BSM CPV: Electric Dipole Moments & More

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About MJRM:

Science


Family

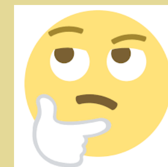

Friends

My pronouns: he/him/his
 # MeToo

USTC Lectures June 4-6, 2024

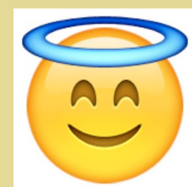
The Search for an EDM: Why Physicists Should Care

- *Theorists think it's interesting*



- *It's something we can do*

- *It addresses fundamental Q's*



EDM's & 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 ?*
- *What is the mass scale associated with Beyond the Standard Model Physics ?*
- *Is BSM physics perturbative or strongly coupled ?*

Themes for This Talk

- *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 and challenges for both experiment and theory*

Outline

I. *EDM Basics & the BSM context*

II. *Experimental Situation*

III. *Theoretical Interpretation*

IV. *BSM Implications*

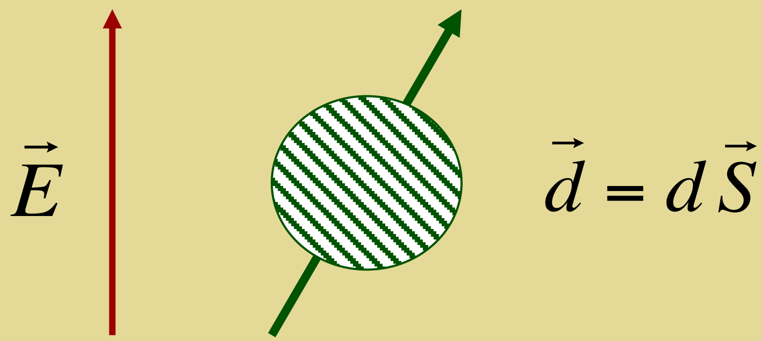
V. *Outlook*

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 [1710.02504]*

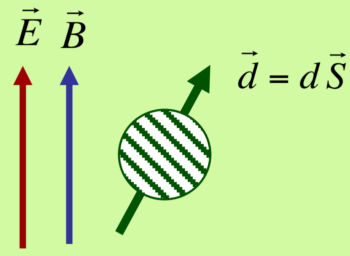
I. EDM Basics

What is an EDM ?



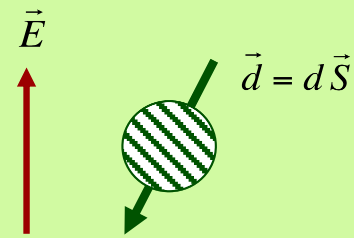
$$\nu_{EDM} = -\frac{d\,\vec{S}\cdot\vec{E}}{h}$$

What is an EDM ?



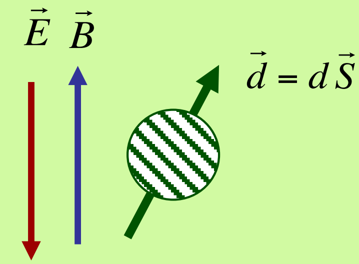
$$\nu_{EDM} = -\frac{d\,\vec{S}\cdot\vec{E}}{h}$$

T-odd , CP-odd
by CPT
theorem



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

T-odd , CP-odd
by CPT
theorem



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

T-odd , CP-odd
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theorem

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

		PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$
Coulomb	C_J	E	X	X	O
Magnetic	$T^M{}_J$	O	X	X	E
Transverse electric	$T^E{}_J$	X	O	E	X

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…*

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…)

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…*

Nuclear Enhancements

EDMs & SM Physics

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

EDMs & SM Physics

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

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

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

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

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

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

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^{-29}
HfF^{+}	4.1×10^{-30} **	10^{-38} *	10^{-28}
n	1.8×10^{-26}	10^{-31}	10^{-26}

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

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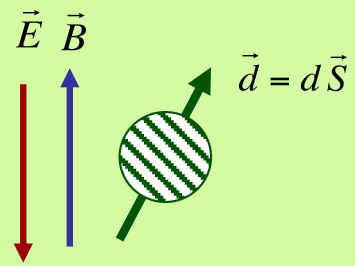

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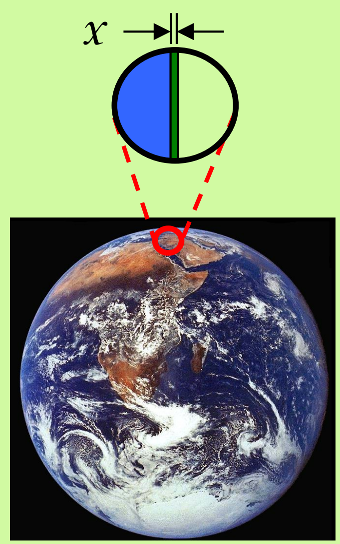
T-odd , CP-odd by CPT theorem



d_n: $x < 0.25$ mm

C-Y Liu

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

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

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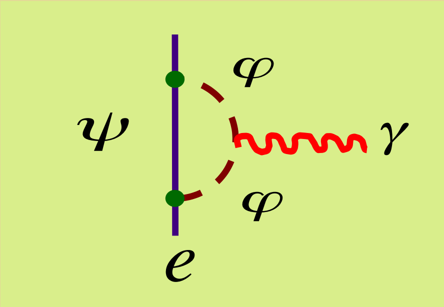
Mass Scale Sensitivity



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

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

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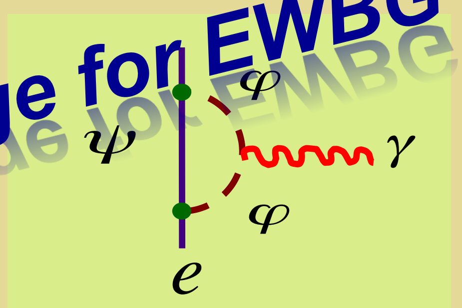
Mass Scale Sensitivity

Challenge for EWBG



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Mass Scale Sensitivity

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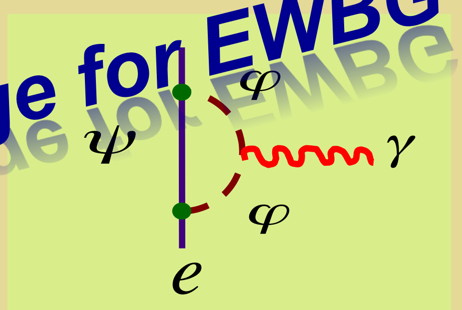


- *EDMs arise at > 1 loop*
- *CPV is flavor non-diagonal*
- *CPV is "partially secluded"*

