Pion-mass dependence of light nuclei.

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יוהנס קירשר

N. Barnea, D. Gazit, U. v. Kolck

Proper references in arXiv:1509.07697 [nucl-th]

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$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}W^b_{\mu\nu}W^{b,\mu\nu} - \frac{1}{2}G^a_{\mu\nu}G^{a,\mu\nu} \\
& + (\overline{\nu}_L, \overline{e}_L)\tilde{\sigma}^\mu i D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \overline{e}_R \sigma^\mu i D_\mu e_R + \overline{\nu}_R \sigma^\mu i D_\mu \nu_R + (\text{h.c.}) \\
& - \frac{\sqrt{2}}{v}\left[(\overline{\nu}_L, \overline{e}_L)\phi M^e e_R + \overline{e}_R \overline{M}^e \overline{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] \\
& - \frac{\sqrt{2}}{v}\left[(-\overline{e}_L, \overline{\nu}_L)\phi^* M^\nu \nu_R + \overline{\nu}_R \overline{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] \\
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\end{aligned}
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Motivation: Fundamental, elegant, and simple theory of nuclei.

arXiv:1509.07697 [nucl-th]

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Parametrization of

i) shell structure (relatively deep α nucleus)

ii) spectral peculiarities (drip line, particle-unstable nuclei)

iii) nuclear response to external probes (electro-weak, gravitation)

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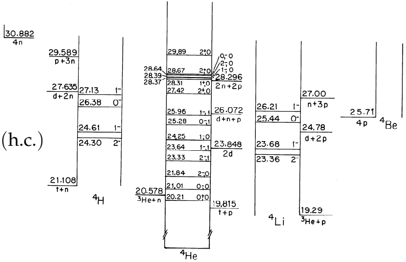

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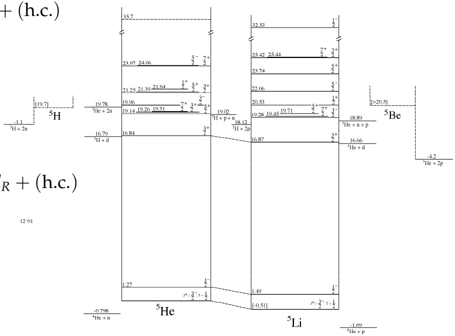

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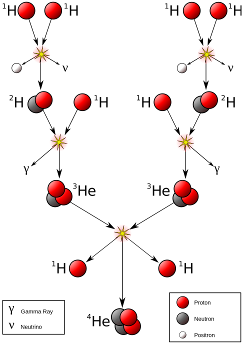

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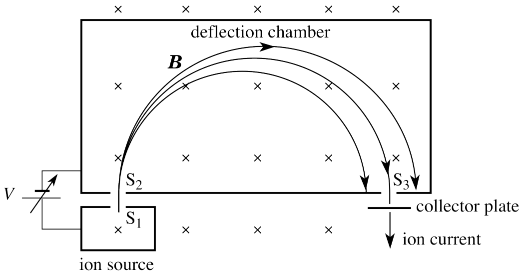
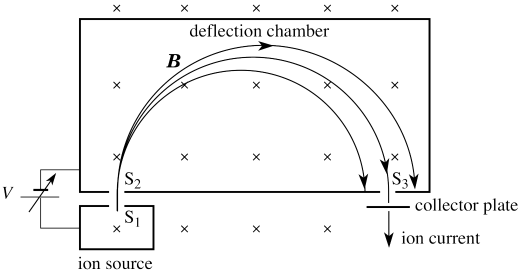
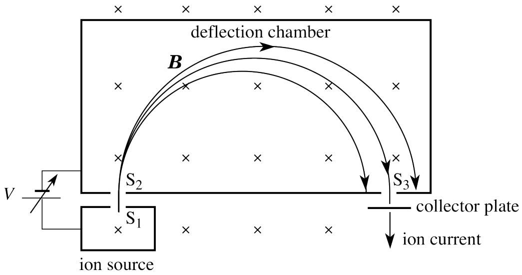

deflection chamber
B
V
S2
S1
S3
collector plate
ion current
ion source



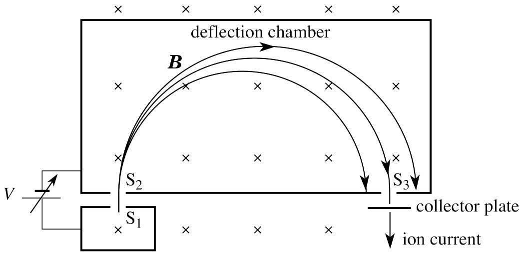
$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A_\mu \mathcal{O} e^{-\int d^4x \left(\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \sum_f \log(\mathrm{Det} M_f)\right)}$$



A hadron prepared at the source

$$\overline{N}^{\alpha}_{\text{source}}(\mathbf{0}, t_0) = \epsilon_{abc}(u^{a,T} C\gamma_5 d^b) u^{c,\alpha}(\mathbf{0}, t_0)$$

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A_\mu \mathcal{O} e^{-\int d^4x (\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \sum_f \log(\text{Det} M_f))}$$



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is detected at the sink.

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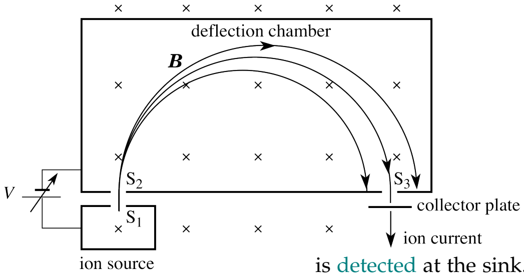

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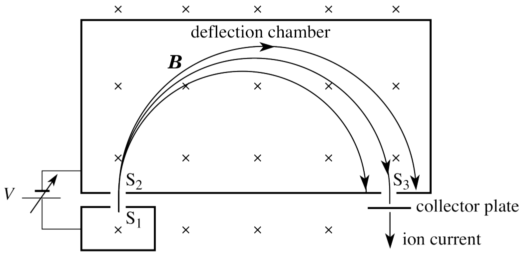

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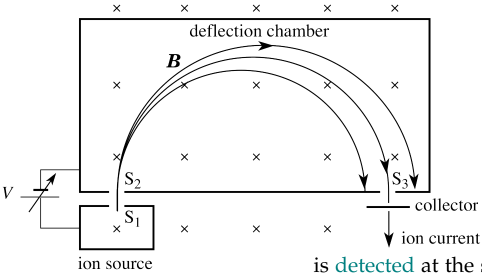

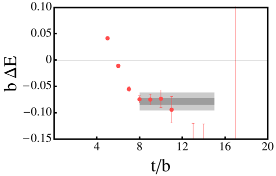

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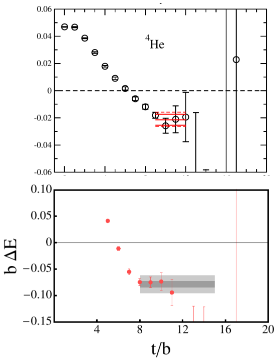
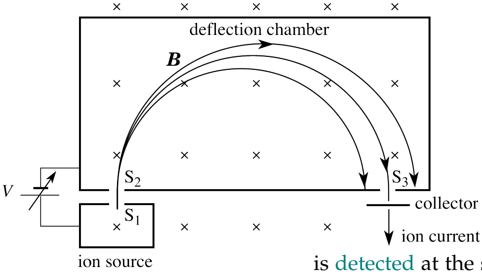
Nuclear amplitudes from lattice QCD.

Bainbridge, HAL, Yamazaki *et al.*, NPLQCD





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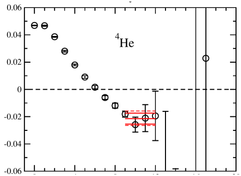
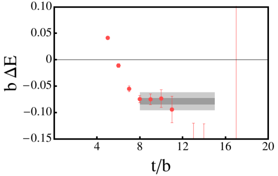
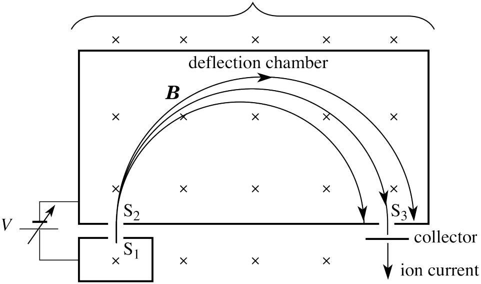
Bainbridge, HAL, Yamazaki *et al.*, NPLQCD





Systematic finite-volume error $\propto e^{-m_\pi L}$



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Nuclear amplitudes from lattice QCD.

Bainbridge, HAL, Yamazaki *et al.*, NPLQCD

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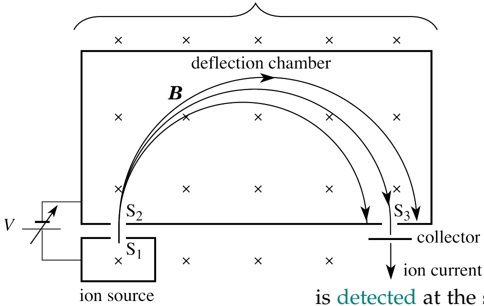

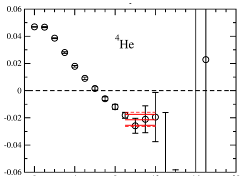

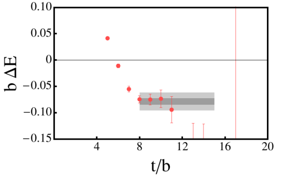

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Statistical monte-carlo-sampling error

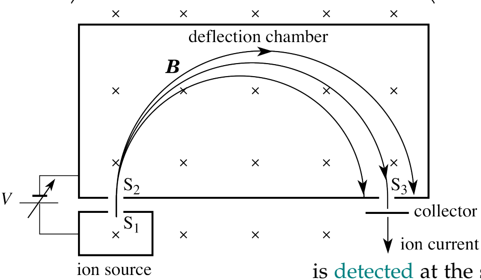
Nuclear amplitudes from lattice QCD.

