Recent developments on light (hyper) nuclei

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NPLQCD Collaboration
www.ub.edu/nplqcd

3rd EMMI Workshop on anti-matter, hyper-matter and exotica production at the LHC
Wroclaw, Poland, December 2-6, 2019

ICCUB Institut de Ciències del Cosmos
Excelencia María de Maeztu
Universitat de Barcelona
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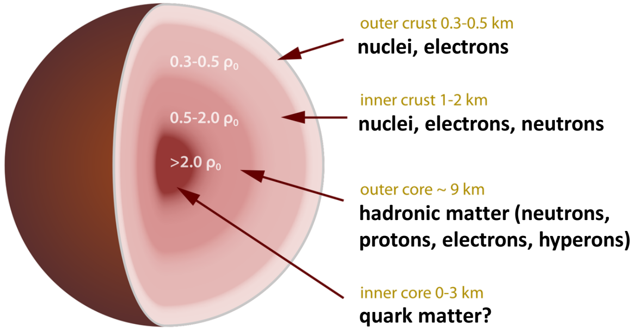
Neutron Stars - Equation of State

The composition of a neutron star depends on the hyperon properties in the medium (i.e. on the YN and YY interactions)



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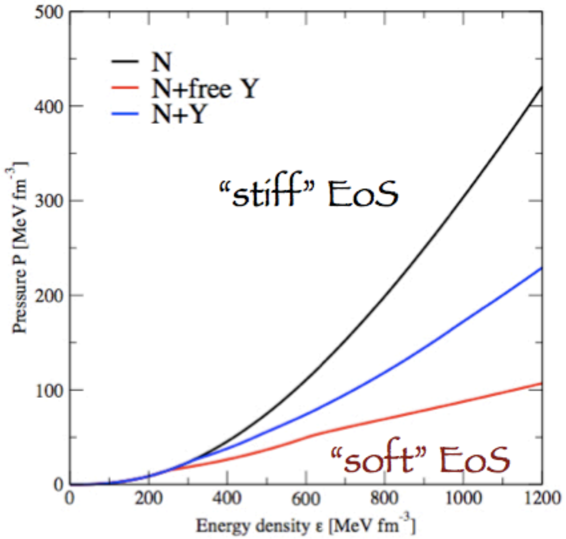

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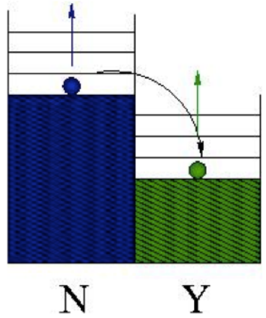
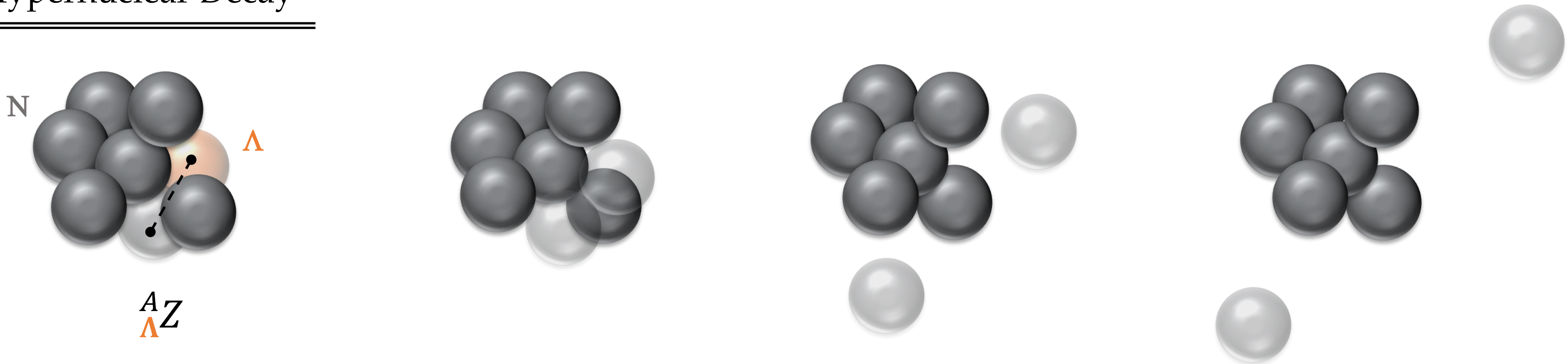
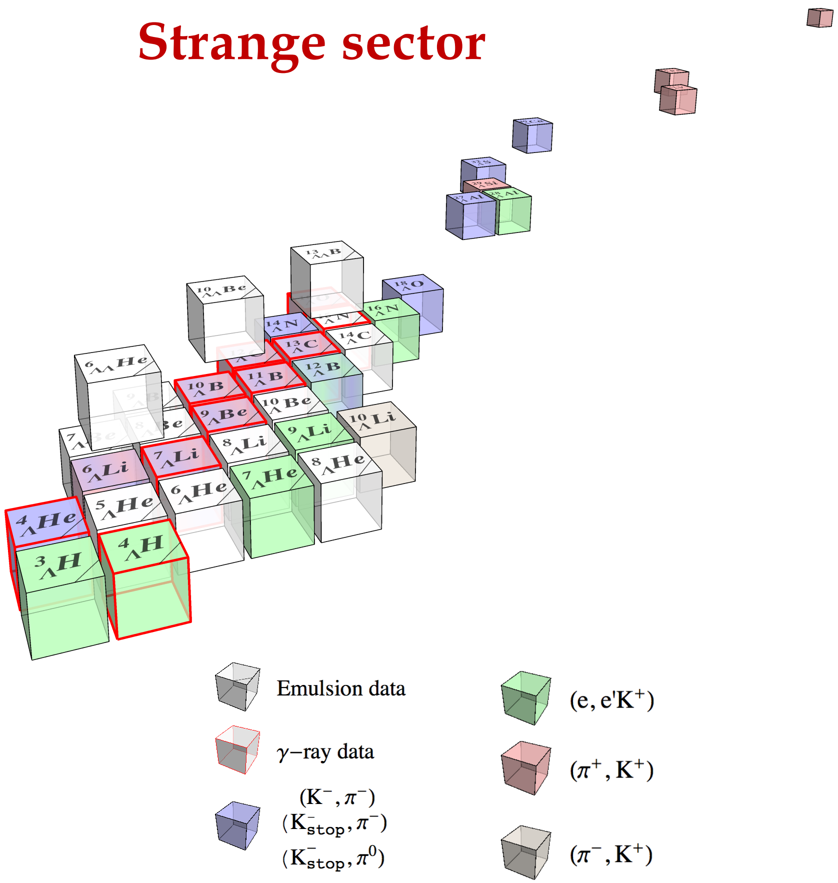


Hypernuclear Decay



How well are hyperon-hyperon and hyperon nucleon interactions constrained?

Strange sector



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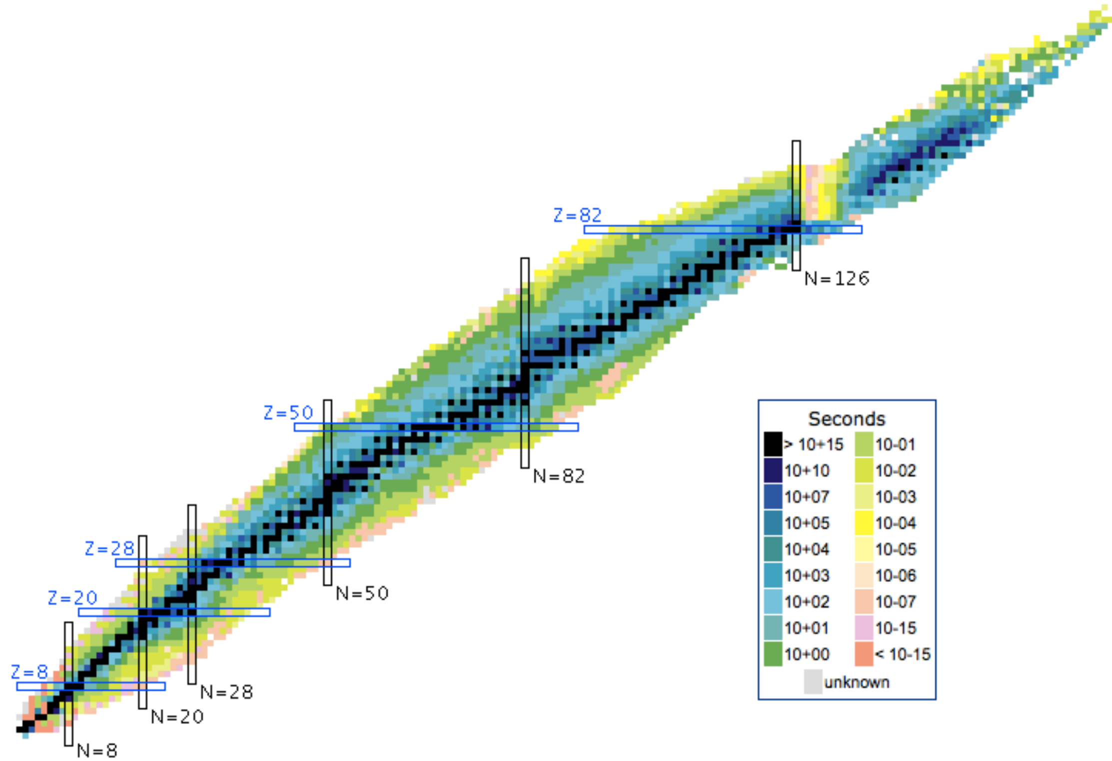
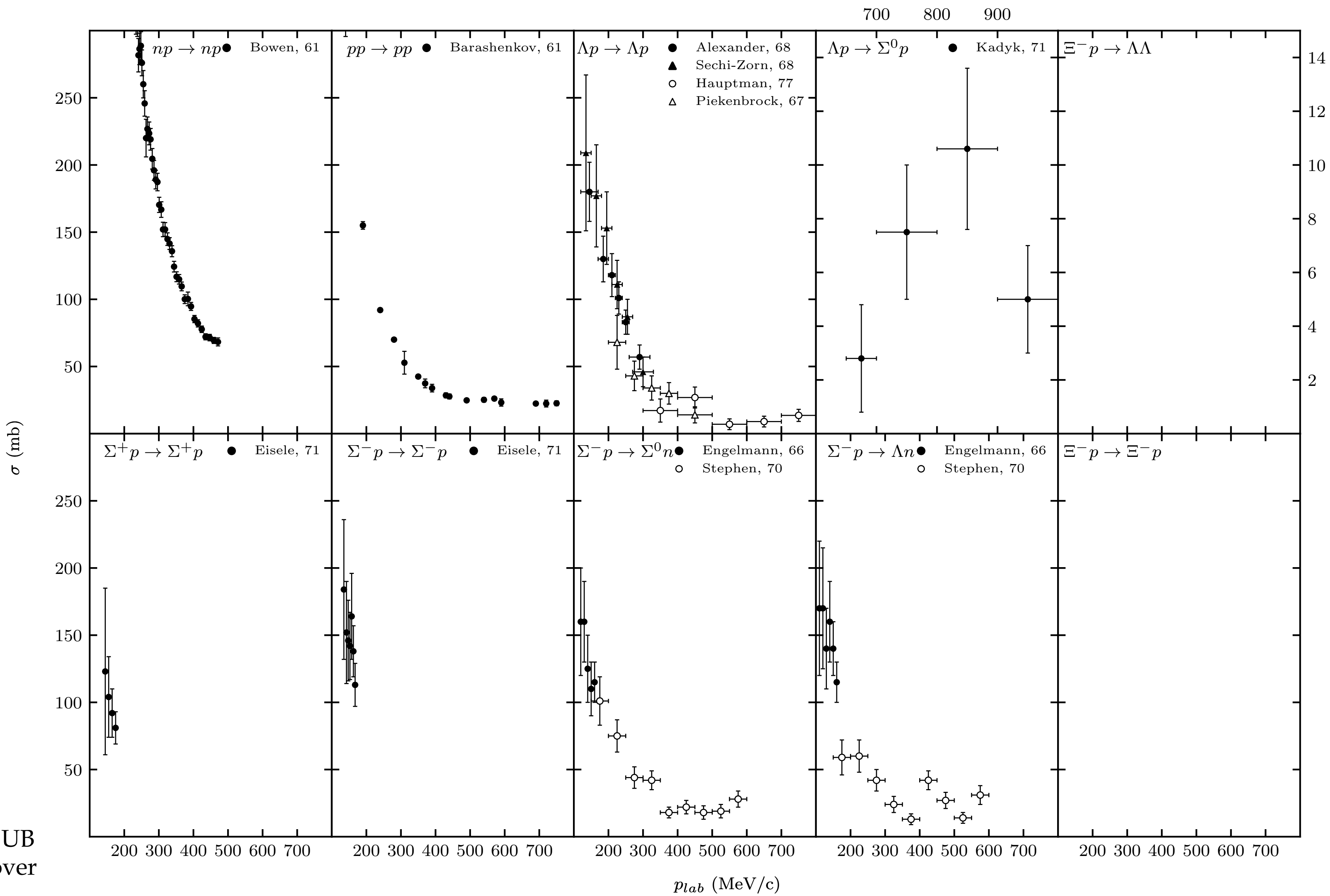
Nonstrange sector



www.nndc.bnl.gov

hyperon nucleon scattering

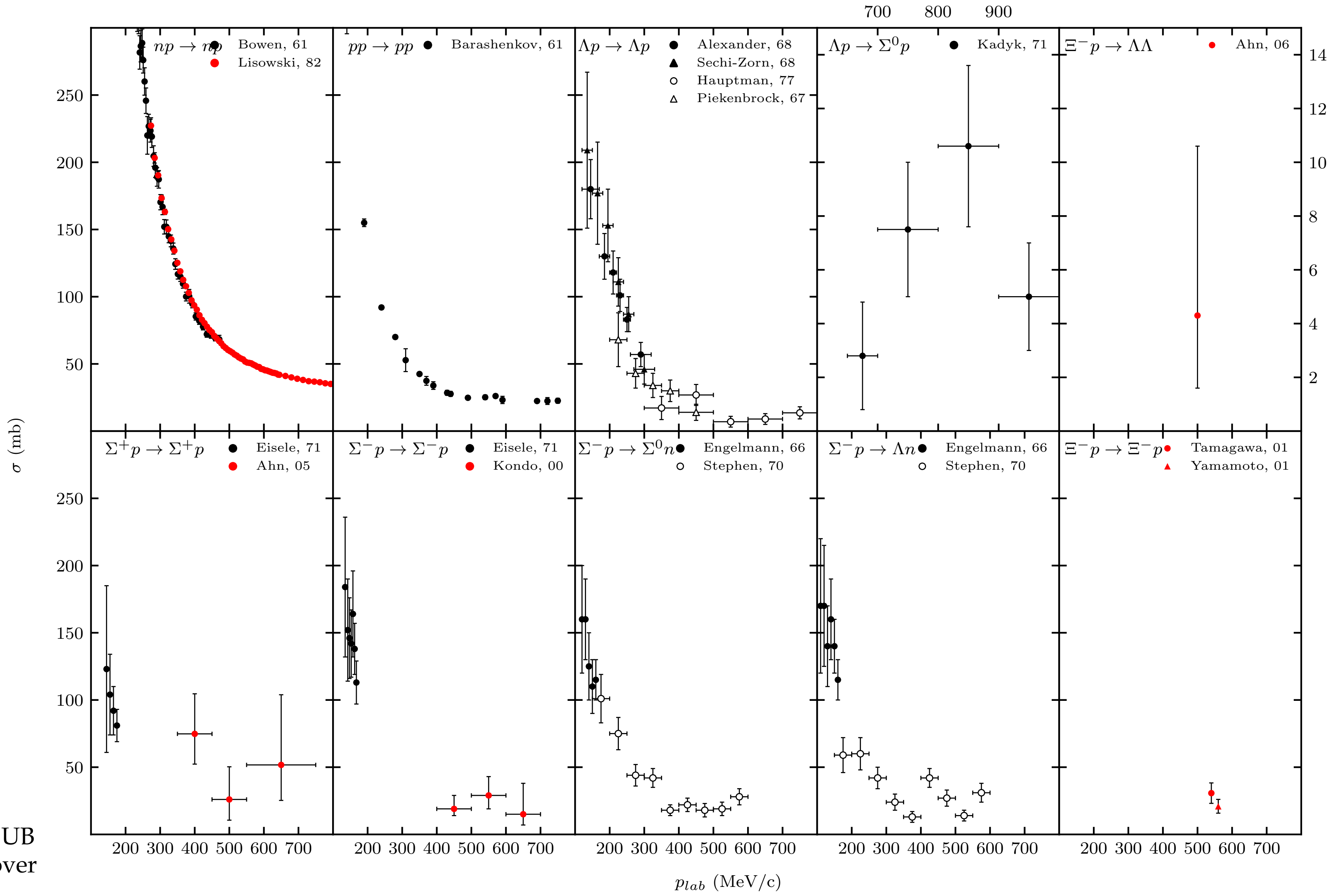
(Data taken 1966-1977)



