Opportunities of exascale computing for lattice QCD + QED

QCDSF - Collaboration

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Charged multi-hadron systems in lattice QCD+QED

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Systems with the quantum numbers of up to twelve charged and neutral pseudoscalar mesons, as well as one- and two-nucleon systems, are studied using dynamical lattice quantum chromodynamics and quantum electrodynamics (QCD+QED) calculations and effective field theory. QED effects on hadronic interactions are determined by comparing systems of charged and neutral hadrons after tuning the quark masses to remove strong isospin breaking effects. A non-relativistic effective field theory including finite-volume Coulomb effects perturbatively is analyzed in detail for systems of multiple charged hadrons and found to accurately reproduce QCD+QED results. QED effects on charged multi-hadron systems besides Coulomb photon exchange are determined by comparing the two- and three-body interaction parameters extracted from QCD+QED results for charged and neutral multi-meson systems.

Projects

Strong CP violation, probed with electric dipole moment — QCD θ term; Quark EDM; Quark & Gluon chromo-EDM

$\eta \to 2\pi$

Hadron structure

PDFs   Regge limit and small x, higher twist

GPDs   Encompasing form factors and PDFs

Dynamical QCD + QED N_f=1+1+1   Clover fms

Isospin violations: Hadron spectroscopy, flavor decomposition of hadron structure, quark masses

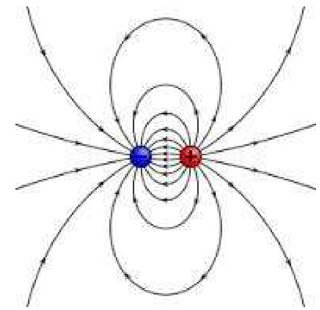
Precision calculations: Muon $(g-2)$, CKM matrix elements, leptonic and semileptonic decay rates, neutron lifetime and axial coupling connection, neutrino-nucleus interactions

Strong CP violation

The new generation of precision searches for electric dipole moments (EDMs) will probe new physics interactions that appear at energies well beyond the reach of high energy colliders. With the increasingly precise experimental efforts to observe EDMs it is now important to have a rigorous calculation directly from QCD

$$\langle p', s'|J_\mu|p, s\rangle = \bar{u}(\vec{p}\,', s')\,\mathcal{J}_\mu\,u(\vec{p}, s) \qquad \mathcal{J}_\mu = \gamma_\mu F_1(q^2) + \sigma_{\mu\nu}q_\nu\frac{F_2(q^2)}{2m_N} + \sigma_{\mu\nu}q_\nu\gamma_5\frac{F_3(q^2)}{2m_N}$$

