

# Effective field theory for the $\Lambda N \rightarrow NN$ interaction

Axel Pérez-Obiol

Universitat de Barcelona and ICC



***September 2013, Berlin***

In collaboration with Assumpta Parreño, Bruno Juliá-Díaz  
(Universitat de Barcelona)  
and David R. Entem (U. Salamanca)

# Outline

- Introduction
  - $\Lambda$  and hypernuclear decay
  - One Meson Exchange, Effective Field Theory
- LO EFT
  - LO fit
  - Resonance saturation
- NLO EFT
  - Calculation of loop diagrams
- Summary & perspectives

## Introduction

Hypernuclei & EFT

## LO EFT

Fit & resonance saturation

## NLO EFT

Diagrams & potentials

## Summary

LO & NLO

### $\Lambda$ Hyperon

Made of u, d and s quarks

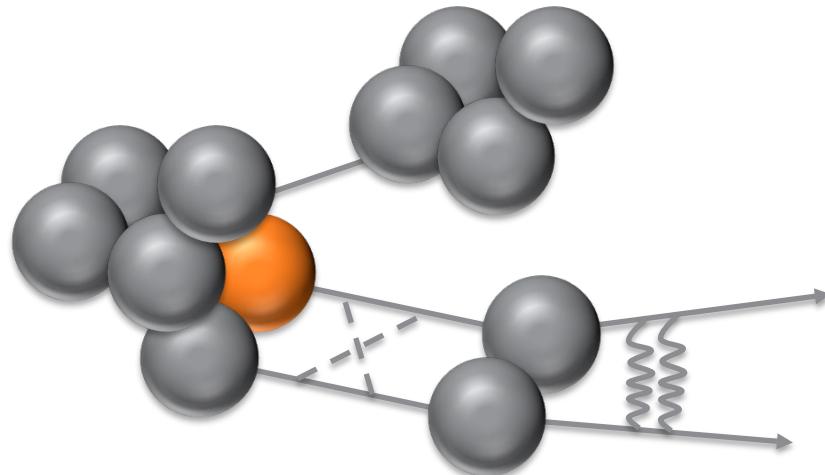
Spin=1/2, s=-1, Q=0, I=0

Mass=1115.683 $\pm$ 0.006 MeV

Life time  $\tau=(2.631\pm 0.020)\cdot 10^{-10}$ s

Free decays:  $\Lambda \rightarrow n\pi^0$  and  $\Lambda \rightarrow p\pi^-$  (36:64)  
( $\Delta I=1/2$  rule)

No stable beams



2-body interaction  $\longleftrightarrow$

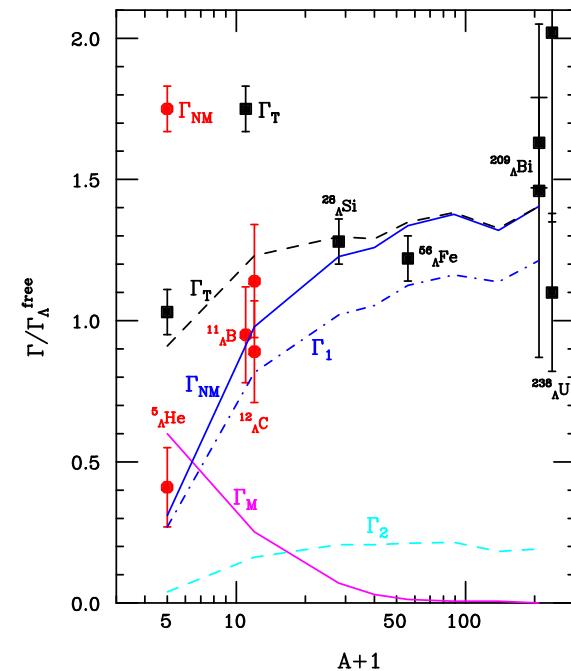
Hypernuclear  
decay observables

### Hypernucleus

Nucleus made of  $\Lambda$  and nucleons

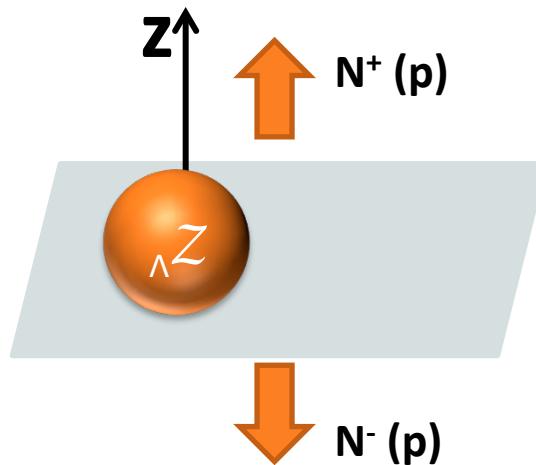
$n(\pi^+, K^+)\Lambda$ ,  $n(\pi^-, K^-)\Lambda$ ,  $p(e, e'K^+)\Lambda$ ,  $p(\gamma, K^+)\Lambda$   
(BNL, CERN, KEK, Jlab, DAPHNE, FAIR...)

New decay modes:  $\Lambda N \rightarrow NN$ ,  $\Lambda NN \rightarrow NNN$



## 3 Hypernuclear Observables

- Total nonmesonic decay rate  $\Gamma(\Lambda N \rightarrow NN)$
- $nn/np \leftrightarrow \Gamma(\Lambda n \rightarrow nn)/\Gamma(\Lambda p \rightarrow np)$
- Asymmetry  $\approx [N^+(p) - N^-(p)]/[N^+(p) + N^-(p)]$

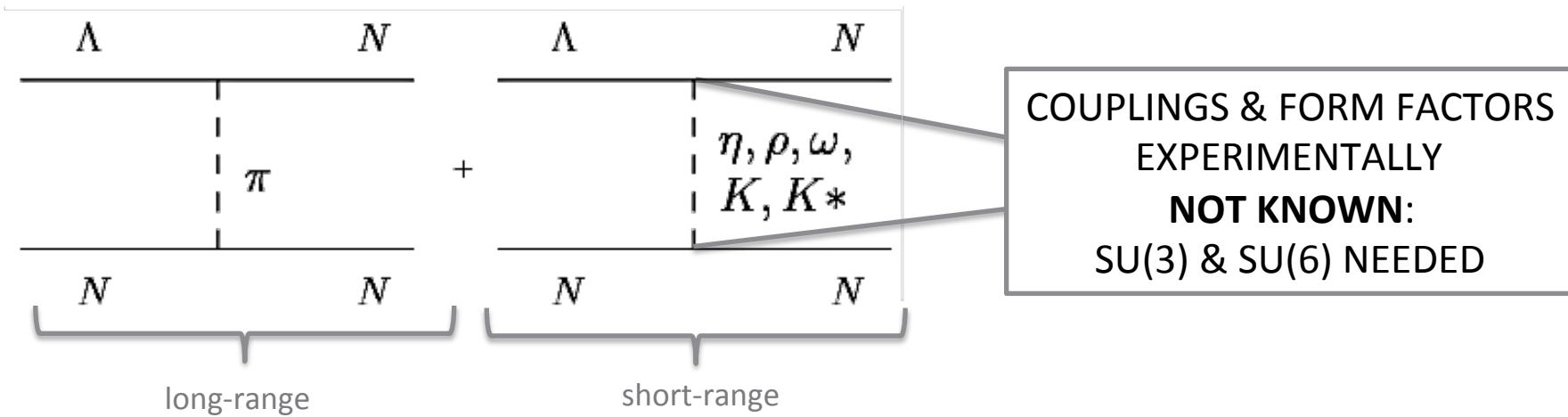


Experimental values (KEK):

