Linking QCD with Hypernuclear Physics

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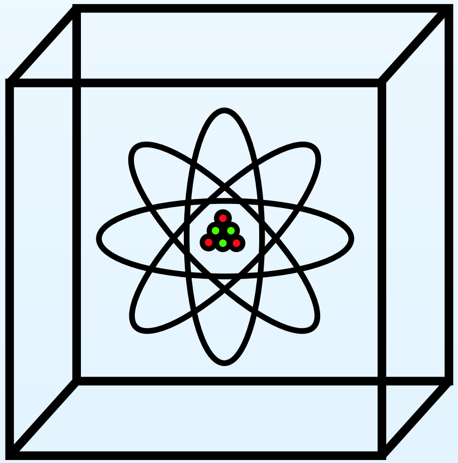

Outline

- Motivation
- Hierarchies of Scales
- Unphysical Simulations
  - Partial quenching
  - Finite-a
- Nuclear Physics
  - Finite-L: EFT $\not\pi$ in a Box
  - NN scattering
  - ΛN scattering
  - Hyperon nonleptonic decays
- Conclusions

Motivation

The Goal

$$\mathcal{L}_{QCD} \Longrightarrow \text{Hadronic and Nuclear Data}$$

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The Present

$$< \Lambda N \,|\exp\left(i \int \mathcal{L}_{QCD}\right)|\, \Lambda N \; > \equiv < \Lambda N \,|\exp\left(i \int \mathcal{L}_{QCD}^{EFT}\right)|\, \Lambda N \; >$$

$$\mathcal{L}_{QCD}^{EFT} \quad \Longleftrightarrow \quad \text{Hadronic and Nuclear Data}$$

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$$\mathcal{L}_{QCD}^{EFT} \quad \Longleftrightarrow \quad \text{Hadronic and Nuclear Data}$$

The Future

$$\mathcal{L}_{QCD}^{LATT} \quad \Longleftrightarrow \quad \mathcal{L}_{QCD}^{EFT} \quad \Longleftrightarrow \quad \text{Hadronic and Nuclear Data}$$

Hierarchies of Scales

QCD:

$$m_\pi \sim M_\Delta - M_N \ll \Lambda_\chi \sim M_N : \quad \frac{p}{\Lambda_\chi}, \quad \frac{m_q}{\Lambda_\chi}, \; \ldots$$

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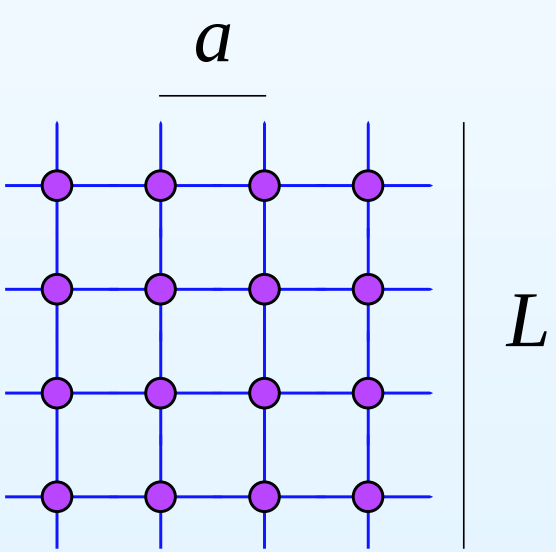

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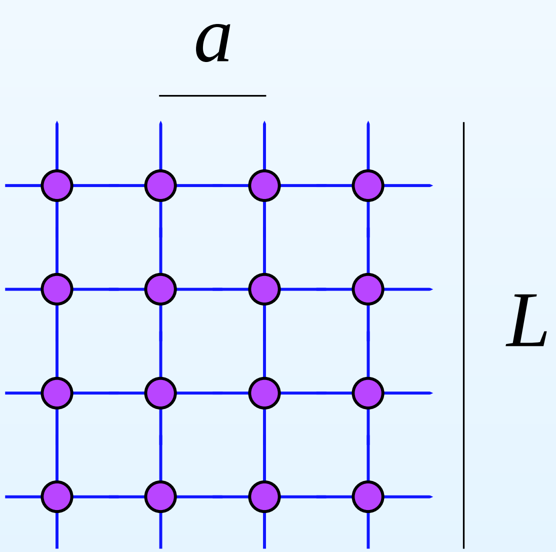

$$L^{-1} \ll m_\pi \ll \Lambda_\chi \ll a^{-1} :$$

$$e^{-m_\pi L}, \quad \frac{1}{L\Lambda_\chi}, \quad \frac{p}{\Lambda_\chi}, \quad \frac{m_q}{\Lambda_\chi}, \quad a\Lambda_\chi$$

Partial Quenching

$$Z_{\rm QCD} = \int [dU] \exp(-S_g) \prod_q \det(\not{D}_{\rm lat} + m_{q_S})$$

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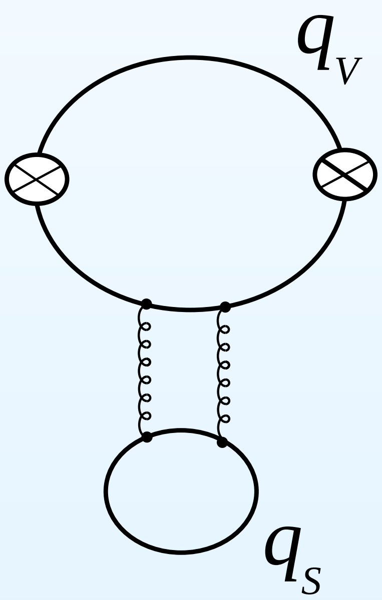

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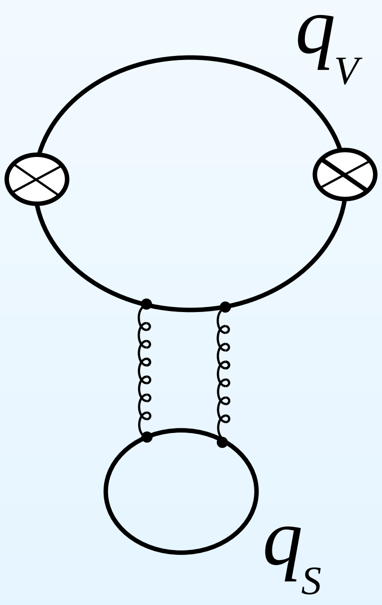

- $m_{q_S} \to \infty$: Quenched limit
- $m_{q_S} \neq m_{q_V}$: Partial-Quenching
- $m_{q_S} = m_{q_V}$: QCD limit

