Flavour and Higgs physics in Z2-symmetric 2HD models near the decoupling limit

Arturo de Giorgi (Madrid, UAM/IFT)

Based on:
arXiv: **2304.10560**

realised in collaboration with:
F. Koutroulis (Warsaw U.), **L. Merlo** (UAM/IFT), **S. Pokorski** (Warsaw U.)

WG2-WG3 joint meeting on CP violation in extended Higgs sector

September 26, 2023

Instituto de Física Teórica UAM-CSIC

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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What is this presentation about?

2HDM + Z_2

"add an extra Electro-Weak doublet"

near decoupling limit

J.F. Gunion et al., The Higgs Hunters' Guide 2000;
M. Carena, H. E. Haber, Prog. Part. Nucl. Phys. 50 (2003) 63
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synergy in different searches

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The Z_2-Basis

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\begin{aligned}
V(\Phi_1, \Phi_2) = &- m_1^2(\Phi_1^\dagger \Phi_1) - m_2^2(\Phi_2^\dagger \Phi_2) - \left[m_{12}^2(\Phi_1^\dagger \Phi_2) + \text{h.c.}\right] \\
&+ \lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_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) \\
&+ \left[\lambda_5(\Phi_1^\dagger \Phi_2)^2 + \lambda_6(\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.}\right] .
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- **Misalignment** between mass and interaction matrix in the Yukawas: **tree-level FCNCs?**

$\longrightarrow$ Z_2-Symmetry

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$\longrightarrow$ Z_2-Symmetry

$$\Phi_1 \to +\Phi_1 \qquad \text{and} \qquad \Phi_2 \to -\Phi_2$$

Model	Φ_1	Φ_2	Q_L	u_R	d_R	L_L	e_R
Type I	+	−	+	−	−	+	−
Type II	+	−	+	−	+	+	+
Type III (X)	+	−	+	−	−	+	+
Type IV (Y)	+	−	+	−	+	+	−

Arturo de Giorgi, arXiv: **2304.10560**

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Type II	$+$	$-$	$+$	$-$	$+$	$+$	$+$
Type III (X)	$+$	$-$	$+$	$-$	$-$	$+$	$+$
Type IV (Y)	$+$	$-$	$+$	$-$	$+$	$+$	$-$

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Z_2 - Softly Broken

$$
\Phi_1 \to +\Phi_1 \qquad \text{and} \qquad \Phi_2 \to -\Phi_2
$$

$$
\lambda_6 = \lambda_7 = 0
$$

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Type III (X)	+	−	+	−	−	+	+
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Higgs Basis

$$\langle H_1^\dagger H_1 \rangle = \frac{v^2}{2}\,, \qquad \langle H_2^\dagger H_2 \rangle = 0$$

$$\begin{aligned} V(H_1,H_2) = &\widetilde{m}_1^2 H_1^\dagger H_1 + \widetilde{m}_2^2 H_2^\dagger H_2 - \left(\widetilde{m}_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right) + \frac{1}{2}\widetilde{\lambda}_1 \left(H_1^\dagger H_1\right)^2 + \\ &+ \frac{1}{2}\widetilde{\lambda}_2 \left(H_2^\dagger H_2\right)^2 + \widetilde{\lambda}_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \widetilde{\lambda}_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \\ &+ \left[\frac{1}{2}\widetilde{\lambda}_5 \left(H_1^\dagger H_2\right)^2 + \widetilde{\lambda}_6 \left(H_1^\dagger H_1\right)\left(H_1^\dagger H_2\right) + \widetilde{\lambda}_7 \left(H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \text{h.c.}\right]. \end{aligned}$$

Decoupling Limit: $\widetilde{m}_2^2 \gg \widetilde{\lambda}_i v^2$

Masses:

$$m_h^2 \approx v^2 \left\{\widetilde{\lambda}_1 - \left|\widetilde{\lambda}_6\right|^2 \frac{v^2}{\widetilde{m}_2^2}\right\}$$

$$m_{H_\pm}^2 \approx \widetilde{m}_2^2 + \frac{1}{2}\widetilde{\lambda}_3 v^2\,,$$

$$m_{A,H}^2 \approx \widetilde{m}_2^2 \left\{1 + \frac{1}{2}\left(\widetilde{\lambda}_3 + \widetilde{\lambda}_4 \mp \left|\widetilde{\lambda}_5\right|\right)\frac{v^2}{\widetilde{m}_2^2}\right\}$$

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Decoupling Limit: $\widetilde{m}_2^2 \gg \widetilde{\lambda}_i v^2$

