Electric Dipole Moments: Phenomenology & Implications

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

ACFI Workshop, Amherst May 2015

Outline

I. Experimental Situation

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

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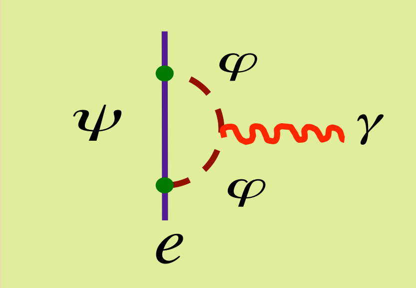
Mass Scale Sensitivity



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

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

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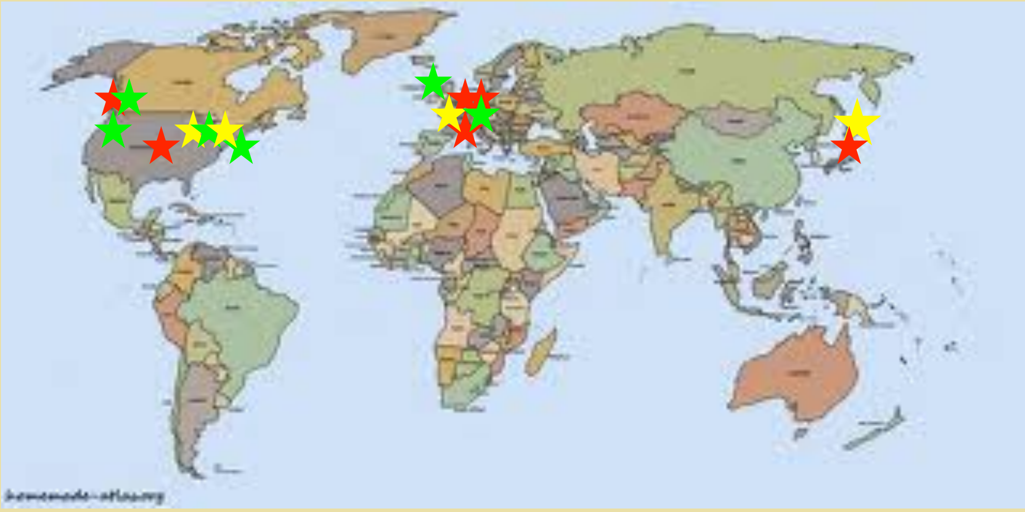


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

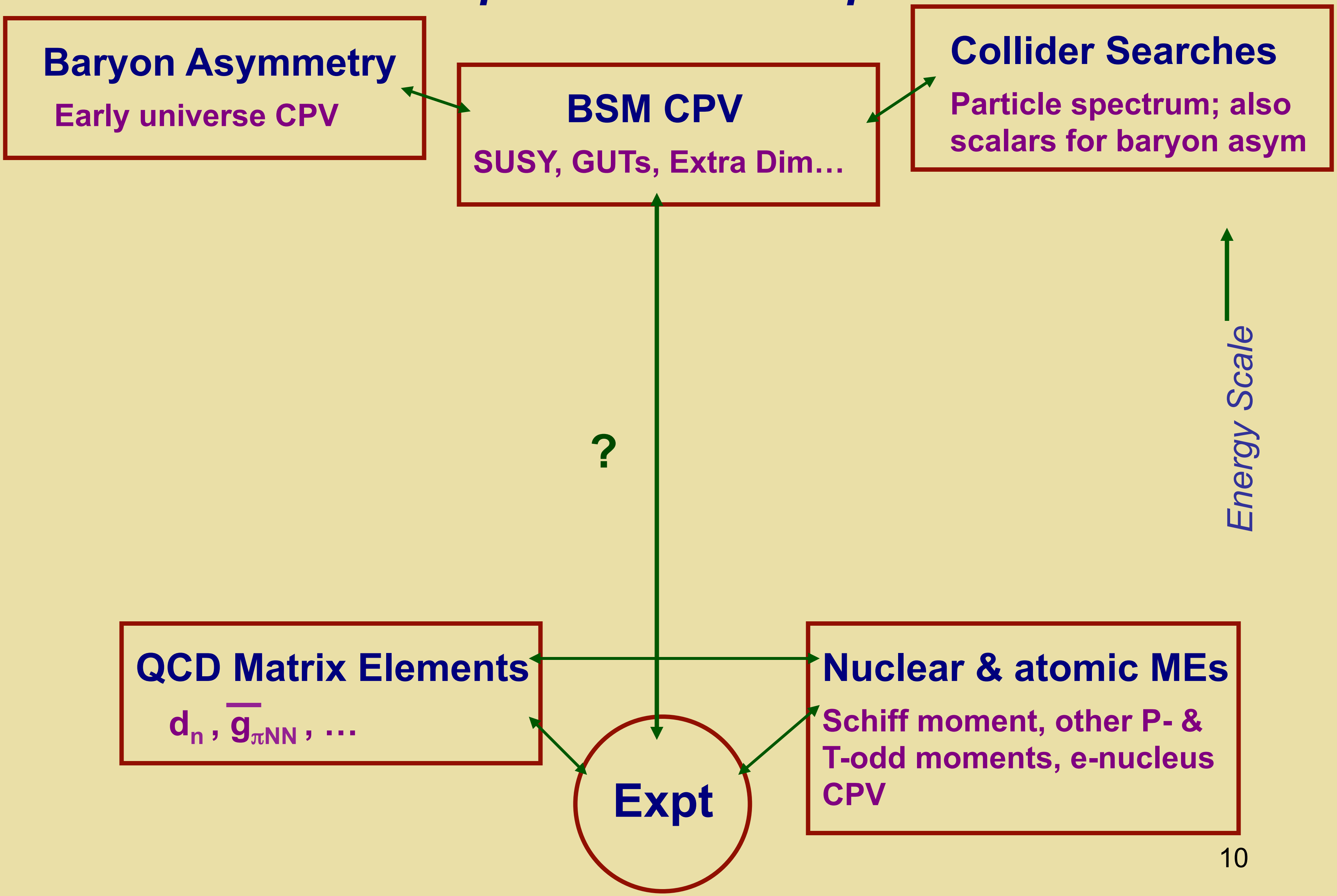
II. Effective Operators

Why Multiple Systems ?

Why Multiple Systems ?

