Electric Dipole Moments

M.J. Ramsey-Musolf

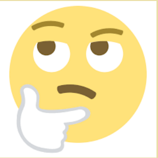
- *T.D. Lee Institute & Shanghai Jiao Tong Univ.*
- *UMass-Amherst*

My pronouns: he/him/his

GDR-InF Workshop
October 12, 2020

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

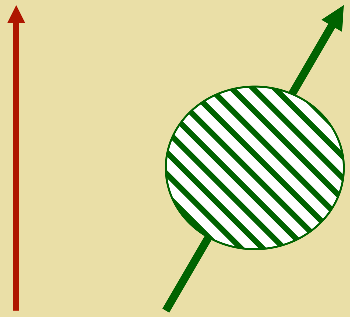
References

- *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 & The BSM Context

What is an EDM ?

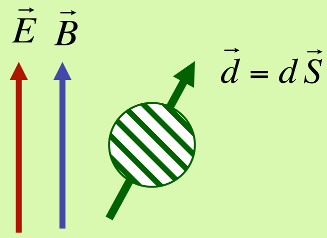
$\vec{E}$



$\vec{d} = d\,\vec{S}$

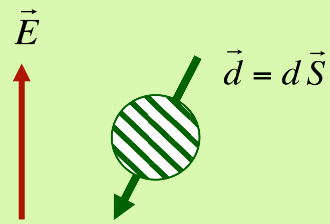
$$\nu_{EDM} = -\frac{d\,\vec{S}\cdot\vec{E}}{h}$$

What is an EDM ?



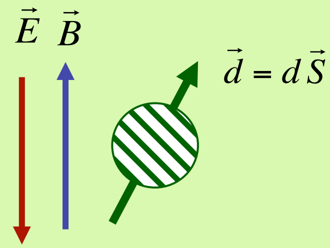
$$\nu_{EDM} = -\frac{d\,\vec{S}\cdot\vec{E}}{h}$$

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 by CPT 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

Coulomb → C_J

Magnetic → $T^M{}_J$

Transverse electric → $T^E{}_J$

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

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	✖	✖	O	*EDM, Schiff…*
Magnetic	$T^M{}_J$	O	✖	✖	E	*MQM….*
Transverse electric	$T^E{}_J$	✖	O	E	✖	*Anapole…*

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	✖	✖	O	*EDM, Schiff…*
T^M_J	O	✖	✖	E	*MQM….*
T^E_J	✖	O	E	✖	*Anapole…*

Coulomb → C_J

Magnetic → T^M_J

Transverse electric → T^E_J

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	✖	✖	O	*EDM, Schiff…*
Magnetic →	$T^M{}_J$	O	✖	✖	E	*MQM….*
Transverse electric →	$T^E{}_J$	✖	O	E	✖	*Anapole…*

Nuclear Enhancements

EDMs & SM Physics

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

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

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

EDMs & BSM Physics

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

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

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

BSM dynamics: perturbative? Strongly coupled?

y_f	*Fermion f Yukawa coupling*
F	*Function of the dynamics*

EDMs & BSM Physics

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

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}
ThO	1.1×10^{-29} **	10^{-38} *	10^{-28}
n	1.8×10^{-26}	10^{-31}	10^{-26}

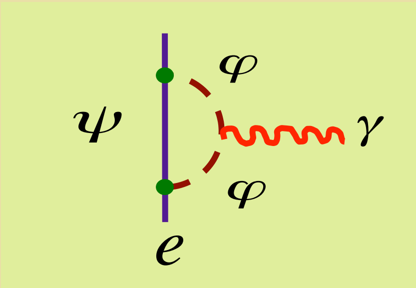
* 95% CL ** e^- equivalent * e^- equivalent from C_S

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-33}	10^{-29}
ThO	1.1×10^{-29} **	10^{-38} *	10^{-28}
n	1.8×10^{-26}	10^{-31}	10^{-26}

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

Mass Scale Sensitivity



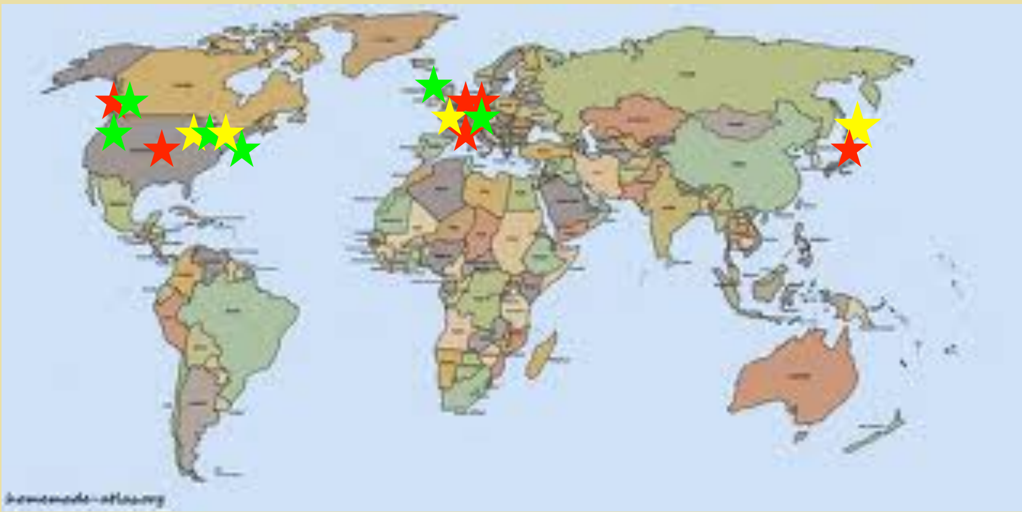
$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

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

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-33}	10^{-29}
ThO	1.1×10^{-29} **	10^{-38} *	10^{-28}
n	1.8×10^{-26}	10^{-31}	10^{-26}

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



★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

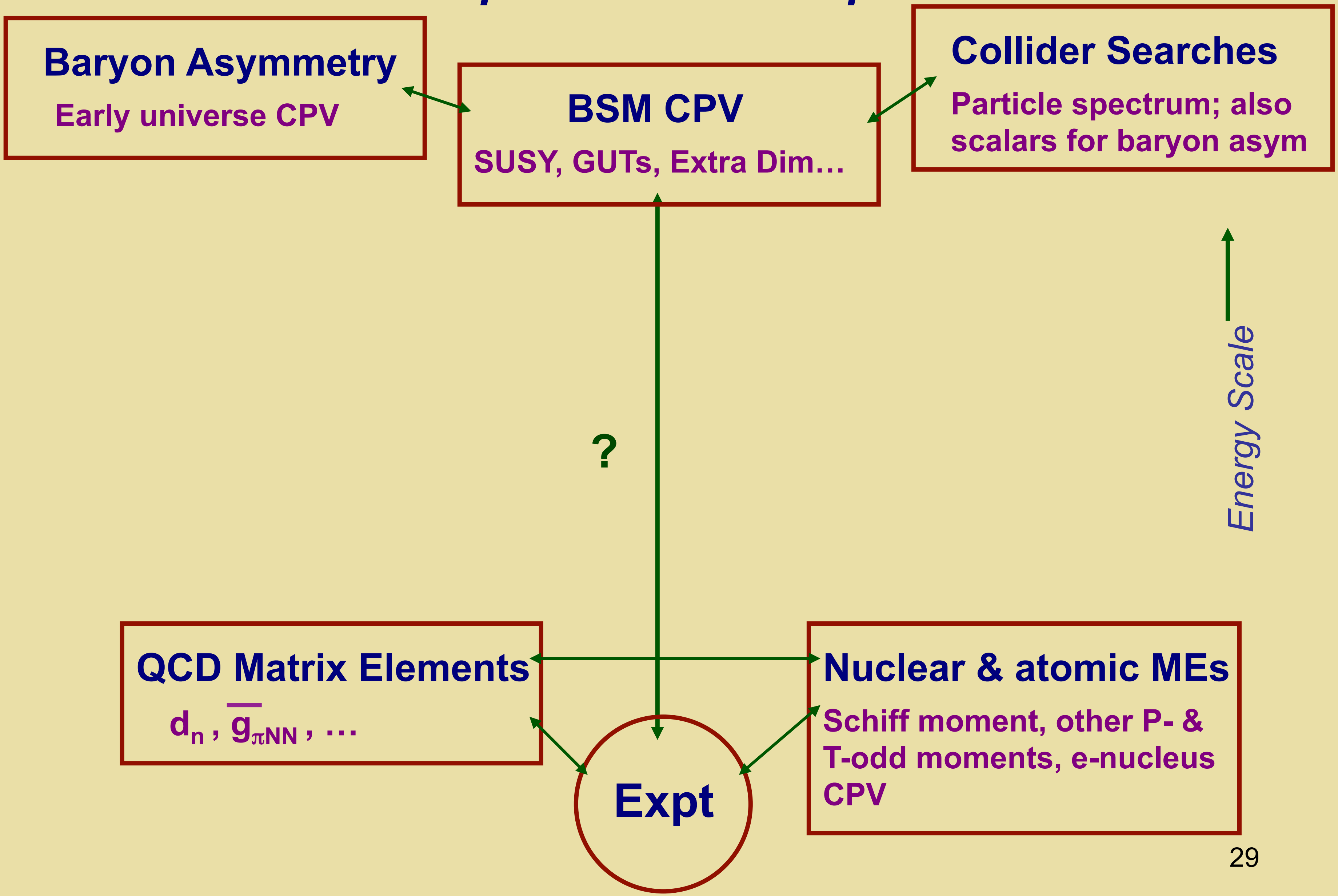
Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

II. Theoretical Interpretation

EDM Interpretation & Multiple Scales

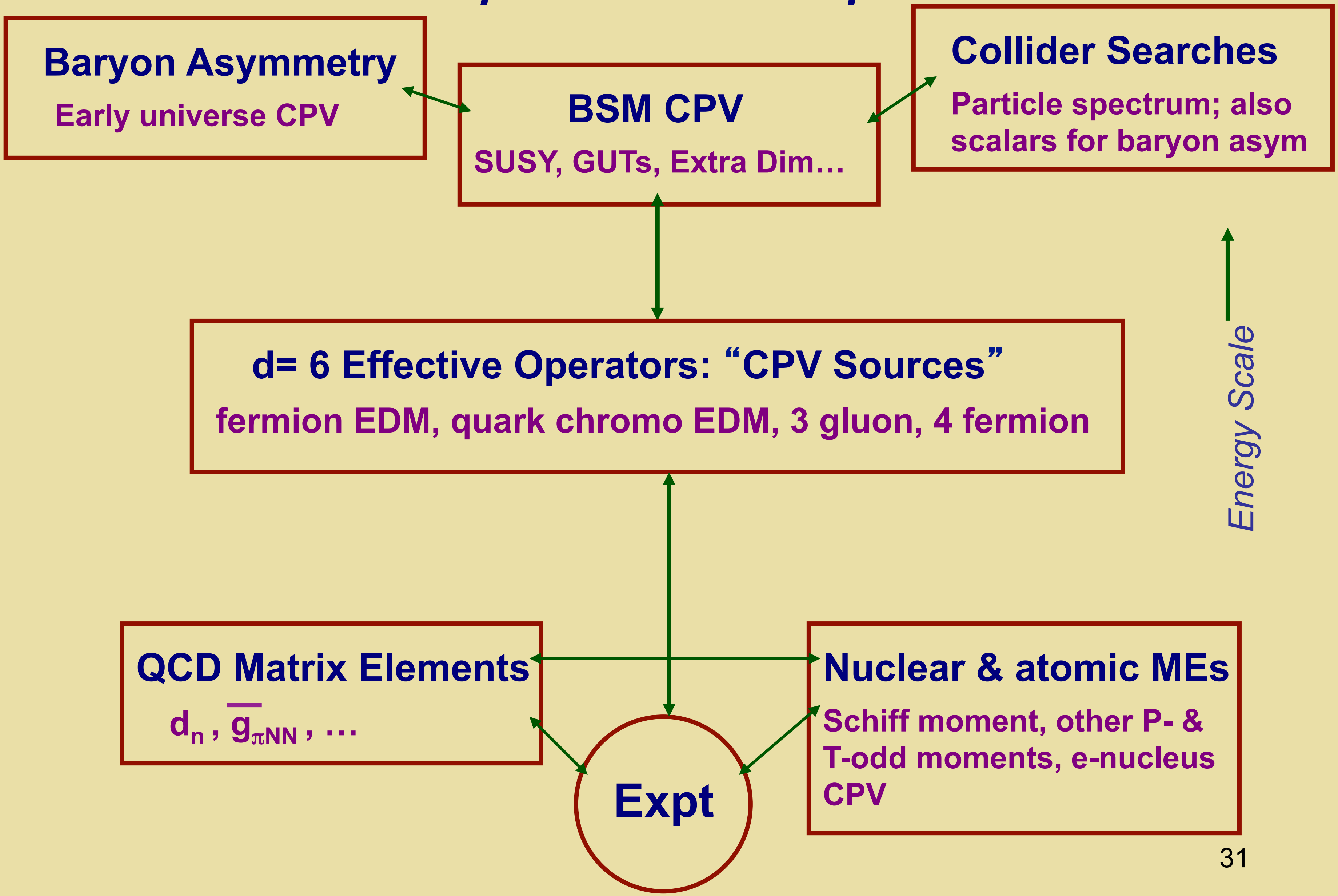


Effective Operators: The Elevator

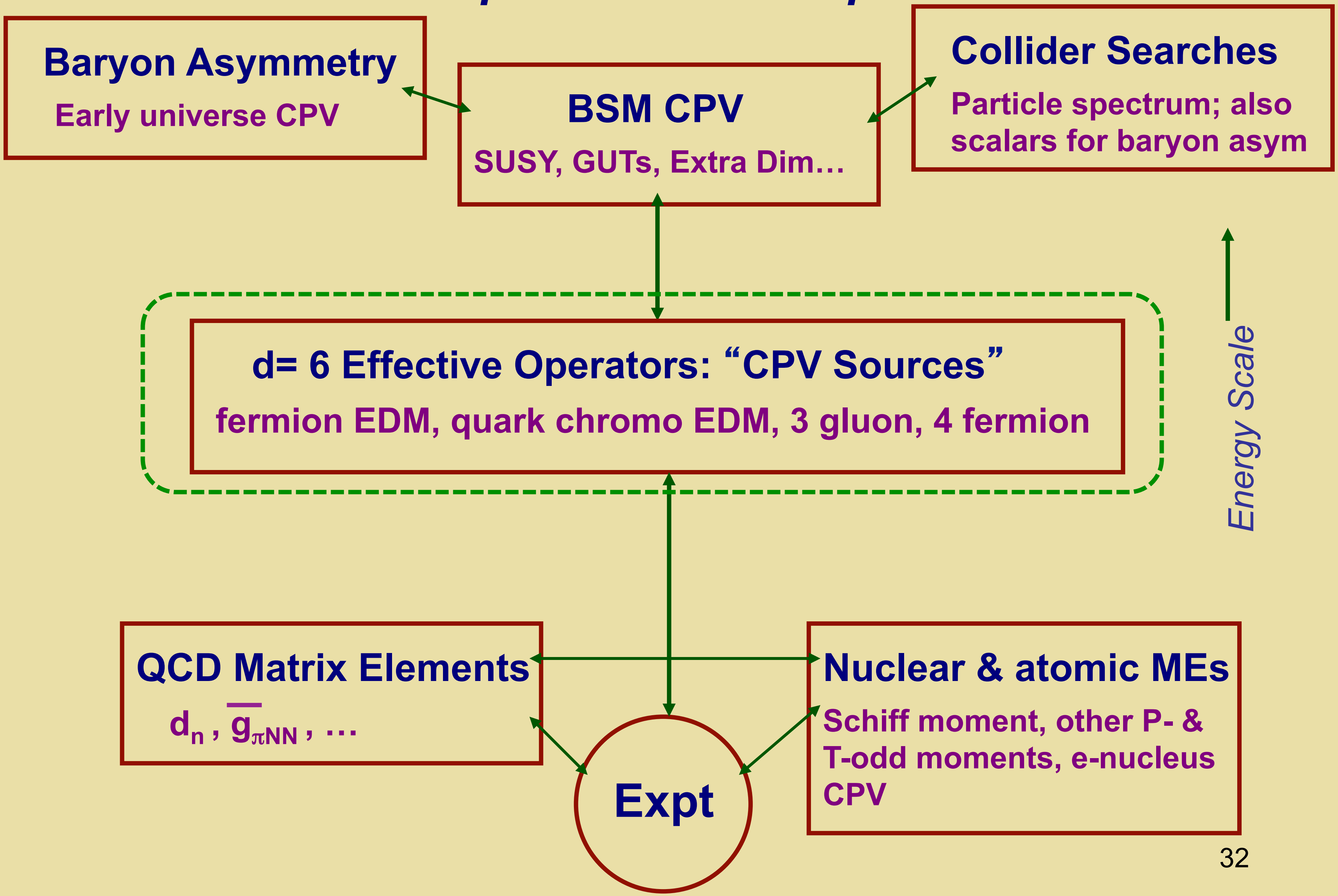
$$\mathcal{L}_{\rm CPV} = \mathcal{L}_{\rm CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{\rm BSM}^{\rm eff}$$

