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CP-Violation, Hadron Physics and QCD Spectroscopy

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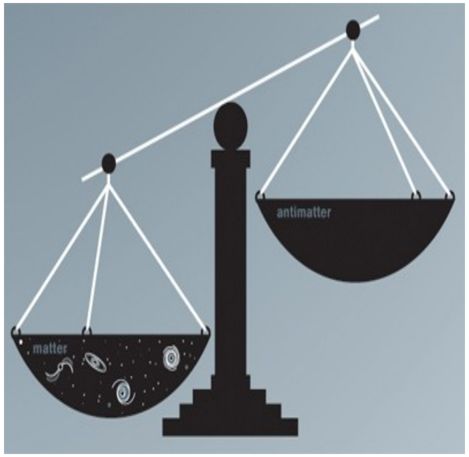
Outline

1. CP-violation in precision experiments
2. EFT description of BSM physics
3. Role of QCD matrix elements
4. Matching relations: CP-odd matrix elements and hadron spectroscopy
5. Brief summary

Why is CP violation interesting?

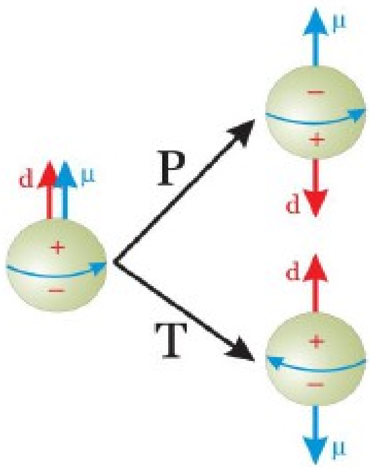
- Baryon asymmetry of the universe (BAU) requires an explanation; $$Y_B = \frac{n_B}{s} = (8.61 \pm 0.09) \times 10^{-11}$$
  Planck Collaboration, A&A 594, A13 (2016)
- Sakharov criteria: *A.D.Sakharov, Pisma Zh. Eksp. Teor. Fiz 5 (1967) 32*
  - B-violation
  - C and CP-violation
  - Interaction out of thermal equilibrium

CP-violation → T-violation by CPT theorem

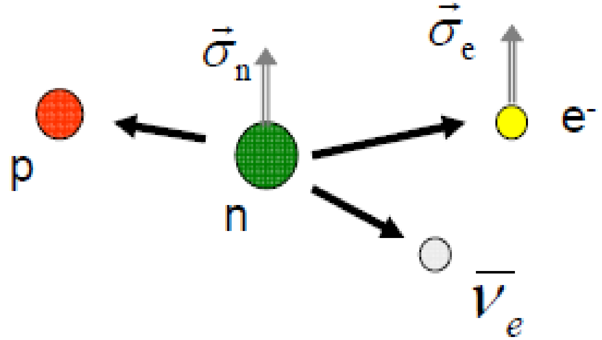


Tests of BSM CP/T-Violations at Low Energy

- Electric Dipole Moments (EDMs)



- Polarized beta decays/
  Electron-nucleon scattering



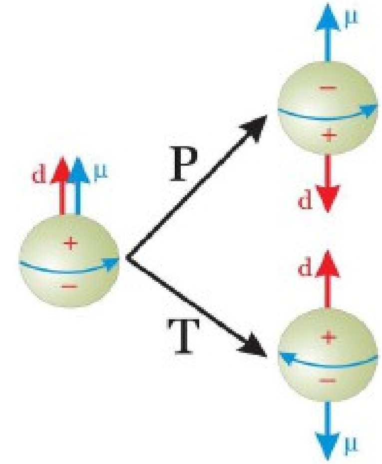
- Rare meson decays

$$\eta \to \pi\pi \quad \eta \to 3\gamma$$

- …

(SM contributions are either negligible or under control)

Tests of BSM CP/T-Violations at Low Energy



Most stringent bounds on EDMs:

System	Present Limit (e cm)	SM Prediction (CKM) (e cm)
e	8.7×10^{-29} ACME 2014	10^{-38}
Hg	7.4×10^{-30} UW-Seattle 2016	10^{-33}
p	7.9×10^{-25} Deduced from Hg	10^{-31}
n	3.0×10^{-26} ILL 2006	10^{-31}

1.6 (deduced from Hg)

Effective Field Theory

- A **bottom-up** and **model-independent** approach to BSM physics
- Instead of new heavy DOFs, we have **higher-dimensional operators** consist of **SM DOFs**

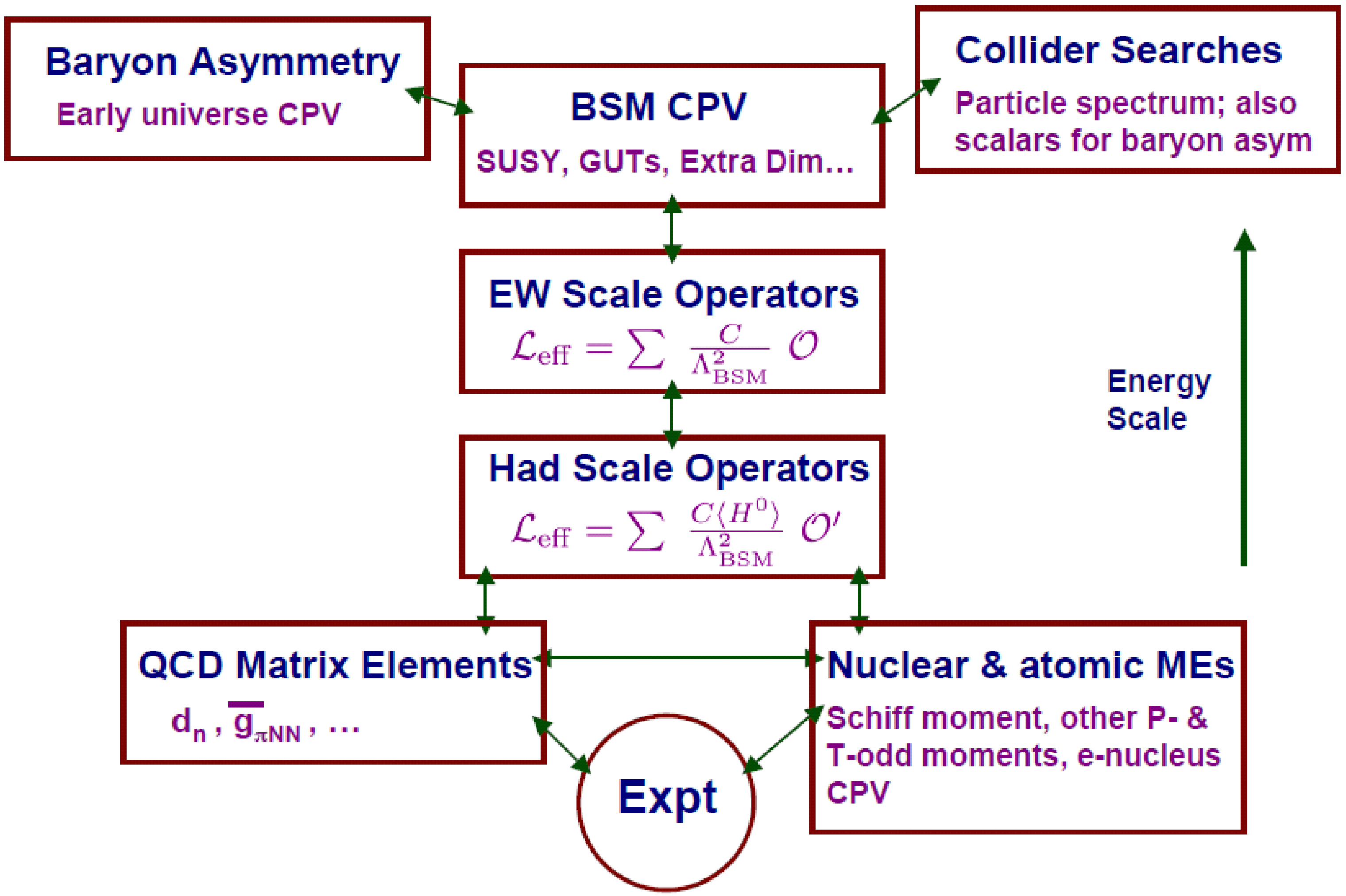
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{BSM}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{BSM}}\mathcal{L}_6 + \ldots$$

