EDMs: The Standard Model & Beyond

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About MJRM:

Science

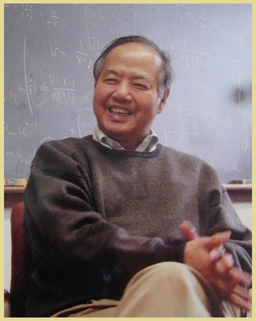
Family

Friends

My pronouns: he/him/his
 # MeToo

Caltech-TDLI EDM Workshop
May 12-14, 2025

T. D. Lee Institute / Shanghai Jiao Tong U.



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

A world famous source of original innovation

Founded 2016

100+

faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

https://tdli.sjtu.edu.cn/EN/

https://www.youtube.com/watch?v=z0awD6q8FTI

Theory & Experiment

- Particle & Nuclear Physics
- Dark Matter & Neutrino
- Astronomy & Astrophysics
- Laboratory Astrophysics
- Quantum Science
- Topological Quantum Computation

About MJRM & EDMs

Volume 196, number 2 PHYSICS LETTERS B 1 October 1987

ELECTRIC DIPOLE MOMENTS OF NUCLEI ☆

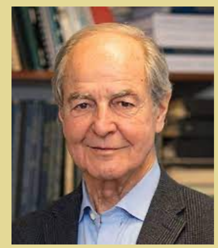
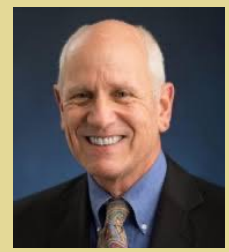
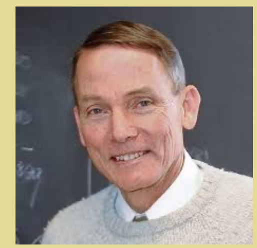
John F. DONOGHUE, Barry R. HOLSTEIN
Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003, USA

and

M.J. MUSOLF
Department of Physics, Princeton University, Princeton, NJ 98540, USA

Received 1 July 1987

Recent calculations by Sushkov, Flambaum and Khriplovich have suggested that the existence of the possibility of kaon exchange within nuclei allows *nuclear* electric dipole moments within the standard model to be enhanced substantially over those of *nucleons*. This suggestion is analysed carefully and it is found that the constraints of chiral symmetry, which were not correctly included in the earlier calculation, reduce this prediction substantially.

First MJRM theory paper


VOLUME 60, NUMBER 21 PHYSICAL REVIEW LETTERS 23 MAY 1988

Nuclear Orientation of Radon Isotopes by Spin-Exchange Optical Pumping

M. Kitano,[a] F. P. Calaprice, M. L. Pitt, J. Clayhold, W. Happer, M. Kadar-Kallen, and M. Musolf
Department of Physics, Princeton University, Princeton, New Jersey 08544

G. Ulm[b] and K. Wendt[c]
ISOLDE, CERN, Geneva Switzerland

T. Chupp
Harvard University, Cambridge, Massachusetts 02138

J. Bonn, R. Neugart, and E. Otten
Universität Mainz, Mainz, Germany

and

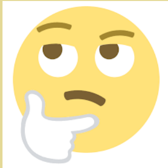
H. T. Duong
Laboratoire Aimè Cotton, Orsay, France
(Received 22 June 1987)

This paper reports the first demonstration of nuclear orientation of radon atoms. The method employed was spin exchange with potassium atoms polarized by optical pumping. The radon isotopes were produced at the ISOLDE isotope separator of CERN. The nuclear alignment of ^{209}Rn and ^{223}Rn has been measured by observation of γ-ray anisotropies and the magnetic dipole moment for ^{209}Rn has been measured by the nuclear-magnetic-resonance method to be $|\mu| = 0.83881(39)\mu_N$.

First MJRM exp't paper

The Search for an EDM: Why Physicists Should Care

- *Theorists think it's interesting*



- *It's something we can do*

- *It addresses fundamental Q's*

EDMs & Fundamental Questions

- *Do the fundamental laws of nature violate CP beyond the known CKM CPV ?*
- *Why does the Universe contain more matter than anti-matter ? Where is the needed CPV ?*
- *What are the implications of BSM scenarios for the foregoing questions ?*
- *What are the corresponding BSM mass scale and dynamics?*

EDM Phenomenology

- *What might EDM searches teach us about these fundamental questions?*
- *How do various EDM searches provide complementary probes ?*
- *What are the prospects for experimental advances & what are the corresponding potential implications ?*

EDMs & Other Frontiers

- *What are the implications of EDM searches for explaining the matter-antimatter asymmetry ?*
- *How do other tests of CP symmetry complement EDM searches ?*
- *What are the implications of searches for new particles (heavy, light) for EDM searches and vice-versa ?*

EDMs: Theory Challenges

- *How can we reliably compute EDMs of hadronic and molecular systems ?*
- *What are the current theoretical uncertainties & how do they impact EDM search implications for fundamental questions?*
- *How reliably can we connect EDM search results with phenomena at other frontiers (cosmology, colliders, etc.) ?*

Goals for This Workshop

- *Review the experimental and theoretical state-of-the-art and prospects for future advances*
- *Share recent developments in theory and experiment*
- *Discuss implications for the foregoing questions*
- *Catalyze new directions, explorations, collaborations*

Outline

I. *EDM Context*

II. *Experimental Situation*

III. *Theoretical Interpretation*

IV. *BSM Implications*

V. *Outlook*

Selected References

- *Engel, MJRM, van Kolck: Prog. Part. Nucl. Phys. 71 (2013) 21 [arXiv:1303.2371]*
- *Pospelov & Ritz, Ann. Phys. 318 (2005) 119 [hep-ph/0504231]*
- *Chupp & MJRM, Phys. Rev. C91 (2015) 035502 [arXiv:1407.1064]*
- *Morrissey & MJRM, New J. Phys. 14 (2012) 125003 [arXiv:1206.2942]*
- *Flambaum & Ginges, Phys. Rept. 397 (2004) 63 [physics/0309054]*
- *Chupp, Fierlinger, MJRM, Singh, Rev. Mod. Phys. 91 (2019) 015001 [1710.02504]*

I. EDM Context

What is an EDM ?

J=1/2, relativistic particles

$$\langle p'|\, J_\mu^{\mathrm{EM}}\, |p\rangle = \bar{U}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \frac{F_A}{M^2}(q^2\gamma_\mu - \not{q}q_\mu)\gamma_5\right]U(p)$$

F_1 :	Dirac (charge) form factor	P, T Conserving
F_2 :	Pauli (magnetic) ff	P, T Conserving
F_3 :	Electric Dipole ff	P, T Violating
F_A :	Anapole ff	P Violating

What is an EDM ?

Non-relativistic diamagnetic systems

Nuclear Moments

	$P\,T$	$\not P\,T$	$P\,\not T$	$\not P\,\not T$
C_J	E	X	X	O
$T^M{}_J$	O	X	X	E
$T^E{}_J$	X	O	E	X

Coulomb → C_J

Magnetic → $T^M{}_J$

Transverse electric → $T^E{}_J$

E: J = 0, 2, …
O: J = 1, 3, ….

What is an EDM ?

Non-relativistic diamagnetic systems

Nuclear Moments

		$P\,T$	$\not{P}\,T$	$P\,\not{T}$	$\not{P}\,\not{T}$	
Coulomb	C_J	E	X	X	O	*EDM, Schiff…*
Magnetic	T^M_J	O	X	X	E	*MQM….*
Transverse electric	T^E_J	X	O	E	X	*Anapole…*

E: J = 0, 2, …
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What is an EDM ?

Non-relativistic diamagnetic systems

Nuclear Moments

	P T	$\not{P}$ T	P $\not{T}$	$\not{P}$ $\not{T}$	
Coulomb → C_J	E	X	X	O	*EDM, Schiff…*
Magnetic → T^M_J	O	X	X	E	*MQM….*
Transverse electric → T^E_J	X	O	E	X	*Anapole…*

Sources of diamagnetic atom EDMS (^{199}Hg…)

E: J = 0, 2, …
O: J = 1, 3, ….

What is an EDM ?

Non-relativistic diamagnetic systems

Nuclear Moments

	$P\ T$	$\not{P}\ T$	$P\ \not{T}$	$\not{P}\ \not{T}$	
Coulomb → C_J	E	X	X	O	EDM, Schiff… (Nuclear Enhancements)
Magnetic → T^M_J	O	X	X	E	MQM….
Transverse electric → T^E_J	X	O	E	X	Anapole…

E: J = 0, 2, …
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EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} +\ d_n^{CKM}$$

EDMs & SM Physics

$$d_n \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} + d_n^{CKM}$$

$$d_n^{CKM} = (1 - 6) \times 10^{-32}\ e\ cm$$

C. Seng arXiv: 1411.1476

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \ (\upsilon / \Lambda)^2\ x\ \ \sin\phi\ \ x\ y_f\, F$$

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \boxed{\sin\phi}\ \times\ y_f\, F$$

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f\, F$$

BSM mass scale: TeV ? Much higher ?

υ = 246 GeV   Higgs vacuum expectation value
Λ > 246 GeV   Mass scale of BSM physics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f F$$

BSM dynamics: perturbative? Strongly coupled?

y_f	Fermion f Yukawa coupling
F	Function of the dynamics

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm) \times \boxed{(\upsilon / \Lambda)^2} \times \boxed{\sin\phi} \times \boxed{y_f F}$$

Need information from at least three "frontiers"

- *Baryon asymmetry* — *Cosmic Frontier*
- *High energy collisions* — *Energy Frontier*
- *EDMs* — *Intensity Frontier*

II. Experimental Situation

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-33}	10^{-30}
HfF^{+}	4.1×10^{-30} **	10^{-38} *	10^{-30}
n	1.8×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^{-} equivalent * e^{-} equivalent from C_S

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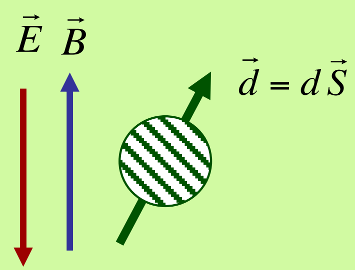
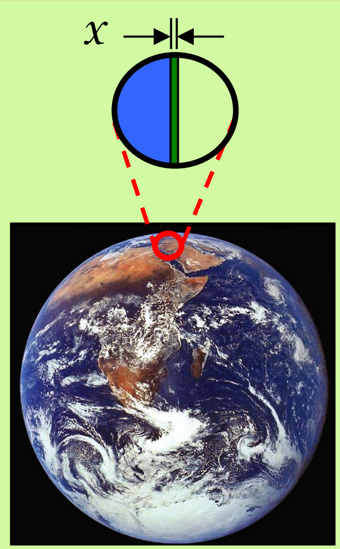


$$\nu_{EDM} = -\frac{d\,\vec{S}\cdot(-\vec{E})}{h}$$

T-odd , CP-odd by CPT theorem



d_n: $x < 0.25$ mm

C-Y Liu

EDMs: New CPV?

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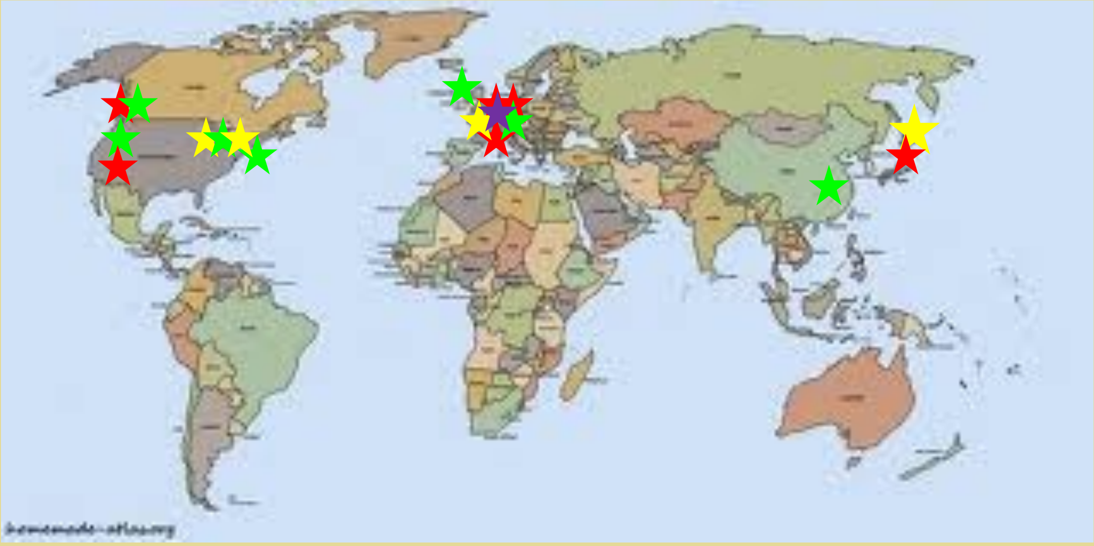
★ muon



★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

EDMs: New CPV?