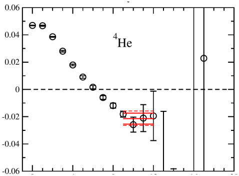
Bainbridge, HAL, Yamazaki *et al.*, NPLQCD

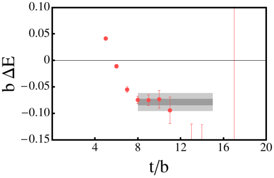
Measure/calculate in an alternate universe with identical symmetry but heavier quark/pion mass

$(M_\pi^+)^2 = B_\pi(m_u + m_d) + C_\pi(m_u + m_d)^2 + \dots$

Systematic finite-volume error $\propto e^{-m_\pi L}$







A hadron prepared at the source

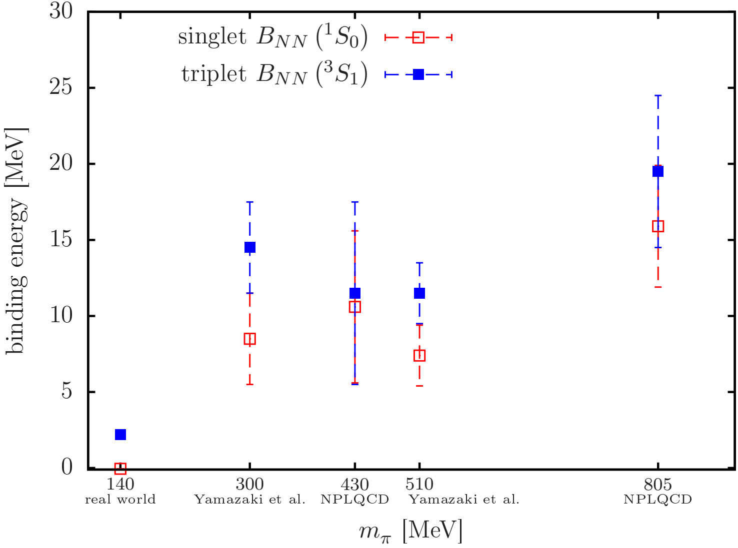
$\overline{N}^{\alpha}_{\text{source}}(\mathbf{0}, t_0) = \epsilon_{abc}(u^{a,T} C\gamma_5 d^b)u^{c,\alpha}(\mathbf{0}, t_0)$

is detected at the sink.

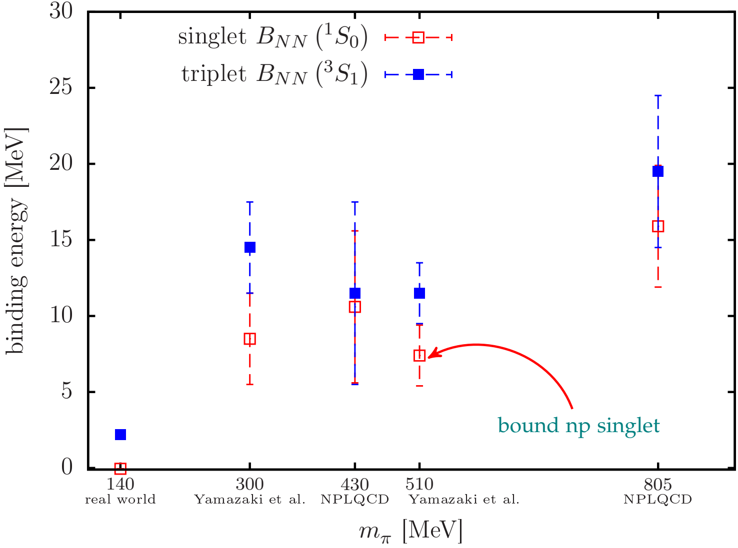
$N^{\alpha}_{\text{sink}}(\boldsymbol{x}, t) = \epsilon_{abc}(u^{a,T} C\gamma_5 d^b)u^{c,\alpha}(\boldsymbol{x}, t)$

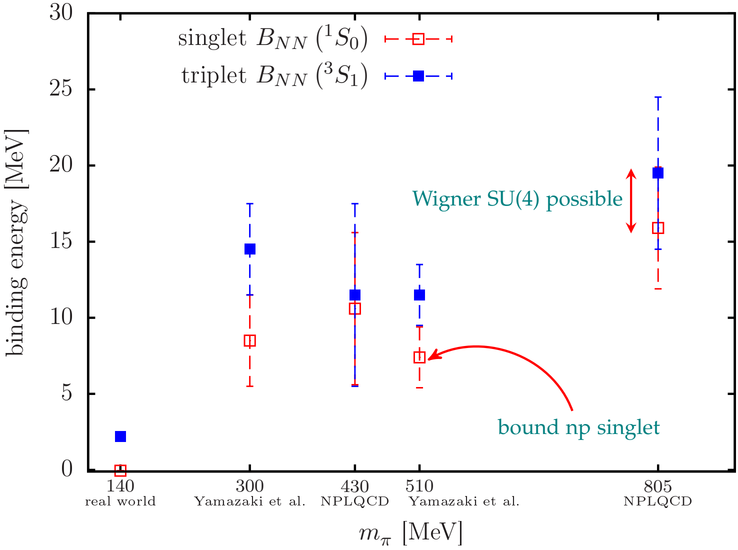
$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A_\mu\, \mathcal{O} e^{-\int d^4x\left(\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \sum_f \log(\mathrm{Det}M_f)\right)} = \sum_n \frac{\langle 0|N_{\text{sink}}|n\rangle\langle n|N_{\text{source}}|0\rangle}{2E_n} e^{-E_n(t-t_0)}$$

Statistical monte-carlo-sampling error


singlet B_{NN} $(^1S_0)$
triplet B_{NN} $(^3S_1)$
binding energy [MeV]
0
5
10
15
20
25
30
140
real world
300
Yamazaki et al.
430
NPLQCD
510
Yamazaki et al.
805
NPLQCD
m_π [MeV]

Lattice QCD measurements of hadron amplitudes at $m_\pi > 140$ MeV.




singlet B_{NN} ($^1S_0$)
triplet B_{NN} ($^3S_1$)
Wigner SU(4) possible
bound np singlet
binding energy [MeV]
0
5
10
15
20
25
30
140
real world
300
Yamazaki et al.
430
NPLQCD
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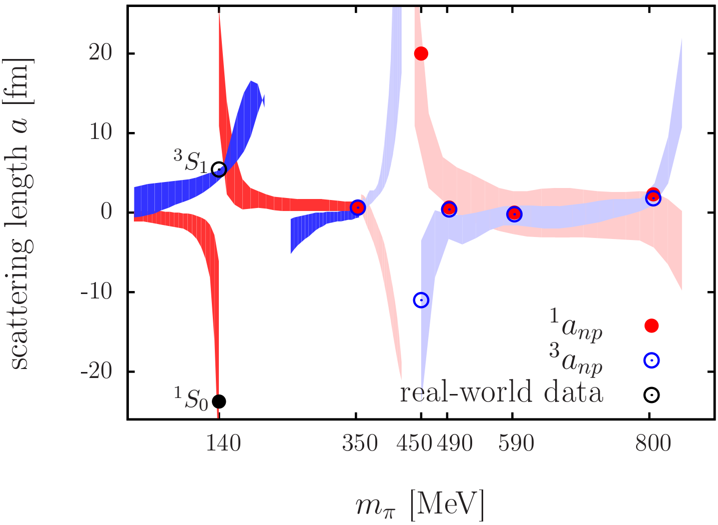
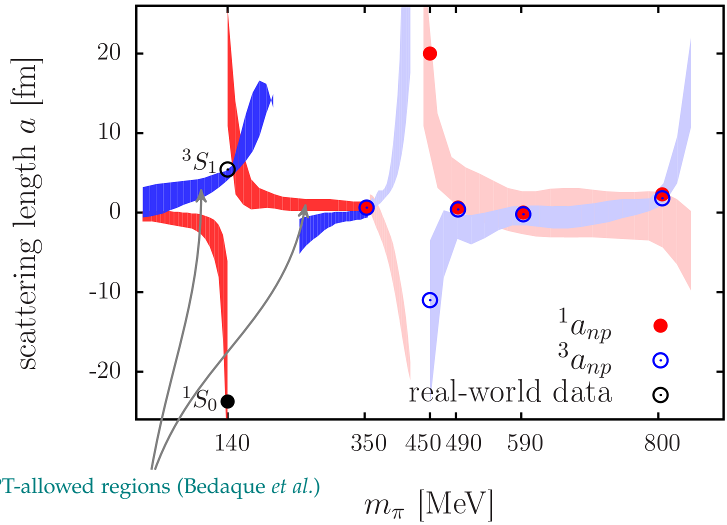
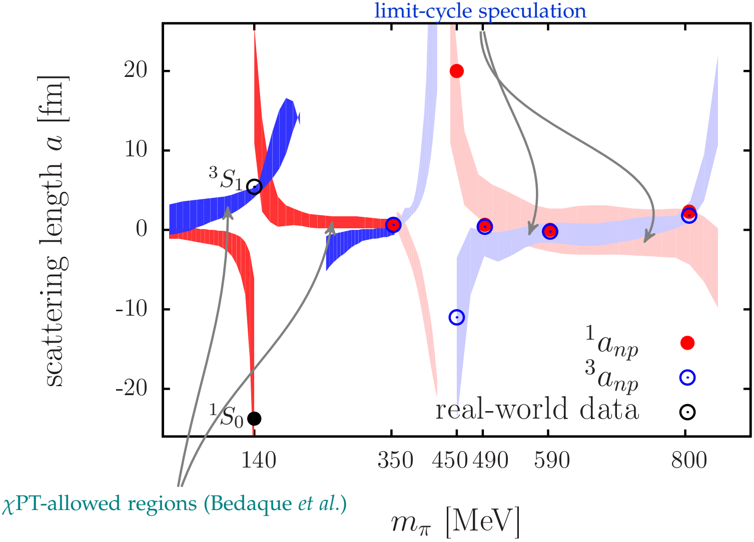
805
NPLQCD
m_π [MeV]


scattering length a [fm]
20
10
0
-10
-20
$^3S_1$
$^1S_0$
$^1a_{np}$
$^3a_{np}$
real-world data
140
350
450
490
590
800
m_π [MeV]



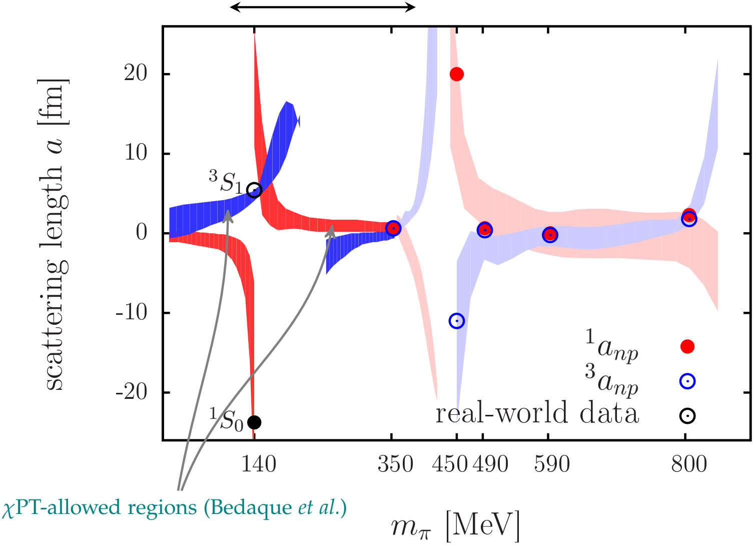
χPT-allowed regions (Bedaque *et al.*)

Lattice QCD measurements of hadron amplitudes at $m_\pi > 140$ MeV.



