Nucleon charges from Lattice QCD and their implications for BSM physics

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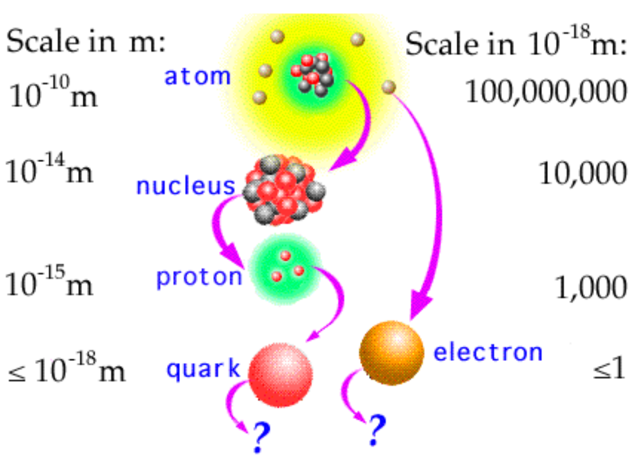

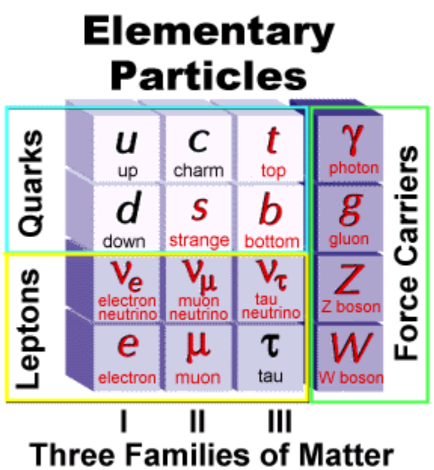

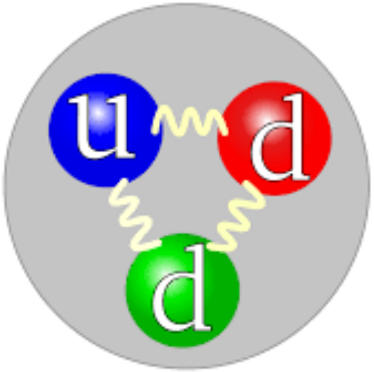

LA-UR: 23-27930

XVI Quark Confinement, 2024, Cairns, Australia

PNDME Collaboration:	**Eleven 2+1+1-flavor HISQ ensembles = clover-on-HISQ formulation**
NME Collaboration:	**Thirteen 2+1-flavor clover ensembles = clover-on-clover formulation**

PNDME and NME members

- Tanmoy Bhattacharya (T-2)
- Vincenzo Cirigliano (T-2 → **INT, UW)**
- Rajan Gupta (T-2)
- Emanuele Mereghetti (T-2)
- Boram Yoon (CCS-7 → **NVIDIA**)
- Junsik Yoo (PD: 2022 May –)
- Yong-Chull Jang (PD: 2017-2018)
- Sungwoo Park (PD: 2018-2021)
- Santanu Mondal (PD: 2019-2021)
- Huey-Wen Lin (MSU)
- Balint Joo (NVIDIA)
- Frank Winter (Jlab)

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MILC for HISQ ensembles.
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USQCD
Institutional Computing at LANL

References

- Charges: Gupta et al, PRD.98 (2018) 034503
- AFF: Gupta et al, PRD 96 (2017) 114503
- AFF: Jang et al, PRL 124 (2020) 072002
- AFF: Jang et al, PRD 109 (2024) 014503
- AFF: Tomalak et al, PRD 108 (2023) 074514
- VFF: Jang et al, PRD 100 (2020) 014507
- $\sigma_{\pi N}$ Gupta et al, PRL 127 (2021) 242002
- d_n from Θ-term Bhattacharya etal, PRD 103 (2021) 114507
- d_n from qEDM Gupta et al, PRD 98 (2018) 091501
- d_n from qcEDM Bhattacharya et al, PRD 98 (2018) 091501
- Moments of PDFs Mondal et al, PRD 102 (2020) 054512
- Proton spin: Lin et al, PRD 98 (2018) 094512

NME

- Charges, FF: Park et al, PRD 105 (2022) 054505
- Moments of PDFs Mondal et al, JHEP 04 (2021) 044

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Outline

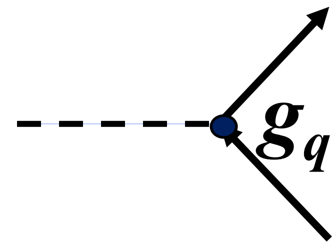
- What is Lattice QCD good for?
  - Properties of QCD: spectrum, EoS, …
  - Matrix elements within hadronic states
- Nucleon charges
  - Isovector axial, scalar, tensor
  - Flavor diagonal axial
  - Flavor diagonal tensor
  - Θ-Term
  - Flavor diagonal scalar

This talk is will emphasize issues in the Lattice QCD calculations and connections to BSM

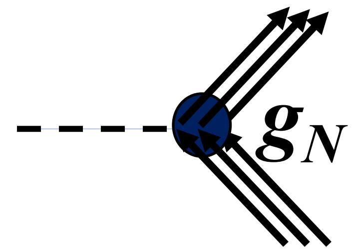
Lattice QCD results for nucleon charges are being reviewed by FLAG: 2019, 2021, 2024

To quote numbers, please use original articles or numbers in the FLAG report

Nucleon charges



- Standard Model specifies the coupling g_q of electroweak currents with quarks



- Similarly, EFT of BSM at few GeV is in terms of quark and gluon operators
- Experiments measure these interactions on hadrons
- QCD gives significant corrections: $g_{\text{quark}} \rightarrow g_{\text{hadron}}$
- Calculation is intrinsically non-perturbative

Example: axial charge of nucleons goes from $1 \rightarrow 1.276$

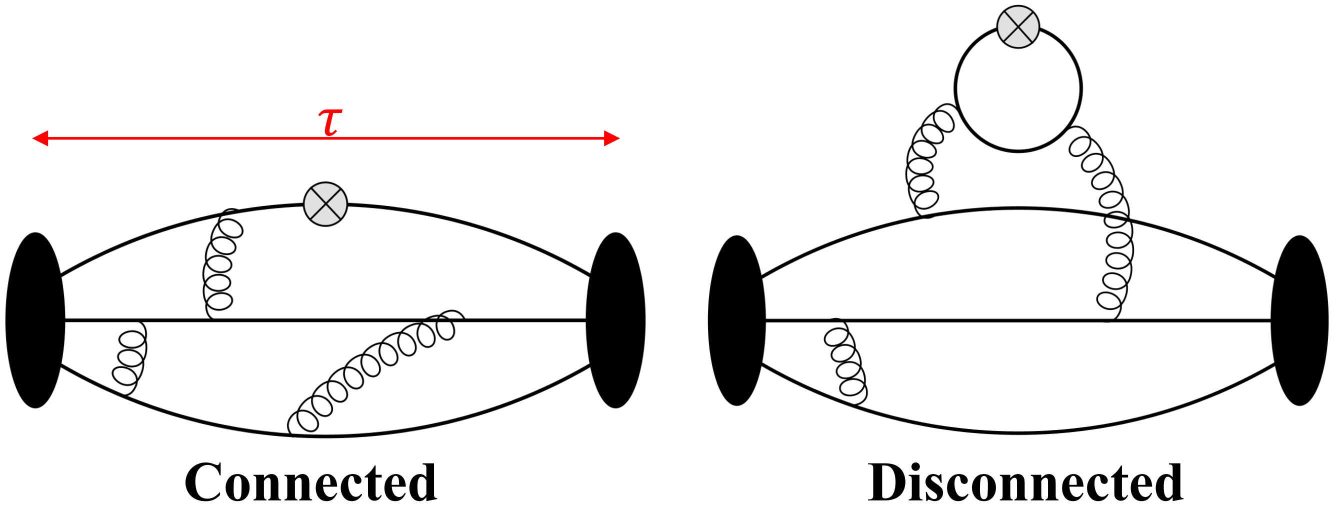
Nucleon charges: $\langle N|\overline{q}\,\Gamma\,\mathrm{q}|\mathrm{N}\rangle \propto g_\Gamma^q\,\Gamma$

- Standard Model
  - Vector charge (CVC) g_V^{u-d} $1 \to 1$
  - Axial charge g_A^{u-d} $1 \to 1.276$
  - Transversity $g_T^{u,d,s,c,b}$
  - Contribution of quark's spin to nucleon spin $g_A^{u,d,s,c,b}$
- BSM
  - Novel scalar and tensor interactions via g_S^{u-d}, g_T^{u-d} and precision measurements of neutron decay
  - Coupling to dark matter: $g_{A,P,S,T,V}^{u,d,s,c,b}$
  - Contribution of quark's EDM to nucleon EDM $g_T^{u,d,s,c,b}$
  - Contributions of the Θ-Term to nEDM

Many thanks to

- Raul Briceno:
  - Three-hadron systems
- Andreas Kronfeld:
  - Perturbation theory, power corrections, renormalons and precise evaluation of quark masses and α_S
- Huey-Wen Lin:
  - Parton distributions from lattice QCD and impacts on global QCD analysis
- Finn Stokes:
  - Review of muon g-2
- Andre Walker-Loud:
  - Beta decay as probe of new physics
- Michael Creutz, William Detmold, Xu Feng, Shoji Hashimoto, Martin Hoferichter, David Lin, Ross Young, James Zanotti, …

Lattice Methodology well established for
"connected" and "disconnected" 3-point correlation functions



stochastic estimates of disconnected contributions are noisier for the same computational cost and smaller in value

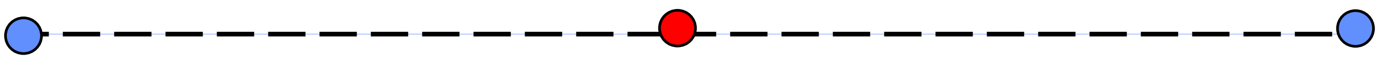
Isoscalar $$g_{A,S,T}^{u+d} = g_{A,S,T}^{u+d,\mathrm{conn}} + 2g_{A,S,T}^{l,disc}$$

