The Strange Proton

Strange quarks in nucleon structure from lattice QCD

THE UNIVERSITY of ADELAIDE

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Massachusetts Institute of Technology

Phiala Shanahan
Massachusetts Institute of Technology

Strangeness in the Nucleon

- Strange nucleon form factors
  - ‘Hidden flavour’ contributions to nucleon observables
  - Test for nonperturbative QCD

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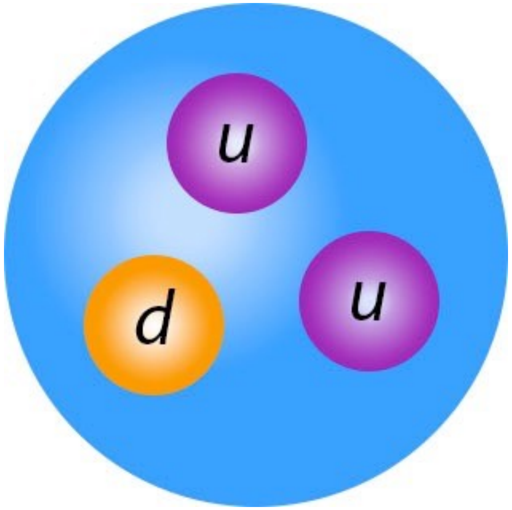

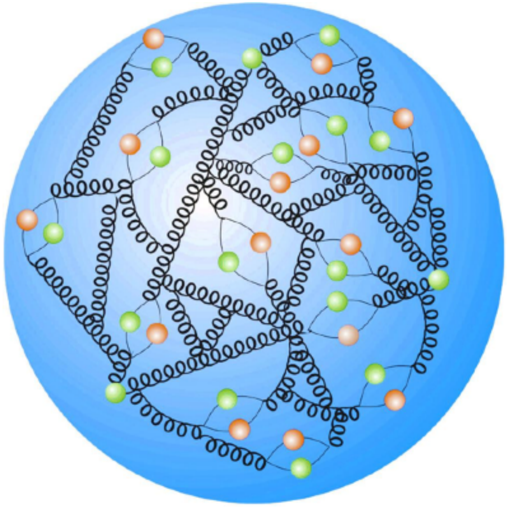

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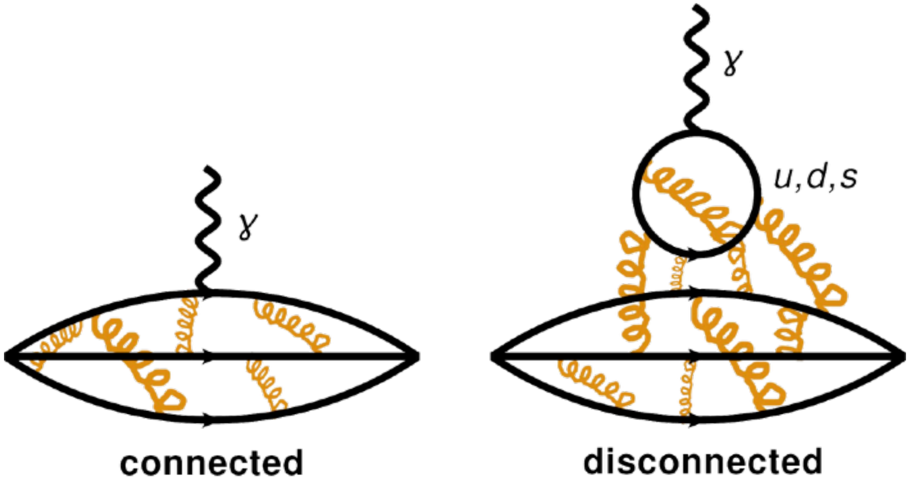
Generated entirely by interactions with the vacuum



Strangeness in the Nucleon

- **Strange nucleon form factors**
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Generated entirely by interactions with the vacuum

Strange quarks
Lightest of the 'sea only' quarks
→ play the largest role

1. **Strange quark electromagnetic form factors**
2. **Strange sigma terms** - relevant to dark matter direct detection experiments

Strangeness in the Nucleon

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Experimental measurements limited by lack of **theory** knowledge of

- **Charge symmetry violating (CSV) form factors**

Strangeness in the Nucleon

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Approach **both** problems through lattice QCD simulations of

- **Nucleon and hyperon EM form factors**

Quantum Chromodynamics

- Interaction strength depends on energy [Gross, Politzer, Wilczek, Nobel 2004]

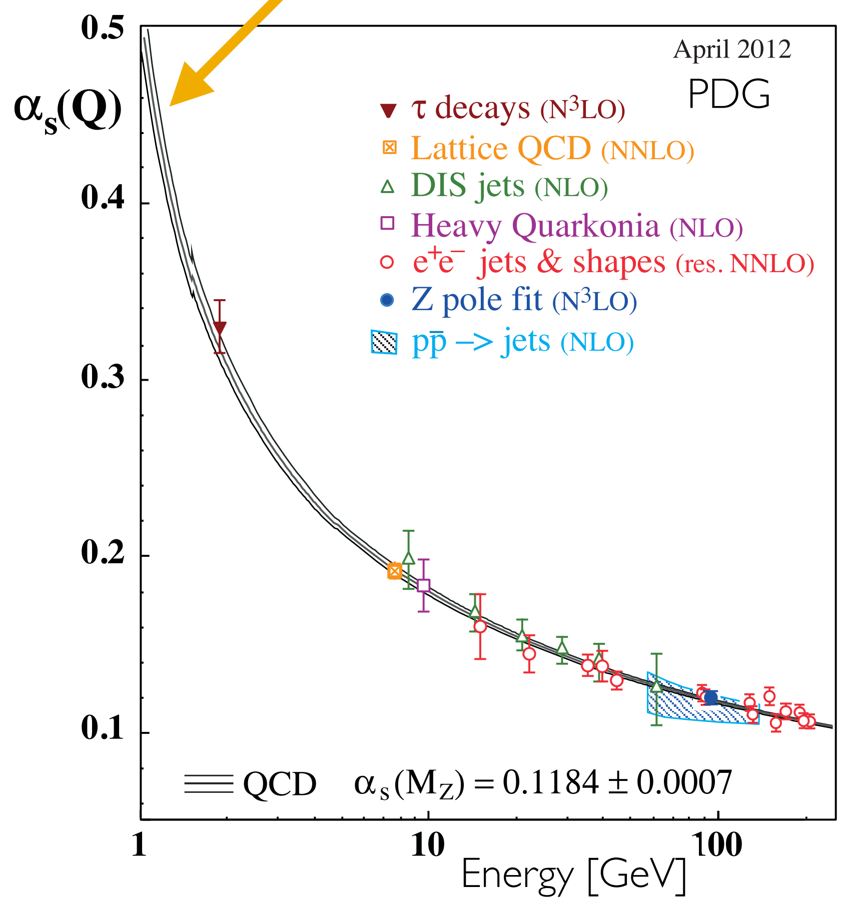
- High energies: can use perturbation theory

$$\mathcal{O}_{\text{exact}} = \mathcal{O}_0 + \mathcal{O}_1\alpha_s + \mathcal{O}_2\alpha_s^2 + \ldots$$

works for QED

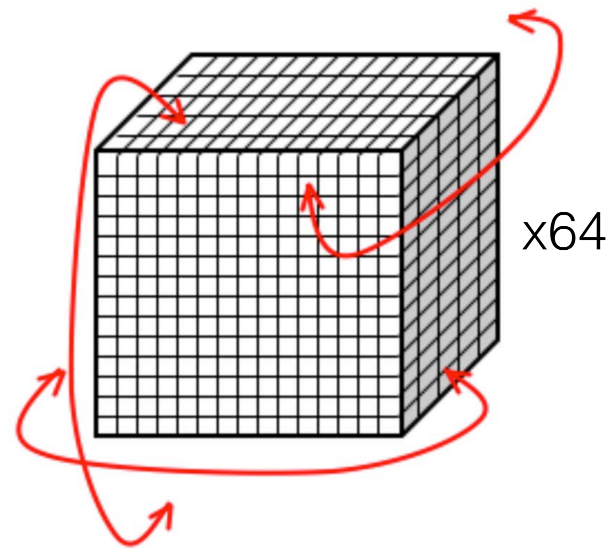
- **Low energies: need an approach that does not require α_s<<1**

Large coupling at low energy



Lattice QCD

- Numerical first-principles approach
- Euclidean space-time $t \to i\tau$
  - Finite lattice spacing a
  - Volume $L^3 \times T \approx 32^3 \times 64$
  - Boundary conditions
- Finite but large number of d.o.f (10[12])



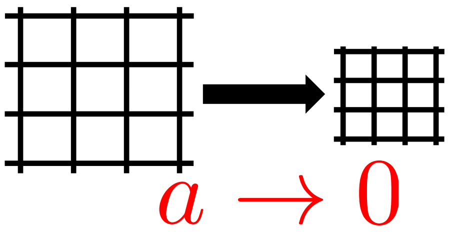
Approximate the QCD path integral by **Monte Carlo**

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

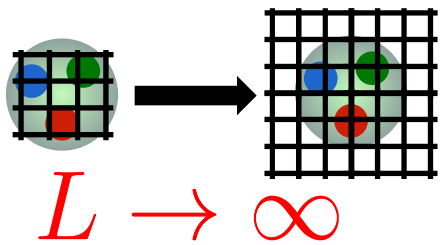
with field configurations U^i distributed according to $e^{-S[U]}$

Lattice QCD Systematics

- **Finite lattice spacing** a
  - Discretisation artifacts
  - Continuum extrapolation



- **Finite box size** L
  - Momentum quantised, finite-volume effects
  - Finite-volume corrections