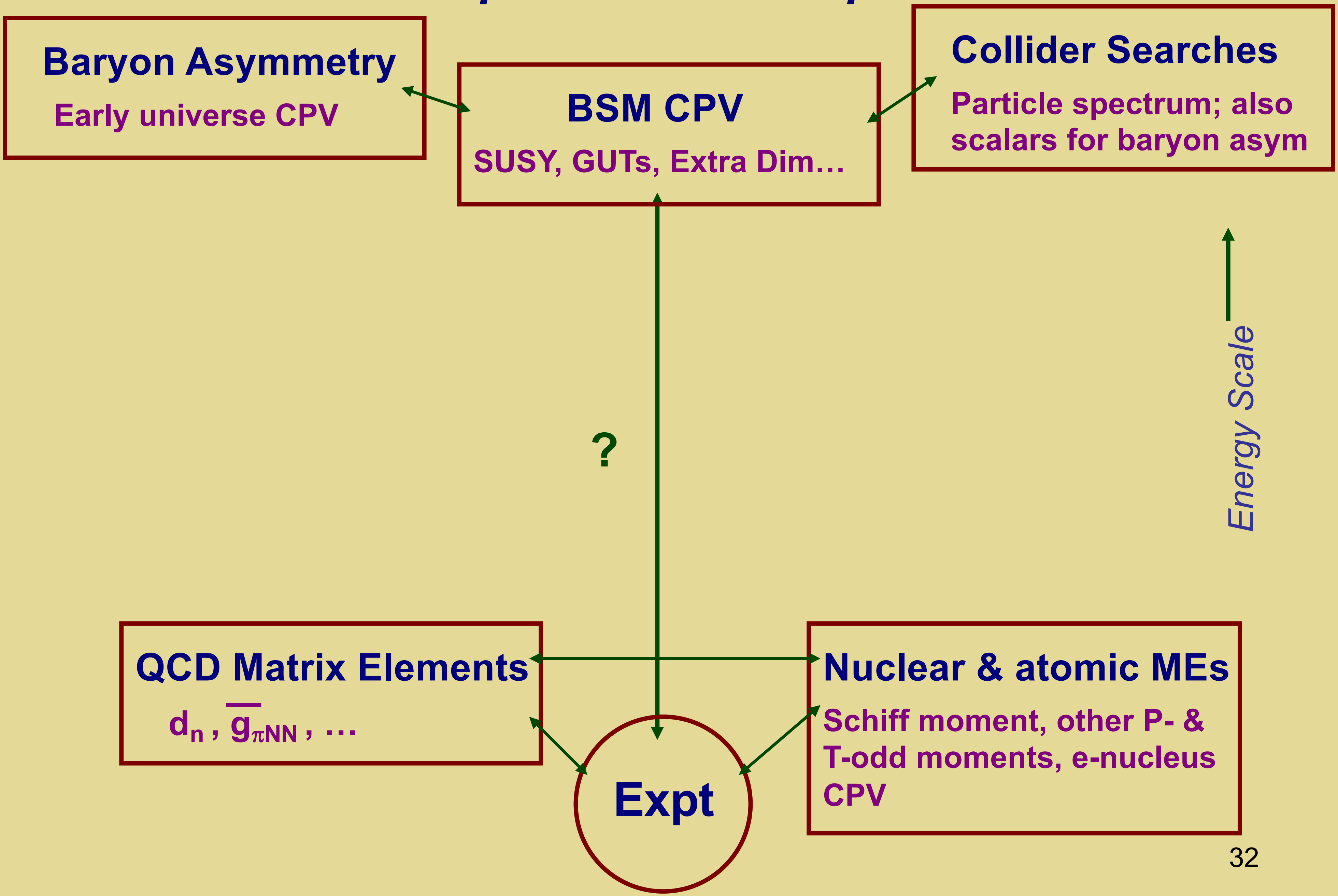
Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