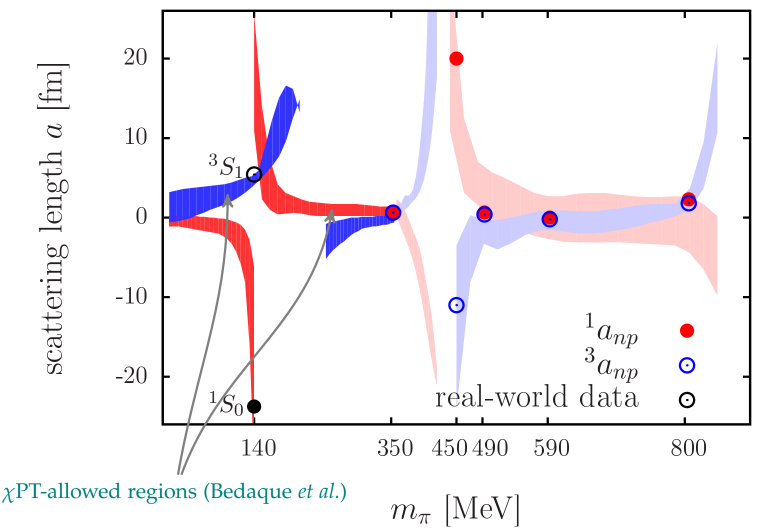
Lattice QCD measurements of hadron amplitudes at $m_\pi > 140$ MeV.

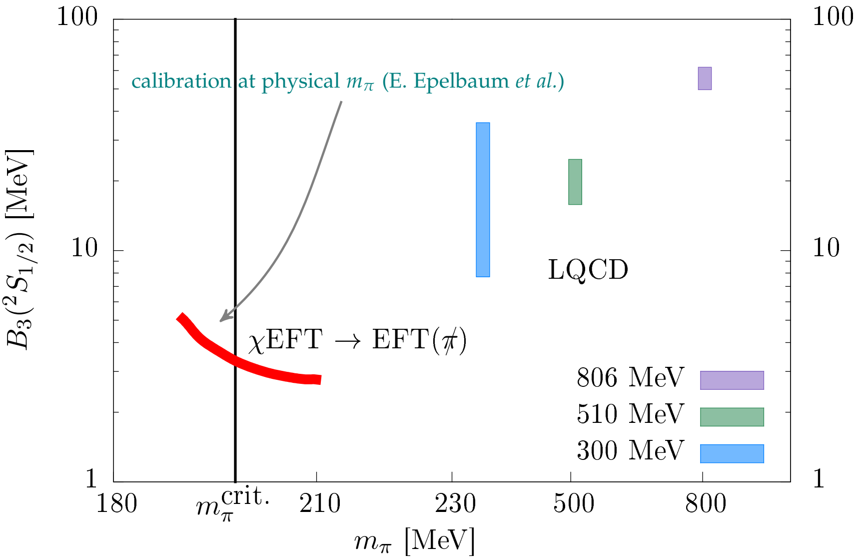
1 bound state for $m_\pi^{(1)}(a \to \infty) < m_\pi < m_\pi^{(2)}(a \to \infty)$

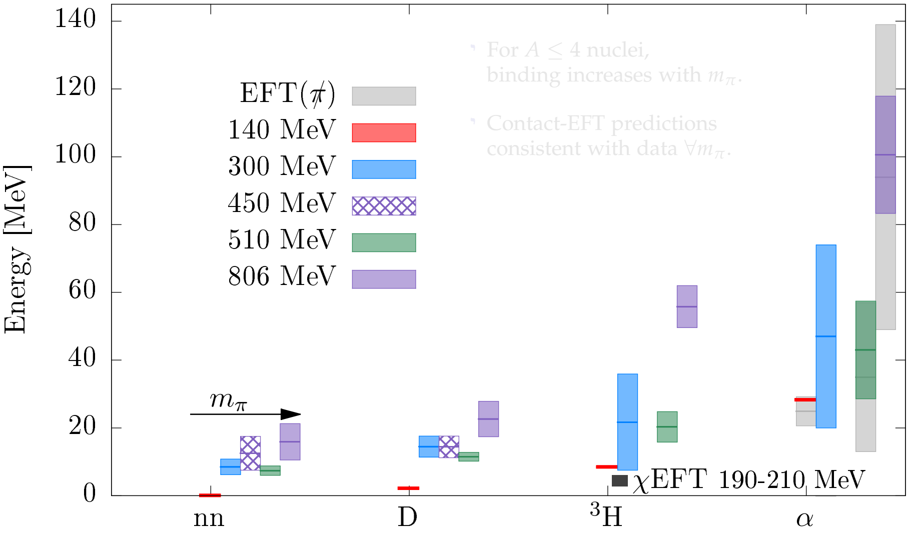


Lattice QCD measurements of hadron amplitudes at $m_\pi > 140$ MeV.

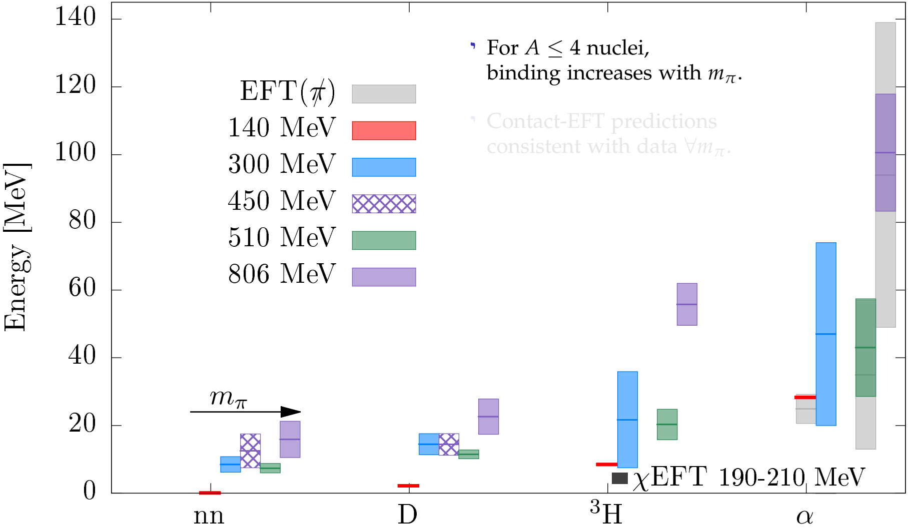
2 bound states for $m_\pi^{(2)}(a \to \infty) < m_\pi$?




100
10
1
100
10
1
180
$m_\pi^{\text{crit.}}$
210
230
500
800
m_π [MeV]
$B_3(^2S_{1/2})$ [MeV]
calibration at physical m_π (E. Epelbaum *et al.*)
LQCD
χEFT $\rightarrow$ EFT($\not\pi$)
806 MeV
510 MeV
300 MeV



Energy [MeV]
0
20
40
60
80
100
120
140
EFT(π̸)
140 MeV
300 MeV
450 MeV
510 MeV
806 MeV
m_π
χEFT 190-210 MeV
nn
D
^{3}H
α
For $A \leq 4$ nuclei,
binding increases with m_π.
Contact-EFT predictions
consistent with data $\forall m_\pi$.



140
120
100
80
60
40
20
0
Energy [MeV]
EFT(π̸)
140 MeV
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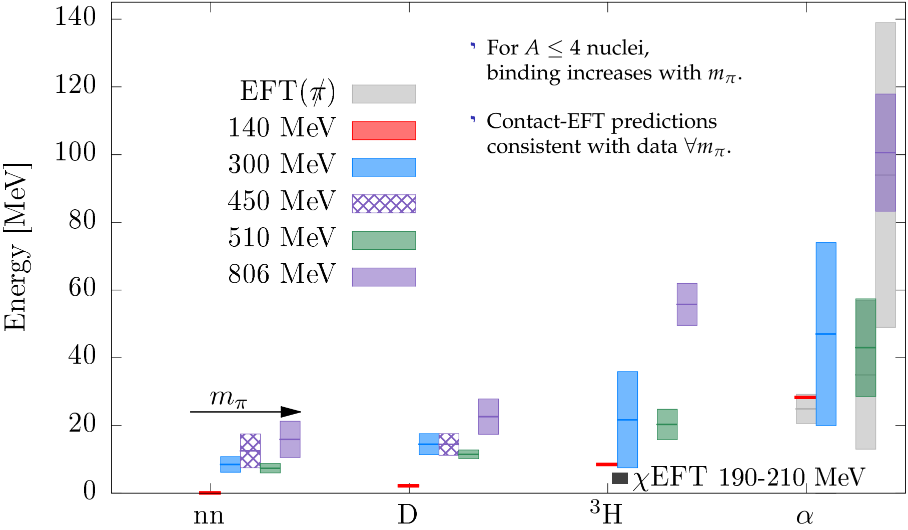

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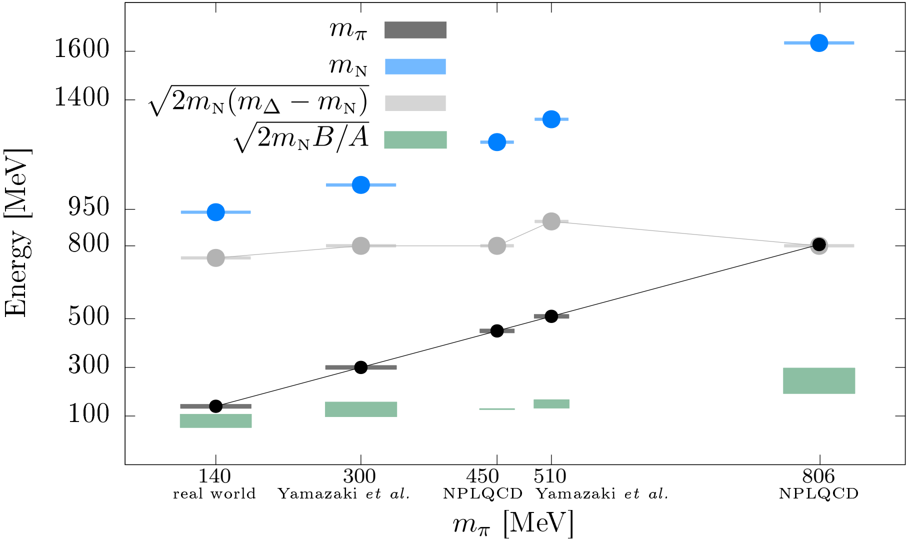
Hadronic scales at $m_\pi > 140$ MeV.



