CPV in 2HDM

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

- Intro to 2HDM - motivations and problems
- CP violation in 2HDM
- Collider signatures (briefly)
- EDM tests
- Summary

2HDM

Self-explanatory - 2 Higgs doublets:

$$\phi_i \to \begin{pmatrix} H_i^+ \\ \frac{1}{\sqrt{2}}\left(v_i + H_i^0 + iA_i^0\right) \end{pmatrix}, \quad i = 1, 2,$$

$$v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}, \tan\beta = |v_2|/|v_1|$$

More structure to Higgs potential and Yukawa:

$$V(\phi) \to V(\phi_1, \phi_2)$$

$$- Y_L \bar{L}\phi l_R - Y_D \bar{Q}\phi d_R - Y_U \bar{Q}(i\tau_2)\phi^* u_R + \text{h.c.}$$

$$\to \sum_{i=1,2} \left[-Y_{L,i}\bar{L}\phi_i l_R - Y_{D,i}\bar{Q}\phi_i d_R - Y_{U,i}\bar{Q}(i\tau_2)\phi_i^* u_R + \text{h.c.}\right]$$

2HDM - Motivations

- We've seen the Higgs.
  Can the scalar sector be minimal?

- 2 doublets exist in SUSY extensions,
  as well as in popular Peccei-Quinn models

- EW baryogenesis - new CPV source(s) and modified EWPT

2HDM - Scalars

Scalar degrees of freedom after EWSB (subtract 3 Goldstones)

SM - 1 complex doublet: $4 - 3 = 1$

2HDM - 2 complex doublets: $8 - 3 = 5$

Start with $\phi_i \rightarrow \begin{pmatrix} H_i^+ \\ \frac{1}{\sqrt{2}} \left(v_i + H_i^0 + i A_i^0 \right) \end{pmatrix}$

end up with $H_1^0, H_2^0, A^0, H^\pm$

CP-odd A^0 is crucial for CPV

Flavor-changing NC

SM Yukawa interaction: $-y_{ij}\phi\bar{\psi}_i\psi_j$

Mass matrix ∝ Yukawa: $M_{ij} = vy_{ij}/\sqrt{2}$

-> Yukawa is diagonal in mass basis (no tree level FCNC)

General 2HDM: $-(y_{1,ij}\phi_1\bar{\psi}_i\psi_j + y_{2,ij}\phi_2\bar{\psi}_i\psi_j)$

No simple proportionality: $M_{ij} = (v_1 y_{1,ij} + v_2 y_{2,ij})/\sqrt{2}$

-> Tree level FCNC (BAD!)

2HDM w/ Z_2

Z_2 symmetry - type II 2HDM example:

$$\phi_1 \to -\phi_1,\, d_R \to -d_R,\, e_R \to -e_R$$

Each fermion type couples to only one doublet:

$$\mathcal{L}_Y = -Y_U \overline{Q}_L (i\tau_2)\phi_2^* u_R - Y_D \overline{Q}_L \phi_1 d_R - Y_L \overline{L} \phi_1 e_R + \text{h.c.}$$

Mass matrix $\propto$ Yukawa as in SM -> No FCNC

Types I, X, Y are different manifestations of this idea

"Aligned" 2HDM is more general: Z_2 models are special limits

2HDM scalar potential

Allowing soft breaking of Z_2 (m_{12} term)

$$V = \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \\ + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\ - \frac{1}{2}\left\{m_{11}^2|\phi_1|^2 + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2|\phi_2|^2\right\}$$

λ_5 and m_{12} terms break CP.

Re-phasing invariant CP phase is $\text{Im}\left[\lambda_5^*(m_{12}^2)^2\right]$

-> Both CPV terms need to be nonzero for CPV physics

Scalar mass matrix

Neutral scalar mass matrix comes from the potential:

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \nu s_\beta^2 & (\lambda_{345} - \nu) c_\beta s_\beta & -\frac{1}{2}\mathrm{Im}\lambda_5 \, s_\beta \\ (\lambda_{345} - \nu) c_\beta s_\beta & \lambda_2 s_\beta^2 + \nu c_\beta^2 & -\frac{1}{2}\mathrm{Im}\lambda_5 \, c_\beta \\ -\frac{1}{2}\mathrm{Im}\lambda_5 \, s_\beta & -\frac{1}{2}\mathrm{Im}\lambda_5 \, c_\beta & -\mathrm{Re}\lambda_5 + \nu \end{pmatrix}$$

in (H_1^0, H_2^0, A^0) basis.

λ_5 generates mixing between CP-even and odd states

(we've rotated to a basis where both vevs are real)

$(\lambda_{345} = \lambda_3 + \lambda_4 + \mathrm{Re}\lambda_5, \; \nu \equiv \mathrm{Re} m_{12}^2 / 2v^2 s_\beta c_\beta)$

Higgs mass basis

3x3 rotation matrix takes us to mass basis (h_1 is 125 GeV Higgs)

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} H_1^0 \\ H_2^0 \\ A^0 \end{pmatrix}$$

Explicitly,

$$\begin{aligned} R =& R_{23}(\alpha_c) R_{13}(\alpha_b) R_{12}(\alpha + \pi/2) \\ =& \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix} \end{aligned}$$

α mixes CP-even states; survives CP-conserving limit

SM-like Yukawas in "aligned" limit $(\alpha = \beta - \pi/2)$

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α_b and α_c both parameterize CP mixing,

but α_b is all you need for lightest Higgs

Counting parameters

Potential parameters	Phenomenological parameters
$\lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \mathrm{Re}\lambda_5,\ \mathrm{Im}\lambda_5$	$v,\ \tan\beta,\ \nu,\ \alpha,\ \alpha_b,\ \alpha_c$
$m_{11}^2,\ m_{22}^2,\ \mathrm{Re}m_{12}^2,\ \mathrm{Im}m_{12}^2$	$m_{h_1},\ m_{h_2},\ m_{h_3},\ m_{H^+}$

Subtlety: 10 input, 10 output, but there should only be 1 CPV

1 of 3 minimization conditions: $\mathrm{Im}(m_{12}^2) = v^2 \sin\beta\cos\beta\mathrm{Im}(\lambda_5)$

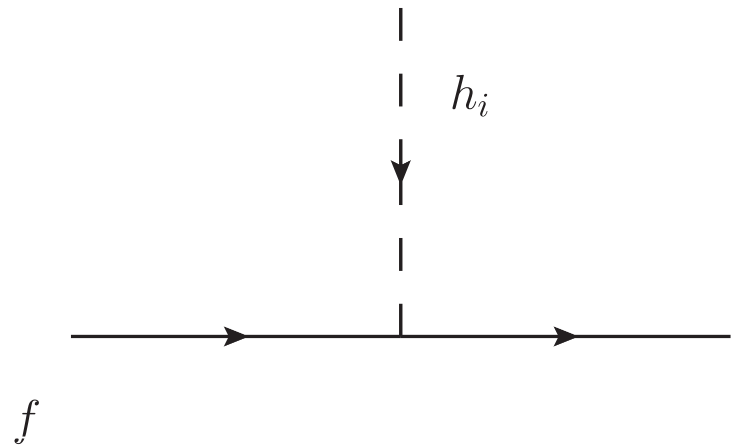
-> $\mathrm{Im}(m_{12}^2)$ and $\mathrm{Im}(\lambda_5)$ are not independent