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

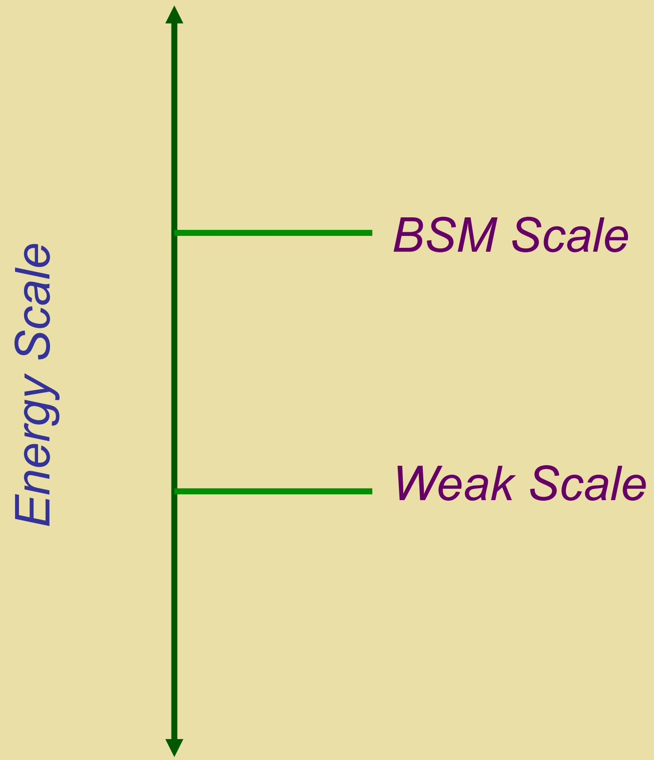
EDM Interpretation & Multiple Scales



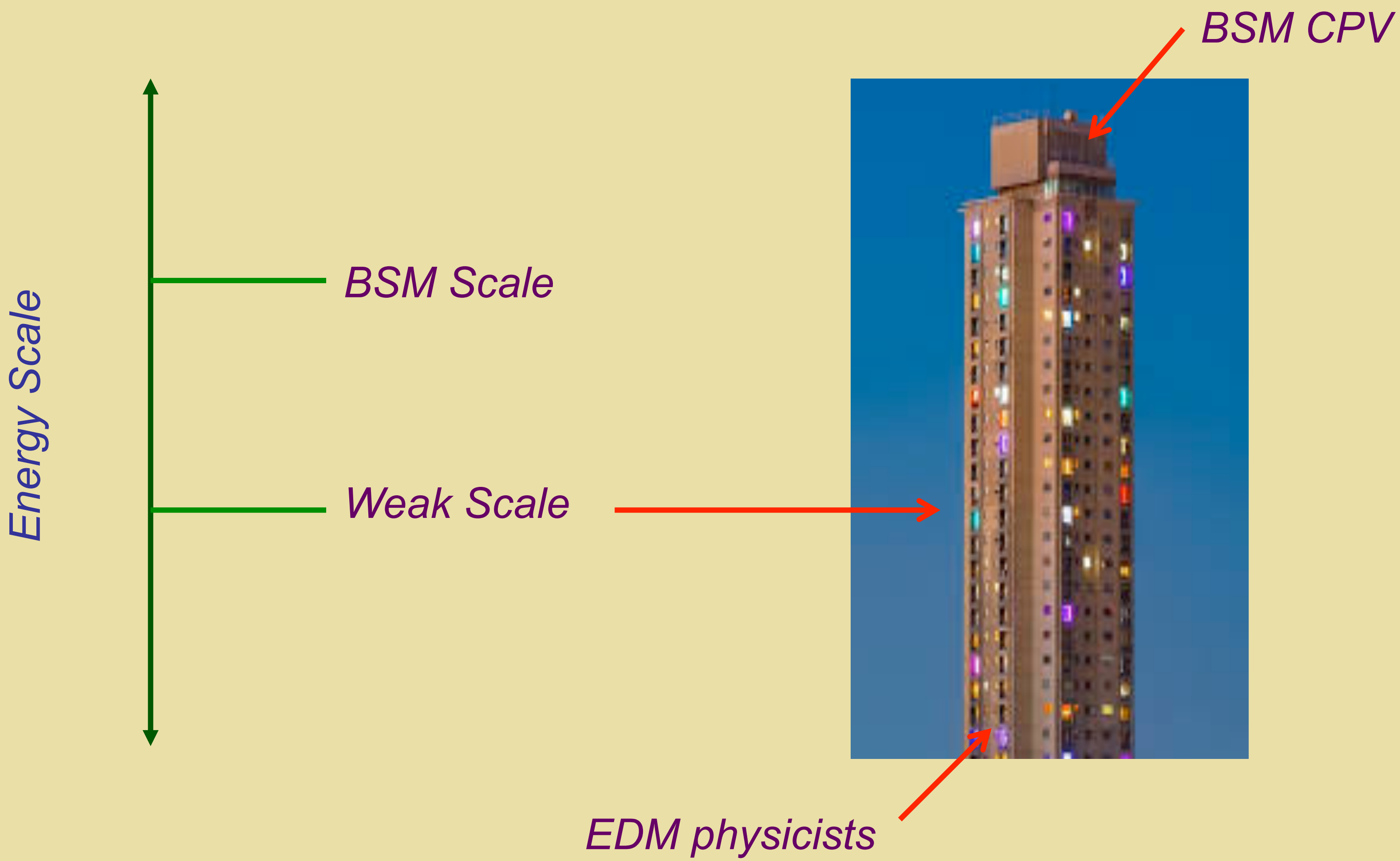
EDM Interpretation & Multiple Scales



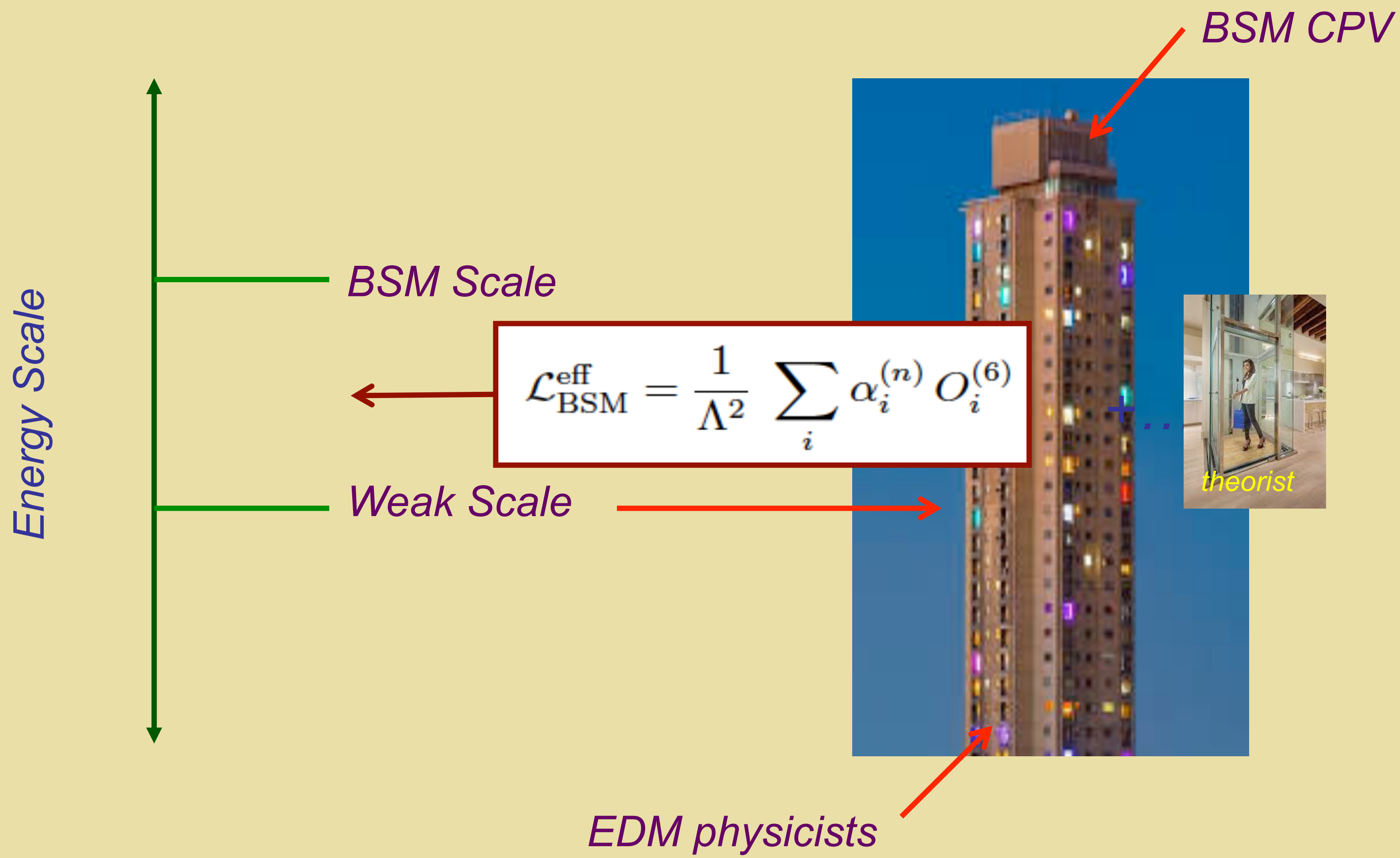
Effective Field Theory



Effective Field Theory



Effective Field Theory

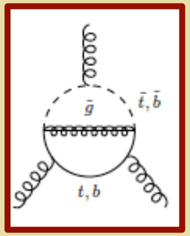


$$\mathcal{L}_{\mathrm{BSM}}^{\mathrm{eff}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} \, O_i^{(6)}$$

Operator Classification

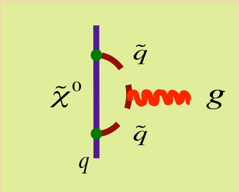
Pure Gauge		Gauge-Higgs		Gauge-Higgs-Fermion	
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_{\mu}^{A\nu}G_{\nu}^{B\rho}G_{\rho}^{C\mu}$	$Q_{\varphi\widetilde{G}}$	$\varphi^{\dagger}\varphi\,\widetilde{G}_{\mu\nu}^{A}G^{A\mu\nu}$	Q_{uG}	$(\bar{Q}\sigma^{\mu\nu}T^{A}u)\widetilde{\varphi}\,G_{\mu\nu}^{A}$
$Q_{\widetilde{W}}$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

Weinberg 3 gluon



Operator Classification

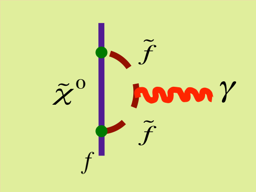
Pure Gauge		Gauge-Higgs		Gauge-Higgs-Fermion	
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_{\mu}^{A\nu}G_{\nu}^{B\rho}G_{\rho}^{C\mu}$	$Q_{\varphi\widetilde{G}}$	$\varphi^{\dagger}\varphi\,\widetilde{G}_{\mu\nu}^{A}G^{A\mu\nu}$	Q_{uG}	$(\bar{Q}\sigma^{\mu\nu}T^{A}u)\tilde{\varphi}\,G_{\mu\nu}^{A}$
$Q_{\widetilde{W}}$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



Quark chromo-EDM

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}	$(\bar{F}\sigma^{\mu\nu}f)\Phi\,B_{\mu\nu}$



Fermion EDM

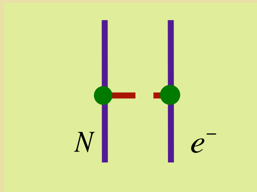
Operator Classification

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{L}^j e)(\bar{d} Q^j)$
$Q_{quqd}^{(1)}$	$(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$
$Q_{quqd}^{(8)}$	$(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$
$Q_{lequ}^{(1)}$	$(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$
$Q_{lequ}^{(3)}$	$(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$

Operator Classification

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{L}^j e)(\bar{d}Q^j)$
$Q_{quqd}^{(1)}$	$(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$
$Q_{quqd}^{(8)}$	$(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$
$Q_{lequ}^{(1)}$	$(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$
$Q_{lequ}^{(3)}$	$(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$

Semileptonic: atomic & molecular EDMs



Operator Classification

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{L}^j e)(\bar{d}Q^j)$
$Q_{quqd}^{(1)}$	$(\bar{Q}^j u)\epsilon_{jk}(\bar{Q}^k d)$
$Q_{quqd}^{(8)}$	$(\bar{Q}^j T^A u)\epsilon_{jk}(\bar{Q}^k T^A d)$
$Q_{lequ}^{(1)}$	$(\bar{L}^j e)\epsilon_{jk}(\bar{Q}^k u)$
$Q_{lequ}^{(3)}$	$(\bar{L}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} u)$

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)