Isovector $$g_{A,S,T}^{u-d} = g_{A,S,T}^{u-d,\mathrm{conn}}$$ In the isospin symmetric limit

Analysis: Spectral decomposition of Γ^2 and Γ^3

Three-point function for matrix elements of axial current $\mathcal{A}_\mu$

$$\langle\Omega|N(\tau)\,\mathcal{A}_\mu(\mathrm{t})\overline{N}(0)|\Omega\rangle$$



Insert $T = e^{-H\Delta t}\sum_i |n_i\rangle\langle n_i|$ at each Δt with $T\,|n_i\rangle = e^{-H\Delta t}|n_i\rangle = e^{-E\Delta t}|n_i\rangle$

$$\langle\Omega|\overline{N}(\tau)\cdots e^{-\mathrm{H}\Delta t}\sum_j |n_j\rangle\langle n_j|\,\mathcal{A}_\mu e^{-\mathrm{H}\Delta t}\sum_i |n_i\rangle\langle n_i|\cdots \mathrm{N}(0)|\Omega\rangle$$

$$\sum_{i,j}\underbrace{\langle\Omega|\overline{N}|n_j\rangle}_{A_j^*}\,e^{-\mathrm{E_j}(\tau-t)}\,\underbrace{\langle n_j|A_\mu|n_i\rangle}_{\text{Matrix Elements}}\,e^{-\mathrm{E_i}t}\,\underbrace{\langle n_i|\mathrm{N}|\Omega\rangle}_{A_i}$$

Extracting Nucleon Charges

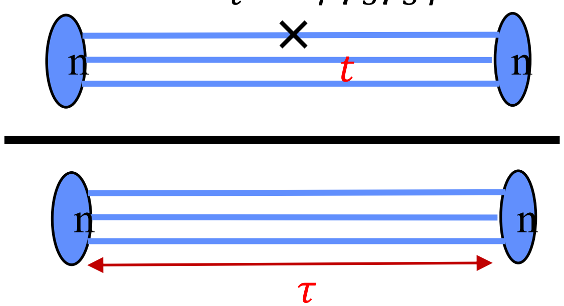
$$\Gamma^2 = \sum_i A_i^* A_i \, e^{-E_i \tau} \qquad \Gamma^3 = \sum_{i,j} A_i^* A_j \langle N_i | O | N_j \rangle e^{-E_i t} \, e^{-E_j (\tau - t)}$$

In the limit ($\tau \to \infty$) only the ground state contributes. Then

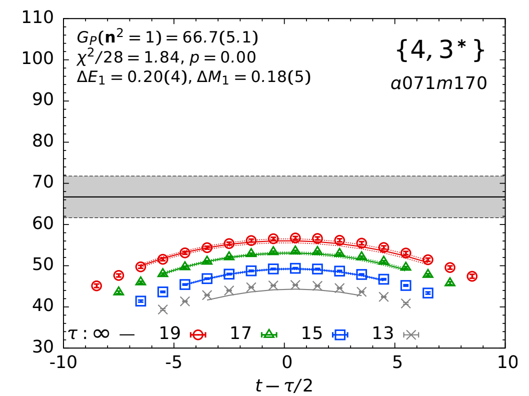
$$\frac{\Gamma^3}{\Gamma^2} = \frac{\langle \Omega | \overline{\mathbb{N}}\, A_\mu \mathbb{N} | \Omega \rangle}{\langle \Omega | \mathbb{N}\, \overline{\mathbb{N}} | \Omega \rangle} \to \langle N(p_i) | A_\mu \, (Q^2 = 0) | N(p_i) \rangle \to \boldsymbol{g_A}$$

$$O_t = \bar{\psi} \gamma_3 \gamma_5 \psi$$

$$\frac{\Gamma^3}{\Gamma^2} =$$



$$\xrightarrow[\tau \to \infty]{} \boldsymbol{g_A}$$



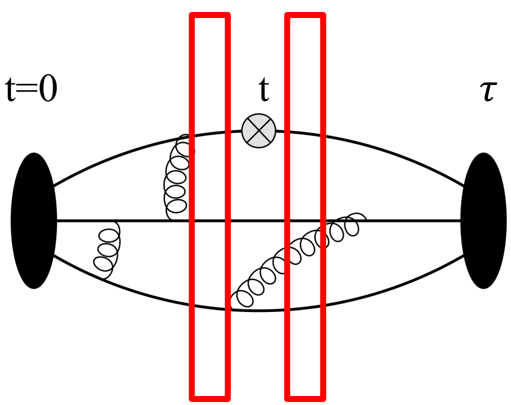
Otherwise, need to make fits to Γ^3. This requires knowing the spectrum (energies E_i) and amplitudes (A_0)

Spectral decomposition of 3-point function

All states with the same quantum numbers as the nucleon are created by $\boldsymbol{N}$

$$\Gamma^{3pt} = \langle 0|\mathcal{O}|0\rangle |A_0|^2 e^{-M_0\tau} \times \Big[1 + \frac{\langle 1|\mathcal{O}|1\rangle}{\langle 0|\mathcal{O}|0\rangle}\frac{|A_1|^2}{|A_0|^2} e^{-\Delta M_1 \tau} + \frac{\langle 2|\mathcal{O}|2\rangle}{\langle 0|\mathcal{O}|0\rangle}\frac{|A_2|^2}{|A_0|^2} e^{-(\Delta M_2 + \Delta M_1)\tau} + \frac{\langle 0|\mathcal{O}|1\rangle}{\langle 0|\mathcal{O}|0\rangle}\frac{|A_1|}{|A_0|} e^{-\Delta M_1 \frac{\tau}{2}} \times 2\cosh\Big(\Delta M_1 (t - \frac{\tau}{2})\Big) + (\cdots)$$

Ground-state matrix element → g_S

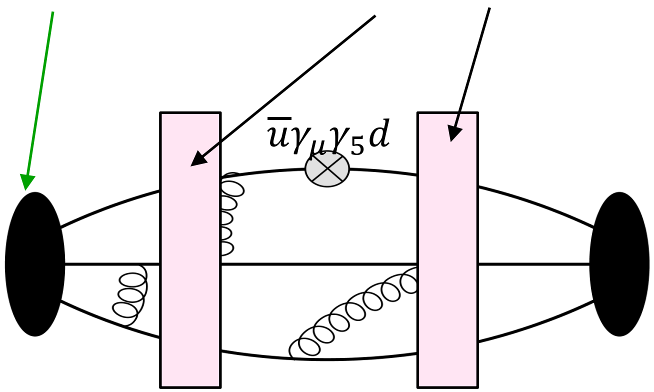


To isolate $\langle 0|O|0\rangle$, the key quantities needed are A_0, M_i

Which excited states make significant contributions to a given correlation function?

Interpolating operators create or annihilate all states with the same quantum numbers as N

All intermediate states with nucleon quantum numbers are suppressed only by $A_i^2 e^{-(M_i - M_N)t}$



Towers of multihadron states

$N(\vec{p})\pi(-\vec{p})$

$N(0)\pi(\vec{p})\pi(-\vec{p})$

$N(\vec{p})2\pi(-\vec{p})$

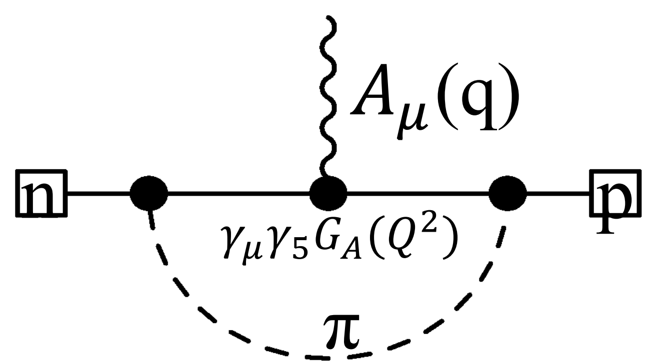
…

Starting at ~1220 MeV

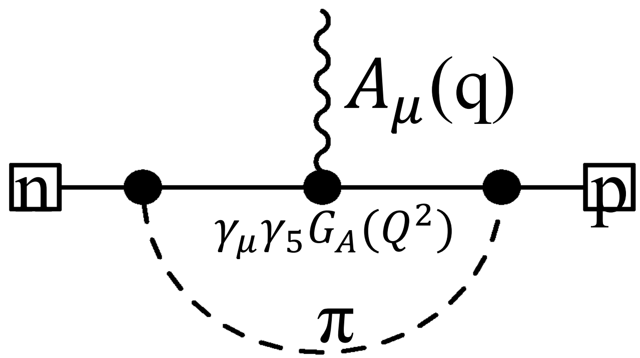
Radial excitations N(1440)

…

χPT suggests that the contribution of a pion loop could be ~5% in all NME



χPT: In all cases, there is excited-state contribution to nucleon charges from when the pion in pion loop is on shell



This, possibly 5%, contribution from $N\pi$ excited-state needs to be understood/resolved for each NME

Need A_0, M_i: but which M_i are significant?

- Mass gaps, ΔM_i, of $N\pi, N\pi\pi, \ldots$ states are smaller than N(1440)
- Their spectrum gets dense as $\vec{p} \to 0$
- We approximately know their energies in a finite box
- Creating each extra state (π) is suppressed by a normalization factor 1/V
- In some cases, the transition ME are large and compensate for the 1/V factor

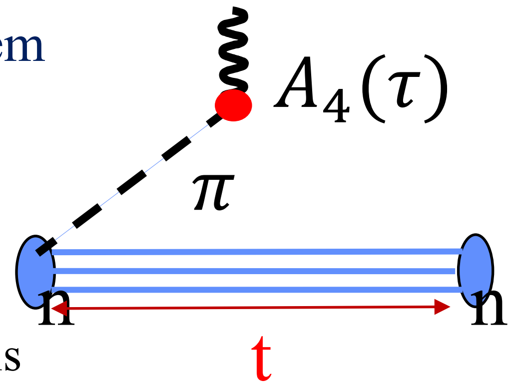
Issue: With current statistics, fits with $\mathrm{M}_1 = \mathrm{M}_{N\pi}$ versus $\mathrm{M}_1 = \mathrm{M}_{N(1440)}$ are not distinguished by the χ^2!