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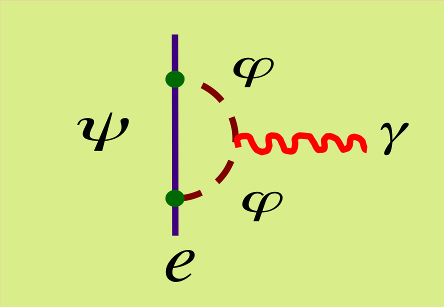
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow M > 5000$ GeV

$M < 500$ GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

EDMs: New CPV?

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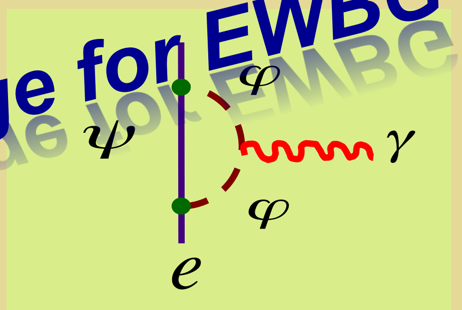
Mass Scale Sensitivity

Challenge for EWBG



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EDMs: New CPV?

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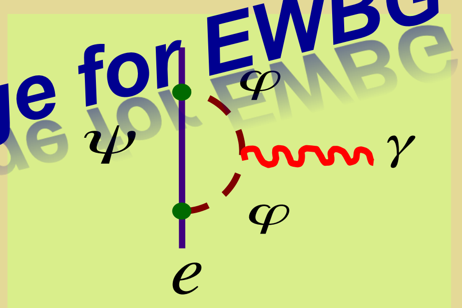
Mass Scale Sensitivity

Challenge for EWBG



- ***EDMs arise at > 1 loop***
- ***CPV is flavor non-diagonal***
- ***CPV is "partially secluded"***

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

III. Theoretical Interpretation

EDM Interpretation & Multiple Scales

Baryon Asymmetry
Early universe CPV

BSM CPV
SUSY, GUTs, Extra Dim…

Collider Searches
Particle spectrum; also scalars for baryon asym

?

Energy Scale

QCD Matrix Elements
d_n , $\bar{g}_{\pi NN}$, …

Expt

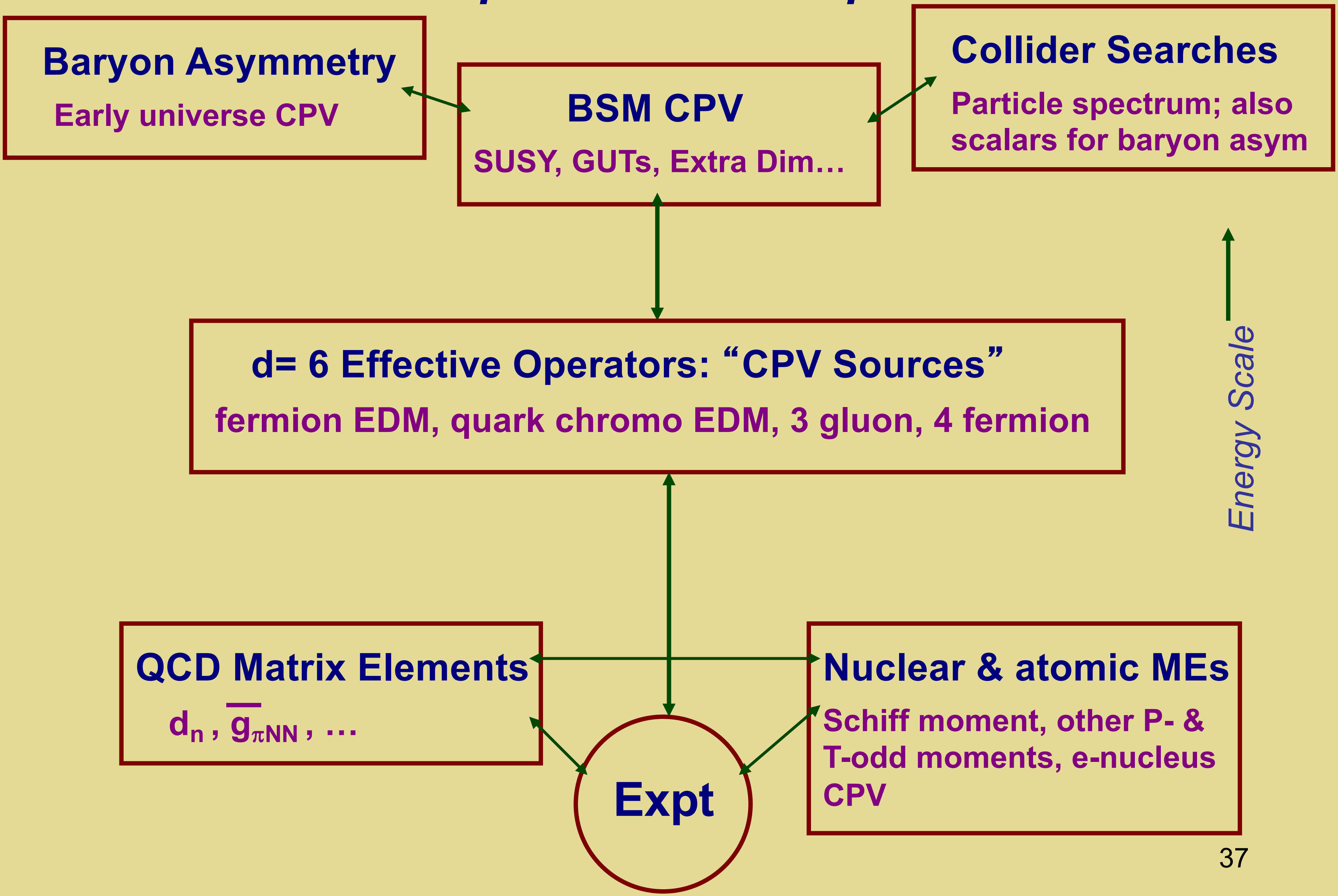
Nuclear & atomic MEs
Schiff moment, other P- & T-odd moments, e-nucleus CPV

Effective Operators: The Elevator

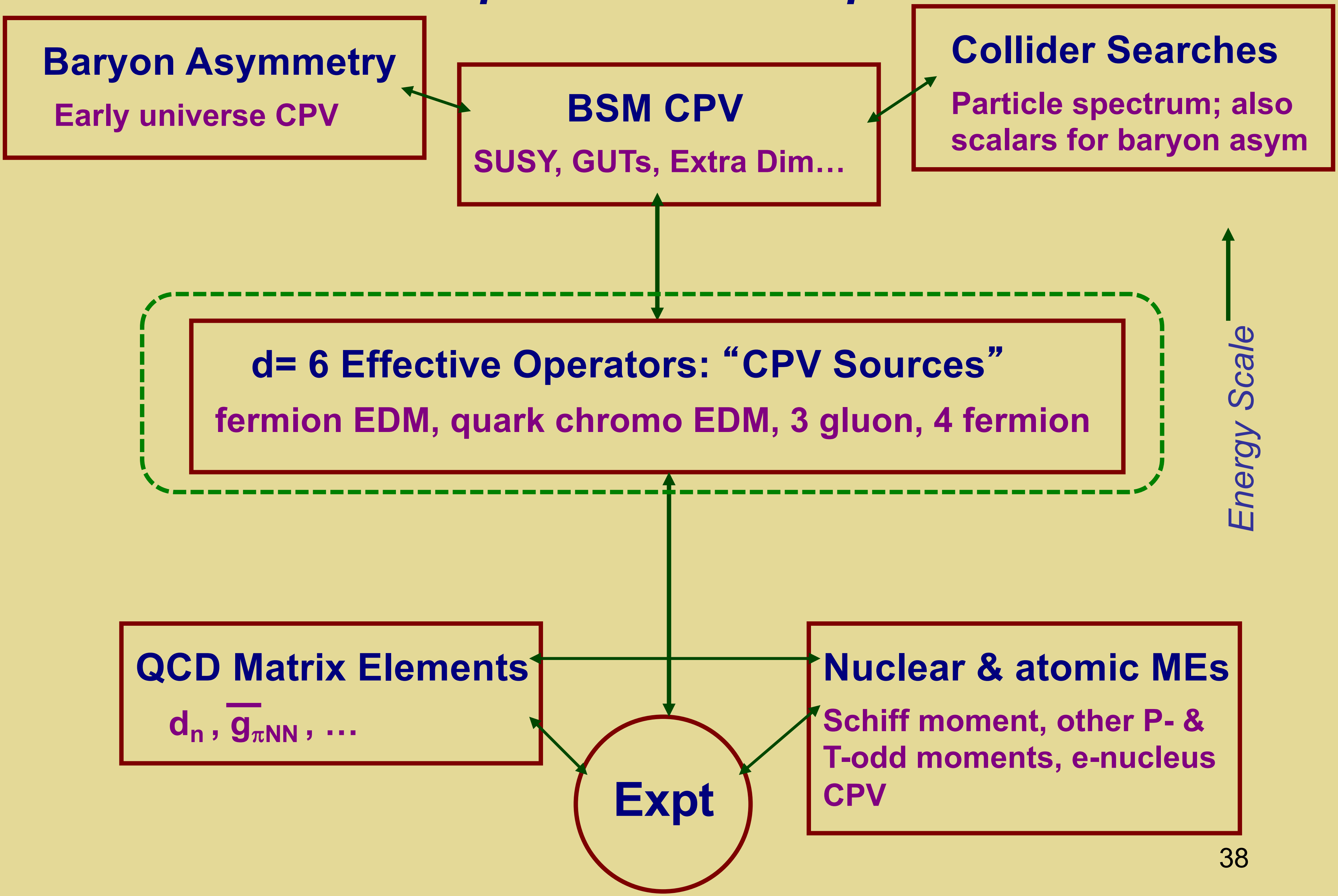
$$\mathcal{L}_{\mathrm{CPV}} = \mathcal{L}_{\mathrm{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}}$$

$$\mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)} \quad + \ldots$$

EDM Interpretation & Multiple Scales



EDM Interpretation & Multiple Scales



Wilson Coefficients: Summary

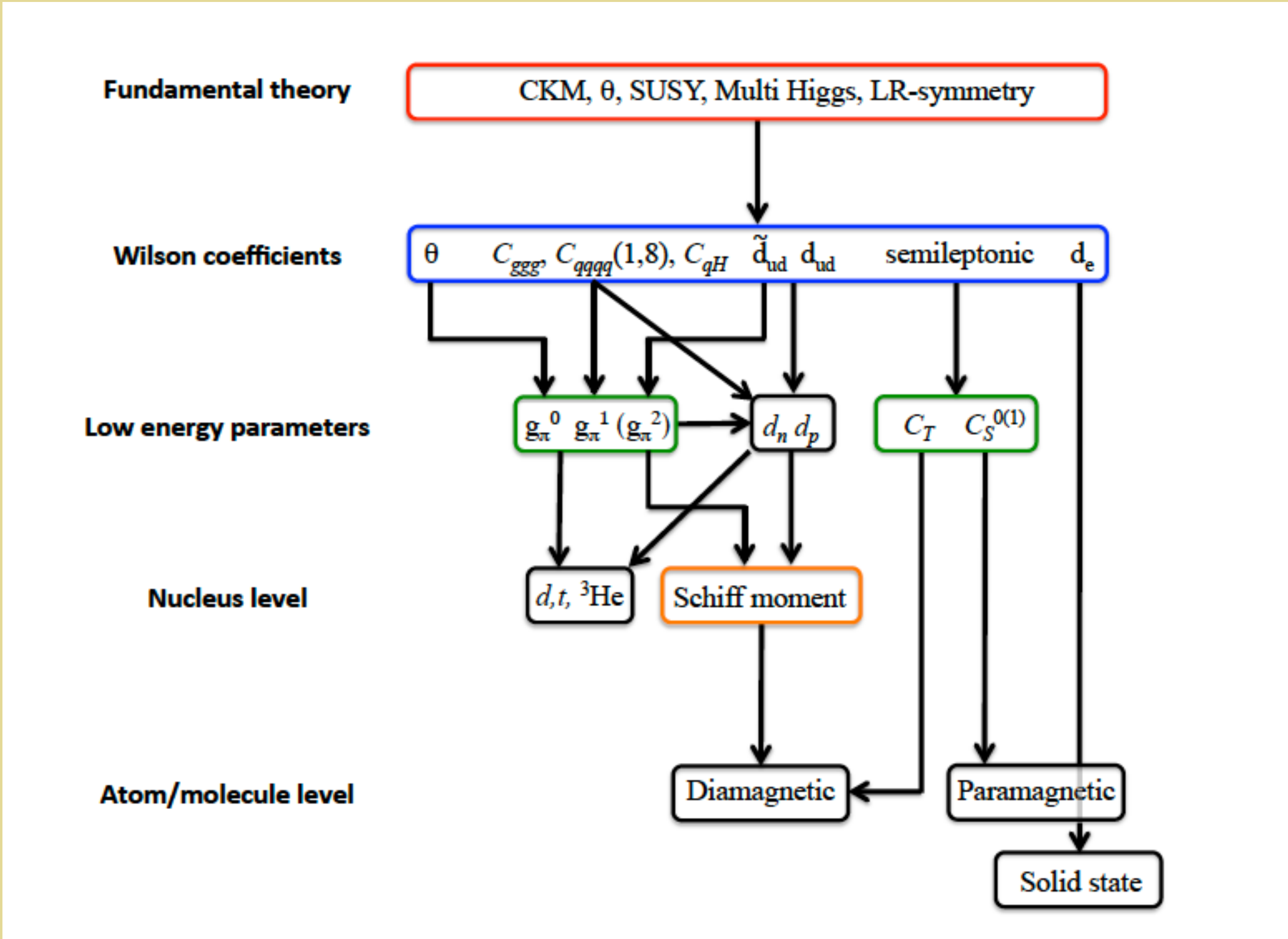
d_f	*fermion EDM*	*(3)*
$\tilde{d}_q$	*quark CEDM*	*(2)*
$C_{\tilde{G}}$	*3 gluon*	*(1)*
C_{quqd}	*non-leptonic*	*(2)*
$C_{lequ,\, ledq}$	*semi-leptonic*	*(3)*
$C_{\varphi ud}$	*induced 4f*	*(1)*

