Left-right symmetry and EDMs. A global analysis

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(Work made in collaboration with Michael Ramsey-Musolf. arXiv: arXiv:2012.02799. https://doi.org/10.1016/j.physletb.2021.136136)

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Outline of the talk

1. Introduction
2. EDM of hadronic and atomic systems
3. The minimal left-right symmetric model
4. Global analysis using several EDM systems
5. Strong CP problem in the mLRSM
6. Interplay with time-reversal symmetry violation in beta decays
7. Summary and conclusions

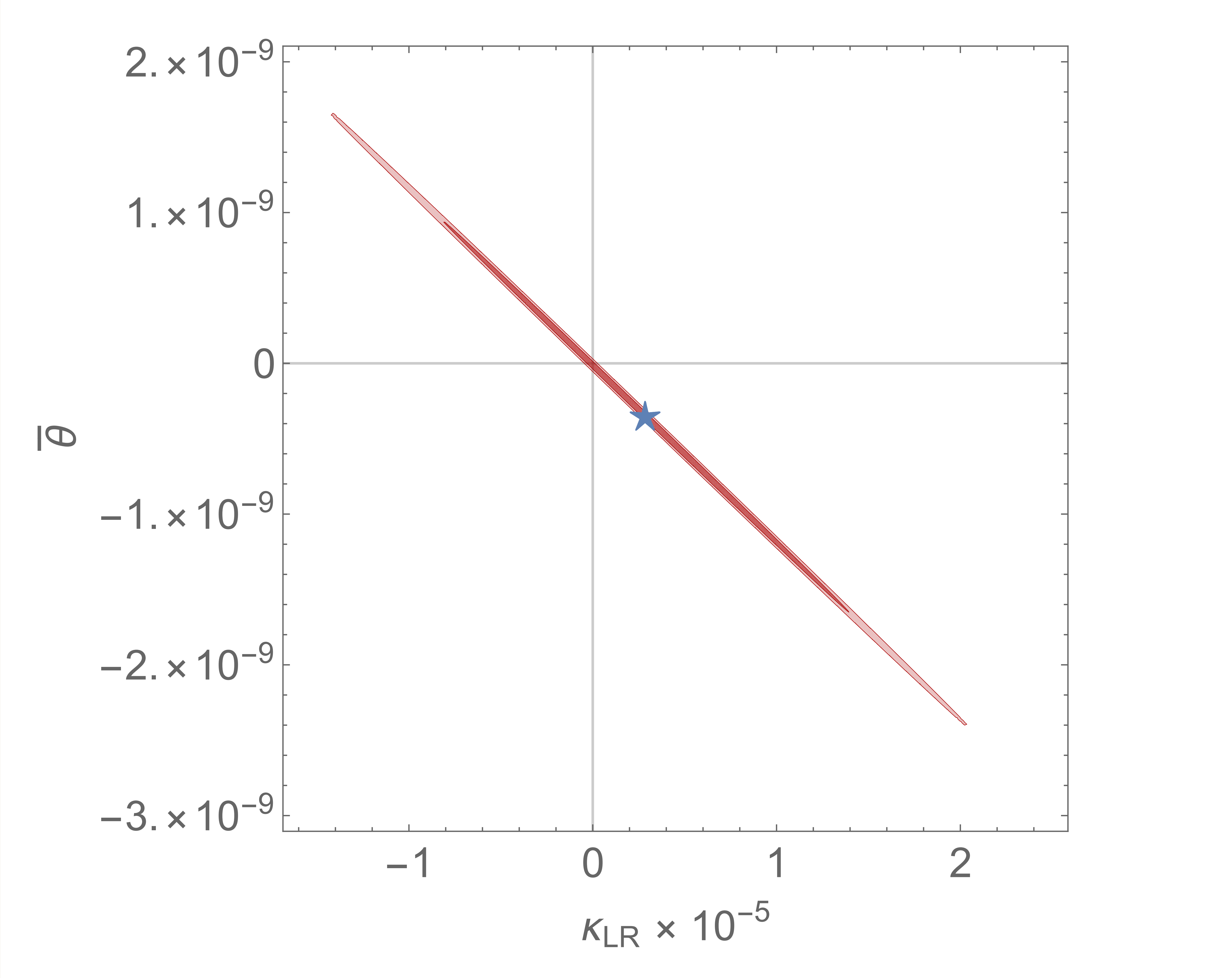
Key results

1. Current limits on BSM physics from EDM systems usually assume the "sole source limit".

   Strictly speaking it does not provide any limit if one EDM system is used

2. We use several EDM systems to perform a global fit and give limits to the relevant mLRSM parameters

3. We study possible connection with CPV in beta decays



We see roughly one order of magnitude relaxed limits

$\bar{\theta} \lesssim 10^{-10}$ and $\left(\frac{v^2}{\Lambda^2}\right)\sum_j \mathrm{Im}\left(C_j\right) \lesssim 10^{-5}$ $(10^{-6}$ Mercury) "sole-source" limits

Electric dipole moments and as probe of CPV

Electric dipole moment

$$\vec{d} = \eta \left(\frac{q}{2mc} \right) \vec{s},$$

EDM would violate P and T (Laundau and Ramsey) since

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}.$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

$$\frac{i}{2} d_e F_{\mu\nu}(x) \sigma^{\mu\nu} \gamma_5 \psi(x)$$

Interaction

Then

$$d_N \sim C_N \frac{m}{\Lambda_N^2}$$

New Physics scale

$$|d_N| \simeq 10^{-32} \, e \cdot \text{cm} \qquad \text{Standard Model}$$

Very suppressed

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Introduction. Current limits

	Result	95% u.l.		ref.
Paramagnetic systems				
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm	b
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm	
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}		
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{\mathrm{Cs}}$	
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm	c
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm	
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm	d
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm	e
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}		
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm	f
Diamagnetic systems				
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm	g
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm	h
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm	i
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm	j
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm	k
Particle systems				

$$|d_N| \simeq 10^{-32}\, e \cdot \mathrm{cm} \qquad \text{Standard Model}$$

Theory computations to date

1. Neutron EDM in SM = O(10^{-32})e cm
 (Seng, Phys. Rev. C91, 025502 (2015) and previous slide)

2. Electron EDM in SM = O(10^{-39})e cm
 (Yamaguchi et al., Phys. Rev. Lett. 125, 241802 (2020))

3. Nuclear EDM in SM = O(10^{-31-32})e cm
 (Yamanaka et al., JHEP 02 (2016) 067.)

4. Diamagnetic atom EDM in SM = O(10^{-32-36})e cm
(Yamanaka et al., JHEP02 (2016) 067.)

5. Paramagnetic atom EDM in SM = O(10^{-33-34})e cm
(Pospelov et al.,Phys. Rev. D 89, 056006 (2014).)

6. Theta term in SM = O(10^{-19})
 (Khriplovich, Phys. Lett. B 173, 193 (1986).)

7. Quark EDM in SM = O(10^{-35})e cm
 (Czarnecki et al., Phys. Rev. Lett.78, 4339 (1997).)

Thanks to N. Yamanaka for this summary

Introduction

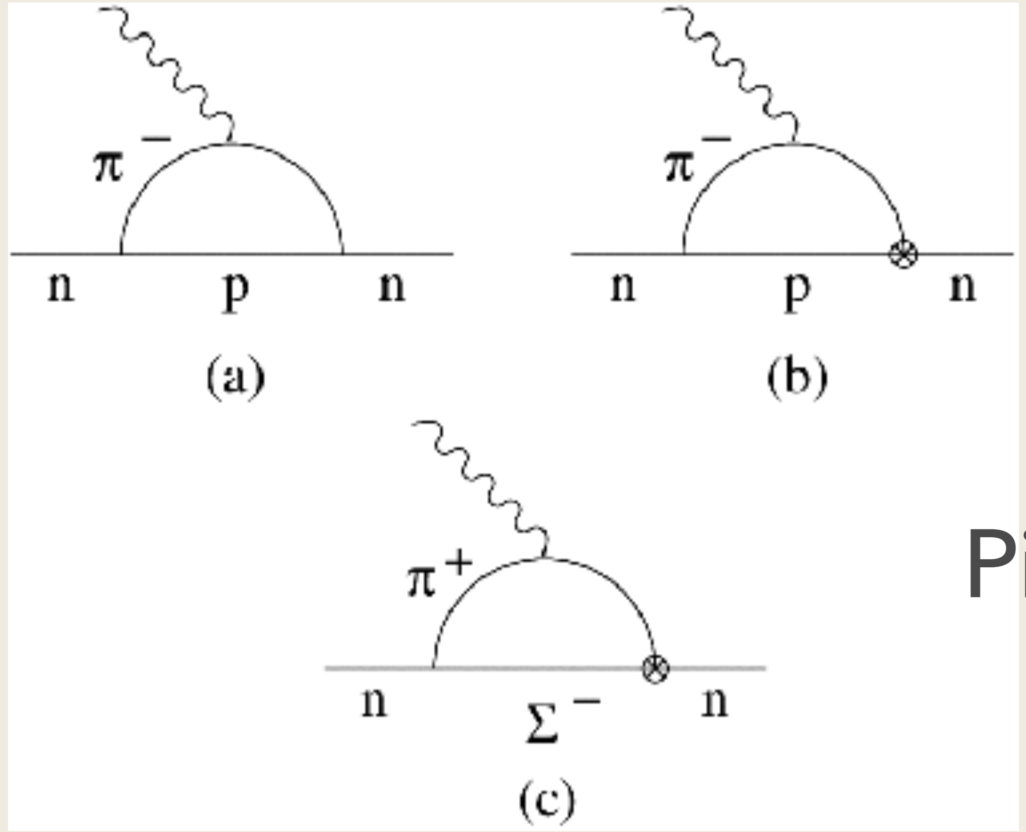
Usually in any BSM model we have EDM

$$d_n = \alpha_n \bar{\theta} + \beta_n^j \left(\frac{v^2}{\Lambda^2}\right) \sum_j \mathrm{Im}\left(C_j\right) + \cdots, \ \alpha_n \sim 10^{-16}\, e \cdot fm \text{ and } \beta_n \sim 10^{-21}\, e \cdot fm$$

where

$$\bar{\theta} = \theta_0 + \text{arg det}(M_u M_d) \text{ and } \mathscr{L}_{instantons} \propto \theta_0\, G_{\mu\nu} \tilde{G}^{\mu\nu} \rightarrow \vec{E} \cdot \vec{B}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	$+$	$+$
C	-	-	-
T	$+$	-	-