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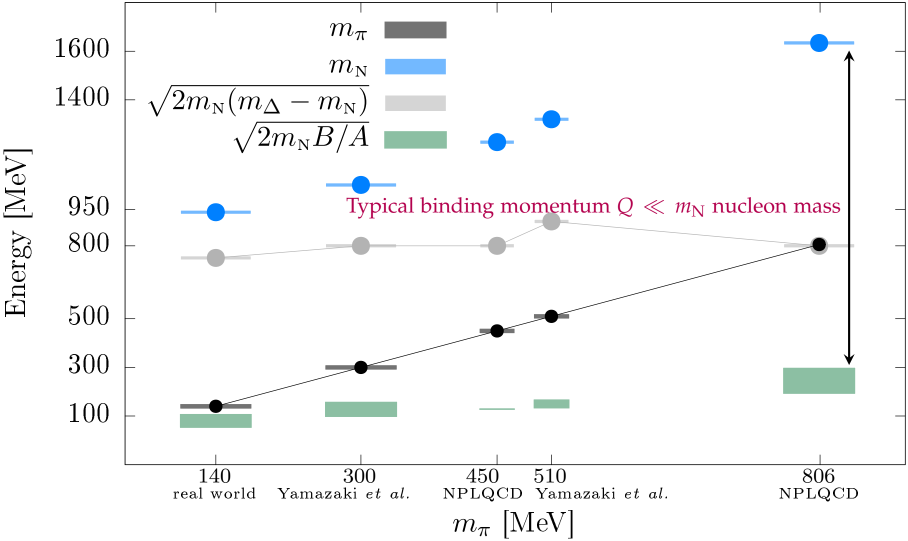

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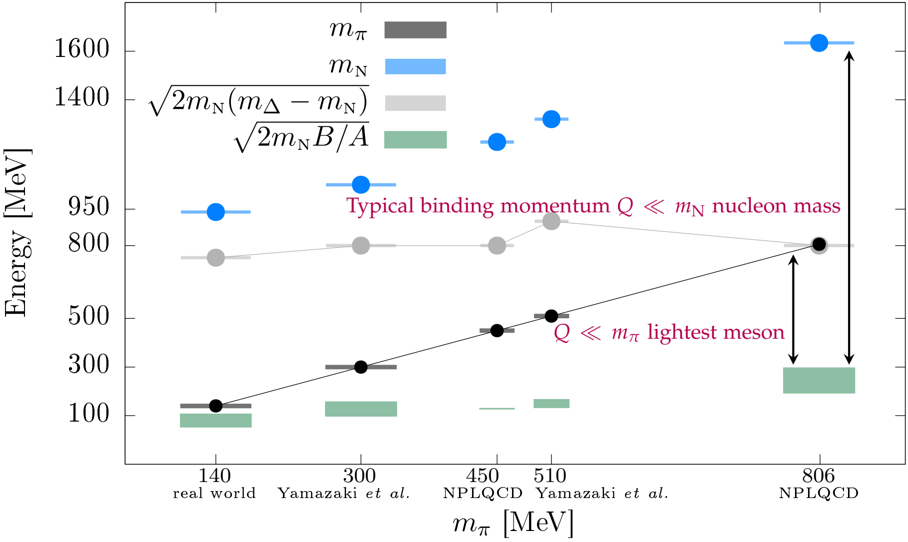

An effective theory for nuclei in a $m_\pi > 140$ MeV universe.

- $m_{\rm N} \gg Q_{\rm typ} \quad \curvearrowright \quad \mathcal{L} = N^\dagger \left[i\partial_0 + \frac{\boldsymbol{\nabla}^2}{2m_N} + \mathcal{O}(m_N^{-3}) \right] N$

  non-relativistic spin/isospin-$\frac{1}{2}$ particles

- $m_\pi \gg Q_{\rm typ} \quad \curvearrowright \quad \sim \frac{1}{q^2 - m_\pi^2} \approx -\frac{1}{m_\pi^2} + \frac{q^2}{m_\pi^4} + \ldots$

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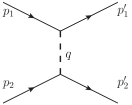

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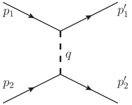

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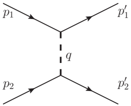

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& + \left(D_1^{(0)} + D_1^{(1)} + \ldots \right) (N^T N)^3 \\
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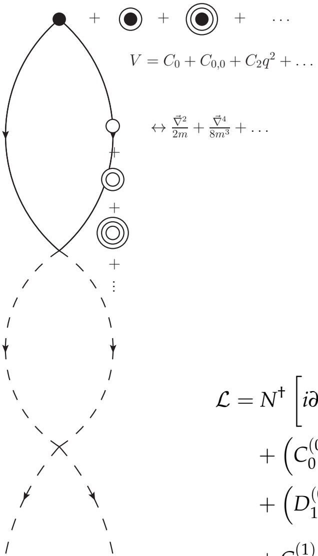
\end{aligned}$$



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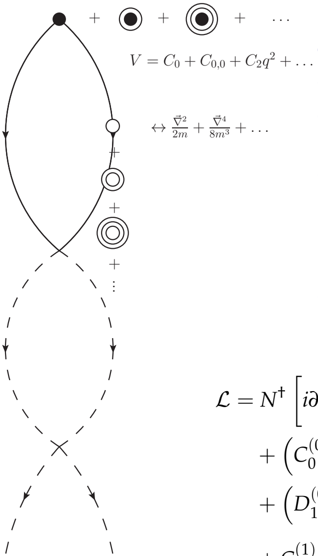

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- mostly natural low-energy (Wilson) coefficients

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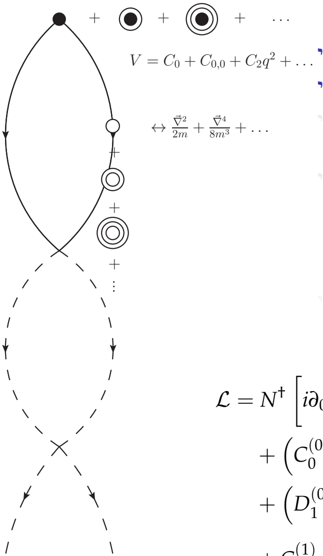

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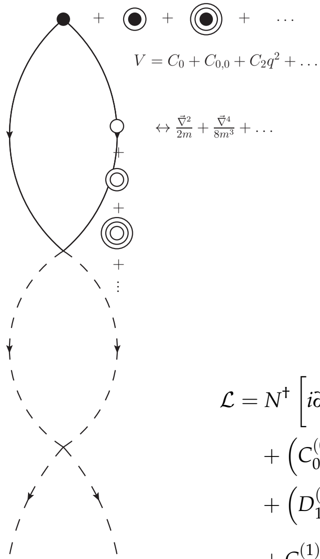

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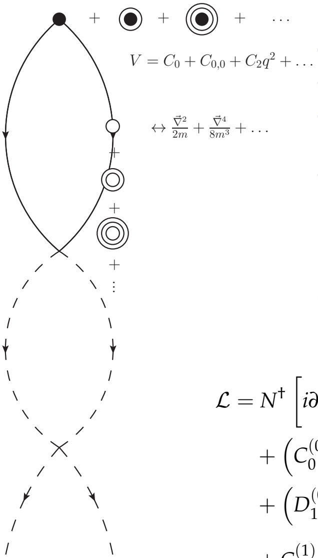

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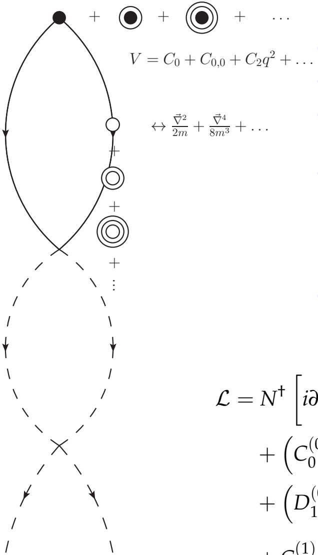

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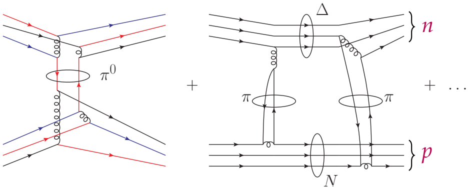
EFT Renormalization with QCD amplitudes.

