EDM Complementarity and the Inter-frontier Interface

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

University of Massachusetts Amherst

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

CERN EDM Workshop,
Geneva, March 2018

Goals for This Talk

- *Illustrate the interplay of EDM searches with baryogenesis and collider searches*
- *Illustrate the complementarity of EDM searches on different systems*
- *Put the opportunities for a proton EDM search in a broader context*

Outline

I. *EDM Interpretation: The SM & BSM context*

II. *The Cosmic Matter-Antimatter Asymmetry*

III. *The Higgs Boson & Top Quark Portals*

IV. *EDM Complementarity: Model Independent*

V. *Outlook*

I. Interpretation: The SM & BSM Context

EDMs & SM Physics

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

EDMs & SM Physics

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

C. Seng arXiv: 1411.1476

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

C. Seng arXiv: 1411.1476

* $3.3\ x\ 10^{-33}\ e\ cm < d_p < 3.3\ x\ 10^{-32}\ e\ cm$

EDMs & BSM Physics

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

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

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

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

BSM mass scale: TeV ? Much higher ?

EDMs & BSM Physics

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

BSM dynamics: perturbative? Strongly coupled?
Dependence on other parameters ?

EDMs & BSM Physics

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

Need information from at least three "frontiers"

EDMs & BSM Physics

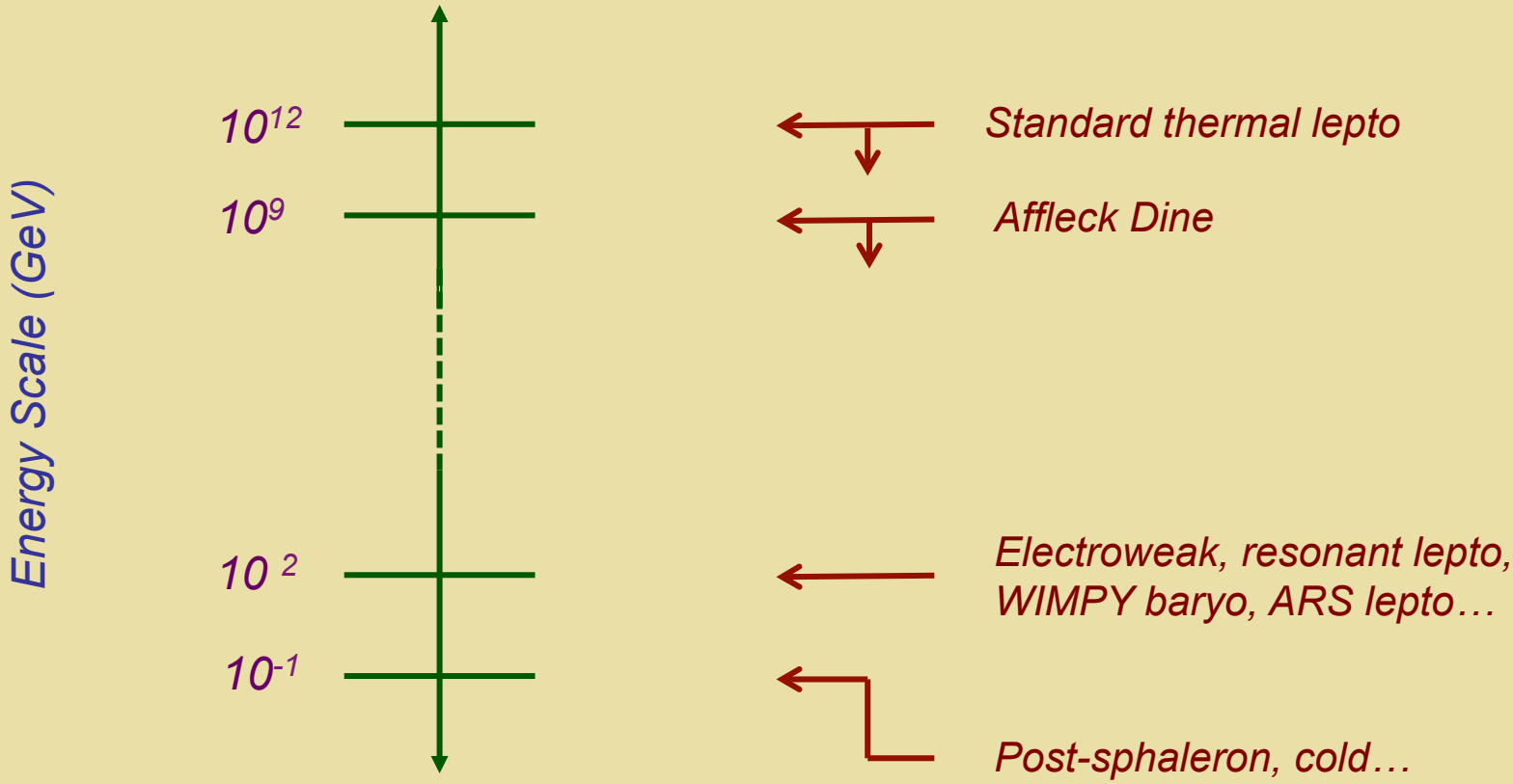
$$d \sim (10^{-16}\ e\ cm) \times \boxed{(\upsilon / \Lambda)^2} \times \boxed{\sin\phi} \times \boxed{y_f F}$$

Need information from at least three "frontiers"

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

II. The Matter-Antimatter Asymmetry

Baryogenesis Scenarios



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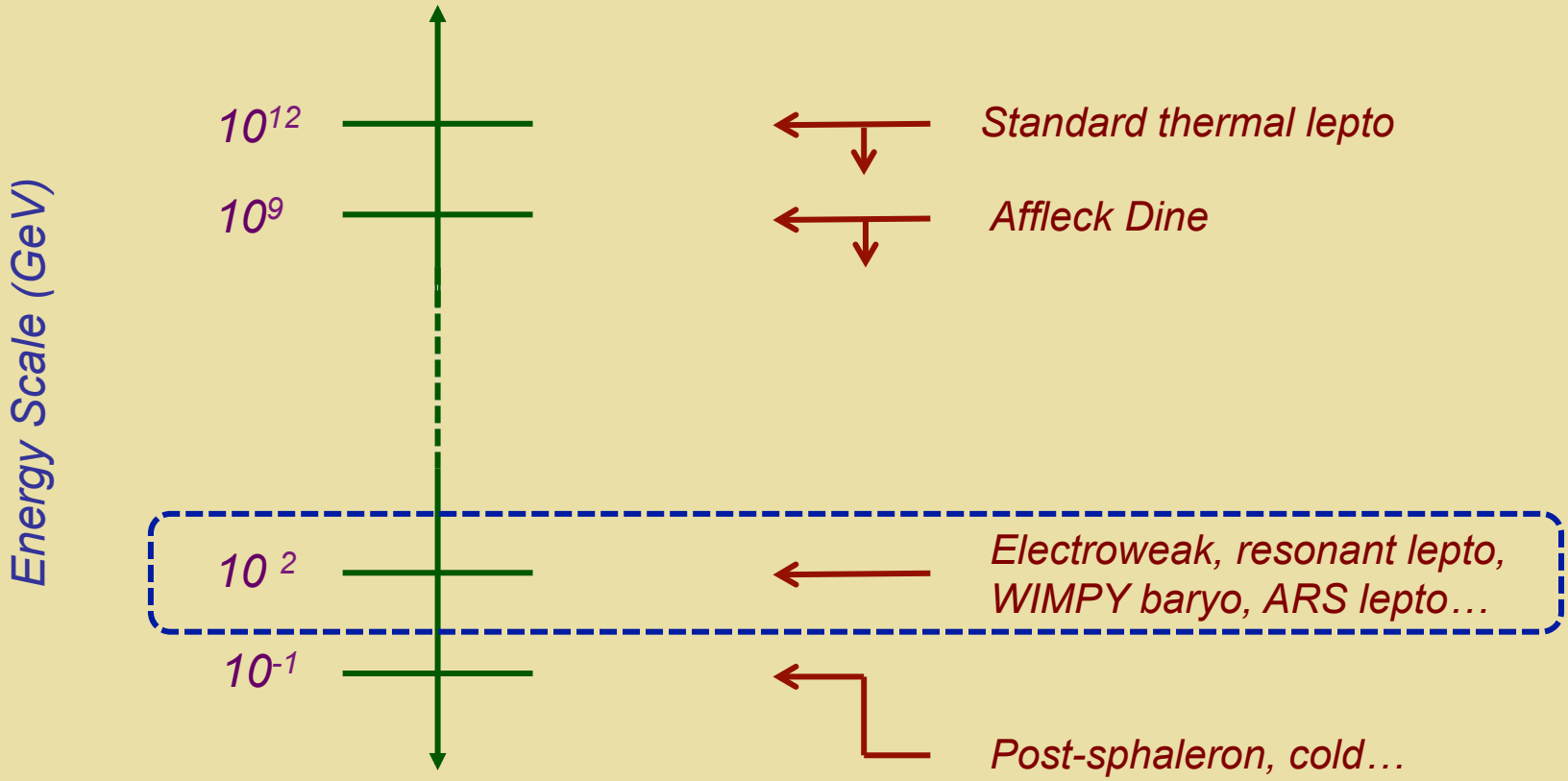


Era of EWSB: t_{univ} ~ 10 ps

Electroweak Baryogenesis

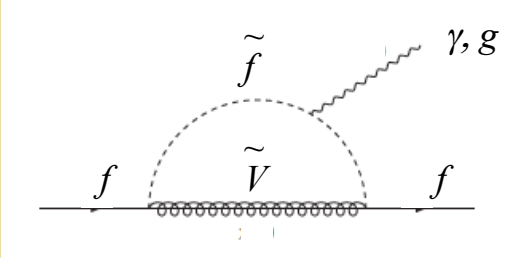
Was Y_B generated in conjunction with electroweak symmetry-breaking?