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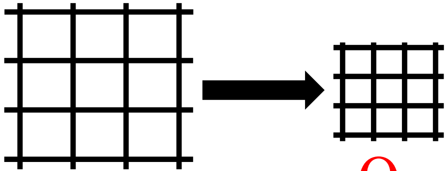
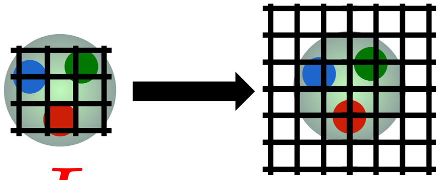


$a \to 0$

- **Finite box size** L

  Momentum quantised, finite-volume effects

  Finite-volume corrections



$L \to \infty$

- **Large pion mass** m_π

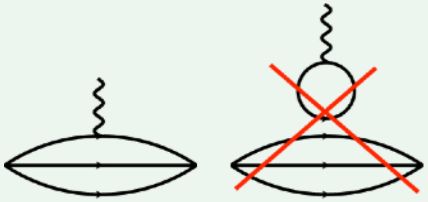
  $m_\pi \to 140\text{MeV}$

  Chiral extrapolation

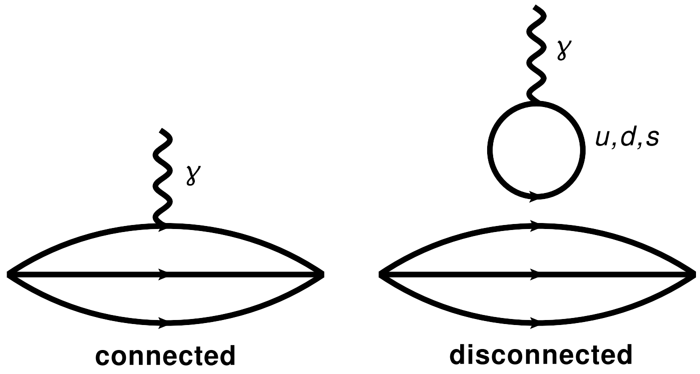
  BUT: Can map out pion mass dependence of observables

- **Omitted disconnected loops**

  BUT: can separate 'connected' and 'disconnected' contributions

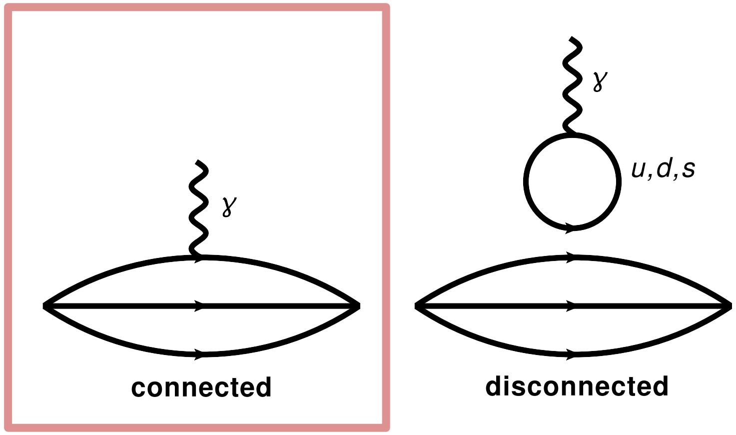


Strange Proton Observables



Strange Proton Observables

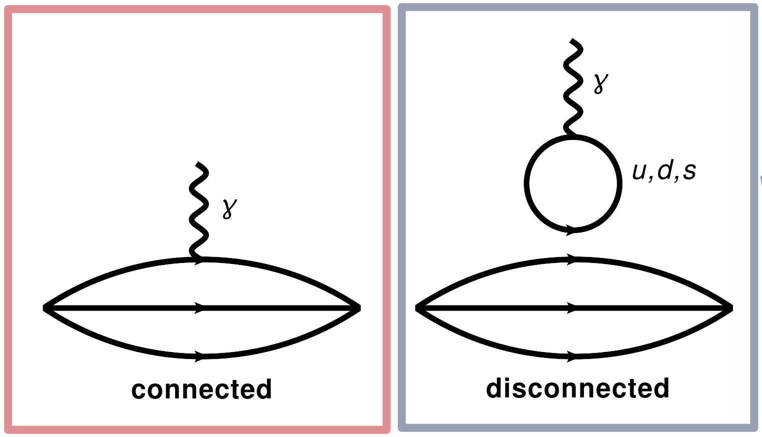
Good control over lattice systematics



Strange Proton Observables

Direct Calculation of Strange Proton Observables is Expensive

Good control over lattice systematics



Naively, factor of the lattice volume (~millions) more expensive

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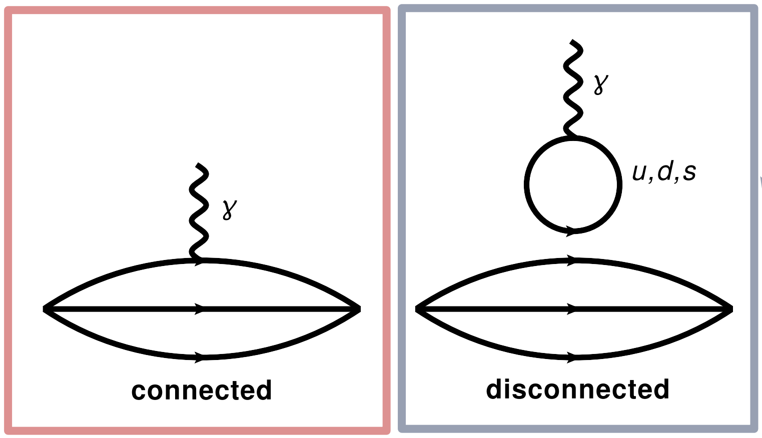


Naively, factor of the lattice volume (~millions) more expensive

A place for indirect lattice methods

Indirect Lattice Methods

A place for indirect approaches

PRECISION lattice results
in unphysical parameter space

+

Clever ways to deal with
systematic effects

→

Physical results

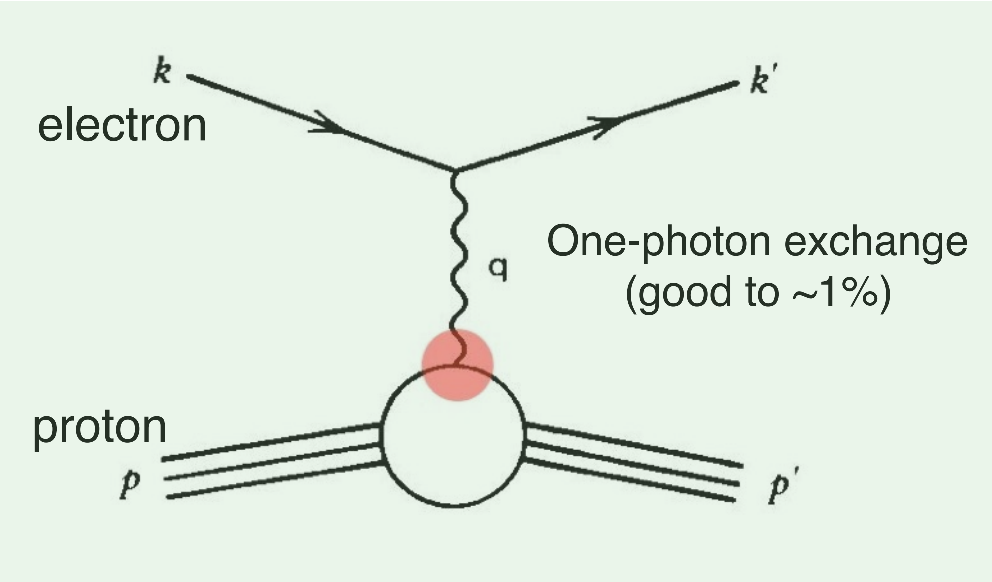
↕

Experiment

Strange Electromagnetic Form Factors

Electromagnetic Form Factors

Form factors characterise the extended nature of composite particles



N current matrix element $\boxed{G_E(Q^2),\, G_M(Q^2)}$

Form factors

Electromagnetic Form Factors

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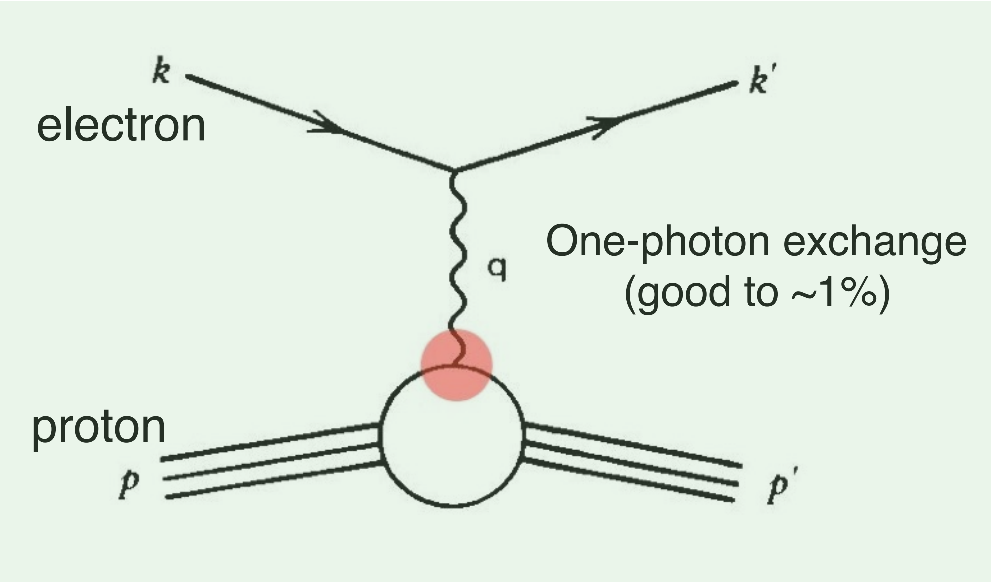


Static limit:
charge and magnetic moment

$$G_E(Q^2=0)=Q_e$$
$$G_M(Q^2=0)=\mu$$

N current matrix element $\boxed{G_E(Q^2),\, G_M(Q^2)}$

Form factors

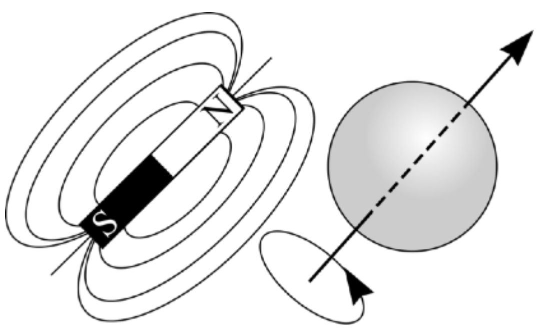
Strange Magnetic Moment

Strange Magnetic Moment

Magnetic moment quantifies how much torque a proton experiences in a magnetic field

Predictions of theory calculations vary widely!