Pion Nucleon Constant

Introduction

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Experimental limit:

$(d_n)_{exp} \lesssim 1.8 \times 10^{-26} e \cdot cm$ (arXiv:2001.11966)

$(d_{Hg})_{exp} \lesssim 7.4 \times 10^{-30} e \cdot cm$ (arXiv:1601.04339)

"sole-source" analysis gives:

$\bar{\theta} \lesssim 10^{-10}$ and $\left(\frac{v^2}{\Lambda^2}\right) \sum_j \mathrm{Im}\left(C_j\right) \lesssim 10^{-5}$ (10^{-6} Mercury) "sole-source" limits

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THESE NAIVE BOUNDS GETS RELAXED WHEN CONSIDERING SEVERAL EDM SYSTEMS

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The minimal left-right symmetric model

(J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 2558 (1975); G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975); G. Senjanovic, Nucl. Phys. B153, 334 (1979).
)

- Extends the SM gauge group

$$SU(3) \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \times Z_2$$

- The Higgs sector

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \langle \Phi \rangle = \mathrm{diag}\{v_1, v_2 e^{i\alpha}\}. \qquad \Delta_R = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}_R$$

One bidoublet and two complex triplets

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- Extends the SM gauge group

$$SU(3) \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \times Z_2$$

- The mixing between the $W - W_R$ bosons give

$$\tan\xi = -\frac{v_1 v_2}{v_R^2} e^{-i\alpha} \simeq \left(\frac{M_W^2}{M_{W_R}^2}\right) \sin 2\beta e^{-i\alpha}, \quad \tan\beta \equiv v_2/v_1$$

v_1 and v_2 are the v.e.vs of the light and heavy doublets

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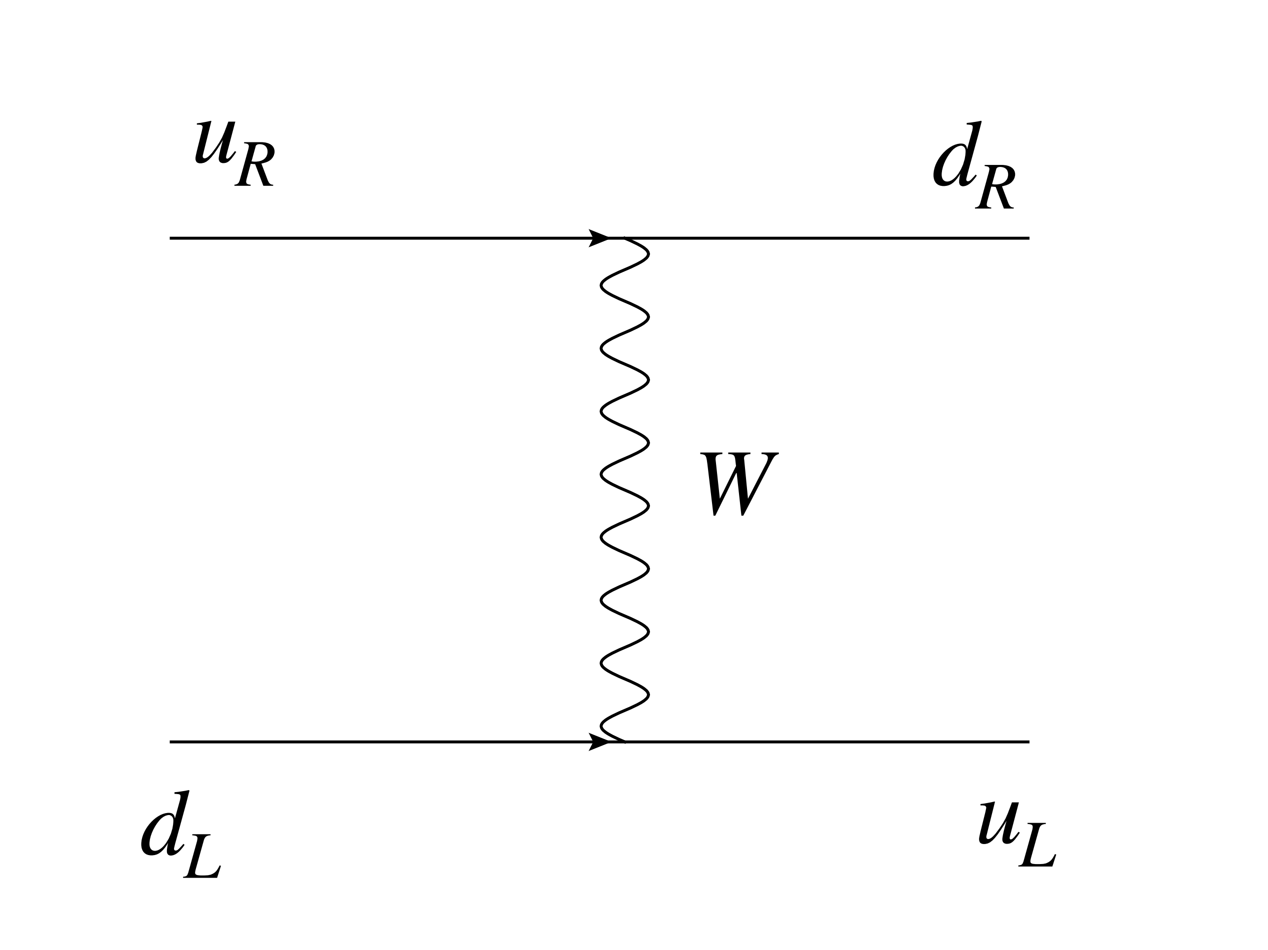
)

- $\tan\beta_{max} \sim 0.5$ from K and B meson systems (Bertolini, Nesti and Maiezza 2019. ArXiv: 1911.09472)

$W_L^+ = \cos\xi W_{1\mu}^+ - \sin\xi e^{-i\alpha} W_{2\mu}^+$ (SM W boson)

$$W_R^+ = \sin\xi e^{i\alpha} W_{1\mu}^+ + \cos\xi W_{2\mu}^+$$

$$\tan\xi = -\frac{v_1 v_2}{v_R^2} \simeq -\frac{M_W^2}{M_{W_R}^2}\sin 2\beta \quad ,$$



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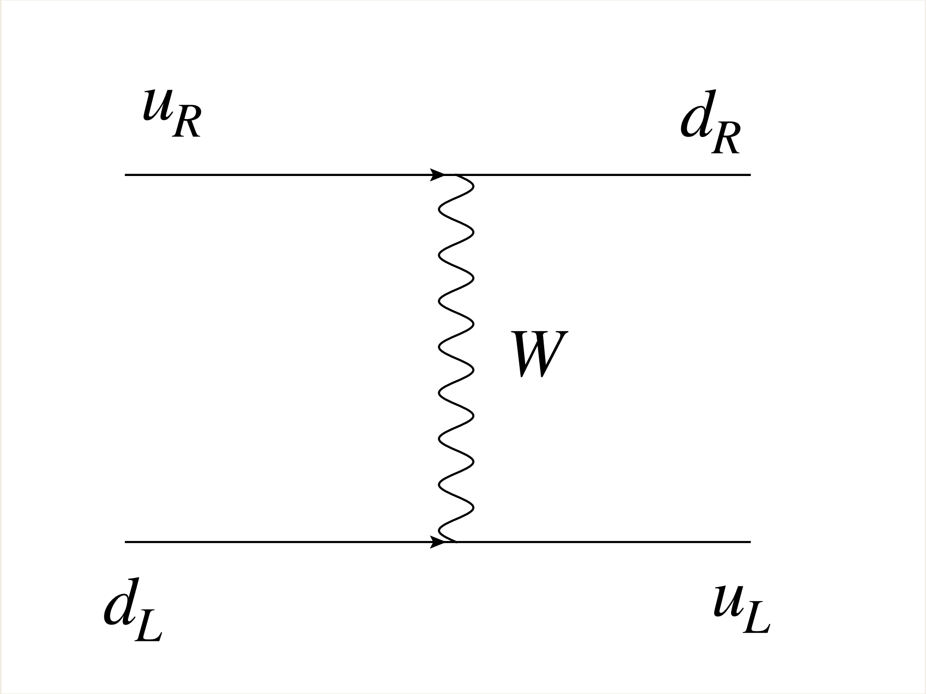
)

The effective CPV Lagrangian valid below the electroweak scale is given by

$$\mathscr{L}_{CPV} = -\frac{g_3^2}{16\pi^2}\bar{\theta}\,\mathrm{Tr}\left(G^{\mu\nu}\tilde{G}_{\mu\nu}\right) - i\frac{4G_F}{\sqrt{2}}\kappa_{LR}\left(\bar{u}_R\gamma_\mu d_R\,\bar{u}_L\gamma_\mu d_L + h.c.\right),$$

$$\kappa_{LR} = \sin\xi Im\left(V_{ud}^L V_{ud}^{R*}e^{-i\alpha}\right) \quad ,$$

