OLCF

April 29, 2013

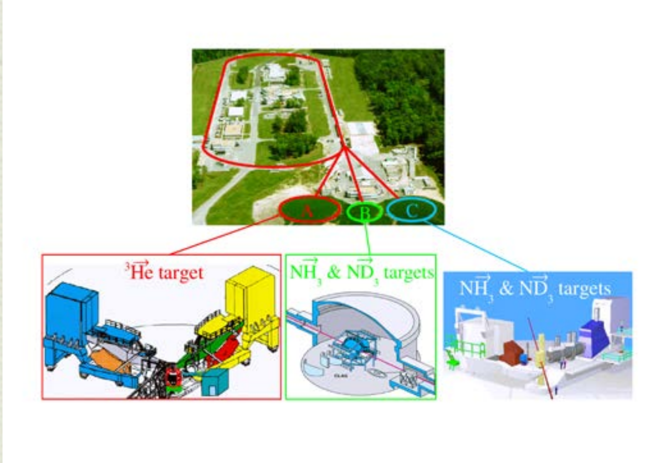
Hadron Structure from LQCD

Kostas Orginos
College of William and Mary
JLAB

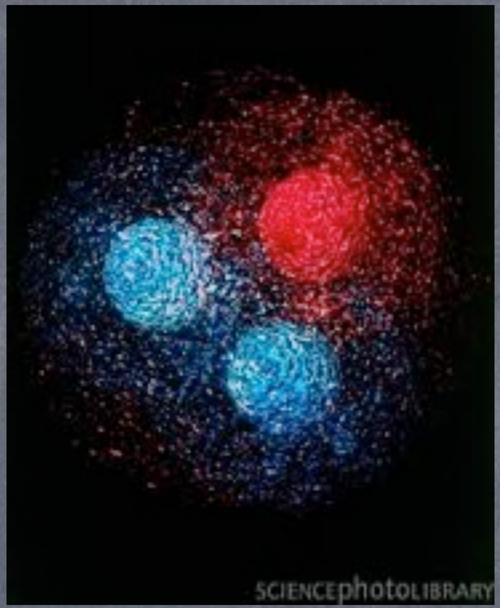
Hadron Structure

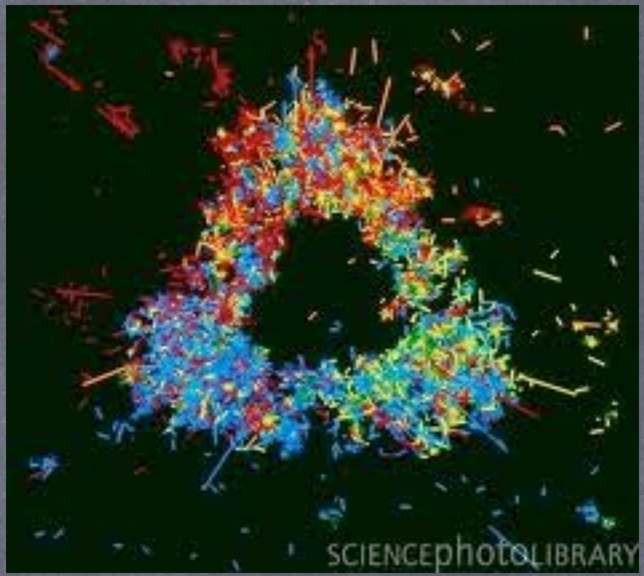
- Importance:
  - How are nucleons made up from the fundamental degrees of freedom (quarks and gluons)
  - Understand the charge and magnetization distributions in the nucleon
  - Complement key elements of DOEs experimental programs
    - quark distributions HERMES, Fermilab, LHC
    - form factors and GPDs: JLab
    - Contributions to the nucleon spin: JLab RHIC-spin, future EIC
    - Transverse momentum dependent distributions: JLab, RHIC-spin, Fermilab,future EIC