- Magnitude?
- Sign?



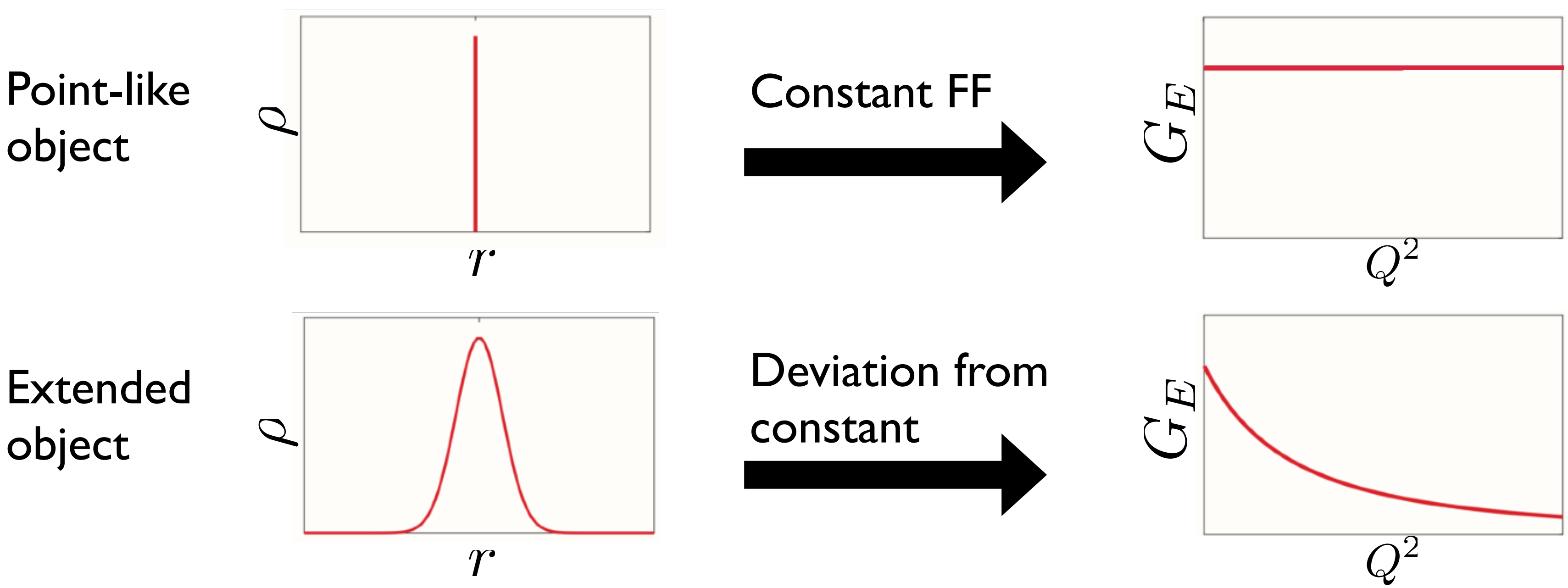
Type of calculation	μ_s (n.m.)
Poles	-0.31 ± 0.09
Kaon loops	$-0.31 \rightarrow -0.40$
Kaon loops	-0.026
Kaon loops	$\lvert\mu_s\rvert = 0.8$
$SU(3)$ Skyrme (broken)	-0.13
$SU(3)$ Skyrme (symmetric)	-0.33
$SU(3)$ chiral hyperbag	$+0.42$
$SU(3)$ chiral color dielectric	$-0.20 \rightarrow -0.026$
$SU(3)$ chiral soliton	-0.45
Poles	-0.24 ± 0.03
Kaon loops	$-0.125 \rightarrow -0.146$
NJL soliton	$-0.05 \rightarrow +0.25$
QCD equalities	-0.75 ± 0.30
Loops	$+0.035$
Dispersion	$-0.10 \rightarrow -0.14$
Chiral models	$-0.25, -0.09$
Poles	0.003
$SU(3)$ Skyrme (broken)	$+0.36$

Beck, McKeown Ann. Rev. Nucl. Part. Sci. 2001

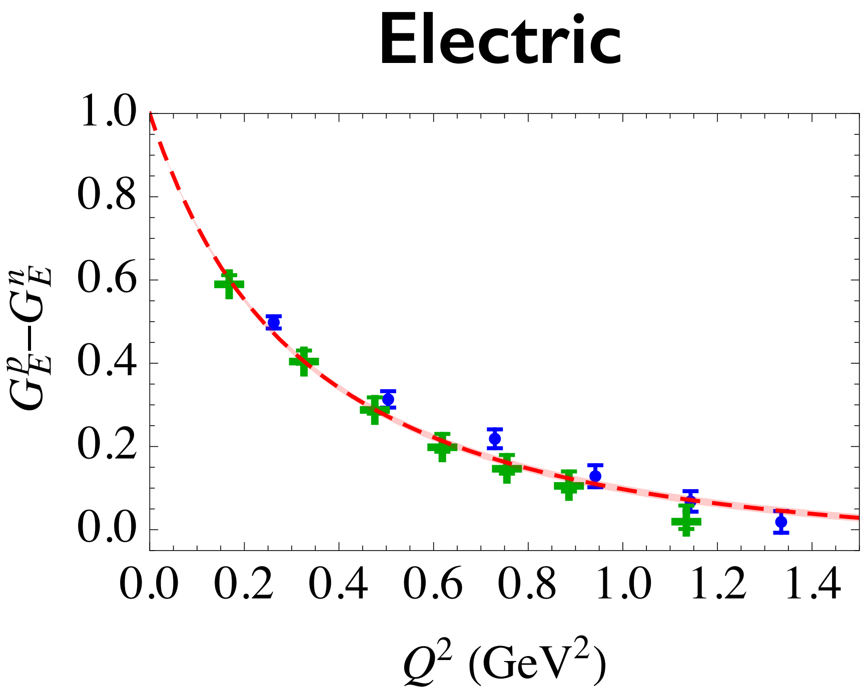
Electromagnetic Form Factors

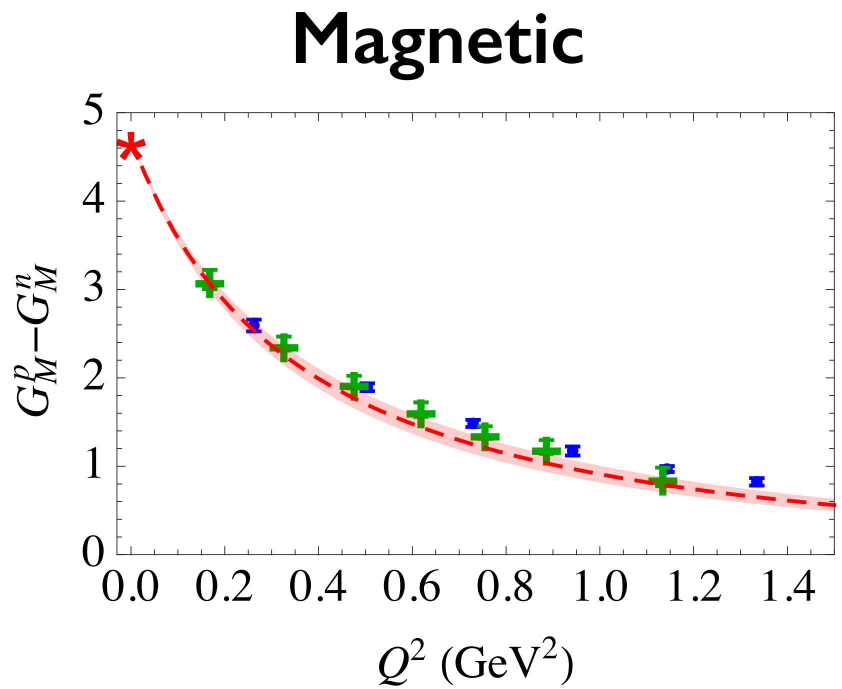
Interpretation (non-relativistic) of G_E as the Fourier transform of the charge distribution