Tree level leading contribution



V_L is the CKM quark mixing matrix and V_R its RH version

EDM of hadronic and atomic systems

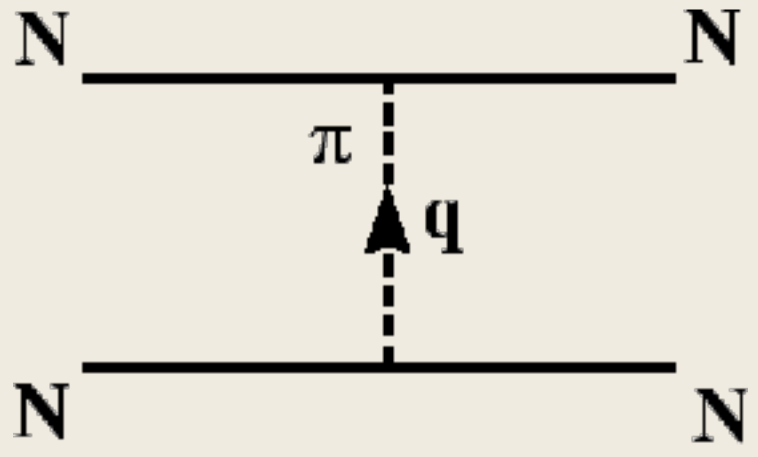
- The EDM of diamagnetic atomic or molecular system is given by

$$d_A = \sum_{N=p,n} \rho_Z^N d_N + \kappa_S S - \left[k_T^{(0)} C_T^{(0)} + k_T^{(1)} C_T^{(1)}\right],$$

ρ_Z^N : sensitivity to individual nucleon EDMs

κ_S : sensitivity of the atomic of molecular system to the Nuclear Schiff moment

$$S \simeq \frac{m_N g_A}{F_\pi}\left[a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)}\right],$$



for detailed assessment see Engel, Ramsey-Musolf, van Kolck arxiv: 1303.2371

a_0 and a_1 calculated using nuclear many-body methods

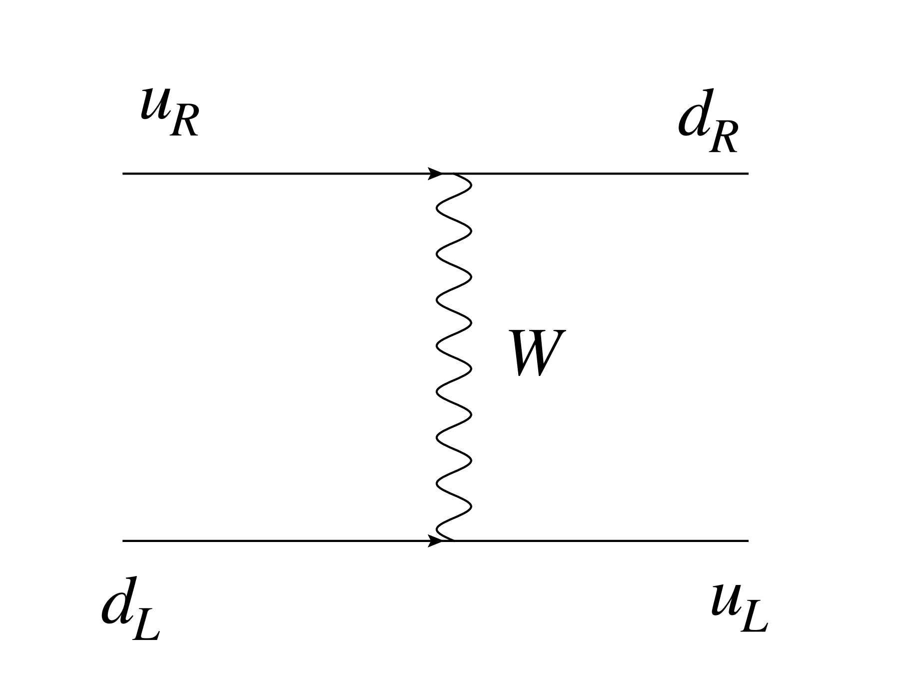
EDM of hadronic and atomic systems

- The couplings $\bar{g}_\pi^{(i)}$ parametrize the T-violating, P-violating pion-nucleon interaction in the chiral Lagrangian

$$\mathcal{L}_\chi^{LR} = \bar{N}\left[\bar{g}_\pi^{(0)}\vec{\tau}\cdot\vec{\pi} + \bar{g}_\pi^{(1)}\pi^0\right]N$$

where

$$\bar{g}_\pi^{(i)} = \lambda_i\bar{\theta} + \gamma_i^{\varphi ud}\frac{v^2}{\Lambda^2}\,\mathrm{Im}(C_{\varphi ud}), \quad i = 0,1$$



Leading tree-level contribution give CP violation dim-6 interaction

$$-i\frac{\mathrm{Im}\,C_{\varphi ud}}{\Lambda^2}\left[\bar{d}_L\gamma^\mu u_L\bar{u}_R\gamma_\mu d_R - \bar{u}_L\gamma^\mu d_L\bar{d}_R\gamma_\mu u_R\right].$$

Global analysis using EDM of nucleons, atoms and molecules

- We perform a global fit (with 2 d.o.f.):

$$\chi^2 = \sum_{i=1}^{N} \frac{\left[(d_i)_{exp} - (d_i)_{th}\right]^2}{\sigma_i^2}$$

N: number of the EDM systems,

$(d_i)_{exp}$ and $(d_i)_{th}$ denotes the experimental centroids and the theoretical values

σ_i denotes the experimental error of the EDM for the system $i = n$, Hg, Xe, Ra, TlF.

Theoretical uncertainties

- Vary the parameters a_0, a_1 and between the best theoretical ranges doing a range fit

System	$\kappa_S = \frac{d}{S}$ (cm/fm^3)	$a_0 = \frac{S}{13.5\bar{g}^0_\pi}$ (e-fm^3)	$a_1 = \frac{S}{13.5\bar{g}^1_\pi}$ (e-fm^3)	$a_2 = \frac{S}{13.5\bar{g}^2_\pi}$ (e-fm^3)
TlF	-7.4×10^{-14} [37]	-0.0124	0.1612	-0.0248
Hg	$-2.8/-4.0 \times 10^{-17}$ [38, 39]	0.01 (0.005-0.05)	$\pm$0.02 (-0.03-0.09)	0.02 (0.01-0.06)
Xe	$0.27/0.38 \times 10^{-17}$ [38, 40]	-0.008 (-0.005-(-0.05))	-0.006 (-0.003-(-0.05))	-0.009 (-0.005-(-0.1))
Ra	$-8.5(-7/-8.5) \times 10^{-17}$ [38, 41]	-1.5 (-6-(-1))	+6.0 (4-24)	-4.0 (-15-(-3))

(taken from Ramsey-Musolf and Chupp arXiv:1407.1064)
(Engel, Ramsey-Musolf, van Kolck arxiv: 1303.2371)

Theoretical uncertainties

- Hadronic uncertainties: $\alpha_n, \beta_n^{\varphi ud}, \lambda_0, \lambda_1$ and $\gamma_1^{\varphi ud}$

$$d_n = \alpha_n \bar{\theta} + \beta_n^j \left(\frac{v^2}{\Lambda^2}\right) \sum_j \mathrm{Im}\left(C_j\right) + \cdots, \text{ and } \bar{g}_\pi^{(i)} = \lambda_i \bar{\theta} + \gamma_i^{\varphi ud} \frac{v^2}{\Lambda^2} \mathrm{Im}(C_{\varphi ud}), \quad i = 0,1$$

Coupling between the pions and the nucleons

- $\gamma_1^{\varphi ud} \in \left(254 - 552\right) \times 10^{-7}$

$\lambda_0 \in 0.013 - 0.018$

$\lambda_1 \in \left(0.5 - 4\right) \times 10^{-4}$ (Ramsey-Musolf and Chupp 2014)

$\alpha_n \in 0.0005 - 0.004 \ e \cdot \mathrm{fm}^{-1}$

$\beta_n^{\varphi ud} \in (1 - 10) \times 10^{-8} \, e \cdot \mathrm{fm}^{-1}$

Best fit values

- For each point in the space spanned by $a_0, a_1, \kappa_s, \alpha_n, \beta_n^{\varphi ud}, \lambda_0, \lambda_1$ and $\gamma_1^{\varphi ud}$ we minimize the χ^2 with respect to the $\bar{\theta}$ and κ_{LR}