Collected by Marc Illa, UB
First collected by C. Dover

hyperon nucleon scattering

(Data taken 1966-1977)



Collected by Marc Illa, UB
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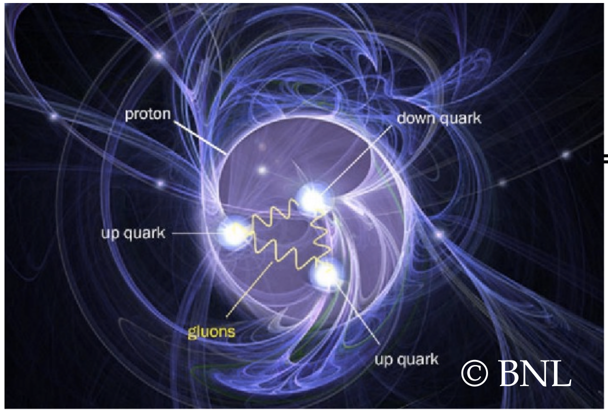


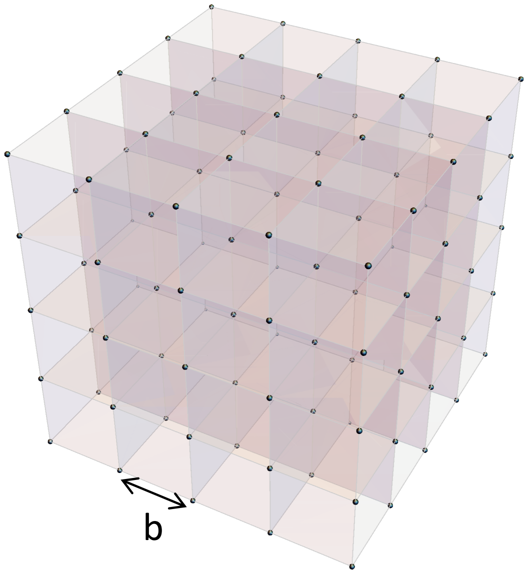
Lattice QCD

Perturbation theory applicable

Nuclear physics, the non-perturbative regime

$$\mathcal{L}_{QCD} = \bar{q}_{ij}\left(i\gamma^{u}\partial_{u} - m_{j}\right)q_{ij} + g(\bar{q}_{ij}\gamma^{u}\lambda_{a}q_{ij})F_{u}^{a} - \frac{1}{4}F_{uv}^{a}F_{a}^{uv}$$

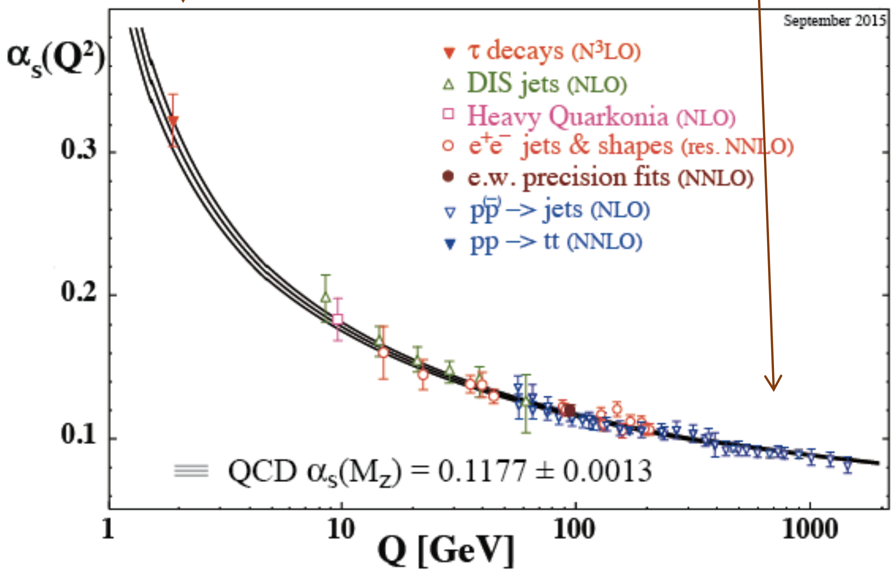
$$i = r,g,b \quad j = u,d,c,s,t,b$$



$$L_x \times L_y \times L_z \times T \;\rightarrow\; (N_s \times N_s \times N_s) \times N_t$$

$$x = b\,(n_1, n_2, n_3, n_4) \qquad n_j \in \mathbb{Z}$$

strong coupling constant *vs* energy



S. Bethke, G.Dissertori, G.P. Salam
EPJ Web of Conferences 120 07005 (2016)

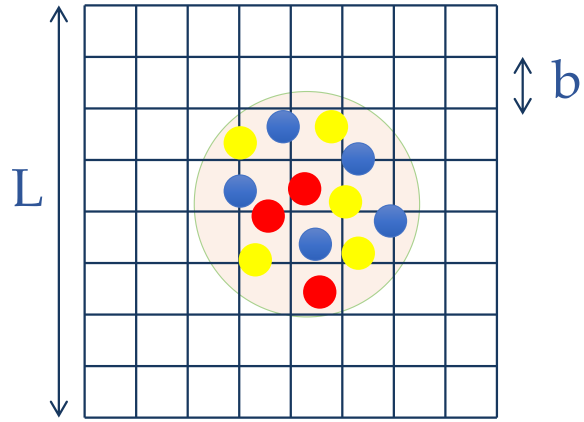
Lattice QCD and nuclear physics

Solve a linear system of equations: $D^{\dagger}(U)[m]\, D(U)[m]\, \chi = \phi$

Condition number $\approx 1/\mathrm{m}$

Finite L, b and unphysical m_q

source of systematic errors in lattice QCD calculations



$$\mathrm{Cost} \;\approx\; \left[\frac{1}{m_q}\right] [L]^a \left[\frac{1}{\mathrm{b}}\right]^{\gamma}$$

USE UNPHYSICAL VALUES
OF THESE PARAMETERS
(LATTICE ARTIFACTS)

$$L >> \text{ relevant scales } >> b$$

$$\left(\frac{1}{L} << m_\pi << \Lambda_\chi << \frac{1}{b}\right)$$

$$b << M_N^{-1}$$

Extrapolate to physical results:
Use of Effective Field Theory

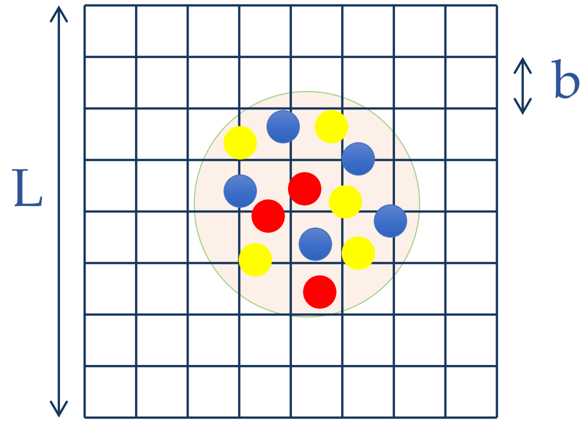
Lattice QCD and nuclear physics

Solve a linear system of equations: $D^{\dagger}(U)[m]\, D(U)[m]\, \chi = \phi$

Condition number ≈ 1/m

Finite L, b and unphysical m_q

source of systematic errors in lattice QCD calculations



Extrapolations to connect with real life

combined chiral, continuum and finite-size extrapolation

$L \to \infty$ $b \to 0$ $m_q \to m_q^{physical}$

Published Works	
World	**NPLQCD**
L ~ 2 - 8 fm	L ~ 3 - 7 fm
b ~ 0.066 - 0.145 fm	b ~ 0.117 – 0.145 fm
m_π ~ 140 – 1100 MeV	m_π ~ 230 – 806 MeV

$L >>$ relevant scales $>> b$

$$\left(\frac{1}{L} << m_\pi << \Lambda_\chi << \frac{1}{b}\right)$$

$$b << M_N^{-1}$$

Extrapolate to physical results:
Use of Effective Field Theory

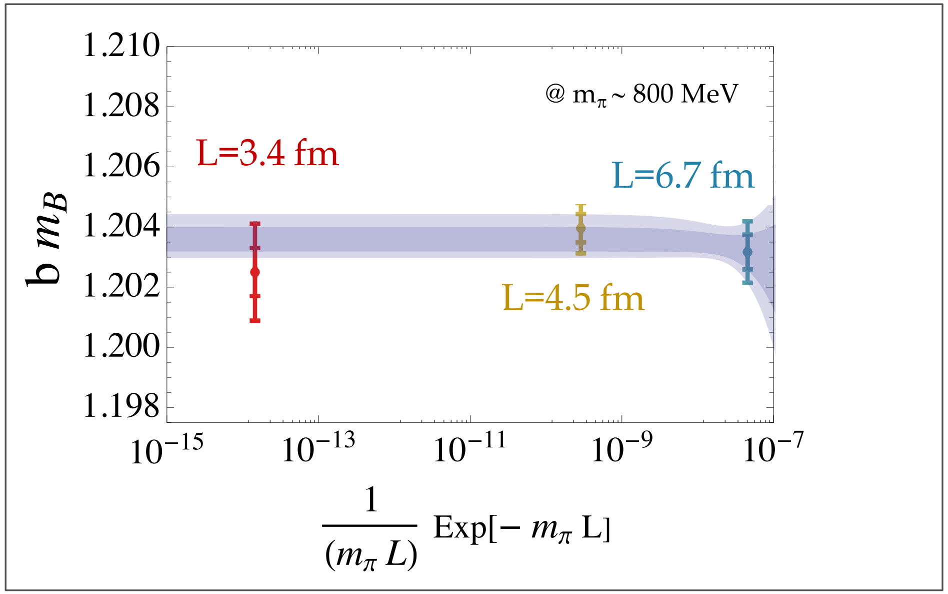
Lattice QCD. Connection with Nature

Extrapolations to connect with real life

$L \to \infty$

$b \to 0$

$m_q \to m_q^{physical}$



LO finite-volume corrections in HBχPT

NPLQCD, Phys. Rev. D ***84****, 014507 (2011)*

$$m_B^{(V)}(m_\pi L) \quad = \quad m_B^{(\infty)} + c_B \frac{e^{-m_\pi L}}{(m_\pi L)}$$

Lattice QCD. Connection with Nature

Extrapolations to connect with real life

$L \to \infty$

$b \to 0$

$m_q \to m_q^{physical}$

discretization errors

LO continuum behaviour depends on the observable

$$\mathcal{O}(b) \sim C\, b^{\,n(\mathcal{O})}$$

Lattice QCD. Connection with Nature

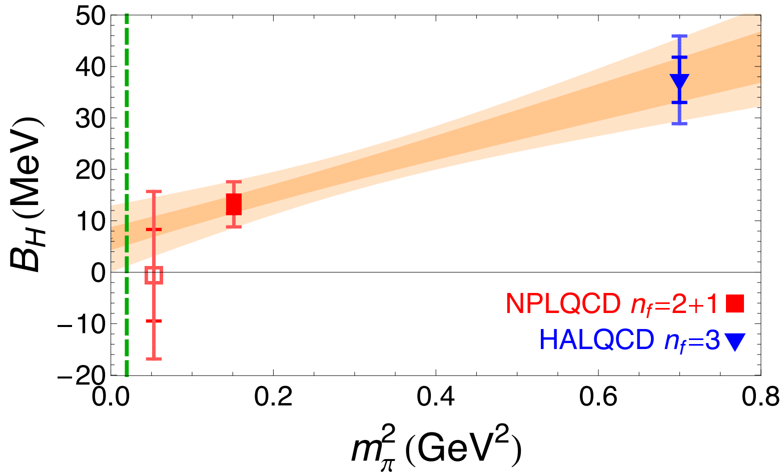
Extrapolations to connect with real life

$L \to \infty$

$b \to 0$

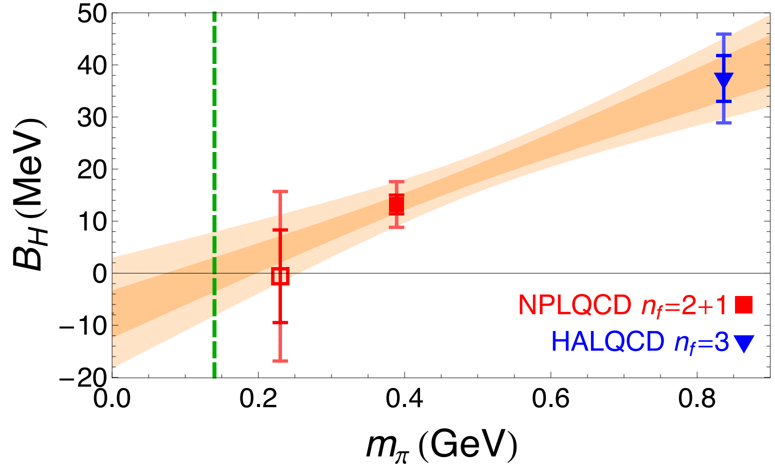
$m_q \to m_q^{physical}$

quark mass dependence of the observables ?



$$B_H(m_\pi) = B_0 + d_1 m_\pi^2$$

$$B_H^{\text{quadratic}} = 7.4 \pm 2.1 \pm 5.8\text{MeV}$$

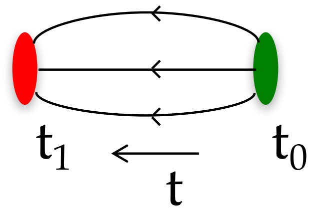


$$B_H(m_\pi) = \tilde{B}_0 + c_1 m_\pi$$

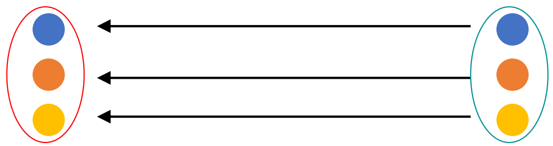
$$B_H^{\text{linear}} = -0.2 \pm 3.3 \pm 7.3\text{MeV}$$

Mod. Phys. Lett. A **26**, 2587 (2011)