Partially-Quenched QCD

$$m_{q_S} \neq m_{q_V}$$

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$$\mathcal{L}_{PQQCD} = \sum_{k,n=u,d,\tilde{u},\tilde{d},j,l} \overline{Q}^k \left[i\not{D} - m_Q \right]_k^n Q_n$$

$$Q = (u, d, j, l, \tilde{u}, \tilde{d})^T \in \square \text{ of } SU(4|2)_V$$

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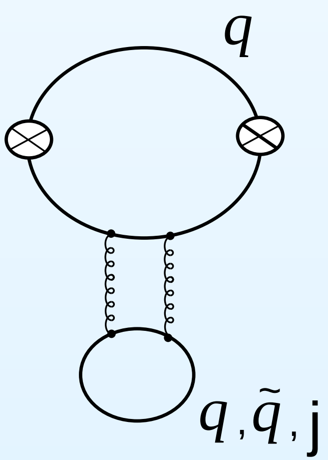

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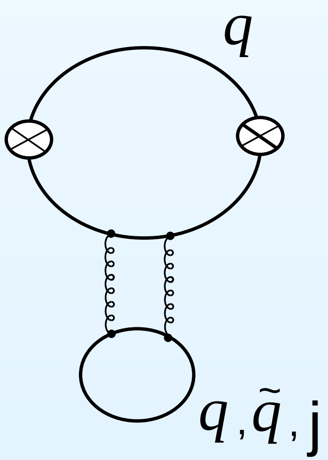
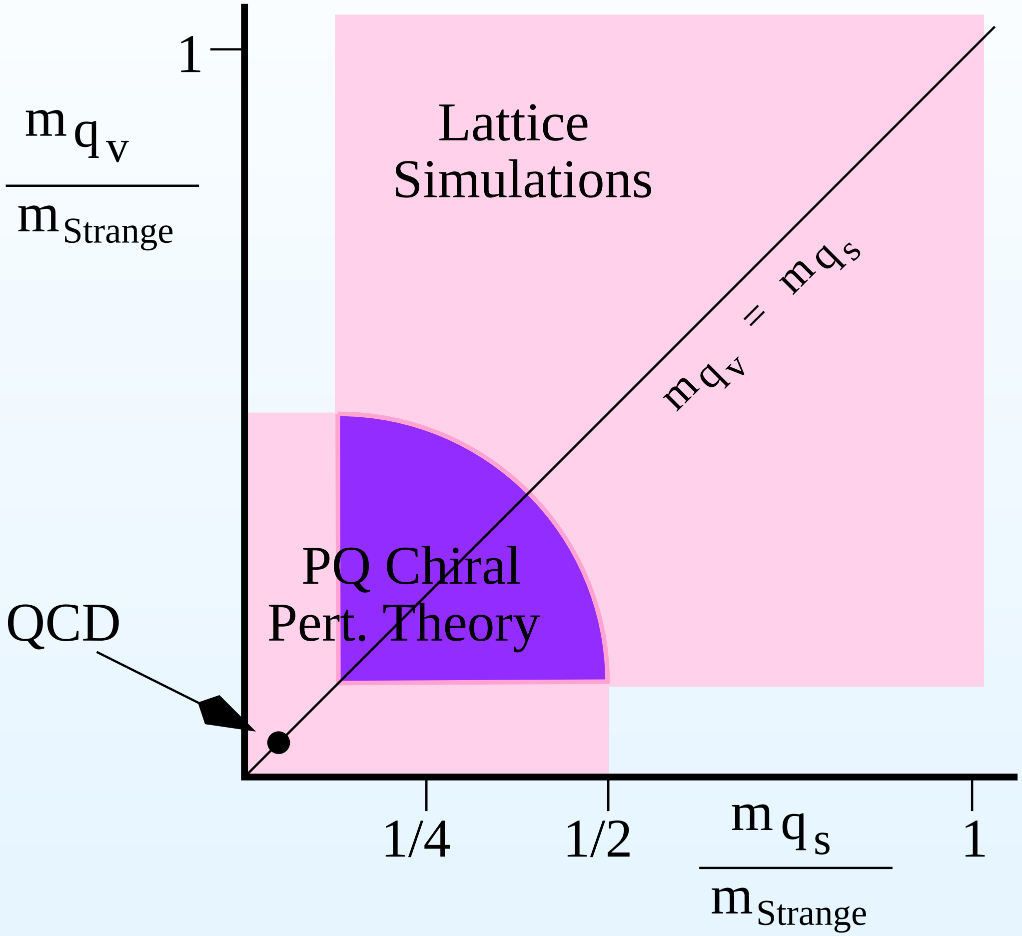


- $Q_i(\mathbf{x})Q_k^\dagger(\mathbf{y}) - (-)^{\eta_i\eta_k} Q_k^\dagger(\mathbf{y})Q_i(\mathbf{x}) = \delta_{ik}\delta^3(\mathbf{x}-\mathbf{y})$
- $SU(4|2)_L \otimes SU(4|2)_R \rightarrow SU(4|2)_V$
  χPT $\Longrightarrow$ PQχPT
- Sick but chiral parameters are physical!
  Sharpe,Shoresh (2000)

The Sharpe Plot



- COST $\sim \ (m_{q_S})^{-2.5}$
- $L \ < \ 4$ fm
- $a \ < \ .2$ fm
- $0.3 < m_q/m_{Strange} < 1.2$

Finite Lattice Spacing

Rupak, Shoresh (2002)   Sharpe, Singleton (1998)

Symanzik action:

$$\mathcal{O}(a): \quad \mathcal{L}_{QCD}^{EFT} = \overline{\psi}\,(\not{D} + m_q)\,\psi \;+\; a c_{sw} \overline{\psi} \sigma^{\mu\nu} G_{\mu\nu} \psi$$

Sheikholeslami-Wohlert

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Sheikholeslami-Wohlert

Low-energy theory:

$$\mathcal{L}_{\chi} = \lambda_M \frac{f^2}{4} \mathrm{tr}\left[m_q \Sigma^{\dagger} + m_q \Sigma \right] + \lambda_A \frac{f^2}{4} \mathrm{tr}\left[A_q \Sigma^{\dagger} + A_q \Sigma \right]$$

$$m_{\pi}^2 = \lambda_M \, (m_u + m_d) \; + \; 2\lambda_A \; a \; c_{sw}^{(V)}$$

Finite-a

$\mathcal{O}(a^2)$: Bär, Rupak, Shoresh (2003) Aoki (2003)