$\sim$ **degenerate scalars!**

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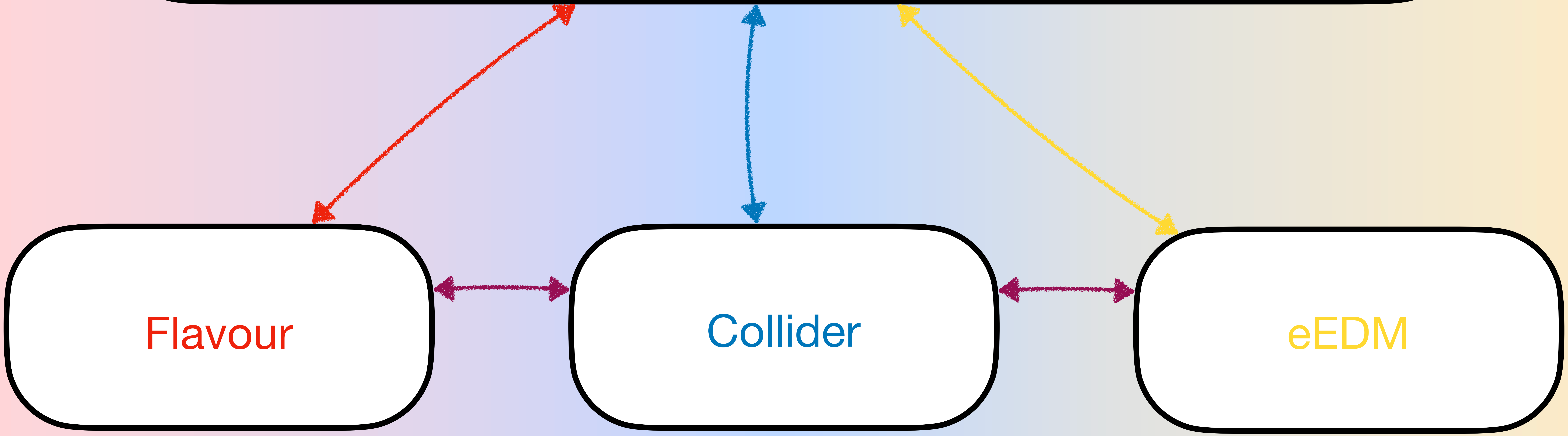
3-Parameters to rule them all

In the **decoupling limit**, the theory depends at **LO** only on **3 parameters**:

$$\tilde{m}_2 \quad , \quad \tan\beta \quad , \quad \tilde{\lambda}_6$$



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Higgs-Fermion Couplings

$$-\mathscr{L}_Y^{\text{eff}} \supset M_f \overline{f} f + \frac{M_f}{v} h \left(\kappa_f \overline{f} f + \widetilde{\kappa}_f \overline{f} i \gamma_5 f \right) + \dots ,$$

$$\kappa_u = \kappa_d = \kappa_e = 1 - \zeta_f \left| \widetilde{\lambda}_6 \right| \cos(\rho) \frac{v^2}{\widetilde{m}_2^2} ,$$

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	Type I	Type II	Type III (X)	Type IV (Y)
ζ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ζ_d	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
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D. Egana-Ugrinovic and S. Thomas, Effective Theory of Higgs Sector Vacuum States, arXiv:1512.00144.

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Universal deviation for each fermion-type
+
Correlations among different ones

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Stronger than flavour symmetries!
(see last year presentation or **2109.07490**)

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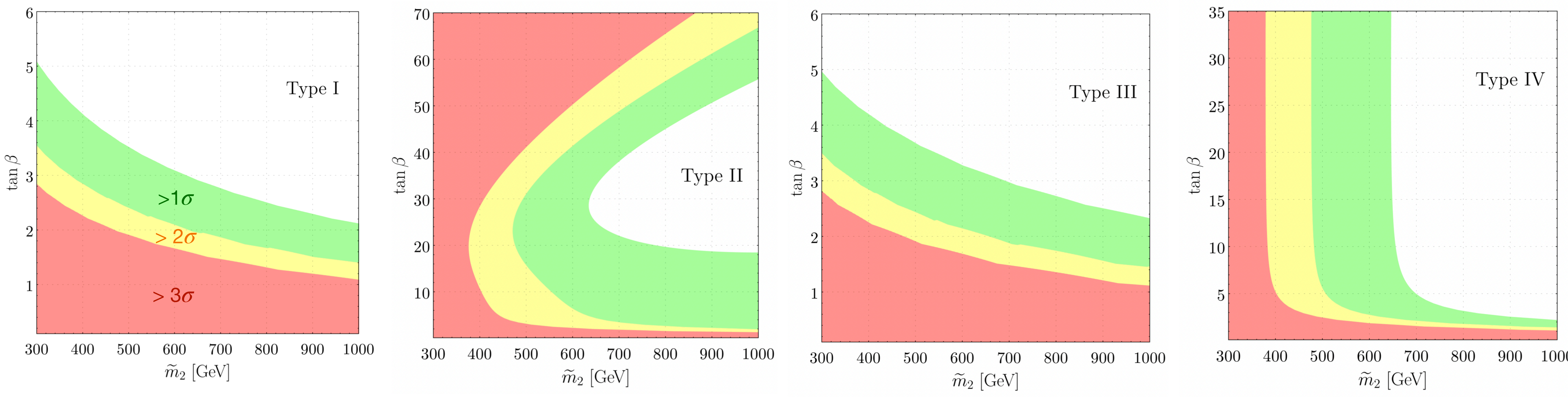
Flavour