12 total + $\bar{\theta}$

light flavors only (e,u,d)

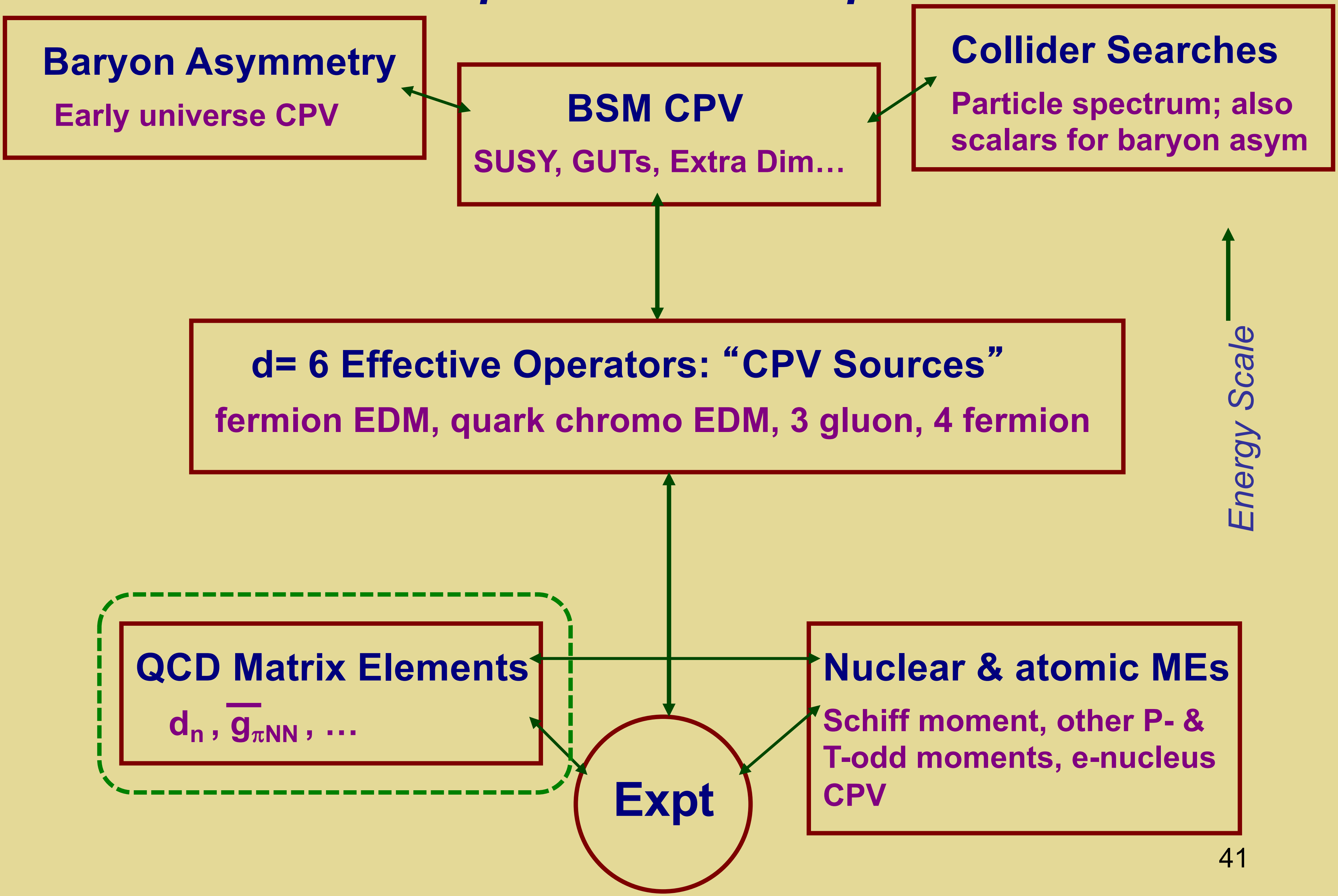
Complementary searches needed

EDM Interpretation & Multiple Scales



Chupp, Fierlinger, MJRM, Singh, Rev. Mod. Phys. 91 (2019) 015001 [1710.02504]

EDM Interpretation & Multiple Scales



TVPV Hadronic & Nuclear Interactions

$$\begin{aligned}\mathcal{L}_{N\pi}^{\mathrm{PVTV}} &= -2\bar{N}\left(\bar{d}_0+\bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu} \\ &+ \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi}+\bar{g}_\pi^{(1)}\pi^0+\bar{g}_\pi^{(2)}\left(3\tau_3\pi^0-\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N \\ &+\bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right)+\bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right)+\cdots\end{aligned}$$

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

TVPV Hadronic & Nuclear Interactions

$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu}$$
$$+\,\bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$
$$+\bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right) + \cdots$$

Nucleon EDMs

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

TVPV Hadronic & Nuclear Interactions

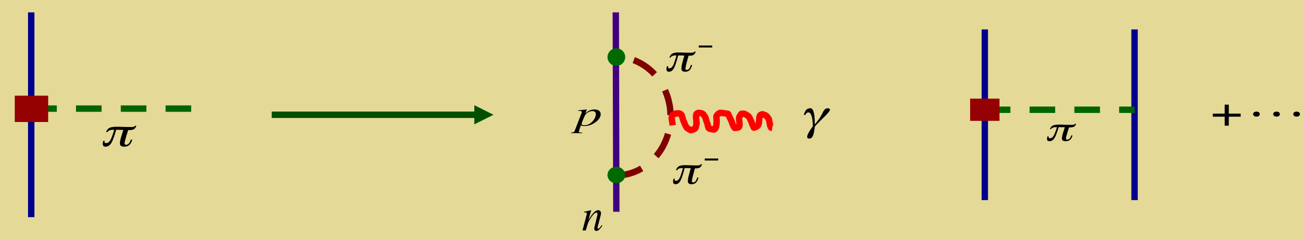
$$\mathcal{L}_{N\pi}^{\rm PVTV} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$

$$+\bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$

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

I = 0, 1, 2

PVTV πN interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

TVPV Hadronic & Nuclear Interactions

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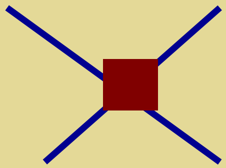
$$+ \bar{N}\left[\bar{g}_\pi^{(0)}\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_\pi^{(1)}\pi^0 + \bar{g}_\pi^{(2)}\left(3\tau_3\pi^0 - \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\right]N$$
$$+ \bar{C}_1\bar{N}N\,\partial_\mu\left(\bar{N}S^\mu N\right) + \bar{C}_2\bar{N}\boldsymbol{\tau}N\cdot\partial_\mu\left(\bar{N}S^\mu\boldsymbol{\tau}N\right) + \cdots$$

PVTV 4N interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Hadronic Matrix Element Challenge

$$d_N = \alpha_N \, \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \beta_N^{(k)} \, (\mathrm{Im}\, C_k)$$

$$\bar{g}_\pi^{(i)} = \lambda_{(i)} \, \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)} \, (\mathrm{Im}\, C_k)$$

d=6 operator coefficients

How well can we compute the β, γ, λ , ... ?

Hadronic Matrix Element Challenge

$$d_N = \alpha_N \, \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \beta_N^{(k)} \, (\mathrm{Im}\, C_k)$$

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Hadronic matrix elements

d=6 operator coefficients

How well can we compute the β, γ, λ, ... ?

Hadronic Matrix Elements

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09-0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2-1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2-20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4-40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2-0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8-2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4-12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16-50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2-40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1-10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10-80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Hadronic Uncertainty

Engel, R-M, van Kolck:

Hadronic Matrix Elements

Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09-0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2-1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2-20) \times 10^{-9}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4-40) \times 10^{-9}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2-0.6) \times 10^{-3}$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8-2.4) \times 10^{-3}$
d_q	ρ_n^u	-0.35	(-0.17)–0.52
	ρ_n^d	1.4	0.7–2.1
δ_q	ζ_n^u	8.2×10^{-9}	$(4-12) \times 10^{-9}$
	ζ_n^d	-33×10^{-9}	$-(16-50) \times 10^{-9}$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2-40) \times 10^{-7}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1-10) \times 10^{-8}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10-80) \times 10^{-7}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11–14.5
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6–1.2

Hadronic Uncertainty

Progress: LANL LQCD

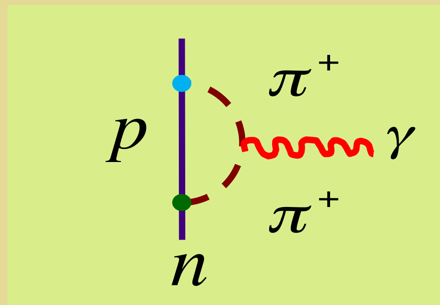
Engel, R-M, van Kolck:

EDMs in the SM: θ_{QCD}

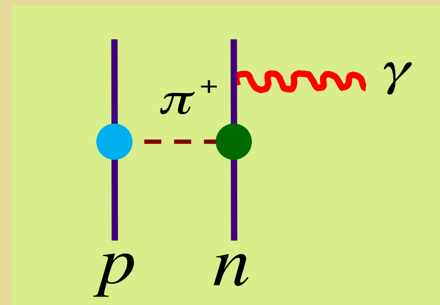
$$\mathcal{L}_{\rm CPV} = \mathcal{L}_{\rm CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\rm BSM}^{\rm eff}$$

$$\frac{\alpha_s \bar{\theta}}{4\pi} \mathrm{Tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

- *vanishes for any m_q=0*
- *"bar" : absorb quark field redefinition*



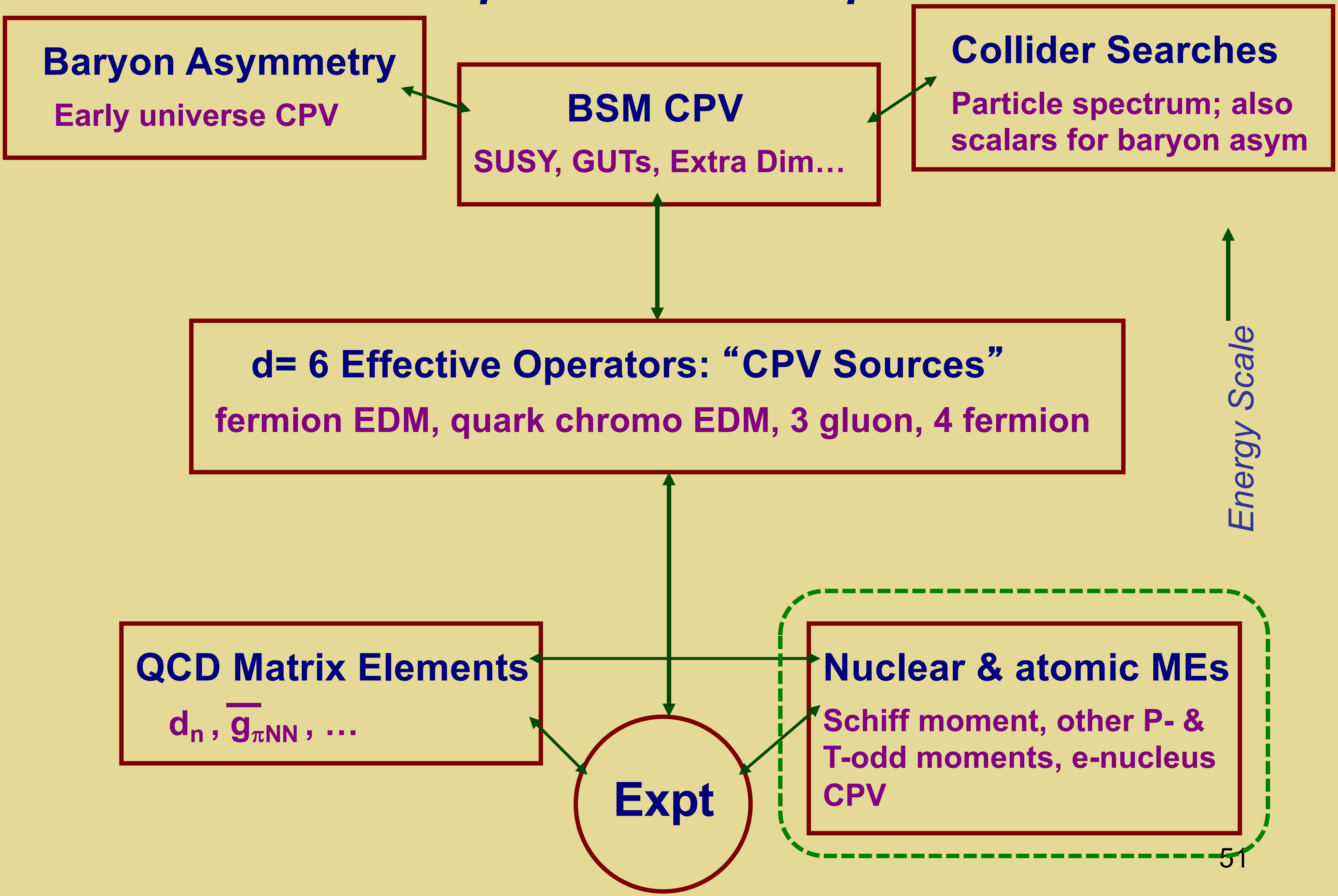
- *Crewther et al; van Kolck et al ; Herczeg*



