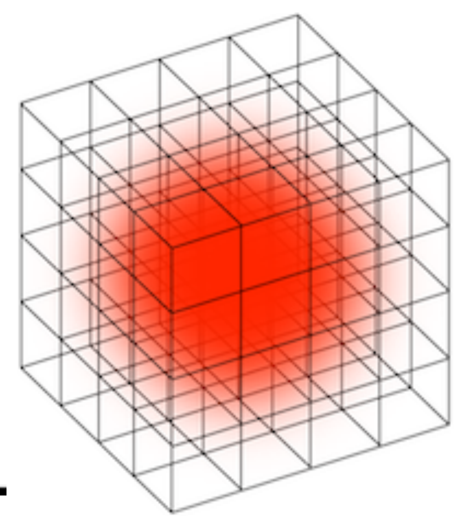
New Features of Baryon Magnetic Moments Uncovered from Lattice QCD

KITP-Program
Frontiers in Nuclear Physics

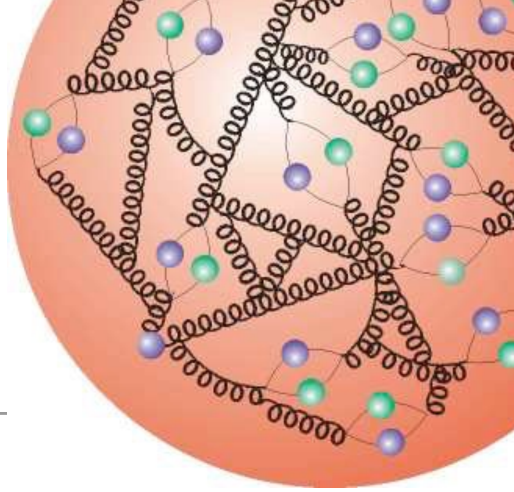


B C Tiburzi

16 September 2016

My work funded by NSF

Done in collaboration with ***Nuclear Physics Lattice QCD*** = NPLQCD



Lattice QCD for Nuclear Physics

Nuclear Physics from QCD → **EW Reactions** → **BSM Physics**

Overview

- **A few results: magnetic moments of light nuclei**
- **A few lattice QCD details**
- **New features of octet baryon magnetic moments**

Strong interactions in unphysical environments, e.g. $\mathrm{m_u = m_d = m_s}$

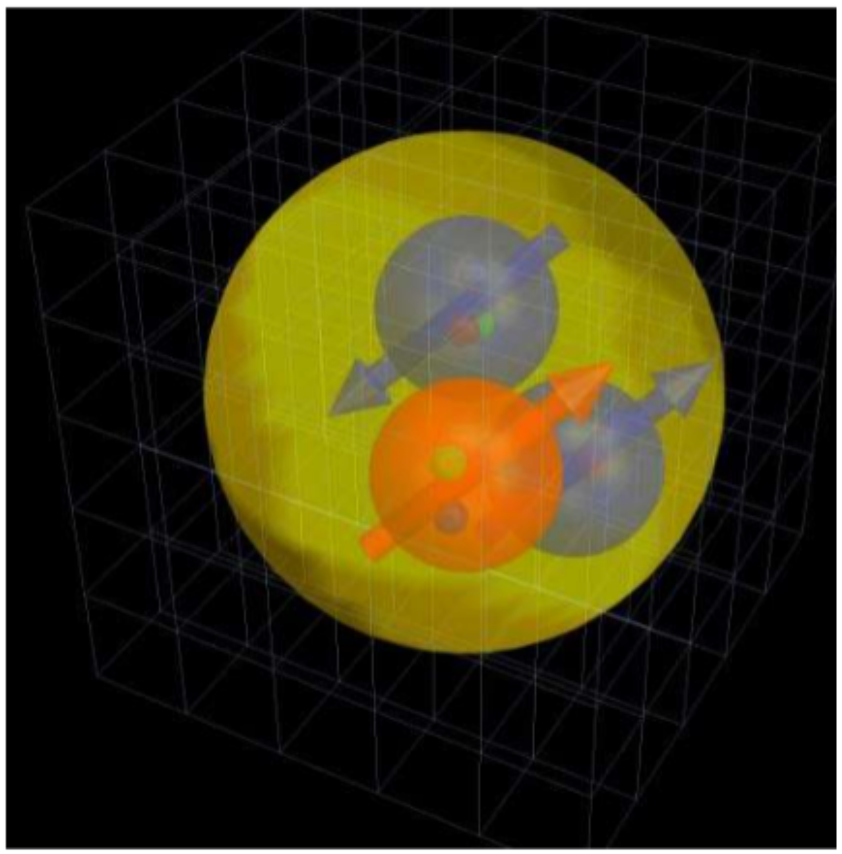
Magnetic Moments of Light Nuclei

Home Physics General Physics February 2, 2015

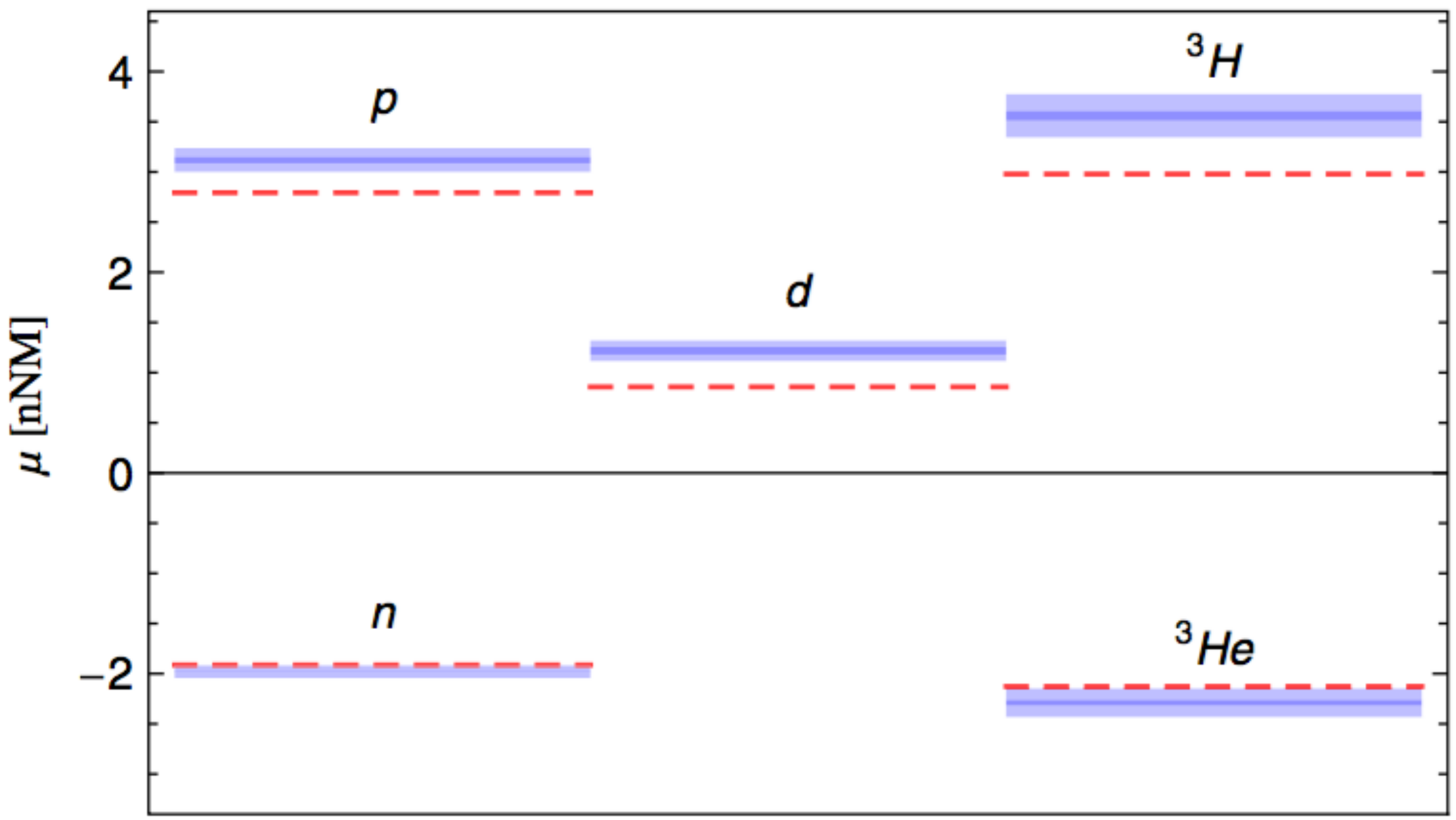
PHYS ORG

Pinpointing the magnetic moments of nuclear matter

February 2, 2015 by Kathy Kincade



Artist's impression of a triton, the atomic nucleus of a tritium atom. The image show a red neutron with quarks inside; the arrows indicate the alignments of the spins. Credit: William Detmold, MIT



A team of nuclear physicists has made a key discovery in its quest to shed light on the structure and behavior of subatomic particles.

Beane, Chang, Cohen, Detmold, Lin, Orginos, Parreño, Savage, and Tiburzi (*NPLQCD*), Phys.Rev.Lett.**113** (2014)

First Computation: $m_u = m_d = (m_s)_{\mathrm{phys}}$ $m_\pi \sim 800\,\mathtt{MeV}$

First "Nuclear Reaction" from QCD

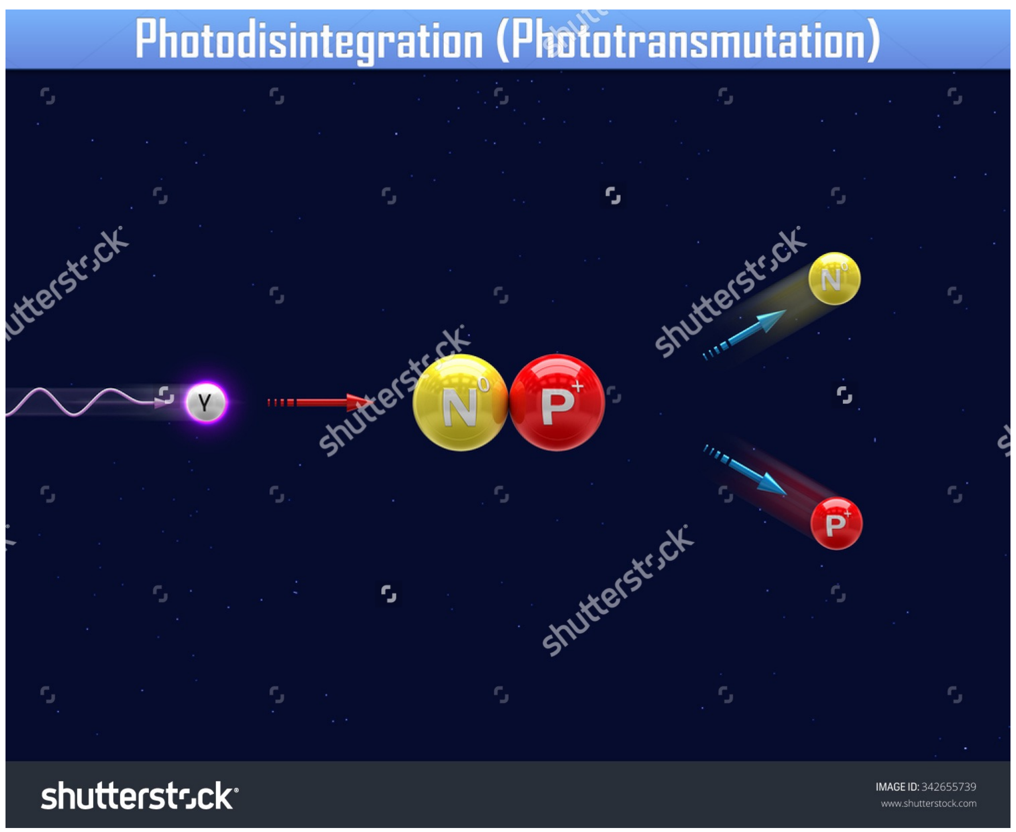
Dominant `M1` transition @ low energy

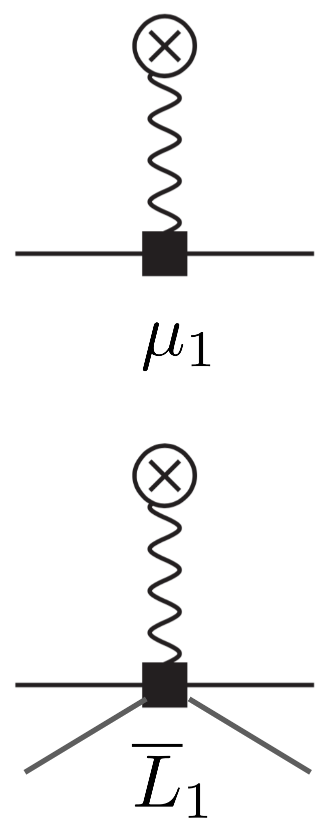
$$n + p \to d + \gamma \qquad \gamma^* + d \to n + p$$

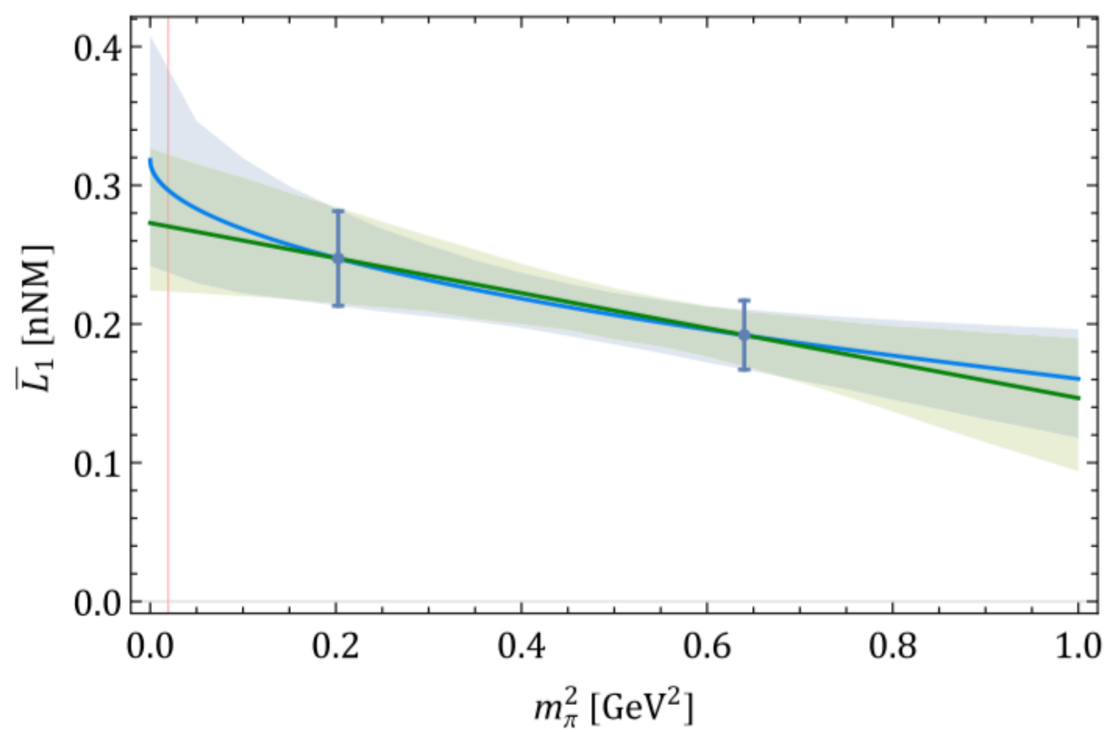
Magnetically Coupled Channels

$$|\Delta I| = |\Delta J| = 1 \qquad I_3 = j_z = 0$$

$$\mathbf{C}(t;\mathbf{B}) = \begin{pmatrix} C_{^3S_1,^3S_1}(t;\mathbf{B}) & C_{^3S_1,^1S_0}(t;\mathbf{B}) \\ C_{^1S_0,^3S_1}(t;\mathbf{B}) & C_{^1S_0,^1S_0}(t;\mathbf{B}) \end{pmatrix}$$



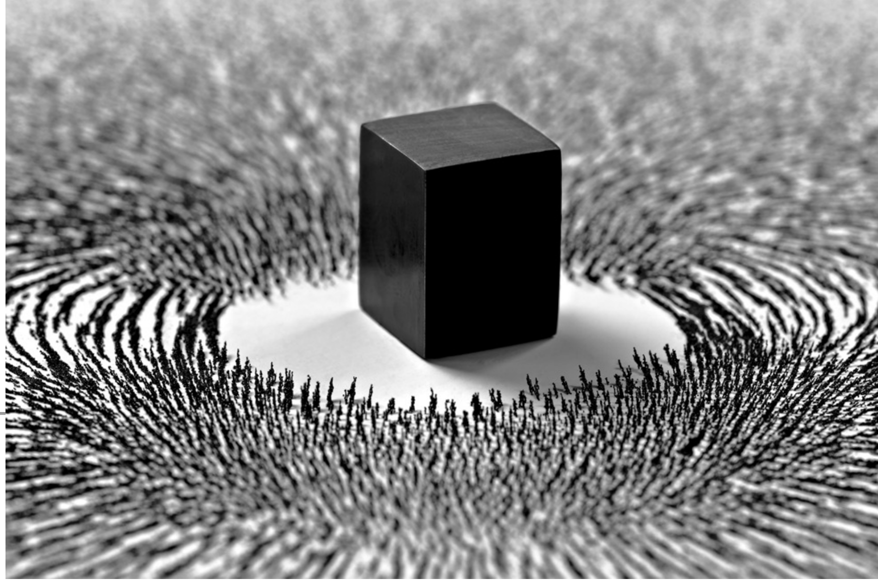




Two-body contribution isolated & compares favorably with EFT($\not\pi$) phenomenology

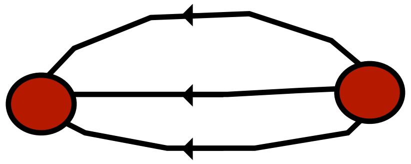
Beane, Chang, Detmold, Orginos, Parreño, Savage, and Tiburzi (*NPLQCD*), Phys.Rev.Lett.**115** (2015)

Lattice QCD in Magnetic Fields

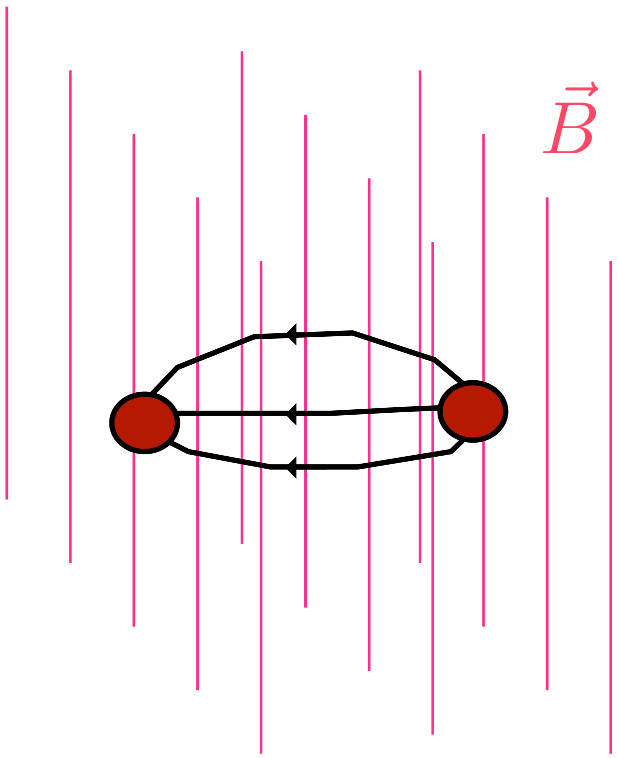


- Lattice QCD spectroscopy

$$G(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle = Z e^{-Mt} + \cdots$$