Wilson Coefficients: Summary

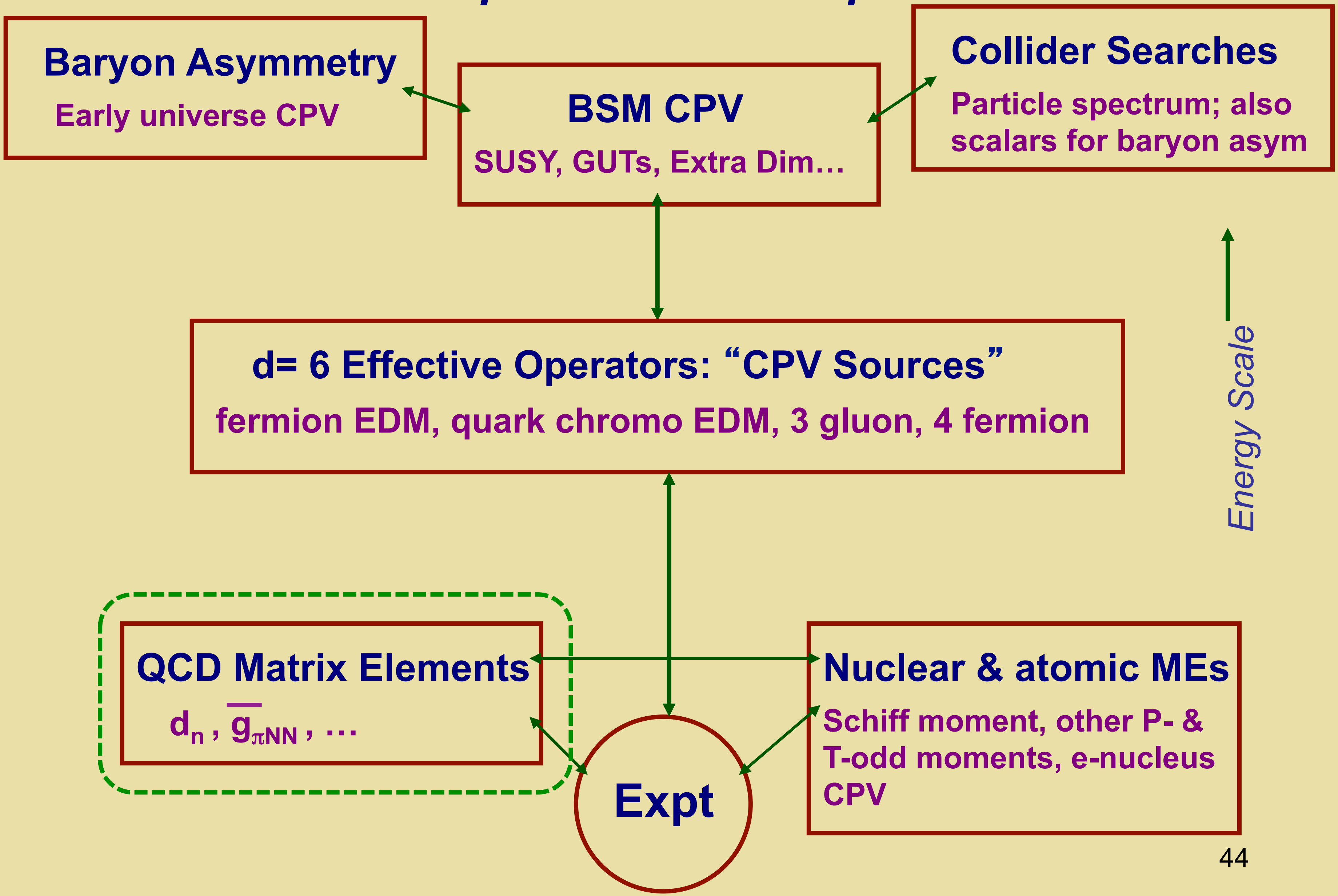
δ_f	*fermion EDM*	*(3)*
$\tilde{\delta}_q$	*quark CEDM*	*(2)*
$C_{\tilde{G}}$	*3 gluon*	*(1)*
C_{quqd}	*non-leptonic*	*(2)*
$C_{lequ,\, ledq}$	*semi-leptonic*	*(3)*
$C_{\varphi ud}$	*induced 4f*	*(1)*

12 total + $\bar{\theta}$

light flavors only (e,u,d)

Complementary searches needed

EDM Interpretation & Multiple Scales



Effective Field Theory

BSM CPV

Energy Scale

BSM Scale

Weak Scale

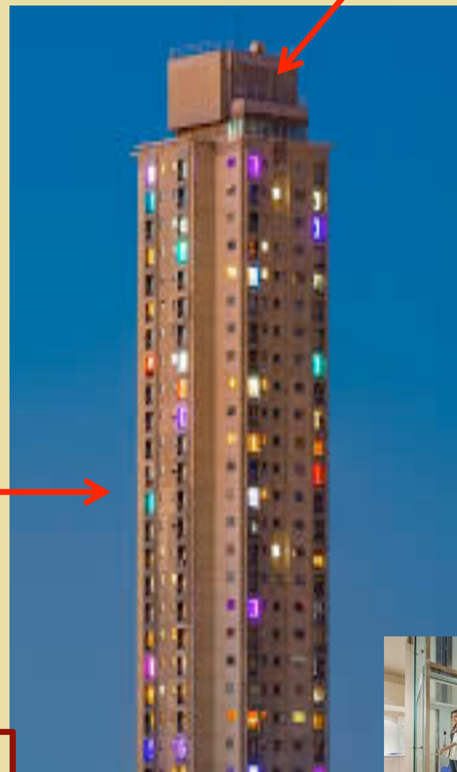
Running & mixing:
d = 6 opertors

Hadronic Scale

EDM physicists

Effective Field Theory

BSM CPV



Energy Scale

BSM Scale

Weak Scale

Hadronic Scale

Now consider this energy regime

TVPV Hadronic & Nuclear Interactions

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

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

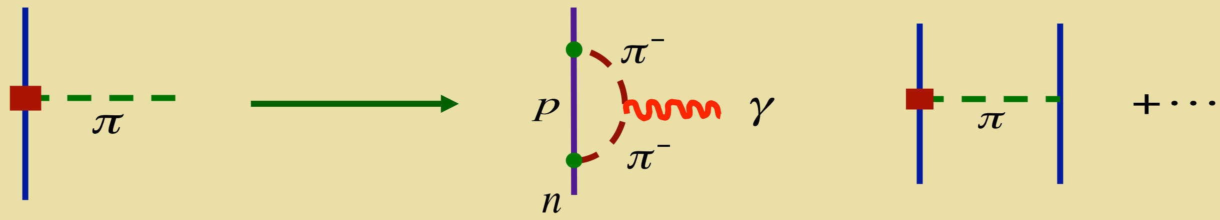
$$\mathcal{L}_{N\pi}^{\rm PVTV} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$

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

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

I = 0, 1, 2

PVTV πN interaction

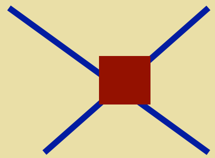


Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

TVPV Hadronic & Nuclear Interactions

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

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

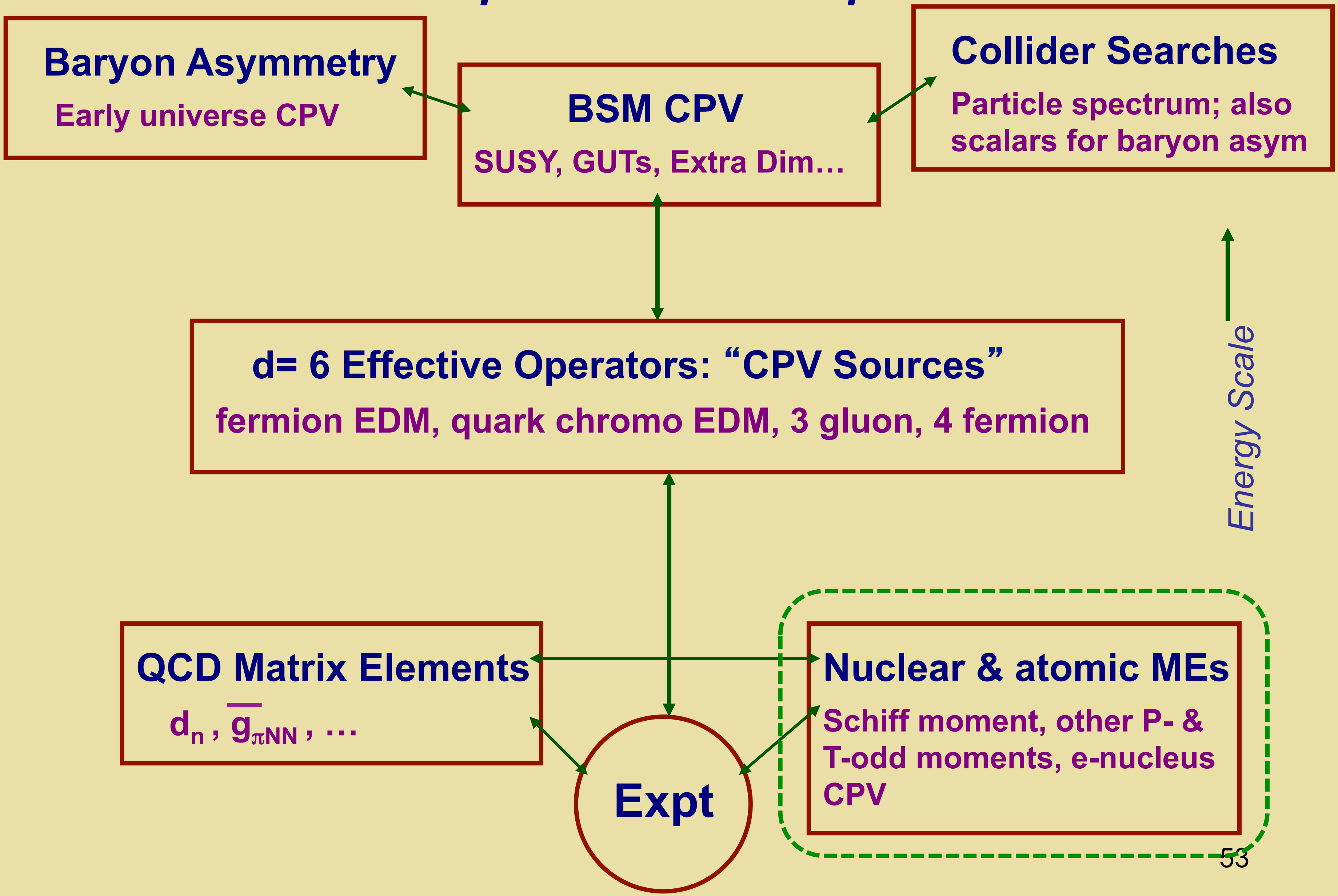
Param	Coeff	Best value[a]	Range
$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
	α_p	0.002	(0.0005–0.004)
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1-10) \times 10^{-4}$
	β_n^{dG}	8×10^{-4}	$(2-18) \times 10^{-4}$
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	−0.35	$-(0.09-0.9)$
	$e\tilde{\rho}_n^d$	−0.7	$-(0.2-1.8)$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

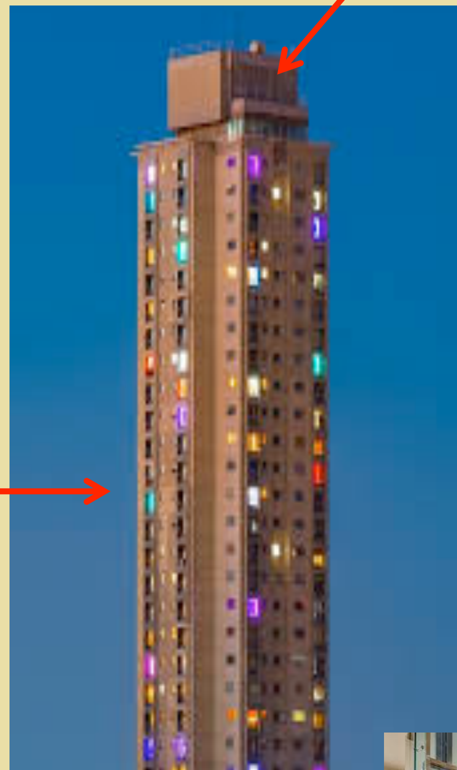


Effective Field Theory

Energy Scale

- BSM Scale
- Weak Scale
- Hadronic Scale
- Nucl & Atomic Scales

BSM CPV

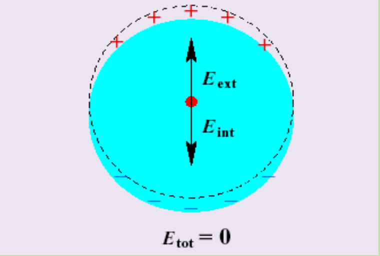


Now consider this energy regime

Schiff Theorem

The Theorem

Schiff Screening



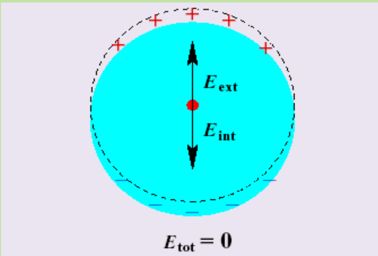
Classical picture: non-acceleration of neutral non-rel system

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

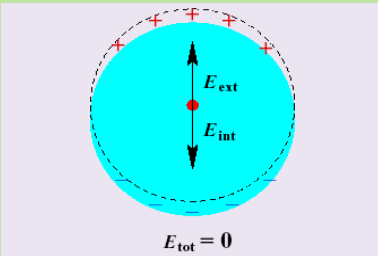
The EDM of a neutral system will vanish if:

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

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

Schiff Screening: Corrections

Schiff Screening



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

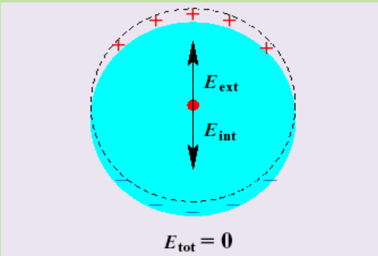
The EDM of a neutral system will vanish if:

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

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

Schiff Screening: Corrections

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*

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

Paramagnetic Systems: d_e

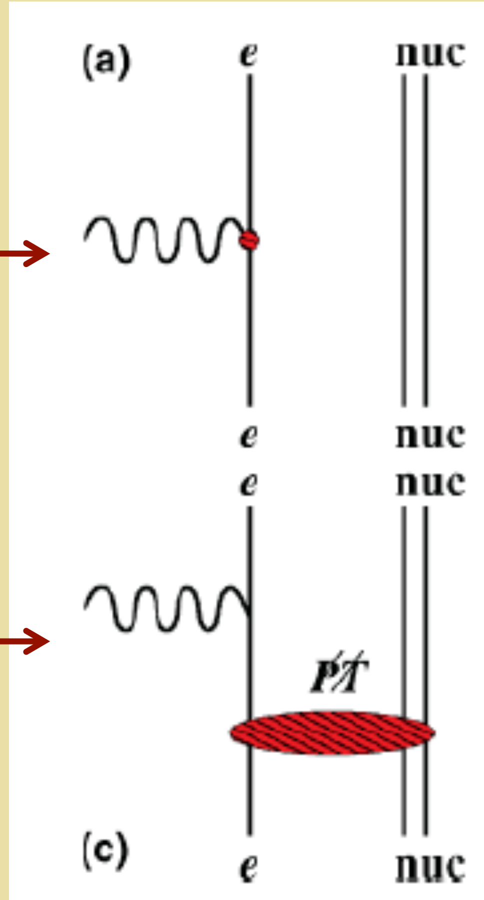
Electron EDM Interactions

External fields: 1st order energy shift

$$\tilde{V}_{\text{ext}}^{(\tilde{e})} = -\alpha \sum_{i=1}^{Z} d_e \beta \left(\sigma_i \cdot E_i^{(\text{ext})} + i\alpha_i \cdot B_i^{(\text{ext})} \right).$$

Internal (nuclear) fields: 2nd order energy shift

$$\tilde{V}_{\text{int}}^{(\tilde{e}\mathcal{N})} = -\alpha \sum_{i=1}^{Z} d_e \beta \left[\sigma_i \cdot E_i^{(\mathcal{N})} + i\alpha_i \cdot B_i^{(\mathcal{N})} \right] + \cdots.$$