Direct Lattice QCD extraction $\longleftrightarrow$ Compute correlation functions



construction of correlation functions
with different interpolators



$$C(\Gamma^\nu,\vec{p},t)=\sum_{\vec{x}_1} e^{-i\vec{p}\vec{x}_1}\,\Gamma^\nu\left\langle J(\vec{x}_1,t)\bar{J}(\vec{x}_0,0)\right\rangle$$

$$p_\alpha(\mathbf{x},t)=\epsilon^{ijk}u^i_\alpha(\mathbf{x},t)\left(u^{j\mathsf{T}}(\mathbf{x},t)C\gamma_5 d^k(\mathbf{x},t)\right)$$

$$\phi(t)=e^{Ht}\,\phi\,e^{-Ht}$$

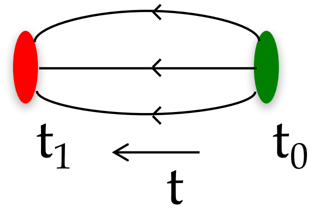
$$\sum_n |n\rangle\langle n|$$

$$C_{\hat{O},\hat{O}'}(t,\vec{d})=\sum_{\vec{x}} e^{2\pi i\vec{d}\vec{x}/L}\,\langle 0|\hat{O}'(\vec{x},t)\hat{O}^\dagger(\vec{0},0)|0\rangle$$

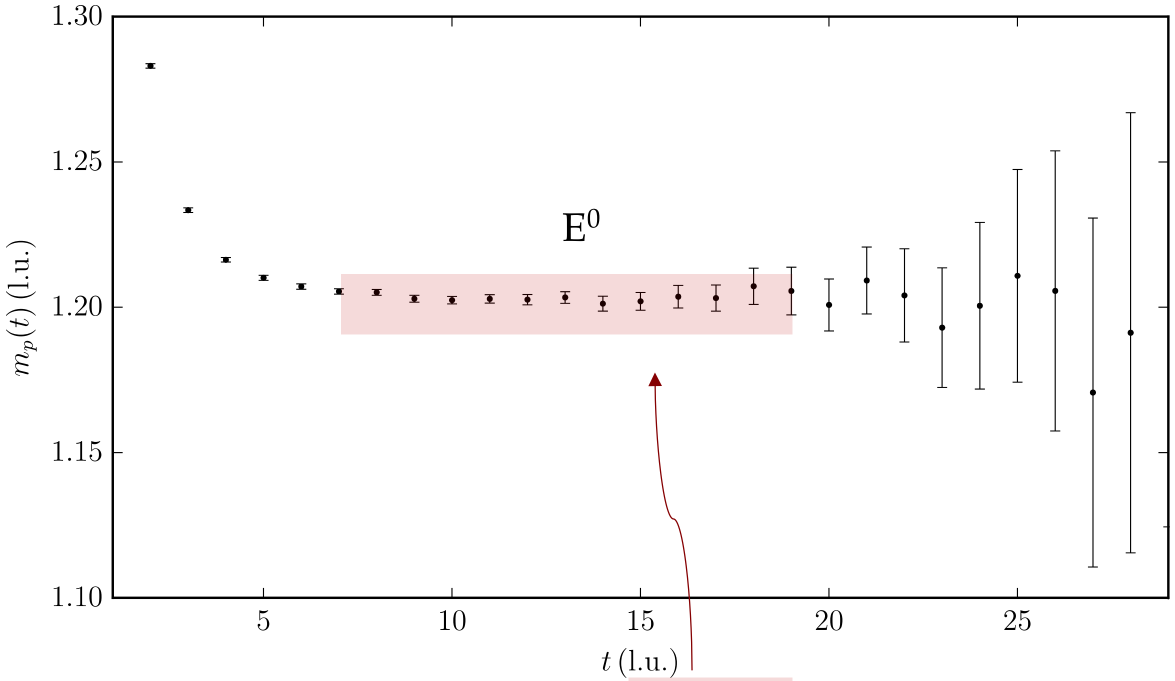
$$=\underbrace{Z_0^{snk}\,Z_0^{\dagger\,src}\;e^{-E^{(0)}t}}_{\text{dominates at large t}}+Z_1^{snk}\,Z_1^{\dagger\,src}\;e^{-E^{(1)}t}+\cdots$$

projected into total momentum $\dfrac{2\pi\vec{d}}{L}$

Direct Lattice QCD extraction $\longleftrightarrow$ Compute correlation functions



$$p_\alpha(\mathbf{x},t) = \epsilon^{ijk} u^i_\alpha(\mathbf{x},t)\left(u^{j\mathsf{T}}(\mathbf{x},t) C\gamma_5 d^k(\mathbf{x},t)\right)$$



example:
interpolating operator for the proton

Effective mass plot → extract the g.s. energy (mass) from plateau

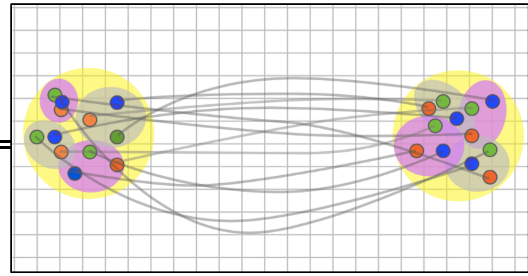
$$\boxed{C_{\hat{O},\hat{O}'}(\tau;\ \vec{d},\tau_J) = \frac{1}{\tau_J}\log\left[\frac{C_{\hat{O},\hat{O}'}(\tau;\ \vec{d})}{C_{\hat{O},\hat{O}'}(\tau+\tau_J;\ \vec{d}\,)}\right]}$$

$$= \underbrace{Z_0^{snk}\, Z_0^{\dagger\, src}\ e^{-E^{(0)}t}}_{\text{dominates at large t}} + Z_1^{snk}\, Z_1^{\dagger\, src}\ e^{-E^{(1)}t} + \cdots$$

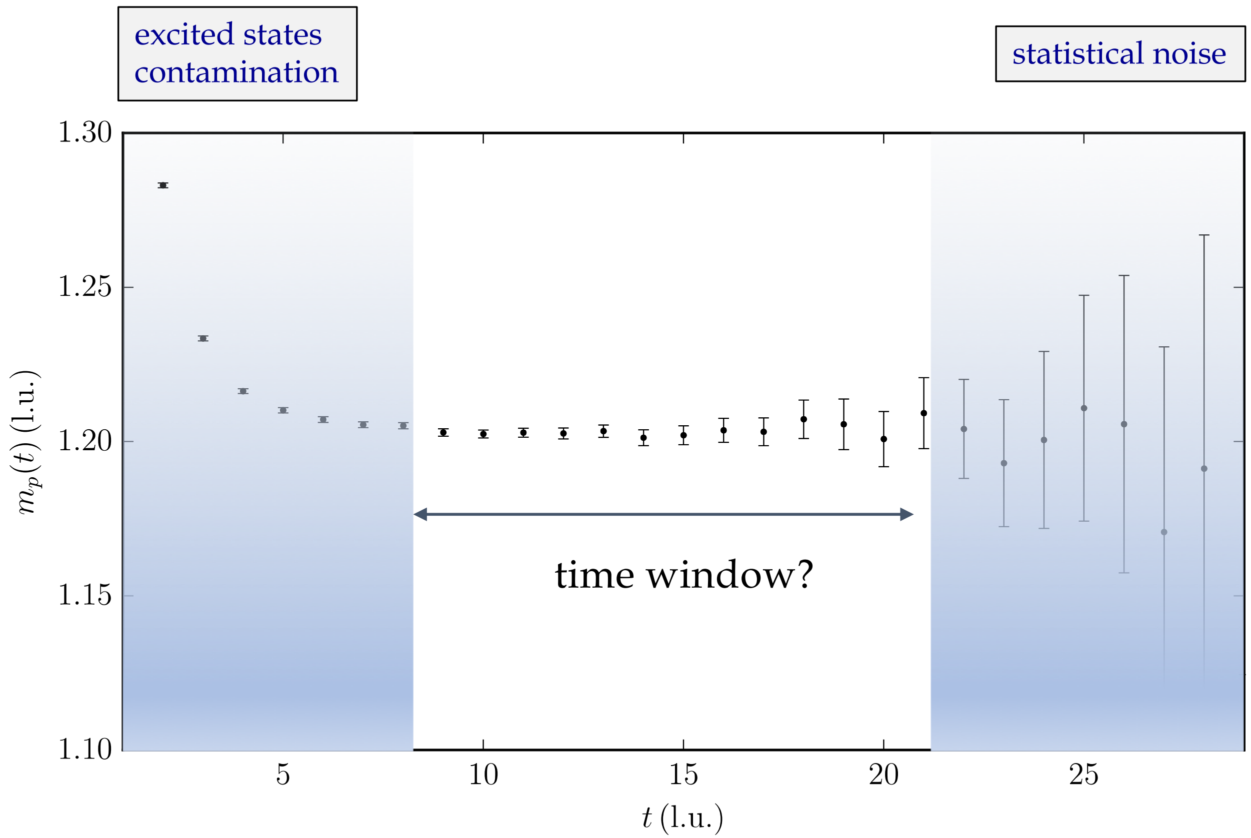
projected into total momentum $\dfrac{2\pi\vec{d}}{L}$

Lattice QCD and nuclear physics

fermions suffer from a serious degradation of the signal with time



factorial growth in the number of contractions



pions:

$$\frac{\sigma}{\langle C\rangle} \to \frac{1}{\sqrt{N}}$$

nucleons:

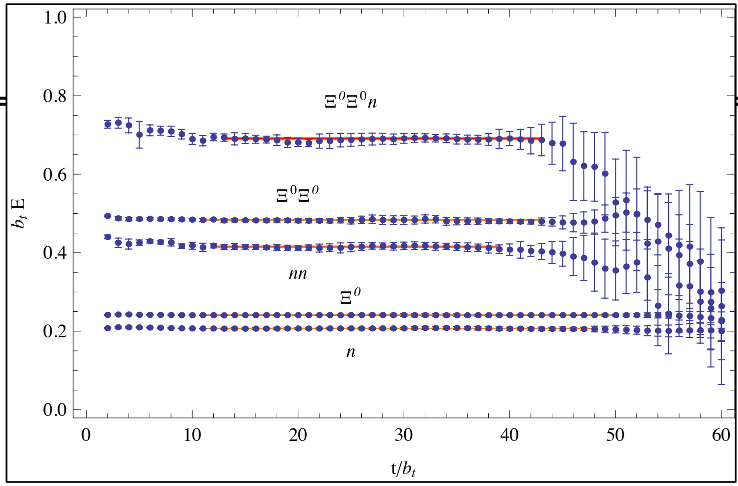
$$\frac{\sigma}{\langle C\rangle} \sim \frac{1}{\sqrt{N}} \times \exp\left(M_N - \frac{3m_\pi}{2}\right)t$$

Expectation is that for A nucleons:

$$\frac{\sigma}{\langle C\rangle} \sim \frac{\exp\left[A\left(M_N - \frac{3m_\pi}{2}\right)t\right]}{\sqrt{N}}$$

Lepage, 1989

for a given {m_π, L, b} set



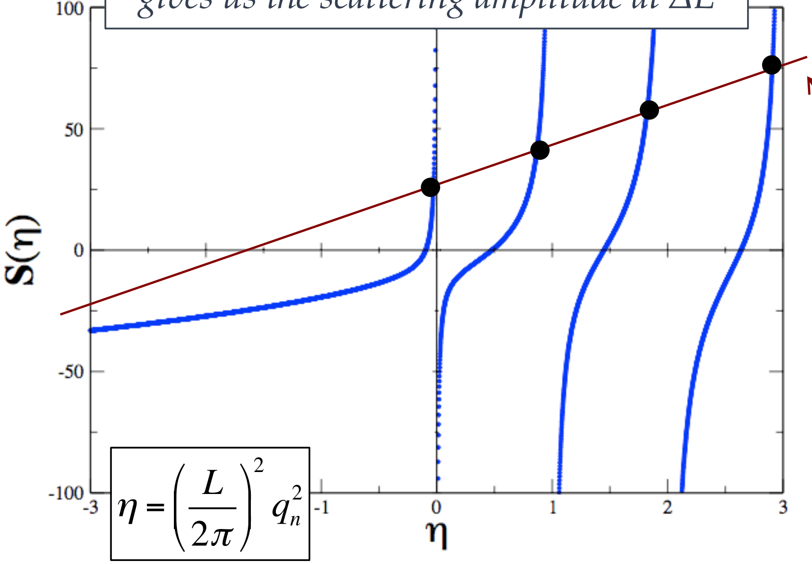
$$\rightarrow \quad \frac{1}{t_J}\log\frac{G(t)}{G(t+t_J)} \rightarrow \text{extract} \quad \Delta E$$

$$q_n \cot\delta(q_n) = \frac{1}{\pi L} S\left(q_n^{\ 2} \left(\frac{L}{2\pi}\right)^2 \right) \equiv \frac{1}{\pi L}\sum_{\vec{j}}^{\Lambda} \frac{1}{|\vec{j}|^2 - \left(\frac{L q_n}{2\pi}\right)^2} - \frac{4\Lambda}{L}$$

(3D Riemann- zeta function) $\quad \frac{2}{\sqrt{\pi}L}\mathcal{Z}_{00}^{(0,0,d)}$

$$+\,O(e^{-m_\pi L})$$

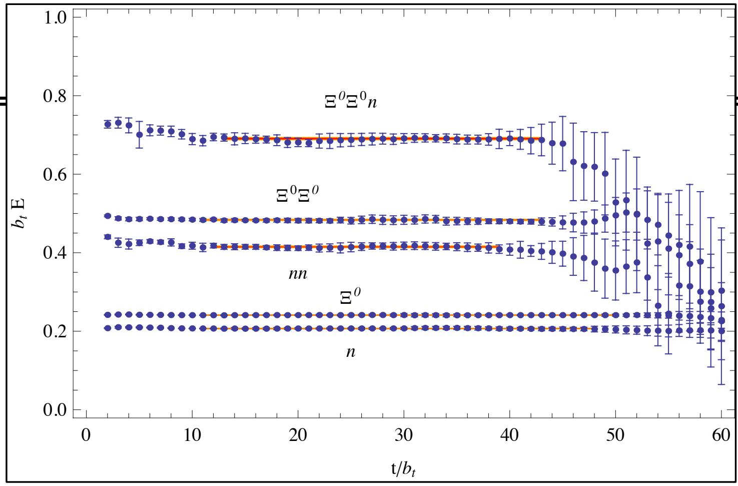
gives us the scattering amplitude at ΔE



$$\eta = \left(\frac{L}{2\pi}\right)^2 q_n^2$$

$$\boxed{q_n \cot\delta(q_n) = -\frac{1}{a} + \frac{1}{2} r_0 q_n^2} + O(q_n^4)$$

● : location of the E eigenstates in the finite volume



for a given {m_π, L, b} set

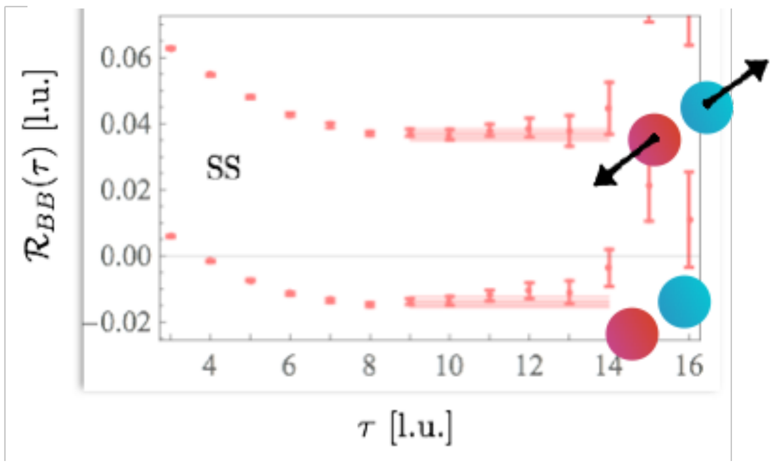
$$\rightarrow \quad \frac{1}{t_J}\log\frac{G(t)}{G(t+t_J)} \rightarrow \text{extract} \quad \Delta E$$

