + B_\pi \gamma_5\right) \vec{\tau}\vec{\phi}^{\pi} \psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

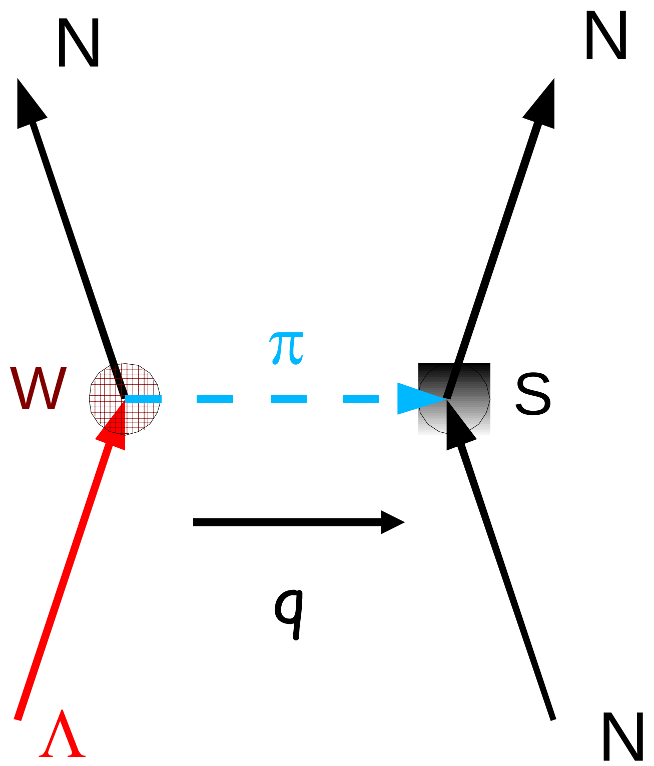
$A_\pi = 1.05$ ⟷ Parity-Violating

$B_\pi = -7.15$ ⟷ Parity-Conserving

$$H^{S}_{NN\pi} = \mathrm{i}\, g_{NN\pi}\, \overline{\psi}_N \gamma_5 \vec{\tau}\vec{\phi}^{\pi} \psi_N$$

$$g_{NN\pi} \approx 13.3$$

Nonmesonic decay rate
Finite nucleus calculation



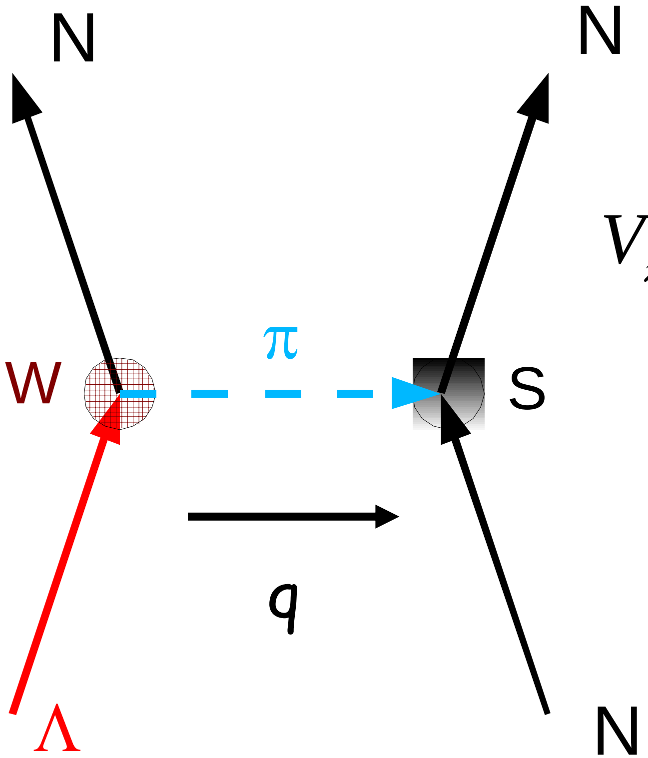
Making a non-relativistic reduction of the Feynman amplitude…

$$V_\pi(\vec{q}) = -G_F m_\pi^2 \frac{g}{2M}\left(\hat{A} + \frac{\hat{B}}{2\overline{M}}\vec{\sigma}_1\vec{q}\right)\frac{\vec{\sigma}_2\vec{q}}{\vec{q}^{\,2}+\mu^2}$$

$$\hat{A} = A\,\vec{\tau}_1\vec{\tau}_2 \quad \text{(PV)}$$

$$\hat{B} = B\,\vec{\tau}_1\vec{\tau}_2 \quad \text{(PC)}$$

Nonmesonic decay rate
Finite nucleus calculation



$$V_\pi(\vec{q}) = -G_F m_\pi^2 \frac{g}{2M}\left(\hat{A} + \frac{\hat{B}}{2\overline{M}}\vec{\sigma}_1\vec{q}\right)\frac{\vec{\sigma}_2\vec{q}}{\vec{q}^2+\mu^2}$$

⇓ r-space

$$\vec{\sigma}_1\vec{\sigma}_2\,, \quad S_{12}(\hat{r}) = 3\vec{\sigma}_1\vec{r}\ \vec{\sigma}_2\vec{r} - \vec{\sigma}_1\vec{\sigma}_2\,, \quad \vec{\sigma}_2\vec{r}$$

central tensor pv

Decay observables. Partial decay widths: neutron-to-proton ratio

Theoretically, and within the framework of the wave function method, one can evaluate separately the decay induced by a neutron

Γ_n : $\Lambda n \rightarrow nn$ (t_{3i} = -1/2)

and the decay induced by a proton,

Γ_p : $\Lambda p \rightarrow np$ (t_{3i} = +1/2)

and evaluate the ratio between both quantities:

$$\frac{\Gamma_n}{\Gamma_p}$$

$$\neq$$

Experimentally, one measures the final states, therefore, the nucleon (s) and the residual bound system left behind, hoping for a determination of:

$$\frac{nn}{np}$$

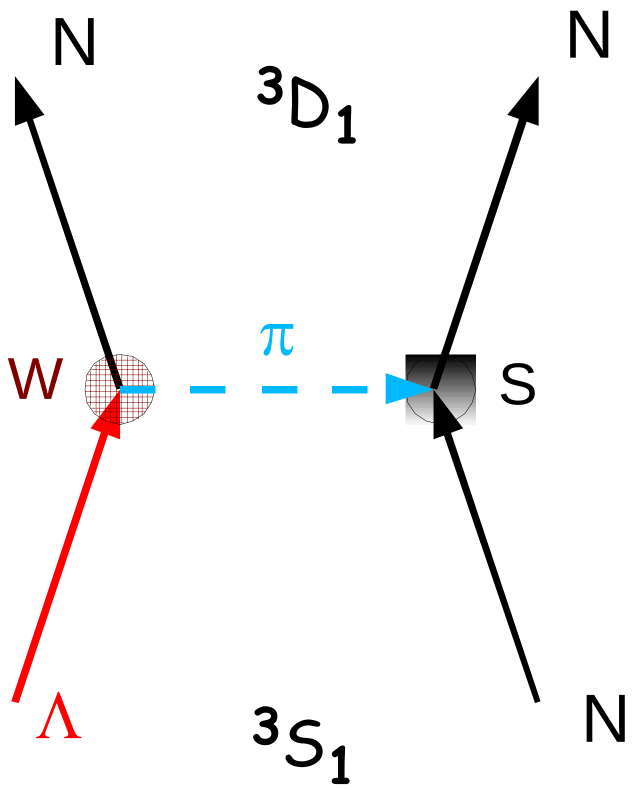
Decay observables. Partial decay widths: neutron-to-proton ratio

For many years:

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{Theor}} << \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{Exp}} \qquad \text{with} \qquad 0.5 \leq \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{Exp}} \leq 2$$

Why is the theoretical value so small?

Decay observables. Partial decay widths: neutron-to-proton ratio



Dominated by the tensor transition:

$(\Lambda N)\ ^3S_1 \rightarrow (NN)\ ^3D_1$

isospin I=0
(antisymmetry)

!! Only possible for np pairs

$\Longrightarrow \Gamma_{nn}$ highly suppressed

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{OPE} = 0.05 \div 0.20$$

Decay observables. Partial decay widths: neutron-to-proton ratio

- Different theoretical mechanisms were proposed to increase the value of n/p…
  - ✓ The large momentum transfer in the weak reaction indicates that short-range effects could be important ⇒ Within a one-meson-exchange picture, include mesons heavier than the pion.

$\pi+\rho$

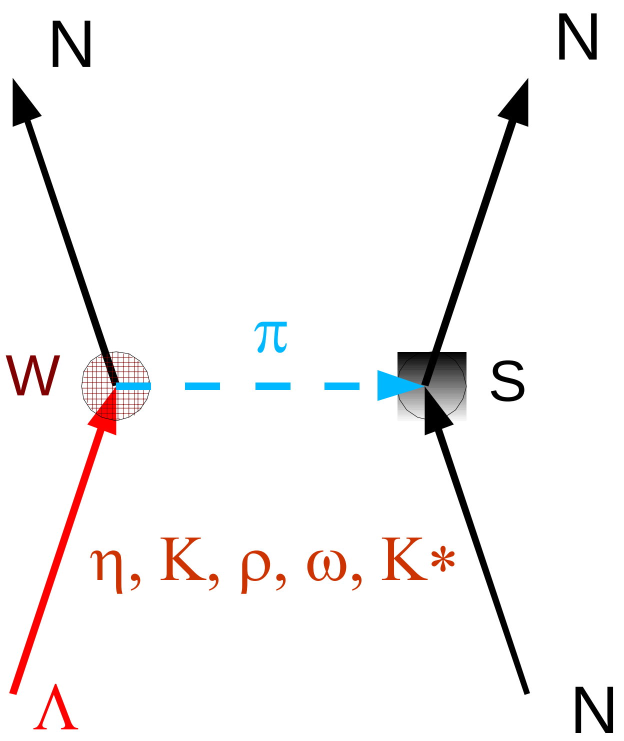
McKellar, Gibson (1984)
Takeuchi, Takaki, Bando (1985)
Parreño, Ramos, Bennhold (1995)

$\pi+\eta+K+\rho+\omega+K^*$

Dubach, Feldman, Holstein, De la Torre (1996)
Parreño, Ramos, Bennhold (1997)

Theoretical models I: One Meson Exchange (OME)

The π meson emitted at the weak vertex is viewed as absorbed by one of the nucleons in the medium.



Dubach, Feldman, Holstein, De la Torre (1996)
Parreño, Ramos, Bennhold (1997)

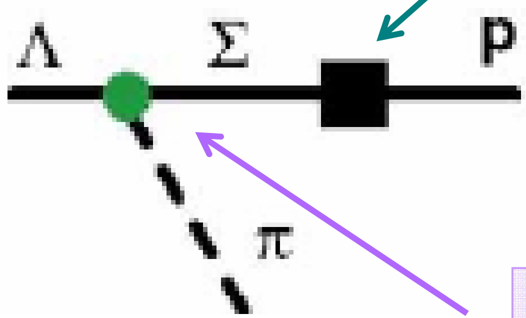
- In order to account for shorter distances, the model includes all physical mesons of the pseudoscalar and vector octects up to 1GeV.
- Phase space: Only the coupling constants at the BBπ vertices are known experimentally $\Rightarrow$ SU(3) is used to obtain the vertices for pseudoscalar mesons

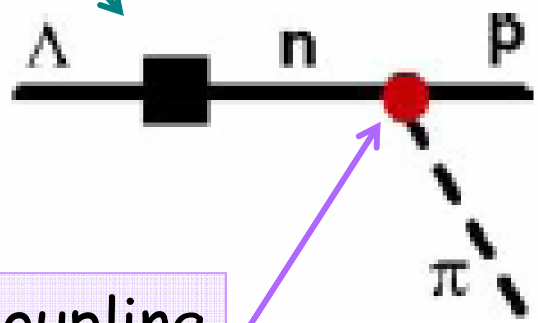
  (SU(6) is used for vector mesons)
- Finite size effects: typically, one includes a form-factor at each vertex to regularize the transition potential.

OME: Weak BBM vertices
(leading order chiral analysis)

Tree level diagram → Leading Order contribution to the S-wave (PV) nonleptonic amplitude

Weak vertex





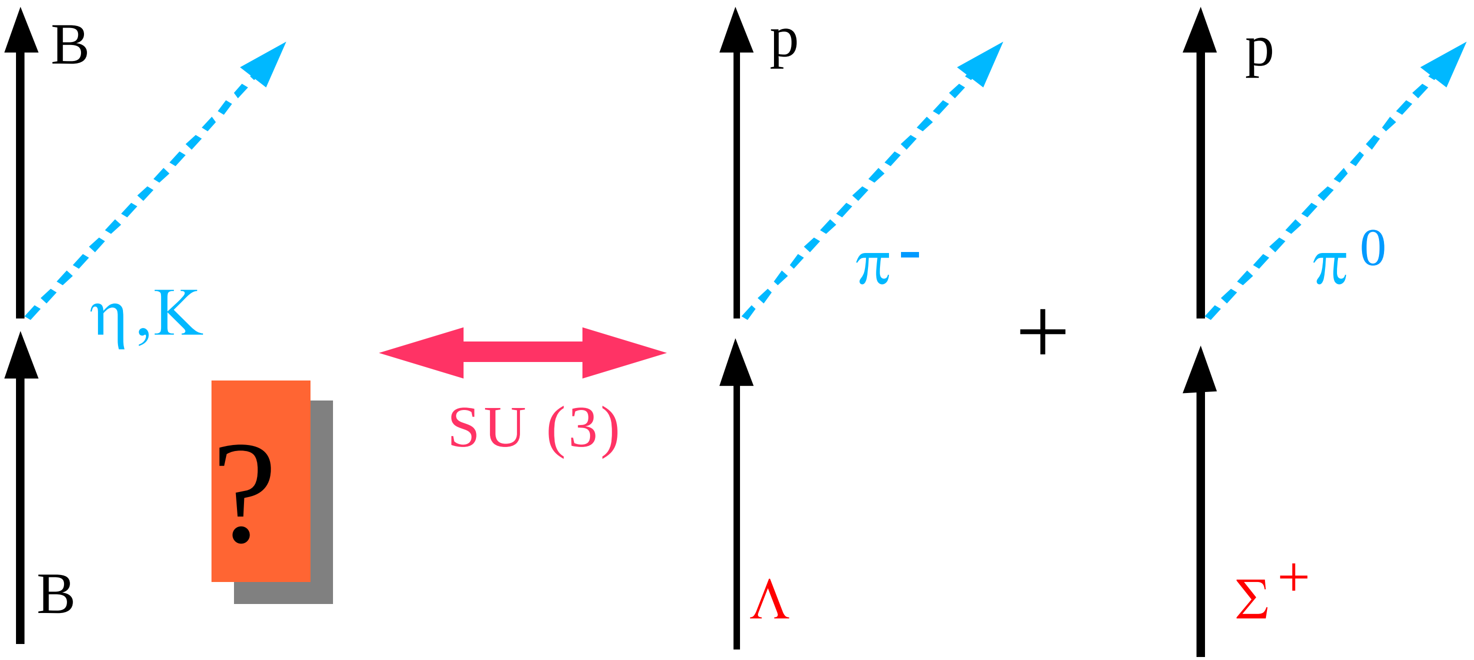
Axial coupling

Tree level diagrams for the P-wave (PV) nonleptonic amplitudes

OME: Weak PV BBM vertices

SU(6)$_W$ for vector mesons
ρ, ω, K^*

For pseudoscalar mesons…

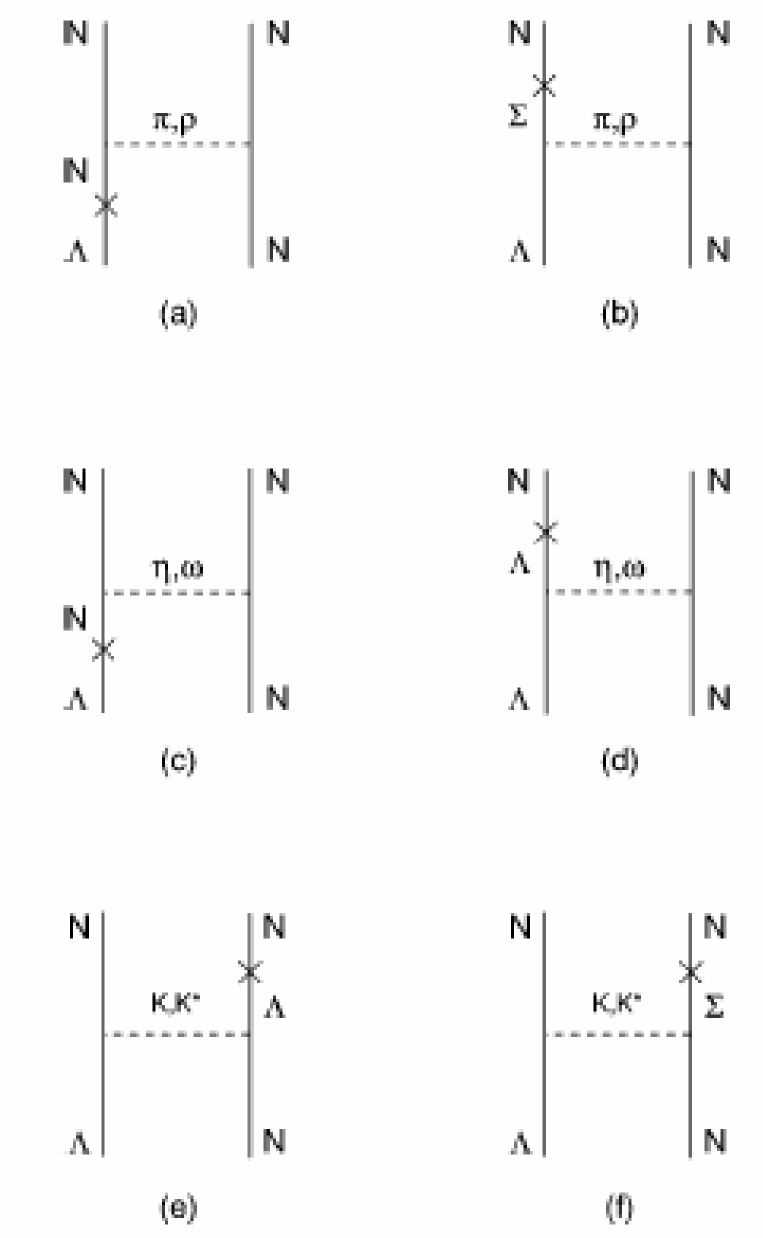


Soft-meson reduction theorem

Experimentally known

J.F. Dubach, G.B. Feldman, B.R. Holstein, L. de la Torre, 1996

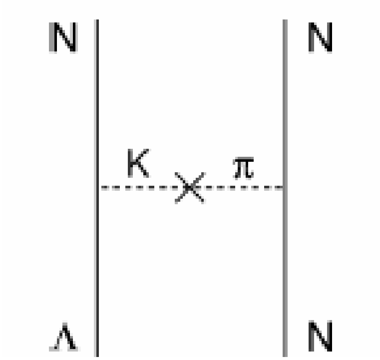
OME: Weak PC BBM vertices



$$B_\eta = g_{NN\eta}\frac{1}{m_\Lambda - m_N}A_{N\Lambda} + g_{\Lambda\Lambda\eta}\frac{1}{m_\Lambda - m_N}A_{N\Lambda}$$

$$\alpha_\rho = g^{\mathrm{v}}_{NN\rho}\frac{1}{m_\Lambda - m_N}A_{N\Lambda} + g^{\mathrm{v}}_{N\Sigma\rho}\frac{1}{m_N - m_\Sigma}A_{N\Sigma}$$

etc.



Smaller contribution from the meson-pole diagrams

Theoretical models: OME
Weak BBM vertices

Adding all (meson) contributions and Fourier transforming...

$$V(\vec{r}) = \frac{1}{(2\pi)^3}\int e^{i\vec{q}\vec{r}}\, V(\vec{q})$$

$$= \sum_i \sum_\alpha V_\alpha^{(i)}(\vec{r}) = \sum_i \sum_\alpha V_\alpha^{(i)}(r)\, \hat{O}_\alpha\, \hat{I}_\alpha^{(i)}$$

$$= \sum_i \Big[V_C^{(i)}(r)\, \hat{I}_C^{(i)} + V_{SS}^{(i)}(r)\, \vec{\sigma}_1\vec{\sigma}_2\, \hat{I}_{SS}^{(i)} + V_T^{(i)}(r)\, S_{12}(\hat{r})\, \hat{I}_T^{(i)}$$

$$+ \left(n^i\, \vec{\sigma}_2\vec{r} + \left(1-n^i\right)[\vec{\sigma}_1\times\vec{\sigma}_2]\vec{r} \right) V_{PV}^{(i)}(r)\, \hat{I}_{PV}^{(i)} \Big]$$

Central spin dependent

Tensor

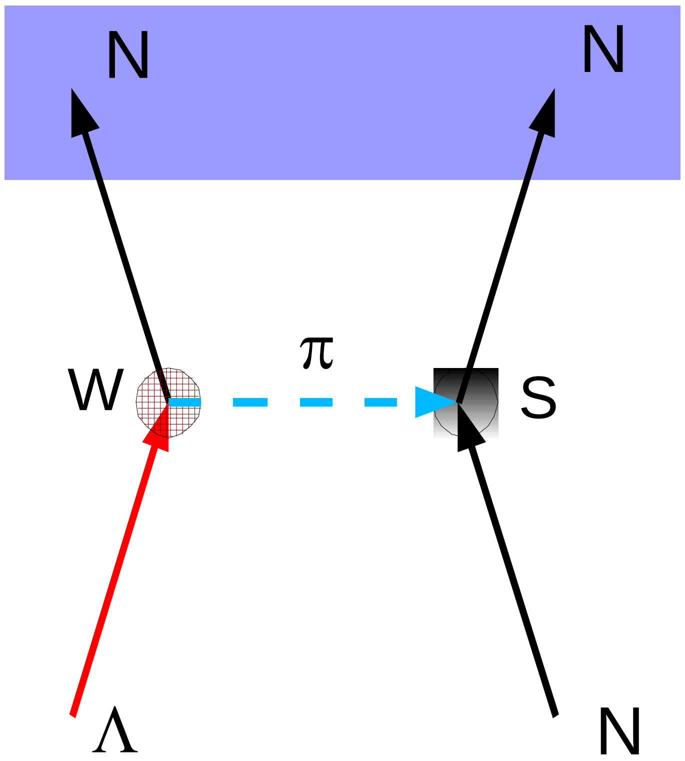
PV

Central spin-indep.

n^i =1 for pseudoscalar mesons
0 for vector mesons

Effects of strong interaction on the final NN state

NN wf: In the absence of correlations, just take plane waves.
But, the wave function describing the relative motion of two-particles moving under the influence of a two-body potential V, is obtained from the Lippmann-Schwinger equation:



$$\left|\Psi^{(\pm)}\right\rangle = \left|\Phi\right\rangle + \frac{1}{E - H_0 \pm i\varepsilon} V \left|\Psi^{(\pm)}\right\rangle$$

more

Effects of strong interaction on the final NN state

NN wf: In the absence of correlations, just take plane waves. But, the wave function describing the relative motion of two-particles moving under the influence of a two-body potential V, is obtained from the Lippmann-Schwinger equation:

$$\left|\Psi^{(\pm)}\right\rangle = \left|\Phi\right\rangle + \frac{1}{E - H_0 \pm i\varepsilon} V \left|\Psi^{(\pm)}\right\rangle$$

Alternatively....

$$\left|\Psi^{(+)}\right\rangle = \left|\Phi\right\rangle + \frac{1}{E - H_0 + i\varepsilon} T \left|\Phi\right\rangle$$

$$\left\langle\Psi^{(-)}\right| = \left\langle\Phi\right| + \left\langle\Phi\right| T \frac{1}{E - H_0 + i\varepsilon}$$

.. and obeys...