Using priors is not the desired solution

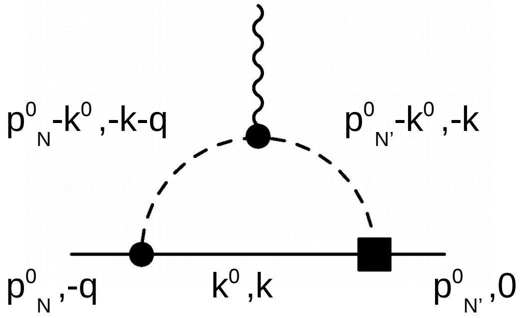
What size statistics are needed to achieve data-driven (χ^2) selection?

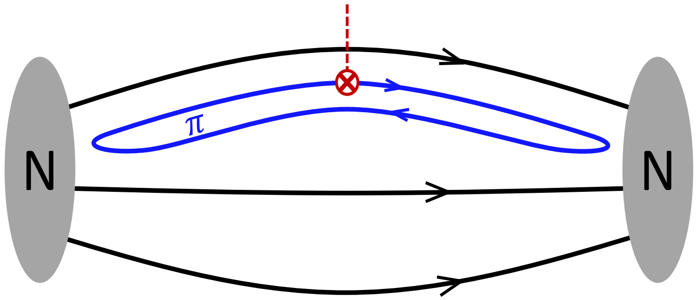
Examples of enhanced excited-state matrix elements

- Axial Form Factors must satisfy PCAC relation between them
  - Need to include $N(\vec{p})\pi(-\vec{p})$ states to satisfy PCAC
  - $\langle\Omega|N(\tau)\ \mathcal{A}_4(\mathrm{t})\overline{N}(0)|\Omega\rangle$ has very large ESC
  - Used $\langle\Omega|N\ A_4\overline{N}|\Omega\rangle$ to include $N\pi$ state. Data-driven method
  - Enhanced ME: Manifestation of pion-pole dominance hypothesis

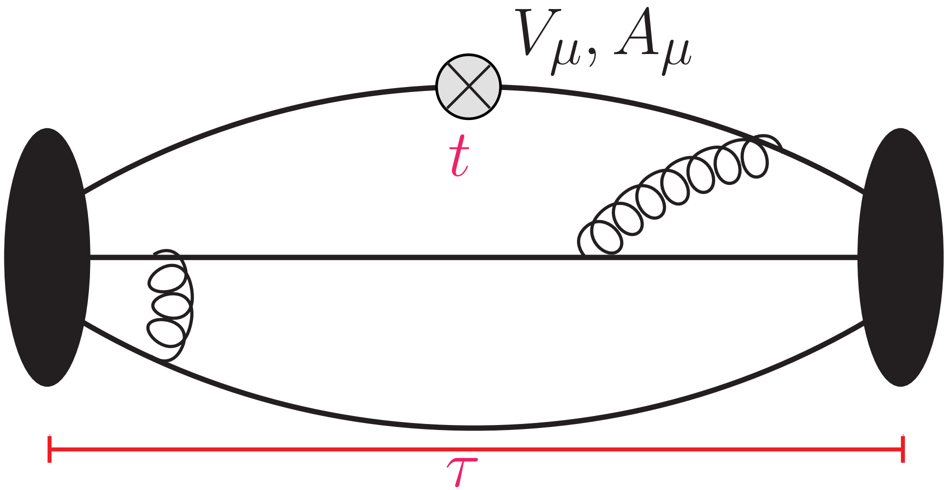


- χPT predicts large contributions from $N\pi$ state in
  - nEDM from Θ-term
  - The pion-nucleon sigma term $\sigma_{\pi N} = \mathrm{m_{ud}}\ g_S^{u+d}$





Isovector charges from forward matrix elements



All (A,P,S,T,V) done at the same time

Isovector axial charge g_A^{u-d}

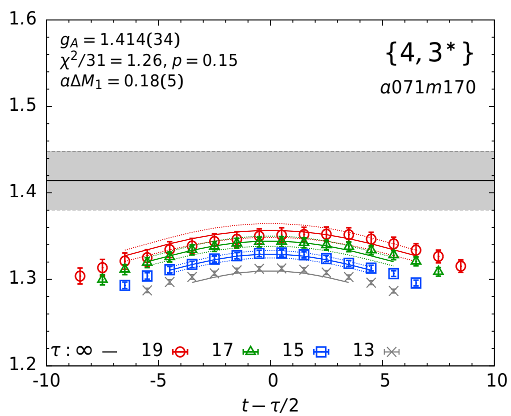
- Benchmark quantity as it is very well measured $g_A^{u-d} = 1.276(1)$
- A fundamental parameter in nuclear physics

2 ways of extracting isovector g_A^{u-d}

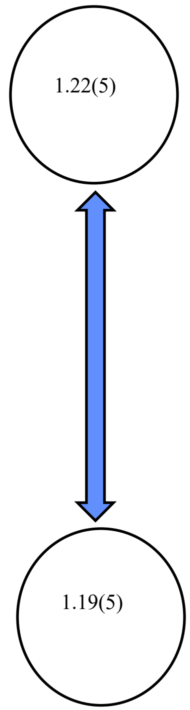
Check control over removing excited-state contributions

Spectrum from Γ^2

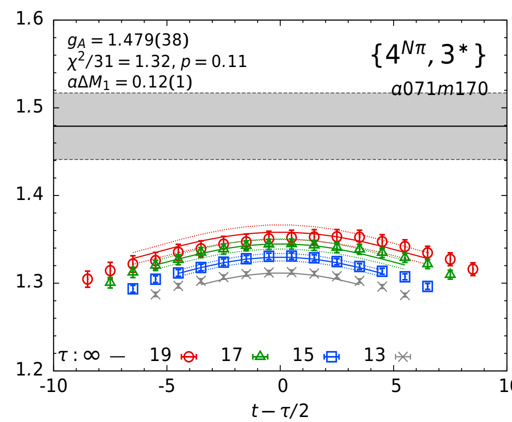
g_A (Forward ME)

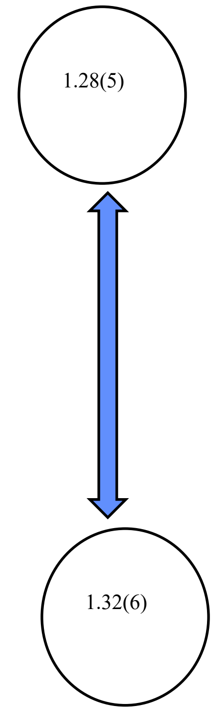


$g_A = G_A(Q^2 \to 0)$



$N\pi$ included in fits (via A_4 or priors)





$G_A, \tilde{G}_P, G_P$ do not satisfy PCAC

$G_A, \tilde{G}_P, G_P$ satisfy PCAC

Status

- Current lattice estimates are mostly in the range g_A^{u-d} =[1.25 – 1.31]
- Precision is improving steadily
- Resolve the possible ~5% excited-state contributions from $N\pi$ ... states
- Isospin breaking and electromagnetic corrections (talk by Walker-loud)

Implication for BSM

- Constraints on right-handed currents once Lattice QCD can provide g_A^{u-d} with few parts per mil precision (see talk by Walker-Loud)
- Neutron decay is a very promising opportunity for extracting V_{ud} and testing the unitarity of the first row of the CKM matrix.
  Need τ_n and g_A^{u-d} from experiments and lattice QCD input in calculating radiative corrections (see talks by Walker-Loud, Xu Feng)

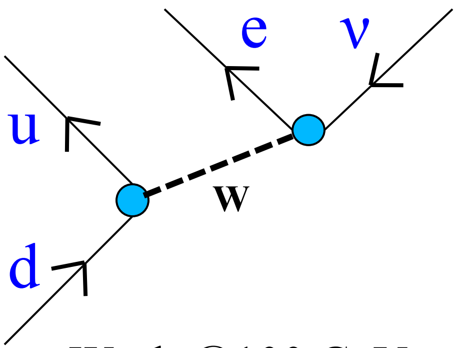
Isovector scalar and tensor charges g_S^{u-d} and g_T^{u-d}

- Combined with high precision measurements of neutron decay, they provide a low energy probe of novel scalar and tensor interactions

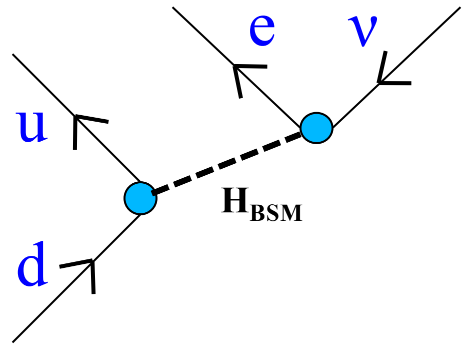
Bhattacharya et al, PRD 85, 054512 (2012)

Probing New Interactions: $M_{BSM} >> M_W >> 1$ GeV

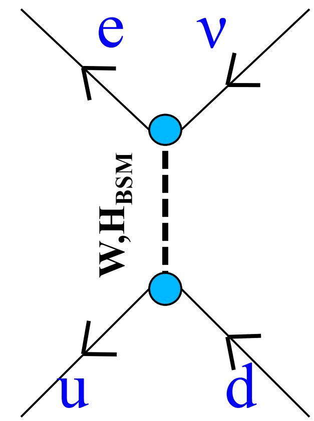
Many BSM possibilities for novel Scalar & Tensor interactions: Higgs-like, leptoquark, loop effects, …