$$d_N = \frac{eF_3(0)}{2m_N} \propto e_q\ell$$

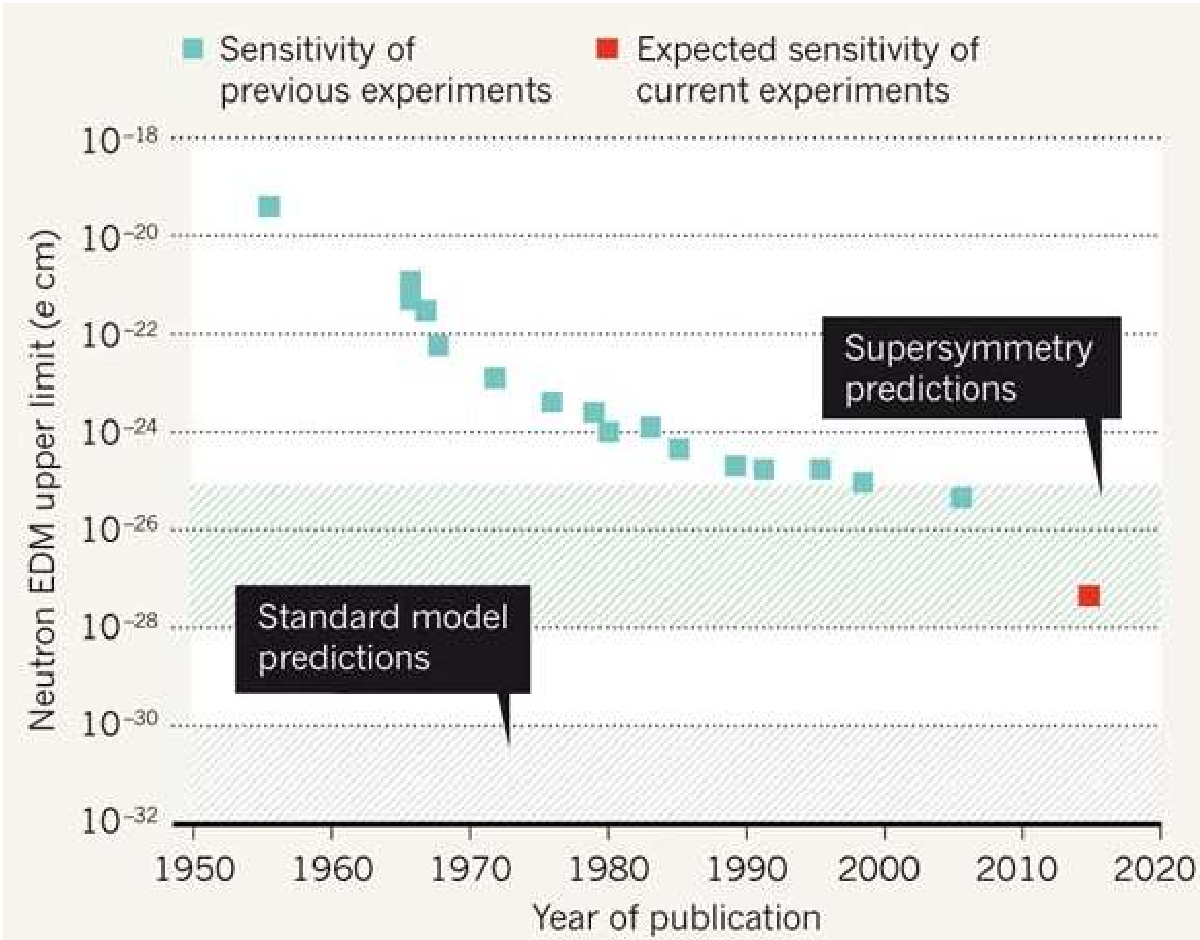


Sources	QCD	GUTs	SUSY	Standard Model
	$S = S_{\mathrm{QCD}} + i\,\theta\,Q$	Quark chromo-EDM		CKM
	Quark EDM $\bar{q}\sigma_{\mu\nu}q$	Gluon chromo-EDM		

Inherent CP violation (GUTs, SUSY, Standard Model)

Experiment

Distances probed $(e = 1)$



QCD

θ

$\mathbf{10^{-10}}$

$\mathbf{10^{-12}}$

$\mathbf{10^{-14}}$

$\uparrow$

Strong CP problem

Monte Carlo simulations of $S_\theta = i\,\theta\,Q$ are not feasible. Instead, we rotate the theta term into mass matrix

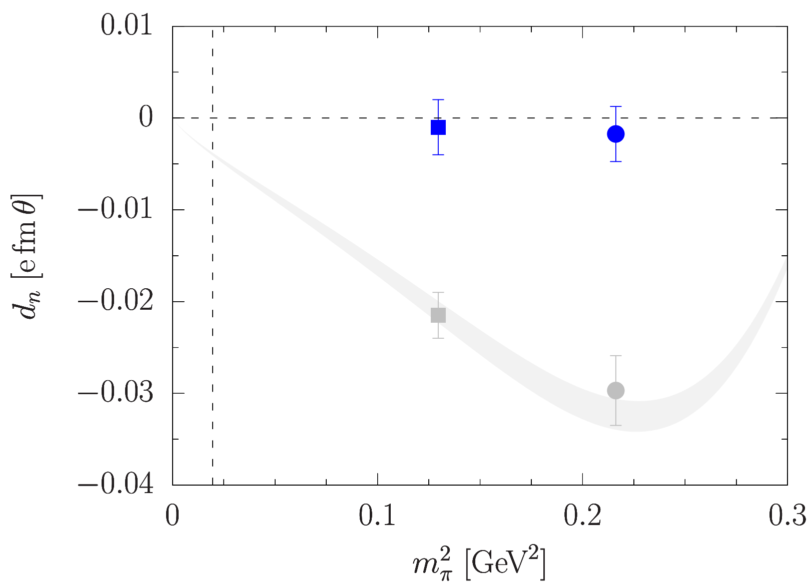
$$S_\theta = \frac{i}{3}\,\theta\,\hat{m}\sum_x(\bar{u}\gamma_5 u + \bar{d}\gamma_5 d + \bar{s}\gamma_5 s)$$