II. Theoretical Interpretation

EDM Interpretation & Multiple Scales

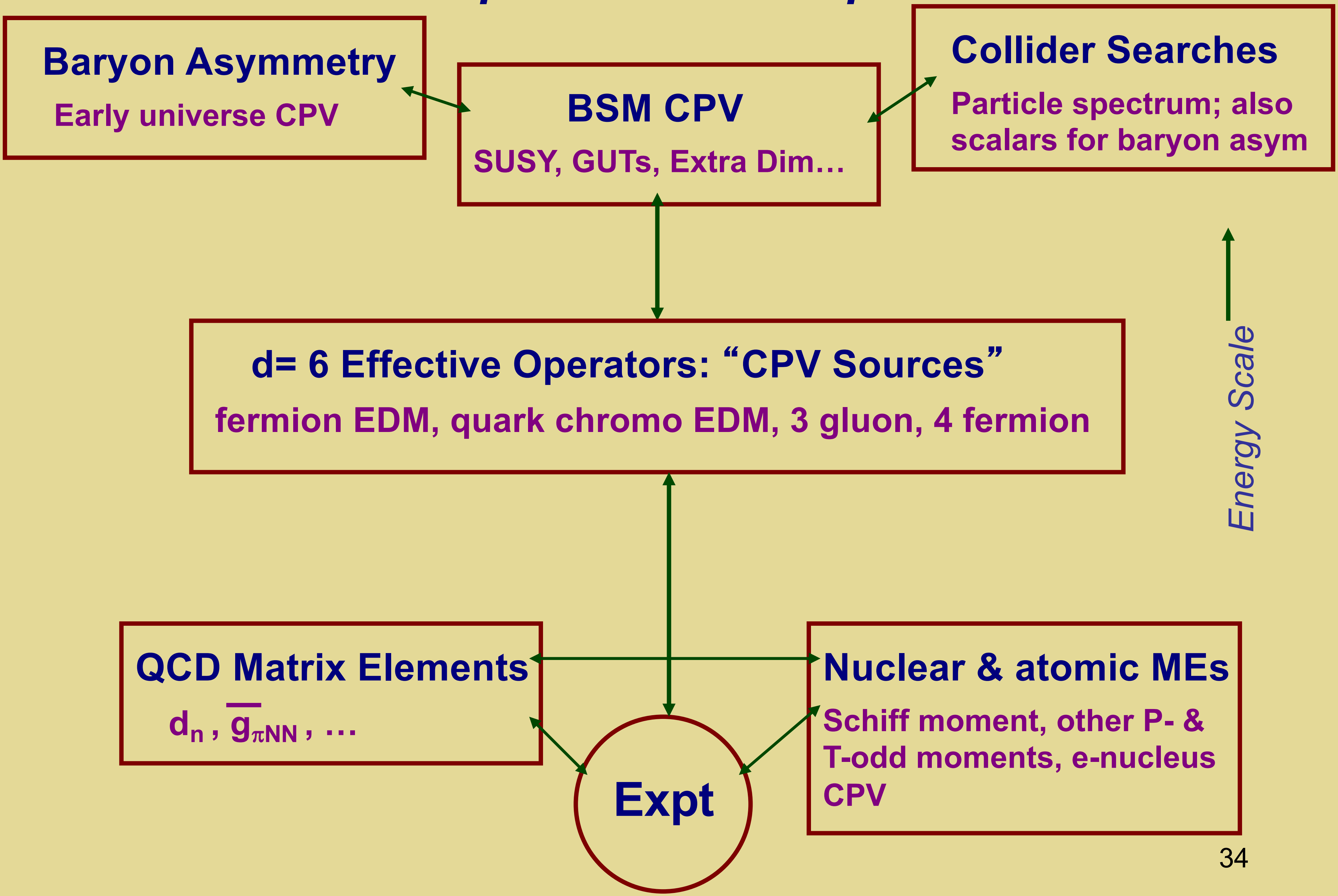


Effective Operators: The Elevator

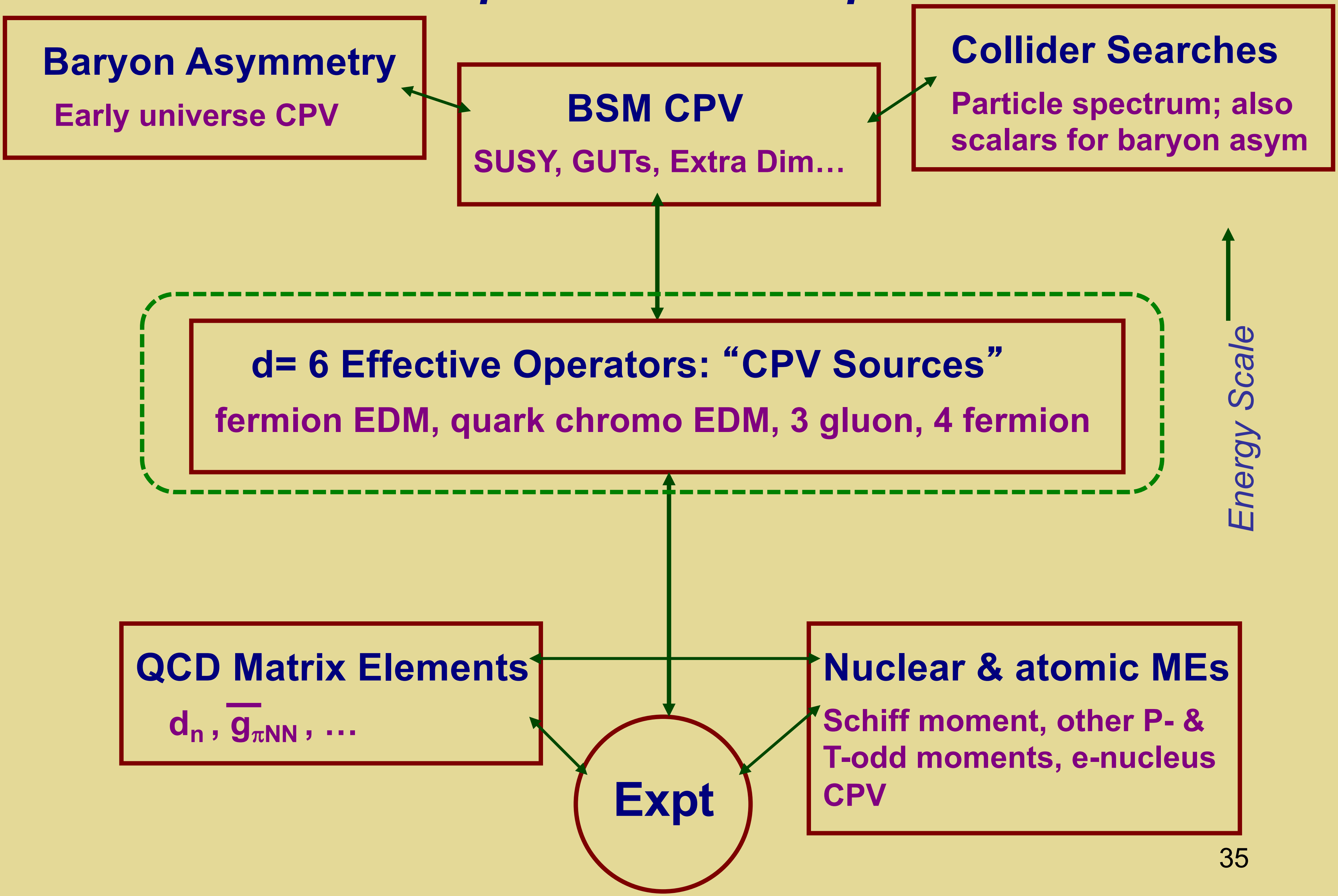
$$\mathcal{L}_{\text{CPV}} = \mathcal{L}_{\text{CKM}} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\text{BSM}}^{\text{eff}}$$

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

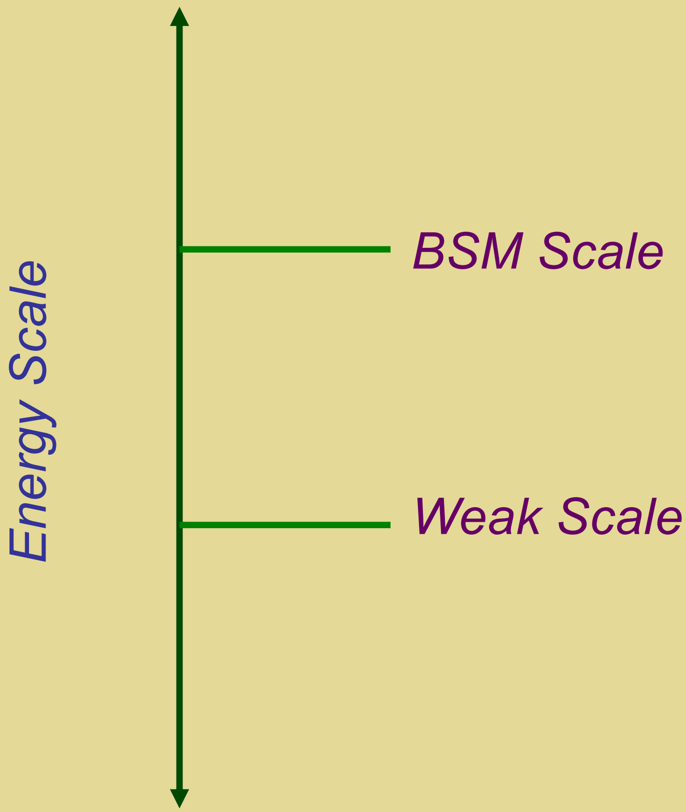
EDM Interpretation & Multiple Scales



EDM Interpretation & Multiple Scales



Effective Field Theory



Effective Field Theory

BSM CPV

Energy Scale

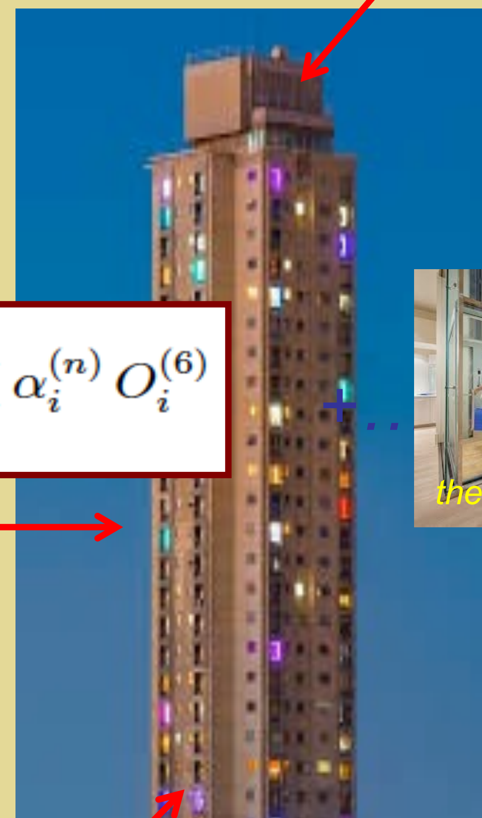
BSM Scale

Weak Scale

EDM physicists

Effective Field Theory

BSM CPV



Energy Scale

BSM Scale

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

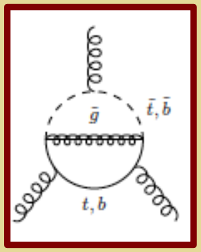
Weak Scale

EDM physicists

Operator Classification

Pure Gauge		Gauge-Higgs		Gauge-Higgs-Fermion	
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{uG}	$(\bar Q\sigma^{\mu\nu}T^A u)\widetilde\varphi\,G^A_{\mu\nu}$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{dG}	$(\bar Q\sigma^{\mu\nu}T^A d)\varphi\,G^A_{\mu\nu}$
		$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{fW}	$(\bar F\sigma^{\mu\nu}f)\tau^I\Phi\,W^I_{\mu\nu}$
		$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{fB}	$(\bar F\sigma^{\mu\nu}f)\Phi\,B_{\mu\nu}$