- *Haxton & Henley; Engel;*

- ***Is θ_{QCD} really there ?***
- ***If so, are lattice computions correctly formulated?***

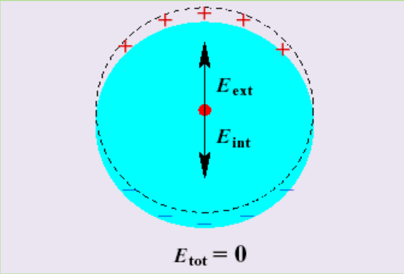
EDM Interpretation & Multiple Scales



Schiff Theorem

The Theorem

Schiff Screening



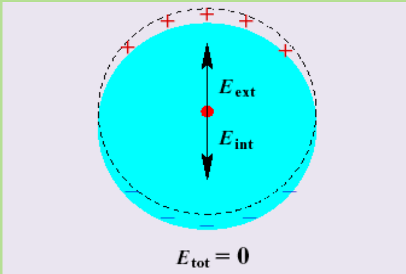
Classical picture: non-acceleration of neutral non-rel system

The EDM of a neutral system will vanish if:

- *Constituents are non-relativistic*
- *Constituents are point-like*
- *Interactions are electrostatic*

Schiff Screening: Corrections

Schiff Screening



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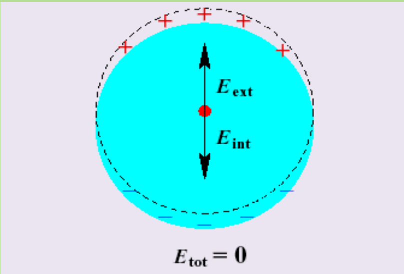
- *Interactions are electrostatic*

Paramagnetic systems w/ large Z: e^- are highly relativistic

Schiff Screening: Corrections

Schiff Screening



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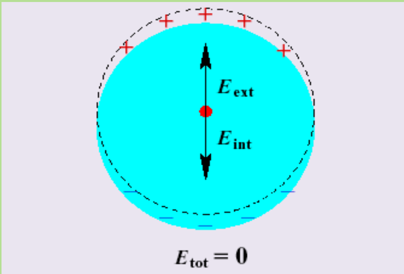
Diamagnetic atoms w/ large A: nuclei are large *$r \sim (1\ \text{fm}) \times A^{1/3}$*

Schiff Screening: Corrections

Schiff Screening



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- Constituents are point-like
- Interactions are electrostatic

St'd Model magnetic interactions, BSM e-q interactions,…

Paramagnetic Systems: d_e

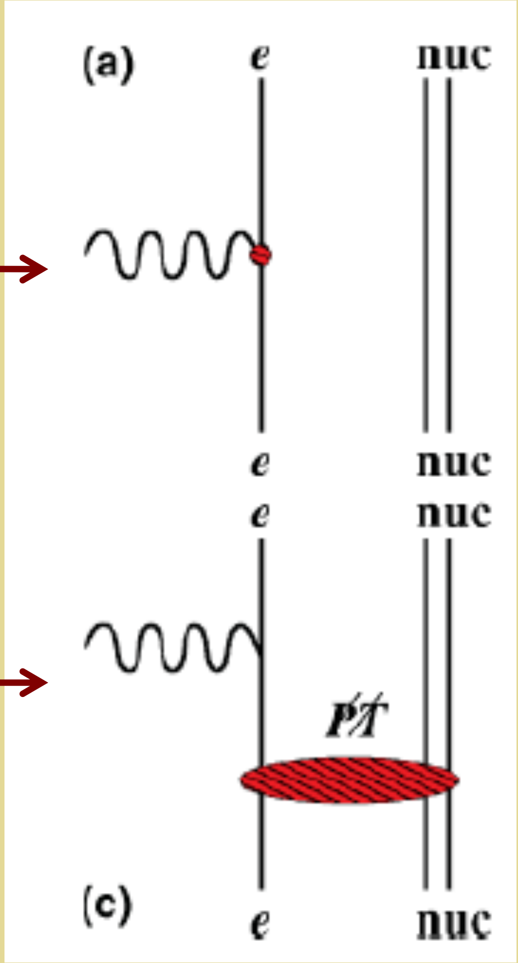
Electron EDM Interactions

External fields: 1st order energy shift

$$\tilde{V}_{\rm ext}^{(\tilde{e})} = -\alpha \sum_{i=1}^{Z} d_e \beta \left(\boldsymbol{\sigma}_i \cdot \boldsymbol{E}_i^{(\rm ext)} + i \boldsymbol{\alpha}_i \cdot \boldsymbol{B}_i^{(\rm ext)} \right).$$

Internal (nuclear) fields: 2nd order energy shift

$$\tilde{V}_{\rm int}^{(\tilde{e}\mathcal{N})} = -\alpha \sum_{i=1}^{Z} d_e \beta \left[\boldsymbol{\sigma}_i \cdot \boldsymbol{E}_i^{(\mathcal{N})} + i \boldsymbol{\alpha}_i \cdot \boldsymbol{B}_i^{(\mathcal{N})} \right] + \cdots .$$



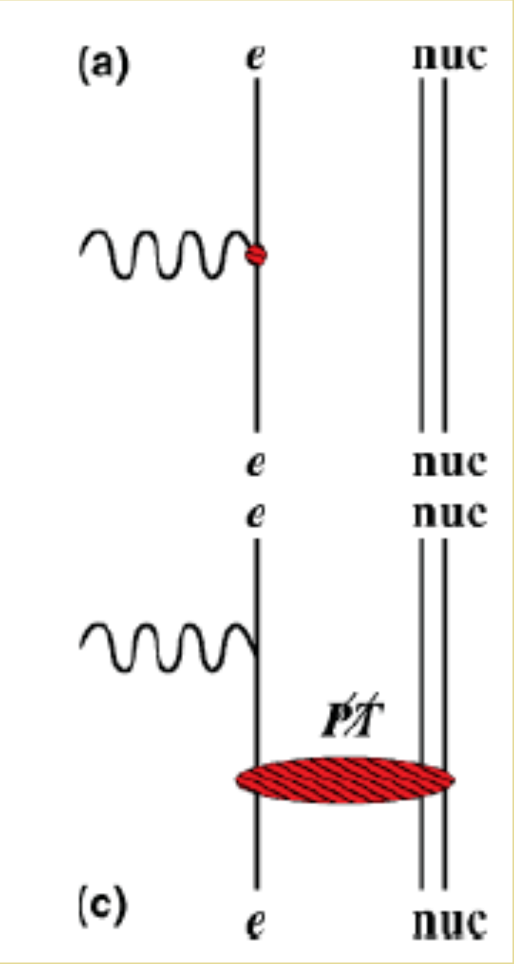
Electron EDM: Heavy Atoms

$$d_A = \rho_A^e \, d_e + \ldots$$

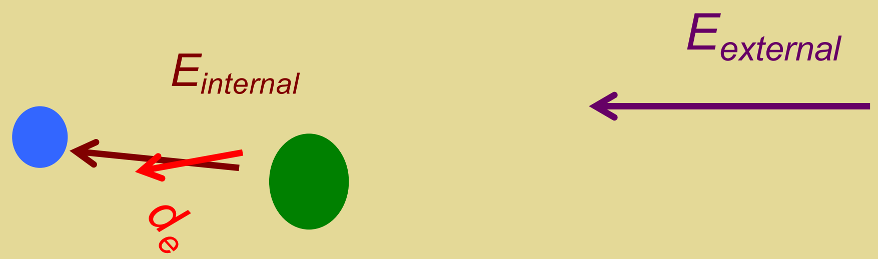
Atom	ρ_A^e
^{205}Tl	−573(20)
^{133}Cs	123(4)
^{85}Rb	25.7(0.8)
^{210}Fr	903(45)
^{199}Hg	0.01

Paramagnetic (^{205}Tl, ^{133}Cs, ^{85}Rb, ^{210}Fr)

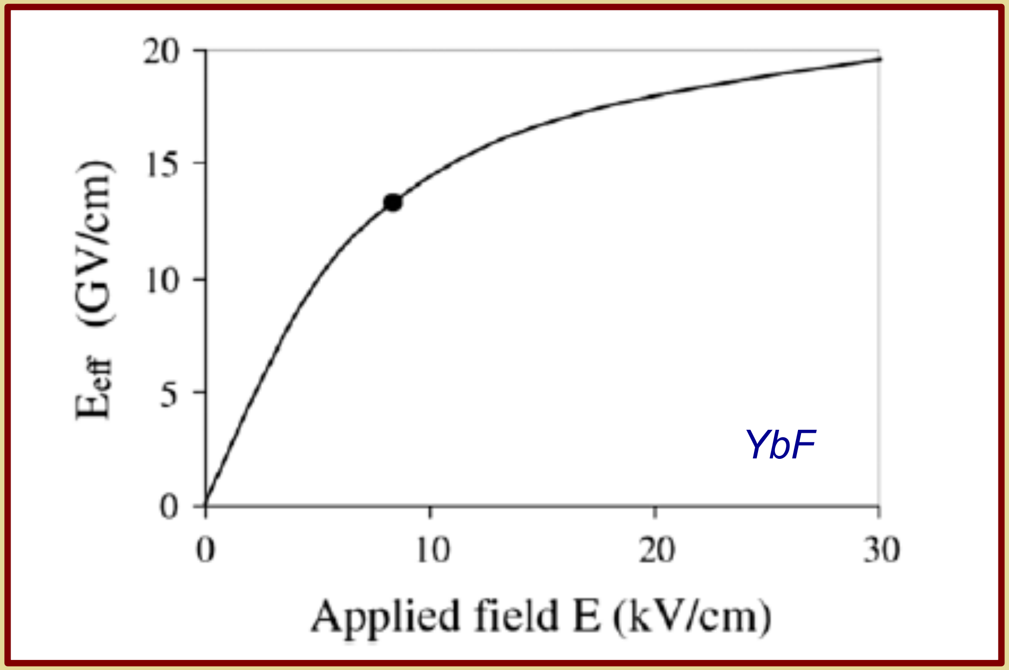
Diamagnetic (^{199}Hg)



Electron EDM: Polar Molecules



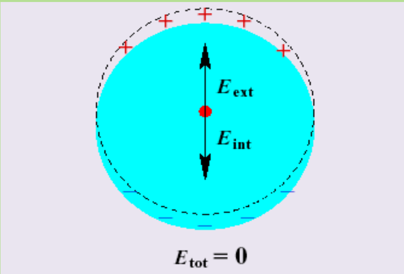
Electron experiences enhanced E_{int} as due to much smaller E_{ext}



Diamagnetic Atoms

Schiff Screening: Corrections

Schiff Screening



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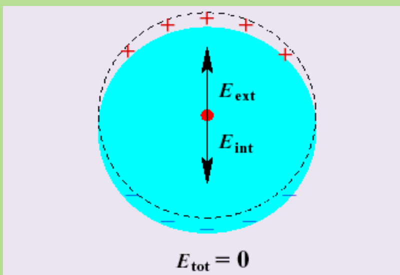
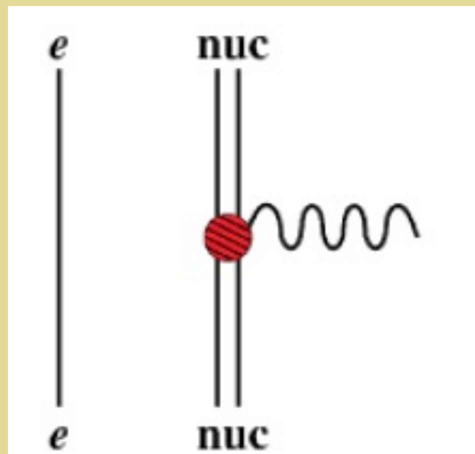
PVTV Nuclear Moments