and simulate at imaginary vacuum angle, $\theta \to i\,\theta$

Preliminary results

PRL 115 (2015) 062001

$24^3 \times 48$



Common practice

$$\langle\mathcal{O}\rangle_\theta \to \langle\mathcal{O}\exp\{i\,\theta\,Q\}\rangle$$

On very large volume one representative field (called the master field) is sufficient. Choose $Q = 0$. Then $d_n = 0$ Lüscher

Projected onto neutron state. Compatible with $d_n = 0$ Strong CP Problem?

To connect EDM measurements to particle physics, we need to improve the precision of the calculation by simulating on larger volumes, at realistic quark masses and at two different lattice spacings at least

Inclusion of chromo-EDM is straightforward

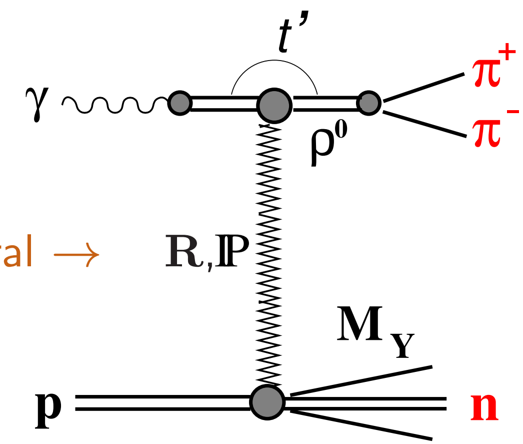
Hadron structure

The partonic structure of hadrons plays an important role in a vast array of high-energy and nuclear physics experiments. It also underpins the theoretical understanding of hadron structure

We have embarked on a program, starting from the Compton amplitude, that allows to compute hadron structure functions down to the Regge region and small x, including higher twist, thus avoiding issues of mixing and renormalization, as well as GPDs

Regge

peripheral $\longrightarrow$



$$x\,q_v(x) = A(1-x)^\eta x^{1-\alpha(0)}\left(1+\epsilon\sqrt{x}+\gamma x\right)$$