Weinberg 3 gluon



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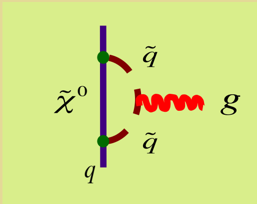

Quark chromo-EDM

Operator Classification

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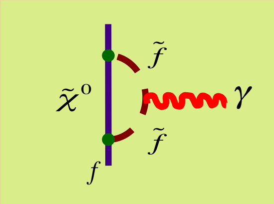

Fermion EDM

Operator Classification

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{L}^j e)(\bar{d} Q^j)$
$Q_{quqd}^{(1)}$	$(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$
$Q_{quqd}^{(8)}$	$(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$
$Q_{lequ}^{(1)}$	$(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$
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Operator Classification

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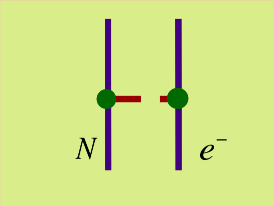
Semileptonic: atomic & molecular EDMs



Operator Classification

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Nonleptonic: hadronic EDMs & Schiff moment

Wilson Coefficients: Summary

δ_f	*fermion EDM*	*(3)*
$\tilde{\delta}_q$	*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)

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δ_f	*fermion EDM*	*(3)*
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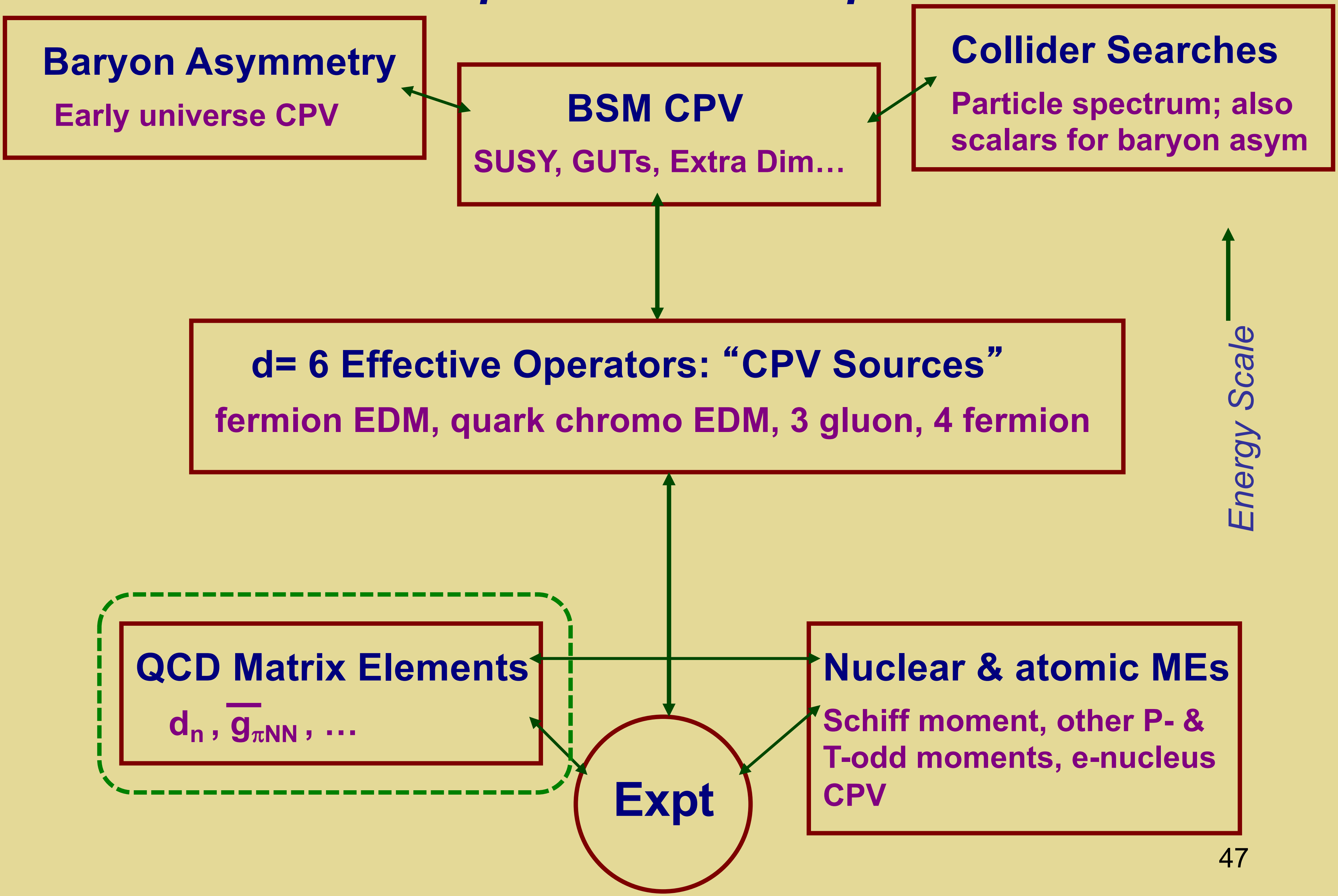
$C_{lequ,\, ledq}$	*semi-leptonic*	*(3)*
$C_{\varphi ud}$	*induced 4f*	*(1)*