JLab @ 12 GeV

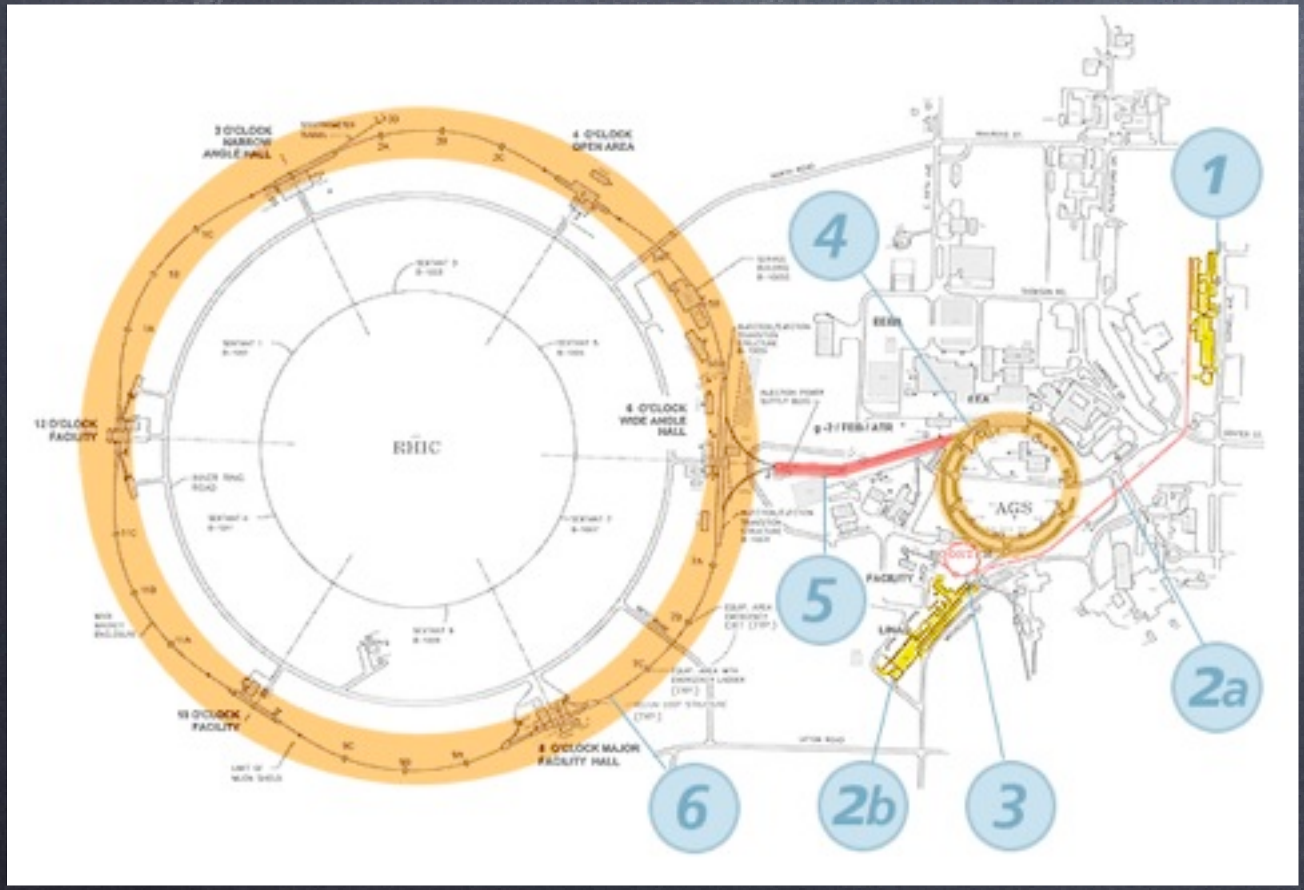


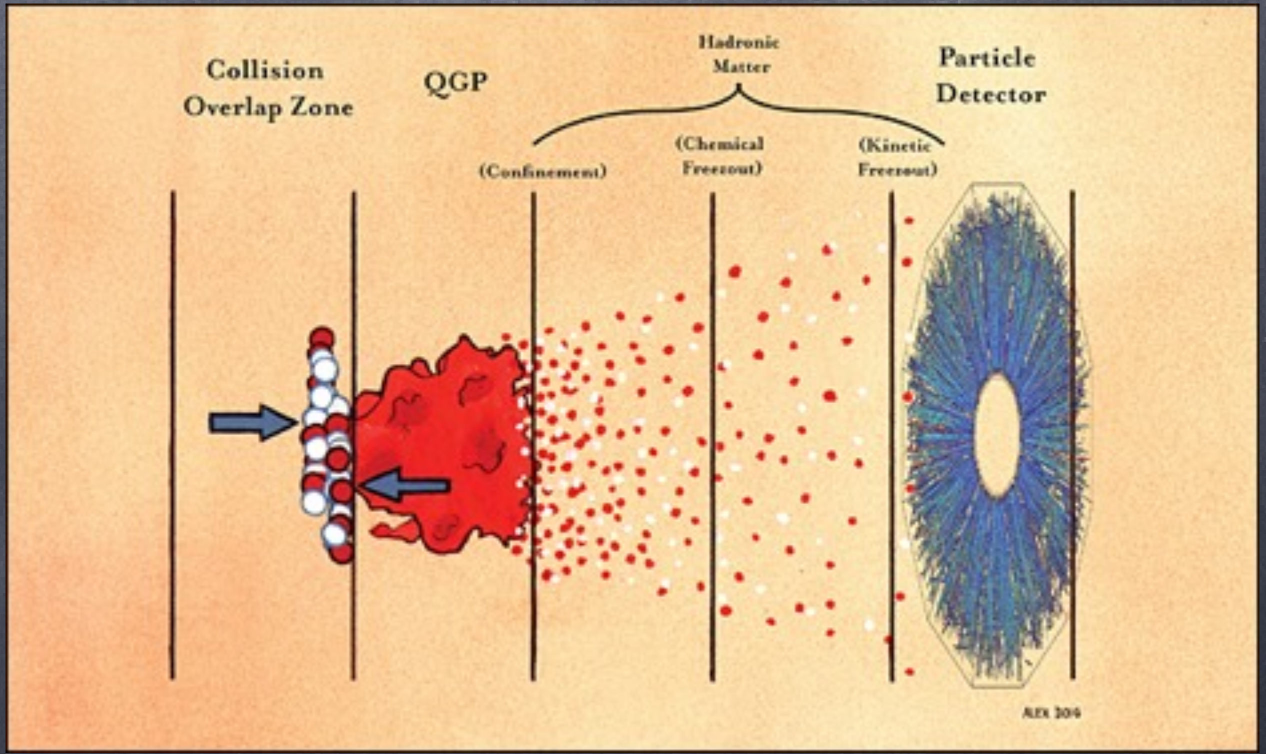
Proton structure



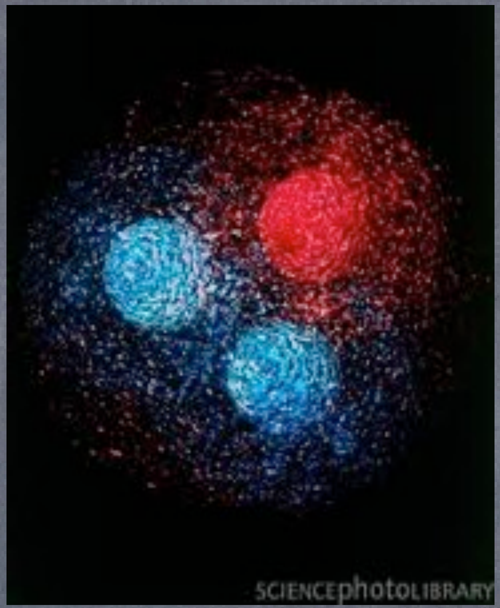


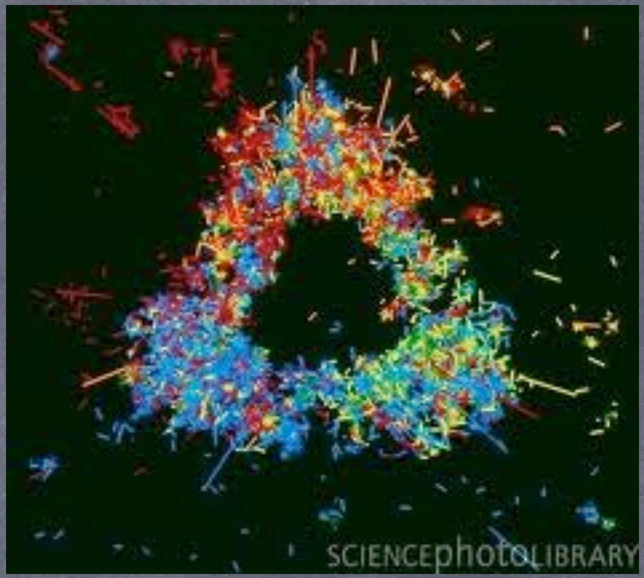
Relativistic Heavy Ion Collider



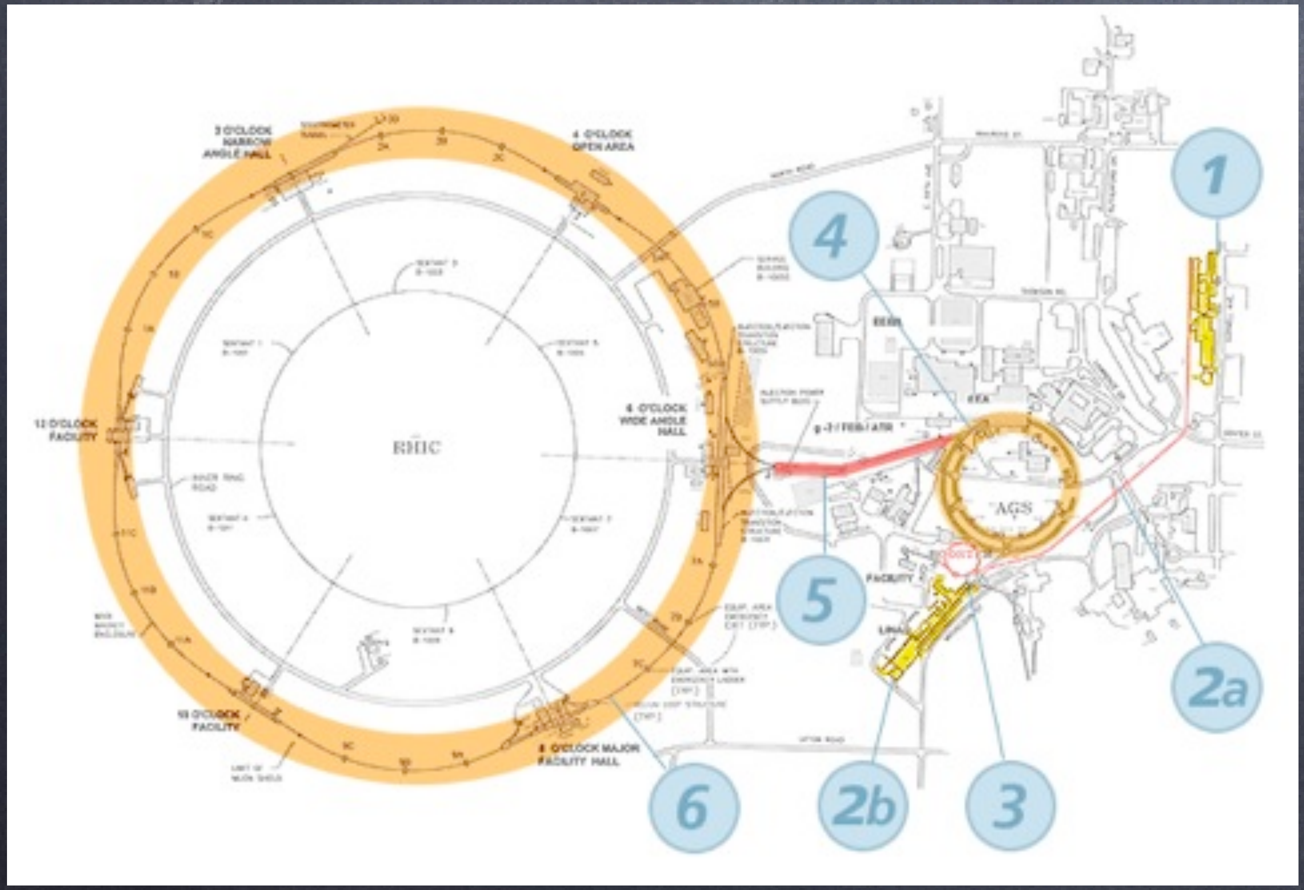


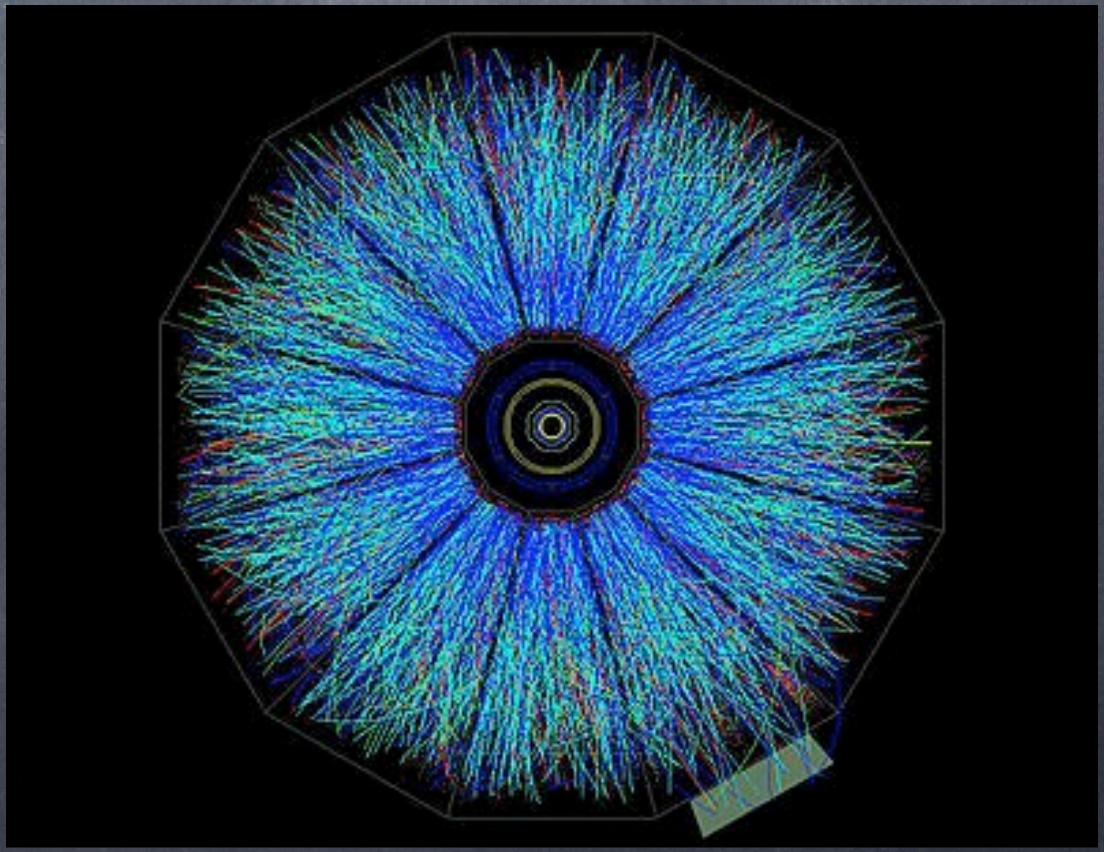
Proton structure



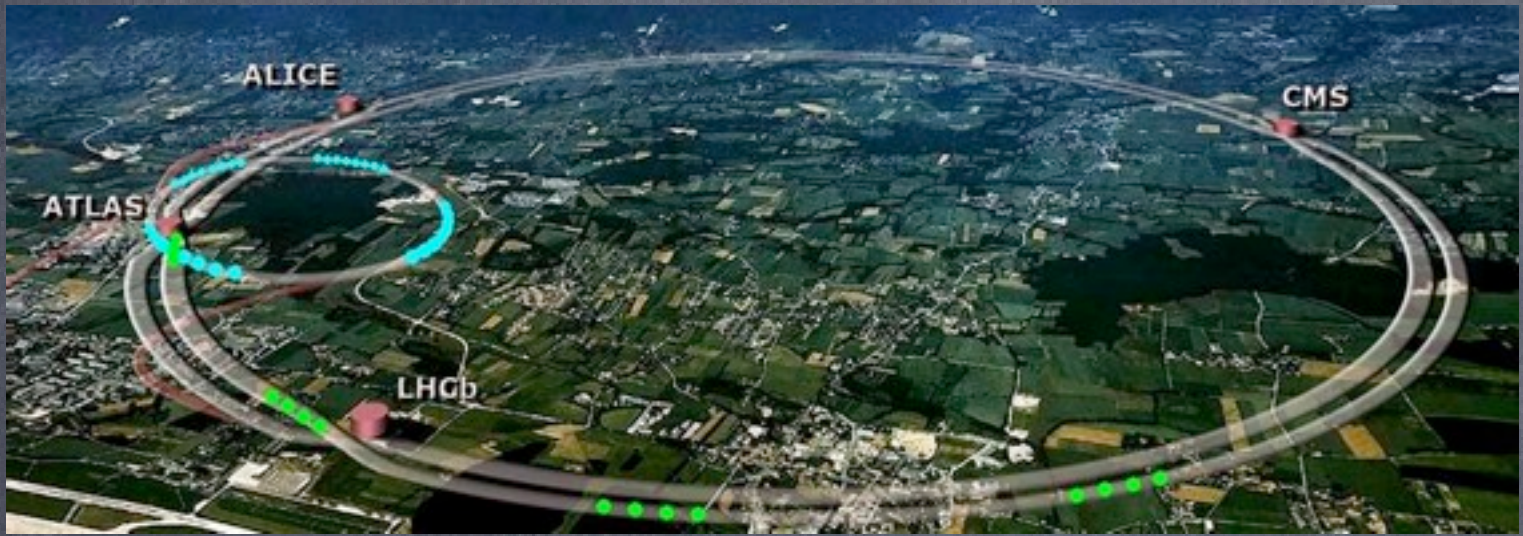


Relativistic Heavy Ion Collider





Large Hadron Collider



Probe the fundamental forces in nature

NSAC Performance Measures in Hadronic Physics

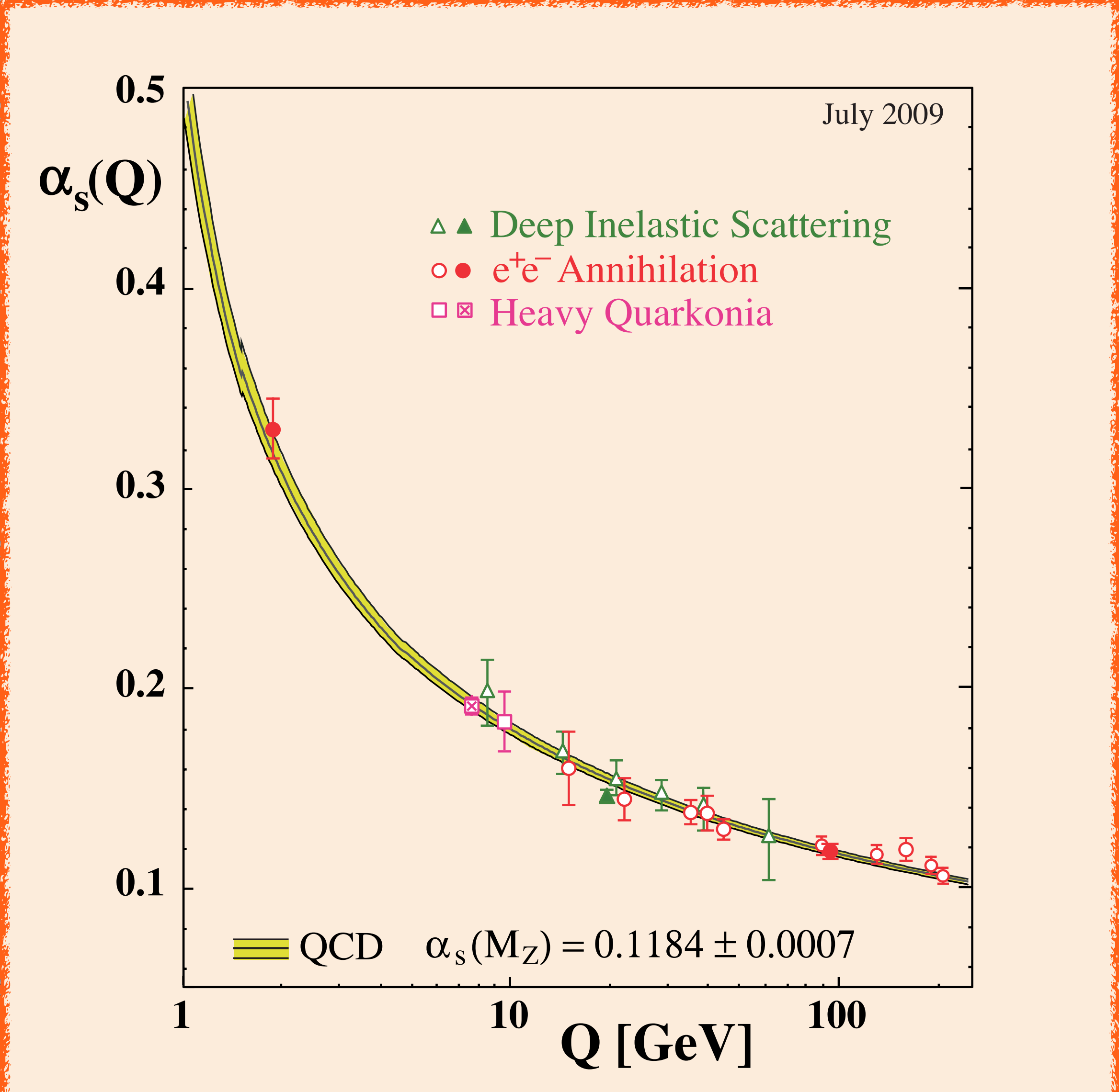
Year	#	Milestone
2012	HP7	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range Q^2=0.1–7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.
2012	HP11	Measure the helicity-dependent and target-polarization-dependent cross-section differences for Deeply Virtual Compton Scattering (DVCS) off the proton and the neutron in order to extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 – 0.4, and squared momentum transfer, t, less than 0.5 GeV^2 .
2013	HP8	Measure flavor-identified q and q contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2013	HP12	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
2014	HP9	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.