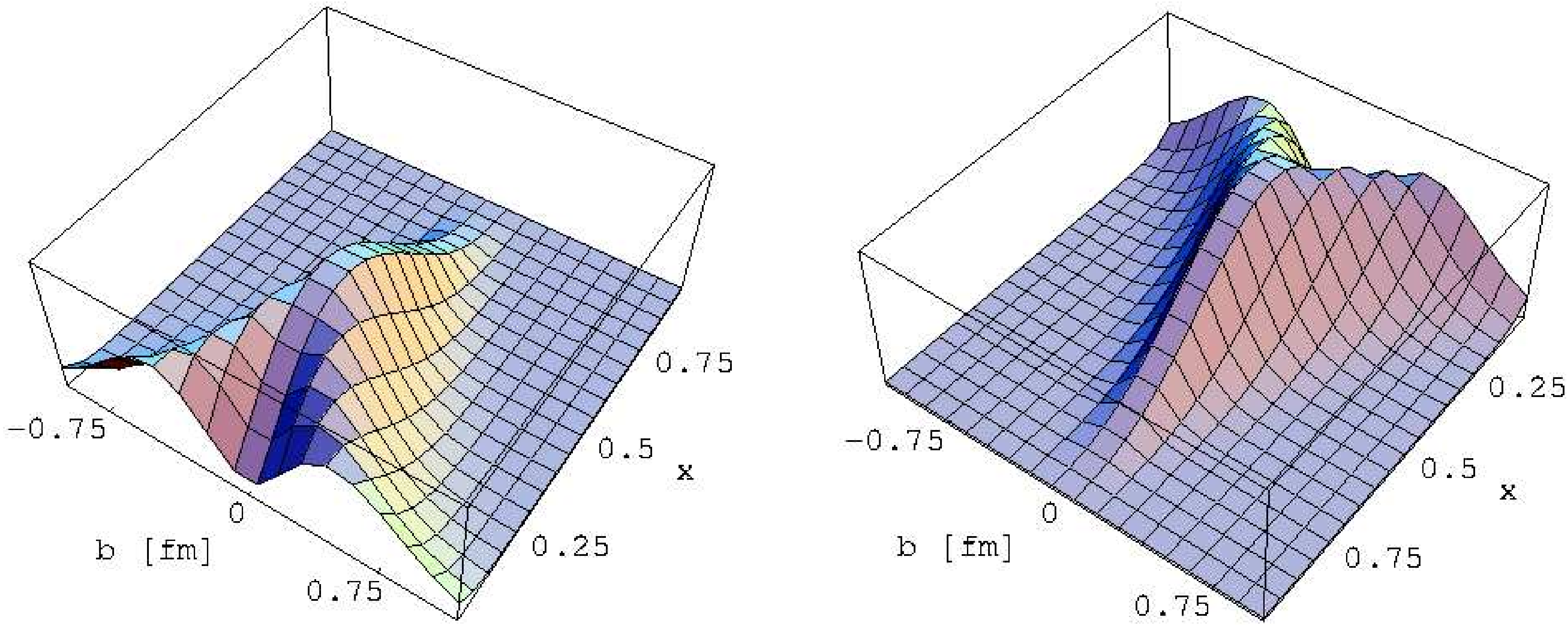
$\uparrow$

Not accessible on the light cone

Computationally, we are able to take advantage of the efficiency of the Feynman-Hellmann approach and avoid the need to compute four-point functions

$H^u(x, \mathbf{b}_\perp^2)$

Valence quarks, $q^2 = 4$ GeV^2

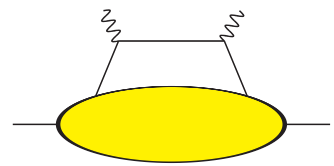


All hadron structure functions (as well as PDFs and GPDs) derive from the Compton Amplitude $T_{\mu\nu}(p,q) = \int \mathrm{d}^4x\, \mathrm{e}^{iqx} \langle N(p)|T J_\mu(x) J_\nu(0)|N(p)\rangle$. For example

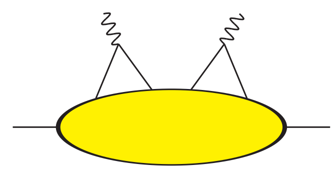
$$T_{33}(p,q) = 4\omega \int_0^1 dx\, \frac{\omega x}{1-(\omega x)^2} F_1(x,q^2)$$

$T_{\mu\nu}(p,q)$ can be computed most efficiently, including singlet (disconnected) matrix elements, by the Feynman-Hellmann technique. By introducing the perturbation to the Lagrangian, $\mathcal{L}(x) \to \mathcal{L}(x) + \lambda_\mu \cos(\mathbf{q}\cdot\mathbf{x})\, J_\mu(x)$, it is obtained by the second derivative of the energy shift,

$$-2E_\lambda(p,q)\, \frac{\partial^2}{\partial \lambda_\mu^2} E_\lambda(p,q)\,\Big|_{\lambda=0} = T_{\mu\mu}(p,q)$$