Multiple sources & multiple scales

EDM Interpretation & Multiple Scales

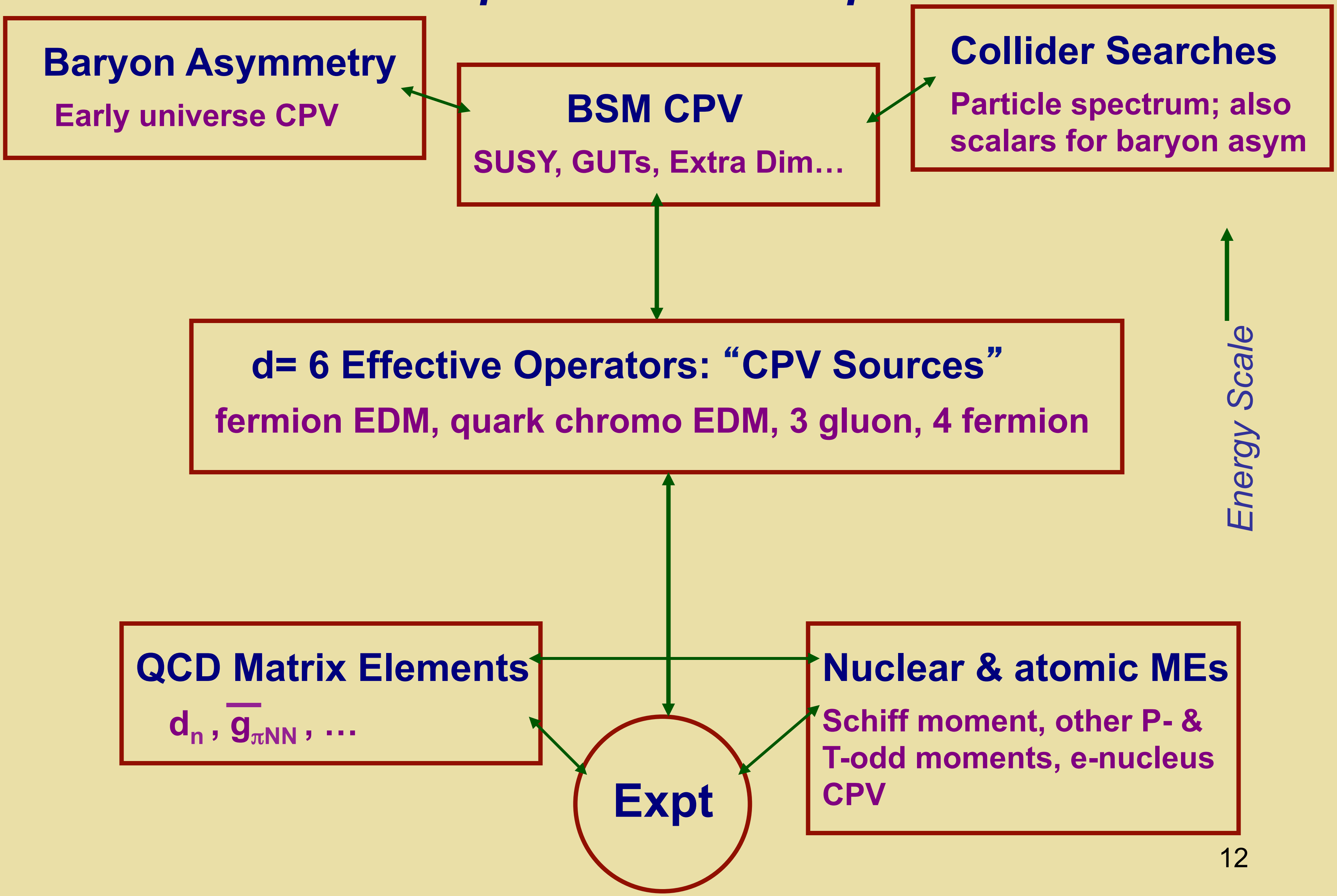


Effective Operators: The Bridge

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

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

EDM Interpretation & Multiple Scales



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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$\varphi^+\varphi \to \upsilon^2$

θ-term renormalization

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$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_{\mu}^{I\nu}W_{\nu}^{J\rho}W_{\rho}^{K\mu}$	$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^{I}W^{I\mu\nu}$	Q_{dG}	$(\bar{Q}\sigma^{\mu\nu}T^{A}d)\varphi\,G_{\mu\nu}^{A}$
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Quark chromo-EDM

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Fermion EDM

Wilson Coefficients: EDM & CEDM

$$(\bar{Q}\sigma^{\mu\nu}T^A u)\widetilde{\varphi}\, G^A_{\mu\nu}$$
$$(\bar{Q}\sigma^{\mu\nu}T^A d)\varphi\, G^A_{\mu\nu}$$
$$(\bar{F}\sigma^{\mu\nu} f)\tau^I \Phi\, W^I_{\mu\nu}$$
$$(\bar{F}\sigma^{\mu\nu} f)\Phi\, B_{\mu\nu}$$

→

$$\mathcal{L}^{\rm CEDM} = -i \sum_q \frac{g_3 \tilde{d}_q}{2}\, \bar{q}\sigma^{\mu\nu}T^A\gamma_5 q\ G^A_{\mu\nu}$$

$$\mathcal{L}^{\rm EDM} = -i \sum_f \frac{d_f}{2} \bar{f}\sigma^{\mu\nu}\gamma_5 f\ F_{\mu\nu}$$

↓

Chirality flipping →

$$\mathrm{Im}\, C_{qG} \ \equiv\ Y_q\, \tilde{\delta}_q \to \tilde{d}_q = -\frac{2m_q}{v^2}\left(\frac{v}{\Lambda}\right)^2 \tilde{\delta}_q,$$
$$\mathrm{Im}\, C_{f\gamma} \ \equiv\ Y_f\, \delta_f \to d_f = -e\frac{2m_f}{v^2}\left(\frac{v}{\Lambda}\right)^2 \delta_f$$

δ_f , $\tilde{\delta}_q$ *appropriate for comparison with other d=6 Wilson coefficients*

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

Nonleptonic

Semileptonic

Semileptonic: atomic & molecular EDMs

Operator Classification

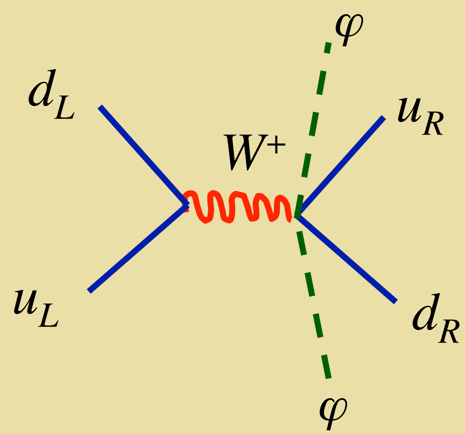
$$\mathcal{L}_{\rm CPV}^{\rm eq} = i\frac{{\rm Im}C_{\ell edq}}{2\Lambda^2}\left[\bar{e}\gamma_5 e\ \bar{d}d - \bar{e}e\ \bar{d}\gamma_5 d\right] - i\frac{{\rm Im}C_{\ell equ}^{(1)}}{2\Lambda^2}\left[\bar{e}\gamma_5 e\ \bar{u}u + \bar{e}e\ \bar{u}\gamma_5 u\right] - \frac{{\rm Im}C_{\ell equ}^{(3)}}{2\Lambda^2}\epsilon_{\mu\nu\alpha\beta}\ \bar{e}\sigma^{\mu\nu}e\ \bar{u}\sigma^{\alpha\beta}u$$

$$\mathcal{L}_{\rm CPV}^{\rm qq} = i\frac{g_3^2\,{\rm Im}C_{quqd}^{(1)}}{2\Lambda^2}\left[\bar{u}\gamma_5 u\ \bar{d}d + \bar{u}u\ \bar{d}\gamma_5 d - \bar{d}\gamma_5 u\ \bar{u}d - \bar{d}u\ \bar{u}\gamma_5 d\right] + i\frac{g_3^2\,{\rm Im}C_{quqd}^{(8)}}{2\Lambda^2}\left[\bar{u}\gamma_5 T^A u\ \bar{d}T^A d + \bar{u}T^A u\ \bar{d}\gamma_5 T^A d - \bar{d}\gamma_5 T^A u\ \bar{u}T^A d - \bar{d}T^A u\ \bar{u}\gamma_5 T^A d\right]$$