- Four-fermion interactions depend only on $\tilde{m}_2$ and $\tan\beta$
- **Strongest bounds** from **FCNCs** at 1-loop, e.g. $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, ΔM_{B_s}
- Fit with **~60 observables**, including $B_0 \to K^*\mu^+\mu^-$ observables



Arturo de Giorgi, arXiv: **2304.10560**

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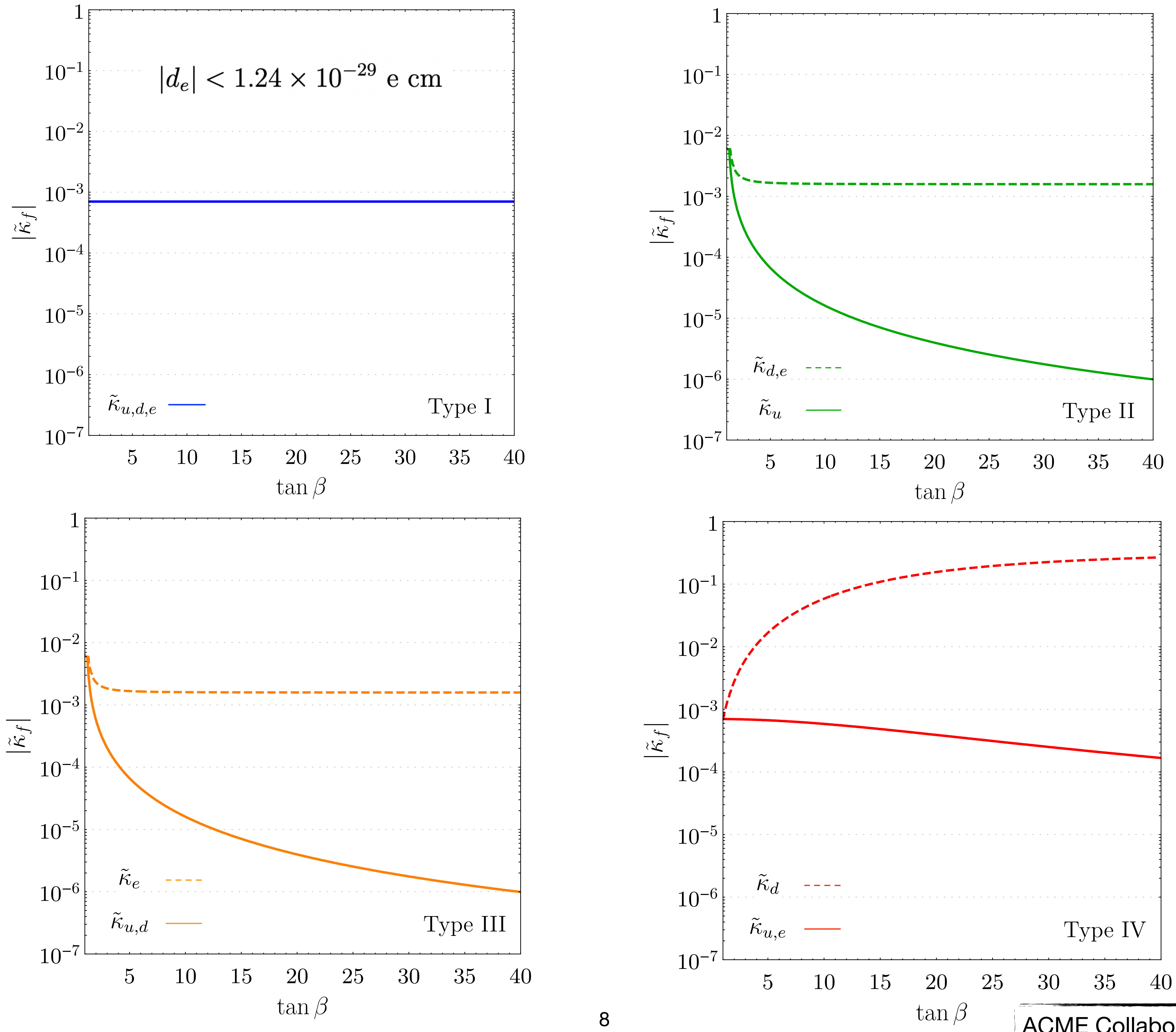
eEDM

W. Altmannshofer, S. Gori, N. Hamer, and H. H. Patel, PRD 102 (2020), no. 11 115042
D. Egana-Ugrinovic and S. Thomas, arXiv:1810.08631



Allowed

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ACME Collaboration, Nature 562 (2018), no. 7727 355–360