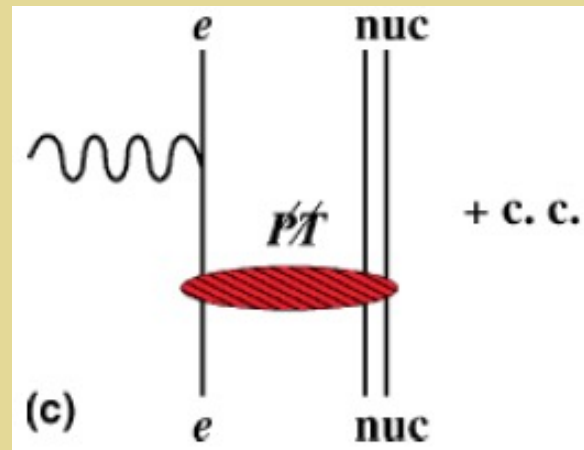
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM

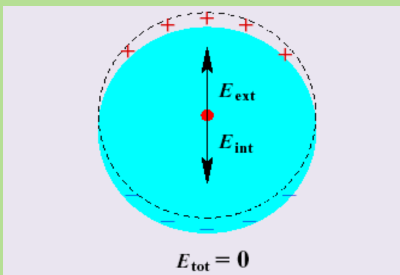


Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Schiff Screening



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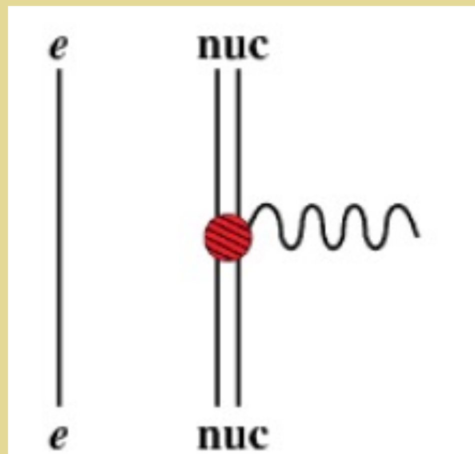
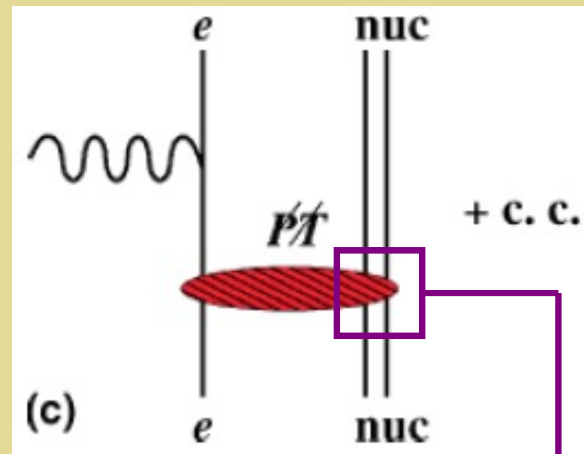


Screened EDM



Nuclear Schiff Moment

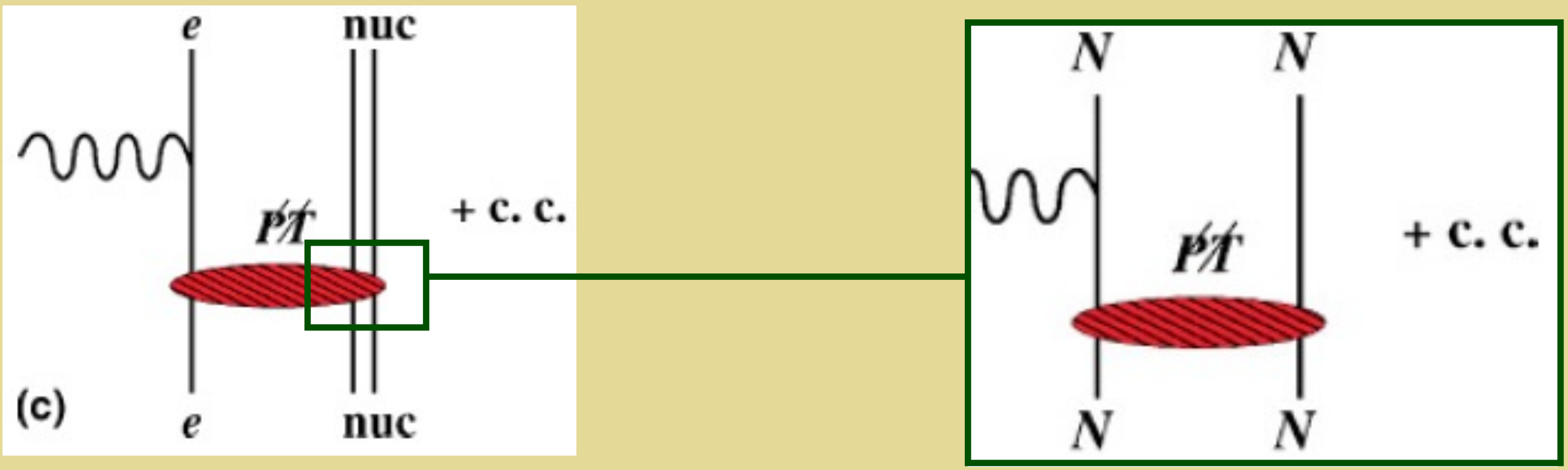
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



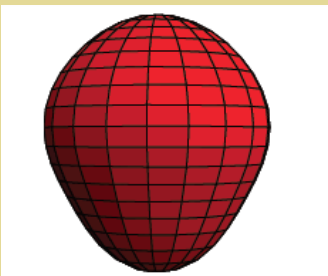
Schiff moment, MQM,…

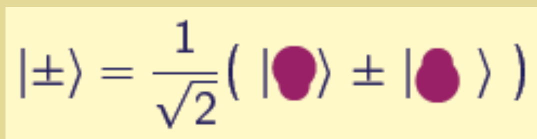
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

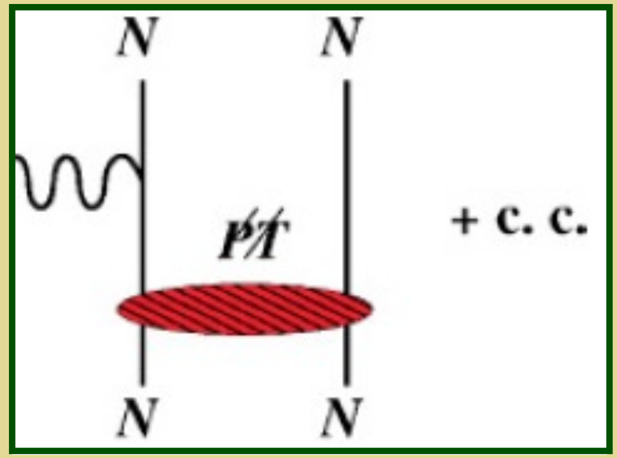
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation


Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}

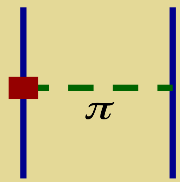


Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment: Pion Exchange

$$S = a_0\, g\, \bar{g}_\pi^{(0)} + a_1\, g\, \bar{g}_\pi^{(1)} + a_2\, g\, \bar{g}_\pi^{(2)}$$



$+ \cdots$

Nuclear Schiff Moment: Pion Exchange

$$S = a_0\, g\, \bar{g}_\pi^{(0)} + a_1\, g\, \bar{g}_\pi^{(1)} + a_2\, g\, \bar{g}_\pi^{(2)}$$

Nuclear many-body computations

$$\bar{g}_\pi^{(i)} \;=\; \lambda_{(i)}\, \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \gamma_{(i)}^{(k)}\, (\mathrm{Im}\, C_k)$$

Non-perturbative hadronic computations

Nuclear Matrix Elements

Nucl.	Best value		
	a_0	a_1	a_2
^{199}Hg	0.01	±0.02	0.02
^{129}Xe	−0.008	−0.006	−0.009
^{225}Ra	−1.5	6.0	−4.0

Range		
a_0	a_1	a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

Theory Challenges

- *Hadronic matrix elements: new lattice computations & resolve questions about θ_{QCD}*
- *Nuclear matrix elements: new generation of many-body computations → relevant for other atomic fundamental symmetry tests*

*IV. BSM Implications***

*** Baryogenesis connection: Tuesday*

The Higgs Portal

What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*

- *Two Higgs doublets ?*

$$H \rightarrow H_1 \, , \, H_2$$

- *New parameters:*

$$\tan \beta = \langle H_1 \rangle / \langle H_2 \rangle$$
$$\sin \alpha_b$$

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- *New parameters:*

$$\tan\beta = \langle H_1 \rangle / \langle H_2 \rangle$$

$$\sin\alpha_b$$

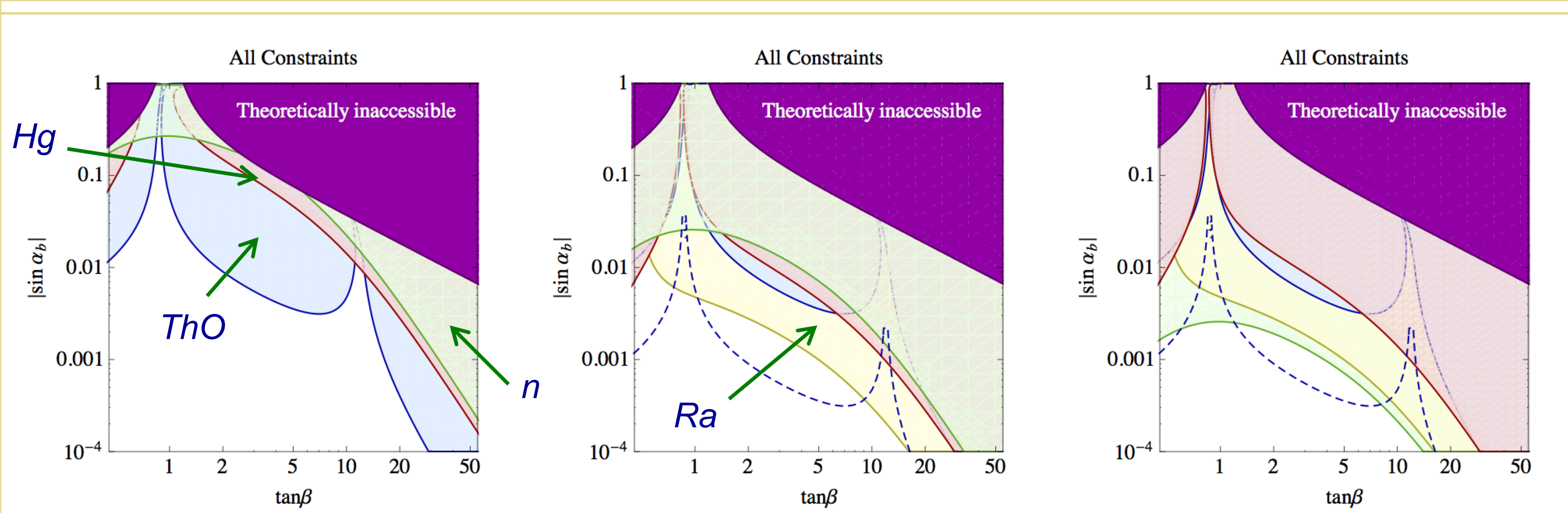
CPV : scalar-pseudoscalar mixing from $V(H_1, H_2)$

EDM Complementarity

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present (2014)

New Hf F+

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra) [10^{-27} e cm]