Nonleptonic: hadronic EDMs & Schiff moment

Operator Classification

$$Q_{\varphi ud} = i\tilde{\varphi}^\dagger D_\mu \varphi \bar{u}_R \gamma^\mu d_R$$



$\varphi \to v$

$$\mathcal{L}^{\text{eff}}_{\text{LR, CPV}} = -i\frac{\text{Im}\, C_{\varphi ud}}{\Lambda^2}\left[\bar{d}_L\gamma^\mu u_L\, \bar{u}_R\gamma_\mu d_R - \bar{u}_L\gamma^\mu d_L\, \bar{d}_R\gamma_\mu u_R\right]$$

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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light flavors only (e,u,d)

Complementary searches needed

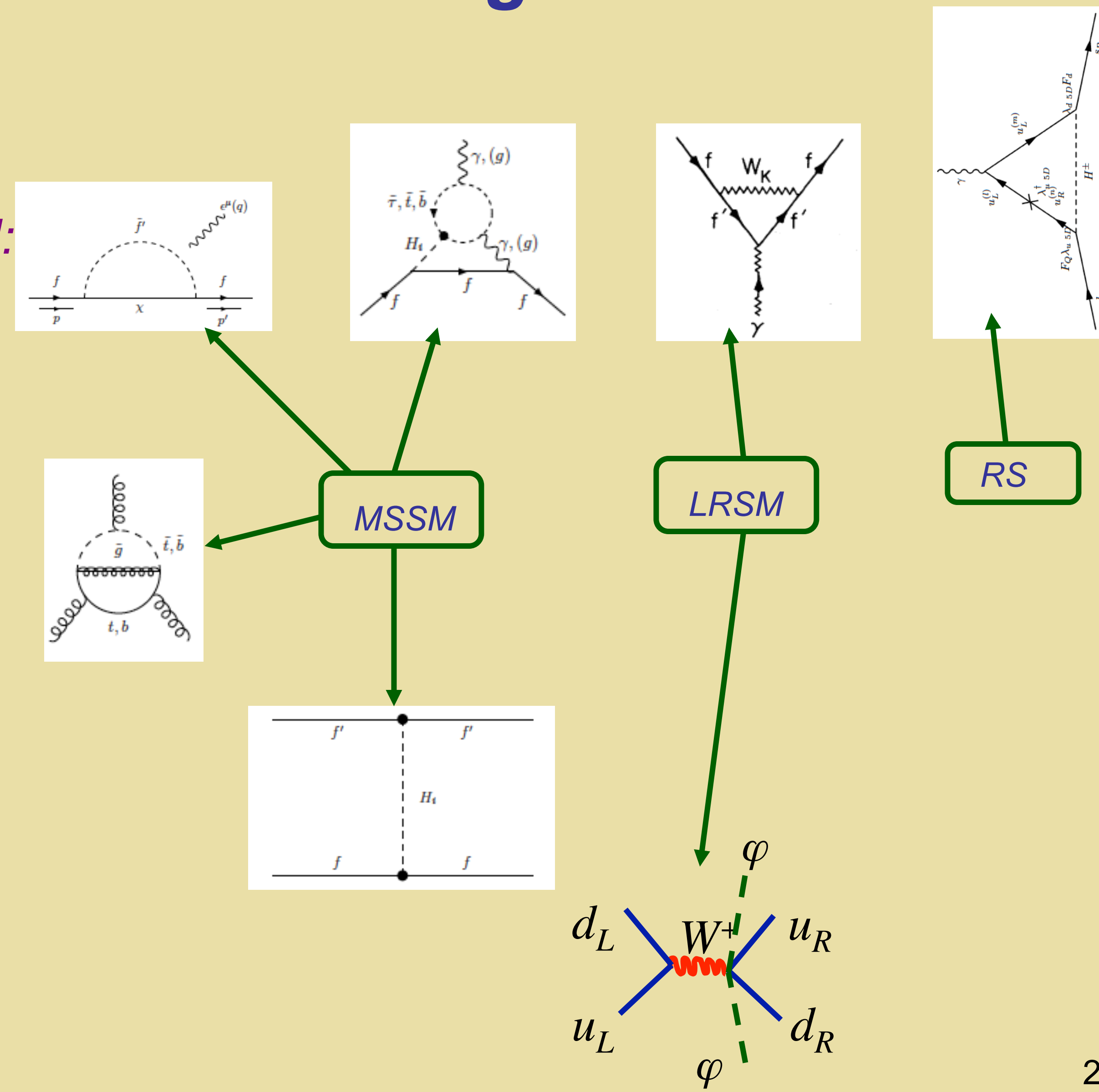
BSM Origins

EDM: γff CEDM: gff

Weinberg ggg:

Four fermion

udHH



III. Illustrative Examples

Complementarity: Three Illustrations

- *CPV in an extended scalar sector (2HDM): "Higgs portal CPV"*
- *Weak scale baryogenesis (MSSM)*
- *Model-independent*

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

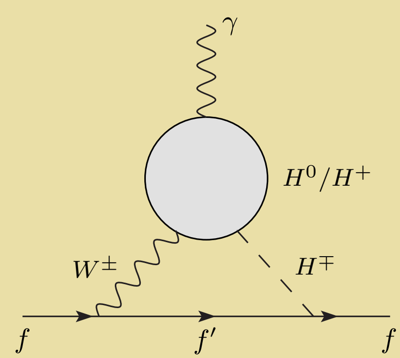
$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right],$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right]$$

EWSB →

$$\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1$$

Viable EWB & CPV:

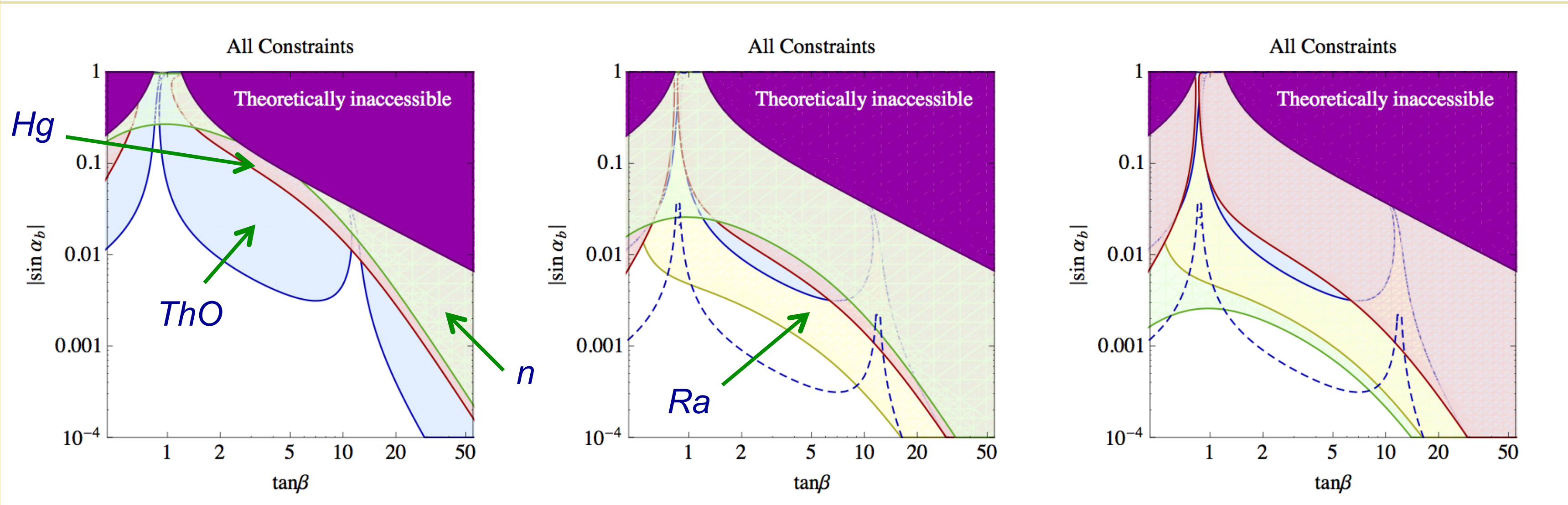
- *EDMs are 2-loop*
- *CPV is flavor non-diag*



Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

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



Present

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

d_A(Hg) x 0.1

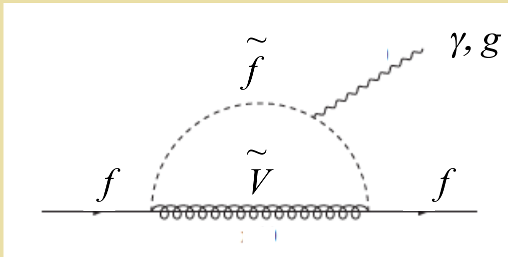
d_{ThO} x 0.1

d_A(Ra)

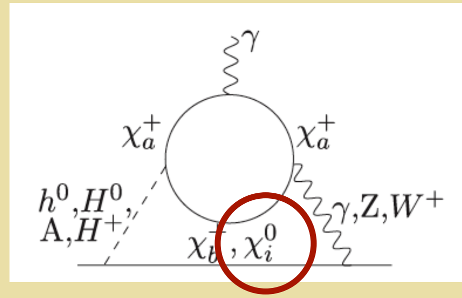
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

EDMs & EW Baryogenesis: MSSM

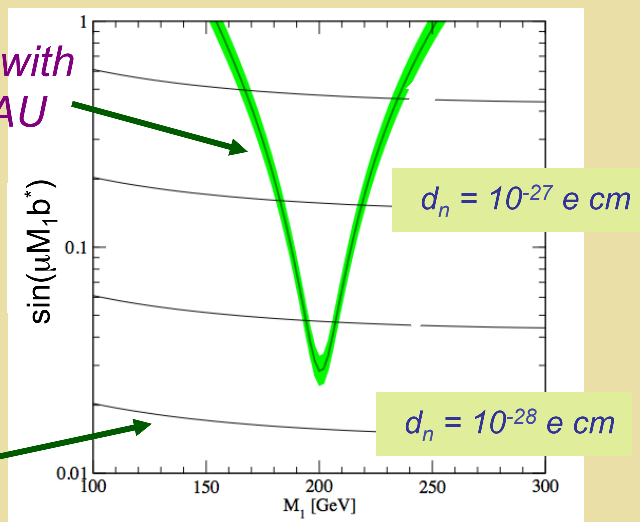


Heavy sfermions: LHC consistent & suppress 1-loop EDMs

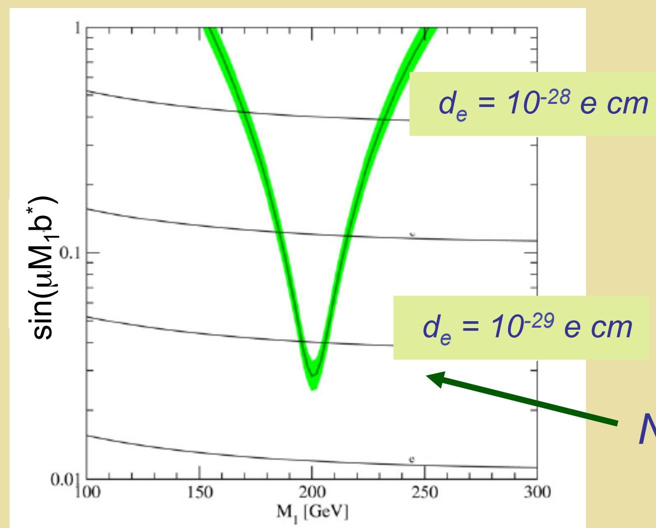


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



Next gen d_n

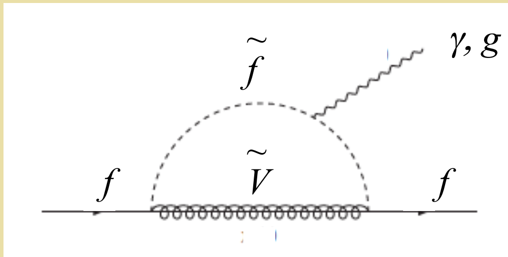


ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EW Baryogenesis: MSSM



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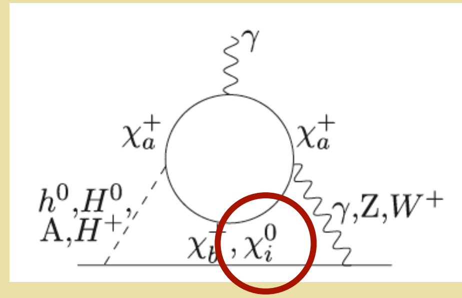

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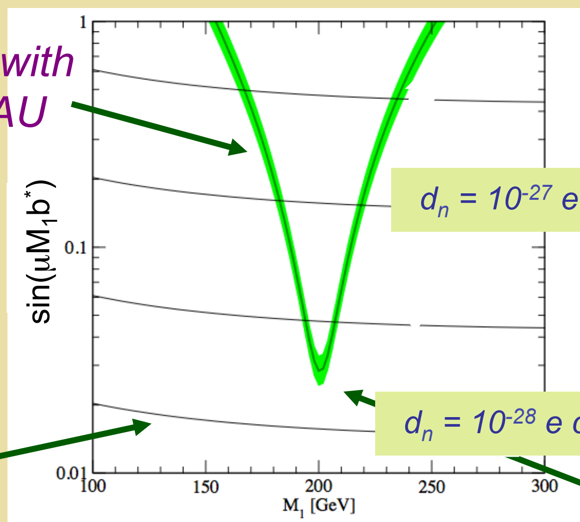
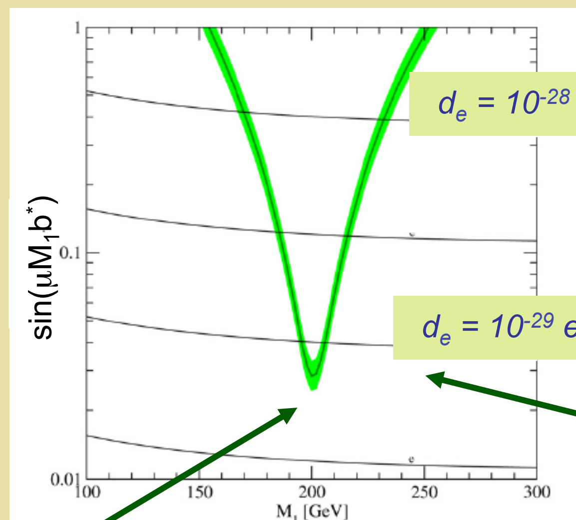