EWBG: MSSM & Beyond

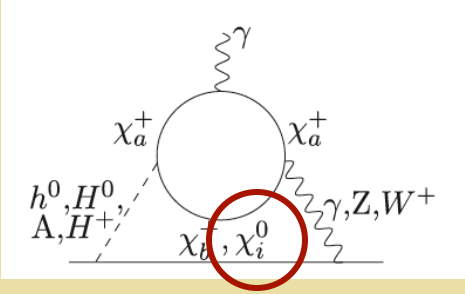
- ***Strong first order EWPT:*** *LHC $\rightarrow$ Excluded for the MSSM $\rightarrow$ Possible w/ extensions (e.g., NMSSM)*

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

EDMs & EWBG: MSSM & Beyond

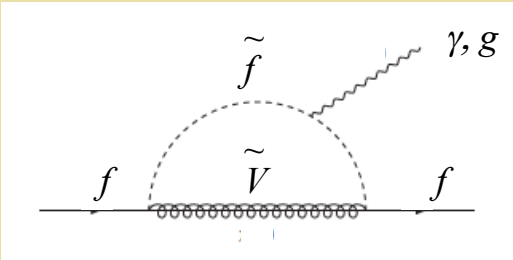


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

EDMs & EWBG: MSSM & Beyond



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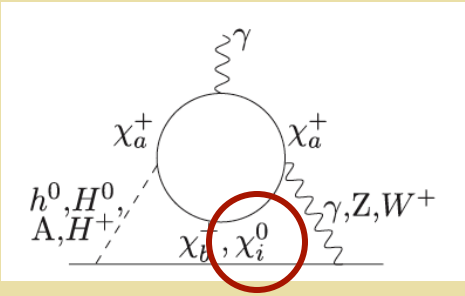

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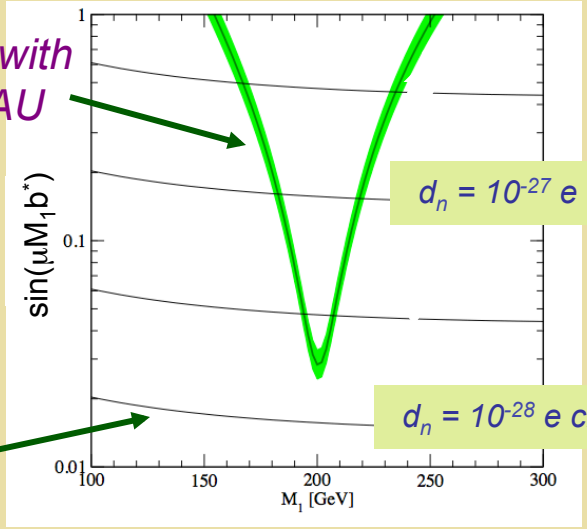
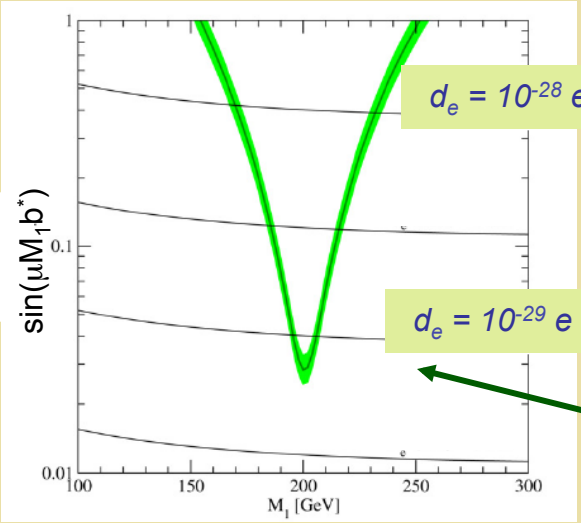
Compatible with observed BAU



Next gen d_n

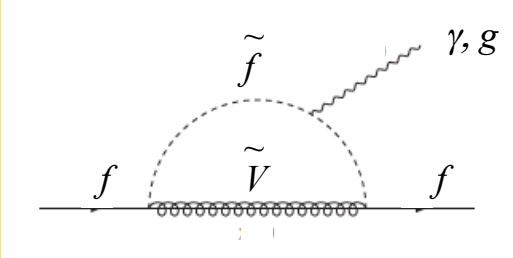


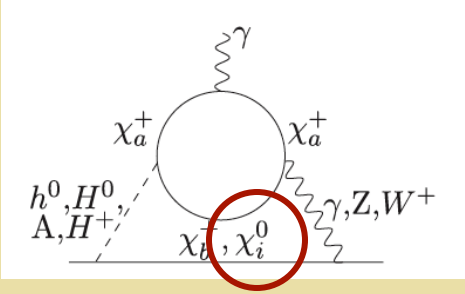
ACME: ThO

Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EWBG: MSSM & Beyond





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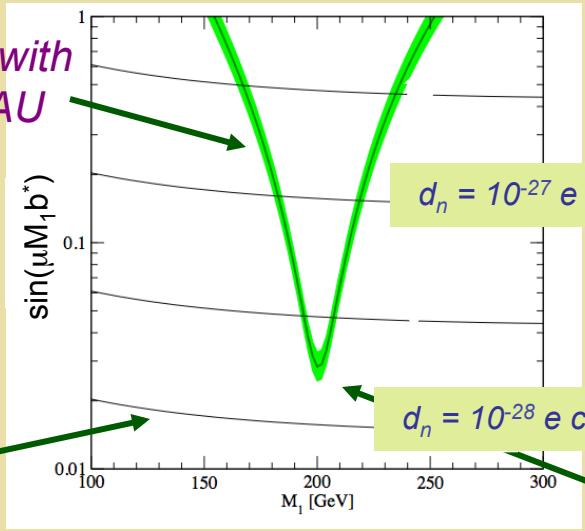

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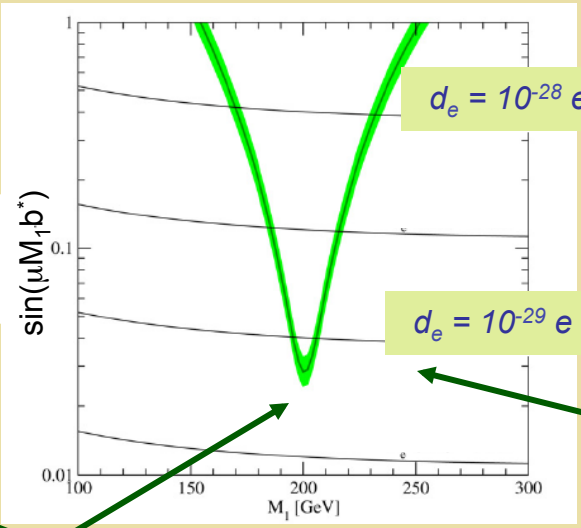

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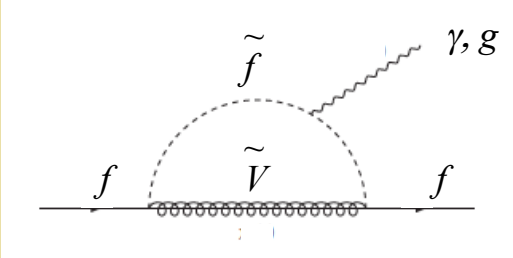
Compressed spectrum

EDMs & EWBG: MSSM & Beyond



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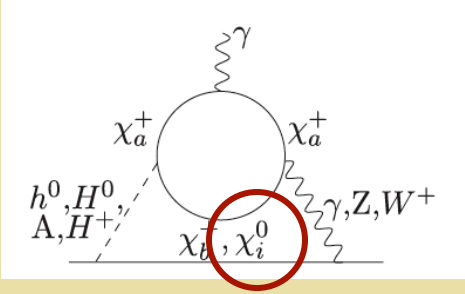

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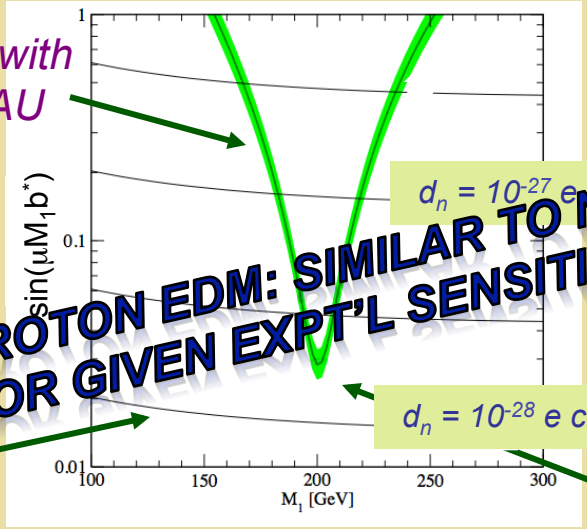
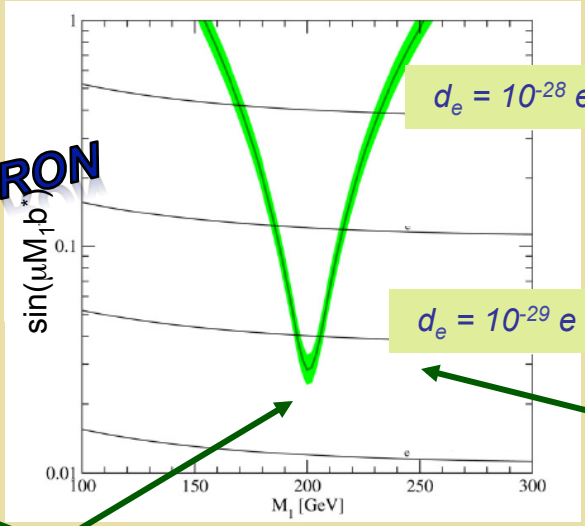