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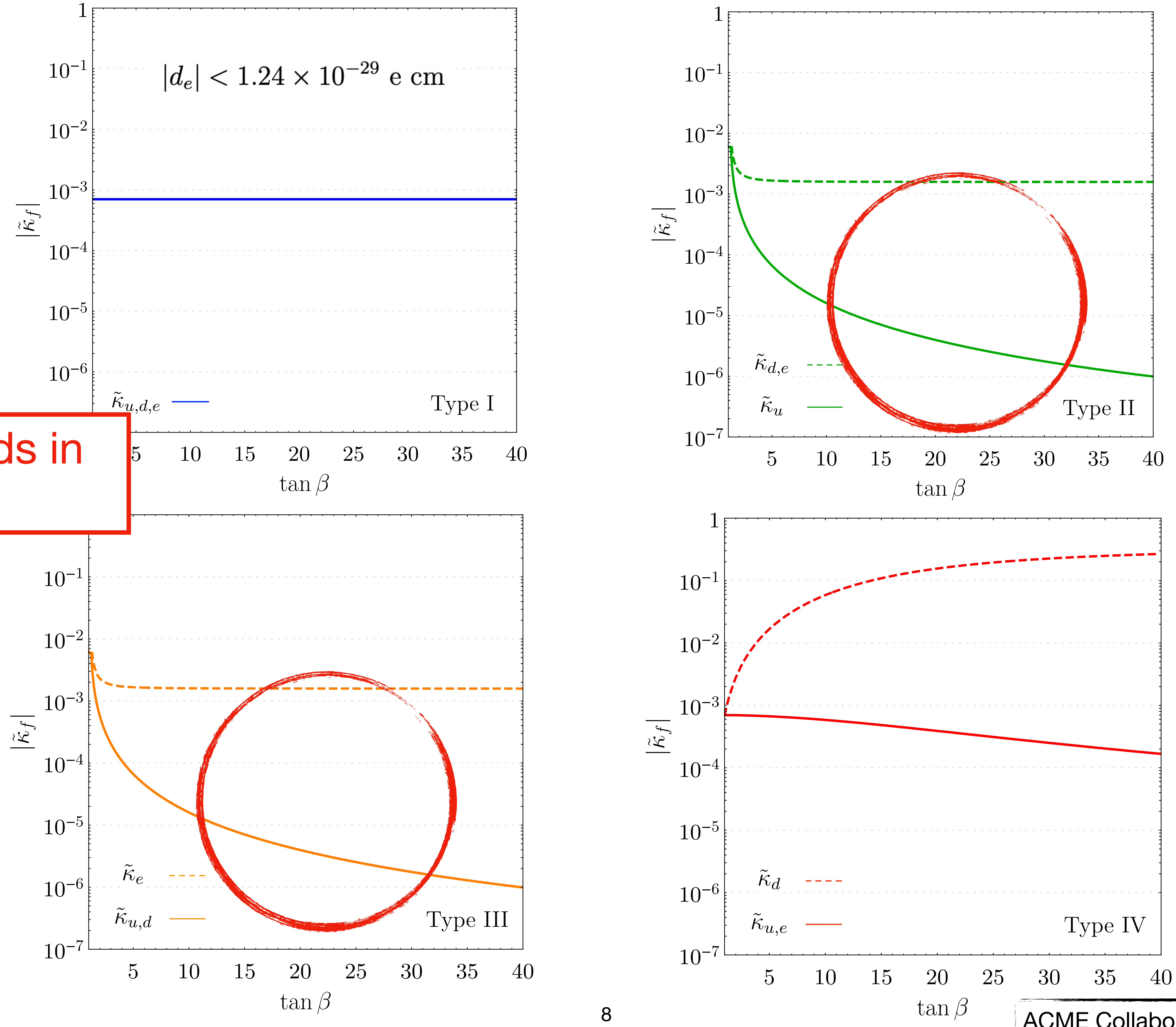