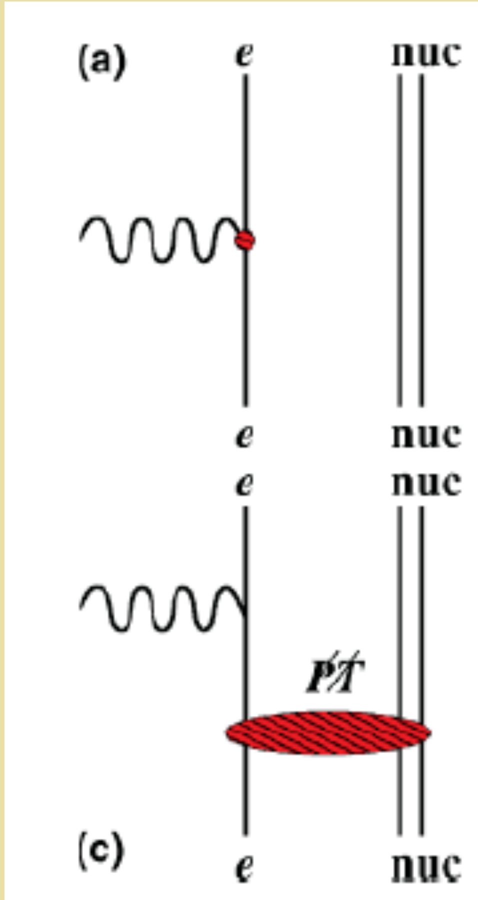
Electron EDM: Heavy Atoms

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

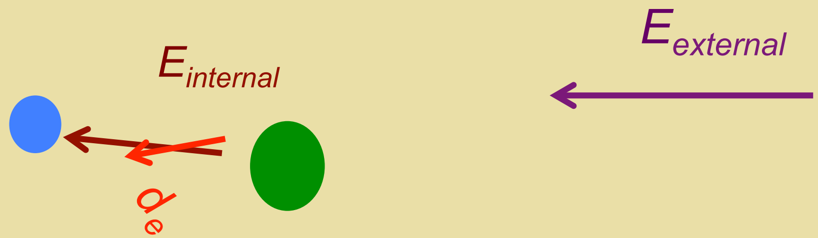
Atom	ρ_A^e
^{205}Tl	−573(20)
^{133}Cs	123(4)
^{85}Rb	25.7(0.8)
^{210}Fr	903(45)
^{199}Hg	0.01

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

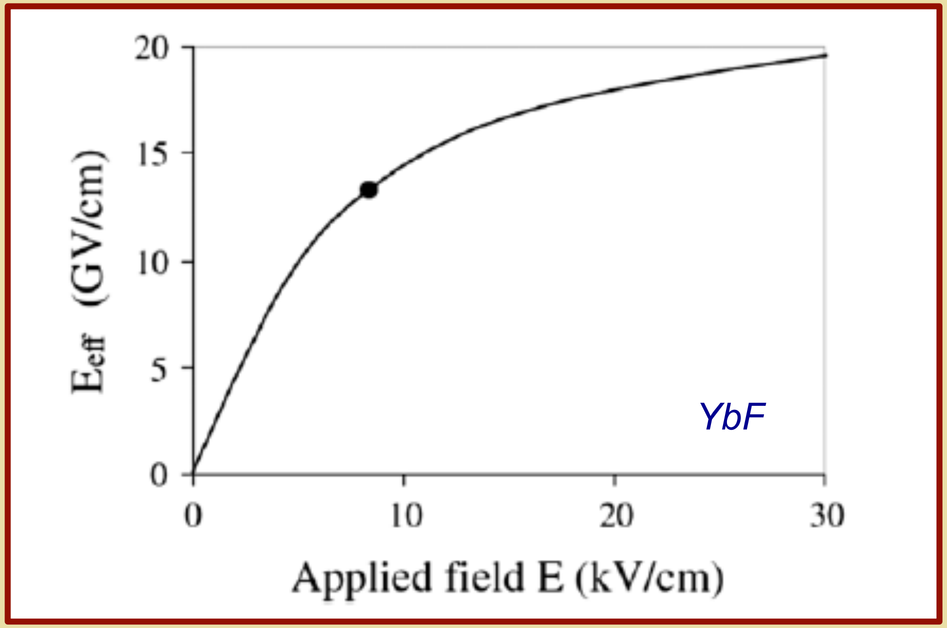
Diamagnetic (^{199}Hg)



Electron EDM: Polar Molecules



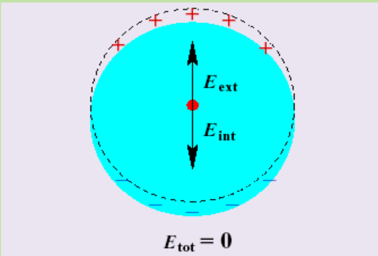
Electron experiences enhanced E_{int} as due to much smaller E_{ext}



Diamagnetic Atoms

Schiff Screening: Corrections

Schiff Screening



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

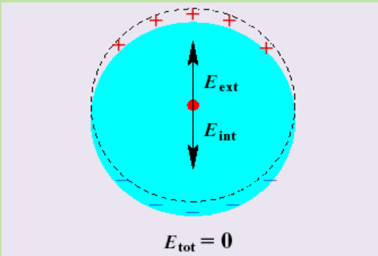
The EDM of a neutral system will vanish if:

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

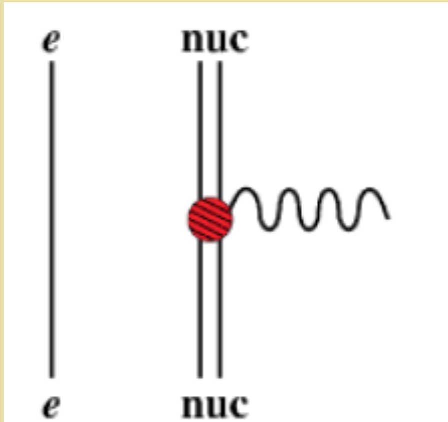
Diamagnetic atoms w/ large A: nuclei are large $r \sim (1\ \mathrm{fm}) \times A^{1/3}$

PVTV Nuclear Moments

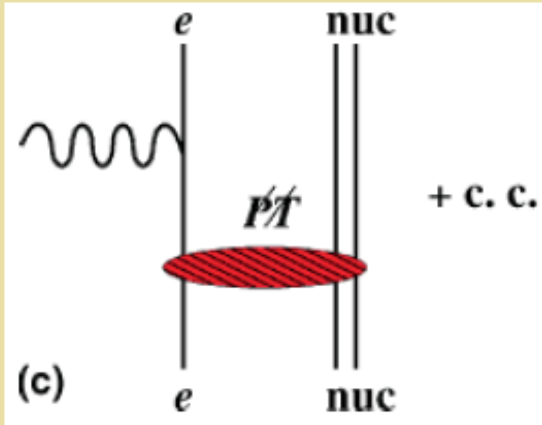
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM

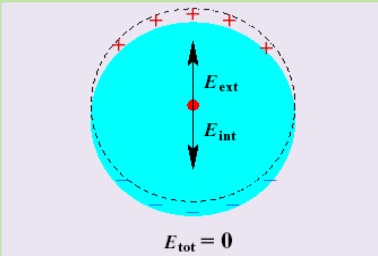


Schiff moment, MQM,…

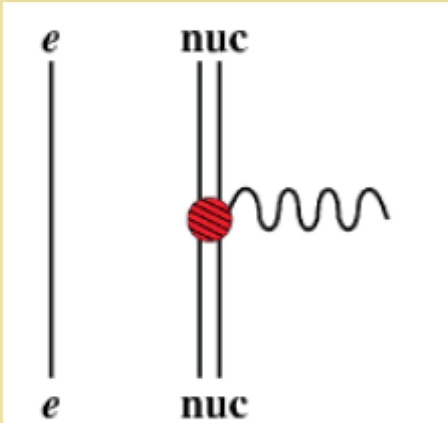
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

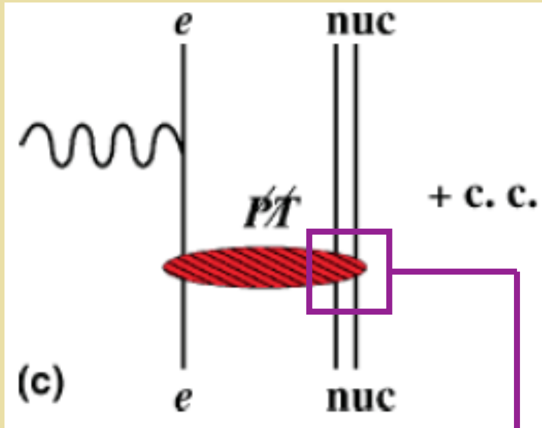
Schiff Screening



Atomic effect from nuclear finite size: Schiff moment



Screened EDM



Nuclear Schiff Moment

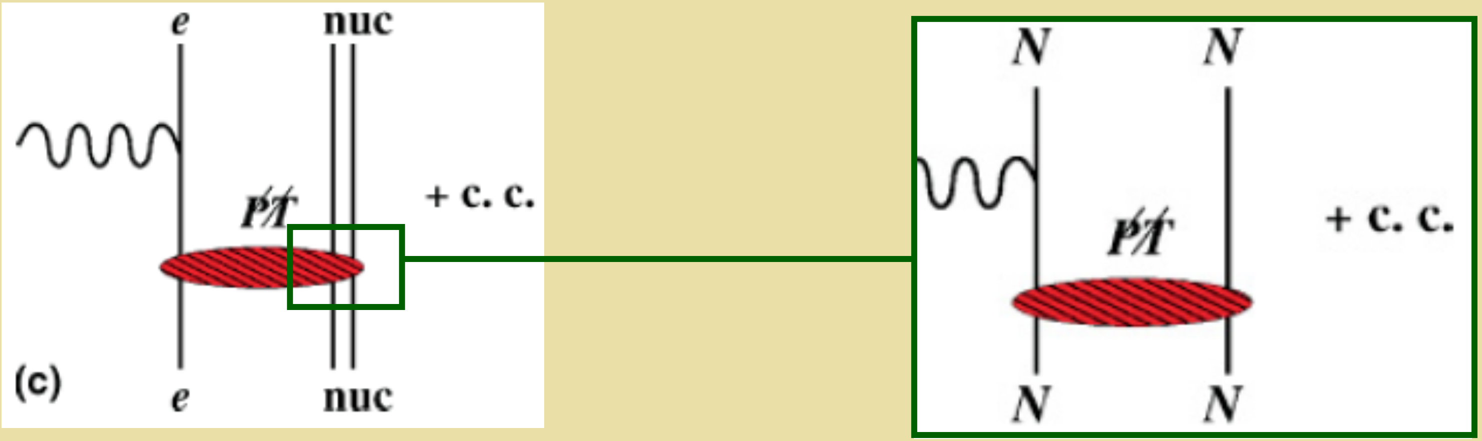
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

$(R_N / R_A)^2$ suppression

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

Nuclear Enhancements



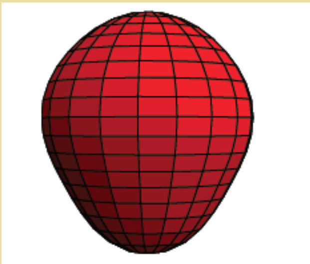
Schiff moment, MQM,…

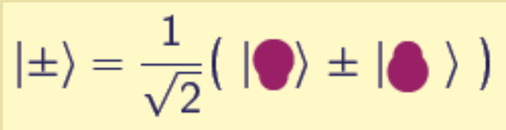
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{199}Hg)

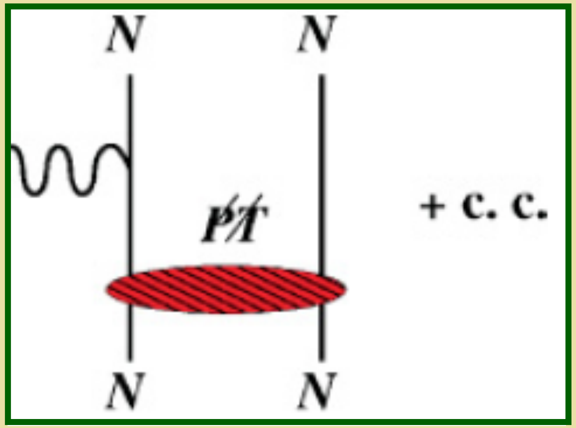
Nuclear Schiff Moment

Nuclear Enhancements:
Octupole Deformation


Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}

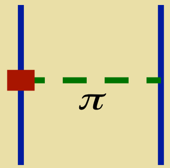


Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

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	$\pm$ 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

Specific Illustrations: "Portals"

- *Higgs boson*

This talk

- *Top quark*
- *Dark photon*

Back up slides / question period

Where is BSM CPV hiding ?

The Higgs Portal

What is the CP Nature of the Higgs Boson ?

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

- *Two Higgs doublets ?*

$$H \to H_1 , H_2$$

- *New parameters:*

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

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:*

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

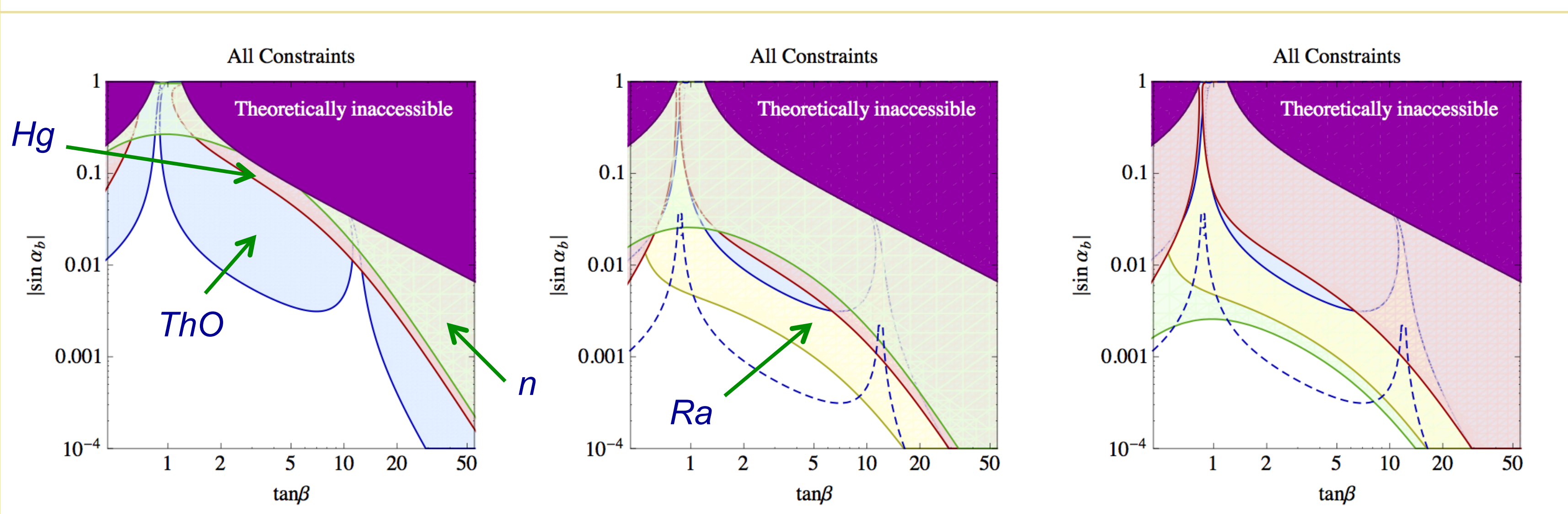
$$\sin\alpha_b$$

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

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

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



Present — *New ThO: ACME*

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)