	${}^5_{\Lambda}He$	${}^{11}_{\Lambda}B$	${}^{12}_{\Lambda}C$
$\Gamma$	$0.50 \pm 0.07$	$0.95 \pm 0.14$ $0.861 \pm 0.096$	$0.828 \pm 0.087,$ $0.89 \pm 0.18, 0.83 \pm 0.11$
$\Gamma n/\Gamma p$	$0.450 \pm 0.114$	[0.6-2.2]	$0.51 \pm 0.14$
$\mathcal{A}$	$0.24 \pm 0.22,$ $0.11 \pm 0.09,$ $0.07 \pm 0.08$		$-0.16 \pm 0.28 + 0.18$

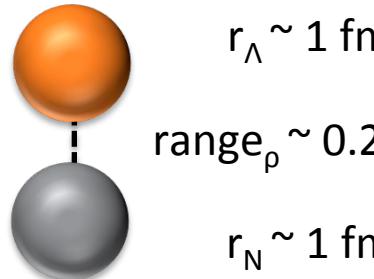
Future/ongoing decay experiments: J-Parc (HYP2012)

## $\Lambda N \rightarrow NN$ : One Meson Exchange model



- $SU(3)/SU(6)$  symmetries  $\rightarrow$  Symmetry breaking effects

- Short range: heavy mesons  $\rightarrow$



$$r_\Lambda \sim 1 \text{ fm}$$

$$\text{range}_\rho \sim 0.25 \text{ fm}$$

$$r_N \sim 1 \text{ fm}$$

(we don't really know what happens at such short range)

## Building the EFT for the $\Lambda N \rightarrow NN$ decay

- Separation of scales  $\rightarrow$  soft (pions) and hard (rho meson/baryons)
- Relevant degrees of freedom  
 $\rightarrow \pi, K, N, \Lambda, \Sigma$  ( $q=300-400$  MeV)
 



**Expansion  $q/M$**   
 (Weinberg power counting  
 + Heavy Baryon expansion)
- Symmetries (and symmetry breakings)  
 $\rightarrow$  Chiral, discrete (PV)

### Recent baryon-baryon EFT's

**Weak YN:** Jung-Hwan Jun (2001); A. Parreño, C. Bennhold, and B.R. Holstein (2004-05); Parreño, A., Bennhold, C, Holstein, B.R., NPA (2004).

**Weak NN:** Zhu, S.-lin, Maekawa, C. M., Holstein, B. R., & Kolck, U. V., NPA (2005).

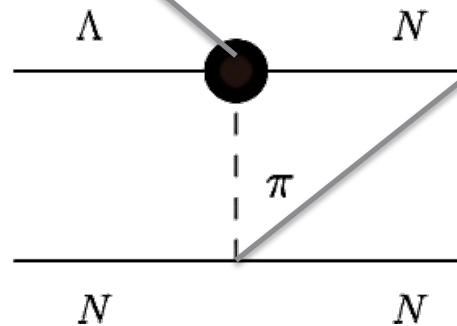
**Strong YN:** Haidenbauer, J., NPA (2010). Haidenbauer, J., Meiñner, Ulf-G., Polinder, H., NPA 779 (2006)

**Strong NN:** Machleidt, R., & Entem, D. R., PR (2011); Epelbaum, E., Hammer, H., Meiñner Ulf-G., RMP (2009).

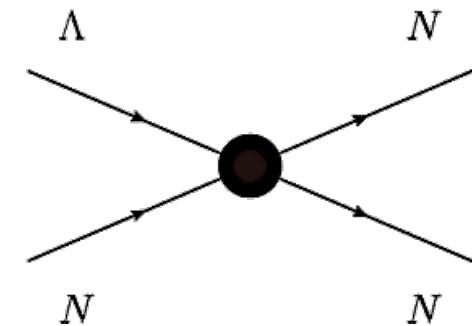
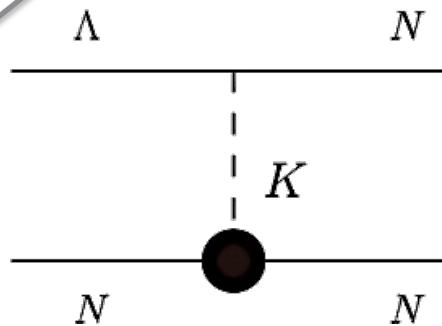
## LO EFT: Feynman diagrams & potential

$$L_W^{\Delta S=1} = -iG_F m_\pi^2 \bar{\psi}_N (A_\Lambda + B_\Lambda \gamma_5) \vec{\tau} \cdot \vec{\phi}_\pi \psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Weak phenomenological Lagrangian



Strong chiral Lagrangian



$$V_\mu(\vec{q}) = -G_F m_\pi^2 \frac{g_{BB\mu}}{2\bar{M}_S} \left( \hat{A}_\mu - \frac{\hat{B}_\mu}{2\bar{M}_W} \vec{\sigma}_1 \cdot \vec{q} \right) \frac{\vec{\sigma}_2 \cdot \vec{q}}{-q_0^2 + \vec{q}^2 + m_\mu^2}$$

$$V_{4P}^{LO} = C_0^0 + C_0^1 \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

with  $\mu = \pi, K$ ;  $\hat{A}_\pi = A_\pi \vec{\tau}_1 \cdot \vec{\tau}_2$ ,  $\hat{B}_\pi = B_\pi \vec{\tau}_1 \cdot \vec{\tau}_2$ ,

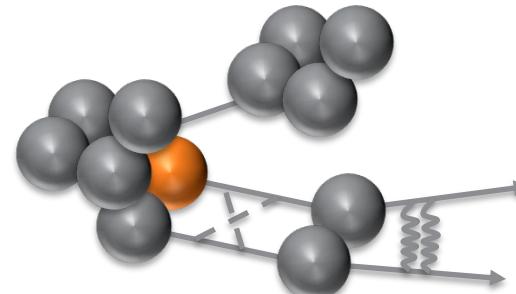
$$\hat{A}_K = \frac{C_K^{PV}}{2} + D_K^{PV} + \frac{C_K^{PV}}{2} \vec{\tau}_1 \cdot \vec{\tau}_2, \quad \hat{B}_K = \frac{C_K^{PC}}{2} + D_K^{PC} + \frac{C_K^{PC}}{2} \vec{\tau}_1 \cdot \vec{\tau}_2$$

## LO EFT: fitting LO LECs $C_0^0$ & $C_0^1$

$$V(\vec{q}) = V_\pi(\vec{q}) + V_K(\vec{q}) + V_{4P}(\vec{q})$$

$$V_{4P}(\vec{q}) = C_0^0 + C_0^1 \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

2 models to obtain strong couplings & final NN wave functions (Nijmegen Soft-Core 97f and Jülich B)



Hypernuclear decay rate:

$$\Gamma_{fi} = \int \frac{d^3 k_r}{(2\pi)^3} \int \frac{d^3 k_{CM}}{(2\pi)^3} \frac{1}{2J+1} \sum_{M_f, \{R\}, \{1\}\{2\}} (2\pi) \delta(M_H - E_R - E_1 - E_2) |M_{fi}|^2$$

Amplitude:

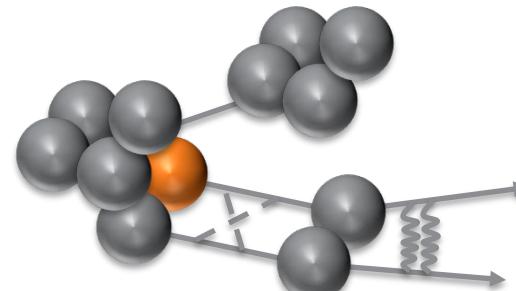
$$M_{fi} = \int d^3 r \Psi_f^*(r) V(r) \Psi_i(r)$$

## LO EFT: fitting LO LECs $C_0^0$ & $C_0^1$

$$V(\vec{q}) = V_\pi(\vec{q}) + V_K(\vec{q}) + V_{4P}(\vec{q})$$

$$V_{4P}(\vec{q}) = C_0^0 + C_0^1 \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

2 models to obtain strong couplings & final NN wave functions (Nijmegen Soft-Core 97f and Jülich B)



Hypernuclear decay rate:

$$\Gamma_{fi} = \int \frac{d^3 k_r}{(2\pi)^3} \int \frac{d^3 k_{CM}}{(2\pi)^3} \frac{1}{2J+1} \sum_{M_f, \{R\}, \{1\}\{2\}} (2\pi) \delta(M_H - E_R - E_1 - E_2) |M_{fi}|^2$$

Amplitude:

$$M_{fi} = \int d^3 r \Psi_f^*(r) V(r) \Psi_i(r)$$

Residual nucleus  
+NN (t-matrix)

2-body potential

Shell model,  
weak coupling  
Scheme for  $\Lambda$ ,  
Uncouple N (F.P.C.),  
Harmonic Oscillator w.f.

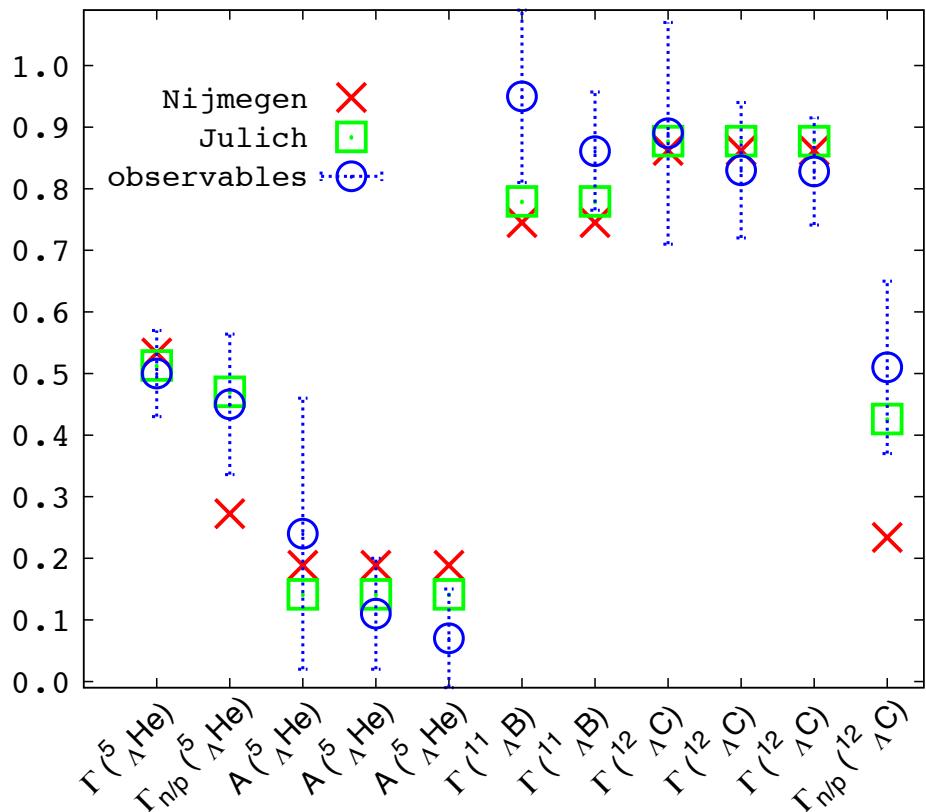
Hypernuclear code  
+MINUIT

$$V(\vec{q}) = V_\pi(\vec{q}) + V_K(\vec{q}) + V_{4P}(\vec{q})$$

$$V_{4P}^{LO} = C_0^0 + C_0^1 \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

Figure 1: Hypernuclear decay observables (total and partial decay rates and asymmetry for  ${}^5\Lambda$ He,  ${}^{11}\Lambda$ B and  ${}^{12}\Lambda$ C), including their error bars and their fitted values. The total decay rates are in units of the  $\Lambda$  decay rate in free space ( $\Gamma_\Lambda = 3.8 \times 10^9 \text{ s}^{-1}$ ). All the quantities are adimensional.

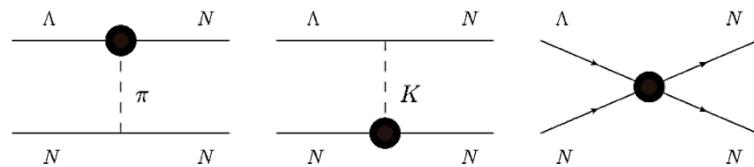
## LO EFT: fitting LO LECs $C_0^0$ & $C_0^1$



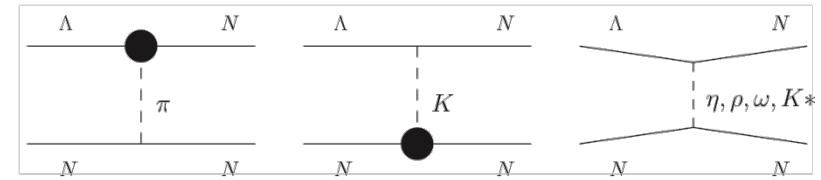
Phys. Rev. C 84, 024606 (2011)  
A. Pérez-Obiol, A. Parreño, B. Juliá-Díaz

## LO EFT: resonance saturation

$$\text{EFT: } V_\pi + V_K + \boxed{C_{00} + C_{01}\sigma_1 \cdot \sigma_2}$$



$$\text{OME: } V_\pi + V_K + \boxed{V_\eta + V_\rho + V_\omega + V_{K^*}}$$



$$C_0^0 = \left[ \frac{g_{\Lambda NK^*}^V}{m_{K^*}^2} \left( -\frac{C_{K^*}^{PC,V}}{2} + D_{K^*}^{PC,V} \right) + \frac{g_{NN\omega}^V \alpha_\omega}{m_\omega^2} - \frac{2 g_{NN\rho}^V \alpha_\rho}{m_\rho^2} \right] m_\pi^2,$$

$$C_0^1 = \left[ -\frac{g_{\Lambda NK^*}^V C_{K^*}^{PC,V}}{2m_{K^*}^2} - \frac{g_{NN\rho}^V \alpha_\rho}{m_\rho^2} \right] m_\pi^2$$

g: strong  
C, D,  $\alpha$ : weak

Expand in  $q$ :