Once you specify {masses, α, β}, α_c can be solved from α_b

Yukawa in mass basis

Higgs mass eigenstate has both S and P Yukawa couplings

$$-\frac{m_f}{v} h_i \left(c_{f,i} \bar{f} f + \tilde{c}_{f,i} \bar{f} i \gamma_5 f \right)$$



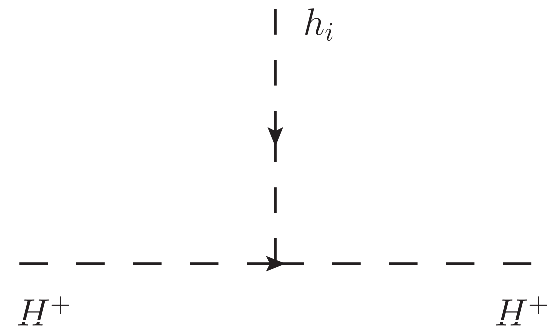
Note: P Yukawa is not by itself CPV; the mixing is CPV

	$c_{t,i}$	$c_{b,i}$	$\tilde{c}_{t,i}$	$\tilde{c}_{b,i}$
Type I	$R_{i2}/\sin\beta$	$R_{i2}/\sin\beta$	$-R_{i3}\cot\beta$	$R_{i3}\cot\beta$
Type II	$R_{i2}/\sin\beta$	$R_{i1}/\cos\beta$	$-R_{i3}\cot\beta$	$-R_{i3}\tan\beta$

Couplings depend on 2HDM type

Other new interactions

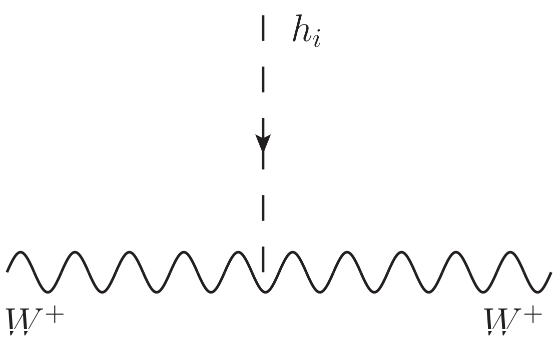
New/modified cubic and quartic interactions: e.g.



Rescaling of gauge-Higgs coupling:

$$a_i h_i \left(\frac{2m_W^2}{v} W_\mu W^\mu + \frac{m_Z^2}{v} Z_\mu Z^\mu \right)$$

$$a_i = R_{i2} s_\beta + R_{i1} c_\beta$$



Recap…

1. We introduced a second Higgs doublet
2. We get 3 neutral (2 CP-even, 1 CP-odd) + charged Higgs
3. FCNC is a serious problem - assume softly broken Z_2
4. One invariant CPV phase in the potential: $\mathrm{Im}\left[\lambda_5^*(m_{12}^2)^2\right]$
5. The phase mixes CP-even and odd scalars
6. Scalar mass eigenstates acquire both S and P Yukawas

Collider signatures

Production and decay rates of 125 GeV Higgs are modified

$$\frac{\sigma_{gg\to h_1}}{\sigma^{\rm SM}_{gg\to h_1}} = \frac{\Gamma_{h_1\to gg}}{\Gamma^{\rm SM}_{h\to gg}} \approx \frac{(1.03c_t - 0.06c_b)^2 + (1.57\tilde{c}_t - 0.06\tilde{c}_b)^2}{(1.03-0.06)^2}$$

$$\frac{\Gamma_{h_1\to\gamma\gamma}}{\Gamma^{\rm SM}_{h\to\gamma\gamma}} \approx \frac{(0.23c_t - 1.04a)^2 + (0.35\tilde{c}_t)^2}{(0.23-1.04)^2}$$

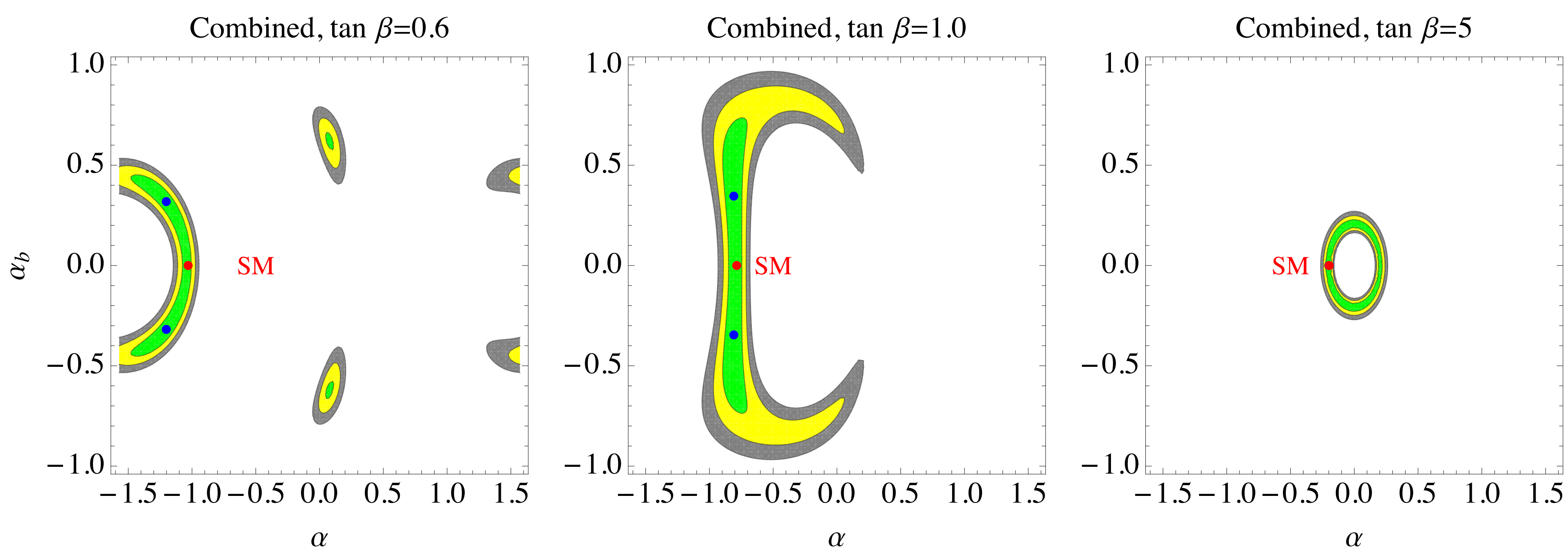
$$\frac{\sigma_{VV\to h_1}}{\sigma^{\rm SM}_{VV\to h}} = \frac{\sigma_{V^*\to Vh_1}}{\sigma^{\rm SM}_{V^*\to Vh}} = \frac{\Gamma_{h_1\to WW}}{\Gamma^{\rm SM}_{h\to WW}} = \frac{\Gamma_{h_1\to ZZ}}{\Gamma^{\rm SM}_{h\to ZZ}} \approx a^2$$