Very strong bounds in Type-II and III

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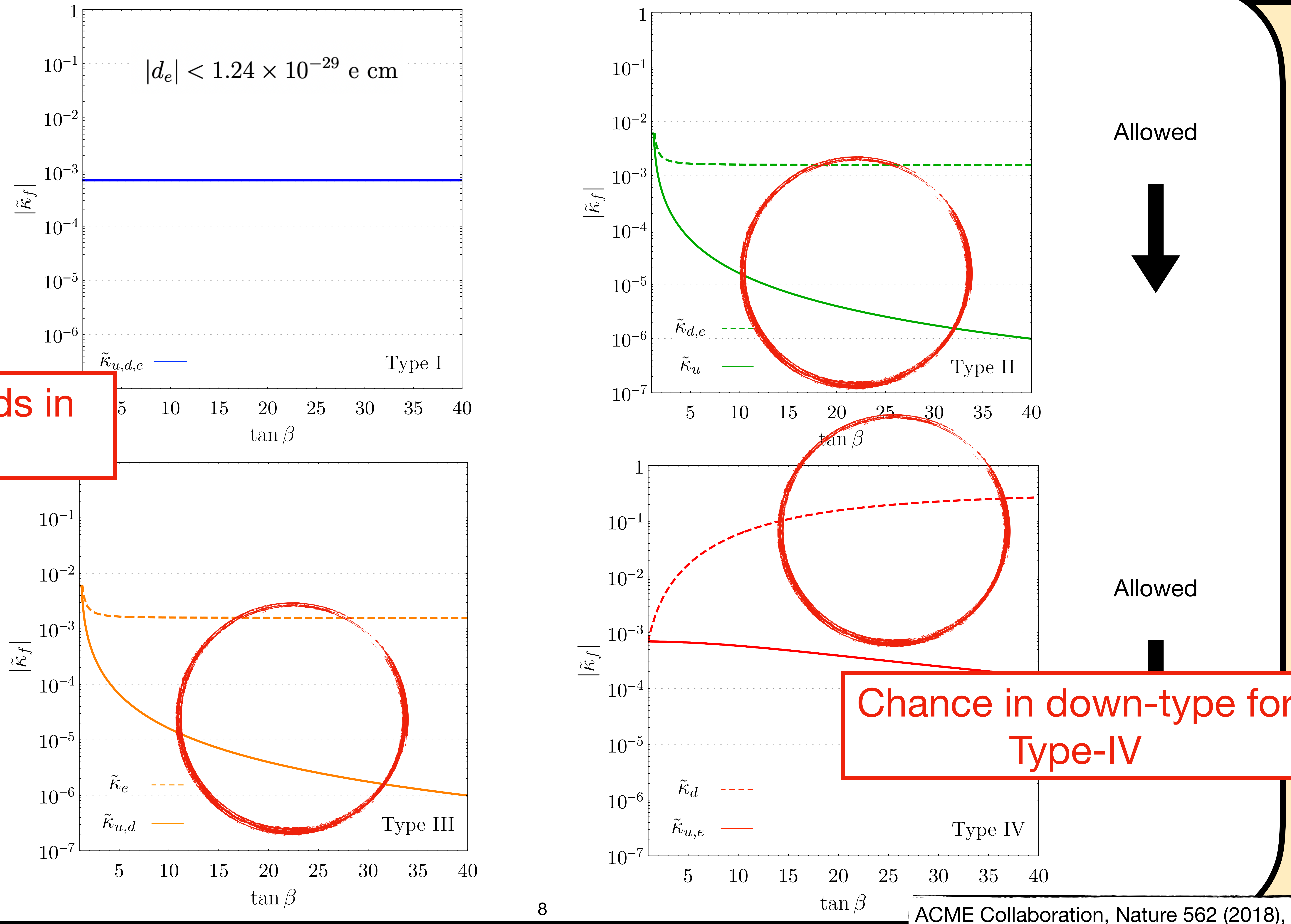