12 total + $\bar{\theta}$

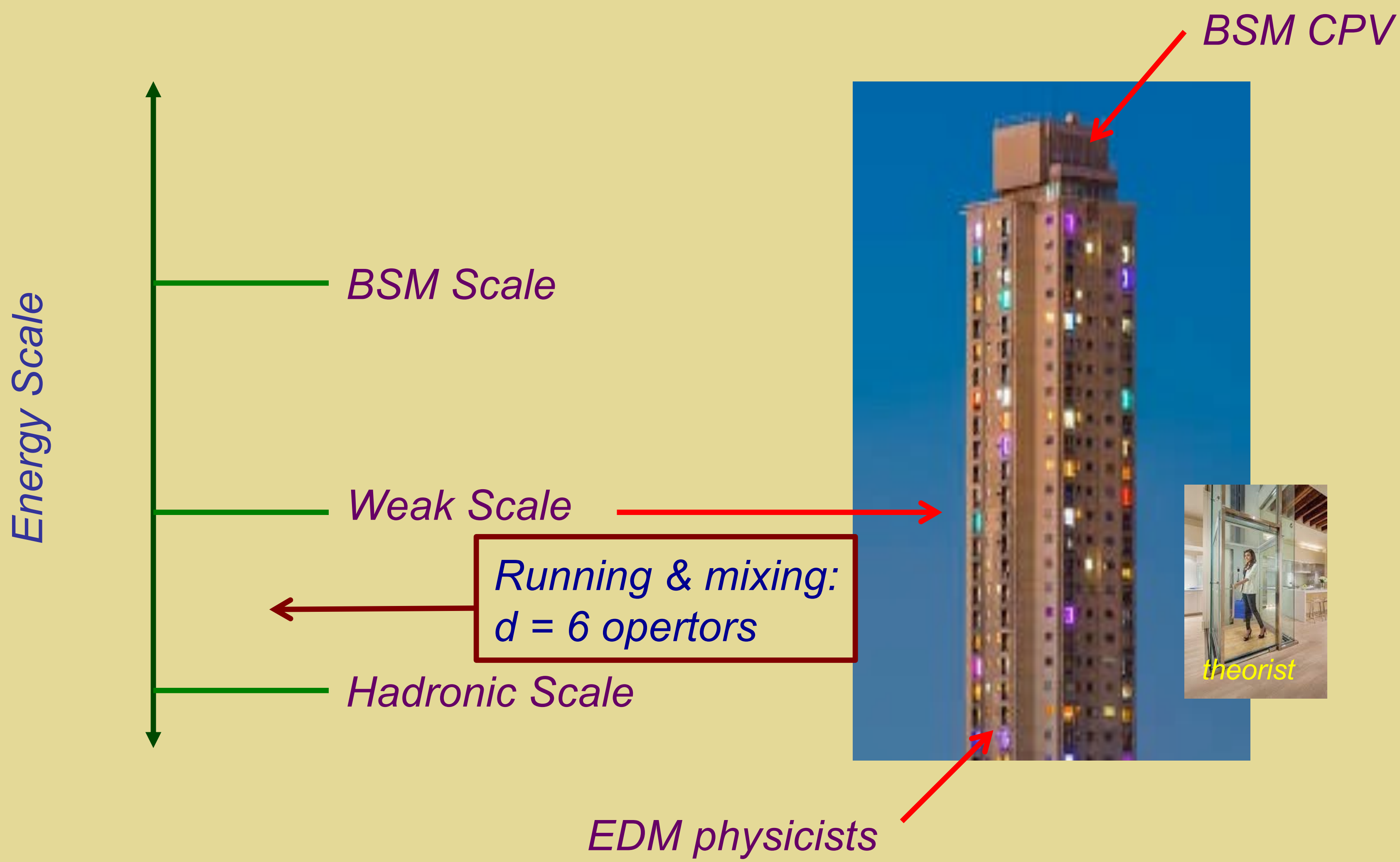
light flavors only (e,u,d)

Complementary searches needed

EDM Interpretation & Multiple Scales



Effective Field Theory



Effective Field Theory

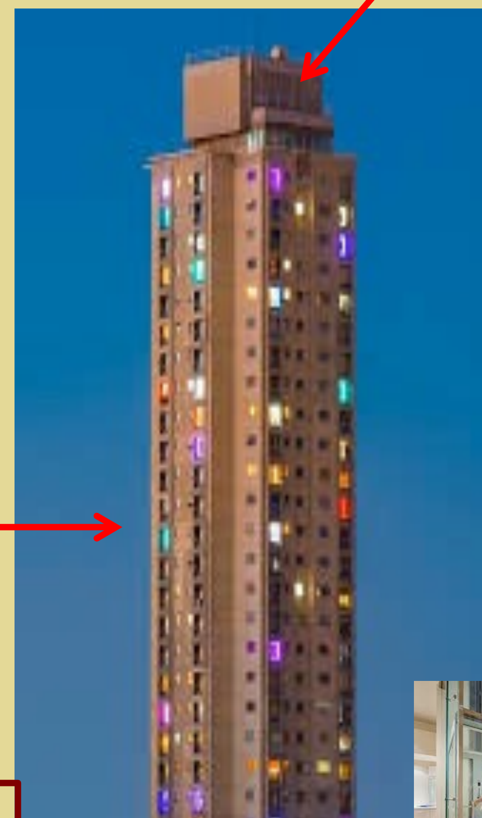
BSM CPV

Energy Scale

BSM Scale

Weak Scale

Hadronic Scale



Now consider this energy regime

TVPV Hadronic & Nuclear Interactions

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

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

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

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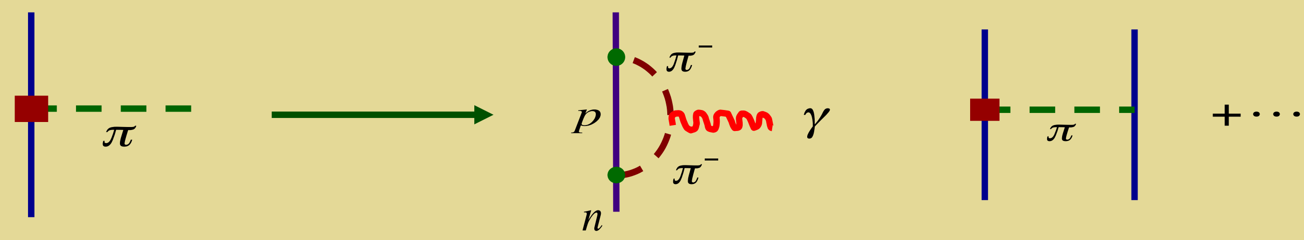
I = 0, 1, 2

PVTV πN interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

TVPV Hadronic & Nuclear Interactions

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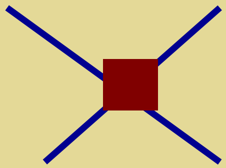
PVTV 4N interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Hadronic Matrix Element Challenge

