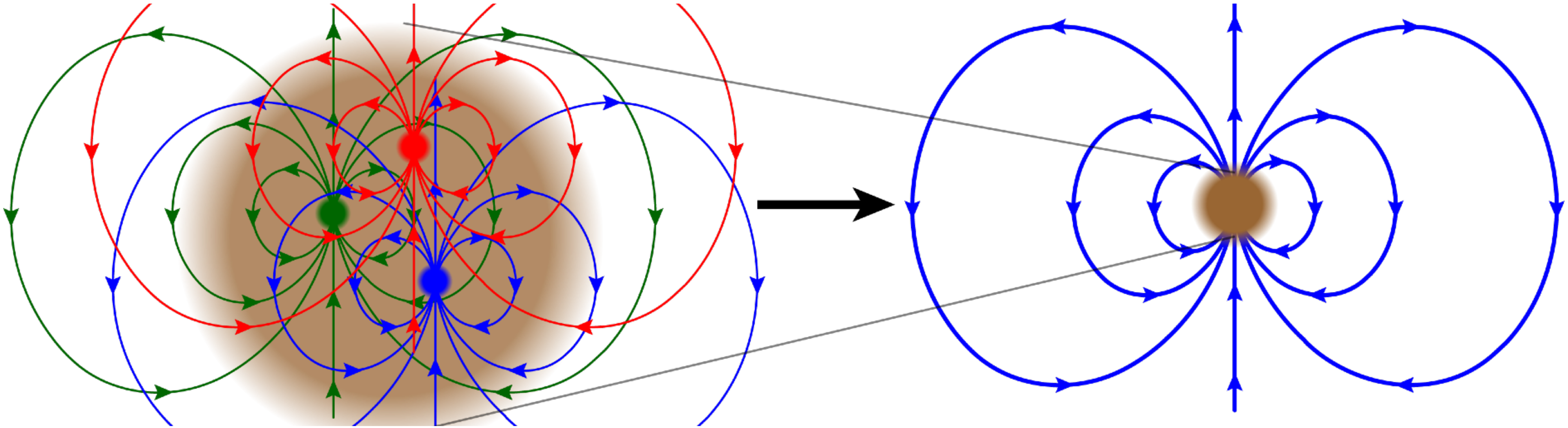

CONSTRAINING BSM PHYSICS (DUE TO CP-VIOLATION) ON THE LATTICE

RDP PHD SCHOOL & WORKSHOP, "ASPECTS OF SYMMETRY" 10.11.2021

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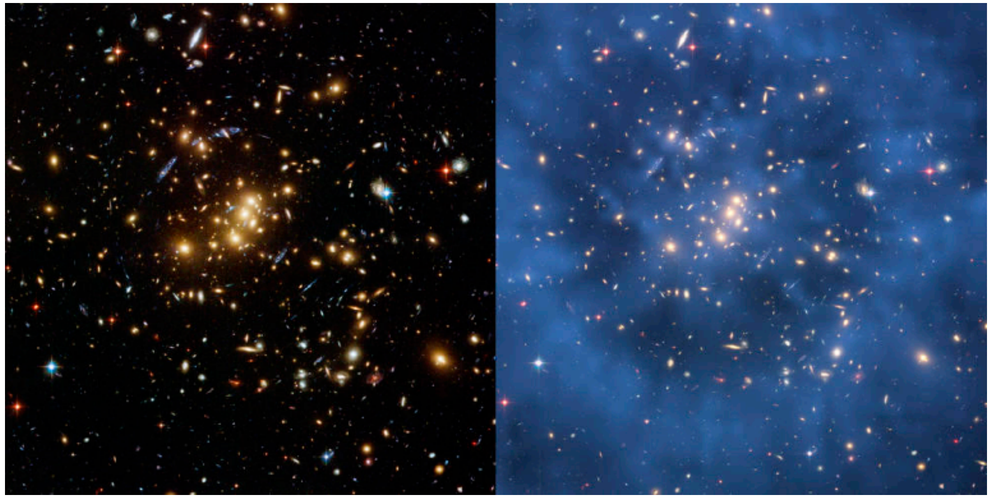
JARA-HPC on the supercomputer JURECA

SYMLAT

JÜLICH Forschungszentrum

WHY DO WE EXPECT BEYOND-THE-STANDARD-MODEL (BSM) PHYSICS?

Perspective

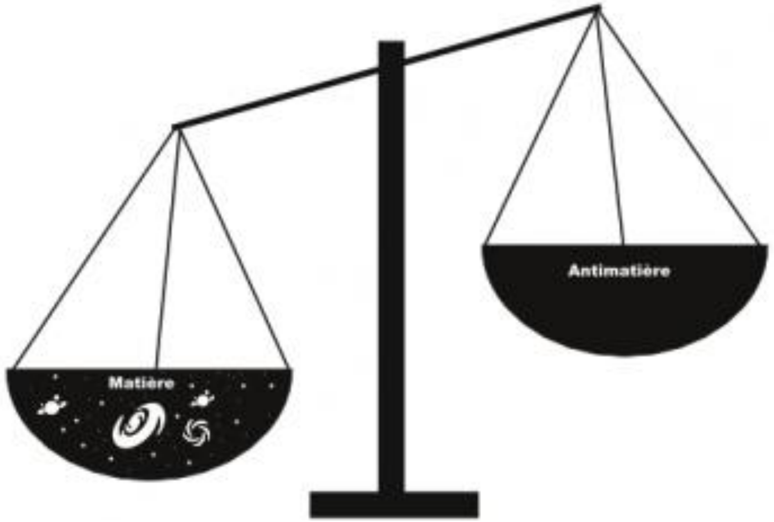


- Our theories are incomplete
  - Quantum Chromodynamics (QCD)
  - Electroweak theory
  - Gravity