- Lorentz-symmetry breaking
- four-quark operators

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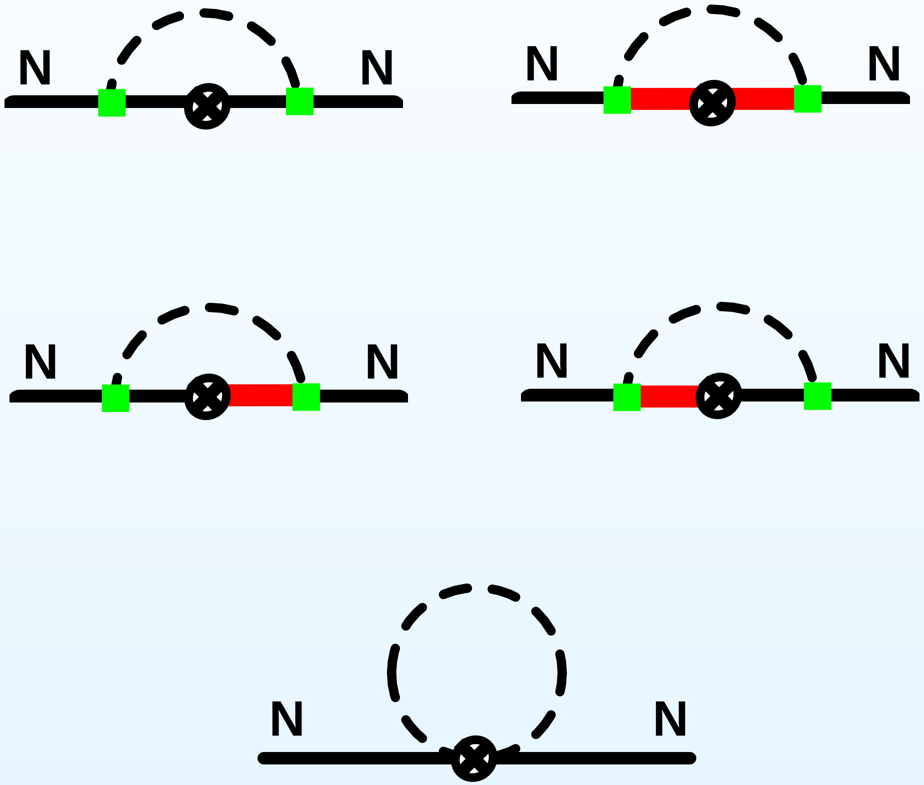
External axial currents: Lüscher *et al* (1996)

$$\mathcal{O}(a): \quad \mathcal{O}^a_{7,\mu} \quad = \quad \overline{q}\,\tau^a\gamma_5\left(i\,\overleftrightarrow{D}_\mu\right)\,q\;, \qquad \mathcal{O}^a_{8,\mu} = \overline{q}\,\tau^a\gamma_\mu\gamma_5\,m_q\,q$$

$\Longrightarrow$ contribute new local operators in the low-energy EFT

Example: g_A

Savage, SB (2003)



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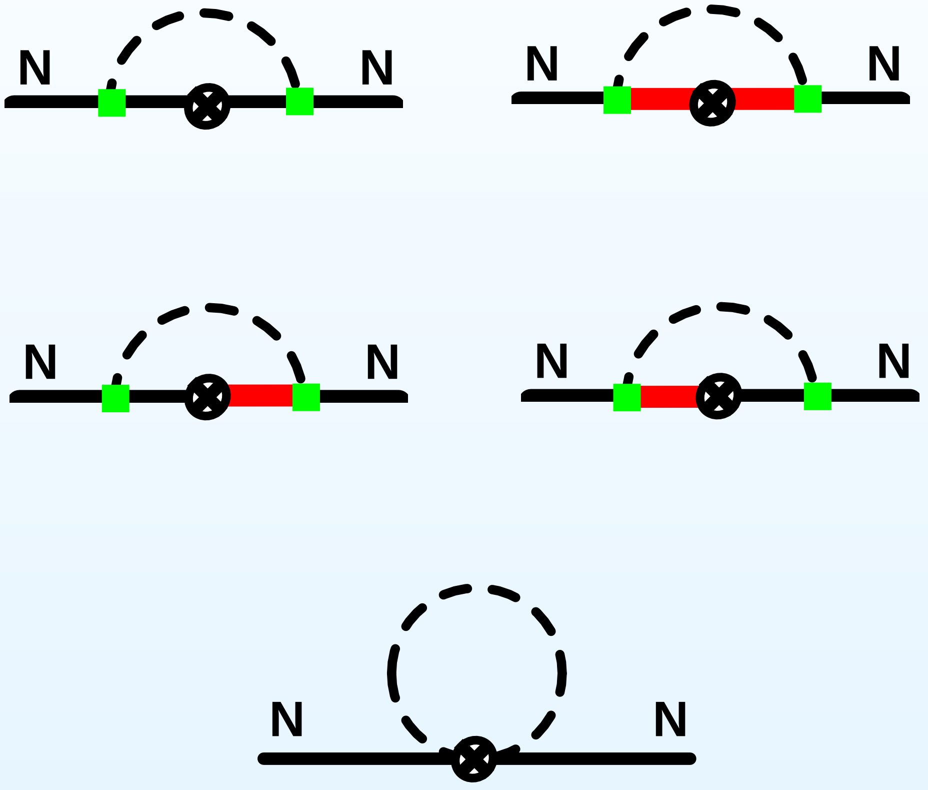


Sources of finite-a:

- Golstone masses
- new contact operators

g_A at Finite-a

$$\langle p | j^3_{\mu,5} | p \rangle =$$

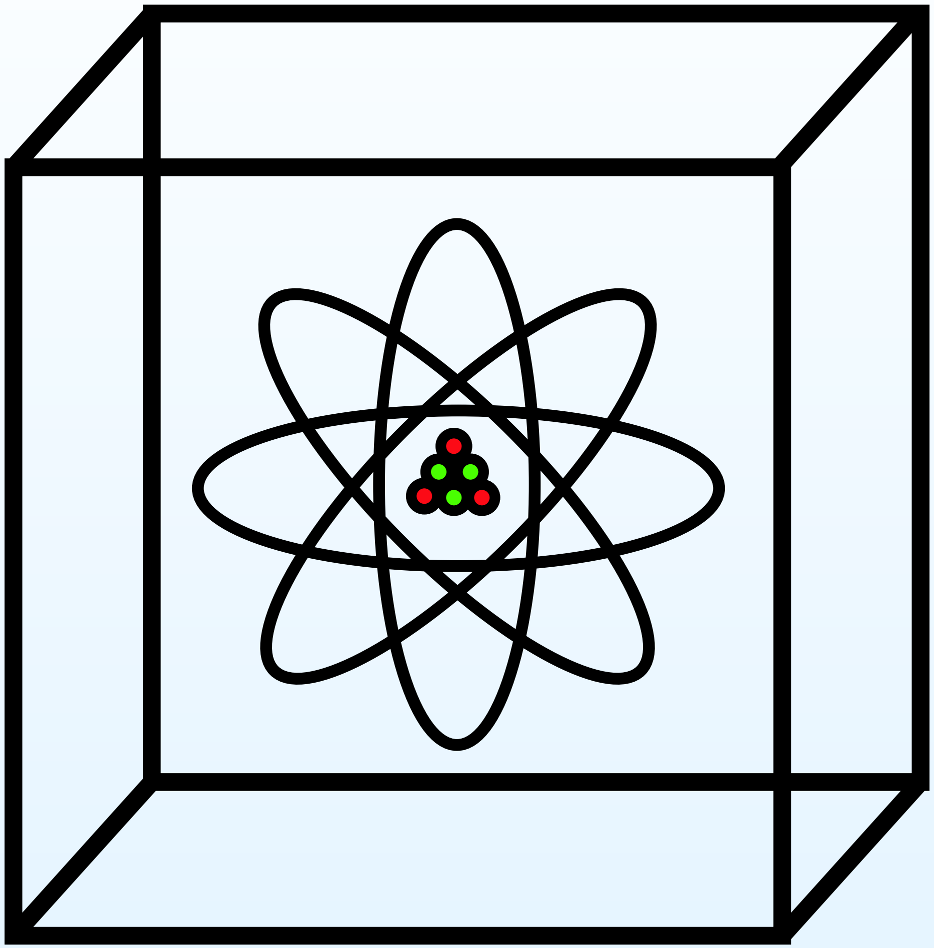
$$g_A \; - \; \frac{1}{8\pi^2 f^2} \left(\, g_A \left(1 + 2 g_A^2 \right) \; L_\pi + (2 g_A + \frac{50}{81} g_{\Delta\Delta}) g^2_{\Delta N} \; J_\pi - \frac{16}{9} g_A g^2_{\Delta N} \; K_\pi \right)$$

$$+ \; \frac{\overline{m}}{3} b_{1,7,M} + \frac{a c^{(V)}_{sw}}{3} b_{1,5,A} \; + \; \frac{2 a c^{(S)}_{sw}}{3} b_{6,7,A}$$

$$+ \; \frac{a c^{(V)}_{A7}}{3} \gamma_{A,1,2} \; + \; (y_j + y_l) b_{8,A} \left(a c^{(S)}_{sw} \; - a c^{(V)}_{sw} \right)$$

coefficients fit to lattice QCD data

Nuclear Physics



Nuclear Scales

QCD:

$$B_d,\ a_s^{-1} \ll m_\pi \ll \Lambda_\chi :$$

- EFT π: $\frac{p}{\Lambda_\chi}$, $\frac{m_q}{\Lambda_\chi}$
- EFT $\not\pi$: $\frac{p}{m_\pi}$, $\frac{1}{a_s m_\pi}$

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Lattice QCD:

$$B_d,\ a_s^{-1} \ll L^{-1} \ll m_\pi \ll \Lambda_\chi \ll a^{-1}$$

$\frac{L}{a_s}$!

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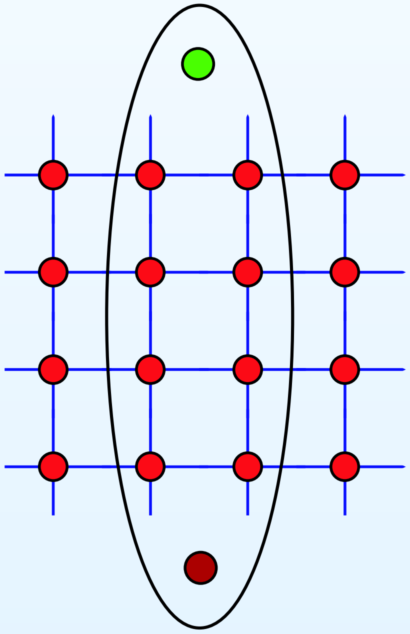

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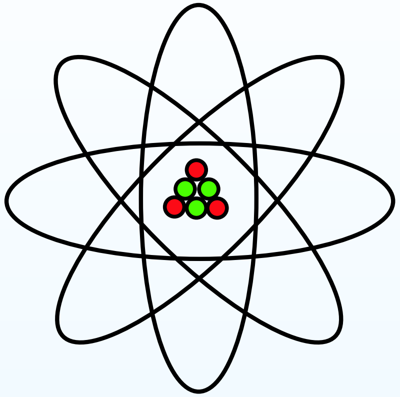
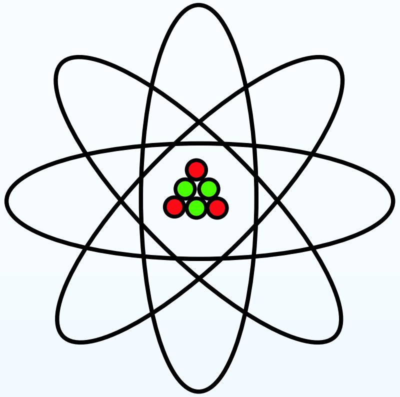


from lattice QCD?



from lattice QCD?

- S-matrix elements from finite volumes

  EFT $\not\pi$ in a Box

  NN$\rightarrow$ NN

  ΛN $\rightarrow$ ΛN
- Hypernuclear decays and the Hyperon puzzle

EFT $\not\pi$ in a Box

$p \ll m_\pi \quad \Longrightarrow \quad$ Integrate out the pion

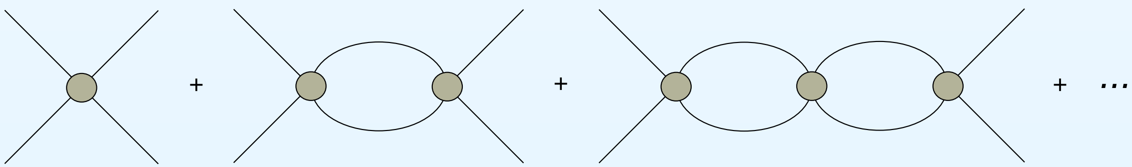
EFT $\not\pi$ in a Box

$$p \ll m_\pi \qquad \Longrightarrow \qquad \text{Integrate out the pion}$$

EFT of contact operators:

$$\mathcal{L} = -\, C_0\, (N^\dagger N)^2 - \, C_2\, (N^\dagger \nabla^2 N)(N^\dagger N) + h.c. + \ldots$$

S-matrix =



Unitary in (partially-)quenched theory!