2014	HP10	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.
2015	HP13	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering
2018	HP14	Extract accurate information on spin-dependent and spin-averaged valence quark distributions to momentum fractions x above 60% of the full nucleon momentum
2018	HP15	The first results on the search for exotic mesons using photon beams will be completed.

We study strong interactions using the worlds largest computers

OAK RIDGE National Laboratory

NVIDIA

QCD

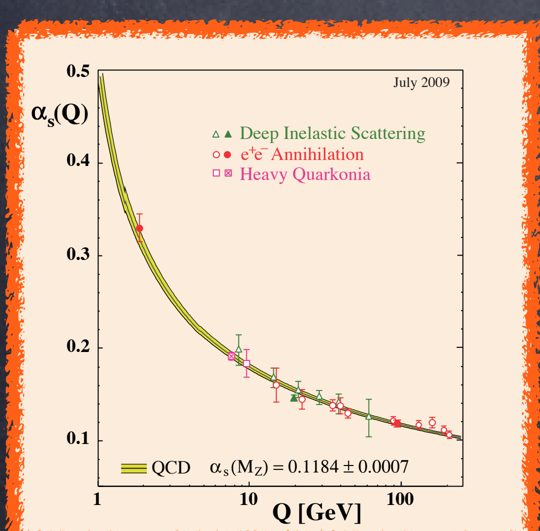


Politzer, Gross, Wilczek 2004 Nobel prize

- The theory of strong interactions
- Coupling constant changes with scale
- Coupling constant becomes weak at high energies
- Characteristic scale arises Λ_{qcd}
- $\alpha_s(\Lambda_{qcd}) \sim 1$

Low energy regime

- Interaction is strong
- Analytic calculations not under control
- Confinement
- Spontaneous chiral symmetry breaking
  - pions: Nambu-Goldstone bosons



Nambu 2008 Nobel prize

Particle masses

(Hadrons)

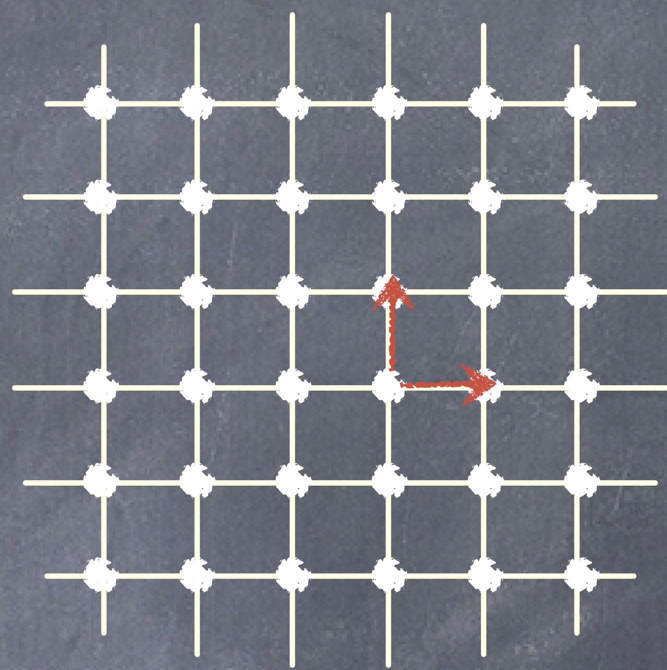
$$m = A \; \Lambda_{qcd}$$

- Can we calculate the dimensionless constants A ?
- Quantum dynamics of strong interactions generates the mass of the visible matter

What does it take?