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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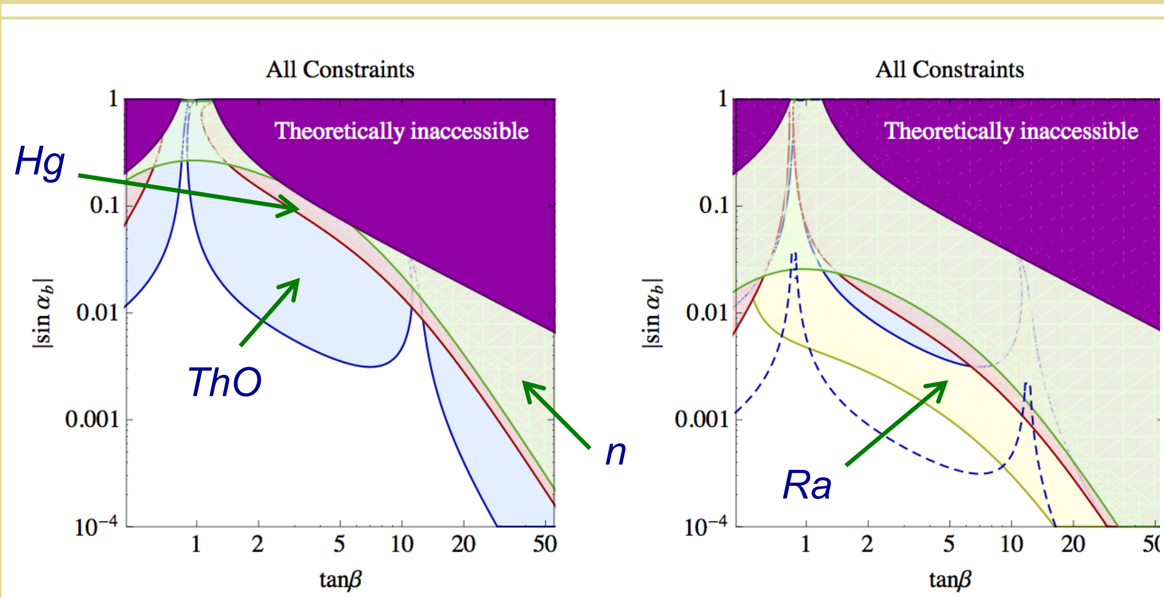

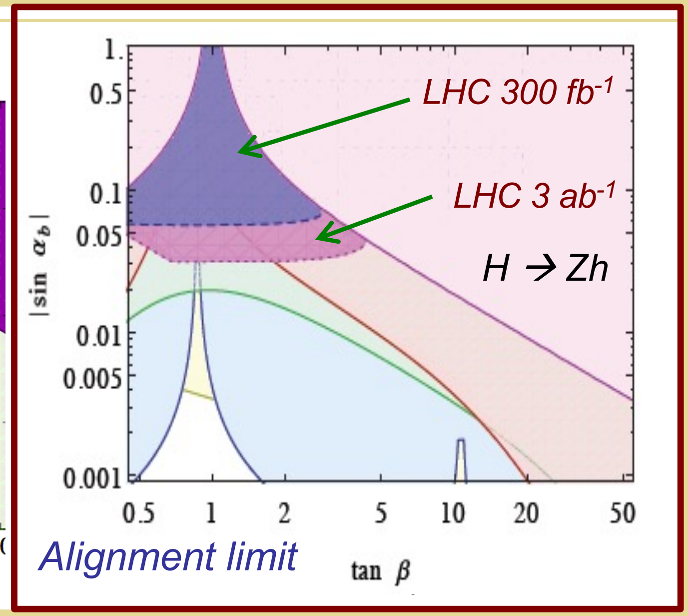

Chen, Li, R-M: 1708.00435

Present (2014)

New Hf F+

Future:

- d_n x 0.1
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra) [10^{-27} e cm]

Future:

- d_n x 0.01
- d_A(Hg) x 0.1
- d_{ThO} x 0.1
- d_A(Ra)

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Muon EDM: A Challenge

Chiral symmetry:

$$\frac{d_\mu}{d_e} \sim \frac{m_\mu}{m_e}$$

EW gauge invariance:

$$\mathcal{O}_{\mathrm{fW}}^{(6)} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H f_R \widetilde{W}^a_{\mu\nu}$$

Loops

$$\mathcal{O}_{\mathrm{f}}^{Y} = \bar{F} H f_R$$

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Loops

$$\mathcal{O}_{\rm f}^{Y} = \bar{F}H f_R$$

Expt sensitivity:

$|d_e| < 4.1 \times 10^{-30}$ e-cm → $|d_\mu| < 10^{-27}$ e-cm

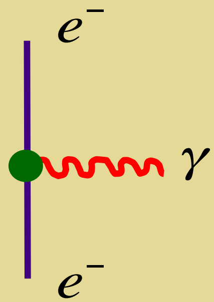
PSI ultimate: $|d_\mu| < 6 \times 10^{-23}$ e-cm

Loophole(s)?

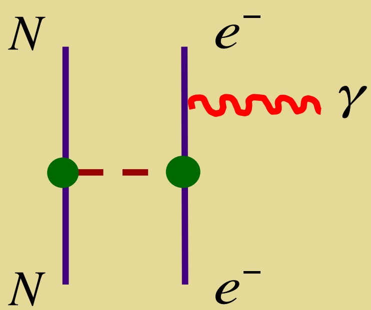
EDM Complementarity

Paramagnetic Systems: Two Sources

Electron EDM



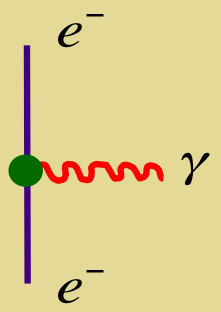
(Scalar q) x (PS e-)



Tl, YbF, ThO…

Paramagnetic Systems: Two Sources

Electron EDM



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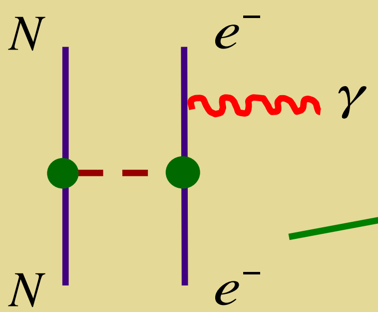

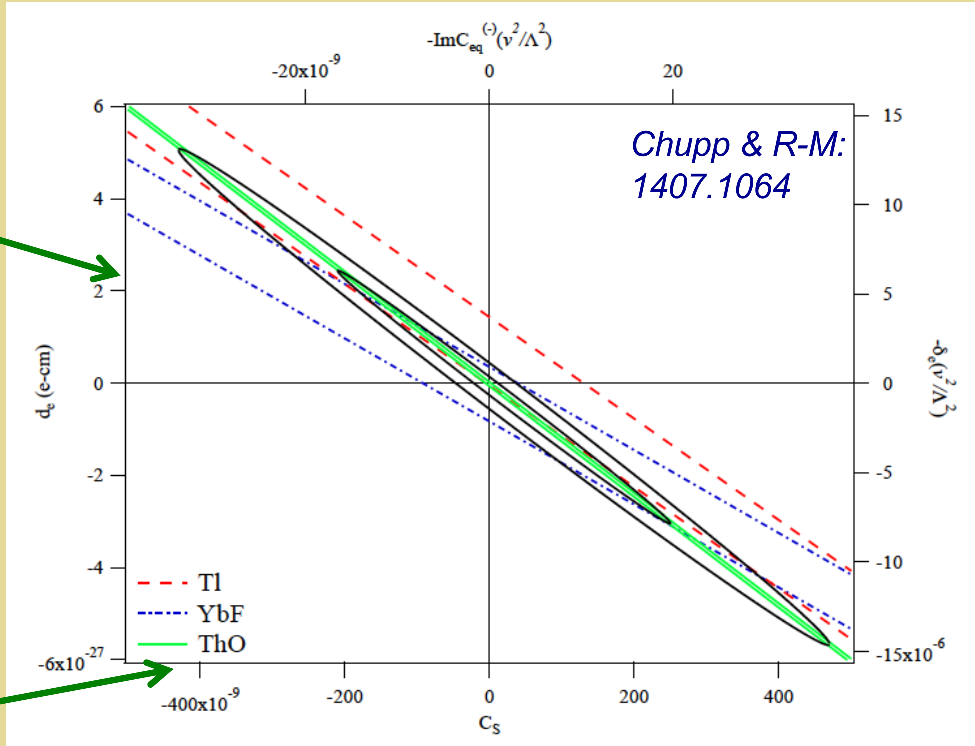

Tl, YbF, ThO…

Paramagnetic Systems: Two Sources

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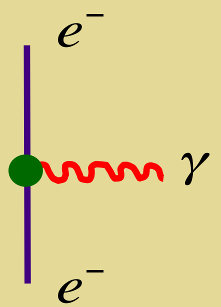

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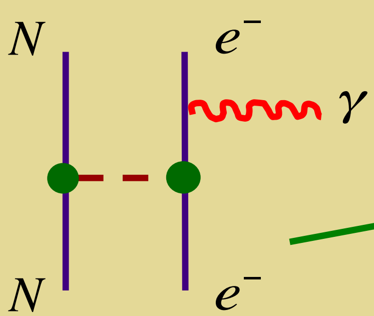
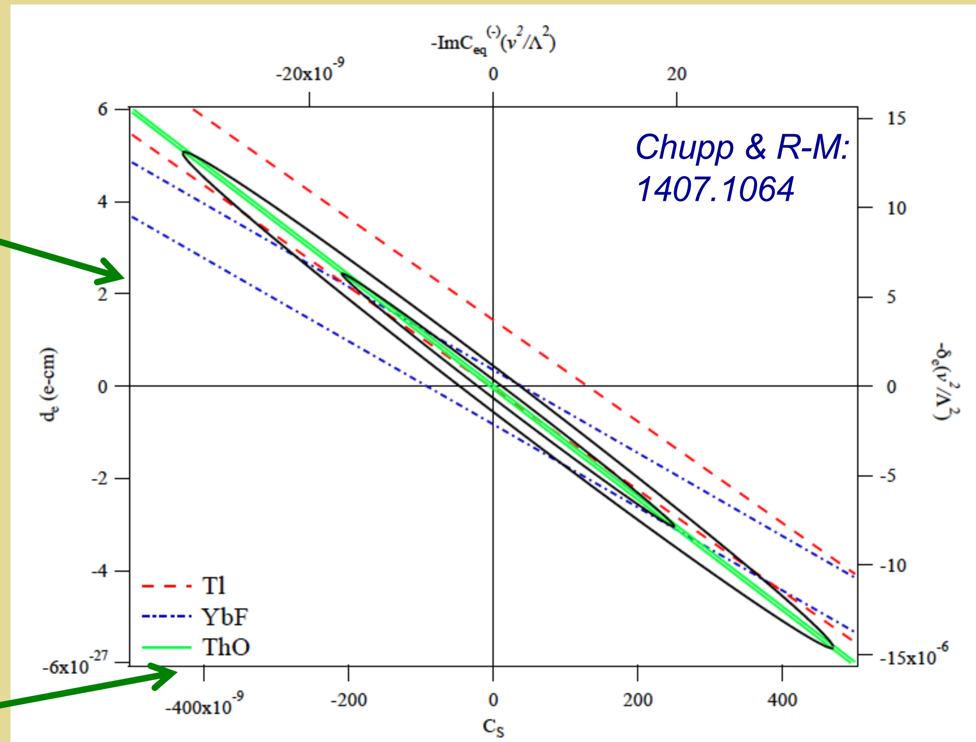




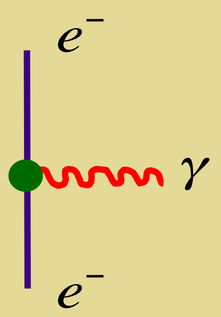
$$\Lambda \gtrsim (1.5\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}} \qquad \text{Electron EDM (global)}$$

$$\Lambda \gtrsim (1300\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}} \qquad C_S\ \text{(global)}$$

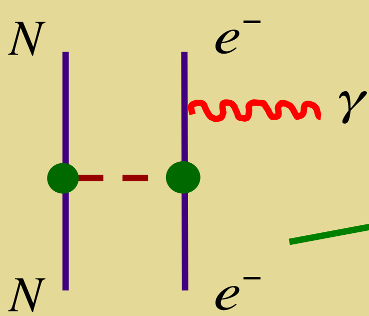
Tl, YbF, ThO…

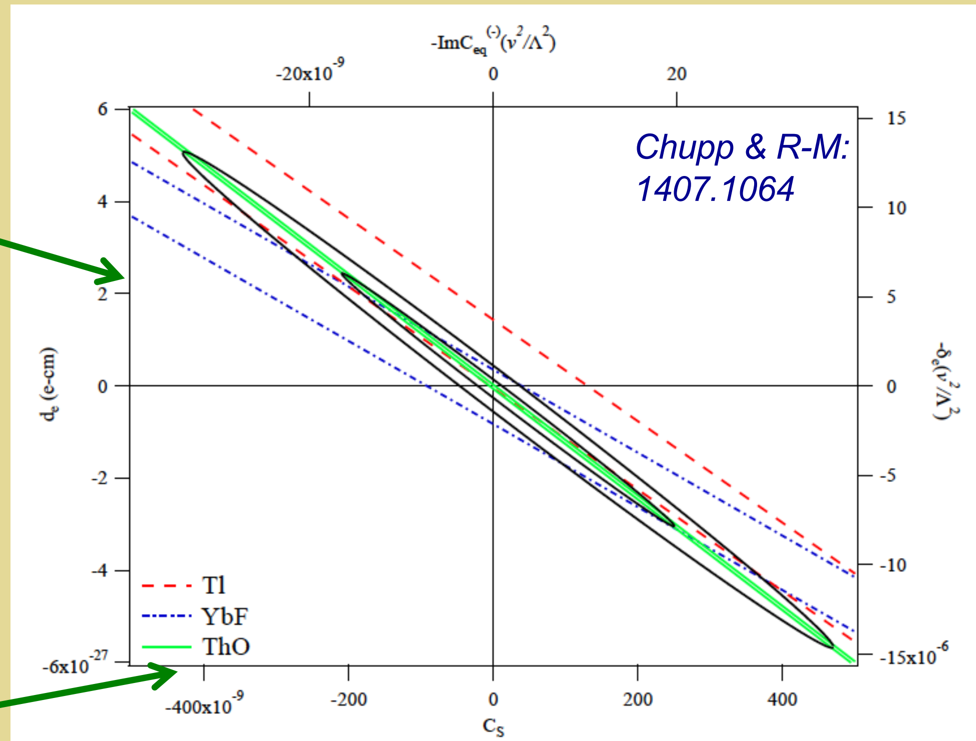
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e-)