Next gen d_n



ACME: ThO

Next gen d_e

Compressed spectrum (stealthy SUSY)

Li, Profumo, RM '09-'10

Wilson Coefficients: Model Independent

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IV. Paramagnetic & Diamagnetic Systems

EDM Classification

- ***Paramagnetic:*** ***unpaired electron spin (ThO & YbF molecules, Tl atom…)***
- ***Diamagnetic:*** ***no unpaired electron spin (neutron, ^{199}Hg, ^{225}Ra…)***

Global Analysis: Input

System	Year/ref	Result	
Paramagnetic systemss			
Cs	1989 [37]	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ $d_e = (-1.5 \pm 5.6) \times 10^{-26}$	e cm e cm
Tl	2002 [9]	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ $d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	e cm e cm
YbF	2011 [8]	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	e cm
ThO	2014 [7]	$\omega^{\mathcal{N}E} = 2.6 \pm 5.8$ $d_e = (-2.1 \pm 4.5) \times 10^{-29}$ $C_S = (-1.3 \pm 3.0) \times 10^{-9}$	mrad/s e cm
Diamagnetic systems			
^{199}Hg	2009 [5]	$d_A = (0.49 \pm 1.5) \times 10^{-29}$	e cm
^{129}Xe	2001 [38]	$d_A = (0.7 \pm 3) \times 10^{-27}$	e cm
TlF	2000 [39]	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	e cm
neutron	2006 [4]	$d_n = (0.2 \pm 1.7) \times 10^{-26}$	e cm

Chupp & R-M: 1407.1064

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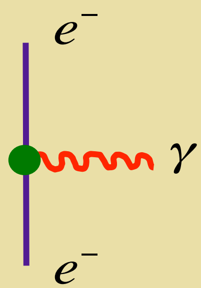
Paramag

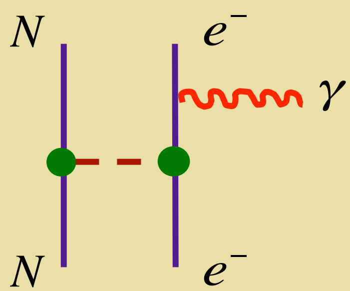
Chupp & R-M: 1407.1064

Paramagnetic Systems: Two Sources

Electron EDM



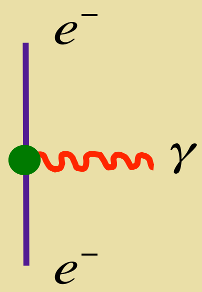
(Scalar q) x (PS e^-)



Tl, YbF, ThO…

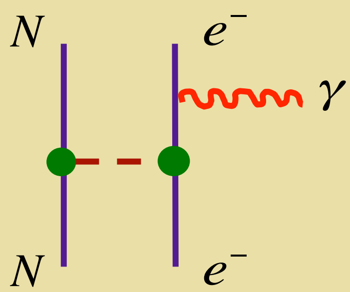
Paramagnetic Systems: Two Sources

Electron EDM



$$d_f = -(1.13 \times 10^{-3}\, e\,\mathrm{fm}) \left(\frac{v}{\Lambda}\right)^2 Y_f\, \delta_f$$

(Scalar q)
x (PS e^-)



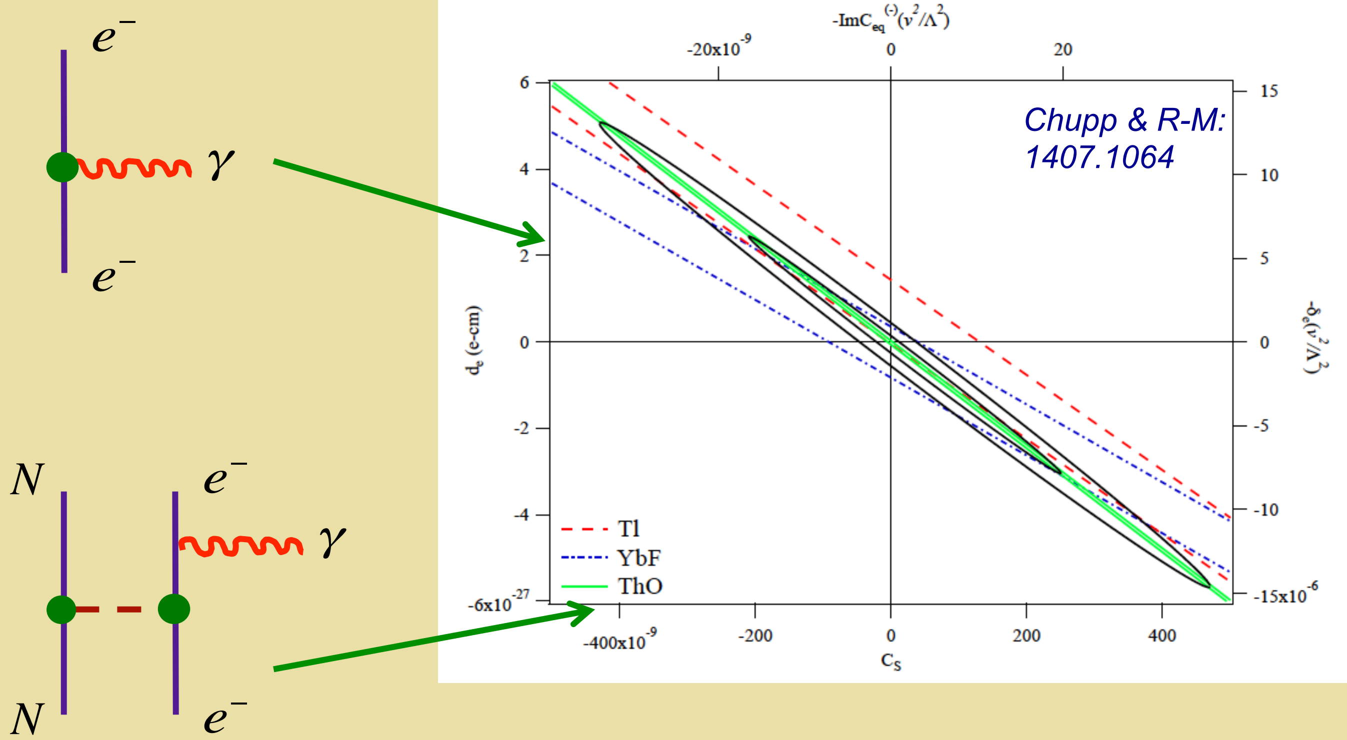
$$C_S^{(0)} = -g_S^{(0)} \left(\frac{v}{\Lambda}\right)^2 \mathrm{Im}\, C_{eq}^{(-)}$$