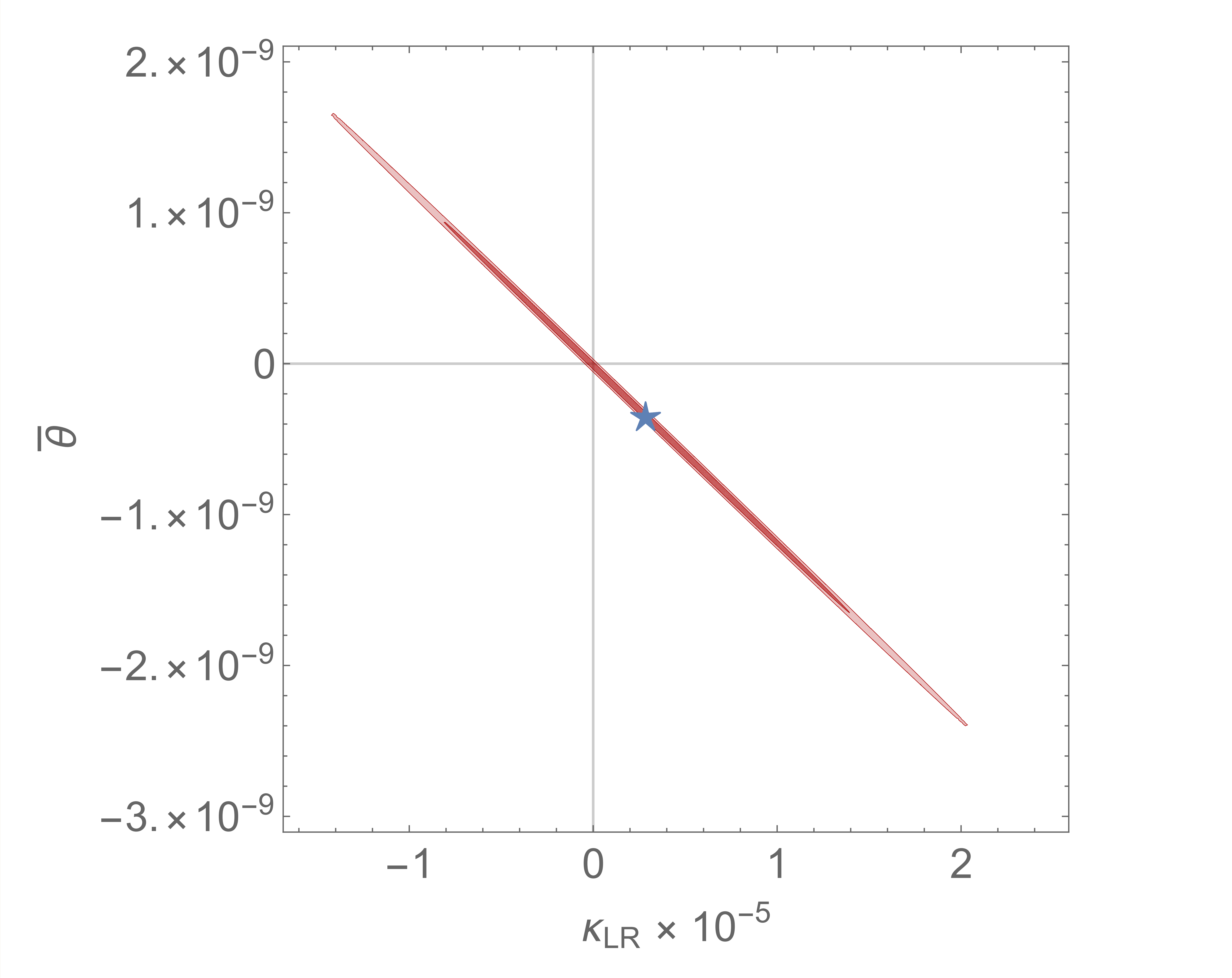
- From all possible values of the χ^2_{min}, we choose those values that give the most conservative bound (this is what we call our best fit values)

Best fit values

- Best fit values for the atomic, nuclear and hadronic parameters

	Atomic and nuclear parameters		
EDM System	$\kappa_S(\mathrm{fm}^{-2})$	a_0	a_1
Mercury (Hg)	-2.8×10^{-4}	0.022	0.0029
Xenon (Xe)	2.7×10^{-5}	-0.036	-0.024
Radium (Ra)	-7.6×10^{-4}	-3.45	5.1
Thallium Fluoride (TlF)	-0.74	-0.012	0.16

Hadronic parameter	Best fit value
$\alpha_n[e\cdot\mathrm{fm}]$	0.5×10^{-3}
$\beta_n^{\varphi ud}[e\cdot\mathrm{fm}]$	8.4×10^{-8}
λ_0	0.017
λ_1	2.7×10^{-4}
$\gamma_1^{\varphi ud}$	311×10^{-7}



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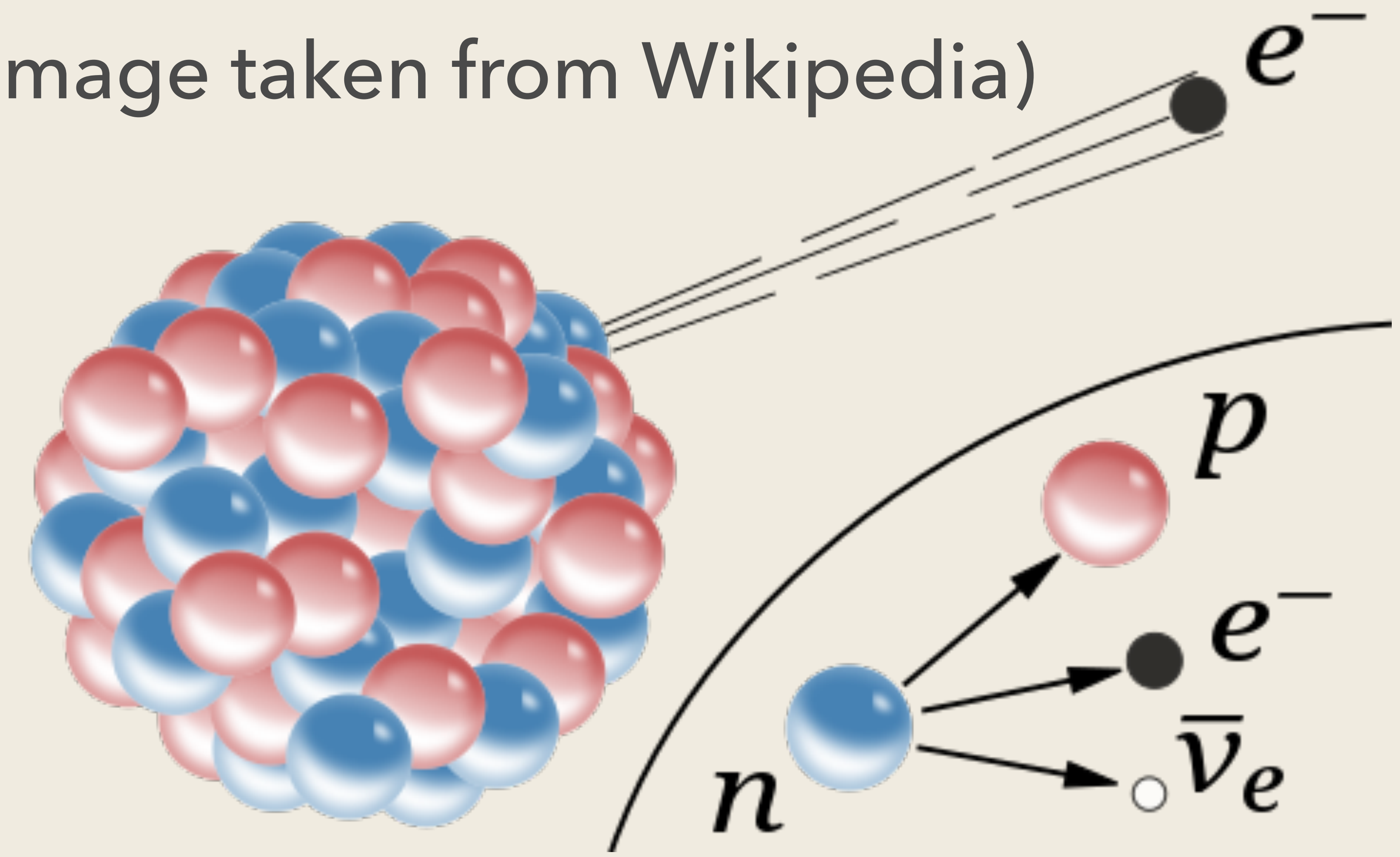
Interplay with T-violation in beta decays

- We examine the relation with the "D" coefficient in beta decays

(J. Jackson, S. Treiman, H. Wyld, Possible tests of time reversal invariance in Beta decay, Phys. Rev. 106 (1957) 517–521)

$$d\Gamma/d\Omega \supset D\langle \vec{\mathbf{J}} \rangle \cdot \vec{p}_e \times \vec{p}_\nu$$

(Image taken from Wikipedia)



$D = D_f + D_t$, f (fsi) and t is fundamental CPV

Experimental limit (arXiv:1104.2778):

$$D_n = (-1.0 \pm 2.1) \times 10^{-4},$$

Theoretical value and uncertainties (arXiv:0902.1194)

$D_f \sim 10^{-5}$ with a $1\ \%$ accuracy (window for NP $10^{-4} - 10^{-7}$)