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

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

Hadronic matrix elements

d=6 operator coefficients

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

Hadronic Matrix Elements

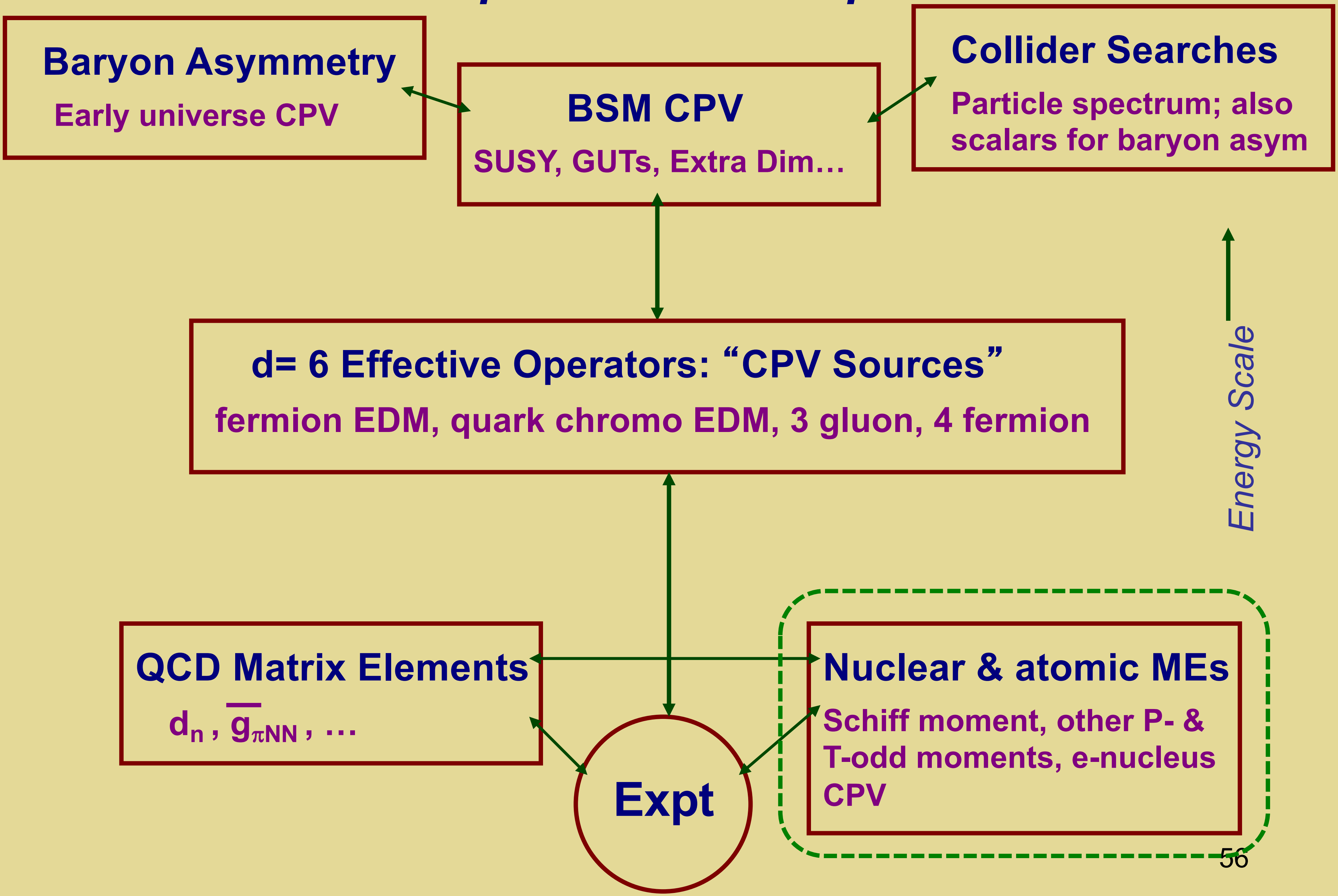
Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09 - 0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2 - 1.8)$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	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

Progress: LANL LQCD

Engel, R-M, van Kolck:

EDM Interpretation & Multiple Scales



Effective Field Theory

BSM CPV

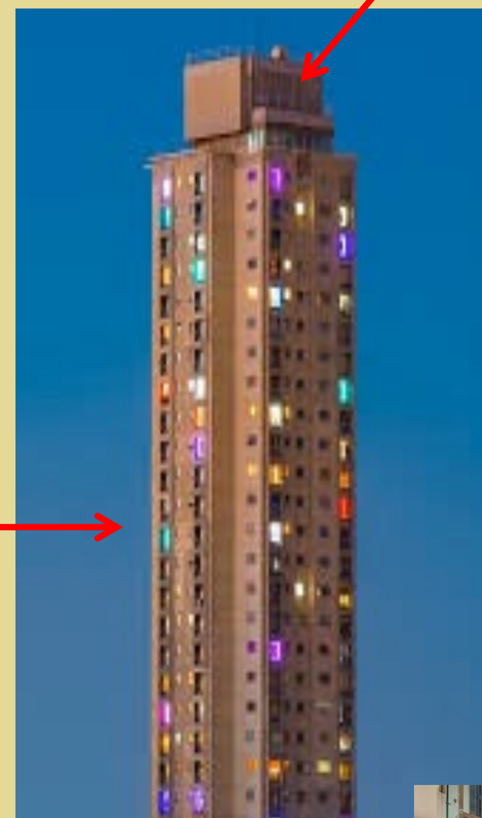
Energy Scale

BSM Scale

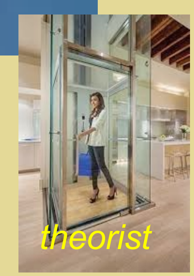
Weak Scale

Hadronic Scale

Nucl & Atomic Scales



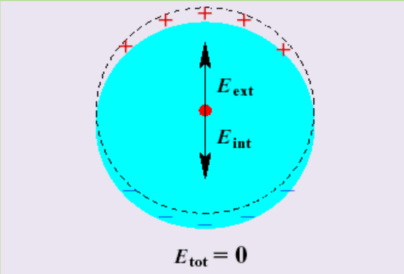
Now consider this energy regime



Schiff Theorem

The Theorem

Schiff Screening



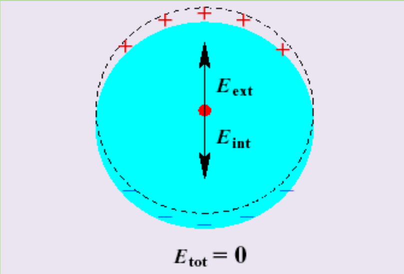
Classical picture: non-acceleration of neutral non-rel system

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



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

The EDM of a neutral system will vanish if:

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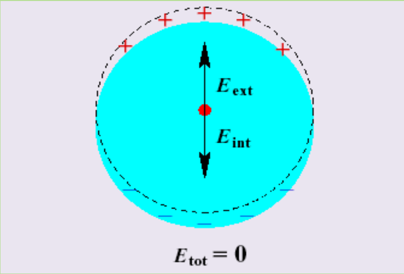
Paramagnetic systems w/ large Z: e^- are highly relativistic

Schiff Screening: Corrections

Schiff Screening



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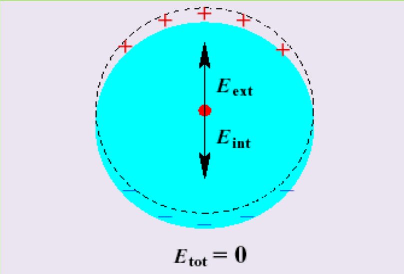
Diamagnetic atoms w/ large A: nuclei are large $r \sim (1\ \text{fm}) \times A^{1/3}$