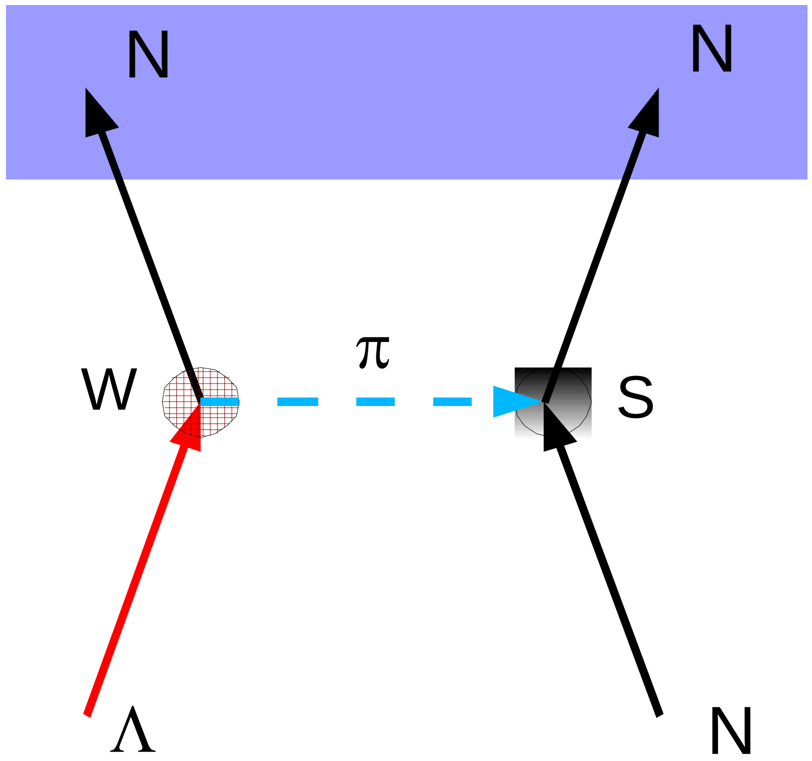
$$T = V + V \frac{1}{E - H_0 + i\varepsilon} T$$

where the T operator, defined as:

$$T\left|\Phi\right\rangle = V\left|\Psi^{(+)}\right\rangle \quad \left\langle\Psi^{(-)}\right|V = \left\langle\Phi\right|T$$

more

Effects of strong interaction on the final NN state



T-matrix

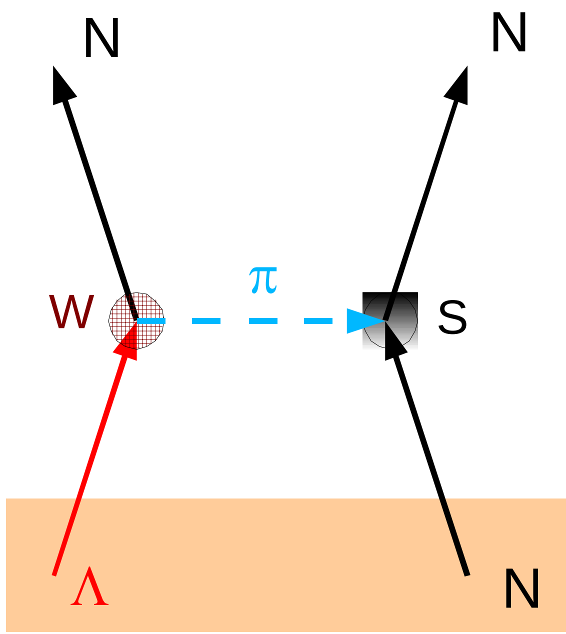
$$T = V + V \frac{1}{E - H_0 + i\varepsilon} T$$

$$V \left| \Psi^{(+)} \right\rangle = T \left| \Phi \right\rangle$$

With the input of realistic potential models (NSC97f, Bonn, ...)

Effects of strong interaction on the Initial State

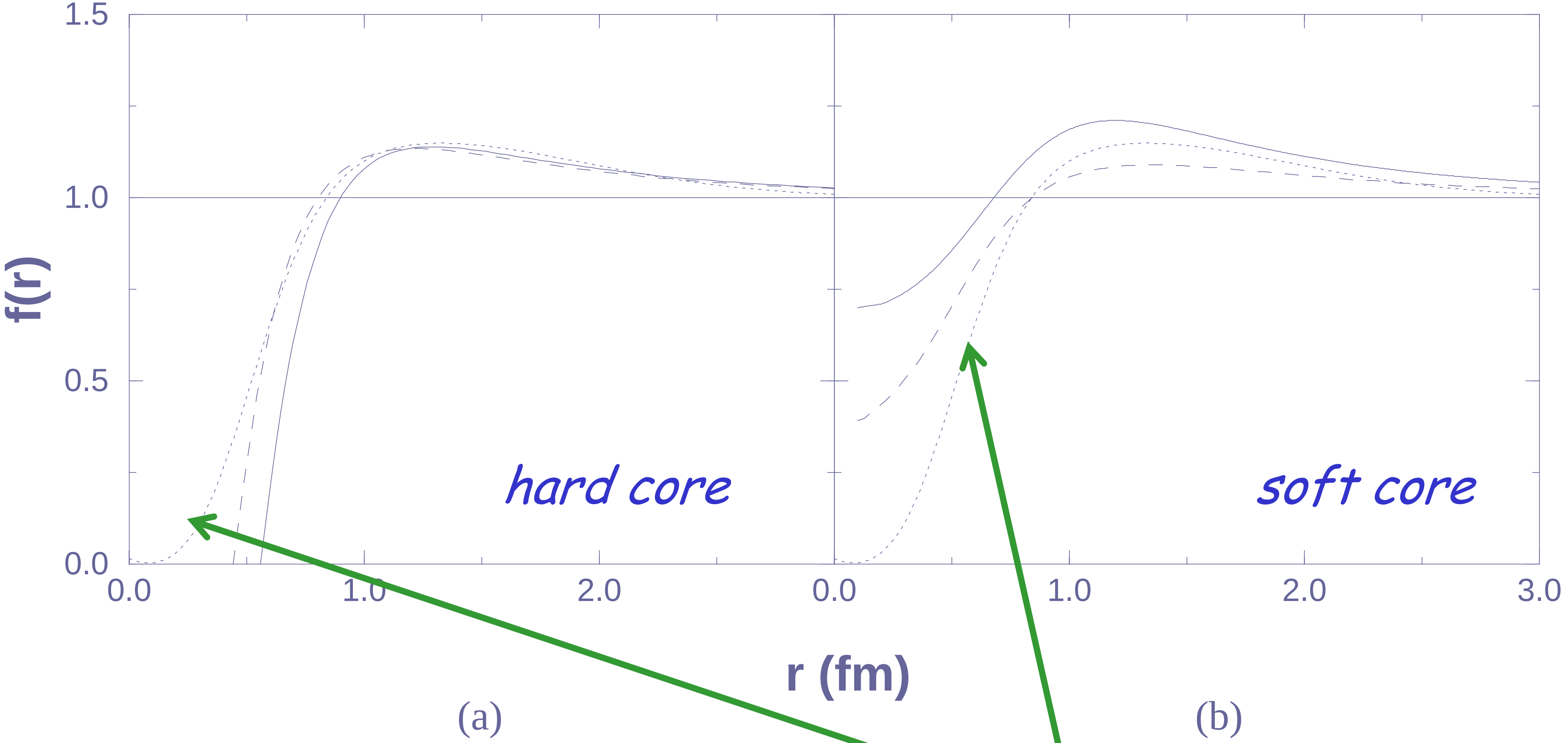
- Ideally, one should solve exactly the A-body wave function, or if not possible, solve thet G-matrix type equation in the medium.
- This can be very complicated for $A > 5$, and in practice, one multiplies the uncorrelated wf (harmonic oscillator, woods-saxon, etc.) by an effective correlation function, adjusted to G-matrix calculations of light systems.
- A typical ΛN correlation function is of the form:

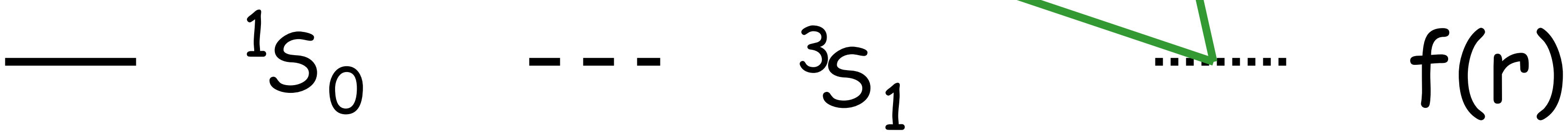


$$f(r) = \left(\left(1 - e^{-\frac{r^2}{a^2}} \right)^n + b r^2 e^{-\frac{r^2}{c^2}} \right)$$

with $\mathrm{a} = 0.5\,\mathrm{fm},\ \mathrm{b} = 0.25,\ \mathrm{c} = 1.28\,\mathrm{fm},\ \mathrm{n} = 2.$

Effects of strong interaction: ISI





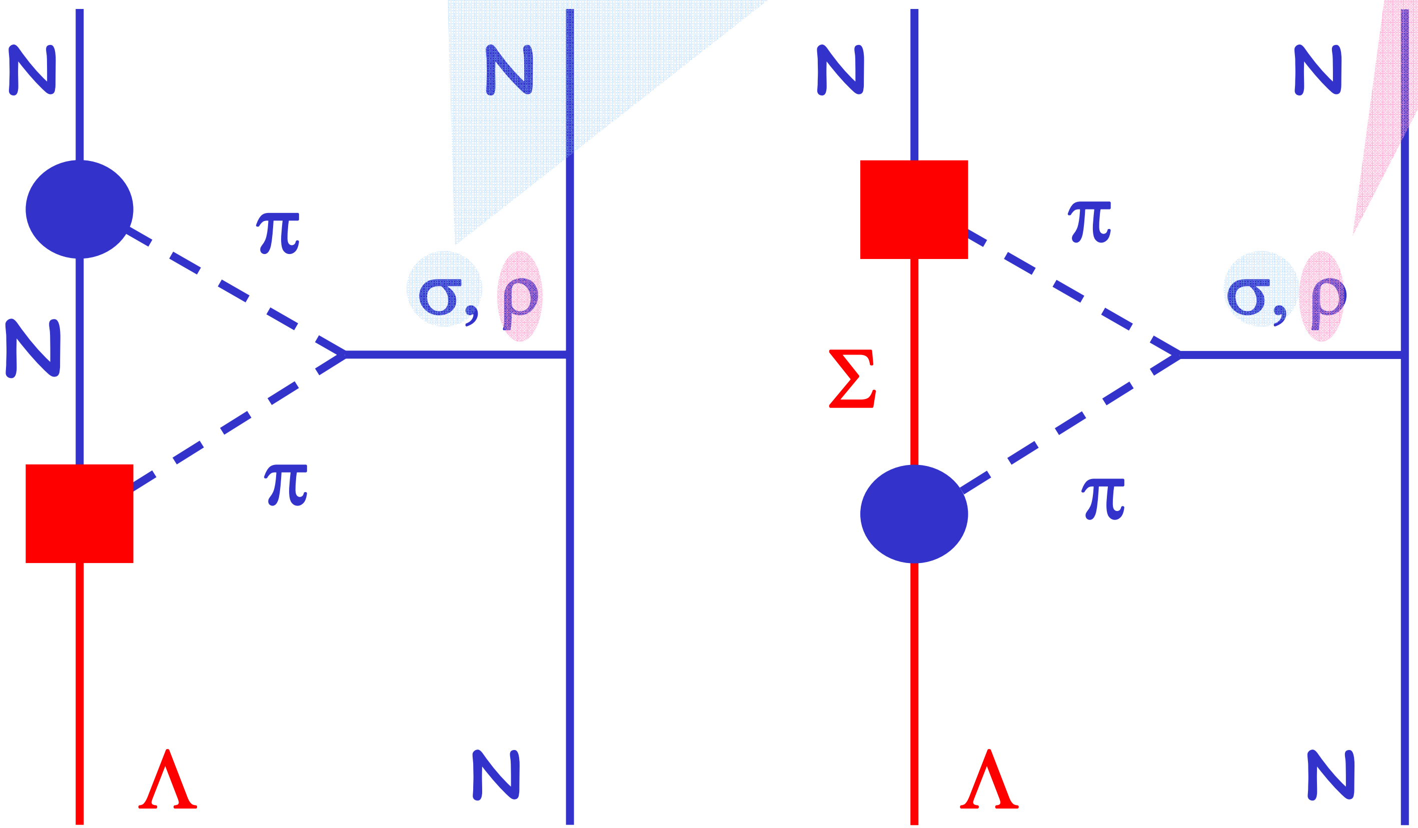
Non-mesonic decay rates. Relevance of NN strong interaction

${}^{5}_{\Lambda}He$	Γ_{nm}	n/p
plane waves	0.72	0.61
$f(r)=1-j_0(q_c r)$ $q_c=3.93\ fm^{-1}$	0.77	0.62
NSC97f	0.32	0.46

Theoretical models II: correlated $2\pi/\sigma$ and $2\pi/\rho$

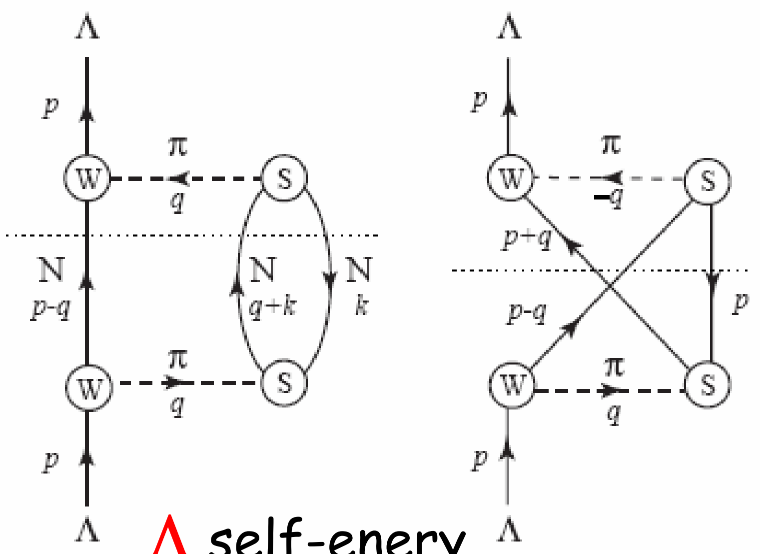
scalar-isoscalar channel → strong central

Strong tensor

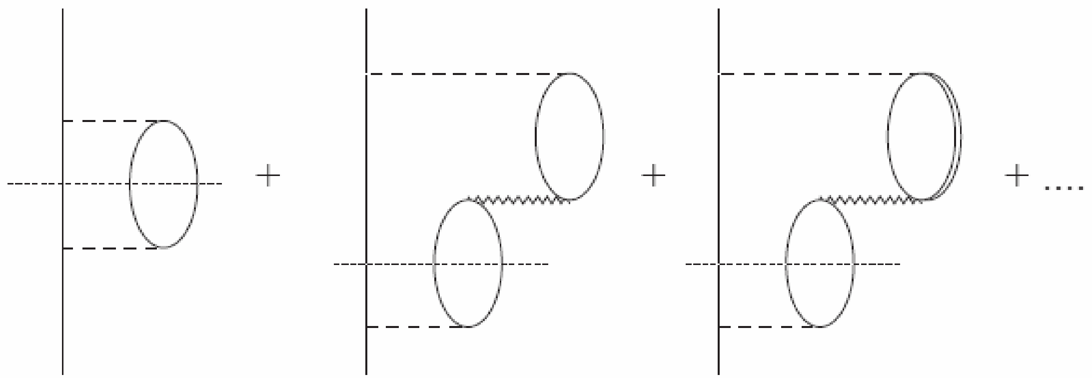


M. Shmatikov, 1994; K.Itonaga, T.Ueda, T.Motoba, 1994,2002

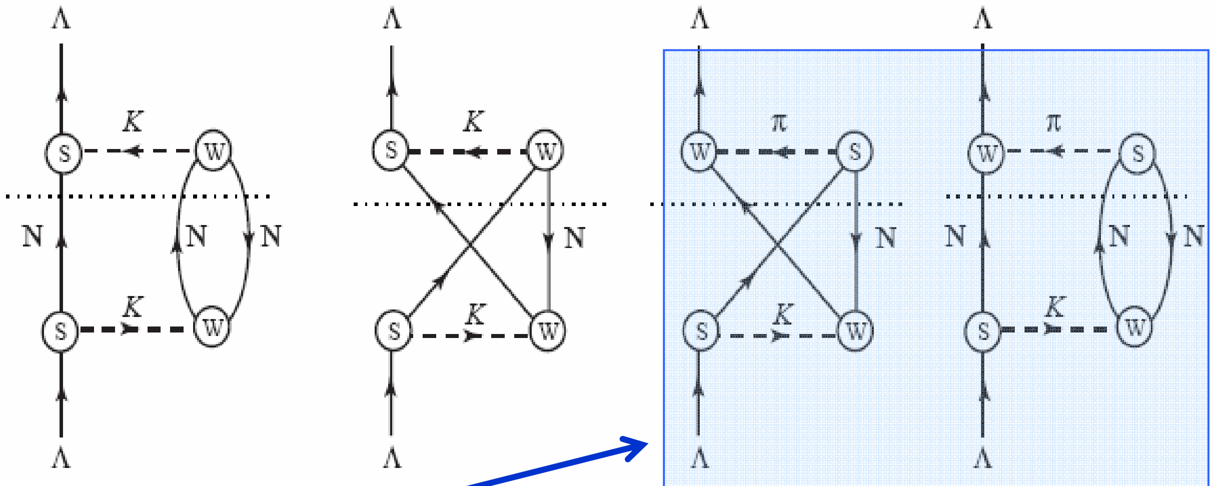
Theoretical models III:
π + K + 2π



Λ self-enery



Medium corrections to the Λ self-enery



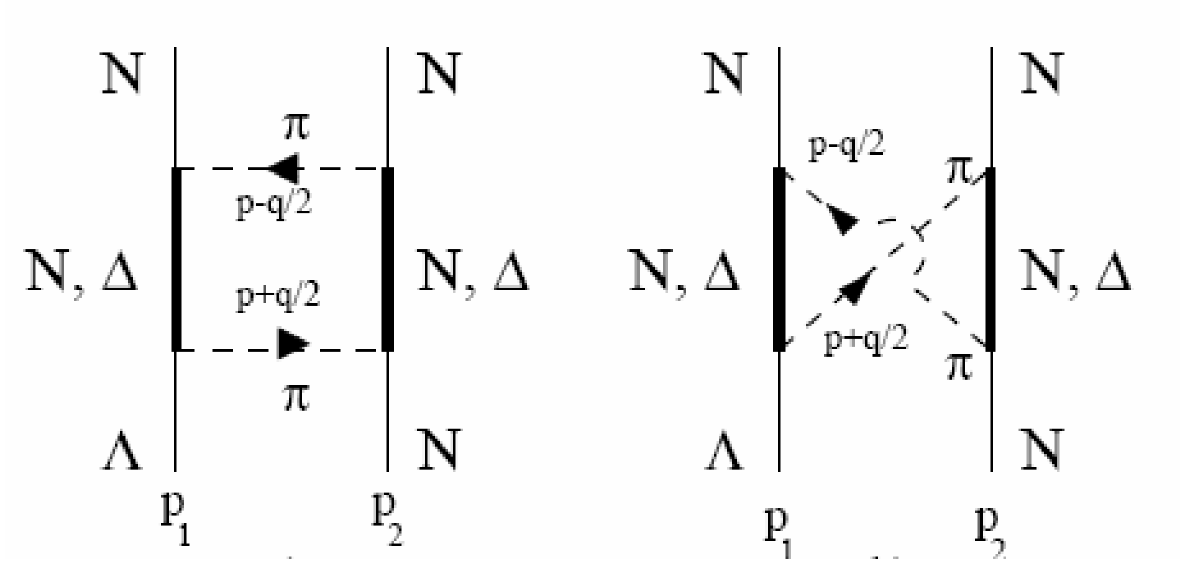
Off-shell

Interference terms

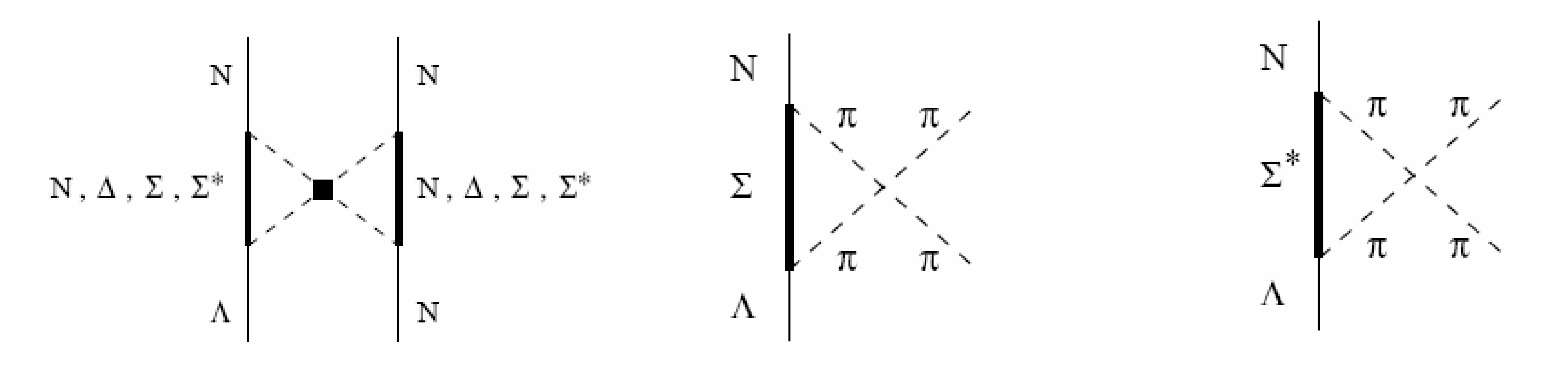
Oset, Palomar, Jido (2001)

Theoretical models III:
π + K + 2π

Uncorrelated 2-pion:

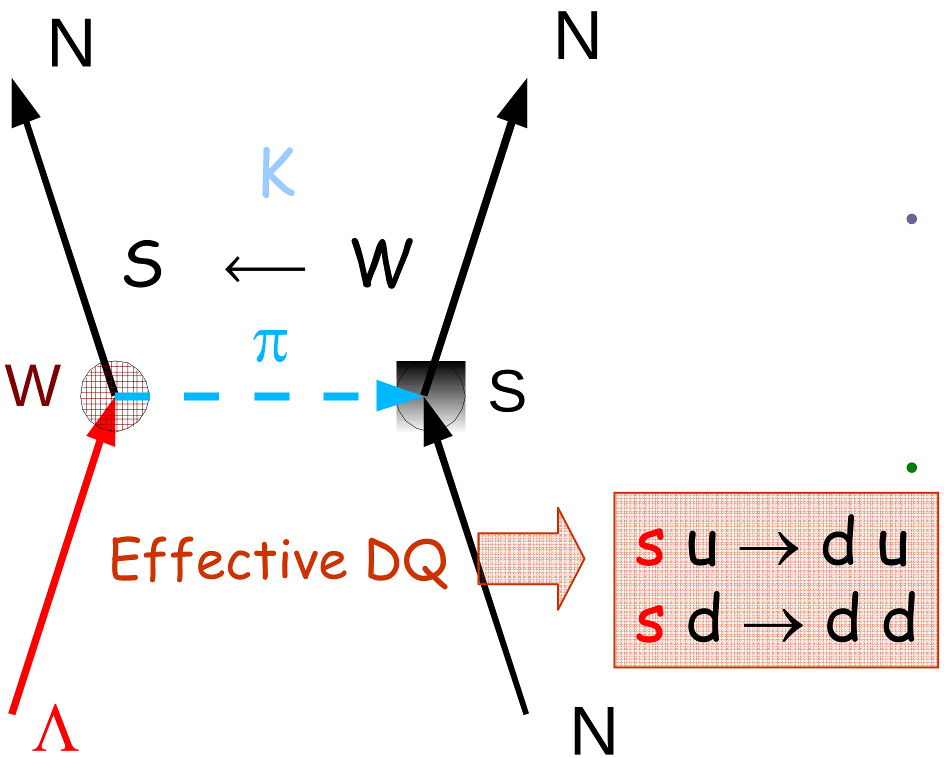


Correlated 2-pion:



Theoretical models IV: Direct Quark Mechanism (+OPE+OKE+...)