Lüscher's formula

Lüscher (1986)

$$\int \to \sum$$

$L \gg a_s, r_s$:

$$E_0 = +\frac{4\pi a_s}{M_N L^3}\left[1 - c_1\left(\frac{a_s}{L}\right) + c_2\left(\frac{a_s}{L}\right)^2 + \ldots\right]$$

$$E_1 = \ldots$$

$$c_1 = -2.837297 \qquad c_2 = 6.375183$$

Exact eigenvalue equation

Lüscher (1986)

$R_V \ll L$:

$$p\cot\delta(p) \;-\; \frac{1}{\pi L}\sum_{\mathbf{j}}^{\Lambda_j}\frac{1}{|\mathbf{j}|^2-(\frac{Lp}{2\pi})^2} \;+\; \frac{4\Lambda_j}{L} \;=\; 0$$

$$\Lambda_j \to \infty$$

$p^2 = M\;E$ gives all energy-eigenstates in the box

$$p\cot\delta \;=\; -\frac{1}{a} \;+\; \frac{1}{2}\,r\,p^2 \;+\; \ldots$$

The Infrared Fixed Point

Bedaque,Parreño,Savage,SB (2003)

$a_s \gg L \gg r_s$:

$$E_0 = +\frac{4\pi^2}{M_N L^2}\left[-0.095896 - 0.025434\left(\frac{L}{a_s}\right) + \ldots\right]$$

$$E_1 = \ldots$$

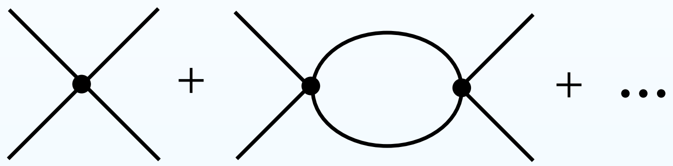
Appropriate limit for nuclear physics?

$$a_s^{^1S_0} = -23.714 \text{ fm} \qquad r_s^{^1S_0} = 2.73 \text{ fm}$$

$$a_s^{^3S_1} = 5.425 \text{ fm} \qquad r_s^{^3S_1} = 1.749 \text{ fm}$$

Near unstable infrared fixed point of QCD

$^1S_0$ of NN at NLO

LO : 

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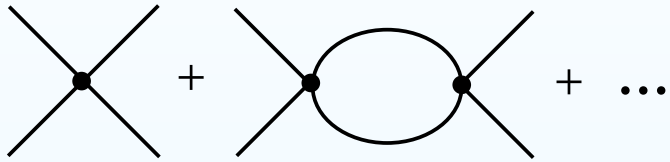

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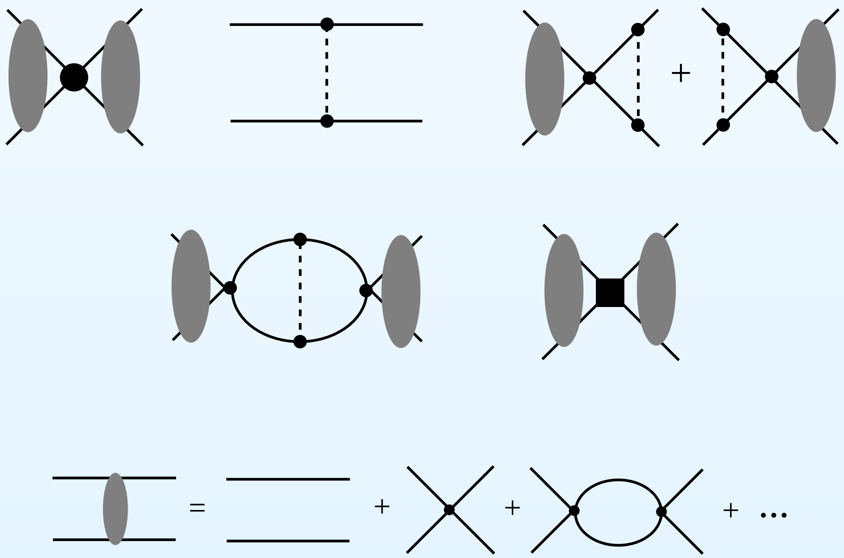