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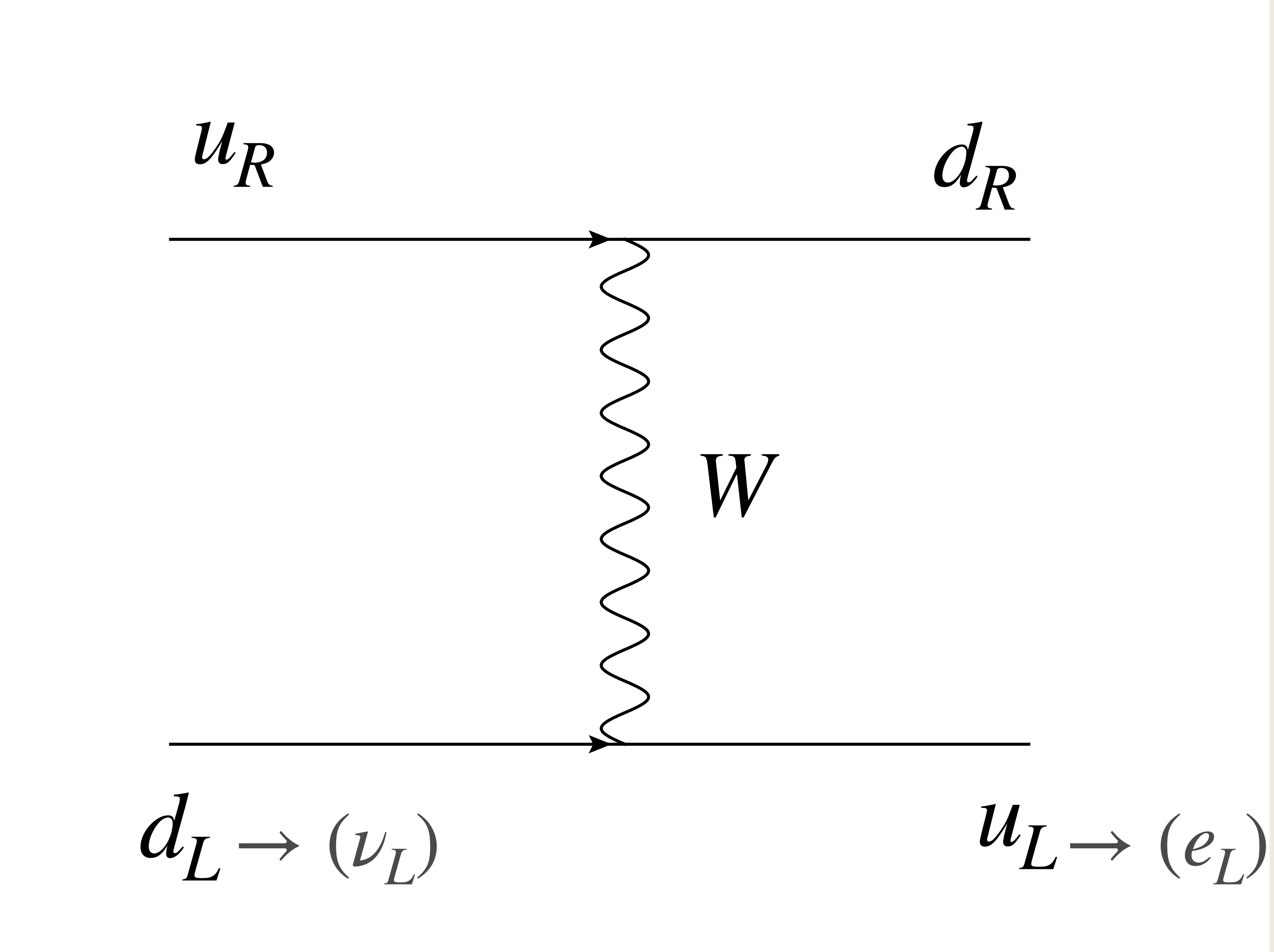
$$d\Gamma/d\Omega \supset D\,\langle \vec{\mathbf{J}} \rangle \cdot \vec{p}_e \times \vec{p}_\nu$$

The effective Lagrangian

$$\mathscr{L}_\beta = -\frac{4G_F V_{ud}}{\sqrt{2}} \sum_{\alpha,\beta,\gamma} a^{\gamma}_{\alpha\beta}\, \bar{e}_\alpha \Gamma^\gamma \nu_e\, \bar{u} \Gamma_\gamma d_\beta + \text{ h.c.}$$

$$a^S_{LL},\ a^S_{LR},\ a^S_{RL},\ a^S_{RR},\ a^V_{LL},\ a^V_{LR},\ a^V_{RL},\ a^V_{RR},\ a^T_{LR},\ a^T_{RL}$$

$$D_t = \kappa\,\mathrm{Im}\left(a^V_{LR} a^{V*}_{LL} + a^V_{RL} a^{V*}_{RR}\right) + \kappa \frac{g_S g_T}{g_V g_A}\,\mathrm{Im}\left(a^S_{L+} a^{T*}_{LR} + a^S_{R+} a^{T*}_{RL}\right)$$

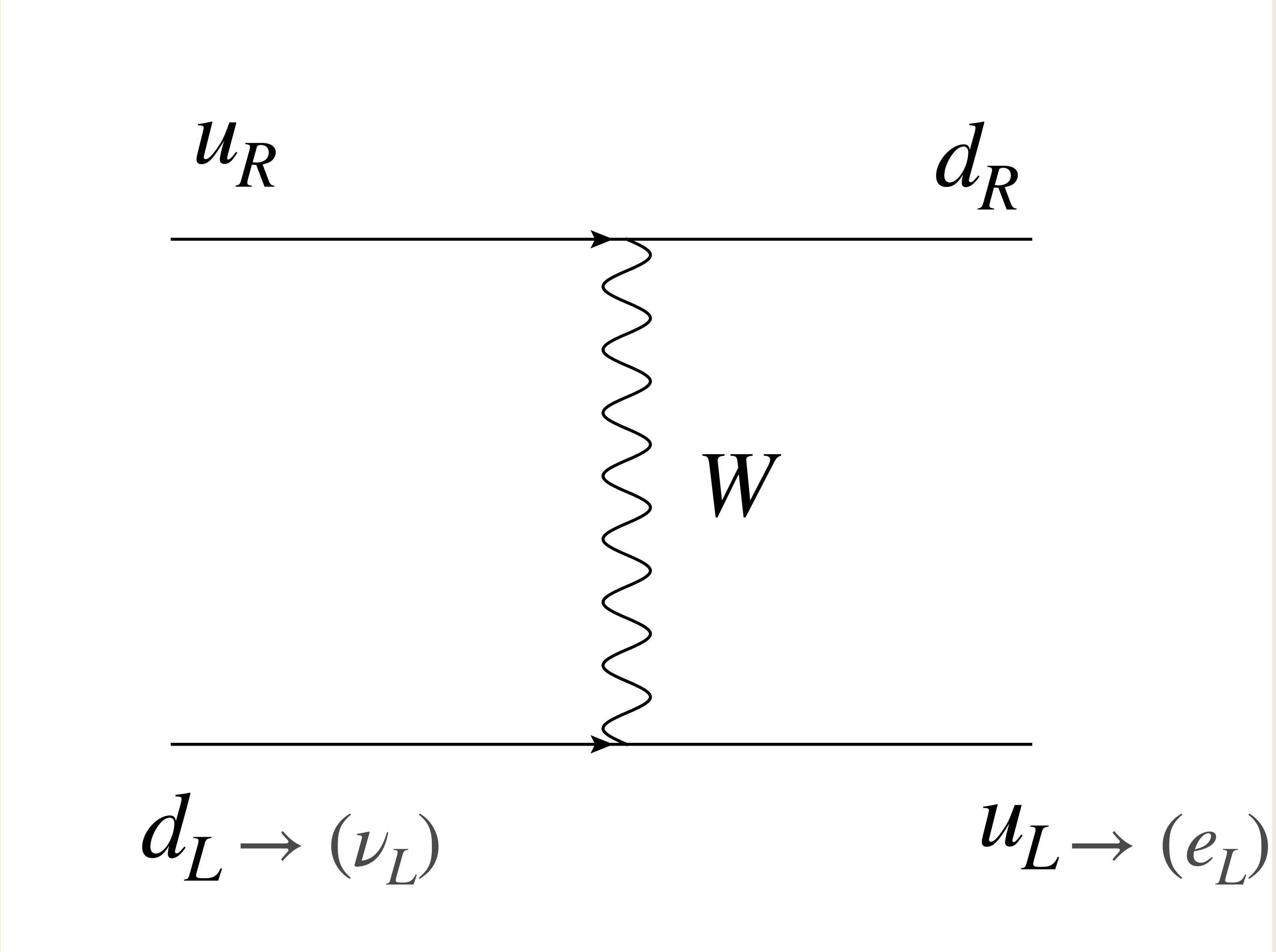


Interplay with T-violation in beta decays

- The same dim-6 coefficient that induces EDM in the mLRSM also generates the D coefficient and (Ng and Tulin arxiv: 1111.0649)

$$d_n \simeq \alpha_n \bar{\theta} + \beta_n^{\varphi ud} \left(\frac{D_t}{\kappa} \right),$$

$\kappa \simeq 0.87$ for the neutron



We update Ng and Tulin work. They concluded

$D_t(mLRSM) \lesssim 10^{-7}$ (Excluding mLRSM contribution to D coefficient)

Interplay with T-violation in beta decays

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$\kappa \simeq 0.87$ for the neutron

From our global fit:

$$\left| \frac{D_t}{\kappa} \right| \leq 2.0 \times 10^{-5} \text{ at } 95\,\% \text{ C.L,}$$