- Cannot explain dark matter/energy

- Cannot explain matter/anti-matter asymmetry

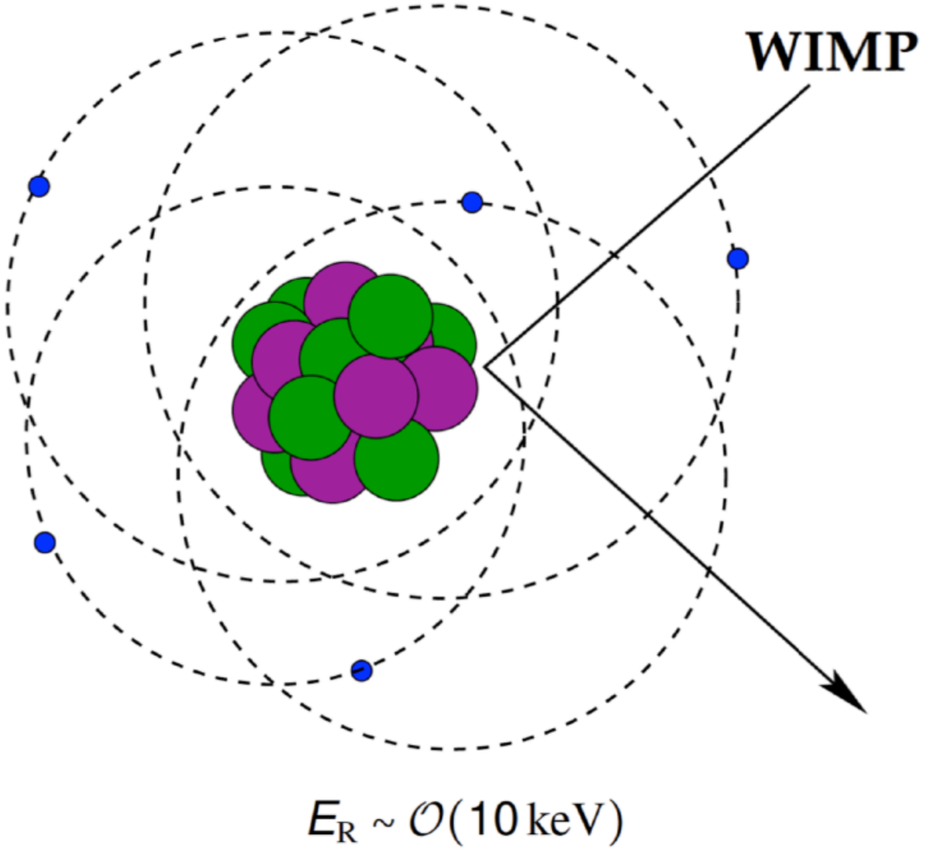
- Effective theories of some greater theory



WHY IS QUANTUM CHROMODYNAMICS (QCD) RELEVANT FOR BSM PHYSICS?

Motivation

- Detection of any **BSM** signal will come from probes involving **hadronic** systems
  - Examples:
    - Recoil scattering of **nuclei** with **WIMPS**
    - Precision measurements of muon g-2
    - **CP violation** in **neutron/nuclei**
- **Hadrons** are governed by QCD (theory of quarks and gluons)
- BSM process will act on a lower/fundamental level (e.g. quarks and gluons), but will be masked by the hadronic (QCD) processes



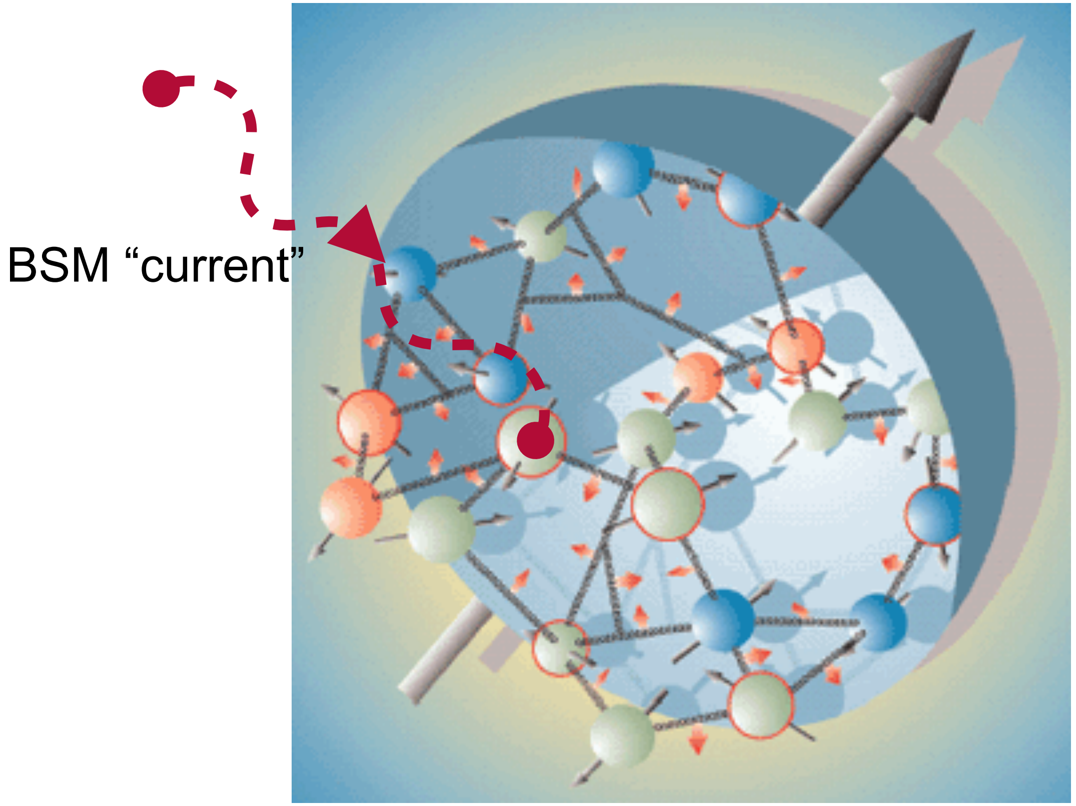
Any (future) BSM signal will be intertwined with QCD physics