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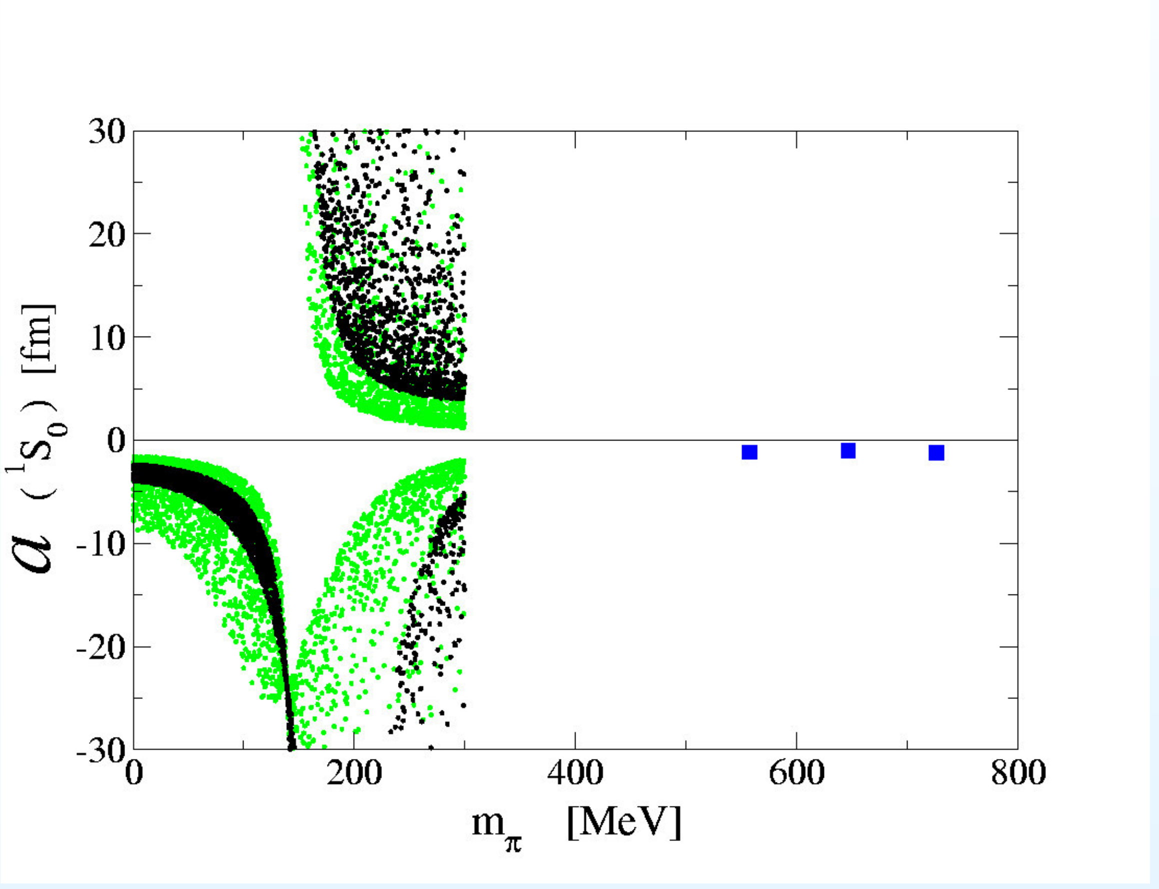
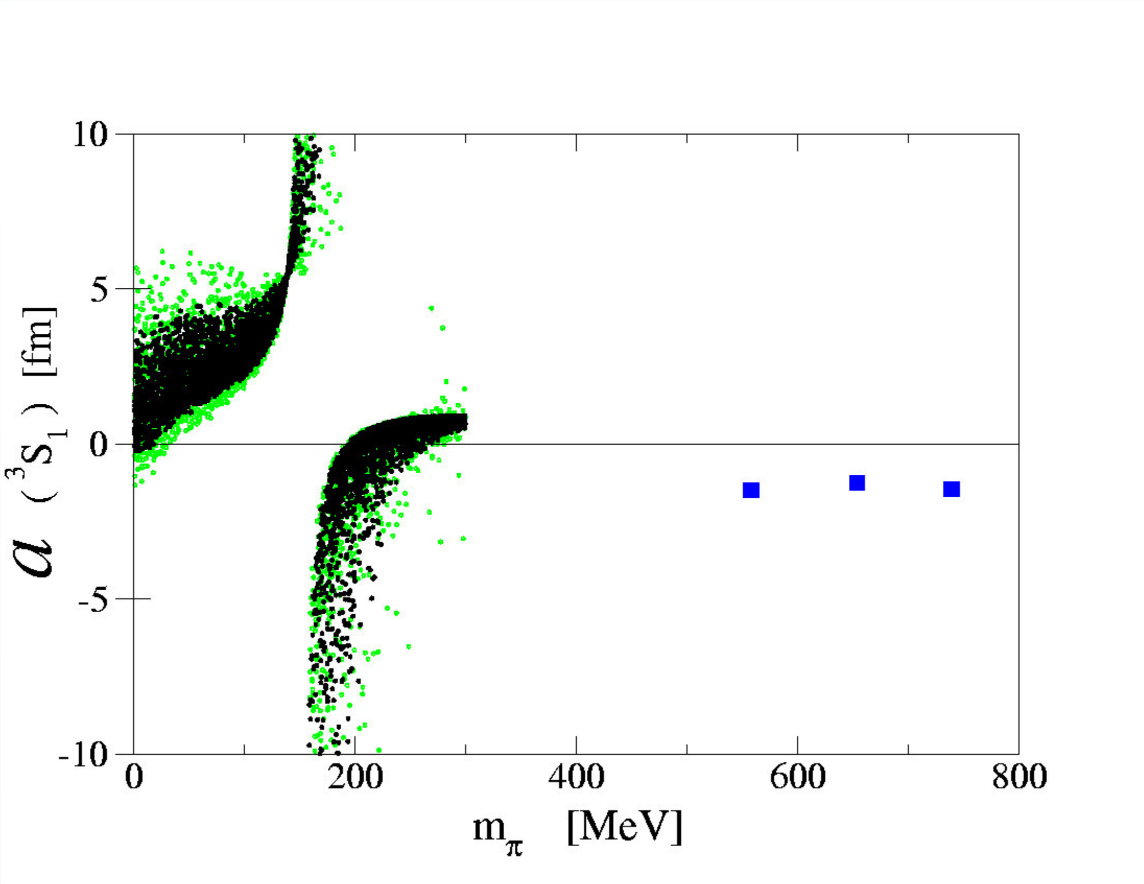
Savage, SB (2003)



$D_2 = 1/5, 1/15$

Lattice data : QQCD from Fukugita (1995)

$^3S_1$ of NN



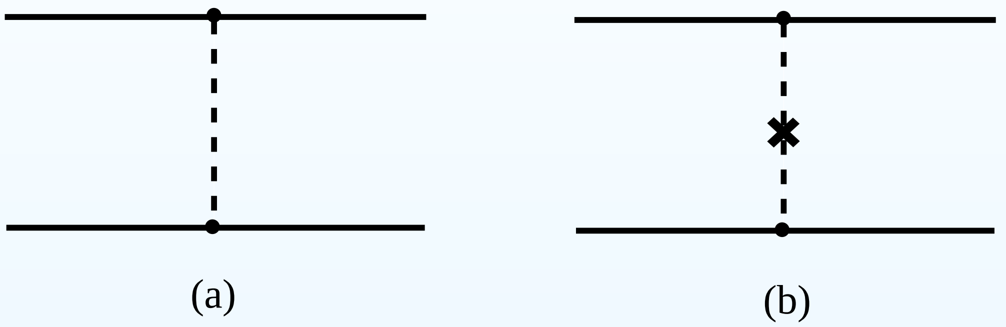
$$D_2 = 1/5, 1/15$$

$$-2.61\ \text{GeV}^{-2} < \bar{d}_{16} < -0.17\ \text{GeV}^{-2} \qquad \bar{d}_{18} = -1.54\ \text{GeV}^{-2}$$

Quenching NN

Savage,SB (2002)

PROBLEM:



PQQCD:

$$V(r) \rightarrow -\frac{g_0^2}{16\pi f^2}\, \sigma_1 \cdot \hat{\mathbf{r}}\, \sigma_2 \cdot \hat{\mathbf{r}}\, m_\pi\, e^{-m_\pi r}\, \left(m_{SS}^2 - m_\pi^2\right)$$

Dominates over Yukawa at large r!!