- **59 operators** at dimension 6 at **EW scale** (barring flavor structures and Hermitian conjugations) that respect SM gauge symmetry and conserve baryon number

Grzadkowski et al, JHEP 1010 (2010) 085

- At hadron scale, quark/gluon DOFs are replaced by **hadronic DOFs**.

EFTs at different scale



Engel, Ramsey-Musolf and van Kolck, Prog. Part. Nucl. Phys. 71 (2013) 21

CP-Odd Effective Operators At $\mu \gtrsim 1\,\mathrm{GeV}$

Wilson Coefficient	Operator (dimension)	Number	Systems
$\bar{\theta}$	theta term (4)	1	hadronic & diamagnetic atoms
δ_e	electron EDM (6)	1	paramagenetic atoms
$\mathrm{Im}\, C_{\ell equ}^{(1,3)}$, $\mathrm{Im}\, C_{\ell eqd}$	semi-leptonic (6)	3	& molecules
δ_q	quark EDM (6)	2	hadronic &
$\tilde{\delta}_q$	quark chromo EDM (6)	2	diamagnetic atoms
$C_{\tilde{G}}$	three-gluon (6)	1	
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	four-quark (6)	2	
$\mathrm{Im}\, C_{\varphi ud}$	induced four-quark (6)	1	
total		13	

Engel, Ramsey-Musolf and van Kolck, Prog. Part. Nucl. Phys. 71 (2013) 21

CP-Odd Effective Operators at Hadron Scale

Non-Leptonic:

$$\mathcal{L}_{N\pi}^{\mathrm{TVPV}} = -2\bar{N}\left(\underline{\bar{d}_0} + \underline{\bar{d}_1}\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu} + \bar{N}\left[\underline{\bar{g}_\pi^{(0)}}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \underline{\bar{g}_\pi^{(1)}}\pi^0 + \underline{\bar{g}_\pi^{(2)}}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right] N$$

$$+\underline{\bar{C}_1}\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \underline{\bar{C}_2}\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right) + \cdots .$$