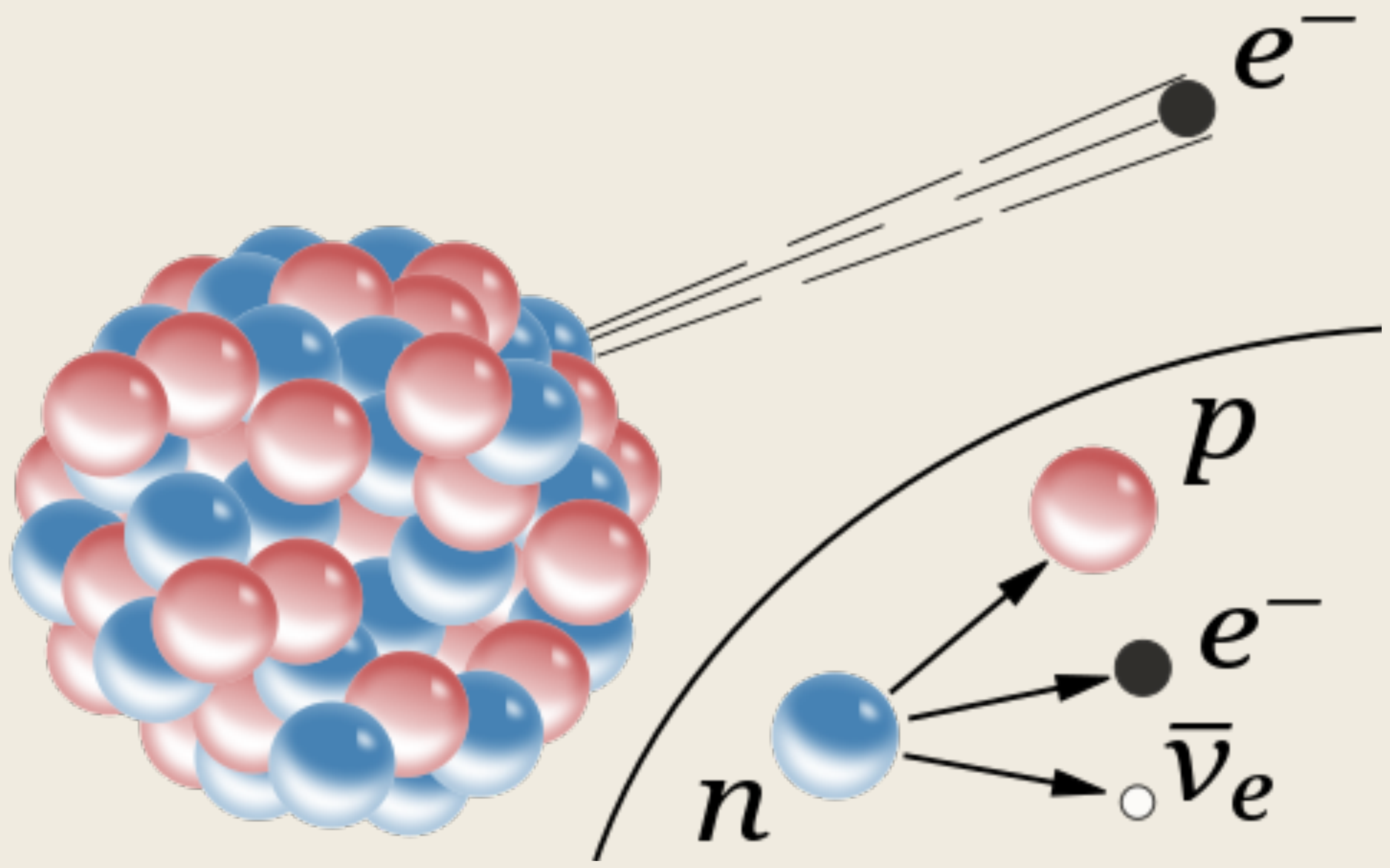
Interplay with T-violation in beta decays

- Reasons are:

  1) Smaller chiral EFT sensitivity to the neutron EDMs (value $\beta_n^{\varphi ud}$ bigger as concluded by Engel, Ramsey-Musolf, van Kolck arxiv: 1303.2371)

  2) Global fit gives a weaker constraint

- We find that there is still room for observation of CPV within mLRSM in beta decays



(Image taken from Wikipedia)

Conclusions

- We perform a global fit using several EDM systems within the mLRSM (applicable to any BSM setup)

- We find relaxed bounds with respects to the “sole source” limits usually done in the literature

$$\bar{\theta} \lesssim 10^{-10} \rightarrow \bar{\theta} \lesssim 10^{-9}$$

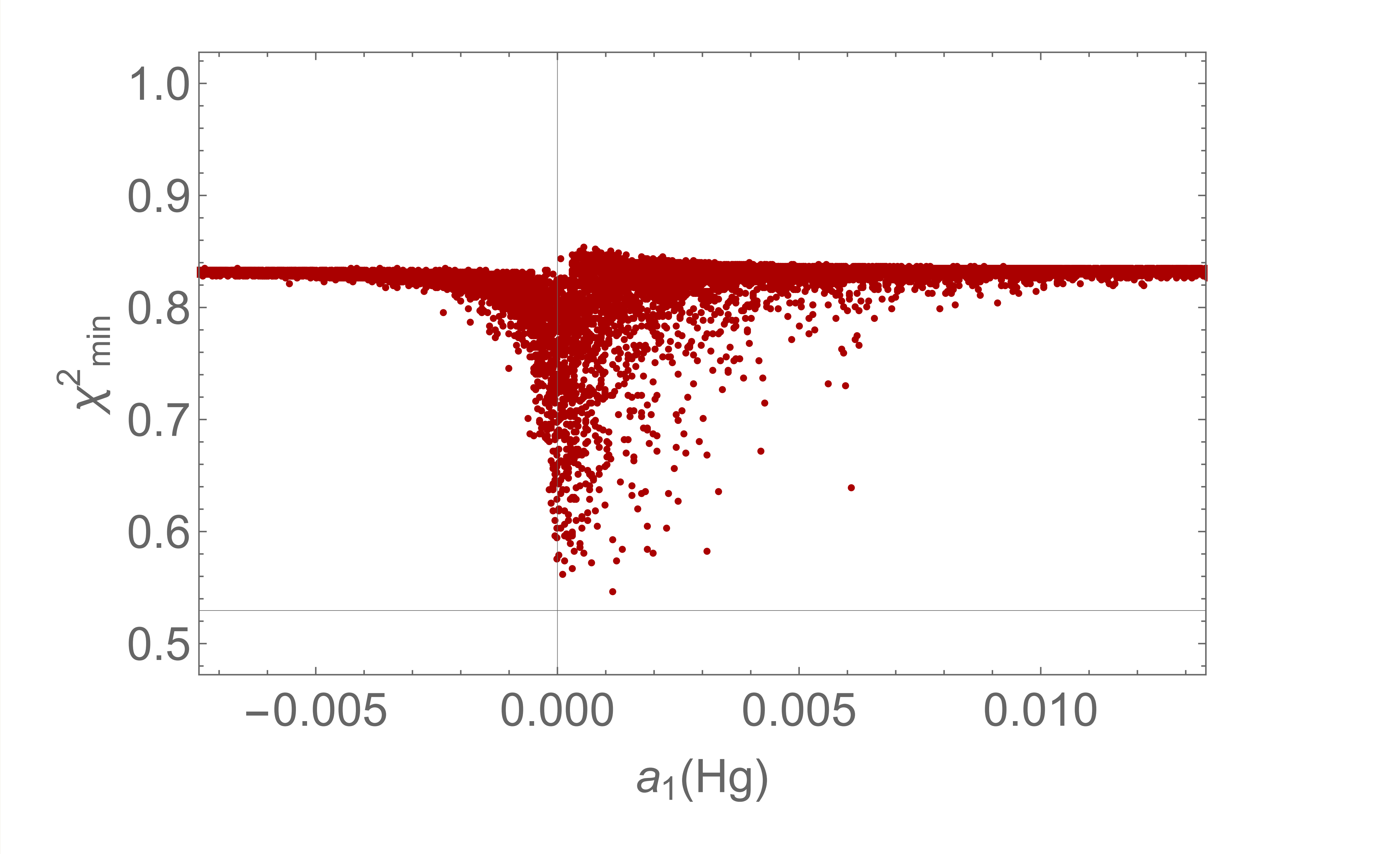
$$\left(\frac{v^2}{\Lambda^2}\right)\sum_j \mathrm{Im}\left(C_j\right) \lesssim 10^{-6} \rightarrow \left(\frac{v^2}{\Lambda^2}\right)\sum_j \mathrm{Im}\left(C_j\right) \lesssim 10^{-5}$$

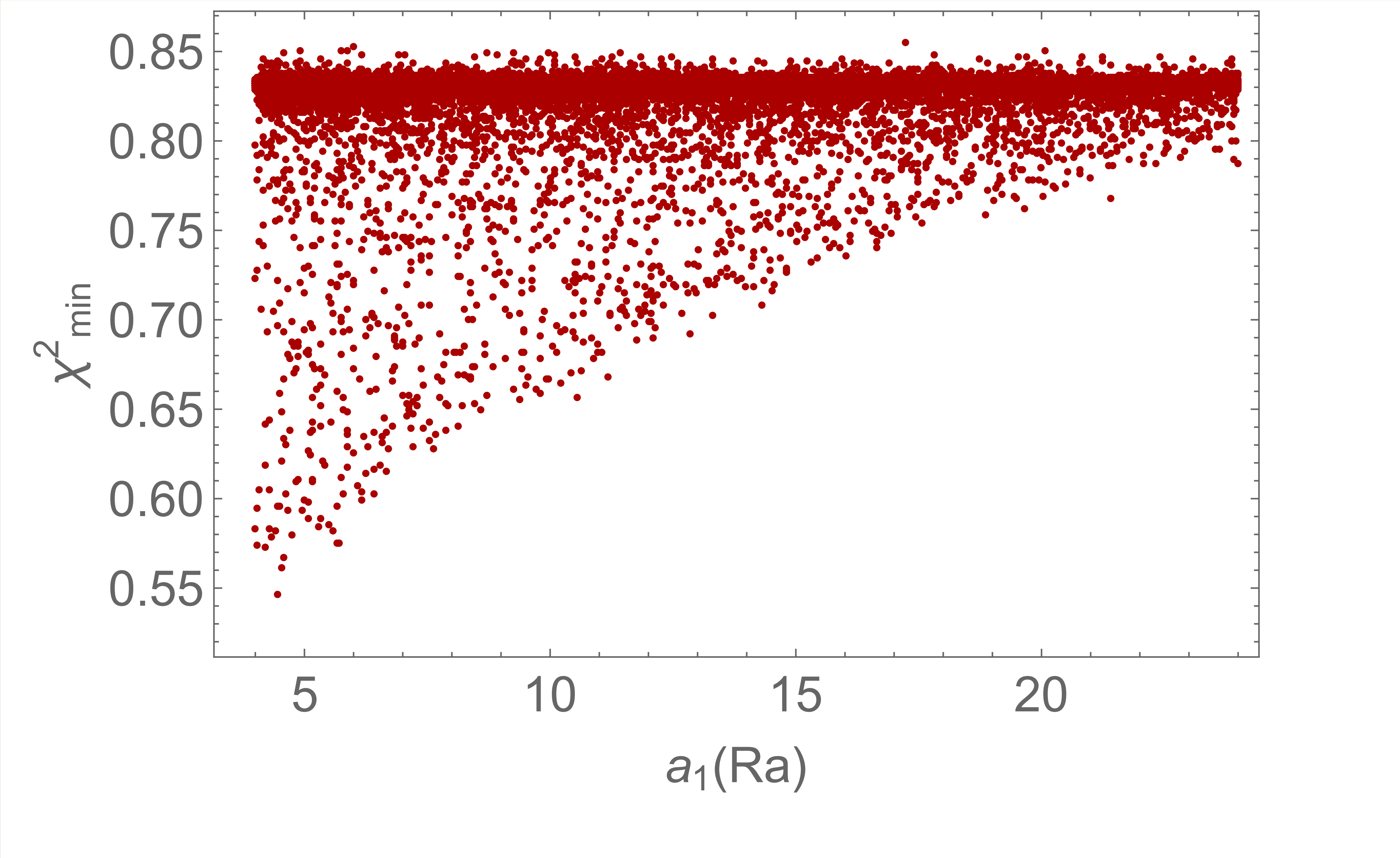
- We analyse the relation with the beta decay and find that in the light of our global fit, there still room for observation of mLRSM CPV in beta decay