BSM PHYSICS REQUIRES *PRECISION* MEASUREMENTS ON HADRONIC SYSTEMS

This requires precision QCD calculations

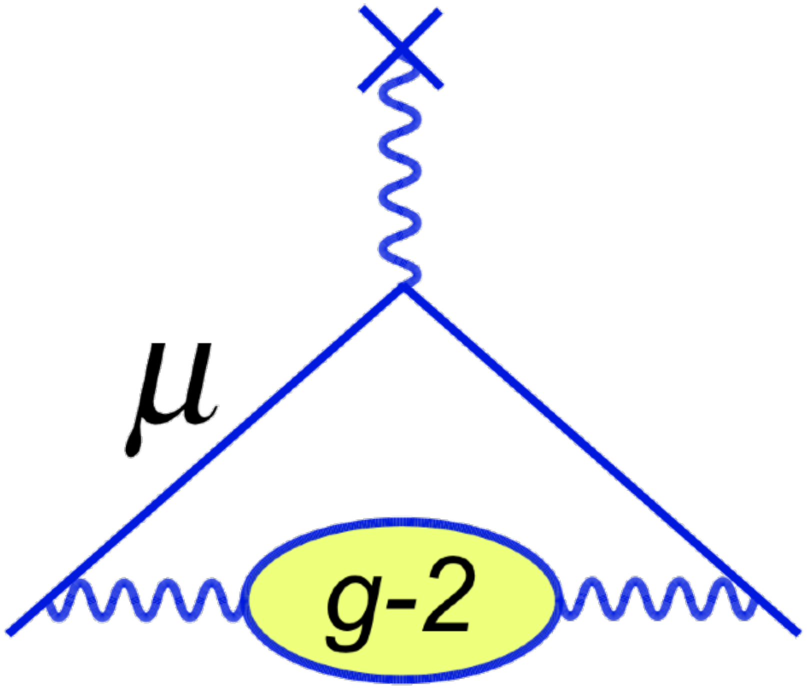
- Any BSM signal will be ***small!***
  - Requires precision physics
  - *Low-energy precision frontier*

$$\langle N | \underbrace{\mathcal{C}\bar{\psi}_q \Gamma \psi_q}_{\text{generic BSM interaction}} | N \rangle \sim \bar{\mathcal{C}} \underbrace{F(Q)}_{\text{form factor, contains QCD part}}$$



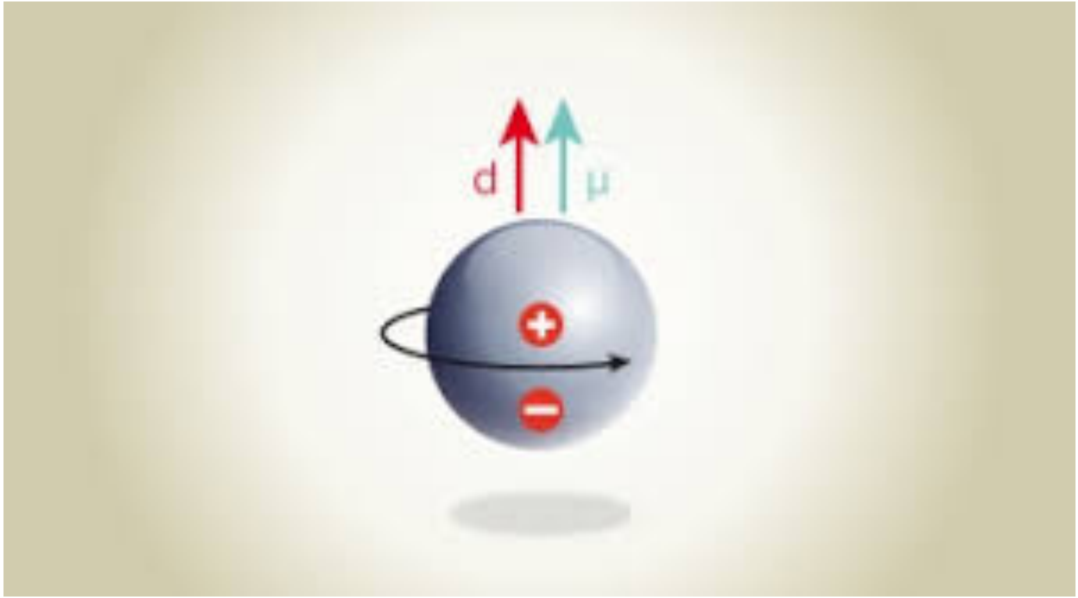
Reliable BSM signature requires equally precise knowledge of hadronic component

EXAMPLES WHERE THE INTERPLAY HADRONIC COMPONENT IMPACTS OUR ASSESSMENT OF BSM



Muon g-2

- Discrepancy between theory and experiment
  - BSM physics?
- Hadronic component provides one of the largest theory uncertainty



Neutron electric dipole moment

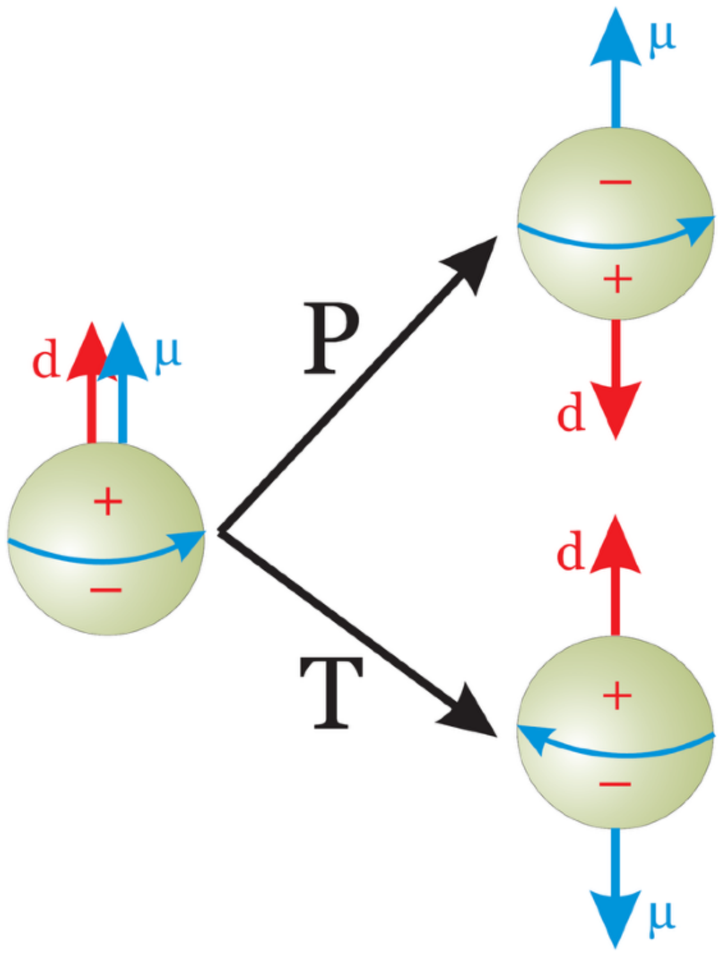
This talk will concentrate on this phenomenon

another BSM/Lattice example

$0\nu\beta\beta$ - CalLat, 1805.02634
- Davoudi & Kadam, 2012.02083

WHAT GIVES NEUTRON AN EDM?