PROTON EDM: SIMILAR TO NEUTRON FOR GIVEN EXPT'L SENSITIVITY

Next gen d_n



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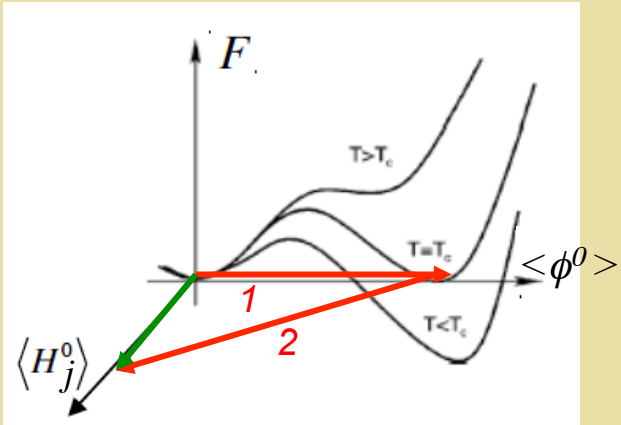
Two-Step EW Baryogenesis



H_j — *St'd Model Scalar Sector*

ϕ — *BSM Scalar Sector: at least one $SU(2)_L$ non-singlet plus possibly gauge singlets: "partially secluded sector CPV"*

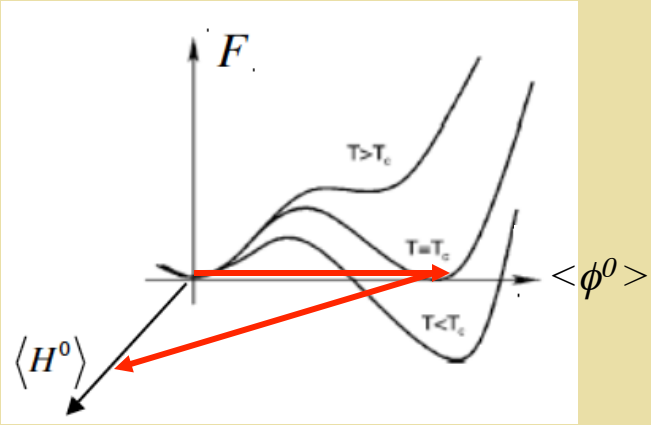
→ *Conventional one step EWSB*

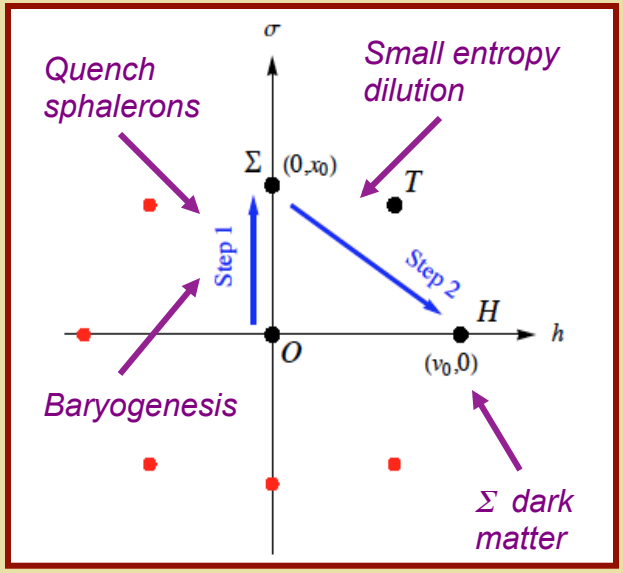
→ *Two step EWSB*

BSM CPV in ϕ H interactions: baryogenesis during step 1

Inoue, Ovanesyan, R-M: 1508.05404;
Patel & R-M: 1212.5652; Blinov, Kozaczuk, Morrissey: 1504.05195

Two-Step EW Baryogenesis





Inoue, Ovanesyan, R-M: 1508.05404

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet S

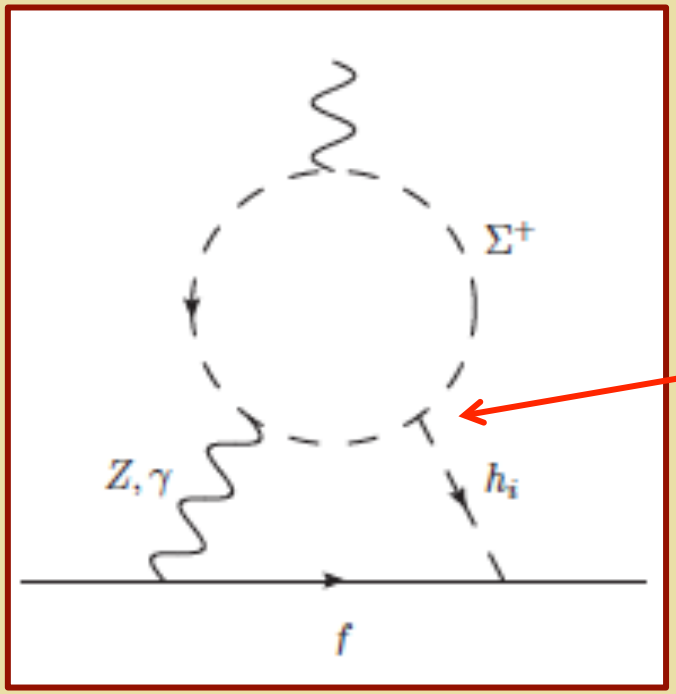
$H \rightarrow$ Set of "SM" fields: 2 HDM

(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

δ_Σ : Triplet phase
δ_S : Singlet phase

Two-Step EW Baryogenesis & EDMs



EDMs are Two Loop

Two CPV Phases:

δ_Σ : *Triplet phase*

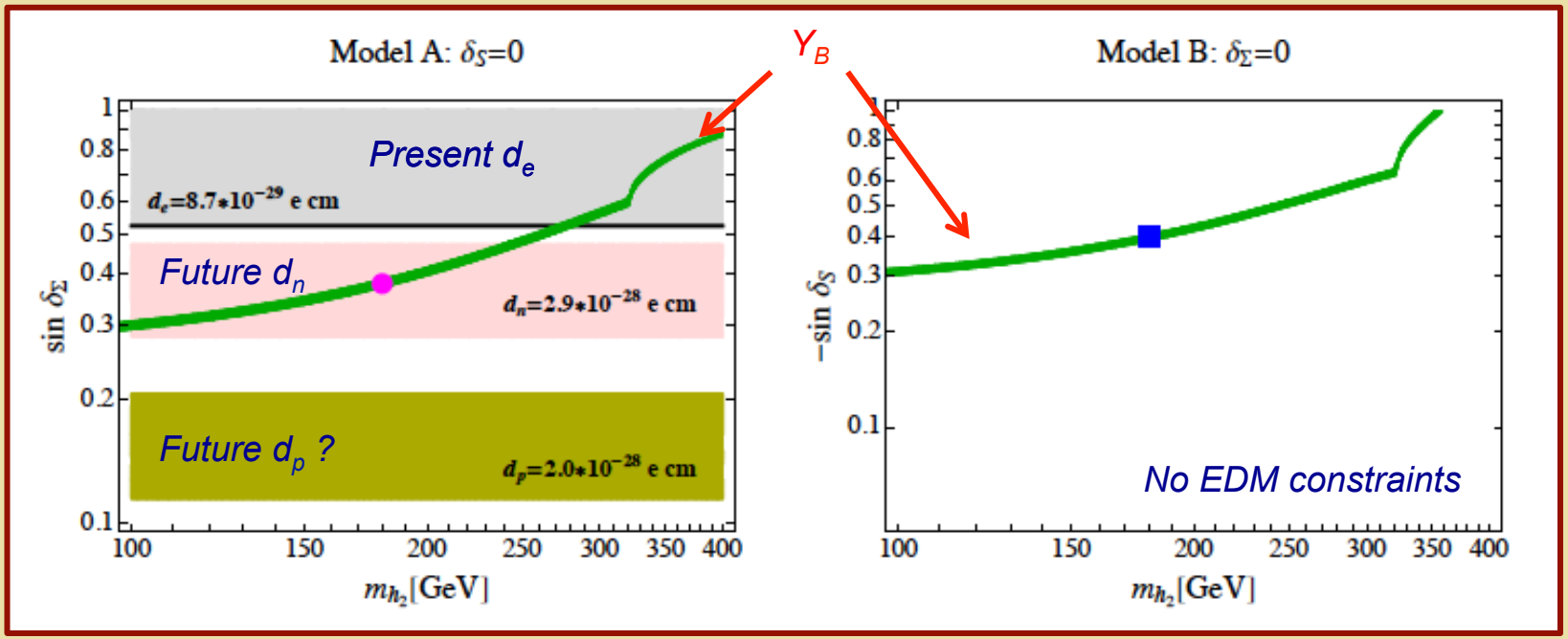
δ_S : *Singlet phase*

Insensitive to δ_S: electrically neutral $\rightarrow$ "partially secluded"

Inoue, Ovanesyan, R-M: 1508.05404

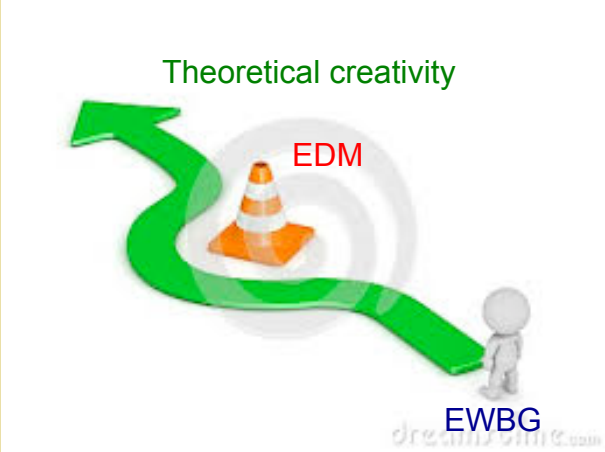
Two-Step EW Baryogenesis

Two cases: (A) $\delta_S = 0$ (B) $\delta_\Sigma = 0$



Inoue, Ovanesyan, R-M: 1508.05404

CPV for EWBG



III. Portals: The BSM Mass Scale & CP

The Higgs Portal

What is the CP Nature of the Higgs Boson ?