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



Electromagnetic Form Factors





Red: Parameterization of experimental results

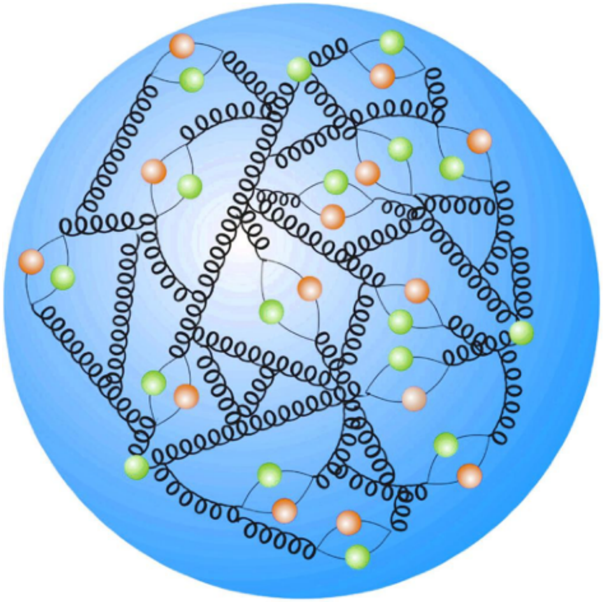
Blue/Green: Numerical simulations of QCD (different lattice sizes/spacings)

PES et al., PRD89 PRD90 (2014)

Strange EM Form Factors

Recall: **Hidden flavor**

- Fundamental challenge for hadronic physics
- Contributions entirely through interactions with QCD vacuum



Strange EM Form Factors

Recall: **Hidden flavor**

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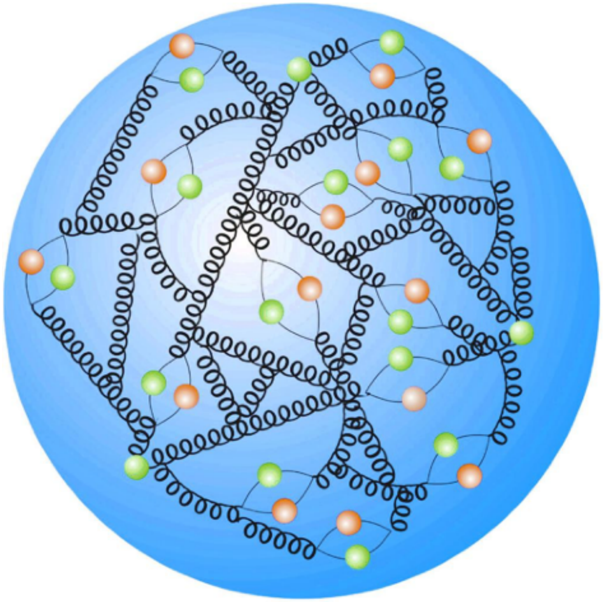
Extensive **experimental** efforts

- JLAB (G0, HAPPEX)
- MIT-Bates (SAMPLE)
- Mainz (A4)



Compare to theory: Lattice QCD

Strange EM Form Factors

Direct lattice calculations:
Expensive, Large systematics

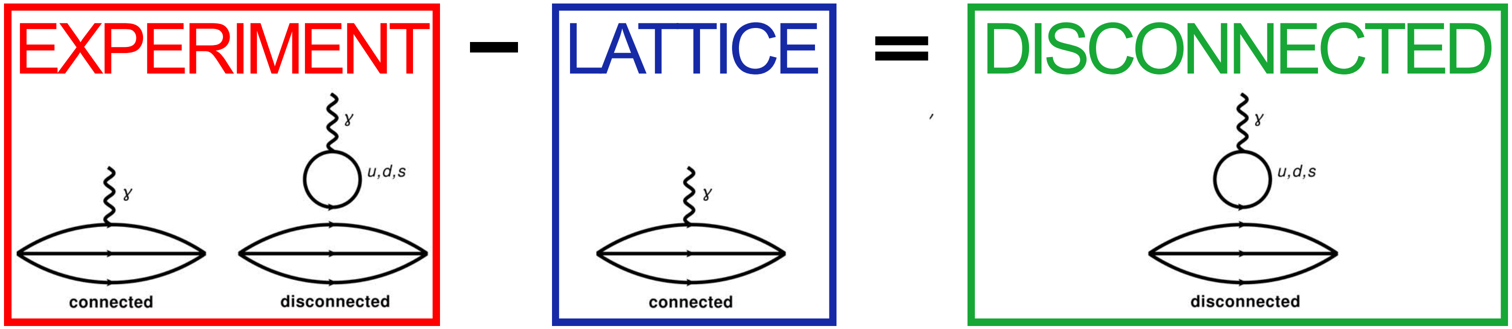
→

INDIRECT
APPROACH

Strange EM Form Factors

Direct lattice calculations:
Expensive, Large systematics

→ INDIRECT APPROACH

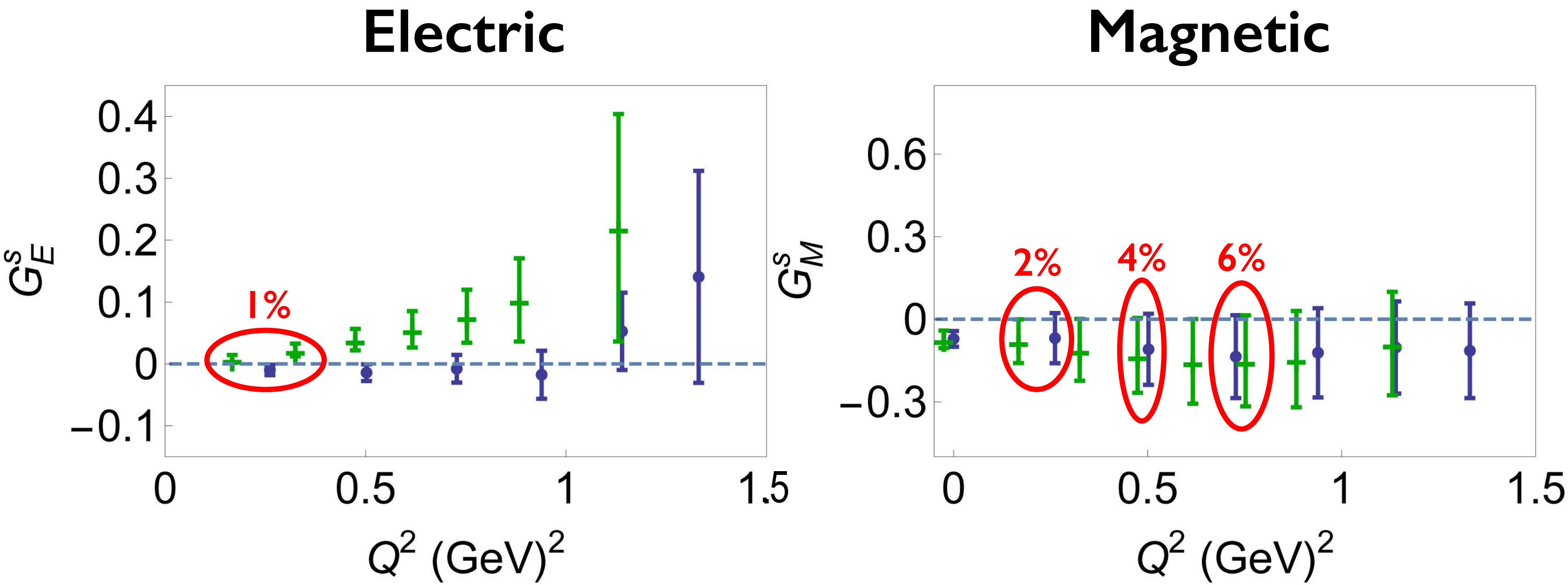


Take advantage of precise results for connected diagrams on the lattice!

ONLY WORKS IF SYSTEMATICS ARE UNDER CONTROL

Simple idea but many technical challenges!

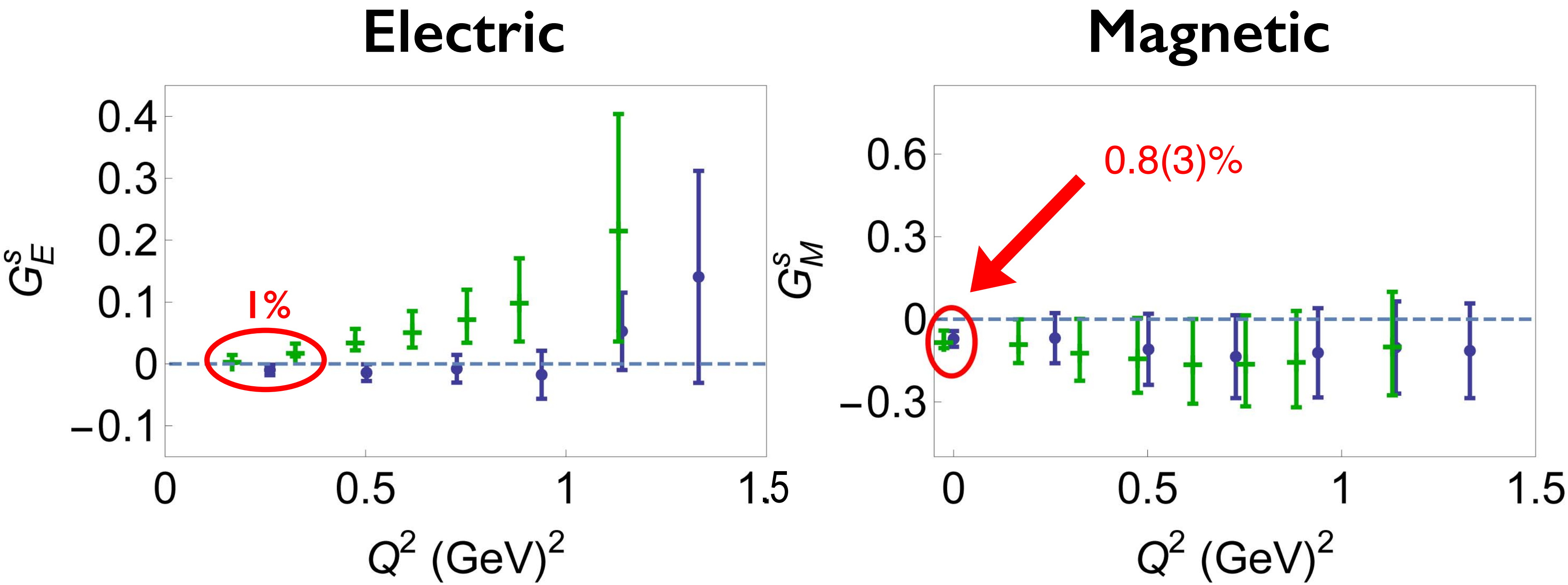
Strange EM Form Factors



Red: Parity-violating electron scattering experiments, JLAB, MIT-BATES, MAINZ
Blue/Green: Lattice (different lattice sizes/spacings)