- Add classical magnetic field to QCD



$$G_B(t) = \langle \mathcal{O}(t)\mathcal{O}^\dagger(0)\rangle_B = Z(B) e^{-E(B)\,t} + \cdots$$

$$E_s(B) = M + \frac{|QeB|}{M}\left(n + \frac{1}{2}\right) - 2\mu\, sB + \cdots$$

- Zeeman effect $\Delta E = E_{+\frac{1}{2}}(B) - E_{-\frac{1}{2}}(B) = -2\mu\, B + \cdots$

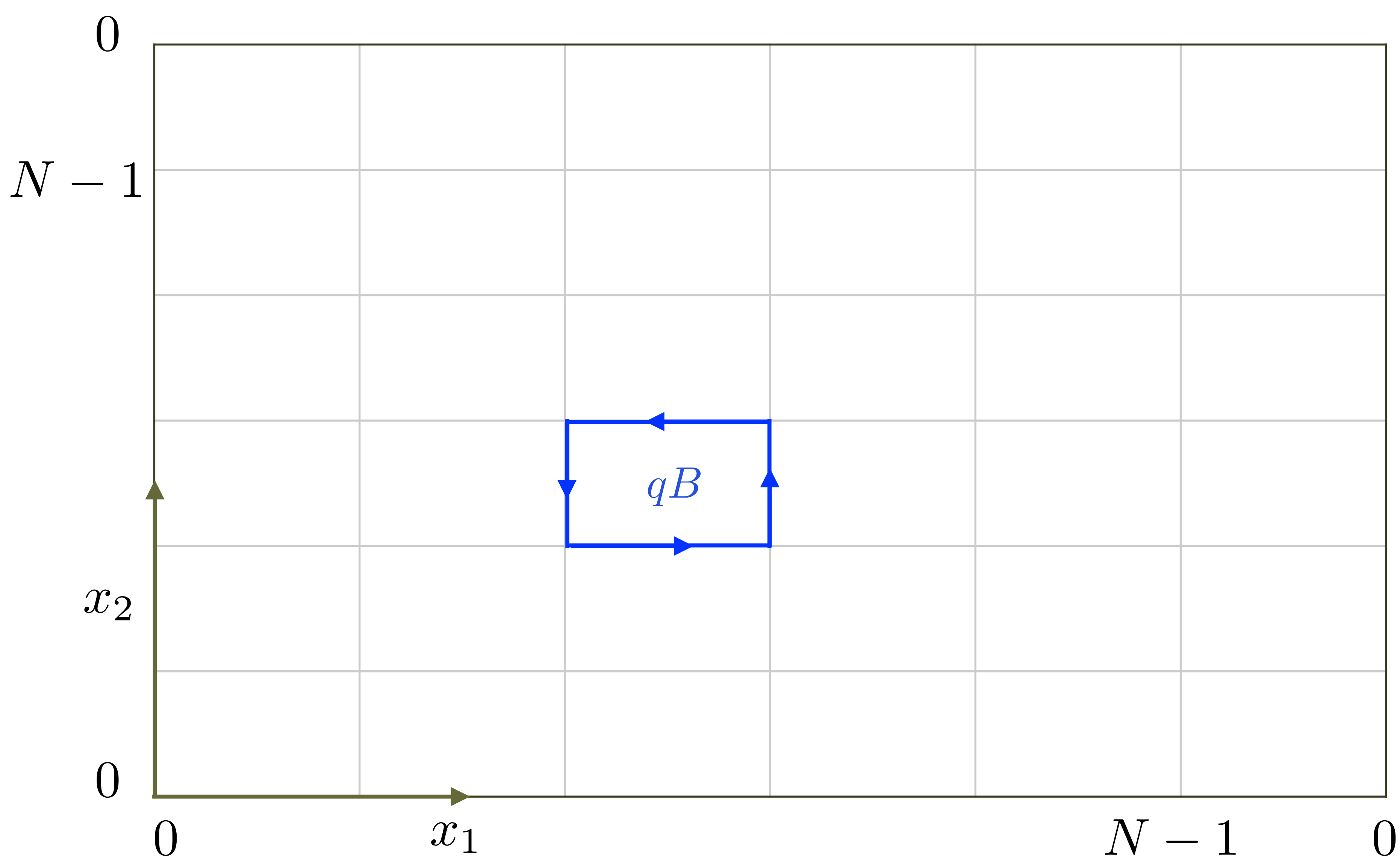
Gauge links:

$$U_\mu(x) = e^{igG_\mu(x)} \in SU(3)$$

$$U_\mu^{\text{e.m.}}(x) = e^{iqA_\mu(x)} \in U(1)$$

Magnetic Field on a Periodic Lattice

Seek uniform B-field $U_\mu(x) = e^{-iqx_2 B\delta_{\mu 1}}$



$$U_1(x)U_2(x+\hat{i})U_2^\dagger(x+\hat{i}+\hat{j})U_1^\dagger(x+\hat{j}) = e^{iqF_{12}} = e^{iqB}$$

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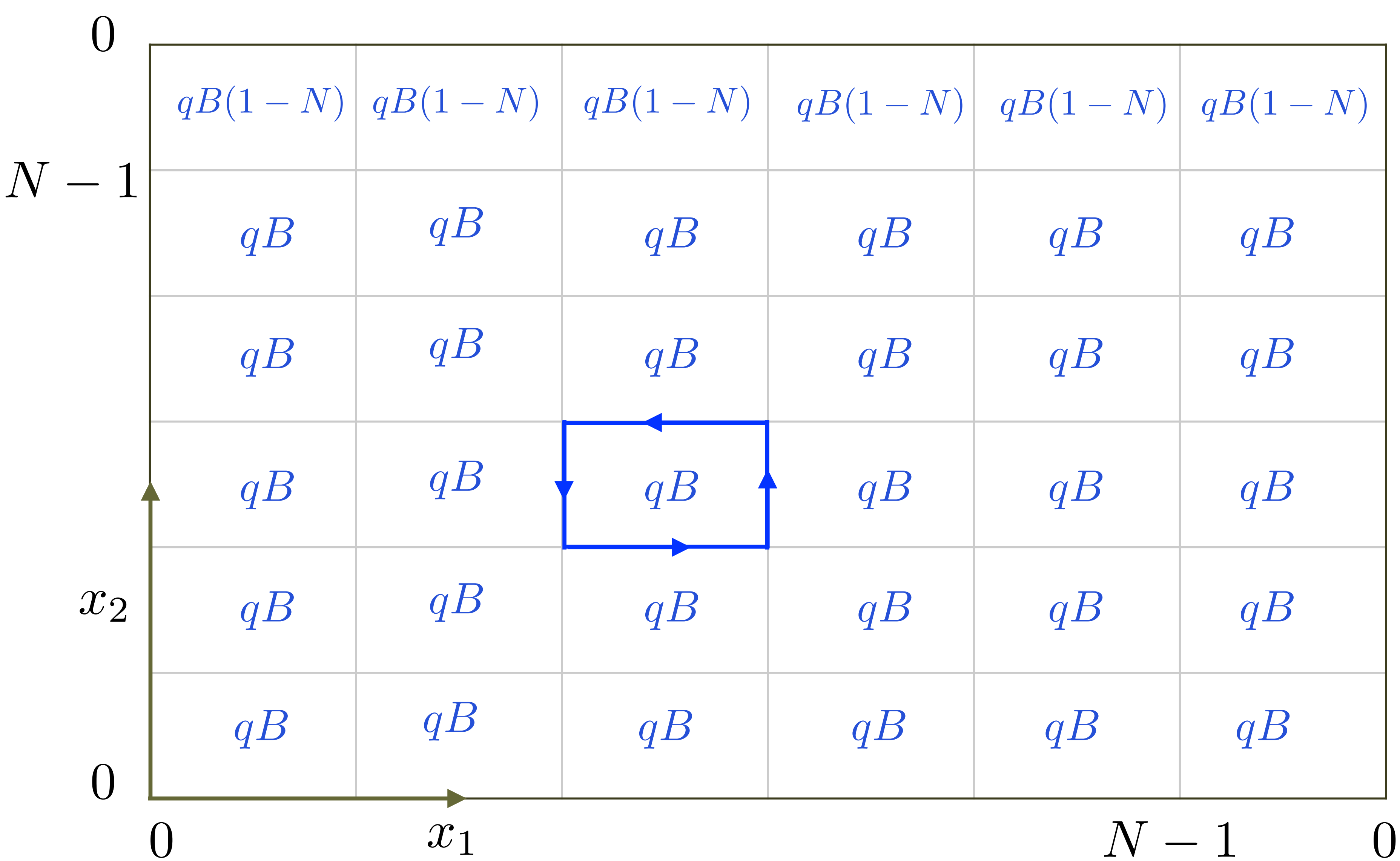

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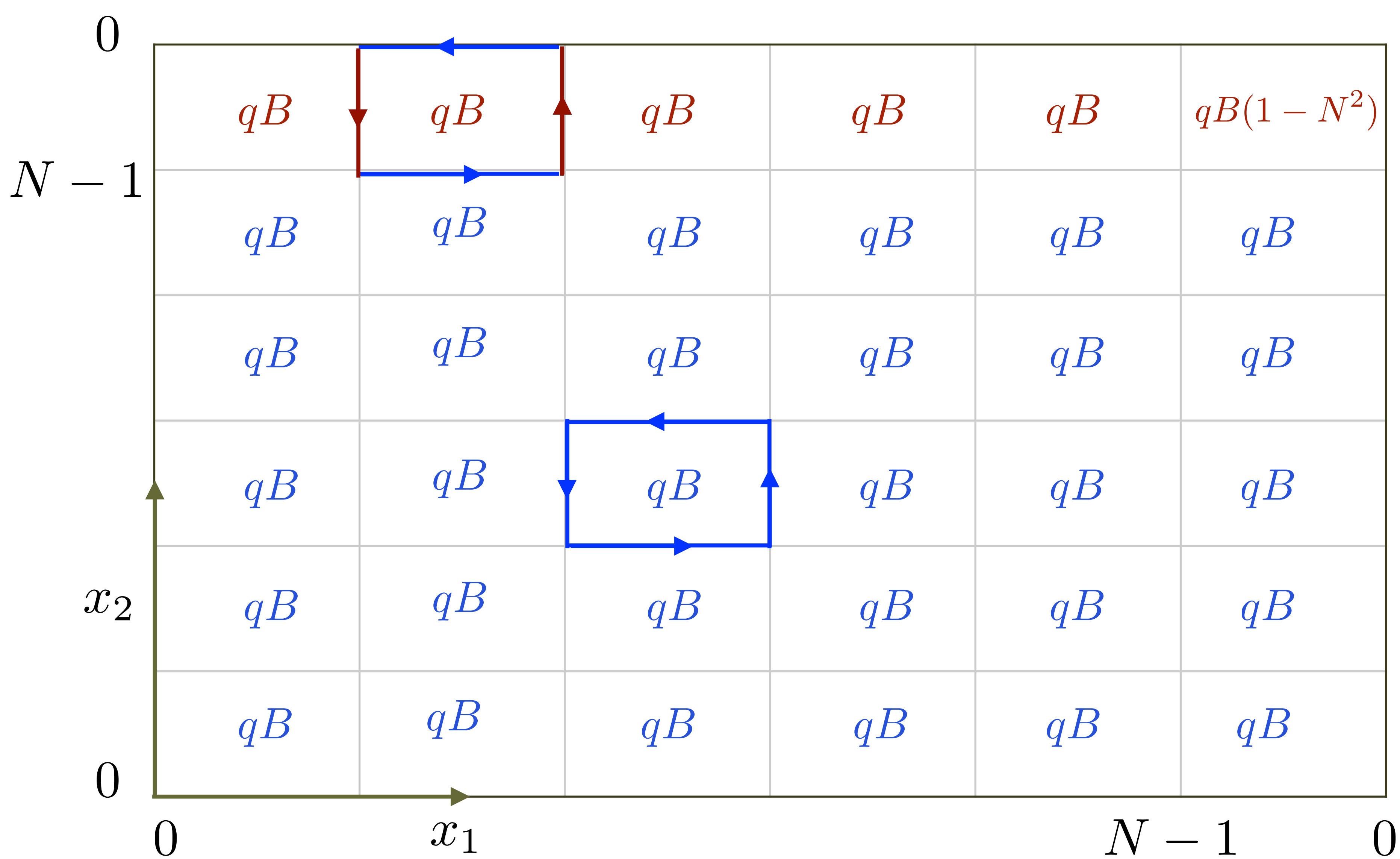
Magnetic Field on a Periodic Lattice

Seek uniform B-field $U_\mu(x) = e^{-iqx_2 B\delta_{\mu 1}} \, e^{+iqx_1 BN\, \delta_{\mu 2}\delta_{x_2, N-1}}$

't Hooft
Flux quantization



$$qB = \frac{2\pi}{N^2} n_\Phi$$

$N = 32$

We choose:

$n_\Phi = +3, -6, +12$

$$U_1(x)U_2(x+\hat{i})U_2^\dagger(x+\hat{i}+\hat{j})U_1^\dagger(x+\hat{j}) = e^{iqF_{12}} = e^{iqB}$$

Magnetic Field on a Periodic Lattice

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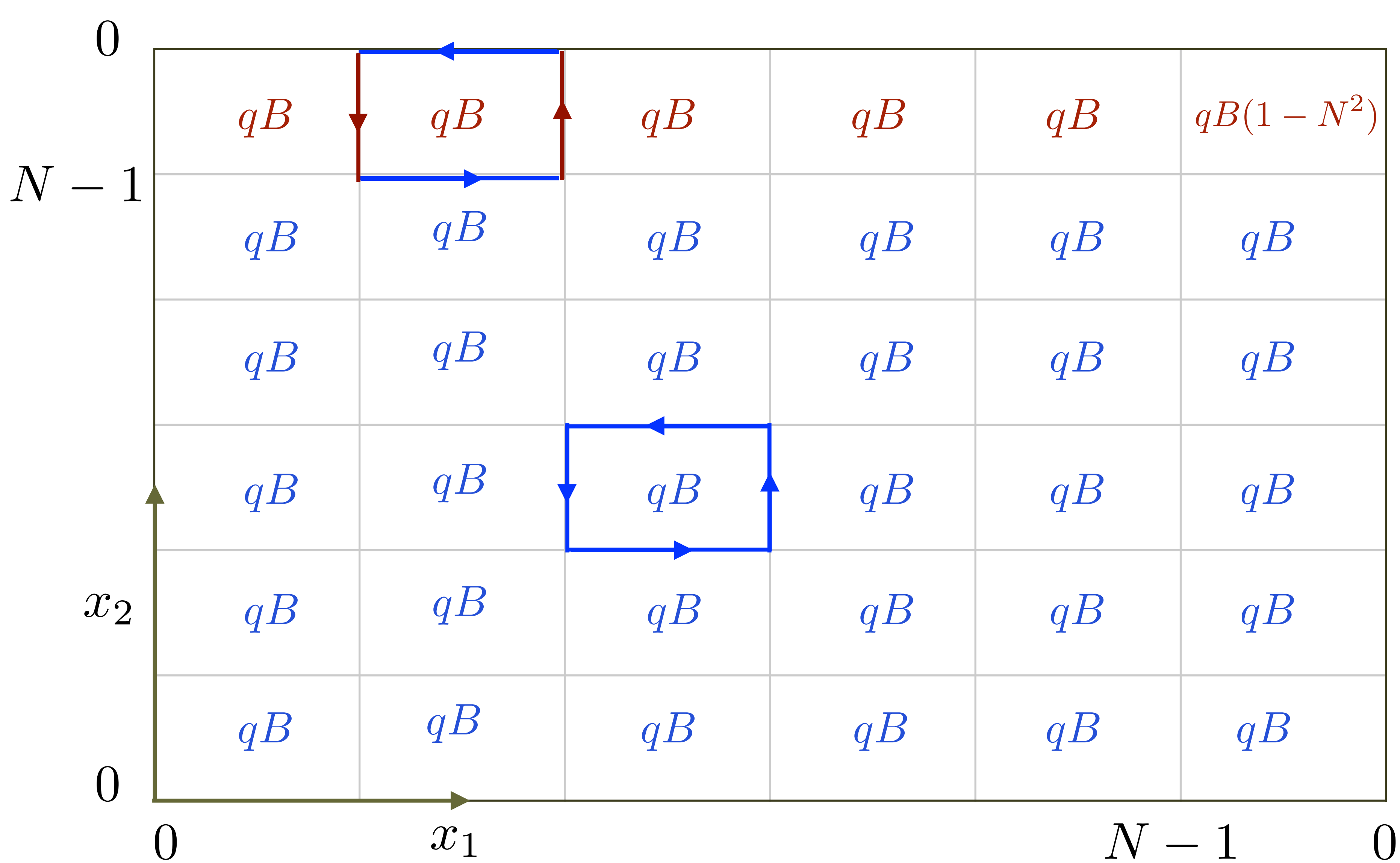


$N = 32$

We choose:

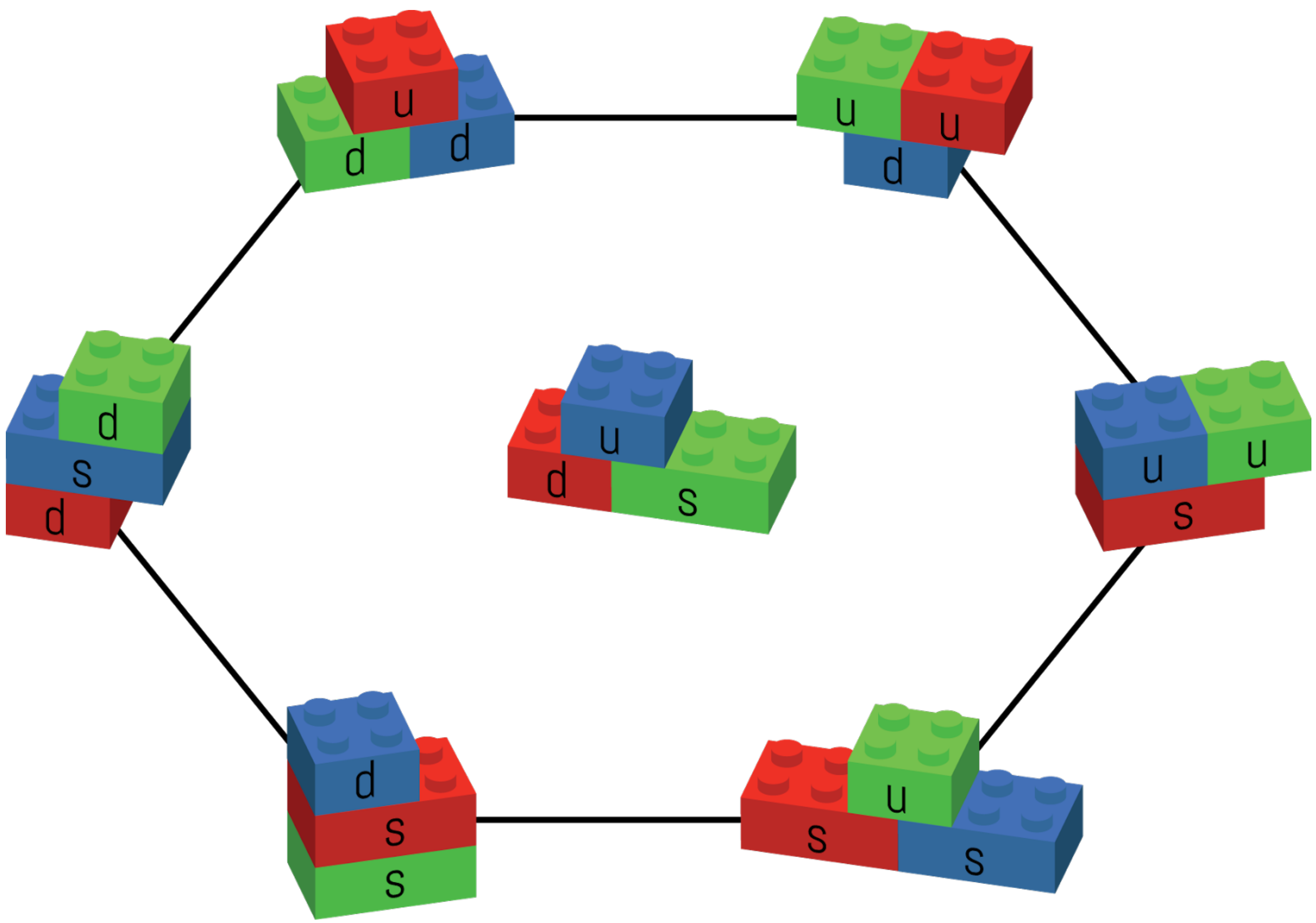
$n_\Phi = +3, -6, +12$

Momentum Quantization

$$k = \frac{2\pi}{N} n$$

$$U_1(x)U_2(x+\hat{i})U_2^\dagger(x+\hat{i}+\hat{j})U_1^\dagger(x+\hat{j}) = e^{iqF_{12}} = e^{iqB}$$