The π (and K) accounts for the long and intermediate ranges of the interaction.



Takeuchi, Oka, Inoue, Sasaki

- In order to account for shorter distances, the model includes an Effective Quark Hamiltonian, which automatically incorporates ΔI=3/2 transitions. DQM
- The model uses the experimental BBπ vertices, and the SU(3) BBK values.
- Finite size effects are included through the same monopole form-factor at each vertex to regularize the transition potential.

more

Non-mesonic decay rates

$^{5}{}_{\Lambda}$He	Γ_{nm}	Γ_n/Γ_p
π	0.43	0.09
π+K	0.24	0.50
all mesons	0.32	0.46
$^{12}{}_{\Lambda}$C	Γ_{nm}	Γ_n/Γ_p
π	0.75	0.08
π+K	0.41	0.34
all mesons	0.55	0.34

NSC97f

Parreño, Ramos (2001)

Non-mesonic decay rates

Alberico, Garbarino (2004)

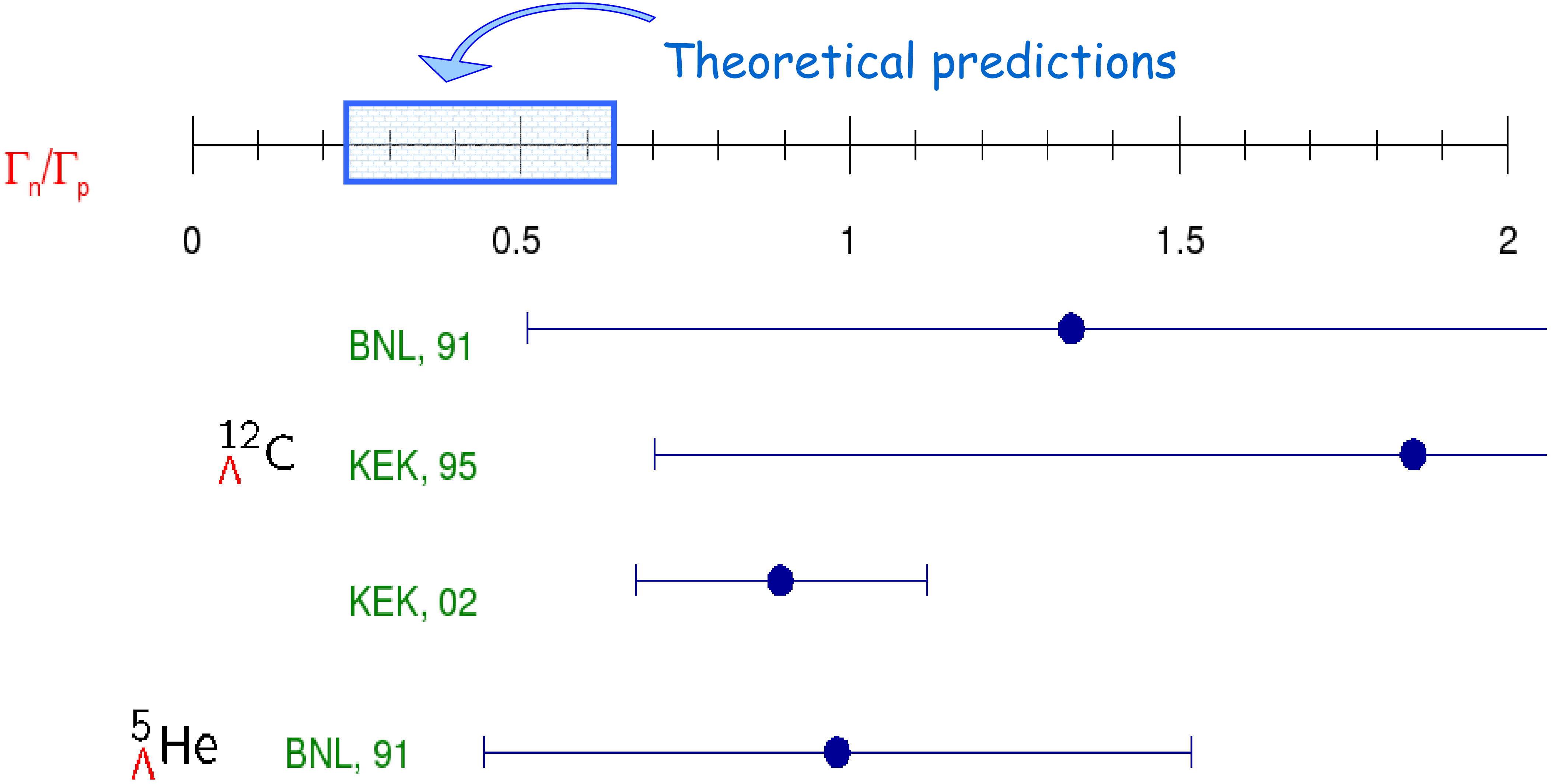
Ref. and Model	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C	Nuclear Matter
Dalitz 1973 [55] (WFM: OPE + 4BPI)	0.5		2
Cheung *et al.* 1983 [20] (WFM: hybrid)		1.28	3
Oset–Salcedo 1985 [24] (PPM: Correlated OPE)	1.15	1.5	2.2
Oset–Salcedo–Usmani 1986 [49] (PPM: Correlated OPE)	0.54		
Sasaki *et al.* 2000 [21] (WFM: $\pi + K +$ DQ)	0.519		2.456
Jun *et al.* 2001 [56] (WFM: OPE + 4BPI)	0.426	1.174	
Jido *et al.* 2001 [18] (PPM: $\pi + K + 2\pi + \omega$)		0.769	
Parreño–Ramos 2001 [17] (WFM: $\pi + \rho + K + K^{*} + \omega + \eta$)	$0.317 \div 0.425$	$0.554 \div 0.726$	
Itonaga *et al.* 2002 [16] (WFM: $\pi + 2\pi/\rho + 2\pi/\sigma + \omega$)	0.422	1.060	
Exp BNL 1991 [37]	0.41 ± 0.14	1.14 ± 0.20	
Exp CERN 1993 [45]			$\bar{p}$+Bi: $1.46^{+1.83}_{-0.52}$ $\bar{p}$+U: $2.02^{+1.74}_{-0.63}$
Exp KEK 1995 [38]		0.89 ± 0.18	
Exp KEK 1995 [57]	0.50 ± 0.07		
Exp COSY 1998 [46]			p+Bi: $1.63^{+0.19}_{-0.14}$
Exp KEK 2000 [39, 40]		0.83 ± 0.11	${}^{56}_{\Lambda}$Fe: 1.22 ± 0.08
Exp COSY 2001 [58]			p+Au: $2.02^{+0.56}_{-0.35}$
Exp COSY 2001 [59]			p+U: $1.91^{+0.28}_{-0.22}$
Exp KEK 2004 [51]	0.406 ± 0.020	0.953 ± 0.032	

neutron-to-proton ratio

Alberico, Garbarino (2004)

Ref. and Model	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
Sasaki *et al.* 2000 [21]	0.701	
$\pi + K + \mathrm{DQ}$		
Jido *et al.* 2001 [18]		0.53
$\pi + K + 2\pi + \omega$		
Parreño–Ramos 2001 [17]	$0.343 \div 0.457$	$0.288 \div 0.341$
$\pi + \rho + K + K^{*} + \omega + \eta$		
Itonaga *et al.* 2002 [16]	0.386	0.368
$\pi + 2\pi/\rho + 2\pi/\sigma + \omega$		
BNL 1991 [37]	0.93 ± 0.55	$1.33^{+1.12}_{-0.81}$
KEK 1995 [38]		$1.87^{+0.67}_{-1.16}$
KEK 1995 [57]	1.97 ± 0.67	
KEK 2004 [41]		0.87 ± 0.23

Decay observables. Partial decay widths: neutron-to-proton ratio



Decay observables. Partial decay widths: neutron-to-proton

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{\Lambda n \to nn}{\Lambda p \to np} \leftrightarrow \left[\frac{N_n}{N_p}\right]^{\exp}$$

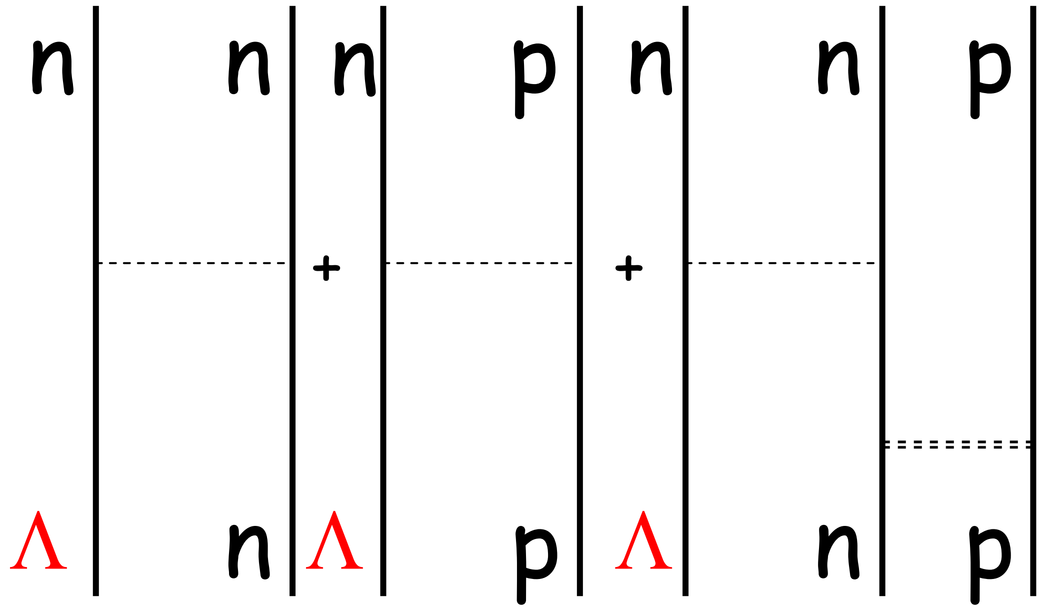
$$N_n = \Gamma_p + 2\Gamma_n + 2\Gamma_{np}$$
$$N_p = \Gamma_p + \Gamma_{np}$$

A realistic analysis must include:

Add Final State Interactions of the final primary nucleons with the residual medium

(energy loss, change in direction, production of secondary nucleons, etc.)

Ramos, Vicente-Vacas, Oset (1997, 2002)



Alberico, De Pace, Ericson, Molinari (1991)

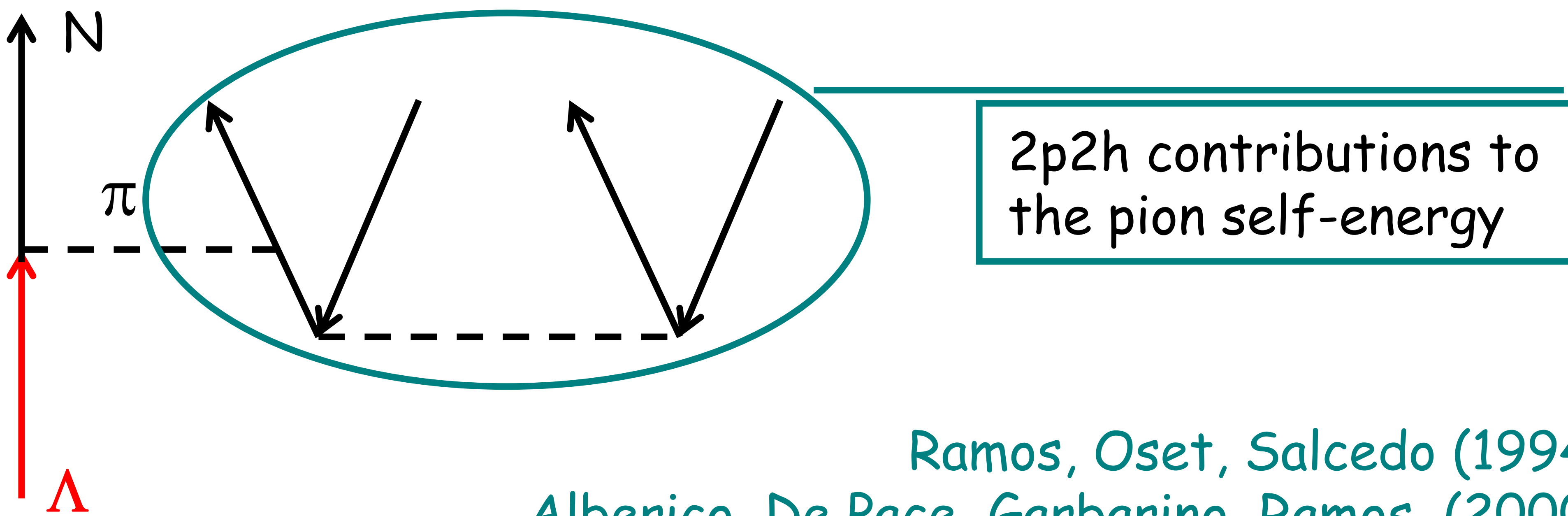
Decay observables. Single nucleon spectra

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{\Lambda n \to nn}{\Lambda p \to np} \leftrightarrow \left[\frac{N_n}{N_p}\right]^{exp}$$

(FSI) Intranuclear cascade calculation

Ramos, Vicente-Vacas, Oset (1997, 2002)

◊1N-induced channel → OME potential (finite nucleus calculation)
◊2N-induced channel → Polarization Propagator Method in LDA:



2p2h contributions to the pion self-energy

Ramos, Oset, Salcedo (1994)
Alberico, De Pace, Garbarino, Ramos, (2000)
Bauer, Krmpotić (2004)

Decay observables. Single nucleon spectra

Study of the single nucleon energy distribution in the NMWD of a hypernucleus

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{\Lambda n \to nn}{\Lambda p \to np} \leftrightarrow \left[\frac{N_n}{N_p}\right]^{exp}$$

(FSI) Intranuclear cascade calculation

Ramos, Vicente-Vacas, Oset (1997, 2002)

Random generator for primary nucleons´ positions, momenta, charges and decay channel (n, p, 2N).

◊ The primary nucleons move under a local Potential:

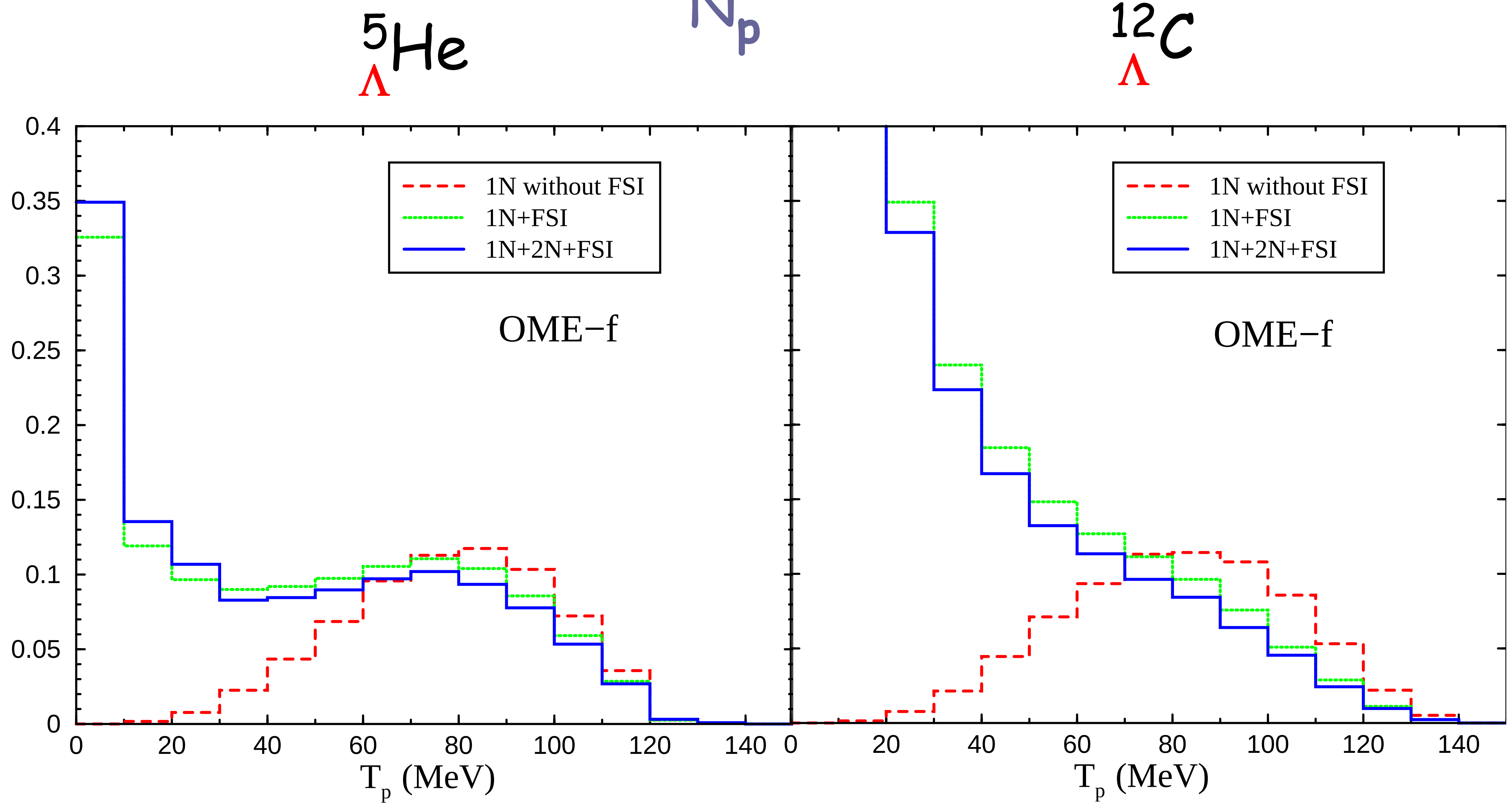
$$V_N(R) = -\frac{k_{F_N}^{\ 2}(R)}{2m_N} \qquad \text{with } k_{F_N}(R) = \left\{3\pi^2\rho_N(R)\right\}^{1/3}$$

◊ The nucleons collide with other nucleons of the medium according to NN cross sections corrected by Pauli blocking.

⇨ **Emission of secondary nucleons**

Decay observables. Single nucleon spectra

N_p



Garbarino, Parreño, Ramos (2004)

Decay observables. Single nucleon spectra

Garbarino, Parreño, Ramos, PRC69, 054603 (2004)

Primary nucleons:

$\Lambda n \to nn$ $\qquad N_n^{wd} \propto 2\Gamma_n + \Gamma_p$

$\Lambda p \to np$ $\qquad N_p^{wd} \propto \Gamma_p$

FSI + 2N-induced:

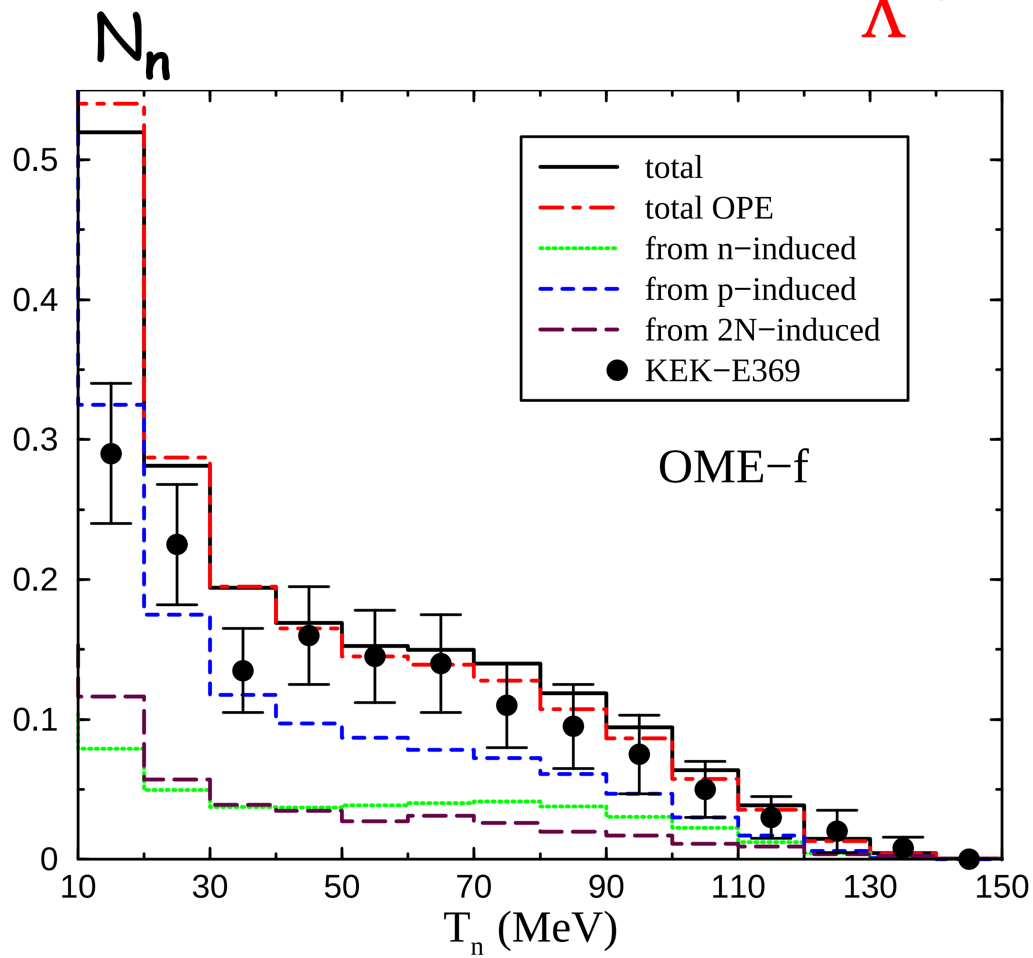
$$\frac{\Gamma_n}{\Gamma_p} \neq \frac{1}{2}\left(\frac{N_n}{N_p} - 1\right) \equiv f\left[\Delta T_n, \Delta T_p, \Gamma_2\right]$$

N_p^{1Bn} ?

Γ_n / Γ_p ?

NOT CLEAR!

$^{12}_{\Lambda}C$



$$N_N = \frac{N_N^{1Bn}\Gamma_n + N_N^{1Bp}\Gamma_p + N_N^{2B}\Gamma_{np}}{\Gamma_n + \Gamma_p + \Gamma_{np}} \equiv N_N^{\Lambda n \to nn} + N_N^{\Lambda p \to np} + N_N^{\Lambda np \to nnp}$$

Decay observables. Single nucleon spectra.