$$\frac{\Gamma_{h_1\to b\bar{b}}}{\Gamma^{\rm SM}_{h\to b\bar{b}}} = \frac{\Gamma_{h_1\to\tau^+\tau^-}}{\Gamma^{\rm SM}_{h\to\tau^+\tau^-}} \approx {c_b}^2 + {\tilde{c}_b}^2$$

Rates are CP-even, so CPV effects enter as squares

LHC fit (NOT latest)

	$\gamma\gamma$	WW	ZZ	Vbb	$\tau\tau$
ATLAS	1.6 ± 0.3	1.0 ± 0.3	1.5 ± 0.4	-0.4 ± 1.0	0.8 ± 0.7
CMS	0.8 ± 0.3	0.8 ± 0.2	0.9 ± 0.2	1.3 ± 0.6	1.1 ± 0.4



α often near alignment limit. α_b not well bounded

…more on collider physics from other talks at this workshop

Current EDM limits (90% CL)

electron: $|d_e| < 8.7 \times 10^{-28} e \text{ cm}$

ACME experiment on ThO molecules (2013) - Ongoing

neutron: $|d_n| < 2.9 \times 10^{-26} e \text{ cm}$

(Grenoble 2006) - New experiments in development

mercury: $|d_{\mathrm{Hg}}| < 2.6 \times 10^{-29} e \text{ cm}$

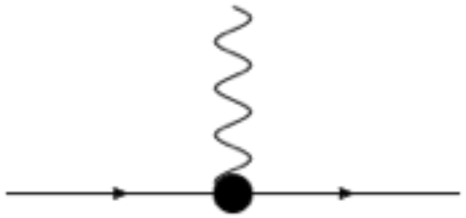
(Seattle 2009) - New limit soon

radium (this week!): $|d_{\mathrm{Ra}}| < 5.0 \times 10^{-22} e \text{ cm}$ (95% CL)

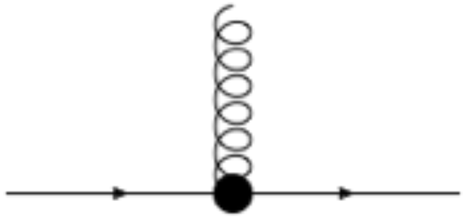
EFT for EDMs

2HDM generates d=6 CPV operators at EW scale:

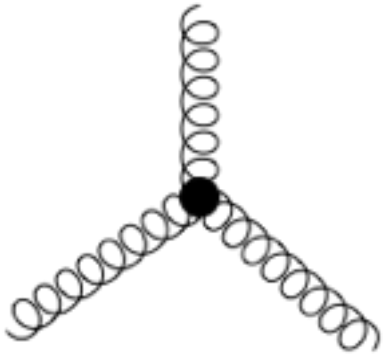
EDM: $\frac{\delta_f}{\Lambda^2} m_f e \bar{f} \sigma_{\mu\nu} \gamma_5 f F^{\mu\nu}$



Chromo-EDM: $\frac{\tilde{\delta}_q}{\Lambda^2} m_q g_s \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q G^{a\mu\nu}$



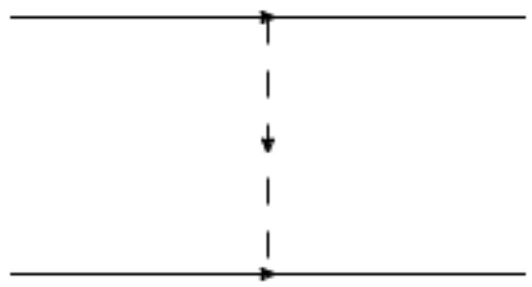
Weinberg: $\frac{C_{\tilde{G}}}{2\Lambda^2} g_s f^{abc} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\lambda} G^{b\,\lambda}_{\nu} G^c_{\rho\sigma}$



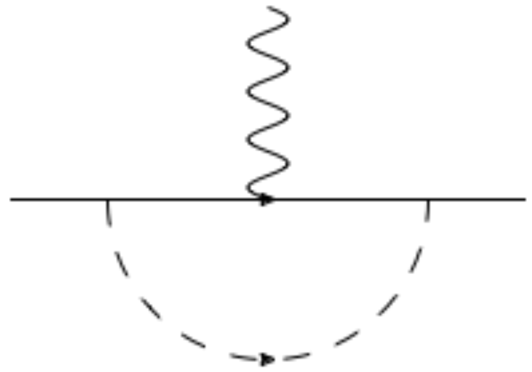
$\delta_f, \tilde{\delta}_q, C_{\tilde{G}}$ - dimensionless Wilson coefficients

Yukawa suppression

4-fermion operators (generated at tree level) are suppressed by 2 powers of small Yukawas for light fermions

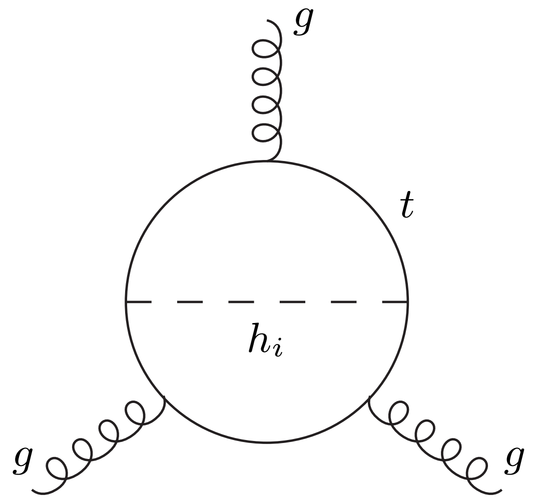


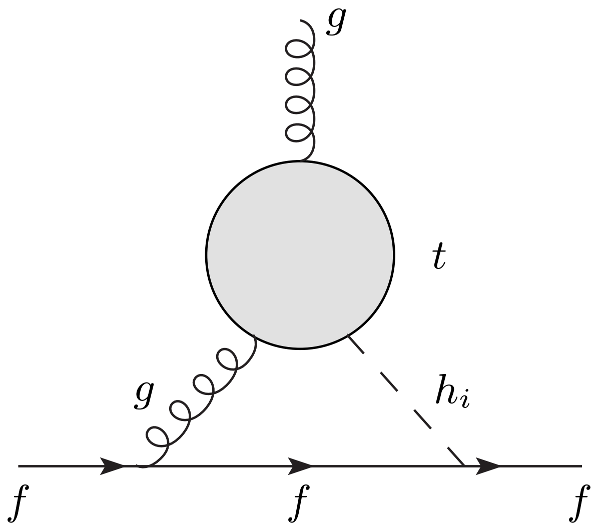
Similarly, 1-loop EDMs for light fermions are small