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

- *Two Higgs doublets ?*

$$H \rightarrow H_1 , H_2$$

- *New parameters:*

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

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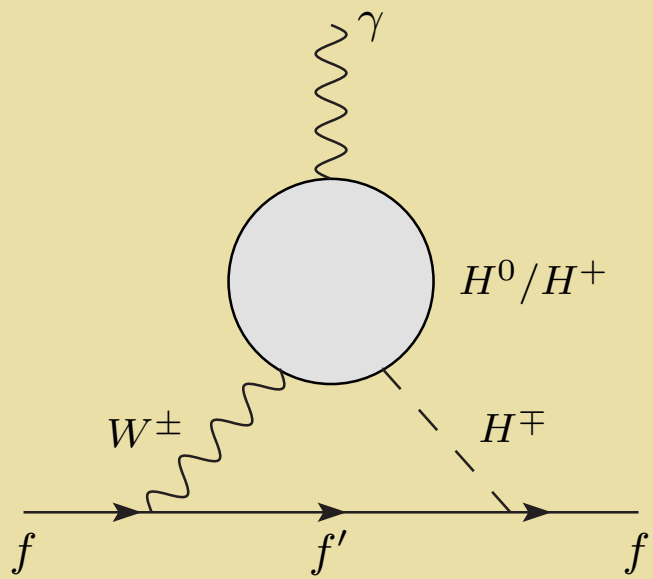
CPV : scalar-pseudoscalar mixing from $V(H_1, H_2)$

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

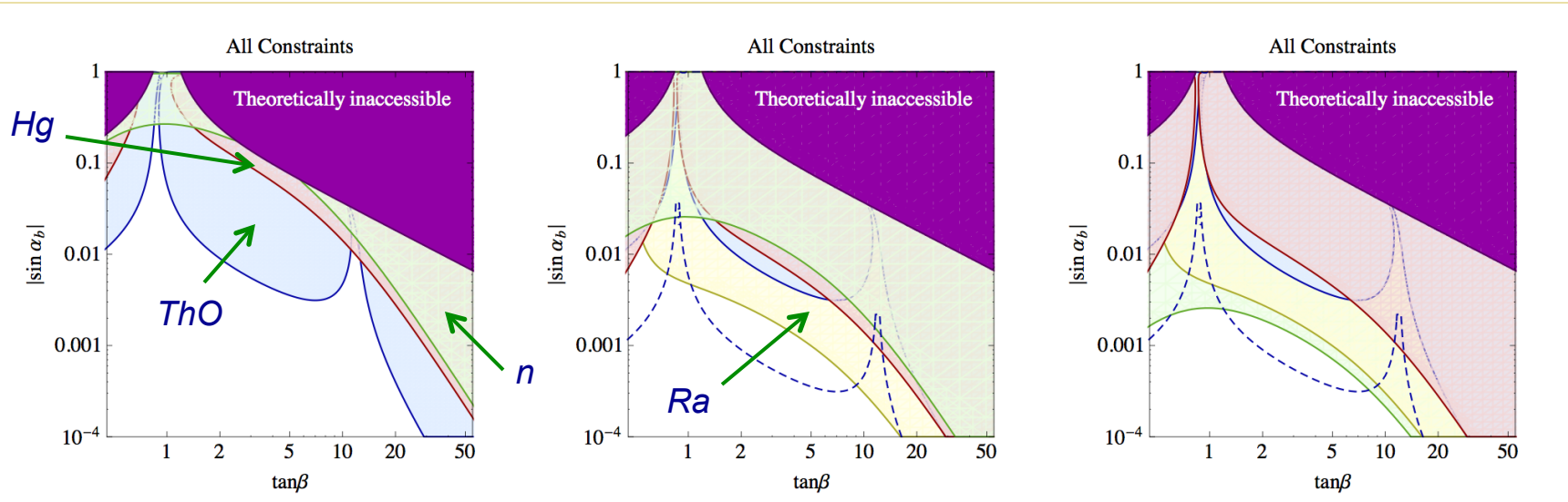
CPV & 2HDM: Type I & II



Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

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



Present

sin α_b : CPV scalar mixing

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

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d_A(Ra)

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs

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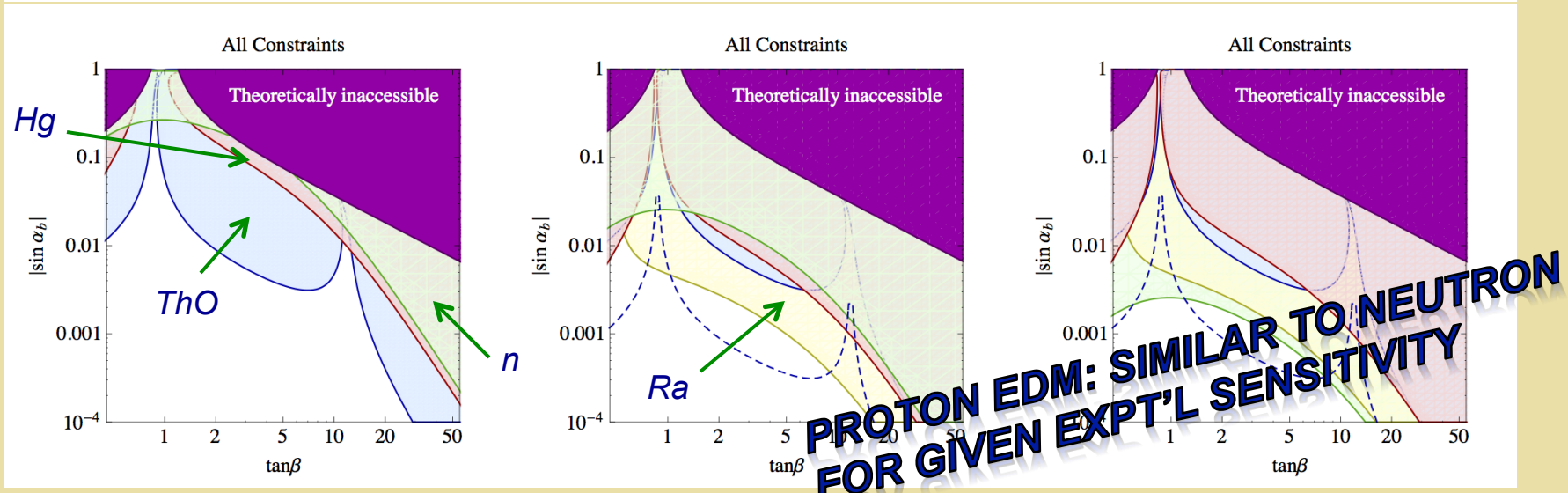

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Higgs Portal CPV: EDMs & LHC

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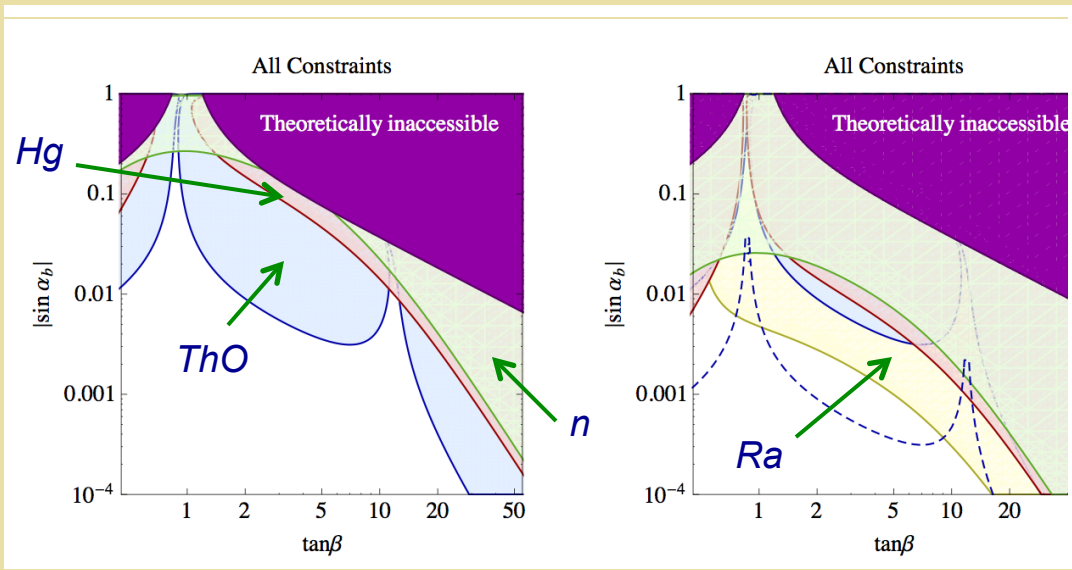

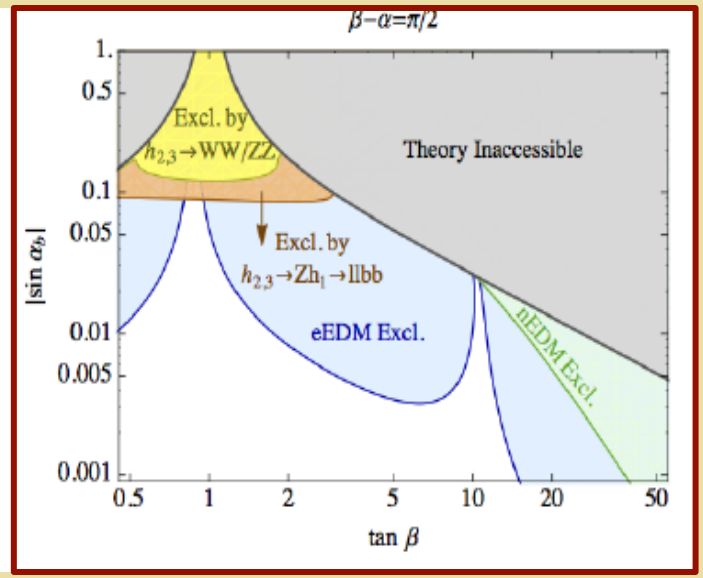

Chen, Lewis, Dawson: 1503.01114

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Inoue, R-M, Zhang: 1403.4257