Magnetic Moments of Octet Baryons

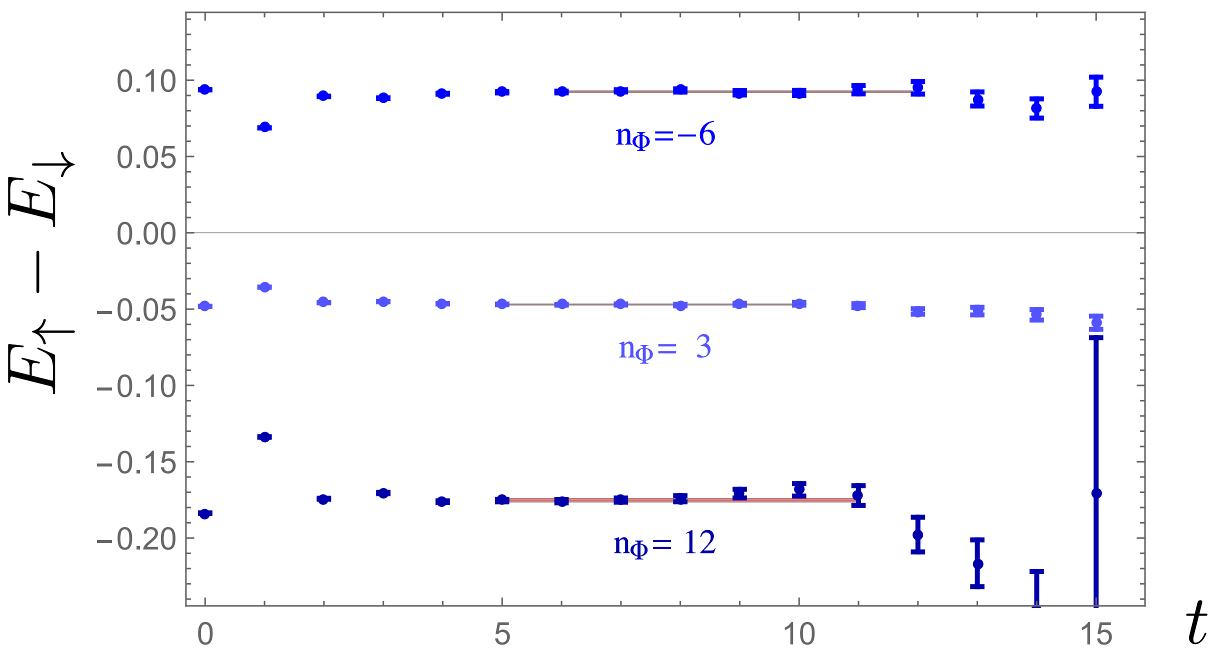


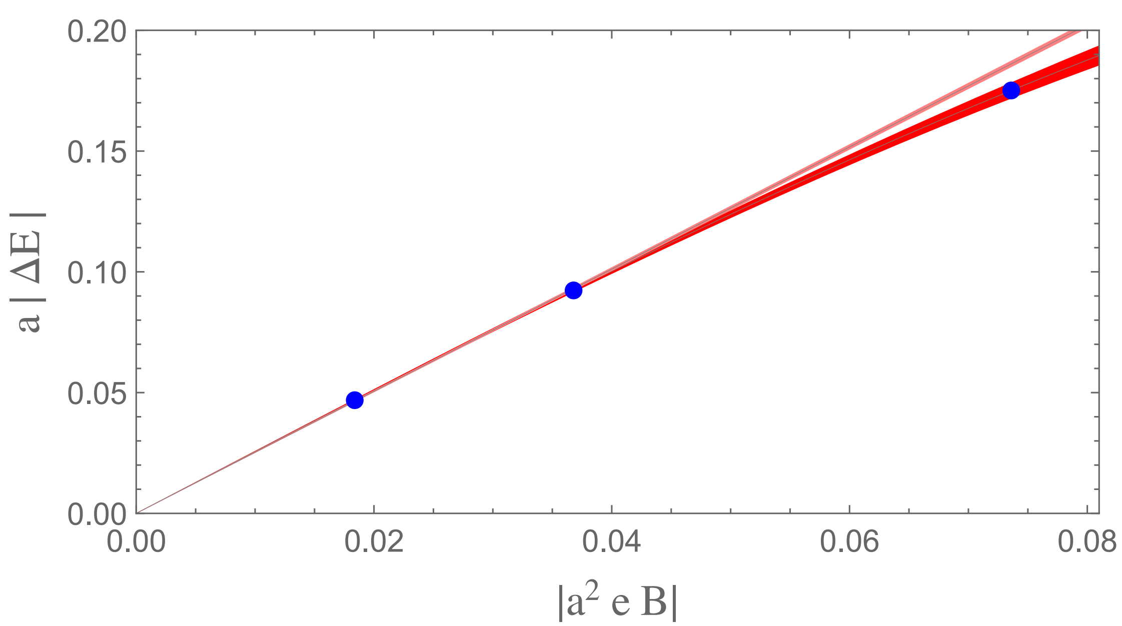
Parreño, Savage, Tiburzi, Wilhelm, Chang, Detmold, Orginos (*NPLQCD*), `arXiv/1609.03985`

Magnetic Moments of Octet Baryons

Compute Zeeman splitting using Lattice QCD + Uniform Magnetic fields

Proton $m_u = m_d = m_s$ $m_\pi \sim 800\,\texttt{MeV}$





Units!

$\mu_p = 2.560(09)(52)\ \texttt{[LatM]}$

$$\texttt{[LatM]} = \frac{e\,a}{2}$$

$$a = 0.145(2)\,\texttt{fm}$$

$\mu_p = 1.770(06)(36)(19)\ \texttt{[NM]}$

$$\texttt{[NM]} = \frac{e}{2M_N}$$

Magnetic Moments of Octet Baryons

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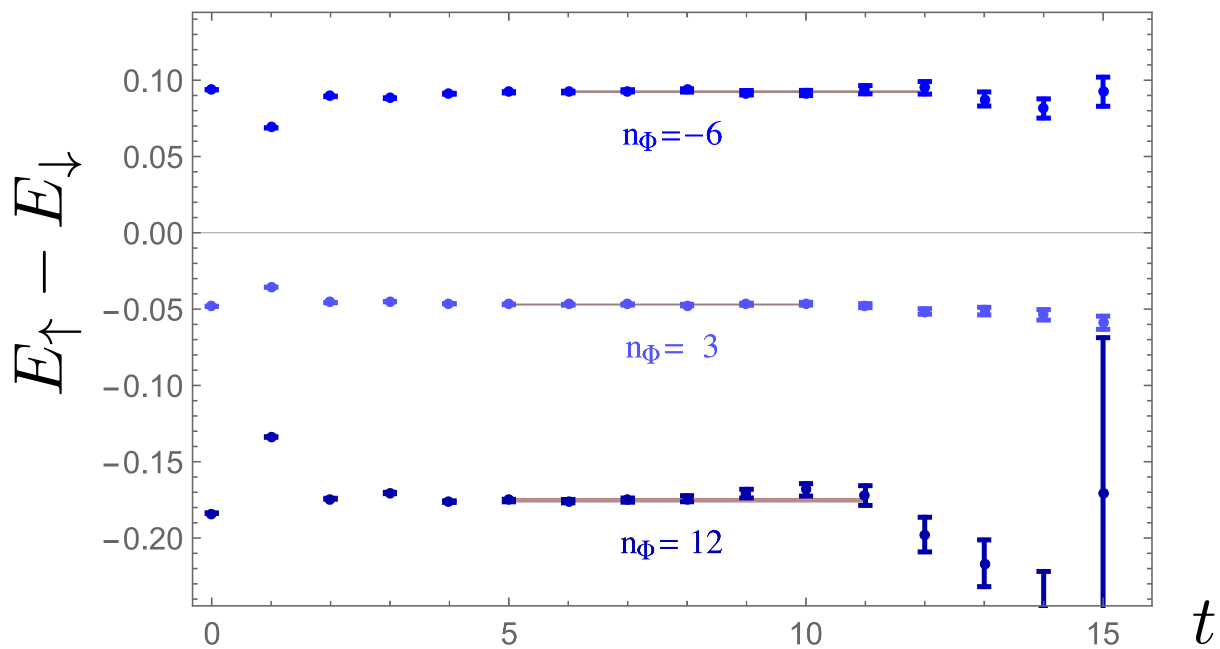
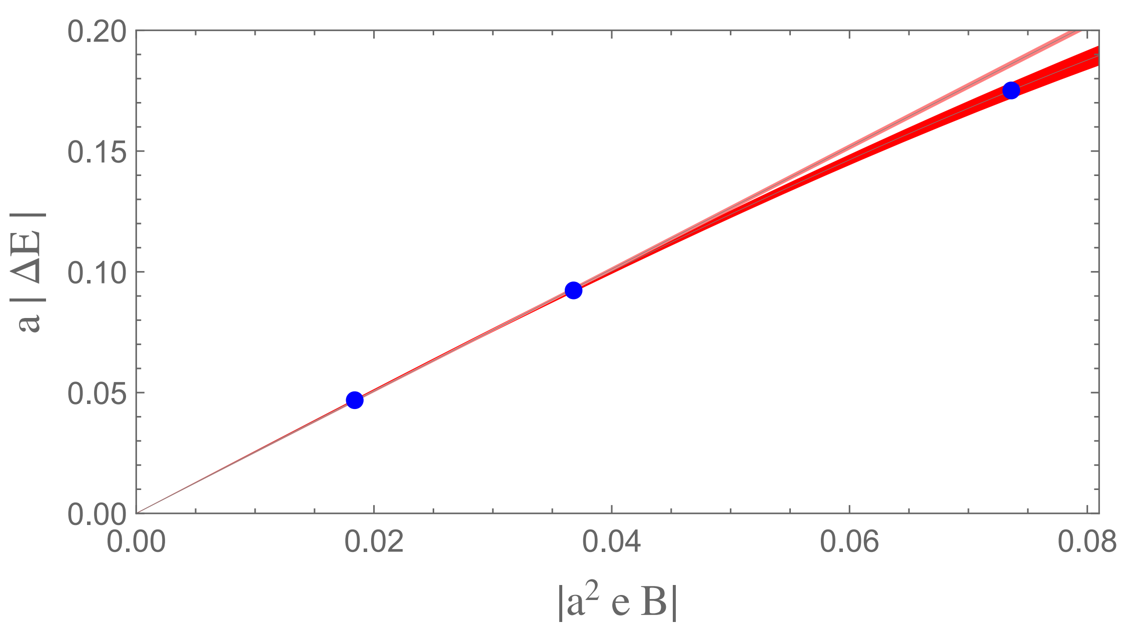


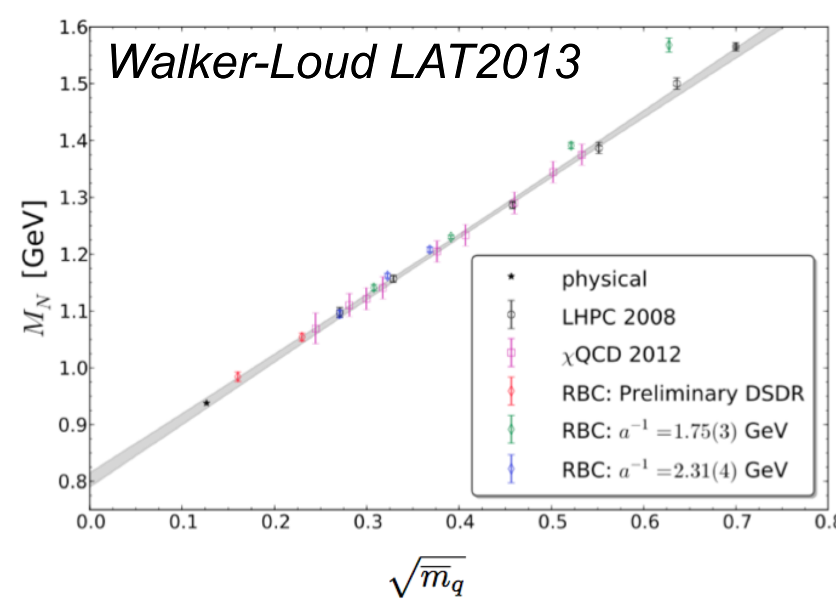


$$\mu_p = 1.770(06)(36)(19)\ \texttt{[NM]}$$

$$\texttt{[NM]} = \frac{e}{2M_N}$$

Ruler Mass Rule *(Walker-Loud, LHPC)*

$$M_N(m_\pi) = 800\ \texttt{MeV} + m_\pi \sim 1,600\,\texttt{MeV}$$

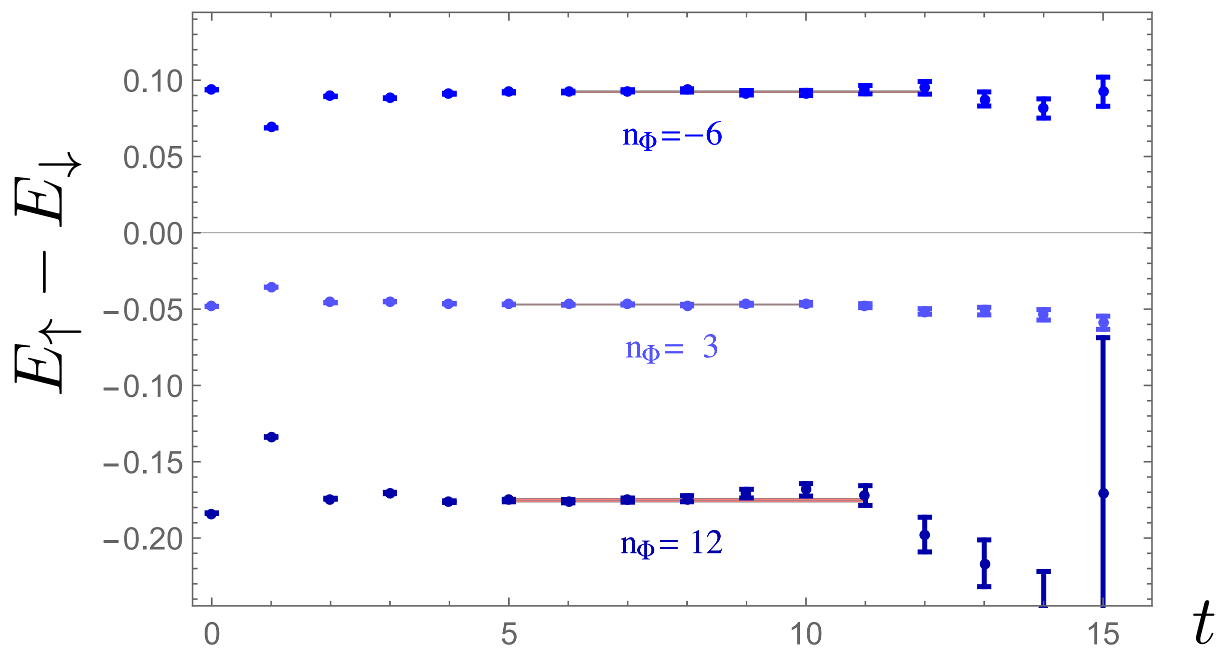


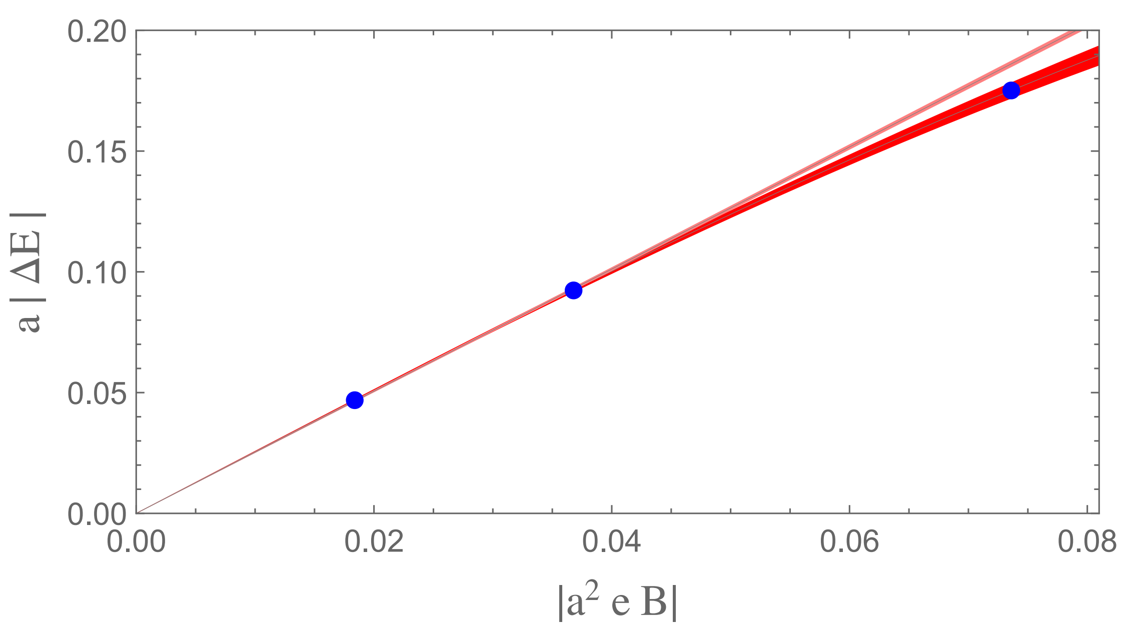
$$\texttt{[nNM]} = \frac{e}{2M_N(m_\pi)}$$