CP violation



Knecht thesis ‘09

- EDM changes orientation relative to particle spin under
  - parity (spatial inversion)
  - time-reversal (running time backwards)
- Therefore permanent EDM is not symmetric with either P or T
- With charge conjugation C, then CPT is preserved
  - CP and T are separately violated

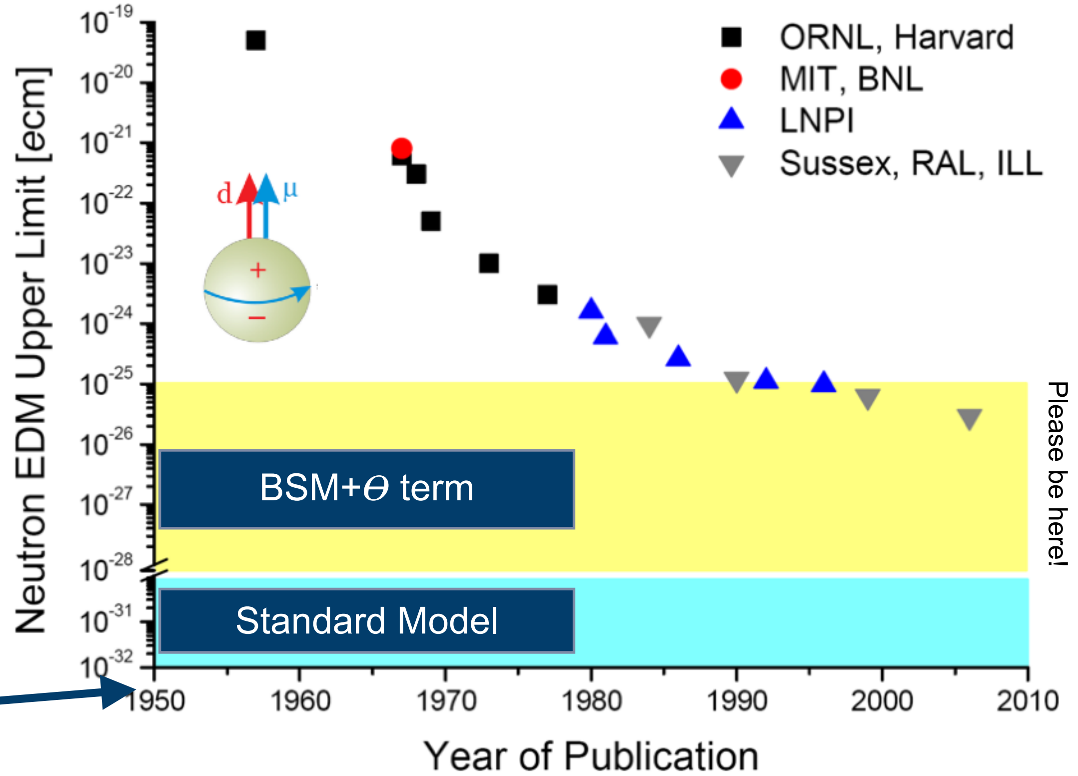
DOESN'T THE STANDARD MODEL (SM) HAVE SOURCES OF CP VIOLATION?

CP violation and the matter/anti-matter asymmetry

- Weak interactions (part of SM) violate CP within CKM matrix

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- CP violation is one of the necessary conditions for matter/anti-matter asymmetry
- However, does not provide sufficient amount of CP violation!



Knecht thesis '09

Non-zero measurement of nEDM could signify BSM physics!!

MORE SOURCES OF CP-VIOLATION

Standard Model

- CKM matrix

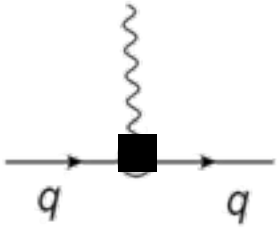
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- Strong θ-term

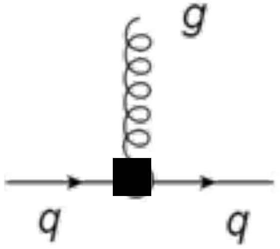
$$-\frac{n_f g^2 \theta}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Beyond Standard Model

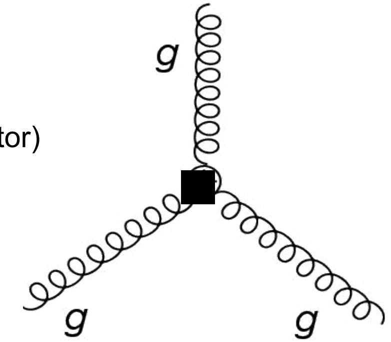
- quark EDM



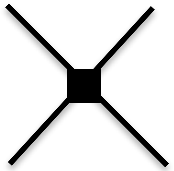
- quark Chromo-EDM



- gluon EDM (Weinberg operator)