- Little sensitivity of single nucleon spectra to the weak interaction mechanism.
- Still, there is a quantity based in single nucleon observables which is more sensitive to different Γ_n/Γ_p values.

$$\frac{\Gamma_n}{\Gamma_p} \neq \frac{1}{2}\left(\frac{N_n}{N_p}-1\right) \equiv \boxed{f\left[\Delta T_n, \Delta T_p, \Gamma_2\right]}$$

$\Rightarrow$Determine n/p with better precision

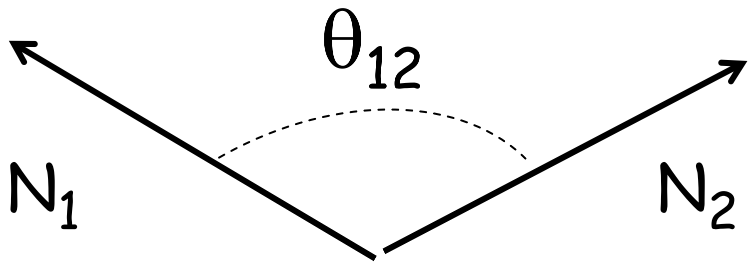
T^{th}		30	60	Γ_n/Γ_p
$^{5}_{\Lambda}He$	OPE	0.13	0.16	0.09
	OME	0.40	0.49	0.46
$^{12}_{\Lambda}C$	OPE	-0.01	0.05	0.08
	OME	0.09	0.21	0.34

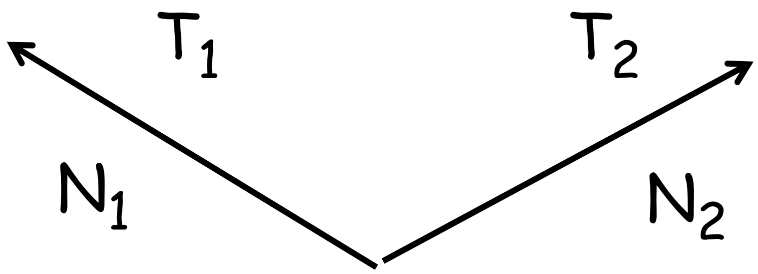
In agreement with analysis of KEK-E462 (Okada et al.) for helium $\rightarrow$ n/p ~ 0.5

NN coincidence distributions

Garbarino, Parreño, Ramos, PRL91, 112501 (2003)

Better determination of the n/p ratio from the study of NN coincidence distributions





Angular correlations Energy correlations

$\Rightarrow$ reduce the contamination produced by Γ_{np}: Λ NN $\rightarrow$ NNN

◊ Correlation observables are less affected by *Quantum Mechanical Interferences* between n- and p- induced processes than single spectra:

$$N_p(T_p) \propto \left| \left\langle p(T_p) \middle| \hat{O}_{FSI} \hat{O}_W \middle| \Psi_H \right\rangle \right|^2 = \left| \alpha \left\langle p(T_p) \middle| \hat{O}_{FSI} \middle| nn, \Psi_R \right\rangle + \beta \left\langle p(T_p) \middle| \hat{O}_{FSI} \middle| np, \Psi_{R'} \right\rangle \right|^2$$

But in the ***Monte Carlo***, they add incoherently !!!

Reduce the quantum interferences: exclusive measure of the final state.

NN coincidence distributions

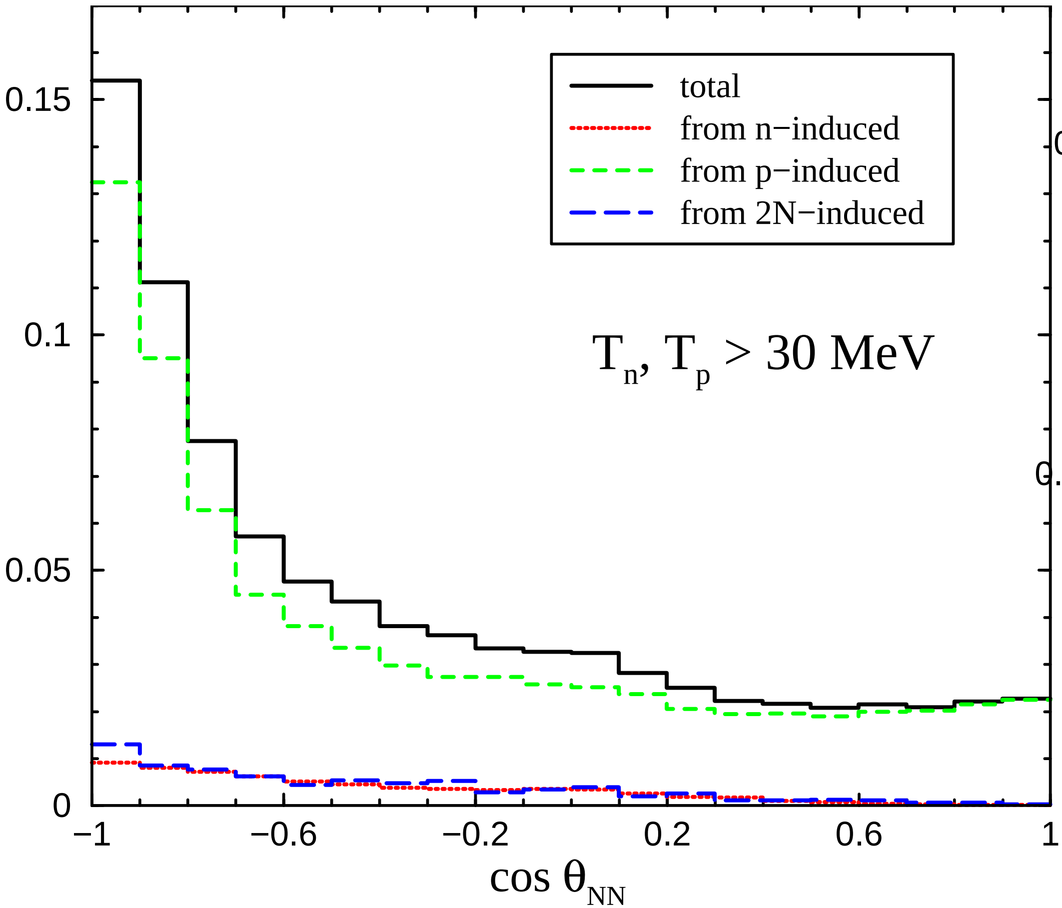
$$\Gamma_i\left(\vec{R}, k_1, \cos\phi_{12}\right) \quad i = n, p$$

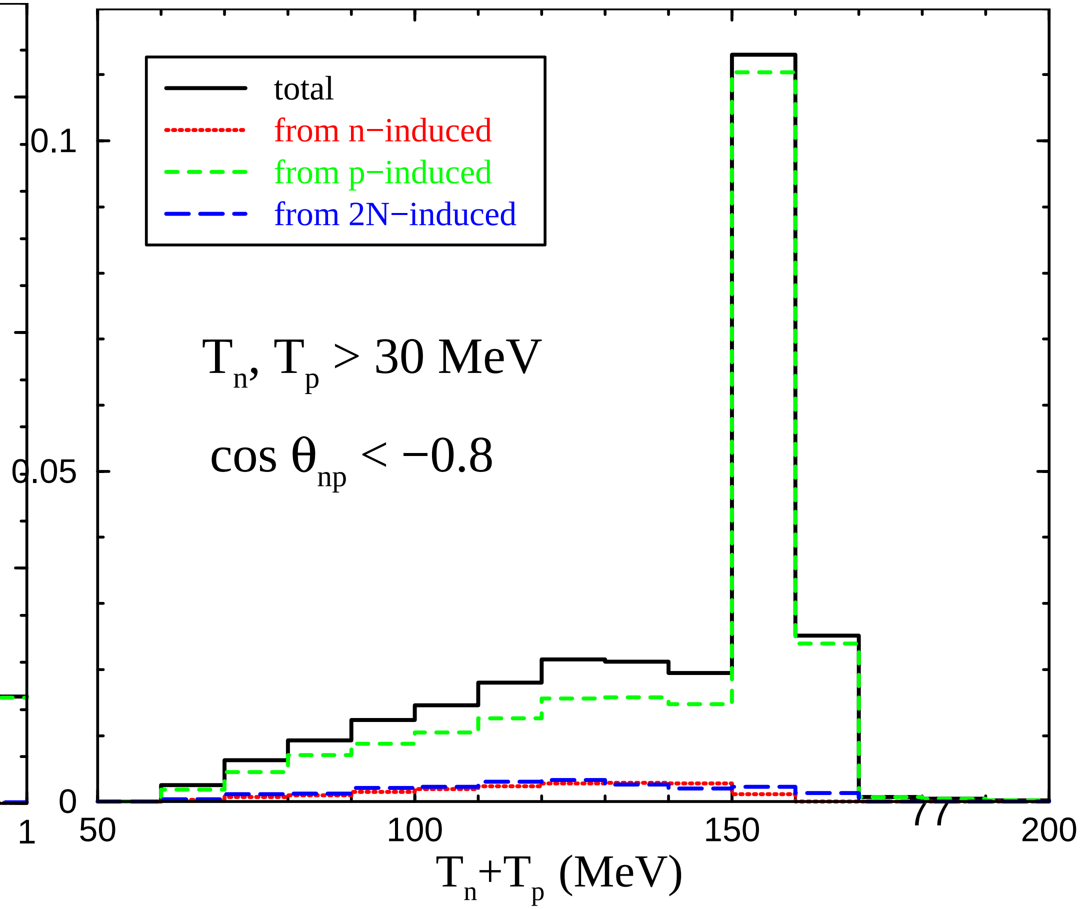
intranuclear cascade calculation

Obtain the weak decay nucleon distributions

Correlated spectra N_{np} for ${}^{12}_{\Lambda}C$

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{N^{wd}_{nn}}{N^{wd}_{np}} \neq \frac{N_{nn}}{N_{np}}; \qquad \frac{\Gamma_n}{\Gamma_p} = f\left(\Delta\theta_{12}, \Delta T_n, \Delta T_p, \Gamma_{2N}\right)$$





Correlated spectra - Experimental results

	${}^{5}_{\Lambda}$He		${}^{12}_{\Lambda}$C	
	N_{nn}/N_{np}	Γ_n/Γ_p	N_{nn}/N_{np}	Γ_n/Γ_p
OPE	0.25	0.09	0.24	0.08
OMEa	0.51	0.34	0.39	0.29
OMEf	0.61	0.46	0.43	0.34
KEK-E462	0.45 ± 0.11 ± 0.03 (coincidence)	≅		
KEK-E508				0.51 ± 0.13 ± 0.05 (coincidence)

T^{th} = 30 MeV

$\cos\theta_{12} \leq -0.8$

"Model independent" analysis

$$\frac{N_{nn}}{N_{np}} = \frac{N_{nn}^{(n)} \frac{\Gamma_n}{\Gamma_p} + N_{nn}^{(p)} + N_{nn}^{(2N)}\, 0.2 \left\{ \frac{\Gamma_n}{\Gamma_p} + 1 \right\}}{N_{np}^{(n)} \frac{\Gamma_n}{\Gamma_p} + N_{np}^{(p)} + N_{np}^{(2N)}\, 0.2 \left\{ \frac{\Gamma_n}{\Gamma_p} + 1 \right\}}$$

* Take ${}^{5}_{\Lambda}He$... assume $\Gamma_{2N} = 0.2\ \Gamma_{1N} = 0.2\ (\Gamma_n + \Gamma_p)$ (PPM+LDA)

* Use the experimental $N_{nn}/N_{np} = 0.45 \pm 0.11$

$\Rightarrow$ $$\frac{\Gamma_n}{\Gamma_p} = 0.26 \pm 0.11$$

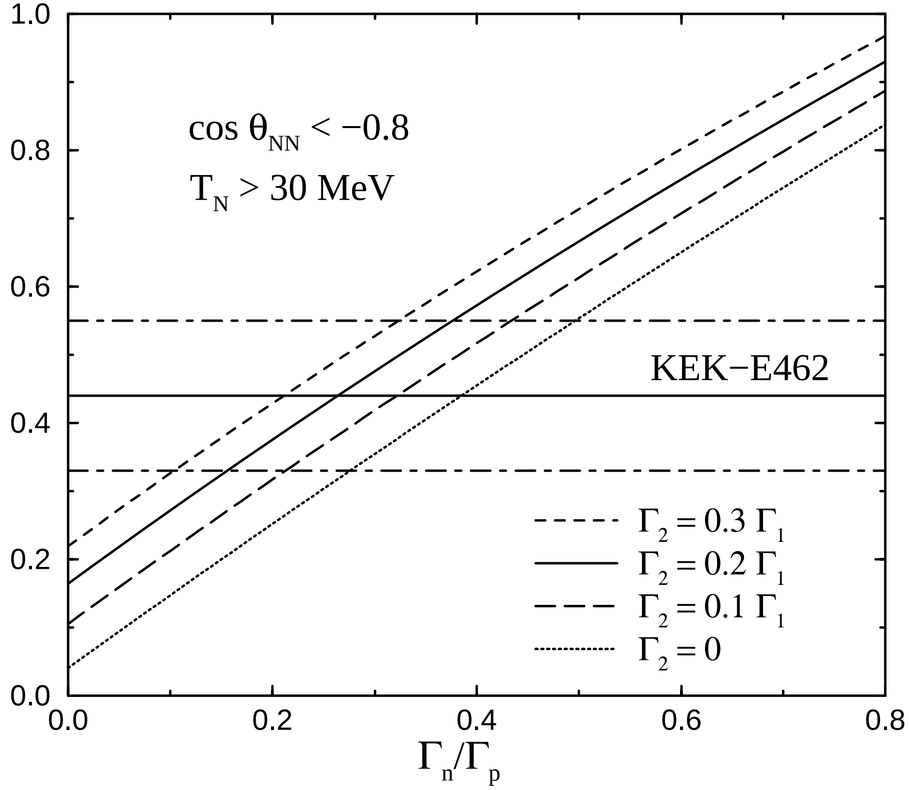
Theoretical predictions:

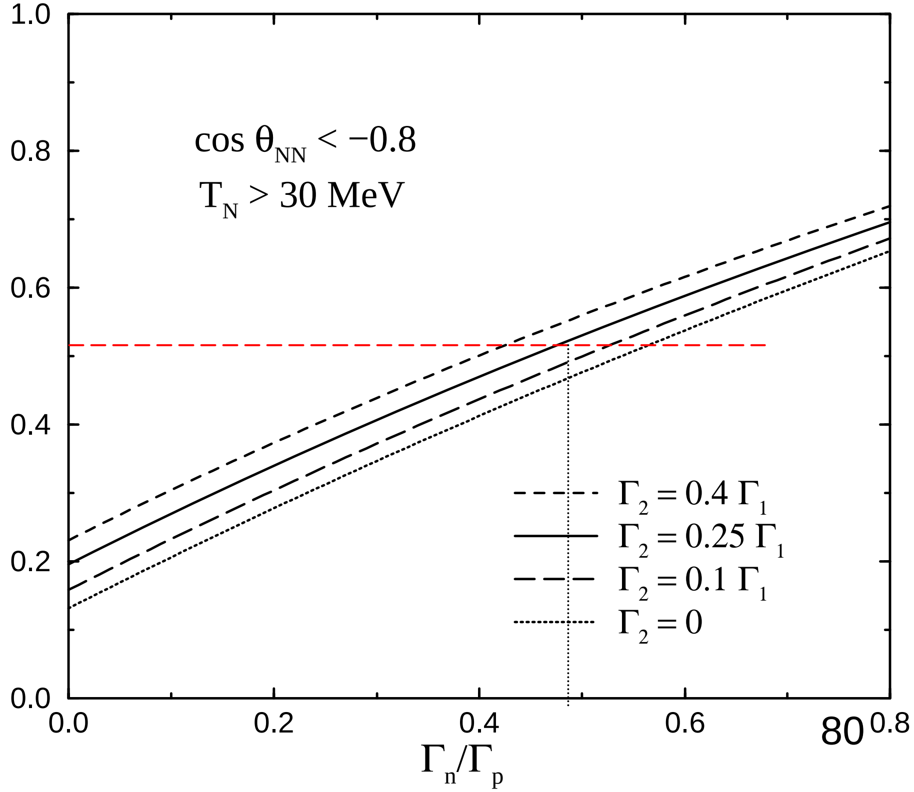
$0.34 \div 0.46$

(for $\Gamma_{2N} = 0 \Rightarrow 0.39 \pm 0.11$)

(weak) Model independent analysis

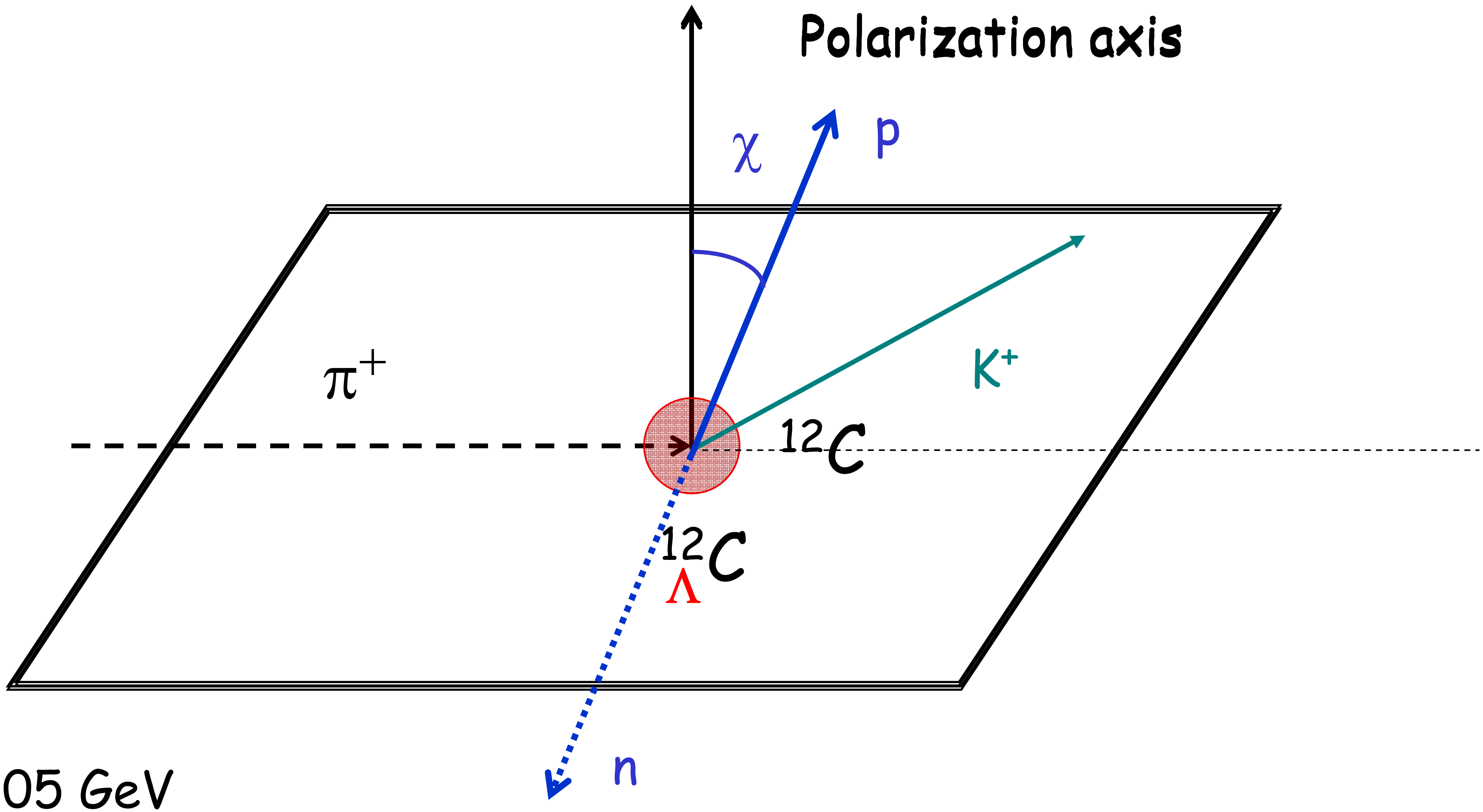
$$\frac{N_{nn}}{N_{np}} = \frac{N_{nn}^{(n)} \frac{\Gamma_n}{\Gamma_p} + N_{nn}^{(p)} + N_{nn}^{(2N)}\, 0.2 \left\{ \frac{\Gamma_n}{\Gamma_p} + 1 \right\}}{N_{np}^{(n)} \frac{\Gamma_n}{\Gamma_p} + N_{np}^{(p)} + N_{np}^{(2N)}\, 0.2 \left\{ \frac{\Gamma_n}{\Gamma_p} + 1 \right\}}$$





Decay observables. Parity-Violating Asymmetry.

KEK $n\,(\pi^+, K^+)\,\Lambda$



p_π=1.05 GeV

$2^\circ \lesssim \theta_K \lesssim 15^\circ$

Decay observables. Parity-Violating Asymmetry.

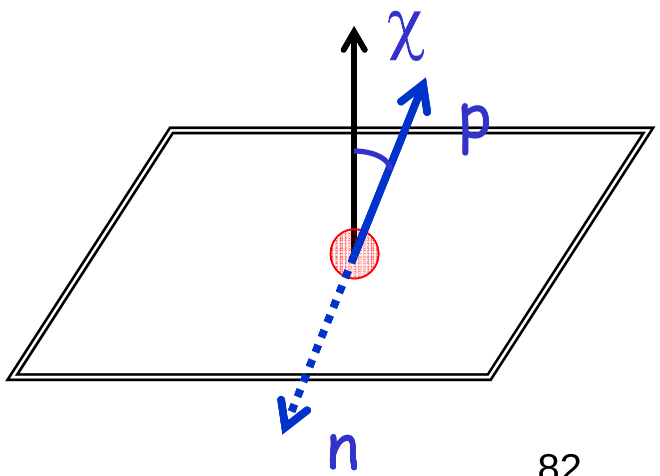
* Asymmetry in the distribution of primary protons coming from the non-mesonic decay of a hypernucleus.

* Appears as a consequence of the interference between the Parity-Conserving and Parity-Violating weak $\vec{\Lambda}p \rightarrow np$ amplitudes.

$$I_p(\chi) = I_0[1 + A(\chi)] = I_0[1 + P_H A_H \cos(\chi)]$$

$$A(0^{o}) = P_H A_H \equiv p_\Lambda a_\Lambda$$

$$A_H = \frac{3}{J+1} \frac{Tr(M S_y M^+)}{Tr(M M^+)}$$



Ramos, Meijgaard, Bennhold, Jennings (1992)

Decay observables. Parity-Violating Asymmetry.