The n-p amplitude with quarks & gluons:



i) Discretization of space time acts as infrared (finite volume L^3) and ultraviolet (lattice spacing) regulator.

ii) Effective-mass plots for hadrons with $A \leq 4$ are available (HAL, NPLQCD, Yamazaki).

iii) Universal volume dependence of the 2-nucleon spectrum ⇒ effective-range parameters (Lüscher):

$$k \cot \delta(k) = \frac{1}{L\pi} \lim_{\lambda \to \infty} \left(\sum_{j}^{\lambda} \frac{1}{|j|^2 - (Lk/2\pi)^2} - 4\pi\lambda \right) = -\frac{1}{a} + \frac{1}{2} r k^2 + \ldots$$

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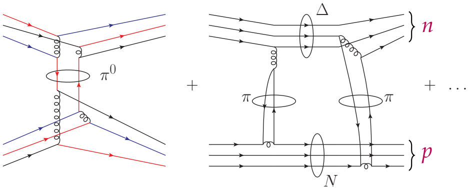

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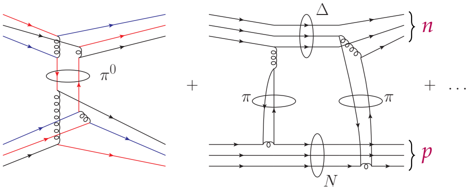

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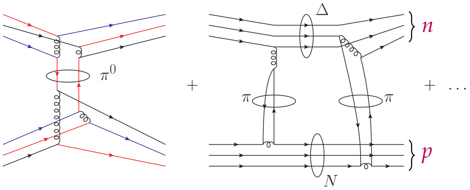


i) Discretization of space time acts as infrared (finite volume L^3) and ultraviolet (lattice spacing) regulator.

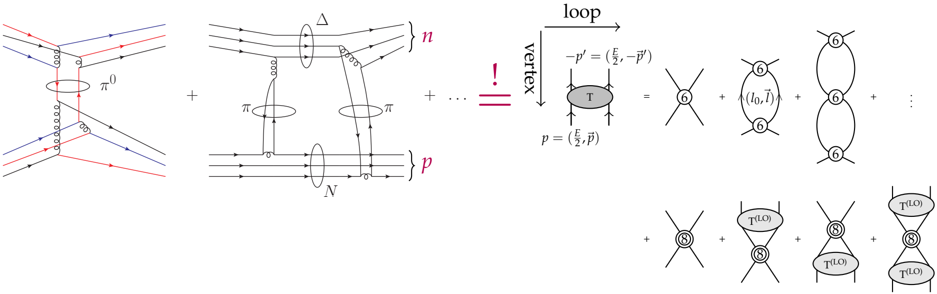
ii) Effective-mass plots for hadrons with $A \leq 4$ are available (HAL, NPLQCD, Yamazaki).

iii) Universal volume dependence of the 2-nucleon spectrum $\Rightarrow$ effective-range parameters (Lüscher):

$$k \cot \delta(k) = \frac{1}{L\pi} \lim_{\lambda \to \infty} \left(\sum_{j}^{\lambda} \frac{1}{|j|^2 - (Lk/2\pi)^2} - 4\pi\lambda \right) = -\frac{1}{a} + \frac{1}{2} r k^2 + \dots$$

EFT Renormalization with QCD amplitudes.

The n-p amplitude with quarks & gluons:



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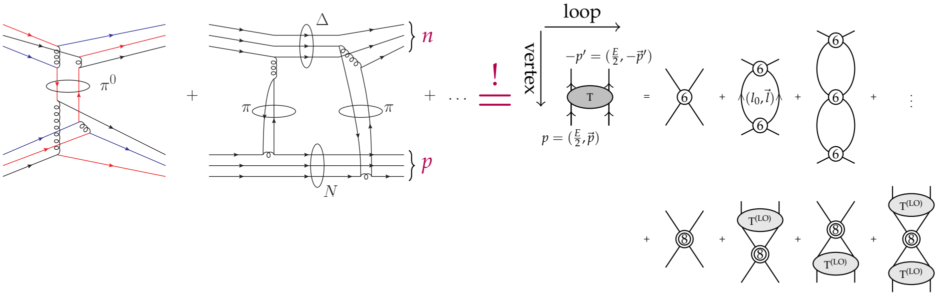
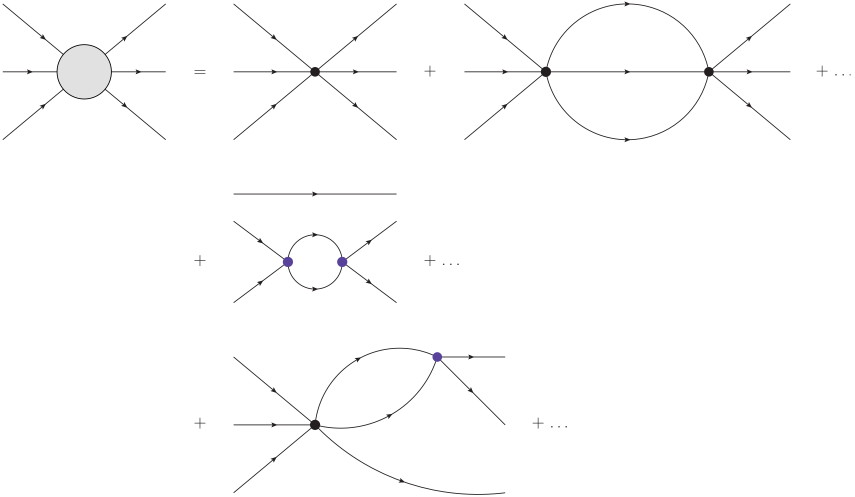
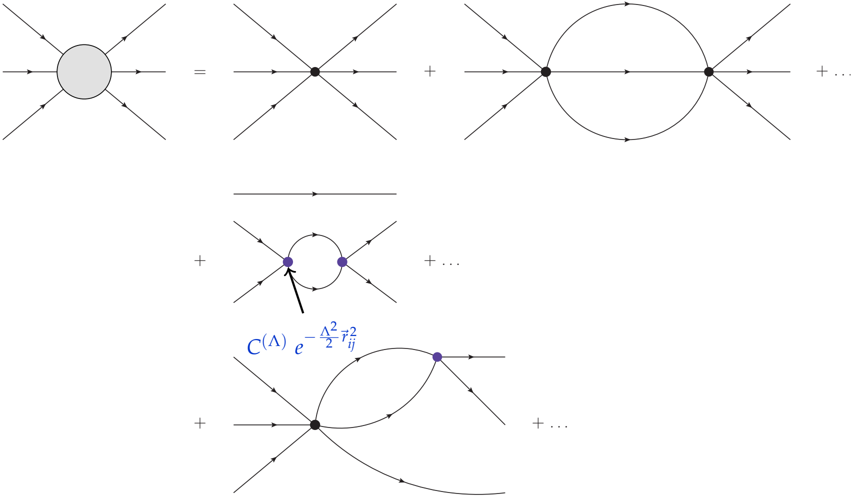


Regularization of the few-body Schrödinger equation?



Regularization and Renormalization.



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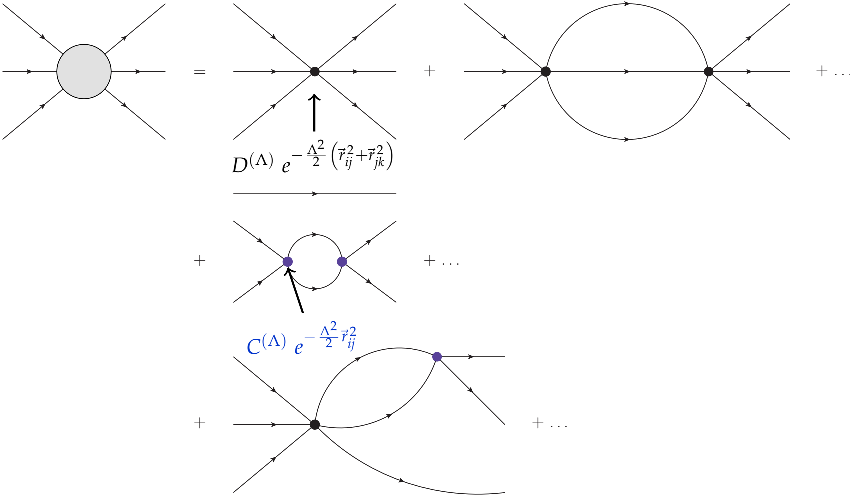
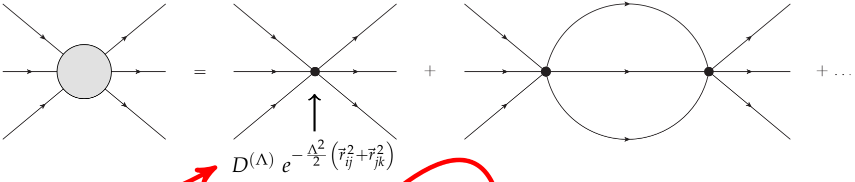
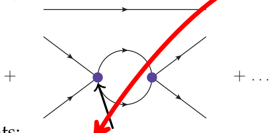




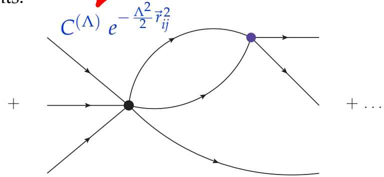


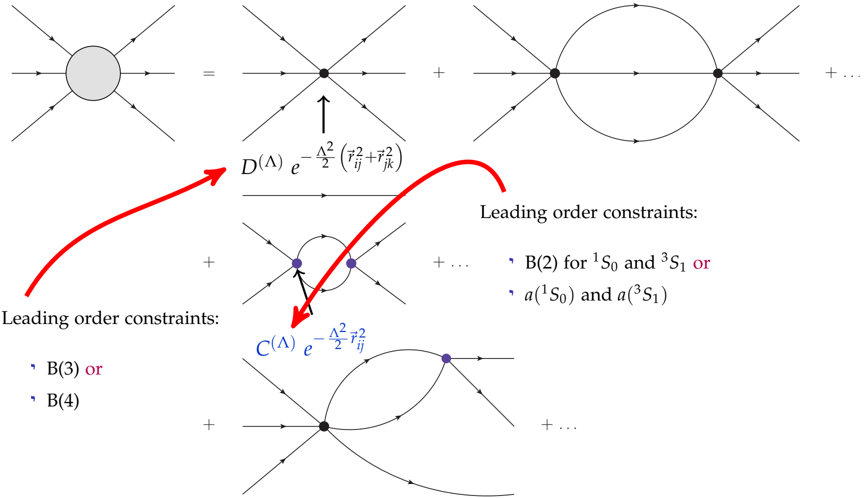
Leading order constraints:

- B(2) for $^1S_0$ and $^3S_1$ or
- $a(^1S_0)$ and $a(^3S_1)$

Leading order constraints:

- B(3) or
- B(4)





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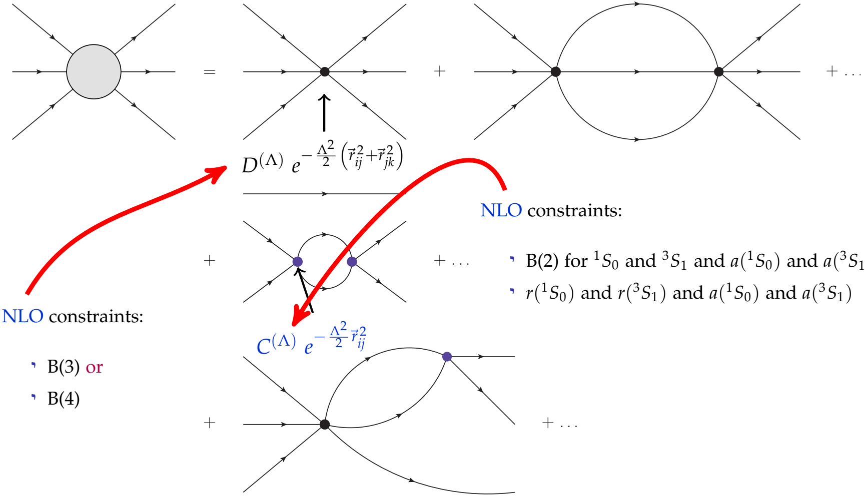
Predictive power with 3 parameters!