PES et al., PRL114 (2015)

Strange EM Form Factors



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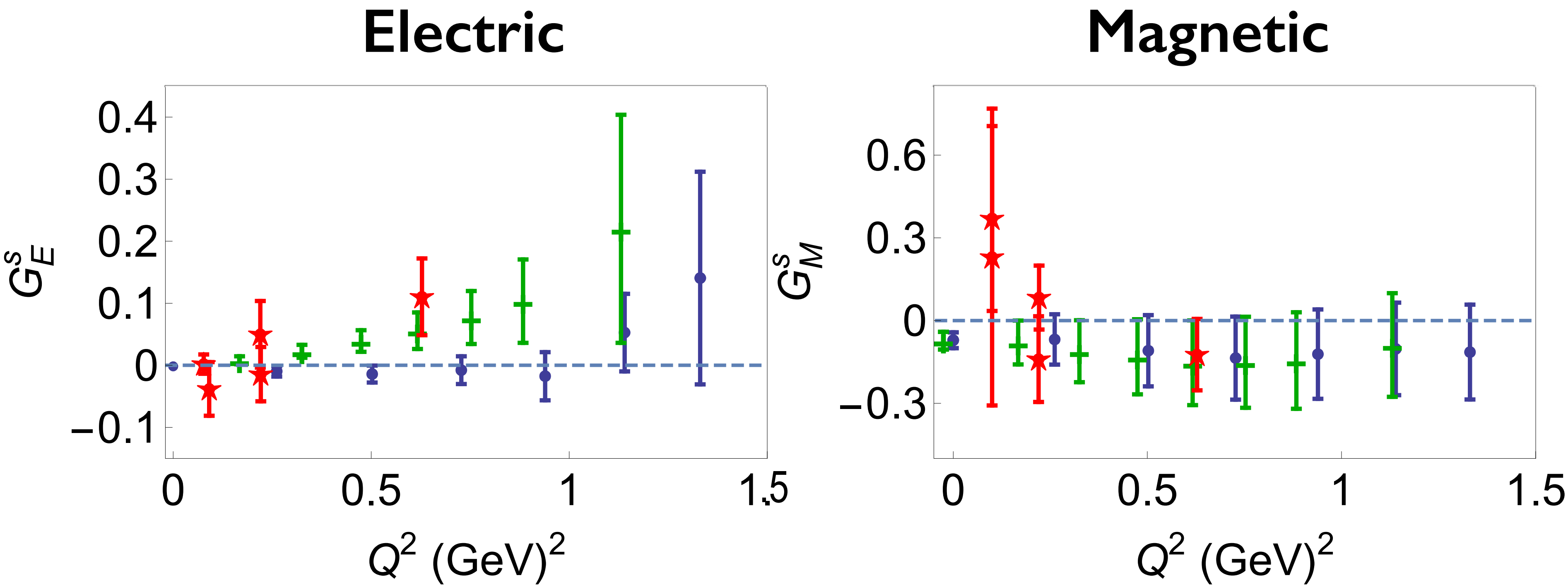

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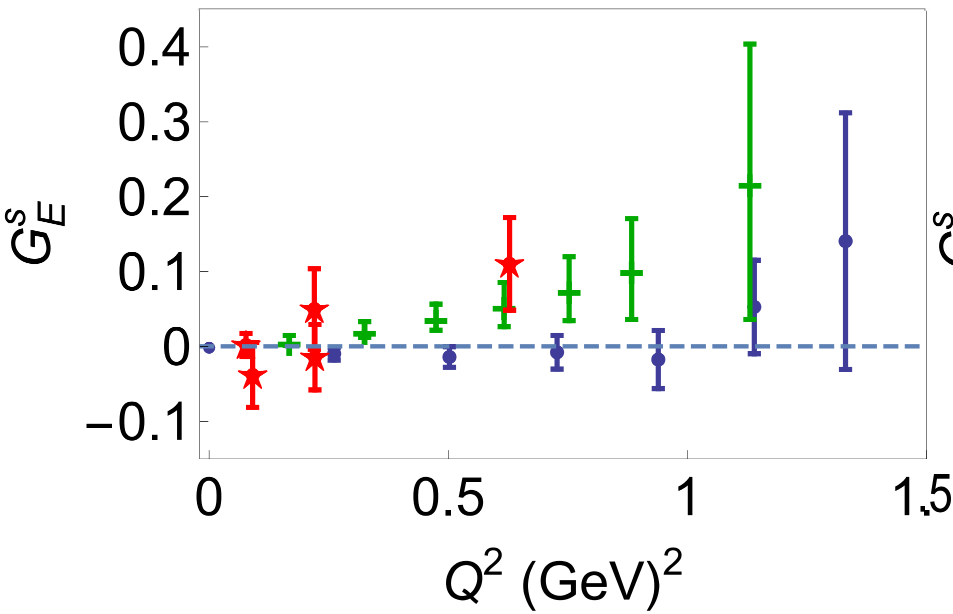
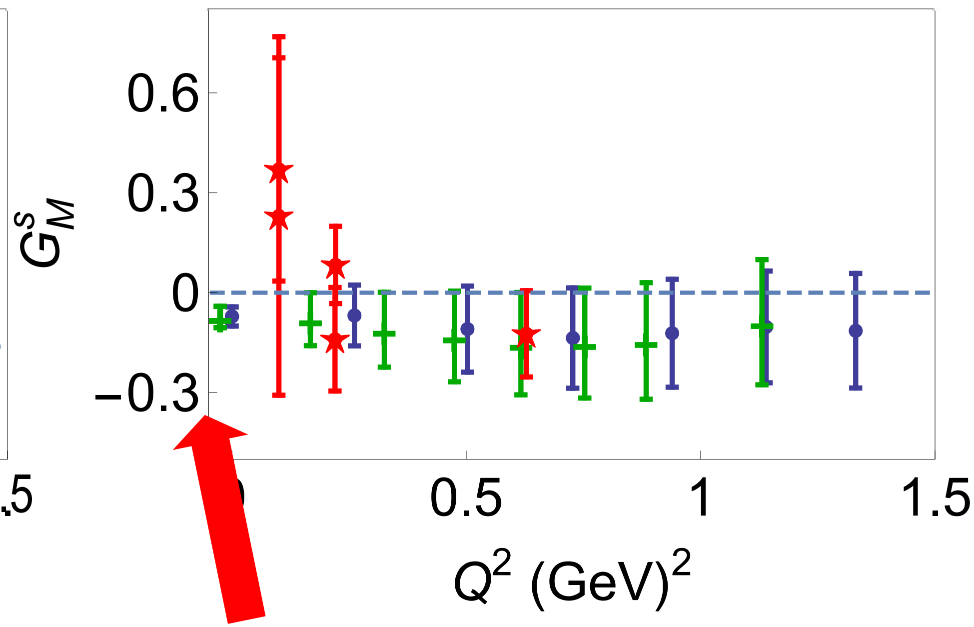
PES et al., PRL114 (2015)

Strange EM Form Factors

Electric



Magnetic



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

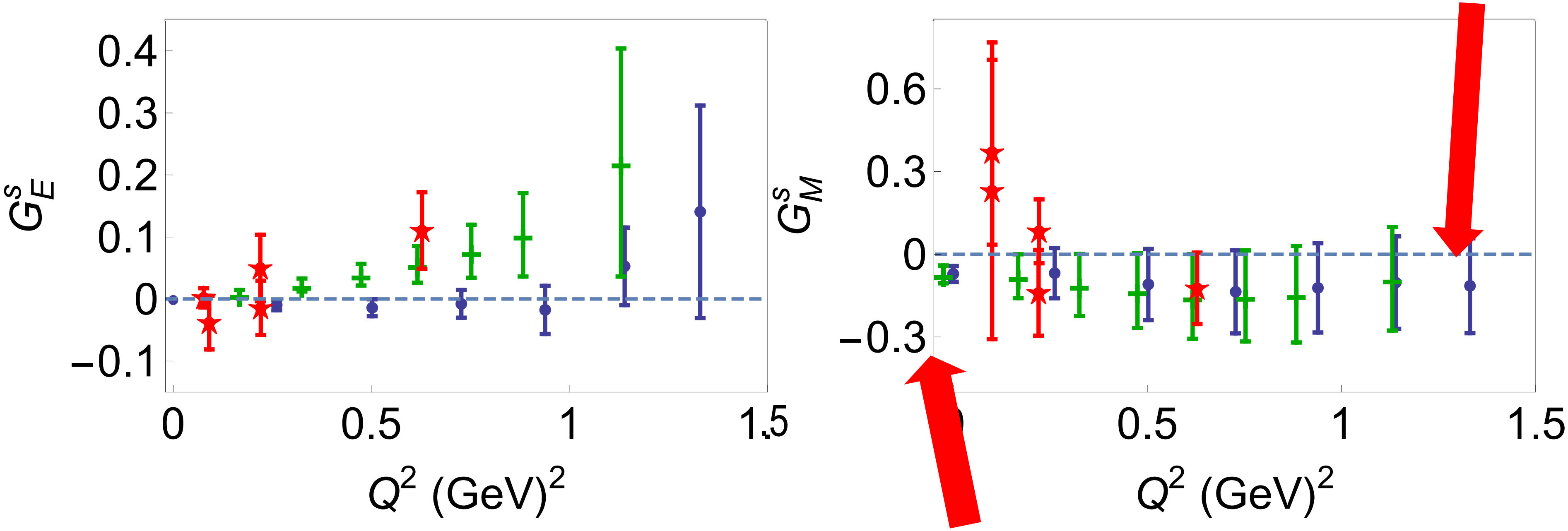
Red: Experiment, JLAB, MIT-BATES, MAINZ
Blue/Green: Lattice (different lattice sizes/spacings)

PES et al., PRL114 (2015)

Strange EM Form Factors

First determination (theory or expt.) at these momenta

Electric **Magn**



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Strange EM Form Factors

Experimental determinations of G^s:

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

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

$$G^s_{E/M} = \left(1 - 4\sin^2\theta_W\right)G^{p,\gamma}_{E/M} - G^{n,\gamma}_{E/M} - G^{p,Z}_{E/M} + G_{\rm CSV}$$

well determined PVES ???