Magnetic Moments of Octet Baryons

Compute Zeeman splitting using Lattice QCD + Uniform Magnetic fields

Proton $\quad m_u = m_d = m_s \quad m_\pi \sim 800\,\texttt{MeV}$





$$\mu_p = 1.770(06)(36)(19)\ \texttt{[NM]}$$

$$\texttt{[NM]} = \frac{e}{2M_N}$$

Natural nucleon magnetons

$$\texttt{[nNM]} = \frac{e}{2M_N(m_\pi)}$$

$$\mu_p = 3.087(10)(62)\ \texttt{[nNM]}$$

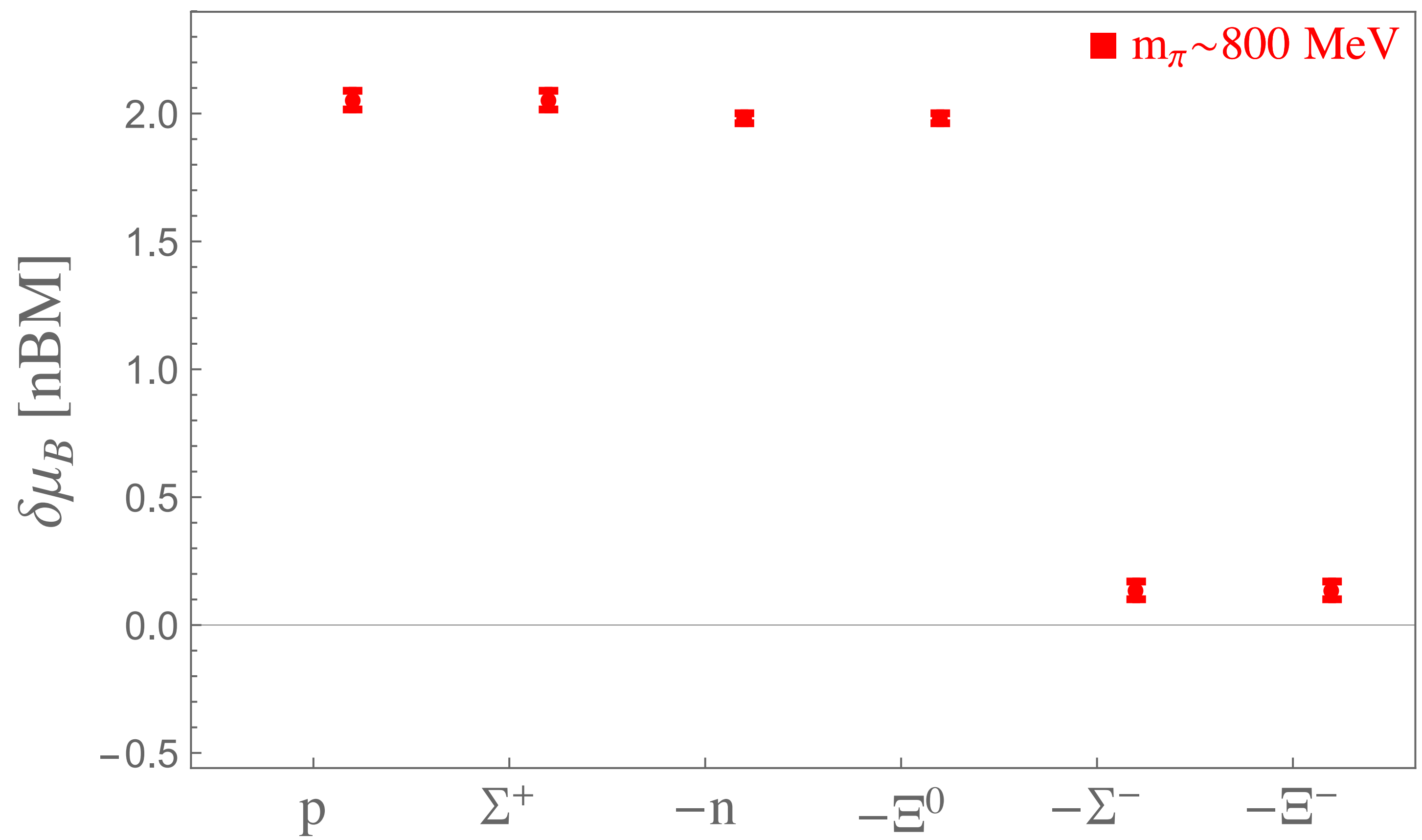
Dirac part is short-distance & guaranteed to $\mathcal{O}(a^2\Lambda^2_{\mathrm{QCD}})$

$$\delta\mu_p = 2.087(10)(62)\ \texttt{[nNM]}$$

$$\delta\mu_p^{\mathrm{exp}} = 1.7929...\ \texttt{[NM]}$$

Magnetic Moments of Octet Baryons

Compute Zeeman splitting using Lattice QCD + Uniform Magnetic fields



$m_u = m_d = m_s$

$$U(3)_F \xrightarrow{Q} U(1)_U \times U(1)_{D+S} \times SU(2)_{U-\text{spin}}$$

Natural baryon magnetons

$$\texttt{[nBM]} = \frac{e}{2M_B(m_\pi)}$$

Anomalous magnetic moments

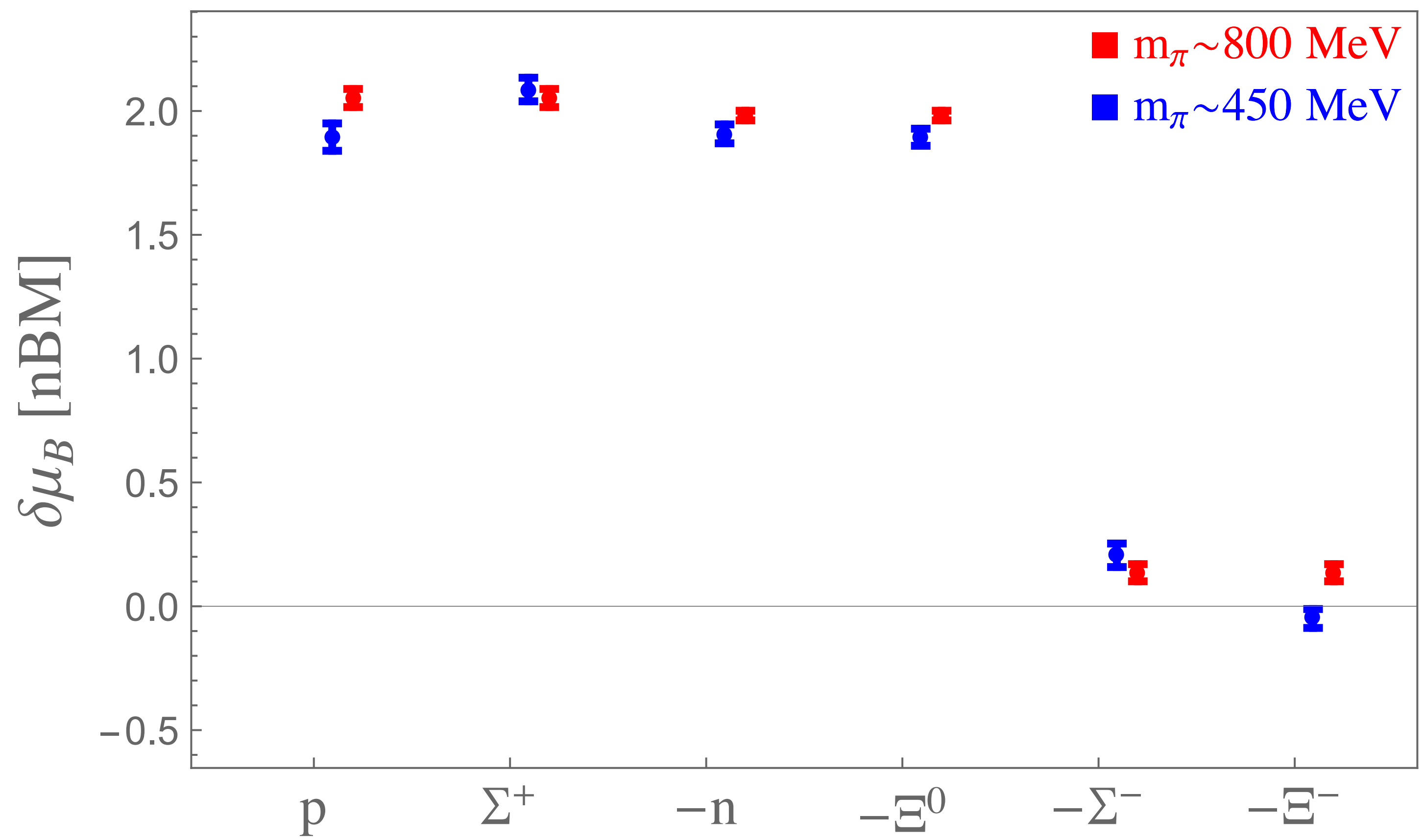
$$\delta\mu_B\ \texttt{[nBM]} = \mu_B\ \texttt{[nBM]} - Q_B$$

U-spin

$$\begin{pmatrix} d \\ s \end{pmatrix} \xrightarrow{SU(2)} U \begin{pmatrix} d \\ s \end{pmatrix}$$

Magnetic Moments of Octet Baryons

Compute Zeeman splitting using Lattice QCD + Uniform Magnetic fields



$m_u = m_d = m_s$

$U(3)_F \xrightarrow{Q} U(1)_U \times U(1)_{D+S} \times SU(2)_{U-\text{spin}}$

$m_u = m_d < m_s$

$U(2)_I \times U(1)_S \xrightarrow{Q} U(1)_B \times U(1)_{I_3} \times U(1)_S$ $\qquad m_\pi \sim 450\,\texttt{MeV}$

Natural baryon magnetons

$$\texttt{[nBM]} = \frac{e}{2M_B(m_\pi)}$$

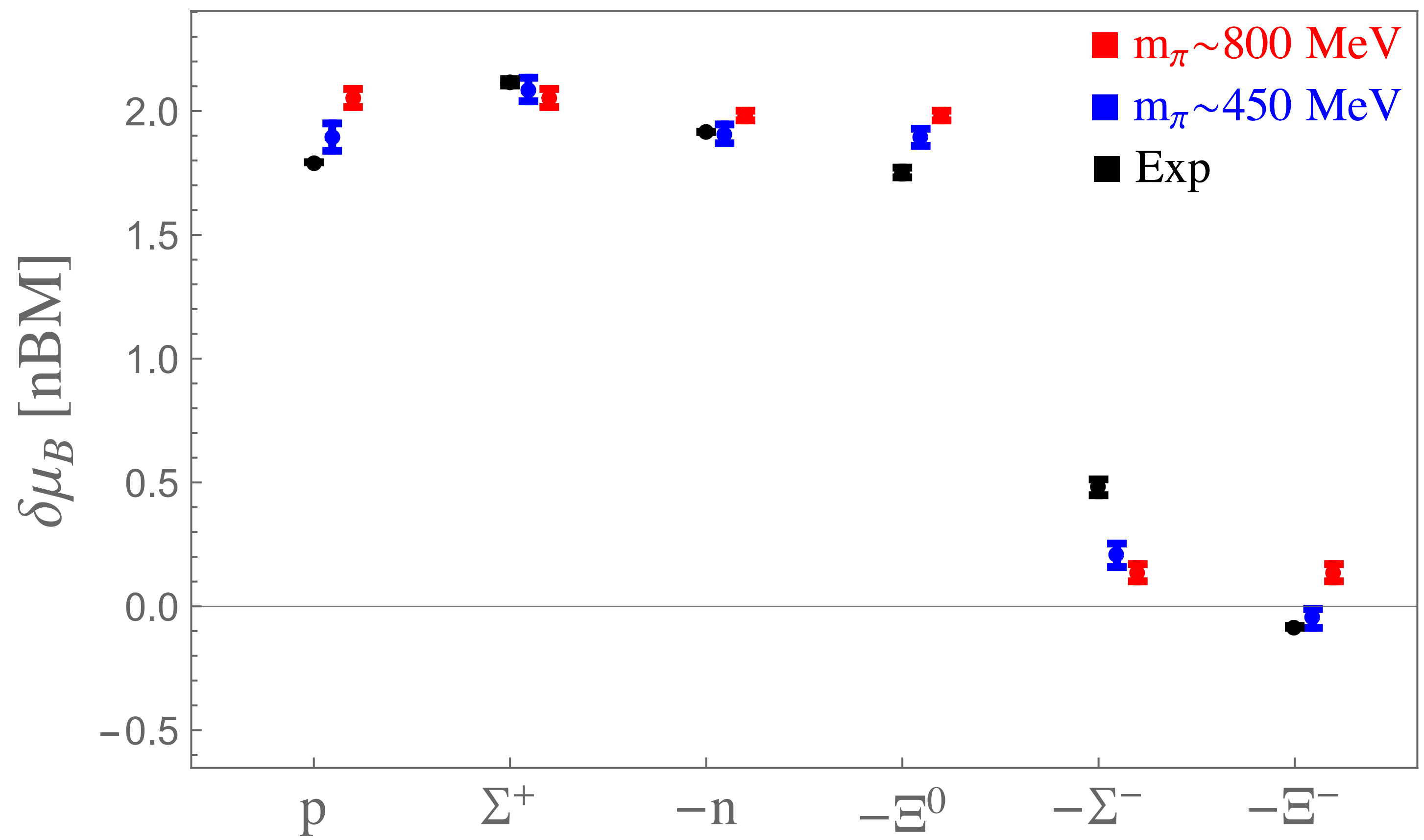
Anomalous magnetic moments

$$\delta\mu_B\ \texttt{[nBM]} = \mu_B\ \texttt{[nBM]} - Q_B$$

[Actually more complicated, our sea quarks are neutral]

Magnetic Moments of Octet Baryons

Compute Zeeman splitting using Lattice QCD + Uniform Magnetic fields



Natural baryon magnetons

$$[\mathtt{nBM}] = \frac{e}{2M_B(m_\pi)}$$

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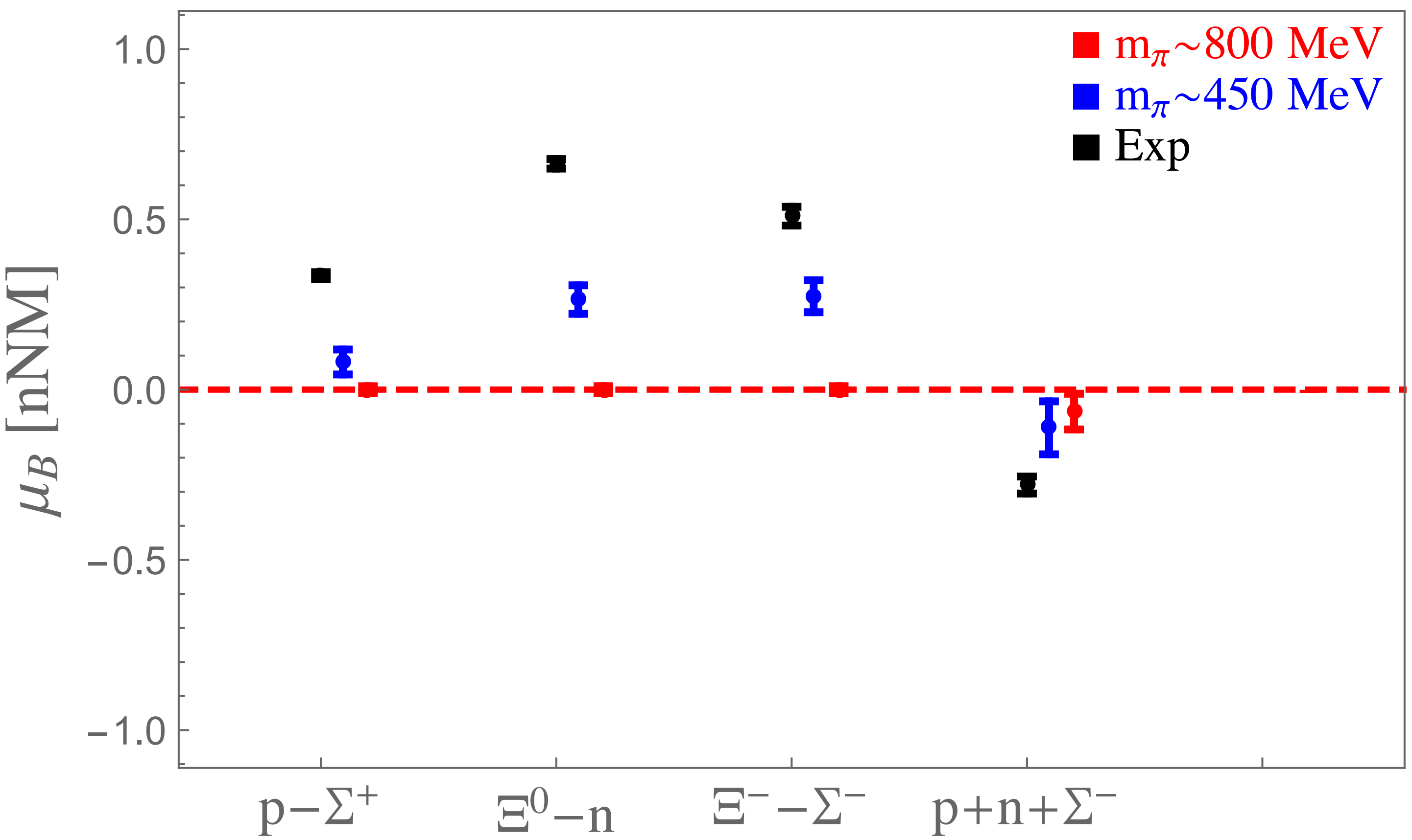
[Actually more complicated, our sea quarks are neutral]

Coleman-Glashow Relations

$$\mathcal{H} = -\frac{e\,\vec{\sigma}\cdot\vec{B}}{2M_B}\left[\mu_D\langle\overline{B}\{Q,B\}\rangle + \mu_F\langle\overline{B}[Q,B]\rangle\right]$$

$$m_u = m_d = m_s$$



$$\mu_p = \frac{1}{3}\mu_D + \mu_F$$
$$\mu_n = -\frac{2}{3}\mu_D$$
$$\mu_{\Sigma^-} = \frac{1}{3}\mu_D - \mu_F$$

$$\mu_D(m_\pi = 800\,\mathtt{MeV}) = 2.958(35)$$
$$\mu_F(m_\pi = 800\,\mathtt{MeV}) = 2.095(34)$$

$$\delta\mu_B = \pm 2, 0$$

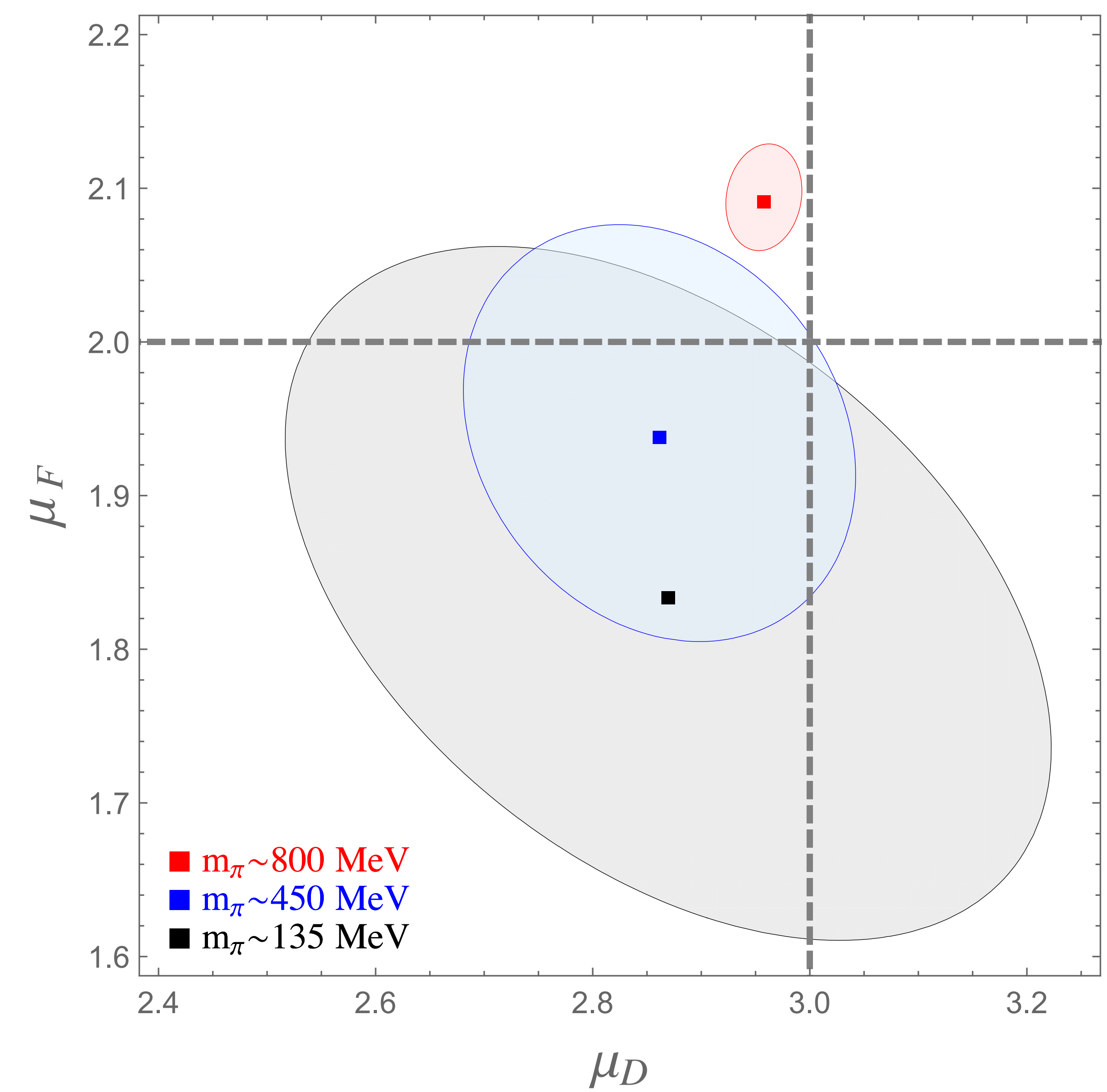
Coleman-Glashow Magnetic Moments

Estimate ***SU(3)*** moments away from ***SU(3)*** point?

