Massachusetts Institute of Technology

Strange Quarks in the Nucleon from Lattice QCD

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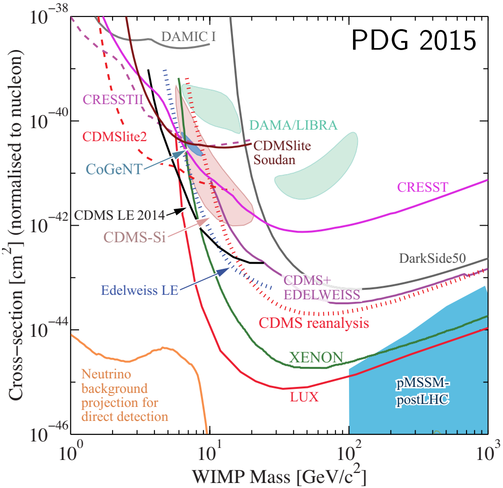
Understanding nucleon strangeness: Dark Matter

Dark Matter direct detection experiments

- Look for scattering of dark matter candidates (e.g., neutralino)



Understanding nucleon strangeness: Dark Matter

Interpret Dark Matter direct detection experiments

- Look for scattering of dark matter candidates (e.g., neutralino)
- Need to know theoretical cross-sections
- Spin-independent scattering amplitude governed by sigma terms:

$$\mathcal{M} \sim \sum_q C_q \langle N | m_q \bar{q} q | N \rangle = \sum_q C_q \sigma_q = \sum_q C_q m_N f_q$$

- Theoretical uncertainty dominated by

Strange sigma term

σ_s

$\Longleftrightarrow$

Contribution of strange quarks to the mass of the proton

Traditional evaluation

$$\boldsymbol{\sigma_{\pi N}} = m_l \langle N | \overline{u}u + \overline{d}d | N \rangle$$

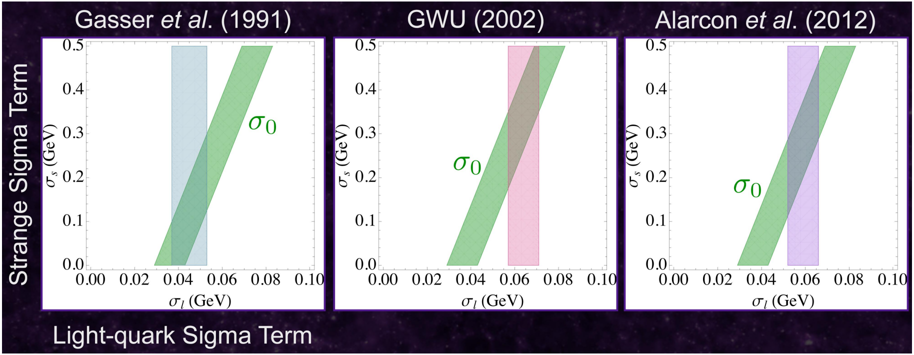
- Experimental: $\sigma_{\pi N}$ determined from πN scattering data
- $\sigma_{\pi N} \sim$ 45-70 MeV
- Controversial (but less so than σ_s)

$\boldsymbol{\sigma_s}$

- Indirect: σ_s evaluated using $\sigma_{\pi N}$ and $\sigma_0 = m_l \langle N | \overline{u}u + \overline{d}d - 2\overline{s}s | N \rangle$
- Determination has limited precision
- Early: $\sigma_s \sim$ 300 MeV
  - up to $\frac{1}{3} M_N$ from non-valence quarks
  - incompatible with constituent quark models

$\boldsymbol{\sigma_s}$ difficult to pin down experimentally

Experiment: σ_s depends on $\sigma_{\pi N}$



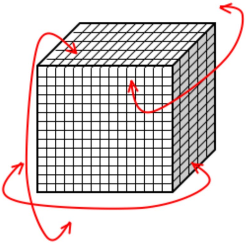
Even if $\sigma_{\pi N}$ perfect

$$\Delta\sigma_s = \frac{m_s}{2m_l}\Delta\sigma_0 \sim 90 \text{ MeV}$$

Figures: Ross Young

Need to reduce uncertainty on σ_s - **lattice QCD**

Numerical first-principles approach



Discretise space-time (4D box)

Lattice spacing a, volume $L^3 \times T$
order $32^3 \times 64 \approx 2 \times 10^6$ lattice sites

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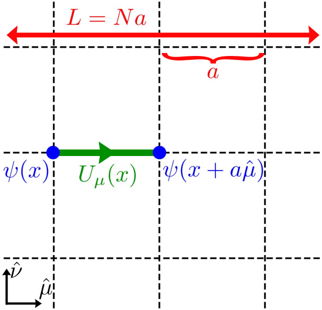


Quark fields reside on sites: $\psi(x)$

Gauge fields on the links: $U_\mu = e^{-iagA_\mu(x)}$

Approximate the QCD path integral by Monte Carlo:

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A\mathcal{D}\overline{\psi}\mathcal{D}\psi \mathcal{O}[A, \overline{\psi}\psi] e^{-S[A,\overline{\psi}\psi]} \longrightarrow \langle \mathcal{O} \rangle \simeq \frac{1}{N_{\mathrm{conf}}} \sum_i^{N_{\mathrm{conf}}} \mathcal{O}([U^i])$$

with field configurations U^i distributed according to $e^{-S[U]}$.