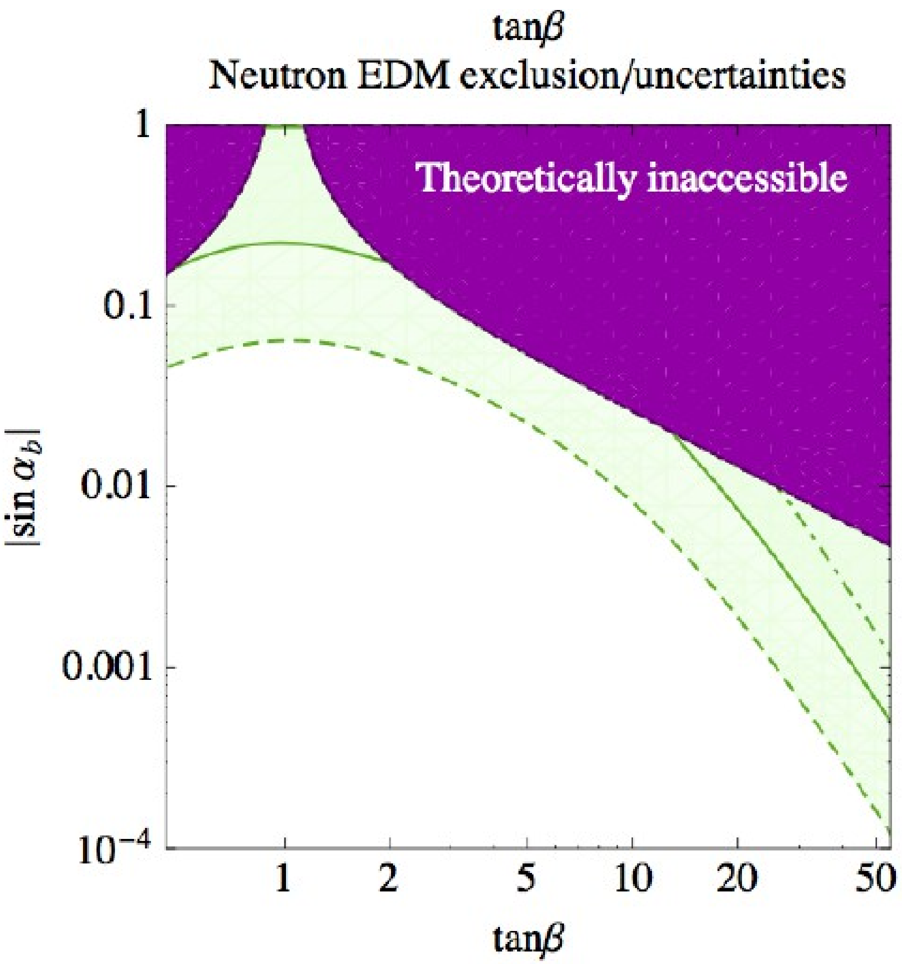
Semi-Leptonic:

$$\mathcal{L}_{eN}^{\mathrm{eff}} = -\frac{G_F}{\sqrt{2}}\left\{\bar{e}i\gamma_5 e\,\bar{N}\left[\underline{C_S^{(0)}} + \underline{C_S^{(1)}}\tau_3\right]N - 8\,\bar{e}\sigma_{\mu\nu}e\,v^\nu\bar{N}\left[\underline{C_T^{(0)}} + \underline{C_T^{(1)}}\tau_3\right]S^\mu N\right\} + \cdots .$$

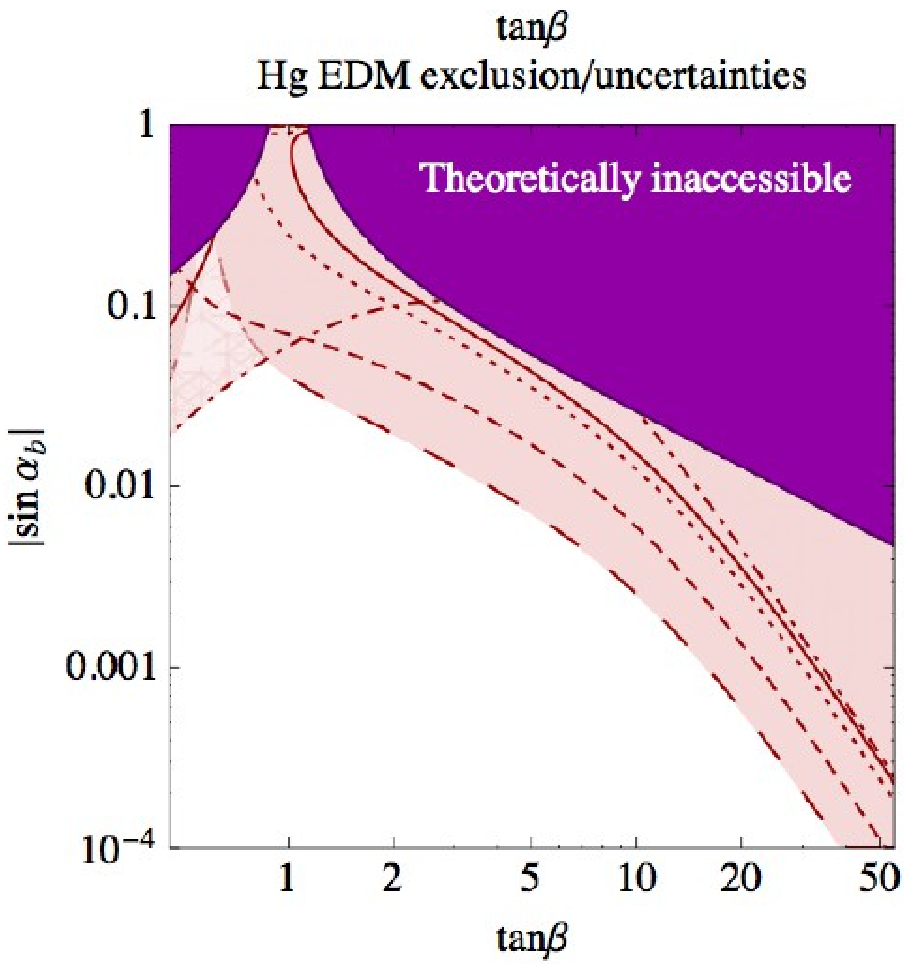
Engel, Ramsey-Musolf and van Kolck, Prog. Part. Nucl. Phys. 71 (2013) 21