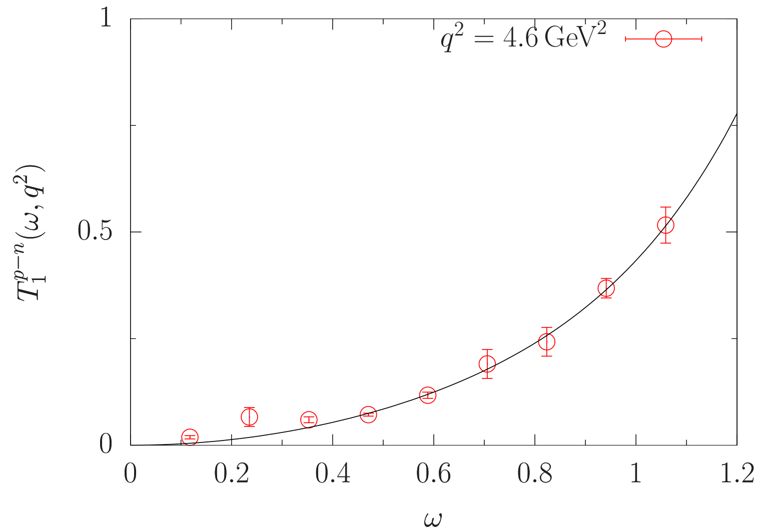
The amplitude encompasses the dominating ‘handbag’ diagram as well as the power-suppressed ‘cats ears’ diagram. Varying q^2 will allow to test the twist expansion