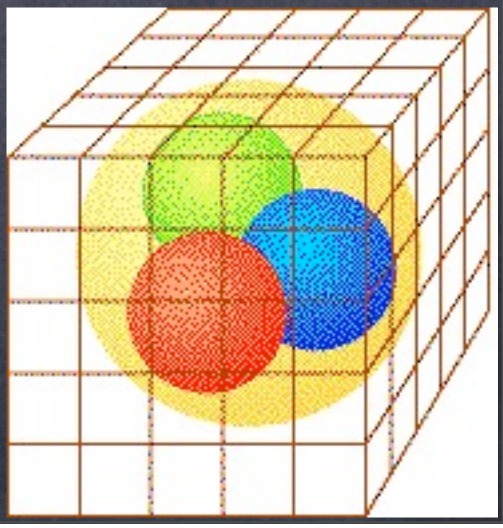
- Hadronic Scale: 1fm ~ 1×10^{-13} cm
- Lattice spacing << 1fm
  - take a=0.1fm
- Lattice size La >> 1fm
  - take La = 6fm
- Lattice 64^4
- Gauge degrees of freedom: $8\times4\times64^4 = 5.4\times10^8$

color → 8, dimensions → 4, sites → 64^4



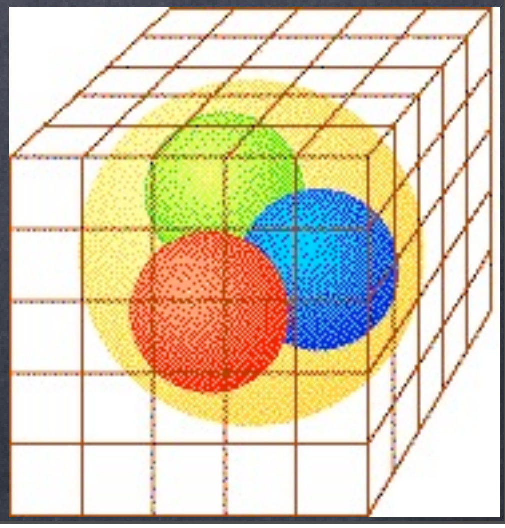
Monte Carlo Integration

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \prod_{\mu,x} dU_\mu(x) \;\; \mathcal{O}[U, D(U)^{-1}] \;\; \det\left(D(U)^\dagger D(U)\right)^{n_f/2} \;\; e^{-S_g(U)}$$



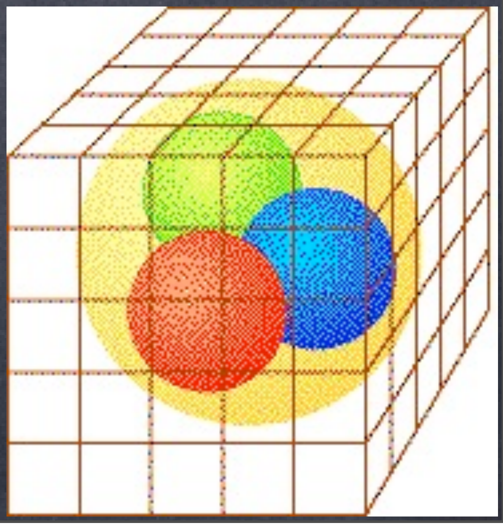
Monte Carlo Integration

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \prod_{\mu,x} dU_\mu(x) \;\; \mathcal{O}[U, D(U)^{-1}] \;\; \det\left(D(U)^\dagger D(U)\right)^{n_f/2} \;\; e^{-S_g(U)}$$



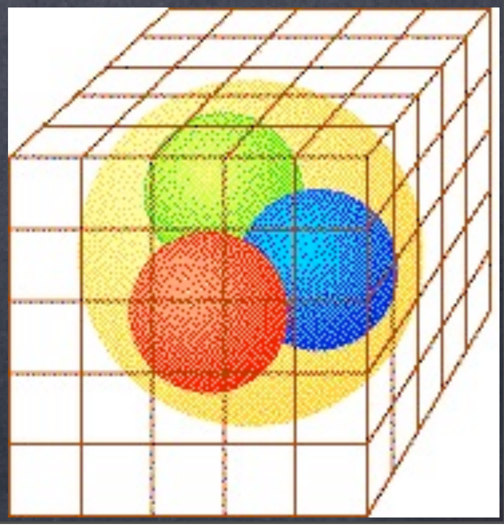
Monte Carlo Integration

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \prod_{\mu,x} dU_\mu(x) \;\; \mathcal{O}[U, D(U)^{-1}] \;\; \det \left(D(U)^\dagger D(U) \right)^{n_f/2} \;\; e^{-S_g(U)}$$



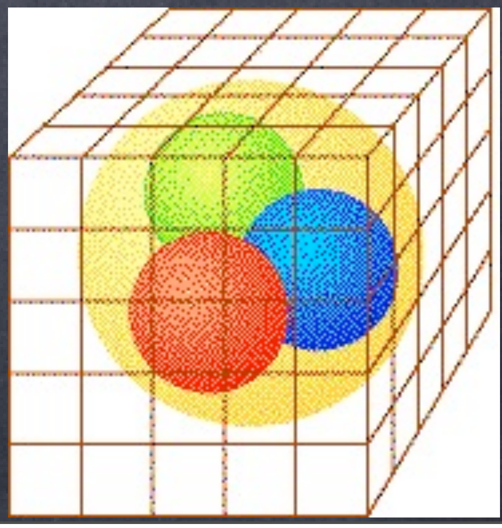
Monte Carlo Integration

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \prod_{\mu,x} dU_\mu(x) \;\; \mathcal{O}[U, D(U)^{-1}] \;\; \det \left(D(U)^\dagger D(U) \right)^{n_f/2} \;\; e^{-S_g(U)}$$



Monte Carlo Integration

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \prod_{\mu,x} dU_\mu(x) \;\; \mathcal{O}[U, D(U)^{-1}] \;\; \det \left(D(U)^\dagger D(U) \right)^{n_f/2} \;\; e^{-S_g(U)}$$



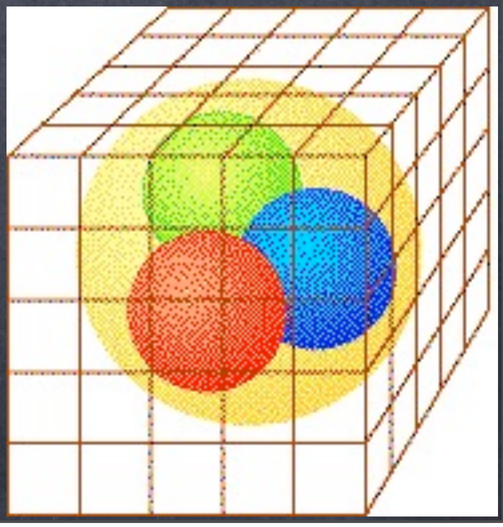
Monte Carlo Integration

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \prod_{\mu,x} dU_\mu(x) \;\; \mathcal{O}[U, D(U)^{-1}] \;\; \det\left(D(U)^\dagger D(U)\right)^{n_f/2} \;\; e^{-S_g(U)}$$

Monte Carlo Evaluation

$$\langle \mathcal{O} \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(U_i)$$

Statistical error $\frac{1}{\sqrt{N}}$



Realistic Calculations

- Include the vacuum polarization effects
  - 2 light (up down) 1 heavy (strange)
  - ... and ... 1 very heavy (charm)
- Finite Volume
  - Compute in multiple and large volumes
- Continuum Limit
  - Compute with several lattice spacings
- Quark masses
  - Compute with several values for the quark masses
  - Study quark mass dependence of QCD
  - Physical light (up down) quark masses

Need big computers to these calculations

OAK RIDGE National Laboratory

NVIDIA.

Ken Wilson @ Lattice '89: "I still believe an extraordinary increase in computer power (10^8 is not enough) and equally powerful algorithmic advances will be necessary before a full interaction with experiment takes place"

Algorithm Improvements

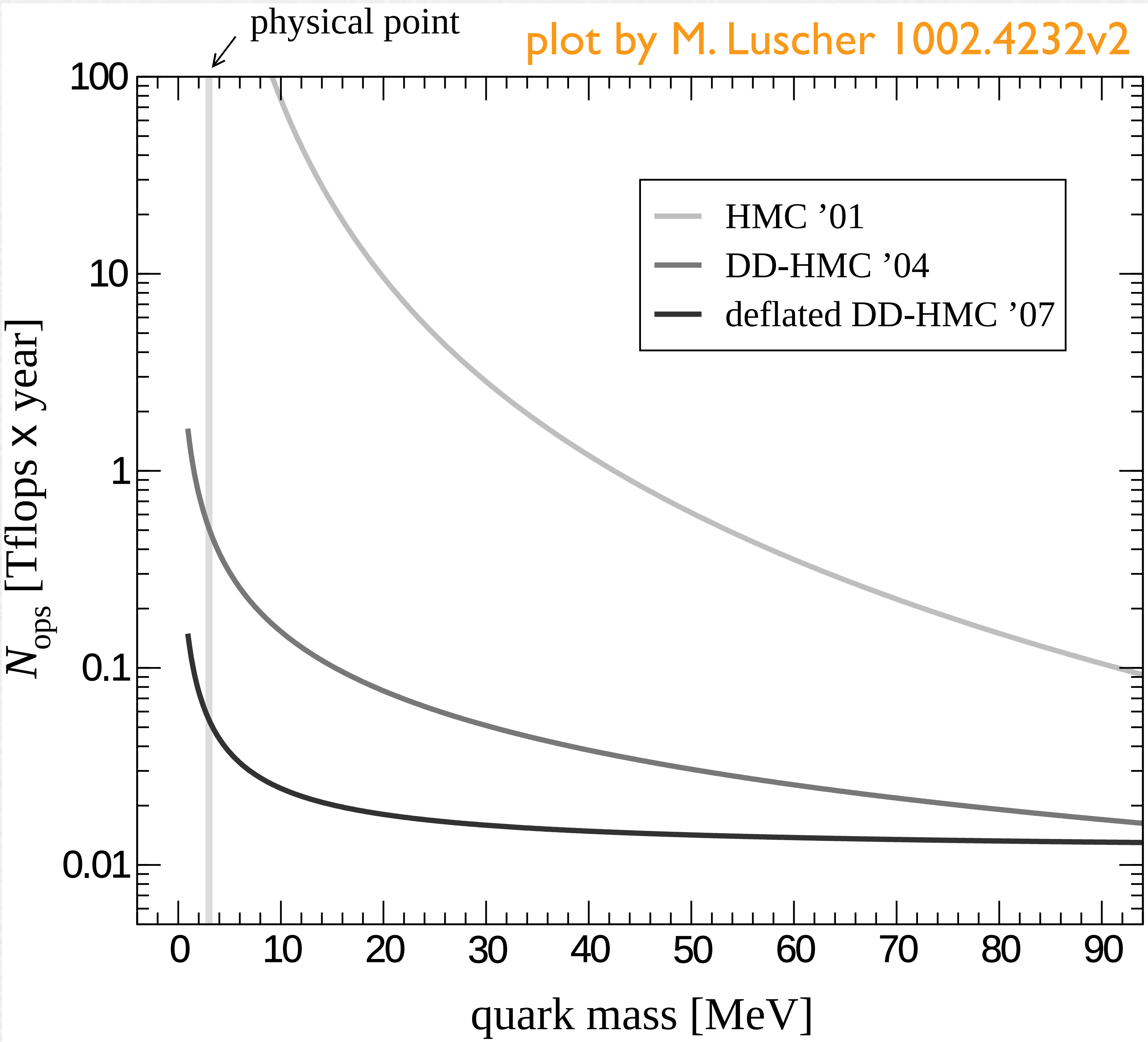
- Hybrid Monte Carlo (HMC)
  - Stochastic sampling of the field configuration space
  - Improved representation of vacuum polarization effects
- Calculation of fermionic observables
  - Solve the Dirac equation

$$D(U)\chi = \phi$$

  - Preconditioned solvers (eigCG), multi-grid, ...