Transition between operators with q/g DOFs and hadronic DOFs involve **QCD matrix elements** that are difficult to be obtained from first principle

Yet, precise QCD matrix elements are crucial for interpretation of experiments



Uncertainty due to hadronic matrix element



Uncertainty due to nuclear matrix element

Inoue, Ramsey-Musolf and Zhang, Phys.Rev. D89 (2014) no.11, 115023

Strategy: Chiral Perturbation Theory+Lattice

- Let us concentrate on chirally non-invariant P, T-odd QCD matrix elements
- May be generated by:

  1. ***P, T-odd***, ***chirally invariant*** operators ⊗ quark mass
  2. ***P, T-odd***, ***chiral symmetry breaking (CSB)*** operators

- For the latter case, the operator may contain ***P, T-even*** and ***P, T-odd*** components. The former may lead to P, T-even QCD matrix elements—**spectroscopic quantities** ⟶ **Calculable on lattice**
- Matching relation exists for these two types of matrix elements

Mereghetti, Hockings and van Kolck, Annals Phys. 325 (2010) 2363-2409

de Vries et al, Annals Phys. 338 (2013) 50-96

Bsaisou et al, Annals Phys. 359 (2015) 317-370

de Vries, Mereghetti and Walker-Loud, Phys. Rev. C. 92 (2015) 4

Strategy: Chiral Perturbation Theory+Lattice

Single CSB source

P, T-even component

P, T-odd component

P, T-even QCD matrix elements:
Spectroscopic quantities

P, T-odd QCD matrix elements

(through ChPT)

Matching Relation

Strategy: Chiral Perturbation Theory+Lattice

One example: the **pion-nucleon coupling** $\bar{g}_\pi^{(0)} \bar{N}\vec{\tau}\cdot\vec{\pi}N + \bar{g}_\pi^{(1)}\pi_0\bar{N}N - 3\bar{g}_\pi^{(2)}\mathcal{I}^{ab}\pi_a\bar{N}\tau_b N$

Contribute to **nucleon /atomic EDMs.**

Underlying sources: : CSB Sources

Wilson Coefficient	Operator (dimension)	Number	Systems
$\bar{\theta}$	theta term (4)	1	hadronic & diamagnetic atoms
δ_q	quark EDM (6)	2	hadronic & diamagnetic atoms
$\tilde{\delta}_q$	quark chromo EDM (6)	2	
$C_{\tilde{G}}$	three-gluon (6)	1	
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	four-quark (6)	2	
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Strategy: Chiral Perturbation Theory+Lattice