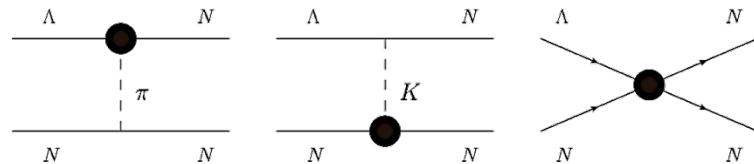
$$V_{mesons}(\vec{q}) \propto \frac{1}{\vec{q}^2 + m_i^2} \left( \frac{\Lambda^2}{\Lambda^2 + \vec{q}^2} \right)^2$$

$$\boxed{C_{00}^{OME} + C_{01}^{OME} \sigma_1 \cdot \sigma_2}$$

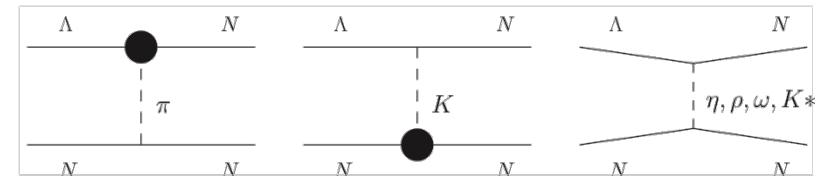
Resonance saturation in NN: Epelbaum, E., Meißner, U-G., Glöckle, W., & Elster, C., PRC (2002)

## LO EFT: resonance saturation

$$\text{EFT: } V_\pi + V_K + \boxed{C_{00} + C_{01}\sigma_1 \cdot \sigma_2}$$



$$\text{OME: } V_\pi + V_K + \boxed{V_\eta + V_\rho + V_\omega + V_{K^*}}$$



$$C_0^0 = \left[ \frac{g_{\Lambda NK^*}^V}{m_{K^*}^2} \left( -\frac{C_{K^*}^{PC,V}}{2} + D_{K^*}^{PC,V} \right) + \frac{g_{NN\omega}^V \alpha_\omega}{m_\omega^2} - \frac{2g_{NN\rho}^V \alpha_\rho}{m_\rho^2} \right] m_\pi^2, \quad C_0^1 = \left[ -\frac{g_{\Lambda NK^*}^V C_{K^*}^{PC,V}}{2m_{K^*}^2} - \frac{g_{NN\rho}^V \alpha_\rho}{m_\rho^2} \right] m_\pi^2$$

Nijmegen Soft-Core 97f		Jülich B	
OME expansion	LO PC calculation	OME expansion	LO PC calculation
$C_0^0$	$1.07 \pm 0.88$	$4.01 \pm 0.23$	$-1.7 \pm 2.6$
$C_0^1$	$0.02 \pm 0.36$	$0.02 \pm 0.33$	$-0.30 \pm 0.28$

## LO EFT: $\sigma$ meson

$$V_\sigma(\vec{q})^{(PS)} = -G_F m_\pi^2 g_{NN\sigma} \left( \hat{A}_\sigma + \frac{\hat{B}_\sigma}{2M_W} \vec{\sigma}_1 \cdot \vec{q} \right) \frac{1}{\vec{q}^2 + m_\sigma^2}, \quad m_\sigma = 550 \text{ MeV}, \quad g_{NN\sigma} = 8.8^*$$

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

$$C_0^0 = \left[ \frac{g_{\Lambda NK^*}^V}{m_{K^*}^2} \left( -\frac{C_{K^*}^{PC,V}}{2} + D_{K^*}^{PC,V} \right) + \frac{g_{NN\omega}^V \alpha_\omega}{m_\omega^2} - \frac{2g_{NN\rho}^V \alpha_\rho}{m_\rho^2} - \frac{A_\sigma g_{NN\sigma}}{m_\sigma^2} \right] m_\pi^2 ,$$

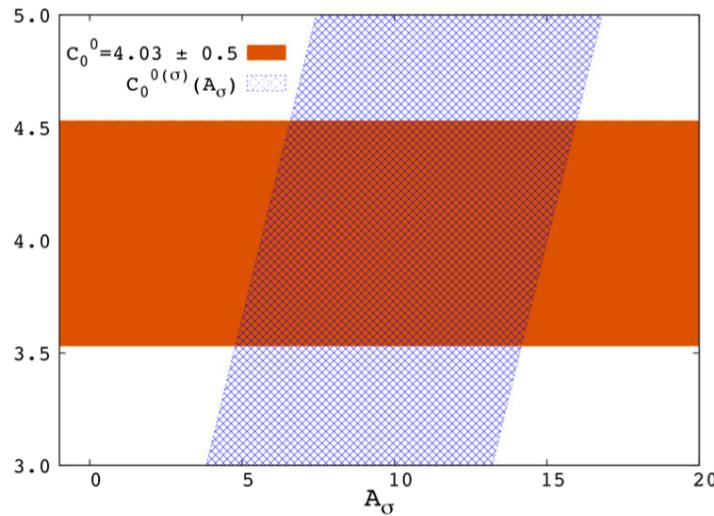
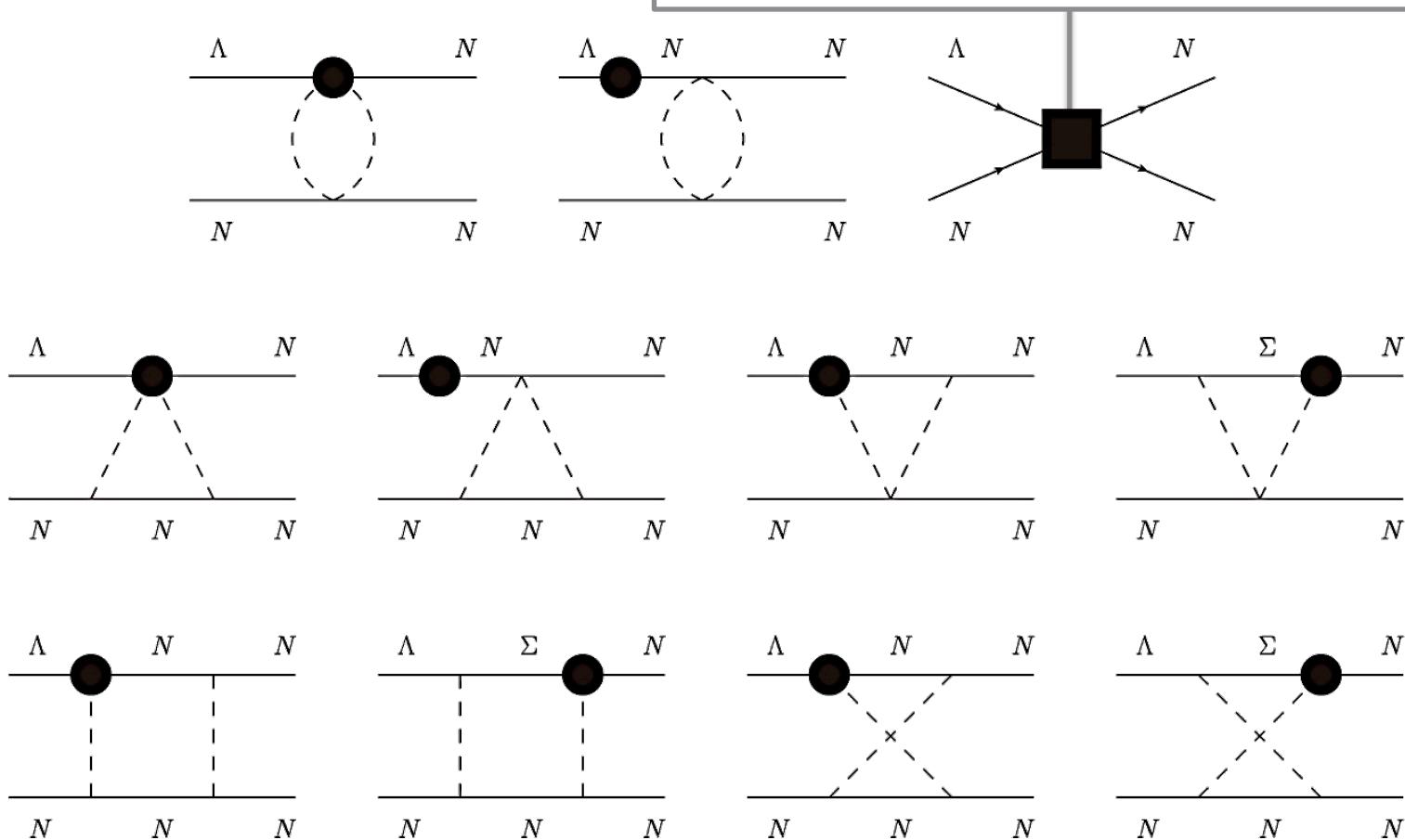