For a s-shell hypernucleus, the expression simplifies…

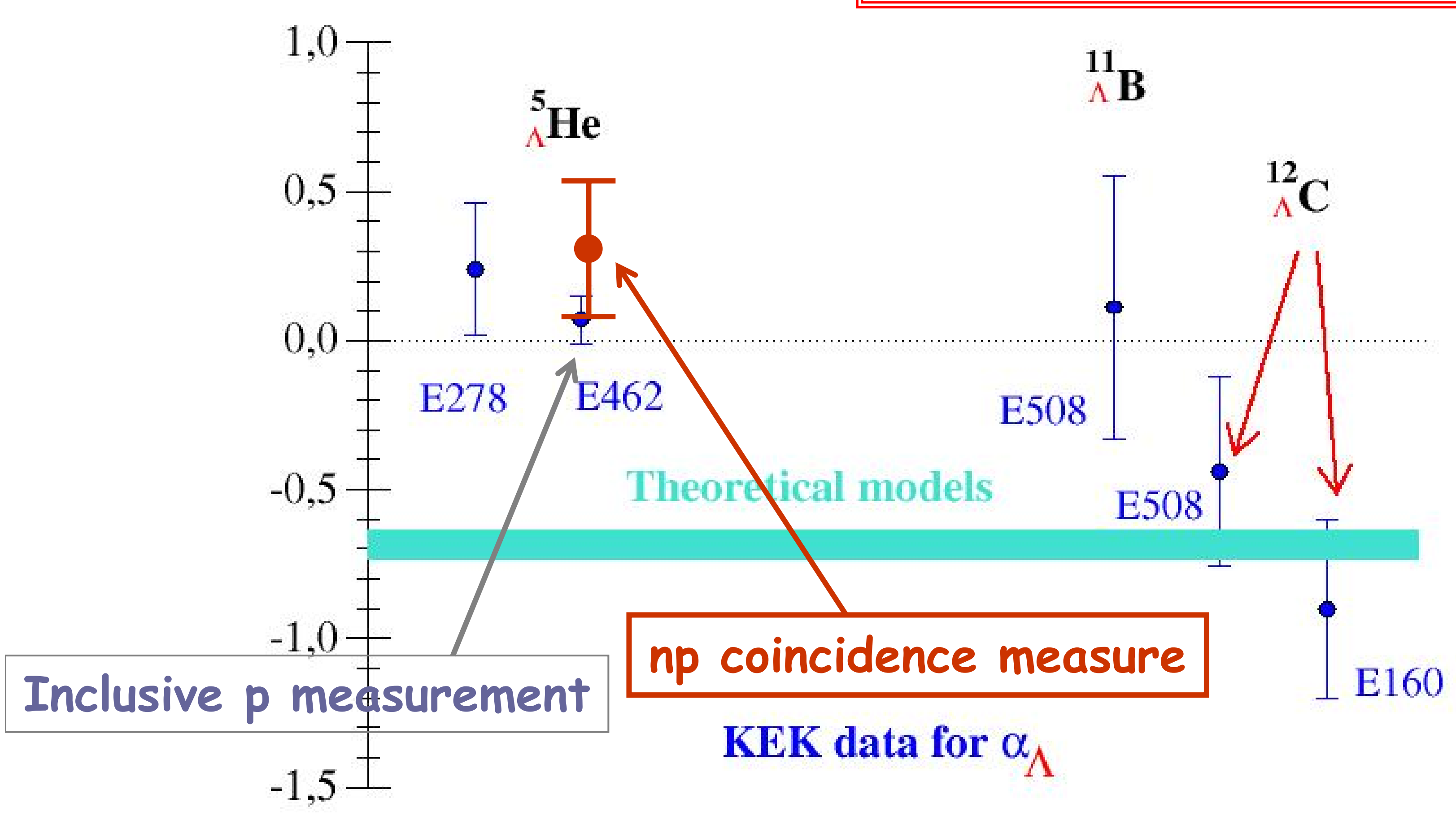
$$a_\Lambda = \frac{2\sqrt{3}\,\mathrm{Re}[ae^* - b(c-\sqrt{2}d)^*/\sqrt{3} + f(\sqrt{2}c+d)^*]}{|a|^2+|b|^2+3[|c|^2+|d|^2+|e|^2+|f|^2]}$$

ΛN $^{(2S+1)}L_J$	NN $^{(2S'+1)}L'_J$	amplitude	**NN isospin**	PC/PV
$^1S_0$	$^1S_0$	a^2	1	PC
	$^3P_0$	b^2	1	PV
$^3S_1$	$^3S_1$	c^2	0	PC
	$^3D_1$	d^2	0	PC
	$^1P_1$	e^2	0	PV
	$^3P_1$	f^2	1	PV

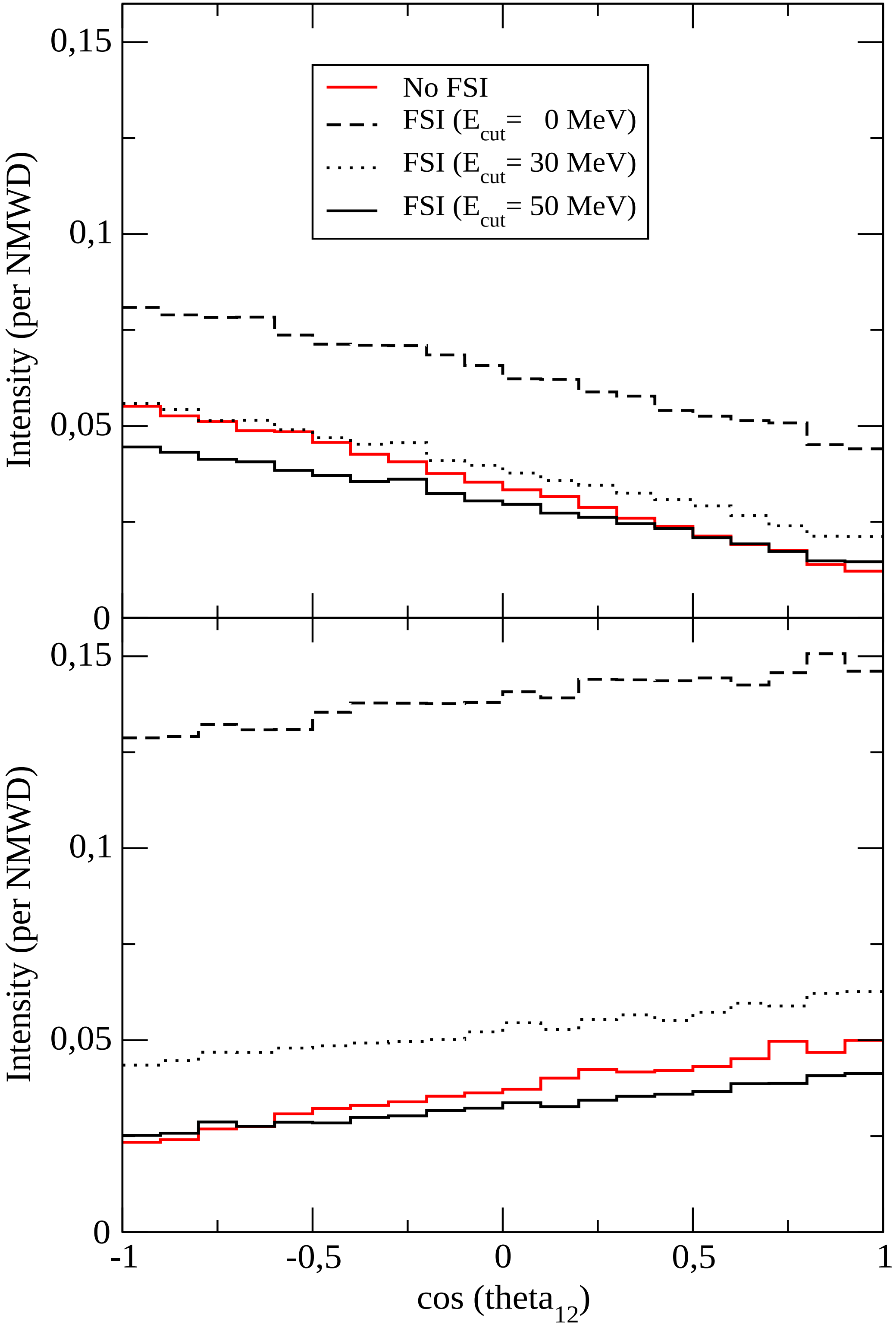
Decay observables. Parity-Violating Asymmetry.

Intrinsic Λ asymmetry parameter

$$a_\Lambda = \frac{A(0^0)}{p_\Lambda}$$



… Include FSI of the emitted nucleons with the residual nucleons to concile Theory with Experiments.



Upper: ${}^{5}_{\Lambda}$He Lower: ${}^{12}_{\Lambda}$C

Calculated proton intensities well fitted by:

$$I_p^M(\chi) = I_0^M \left[1 + p_\Lambda \, a_\Lambda \cos(\chi)\right]$$

Normalizing per NMWD and assuming P_H =1 :

$$p_\Lambda = \begin{cases} 1 & \text{for } {}^{5}_{\Lambda}\text{He} \\ -\dfrac{1}{2} & \text{for } {}^{12}_{\Lambda}\text{C} \end{cases}$$

Experimentally:

$$a_\Lambda^M = \frac{1}{p_\Lambda} \frac{I_p(0^o) - I_p(180^o)}{I_p(0^o) + I_p(180^o)}$$

FSI effects on the PV Asymmetry

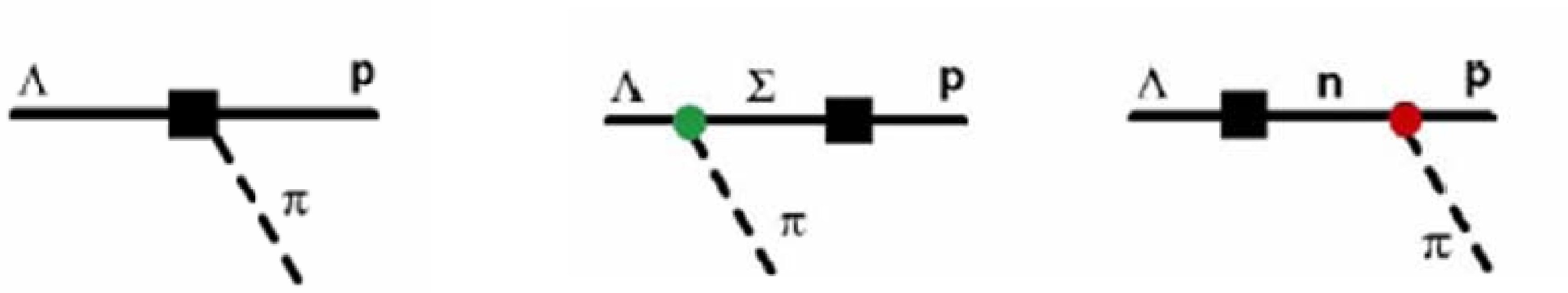
a_Λ^M	${}^5_\Lambda He$	${}^{12}_\Lambda C$
OPE	-0.25	-0.34
OME	-0.68	-0.73
FSI T_p^{th} = 0 MeV	-0.30	-0.16
FSI T_p^{th} = 30 MeV	-0.46	-0.37
FSI T_p^{th} = 50 MeV	-0.52	-0.51
FSI T_p^{th} = 70 MeV	-0.55	-0.65
KEK-E462 (80 MeV)	0.09 ± 0.14 ± 0.04 (incl) 0.31 ± 0.22 (np coincidence)	
KEK-E508 (preliminary)		-0.44 ± 0.32

Disagreement Theory-Experiment ☹

- Model dependencies:
  1. Weak interaction model
  2. Strong interaction ingredients:
     - Shell model, coupling constants, initial particle wf, form factors, final wf…
- Problems:
  - discrepancy between theoretical and experimental PV asymmetry.
  - significant degree of SU(3) breaking:
    - accounted by using the physical masses of the baryons and mesons, but assuming SU(3)/SU(6) couplings.

Non-leptonic decays in SU(3)

- Significant degree of SU(3) breaking
- Problems facing SU(3) χPT: fails to reproduce simultaneously the weak PC and PV non-leptonic **Y** $\rightarrow$**N** π amplitudes



- At leading order in the chiral expansion…

$$L = G_F m_{\pi^+}^2 \; f \left(h_D \, Tr\left[\overline{B}\left\{h_\xi , B\right\}\right] + h_F \, Tr\left[\overline{B}\left[h_\xi , B\right]\right]\right)$$

Non-leptonic decays in SU(3)

$$L = G_F m_{\pi^+}^2 \; f \left(h_D \, Tr\left[\overline{B}\left\{h_\xi, B\right\}\right] + h_F \, Tr\left[\overline{B}\left[h_\xi, B\right]\right]\right)$$

where

$$\xi^\dagger \, h \, \xi \quad \text{with} \quad h = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{and} \quad \xi = exp\,\{\mathrm{i}\, M/f\}$$

$$M = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix},$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}.$$

Non-leptonic decays in SU(3)

Expanding to linear order in the π field,

- S-waves

$$\mathcal{A}^{(S)}_{\Lambda p\pi^-} = -\frac{1}{\sqrt{6}}(h_D + 3h_F) \qquad \mathcal{A}^{(S)}_{\Sigma^- n\pi^-} = h_D - h_F$$

$$\mathcal{A}^{(S)}_{\Sigma^+ n\pi^+} = 0 \qquad \mathcal{A}^{(S)}_{\Xi^-\Lambda\pi^-} = \frac{1}{\sqrt{6}}(3h_F - h_D)$$

- P-waves

$$\mathcal{A}^{(P)}_{\Lambda p\pi^-} = \frac{\sqrt{\frac{2}{3}}D(h_D - h_F)}{M_p - M_{\Sigma^+}} - \frac{(D+F)(h_D+3h_F)}{\sqrt{6}(M_\Lambda - M_n)}$$

$$\mathcal{A}^{(P)}_{\Sigma^- n\pi^-} = \frac{F(h_F - h_D)}{M_n - M_{\Sigma^0}} - \frac{D(h_D+3h_F)}{3(M_n - M_\Lambda)}$$

$$\mathcal{A}^{(P)}_{\Sigma^+ n\pi^+} = -\frac{D(h_D+3h_F)}{3(M_n - M_\Lambda)} - \frac{F(h_F - h_D)}{M_n - M_{\Sigma^0}} + \frac{(D+F)(h_D - h_F)}{M_{\Sigma^+} - M_p}$$

$$\mathcal{A}^{(S)}_{\Xi^-\to\Lambda\pi^-} = \frac{(D-F)(3h_F - h_D)}{\sqrt{6}(M_\Lambda - M_{\Xi^0})} + \sqrt{\frac{2}{3}}\frac{D(h_D+h_F)}{M_{\Xi^-} - M_{\Sigma^-}} \quad .$$

Non-leptonic decays in SU(3)

Fit to S-waves $\Rightarrow h_D = 0.58$ and $h_F = -1.40$

Tree level $D = 0.80$ and $F = 0.50$

$\longrightarrow$ Predict the P-waves

Decay	$\mathcal{A}^{(S)}$ LO	$\mathcal{A}^{(S)}$ Expt	$\mathcal{A}^{(P)}$ LO	$\mathcal{A}^{(P)}$ Expt
$\Lambda \to p\pi^-$	1.48	1.42 ± 0.01	0.59	0.52 ± 0.02
$\Sigma^- \to n\pi^-$	1.98	1.88 ± 0.01	-0.30	-0.06 ± 0.01
$\Sigma^+ \to n\pi^+$	0.0	0.06 ± 0.01	0.16	1.81 ± 0.01
$\Xi^- \to \Lambda\pi^-$	-1.95	-1.98 ± 0.01	-0.19	0.48 ± 0.02

Decay	$\mathcal{A}^{(S)}$ NLO [RPS99]	$\mathcal{A}^{(S)}$ Expt	$\mathcal{A}^{(P)}$ NLO [RPS99]	$\mathcal{A}^{(P)}$ Expt
$\Lambda \to p\pi^-$	1.44	1.42 ± 0.01	-0.73 ± 0.18	0.52 ± 0.02
$\Sigma^- \to n\pi^-$	1.89	1.88 ± 0.01	0.46 ± 0.21	-0.06 ± 0.01
$\Sigma^+ \to n\pi^+$	0.01	0.06 ± 0.01	-0.18 ± 0.21	1.81 ± 0.01
$\Xi^- \to \Lambda\pi^-$	-2.01	-1.98 ± 0.01	0.52 ± 0.29	0.48 ± 0.02

R.P. Springer (1999)

Non-leptonic decays in SU(3)

Large failure….

Large SU(3) breaking?
Strong Final State Interactions?
Narrow hadronic resonances?
Cancellations at LO?

$\Rightarrow$ A NNLO is ultimately required

EFTs and hypernuclear decay

- Is it possible to build a model independent theory for the $\Delta S=1$ ΛN interaction?
- Can a low order EFT describe the present available data for $\Lambda N \rightarrow NN$ (hypernuclear decay data)?
- Is this a valid scenario to learn something new on the $\Delta S=1$ interaction?

  Δ I=3/2 transitions?

  SU(3) breaking?

Block, Dalitz (1963)
Jun, Bhang (1998, 2001)
Parreño, Bennhold, Holstein (2003, 2005)

more

EFTs and hypernuclear decay

- Effective Field Theories based in chiral expansions
- Remarkable success in the SU(2) sector

- Idea: Low energy physics cannot be sensitive to high energy details $\Rightarrow$ Integrate out the heavy degrees of freedom.

- It is mainly build up by allowing for all possible contact terms in the 4-fermion interaction Lagrangian (model independent)

- Truncate the momentum expansion at some order $\Rightarrow$ Leads to a finite number of *Low Energy Coefficients* (LEC) of order *n:*

$$C_n \, O\left(\left[\frac{p}{M}\right]^n\right)$$

EFTs and hypernuclear decay

- The LEC's are then fitted to experimental data
- The goal being to get a systematic, stable (convergent) expansion

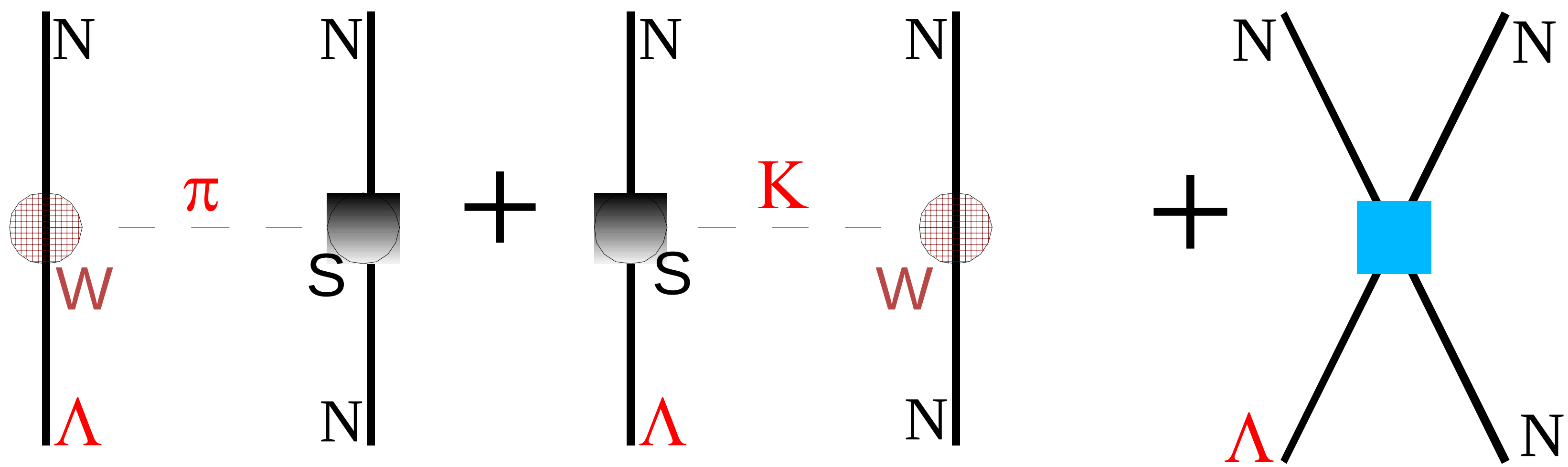
⇨ Successful extension to SU(3)?

In particular, our decay process involves a large amount of energy to be released at threshold…

$(\Lambda N \rightarrow NN)_{th} \sim 177$ MeV $\Rightarrow$ p ~ 417 MeV/c

EFTs and hypernuclear decay

- Incorporate the correct long range behaviour (it must be built into the ET)
- Add local correction terms to mimic the effect of excluded momenta



Parreño, Bennhold, Holstein (2003,2005)

EFTs and hypernuclear decay

Energy release in $(\Lambda N \rightarrow NN)_{th}$ is ~ 177 MeV

$\Rightarrow$ (p ~ 417 MeV/c)

m_π ~ 138 MeV

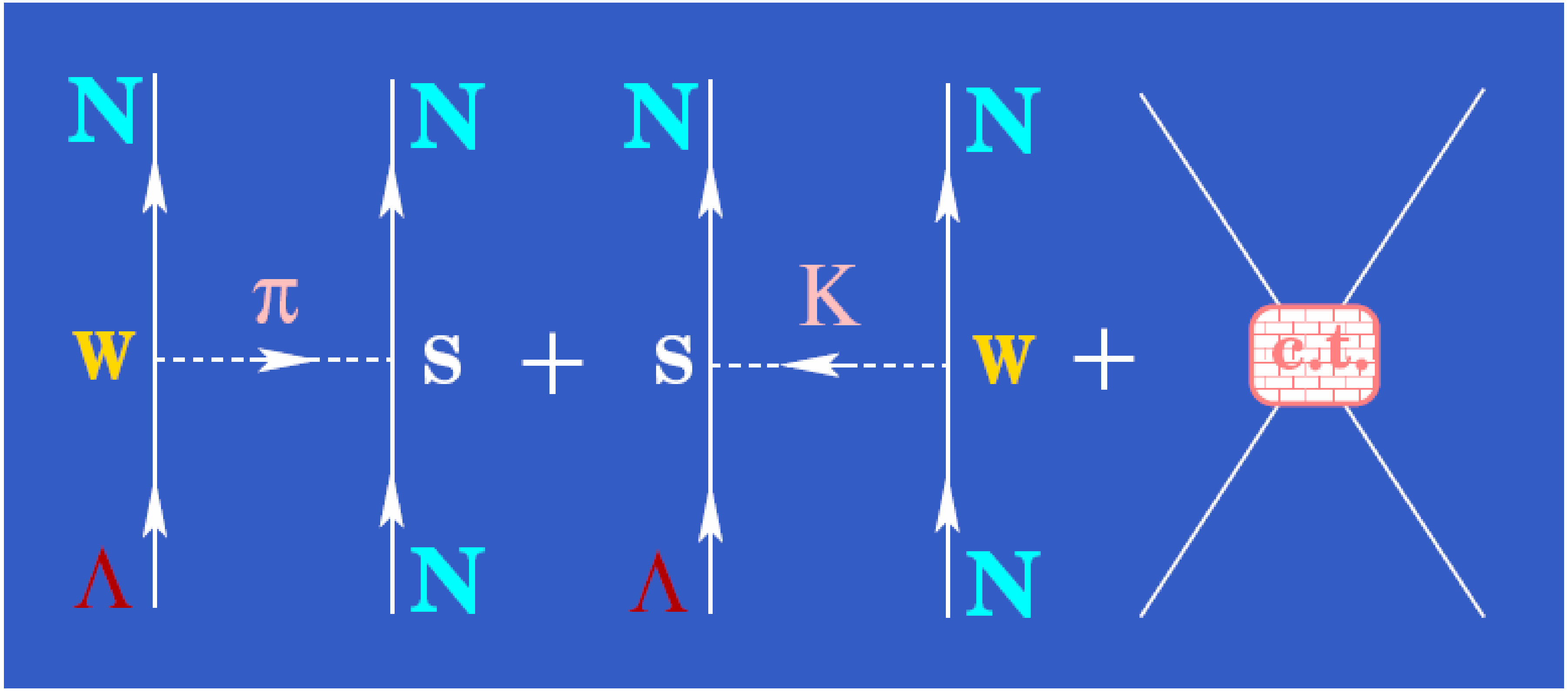
inclusion of the kaon supported by SU(3),

although m_K ~ 494 MeV

$\Rightarrow$ dynamical fields

EFTs and hypernuclear decay

At LO:



EFTs and hypernuclear decay

$$\mathcal{L}^{W}_{\Lambda N\pi} = -\mathrm{i}G_F m_\pi^2 \overline{\psi}_N (A_\pi + B_\pi \gamma_5 \gamma^\mu) \vec{\tau} \cdot \partial_\mu \vec{\phi}^{\,\pi} \psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\mathcal{L}^{S}_{NN\pi} = -\mathrm{i}\, g_{NN\pi}\, \overline{\psi}_N \gamma_5 \gamma^\mu\, \vec{\tau} \cdot \partial_\mu \vec{\phi}^{\,\pi} \psi_N$$

$$V_{OPE}(\vec{q}) = -G_F m_\pi^2 \frac{g_{NN\pi}}{2M_S} \left(A_\pi + \frac{B_\pi}{2M_W} \vec{\sigma}_1 \vec{q} \right) \frac{\vec{\sigma}_2 \vec{q}}{\vec{q}^{\,2} + \mu_\pi^{\,2}} \vec{\tau}_1 \vec{\tau}_2$$

$$\mathcal{L}^{W}_{NNK} = -\mathrm{i}\, G_F m_\pi^2 \left[\overline{\psi}_N \begin{pmatrix} 0 \\ 1 \end{pmatrix} (C_K^{PV} + C_K^{PC} \gamma_5 \gamma^\mu \partial_\mu)(\phi^K)^\dagger \psi_N + \overline{\psi}_N \psi_N (D_K^{PV} + D_K^{PC} \gamma_5 \gamma^\mu \partial_\mu)(\phi^K)^\dagger \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right]$$

$$\mathcal{L}^{S}_{\Lambda NK} = -\mathrm{i}\, g_{\Lambda NK}\, \overline{\psi}_N \gamma_5 \gamma^\mu \partial_\mu \phi^K \psi_\Lambda$$

$$g_{NN\pi} \to g_{\Lambda NK} \;,\; \mu_\pi \to \mu_K$$

$$\hat{A}_\pi \to \left(\frac{C_K^{PV}}{2} + D_K^{PV} + \frac{C_K^{PV}}{2} \vec{\tau}_1 \vec{\tau}_2 \right) \frac{M_S}{M_W}, \quad \hat{B}_\pi \to \left(\frac{C_K^{PC}}{2} + D_K^{PC} + \frac{C_K^{PC}}{2} \vec{\tau}_1 \vec{\tau}_2 \right)$$

EFTs and hypernuclear decay

Contact terms

PV $\Lambda N \to NN$ transitions:

$$^3S_1 \to ^3P_1, \quad A\,(\sigma_1+\sigma_2)\,\{p_1-p_2\,,\,\delta(\vec{r})\,\} + B\,(\sigma_1+\sigma_2)\,[\,p_1-p_2\,,\,\delta(\vec{r})\,]$$

$$^3S_1 \to ^1P_1, \quad C\,(\sigma_1-\sigma_2)\,\{p_1-p_2\,,\,\delta(\vec{r})\,\} + D\,(\sigma_1-\sigma_2)\,[\,p_1-p_2\,,\,\delta(\vec{r})\,]$$

$$^1S_0 \to ^3P_0, \quad +E\,\mathrm{i}\,(\sigma_1\times\sigma_2)\,\{p_1-p_2\,,\,\delta(\vec{r})\,\} + F\,\mathrm{i}\,(\sigma_1\times\sigma_2)\,[\,p_1-p_2\,,\,\delta(\vec{r})\,]$$

PC $\Lambda N \to NN$ transitions:

$$^1S_0 \to ^1S_0, \quad A'\,\hat{1}\,\delta(\vec{r}) + B'\,\sigma_1\sigma_2\,\delta(\vec{r})$$

$$^3S_1 \to ^3S_1, \quad \text{"}$$

EFTs and hypernuclear decay

partial wave	operator	order	isospin
$^1S_0 \rightarrow ^1S_0$	$\hat{1},\ \vec{\sigma}_1\vec{\sigma}_2$	1	1
$^1S_0 \rightarrow ^3P_0$	$(\vec{\sigma}_1 - \vec{\sigma}_2)\vec{q},\ (\vec{\sigma}_1 \times \vec{\sigma}_2)\vec{q}$	q/M_N	1
$^3S_1 \rightarrow ^3S_1$	$\hat{1}, \vec{\sigma}_1\vec{\sigma}_2$	1	0
$^3S_1 \rightarrow ^1P_1$	$(\vec{\sigma}_1 - \vec{\sigma}_2)\vec{q},\ (\vec{\sigma}_1 \times \vec{\sigma}_2)\vec{q}$	q/M_N	0
$^3S_1 \rightarrow ^3P_1$	$(\vec{\sigma}_1 + \vec{\sigma}_2)\vec{q}$	q/M_N	1
$^3S_1 \rightarrow ^3D_1$	$(\vec{\sigma}_1 \times \vec{q})(\vec{\sigma}_2 \times \vec{q})$	$q^2/{M_N}^2$	0

Equivalently, build up the Lorentz invariant Lagrangian from:

$$\overline{\Psi}\Psi,\ \overline{\Psi}\gamma^\mu\Psi,\ i\overline{\Psi}[\gamma^\mu, \gamma^\nu]\Psi = \overline{\Psi}2\sigma^{\mu\nu}\Psi,\ \overline{\Psi}\gamma^\mu\gamma^5\Psi,\ i\overline{\Psi}\gamma^5\Psi$$

Chiral effective theory of the weak interaction.

$$V_{4P}(\vec{q}) = \begin{cases} C_0^0 + C_0^1\, \vec{\sigma}_1 \vec{\sigma}_2 & \text{LO PC} \\ +C_1^0\, \dfrac{\vec{\sigma}_1 \vec{q}}{2\overline{M}} + C_1^1\, \dfrac{\vec{\sigma}_2 \vec{q}}{2M} + \mathrm{i}\, C_1^2\, \dfrac{(\vec{\sigma}_1 \times \vec{\sigma}_2)\, \vec{q}}{2\tilde{M}} & \text{LO PV} \\ +C_2^0\, \dfrac{\vec{\sigma}_1 \vec{q}\, \vec{\sigma}_2 \vec{q}}{4M\overline{M}} + C_2^1\, \dfrac{\vec{\sigma}_1 \vec{\sigma}_2\, \vec{q}^{\,2}}{4M\overline{M}} + C_2^2\, \dfrac{\vec{q}^{\,2}}{4M\tilde{M}} & \text{NLO PC} \end{cases}$$

$$\hat{I} \sim C_{sc}\hat{1} + C_v\, \vec{\tau}_1 \vec{\tau}_2 + C_{3/2}\, \vec{T}_{(3/2)} \vec{\tau}_2 \;\Leftarrow\; \left\langle \frac{3}{2}\, m' \middle| T^{(i)}_{(3/2)} \middle| \frac{1}{2}\, m \right\rangle = \left\langle \frac{1}{2}\, m 1 i \middle| \frac{3}{2}\, m' \right\rangle$$

Number of parameters:

to LO PC:2+2+1

to LOPV: 3 new parameters

to NLO PC: 3 new parameters

method: MIGRAD minimizer (MINUIT)

$V(\vec{r})$ at Lowest Order

$V(\vec{q}) \Rightarrow$ F.T.$\Rightarrow V(\vec{r})$ $\qquad$ $V(\vec{r}) = V_\pi(\vec{r}) + V_K(\vec{r}) + V_{4P}(\vec{r})$

$$V_\mu(\vec{r}) = \frac{e^{-\mu r}}{4\pi r} \times \left[C_\mu^{SC} \vec{\sigma}_1 \vec{\sigma}_2 + C_\mu^T \left(1 + \frac{3}{\mu r} + \frac{3}{(\mu r)^2}\right) \times S_{12}(\hat{r}) \right.$$
$$\left. + C_\mu^{PV} \left(1 + \frac{1}{\mu r}\right) \vec{\sigma}_2 \cdot \hat{r} \right] \times [\hat{1}, \vec{\tau}_1 \vec{\tau}_2]$$

$$V_{4P}(\vec{r}) = \left\{ \begin{array}{ll} C_0^0 + C_0^1 \vec{\sigma}_1 \vec{\sigma}_2 & \text{LO PC} \\ + \frac{2r}{\delta^2} \left[C_1^0 \frac{\vec{\sigma}_1 \hat{r}}{2M} + C_1^1 \frac{\vec{\sigma}_2 \hat{r}}{2M} + C_1^2 \frac{(\vec{\sigma}_1 \times \vec{\sigma}_2)\, \hat{r}}{2M} \right] & \text{LO PV} \\ \times \frac{e^{-\frac{r^2}{\delta^2}}}{\delta^2 \pi^{3/2}} \times [C_{IS}\, \hat{1} + C_{IV}\, \vec{\tau}_1 \vec{\tau}_2] & \end{array} \right.$$

$\delta \sim \rho$ meson range $\sqrt{2} m_\rho^{-1} \approx 0.36$ fm

RESULTS

	π	$+K$	$+$ LO PC	$+$ LO PC+PV	EXP:
$\Gamma(^5_\Lambda\mathrm{He})$	0.42	0.23	0.43	0.44 (0.44)	0.41 ± 0.14[B91]
					0.50 ± 0.07[K95]
$n/p(^5_\Lambda\mathrm{He})$	0.09	0.50	0.56	0.55 (0.55)	0.93 ± 0.55[B91]
					0.50 ± 0.10[K02]
$\mathcal{A}(^5_\Lambda\mathrm{He})$	-0.25	-0.60	-0.80	0.15 (0.24)	0.24 ± 0.22[K00] $\Leftarrow$
$\Gamma(^{11}_\Lambda\mathrm{B})$	0.62	0.36	0.87	0.88 (0.88)	0.95 ± 0.14[K95]
$n/p(^{11}_\Lambda\mathrm{B})$	0.10	0.43	0.84	0.92 (0.92)	$1.04^{+0.59}_{-0.48}$[B91]
$\mathcal{A}(^{11}_\Lambda\mathrm{B})$	-0.09	-0.22	-0.22	0.06 (0.09)	-0.20 ± 0.10[K92]
$\Gamma(^{12}_\Lambda\mathrm{C})$	0.74	0.41	0.95	0.93 (0.93)	1.14 ± 0.2[B91]
					0.89 ± 0.15[K95]
					0.83 ± 0.11[K98]
$n/p(^{12}_\Lambda\mathrm{C})$	0.08	0.35	0.67	0.77 (0.77)	0.87 ± 0.23[K02]
$\mathcal{A}(^{12}_\Lambda\mathrm{C})$	-0.03	-0.06	-0.05	0.02 (0.03)	-0.01 ± 0.10[K92]
$\hat{\chi}^2$			0.98	1.50 (1.15)	

Low-Energy Coefficients

	+ LO PC	+LO PC+PV	
C_0^0	-1.51 ± 0.38	-1.09 ± 0.36	(-1.02 ± 0.35)
C_0^1	-0.86 ± 0.24	-0.63 ± 0.35	(-0.57 ± 0.29)
C_1^0	$---$	-0.45 ± 0.42	(-0.47 ± 0.17)
C_1^1	$---$	0.17 ± 0.22	(0.20 ± 0.19)
C_1^2	$---$	-0.48 ± 0.20	(-0.48 ± 0.22)
C_{IS}	5.08 ± 1.27	5.69 ± 0.74	(5.83 ± 0.82)
C_{IV}	1.47 ± 0.39	1.49 ± 0.23	(1.52 ± 0.24)
$\hat{\chi}^2$	0.98	1.50	(1.15)

Strong interaction model dependence

$\pi + K + \text{LO PC} + \text{LO PV}$		
	NSC97f	NSC97a
$\Gamma({}^{5}_{\Lambda}\text{He})$	0.44	0.44
$n/p({}^{5}_{\Lambda}\text{He})$	0.55	0.55
$\mathcal{A}({}^{5}_{\Lambda}\text{He})$	0.24	0.24
$\Gamma({}^{11}_{\Lambda}\text{B})$	0.88	0.88
$n/p({}^{11}_{\Lambda}\text{B})$	0.92	0.92
$\mathcal{A}({}^{11}_{\Lambda}\text{B})$	0.09 ♠	0.11 ♠
$\Gamma({}^{12}_{\Lambda}\text{C})$	0.93	0.93
$n/p({}^{12}_{\Lambda}\text{C})$	0.77	0.78
$\mathcal{A}({}^{12}_{\Lambda}\text{C})$	0.03 ♠	0.03 ♠
C^0_0	-1.02 ± 0.35	-0.87 ± 0.46
C^0_1	-0.57 ± 0.29	-0.53 ± 0.37
C^1_0	-0.47 ± 0.17	-0.53 ± 0.22
C^1_1	0.20 ± 0.19	0.25 ± 0.16
C^1_2	-0.48 ± 0.22	-0.57 ± 0.17
C_{IS}	5.83 ± 0.82	5.76 ± 0.74
C_{IV}	1.52 ± 0.24	1.50 ± 0.22
$\hat{\chi}^2$	1.15	1.15

Dependence on the smearing (δ) function

	$\delta \approx 0.3$fm (≈ 900MeV)	$\delta \approx 0.36$fm (≈ 770MeV)	$\delta \approx 0.4$fm (≈ 500MeV)
$\Gamma({}^5_\Lambda\mathrm{He})$	0.44	0.44	0.44
$n/p({}^5_\Lambda\mathrm{He})$	0.55	0.55	0.55
$\mathcal{A}({}^5_\Lambda\mathrm{He})$	0.24	0.24	0.24
$\Gamma({}^{11}_\Lambda\mathrm{B})$	0.88	0.88	0.88
$n/p({}^{11}_\Lambda\mathrm{B})$	0.93	0.92	0.94
$\mathcal{A}({}^{11}_\Lambda\mathrm{B})$	$\diamondsuit$ 0.08 $\diamondsuit$	$\diamondsuit$ 0.09 $\diamondsuit$	$\diamondsuit$ 0.06 $\diamondsuit$
$\Gamma({}^{12}_\Lambda\mathrm{C})$	0.93	0.93	0.93
$n/p({}^{12}_\Lambda\mathrm{C})$	0.78	0.77	0.78
$\mathcal{A}({}^{12}_\Lambda\mathrm{C})$	$\diamondsuit$ 0.02 $\diamondsuit$	$\diamondsuit$ 0.03 $\diamondsuit$	$\diamondsuit$ 0.02 $\diamondsuit$
C_0^0	-1.91 ± 0.56	-1.02 ± 0.35	-0.73 ± 0.19
C_0^1	-1.08 ± 0.52	-0.57 ± 0.29	-0.73 ± 0.16
C_1^0	-0.61 ± 0.28	-0.47 ± 0.17	-0.39 ± 0.26
C_1^1	0.24 ± 0.35	0.20 ± 0.19	0.17 ± 0.26
C_1^2	-0.60 ± 0.46	-0.48 ± 0.22	-0.25 ± 0.23
C_{IS}	6.45 ± 0.66	5.83 ± 0.82	5.83 ± 0.96
C_{IV}	1.79 ± 0.26	1.52 ± 0.24	1.48 ± 0.29
$\hat{\chi}^2$	1.15	1.15	1.15

EFT and hypernuclear decay

- From this analysis, we see that the largest contribution corresponds to a scalar-isoscalar low-energy coefficient.

- Also, although not shown, there is no indication of $\Delta I=1/2$ rule breaking…

  $\rightarrow$ needs more exploration

σ- exchange

- Barbero, Mariano (2006)

$$\mathcal{H}^{W}_{\Lambda N\sigma} = G_F \mu_\pi^2 \bar{\psi}_N (A_\sigma + B_\sigma \gamma_5) \phi_\sigma \begin{pmatrix} 0 \\ 1 \end{pmatrix} \psi_\Lambda ,$$

$$\mathcal{H}^{S}_{NN\sigma} = g_{NN\sigma} \bar{\psi}_N \phi_\sigma \psi_N ,$$

μ_σ [MeV]	A_σ	B_σ	${}^{5}_{\Lambda}He$			${}^{12}_{\Lambda}C$		
			Γ_{NM}	$\Gamma_{n/p}$	a_Λ	Γ_{NM}	$\Gamma_{n/p}$	a_Λ
–	0	0	0.720	0.329	−0.507	1.166	0.267	−0.508
550	0.67	13.39	0.424	0.450	−0.326	0.776	0.427	−0.322
550	2.08	13.08	0.424	0.450	−0.362	0.793	0.435	−0.348
650	1.16	22.03	0.424	0.450	−0.326	0.771	0.421	−0.323
650	3.60	21.52	0.424	0.450	−0.362	0.786	0.428	−0.344
750	2.12	38.39	0.424	0.450	−0.326	0.767	0.416	−0.324
750	6.56	37.50	0.424	0.450	−0.362	0.780	0.423	−0.342

σ- exchange

- Sasaki, Izaki, Oka (2006)

$\pi + \mathrm{K} + \sigma$ + DQ

$$\mathcal{H}_s^{\sigma NN} = g_s \bar{\psi}_N(x)\phi_\sigma(x)\psi_N(x)$$
$$\mathcal{H}_w^{\sigma \Lambda N} = g_w \bar{\psi}_n(x)(A_\sigma + B_\sigma \gamma_5)\phi_\sigma(x)\psi_\Lambda(x).$$

$$m_\sigma = 550\ \mathrm{MeV} \quad \Lambda_\sigma = 1200\ \mathrm{MeV} \quad g_{\sigma NN} = g_{\pi NN}$$

$$\Gamma_{NM}({}^4_\Lambda\mathrm{H}) = \Gamma_p({}^4_\Lambda\mathrm{H}) + \Gamma_n({}^4_\Lambda\mathrm{H})$$
$$\Gamma_p({}^4_\Lambda\mathrm{H}) = \frac{\bar{\rho}_4}{6} 2R_{p0}, \qquad \Gamma_n({}^4_\Lambda\mathrm{H}) = \frac{\bar{\rho}_4}{6}(R_{n0} + 3R_{n1})$$
$$\Gamma_{NM}({}^4_\Lambda\mathrm{He}) = \Gamma_p({}^4_\Lambda\mathrm{He}) + \Gamma_n({}^4_\Lambda\mathrm{He})$$
$$\Gamma_p({}^4_\Lambda\mathrm{He}) = \frac{\bar{\rho}_4}{6}(R_{p0} + 3R_{p1}), \qquad \Gamma_n({}^4_\Lambda\mathrm{He}) = \frac{\bar{\rho}_4}{6} 2R_{n0}$$
$$\Gamma_{NM}({}^5_\Lambda\mathrm{He}) = \Gamma_p({}^5_\Lambda\mathrm{He}) + \Gamma_n({}^5_\Lambda\mathrm{He})$$
$$\Gamma_p({}^5_\Lambda\mathrm{He}) = \frac{\bar{\rho}_5}{8}(R_{p0} + 3R_{p1}), \qquad \Gamma_n({}^5_\Lambda\mathrm{He}) = \frac{\bar{\rho}_5}{8}(R_{n0} + 3R_{n1}),$$

σ- exchange

- Sasaki, Izaki, Oka (2006)

π + K + σ + DQ

$$\kappa = \frac{\Gamma_n({}^4_\Lambda\mathrm{He})}{\Gamma_p({}^4_\Lambda\mathrm{H})} = \frac{R_{n0}}{R_{p0}} = \begin{cases} 2 & \text{for } \Delta I = 1/2 \\ 1/2 & \text{for } \Delta I = 3/2 \end{cases}$$

$$\Gamma_{NM}({}^4_\Lambda\mathrm{H}) = \Gamma_p({}^4_\Lambda\mathrm{H}) + \Gamma_n({}^4_\Lambda\mathrm{H})$$

$$\Gamma_p({}^4_\Lambda\mathrm{H}) = \frac{\bar{\rho}_4}{6} 2R_{p0}, \qquad \Gamma_n({}^4_\Lambda\mathrm{H}) = \frac{\bar{\rho}_4}{6}(R_{n0} + 3R_{n1})$$

$$\Gamma_{NM}({}^4_\Lambda\mathrm{He}) = \Gamma_p({}^4_\Lambda\mathrm{He}) + \Gamma_n({}^4_\Lambda\mathrm{He})$$

$$\Gamma_p({}^4_\Lambda\mathrm{He}) = \frac{\bar{\rho}_4}{6}(R_{p0} + 3R_{p1}), \qquad \Gamma_n({}^4_\Lambda\mathrm{He}) = \frac{\bar{\rho}_4}{6} 2R_{n0}$$

$$\Gamma_{NM}({}^5_\Lambda\mathrm{He}) = \Gamma_p({}^5_\Lambda\mathrm{He}) + \Gamma_n({}^5_\Lambda\mathrm{He})$$

$$\Gamma_p({}^5_\Lambda\mathrm{He}) = \frac{\bar{\rho}_5}{8}(R_{p0} + 3R_{p1}), \qquad \Gamma_n({}^5_\Lambda\mathrm{He}) = \frac{\bar{\rho}_5}{8}(R_{n0} + 3R_{n1}),$$

σ- exchange

- Sasaki, Izaki, Oka (2006)

$\pi + K + \sigma$ + DQ

	A_σ	3.0	-0.8	3.8	-1.7	4.5	-2.3	
	B_σ	-1.2		1.2		4.4		EXP
	Γ_{NM}	0.405	0.400	0.392	0.398	0.407	0.398	0.395 ± 0.016
${}^5_\Lambda$He	γ_5	0.675	0.721	0.548	0.603	0.472	0.553	0.44 ± 0.11
	α	0.536	-0.857	0.571	-0.903	0.364	-0.684	0.07 ± 0.08
${}^4_\Lambda$He	Γ_{NM}	0.199	0.195	0.235	0.240	0.298	0.291	0.20 ± 0.03
	γ_4^{He}	0.219	0.249	0.417	0.492	0.692	0.781	0.25 ± 0.16
${}^4_\Lambda$H	Γ_{NM}	0.132	0.135	0.128	0.138	0.145	0.151	0.22 ± 0.09
	γ_4^{H}	6.400	5.946	2.705	2.488	1.379	1.362	—

Prospects

- EFT treatment → needs more and better data, also independent data

  n p → Λ p (RCNP ? COSY?)

↪ Model independent analysis

- Implement carefully the strong interaction in the initial state (ΛN-ΣN).
- Inclusion of a explicit scalar-isoscalar "sigma" meson in (OBE) models → Needs more work.
- Study of multistrange systems.
- Lattice QCD simulation of nonleptonic amplitudes....

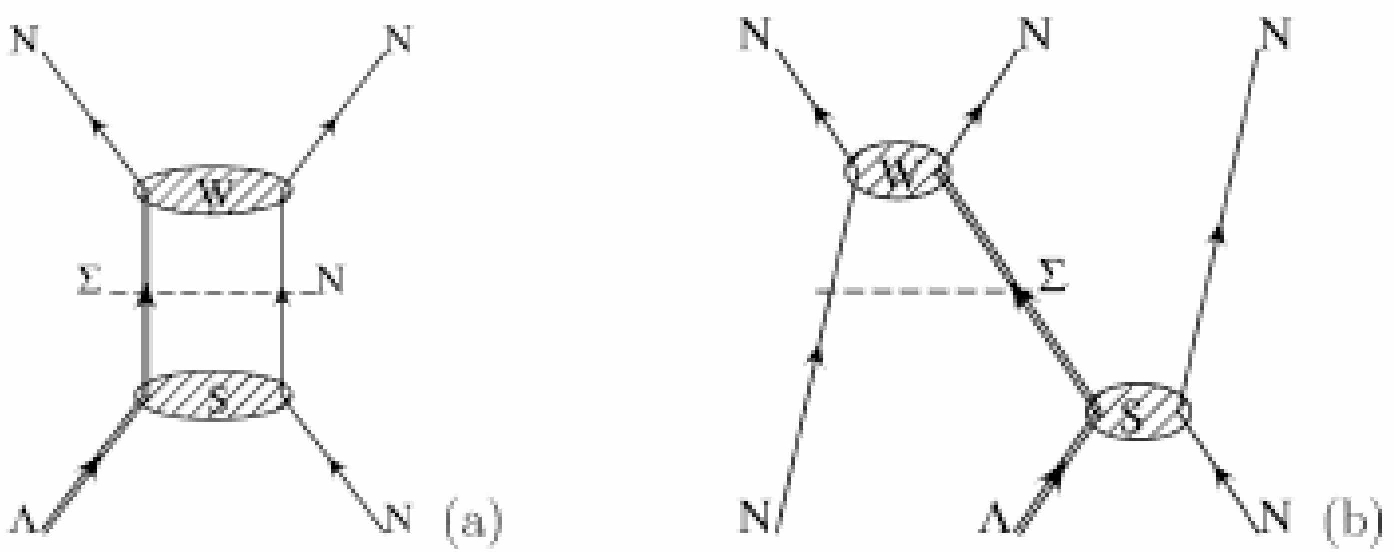
not today....