Parity-violating electron scattering

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

Models and/or lattice QCD

Charge Symmetry Violation

Breaking of symmetry between
u quark in proton and *d* quark in neutron

$$G_{\text{CSV}} = \frac{2}{3}(G_{E/M}^{p,u} - G_{E/M}^{n,d}) - \frac{1}{3}(G_{E/M}^{p,d} - G_{E/M}^{n,u})$$

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CSV indirectly from the lattice

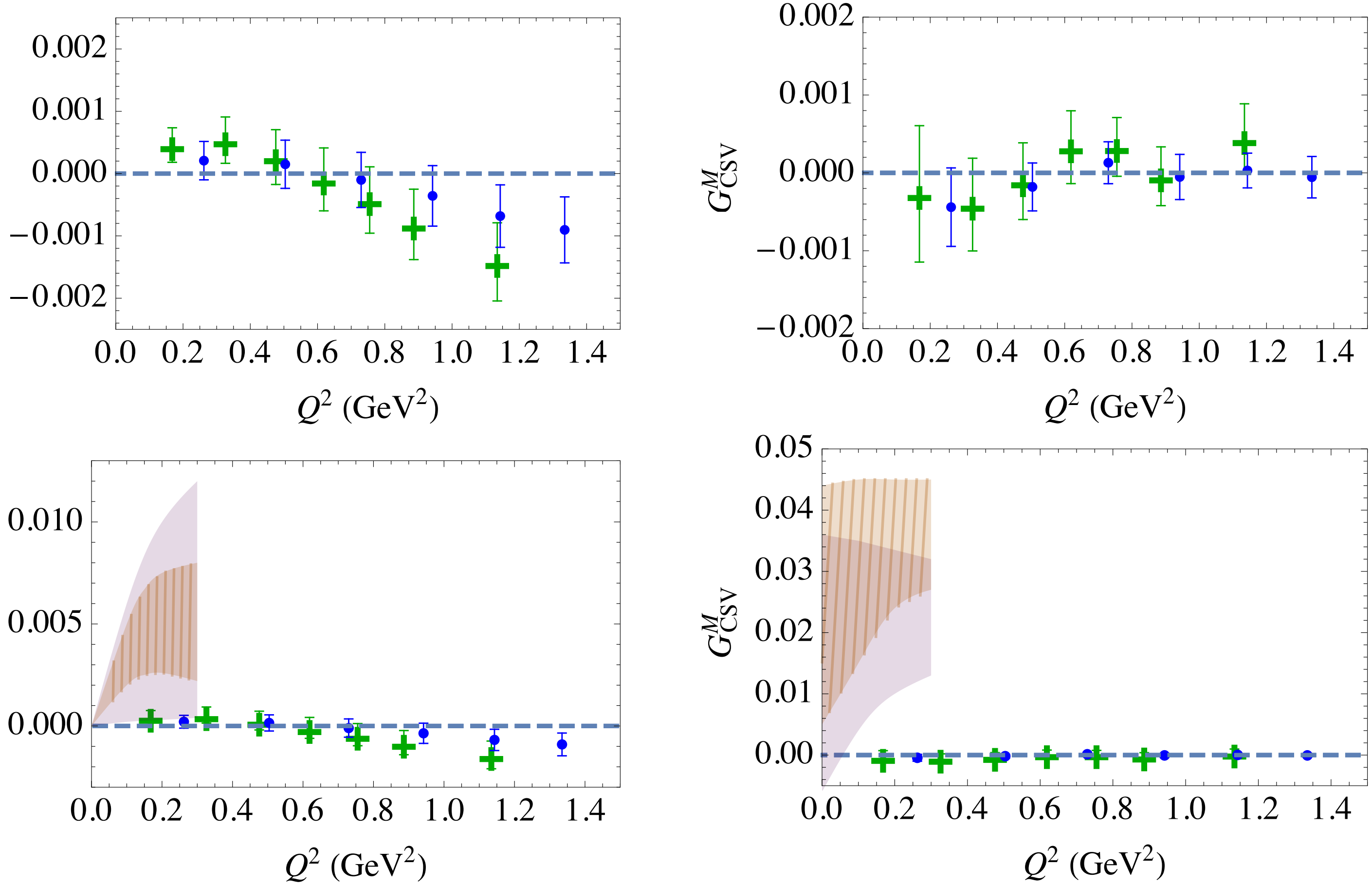
- lattice simulations have $m_u = m_d$

Chiral perturbation theory expressions for $m_u \neq m_d$
have the **same free parameters** as isospin-averaged case

- Determine free parameters from isospin-averaged fits
- Input m_u/m_d from experiment or lattice

Charge Symmetry Violation

Electric | **Magnetic**



Kubis & Lewis, PRC (2006), Wagman & Miller, PRC (2014)

Charge Symmetry Violation

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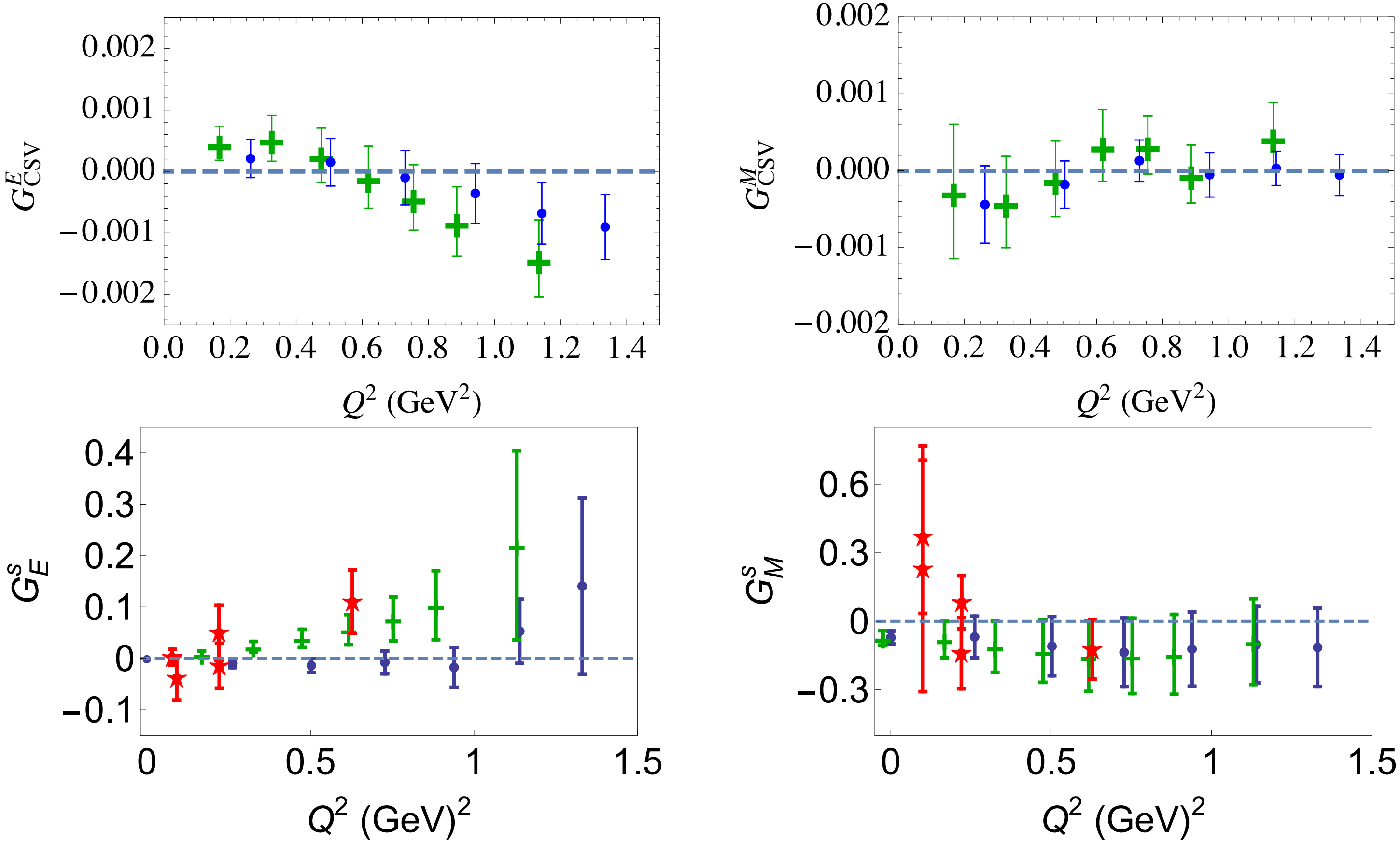