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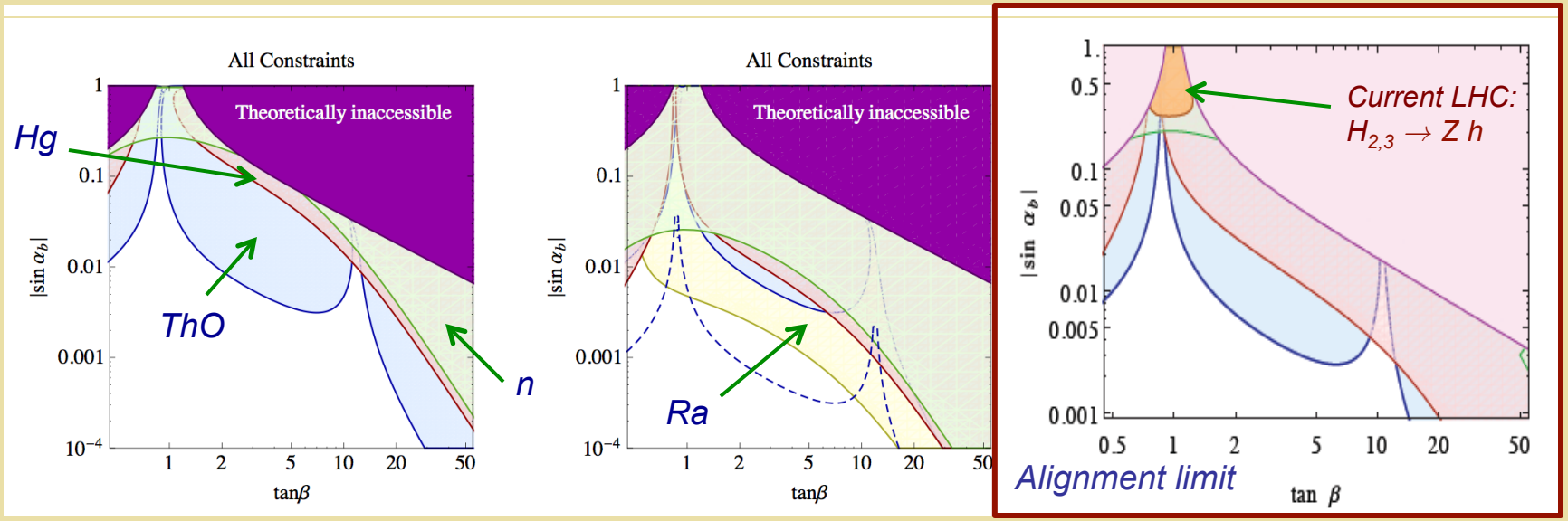

Chen, Li, R-M: 1708.00435

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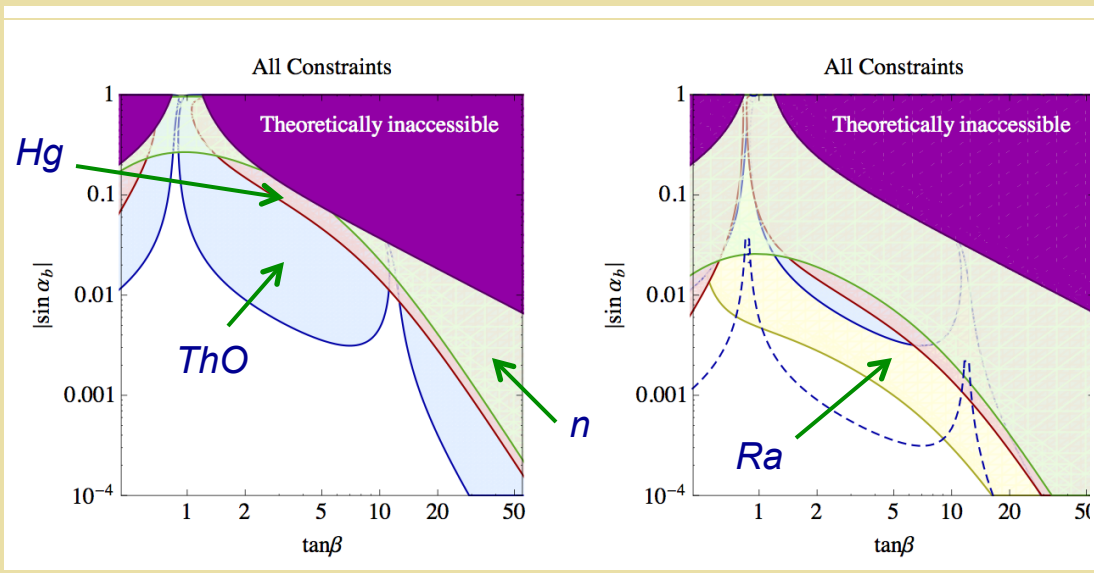

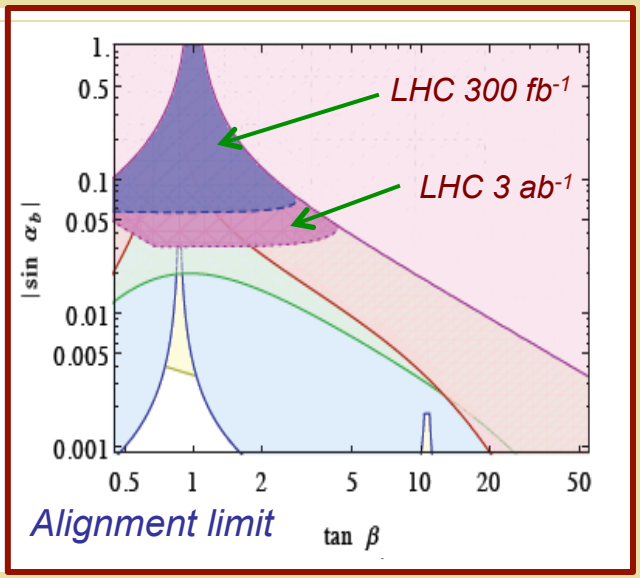

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Inoue, R-M, Zhang: 1403.4257

The Top Quark Portal

CPV Top Quark Interactions?

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

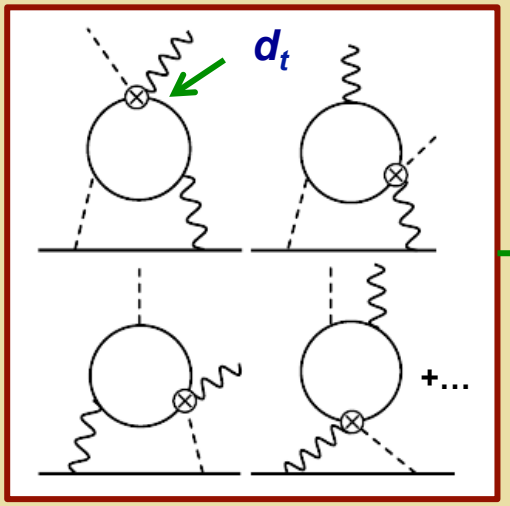
- *Top EDMs difficult to probe experimentally*

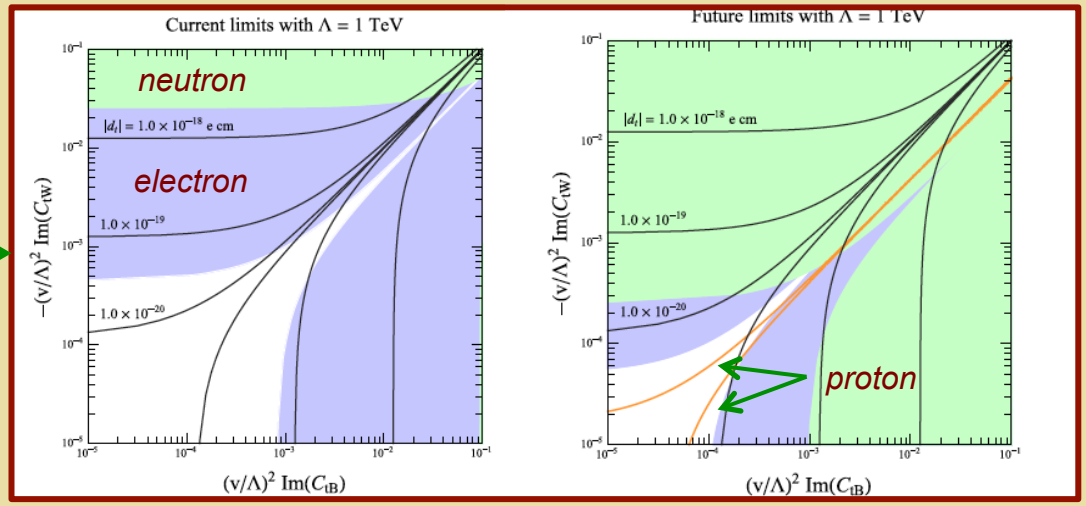
- *Light fermion EDMs to the rescue !*

CPV Top Quark Interactions?

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

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





Induced d_e , $d_{light\ quark}$

Fuyuto & MRM '17

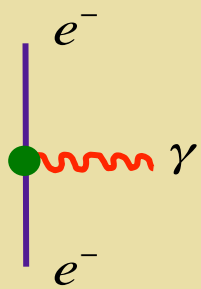
IV. Complementarity: Model Independent

Why Multiple Systems ?