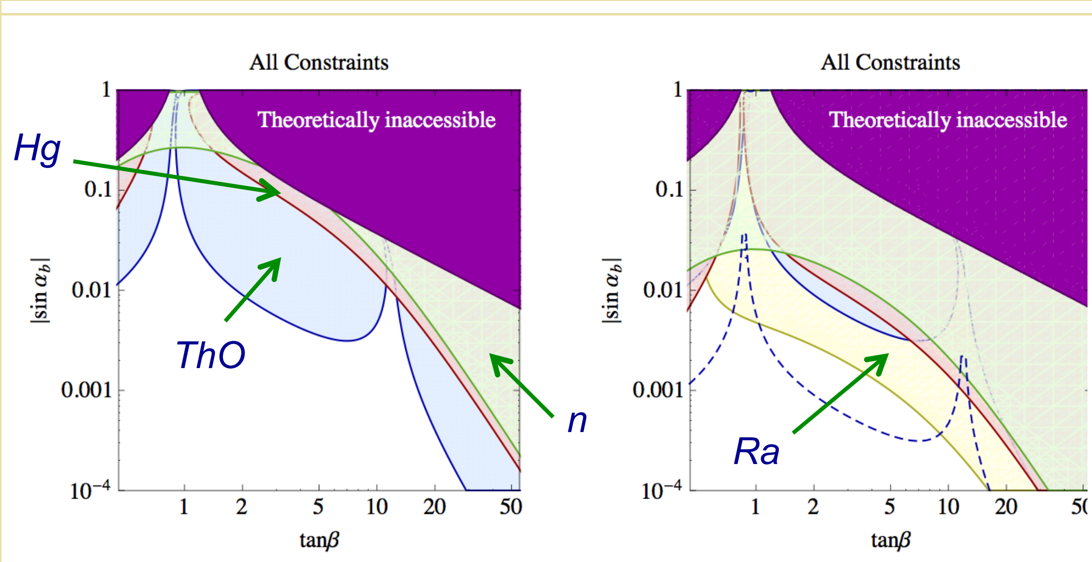
sin α_b : CPV scalar mixing

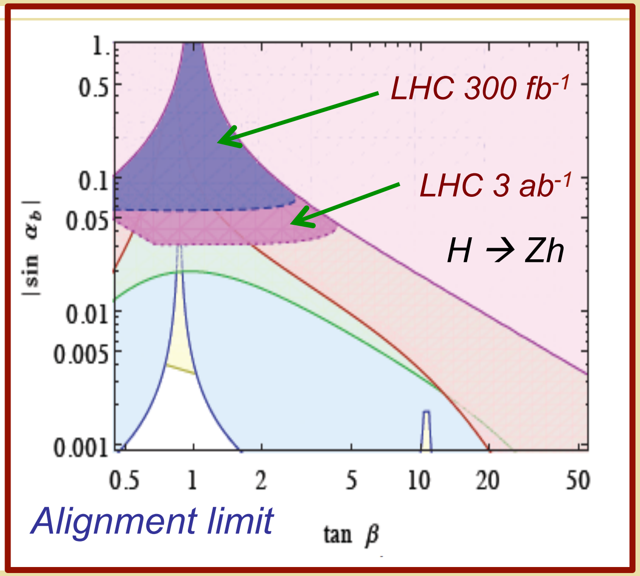
Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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





Chen, Li, R-M: 1708.00435

Present

New ThO: ACME

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)

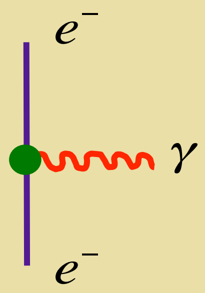
sin α_b : CPV
scalar mixing

Inoue, R-M, Zhang: 1403.4257

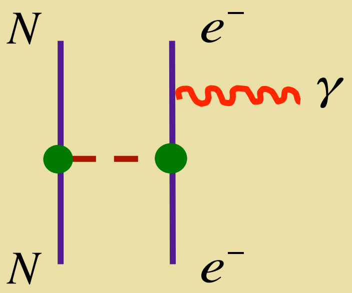
EDM Complementarity

Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)

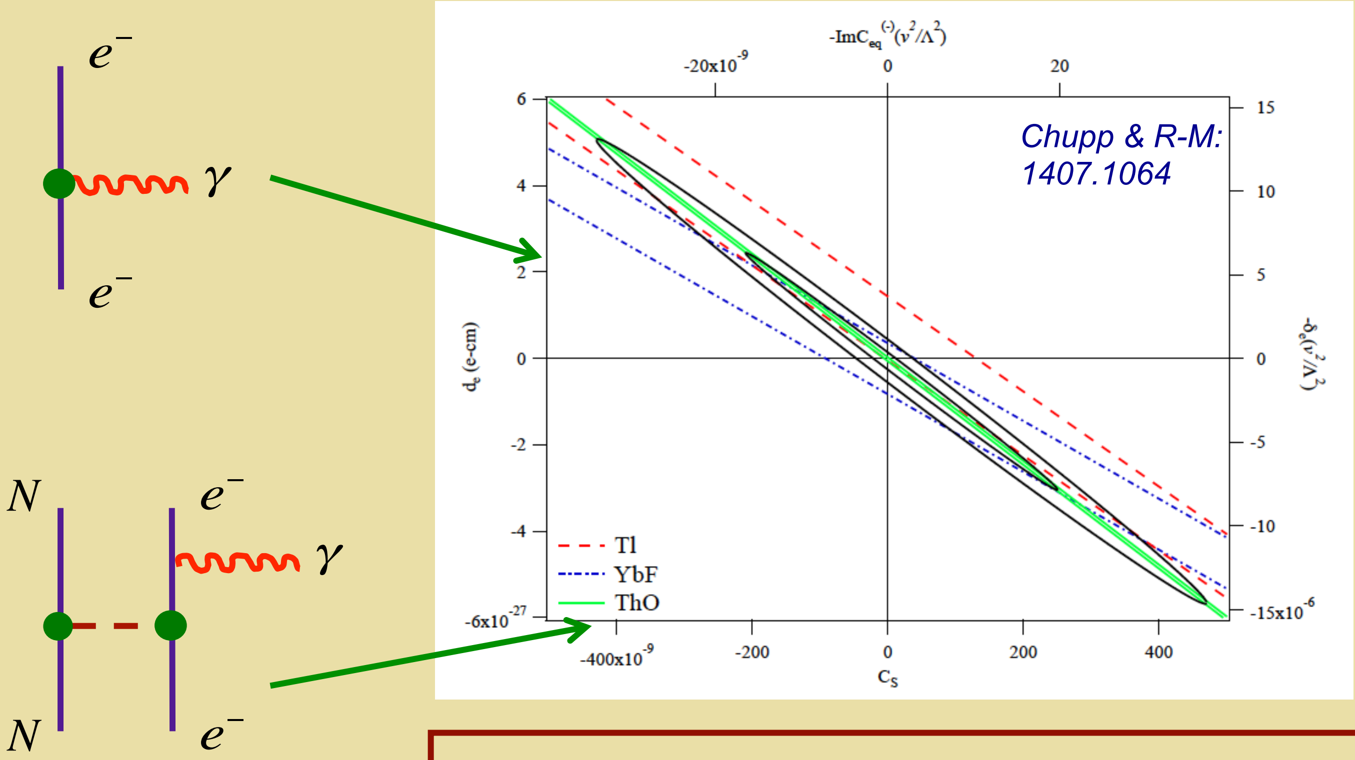


Tl, YbF, ThO…

Paramagnetic Systems: Two Sources

Electron EDM

(Scalar q) x (PS e⁻)



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

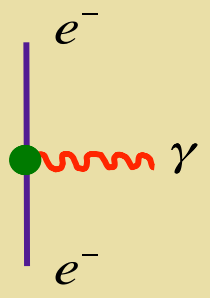
$$\Lambda \gtrsim (1300\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}} \qquad C_S\ \text{(global)}$$

LHC inaccessible

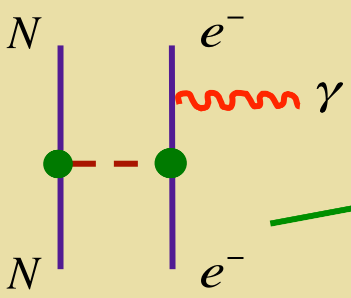
Tl, YbF, ThO…

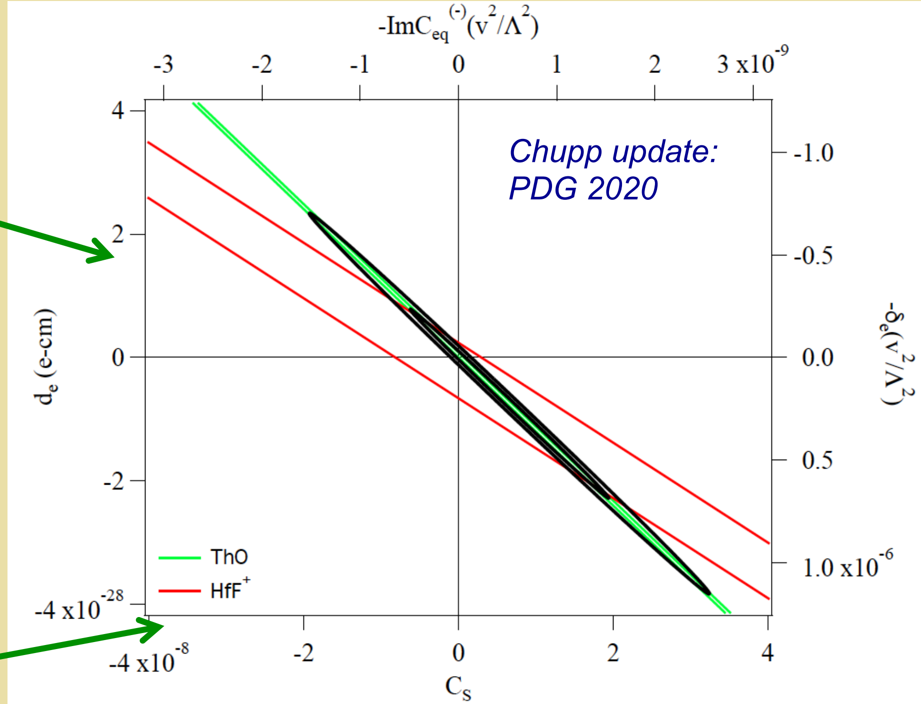
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





Update: slightly stronger

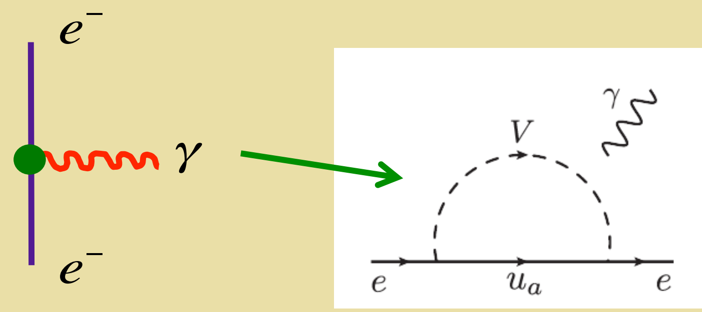
$\Lambda \gtrsim (1.5\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \text{TeV}) \times \sqrt{\sin\phi_{\text{CPV}}}$	C_S (global)

LHC inaccessible

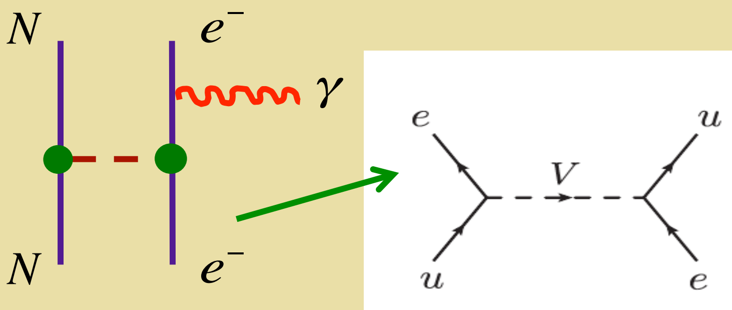
ThO, Hf+

Illustrative Example: Leptoquark Model

Electron EDM



(Scalar q) x (PS e⁻)



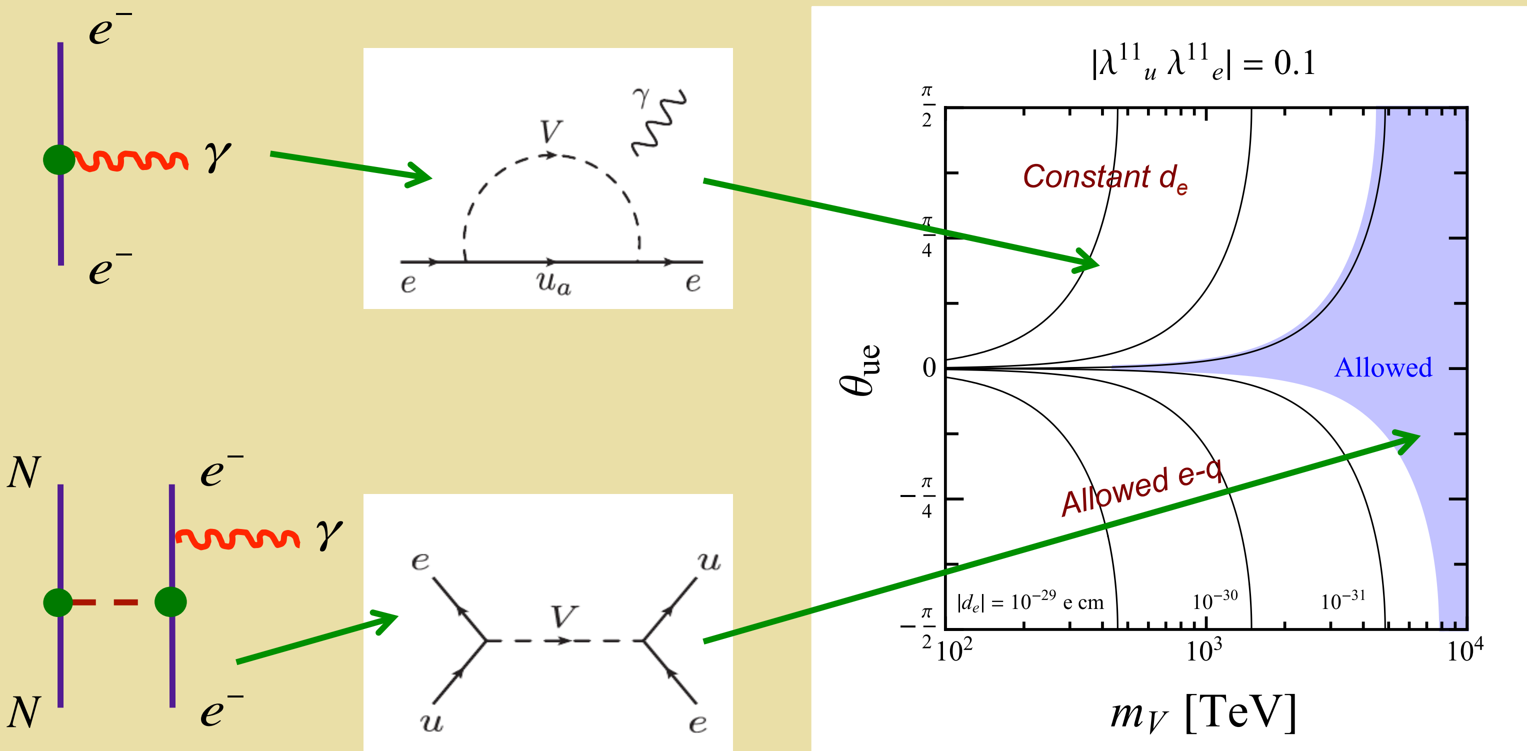
(3, 2, 7/6)

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

Illustrative Example: Leptoquark Model

Electron EDM

(Scalar q) x (PS e^-)



Fuyuto, R-M, Shen 1804.01137

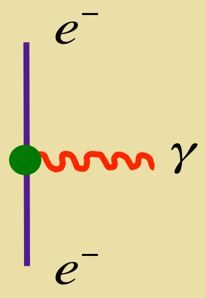
See also: Dekens et al 1809.09114

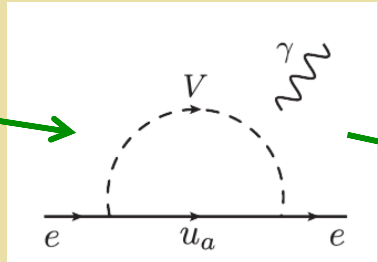
(3, 2, 7/6)