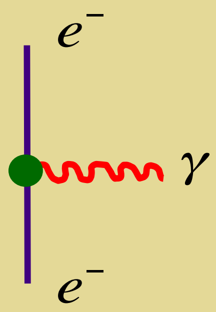
$\Lambda \gtrsim (1.5\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$	C_S (global)

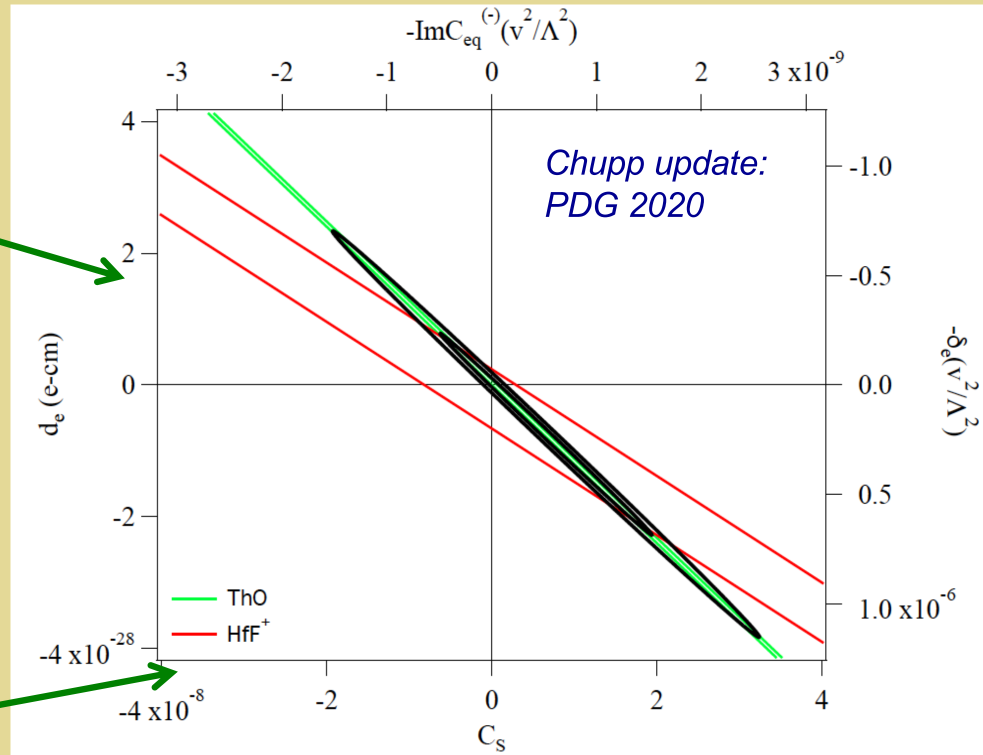
LHC inaccessible

Tl, YbF, ThO…

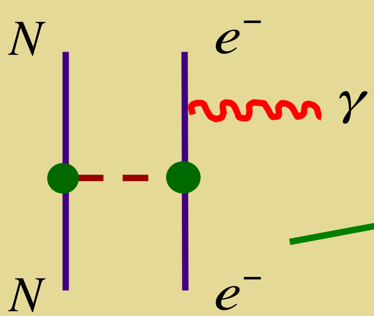
Paramagnetic Systems: Two Sources

Electron EDM





(Scalar q) x (PS e-)



Update: slightly stronger

$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ Electron EDM (global)

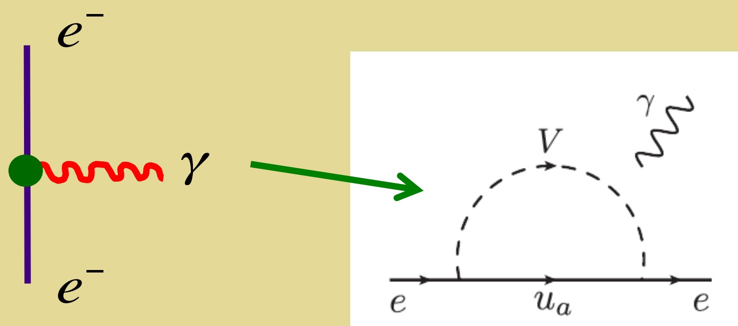
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ C_S (global)

LHC inaccessible

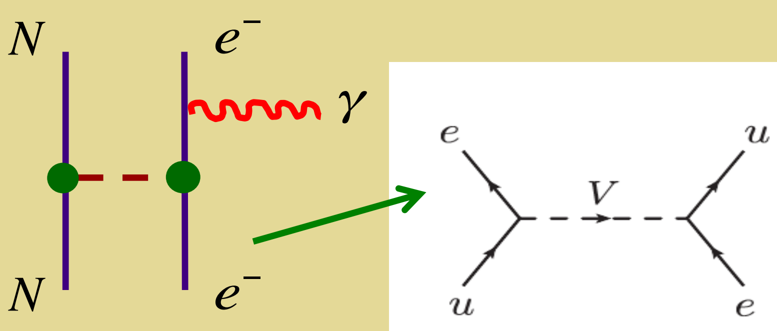
ThO, Hf+

Illustrative Example: Leptoquark Model

Electron EDM



(Scalar q) x (PS e⁻)



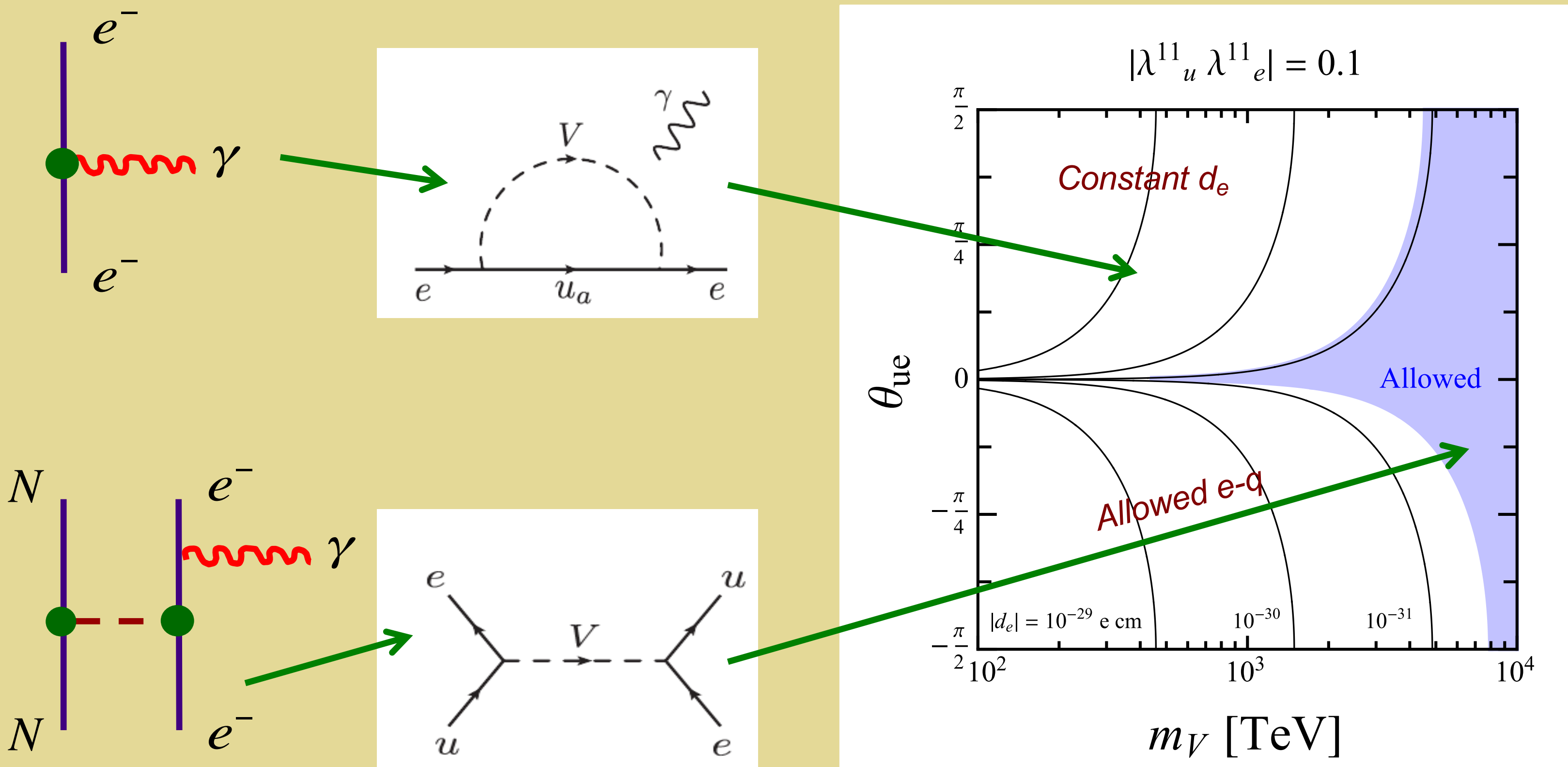
(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

Illustrative Example: Leptoquark Model

Electron EDM

(Scalar q) x (PS e-)



Fuyuto, R-M, Shen 1804.01137

See also: Dekens et al 1809.09114

(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

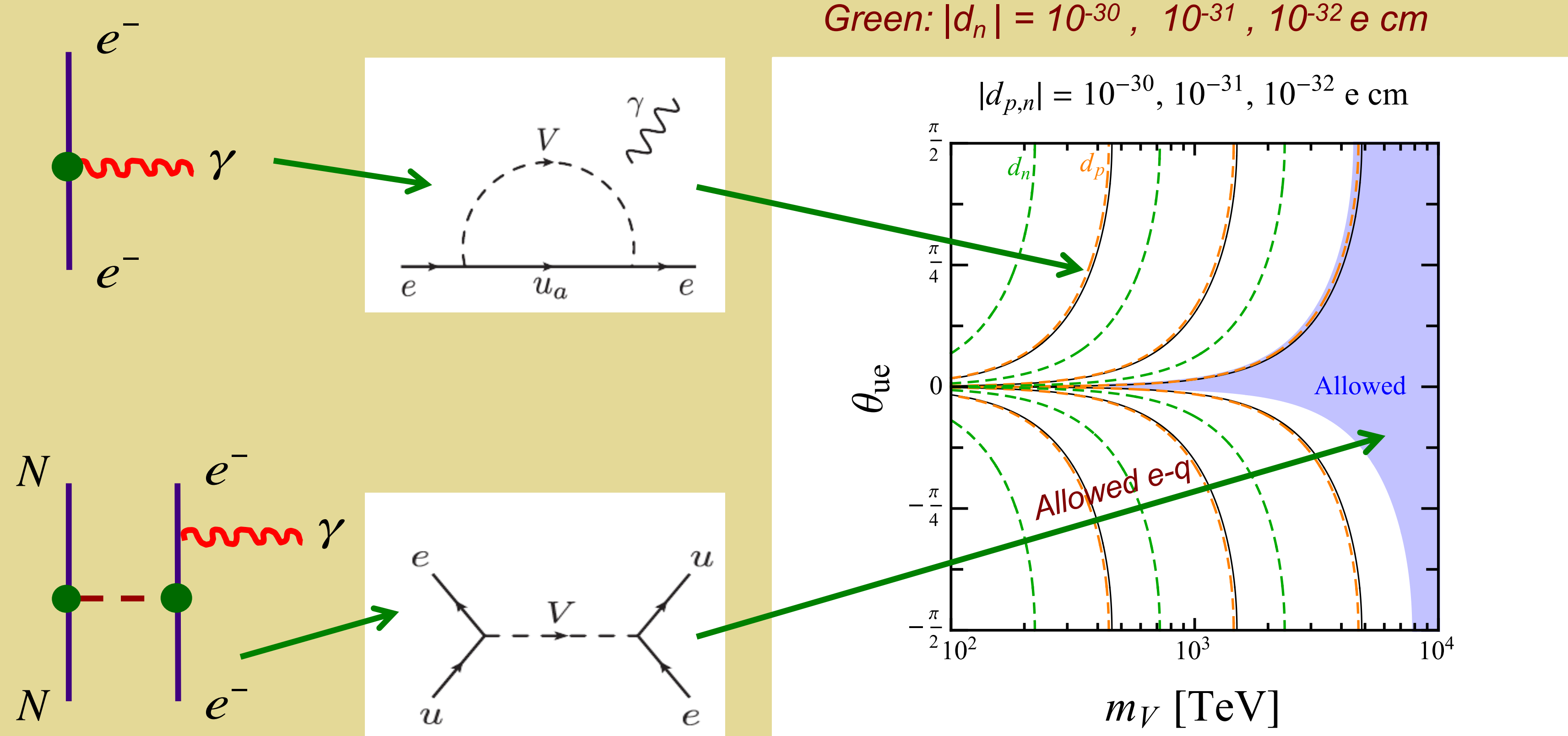
Illustrative Example: Leptoquark Model

Orange: $|d_p|$ = 10^{-30} , 10^{-31} , 10^{-32} e cm

Green: $|d_n|$ = 10^{-30} , 10^{-31} , 10^{-32} e cm

Electron EDM

(Scalar q) x (PS e^-)



Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

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See also: Dekens et al 1809.09114

Outlook

- *EDMs provide powerful "tabletop" probe of high energy and/or early universe fundamental physics*
- *Searches with multiple, complementary systems are essential*
- *The theoretical interpretation of EDMs entails a rich and challenging interplay of physics at multiple scales*
- *Significant discoveries are possible, while limits yield tremendous insight*
- *This is an area of exciting opportunities for Intensity Frontier physics*

Back Up Slides

The Top Quark Portal

CPV Top Quark Interactions?