Red stars: G0, SAMPLE, HAPPEX, A4

Green/**Blue** points: Lattice QCD (PES *et al.* PRL (2015))

Charge Symmetry Violation

CSV in the nucleon EMFFs < 1%

i.e., order of magnitude smaller than the precision of existing PVES studies measuring the strange nucleon form factors

HAPPEX $(Q^2 = 0.109\text{GeV}^2)$ [PRL 98 (2007)]

	$G_E^s + 0.09 G_M^s$
Experimental	0.007(14)
Previous CSV uncertainty (theory):	0.009
New CSV uncertainty (this work):	0.0009

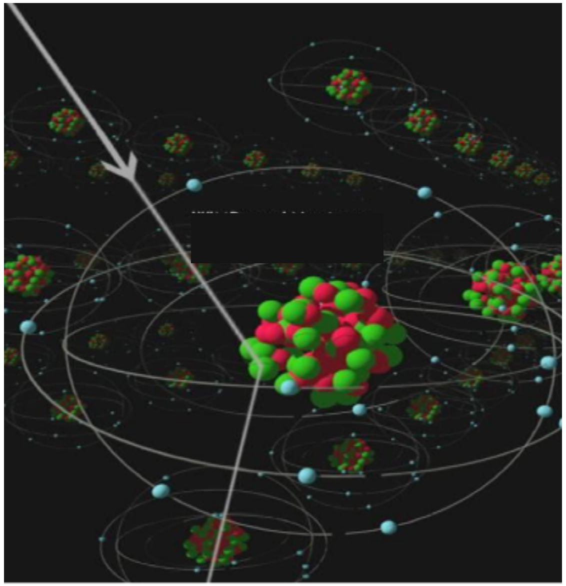
Strange Sigma Terms

➡ Dark Matter Cross Sections

Sigma Terms

q-quark **sigma term** ⟷ contribution of *q*-quarks to the proton mass

- **Strange quark sigma term**: Measure of vacuum-quark contributions to proton mass
- Dominant uncertainty in amplitude for spin-independent scattering of **weakly-interacting dark matter** from nucleons



Strange Sigma Term

- Not directly accessible to experiment

→ **LATTICE QCD**

Strange Sigma Term

- Not directly accessible to experiment

→ **LATTICE QCD**

- **RECALL:** Disconnected terms expensive + noisy
- **BUT:** Feynman-Hellmann Theorem relates sigma terms to mass-dependence

$$\sigma_s = \langle N | m_s \bar{s} s | N \rangle = m_s \frac{\partial M_N}{\partial m_s}$$

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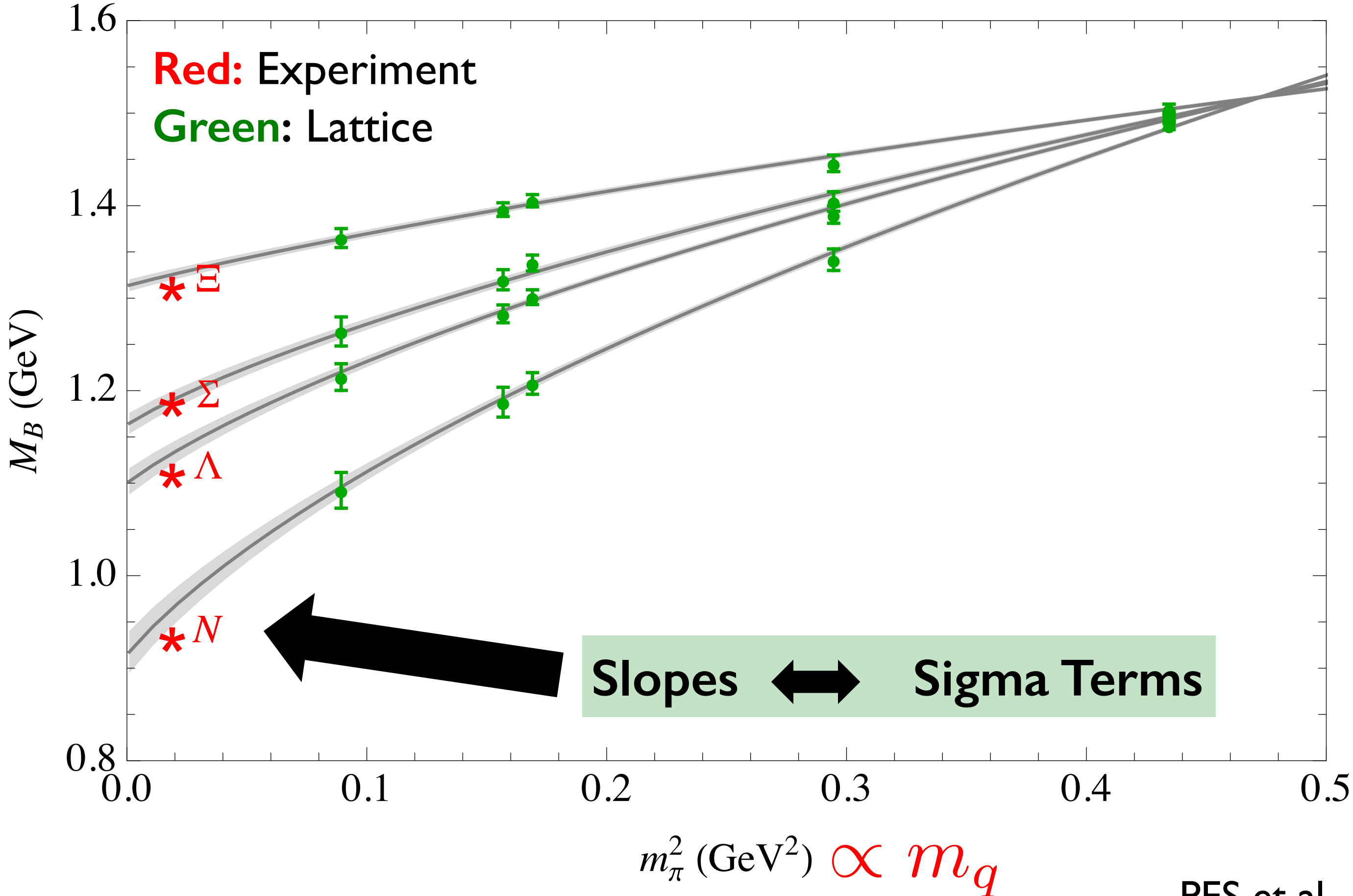
Can vary quark masses on the lattice!

Strange Sigma Term

Baryon masses as a function of quark mass!

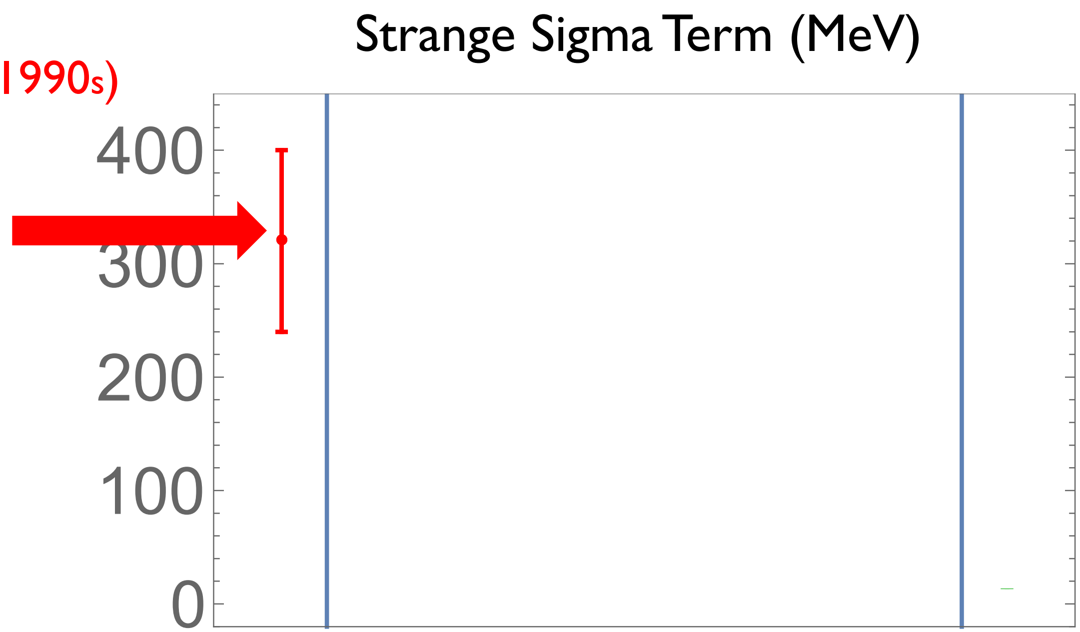


PES et al., PRD87 (2013)

Strange Sigma Term

Phenomenology (1990s)