Improved HMC

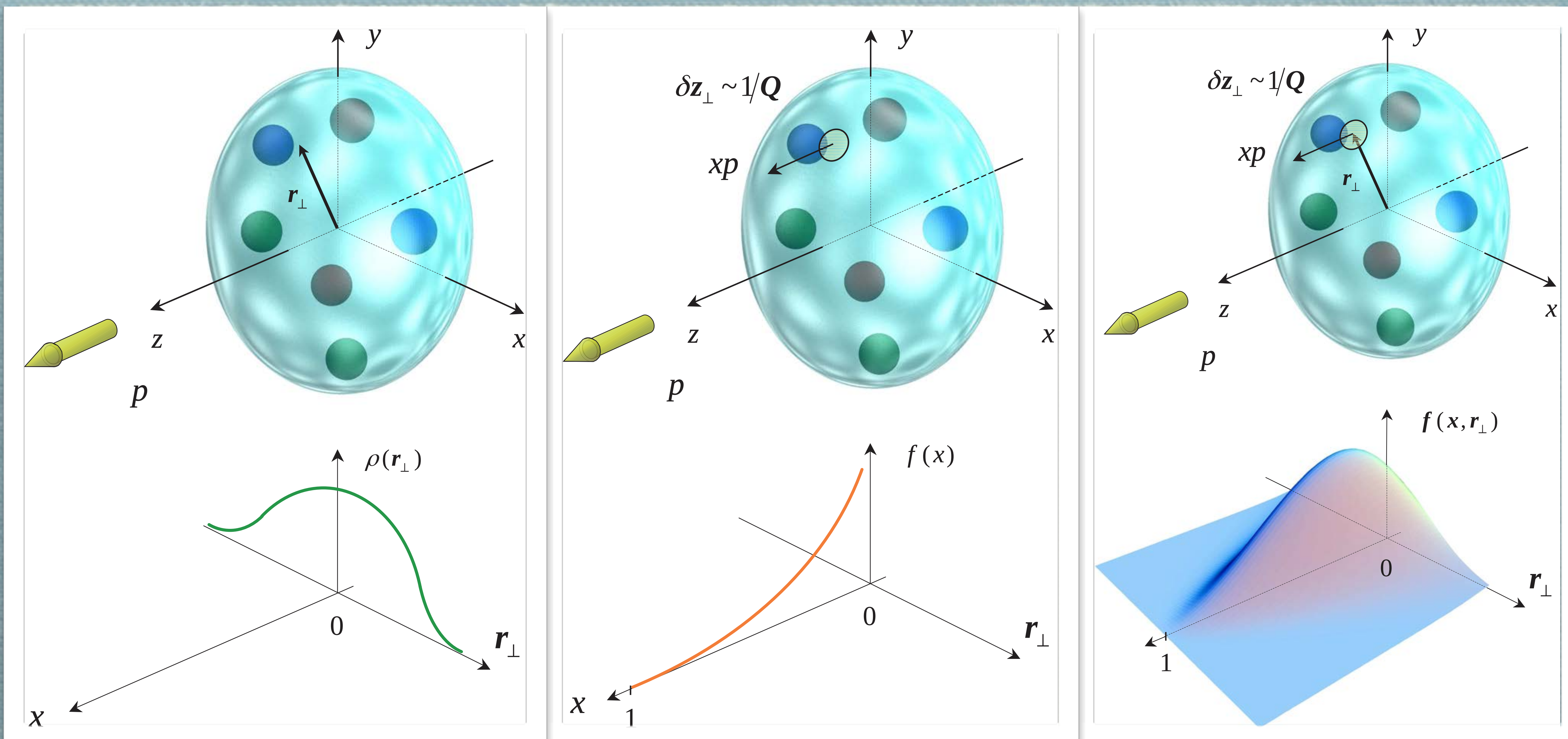
[Luscher 0710.5417]



- Uses an GCR with an AMG preconditioner
    - [Luscher 0706.2298v4]
- Chronology reduces the refresh of the preconditioner
- Nearly removes critical slowing down
- Lattice 32^3 x 64 a = 0.08fm

GPDs

X. Ji, D. Muller, A. Radyushkin (1994-1997)

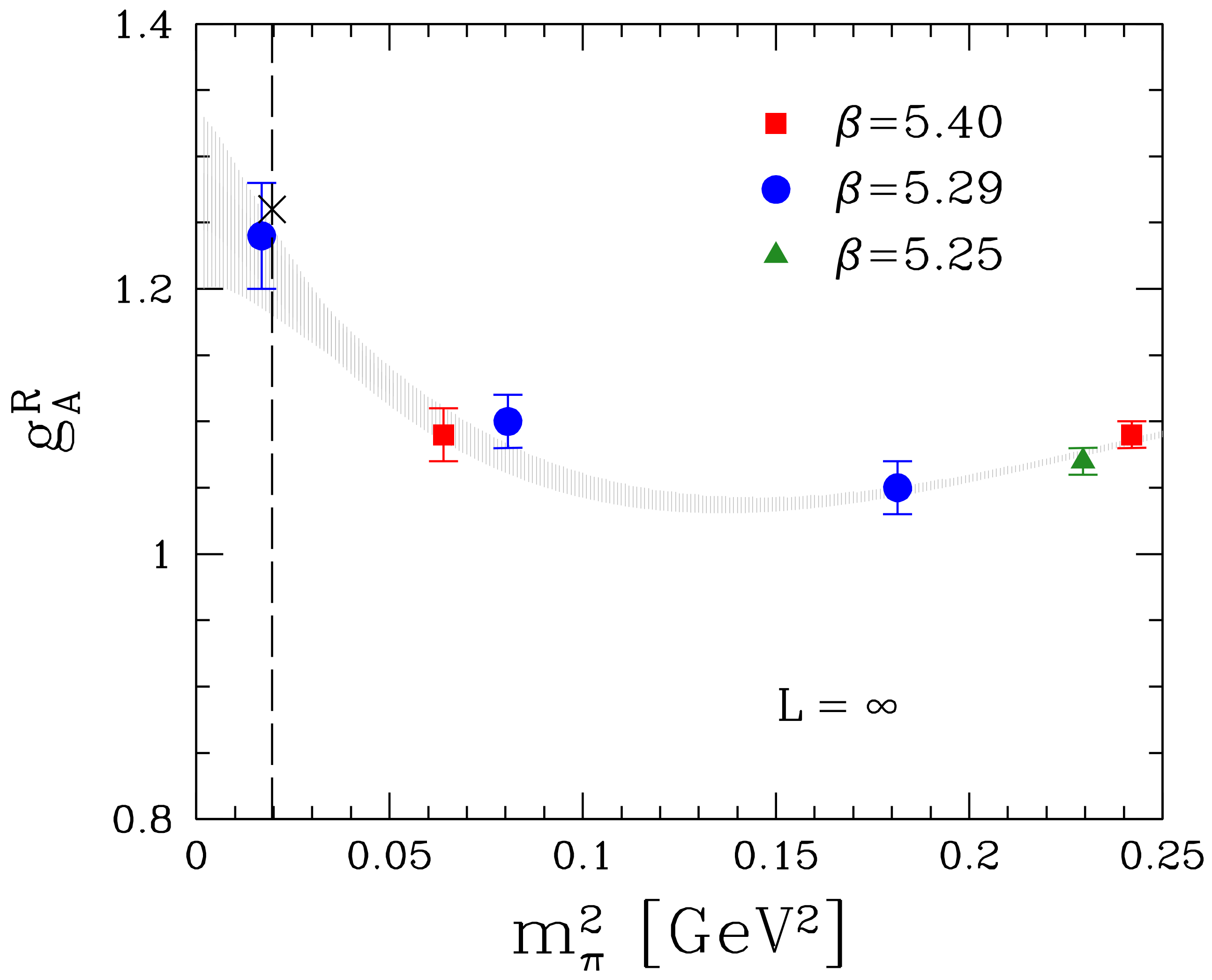


Form Factors

Parton Distribution functions

Generalized Parton Distribution functions

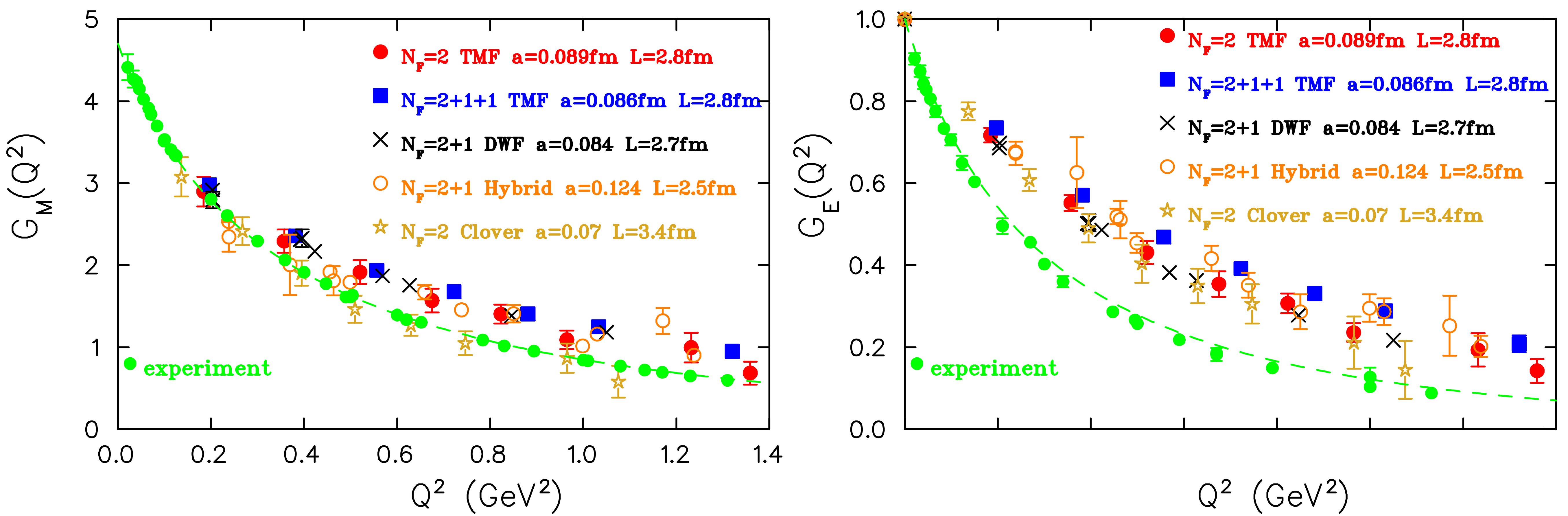
Axial Charge



- Experimentally measured precisely gA = 1.2701 (25)
- Lattice calculations underestimate it
- Recent work with better control of the systematics seems promising (QCDSF, LHPC, RBC/UKQCD)