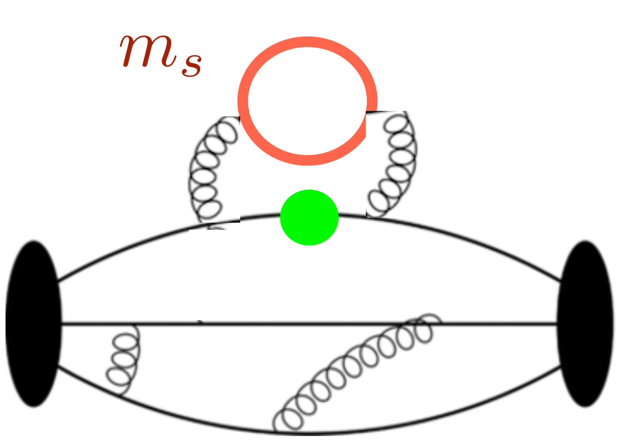
Stick with proton and neutron moments **!!!**

$$m_\pi = 450\ \texttt{[MeV]}: \quad \frac{1}{2}\, 33\% \Big/ 3 \sim 6\%$$

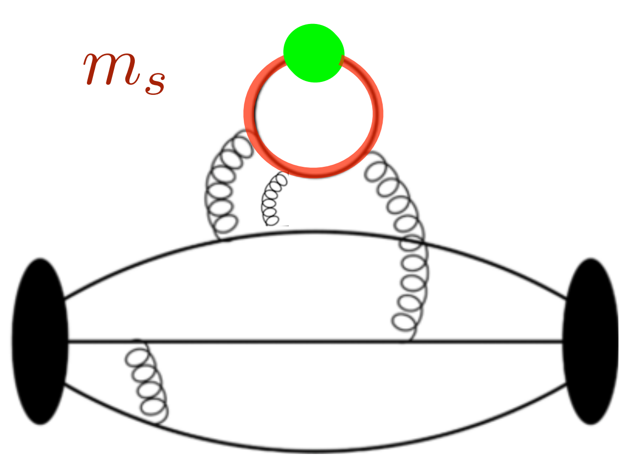
$$m_\pi = 135\ \texttt{[MeV]}: \quad 33\% \Big/ 3 \sim 11\%$$



$\Delta m_q / N_c$



$\Delta m_q / N_c^2$



Current is C-odd

$\mu_D \sim +3$

$\mu_F \sim +2$

$\delta \mu_B = \pm 2, 0$

Coleman-Glashow Magnetic Moments

Estimate ***SU(3)*** moments in ***SU(3)*** *chiral limit*?

$$\langle \overline{B}\{Q,B\}\rangle\langle m_q\rangle \qquad \langle \overline{B}[Q,B]\rangle\langle m_q\rangle$$

Quark-mass dependence subsumed!

Meißner, Steininger (1997)
Durand, Ha (1998)
Puglia, Ramsey-Musolf (2000)

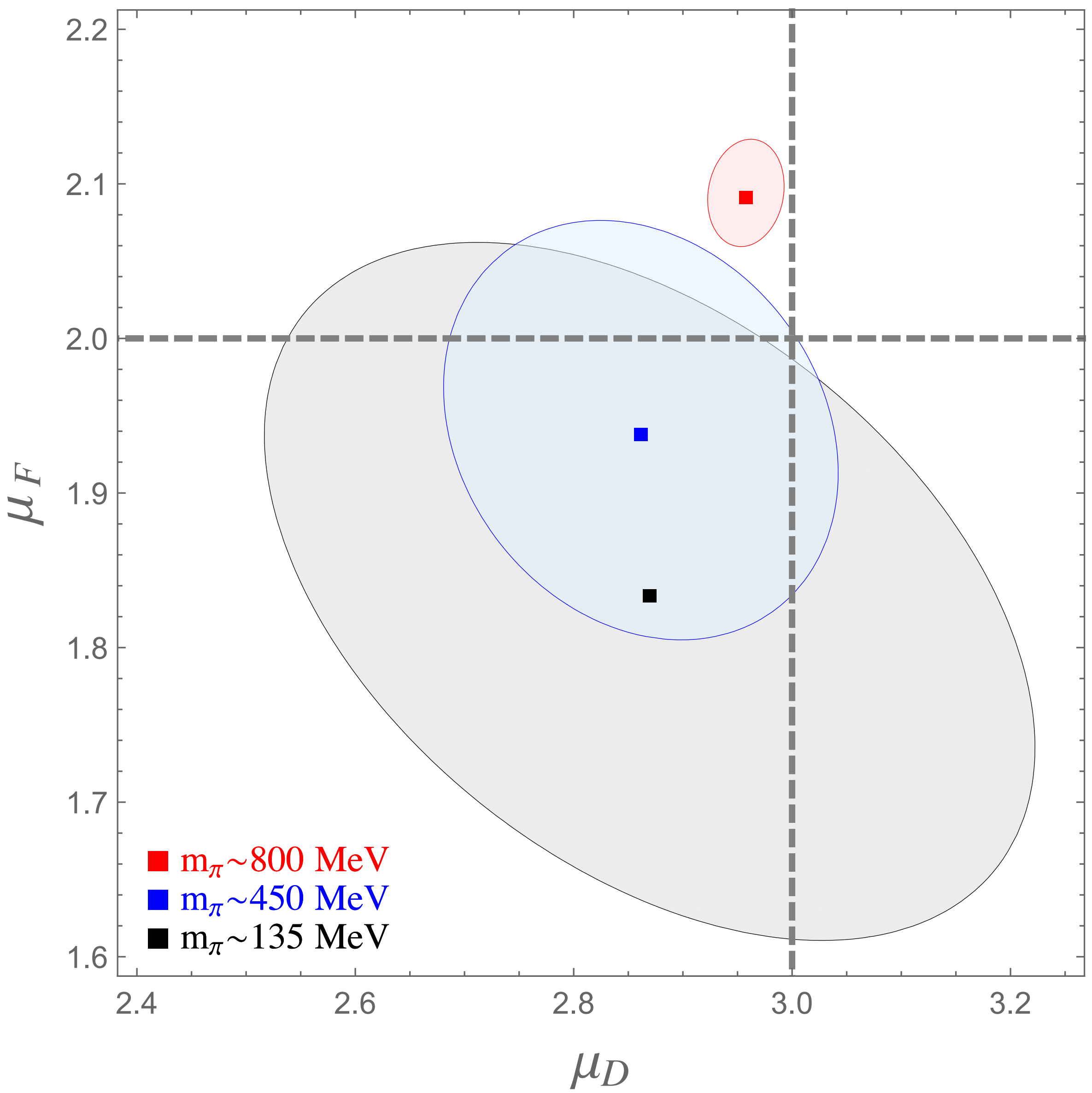
[nBM]

Requires chiral limit octet baryon mass!

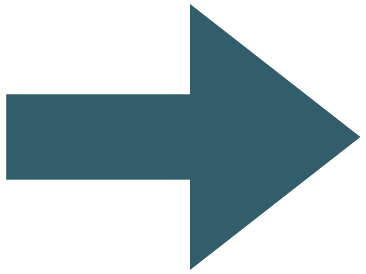
Dürr *et al.*, BMWc (2012)

$$\mu_D(m_\pi = 0\,\mathtt{MeV}) = 3.8(1.1)$$
$$\mu_F(m_\pi = 0\,\mathtt{MeV}) = 2.5(0.6)$$

Need ***SU(3)*** lattice calculation near *chiral limit…*



$$\mu_D \sim +3 \qquad \mu_F \sim +2$$



$$\delta\mu_B = \pm 2, 0$$

Coleman-Glashow Magic Moments?

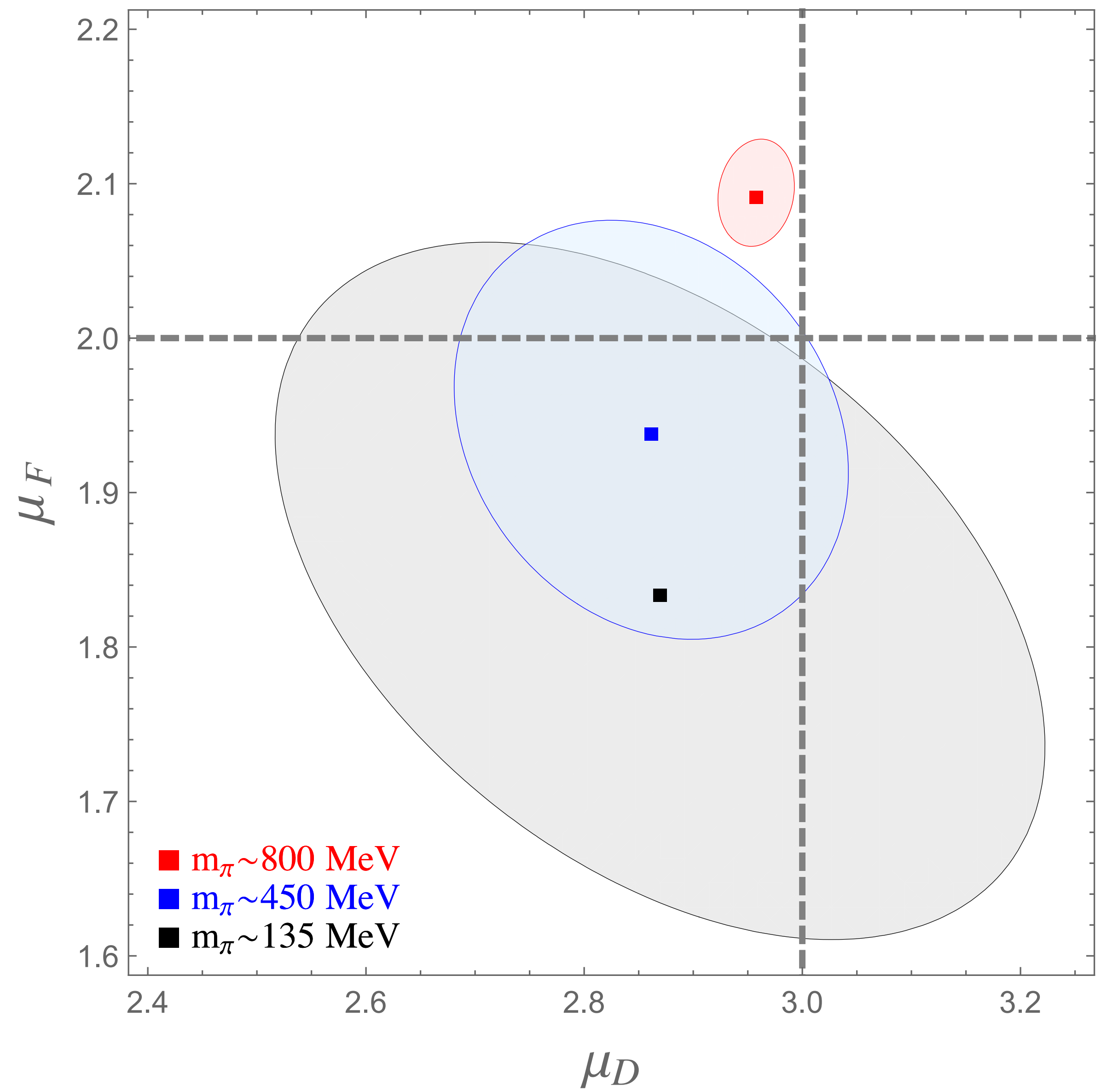
$$\mu_p = \frac{1}{3}\mu_D + \mu_F \qquad \text{[nBM]}$$
$$\mu_n = -\frac{2}{3}\mu_D$$

Whole number **CG** moments imply counting?

$$\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d = 1\ \text{[cQM]}$$
$$\mu_n = -\frac{1}{3}\mu_u + \frac{4}{3}\mu_d = -\frac{2}{3}\ \text{[cQM]}$$

NRQM $\quad \frac{e}{2M_Q} = \text{[cQM]}$

$$\mu_D = \text{[cQM]} / \text{[nBM]} = M_B / M_Q$$



$\mu_D \sim +3$

$\mu_F \sim +2$

$\delta\mu_B = \pm 2, 0$

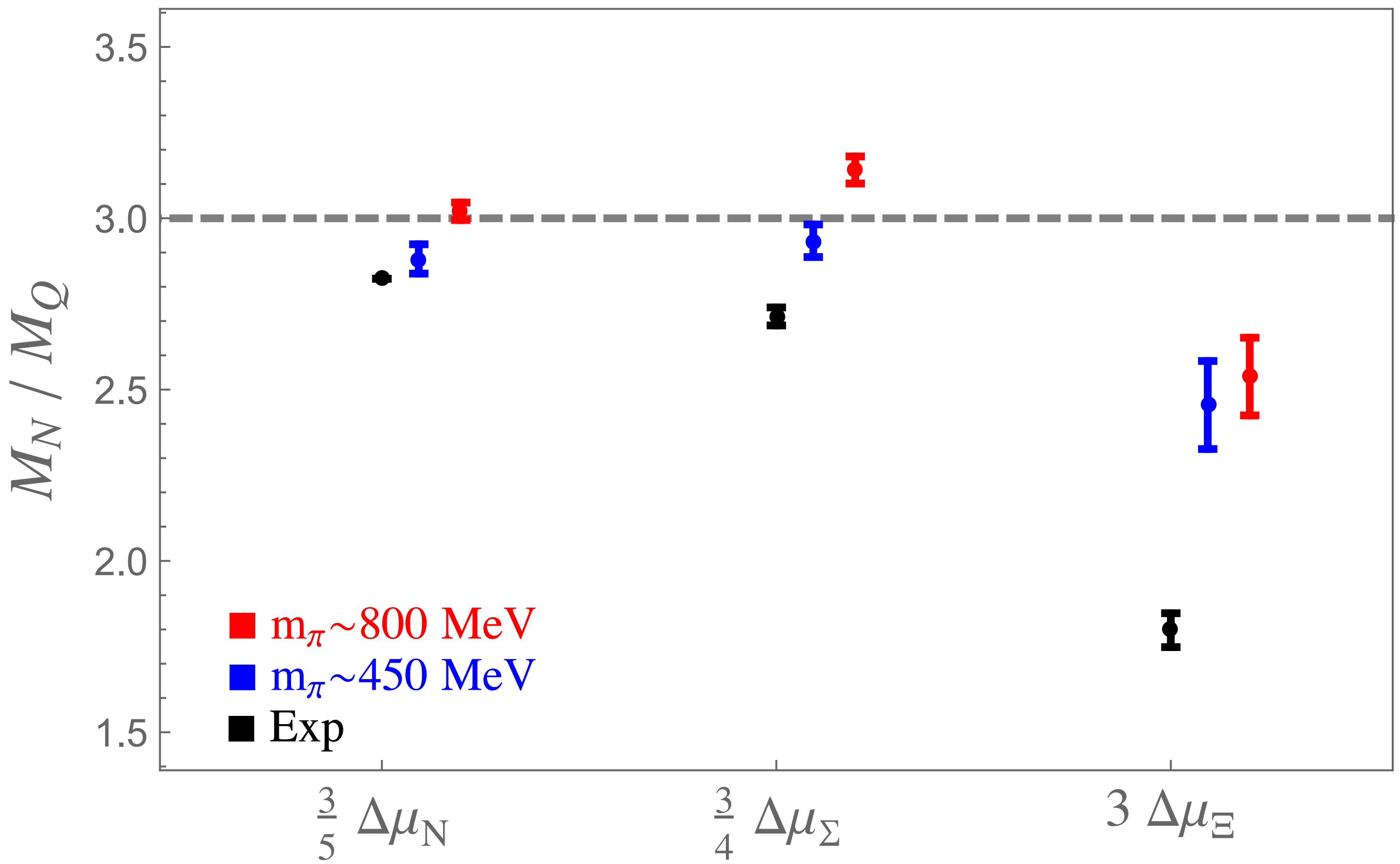
Naïve Quark Model

Isovector moments in ***NRQM*** give light constituent quark mass

$$\Delta\mu_N = \mu_p - \mu_n = \frac{5}{3}\,\texttt{[cQM]}$$

$$\Delta\mu_\Sigma = \mu_{\Sigma^+} - \mu_{\Sigma^-} = \frac{4}{3}\,\texttt{[cQM]}$$