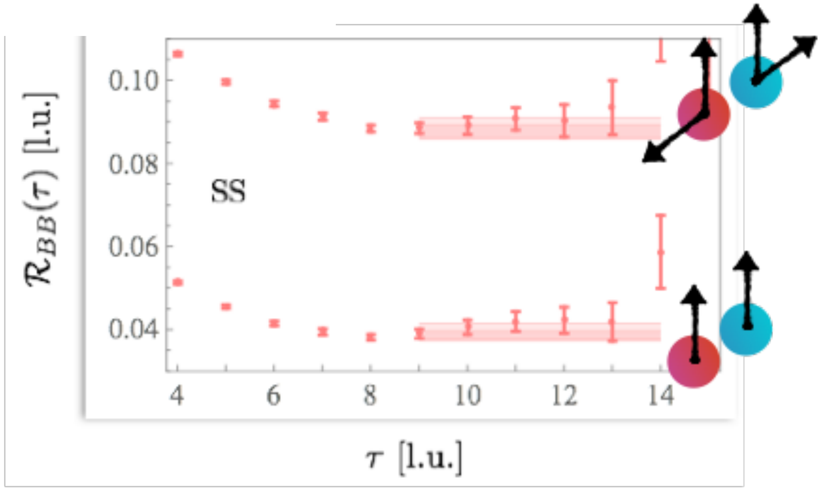
$$q_n \cot\delta(q_n) = \frac{1}{\pi L} S\left(q_n^{\,2}\left(\frac{L}{2\pi}\right)^2\right) \equiv \frac{1}{\pi L}\sum_{\vec{j}}^{\Lambda} \frac{1}{|\vec{j}|^2 - \left(\frac{L q_n}{2\pi}\right)^2} - \frac{4\Lambda}{L}$$

$$\frac{2}{\sqrt{\pi}L}\mathcal{Z}_{00}^{(0,0,d)}$$

$\mathbf{d} = (0,0,0)$
$\mathbf{d} = (0,0,2)$

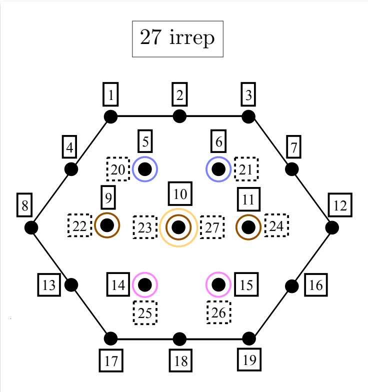
To extract more than one kinematical point for given {m_π, L, b}



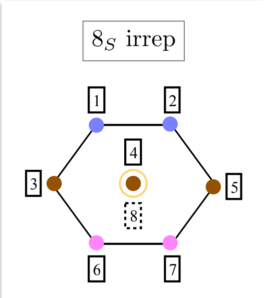


boost

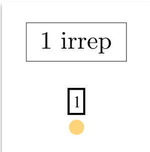
$SU(3)_f$ content of the BB interaction channels



	Flavor channel		Flavor channel
1	nn	14	$-\sqrt{\frac{2}{3}}\Sigma^0\Xi^- + \sqrt{\frac{1}{3}}\Sigma^-\Xi^0$
2	$\frac{1}{\sqrt{2}}(np+pn)$	15	$\sqrt{\frac{1}{3}}\Sigma^+\Xi^- + \sqrt{\frac{2}{3}}\Sigma^0\Xi^0$
3	pp	16	$\Sigma^+\Xi^0$
4	Σ^-n	17	$\Xi^-\Xi^-$
5	$\sqrt{\frac{2}{3}}\Sigma^0 n + \sqrt{\frac{1}{3}}\Sigma^- p$	18	$\frac{1}{\sqrt{2}}(\Xi^-\Xi^0 + \Xi^0\Xi^-)$
6	$-\sqrt{\frac{1}{3}}\Sigma^+ n + \sqrt{\frac{2}{3}}\Sigma^0 p$	19	$\Xi^0\Xi^0$
7	Σ^+p	20	$\Lambda n / -\sqrt{\frac{1}{3}}\Sigma^0 n + \sqrt{\frac{2}{3}}\Sigma^- p$
8	$\Sigma^-\Sigma^-$	21	$\Lambda p / \sqrt{\frac{2}{3}}\Sigma^+ n + \sqrt{\frac{1}{3}}\Sigma^0 p$
9	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^0 + \Sigma^0\Sigma^-)$	22	$\Lambda\Sigma^- / \Xi^- n$
10	$\frac{1}{\sqrt{6}}(\Sigma^-\Sigma^+ - 2\Sigma^0\Sigma^0 + \Sigma^+\Sigma^-)$	23	$\Lambda\Sigma^0 / \frac{1}{\sqrt{2}}(\Xi^- p - \Xi^0 n)$
11	$\frac{1}{\sqrt{2}}(\Sigma^0\Sigma^+ + \Sigma^+\Sigma^0)$	24	$\Lambda\Sigma^+ / \Xi^0 p$
12	$\Sigma^+\Sigma^+$	25	$\Lambda\Xi^- / \sqrt{\frac{1}{3}}\Sigma^0\Xi^- + \sqrt{\frac{2}{3}}\Sigma^-\Xi^0$
13	$\Sigma^-\Xi^-$	26	$\Lambda\Xi^0 / -\sqrt{\frac{2}{3}}\Sigma^+\Xi^- + \sqrt{\frac{1}{3}}\Sigma^0\Xi^0$
27	$\frac{1}{\sqrt{3}}(\Sigma^+\Sigma^- + \Sigma^0\Sigma^0 + \Sigma^-\Sigma^+) / \frac{1}{\sqrt{2}}(\Xi^0 n + \Xi^- p) / \Lambda\Lambda$		



	Flavor channel
1	$\Lambda n / -\sqrt{\frac{1}{3}}\Sigma^0 n + \sqrt{\frac{2}{3}}\Sigma^- p$
2	$\Lambda p / \sqrt{\frac{2}{3}}\Sigma^+ n + \sqrt{\frac{1}{3}}\Sigma^0 p$
3	$\Lambda\Sigma^- / \Xi^- n$
4	$\Lambda\Sigma^0 / \frac{1}{\sqrt{2}}(\Xi^- p - \Xi^0 n)$
5	$\Lambda\Sigma^+ / \Xi^0 p$
6	$\Lambda\Xi^- / \sqrt{\frac{1}{3}}\Sigma^0\Xi^- + \sqrt{\frac{2}{3}}\Sigma^-\Xi^0$
7	$\Lambda\Xi^0 / -\sqrt{\frac{2}{3}}\Sigma^+\Xi^- + \sqrt{\frac{1}{3}}\Sigma^0\Xi^0$
8	$\frac{1}{\sqrt{3}}(\Sigma^+\Sigma^- + \Sigma^0\Sigma^0 + \Sigma^-\Sigma^+) / \frac{1}{\sqrt{2}}(\Xi^0 n + \Xi^- p) / \Lambda\Lambda$



	Flavor channel
1	$\frac{1}{\sqrt{3}}(\Sigma^+\Sigma^- + \Sigma^0\Sigma^0 + \Sigma^-\Sigma^+) / \frac{1}{\sqrt{2}}(\Xi^0 n + \Xi^- p) / \Lambda\Lambda$

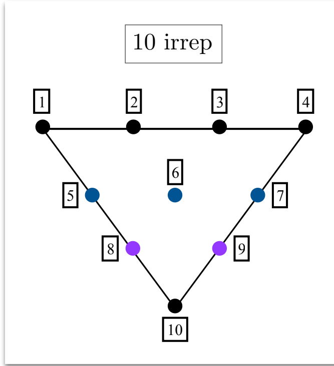
strangeness

I_3

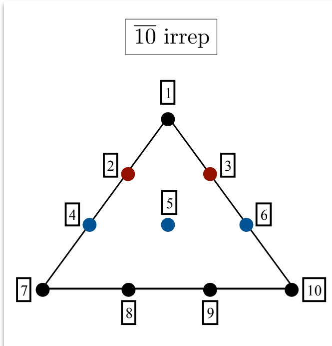
$$8 \otimes 8 = \boxed{27 \oplus 8_S \oplus 1} \oplus \boxed{10 \oplus \overline{10} \oplus 8_A}$$

J=0

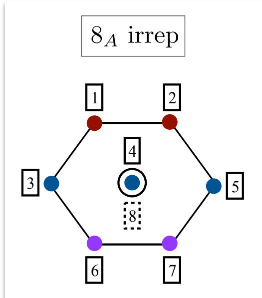
J=1



	Flavor channel
1	$\Sigma^- n$
2	$\sqrt{\frac{2}{3}}\Sigma^0 n + \sqrt{\frac{1}{3}}\Sigma^- p$
3	$-\sqrt{\frac{1}{3}}\Sigma^+ n + \sqrt{\frac{2}{3}}\Sigma^0 p$
4	$\Sigma^+ p$
5	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^0 - \Sigma^0\Sigma^-) / \Xi^- n / \Lambda\Sigma^-$
6	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^+ - \Sigma^+\Sigma^-) / \frac{1}{\sqrt{2}}(\Xi^- p - \Xi^0 n) / \Lambda\Sigma^0$
7	$\frac{1}{\sqrt{2}}(\Sigma^0\Sigma^+ - \Sigma^+\Sigma^0) / \Xi^0 p / \Lambda\Sigma^+$
8	$\sqrt{\frac{1}{3}}\Sigma^0\Xi^- + \sqrt{\frac{2}{3}}\Sigma^-\Xi^0 / \Lambda\Xi^-$
9	$-\sqrt{\frac{2}{3}}\Sigma^+\Xi^- + \sqrt{\frac{1}{3}}\Sigma^0\Xi^0 / \Lambda\Xi^0$
10	$\frac{1}{\sqrt{2}}(\Xi^0\Xi^- - \Xi^-\Xi^0)$



	Flavor channel
1	$\frac{1}{\sqrt{2}}(pn - np)$
2	$-\sqrt{\frac{1}{3}}\Sigma^0 n + \sqrt{\frac{2}{3}}\Sigma^- p / \Lambda n$
3	$\sqrt{\frac{2}{3}}\Sigma^+ n + \sqrt{\frac{1}{3}}\Sigma^0 p / \Lambda p$
4	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^0 - \Sigma^0\Sigma^-) / \Xi^- n / \Lambda\Sigma^-$
5	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^+ - \Sigma^+\Sigma^-) / \frac{1}{\sqrt{2}}(\Xi^- p - \Xi^0 n) / \Lambda\Sigma^0$
6	$\frac{1}{\sqrt{2}}(\Sigma^0\Sigma^+ - \Sigma^+\Sigma^0) / \Xi^0 p / \Lambda\Sigma^+$
7	$\Sigma^-\Xi^-$
8	$-\sqrt{\frac{2}{3}}\Sigma^0\Xi^- + \sqrt{\frac{1}{3}}\Sigma^-\Xi^0$
9	$\sqrt{\frac{1}{3}}\Sigma^+\Xi^- + \sqrt{\frac{2}{3}}\Sigma^0\Xi^0$
10	$\Sigma^+\Xi^0$



	Flavor channel
1	$-\sqrt{\frac{1}{3}}\Sigma^0 n + \sqrt{\frac{2}{3}}\Sigma^- p / \Lambda n$
2	$\sqrt{\frac{2}{3}}\Sigma^+ n + \sqrt{\frac{1}{3}}\Sigma^0 p / \Lambda p$
3	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^0 - \Sigma^0\Sigma^-) / \Xi^- n / \Lambda\Sigma^-$
4	$\frac{1}{\sqrt{2}}(\Sigma^-\Sigma^+ - \Sigma^+\Sigma^-) / \frac{1}{\sqrt{2}}(\Xi^- p - \Xi^0 n) / \Lambda\Sigma^0$
5	$\frac{1}{\sqrt{2}}(\Sigma^0\Sigma^+ - \Sigma^+\Sigma^0) / \Xi^0 p / \Lambda\Sigma^+$
6	$\sqrt{\frac{1}{3}}\Sigma^0\Xi^- + \sqrt{\frac{2}{3}}\Sigma^-\Xi^0 / \Lambda\Xi^-$
7	$-\sqrt{\frac{2}{3}}\Sigma^+\Xi^- + \sqrt{\frac{1}{3}}\Sigma^0\Xi^0 / \Lambda\Xi^0$
8	$\frac{1}{\sqrt{2}}(\Xi^0 n + \Xi^- p)$

M.L. Wagman et al (NPLQCD) PRD 96, 114510 (2017)

Label	A	s	I	J^π	Local SU(3) irreps	This work
N	1	0	1/2	$1/2^+$	$\mathbf{8}$	$\mathbf{8}$
Λ	1	-1	0	$1/2^+$	$\mathbf{8}$	$\mathbf{8}$
Σ	1	-1	1	$1/2^+$	$\mathbf{8}$	$\mathbf{8}$
Ξ	1	-2	1/2	$1/2^+$	$\mathbf{8}$	$\mathbf{8}$
d	2	0	0	1^+	$\overline{\mathbf{10}}$	$\overline{\mathbf{10}}$
nn	2	0	1	0^+	$\mathbf{27}$	$\mathbf{27}$
$n\Lambda$	2	-1	1/2	0^+	$\mathbf{27}$	$\mathbf{27}$
$n\Lambda$	2	-1	1/2	1^+	$\mathbf{8}_A$, $\overline{\mathbf{10}}$	—
$n\Sigma$	2	-1	3/2	0^+	$\mathbf{27}$	$\mathbf{27}$
$n\Sigma$	2	-1	3/2	1^+	$\mathbf{10}$	$\mathbf{10}$
$n\Xi$	2	-2	0	1^+	$\mathbf{8}_A$	$\mathbf{8}_A$
$n\Xi$	2	-2	1	1^+	$\mathbf{8}_A$, $\mathbf{10}$, $\overline{\mathbf{10}}$	—
H	2	-2	0	0^+	$\mathbf{1}$, $\mathbf{27}$	$\mathbf{1}$, $\mathbf{27}$
^{3}H, ^{3}He	3	0	1/2	$1/2^+$	$\overline{\mathbf{35}}$	$\overline{\mathbf{35}}$
$^3_\Lambda$H$(1/2^+)$	3	-1	0	$1/2^+$	$\overline{\mathbf{35}}$	—
$^3_\Lambda$H$(3/2^+)$	3	-1	0	$3/2^+$	$\overline{\mathbf{10}}$	$\overline{\mathbf{10}}$
$^3_\Lambda$He, $^3_\Lambda\tilde{\mathrm{H}}$, $nn\Lambda$	3	-1	1	$1/2^+$	$\mathbf{27}$, $\overline{\mathbf{35}}$	$\mathbf{27}$, $\overline{\mathbf{35}}$
$^3_\Sigma$He	3	-1	1	$3/2^+$	$\mathbf{27}$	$\mathbf{27}$
^{4}He	4	0	0	0^+	$\overline{\mathbf{28}}$	$\overline{\mathbf{28}}$
$^4_\Lambda$He, $^4_\Lambda$H	4	-1	1/2	0^+	$\overline{\mathbf{28}}$	—
$^4_{\Lambda\Lambda}$He	4	-2	0	0^+	$\mathbf{27}$, $\overline{\mathbf{28}}$	$\mathbf{27}$, $\overline{\mathbf{28}}$
$\Lambda\Xi^0 pnn$	5	-3	0	$3/2^+$	$\overline{\mathbf{10}}$ + ...	$\overline{\mathbf{10}}$