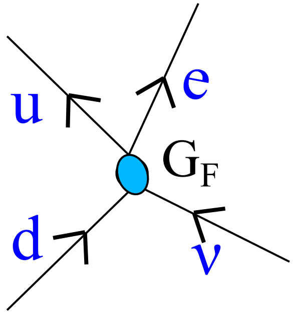
Weak @100 GeV
V-A: e_L with a ν_L

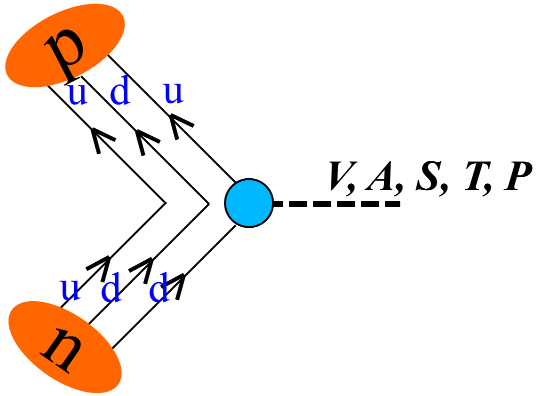


Novel S,T Interactions
@ TeV: e_R with a ν_L



LHC



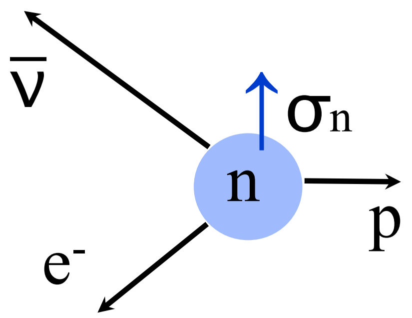


Effective Theory @ ~2 GeV
Characterized by G_F

New S, T Interactions (ε_S , ε_T)

Measure in [Ultra]Cold Neutron Decay: Parameters sensitive to new physics

Neutron decay can be parameterized as



$$d\Gamma \propto F(E_e)\left[1 + b\frac{m_e}{E_e} + \left(B_0 + B_1\frac{m_e}{E_e}\right)\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu} + \cdots\right]$$

b: Deviations from the leading order electron spectrum: Fierz interference term

B_1: Energy dependent part of the correlation of antineutrino momentum with the neutron spin

Relating b, B_1 to $g_{S,T}$ & BSM couplings $\varepsilon_{S,T}$

$$H_{eff} \supset G_F \left[\varepsilon_S \, \bar{u}d \; \bar{e}(1-\gamma_5)\nu_e + \varepsilon_T \, \bar{u}\sigma_{\mu\nu}d \; \bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e \right]$$

$$g_S = Z_S \langle p | \bar{u} d | n \rangle \qquad g_T = Z_T \langle p | \bar{u}\, \sigma_{\mu\nu}\, d | n \rangle$$

Lattice QCD

Analysis of $n \to p\, e\, \bar{\nu}$ decay at leading order in $\varepsilon_{S,T}$ gives the linear relations

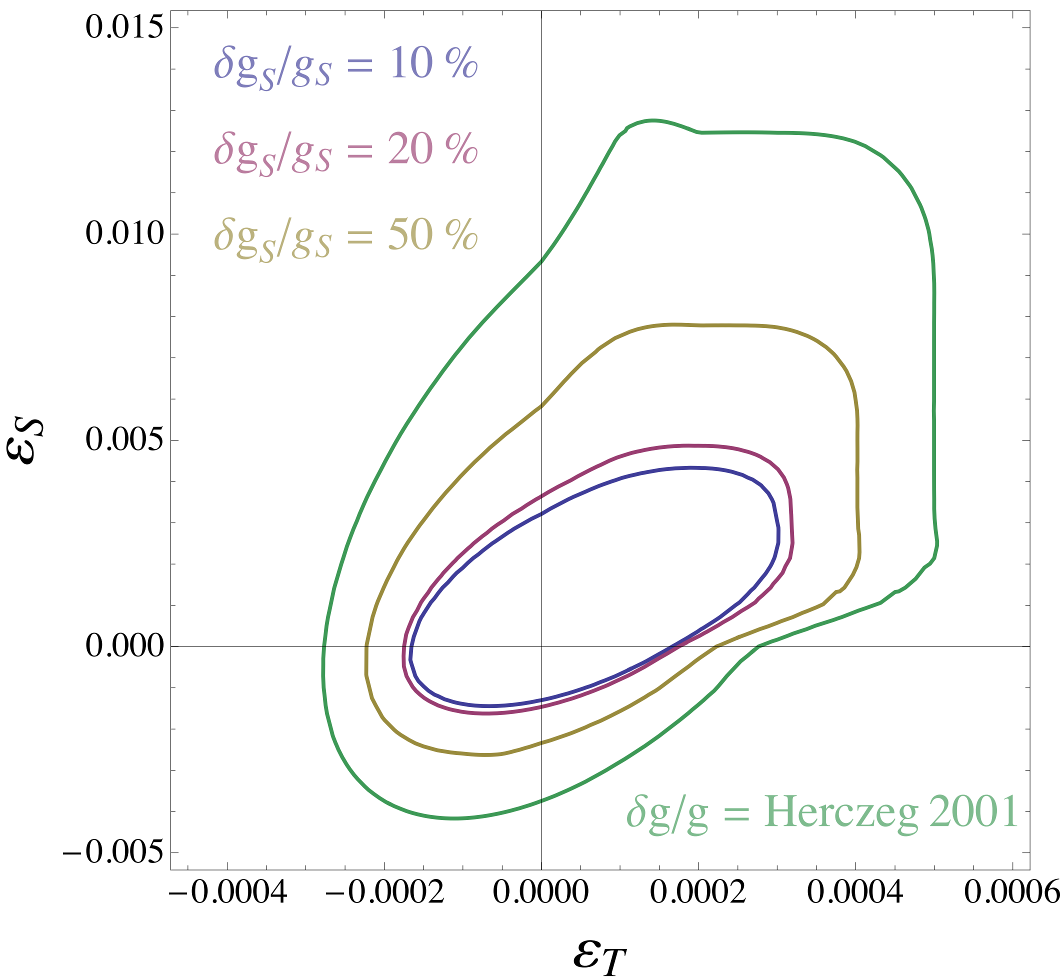
$$b^{BSM} \approx 0.34\, g_S \varepsilon_S - 5.22\, g_T \varepsilon_T$$

$$b_\nu^{BSM} \equiv B_1^{BSM} = E_e \frac{\partial B^{BSM}(E_e)}{\partial m_e} \approx 0.44\, g_S \varepsilon_S - 4.85\, g_T \varepsilon_T$$

Bhattacharya et al, PRD 85, 054512 (2012)

Impact of reducing errors in g_S and g_T from 50→10%

Allowed region in [ε_S , ε_T] (90% contours)



Experimental input

$|B_1\text{-}b| < 10^{-3}$
$|b| < 10^{-3}$
$b_{0+} = 2.6\ (4.3) * 10^{-3}$

Impact limited by precision of ME from Lattice QCD

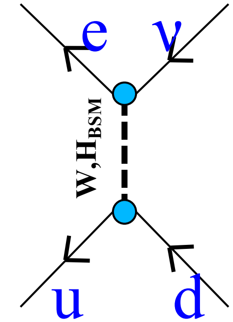
$$g_S = Z_S \langle p | \bar{u} d | n \rangle$$
$$g_T = Z_T \langle p | \bar{u} \sigma_{\mu\nu} d | n \rangle$$

Goal: 10% accuracy in g_S and g_T

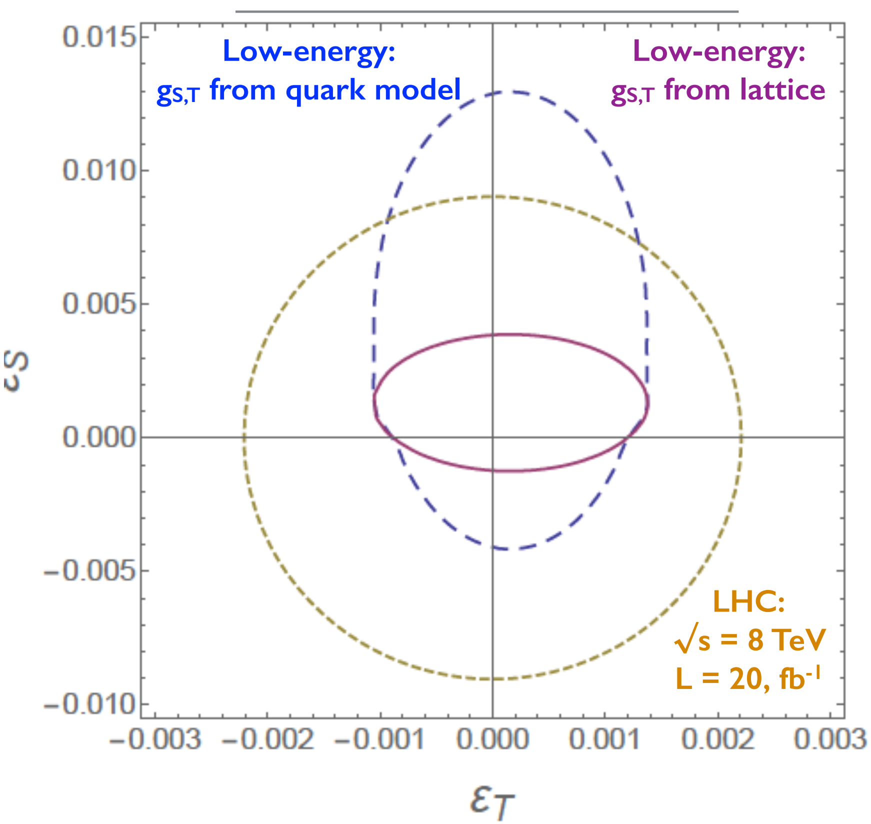
PRD 85, 054512 (2012)