$$\Delta\mu_\Xi = \mu_{\Xi^-} - \mu_{\Xi^0} = \frac{1}{3}\,\texttt{[cQM]}$$



NRQM $\quad \frac{e}{2M_Q} = \texttt{[cQM]}$

$$\texttt{[cQM]}/\texttt{[nNM]} = M_N/M_Q$$

$$\texttt{[cQM]}/\texttt{[nBM]} = M_B/M_Q$$

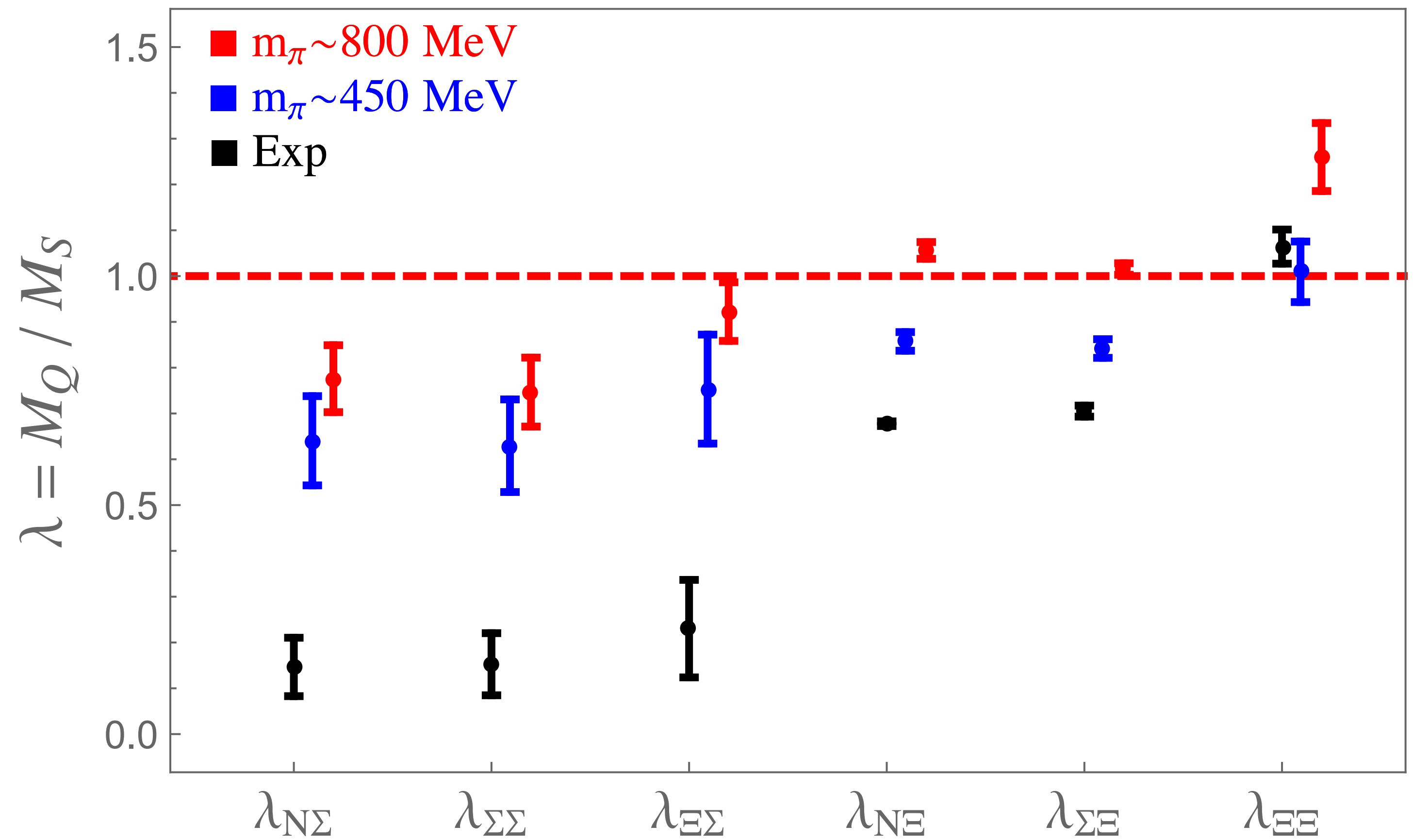
Naïve Quark Model

Isovector moments in ***NRQM*** give light constituent quark mass

$$\Delta\mu_N = \mu_p - \mu_n = \frac{5}{3}\,\texttt{[cQM]}$$

$$\Delta\mu_\Sigma = \mu_{\Sigma^+} - \mu_{\Sigma^-} = \frac{4}{3}\,\texttt{[cQM]}$$

$$\Delta\mu_\Xi = \mu_{\Xi^-} - \mu_{\Xi^0} = \frac{1}{3}\,\texttt{[cQM]}$$



SU(3) breaking:
strange constituent quark

NRQM $\quad \frac{e}{2M_Q} = \texttt{[cQM]}$

$$\frac{e}{2M_S} = \texttt{[sQM]}$$

$$\mu_{\Sigma^+} + 2\mu_{\Sigma^-} = \frac{1}{3}\,\texttt{[sQM]}$$

$$\mu_{\Xi^0} + 2\mu_{\Xi^-} = -\frac{4}{3}\,\texttt{[sQM]}$$

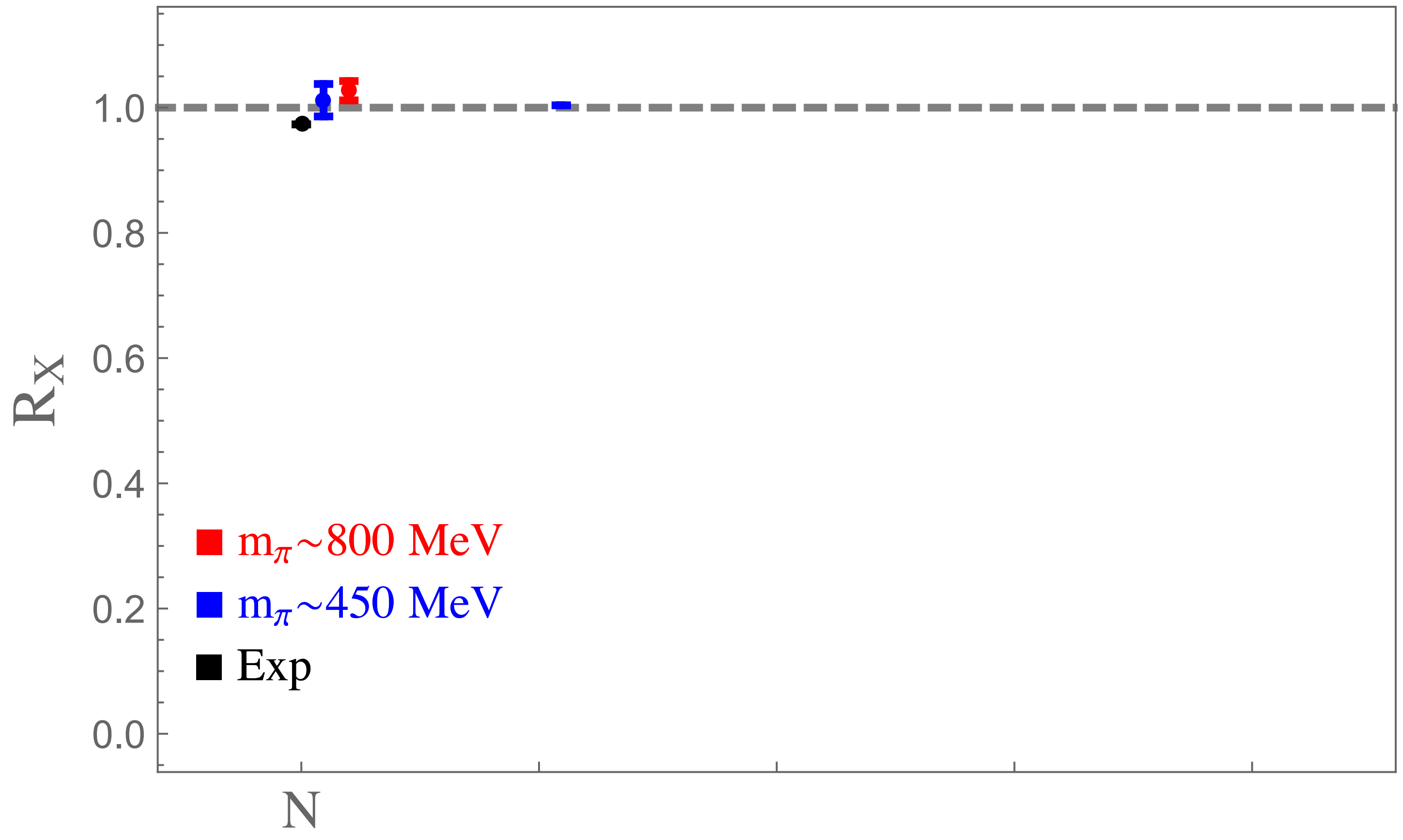
$$\lambda = M_Q/M_S \sim 0.6\,?$$

1 = SU(3) & no binding

Naïve Quark Model Moment Ratio

Grand success of ***NRQM*** is the ratio

$$1 = R_N = -\frac{2}{3}\frac{\mu_p}{\mu_n}$$



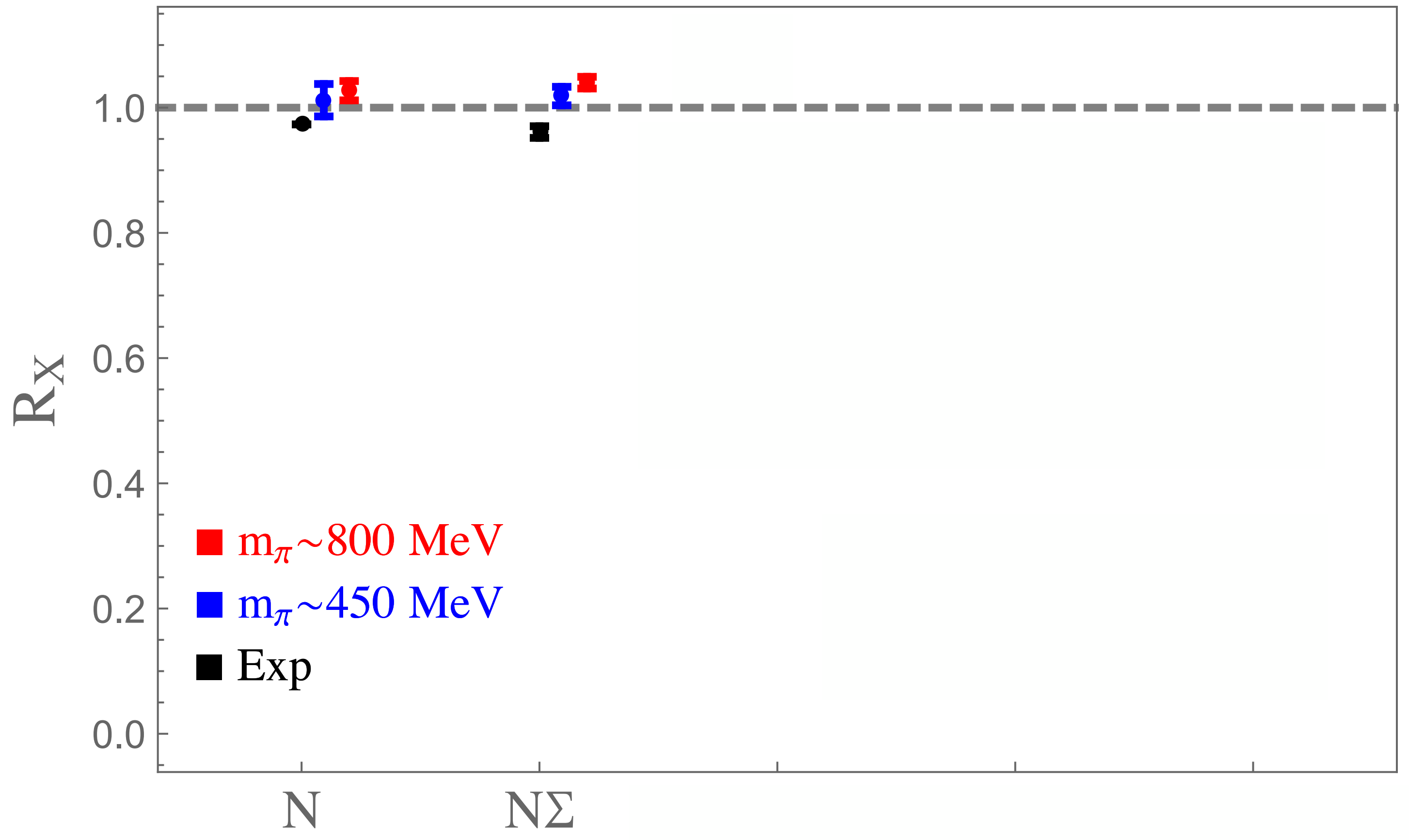
Naïve Quark Model Moment Ratios

Grand success of ***NRQM*** is the ratio

$$1 = R_N = -\frac{2}{3}\frac{\mu_p}{\mu_n}$$

But there are other ***NRQM*** ratios too

$$1 = R_{N\Sigma} = \frac{5}{4}\frac{\Delta\mu_\Sigma}{\Delta\mu_N}$$



Naïve Quark Model Moment Ratios

Grand success of ***NRQM*** is the ratio

$$1 = R_N = -\frac{2}{3}\frac{\mu_p}{\mu_n}$$

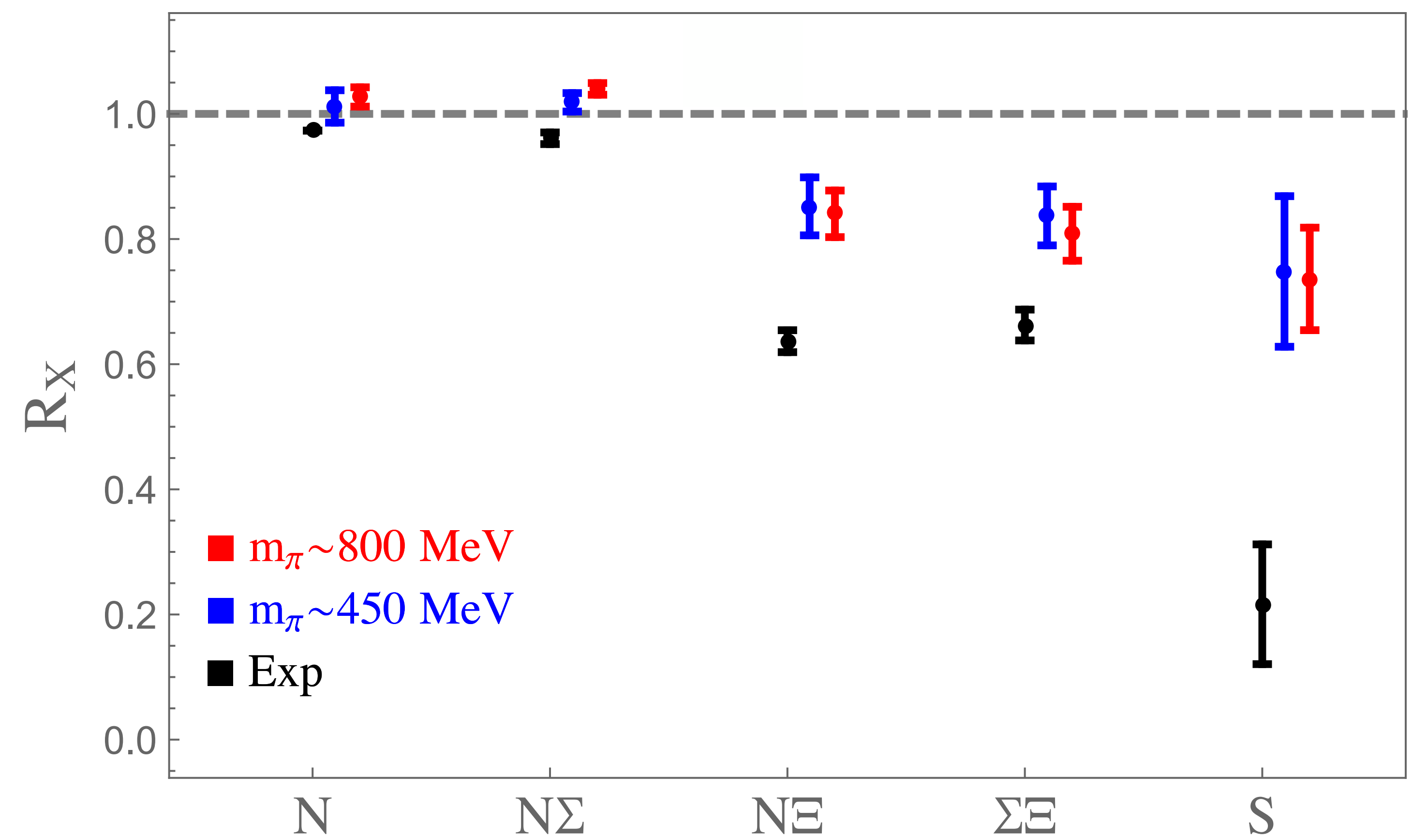
But there are other ***NRQM*** ratios too

$$1 = R_{N\Sigma} = \frac{5}{4}\frac{\Delta\mu_\Sigma}{\Delta\mu_N}$$

$$1 = R_{N\Xi} = 5\frac{\Delta\mu_\Xi}{\Delta\mu_N}$$

$$1 = R_{\Sigma\Xi} = 4\frac{\Delta\mu_\Xi}{\Delta\mu_\Sigma}$$

$$1 = R_S = -4\frac{\mu_{\Sigma^+} + 2\mu_{\Sigma^-}}{\mu_{\Xi^0} + 2\mu_{\Xi^-}}$$



Lattice **QCD** results generally agree better with ***NRQM*** than experiment

Why do some *NRQM* predictions work better than others?

Large-N_c Limit

Dashen, Jenkins, Manohar (1994)

Our calculations & nature have $N_c = 3$ …

$$\mathcal{R}_{S7} = \frac{5(\mu_p + \mu_n) - (\mu_{\Xi^0} + \mu_{\Xi^-})}{4(\mu_{\Sigma^+} + \mu_{\Sigma^-})}$$

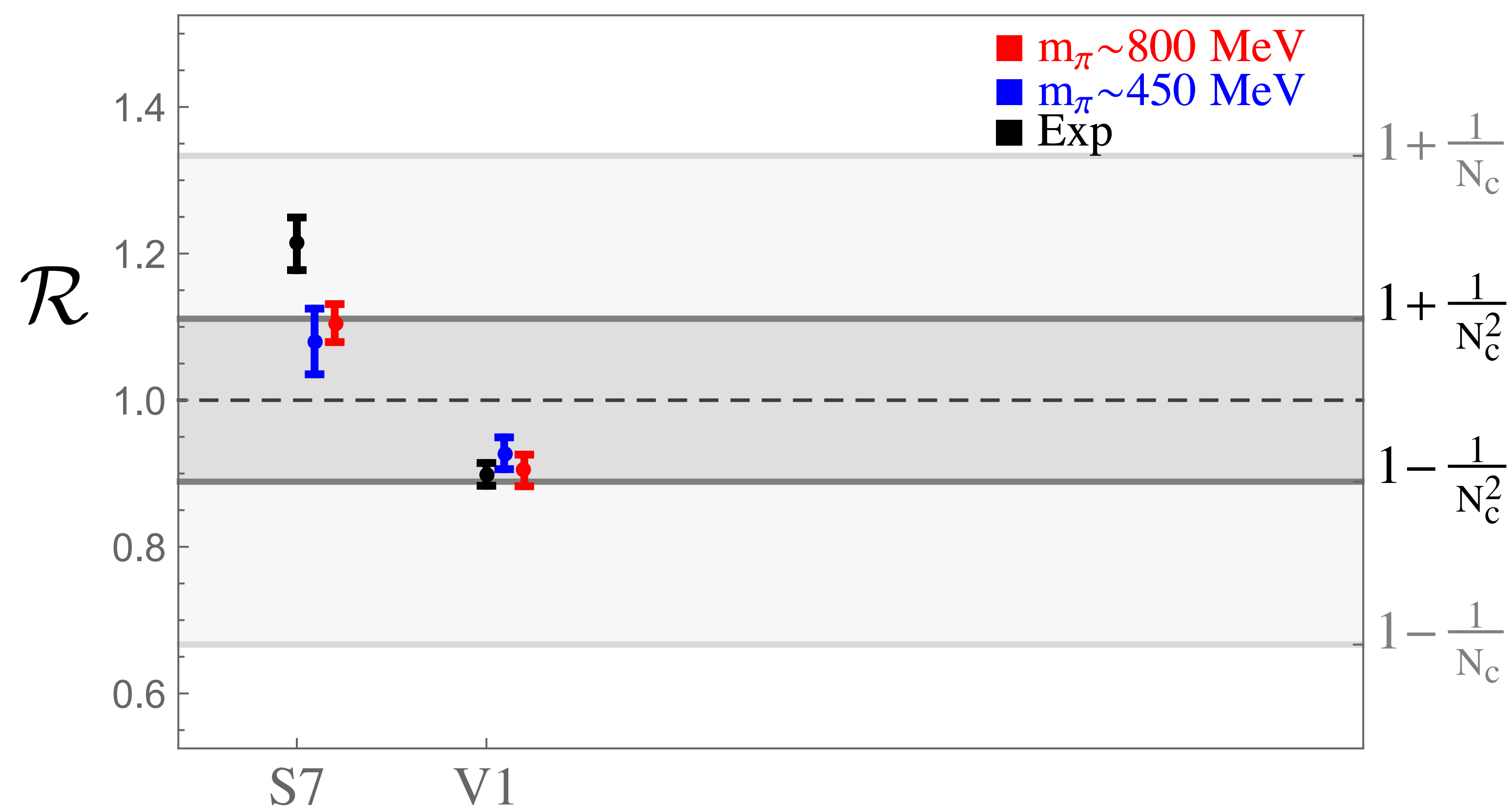
$$= 1 \quad NRQM$$

$$= 1 + \mathcal{O}(1/N_c)$$

$$\mathcal{R}_{V1} = \frac{\Delta\mu_N + 3\,\Delta\mu_\Xi}{2\,\Delta\mu_\Sigma}$$

$$= 1 \quad NRQM$$

$$= 1 + \mathcal{O}(1/N_c^2)$$



Why do some *NRQM* predictions work better than others?