Figure 2: We plot (for the Jülich model) the dependence of the coefficient on the weak  $A_\sigma$  coupling, represented by the shaded blue area, and compare it to the fitted EFT value (solid orange area).

Other works with sigma meson in hypernuclear decay: K. Sasaki, M. Izaki, M. Oka, PRC71, 035502 (2005)

# NLO $(q/M)^1$ and NNLO $(q/M)^2$ Feynman diagrams

Higher orders in the derivative expansion



## NLO $(q/M)^1$ and NNLO $(q/M)^2$

- Short range:  $q/M$  expansion up to  $(q/M)^2$

	Order	Parity	Structures
Possible structures given two momenta:	0	PC	$1, \vec{\sigma}_1 \cdot \vec{\sigma}_2$
	1	PV	$\vec{\sigma}_1 \cdot \vec{q}, \vec{\sigma}_1 \cdot \vec{p}, \vec{\sigma}_2 \cdot \vec{q},$ $\vec{\sigma}_2 \cdot \vec{p}, (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{q}, (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{p},$
	2	PC	$\vec{q}^2, \vec{p}^2, (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\vec{q}^2, (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\vec{p}^2, (\vec{\sigma}_1 \cdot \vec{q})(\vec{\sigma}_2 \cdot \vec{q}),$ $(\vec{\sigma}_1 \cdot \vec{p})(\vec{\sigma}_2 \cdot \vec{p}), (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot (\vec{q} \times \vec{p})$

Contact interaction  
potential neglecting  
initial momenta:

$$V_{4P}(\vec{q}) = C_1^0 \frac{\vec{\sigma}_1 \vec{q}}{2M_N} + C_1^1 \frac{\vec{\sigma}_2 \vec{q}}{2M_N} + i C_1^2 \frac{(\vec{\sigma}_1 \times \vec{\sigma}_2) \vec{q}}{2M_N}$$

$$+ C_2^0 \frac{\vec{\sigma}_1 \vec{q} \vec{\sigma}_2 \vec{q}}{4M_N^2} + C_2^1 \frac{\vec{\sigma}_1 \vec{\sigma}_2 \vec{q}^2}{4M_N^2} + C_2^2 \frac{\vec{q}^2}{4M_N^2}$$

## NLO $(q/M)^1$ and NNLO $(q/M)^2$ master integrals

$$B_{;\mu;\mu\nu} \equiv \frac{1}{i} \int \frac{d^4 l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{(1;l_\mu;l_\mu l_\nu)}{(l+q)^2 - m^2 + i\epsilon}$$

$$I_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4 l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{(1;l_\mu;l_\mu l_\nu;l_\mu l_\nu l_\rho)}{-l_0 - q'_0 + i\epsilon}$$

$$J_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4 l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{1}{-l_0 - q'_0 + i\epsilon} \frac{(1;l_\mu;l_\mu l_\nu;l_\mu l_\nu l_\rho)}{-l_0 - r_0 + i\epsilon}$$

$$K_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4 l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{1}{-l_0 - q'_0 + i\epsilon} \frac{(1;l_\mu;l_\mu l_\nu;l_\mu l_\nu l_\rho)}{l_0 + r_0 + i\epsilon}$$

## NLO $(q/M)^1$ and NNLO $(q/M)^2$ master integrals

1. Calculate  $B, I, J, K$
2. Relate  $B_\mu$  with  $B$ , etc

$$B_{;\mu;\mu\nu} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu)}{(l+q)^2 - m^2 + i\epsilon}$$

$$I_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu; l_\mu l_\nu l_\rho)}{-l_0 - q'_0 + i\epsilon}$$

$$J_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{1}{-l_0 - q'_0 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu; l_\mu l_\nu l_\rho)}{-l_0 - r_0 + i\epsilon}$$

$$K_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{1}{-l_0 - q'_0 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu; l_\mu l_\nu l_\rho)}{l_0 + r_0 + i\epsilon}$$

## NLO $(q/M)^1$ and NNLO $(q/M)^2$ master integrals

1. Calculate  $B, I, J, K$
2. Relate  $B_\mu$  with  $B$ , etc

$$B_{;\mu;\mu\nu} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu)}{(l+q)^2 - m^2 + i\epsilon}$$

$$I_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu; l_\mu l_\nu l_\rho)}{-l_0 - q'_0 + i\epsilon}$$

$$J_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{1}{-l_0 - q'_0 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu; l_\mu l_\nu l_\rho)}{-l_0 - r_0 + i\epsilon}$$

$$K_{;\mu;\mu\nu;\mu\nu\rho} \equiv \frac{1}{i} \int \frac{d^4l}{(2\pi)^4} \frac{1}{l^2 - m^2 + i\epsilon} \frac{1}{(l+q)^2 - m^2 + i\epsilon} \frac{1}{-l_0 - q'_0 + i\epsilon} \frac{(1; l_\mu; l_\mu l_\nu; l_\mu l_\nu l_\rho)}{l_0 + r_0 + i\epsilon}$$

# NLO $(q/M)^1$ and NNLO $(q/M)^2$ potentials

- Potential

$$V_a = c_{a1} \vec{r}_1 \cdot \vec{r}_2$$

$$V_b = c_{b1}$$

$$V_c = c_{c1} \vec{r}_1 \cdot \vec{r}_2$$

$$V_d = [c_{d1} + c_{d2} \vec{\sigma}_1 \cdot \vec{q} + c_{d3} (\vec{q} \cdot \vec{p}) + c_{d4} \vec{\sigma}_1 \cdot (\vec{q} \times \vec{p})] (\vec{r}_1 \cdot \vec{r}_2)$$

$$V_e = (c_{e1} + c_{e2} \vec{\sigma}_1 \cdot \vec{q}) (\vec{r}_1 \cdot \vec{r}_2)$$