Tl, YbF, ThO…

Paramagnetic Systems: Two Sources

Electron EDM

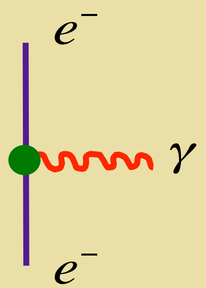
(Scalar q) x (PS e-)



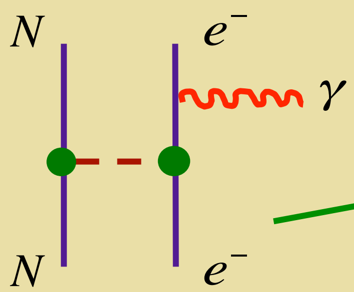
Tl, YbF, ThO…

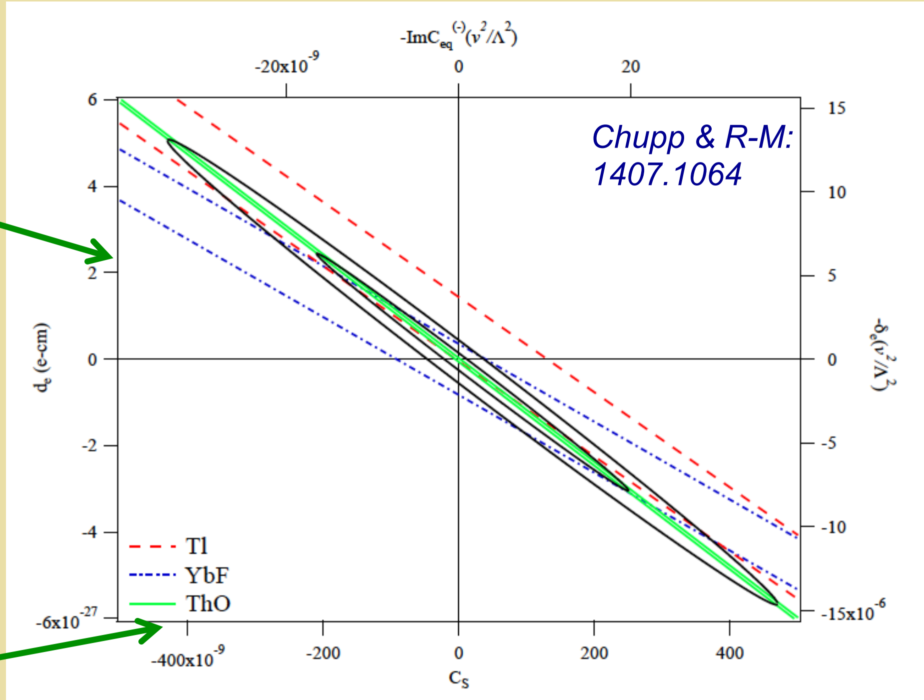
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





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

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

Tl, YbF, ThO…

Global Analysis: Diamagnetic Systems

System	Year/ref	Result	
Paramagnetic systemss			
Cs	1989 [37]	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	e cm
		$d_e = (-1.5 \pm 5.6) \times 10^{-26}$	e cm
Tl	2002 [9]	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	e cm
		$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	e cm
YbF	2011 [8]	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	e cm
ThO	2014 [7]	$\omega^{NE} = 2.6 \pm 5.8$	mrad/s
		$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	e cm
		$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	
Diamagnetic systems			
^{199}Hg	2009 [5]	$d_A = (0.49 \pm 1.5) \times 10^{-29}$	e cm
^{129}Xe	2001 [38]	$d_A = (0.7 \pm 3) \times 10^{-27}$	e cm
TlF	2000 [39]	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	e cm
neutron	2006 [4]	$d_n = (0.2 \pm 1.7) \times 10^{-26}$	e cm

Chupp & R-M: 1407.1064

Diamagnetic Systems

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

Nucleon EDMs

Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Diamagnetic Systems

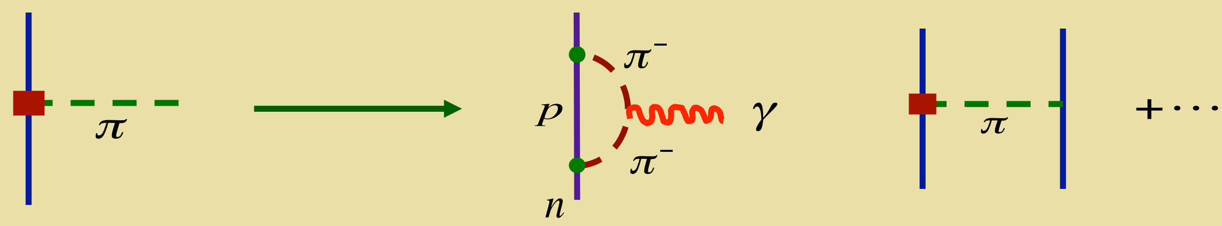
$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0+\bar{d}_1\tau_3\right)S_\mu N\, v_\nu F^{\mu\nu}$$

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

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

I = 0, 1, 2

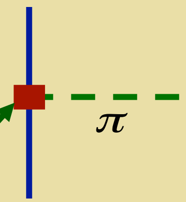
PVTV πN interaction

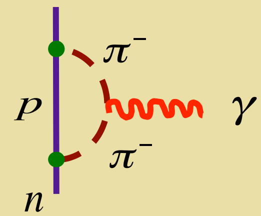


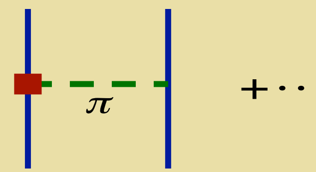
Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Hadronic CPV: Nucleons, Nuclei, Atoms

PVTV πN interaction







- *chromo EDM*
- *3 gluon*
- *4 quark*
- θ_{QCD}

Nucleon EDM

+ quark EDM

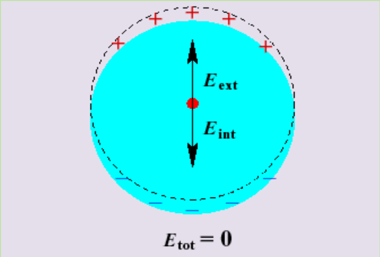
Nuclear EDM & Schiff moment

+ ~~quark EDM~~

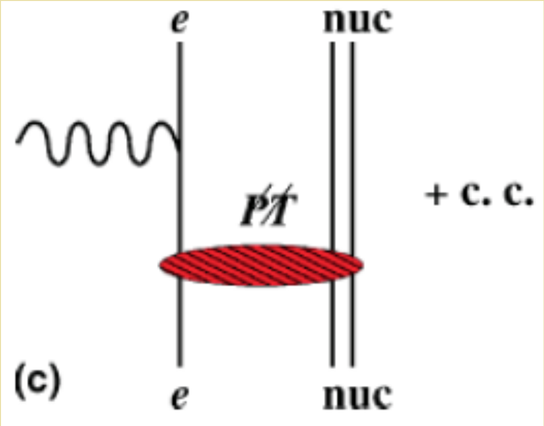
Neutron, proton & light nuclei (future), diamagnetic atoms