Large-N_c Limit

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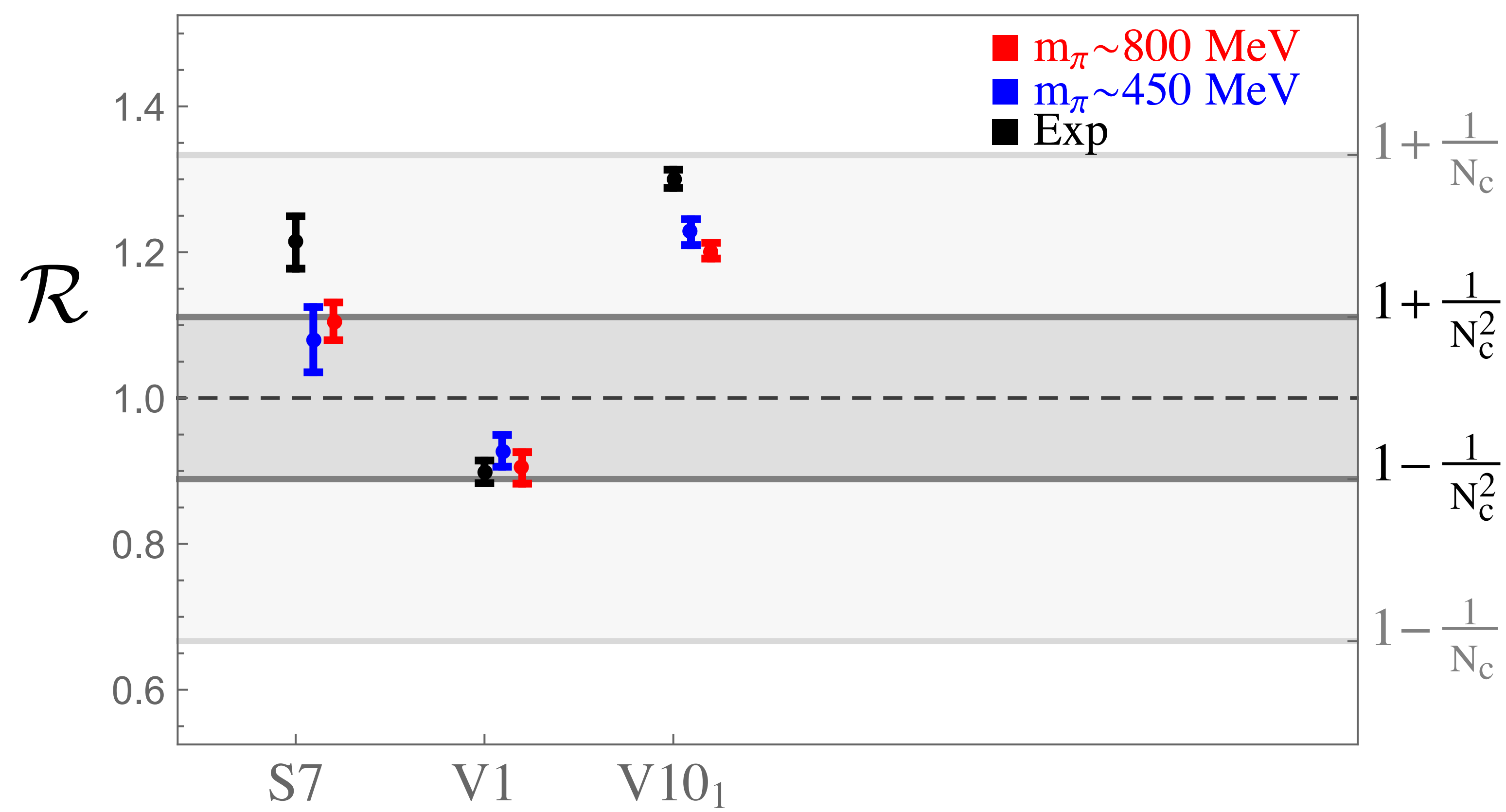
Our calculations & nature have N_c = 3 …

$$\mathcal{R}_{V10_1} = \frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

$$= 1.25 \quad NRQM$$

$$= 1 + \mathcal{O}(1/N_c)$$



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$$\mathcal{R}_{V10_1} = \frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

$$= 1.25 \quad NRQM$$

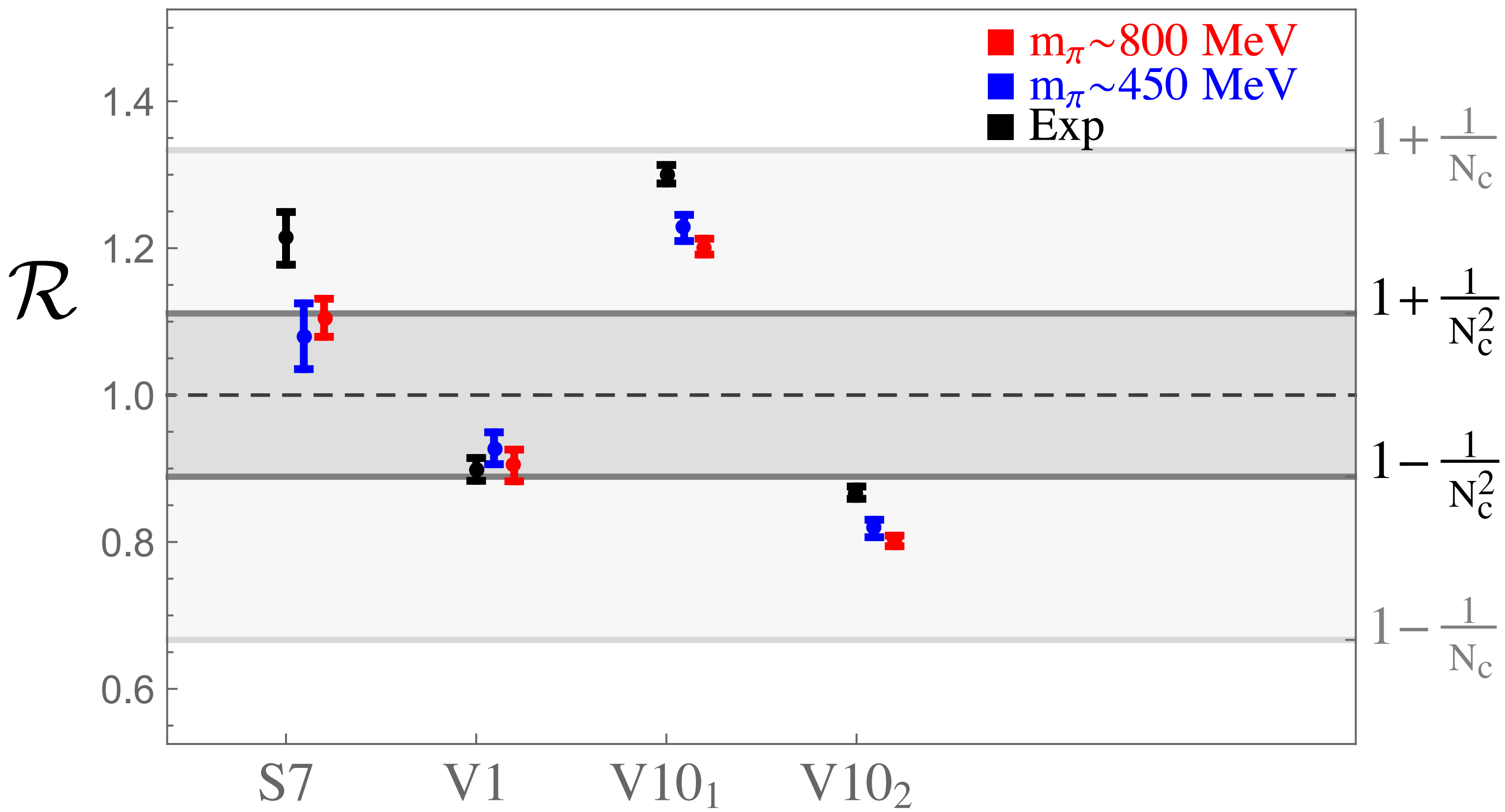
$$= 1 + \mathcal{O}(1/N_c)$$

$$\mathcal{R}_{V10_2} = (1 - 1/N_c)\,\frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

$$= 0.83 \quad NRQM$$

$$= 1 + \mathcal{O}(\Delta m_q/N_c)$$

$$= 1 + \mathcal{O}(1/N_c^2)$$



Large-N_c Limit

Dashen, Jenkins, Manohar (1994)

NPLQCD

Our calculations & nature have $N_c = 3$ …

$$\mathcal{R}_{V10_1} = \frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

$$= 1.25 \quad NRQM$$

$$= 1 + \mathcal{O}(1/N_c)$$

$$\mathcal{R}_{V10_2} = (1 - 1/N_c)\,\frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

$$= 0.83 \quad NRQM$$

$$= 1 + \mathcal{O}(\Delta m_q/N_c)$$

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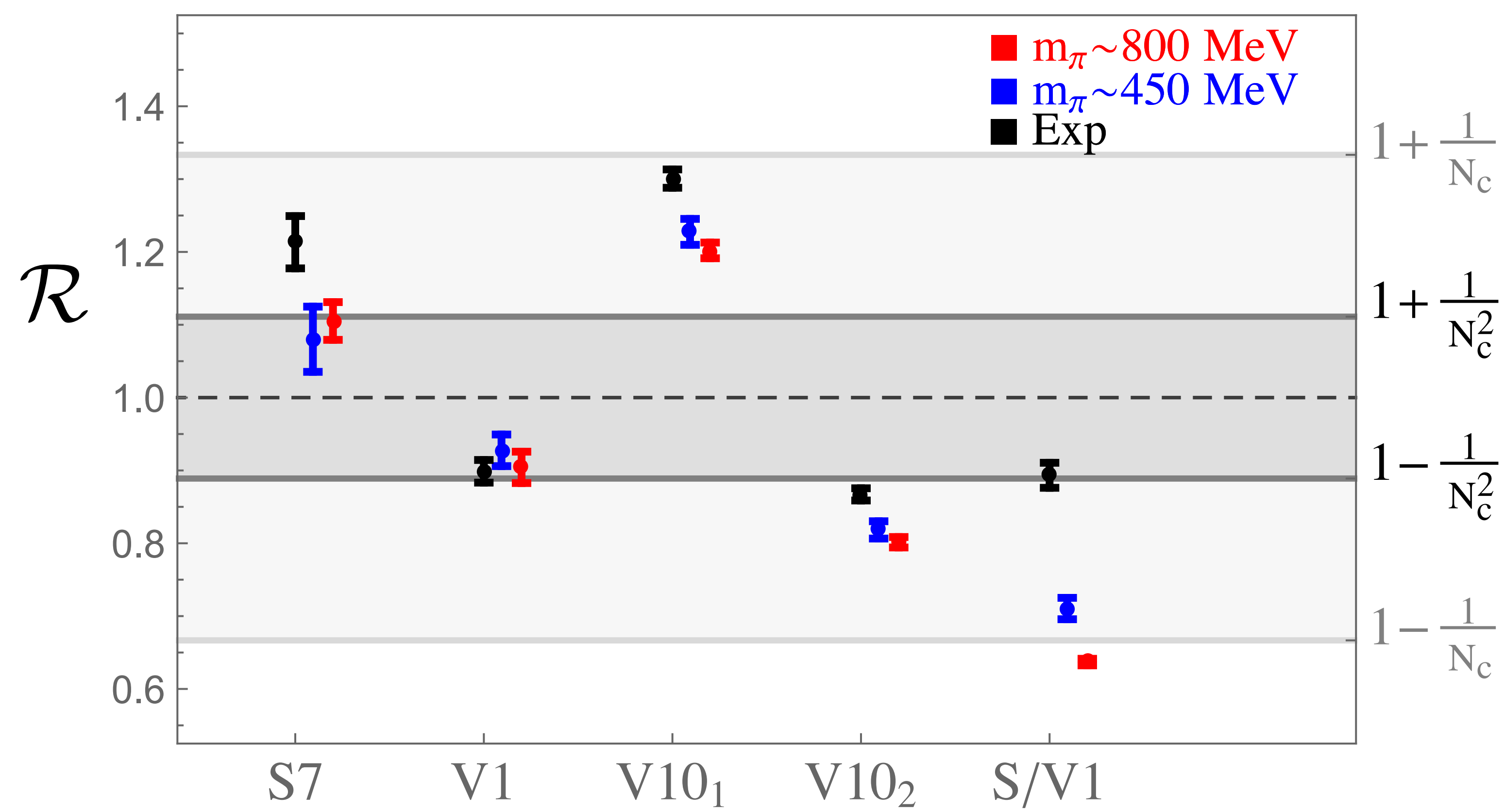

$$\mathcal{R}_{S/V1} = \frac{\frac{1}{2}(\mu_p + \mu_n) + 3(1/N_c - 2/N_c^2)\Delta\mu_N}{\mu_{\Sigma^+} + \mu_{\Sigma^-} - \frac{1}{2}(\mu_{\Xi^0} + \mu_{\Xi^-})}$$

$$= 0.62 \quad NRQM$$

$$= 1 + \mathcal{O}(\Delta m_q) + \mathcal{O}(\Delta m_q/N_c) + \mathcal{O}(1/N_c^2)$$

Large-N_c Limit

Dashen, Jenkins, Manohar (1994)

Our calculations & nature have $N_c = 3$ …

$$\mathcal{R}_{V10_1} = \frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

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$$= 1 + \mathcal{O}(1/N_c)$$

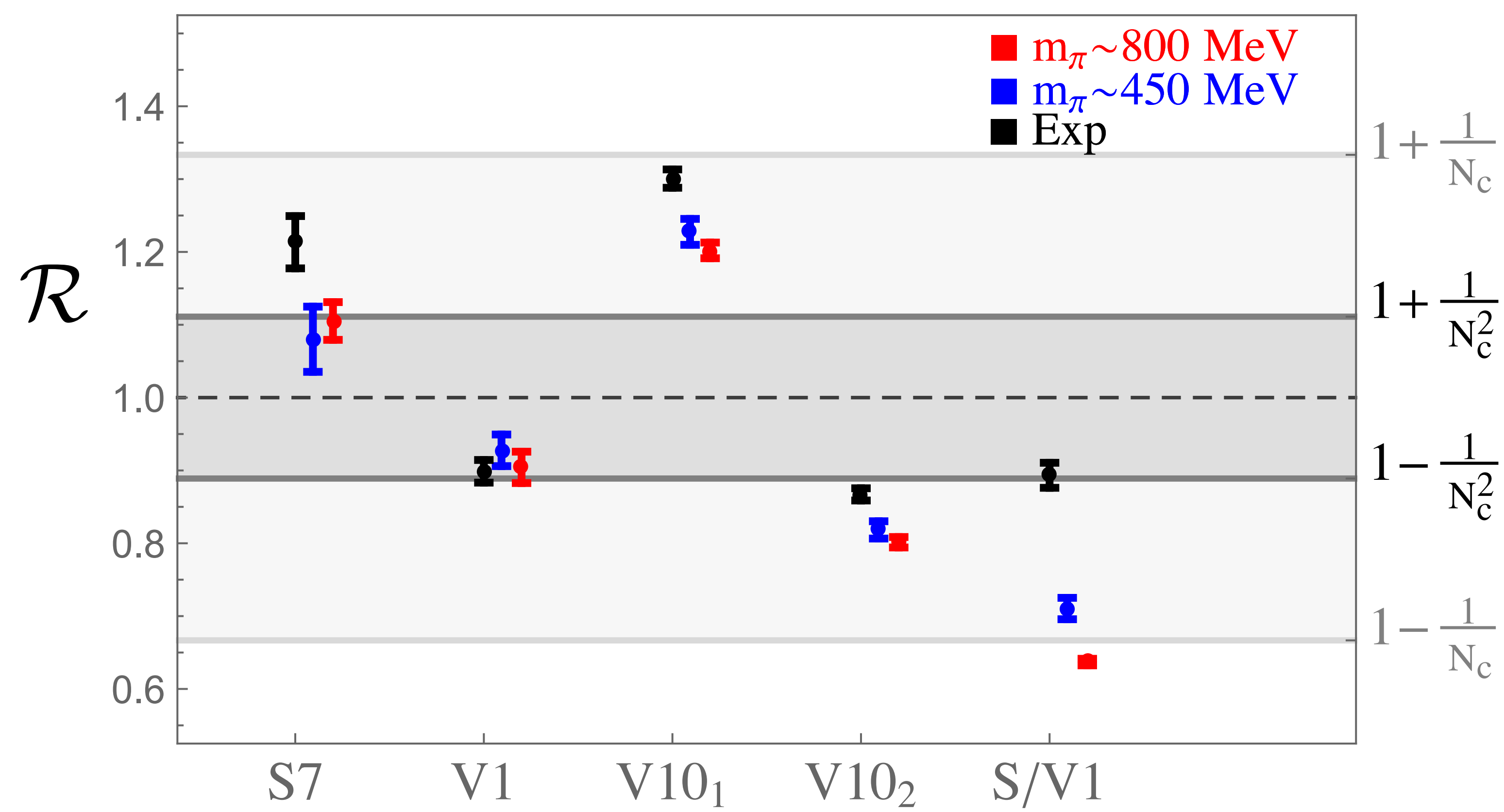
$$\mathcal{R}_{V10_2} = (1 - 1/N_c)\,\frac{\Delta\mu_N}{\Delta\mu_\Sigma}$$

$$= 0.83 \quad NRQM$$

$$= 1 + \mathcal{O}(\Delta m_q/N_c)$$

$$= 1 + \mathcal{O}(1/N_c^2)$$

Why do some large-N_c predictions work better than others?