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

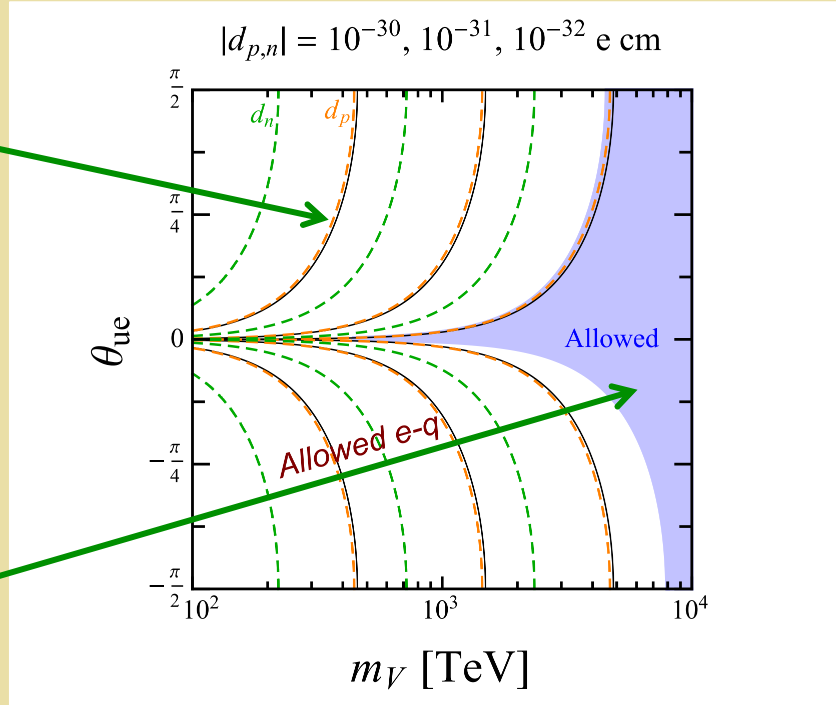
Illustrative Example: Leptoquark Model

Electron EDM

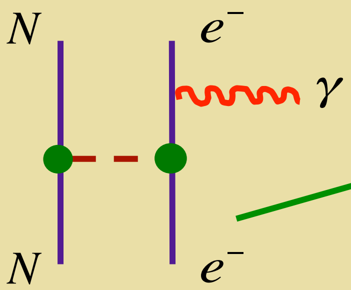


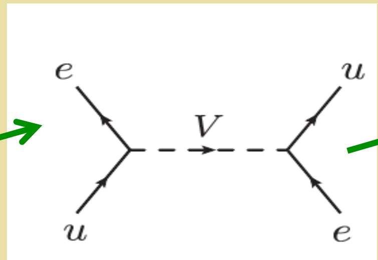


Orange: $|d_p| = 10^{-30}$, 10^{-31} , 10^{-32} e cm
Green: $|d_n| = 10^{-30}$, 10^{-31} , 10^{-32} e cm



(Scalar q)
x (PS e⁻)





Fuyuto, R-M, Shen 1804.01137

See also: Dekens et al 1809.09114

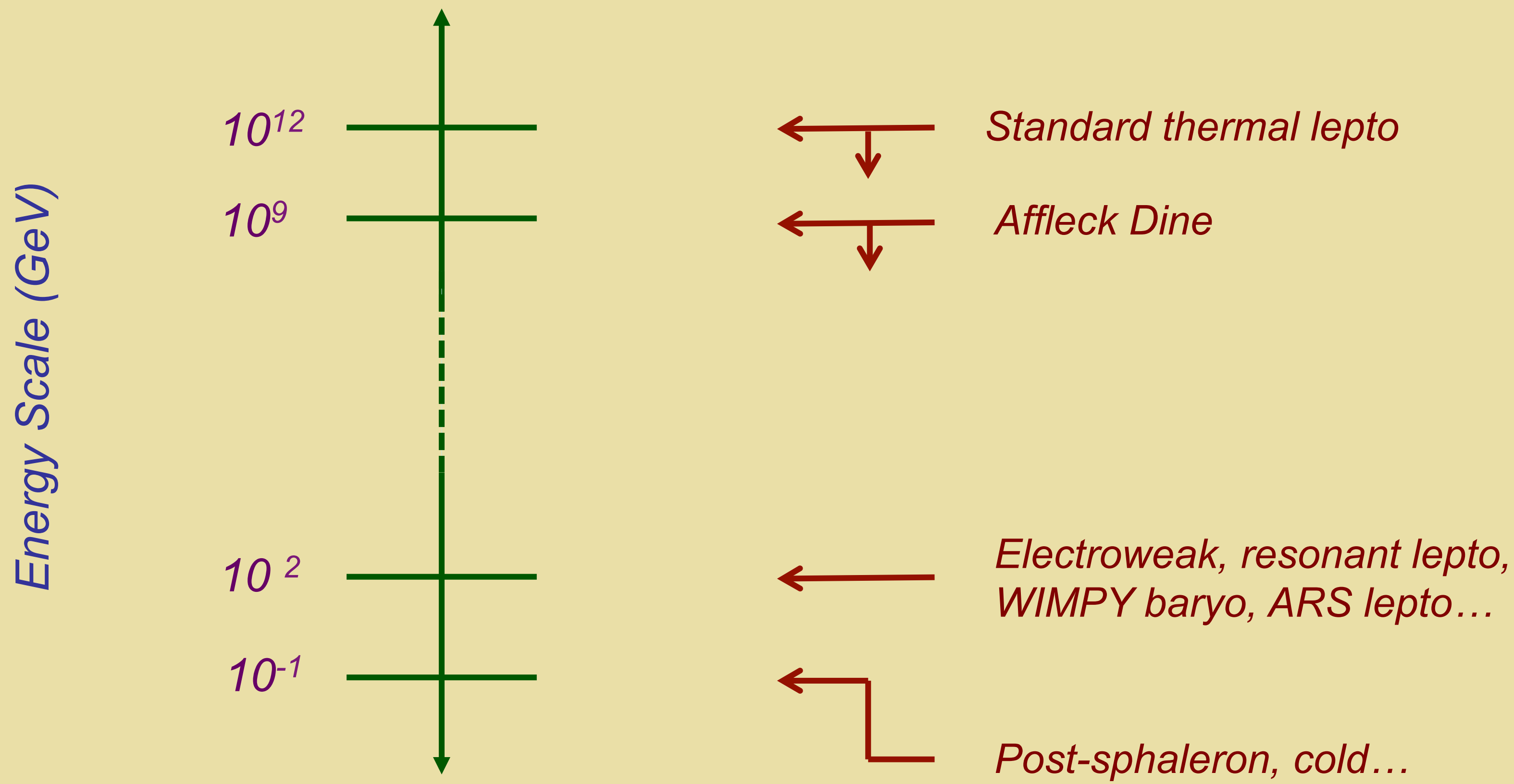
(3, 2, 7/6)

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

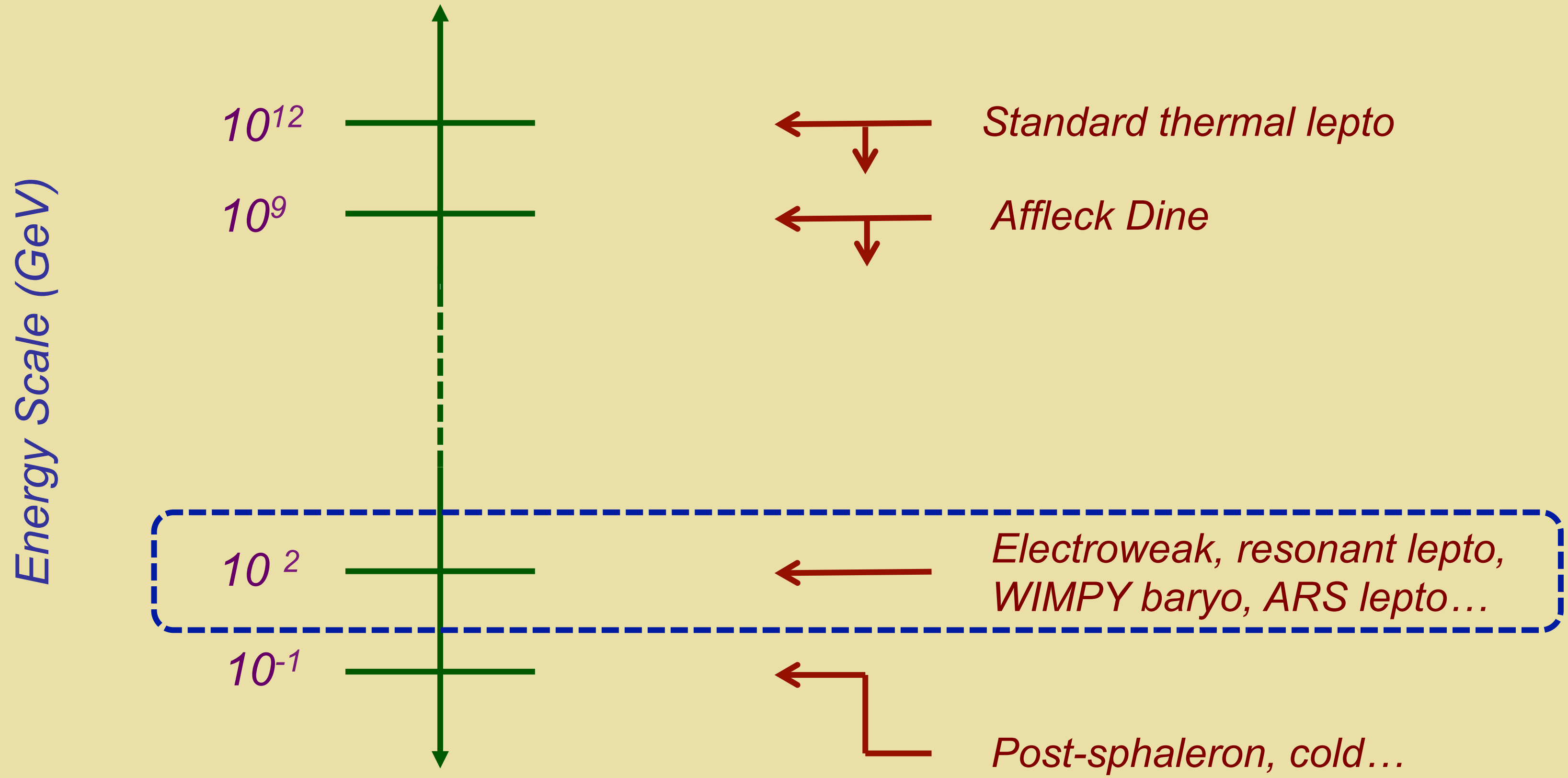
Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

Baryogenesis Scenarios



Baryogenesis Scenarios



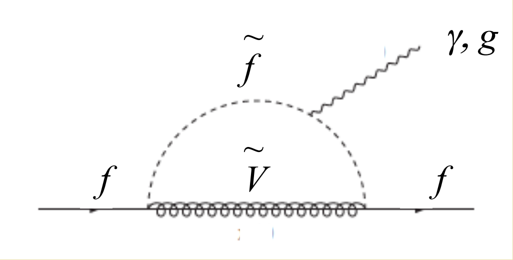
Era of EWSB: t_{univ} ~ 10 ps

EWBG: MSSM & Beyond

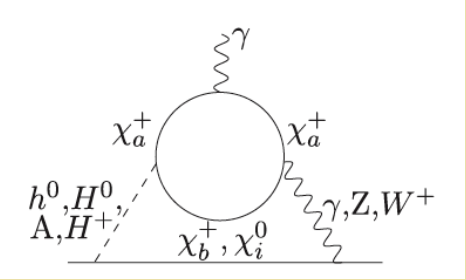
- ***Strong first order EWPT:*** *LHC $\rightarrow$ Excluded for the MSSM $\rightarrow$ Possible w/ extensions (e.g., NMSSM)*