QCDSF arXiv:1302.2233

Form Factors



Results from QCDSF, LHPC, RBC/UKQCD, ETM-QCD

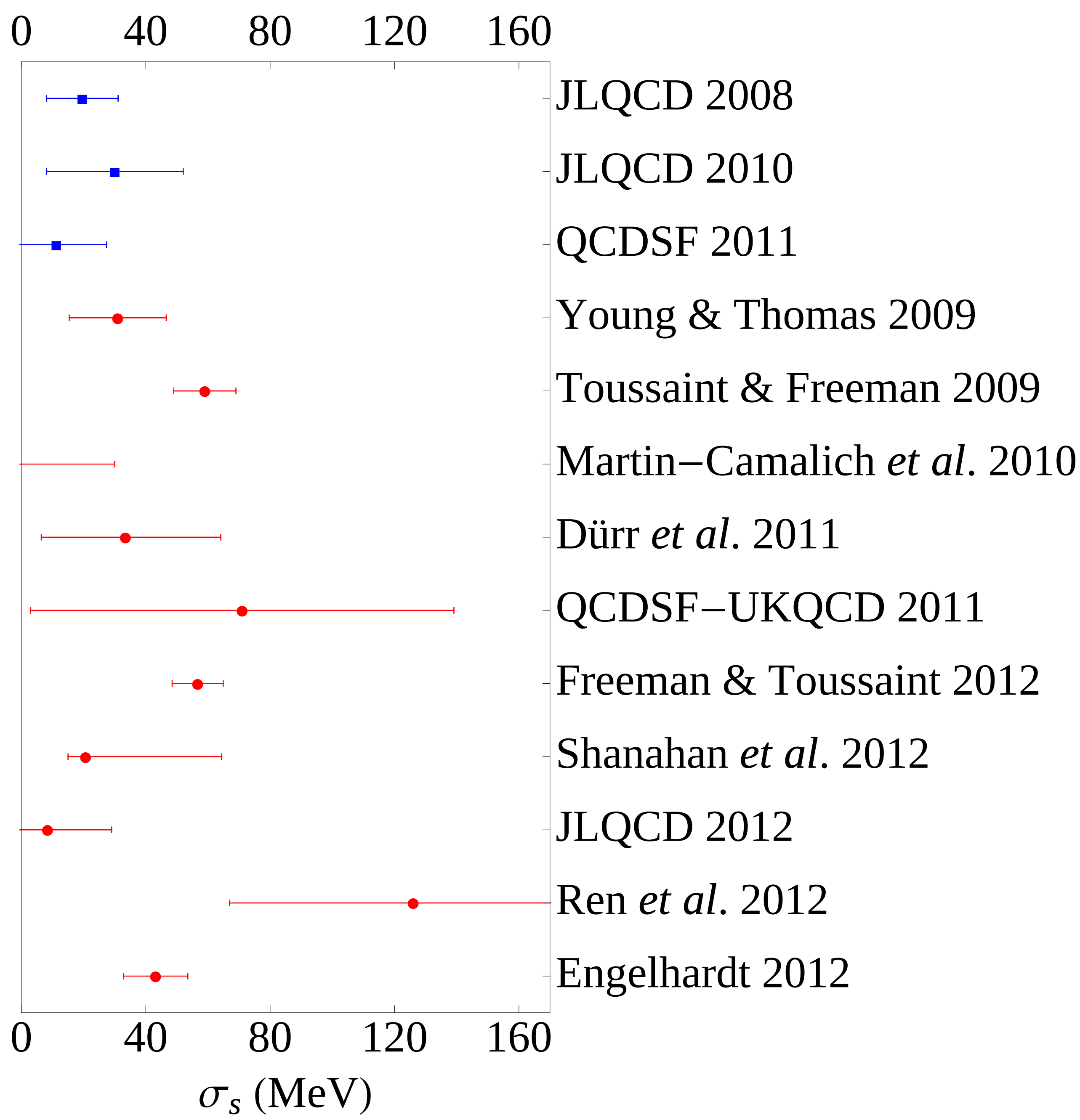
Alexandrou et al arXiv:1303.5979

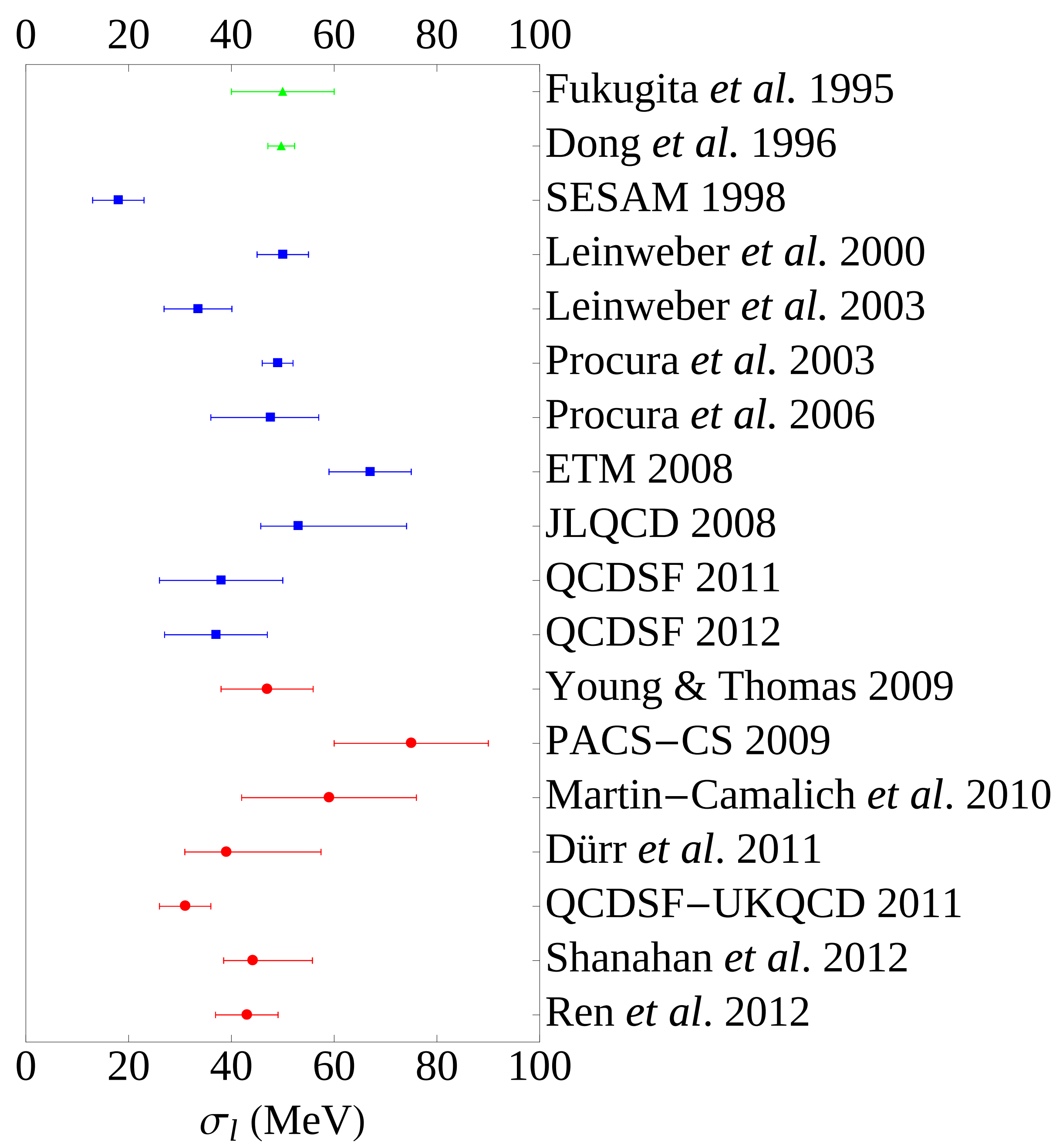
The nucleon sigma term

$$\sigma_l \equiv m_l \langle N | \overline{u}u + \overline{d}d | N \rangle \qquad\qquad \sigma_s \equiv m_s \langle N | \overline{s}s | N \rangle$$

- Dark Matter search experiments
- Controls uncertainty of hadronic uncertainties in dark matter cross sections for a large class of models
- LQCD determinations of the sigma term may prove important