Destroys fine-tuning!

PQ Scattering Lengths

Savage,SB (2002)

$$\frac{1}{a^{(^1S_0)}} = \gamma - \frac{M_N}{4\pi}(\mu-\gamma)^2 D_2^{(^1S_0)}(\mu)\, m_\pi^2 - \frac{M_N}{4\pi}(\mu-\gamma)^2 D_{2B}^{(^1S_0)}(\mu)\left(m_{SS}^2 - m_\pi^2\right)$$
$$+ \frac{g_A^2 M_N}{8\pi f^2}\left[m_\pi^2 \log\left(\frac{\mu}{m_\pi}\right) + (m_\pi-\gamma)^2 - (\mu-\gamma)^2 \right]$$
$$+ \frac{g_0^2 M_N}{8\pi f^2}\left(m_{SS}^2 - m_\pi^2 \right)\left[\log\left(\frac{\mu}{m_\pi}\right) + \frac{1}{2} - \frac{\gamma}{m_\pi} \right]$$

D_2 is unknown!

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D_2 is unknown!

$$a(^1P_1) = \frac{g_A^2 M_N}{4\pi f^2 m_\pi^2} + \frac{g_0^2 M_N}{12\pi f^2 m_\pi^2}\,\frac{m_{SS}^2 - m_\pi^2}{m_\pi^2}$$

Hypernuclear physics

Bedaque,Parreño,Savage,SB (2003)

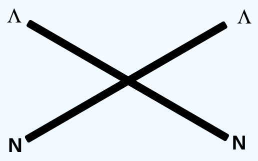
$\Lambda N \rightarrow \Lambda N$ in QCD

Hypernuclear physics

Bedaque,Parreño,Savage,SB (2003)

$\Lambda N \to \Lambda N$ in QCD

LO :



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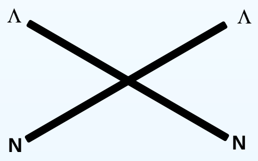
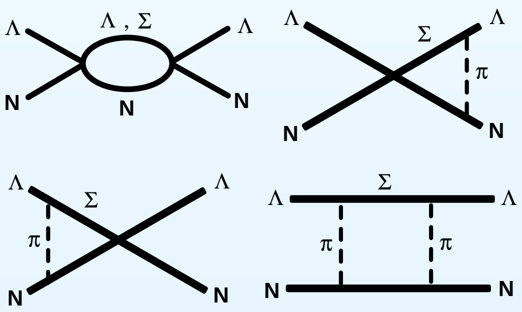


NLO :



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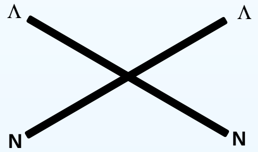

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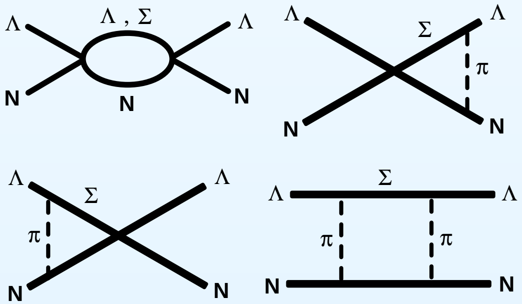

Two parameters at NLO:

- ${}_{\Sigma\Lambda}C_0$
- ${}_{\Lambda\Lambda}C_0$

Match to a_s and r_s at Finite-L!

Can lattice QCD compete with experiment?

Experimental Situation

R. Timmermans, *p.c.*

$$
\begin{array}{rcccl}
0.0 & > & a^{(^1S_0)} & > & -15\ \mathrm{fm} \\
-0.6 & > & a^{(^3S_1)} & > & -3.2\ \mathrm{fm}
\end{array}
\qquad
\begin{array}{rcccl}
0.0 & > & r^{(^1S_0)} & > & 15\ \mathrm{fm} \\
2.5 & > & r^{(^3S_1)} & > & 15\ \mathrm{fm}
\end{array}
$$

..from CERN bubblechambers in the late 60's..

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\end{array}
$$

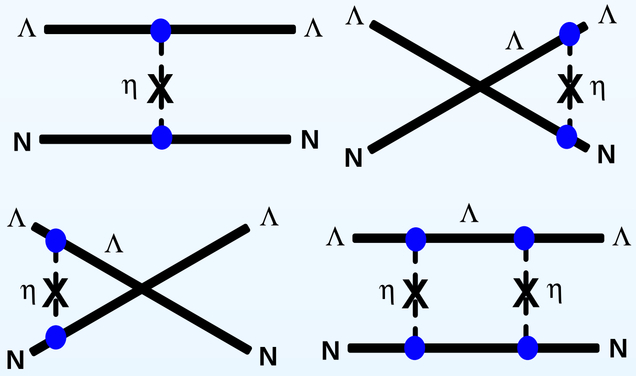
..from CERN bubblechambers in the late 60's..

What do we know?

- $a^{(^1S_0)} < 0, \quad a^{(^3S_1)} < 0$ no hyperdeuteron!
- $|a^{(^1S_0)}| > |a^{(^3S_1)}|$
- a, r may be natural or unnatural

$\Lambda N \to \Lambda N$ in PQQCD

Hairpins!



Dominate r_s..

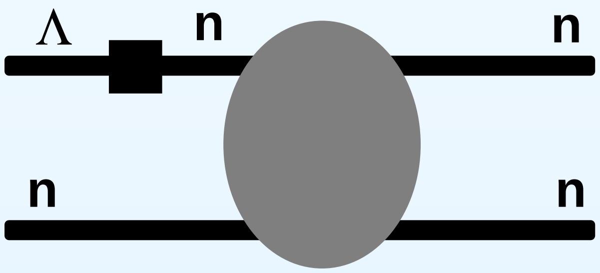
Hypernuclear decay

Parreño,Bennhold,Holstein (2003)

Hypernuclear decay

Parreño,Bennhold,Holstein (2003)

Reasonable fits in $SU(3)$ χ-PT to ${}^{5}_{\Lambda}He$, ${}^{11}_{\Lambda}B$ and ${}^{12}_{\Lambda}C$