- 4-quark interaction



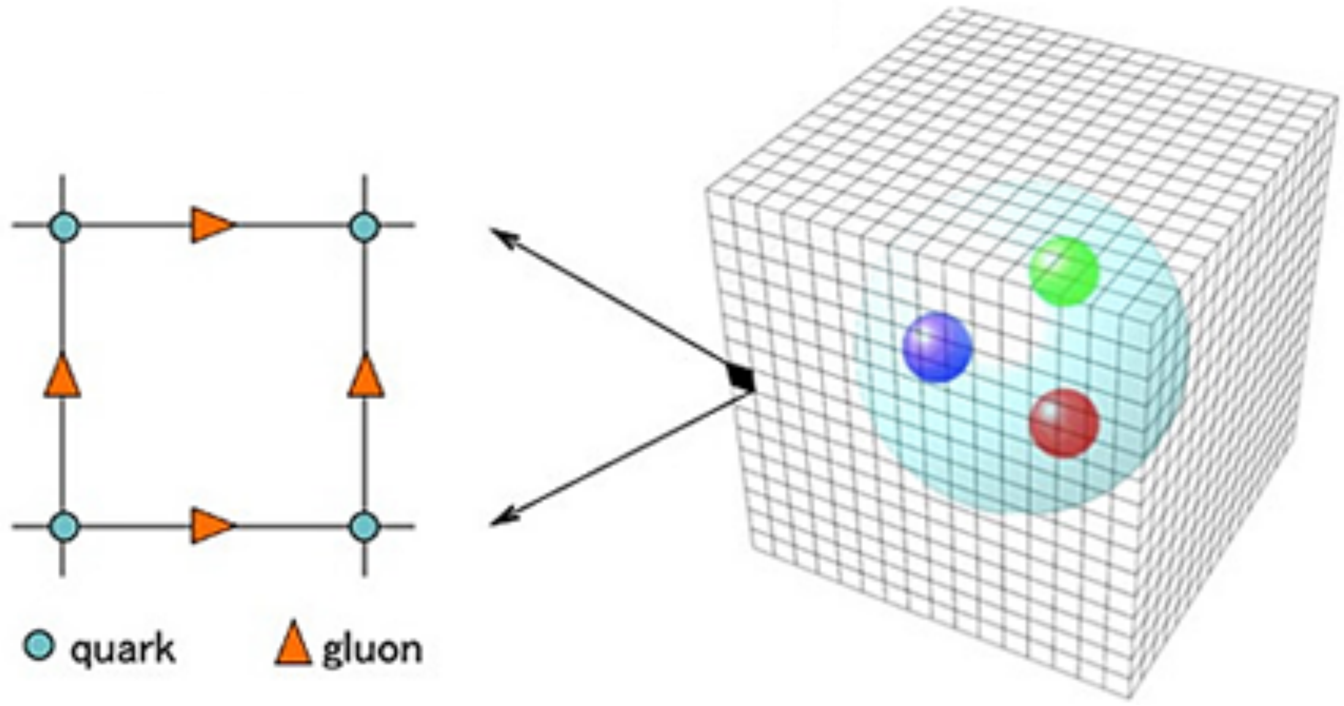
Dimension $\geq$ 5 operators

LATTICE QCD 101

Introduction to living in a discretised, finite world

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s} \bar{q}\left[i\gamma^{\mu}\left(\partial_{\mu} - igA_{\mu}\right) - m_q\right]q$$



Perform Path Integral

$$\langle \hat{O} \rangle = \frac{\int dA\ O[A]\ e^{-S[A]}}{\int dA\ e^{-S[A]}}$$

Sample relevant configurations

$$A_i\ dA \sim \frac{e^{-S[A_i]}\ dA}{\int dA\ e^{-S[A]}}$$

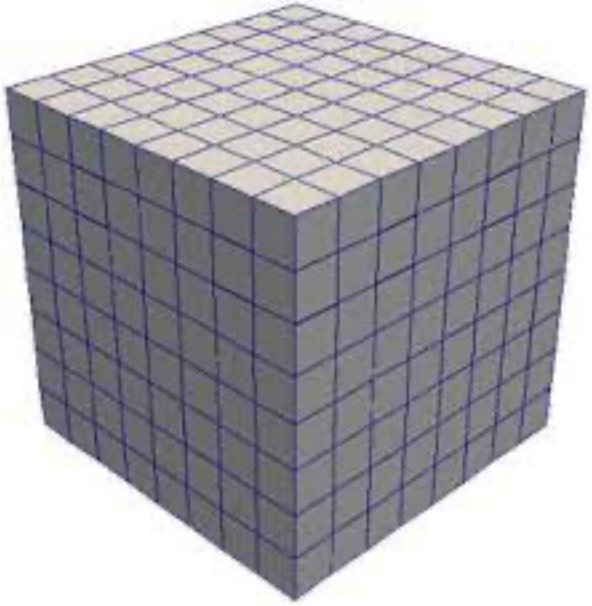
Monte-Carlo estimate

$$\langle \hat{O} \rangle = \frac{1}{N_{cfg}} \sum_{A_i \in \{A\}} O[A_i] + \mathcal{O}\left(N_{cfg}^{-1/2}\right)$$

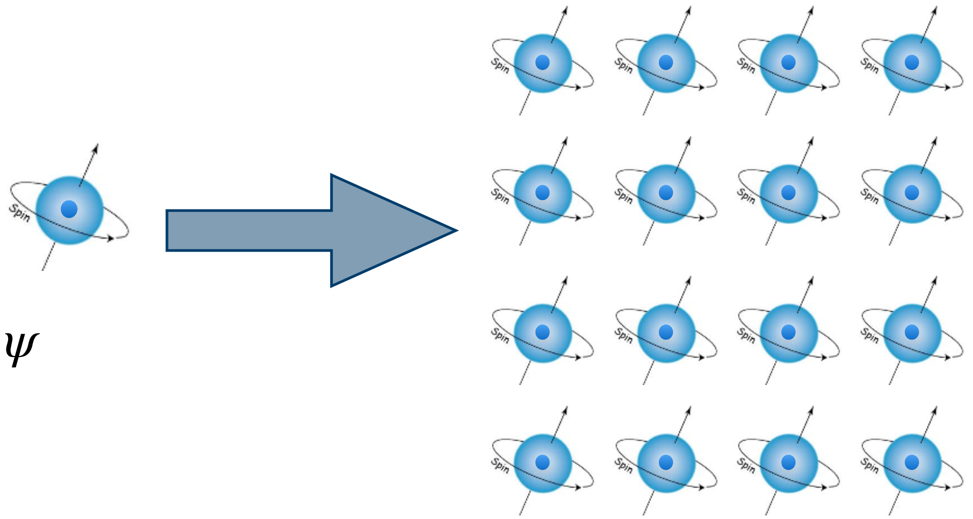
Only known first principles calculation
of QCD in confinement regime