Constraints on $[\varepsilon_S, \varepsilon_T]$: β-decay versus LHC

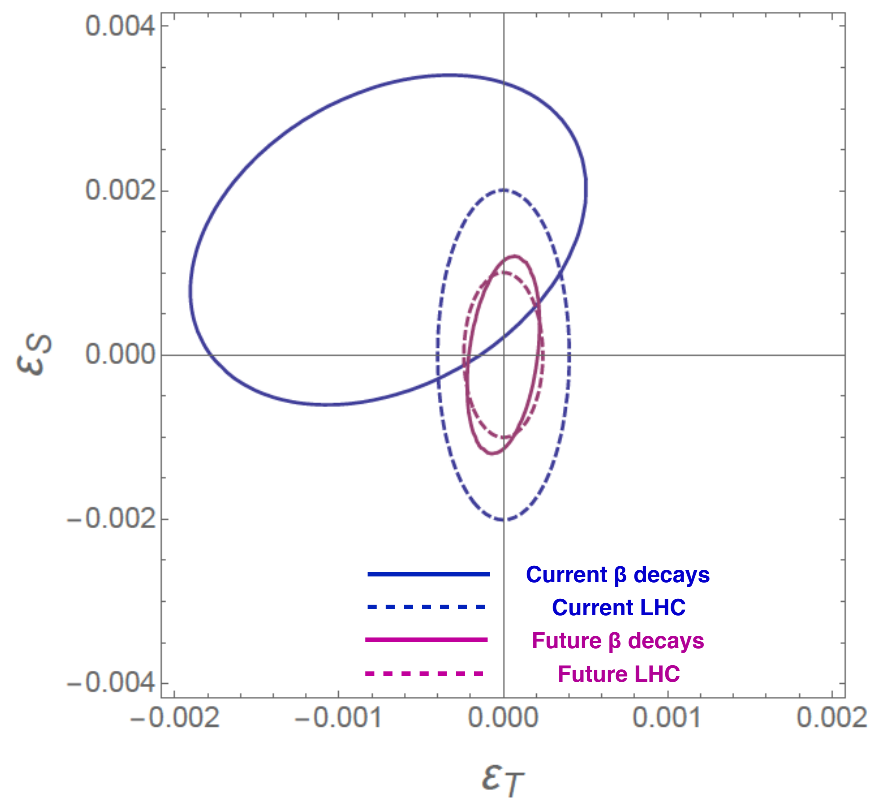
- LHC: $(u+d \rightarrow e+\nu)$ look for events with an electron and missing energy at high transverse mass
- low-energy experiments + lattice with $\delta g_S/g_S \sim 10\%$



LHC



PRD 85, 054512 (2012)

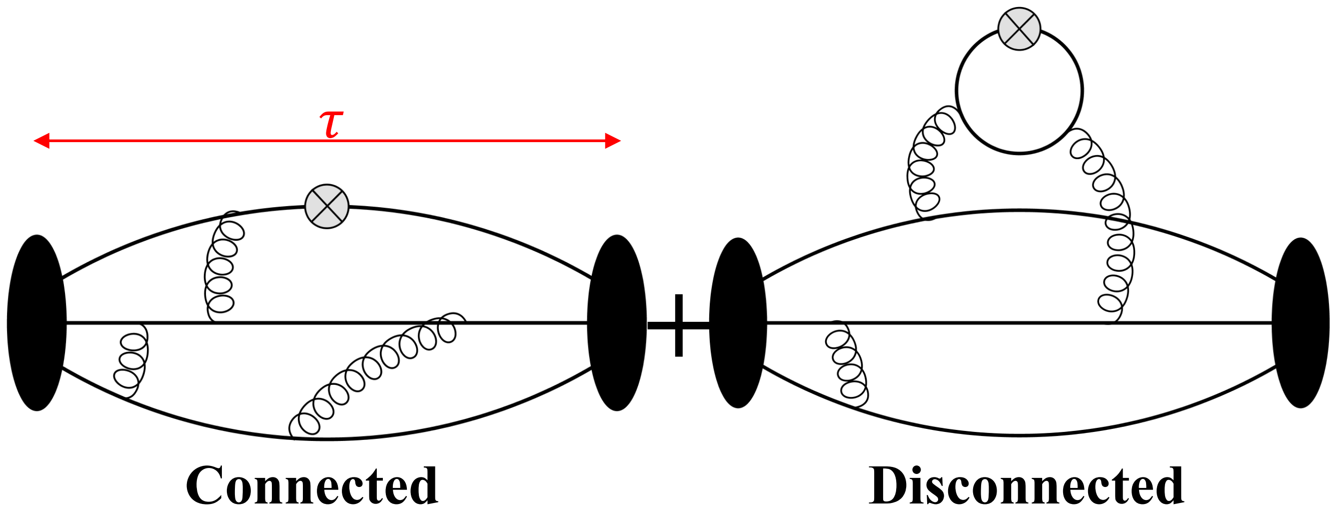


PRD 98, 034503 (2018)

Implication for BSM

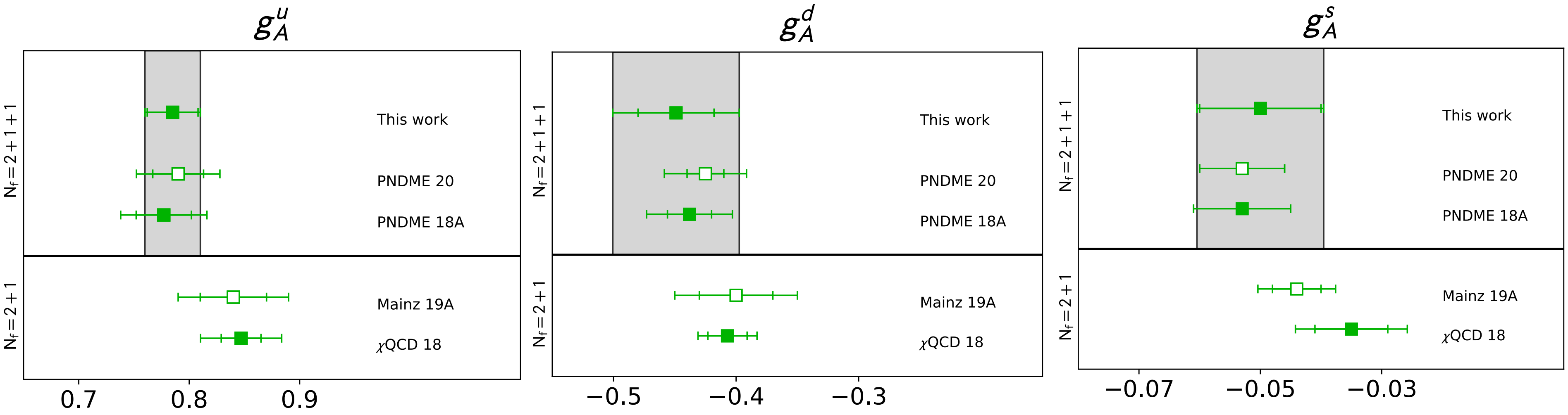
- For next generation low energy search for novel scalar and tensor interactions, the main improvement needed is in neutron decay experiments to get $\boldsymbol{b}$ and $\boldsymbol{B_1}$ to 10^{-4} precision.
- Need g_S^{u-d} and g_T^{u-d} to within a few percent, which is on track
- LHC constraints are currently stronger

Flavor diagonal charges



- All (A,P,S,T,V) done at the same time
- Calculation of disconnected contributions is more costly and noisy

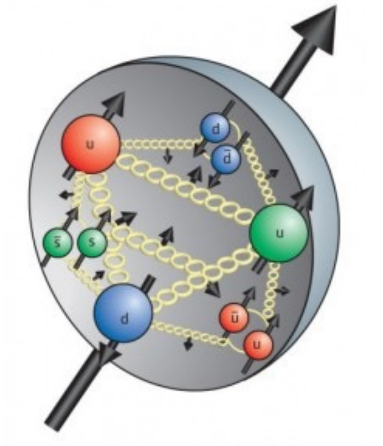
FD axial charges $g_A^{u,d,s,c}$



Issues

- Disconnected contribution is small, ~5%
- Need much higher statistics to reduce uncertainty to ~1%

FD axial charges
Intrinsic quark spin contribution to proton spin



gauge invariant decomposition of the proton spin is given by

$$\frac{1}{2} = \sum_{\{u,d,s,c\}} \left(\frac{1}{2}\Delta q + L_q\right) + J_g$$

$$S_P^q = \sum_q S_q \equiv \sum_q \frac{\Delta q}{2} \equiv 0.5 \sum_q g_A^q \qquad g_A^q = \langle N(p_i)|Z_A A_\mu^q(0)|N(p_i)\rangle$$

[X. Ji, PRL 78 (1997) 610]

LANL (PNDME) result (PRD 98 (2018) 094512):

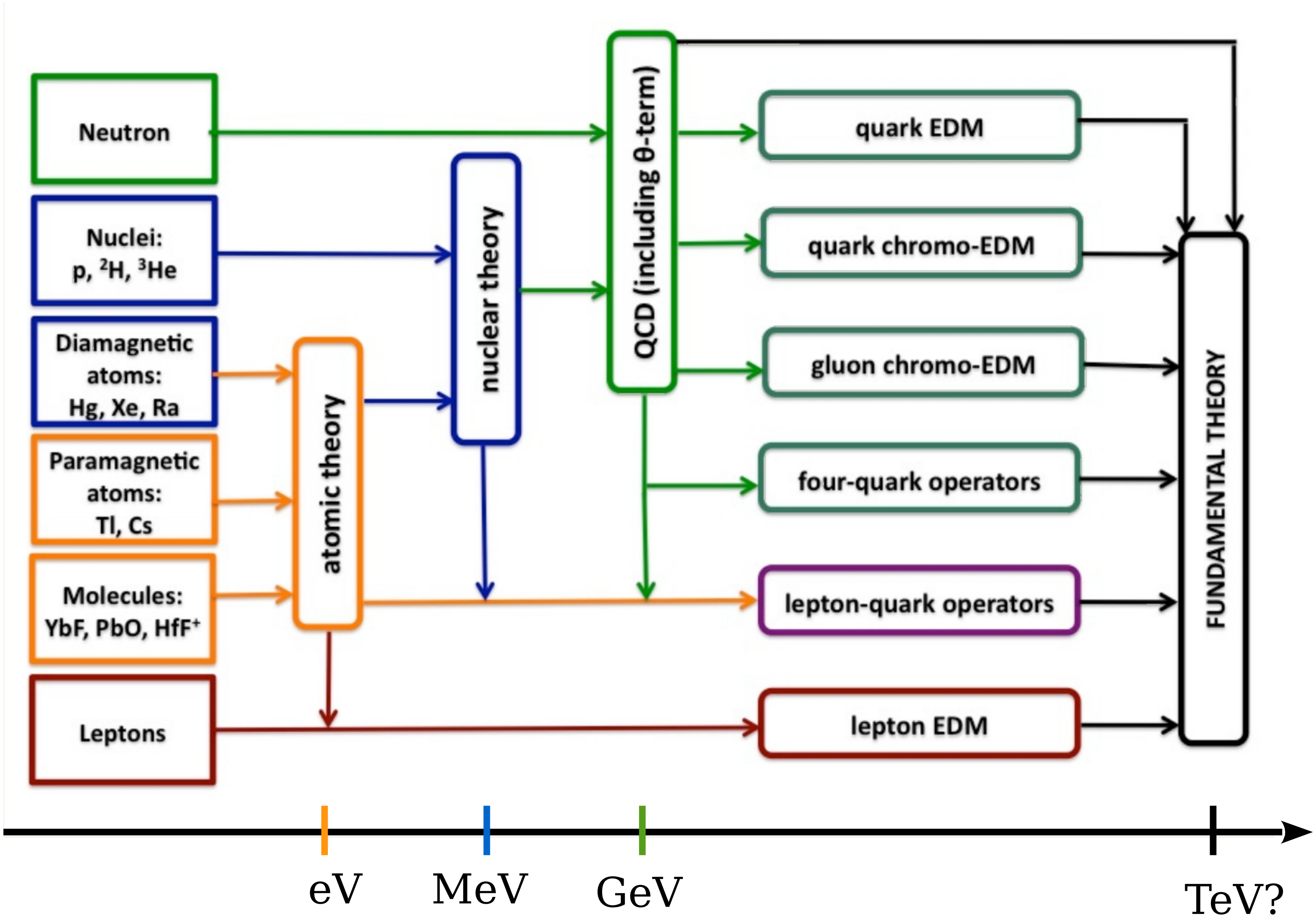
$$0.5 \sum_q g_A^q = (0.777(39) - 0.438(35) - 0.053(8))/2 = 0.143(31)(36)$$