Thank you

Backup slides

Correlations between χ_{min} and mLRSM parameters



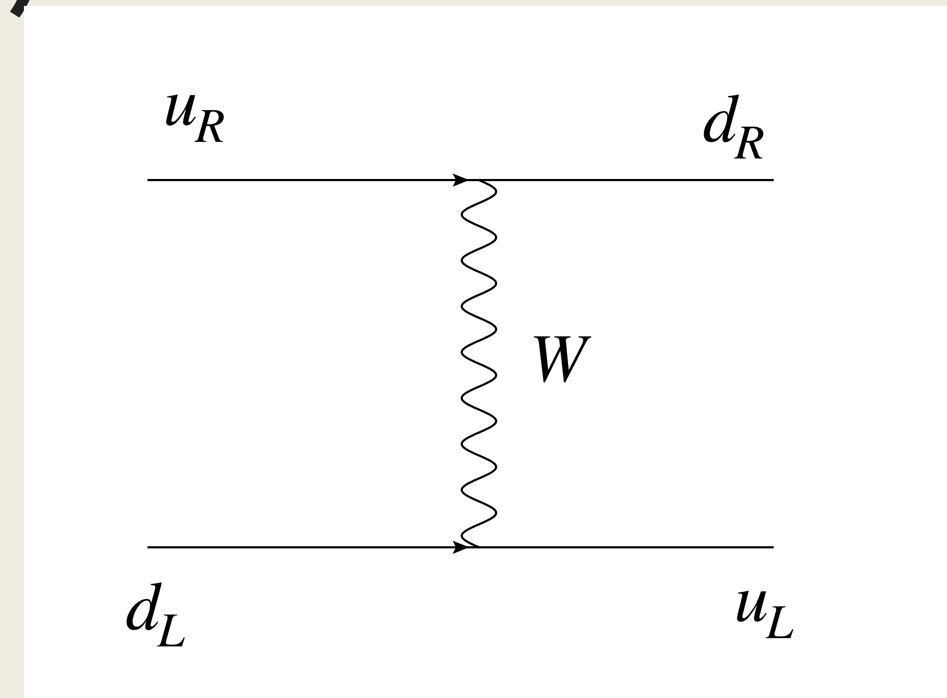


Different contributions

- Quark Chromo-EDM suppressed by small Yukawa couplings of light quarks
  (Engel, Ramsey-Musolf, van Kolck arxiv: 1303.2371)

- Three-gluon operator arises at two loops and can be neglected (arXiv:0910.2265, 1802.09903, 1911.09472)

- The tree-level exchange of W through the LR mixing gives the leading contribution



Different contributions

- Electron EDM gives a bound to M_D

  $M_D \lesssim (10^{-2} - 1)$ MeV (Tello Ph.D. thesis SISSA)

  in addition

  $(d_e)_{exp} < 10^{-29}$ e. cm (arXiv:1310.7534)

  which implies a contribution

  $d_A\left({}^{199}\mathrm{Hg}\right) \lesssim 10^{-31}$ e.cm

  below the current sensitivity

  $d_A\left({}^{199}\mathrm{Hg}\right) = (2.20 \pm 2.75(\text{ stat }) \pm 1.48(\text{sys})) \times 10^{-30} e \cdot \mathrm{cm}$

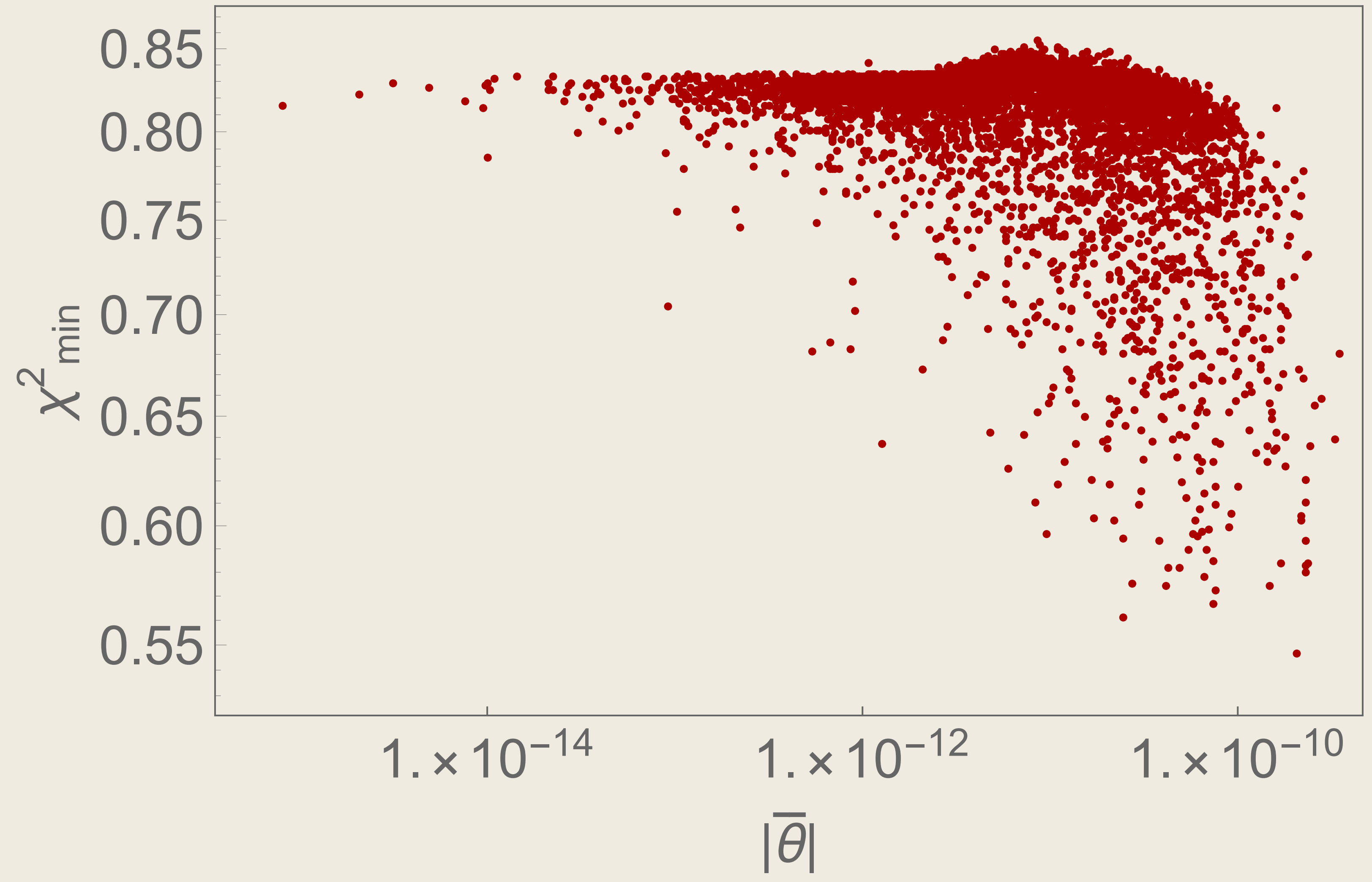
  phys. rev. lett. 116, 161601 (2016)