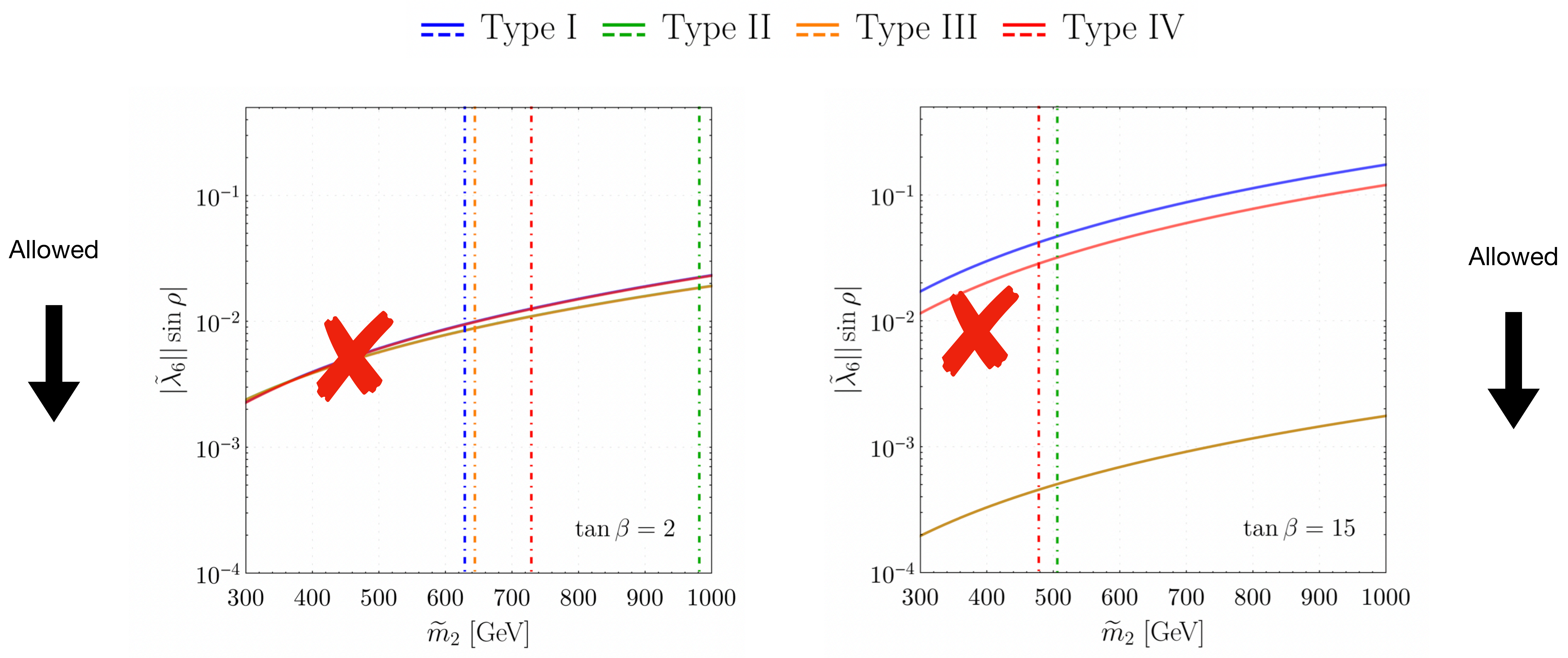
Very strong bounds in Type-II and III

Chance in down-type for Type-IV

ACME Collaboration, Nature 562 (2018), no. 7727 355–360

Bounds on the parameters

- Combine with flavour bounds

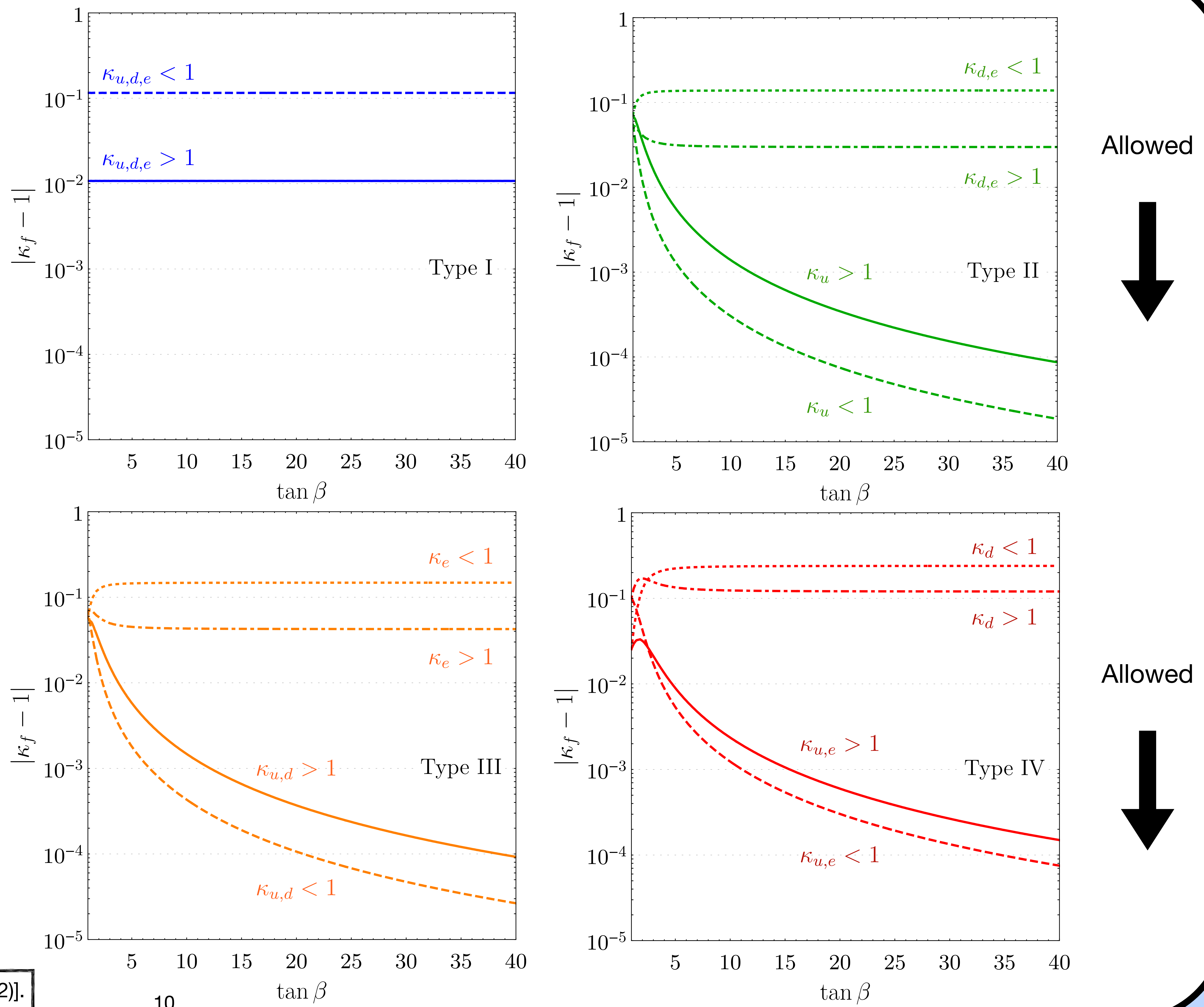


Arturo de Giorgi, arXiv: **2304.10560**

Collider

$$r_f^2 \equiv \kappa_f^2 + \tilde{\kappa}_f^2$$

	ATLAS	CMS
r_μ	1.07(26)	1.11(21)
r_τ	0.94(7)	0.925(75)
r_b	0.90(11)	1.02(16)