COMPASS result: $0.13 \leq \sum_q S_q \equiv 0.5 \sum_q g_A^q \leq 0.18$

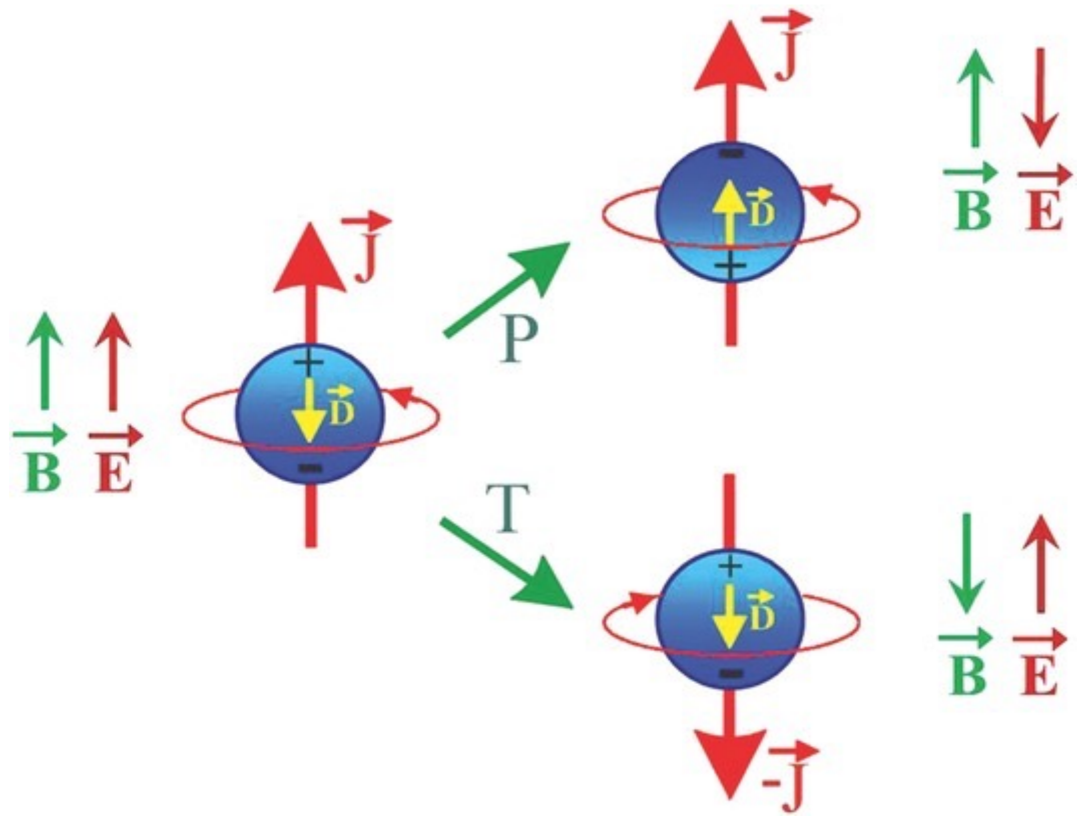
$$\boldsymbol{g_T^{u,d,s,c}}$$

Contribution of the quark EDM to neutron EDM

Novel CP violation in BSM → EDMs



EDMs violate P and T invariance



CP(T)-violation and EDMs

Effective CPV Lagrangian at Hadronic Scale

$$\mathcal{L}_{\rm CPV}^{d\leq 6} = -\frac{g_s^2}{32\pi^2}\overline{\theta} G\tilde{G} \qquad \text{dim=4 QCD } \theta\text{-term}$$

$$-\frac{i}{2}\sum_{q=u,d,s,c} d_q \overline{q}(\sigma\cdot F)\gamma_5 q \qquad \text{dim=5 Quark EDM (qEDM)}$$

$$-\frac{i}{2}\sum_{q=u,d,s,c} \tilde{d}_q g_s \overline{q}(\sigma\cdot G)\gamma_5 q \qquad \text{dim=5 Quark Chromo EDM (CEDM)}$$

$$+ d_w \frac{g_s}{6} G\tilde{G}G \qquad \text{dim=6 Weinberg's 3g operator}$$

$$+\sum_i C_i^{(4q)} O_i^{(4q)} \qquad \text{dim=6 Four-quark operators}$$

- $\overline{\theta} \leq \mathcal{O}(10^{-8} - 10^{-11})$: Strong CP problem
- Dim=5 terms suppressed by $d_q \approx \langle \mathrm{v}\rangle/\Lambda_{BSM}^2$; effectively dim=6
- All terms up to $d = 6$ are leading order

Each CP violating interaction gives a contribution to neutron EDM

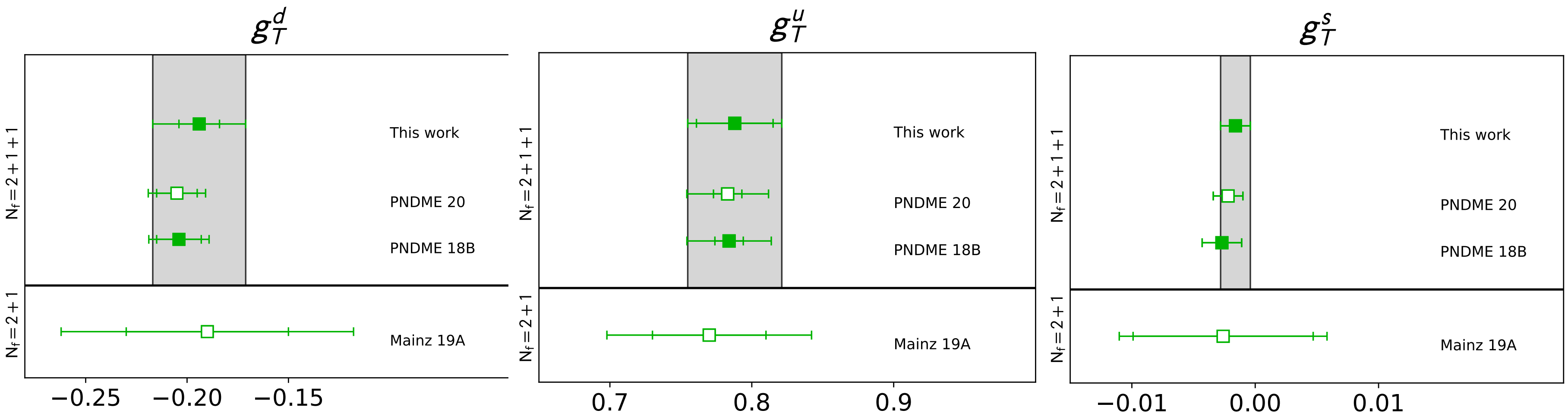
- Θ-term
- Quark EDM → Flavor diagonal tensor charges $g_T^{u,d,s,c}$

$$d_n = \bar{\Theta} \langle N \mid J_{EM} \int d^4x \frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{32\pi^2} |\mathrm{N}\rangle|_{CPV}$$

$$+ d^u g_T^u + d^d g_T^d + d^s g_T^s + d^c g_T^c$$

$$+ \cdots$$

$g_T^{u,d,s,c}$: Contribution of the quark EDM to neutron EDM

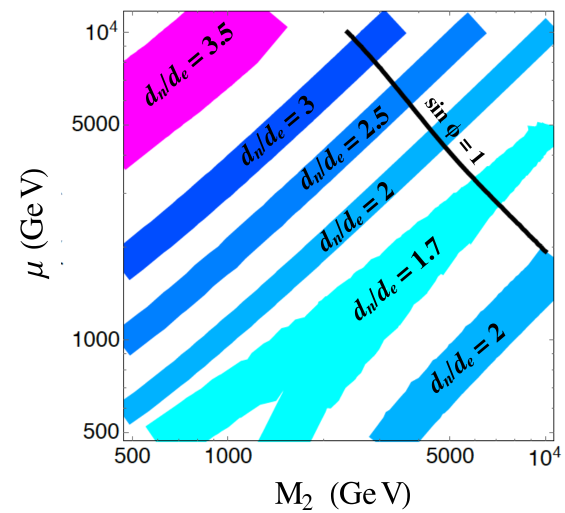


LANL (PNDME) results:

- $g_T^u = 0.784(28)(10)$
- $g_T^d = -0.204(11)(10)$
- $g_T^s = -0.0027(16)$

→

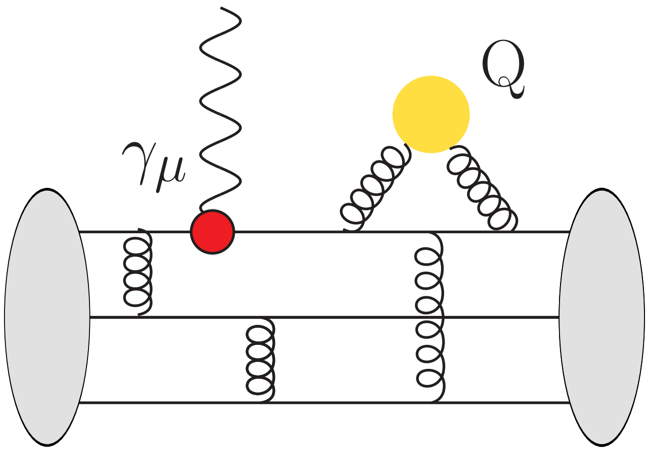
Constrains using nEDM on the parameter space of split SUSY model

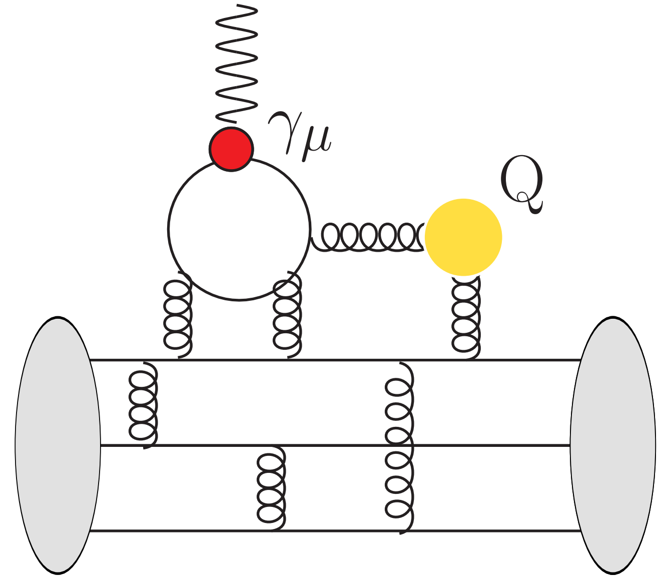


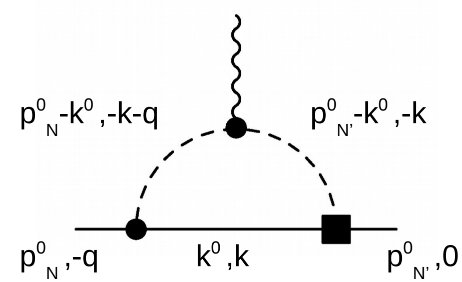
PRD 98 (2018) 091501

$$d_N = d^u g_T^u + d^d g_T^d + d^s g_T^s + d^c g_T^c$$

Θ-term







- Weight Γ^3 with the topological charge
- Remove excited-state contributions
- Expand ME in terms of form factors
- Extract the contribution to the CP violating FF F_3
- Status
  - Large error in the extraction of F_3 (statistics)
  - Resolving and controlling $N\pi$ contributions

Implication for BSM

- Knowing the bound [value] on nucleon EDM d_n and $\boldsymbol{g_T^{u,d,s,c}}$, we can constrain BSM models in which quark EDM is the dominant CP violating operator.

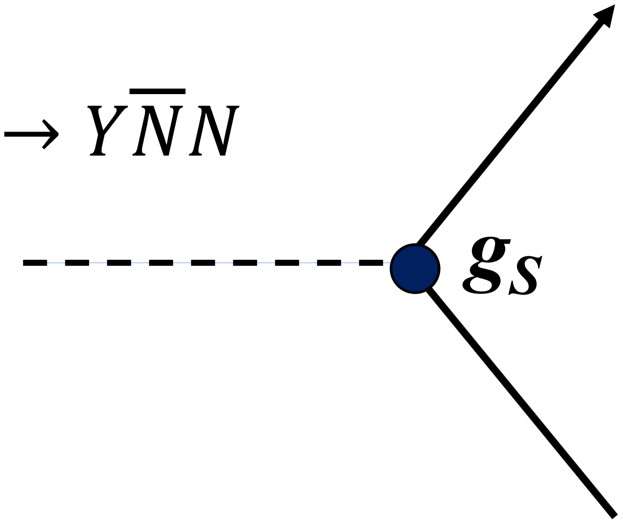
- The coupling $\overline{\Theta}$ is the sum of the SM and BSM. LQCD provides the contribution of the CP violating $G_{\mu\nu}\tilde{G}^{\mu\nu}$ operator to the nucleon EDM.
  - To disentangle sources of $\overline{\Theta}$, need to measure EDMs of many systems

Flavor diagonal scalar charges

$g_S^{u,d,s,c}$

Scalar charges $g_S^{u,d,s,c}$

Effective operator: $X\overline{q}q \rightarrow Y\overline{N}N$



g_S^{u-d}: novel scalar interaction measured in neutron decay

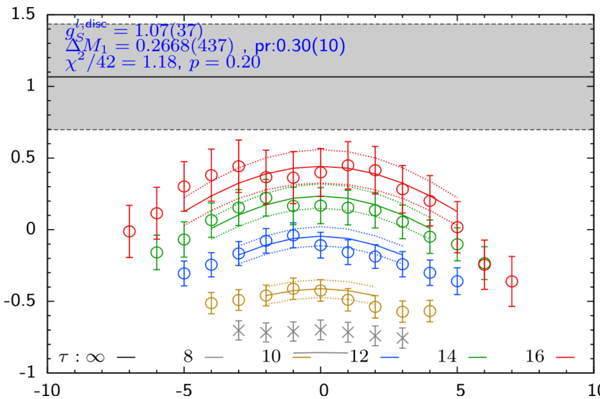
$g_S^{u,d,s,c}$: flavor independent interactions (dark matter)

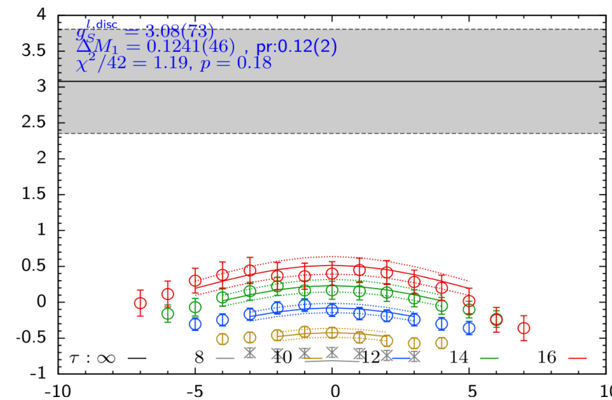
g_S^{u+d} : rate of change of nucleon mass with u,d quark mass

$g_S^{u,d}$: Excited-state effects are large and results very sensitive to $N\pi$ / $N\pi\pi$ states

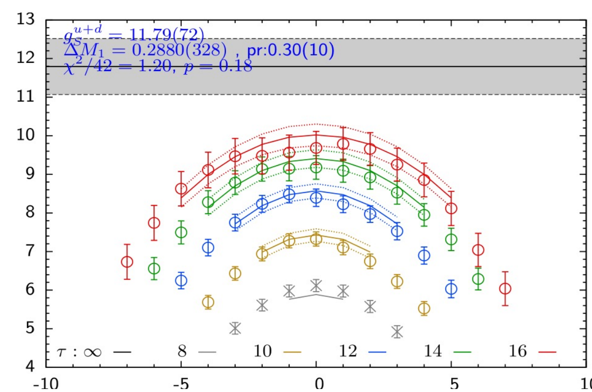
Fits without $N\pi/N\pi\pi$ $(M_1 \approx 1.6\ GeV)$ with $N\pi$ / $N\pi\pi$ $(M_1 \approx 1.2\ GeV)$