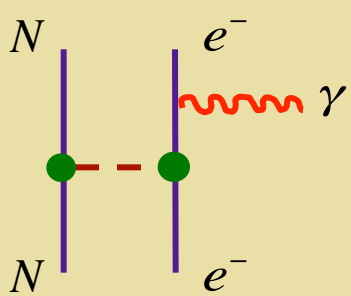
Multiple sources & multiple scales

Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e⁻)



Tl, YbF, ThO…

Paramagnetic Systems: Two Sources

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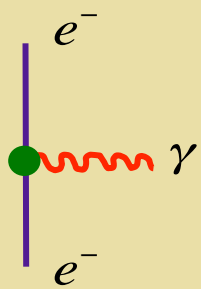

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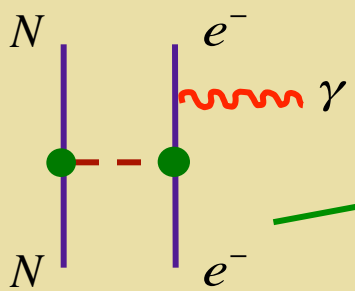

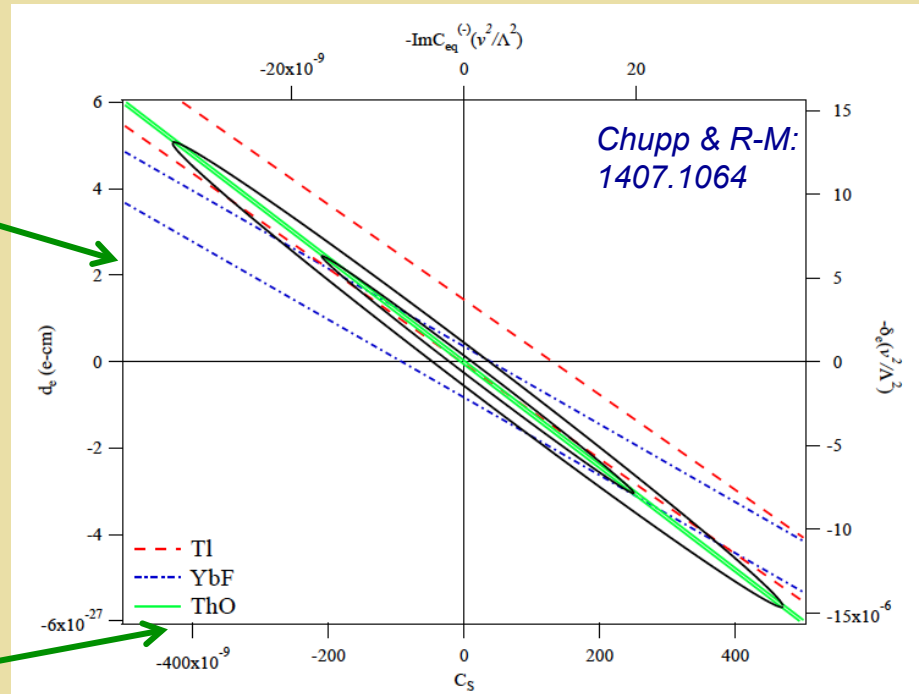

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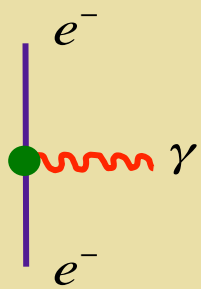
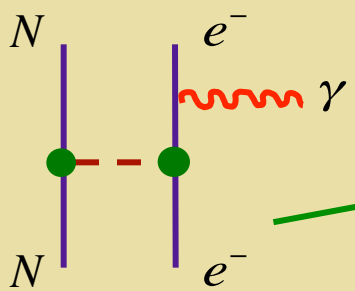
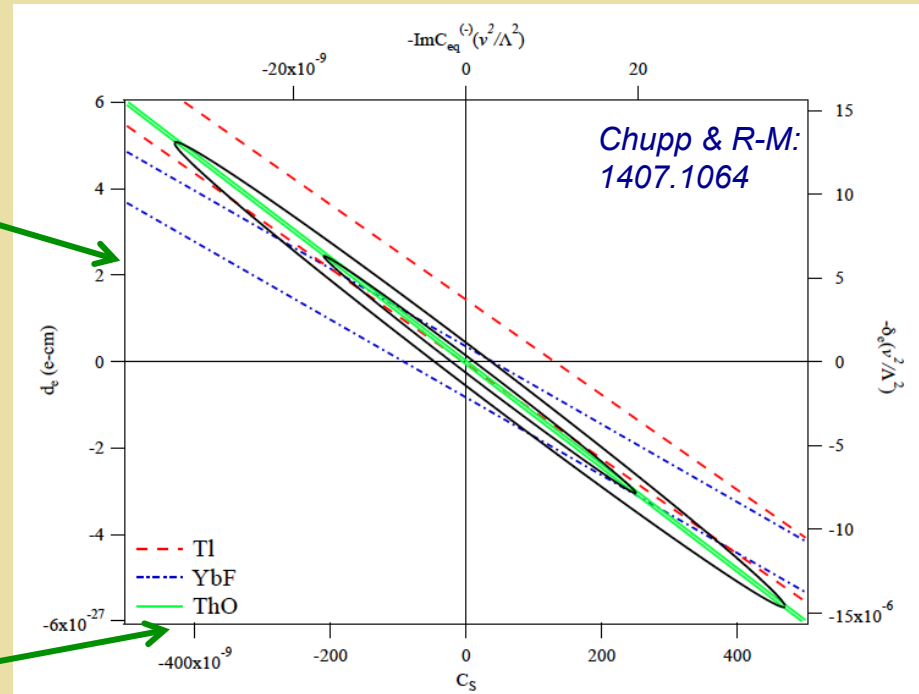
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e-)



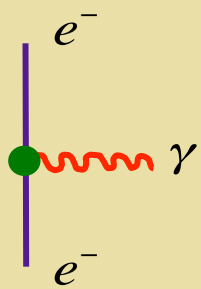


$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	C_S (global)

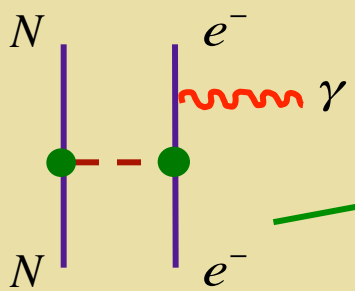
Tl, YbF, ThO…

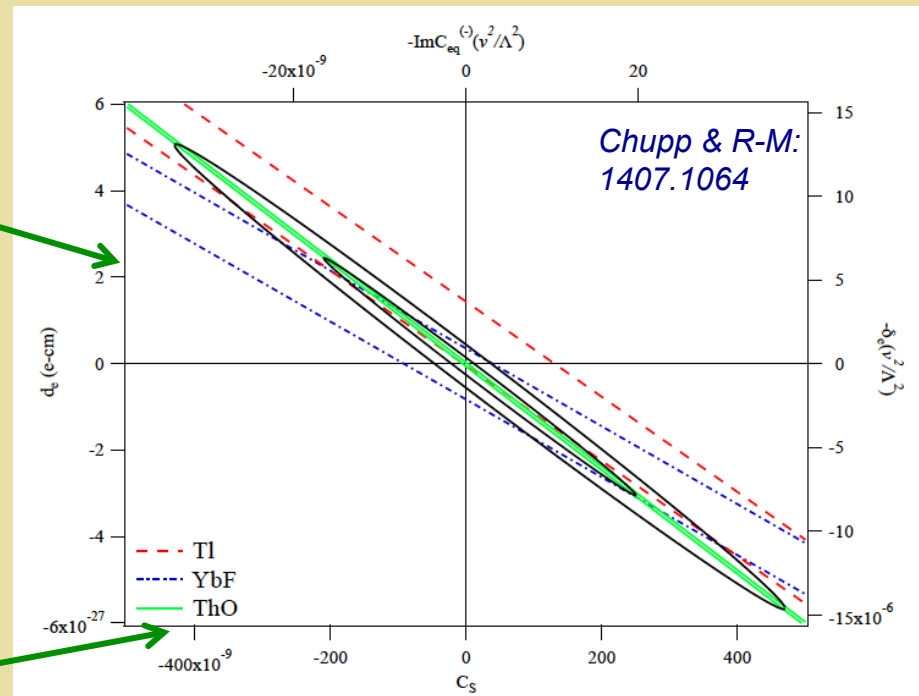
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e-)





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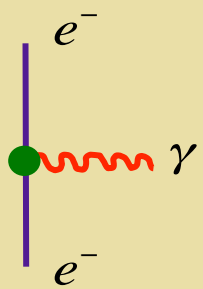
Tl, YbF, ThO…

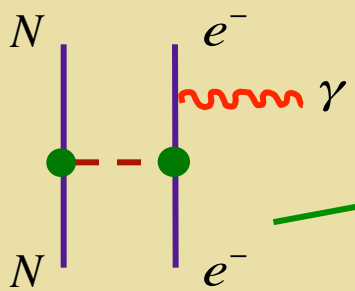
LHC inaccessible

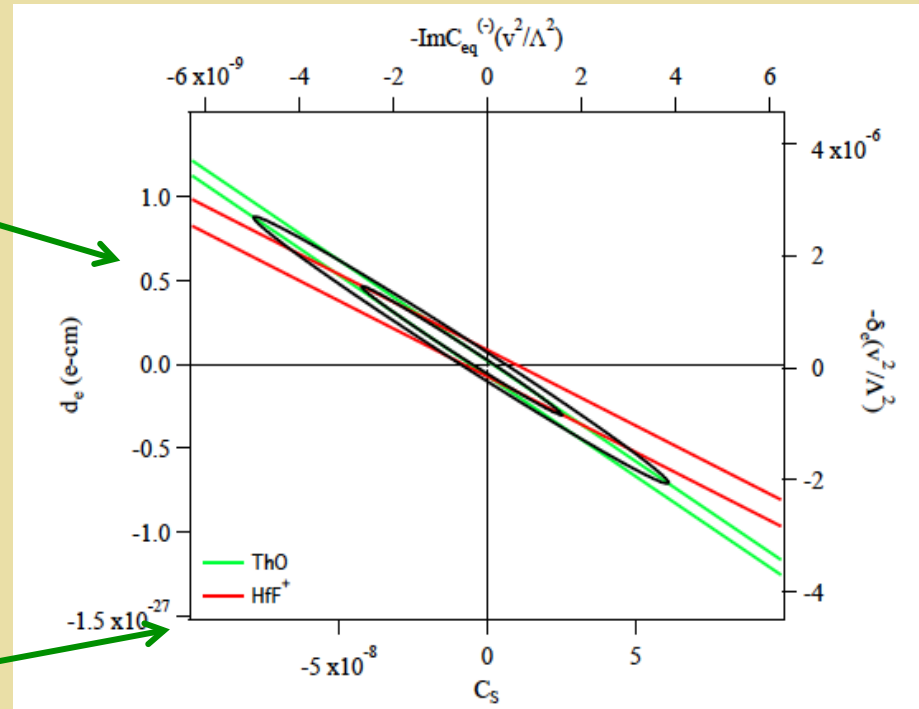
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