One example: the **pion-nucleon coupling** $\bar{g}_\pi^{(0)} \bar{N}\vec{\tau} \cdot \vec{\pi} N + \bar{g}_\pi^{(1)} \pi_0 \bar{N} N - 3\bar{g}_\pi^{(2)} \mathcal{I}^{ab} \pi_a \bar{N} \tau_b N$

Contribute to **nucleon /atomic EDMs.**

Leading T-odd, CSB operators:

$$
\begin{aligned}
\theta - \mathrm{term} \quad &: \quad -\bar{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \\
\mathrm{cMDM/cEDM} \quad &: \quad \sum_q g_s \tilde{d}^M_q \bar{q} \sigma^{\mu\nu} \frac{\lambda^a}{2} G^a_{\mu\nu} q - i \sum_q g_s \tilde{d}_q \bar{q} \sigma^{\mu\nu} \gamma_5 \frac{\lambda^a}{2} G^a_{\mu\nu} q \\
\mathrm{LR4Q} \quad &: \quad c_{4q} \bar{d}_L \gamma^\mu u_L \bar{u}_R \gamma_\mu d_R + h.c.
\end{aligned}
$$

Strategy: Chiral Perturbation Theory+Lattice

- **One case in detail: the QCD θ–term**

Complex quark mass matrix

$$\mathcal{L} = c_1 \bar{N} u^\dagger M u N + c_1' \mathrm{Tr}[U^\dagger M] \bar{N} N + h.c.$$

$$= 2\bar{m}_q(c_1 + 2c_1')\bar{N}N - 2\bar{m}_q \varepsilon c_1 \bar{N}\tau_3 N - \frac{2\bar{m}_q(1-\varepsilon^2)\bar{\theta}c_1}{F_\pi}\bar{N}\vec{\tau}\cdot\vec{\pi}N + \ldots$$

Nucleon mass splitting

I=0 CP-odd pion-nucleon coupling

- **The matching relation:**

$$\bar{g}_\pi^{(0)} = \frac{1-\varepsilon^2}{2\varepsilon} \frac{(\delta m_N)_q}{F_\pi} \bar{\theta}$$

- Once we know the **nucleon mass splitting** (induced by quark mass), then we know gpibar **automatically**.
- The former—a spectroscopic quantity—can be calculated on lattice.

$$\bar{g}_\pi^{(0)} = (0.0155 \pm 0.0025)\bar{\theta}$$

de Vries, Mereghetti and Walker-Loud, Phys. Rev. C. 92 (2015) 4

Strategy: Chiral Perturbation Theory+Lattice

- Generalization to other CSB operators:

CYS and Ramsey-Musolf, arXiv:1611.08063 [hep-ph]

$\theta-\text{term}:$

$$\bar{g}_\pi^{(0)} = \frac{1-\varepsilon^2}{2\varepsilon}\frac{(\delta m_N)_q}{F_\pi}\bar{\theta}$$

$\text{quark cEDM}:$

$$\bar{g}_\pi^{(0)} = \frac{1}{F_\pi}\left(-(\delta m_N)_q\frac{(\Delta m_\pi^2)_c}{m_\pi^2}\frac{\tilde{d}_1}{\tilde{d}_0^M} + (\delta m_N)_c\frac{\tilde{d}_0}{\tilde{d}_1^M}\right)$$

$$\bar{g}_\pi^{(1)} = \frac{2}{F_\pi}\left(-(\Delta m_N)_q\frac{(\Delta m_\pi^2)_c}{m_\pi^2} + (\Delta m_N)_c\right)\frac{\tilde{d}_1}{\tilde{d}_0^M}$$