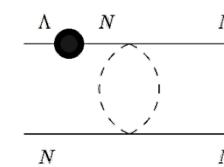
$$\begin{aligned} V_f = & \left[ c_{f1} + c_{f2} \vec{\sigma}_1 \cdot \vec{\sigma}_2 + c_{f3} \vec{\sigma}_1 \cdot \vec{q} + c_{f4} (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{q} \right. \\ & + c_{f5} (\vec{\sigma}_1 \cdot \vec{q}) (\vec{\sigma}_2 \cdot \vec{q}) + c_{f6} (\vec{\sigma}_1 \cdot \vec{q}) (\vec{\sigma}_2 \cdot \vec{p}) \\ & \left. + c_{f7} \vec{\sigma}_1 \cdot (\vec{p} \times \vec{q}) + c_{f8} \vec{\sigma}_2 \cdot (\vec{p} \times \vec{q}) \right] (c'_{f1} + c'_{f2} \vec{r}_1 \cdot \vec{r}_2) \end{aligned}$$

$$\begin{aligned} V_g = & \left[ c_{g1} + c_{g2} \vec{\sigma}_1 \cdot \vec{\sigma}_2 + c_{g3} (\vec{\sigma}_1 \cdot \vec{q}) (\vec{\sigma}_2 \cdot \vec{q}) \right] (c'_{g1} + c'_{g2} \vec{r}_1 \cdot \vec{r}_2) \\ & + \left[ c_{g4} \vec{\sigma}_1 \cdot \vec{q} + c_{g5} (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{q} \right] (c''_{g1} + c''_{g2} \vec{r}_1 \cdot \vec{r}_2) \end{aligned}$$

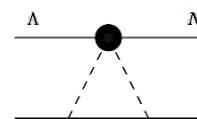
$$\begin{aligned} V_h = & \left[ c_{h1} + c_{h2} \vec{\sigma}_1 \cdot \vec{\sigma}_2 + c_{h3} \vec{\sigma}_1 \cdot \vec{q} + c_{h4} (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{q} \right. \\ & + c_{h5} (\vec{\sigma}_1 \cdot \vec{q}) (\vec{\sigma}_2 \cdot \vec{q}) + c_{h6} (\vec{\sigma}_1 \cdot \vec{q}) (\vec{\sigma}_2 \cdot \vec{p}) \\ & \left. + c_{h7} \vec{\sigma}_1 \cdot (\vec{p} \times \vec{q}) + c_{h8} \vec{\sigma}_2 \cdot (\vec{p} \times \vec{q}) \right] (c'_{h1} + c'_{h2} \vec{r}_1 \cdot \vec{r}_2) \end{aligned}$$

$$\begin{aligned} V_i = & \left[ c_{i1} + c_{i2} \vec{\sigma}_1 \cdot \vec{\sigma}_2 + c_{i3} (\vec{\sigma}_1 \cdot \vec{q}) (\vec{\sigma}_2 \cdot \vec{q}) \right] (c'_{i1} + c'_{i2} \vec{r}_1 \cdot \vec{r}_2) \\ & + \left[ c_{i4} \vec{\sigma}_1 \cdot \vec{q} + c_{i5} (\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \vec{q} \right] (c''_{i1} + c''_{i2} \vec{r}_1 \cdot \vec{r}_2) \end{aligned}$$

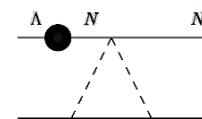
Computed numerically



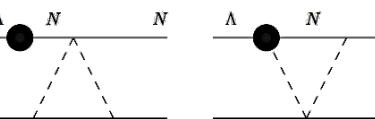
(a)



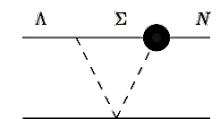
(b)



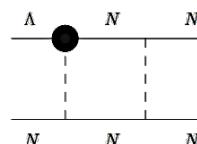
(c)



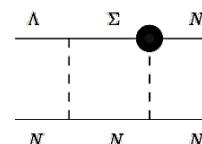
(d)



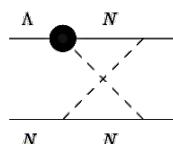
(e)



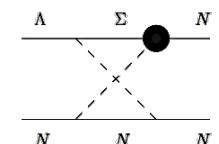
(f)



(g)

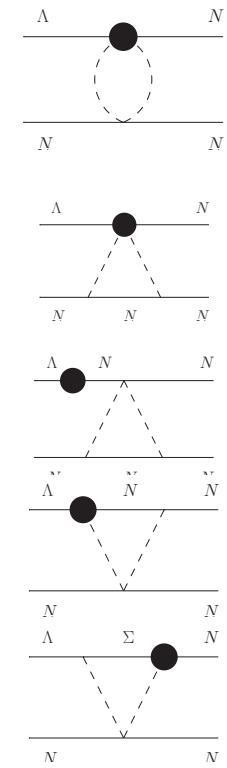
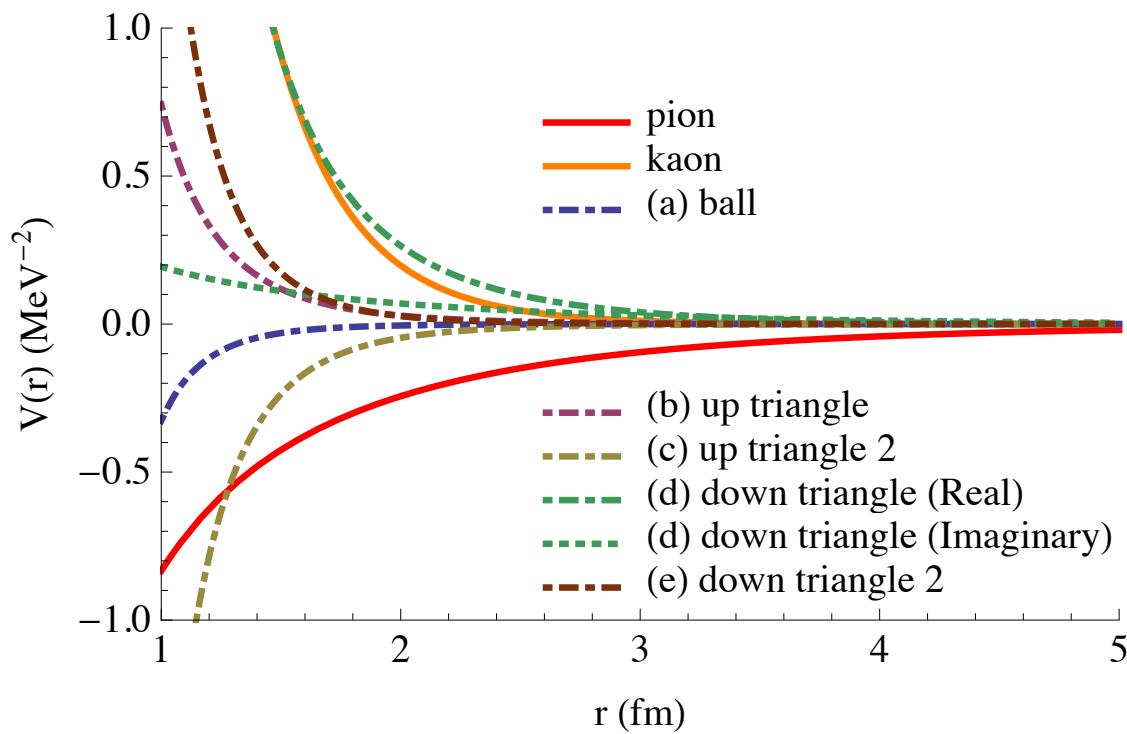


(h)