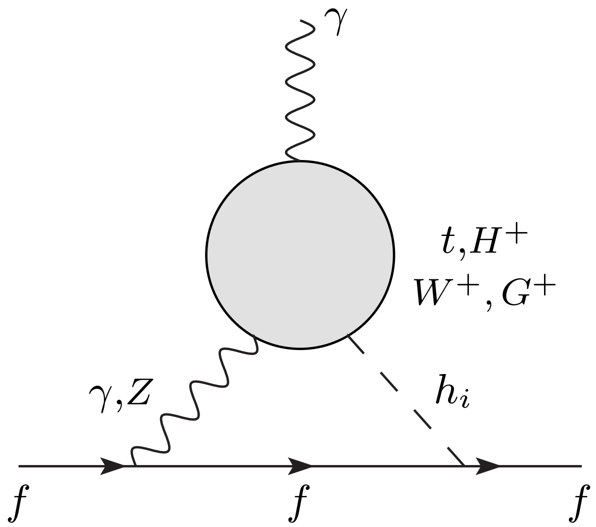


2-loop diagrams

Leading contributions to d=6 operators are 2-loop:







Abe et al. 2013 - most complete calculation of 2-loop EDM

QCD running

We need Wilson coefficients at low scale.

Anomalous dimensions matrix for EDM, CEDM, Weinberg (Degrassi et al. 2012, Hisano et al. 2012, Dekens & de Vries 2013):

$$\frac{\alpha_S}{4\pi}\begin{pmatrix} 8C_F & 0 & 0 \\ -8C_F & 16C_F - 4N & 0 \\ 0 & 2N & N + 2n_f + \beta_0 \end{pmatrix}$$

There is nontrivial mixing among the 3 types of operators

All 3 must be calculated and run down to QCD scale

Low-energy QCD

Neutron and atomic EDMs are connected to the Wilson coefficients by hadronic/nuclear matrix elements, e.g.

$$d_n = \left(e\zeta_n^u\delta_u + e\zeta_n^d\delta_d\right) + \left(e\tilde{\zeta}_n^u\tilde{\delta}_u + e\tilde{\zeta}_n^d\tilde{\delta}_d\right) + \beta_n^G C_{\tilde{G}}$$

EDM CEDM Weinberg

$\zeta_n^u = (4-12)\times 10^{-9}$ with best value 8.2×10^{-9}, etc.