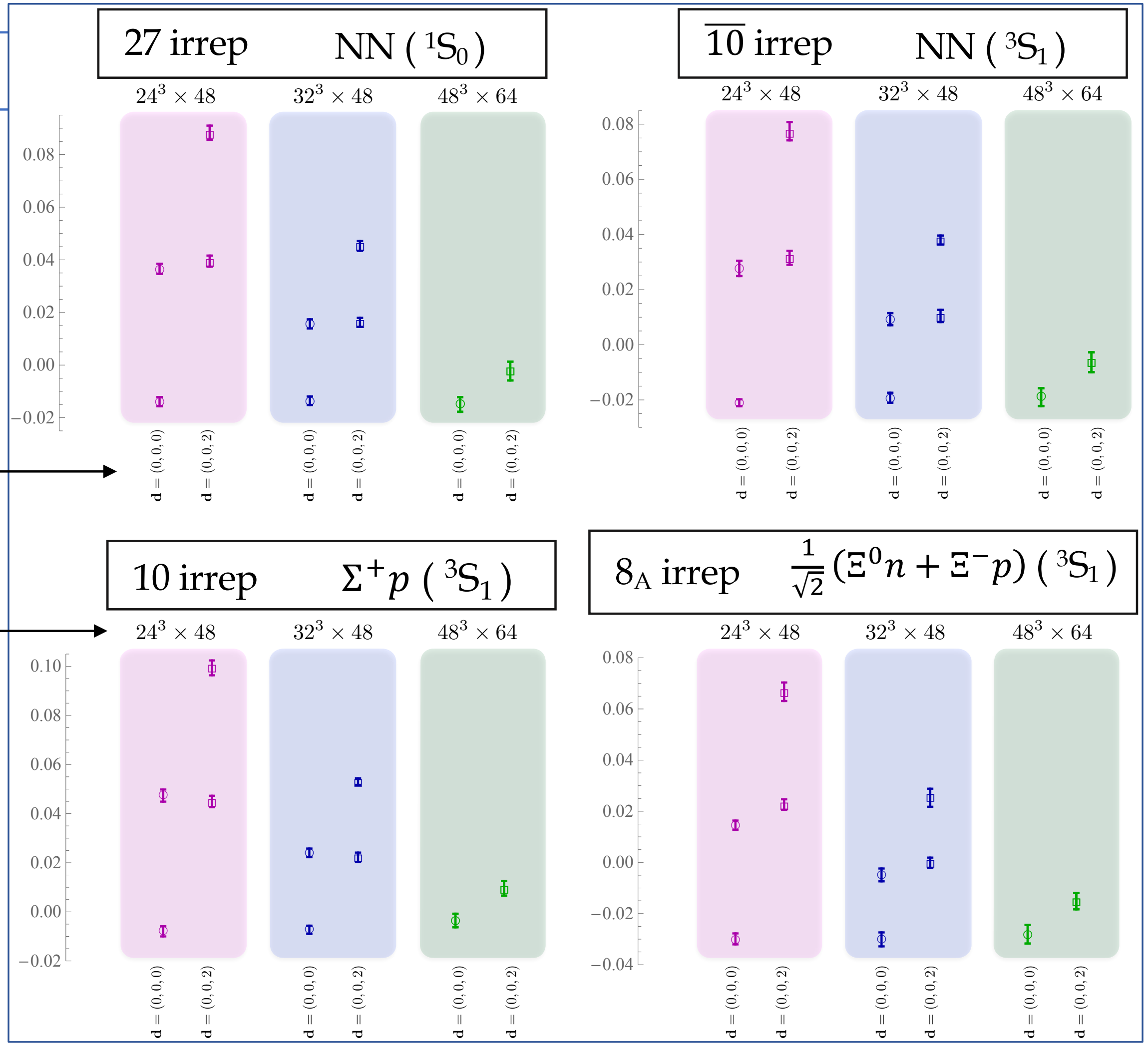
TABLE II: The baryon number, A, strangeness, s, total isospin, I, total spin and parity, J^π quantum numbers of the states and interpolating operators studied in the current work. For each set of quantum numbers, the SU(3) irreps that are possible to construct with local interpolating operators are listed. The last column lists the SU(3) irrep(s) of the interpolating operators used in this work, and the dashes indicate that the state is inferred using SU(3) symmetry.

Energy shifts

10 kinematical points for each irrep

total CoM momentum

volume



- L=24 l.u. (3.4 fm)
- L=32 l.u. (4.5 fm)
- L=48 l.u. (6.7 fm)

$SU(3)_f$

$m_\pi \sim 800$ MeV

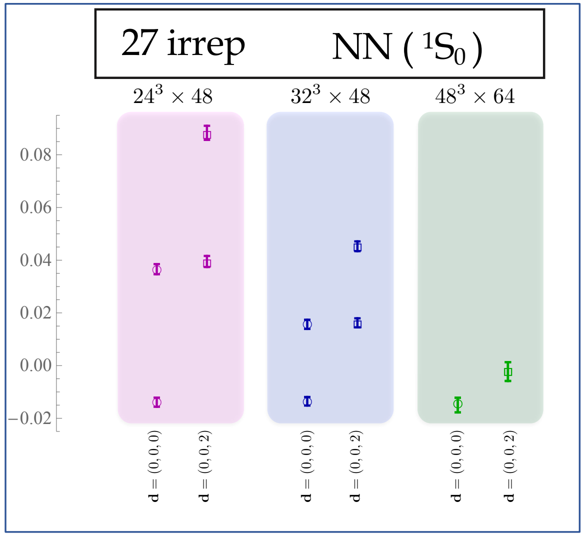
M.L. Wagman et al (NPLQCD), PRD, ARXIV:1706.06550

$SU(3)_f$

$m_\pi \sim 800$ MeV

10 kinematical points
for each irrep

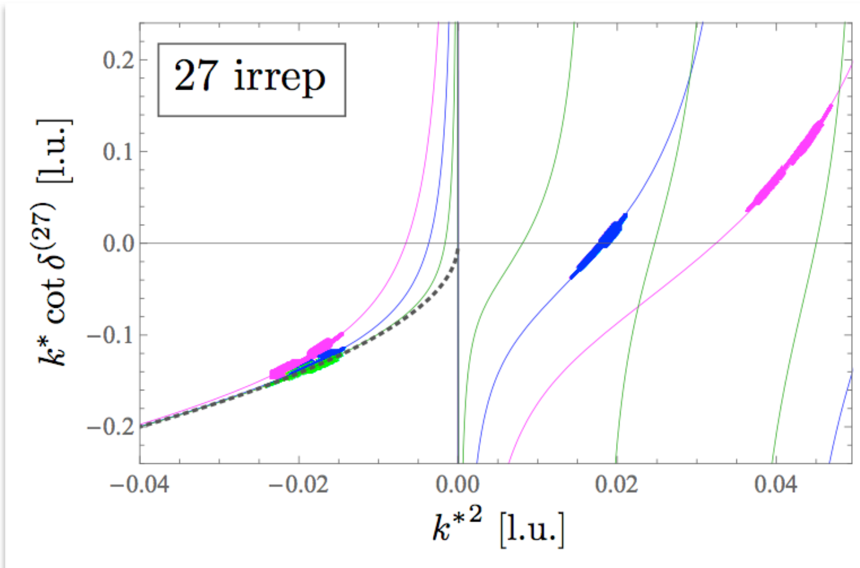
input to constrain



$$\frac{2}{\sqrt{\pi}L} Z_{00}^{(0,0,0(2))}$$

$$k \cot \delta(k) = \frac{1}{\pi L} \sum_{\vec{n}} \frac{1}{\vec{n}^2 - q^2} \qquad \vec{n} \in Z^3 \qquad q = \frac{Lk}{2\pi}$$

L=24 l.u. (3.4 fm)
L=32 l.u. (4.5 fm)
L=48 l.u. (6.7 fm)

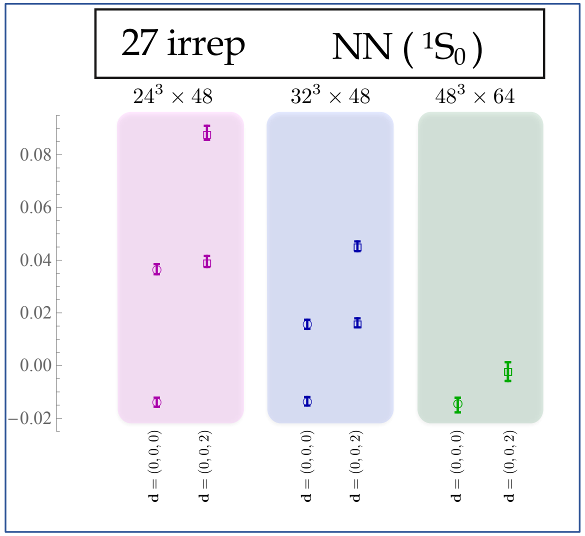


M.L. Wagman *et al* (NPLQCD), PRD, ARXIV:1706.06550

$SU(3)_f$

$m_\pi \sim 800$ MeV

10 kinematical points
for each irrep



L=24 l.u. (3.4 fm)
L=32 l.u. (4.5 fm)
L=48 l.u. (6.7 fm)

$$k^* \cot\delta(k^*) = -\sqrt{-k^{*2}} \quad \text{............}$$

$$\mathcal{A} = \frac{4\pi}{M} \frac{1}{p\cot\delta(p) - ip}$$

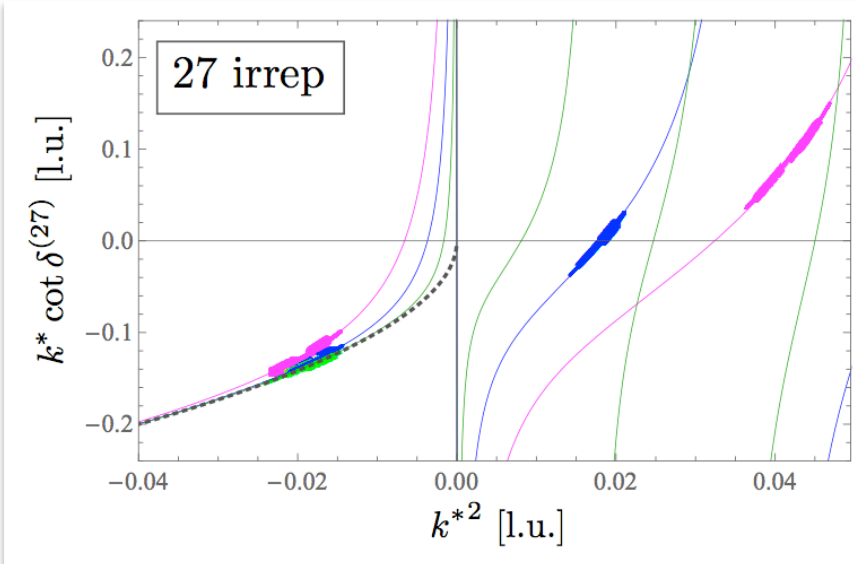
infinite volume

b.s. $\quad p^2 = -\gamma^2$

$\cot\delta(i\gamma) = i$

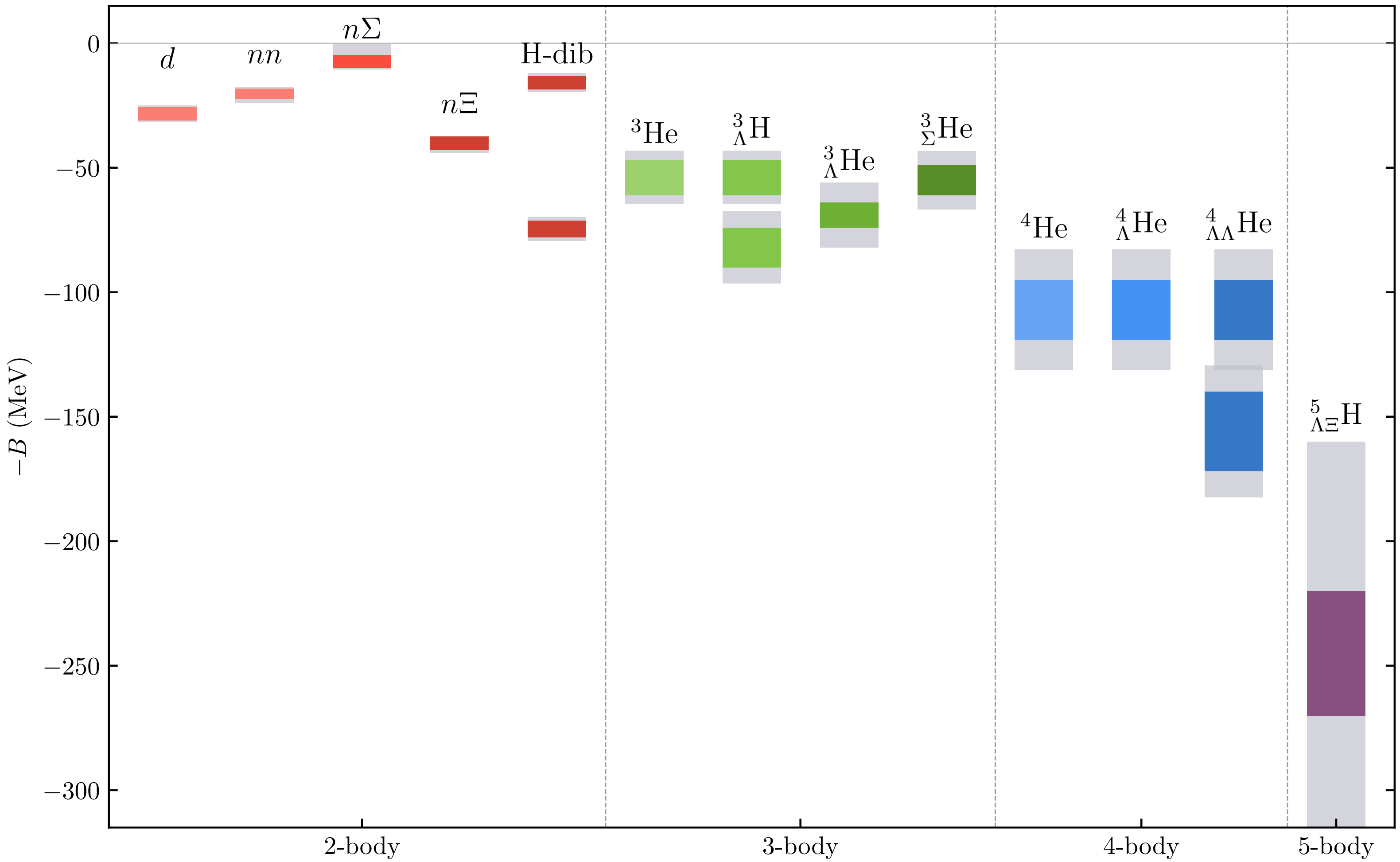
finite volume:

$$\cot\delta(i\gamma)\big|_{k=i\gamma} = i - i\sum_{\vec{m}\neq\vec{0}} \frac{e^{-|\vec{m}|\gamma L}}{|\vec{m}|\gamma L}$$