- ***CPV:*** *Sources same as in MSSM + possible additional*

EDMs & EW Baryogenesis: MSSM+

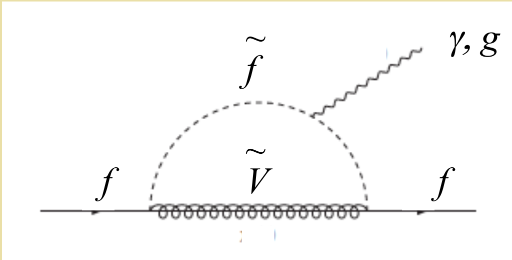


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

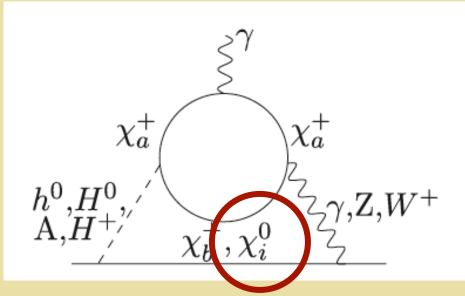


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

EDMs & EW Baryogenesis: MSSM+

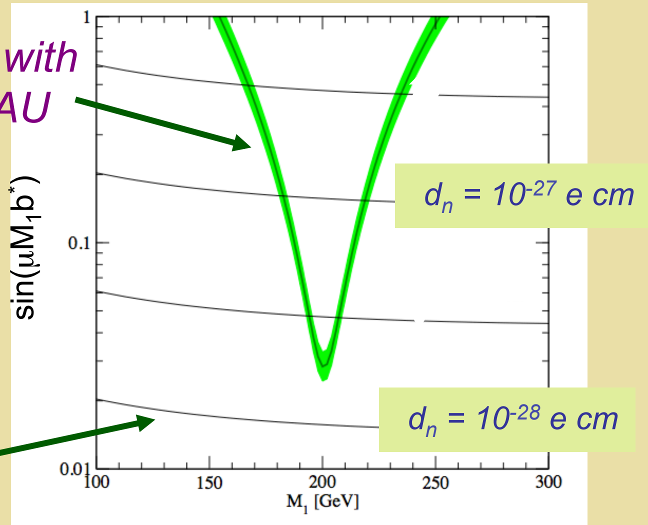


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

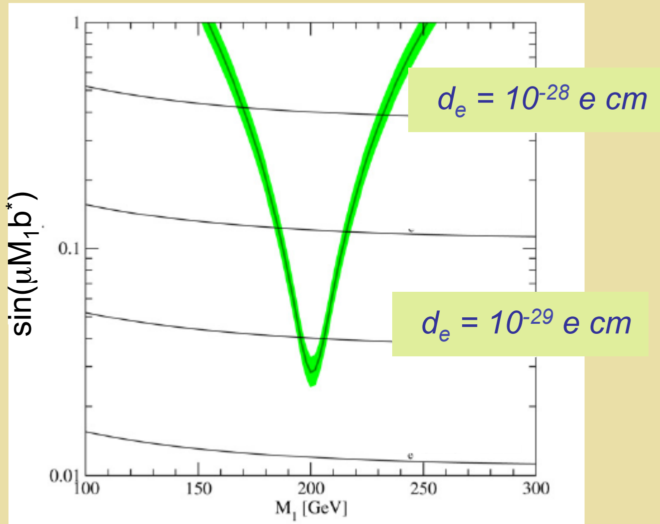


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



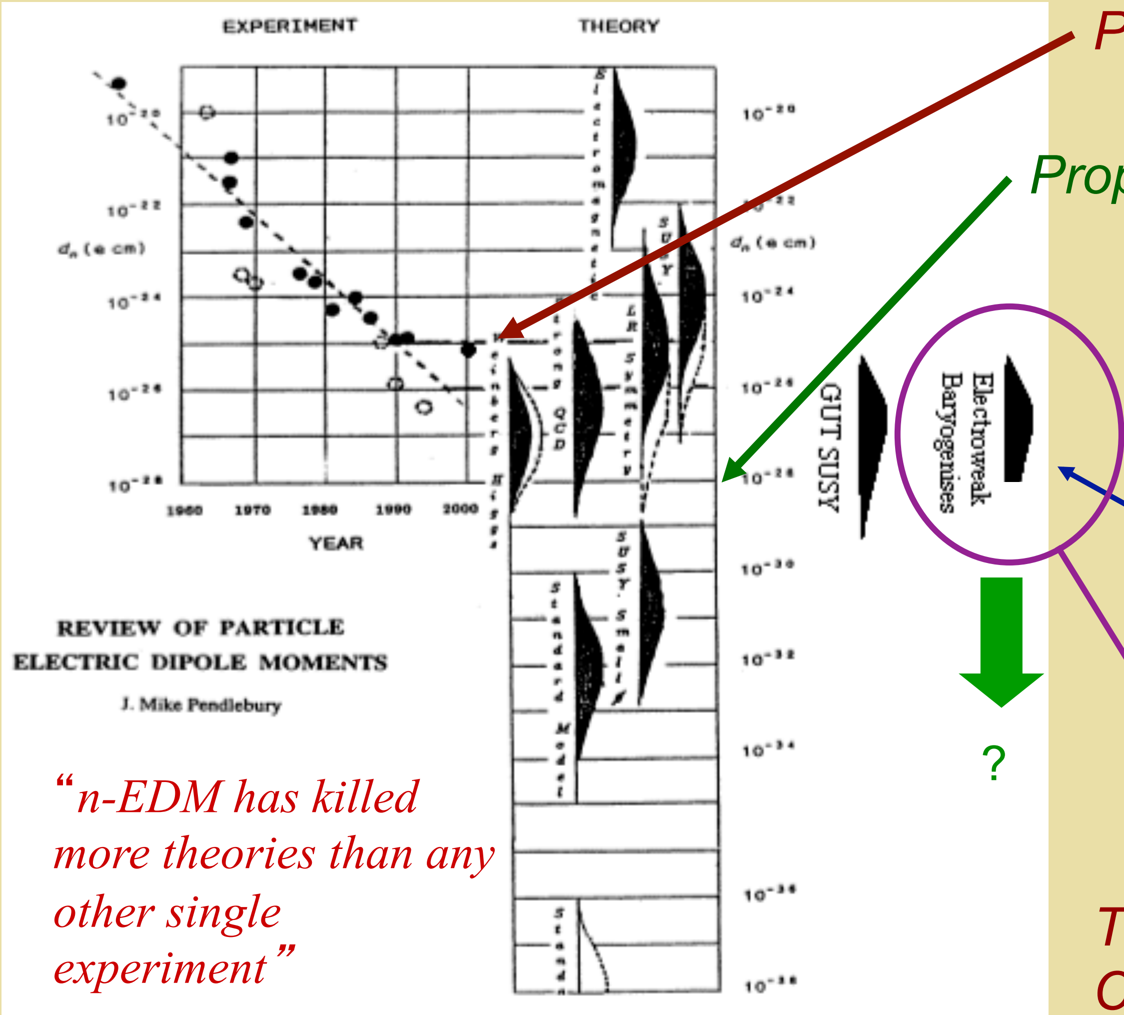
Next gen d_n



ACME: ThO

Li, Profumo, RM '09-'10

EDMs: What We May Learn



"n-EDM has killed more theories than any other single experiment"

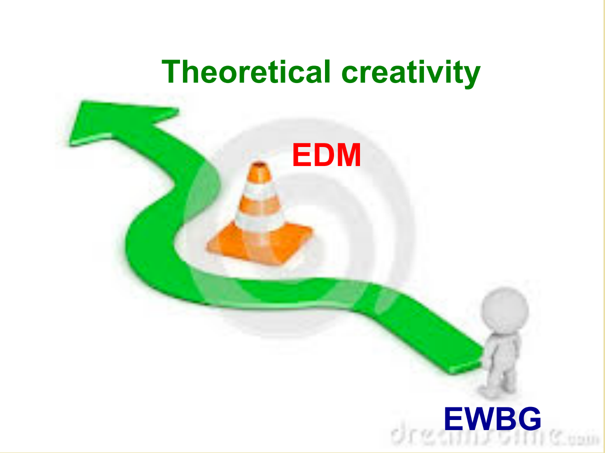
Present n-EDM limit

Proposed n-EDM limit

Matter-Antimatter Asymmetry in the Universe: **MSSM**

Theory: How robust ? Can EDMs kill EW baryogenesis ?

CPV for EWBG



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*

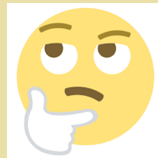
Back Up Slides

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*



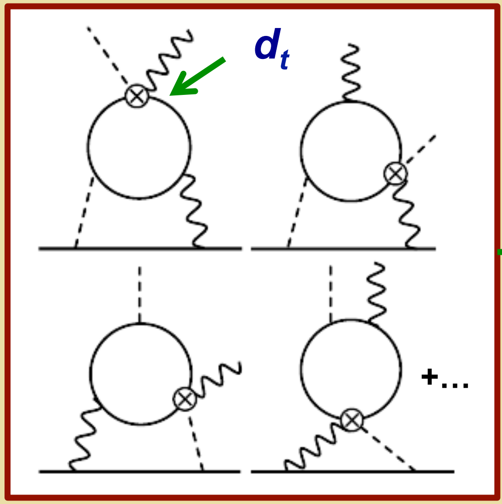
- *Top EDMs difficult to probe experimentally*

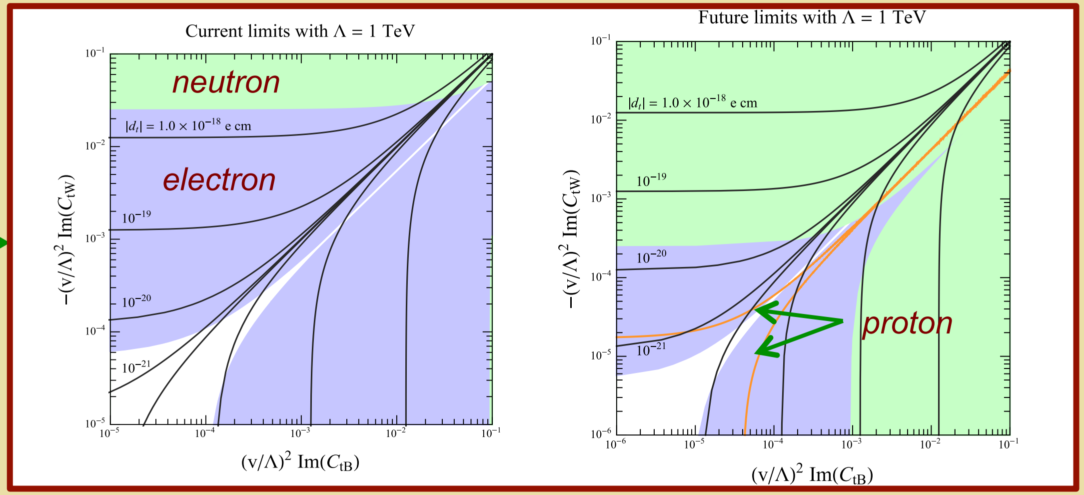
- *Light fermion EDMs to the rescue !*

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} $\to$ Tree level d_t & loop level d_e , $d_{light\ q}$



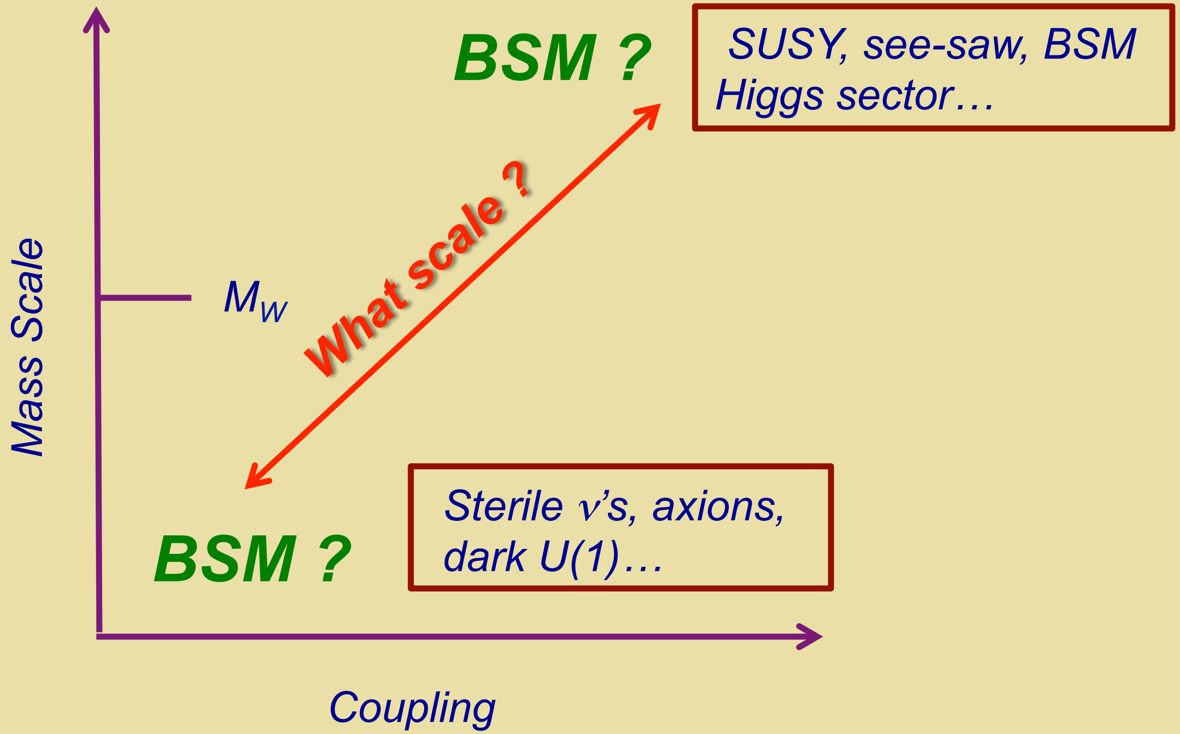


Induced d_e , $d_{light\ quark}$

Fuyuto & MRM ’17
Fuyuto ‘19: Updated for new ThO

Dark Photon Portal

BSM Physics: Where Does it Live ?

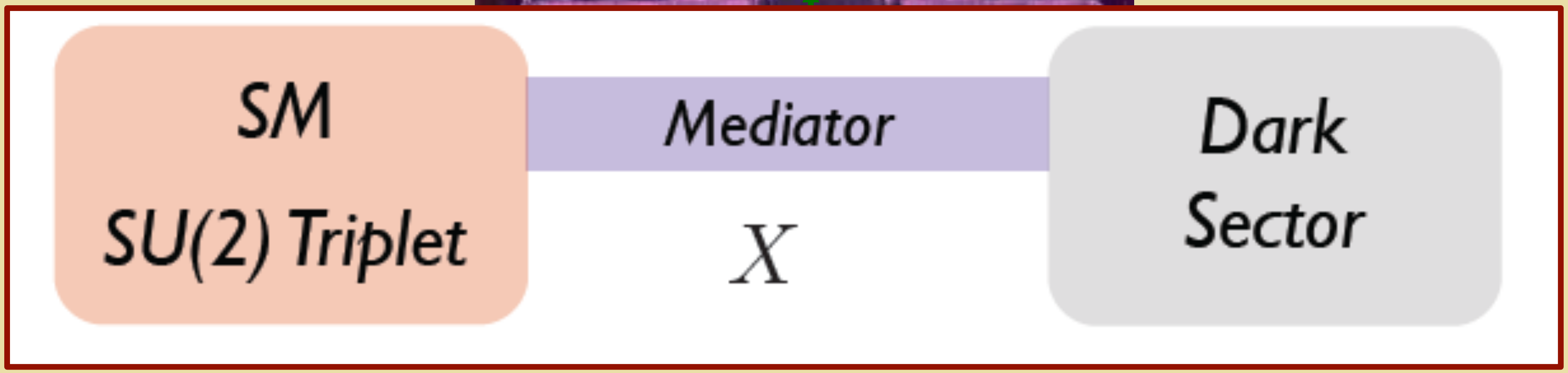


Dark Photon Portal

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.XXXXX

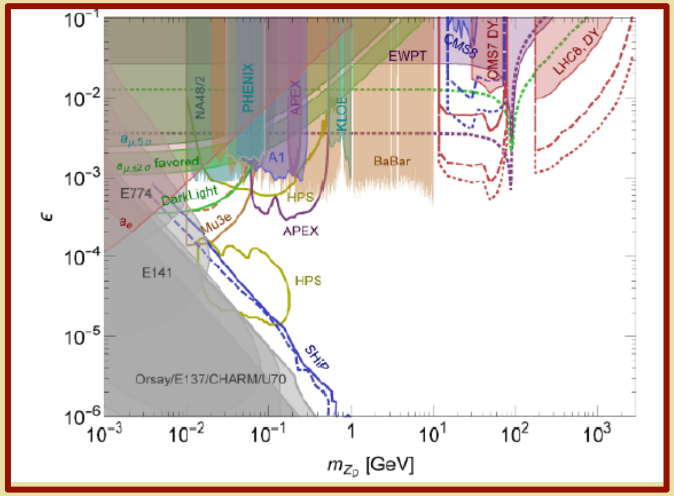
CPV Dark Photon

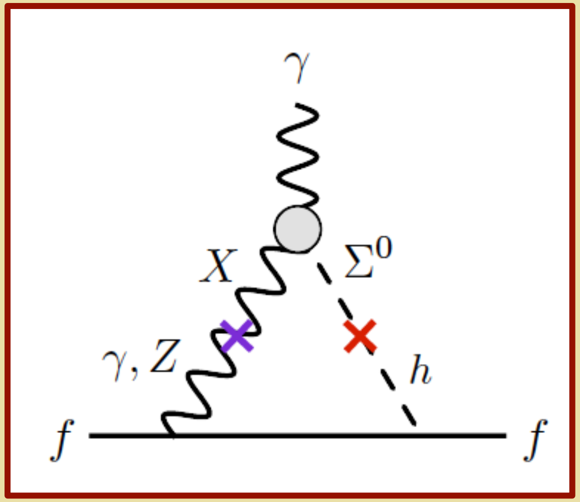
$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