NLO constraints:

- B(2) for $^1S_0$ and $^3S_1$ and $a(^1S_0)$ and $a(^3S_1)$ or
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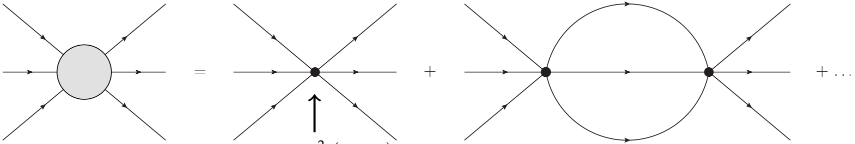
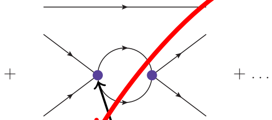


$D^{(\Lambda)}\; e^{-\frac{\Lambda^2}{2}\left(\vec{r}_{ij}^{\,2}+\vec{r}_{jk}^{\,2}\right)}$



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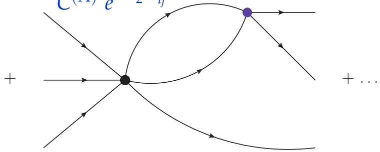

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Predictive power with 5 parameters?

The Refined Resonating Group Method.

"My" laboratory.

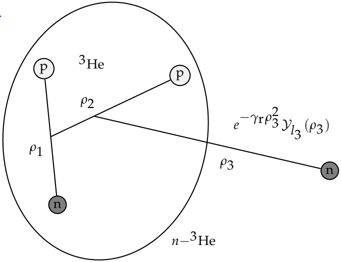
$$\hat{H}\Psi = E\Psi$$

$$\Psi_l = \mathcal{A}\left\{\sum_k \phi^k_{ch}\phi^{lk}_{rel}\right\}$$

boundary condition

$\overset{r\to\infty}{\curvearrowright}$ Coulomb wave function

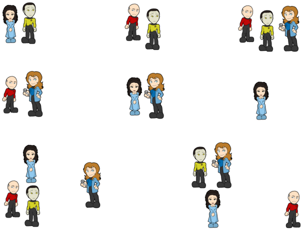
inspired by cluster decomposition



$$\langle\vec{r}|(n-p)\rangle = \sum_{a,d}\left\{c_a\left[|S=1\rangle e^{-\beta_a r^2}\mathcal{Y}_0(\vec{r})\right]^{J=1} + c_d\left[|S=1\rangle e^{-\beta_d r^2}\mathcal{Y}_2(\vec{r})\right]^{J=1}\right\}$$

Ritz variation $\Rightarrow$ bound states

Kohn-Hulthén variation $\Rightarrow$ S-matrix

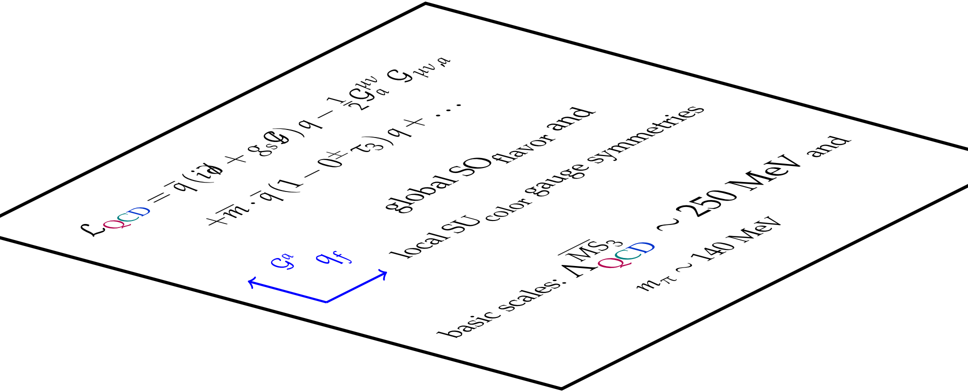


John Wheeler's idea:

[...] It was as if, at a party, all the tall people clustered together at one moment, with all the short people in another cluster; then at the next moment [...] four groups formed, consisting of guests from the north, east, west, and south parts of the city; and so on, [...]

The transcription of QCD for low-energy scales.

for small nuclei: Barnea, Gazit, van Kolck, Pederiva (2013)



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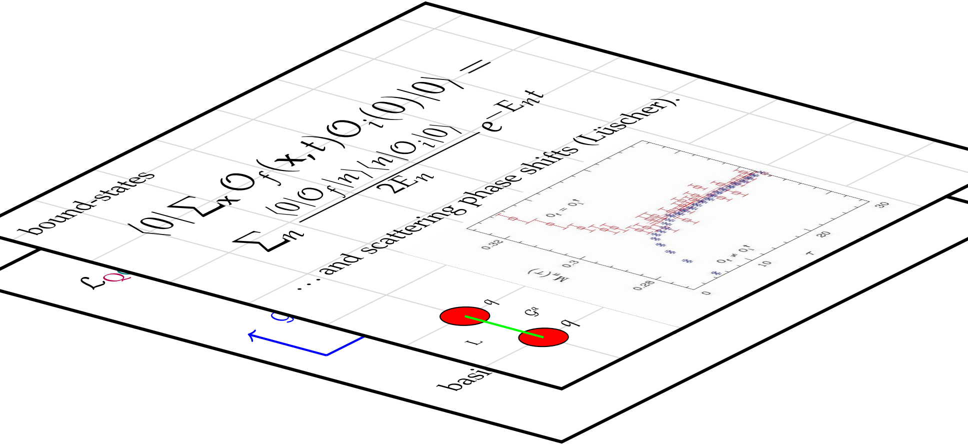

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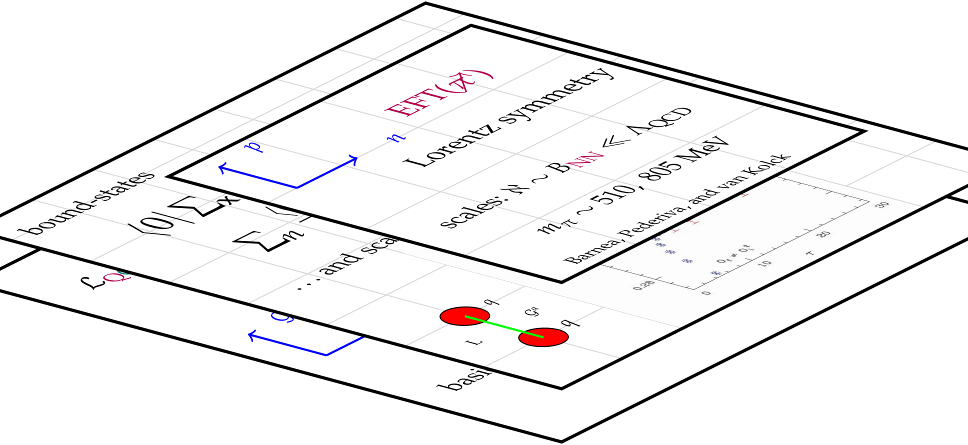

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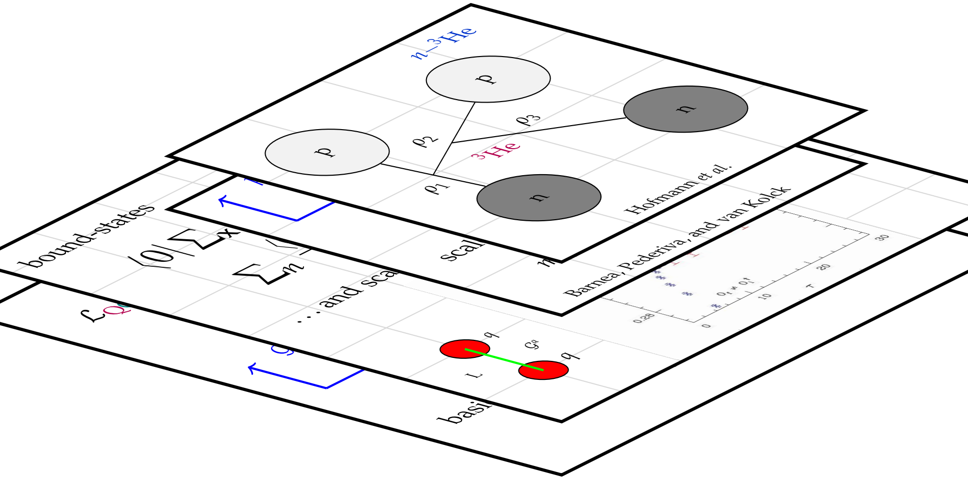
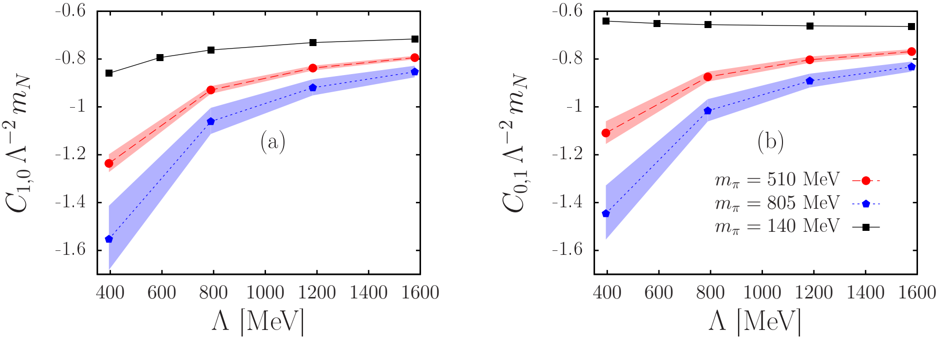