Diamagnetic Systems: P- & T-Odd Moments

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment

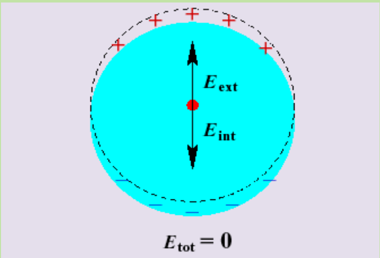


Schiff moment, MQM,…

EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment I

Schiff Screening



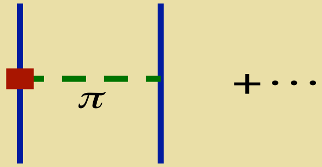
Atomic effect from nuclear finite size: Schiff moment

Nuclear Schiff Moment

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

Nuclear EDM: Screened in atoms

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



EDMs of diamagnetic atoms (^{199}Hg)

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…*

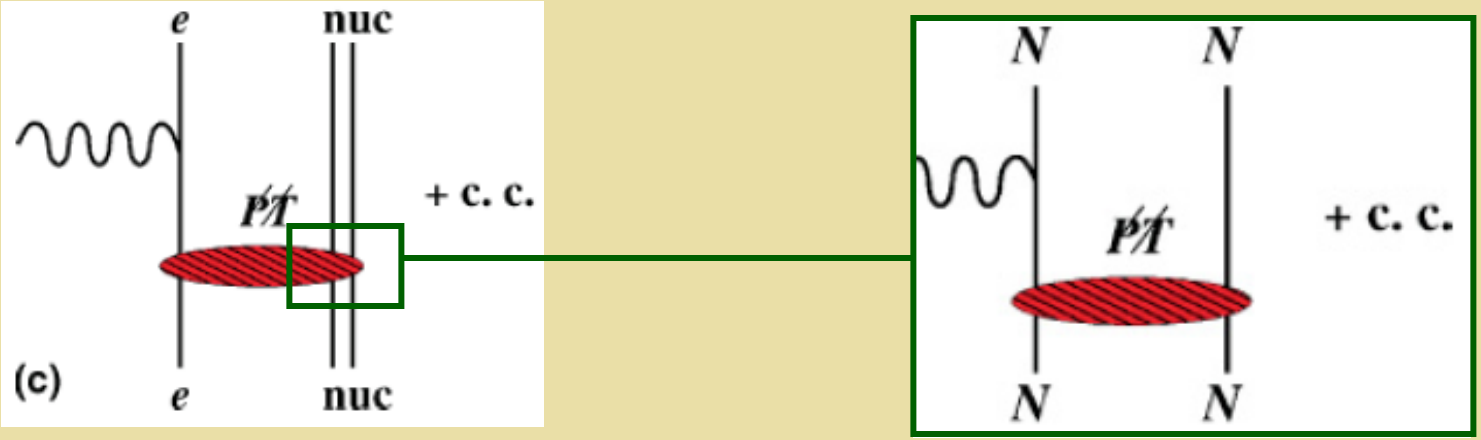
Diamagnetic Systems

Nuclear Moments

	PT	$\not{P}T$	$P\not{T}$	$\not{P}\not{T}$		
C_J	E	✖	✖	[O]	[*EDM, Schiff…*]	*Nuclear Enhancements*
$T^M{}_J$	O	✖	✖	[E]	*MQM….*	
$T^E{}_J$	✖	[O]	E	✖	*Anapole…*	

Nuclear Schiff Moment

Nuclear Enhancements



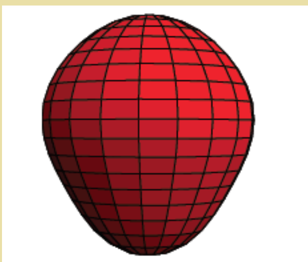
Schiff moment, MQM,…

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

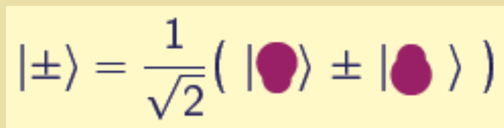
EDMs of diamagnetic atoms (^{199}Hg)

Nuclear Schiff Moment

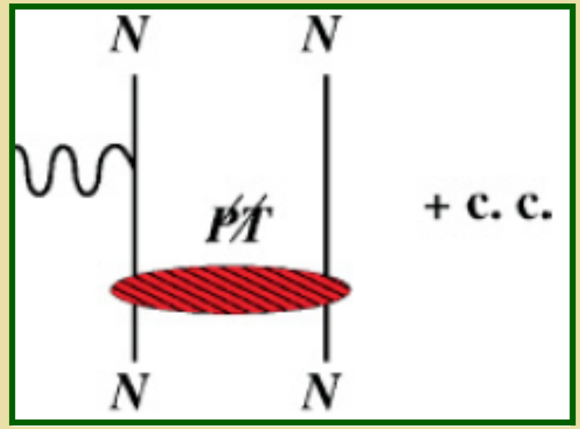
Nuclear Enhancements:
Octupole Deformation



Calculated ^{225}Ra density



Opposite parity states mixed by H^{TVPV}



"Nuclear amplifier"

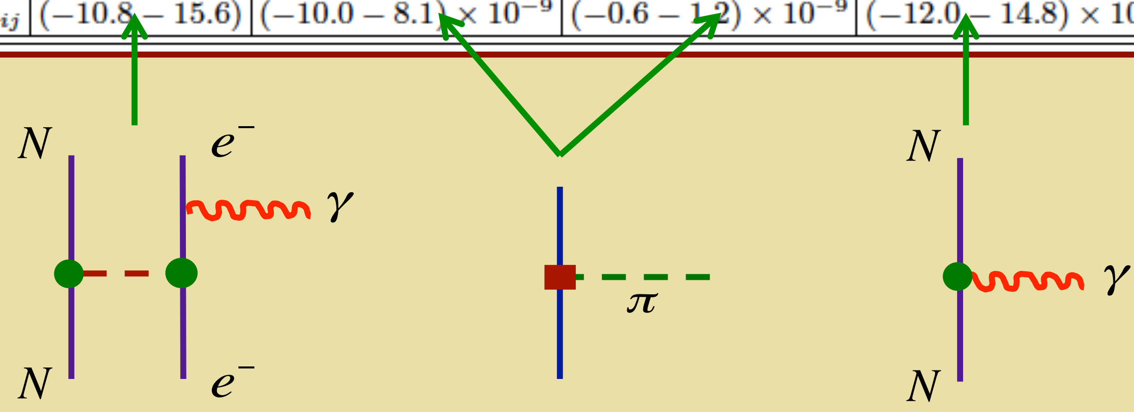
Nuclear polarization: mixing of opposite parity states by H^{TVPV} ~ 1 / ΔE