SYMMETRIES ON THE LATTICE

The consequences of living in a (discretised) box



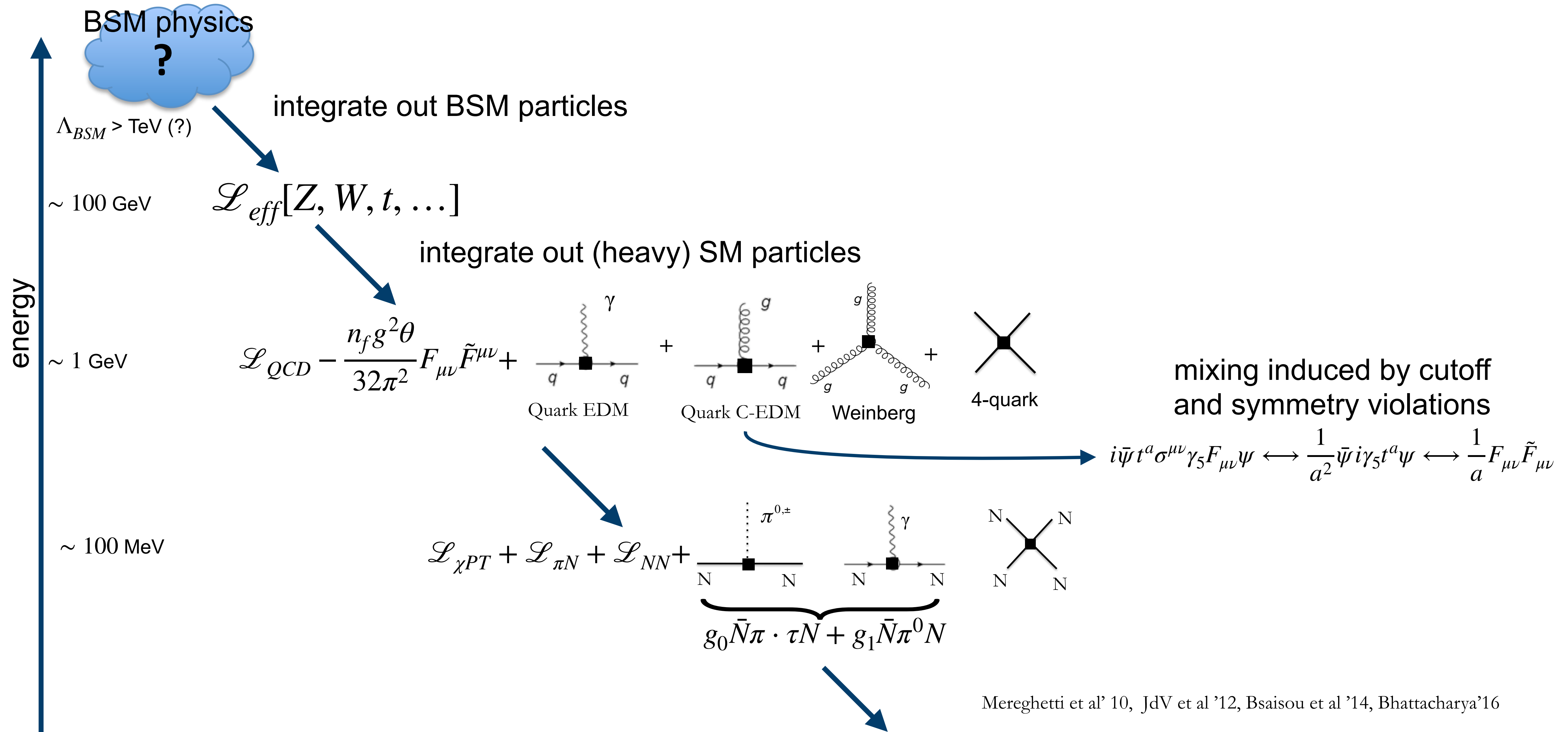
- Box implies Octahedral group O: finite dimensional A_1, A_2, T_1, T_2, E
  - Infinite volume have O(3): J=0,1,2,3,. . .
  - $\Longrightarrow$ mixing of angular momenta in a finite volume
    - A_1^+; J=0,4,6,8,. . . ; T_1^-; J=1,3,5,7,. . .
    - More complicated mixing with boosted systems
    - But we know how to deal with this mixing



- *Harder problem:* consequences of discretisation
  - *Nielsen-Ninomiya* theorem: chiral symmetry $\Longrightarrow$ fermion doublers
  - Removal of doublers: Wilson action breaks *chiral symmetry*: $\frac{a}{2}\bar{\psi}\nabla_\mu\nabla_\mu^*\psi$
  - Consequence: *Additive* renormalisations

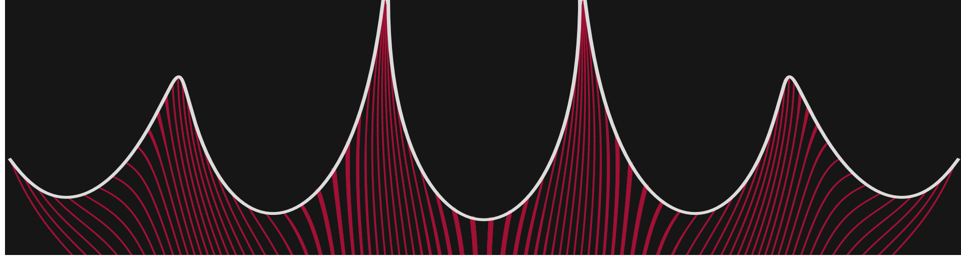
BSM PHYSICS AT LOW ENERGIES VIA EFFECTIVE FIELD THEORIES

How BSM CP violating operators generalise at low energies (i.e. renormalization)



ENTER THE GRADIENT FLOW

Introducing yet another dimension



- Define extra “flow time” dimension
- Fields (gluon and fermion) in this extra dimension via differential equations
- Initial conditions of the differential operator are the original fields, e.g. $B_{t=0,\mu} = A_\mu$

Lüscher, 2010

GRADIENT FLOW

Heat equation applied to configurations

$$\partial_t B_{t,\mu} = D_{\nu,t} G_{t,\nu\mu}$$ ← element of SU(N)

$$D_\mu G_{\nu\sigma} = \partial_\mu G_{\nu\sigma} + \left[B_\mu, G_{\nu\sigma}\right]$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu + [B_\mu, B_\nu]$$

“Smooths” high-energy fluctuations

$$B_{t,\mu}(x) = \int d^4y K_t(x-y)\, A_\mu(y)\ , \quad K_t(x) = \frac{\mathrm{e}^{-\frac{x^2}{4t}}}{(4\pi t)^2}$$