Finding the matrix elements is a non-perturbative QCD problem

-> Large uncertainties

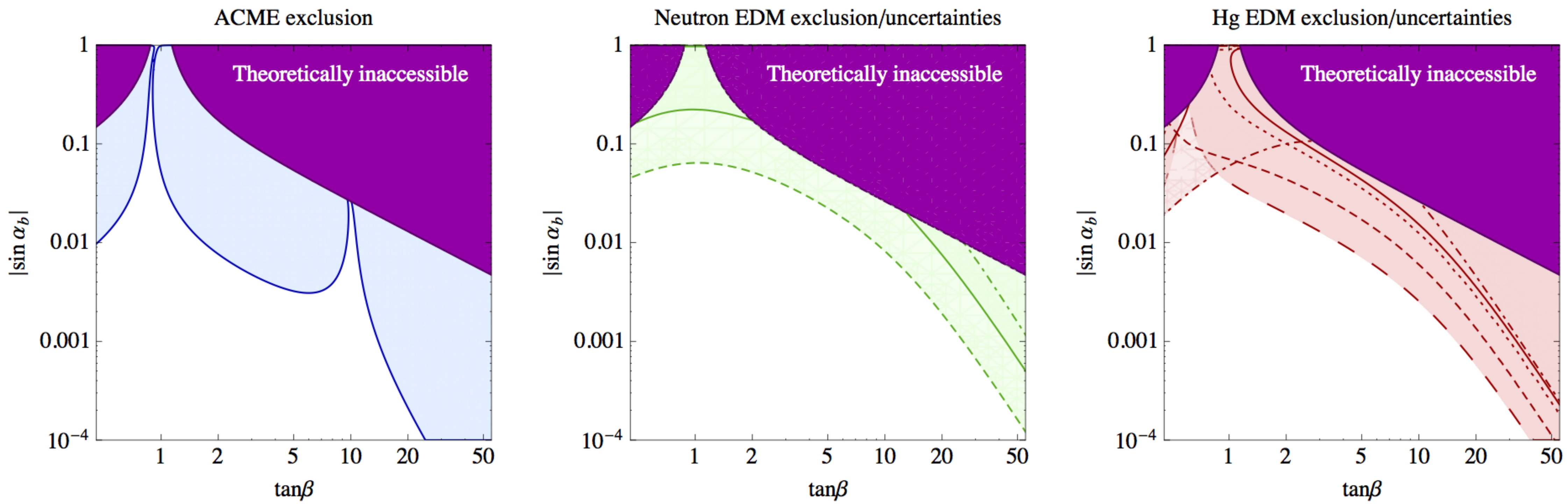
Low-energy QCD

Param	Coeff	Best Value[a]	Range	Coeff	Best Value[b,c]	Range[b,c]
$\bar{\theta}$	α_n	0.002	(0.0005-0.004)	$\lambda_{(0)}$	0.02	(0.005-0.04)
	α_p			$\lambda_{(1)}$	2×10^{-4}	$(0.5 - 4) \times 10^{-4}$
$\mathrm{Im}\, C_{qG}$	β_n^{uG}	4×10^{-4}	$(1 - 10) \times 10^{-4}$	$\gamma_{(0)}^{+G}$	-0.01	(-0.03) $-$ 0.03
	β_n^{dG}	8×10^{-4}	$(2 - 18) \times 10^{-4}$	$\gamma_{(1)}^{-G}$	-0.02	(-0.07) $-$ (-0.01)
$\tilde{d}_q$	$e\tilde{\rho}_n^u$	-0.35	$-(0.09 - 0.9)$	$\tilde{\omega}_{(0)}$	8.8	(-25) $-$ 25
	$e\tilde{\rho}_n^d$	-0.7	$-(0.2 - 1.8)$	$\tilde{\omega}_{(1)}$	17.7	$9 - 62$
$\tilde{\delta}_q$	$e\tilde{\zeta}_n^u$	8.2×10^{-9}	$(2 - 20) \times 10^{-9}$	$\tilde{\eta}_{(0)}$	-2×10^{-7}	(-6 $-$ 6) $\times 10^{-7}$
	$e\tilde{\zeta}_n^d$	16.3×10^{-9}	$(4 - 40) \times 10^{-9}$	$\tilde{\eta}_{(1)}$	-4×10^{-7}	$-(2 - 14) \times 10^{-7}$
$\mathrm{Im}\, C_{q\gamma}$	$\beta_n^{u\gamma}$	0.4×10^{-3}	$(0.2 - 0.6) \times 10^{-3}$	$\gamma_{(0)}^{+\gamma}$	$-$	$-$
	$\beta_n^{d\gamma}$	-1.6×10^{-3}	$-(0.8 - 2.4) \times 10^{-3}$	$\gamma_{(1)}^{-\gamma}$	$-$	$-$
d_q	ρ_n^u	-0.35	$(-0.17) - 0.52$	$\omega_{(0)}$	$-$	$-$
	ρ_n^d	1.4	0.7-2.1	$\omega_{(1)}$	$-$	$-$
δ_q	ζ_n^u	8.2×10^{-9}	$(4 - 12) \times 10^{-9}$	$\eta_{(0)}$	$-$	$-$
	ζ_n^d	-33×10^{-9}	$-(16 - 50) \times 10^{-9}$	$\eta_{(1)}$	$-$	$-$
$C_{\tilde{G}}$	$\beta_n^{\tilde{G}}$	2×10^{-7}	$(0.2 - 40) \times 10^{-7}$	$\gamma_{(i)}^{\tilde{G}}$	2×10^{-6}	$(1 - 10) \times 10^{-6}$
$\mathrm{Im}\, C_{\varphi ud}$	$\beta_n^{\varphi ud}$	3×10^{-8}	$(1 - 10) \times 10^{-8}$	$\gamma_{(1)}^{\varphi ud}$	1×10^{-6}	$(5 - 150) \times 10^{-7}$
$\mathrm{Im}\, C_{quqd}^{(1,8)}$	β_n^{quqd}	40×10^{-7}	$(10 - 80) \times 10^{-7}$	$\gamma_{(i)}^{quqd}$	2×10^{-6}	$(1 - 10) \times 10^{-6}$
$\mathrm{Im}\, C_{eq}^{(-)}$	$g_S^{(0)}$	12.7	11-14.5			
$\mathrm{Im}\, C_{eq}^{(+)}$	$g_S^{(1)}$	0.9	0.6-1.2			

Matrix elements from appendix of Engel et al. 2013

Current EDM constraints

Exclusion plots from electron, neutron, mercury

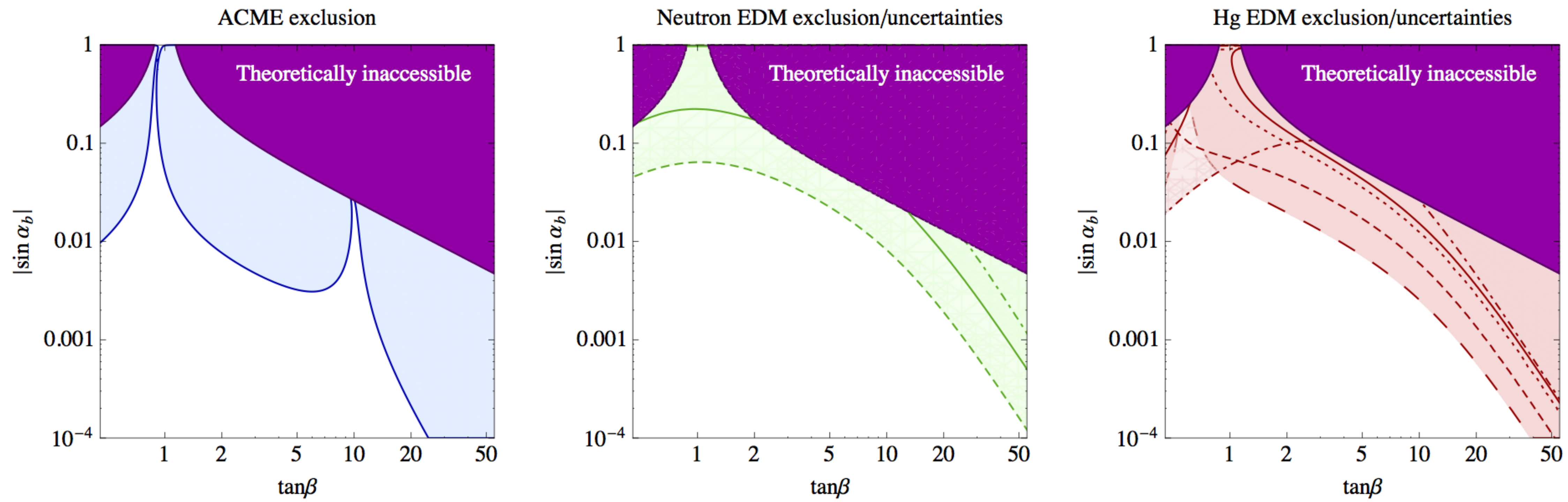


Mixing angle α_b must be $\lesssim 10^{-2}$ from eEDM

But there are cancellation regions (t- and W-loop, h and H)