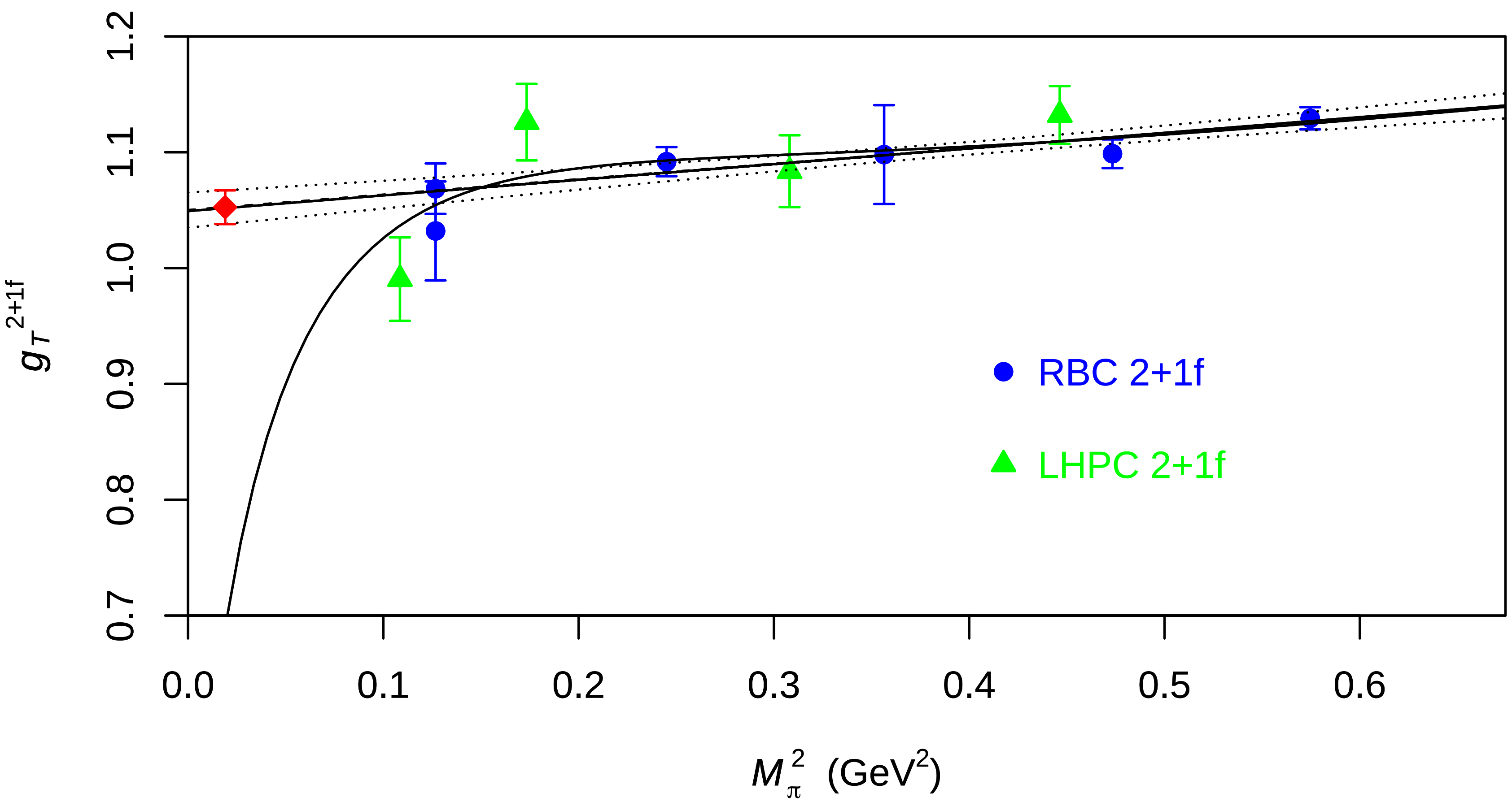
Nucleon Sigma Term





Young et al. arXiv:1301.1765

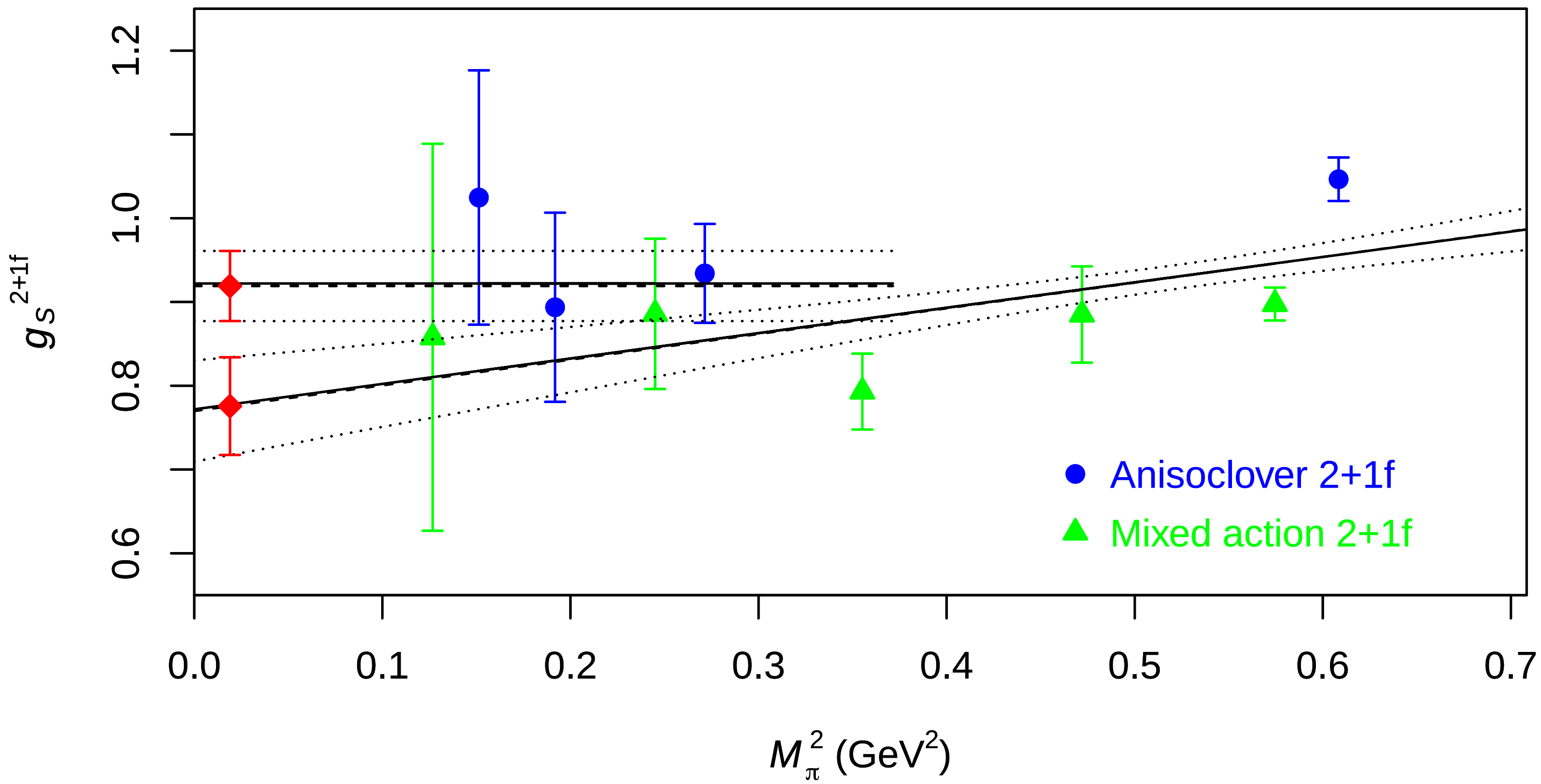
Scalar and Tensor charges



- Search for new physics with precision measurements of Ultra Cold Neutrons decays
- The scalar and tensor iso-vector charges of the neutron are required to ~10%

Gupta et al. arXiv:1110.6448

Scalar and Tensor charges

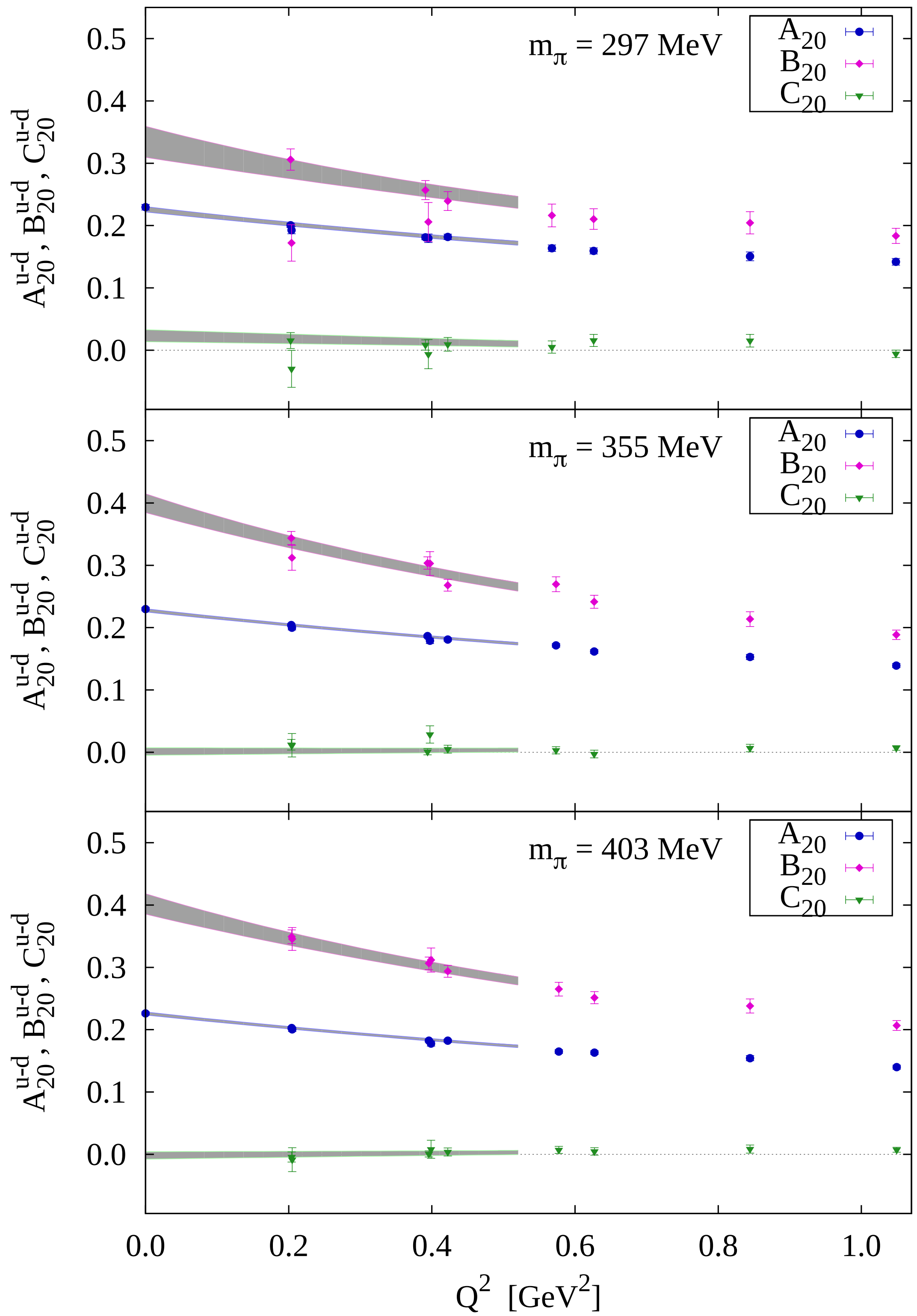


- Search for new physics with precision measurements of Ultra Cold Neutrons decays
- The scalar and tensor iso-vector charges of the neutron are required to ~10%