M.L. Wagman et al (NPLQCD), PRD, ARXIV:1706.06550

NPLQCD, Phys.Rev. D87 (2013) no.3, 034506; Phys.Rev. D96 (2017) no.11, 114510



$SU(3)_f$

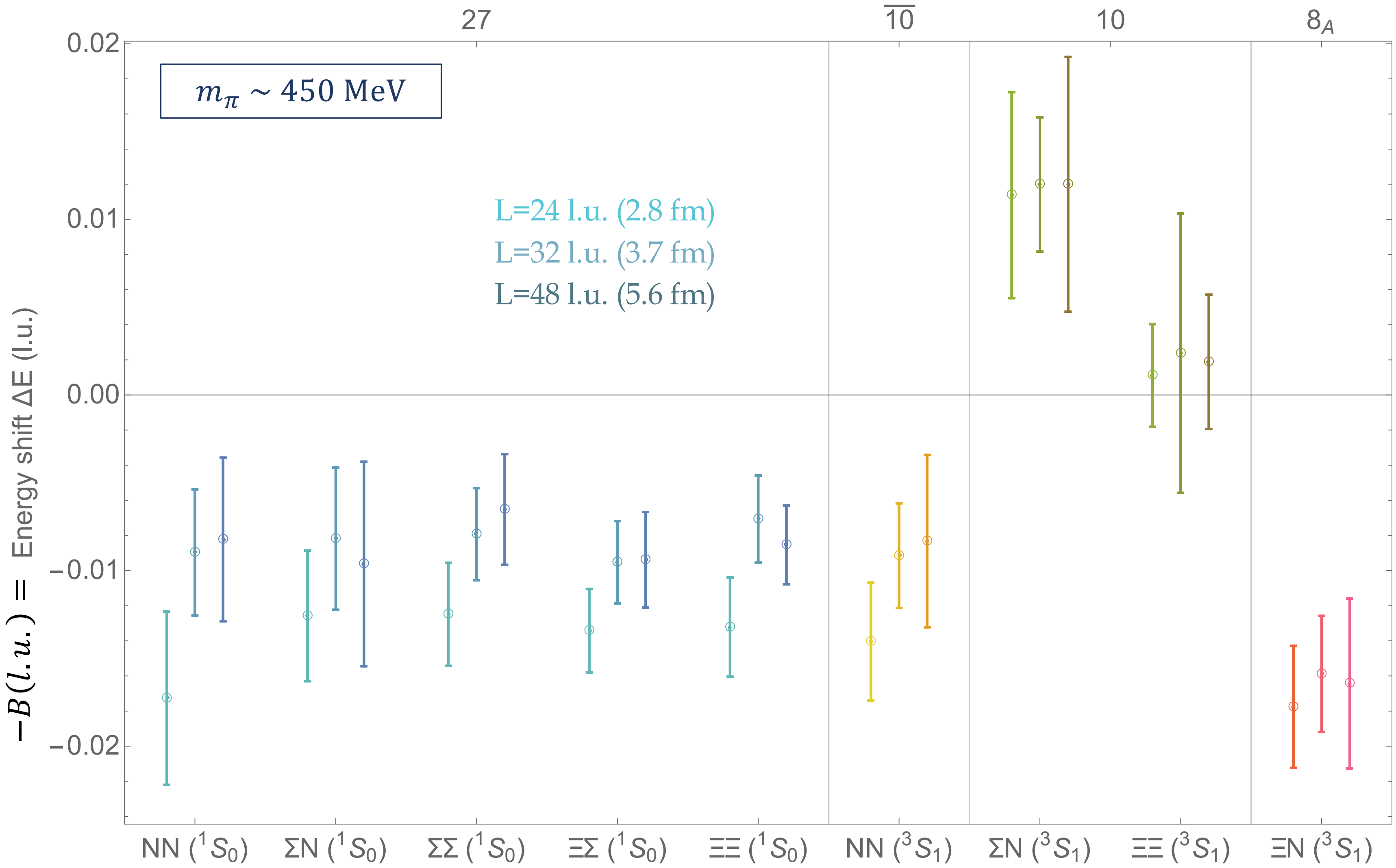
$m_\pi \sim 800$ MeV

no e.m. interactions

Collected by Marc Illa, UB

Ligther quark masses. **Ongoing production @ 450 MeV**

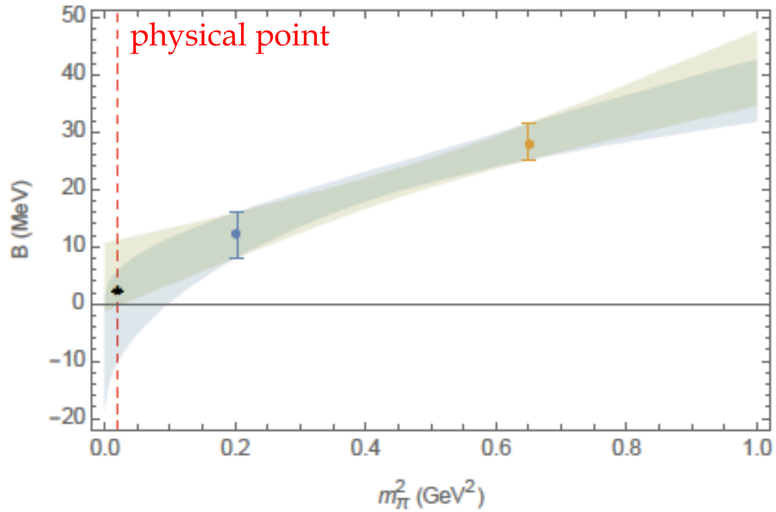
PRELIMINARY

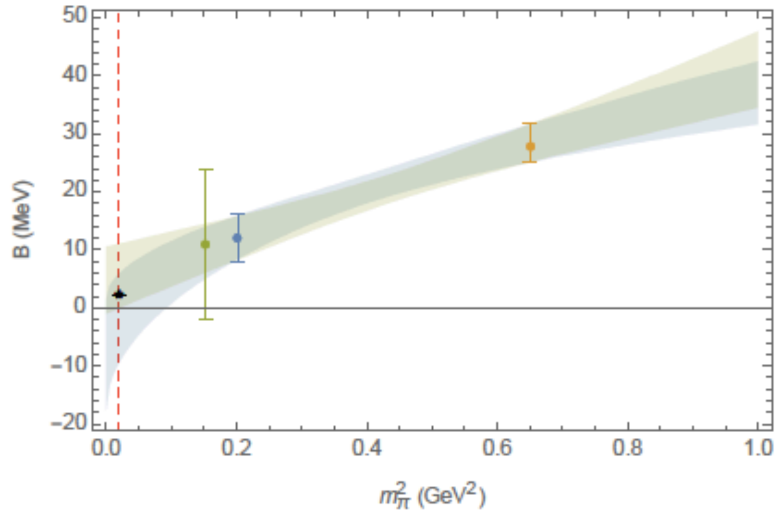


Ongoing production @ 450 MeV

PRELIMINARY

$NN\ ({}^3S_1)$





$A + B\, m\pi$

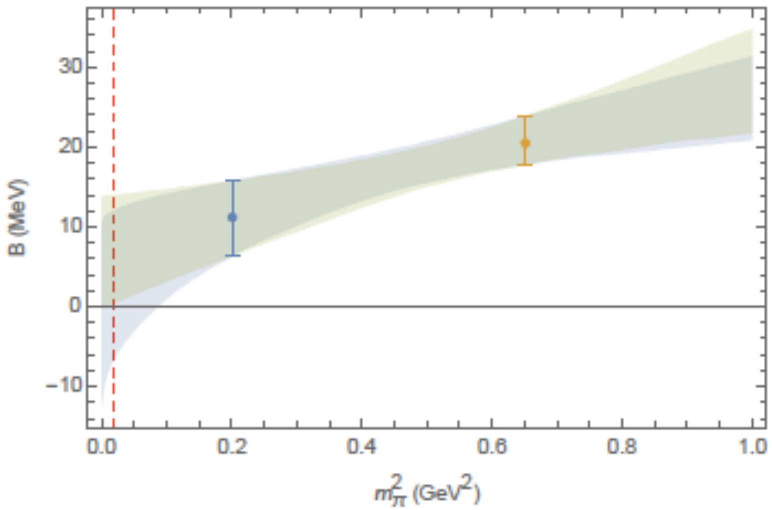
$C + D\, m_\pi^2$

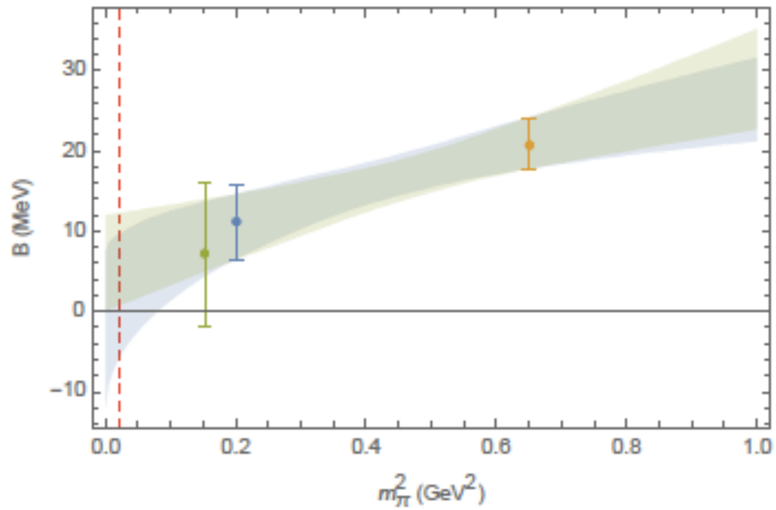
m_π = 390 MeV

m_π = 450 MeV

m_π = 800 MeV

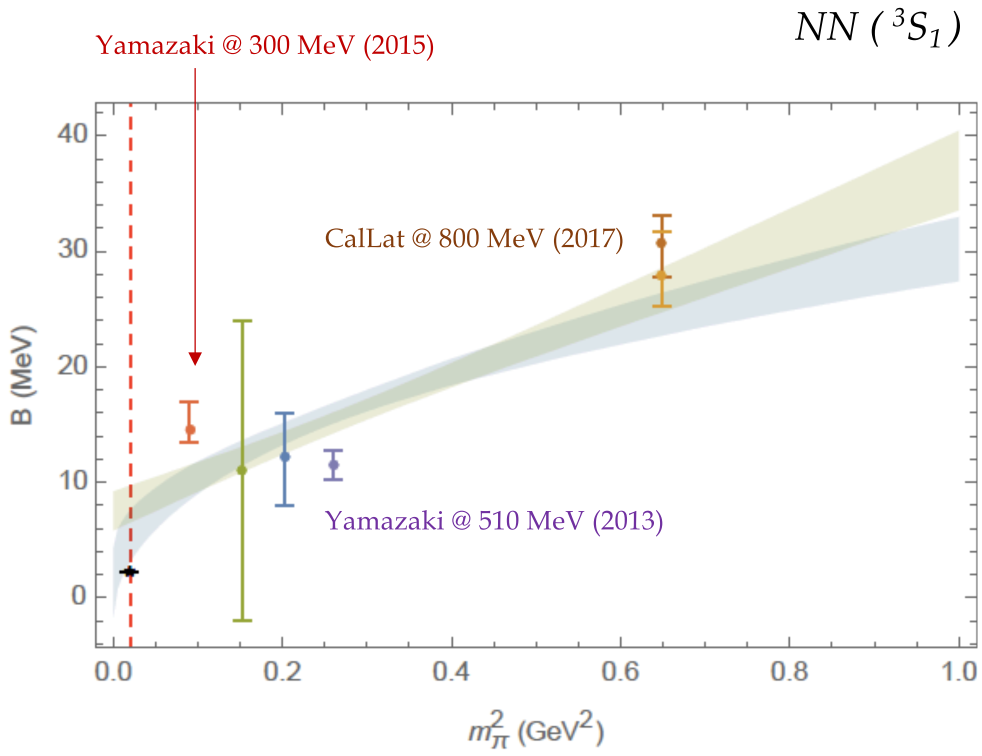
$NN\ ({}^1S_0)$

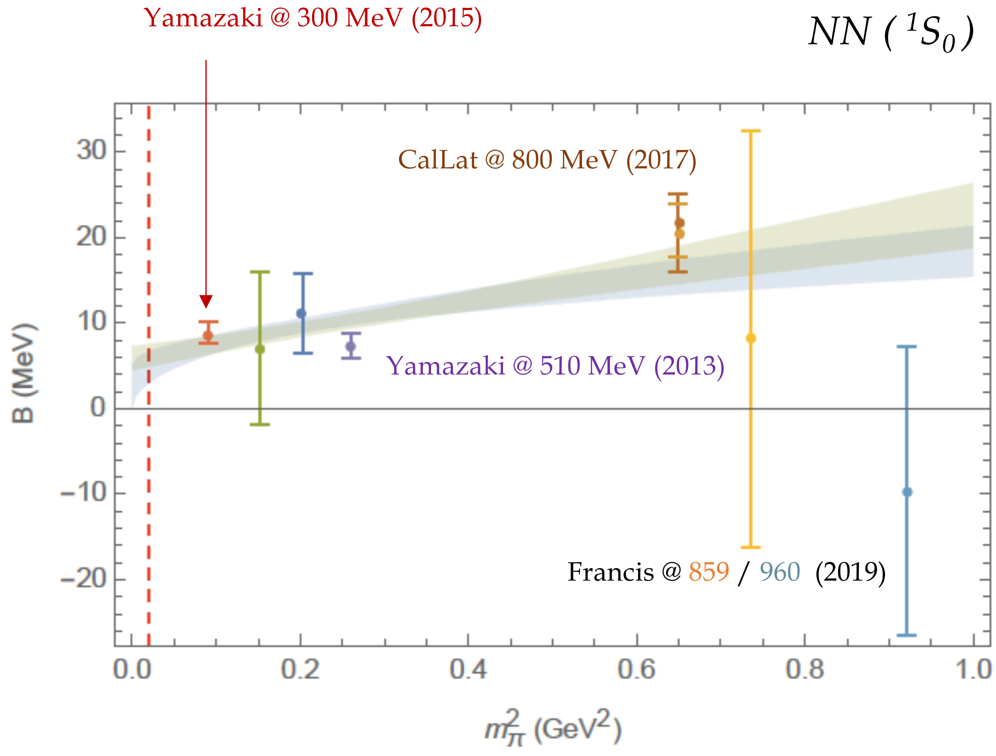




Ongoing production @ 450 MeV

P R E L I M I N A R Y





m_π = 390 MeV

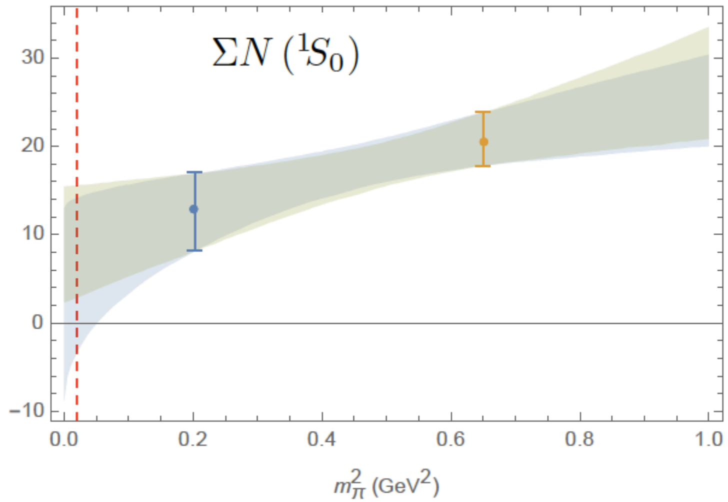
m_π = 450 MeV

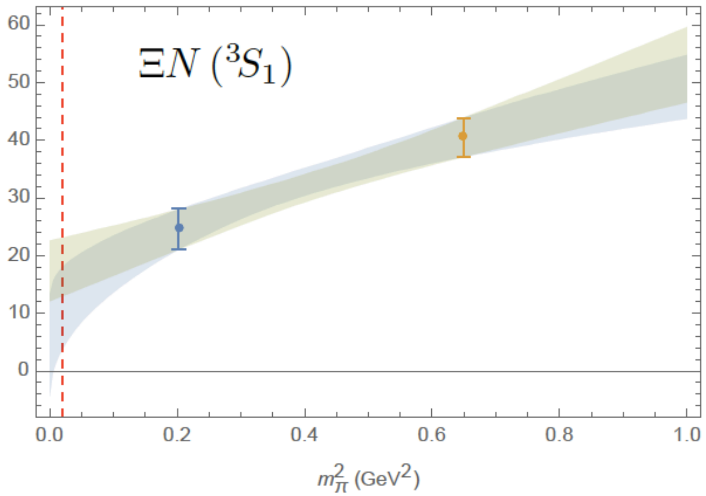
m_π = 800 MeV

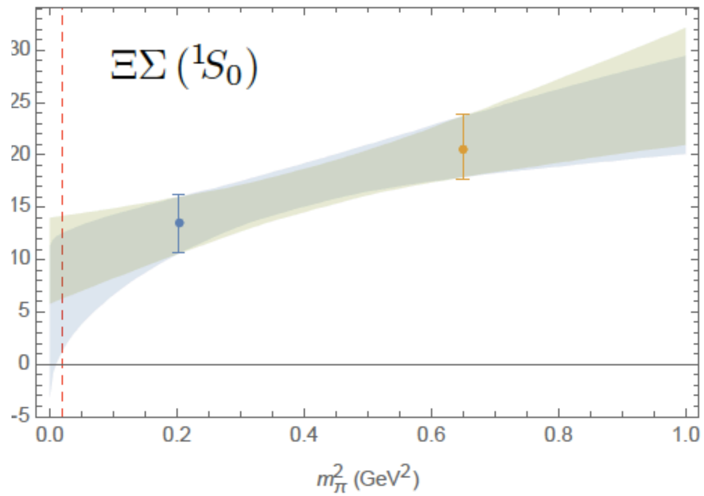
$A + B\, m\pi$

$C + D\, m_\pi^2$

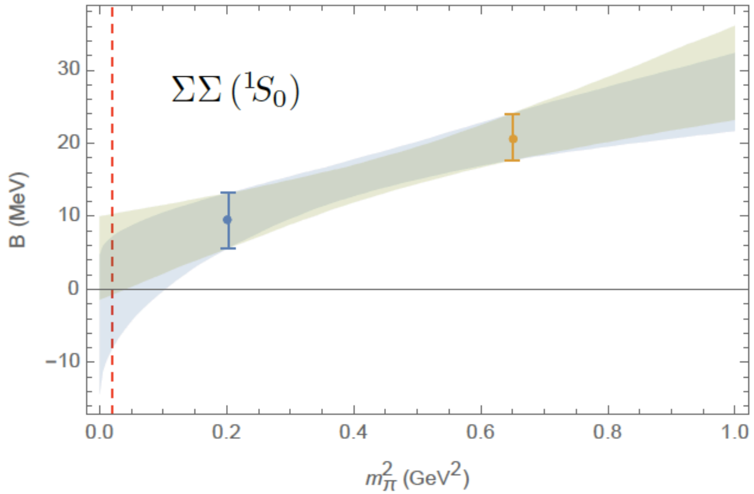
STRANGE CHANNELS. PRELIMINARY







Ongoing production
@ 450 MeV



B (MeV)