- *3rd generation quarks often have a special role in BSM scenarios, given m_t >> all other m_f*
- *If BSM CPV exists, d_t may be enhanced*

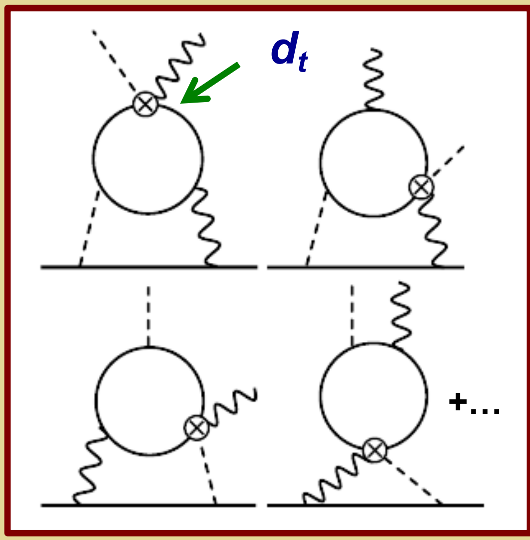
- *Top EDMs difficult to probe experimentally*

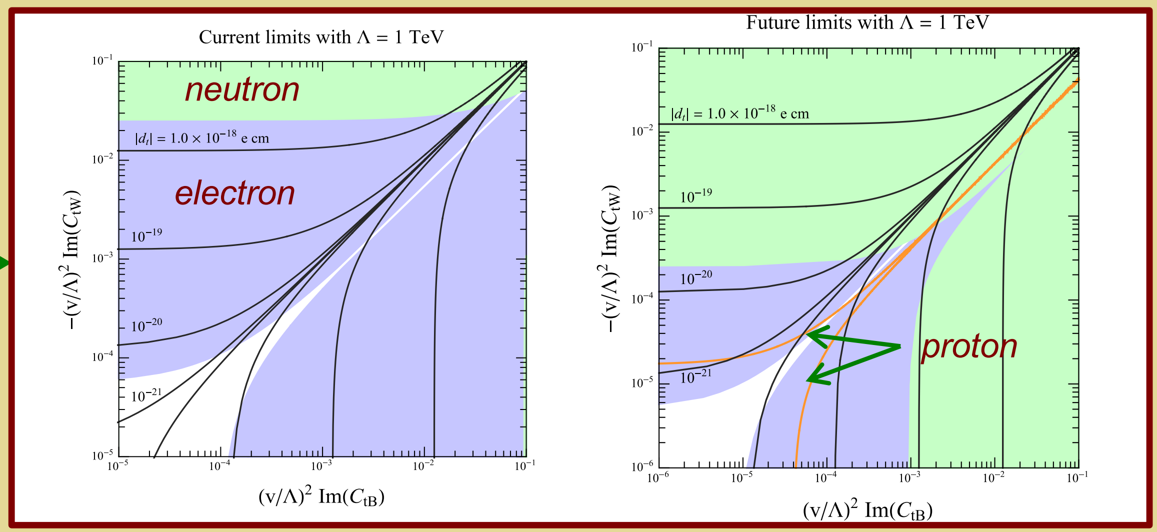
- *Light fermion EDMs to the rescue !*

CPV Top Quark Interactions?

Cordero-Cid et al '08, Kamenik et al '12, Cirigliano et al '16, Fuyuto & MRM in 1706.08548

Model-indep: independent $SU(2)_L$ & $U(1)_Y$ dipole operators: C_{tB} , $C_{tW} \rightarrow$ Tree level d_t & loop level d_e , $d_{light\ q}$



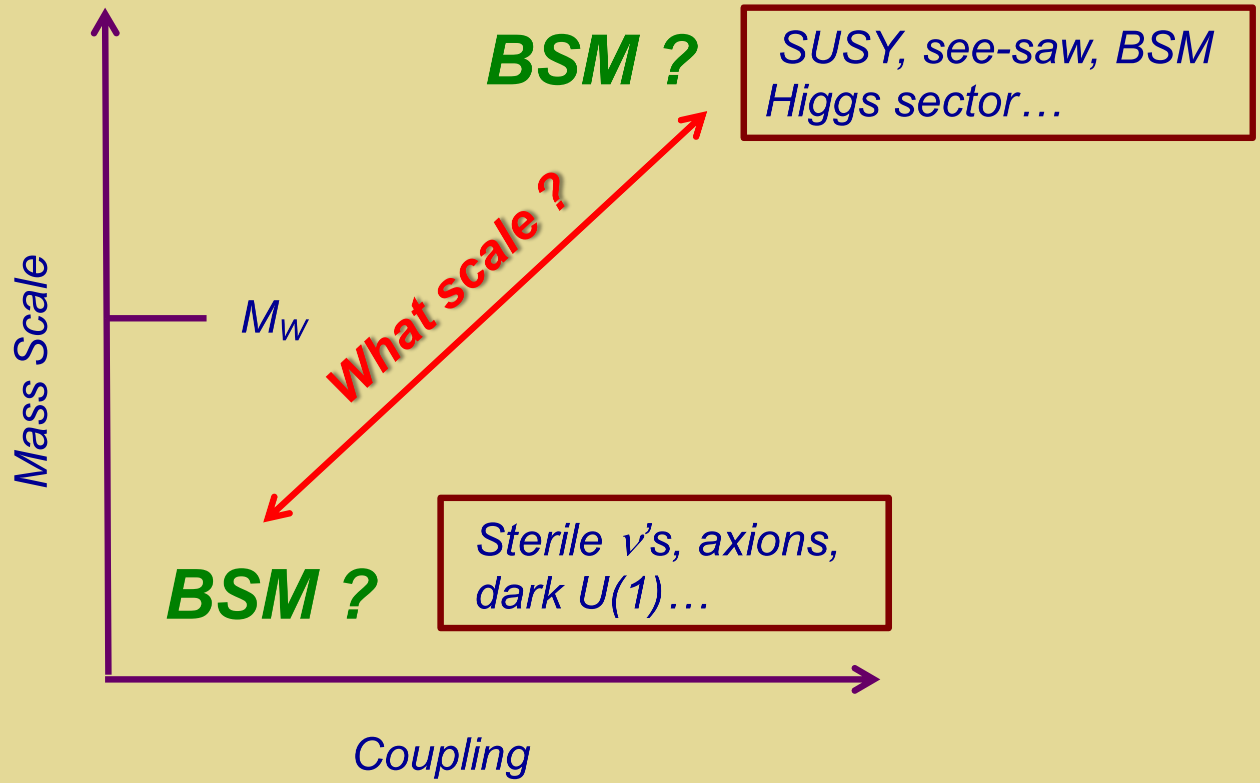


Induced d_e , $d_{light\ quark}$

Fuyuto & MRM '17
Fuyuto '19: Updated for new ThO

Dark Photon Portal

BSM Physics: Where Does it Live ?

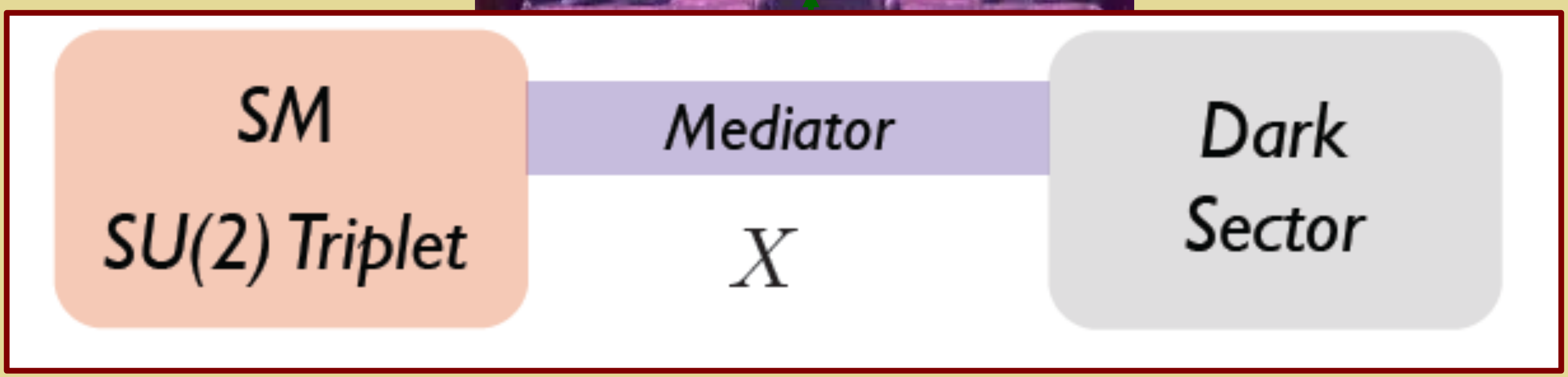


Dark Photon Portal

Standard Model ↔ ***Hidden Sector***

New CPV ?

Dark Photon Portal



Thanks: K. Fuyuto

CPV Dark Photon

$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

CP-conserving CP-violating

Thanks: K. Fuyuto

K. Fuyuto, X.-G. He, G. Li, MJRM 1902.10340

CPV Dark Photon

$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

CP-conserving CP-violating

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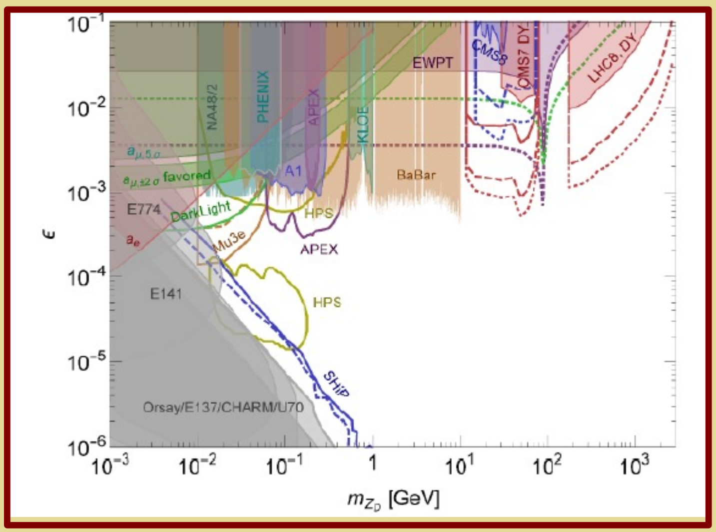
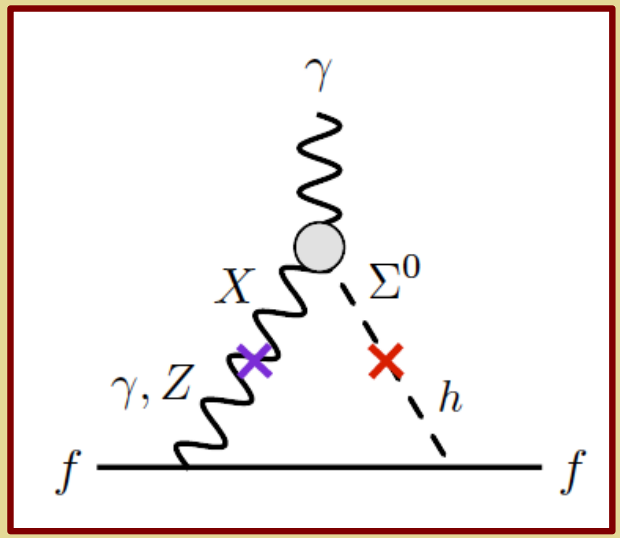
***X* – γ Mixing**



EDM



CPV Dark Photon

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Thanks: K. Fuyuto

***X – γ* Mixing**

EDM