Schiff Screening: Corrections

Schiff Screening



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

Paramagnetic Systems: d_e

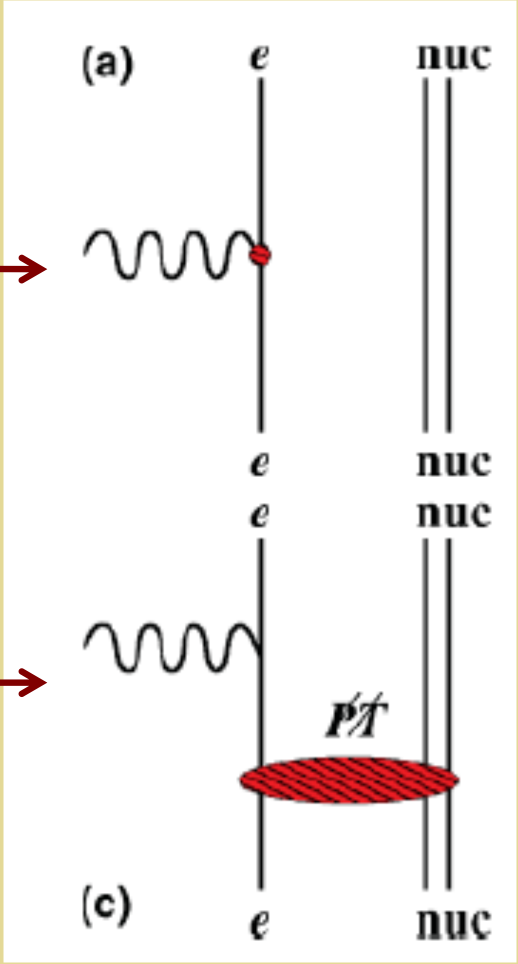
Electron EDM Interactions

External fields: 1st order energy shift

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

Internal (nuclear) fields: 2nd order energy shift

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



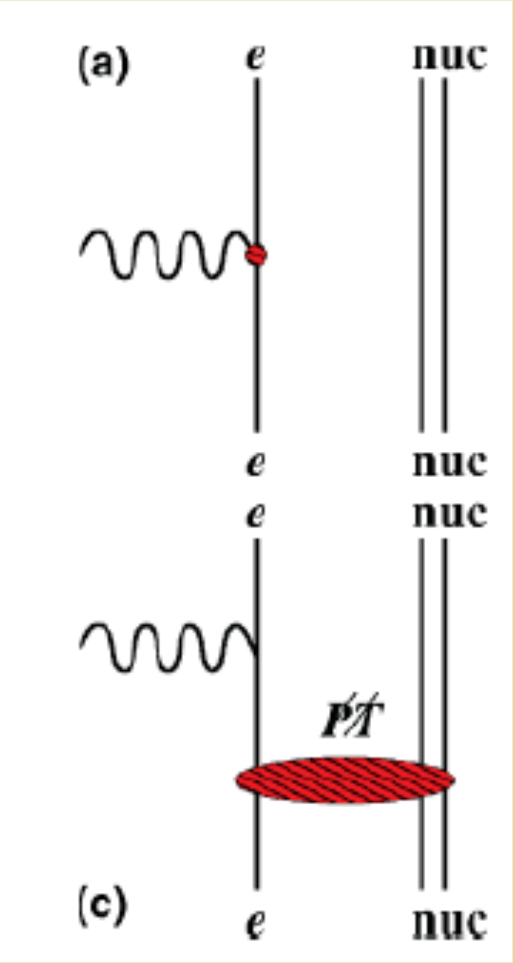
Electron EDM: Heavy Atoms

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

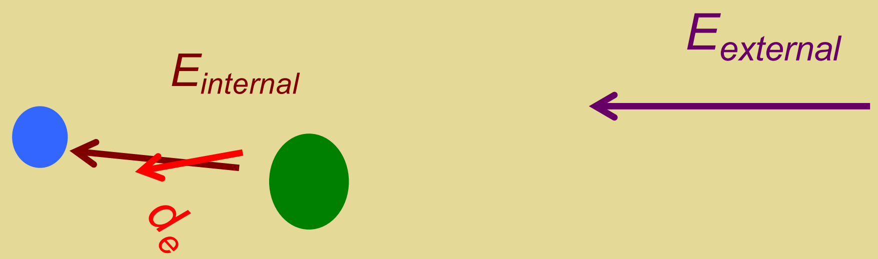
Atom	ρ_A^e
^{205}Tl	−573(20)
^{133}Cs	123(4)
^{85}Rb	25.7(0.8)
^{210}Fr	903(45)
^{199}Hg	0.01

Paramagnetic

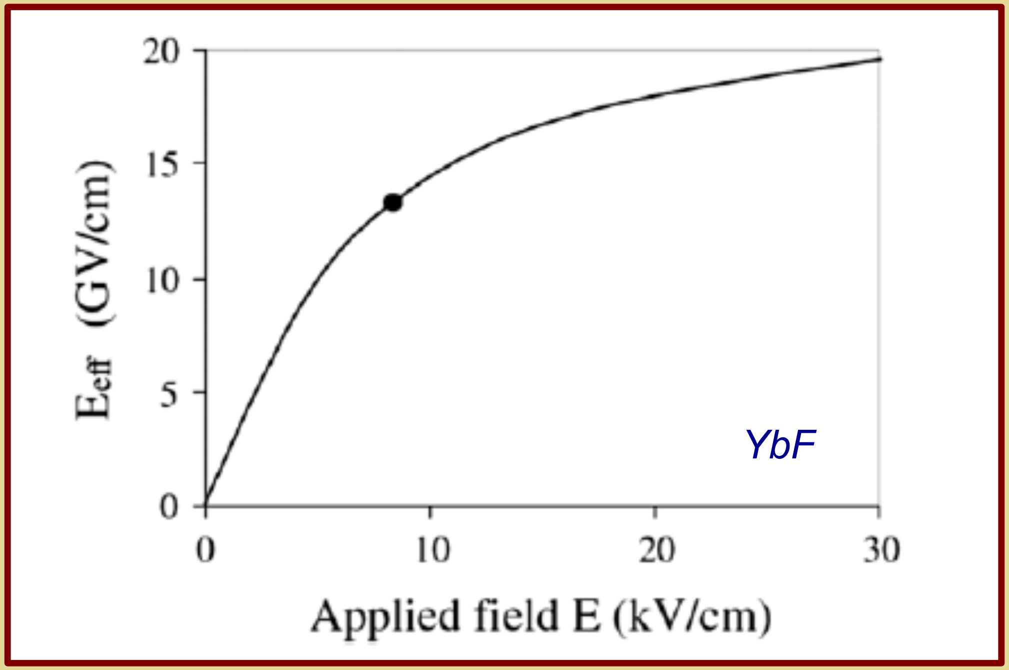
Diamagnetic



Electron EDM: Polar Molecules



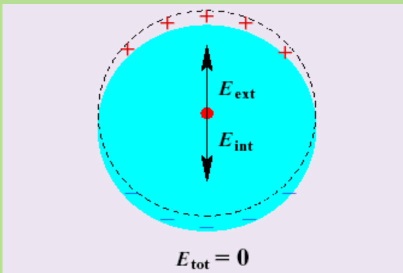
Electron experiences enhanced E_{int} as due to much smaller E_{ext}



Diamagnetic Atoms

Schiff Screening: Corrections

Schiff Screening



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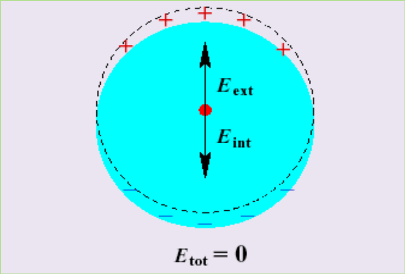
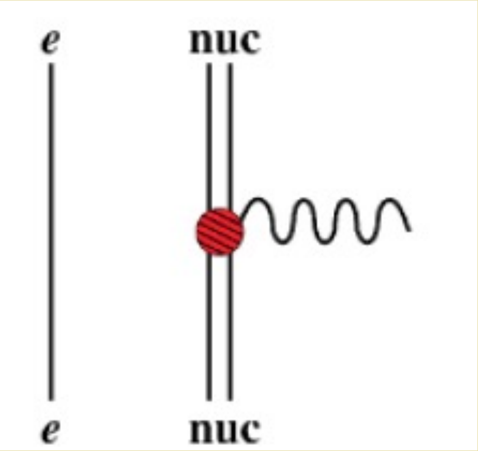
PVTV Nuclear Moments