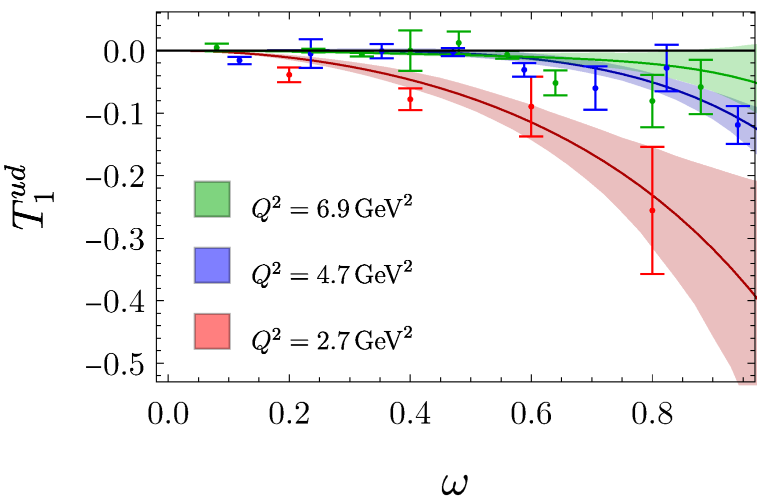


No renormalization is needed

Preliminary results

$m_\pi = 410\,\mathrm{MeV}$

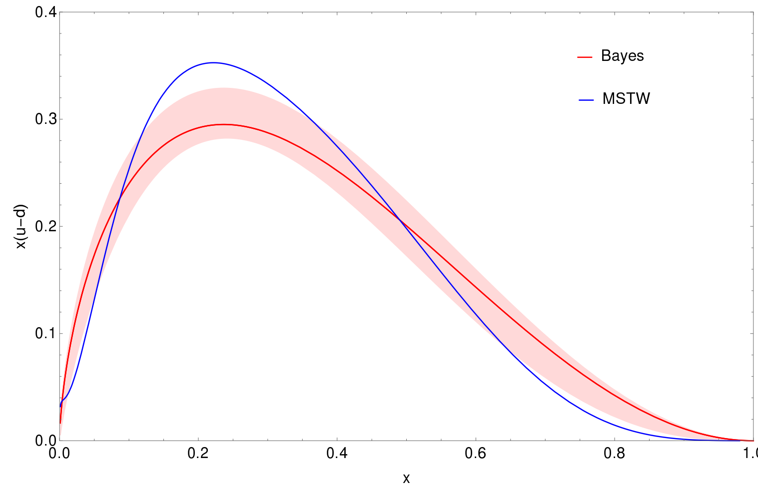




Higher twist

Regge

$\longleftarrow$



Handbag diagram

$\uparrow$

Prior: $Ax^B(1-x)^C$

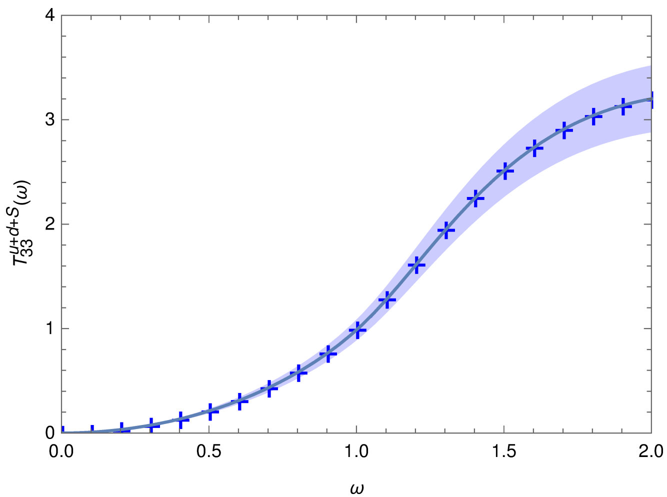
arXiv:2001.05366

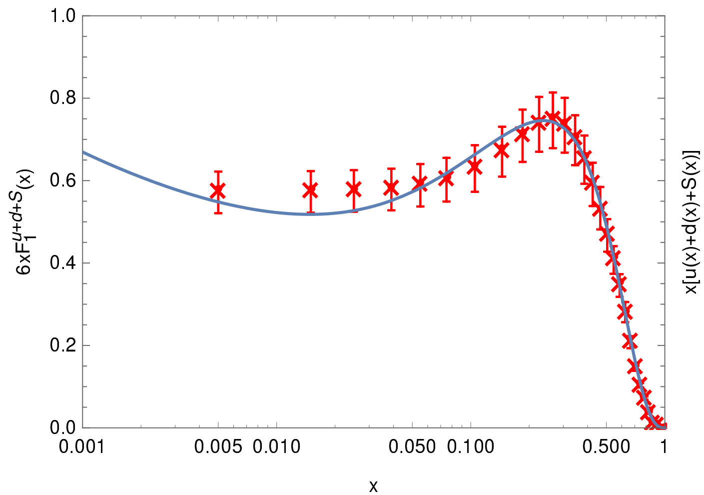
What is possible?

In | **Out**

$$T_{33}^{u+d+S}(\omega) = 4\omega \int_0^1 dx \, \frac{\omega x}{1-(\omega x)^2} F_1^{u+d+S}(x)$$

$$2xF_1^{u+d+S}(x) = \frac{1}{3} x[u(x)+d(x)+S(x)]$$





MSTW-lo

Singlet structure functions require extra simulations with the Lagrangian $\mathcal{L}(x) + \lambda_\mu \cos(\mathbf{q}\cdot\mathbf{x})\, J_\mu(x)$ for each value of photon momentum q

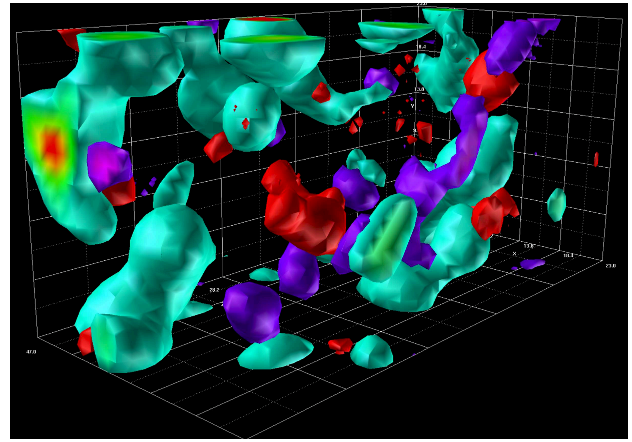
GPDs require calculation of off-forward Compton amplitude