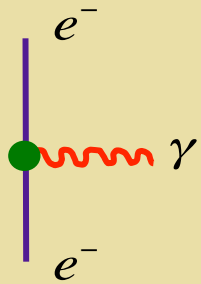
Chupp, Fierlinger, R-M, Singh 1710.02504; Fleig & Jung 1802.02171

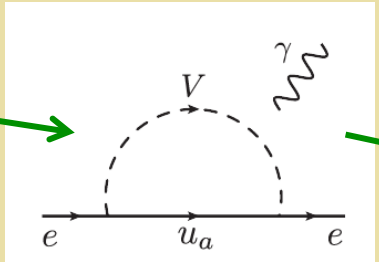
Inclusion of HfF+ : ~ 6 times stronger bounds on d_e & C_S $\rightarrow$ 2.5 higher on Λ

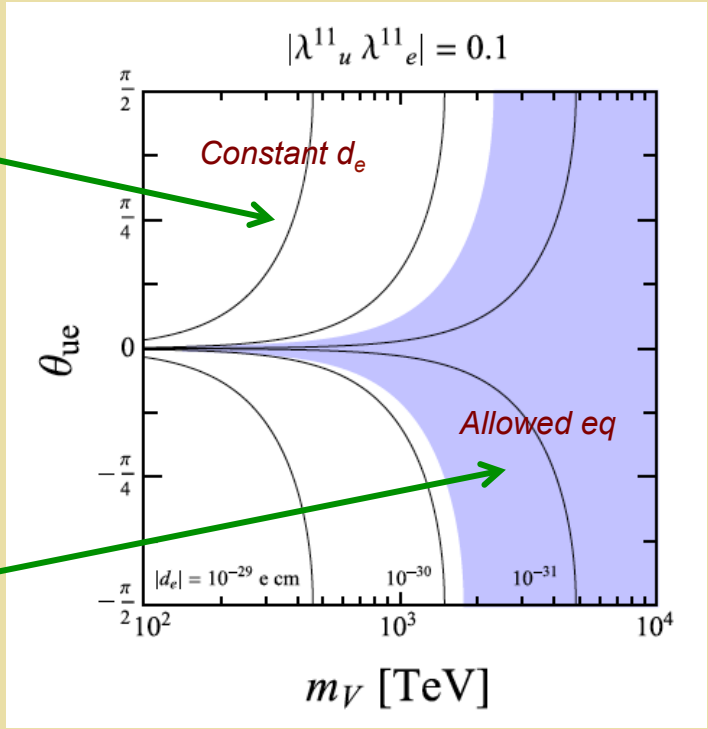
Tl, YbF, ThO, HfF+

Illustrative Example: Leptoquark Model

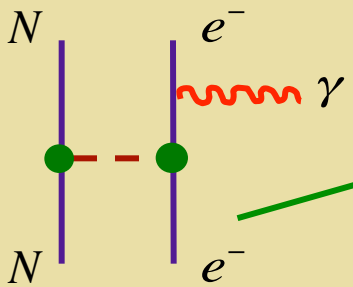
Electron EDM

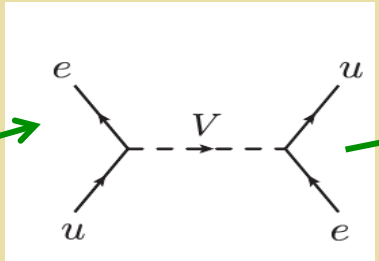






(Scalar q) x (PS e⁻)





Fuyuto, R-M, Shen 1804.XXXX

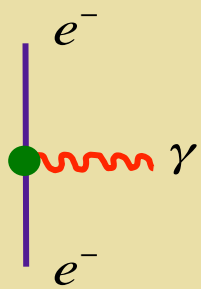
(3, 2, 7/6)

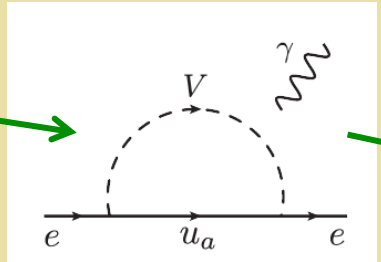
$$\mathcal{L} \ni -\lambda_u^{ab} \bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab} \bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

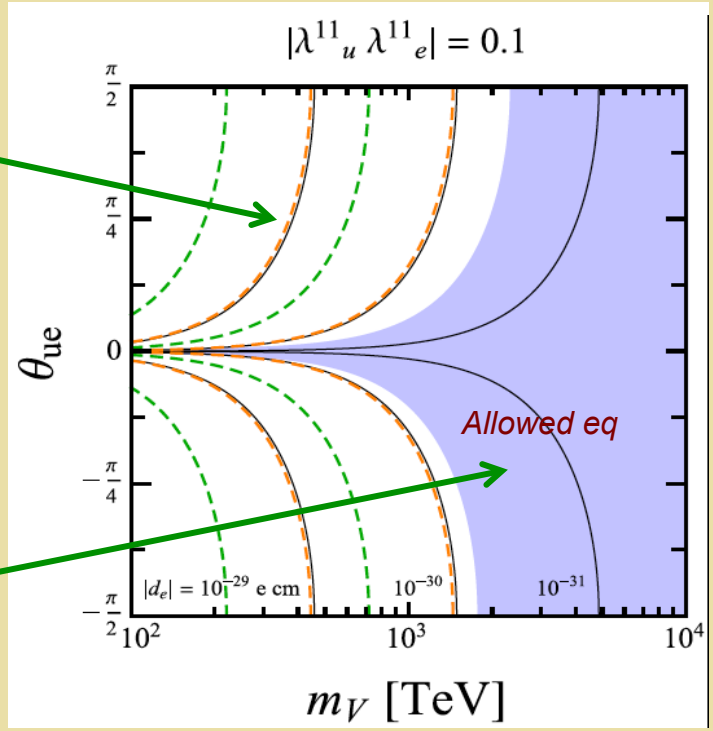
Illustrative Example: Leptoquark Model

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

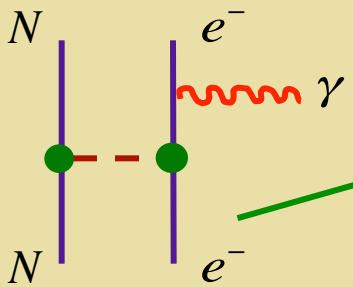
Electron EDM

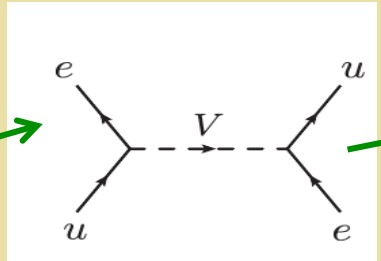






(Scalar q) x (PS e^-)





Fuyuto, R-M, Shen 1804.XXXX

(3, 2, 7/6)

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

Diamagnetic Systems: LR Sym Model

TVPV Hadronic & Nuclear Interactions

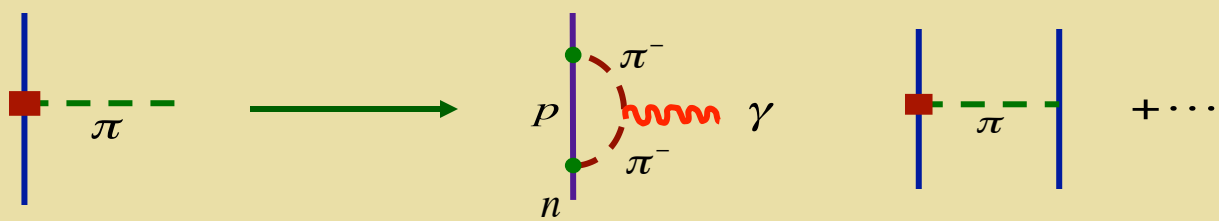
$$\mathcal{L}_{N\pi}^{\mathrm{PVTV}} = -2\bar{N}\left(\bar{d}_0 + \bar{d}_1\tau_3\right) S_\mu N\, v_\nu F^{\mu\nu}$$

I = 0, 1, 2

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

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

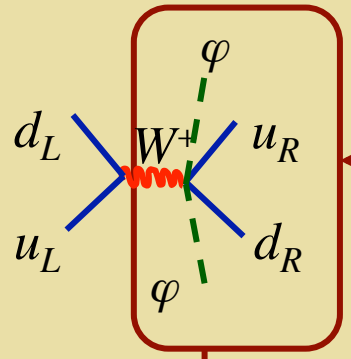
PVTV πN interaction



Nonleptonic: hadronic EDMs, Schiff moment (atomic EDMs)

Left-Right Symmetric Model

Four quark operator:

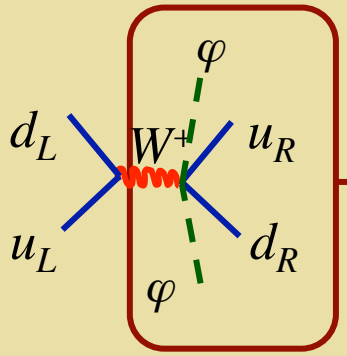


$$\frac{\mathrm{Im}C_{\varphi ud}}{\Lambda^2} = \frac{2\sqrt{2}}{3} G_F K^{(-)} \sin\xi \, \mathrm{Im}\left(e^{-i\alpha} V^L_{uq} V^{R*}_{uq}\right)$$

$$\bar{g}^{(1)}_\pi \approx -10^{-4}\left(1 - \frac{M_1^2}{M_2^2}\right) \sin\xi \, \cos\theta_L \cos\theta_R \sin\alpha .$$

Left-Right Symmetric Model

Four quark operator:



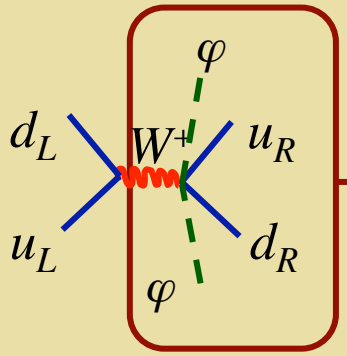
$$\bar{g}_\pi^{(1)} \approx -10^{-4} \left(1 - \frac{M_1^2}{M_2^2}\right) \sin\xi \, \cos\theta_L \cos\theta_R \sin\alpha .$$

$$|d_A(^{199}\mathrm{Hg})| \lesssim (1.1 \times 10^{-11} e \text{ fm}) \left(1 - \frac{M_1^2}{M_2^2}\right) \cos\theta_L \cos\theta_R \sin\alpha$$

Caveat: large nuclear theory uncertainty !