σ_s on the lattice: two methods

Direct:

- Computationally expensive
- Noisy
- First physical-point results beginning to appear

Feynman-Hellmann:

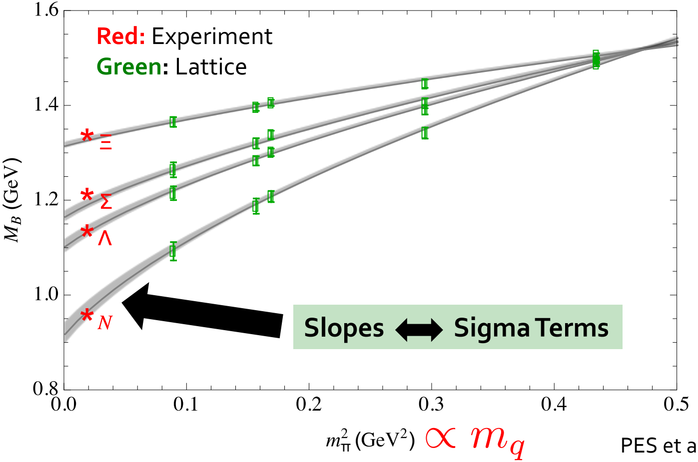
$$\sigma_{Bq} = m_q \frac{\partial M_B}{\partial m_q}$$

Can vary quark masses on the lattice!

- Computationally cheaper
- May have scale-setting ambiguities [arXiv:1301.3231]
- Several physical-point results available

Feynman-Hellmann sigma terms

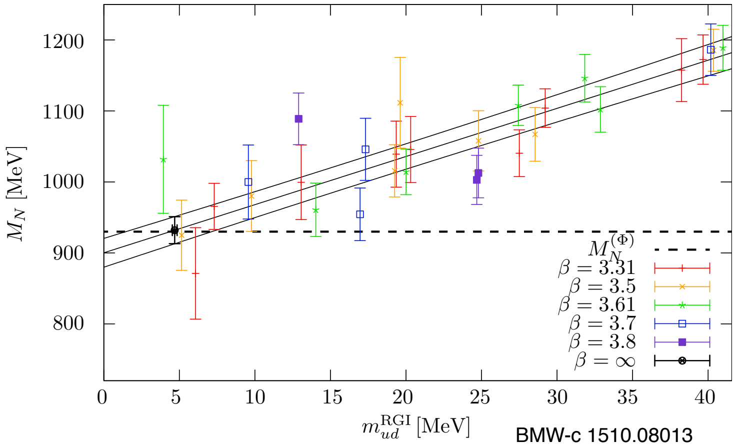
Results with Chiral EFT:



PES et al., PRD87 (2013)

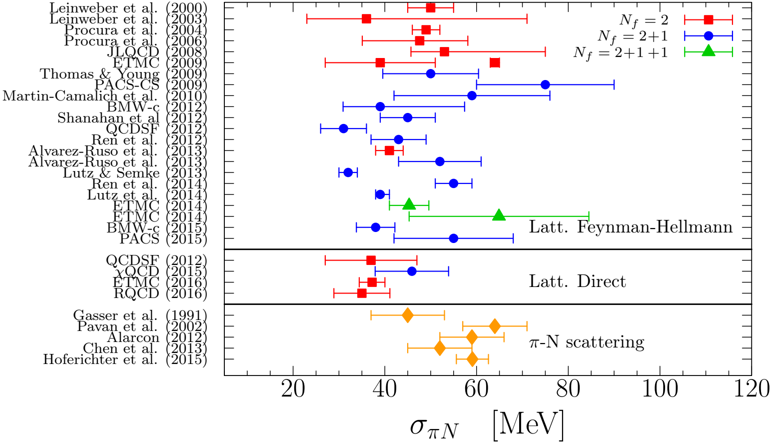
Feynman-Hellmann sigma terms

Most recent results:



BMW-c 1510.08013

Summary of lattice sigma terms

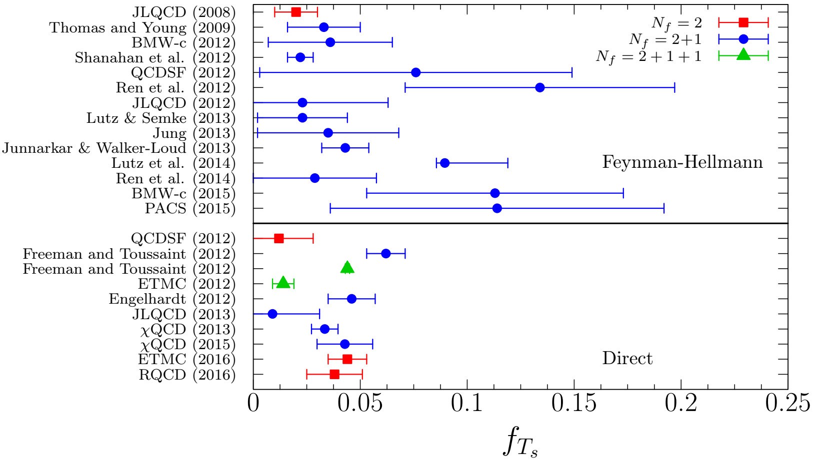


Direct lattice and recent FH values consistent

Values from phenomenological analyses of π-N scattering trend higher

[Hoferichter,1506.04142] $\sigma_{\pi N} = 59.1(3.5)$ MeV

Summary of lattice sigma terms



Precise, small values of $f_{T_s} = \sigma_s/M_N$: $\approx 2\%$ nucleon mass from s quarks

Strange quarks in the proton

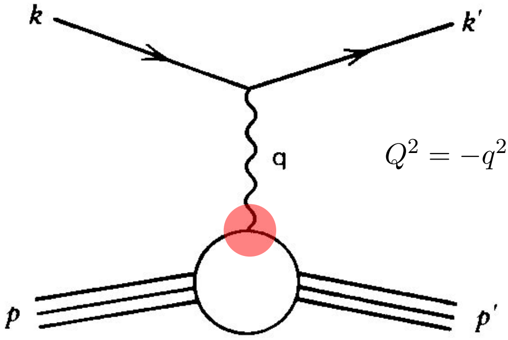
Test for nonperturbative QCD

strange quarks
lightest of the 'sea only' quarks
$\rightarrow$ play the largest role

- **strange sigma terms** - needed for calculation/prediction of dark matter cross sections
- strange contribution to proton spin
- strange PDFs
- **strange electromagnetic form factors**

Electromagnetic form factors

Form factors characterize the extended nature of composite particles



$$Q^2 = -q^2$$

$$\langle P' | J^{\mu}_{\mathrm{EM}} | P \rangle \propto G_E(Q^2), G_M(Q^2)$$

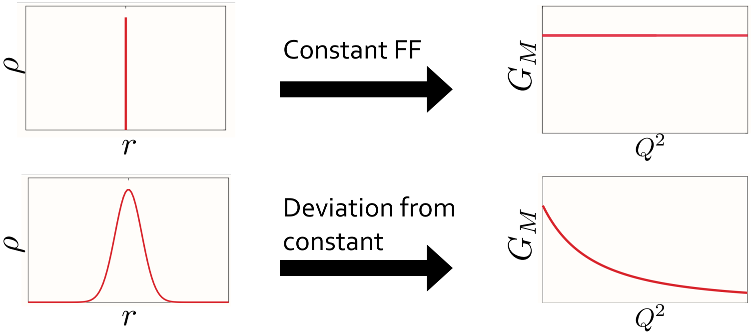
Electromagnetic form factors

Interpretation (non-relativistic) of G_M as the Fourier transform of the magnetisation distribution

$$G_M(Q^2) = \int e^{i\vec{q}\cdot\vec{x}} \rho(r) d^3 r$$

Point-like object

Extended object

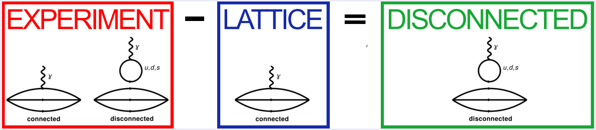


Strange form factors on the lattice: two methods

Direct:

- Computationally expensive
- Noisy
- First physical-point results beginning to appear

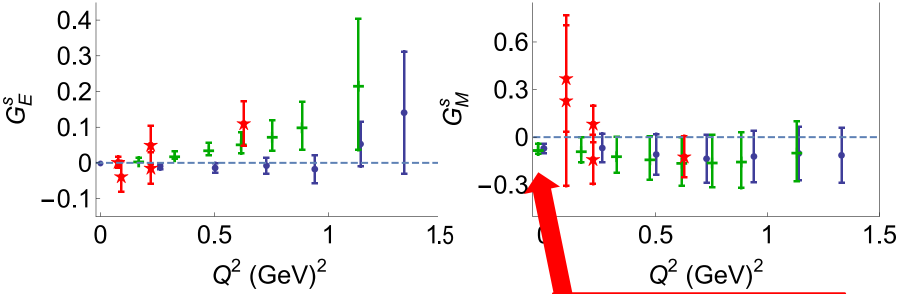
Indirect:



- Computationally cheaper
- Needs careful control of systematics
- Relies on experimental input for total form factors

Strange EM form factors: INDIRECT

Electric **Magnetic**

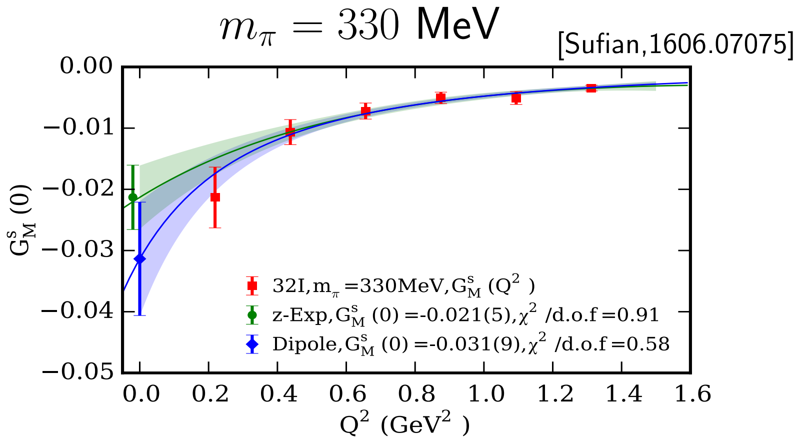


Theory uncertainties leading experiment by an order of magnitude : **PREDICTION**

Red: Experiment, JLAB, MIT-BATES, MAINZ
Blue/Green: Lattice (different lattice sizes/spacings)

PES et al., PRL114 (2015)

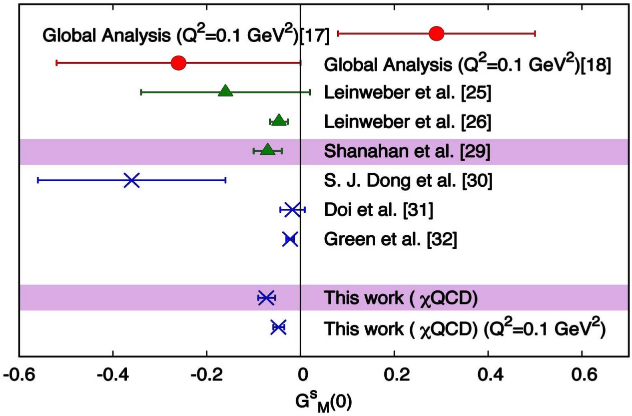
Strange EM form factors: DIRECT



Precise direct results — physical-point results likely soon

Strange magnetic moment

[Sufian,1606.07075]



Red: Analysis of world expt. data

Blue: Direct lattice QCD

Green: Indirect lattice QCD

Bands: physical-point results

Summary

Consistent picture: strange quarks contribute

- $\sim 1\text{-}5\%$ to the mass of the nucleon
  Direct calculations strange sigma term are consistent and precise
  $\rightarrow$ new level of precision for DM searches

Strange sigma term
$\sigma_s = 10 \text{ - } 50 \text{ MeV}$

- $\sim 1\%$ to the nucleon magnetic moment
  $\rightarrow$ new benchmark for experiment

Strange magnetic moment
$G_M^s(Q^2 = 0) = -0.07 \pm 0.03\mu_N$

Experimental determinations of $G^s_{E/M}$

EM and **weak** vector currents give access to different combinations of $G^{p,(u/d/s)}$:

$$G^{p,\gamma} = \frac{2}{3}G^{p,u} - \frac{1}{3}\left(G^{p,d} + G^{p,s}\right)$$
$$G^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G^{p,u} - \left(1 - \frac{4}{3}\sin^2\theta_W\right)\left(G^{p,d} + G^{p,s}\right)$$

Assume **charge symmetry** ($G^{p,u} = G^{n,d}$, $G^{p,d} = G^{n,u}$, $G^{p,s} = G^{n,s}$)

$$G^{p,s}_{E/M} = \left(1 - 4\,\underline{\sin^2\theta_W}\right)\underline{G^{p,\gamma}_{E/M}} - \underline{G^{n,\gamma}_{E/M}} - \underline{G^{p,Z}_{E/M}}$$

well determined

PVES

Parity-violating electron scattering

JLab (*G0, HAPPEX*), MIT-Bates (*SAMPLE*), Mainz (*A4*)