Predictions for a universe with $m_\pi > 140$ MeV. $A = 2, 3$



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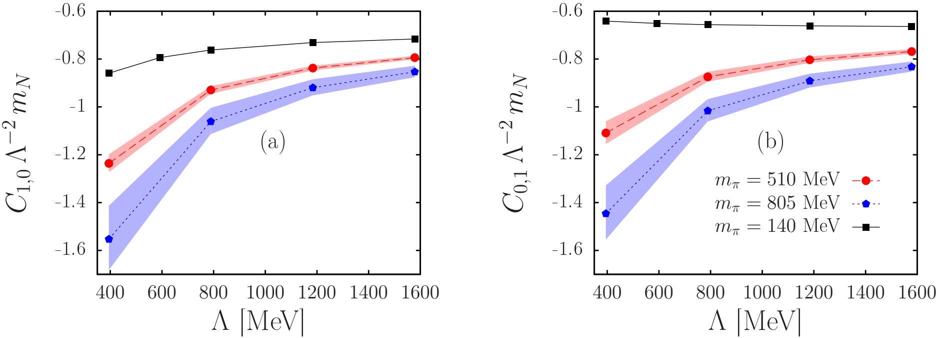

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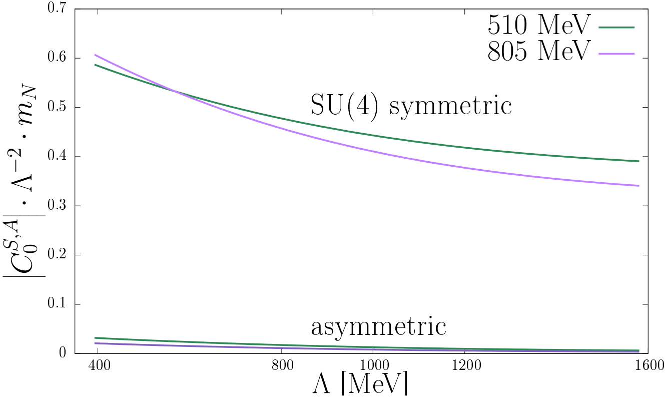

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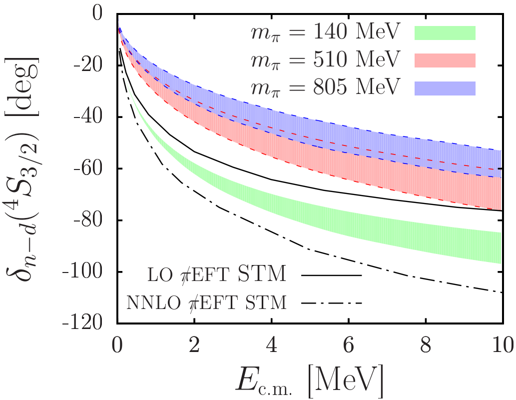

Observations:

i) No bound $^4S_{\frac{3}{2}}$ 3-nucleon state.

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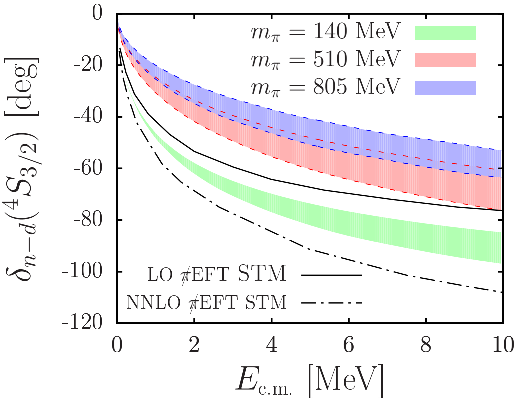

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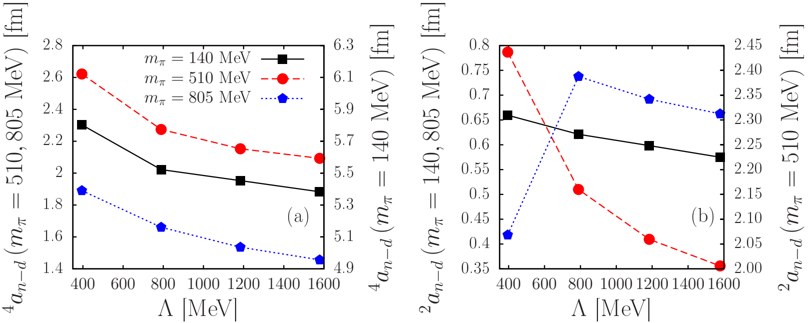

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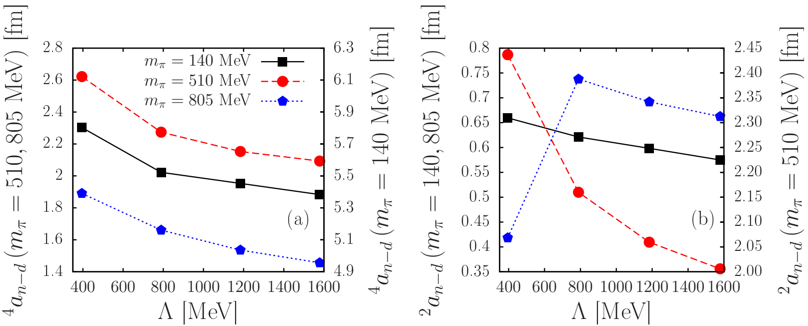

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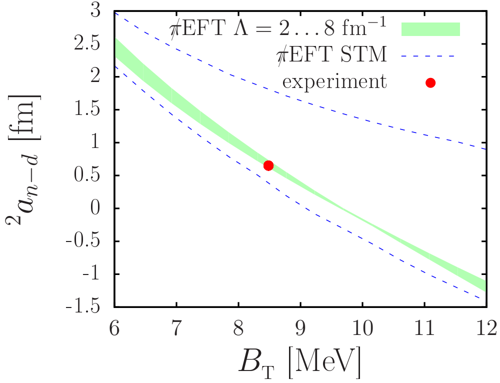

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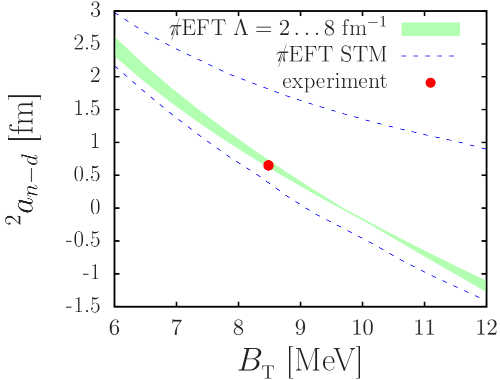

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What happens at larger m_π?

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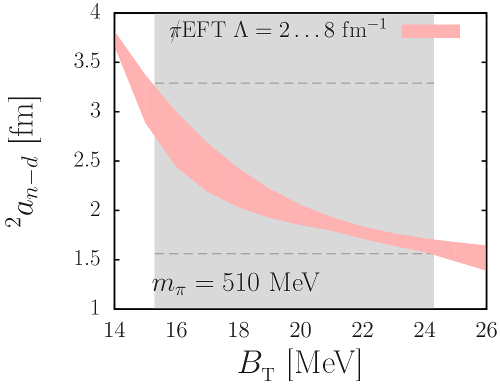

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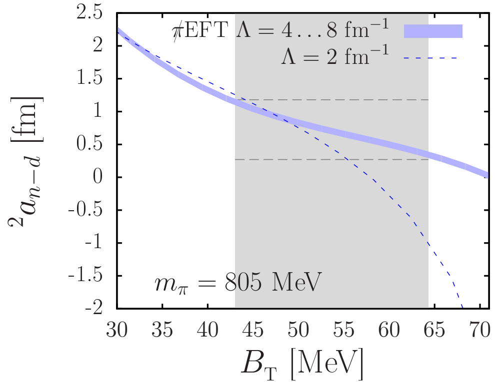

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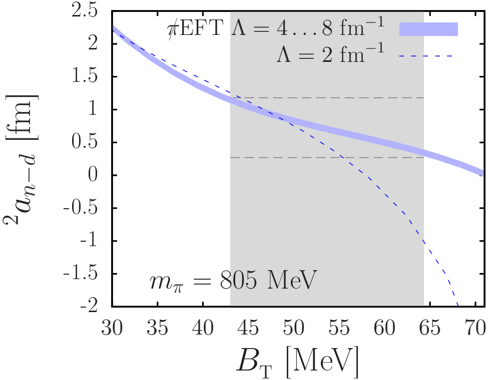

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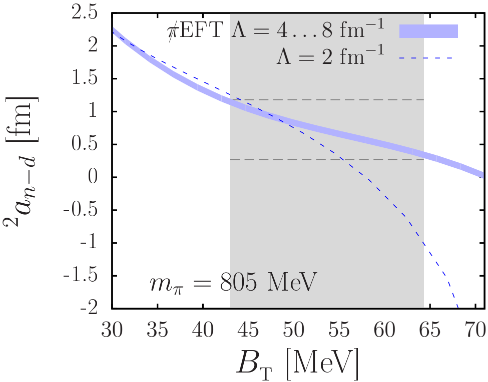