Current EDM constraints

Exclusion plots from electron, neutron, mercury

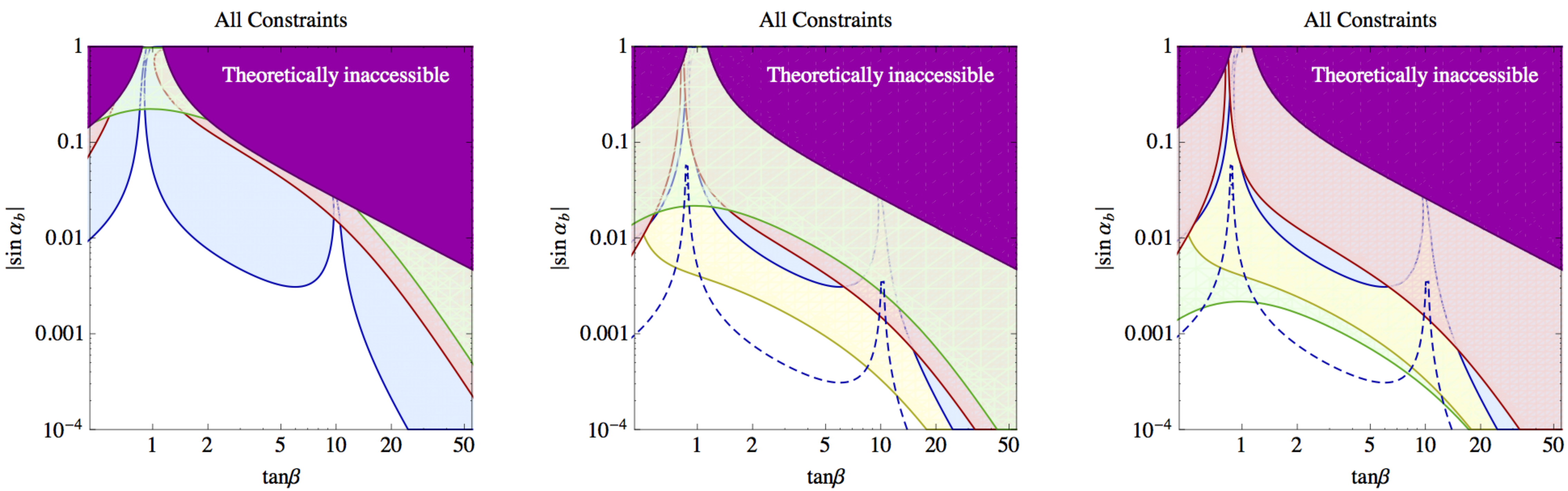


Different lines for n & Hg: possible values of matrix elements

~order of magnitude uncertainty in low energy QCD

Future EDM constraints

electron, neutron, mercury, radium



middle: 10x improvement in each + radium

right: 100x improvement in nEDM

Summary

- 2HDM is a well-motivated framework to explore CPV Higgs
- New CPV source results in CP mixing of scalars
- LHC results mainly constrain CP-conserving angle α
- EDMs constrain CP mixing angle α_b to $\sim 10^{-2}$
- Electron EDMs currently put tightest bounds, but others can become competitive in the foreseeable future
- …but hadronic uncertainties are troublesome

Backup

Precision constraints

Important phenomenological constraints on heavy Higgs:

1. Oblique parameter

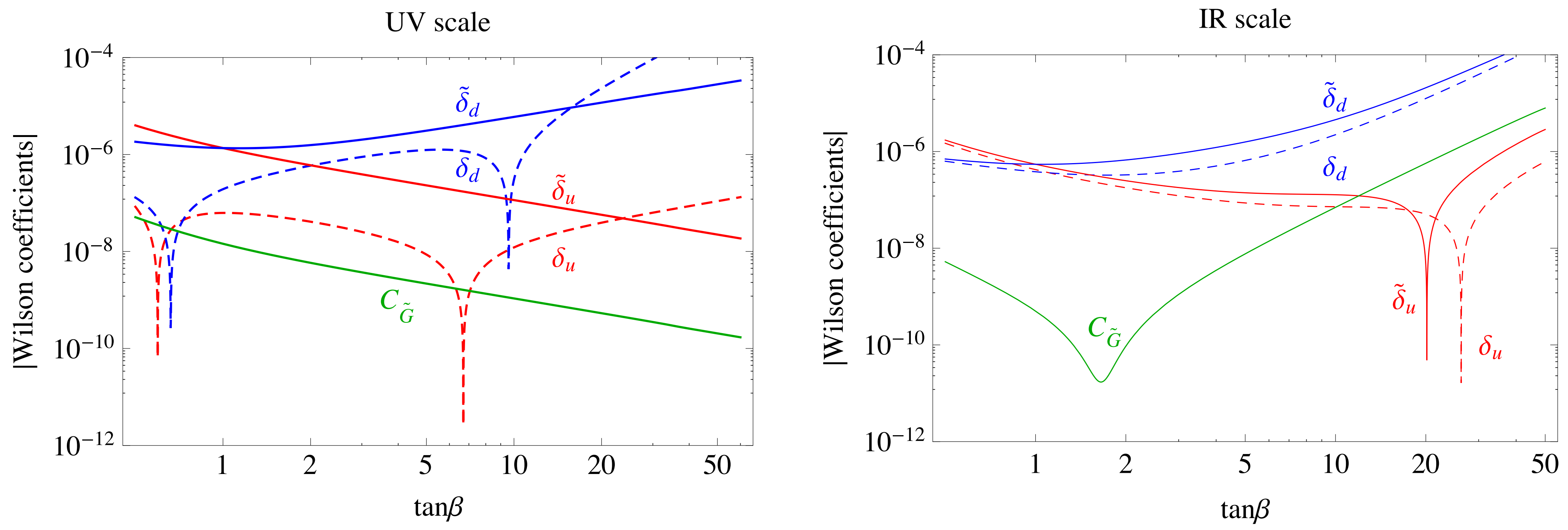
    T parameter forces mass splitting between charged and neutral heavy Higgses to be small