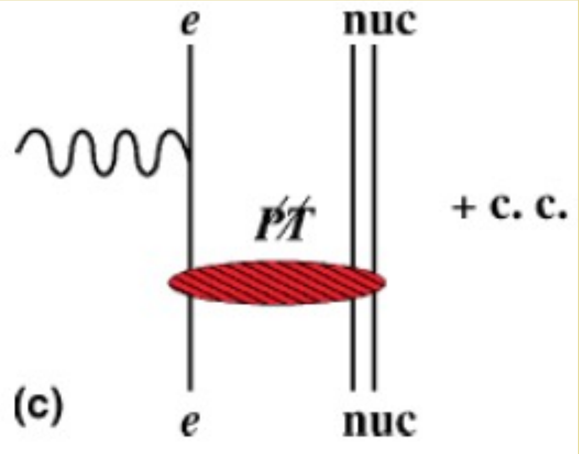
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM

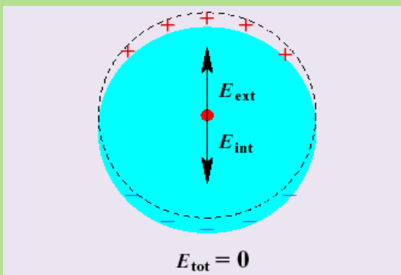


Schiff moment, MQM,…

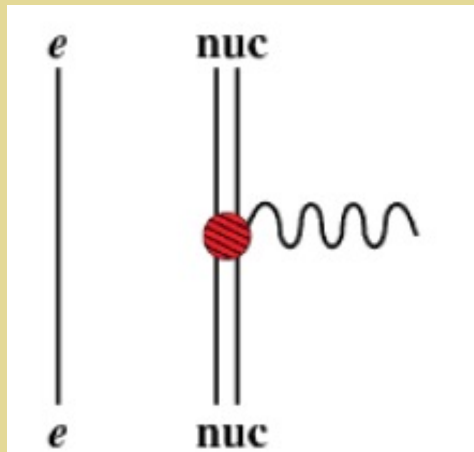
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

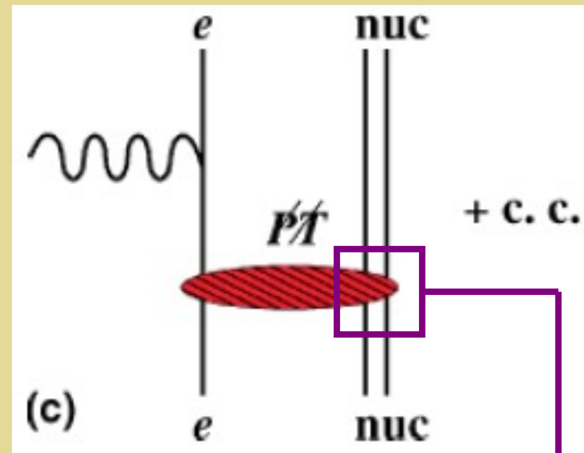
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM



Nuclear Schiff Moment

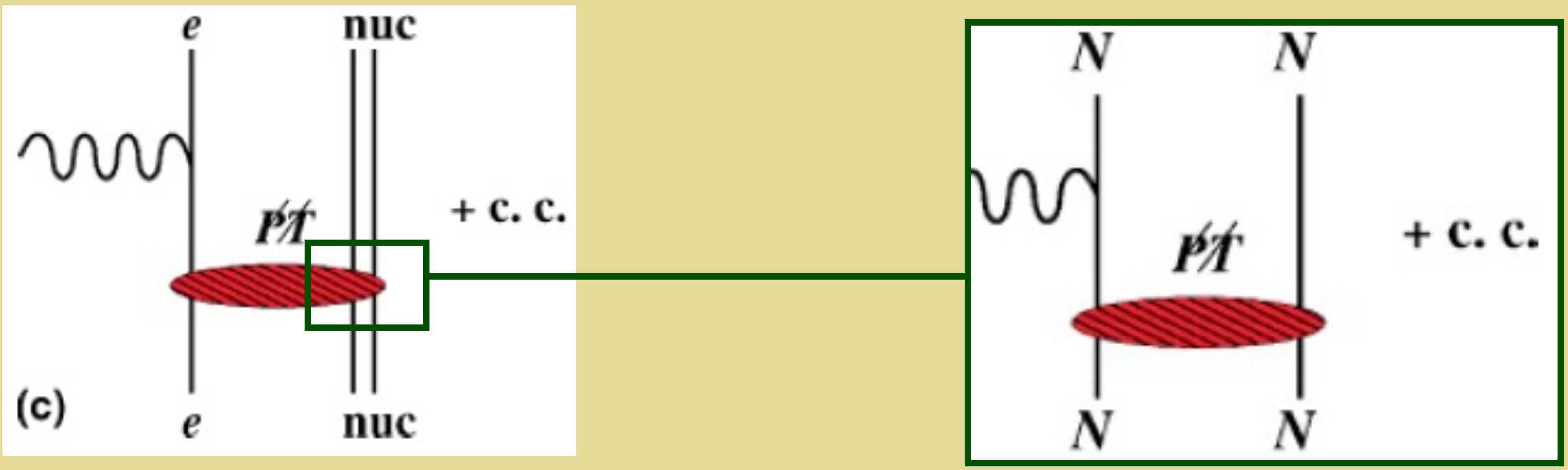
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



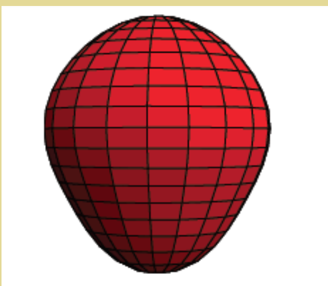
Schiff moment, MQM,…

Nuclear polarization: mixing of opposite parity states by $H^{TVPV} \sim 1 / \Delta E$

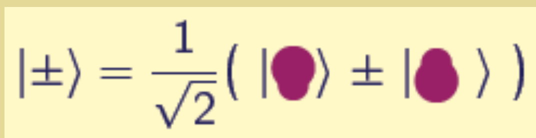
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

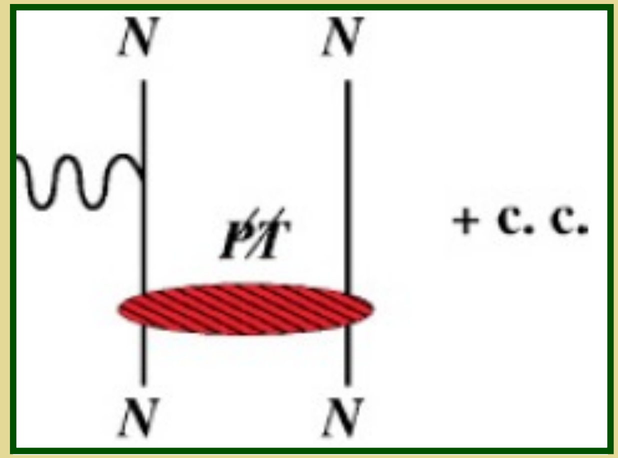
Nuclear Enhancements:
Octupole Deformation



Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}

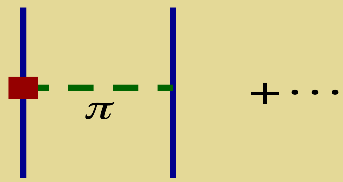


Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment: Pion Exchange

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



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)

IV. BSM Implications