Analogous flow equations for fermionic fields

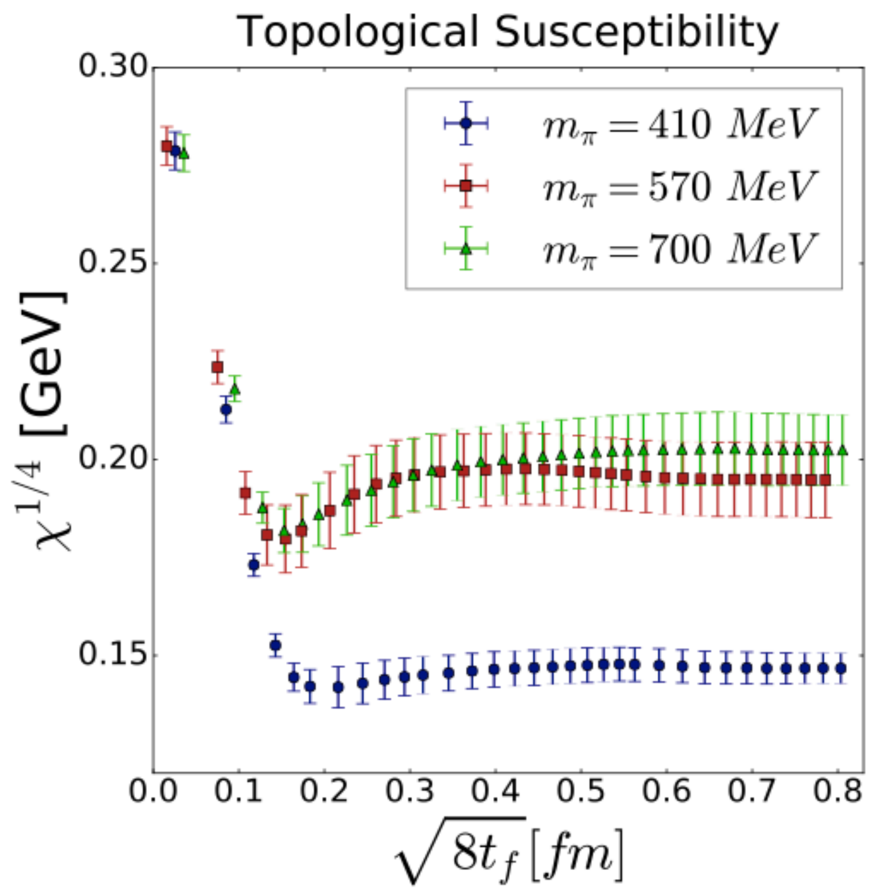
BENEFITS OF THE GRADIENT FLOW

Removing unwanted lattice artifacts

- Can use standard field theoretical techniques at non-zero flow time
  - Shindler et al., 2014, 2015

- Power divergences at t=0 turn into milder 1/t dependence at nonzero flow time
  - have control over dependence by integrating longer in flow time

- Can formulate theory at non-zero flow time in the continuum
  - Perform perturbative expansion in 1/t (“short flow time expansion”)
  - Continuum theory avoids *additive* renormalizations, only have *multiplicative* renormalizations



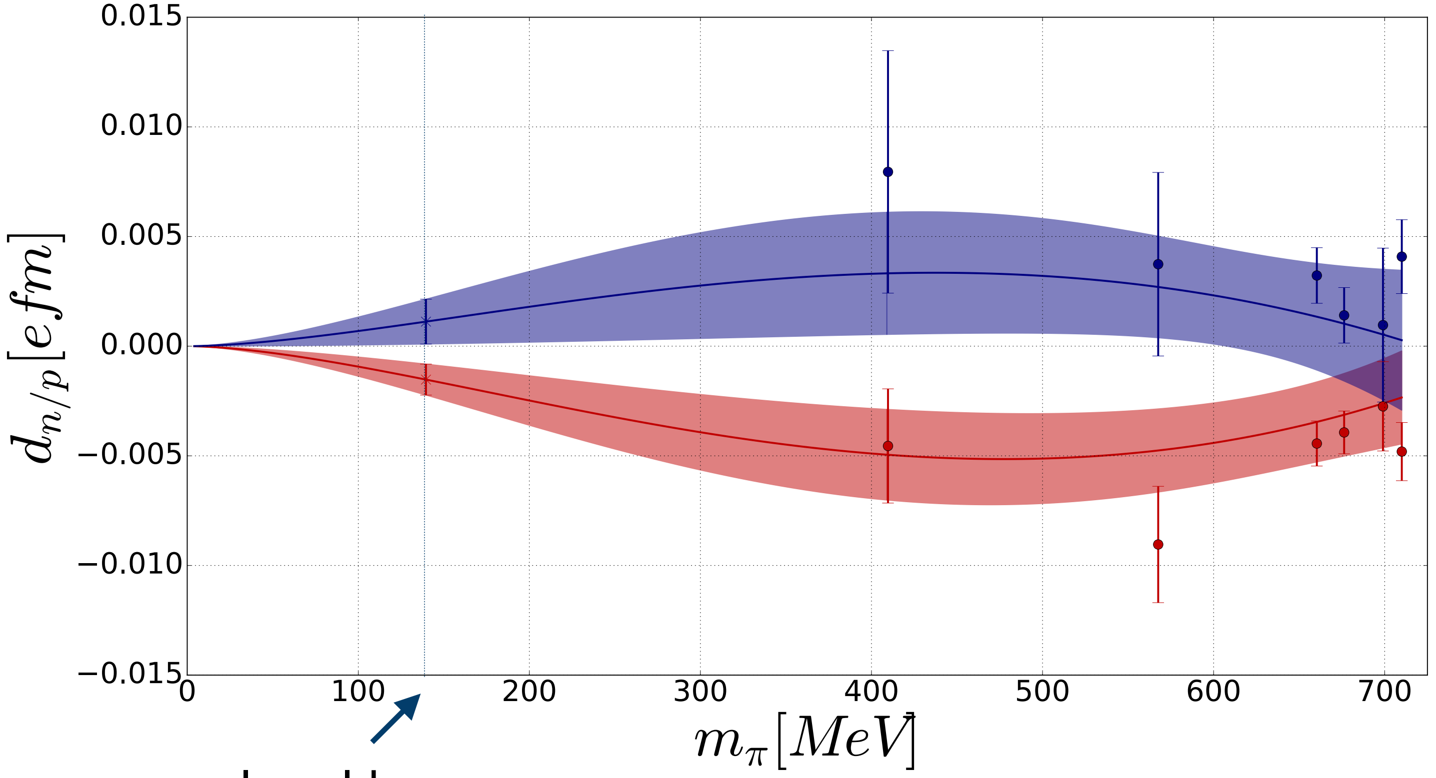
arXiv:1902.03254

In many cases, the gradient flow protects us from systematic errors associated with the lattice spacing