ΛN-ΣN coupling

Bando, Shono, Takaki (1998) Sasaki, Inoue, Oka (2002)

coherent mixing of Σ

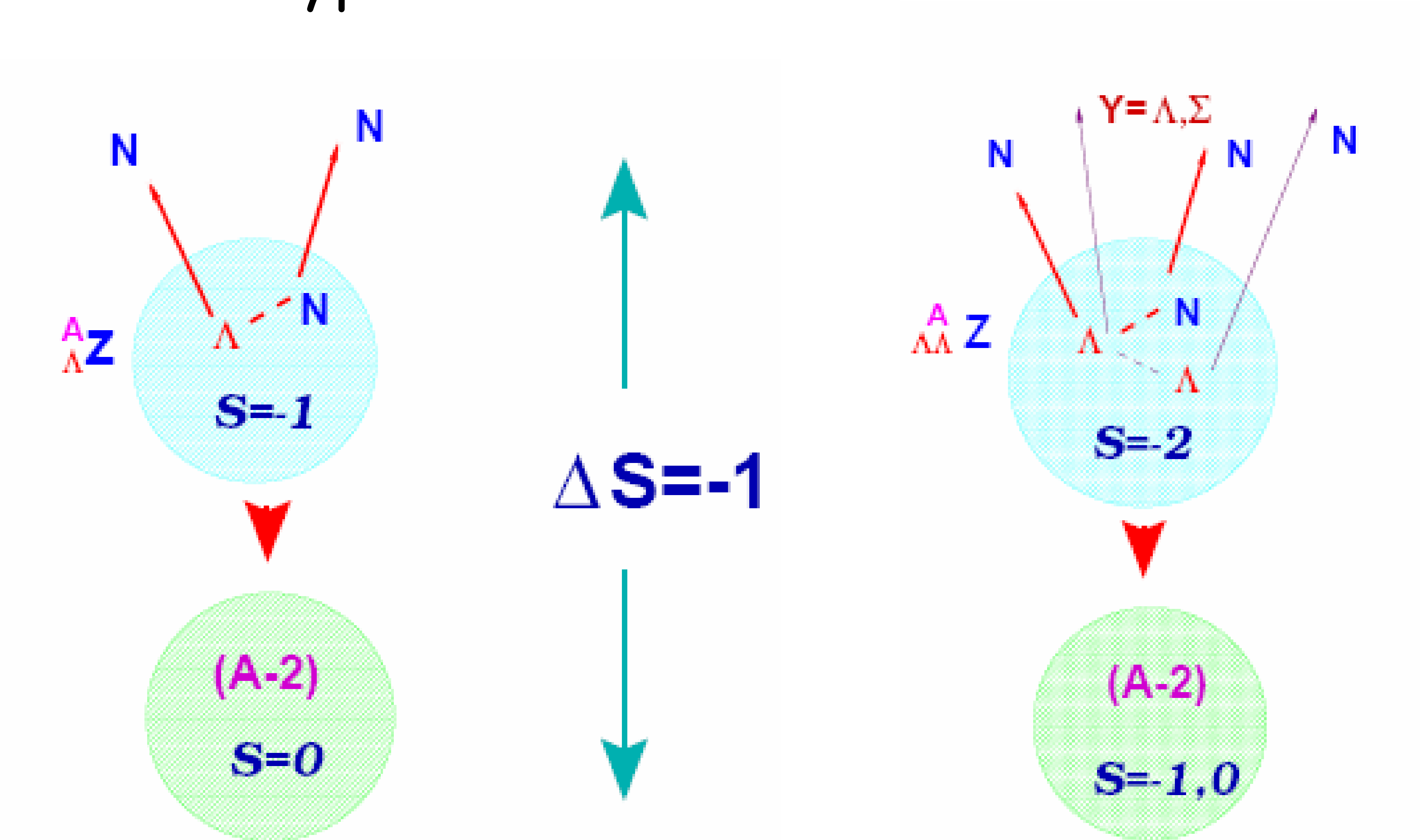
10% effects on A=4 hypernuclei



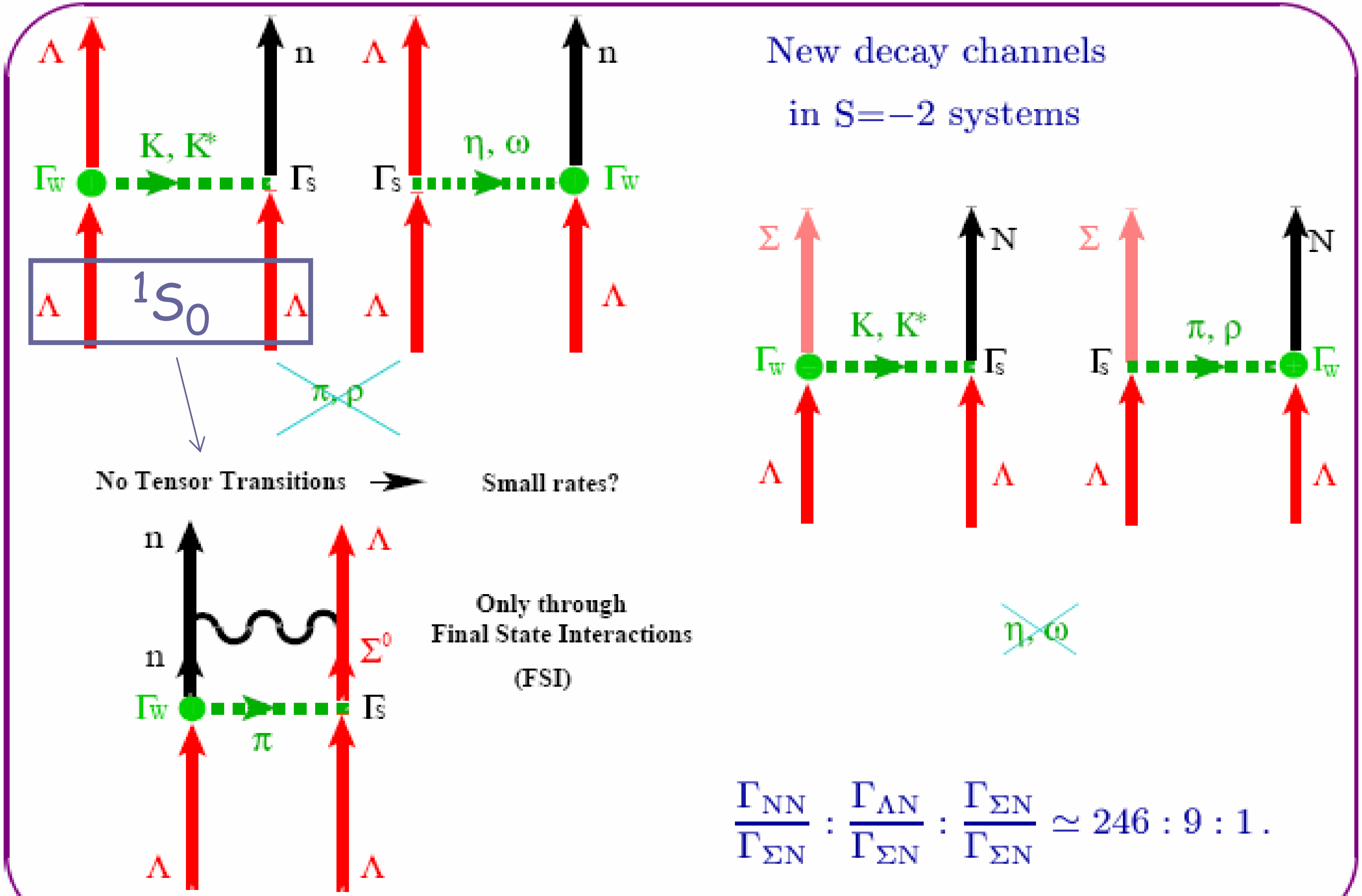
C. Chumillas (tuesday´s talk) ⟵ G-matrix calculation

Even more strange systems

- Double-Λ hypernuclei…



Even more strange systems



$$\frac{\Gamma_{NN}}{\Gamma_{\Sigma N}} : \frac{\Gamma_{\Lambda N}}{\Gamma_{\Sigma N}} : \frac{\Gamma_{\Sigma N}}{\Gamma_{\Sigma N}} \simeq 246 : 9 : 1 .$$

Even more strange systems

NMD rates for ${}^{6}_{\Lambda\Lambda}\mathrm{He}$

	NSC97f
$\Lambda n \to nn$	0.30
$\Lambda p \to np$	0.66
$\Lambda N \to NN$	0.96
$\Gamma_{\rm n}/\Gamma_{\rm p}$	0.46
$\Lambda\Lambda \to \Lambda n$	3.6×10^{-2}
$\Lambda\Lambda \to \Sigma^0 n$	1.3×10^{-3}
$\Lambda\Lambda \to \Sigma^- p$	2.6×10^{-3}
$\Lambda\Lambda \to YN$	4.0×10^{-2}

Tiny!

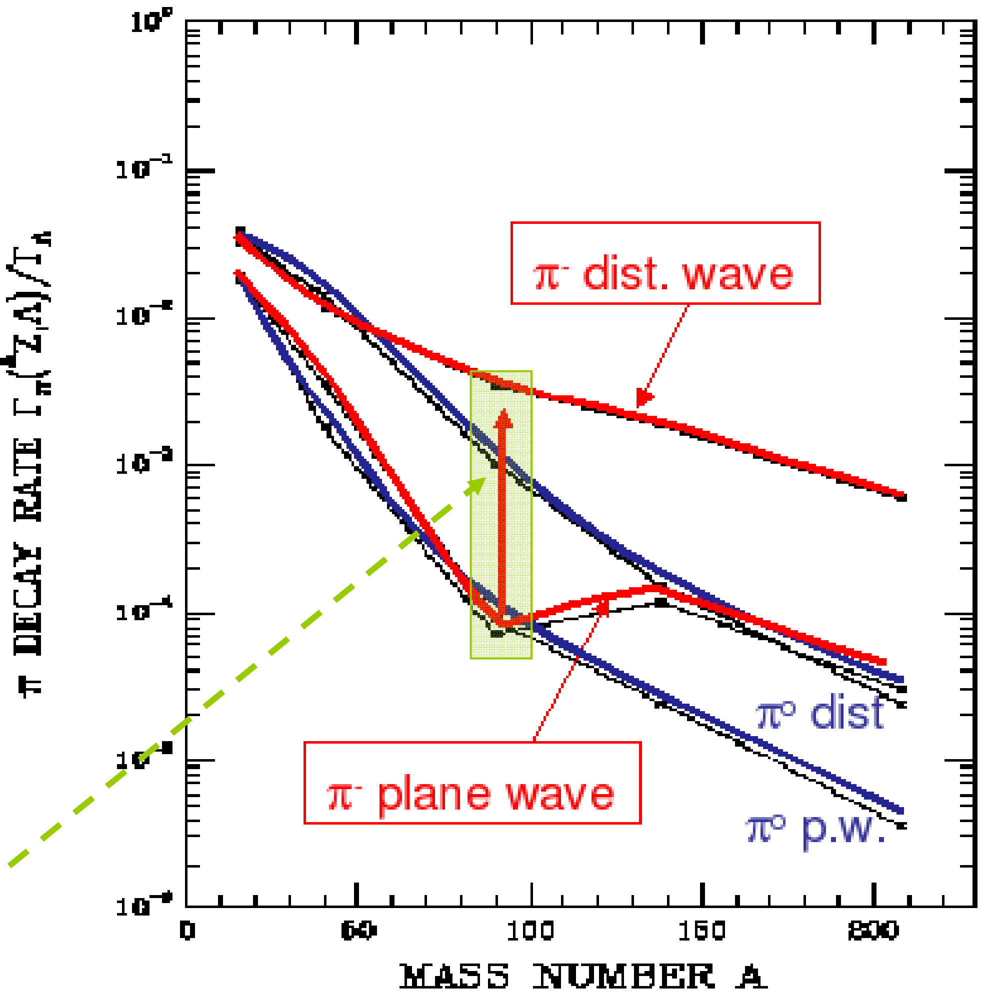
Parreño, Ramos, Bennhold (2001)

π-nucleus optical potential

The mesonic channel, with $Q \sim 35$ MeV ($= m_\Lambda - m_N - m_\pi$), is very sensitive to:

1. the optical potential of the pion

→ pion-nucleus optical potential:

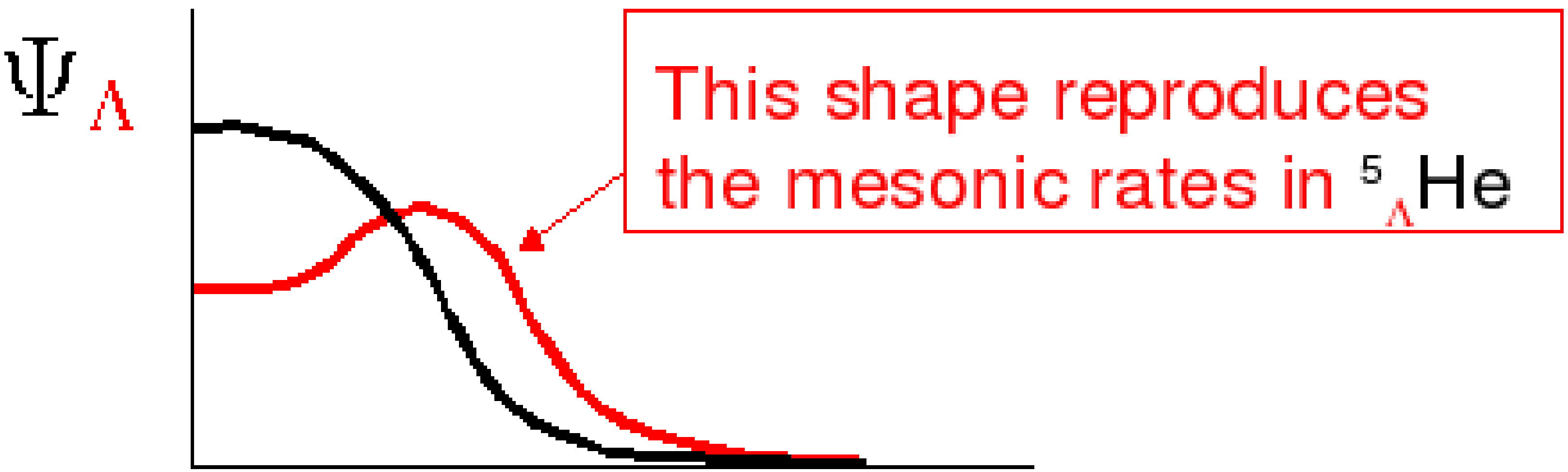


Enhancement of up two orders of magnitude !!

[Go back]

What do we learn from those decays?

- the Λ wave function in the nucleus



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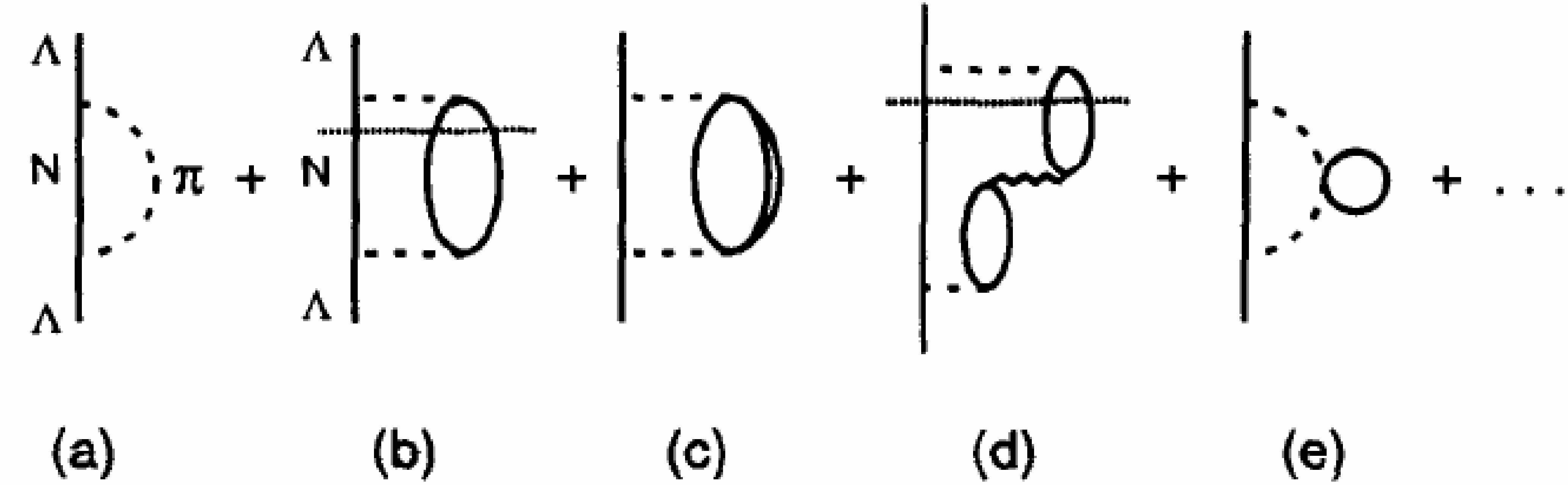
Λ self-energy



Free P-wave π self-energy at LO RPA LO s-wave π self-en

$$G(p) = \frac{1 - n(\vec{p})}{p^0 - E(\vec{p}) - V_N + \mathrm{i}\varepsilon} + \frac{n(\vec{p})}{p^0 - E(\vec{p}) - V_N - \mathrm{i}\varepsilon}$$

$$D(q) = \frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^{\,2} + \Pi\left(q^0, \vec{q}\right)}$$

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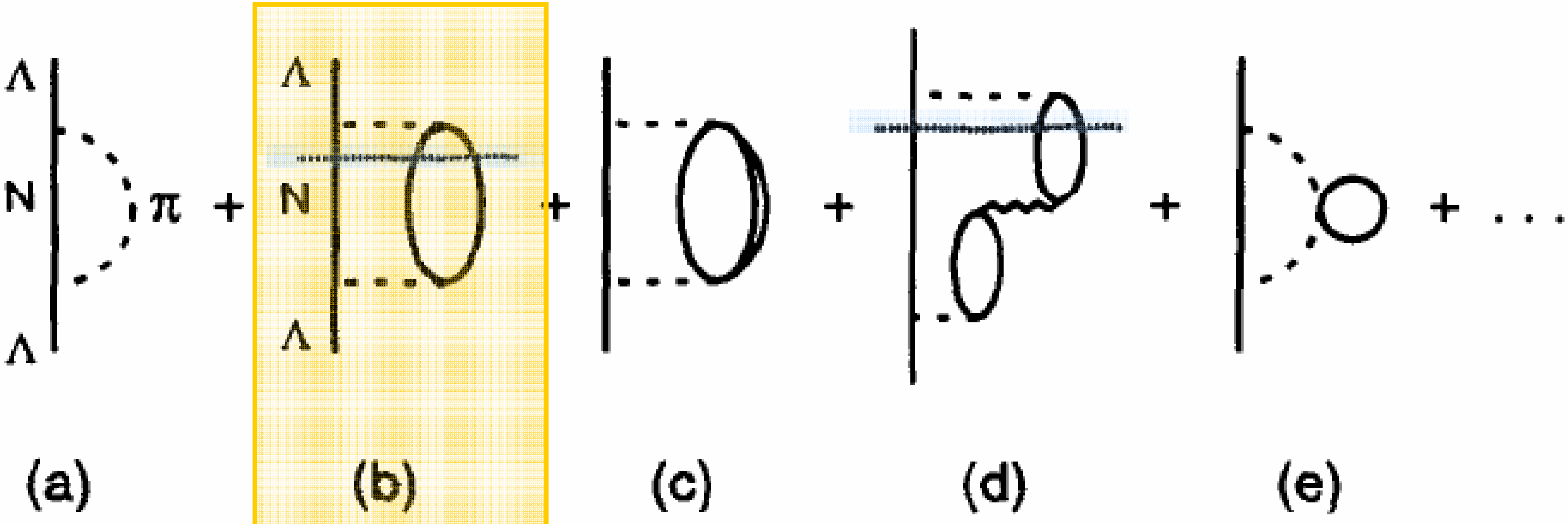
Λ self-energy

Non-mesonic



Put on-shell a nucleon and the ph of the pion self-energy

Channel where there are no pions and only nucleons in the final state

$\Lambda N \rightarrow NN$

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Λ self-energy

$$\Gamma_\Lambda(k) = -6\left(Gm_\pi^2\right)^2 \int \frac{d^3\vec{q}}{(2\pi)^3}$$

$$\times\left[1 - n\left(\vec{k} - \vec{q}\right)\right]\theta\left(k^0 - E\left(\vec{k} - \vec{q}\right) - V_N\right)\left(S^2 + \frac{P^2}{m_\pi^2}\vec{q}^{\,2}\right)$$

$$\times \operatorname{Im} \left.\frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^2 - \Pi\left(q^0, q\right)}\right|_{q^0 = k^0 - E\left(\vec{k} - \vec{q}\right) - V_N}$$

Technically….

$$\operatorname{Im}\frac{1}{\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^2 - \Pi} \rightarrow \frac{\operatorname{Im}\Pi_{ph}}{\left|\left(q^0\right)^2 - \vec{q}^{\,2} - m_\pi^2 - \Pi\right|^2}$$

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DQM

Effective 6-quark hamiltonian

$$O_1 = (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta)_{V-A} - (\bar{u}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta u_\beta)_{V-A},$$