Dynamical QCD + QED

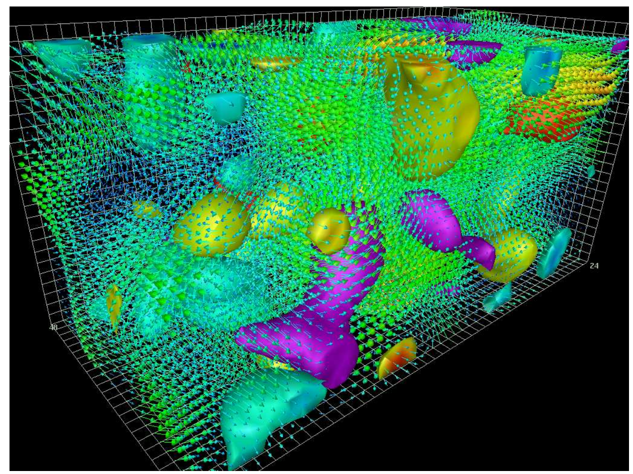
Lattice simulations of QCD are now reaching a precision, where isospin breaking effects can be investigated and QED corrections become important, due to the difference of mass and charge of the quarks

We perform simulations of dynamically-coupled QCD + QED, where the electric charges of sea-quark loops are included in the fermion determinant. Starting from an SU(3) symmetric point inspired by Dashen's scheme, we use a flavor symmetry breaking expansion to extrapolate to the physical quark masses and interpolate to the physical QED coupling

These new gauge field configurations will allow us to resolve the influence of electromagnetic interactions on hadronic masses, structure and processes