Hypernuclear decay

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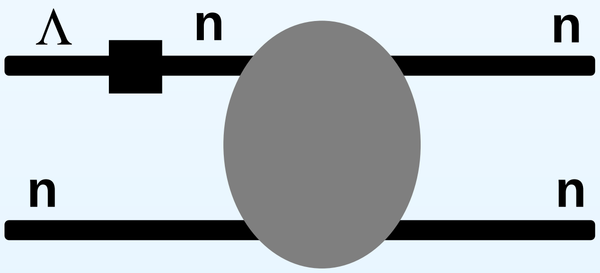

Issues:

- $p \sim 420$ MeV
- Hyperon non-leptonic decays in $SU(3)$

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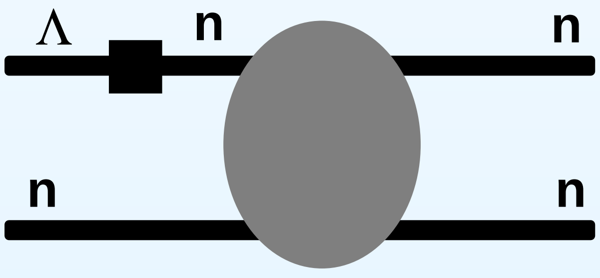

Issues:

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Do problems in Hyperon non-leptonic decays persist in $SU(2)$?

Primer on the Hyperon Puzzle

$$\mathcal{M} \quad \sim \quad \mathcal{A}^{(S)} \quad + \quad \vec{\sigma}\cdot\hat{k} \quad \mathcal{A}^{(P)}$$

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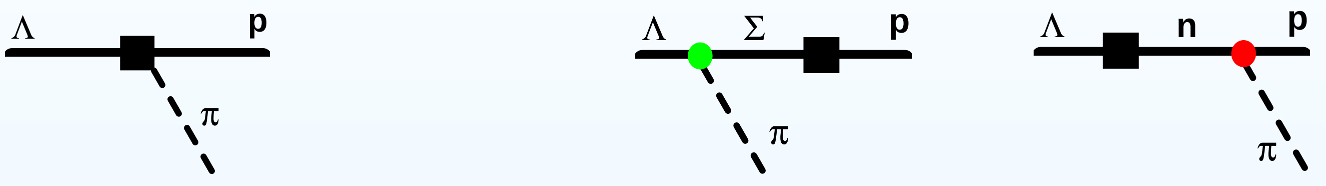

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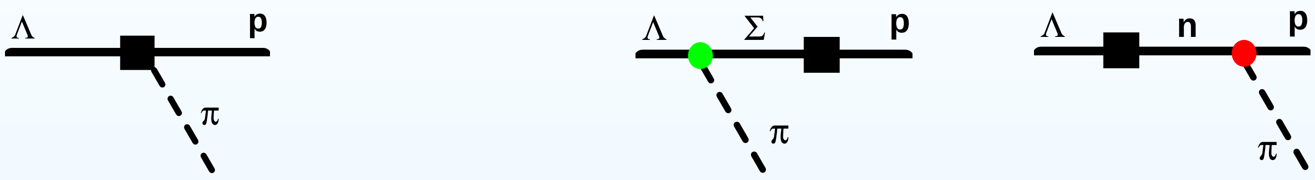

$$SU(3)\ \chi - \mathrm{PT}: \quad \mathcal{A}^{(S,P)}(D, F, h_D, h_F)$$

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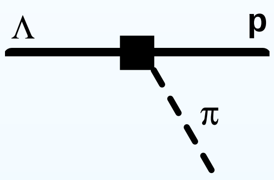

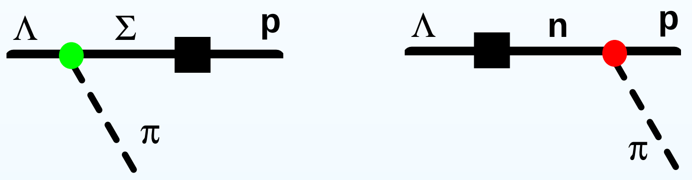

$$SU(3)\ \chi-\mathrm{PT}: \quad \mathcal{A}^{(S,P)}(D,F,h_D,h_F)$$

Decay	$\mathcal{A}^{(S)}$ LO	NLO	Expt	$\mathcal{A}^{(P)}$ LO	NLO	Expt
$\Lambda \to p\pi^-$	1.48	1.44	1.42 ± 0.01	0.59	-0.73 ± 0.18	0.52 ± 0.02
$\Sigma^- \to n\pi^-$	1.98	1.89	1.88 ± 0.01	-0.30	0.46 ± 0.21	-0.06 ± 0.01
$\Sigma^+ \to n\pi^+$	0.0	0.01	0.06 ± 0.01	0.16	-0.18 ± 0.21	1.81 ± 0.01
$\Xi^- \to \Lambda\pi^-$	-1.95	-2.01	-1.98 ± 0.01	-0.19	0.52 ± 0.29	0.48 ± 0.02

$SU(2)$

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$$SU(2)\ \chi - \mathrm{PT}: \quad \mathcal{A}^{(S,P)}(g_A, g_{\Sigma\Lambda}, g_{\Sigma\Sigma}, h_\Lambda, h_\Sigma)$$

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Decay	$\mathcal{A}^{(S)}$ Theory	Expt	$\mathcal{A}^{(P)}$ Theory	Expt
$\Lambda \to p\pi^-$	1.42 (input)	1.42 ± 0.01	0.56	0.52 ± 0.02
$\Sigma^- \to n\pi^-$	1.88 (input)	1.88 ± 0.01	$-0.50 \to -0.14$	-0.06 ± 0.01
$\Sigma^+ \to n\pi^+$	0.0	0.06 ± 0.01	$+0.42 \to +0.08$	1.81 ± 0.01

$$0.30 \lesssim g_{\Sigma\Sigma} \lesssim 0.55$$

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$$0.30 \lesssim g_{\Sigma\Sigma} \lesssim 0.55$$

Can lattice QCD help?

- $g_{\Sigma\Sigma}$
- h_Λ, h_Σ
- $\Lambda \to p\pi$, etc.

Conclusions

- Lattice QCD scales: gauge-invariant IR (L) and UV (a) cutoffs.
- Scales sufficiently separated to allow EFT construction.
- Cost and desirability of “knobs” suggest (partial-)quenching.
- Finite-a effects calculable in EFT.
- The m_q dependence of NN depends on parameter not constrained by experiment.
- The ΛN phase shifts are poorly known.
- Finite-L trickery will allow extraction of low-energy NN and ΛN S-matrices.
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The Future

$$\mathcal{L}_{QCD}^{LATT} \Longleftrightarrow \mathcal{L}_{QCD}^{EFT} \Longleftrightarrow \text{Hadronic and Nuclear Data}$$