$\text{LR4Q}:$

$$\bar{g}_\pi^{(0)} = -\frac{3(\Delta m_\pi^2)_{4q}}{4F_\pi m_\pi^2}(\delta m_N)_q\frac{\mathrm{Im}c_{4q}}{\mathrm{Re}c_{4q}}$$

$$\bar{g}_\pi^{(1)} = \frac{1}{F_\pi}\left(-\frac{3(\Delta m_\pi^2)_{4q}}{2m_\pi^2}(\Delta m_N)_q + 4(\Delta m_N)_{4q}\right)\frac{\mathrm{Im}c_{4q}}{\mathrm{Re}c_{4q}}$$

(not assuming PQ)

Strategy: Chiral Perturbation Theory+Lattice

- **Caveat**: these relations are derived at tree-level and are subject to **higher-order corrections**:
  - Loop corrections
  - Higher-order LECs

- **θ-term**: once expressed **in terms of nucleon mass splitting**, the tree-level matching relation is **obeyed by 1-loop corrections**. Deviations (due to LECs) appear at NNLO and are not log-enhanced.

de Vries, Mereghetti and Walker-Loud, Phys.Rev. C92 (2015) 4, 045201

- For **cEDM** and **LR4Q**, the tree-level matching relation **breaks down at NLO and NNLO** and the deviations are log-enhanced.

CYS and Ramsey-Musolf, arXiv:1611.08063 [hep-ph]

Strategy: Chiral Perturbation Theory+Lattice

- **The error budget:** *CYS and Ramsey-Musolf, arXiv:1611.08063 [hep-ph]*

TV-source \ Correction		Loop	LEC (*)
Theta term		0	$\gtrsim 10\%$
cEDM	I=0	~2%	$\gtrsim 20\%$
	I=1	Uncontrolled	$\gtrsim 1\%$
LR4Q	I=0	~10%	$\gtrsim 10\%$
	I=1	Uncontrolled	$\gtrsim 1\%$

(*) : Naïve dimensional analysis *(Not assuming PQ)*

Strategy: Chiral Perturbation Theory+Lattice

- **Modified matching relation:**
  - Re-express the dependence on hadron masses in terms of **derivatives (sigma-terms):**

$$
\begin{aligned}
\bar{g}_0 &= \tilde{d}_0 \left(\frac{d}{d\tilde{c}_3} + r \frac{d}{d(\bar{m}\varepsilon)} \right) \delta m_N + \delta m_{N,\mathrm{QCD}} \frac{1-\varepsilon^2}{2\varepsilon} (\bar{\theta} - \bar{\theta}_{\mathrm{ind}}) \\
\bar{g}_1 &= -2\tilde{d}_3 \left(\frac{d}{d\tilde{c}_0} - r \frac{d}{d\bar{m}} \right) \Delta m_N \ ,
\end{aligned}
$$

(for cEDM-induced operators; assuming PQ)

de Vries, Mereghetti, CYS and Walker-Loud, arXiv:1612.01567 [hep-ph]

  - For **cEDM**: NLO and NNLO loop corrections vanish. LEC corrections remain but under control.
  - For **LR4Q** (unpublished): NLO loop correction vanishes but NNLO corrections (loop+LEC) remain.

Strategy: Chiral Perturbation Theory+Lattice

- **Updated error budget:**

TV-source \ Correction		Loop	LEC
Theta term		0	~10%
cEDM (**)	I=0	0	~4%
	I=1	0	~8%
LR4Q	I=0	~10%	~10% (*)
	I=1	Uncontrolled	~1% (*)

(*) : Naïve dimensional analysis

(**) : Assuming PQ

Brief Summary

- Low-energy **precision experiments** offer sensitive probes of **CP-violation** in BSM physics
- It is a crucial yet challenging task to determine the CP-odd Wilson coefficients of hadronic EFTs in terms of BSM parameters: **QCD matrix elements** involved
- **Chiral symmetry** provides matching relations between (a subset of) CP-odd matrix elements to **hadron spectroscopy**. The latter is calculable on lattice
- Higher-order effects up to NNLO are properly taken into account.