Density of +ve (red) & -ve (purple) chg compared with QCD action density

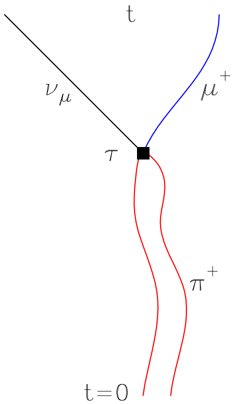


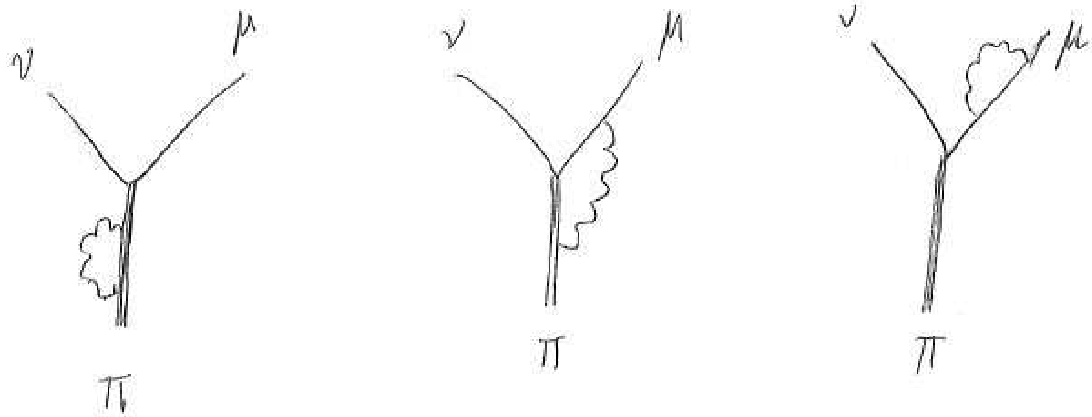
Chiral magnetic effect

Pion and Kaon decays

$\pi^+ \to \mu^+ \nu_\mu$

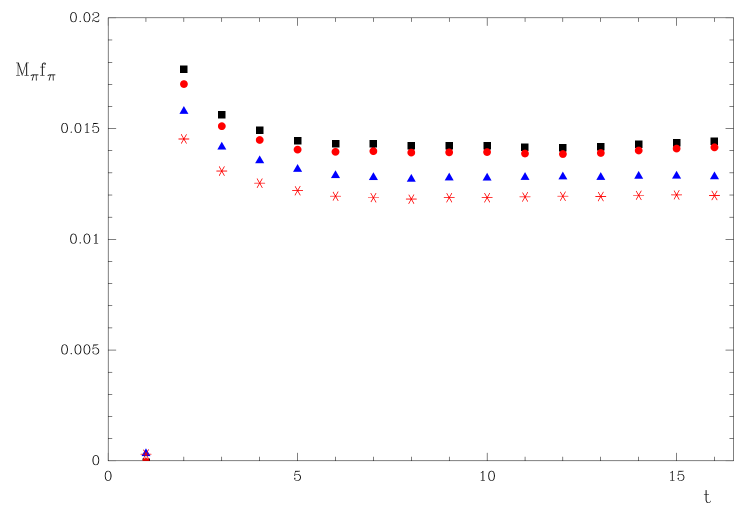
Diagrammatically



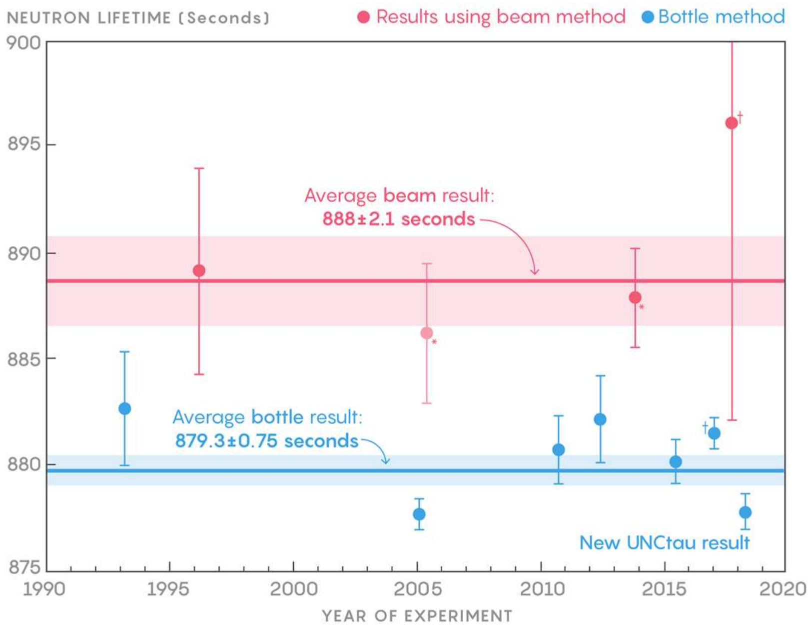


Green function

$$\bar{u}_\nu G u_\mu = M_\pi f_\pi e^{(E_\mu - M_\pi)\tau} \frac{2m_\mu}{E_\mu} \sqrt{E_\mu - p}$$



Neutron lifetime puzzle



$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{ud}|^2}{2\pi^3} m_e^5 \,(1 + 3\, g_A^2)\,(1 + RC)$$

$\uparrow$

main uncertainty

It has been argued that neutrons sometimes decay into dark matter instead of protons, disappearing from bottles at a faster rate than protons appear in beams, exactly as observed

Fornal & Grinstein

$\updownarrow$

$\boxed{g_A}$

Summary

– CP violation in nucleon and nuclei from EDM ($\bar{q}\gamma_5 q$), quark chromo–EDM ($\bar{q}\gamma_5\sigma_{\mu\nu} q G_{\mu\nu}$) and gluon chromo–EDM ($G_{\mu\nu}G_{\nu\rho}G_{\rho\sigma}$)

– Unpolarized and polarized nucleon structure functions, down to small x including higher twist, and generalized parton distribution functions (GPDs)

– Isospin violation and precision calculation of hadronic processes from $N_f = 1 + 1 + 1$ lattice QCD + QED using $O(a)$ improved clover fermions

Benefit to EU Research Infrastructures: Lattice calculations have become an essential tool to realize and exploit the full potential of the investment in accelerators and detectors