r_t	0.95(7)	0.95(7)
κ_W	1.02(5)	1.03(3)
κ_Z	0.99(6)	1.02(3)



ATLAS Collaboration, Nature 607 (2022), no. 7917 52–59 [Erratum: Nature 612, E24 (2022)].
CMS Collaboration, Nature 607 (2022), no. 7917 60–68

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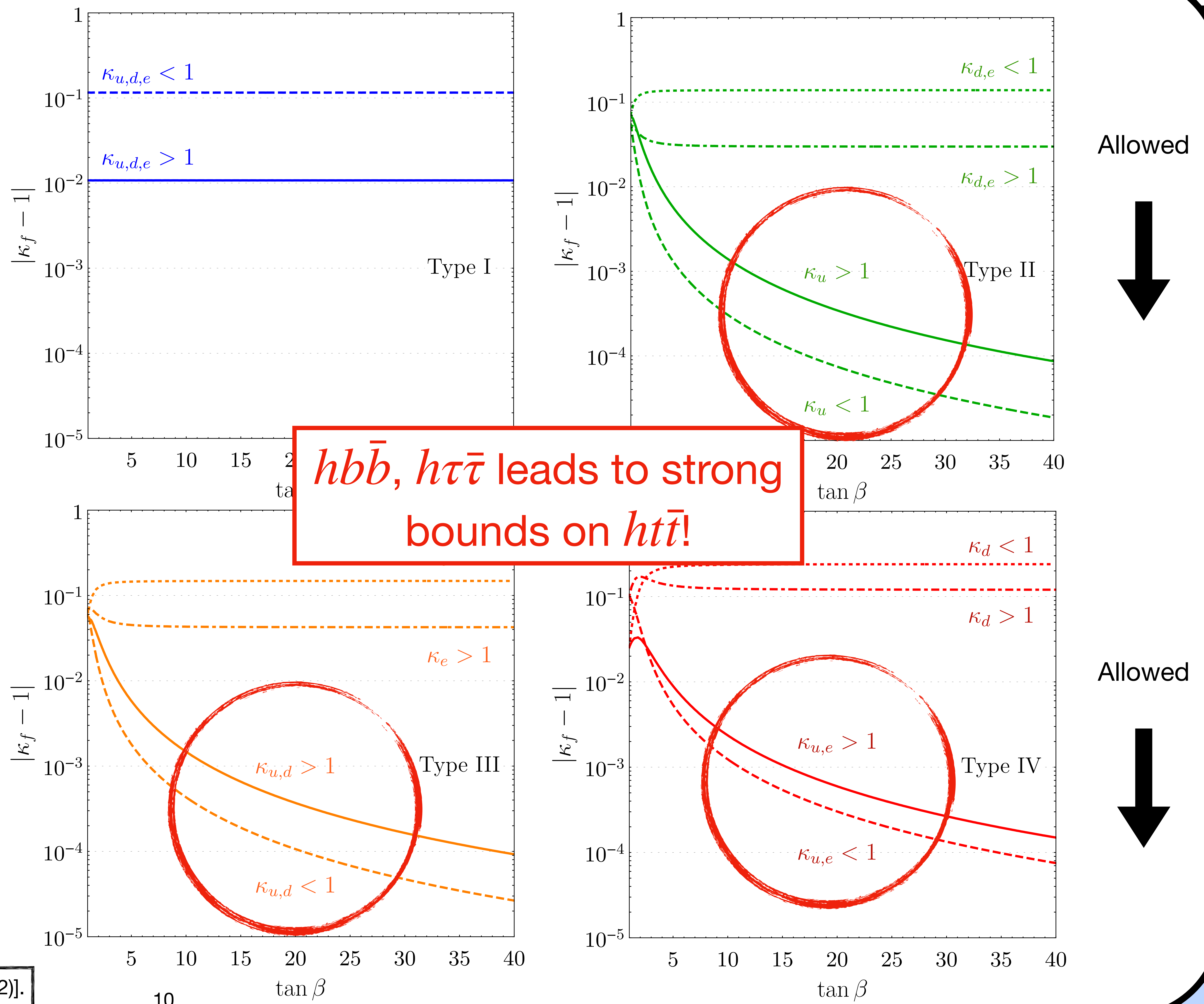
r_μ	1.07(26)	1.11(21)
r_τ	0.94(7)	0.925(75)
r_b	0.90(11)	1.02(16)
r_t	0.95(7)	0.95(7)
κ_W	1.02(5)	1.03(3)
κ_Z	0.99(6)	1.02(3)