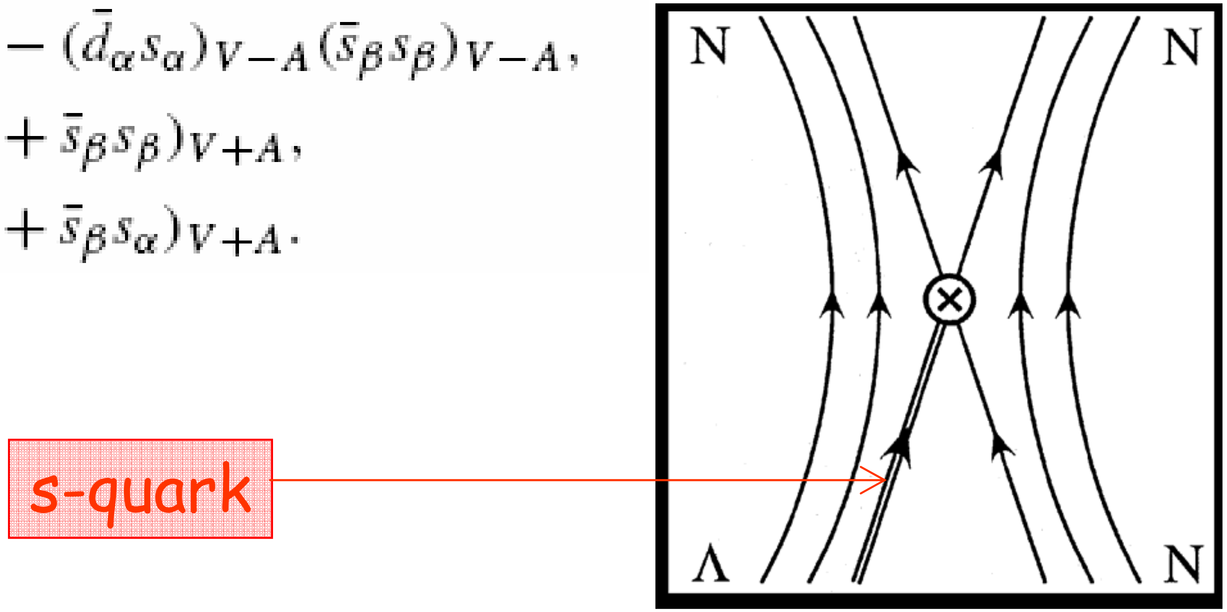
$$O_2 = (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta)_{V-A} + (\bar{u}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta u_\beta)_{V-A} + 2(\bar{d}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta d_\beta)_{V-A} + 2(\bar{d}_\alpha s_\alpha)_{V-A}(\bar{s}_\beta s_\beta)_{V-A},$$

$$O_3 = 2(\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta)_{V-A} + 2(\bar{u}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta u_\beta)_{V-A} - (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{d}_\beta d_\beta)_{V-A} - (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{s}_\beta s_\beta)_{V-A},$$

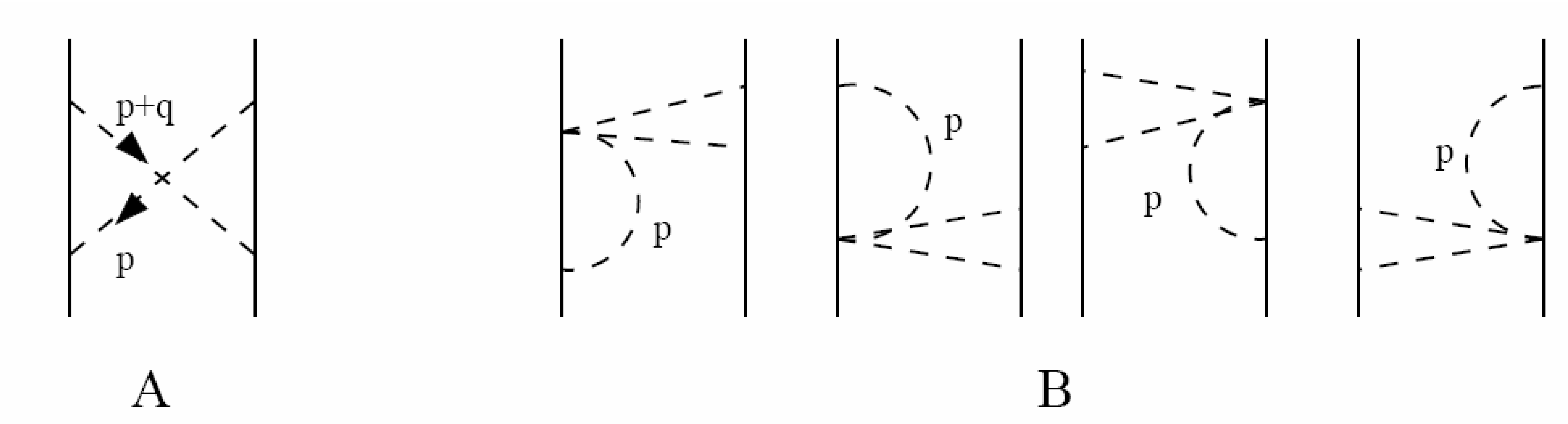
$$O_5 = (\bar{d}_\alpha s_\alpha)_{V-A}(\bar{u}_\beta u_\beta + \bar{d}_\beta d_\beta + \bar{s}_\beta s_\beta)_{V+A},$$

$$O_6 = (\bar{d}_\alpha s_\beta)_{V-A}(\bar{u}_\beta u_\alpha + \bar{d}_\beta d_\alpha + \bar{s}_\beta s_\alpha)_{V+A}.$$

Go back



Off-shell cancellations



Off-shell cancellations:
The off-shell part of the pion lines in diagram A cancels diagrams B.

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Theoretical models II: Direct Quark Mechanism (+OPE+OKE+…)

- C.Y. Cheung, D.P. Heddle, L.S. Kisslinger (1983)
  - The weak vertex was not correct
- K. Maltman, M. Shmatikov (1994) DQ + π, K

  ΔI=1/2 violation
- T. Inoue, S. Takeuchi, M. Oka (1994) DQ, DQ + π
  - DQ gives a large n/p ratio
  - Strong ΔI=3/2 in J=0 amplitudes
- K. Sasaki, T. Inoue, M. Oka (2000) π+K, **DQ** + π, K
  - Larger n/p ratio ($\gtrsim$ 0.5)

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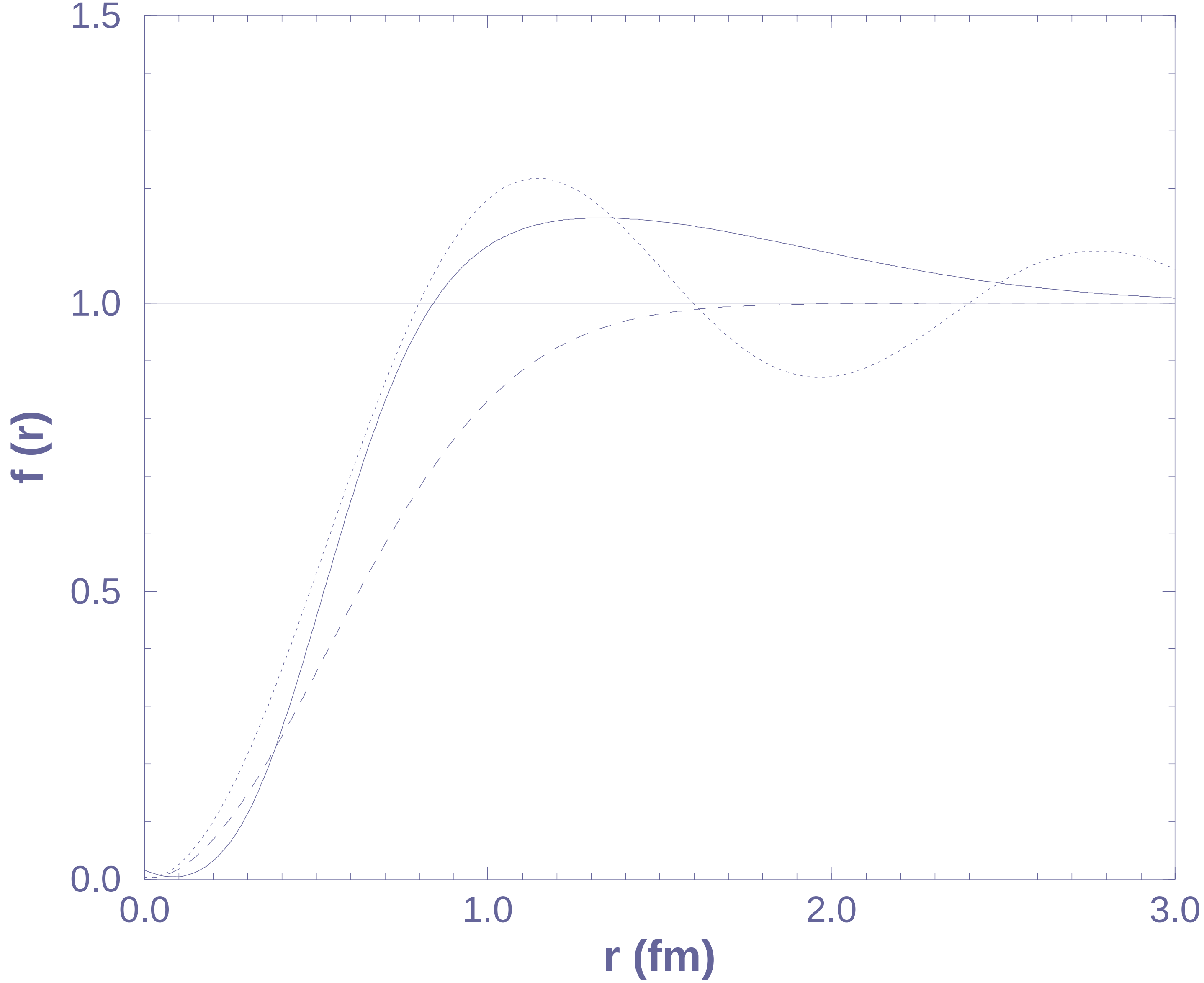
Effects of strong interaction: ISI



Effects of strong interaction. FSI
NN wave function

$$|\Psi\rangle = |\Phi\rangle + \frac{1}{E - H_0 + i\varepsilon} T|\Phi\rangle$$

One can solve the T-matrix equation in momentum space

$$T(\vec{k}|\vec{k}_0) = V(\vec{k}|\vec{k}_0) + \int d^3q \, \frac{V(\vec{k}|\vec{q})T(\vec{q}|\vec{k}_0)}{E(k_0) - E(q)}$$

For standing waves:

$$\Psi(\vec{k}_0;\vec{r}) \ \chi_S^{M_S} = \Phi(\vec{k}_0;\vec{r}) \ \chi_S^{M_S} - \sum_{M'_S} \int d^3k \ \frac{T(\vec{k}SM'_S|\vec{k}_0SM_S)\,\Phi(\vec{k};\vec{r})\,\chi_S^{M'_S}}{E(k) - E(k_0)}$$

Effects of strong interaction. FSI
NN wave function

Using a partial-wave decomposition and working in a coupled scheme (LS)J:

Correlated wave function:

$$\left|\Psi(\vec{k}_0;\vec{r})\right\rangle \chi_S^{M_S} = \sum_{J,M_J} \sum_{L,M_L} \sum_{L'} \mathrm{i}^{L'} 4\pi \, \Psi_{LL'}^{J}(k_0,r)\, Y_{LM_L}^{*}(\hat{k}_0) \left\langle LM_L SM_S \middle| JM_J \right\rangle \Im_{L',S,J}^{M_J}(\hat{r})$$

Uncorrelated wave function:

$$\begin{aligned}\left|\Phi(\vec{k}_0;\vec{r})\right\rangle \chi_S^{M_S} &= e^{i\vec{k}_0\vec{r}} \chi_S^{M_S} \\ &= \sum_{L,M_L} \sum_{L',M'_L} \mathrm{i}^{L'} 4\pi \; j_L(k_0 r)\, \delta_{L,L'} Y_{LM_L}^{*}(\hat{k}_0)\, Y_{L'M'_L}(\hat{r})\, \chi_S^{M_S} \\ &= \sum_{J,M_J} \sum_{L,M_L} \sum_{L'} \mathrm{i}^{L'} 4\pi \; j_L(k_0 r)\, \delta_{L,L'} Y_{LM_L}^{*}(\hat{k}_0) \left\langle LM_L SM_S \middle| JM_J \right\rangle \Im_{L',S,J}^{M_J}(\hat{r})\end{aligned}$$

where, $\Im_{L',S,J}^{M_J}(\hat{r}) = \sum_{M_L,M_S} \left\langle JM_J \middle| L'M'_L \, SM_S \right\rangle Y_{L'M'_L}(\hat{r})\, \chi_{M_S}^{S}$

Effects of strong interaction. FSI
NN wave function

$$\Psi^{J}_{LL'}(k_0 r) = j_L(k_0 r)\,\delta_{L,L'} - \int k^2 dk\, \frac{\langle k;(L'S)JM_J\,|T|\,k_0;(LS)JM_J\rangle}{E(k)-E(k_0)}\, j_{L'}(kr)$$

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including form factors

$$V(\vec{r}) = \int \frac{d^3 q}{(2\pi)^3} \frac{e^{i\vec{q}\vec{r}}}{\vec{q}^{\,2} + \mu^2 - q_0^2} O(\vec{q}) F^2(\vec{q}^{\,2})$$

standard choices…

$$F_{DP}^2(\vec{q}^{\,2}) = \left(\frac{\Lambda_{DP}^2 - \mu^2}{\Lambda_{DP}^2 + \vec{q}^{\,2}} \right)^2$$

$$F_{SP}^2(\vec{q}^{\,2}) = \left(\frac{\Lambda_{SP}^2 - \mu^2}{\Lambda_{SP}^2 + \vec{q}^{\,2}} \right)$$

$$F_{SP}^2(\vec{q}^{\,2}) = \exp\left(-\frac{\vec{q}^{\,2}}{\Lambda^2} \right)$$

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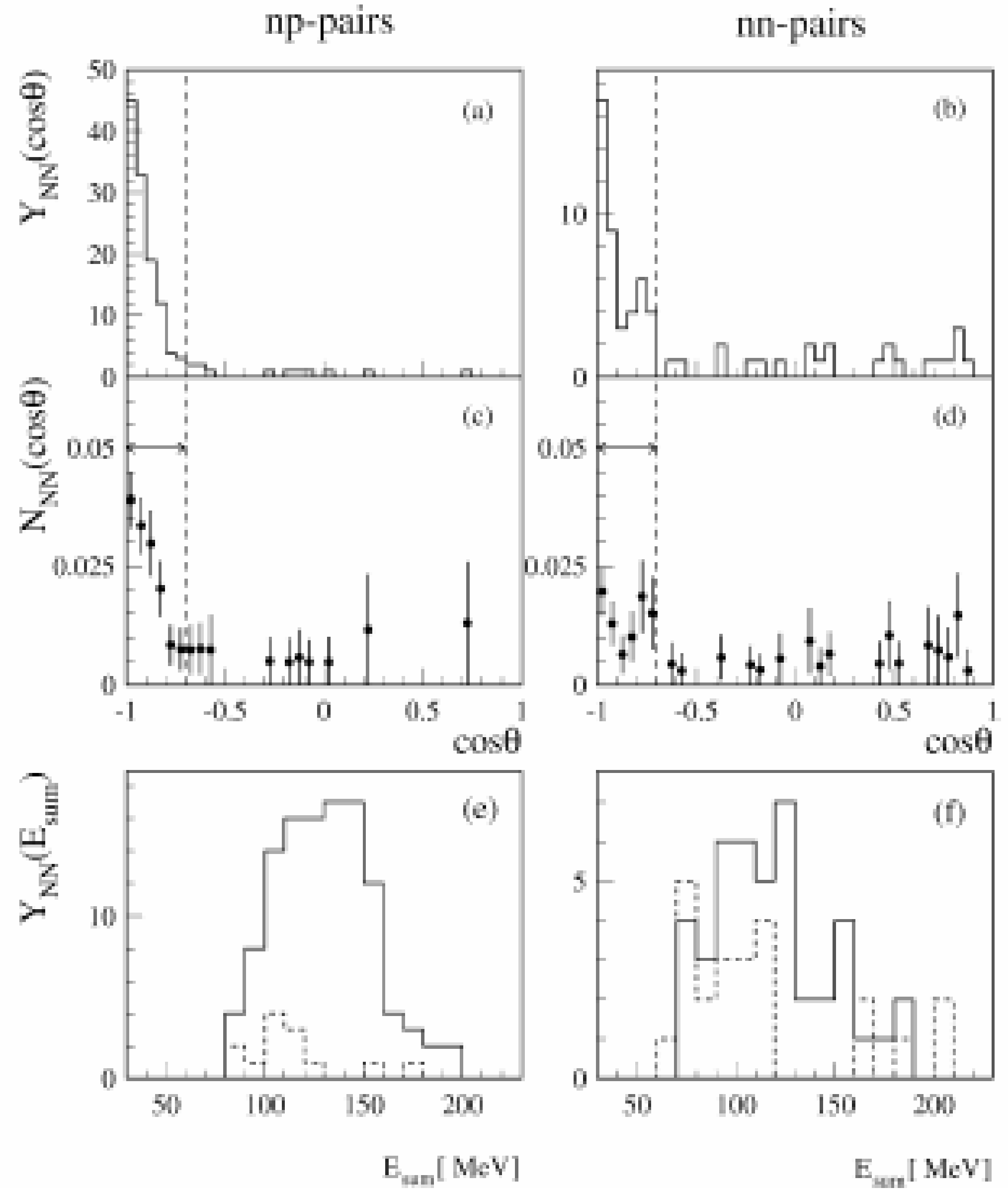
Correlated spectra N_{np} for ${}^{12}_{\Lambda}C$

M.J. Kim et al. Phys. Lett. B641 (2006) 28-33

KEK-E508



Correlated spectra N_{np} for ${}^{12}_{\Lambda}C$

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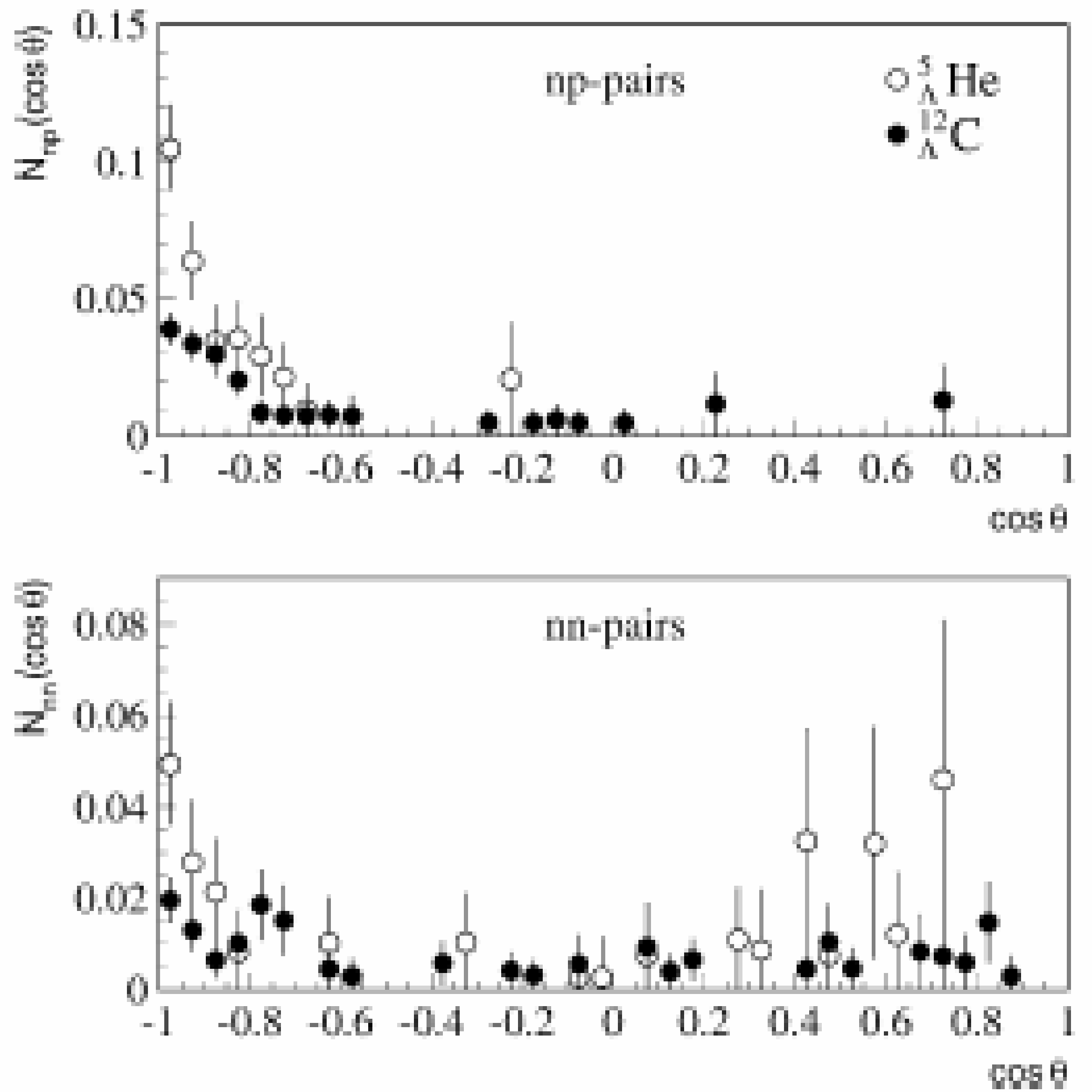

2N-induced over 1N-induced

The calculation mixes two different formalisms:

1N-induced $\rightarrow$ OME

2N-induced $\rightarrow$ PPM+LDA

This implies that the obtained distributions of the weak decay nucleons and the Γ_{2N} value for the 2N-induced channel have been properly normalized to keep the Γ_2/Γ_1 ratio unchanged.

$$\frac{\Gamma_2}{\Gamma_1} \equiv \left(\frac{\Gamma_2}{\Gamma_1}\right)^{LDA} = 0.20 \quad \text{for } {}^{5}_{\Lambda}\text{He}$$

$$= 0.25 \quad \text{for } {}^{12}_{\Lambda}\text{C}$$

The effective field theory approach

Associated to the existence of two scales: one heavy and one light.
For energies small compared to the heavy scale, describe the interactions in terms of an effective picture written only in terms of the light degrees of freedom, but which fully includes the influences of the heavy scale through its virtual effects.

As in a multipole expansion, we believe we can mimic the complex high-momentum, short-distance structure of the real theory, whatever it is, by a generic set of simple point-like interactions.

Low-momentum processes: Real theory $\rightarrow$ Effective theory

- ♠ Introduce a momentum cutoff, Q, of the order of the momentum at which new (unknown) physics becomes important.
  Only $k < Q$ are retained explicitely
- ♠ Add local interactions to mimic the effect of the SR physics
  Such corrections will appear to be local to low-momentum probes, with wavelengths large compared to $1/Q$

Experimental numbers included in the fit (2005)

	Γ	Γ_n/Γ_p	Γ_p	$\mathcal{A}$
${}^{5}_{\Lambda}$He	$\underline{0.41 \pm 0.14}$ [19]	0.93 ± 0.55 [19]	$\underline{0.21 \pm 0.07}$ [19]	$\underline{0.24 \pm 0.22}$ [20]
	$\underline{0.50 \pm 0.07}$ [21]	1.97 ± 0.67 [21]		
		$\underline{0.50 \pm 0.10}$ [22]		
${}^{11}_{\Lambda}$B	$\underline{0.95 \pm 0.14}$ [21]	$\underline{1.04^{+0.59}_{-0.48}}$ [19]	$0.30^{+0.15}_{-0.11}$ [21]	-0.20 ± 0.10 [23]
		$2.16 \pm 0.58^{+0.45}_{-0.95}$ [21]		
		$0.59^{+0.17}_{-0.14}$ [24]		
${}^{12}_{\Lambda}$C	$\underline{0.83 \pm 0.11}$ [25]	$1.33^{+1.12}_{-0.81}$ [19]	$0.31^{+0.18}_{-0.11}$ [21]	-0.01 ± 0.10 [23]
	$\underline{0.89 \pm 0.15}$ [21]	$1.87 \pm 0.59^{+0.32}_{-1.00}$ [21]		
	$\underline{1.14 \pm 0.2}$ [19]	$0.59^{+0.17}_{-0.14}$ [24]		
		$\underline{0.87 \pm 0.23}$ [26]		

Parreño, Bennhold, Holstein (2005)