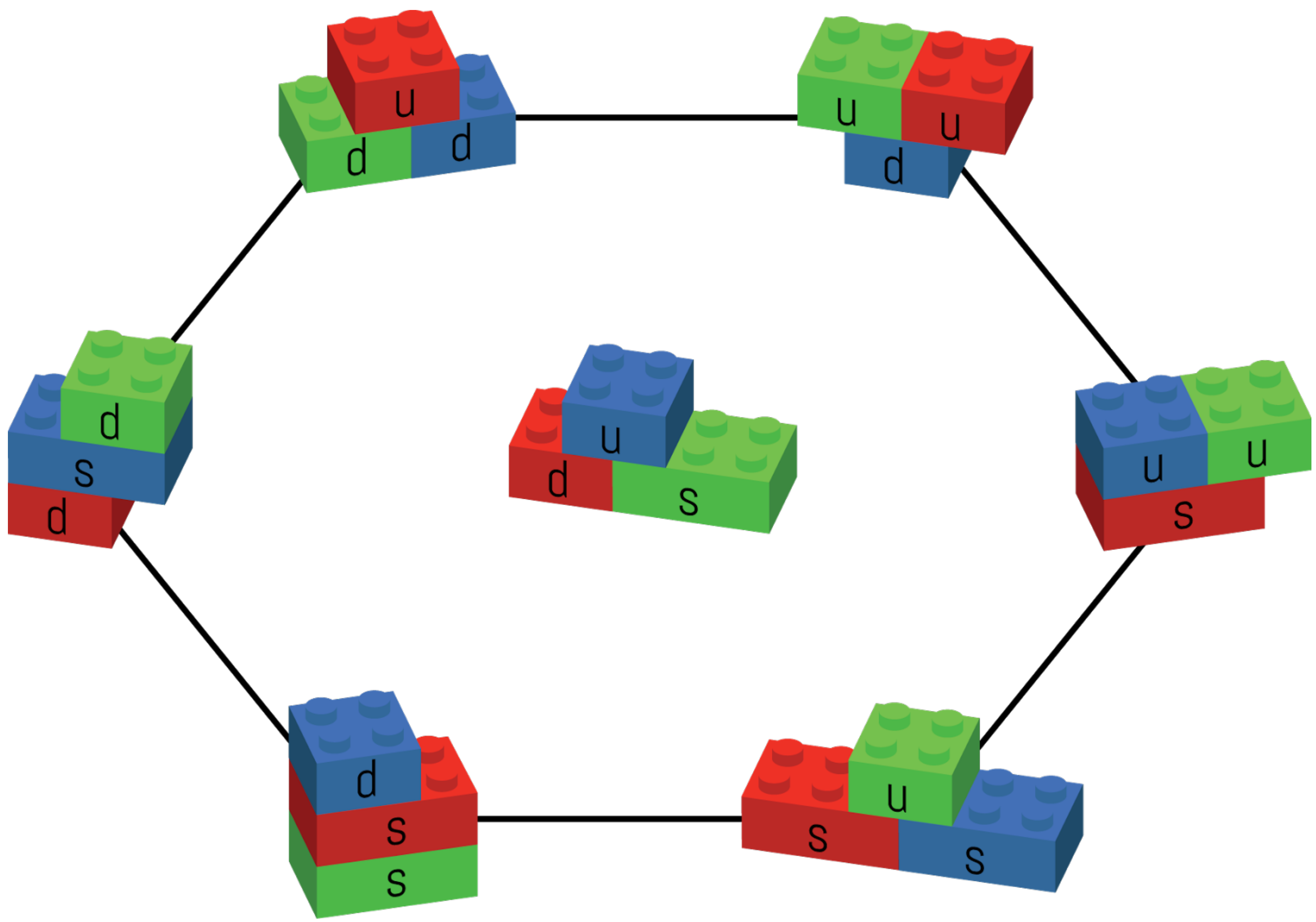


$$\mathcal{R}_{S/V1} = \frac{\frac{1}{2}(\mu_p + \mu_n) + 3(1/N_c - 2/N_c^2)\Delta\mu_N}{\mu_{\Sigma^+} + \mu_{\Sigma^-} - \frac{1}{2}(\mu_{\Xi^0} + \mu_{\Xi^-})}$$

$$= 0.62 \quad NRQM$$

$$= 1 + \mathcal{O}(\Delta m_q) + \mathcal{O}(\Delta m_q/N_c) + \mathcal{O}(1/N_c^2)$$

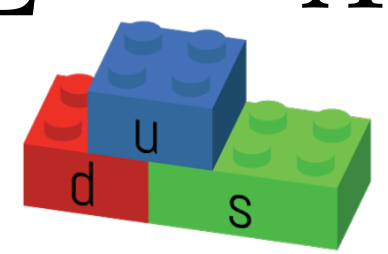
Magnetic Moments of Octet Baryons



Parreño, Savage, Tiburzi, Wilhelm, Chang, Detmold, Orginos (*NPLQCD*), `arXiv/1609.03985`

Magnetic Moments of Octet Baryons

Σ^0 Λ



$$H_{I_3=0} = \Delta_{\Lambda\Sigma} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} - \frac{e\,\vec{\sigma}\cdot\vec{B}}{2M_N} \begin{pmatrix} \mu_{\Sigma^0} & \mu_{\Lambda\Sigma} \\ \mu_{\Lambda\Sigma} & \mu_{\Lambda} \end{pmatrix} + \mathcal{O}(B^2)$$

Parreño, Savage, Tiburzi, Wilhelm, Chang, Detmold, Orginos (*NPLQCD*), `arXiv/1609.03985`

$\Sigma^0\,\Lambda$ Coupled-Channels Analysis

Diagonalize matrix of correlation functions

$$\mathbb{G}^{(s)}(t,n_\Phi) = \begin{pmatrix} G^{(s)}_{\Sigma\Sigma}(t,n_\Phi) & G^{(s)}_{\Sigma\Lambda}(t,n_\Phi) \\ G^{(s)}_{\Lambda\Sigma}(t,n_\Phi) & G^{(s)}_{\Lambda\Lambda}(t,n_\Phi) \end{pmatrix}$$

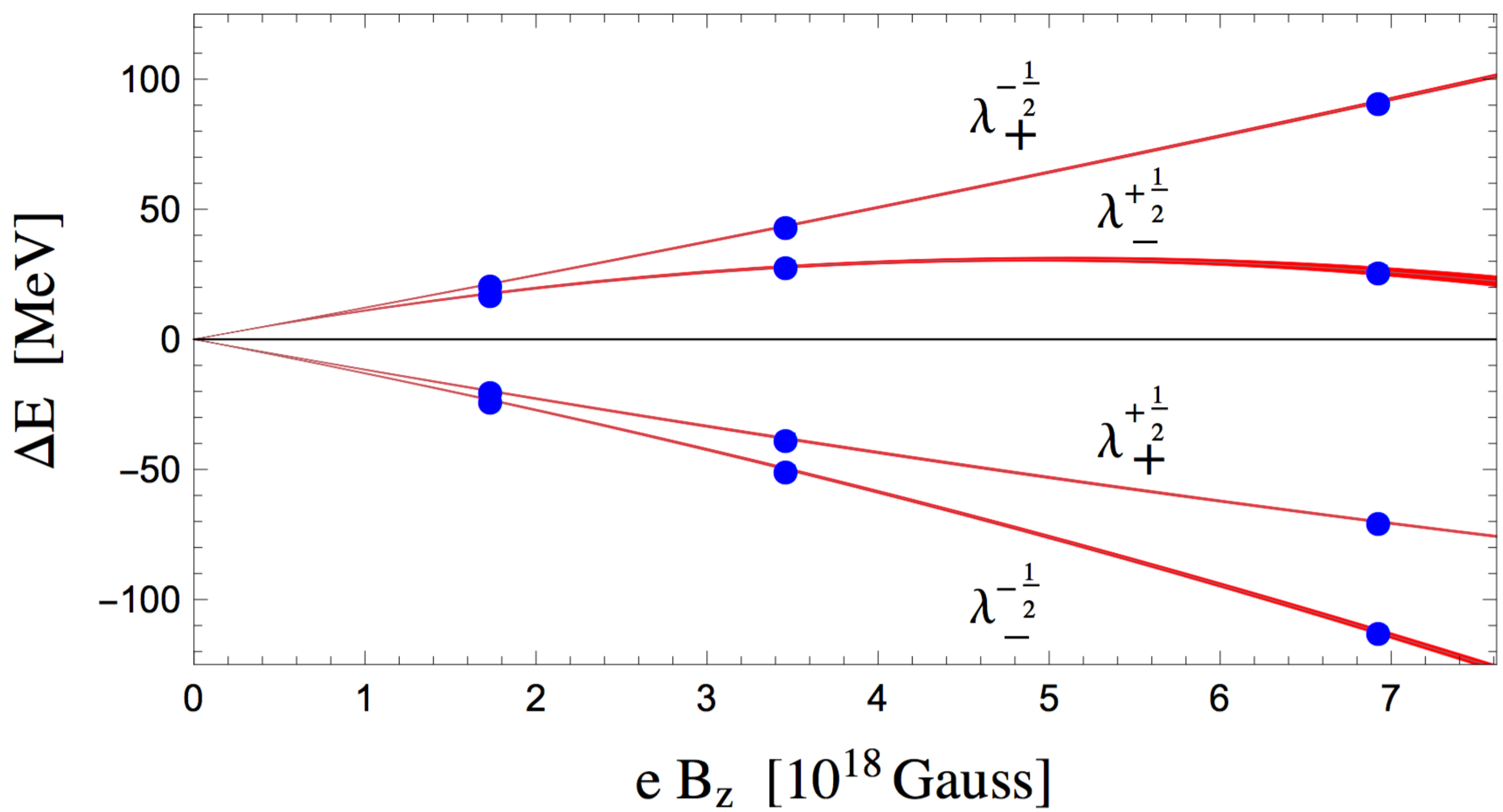
$$E^{(-\frac{1}{2})}_{\lambda_-}(B_z) = M_B + \mu_n \frac{eB_z}{2M_B} - 2\pi\beta_n B_z^2,$$

$$E^{(+\frac{1}{2})}_{\lambda_+}(B_z) = M_B + \mu_n \frac{eB_z}{2M_B} - 2\pi\left(\beta_n + \frac{4}{\sqrt{3}}\beta_{\Lambda\Sigma}\right) B_z^2,$$

$$E^{(+\frac{1}{2})}_{\lambda_-}(B_z) = M_B - \mu_n \frac{eB_z}{2M_B} - 2\pi\beta_n B_z^2,$$

$$E^{(-\frac{1}{2})}_{\lambda_+}(B_z) = M_B - \mu_n \frac{eB_z}{2M_B} - 2\pi\left(\beta_n + \frac{4}{\sqrt{3}}\beta_{\Lambda\Sigma}\right) B_z^2,$$

$$\mathbf{m_u = m_d = m_s}$$



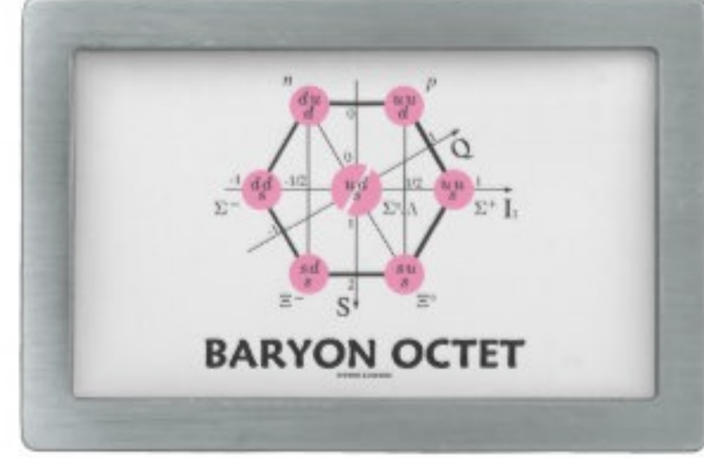
Coleman-Glashow
+ magnetic polarizability

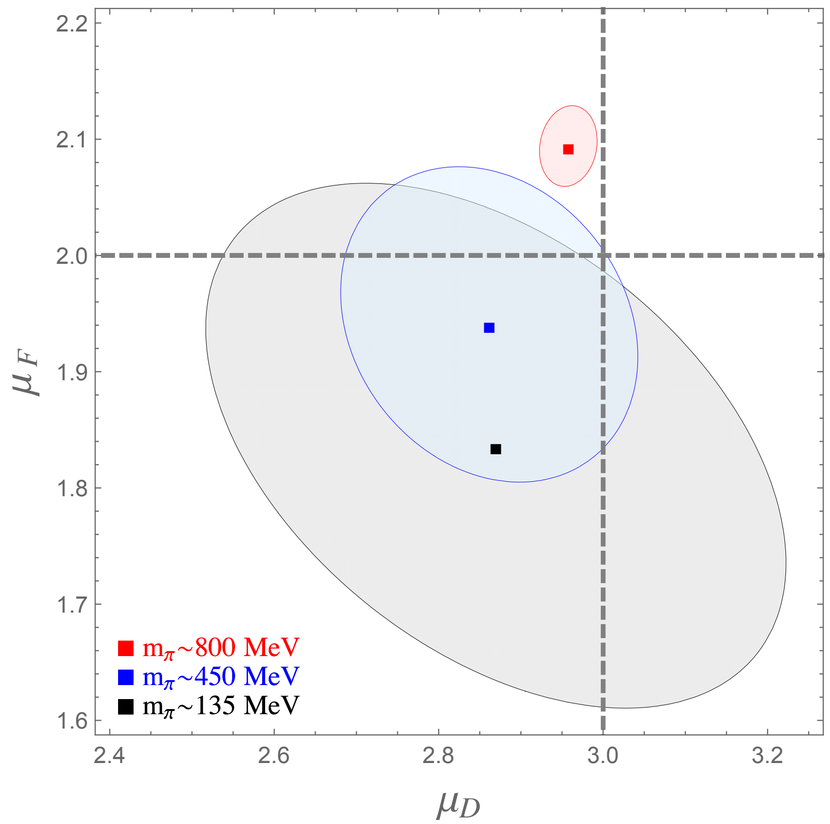
$$\mu_{\lambda_\pm} = \mp\mu_n \sim \pm 2\ \texttt{[nBM]}$$

$$\beta_n = 3.48(12)(26)(04)\,[10^{-4}\,\mathrm{fm}^3]$$

$$\beta_{\Lambda\Sigma} = -1.82(06)(12)(02)\,[10^{-4}\,\mathrm{fm}^3]$$

New Features = New Puzzles



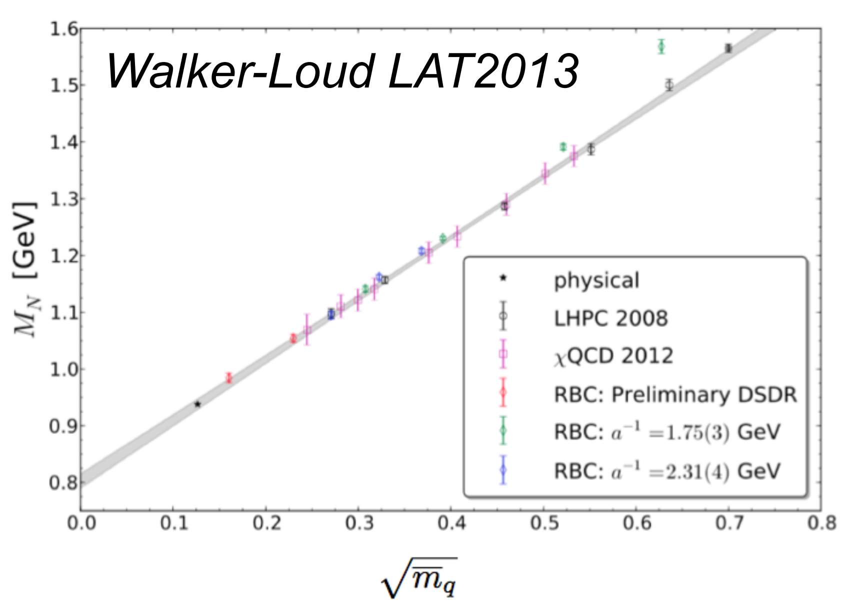


- **Mild pion-mass dependence** `[nBM]`
- **Nearness to SU(3) really nearness to SU(6)?**
- ***NRQM* explains large-*Nc* relations for *Nc* = 3?**

Need to compute octet, decuplet, and their transition moments

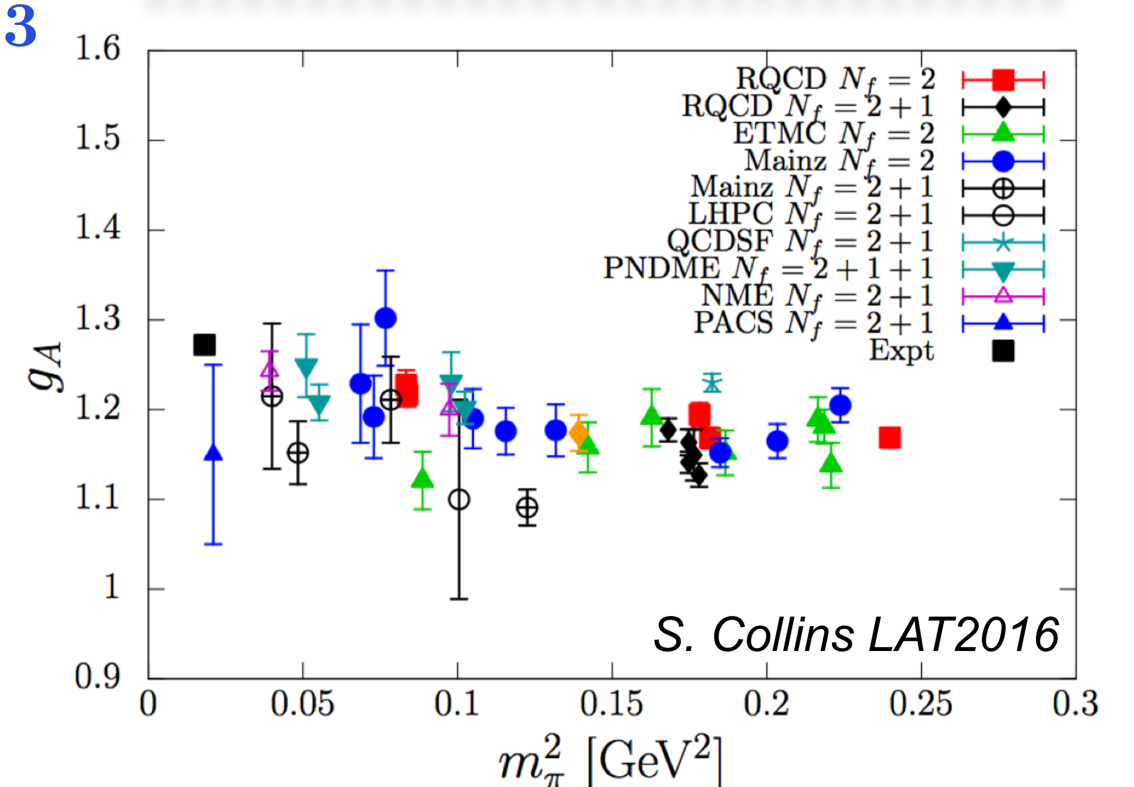
Need further pion masses, even light SU(3) symmetric ensembles

- **Why is *NRQM* successful @ spectrum & moments?**



?

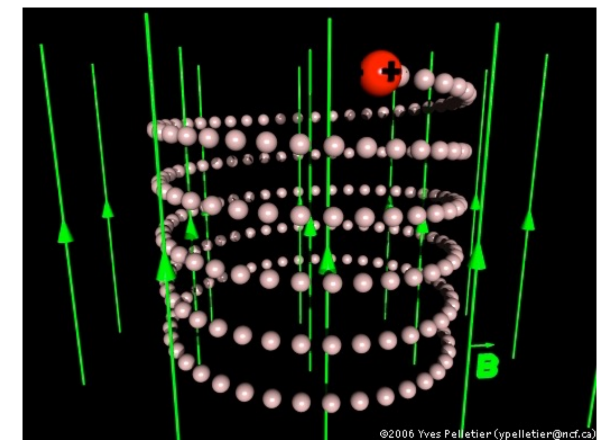
$$g_A = \frac{5}{3}$$



Future Directions

- **Magnetic Structure of Baryons & Nuclei**

  Move beyond initial studies: remove systematics, lower pion mass, better treat Landau levels, sea quarks, …



- **Electric Structure of Baryons & Nuclei**

  Electric polarizabilities?
  EDMs of light nuclei from θ-term?, BSM sources?

- **Baryons & Nuclei in other classical fields…**

  Gravitational?, Weak?

Nuclear Physics from QCD → **EW Reactions** → **BSM Physics**