Left-Right Symmetric Model

Four quark operator:



$$\bar{g}_\pi^{(1)} \approx -10^{-4}\left(1-\frac{M_1^2}{M_2^2}\right)\sin\xi\,\cos\theta_L\cos\theta_R\sin\alpha.$$

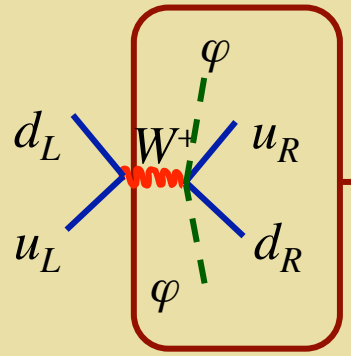
$$d_n = \bar{d}_n - \frac{e g_A}{4\pi^2 F_\pi}\left\{\bar{g}_\pi^{(0)}\left(\ln\frac{m_\pi^2}{m_N^2}-\frac{\pi m_\pi}{2m_N}\right) + \frac{\bar{g}_\pi^{(1)}}{4}(\kappa_1-\kappa_0)\frac{m_\pi^2}{m_N^2}\ln\frac{m_\pi^2}{m_N^2}\right\},$$

$$d_p = \bar{d}_p + \frac{e g_A}{4\pi^2 F_\pi}\left\{\bar{g}_\pi^{(0)}\left(\ln\frac{m_\pi^2}{m_N^2}-\frac{2\pi m_\pi}{m_N}\right) - \frac{\bar{g}_\pi^{(1)}}{4}\left[\frac{2\pi m_\pi}{m_N}+\left(\frac{5}{2}+\kappa_0+\kappa_1\right)\frac{m_\pi^2}{m_N^2}\ln\frac{m_\pi^2}{m_N^2}\right]\right\},$$

C. Seng et al
1401.1046

Left-Right Symmetric Model

Four quark operator:



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C. Seng et al
1401.1046

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*
- *There exists a rich interplay between EDM searches and the quest to discover BSM physics at the Energy and Cosmic frontiers*
- *Exciting opportunities exist for a proton EDM search with sensitivity of* $d_p \sim 10^{-29}$ *e cm*

Back Up Slides

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

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

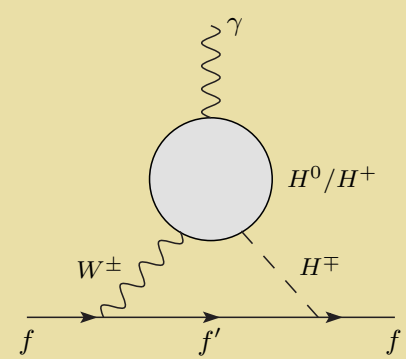
$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] ,$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]$$

EWSB →

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

$h, H^0, A^0 \to h_{1,2,3}$

$$\begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}$$



Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

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$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

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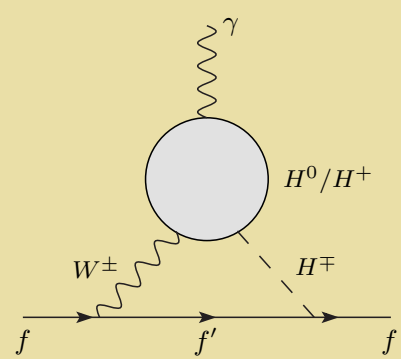
EWSB →

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

$h, H^0, A^0 \to h_{1,2,3}$

$$\begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}$$

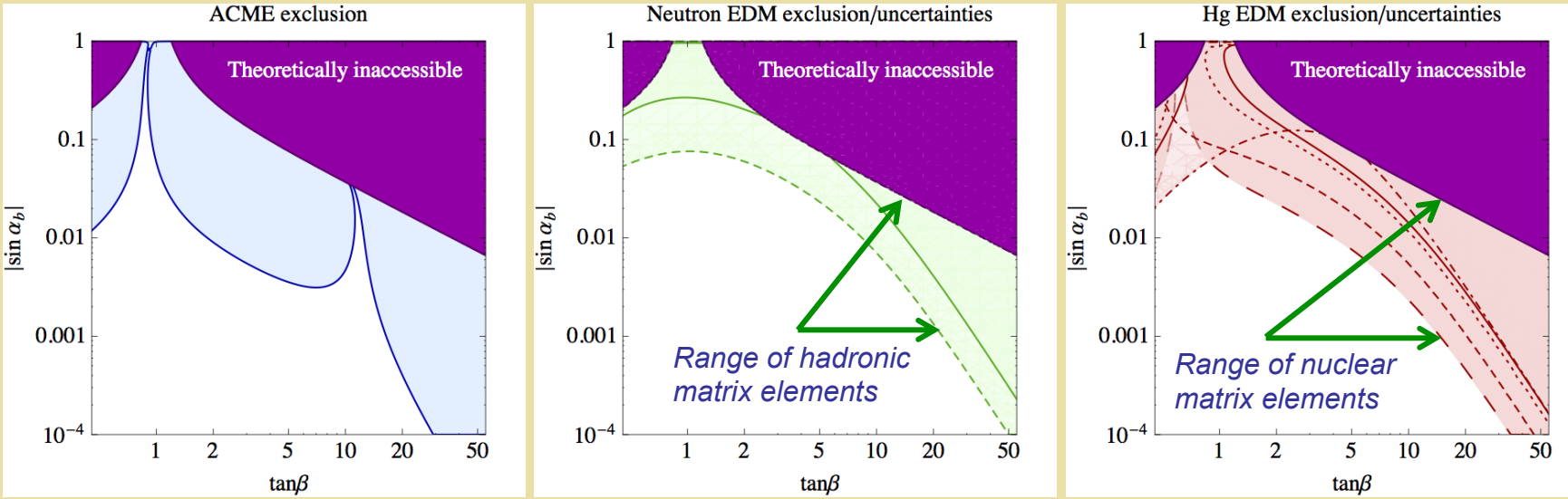


CP mixing: α_b & α_c not independent

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

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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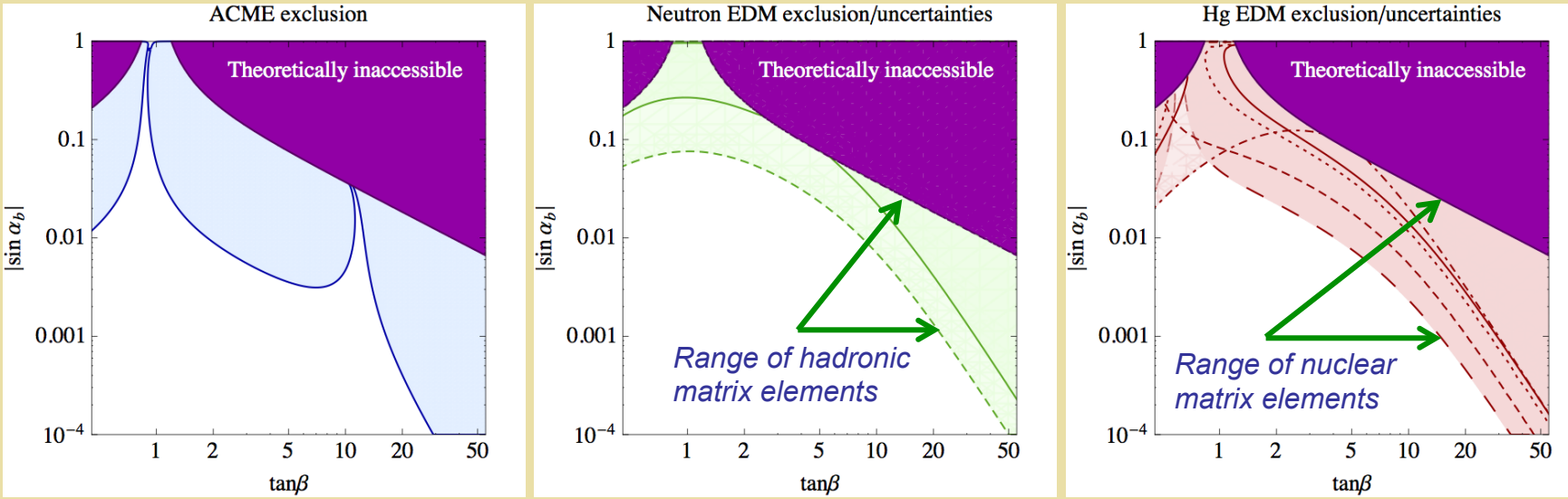

Present

Challenge

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

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}	$(-10.8 - 15.6)$	$(-10.0 - 8.1) \times 10^{-9}$	$(-0.6 - 1.2) \times 10^{-9}$	$(-12.0 - 14.8) \times 10^{-23}$

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