2. Flavor

    Charged Higgs must be heavy, from $B \to X_s \gamma$

    Type-II can't explain $\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau$

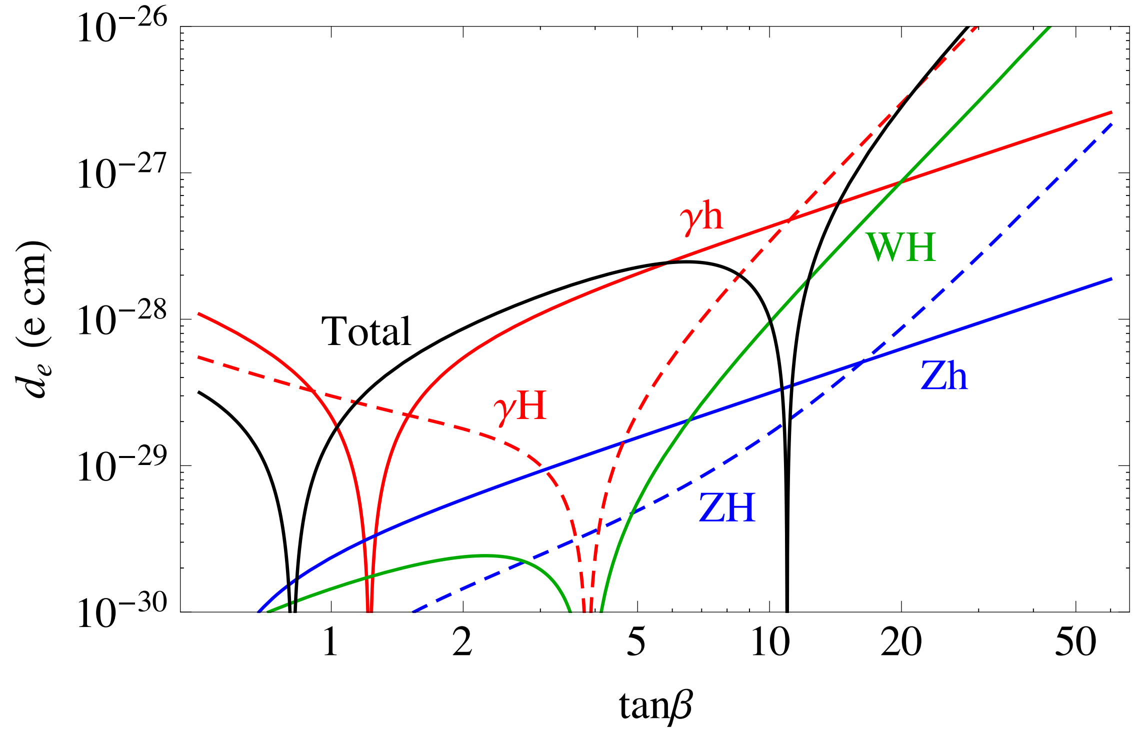
QCD running



Values of EDMs and CEDMs do change due to running

Weinberg term was not important for our parameter space

Anatomy of eEDM

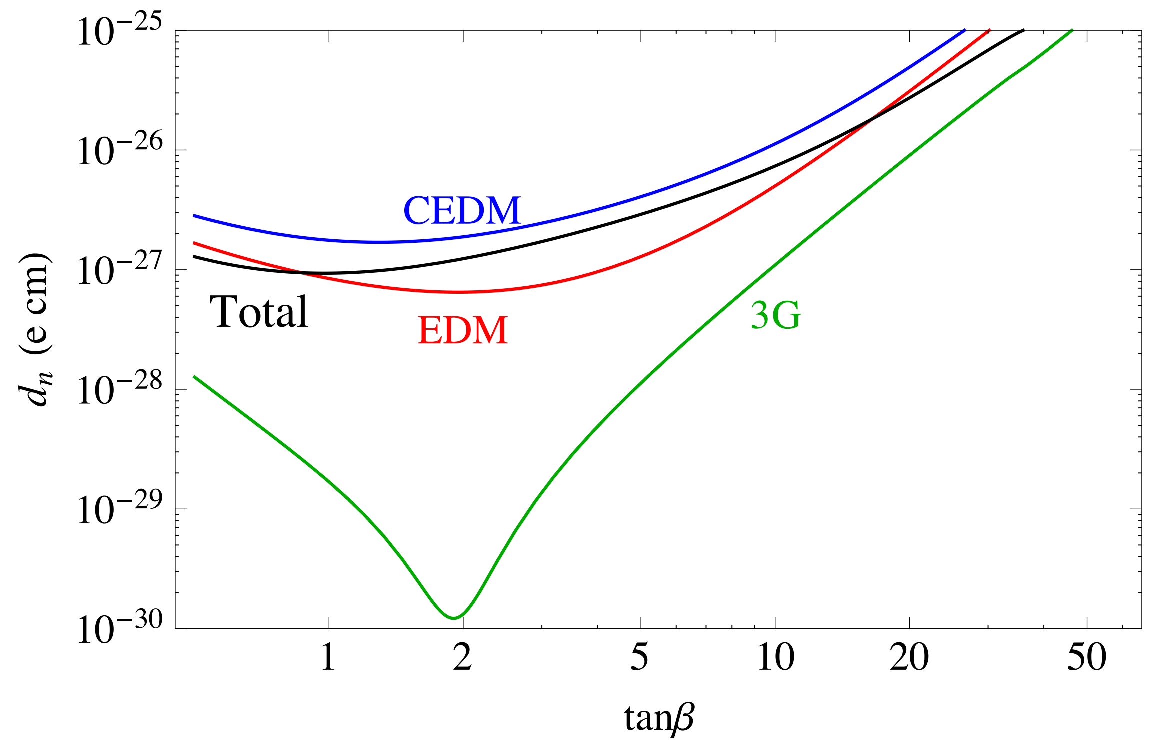


2 cancellation regions:

tan β ~ 1 t-loop and W-loop cancellation in hγγ

large tan β cancellation between hγγ and Hγγ

Anatomy of eEDM



Not as intricate as eEDM

No cancellation regions (depends on choice of M.E.s)

Charged Higgs and Goldstones

The charged sector divides up into the physical charged Higgs H^+ and charged Goldstone G^+:

$$H^+ = -\sin\beta H_1^+ + \cos\beta H_2^+, \quad G^+ = \cos\beta H_1^+ + \sin\beta H_2^+$$

Charged Higgs mass is $m_{H^+}^2 = \frac{1}{2}\left(2\nu - \lambda_4 - \mathrm{Re}\lambda_5\right) v^2$

There are also neutral Goldstones, from CP-odd sector:

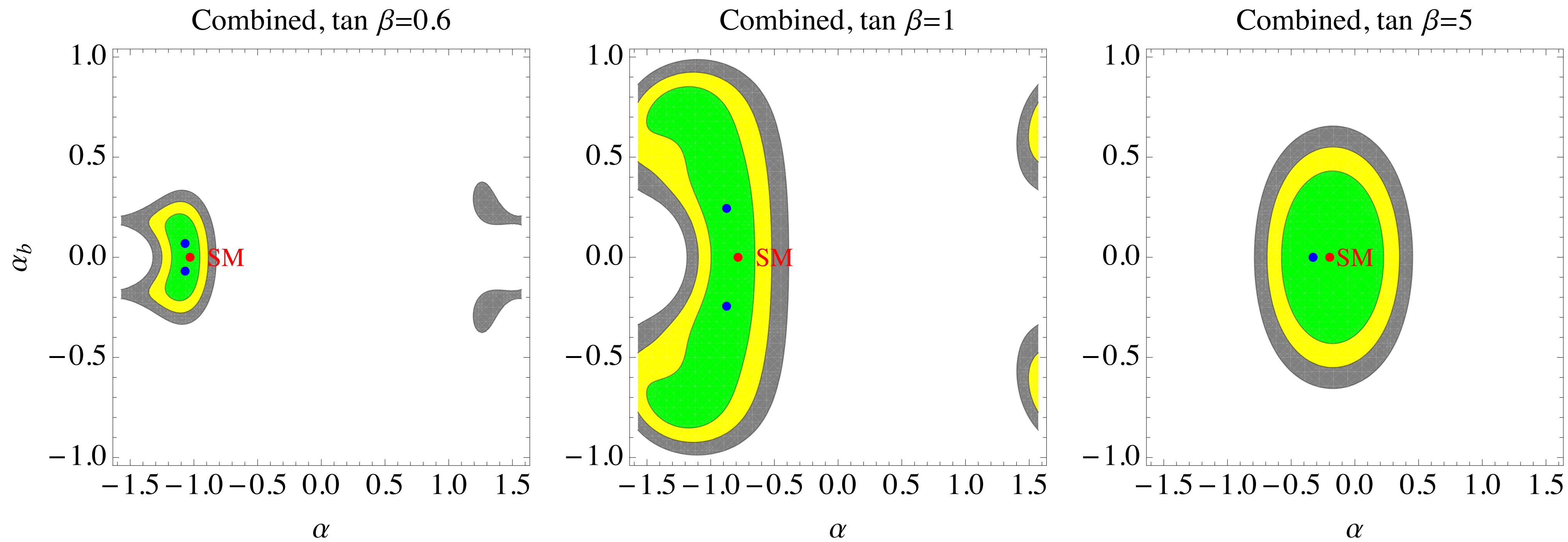
$$A^0 = -\sin\beta A_1^0 + \cos\beta A_2^0, \quad G^0 = \cos\beta A_1^0 + \sin\beta A_2^0$$