Implies up to 1/3 nucleon mass from strange quarks

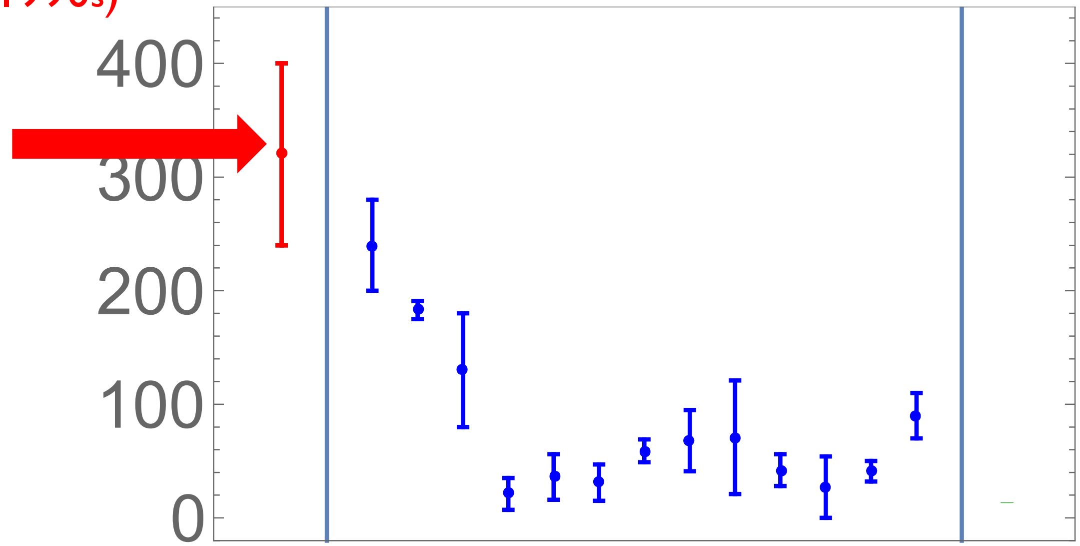


Strange Sigma Term

Strange Sigma Term (MeV)

Phenomenology (1990s)

Implies up to 1/3 nucleon mass from strange quarks



The Evolution of Lattice QCD 1990-2013

Fukugita '95, Dong '96
SESAM '98, Toussaint, Freeman '09,
JLQCD '11, Durr '11, Alexandrou '13,
Ren '14, Abdel-Rehim '16

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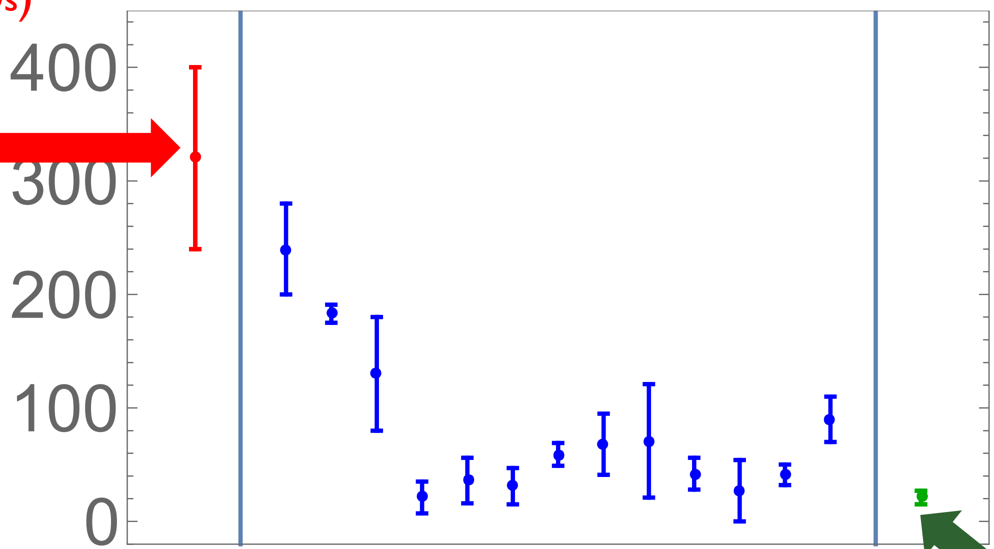
Strange Sigma Term (MeV)



The Evolution of Lattice QCD
1990-2013

Unphysical lattice + Chiral Perturbation Theory

20(6)MeV

PES et al., PRD87 (2013)

Predicted dark matter cross-sections reduced by an order of magnitude

Fukugita '95, Dong '96
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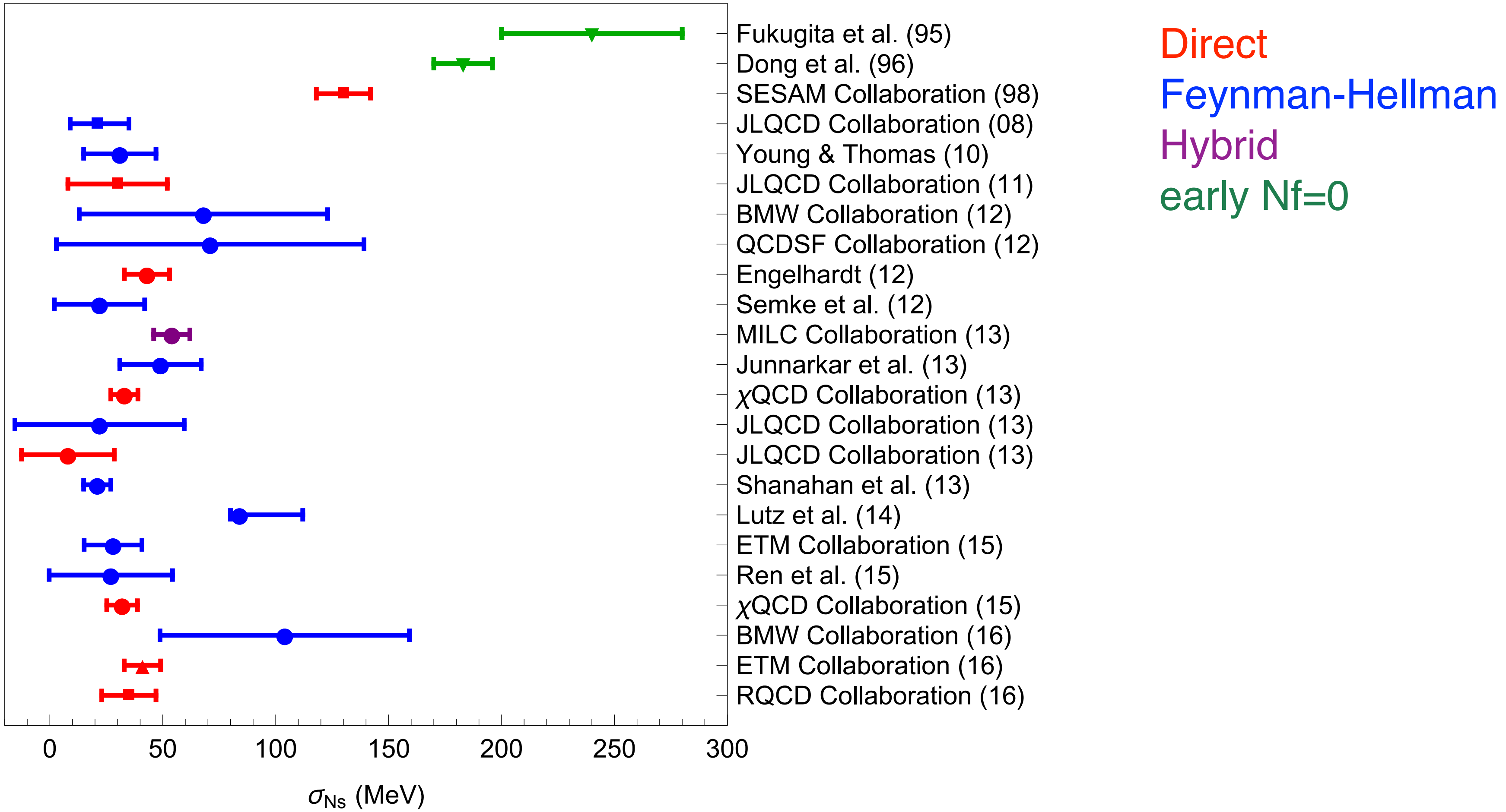
Strange Sigma Term

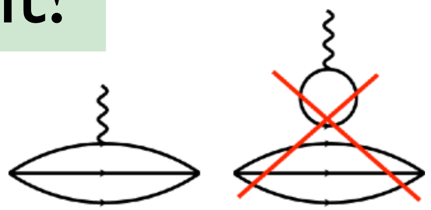
- Sigma term ~ 2016



Summary

Quantitatively understanding proton strangeness is important!

- Direct calculations from QCD are **hard**.



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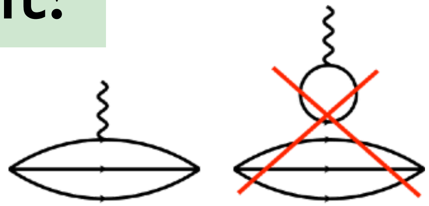

- Direct calculations from QCD are **hard**.
- Precise physics results available **NOW** by combining information from numerical simulations with experiment and models
- Set benchmarks for experimental tests of **nonperturbative QCD**
- Strange quark effects ~ a few percent for proton properties
  - **Strange sigma terms:** new level of precision for direct dark matter searches
  - **Strange magnetic moment:** new benchmark for experiment

Summary

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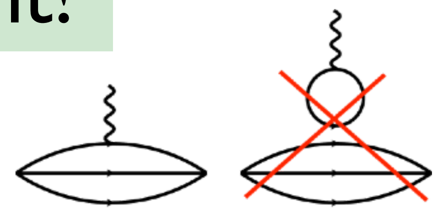

- Direct calculations from QCD are **hard**.
- Precise physics results available **NOW** by combining information from numerical simulations with experiment and models
- Set benchmarks for experimental tests of **nonperturbative QCD**
- Strange quark effects ~ a few percent for proton properties
  - **Strange sigma terms:** new level of precision for direct dark matter searches
  - **Strange magnetic moment:** new benchmark for experiment
- What next? **Gluon distributions:** predictions for studies at a proposed electron-ion collider

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