CP-conserving CP-violating

Thanks: K. Fuyuto

X − γ Mixing **EDM**





CPV Dark Photon

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

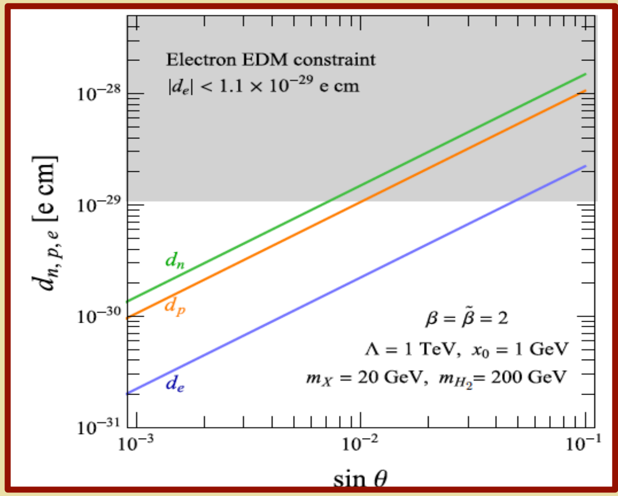
CP-conserving

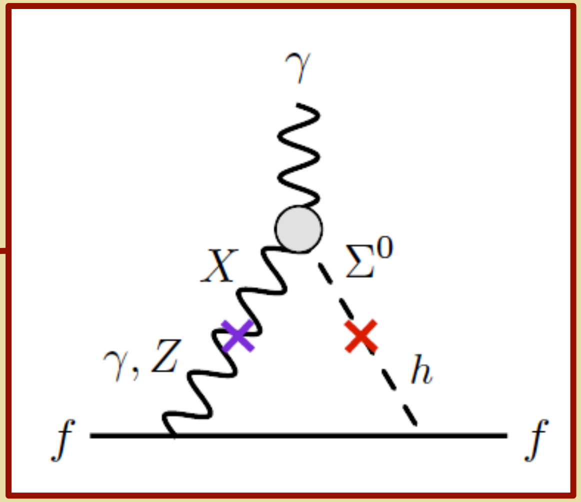
CP-violating

Thanks: K. Fuyuto

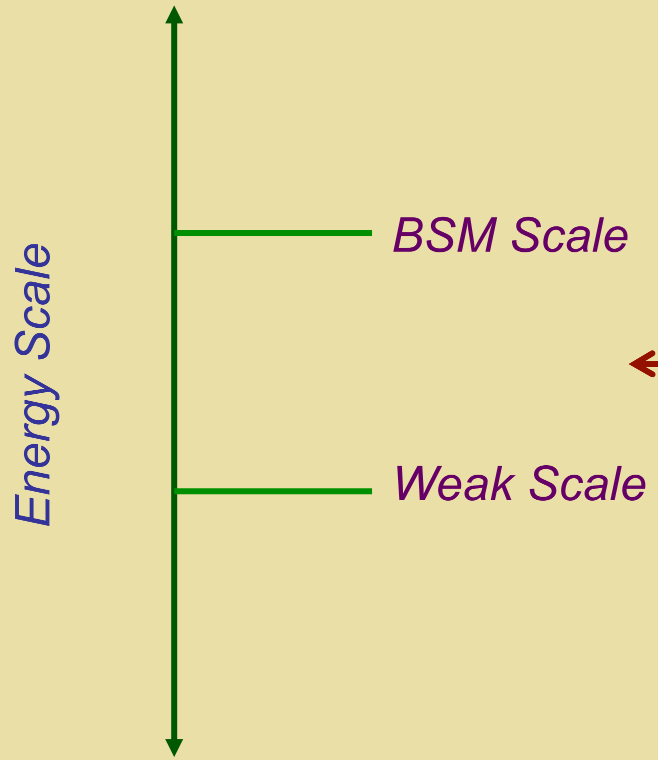
***X* − *γ* Mixing**

EDM





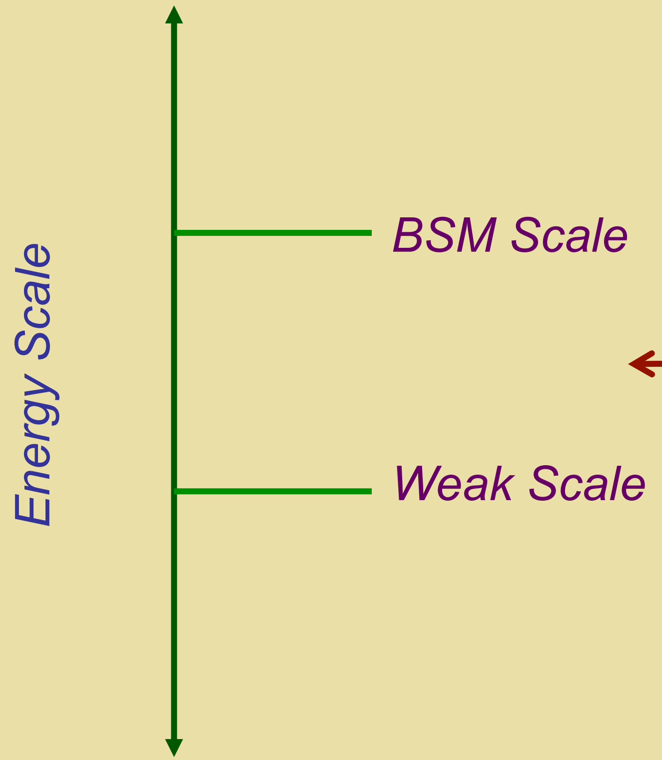
Effective Field Theory



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

$+\ldots$

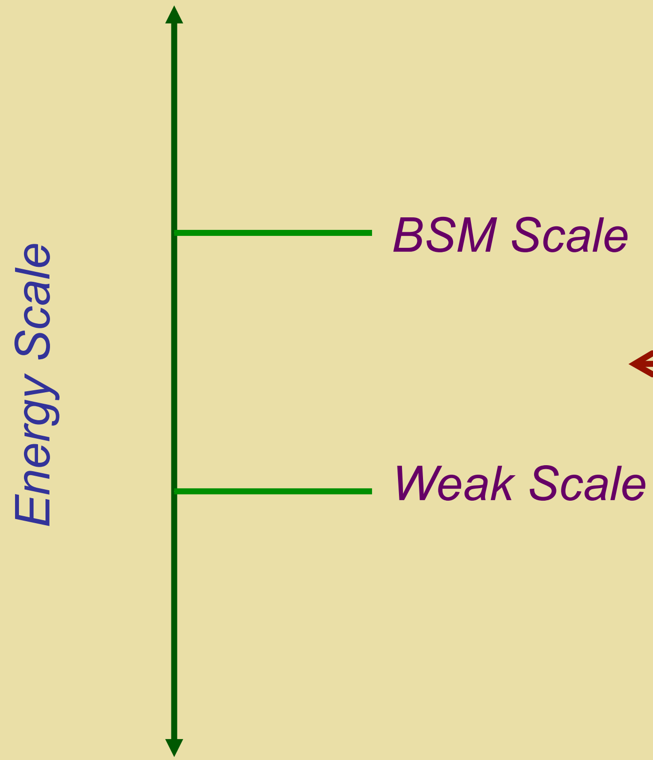
Effective Field Theory



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

- *Write down all operators consistent with EW symmetry*
- *Classify by successively higher mass dimension*
- *Truncate at a given order: error of order $(\upsilon / \Lambda)^2$*

Effective Field Theory

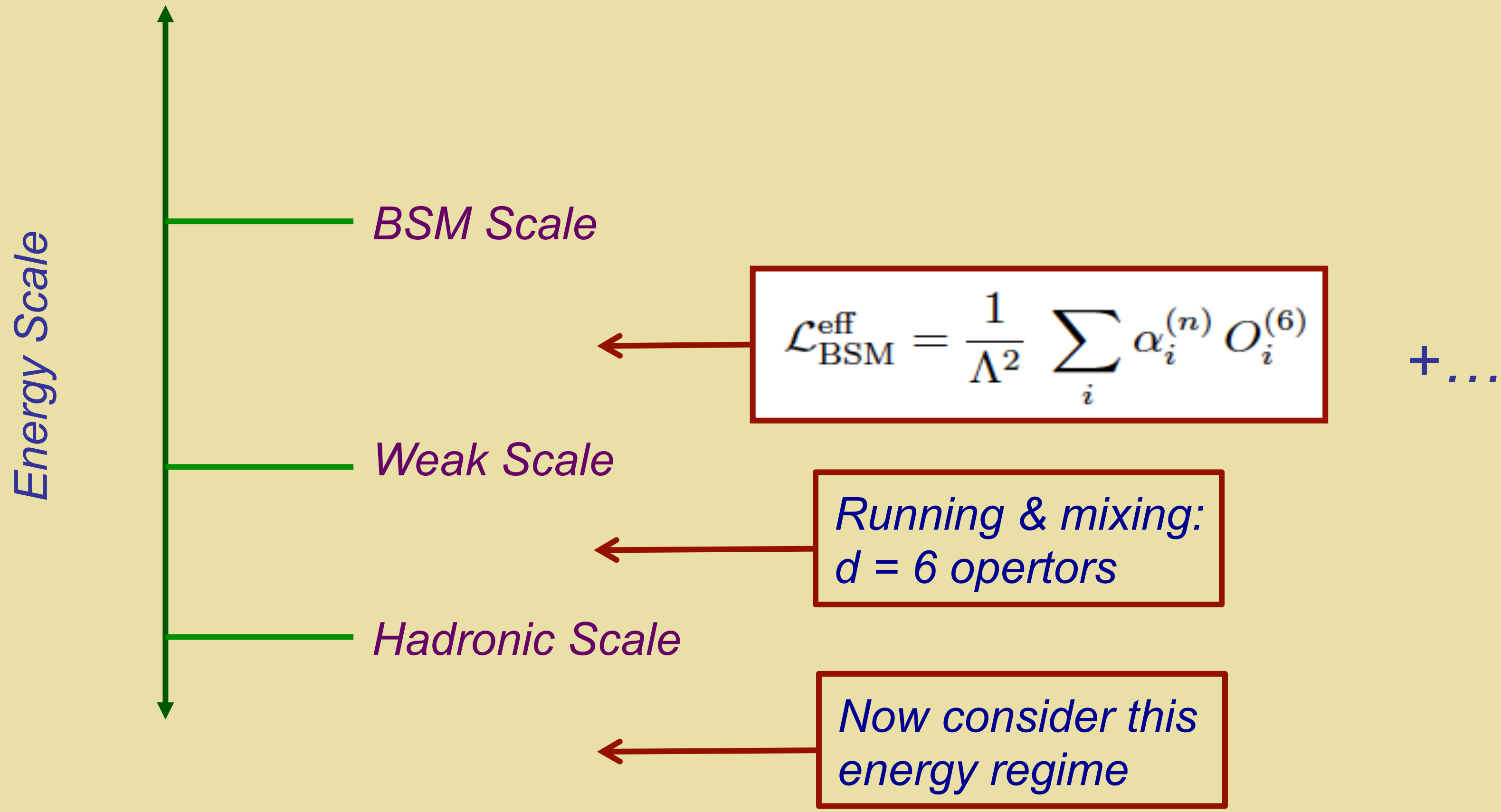


- *Wilson coefficients encode details of particles & dynamics above BSM scale Λ*
- *Wilson coeffs "parameterize our ignorance"*

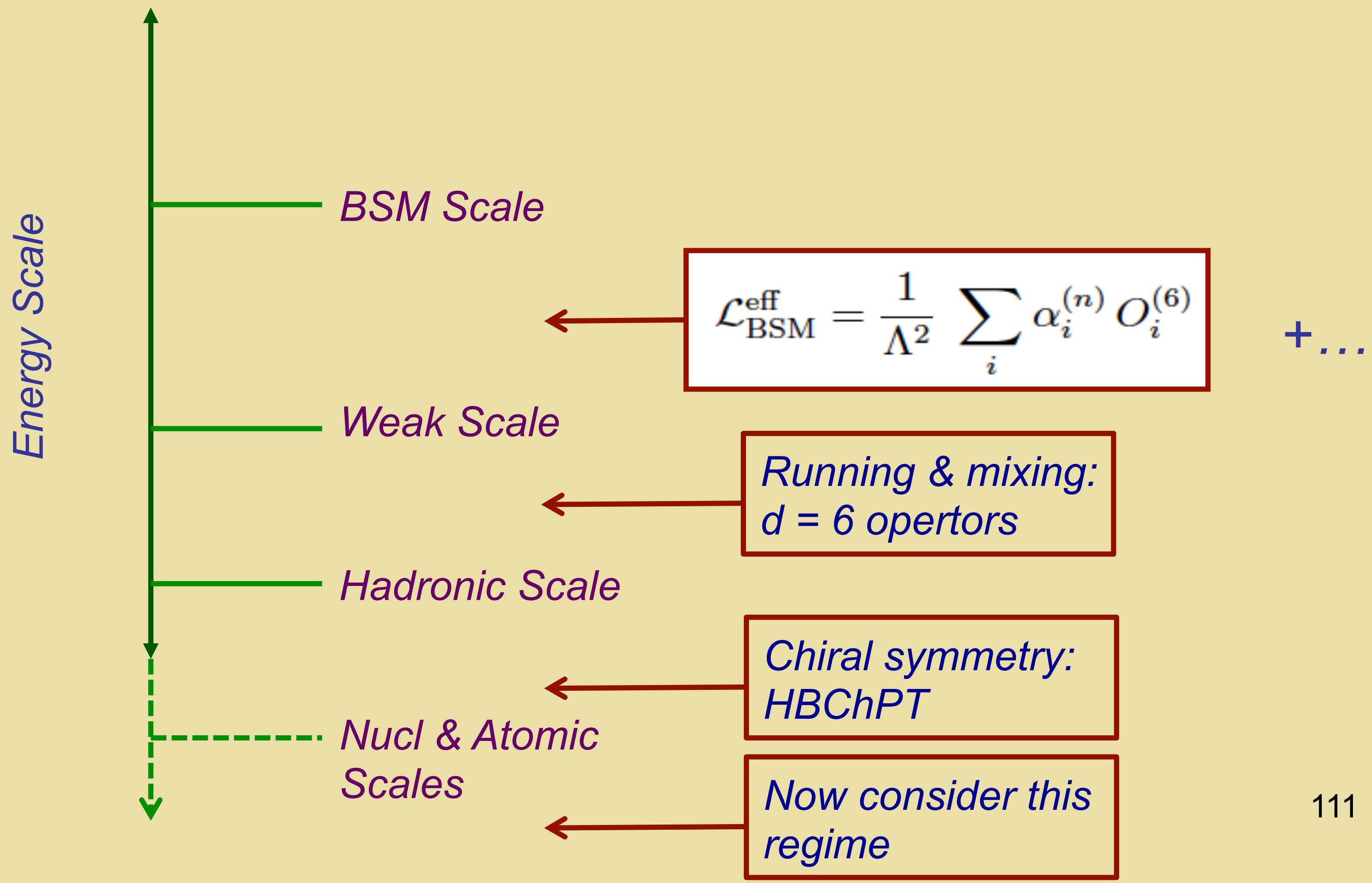
$$\mathcal{L}^{\text{eff}}_{\text{BSM}} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} \, O_i^{(6)} \quad + \ldots$$

- *Write down all operators consistent with EW symmetry*
- *Classify by successively higher mass dimension*
- *Truncate at a given order: error of order $(v / \Lambda)^2$*

Effective Field Theory

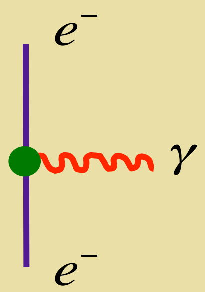


Effective Field Theory

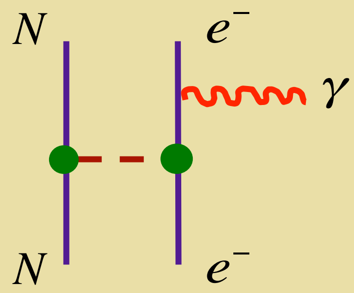


Leptonic & SemileptonicCPV

Electron
EDM



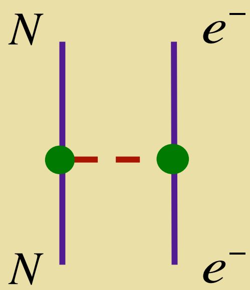
(Scalar q)
x (PS e^-)



EDMs of paramagnetic atoms & molecules
(Tl, ThO, HfF^+…)

Semileptonic CPV

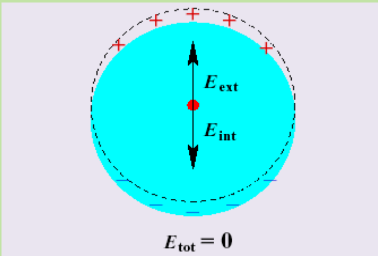
- (PS q) x (Scalar e^-)
- (Tensor q) x (Tensor e^-)



EDMs of diamagnetic atoms (Hg, Ra. Xe⋯)

Nuclear Schiff Moment

Schiff Screening



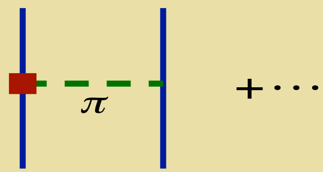
Atomic effect from nuclear finite size: Schiff moment

Nuclear Schiff Moment

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

Nuclear EDM: Screened in atoms

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



EDMs of diamagnetic atoms (^{199}Hg)