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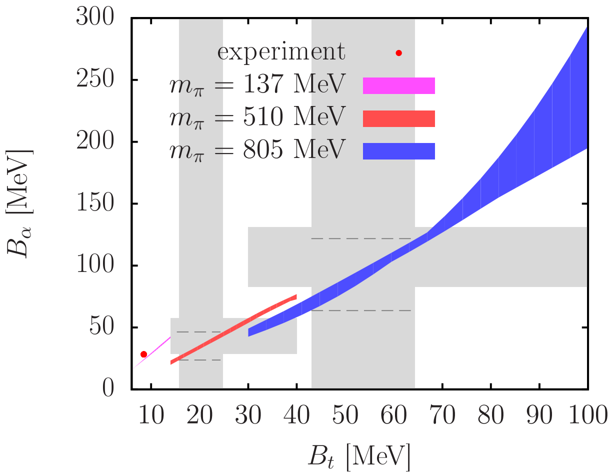

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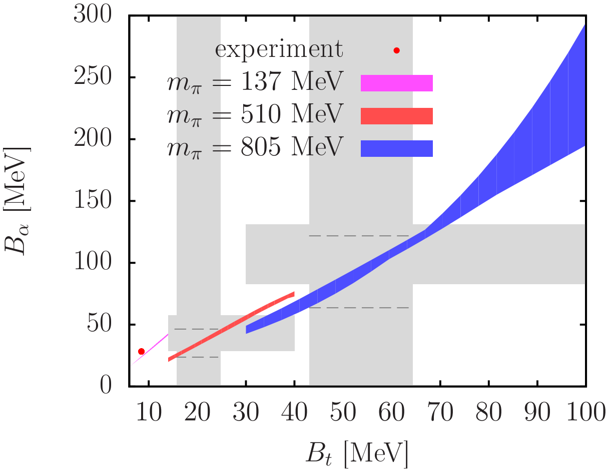

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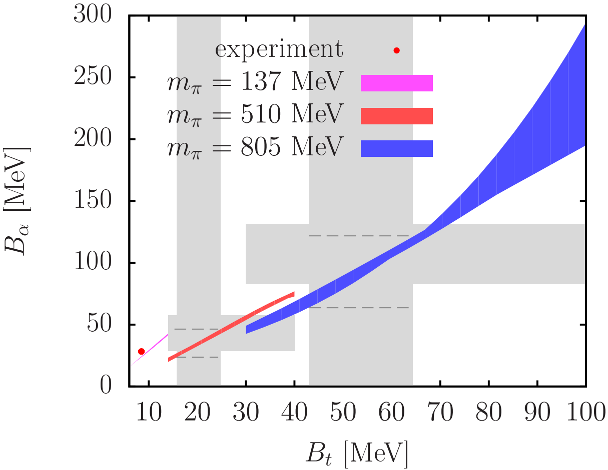

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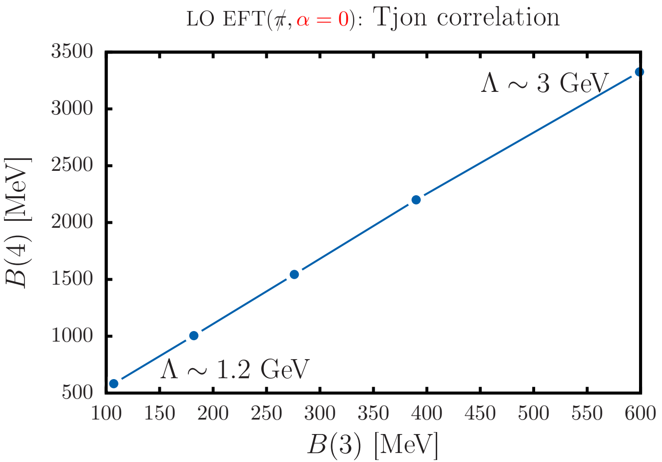

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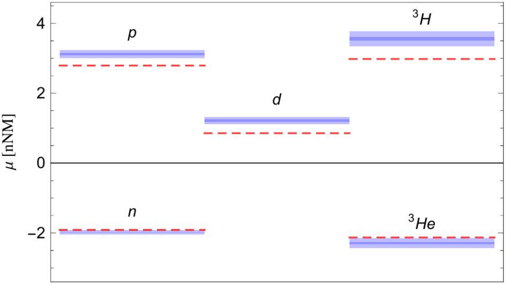

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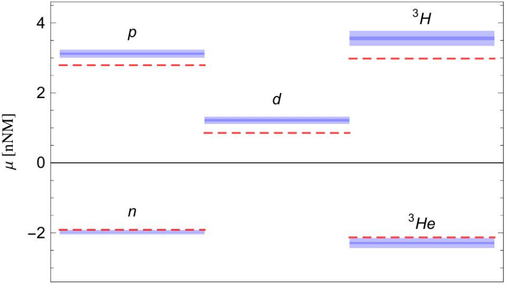

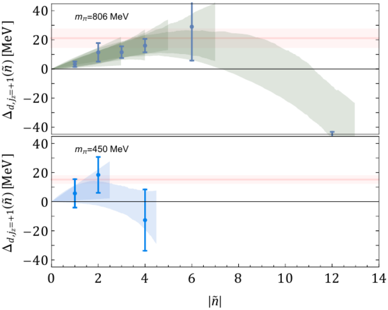

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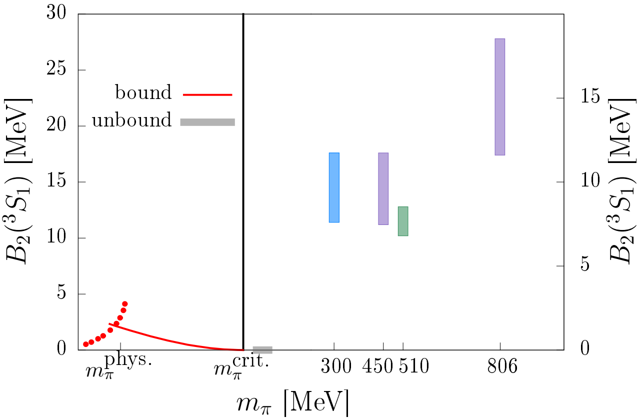
Laboratory to assess validity/consistency of the various χEFTs,



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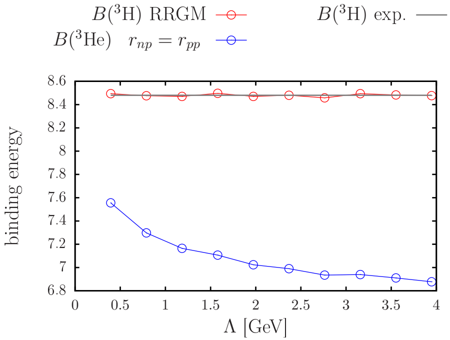
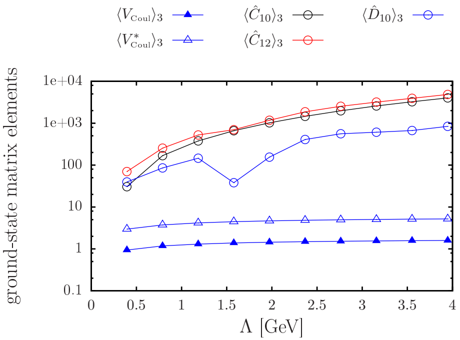
e.g. perturbative π's in bound nuclei analogous to Coulomb A_0's.





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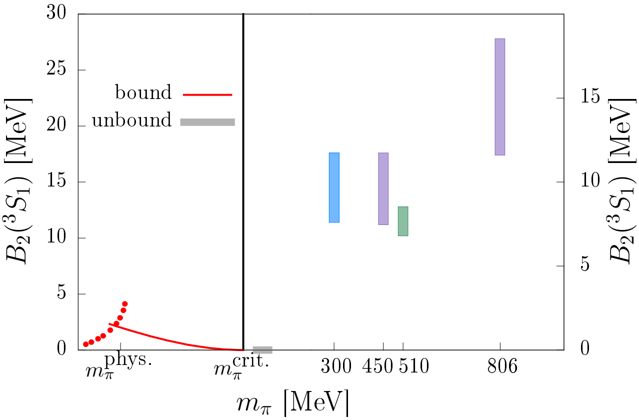
Laboratory to assess validity/consistency of the various χEFTs,
Guiding LQCD to the critical pion masses.



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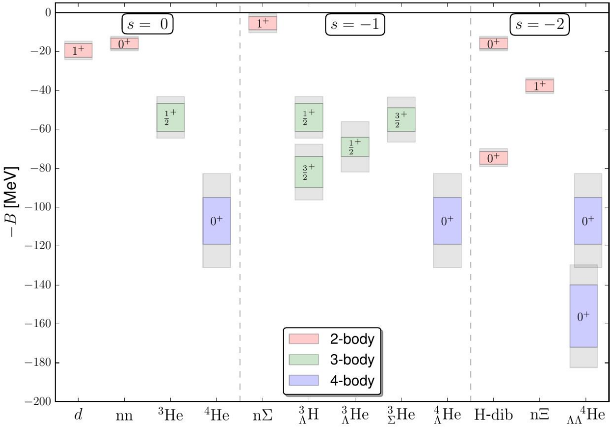
Fundamental understanding of the *strangeness* of the strange sector.



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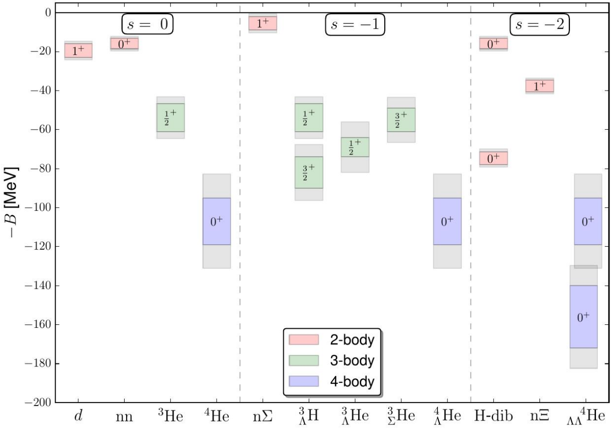
Extrapolation most useful here! (insufficient of real-world data)



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i.e. how does the shell model react to changes in m_π?

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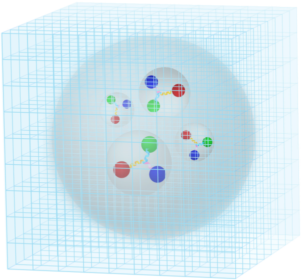
סיכום: Analysis of lattice "experiments" as cool as ...



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