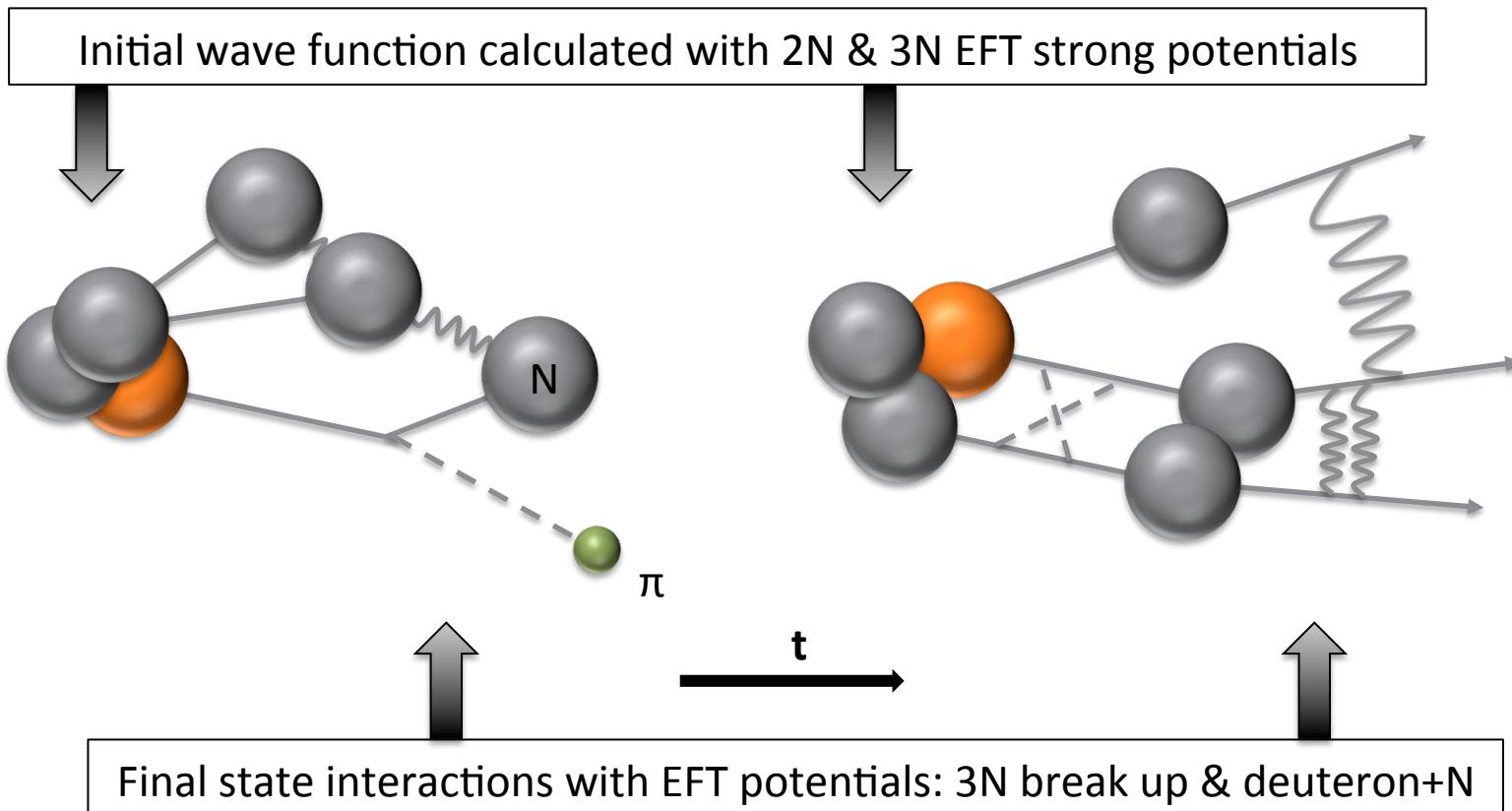
(i)

## NLO $(q/M)^1$ and NNLO $(q/M)^2$ potentials for ${}^3S_1 \rightarrow {}^3S_1$



$$\tilde{V}(r) = \int_{-\infty}^{\infty} \frac{d^3 q}{(2\pi)^3} e^{i\vec{q}\cdot\vec{r}} V(\vec{q}^2) = \frac{1}{2\pi^2 r} \int_0^{\infty} dq \sin(qr) q V(q^2)$$

## Current & future work: Hypertriton (LO) decay with Andreas Nogga (IKP, Jülich)



## **Summary & Conclusions**

**Thanks!**

We have developed an EFT for the two-body  $\Lambda N \rightarrow NN$  transition driving the decay of hypernuclei.

The numerical values for the LO EFT LECs have been obtained by fitting the available experimental data for hypernuclear decay observables.

We have compared the LO EFT to the OME and have written the LO LECs in terms of meson couplings and masses.

The experimental database of hypernuclear decay observables can be described with good accuracy within a LO EFT supplemented by the pion and kaon meson exchanges.

The  $2\pi$  exchange mechanism has been incorporated systematically in the EFT.

In progress: Reduce the model dependencies coming from the strong BB interaction by using EFT in the strong sector.

Expected PhD defense in a few months

## NLO ( $q/M$ )<sup>1</sup> and NNLO ( $q/M$ )<sup>2</sup>

- Strong chiral Lagrangian

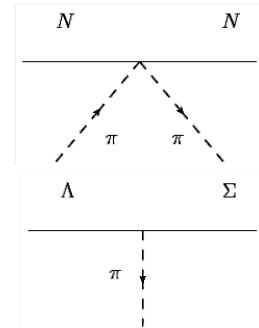
$$L_S = i \cdot Tr(\bar{B} \gamma^\mu [V_\mu, B]) - D \cdot Tr(\bar{B} \gamma^\mu \gamma^5 [A_\mu, B]) - F \cdot Tr(\bar{B} \gamma^\mu \gamma^5 \{A_\mu, B\})$$

- Weak phenomenological Lagrangian

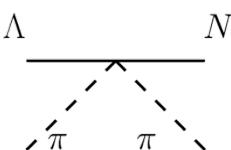
$$L_W^{\Delta S=1} = -iG_F m_\pi^2 \overline{\psi}_N^i (A_\Sigma^i + B_\Sigma^i \gamma_5) \cdot \overline{\phi}_\pi^i \psi_\Sigma^i$$

- Weak chiral Lagrangian

$$L_W^{\Delta S=1} = D_W \cdot Tr\left(\bar{B}\left\{\xi^+ \lambda_6 \xi, B\right\}\right) + F_W \cdot Tr\left(\bar{B}\left[\xi^+ \lambda_6 \xi, B\right]\right)$$



- Reproduces Decay
  - No chiral symmetry
  - Mixes  $q/M$  orders  
  - Can't reproduce decay
  - Chiral symmetry



## Sub-leading and leading $(q/M)^0$ orders

- Strong chiral Lagrangian

$$L_S = i \cdot Tr(\bar{B} \gamma^\mu [V_\mu, B]) - D \cdot Tr(\bar{B} \gamma^\mu \gamma^5 [A_\mu, B]) - F \cdot Tr(\bar{B} \gamma^\mu \gamma^5 \{A_\mu, B\})$$

- Weak phenomenological Lagrangian

$$L_W^{\Delta S=1} = -iG_F m_\pi^2 \bar{\psi}_N (A_\Lambda + B_\Lambda \gamma_5) \bar{\tau} \cdot \bar{\phi}_\pi \psi_\Lambda \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$\Lambda \xrightarrow{\quad} N$   
 $\Lambda \xrightarrow{\quad} K + \pi$