NUCLEON EDM VIA THE STRONG θ TERM

SymLat:
arXiv:1902.03254
arXiv:1809.03487
arXiv:1711.04730
arXiv:1507.02343
arXiv:1409.2735

CJIAS40 JARA-HPC



$\times\ \bar{\theta}\ e\ \text{fm}$

- Correctly accounts for mixing of form factors in finite volume
- Statistically non-zero result from LQCD

$|\bar{\theta}| < 1.98 \times 10^{-10}$ at 90% CL

real world

$d_n = -0.00152(71)\bar{\theta}e\text{fm}$

$d_p = 0.0011(10)\bar{\theta}e\text{fm}$

→ $\bar{g}_0 = -12.8(6.4) \times 10^{-3}\bar{\theta}$ →

in agreement with results from nucleon mass splittings
de Vries, Mereghetti, Walker-Loud, 1506.06247, 1612.01567, 1612.07733

$d_{^2\text{H}}(\bar{\theta}) = 0.2(1.2) \times 10^{-3}\bar{\theta}e\text{fm}$

$d_{^3\text{H}}(\bar{\theta}) = 3.2(1.0) \times 10^{-3}\bar{\theta}e\text{fm}$

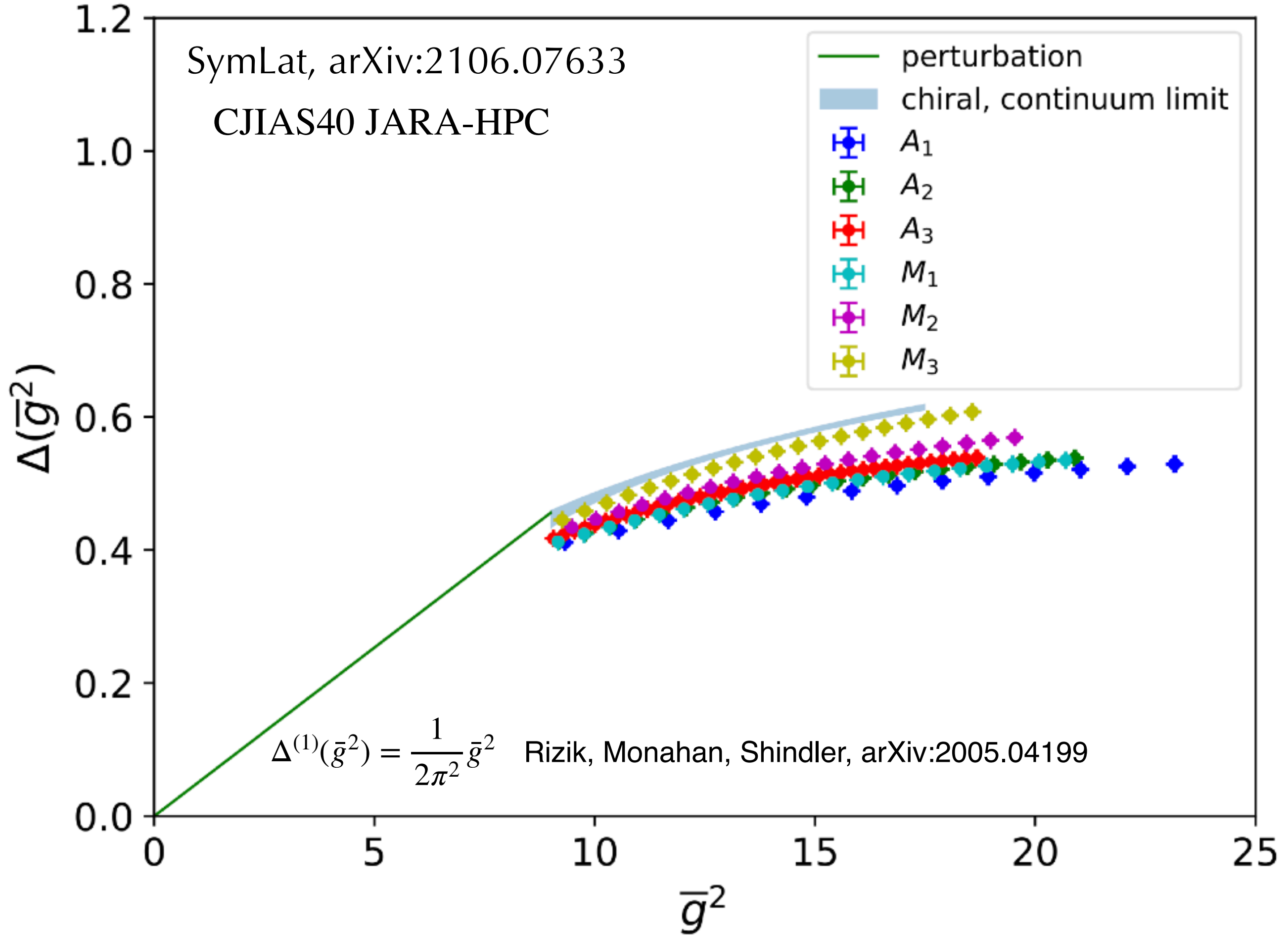
$d_{^3\text{He}}(\bar{\theta}) = -2.5(0.8) \times 10^{-3}\bar{\theta}e\text{fm}$

prediction

imaginary θ rotation Guo et al., 1502.02295

NON-PERTURBATIVE RENORMALISATION OF THE QUARK CHROMO-EDM OPERATOR

Using the gradient flow to determine the renormalised coupling to the pseudoscalar density



$$\langle O_{qEDM} \rangle \propto \Delta(\bar{g}^2)\langle P \rangle$$

Similar investigations are ongoing with the Weinberg operator

Dragos, **TL**, Shindler, de Vries arXiv:1711.04730
Rizik, Monahan, Shindler, arXiv:2005.04199

SymLat, arXiv:1810.10301, 1902.03254

SO WHERE DO WE STAND?
Flavor diagonal CP violation, from a LQCD perspective