Gupta et al. arXiv:1110.6448

GPDs: Lattice QCD

[S. Syritsyn et. al. arXiv:1111.0718 PoS(Lattice 2011)]



Angular momentum

RBC/UKQCD:
gauge fields
2+1 flavors
domain wall fermions

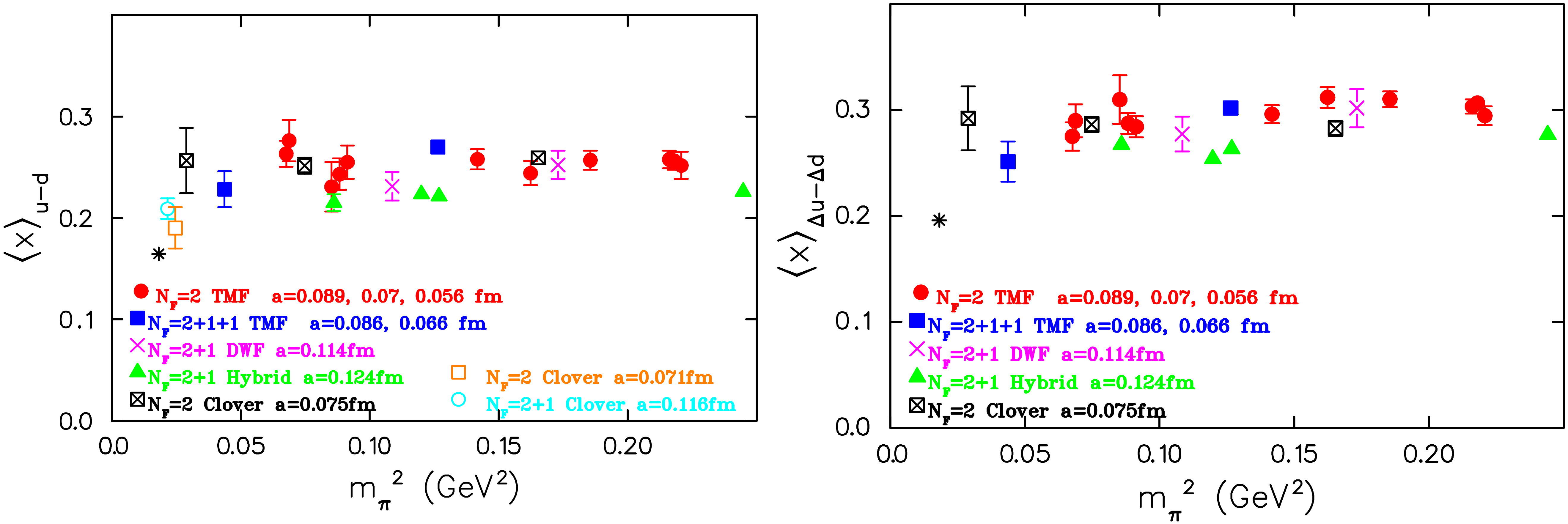
MILC:
gauge fields
2+1 flavors
asqtad fermions

Momentum faction

Puzzle:
Why the difference from experiment?

- Excited state contamination in nucleon structure
  - [J. Green et. al. arXiv:1111.0255 PoS(Lattice 2011) 157]

Moments of structure functions



Alexandrou et al. arXiv:1303.6818

The Proton Spin

- What is the contribution of the quark spin to the spin of the proton?
  - EMC (1988) $Q^2 = 10\ \text{GeV}^2$ $\Delta\Sigma = 0.00(24)$
  - SMC (1998) $Q^2 = 5\ \text{GeV}^2$ $\Delta\Sigma = 0.13(17)$
- Quarks contribute very little to the spin of the proton!
- $\Delta\Sigma$ should be 1 if all the proton spin is due to the spin of the quarks
- Spin crisis

The Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_z$$ or $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + J_z^g$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

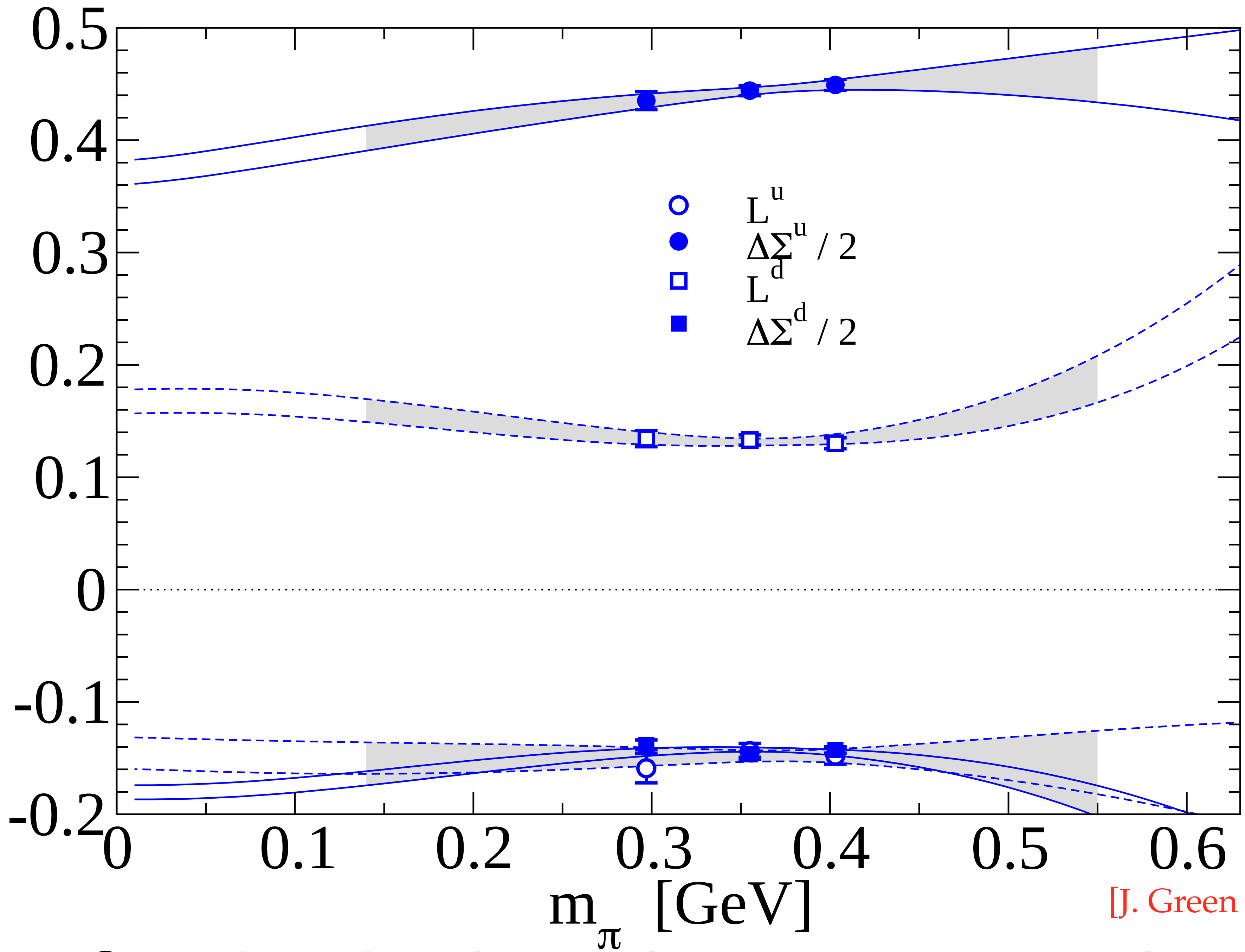
- The quark angular momentum can be computed on the lattice
- $$J_z^q = \frac{1}{2}\left[A_{20}(0) + B_{20}(0)\right]$$ [Ji,'98]
- A and B are the generalized form factors of

$$\mathcal{O}_{\mu\nu} = \bar{q}\gamma_{\{\mu}\overleftrightarrow{D}_{\nu\}}\, q = T_{\mu\nu}$$

[Mathur et. al. '00] [LHPC: Hagler et. al. '03] [QCDSF: Hagler et. al. '03]

Proton SPIN

μ = 2 GeV



[J. Green et. al. arXiv:1111.0255

- Quark orbital angular momentum almost zero
- Disconnected diagrams are missing

Computational Needs

Gauge Field generation only

$$\mathrm{Cost}_{\mathrm{traj}} = \left[\left(\frac{\mathrm{fm}}{a}\right)^4 \left(\frac{L_s}{\mathrm{fm}}\right)^3 \left(\frac{L_t}{\mathrm{fm}}\right)\right]^{5/4} \cdot \left\{B \cdot \left[\left(\frac{\mathrm{MeV}}{m_\pi}\right)\right]^{\gamma} + A\right\} (\mathrm{core\ \ hours})$$

Example:

Physical pion mass, a=0.075fm 1K lattices, 6fm box

Costs about 120 TFlop-Years

.....

Conclusions

- Lattice QCD is a mature field
  - Direct comparison with experiment is now possible for several observables
  - Predictions are now emerging
- Hadron structure is now probed with lattice calculations
- LQCD calculations complement existing experimental program
- Improved precision is required
  - Control systematic errors
- Potential impact to searches for new physics
- multi-Petaflop computing is required for precision calculations