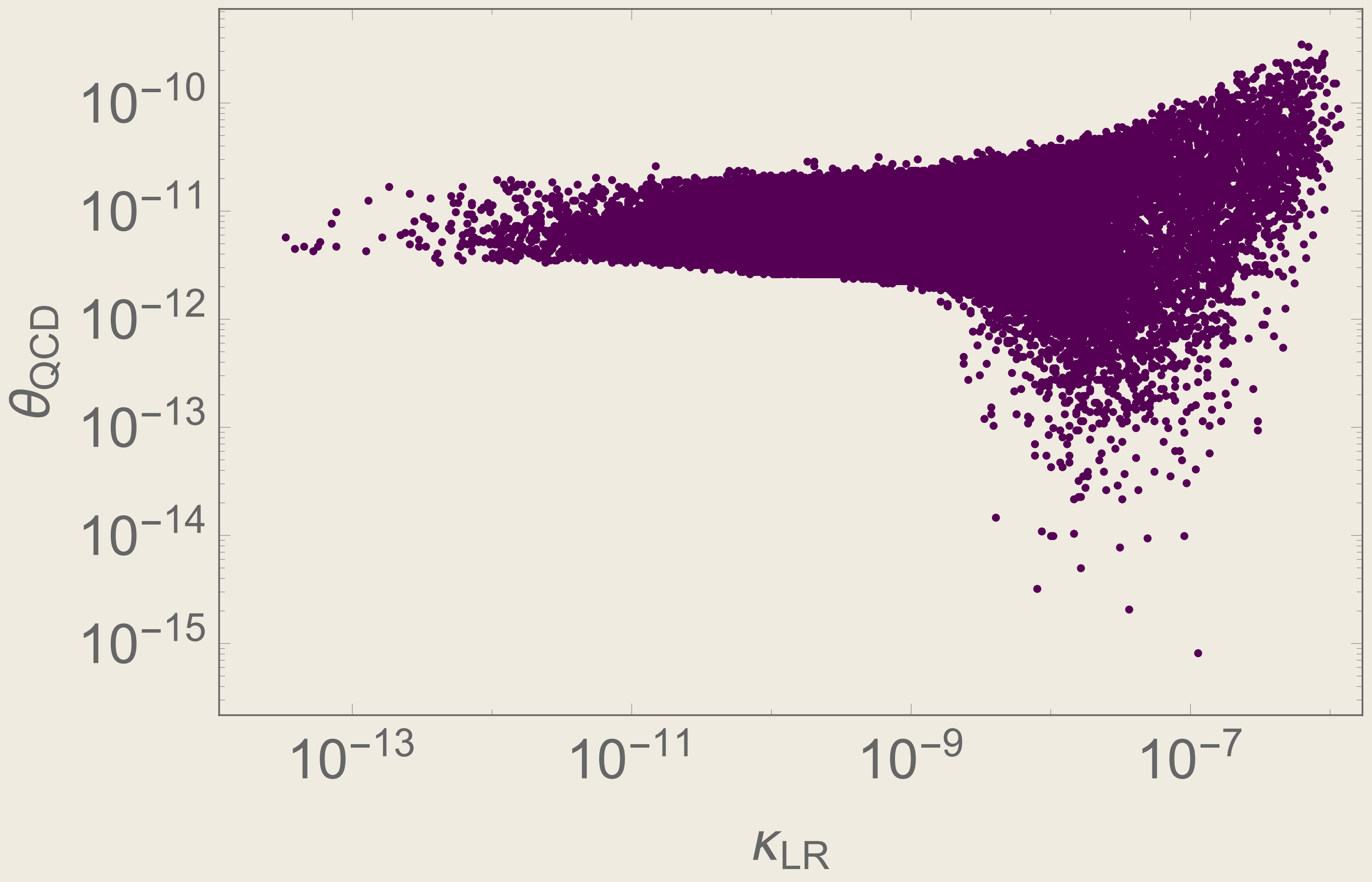
- The EDM of diamagnetic atoms receives a contribution from the semi-leptonic dim-6 four fermion operator

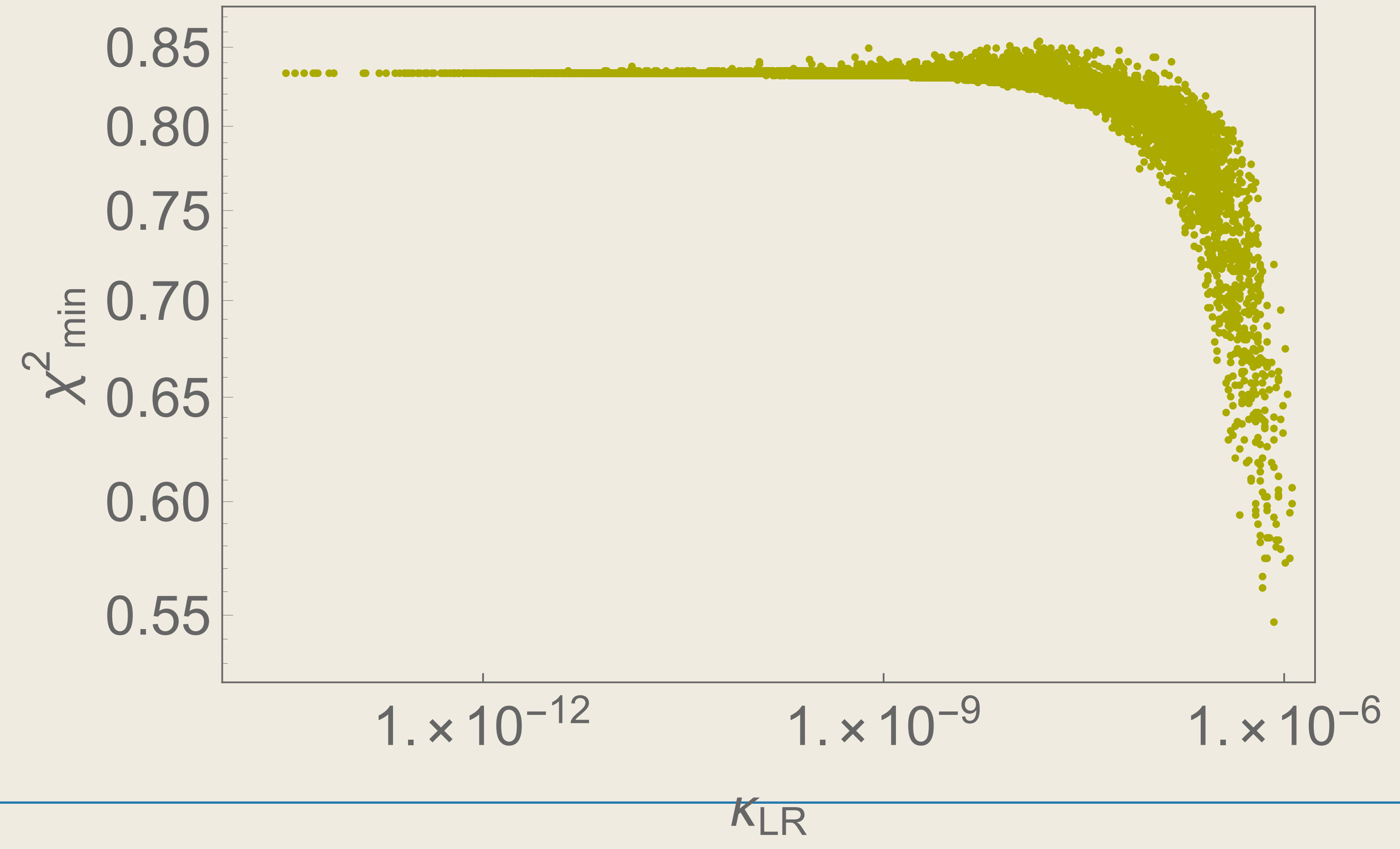
$$\mathscr{L}_{eN}^{\mathrm{NSD}} = \frac{8G_F}{\sqrt{2}} \bar{e}\sigma_{\mu\nu} e v^{\nu} \bar{N}\left[C_T^{(0)} + C_T^{(1)}\tau_3\right] S^{\mu} N + \cdots .$$

No tree level exchange of any scalar or vector can induce it. Electron EDM is not relevant for our analysis

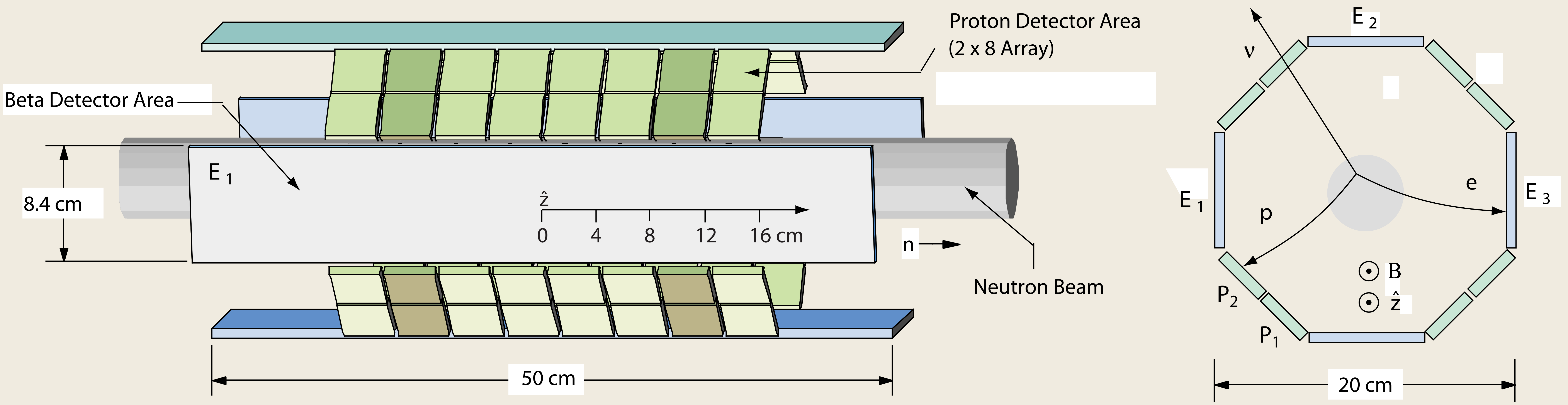
Correlations between χ_{min} and mLRSM parameters







Emit experimental setup



$$dW \propto 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \mathbf{P} \cdot \left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right).$$

Taken from emiT paper

arXiv: 1104.2778.

Semileptonic interaction and the electron EDM in paramagnetic systems

- For semileptonic interactions in paramagnetic systems

$$\mathcal{L}_{eN}^{\mathrm{NSID}} = -\frac{G_F}{\sqrt{2}}\bar{e}i\gamma_5 e\ \bar{N}\left[C_S^{(0)} + C_S^{(1)}\tau_3\right]N$$

This interaction is suppressed at the tree level by either small Yukawa coupling of the SM [85] Higgs or by the mass of the heavy neutral scalars of the mLRSM