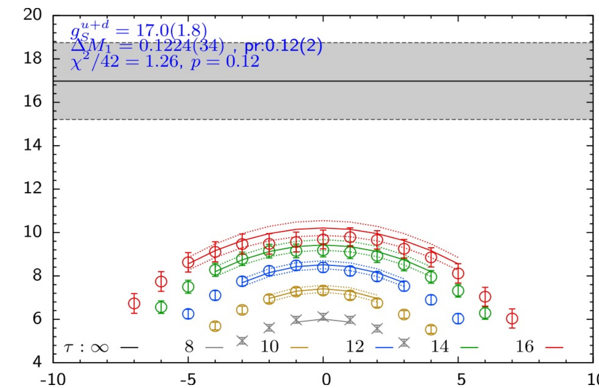
$g_S^{l,\text{disc}}$





$$g_S^{u+d} = g_S^{u+d,conn} + 2g_S^{l,disc}$$



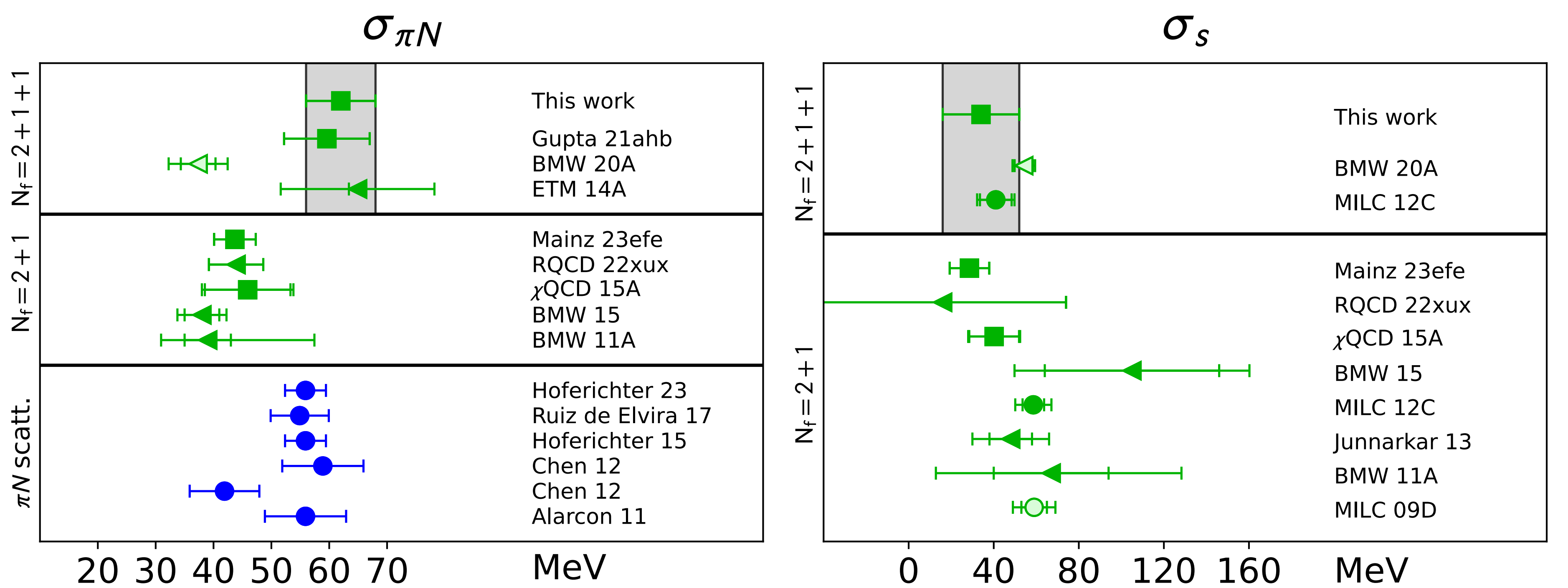


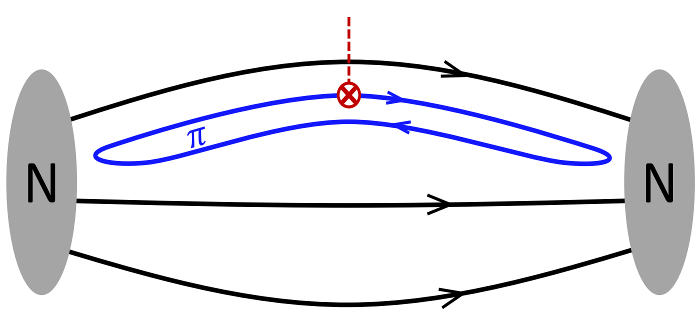
PRL 127 (2021) 242002

$\sigma_{\pi N} = m_l g_S^{u+d} \sim 40$ MeV

$\sigma_{\pi N} = m_l g_S^{u+d} \sim 60$ MeV

Sigma terms





Enhanced contribution

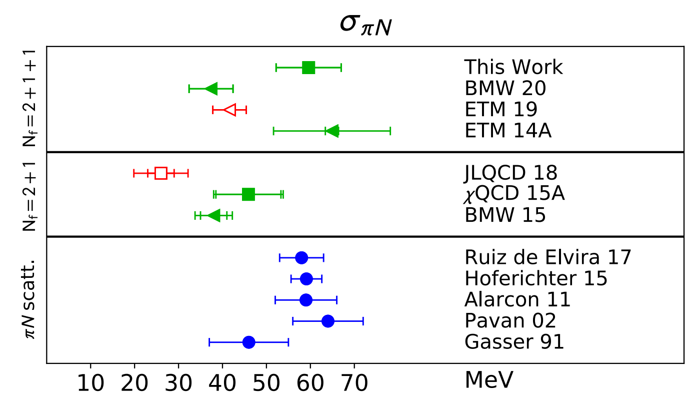
No enhancement expected as KΣ is the lowest state

The pion-nucleon sigma term: Resolving tension between Lattice QCD and Phenomenology

$$\sigma_{\pi N} \equiv m_{ud} g_S^{u+d} \equiv m_{ud} \langle N | \bar{u}u + \bar{d}d | N \rangle$$

FLAG Reports 2019, 2021:

- Lattice results ~40 MeV
- Phenomenology favors ~60 MeV



Post FLAG 2021 results

BMW (arXiv:2007.03319) $\sigma_{\pi N}$ = 37.4(5.1) MeV (FH)

RQCD (JHEP 05 (2023) 035) $\sigma_{\pi N}$ = 43.9(4.7) MeV (FH)

Mainz (PRL 131 (2023) 261902) $\sigma_{\pi N}$ = 43.7(3.6) MeV (FH)

ETM (PRD **102**, 054517) $\sigma_{\pi N}$ = 41.6(3.8) MeV (Direct)

LANL Results: PRL 127 (2021) 242002; e-Print: 2105.12095

- Without including $N(\vec{k})\pi(-\vec{k})$ and $N(0)\pi(\vec{k})\pi(-\vec{k})$ states: = 41.9 (4.9) MeV
- Including $N(\vec{k})\pi(-\vec{k})$ and $N(0)\pi(\vec{k})\pi(-\vec{k})$ states: = 59.6 (7.4) MeV

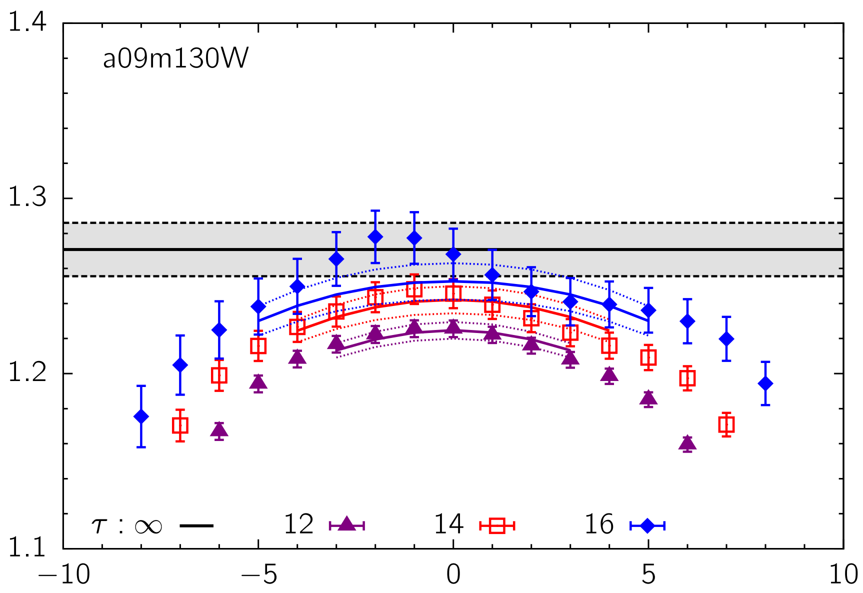
See talk by M. Hoferichter

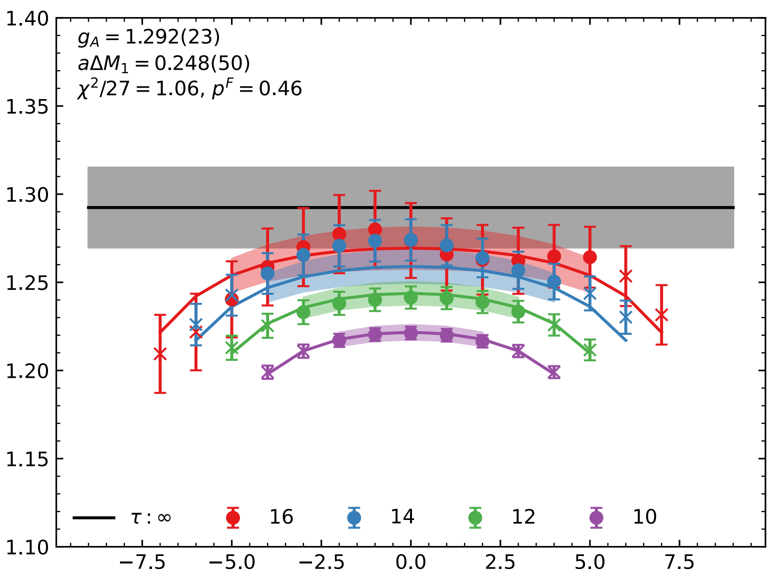
Implication for BSM

- Whether $\sigma_{\pi N} \equiv m_{ud} g_S^{u+d}$ is $\approx$ 40 MeV or 60 MeV comes from whether g_S^{u+d} is 12 or 18
- This factor of 1.5 in coupling translates to 2.25 in cross-section for the favored scalar channel, and thus the reach of the dark matter direct detection experiments
- Enters in the analysis of $\mu \rightarrow e$ conversion
- $\sigma_{\pi N}$ is a fundamental parameter in nuclear physics

Future

- Brute force: increase statistics to get to larger τ
  - Will 5X in statistics yield data-driven fits that resolve excited state contributions?
- Variational basis of interpolating operators including $N\pi$ to get results from smaller τ



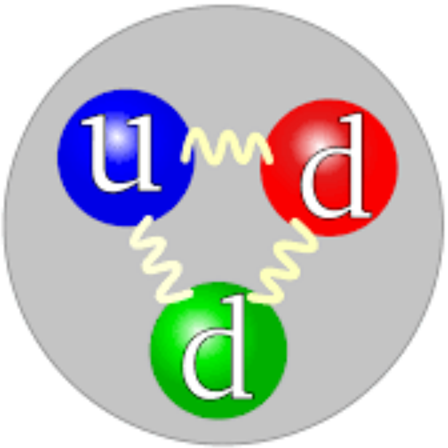


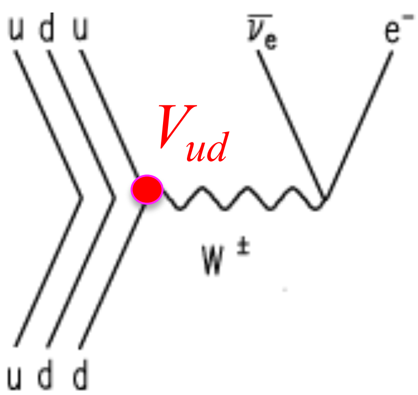
The neutron is a clean but challenging system

Decays weakly ⇒ a stable bound state of QCD

Properties:

- Charges g_A , g_P, g_S , g_T, g_V
- Spin content
  - Quark contribution
  - Gluon contribution
- Contributions to nEDM
- Form factors
  - Electric, Magnetic
  - Axial
- Distribution functions, moments
  - PDF
  - GPD
- Radiative corrections to n-decay → V_{ud}





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  - DOE NERSC through ERDCAP
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