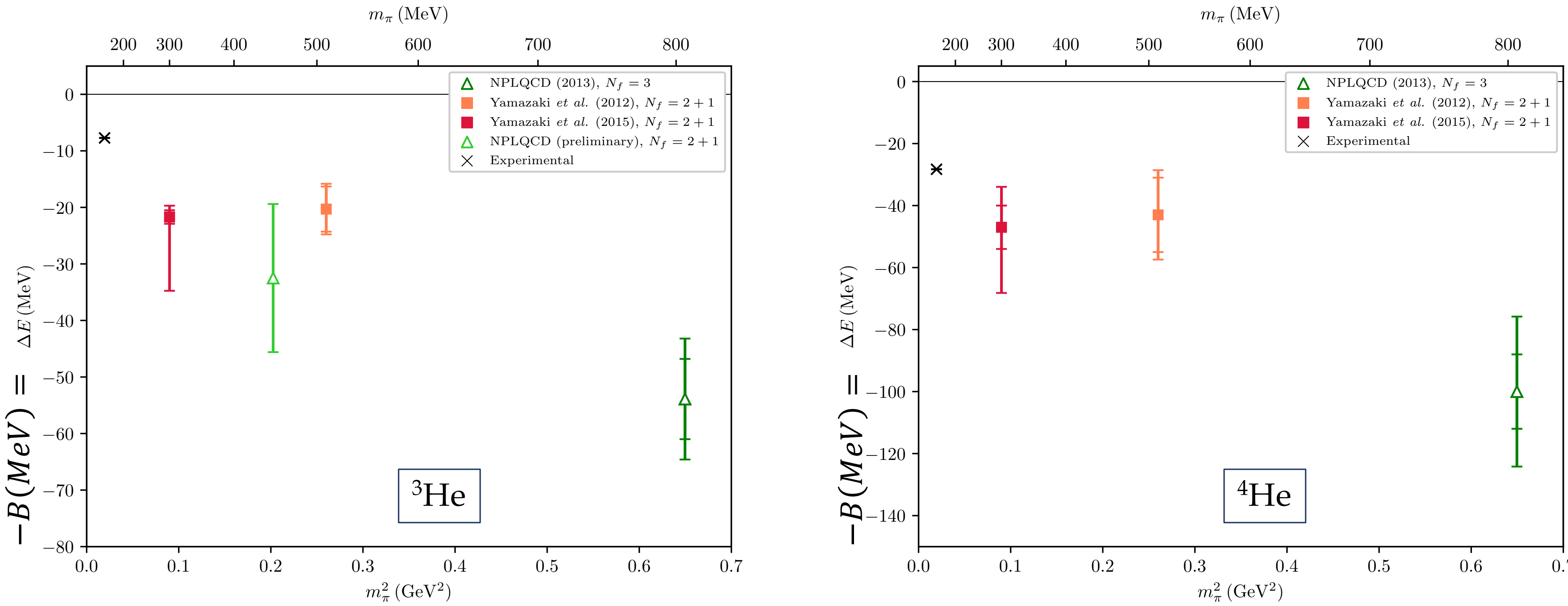
$A + B\, m\pi$

$C + D\, m_\pi^2$

$m_\pi = 450$ MeV

$m_\pi = 800$ MeV

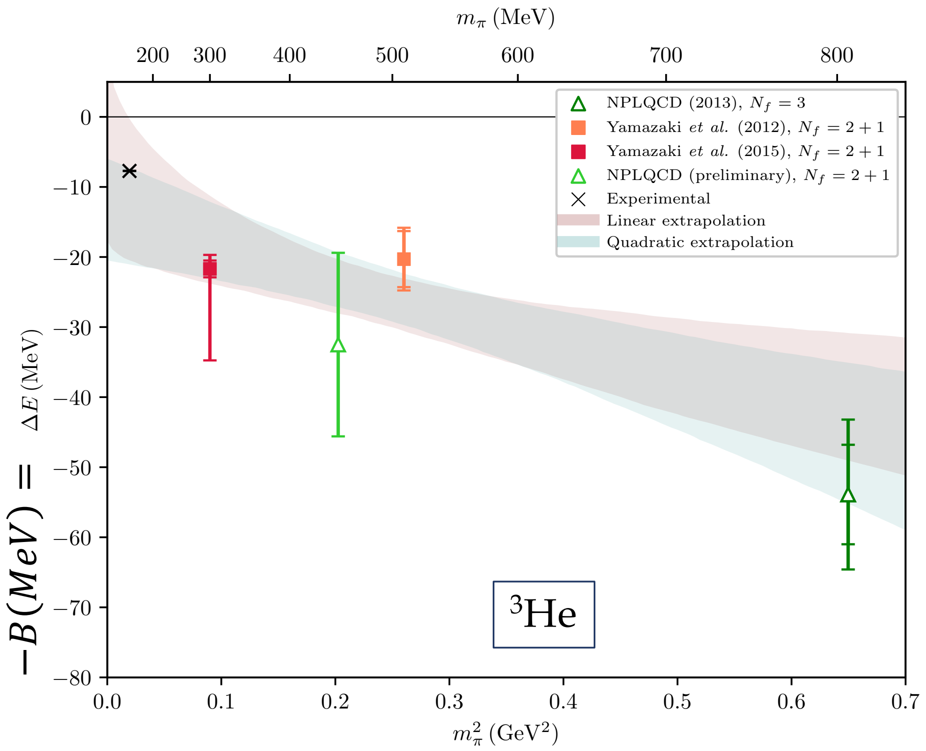
PRELIMINARY

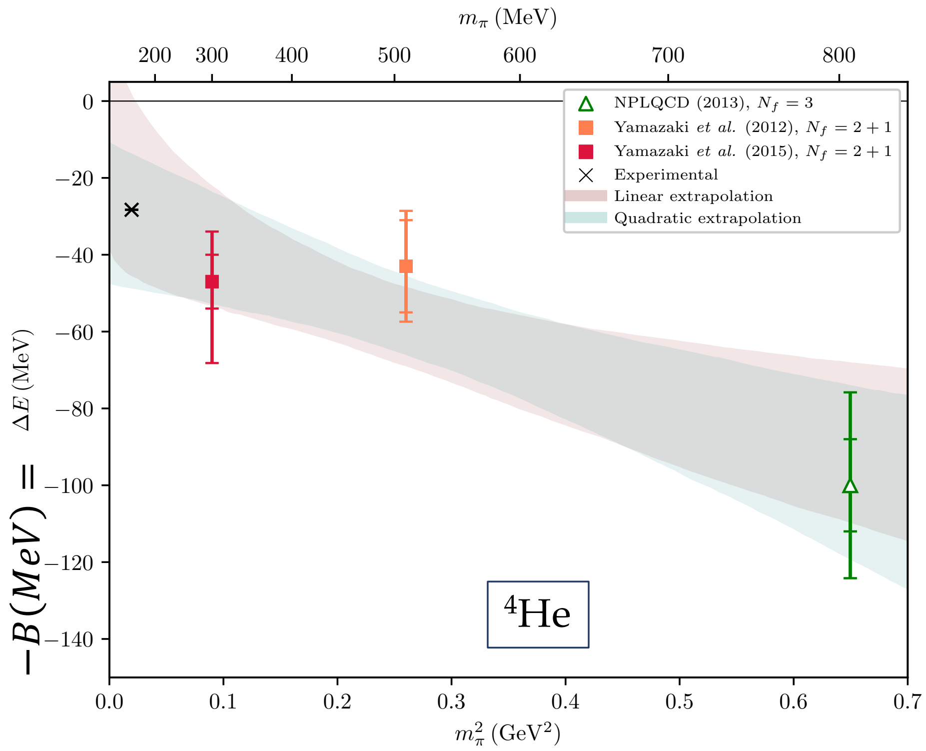


Ongoing production @ 450 MeV

collected by Marc Illa, UB

PRELIMINARY

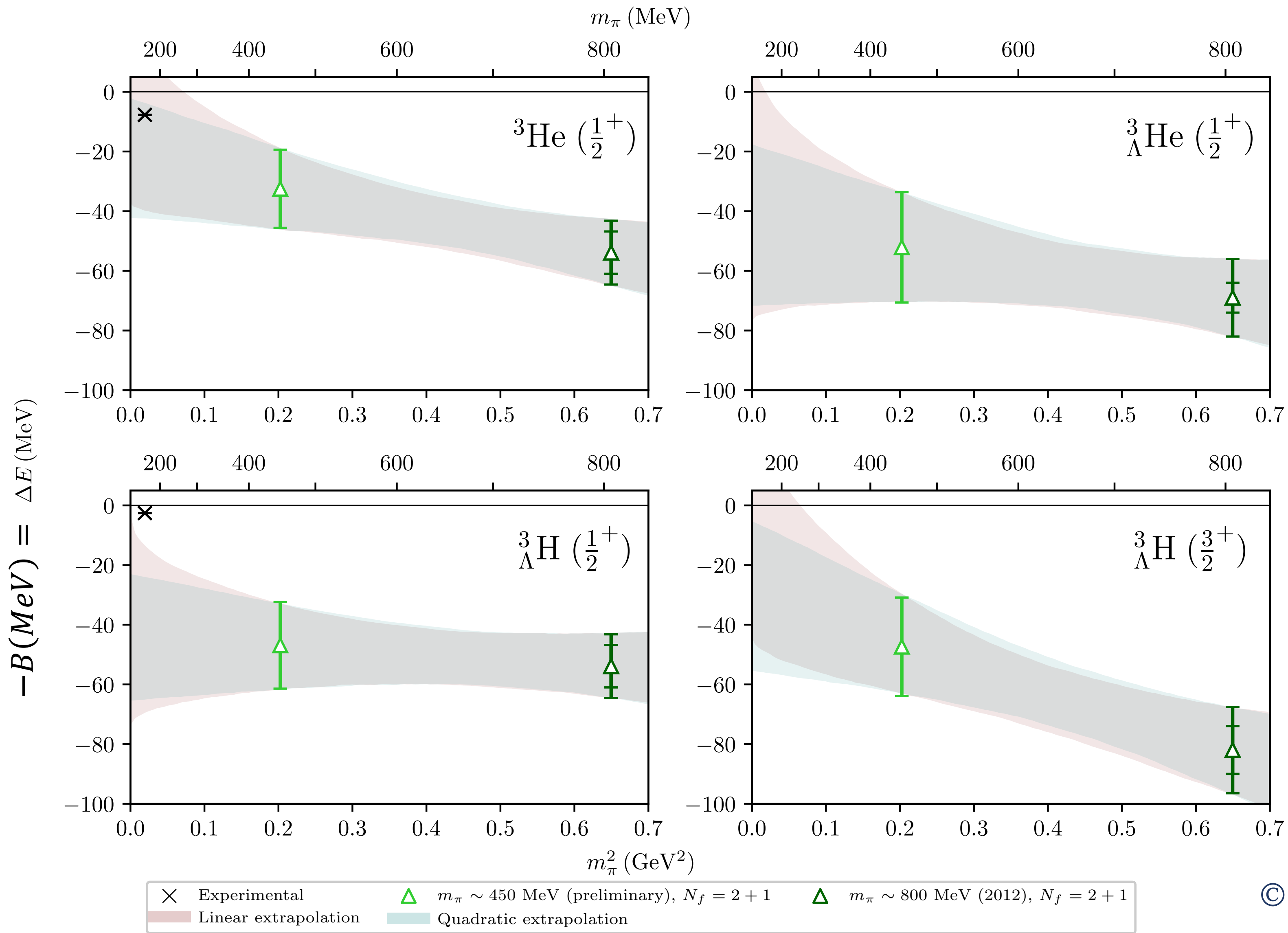




Ongoing production @ 450 MeV

collected by Marc Illa, UB

P R E L I M I N A R Y



A=3

Ongoing production @ 450 MeV

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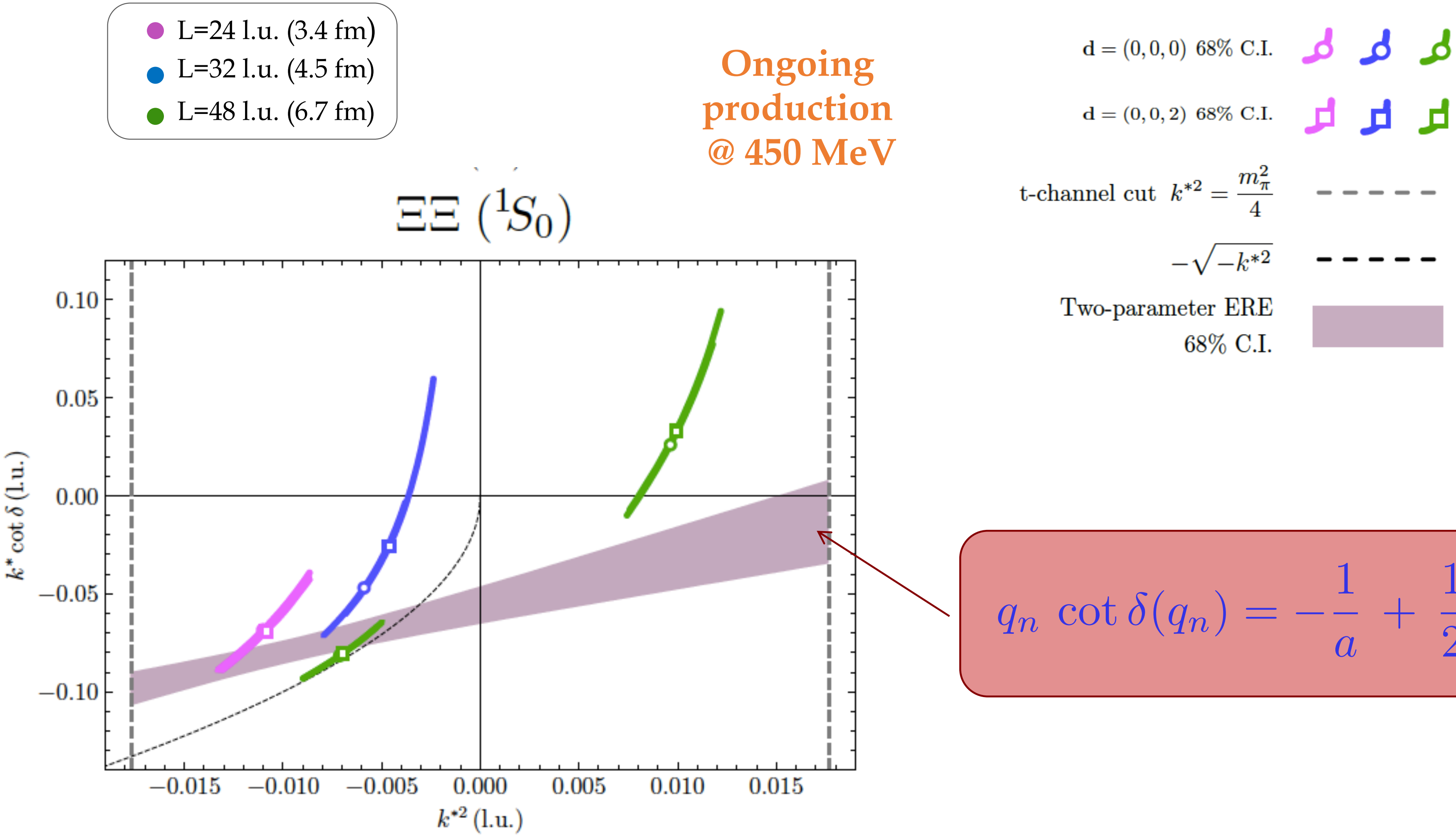
PRELIMINARY