Physical pseudoscalar A^0 can mix with scalar Higgs $H_{1,2}^0$

Fit to LHC Higgs data (type-I)

Fit to Higgs decay signal strengths ($\sim 25\ \mathrm{fb}^{-1}$)

	$\gamma\gamma$	WW	ZZ	Vbb	$\tau\tau$
ATLAS	1.6 ± 0.3	1.0 ± 0.3	1.5 ± 0.4	-0.4 ± 1.0	0.8 ± 0.7
CMS	0.8 ± 0.3	0.8 ± 0.2	0.9 ± 0.2	1.3 ± 0.6	1.1 ± 0.4

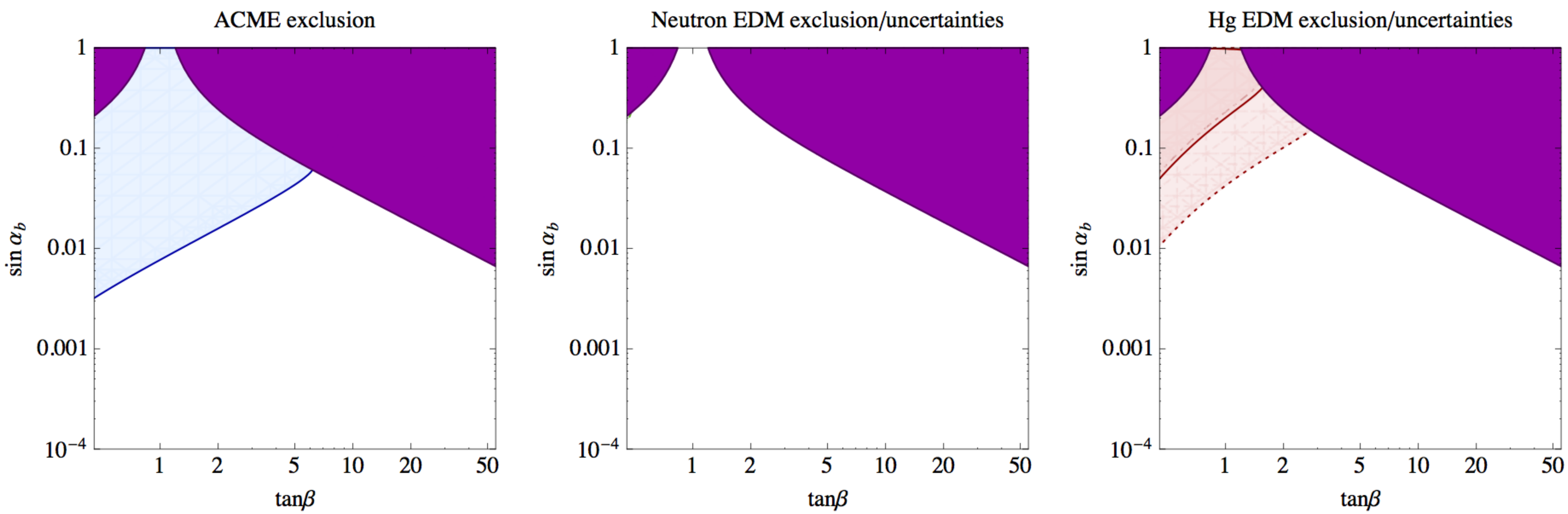


α mostly constrained near SM value ($\beta - \pi/2$)

α_b not well constrained

EDM current bounds (type-I)

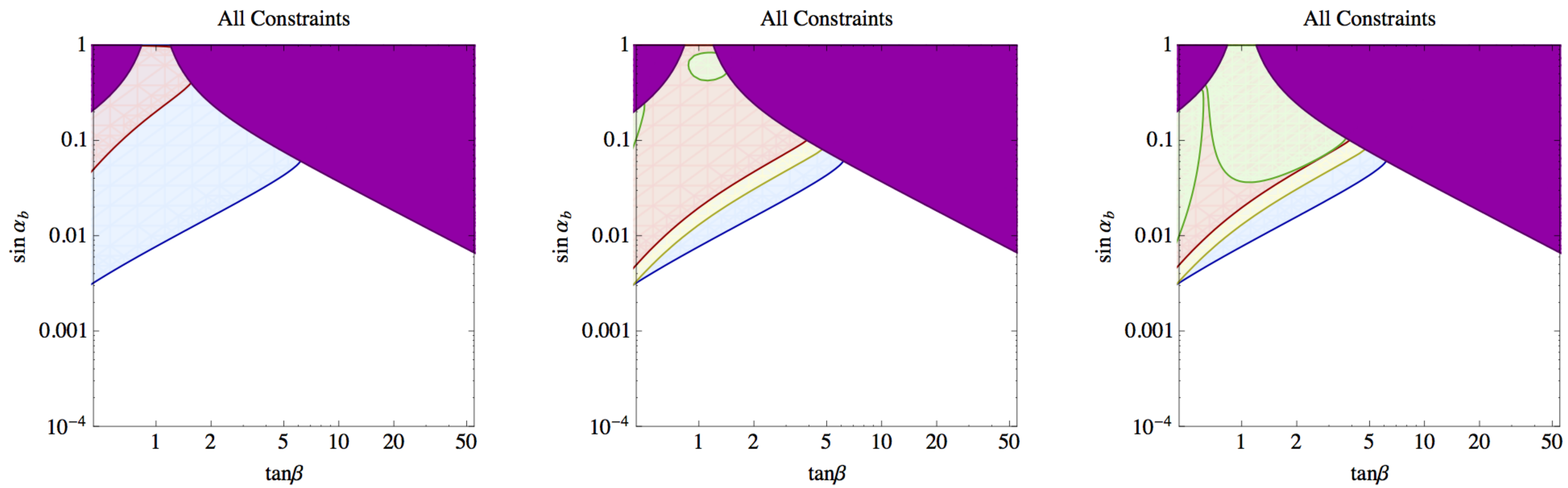
Exclusion plots on $\tan\beta - \sin\alpha_b$ plane:
electron, neutron, Hg
(magenta - theoretically inaccessible)



eEDM places strongest constraints: $\sin\alpha_b \lesssim .01$ for small $\tan\beta$
nEDM does not constrain this model

EDM future bounds (type-I)

electron, neutron, Hg, Ra



Left - current

Center - 10x improvement for neutron and Hg

Right - 100x improvement for neutron

eEDM is the most sensitive channel for type-I