EDMs of diamagnetic atoms (^{225}Ra)

Thanks: J. Engel

Diamagnetic Global Fit

	$C_T \times 10^7$	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$\bar{d}_n$ (e-cm)
Exact solution	1.265	-6.687×10^{-10}	1.4308×10^{-10}	9.878×10^{-24}
Range from best values of α_{ij}	$(-7.6 - 9.5)$	$(-5.0 - 4.0) \times 10^{-9}$	$(-0.2 - 0.4) \times 10^{-9}$	$(-5.9 - 7.4) \times 10^{-23}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-7.6 - 8.4)$	$(-7.0 - 4.0) \times 10^{-9}$	$(0 - 0.2) \times 10^{-9}$	$(5.9 - 10.4) \times 10^{-23}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-9.2 - 12.4)$	$(-4.0 - 4.0) \times 10^{-9}$	$(-0.4 - 0.8) \times 10^{-9}$	$(-5.9 - 5.9) \times 10^{-23}$
Range from full variation of α_{ij}	$(-10.8 - 15.6)$	$(-10.0 - 8.1) \times 10^{-9}$	$(-0.6 - 1.2) \times 10^{-9}$	$(-12.0 - 14.8) \times 10^{-23}$



Tensor eq *TVPV πNN* *Short distance d_n*

Chupp & R-M: 1407.1064

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Isoscalar CEDM

$$\tilde{\delta}_q^{(+)} \left(\frac{v}{\Lambda}\right)^2 \lesssim 0.01 \qquad \Lambda \gtrsim (2\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$$

Caveat: Large hadronic uncertainty

Chupp & R-M: 1407.1064

V. Theoretical Issues

Hadronic Matrix Elements

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

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

$$\bar{C}_i = \kappa_i\, \bar{\theta} + \left(\frac{v}{\Lambda}\right)^2 \sum_k \delta_i^{(k)}\, \mathrm{Im}\, C_k,$$

$$\left(\frac{v}{\Lambda}\right)^2 \left[\beta_N^{qG}\, \mathrm{Im}\, C_{qG} + \beta_N^{q\gamma}\, \mathrm{Im}\, C_{q\gamma}\right] = e\, \tilde{\rho}_N^q\, \tilde{d}_q + \rho_N^q\, d_q = \left(\frac{v}{\Lambda}\right)^2 \left[e\, \tilde{\zeta}_N^q\, \tilde{\delta}_q + e\, \zeta_N^q\, \delta_q\right],$$

$$\left(\frac{v}{\Lambda}\right)^2 \left[\gamma_{(i)}^{qG}\, \mathrm{Im}\, C_{qG} + \gamma_{(i)}^{q\gamma}\, \mathrm{Im}\, C_{q\gamma}\right] = \tilde{\omega}_{(i)}^q\, \tilde{d}_q + \omega_{(i)}^q\, d_q = \left(\frac{v}{\Lambda}\right)^2 \left[\tilde{\eta}_{(i)}^q\, \tilde{\delta}_q + \eta_{(i)}^q\, \delta_q\right].$$

Engel, R-M,
van Kolck ‘13

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

Engel, R-M, van Kolck '13

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$\bar{\theta}$	α_n	0.002	(0.0005–0.004)
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$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09 - 0.9)$
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2 - 1.8)$
$\tilde{\delta}_q$ (CEDM)	$e\tilde{\zeta}_n^u$	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}	$-(0.8 - 2.4) \times 10^{-3}$
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	ρ_n^d	1.4	0.7–2.1
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$\mathrm{Im}\, C_{quqd}^{(1,8)}$	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

Engel, R-M, van Kolck '13

Nuclear Matrix Elements

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

Nucl.	Best value a_0	Best value a_1	Best value 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

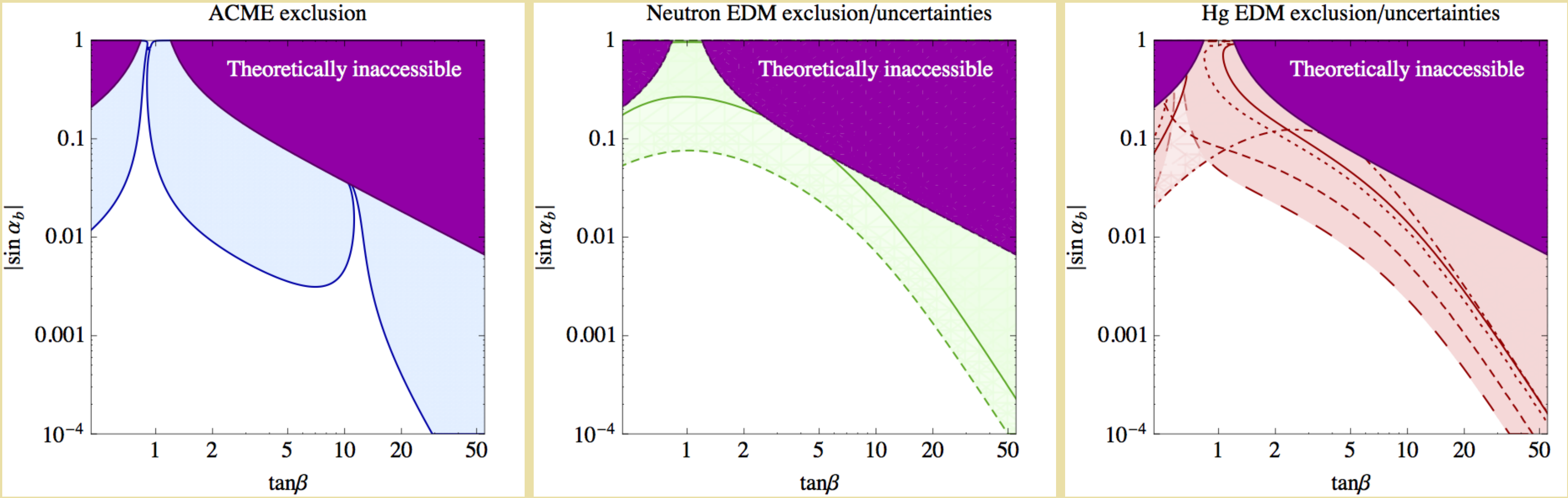
Range a_0	Range a_1	Range a_2
0.005–0.05	−0.03–(+0.09)	0.01–0.06
−0.005–(−0.05)	−0.003–(−0.05)	−0.005–(−0.1)
−1–(−6)	4–24	−3–(−15)

Engel, R-M, van Kolck ‘13

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



Present

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

IV. Outlook

- *Searches for permanent EDMs of atoms, molecules, hadrons and nuclei provide powerful probes of BSM physics at the TeV scale and above and constitute important tests of weak scale baryogenesis*
- *Studies on complementary systems is essential for first finding and then disentangling new CPV*
- *The interpretation of diamagnetic system EDMs (including the nucleon) is plagued by substantial hadronic and nuclear many-body uncertainties*
- *The advancing experimental sensitivity challenges hadronic structure theory to aim for an unprecedented level of reliability*