Ongoing production @ 450 MeV

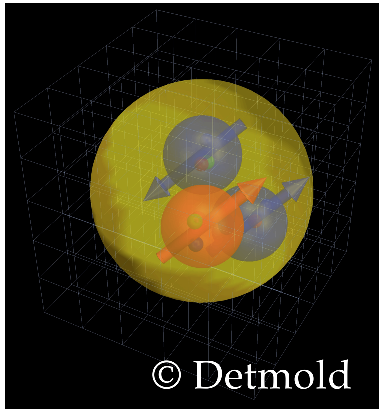


$$q_n \cot\delta(q_n) = -\frac{1}{a} + \frac{1}{2} r_0 q_n^2 + O(q_n^4)$$

Calculations on baryons and light nuclei

Interaction of nucleons/nuclei with external currents

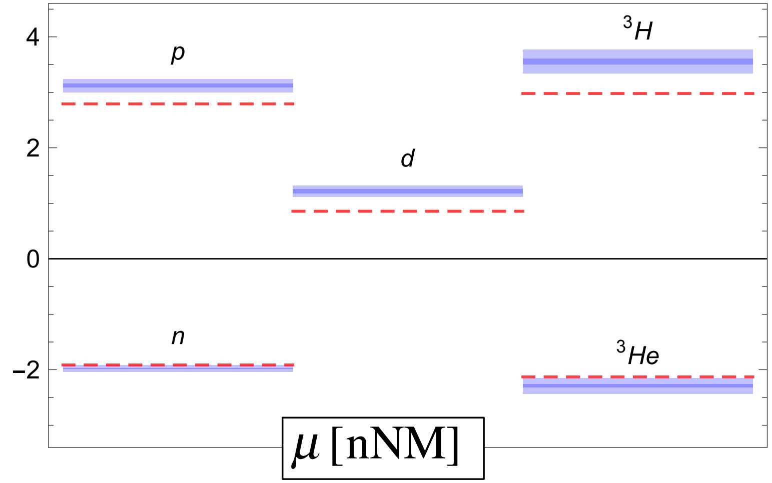
Magnetic Moments and polarizabilities



PRD **95**, 114513 (2017)
PRL **116**, 112301 (2016)
PRD **92**, 114502 (2015)
PRL **113**, 252001 (2014)

LQCD calculations with uniform,
time-independent, background magnetic fields

$SU(3)_f$ *NPLQCD, Phys. Rev .Lett. 113 (2014)*



$$\text{nNM} = \frac{e}{2M_N^{\text{latt}}} = \frac{e}{2M_N(m_\pi^{\text{latt}})}$$

LQCD @ $m_\pi \sim 800$ MeV

experiment

Shell-model predictions

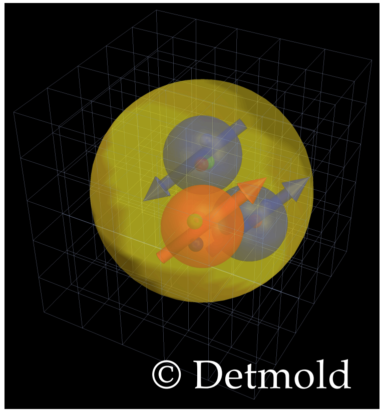
$$\mu(^3H) = \mu_p$$
$$\mu(^3He) = \mu_n$$
$$\mu_d = \mu_n + \mu_p$$

Calculations on baryons and light nuclei

Octet baryon magnetic moments @ ~800 MeV @ ~450 MeV

Interaction of nucleons/nuclei with external currents

Magnetic Moments and polarizabilities



PRD **95**, 114513 (2017)
PRL **116**, 112301 (2016)
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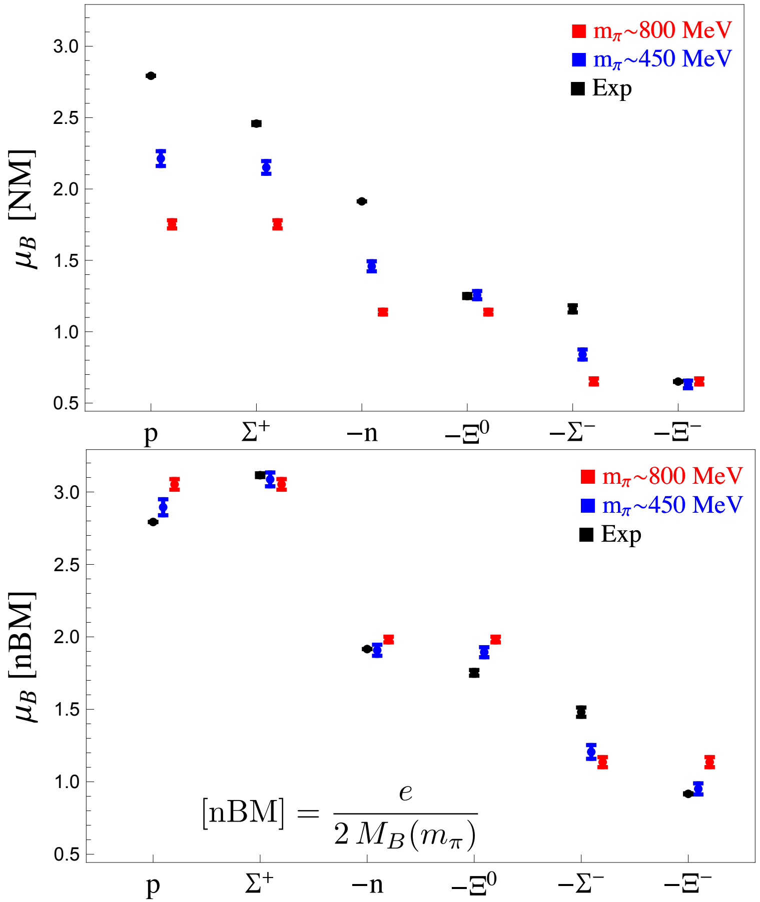
LQCD calculations with uniform, time-independent, background magnetic fields

NPLQCD, PRD95, 114513 (2017)

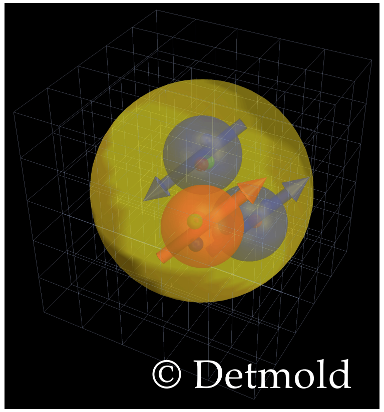


$(\mu_{-B} \equiv -\mu_B)$

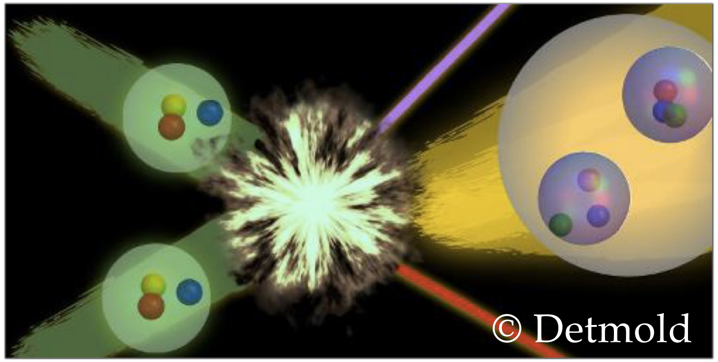
Calculations on baryons and light nuclei

Interaction of nucleons/nuclei with external currents

Magnetic Moments

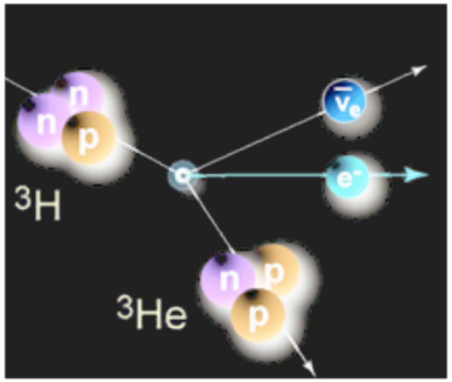


PRD **95**, 114513 (2017)
PRL **116**, 112301 (2016)
PRD **92**, 114502 (2015)
PRL **113**, 252001 (2014)



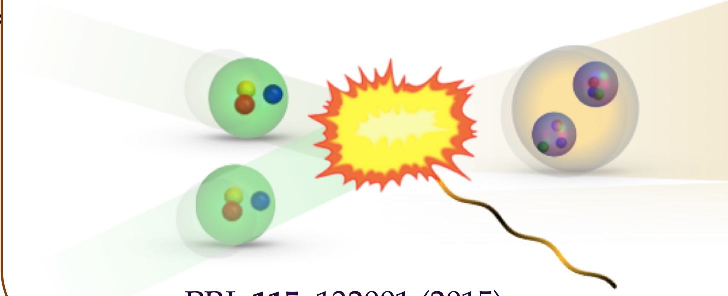
Proton-Proton Fusion

PRL **119**, 062002 (2017)

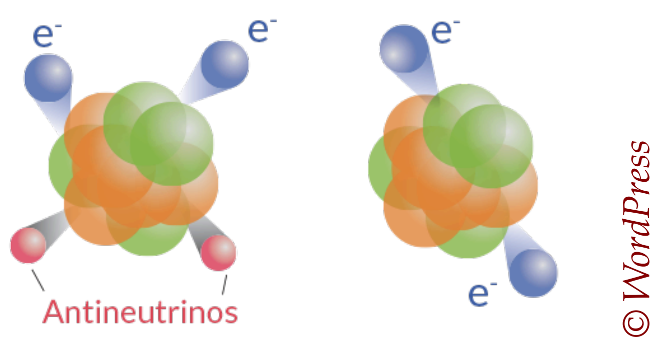


Tritium β Decay

$np \to d\gamma$ cross section



PRL **115**, 132001 (2015)



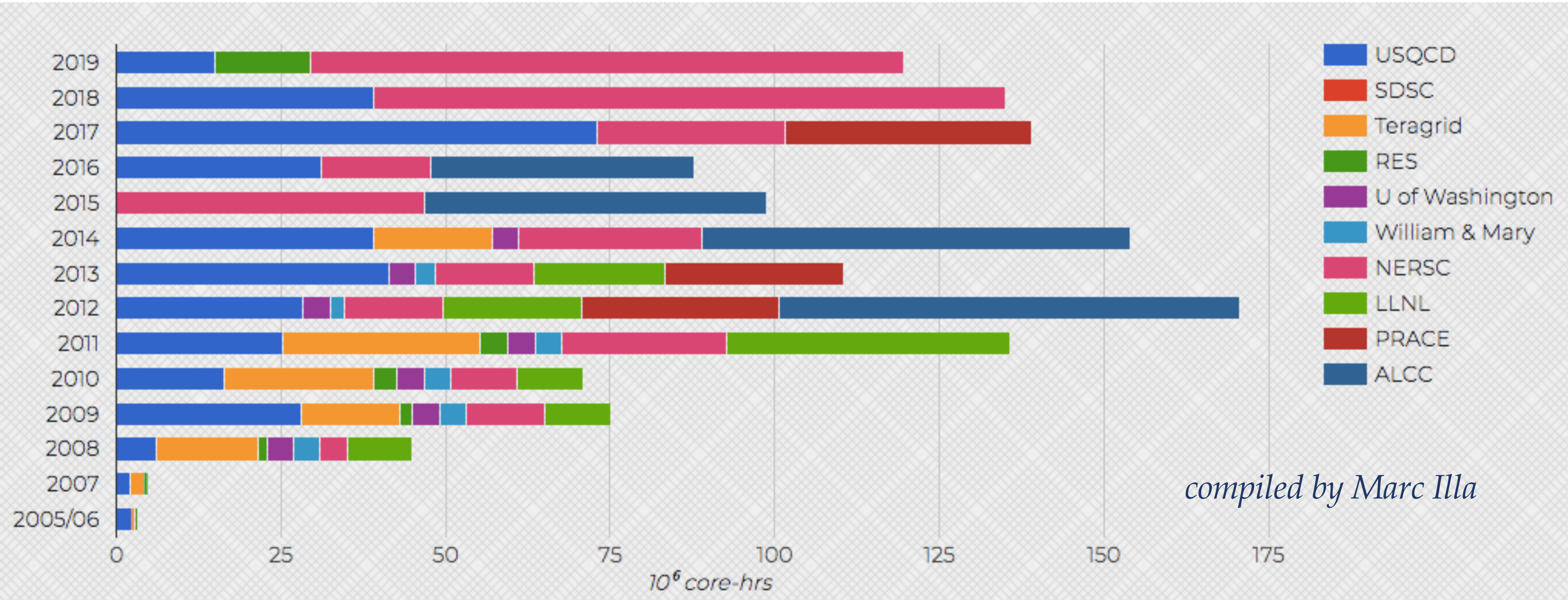
PRD 96, 054505 (2017)
PRL 119, 062003 (2017)

Acknowledgments

NPLQCD

Nuclear Physics with Lattice QCD

Computational resources, in units of 10^6 core-hrs



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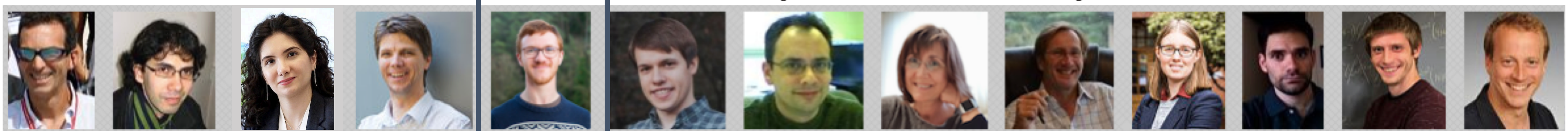

Chang *Detmold* *Murphy* *Parreño* *Shanahan* *Wagman*