- Reproduces Decay
- No chiral symmetry
- Mixes q/M orders ( $B_\Lambda \approx 7, A_\Lambda \approx 1$ )

$$L_W^{\Delta S=1} = -iG_F m_\pi^2 \left[ \bar{\psi}_N \begin{pmatrix} 0 \\ 1 \end{pmatrix} (C_K^{PV} + C_K^{PC} \gamma_5) \cdot (\bar{\phi}_K)^\dagger \psi_N + \bar{\psi}_N \psi_N (D_K^{PV} + D_K^{PC} \gamma_5) \cdot (\bar{\phi}_K)^\dagger \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right]$$

$N \xrightarrow{\quad} N$   
 $\Lambda \xrightarrow{\quad} K + \pi$

- Contact Interactions  $C_0^0 + C_0^1 \vec{\sigma}_1 \cdot \vec{\sigma}_2$

## Decay amplitude:

$$M \sim \langle \phi_{3N} | (1 + P) V^w | \phi_{\Lambda H}^3 \rangle + \langle \phi_{3N} | (1 + P) (V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H} (1 + P) V^w | \phi_{\Lambda H}^3 \rangle$$

**weak**                                   **strong**                                   **weak**

**plane wave**                                   **rescattering**

↓

**Solve:**    $|U\rangle \equiv (1 + P)(V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H} (1 + P) V^w | \phi_{\Lambda H}^3 \rangle$

## Solving the rescattering part

$$|U\rangle \equiv (1 + P)(V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H} (1 + P) V^w |\phi_{\Lambda^H}^3\rangle$$



**using:**  $G = G_0 + G_0 V G$

$$|U\rangle = (V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H_0} (1 + P) V^w |\phi_{\Lambda^H}^3\rangle + (V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H_0} (1 + P) |U\rangle$$

## Solving the rescattering part

$$|U\rangle \equiv (1 + P)(V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H} (1 + P)V^w |\phi_{\Lambda^3 H}^3\rangle$$



**using:**  $G = G_0 + G_0 V G$

$$|U\rangle = (V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H_0} (1 + P)V^w |\phi_{\Lambda^3 H}^3\rangle + (V_{12} + V_{123}^{(3)}) \frac{1}{E + i\epsilon - H_0} (1 + P)|U\rangle$$



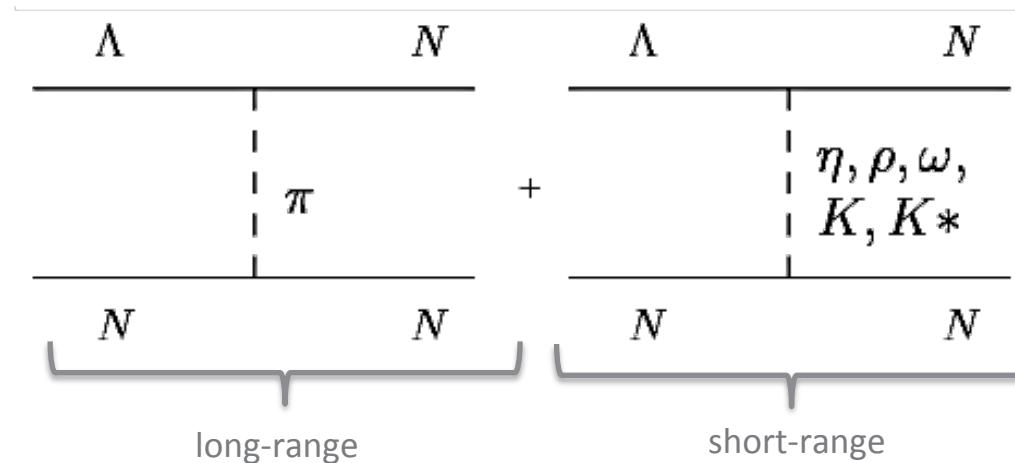
**solve 2-body force:**  $(1 + t_{12}G_0)(1 - V_{12}G_0) = 1$

$$\begin{aligned} |U\rangle = & t_{12}G_0(1 + P)V^w |\phi_{\Lambda^3 H}^3\rangle + (1 + t_{12}G_0)V_{123}^{(3)}G_0(1 + P)V^w |\phi_{\Lambda^3 H}^3\rangle \\ & + t_{12}G_0P|U\rangle + (1 + t_{12}G_0)V_{123}^{(3)}G_0(1 + P)|U\rangle \end{aligned}$$

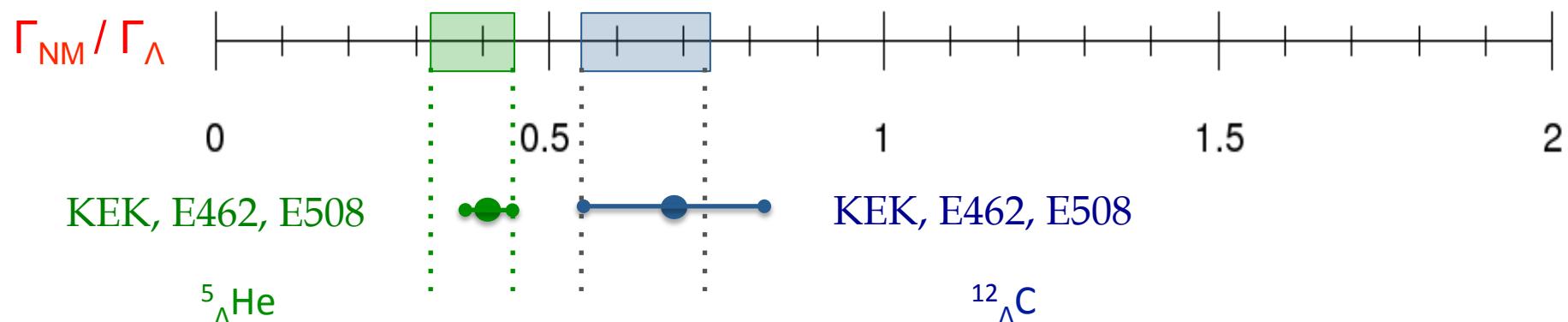


**iterate U**

# $\Lambda N \rightarrow NN$ : One Meson Exchange model



Theoretical predictions OME



$$\begin{aligned}
| {}_\Lambda A \rangle_{T_I T_{3I}}^{J_I M_I} &= | \alpha_\Lambda \rangle \otimes | A - 1 \rangle \\
&= \sum_{m_\Lambda M_C} \langle j_\Lambda m_\Lambda J_C M_C | J_I M_I \rangle | (n_\Lambda l_\Lambda s_\Lambda) j_\Lambda m_\Lambda \rangle | J_C M_C T_I T_{3I} \rangle
\end{aligned}$$

$$\begin{aligned}
\Psi_{\text{as}}^{J_C T_C \alpha}(1....N) &= \sum_{J_{R_0} T_{R_0} \alpha_0 j_N} \langle J_C T_C \alpha \{ | J_{R_0} T_{R_0} \alpha_0, j_N \rangle \\
&\times [ \Psi_{\text{as}}^{J_{R_0} T_{R_0} \alpha_0}(1....N-1) \otimes \phi^{j_N}(N) ]^{J_C T_C}
\end{aligned}$$

↓

Amplitude:  $M_{fi} = \int d^3r \Psi_f^*(r) V(r) \Psi_i(r)$

Residual nucleus +NN (t-matrix)      2-body potential      Shell model,  
weak coupling Scheme for  $\Lambda$ ,  
Uncouple N (F.P.C.),  
Harmonic Oscillator w.f.