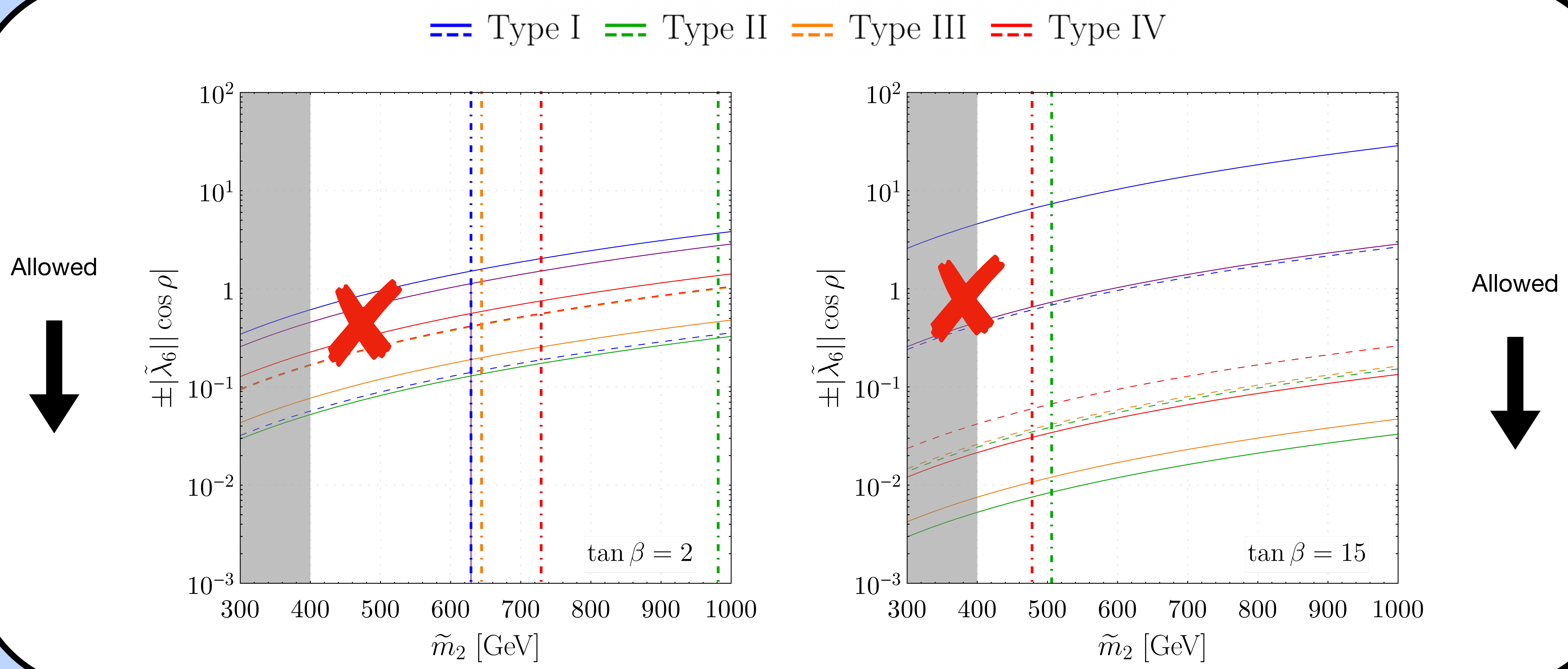


$hb\bar{b}$, $h\tau\bar{\tau}$ leads to strong bounds on $ht\bar{t}$!

ATLAS Collaboration, Nature 607 (2022), no. 7917 52–59 [Erratum: Nature 612, E24 (2022)].
CMS Collaboration, Nature 607 (2022), no. 7917 60–68

Bounds on the parameters

$$g_{hVV} = \frac{2\,m_V^2}{v^2}\left[1 - \frac{1}{2}\left|\widetilde{\lambda}_6\right|^2\left(\frac{v^2}{\widetilde{m}_2^2}\right)^2\right] \equiv \frac{2\,m_V^2}{v^2}\kappa_V \qquad \left|\widetilde{\lambda}_6\right|\left(\frac{v^2}{\widetilde{m}_2^2}\right) \leq 0.17\,.$$

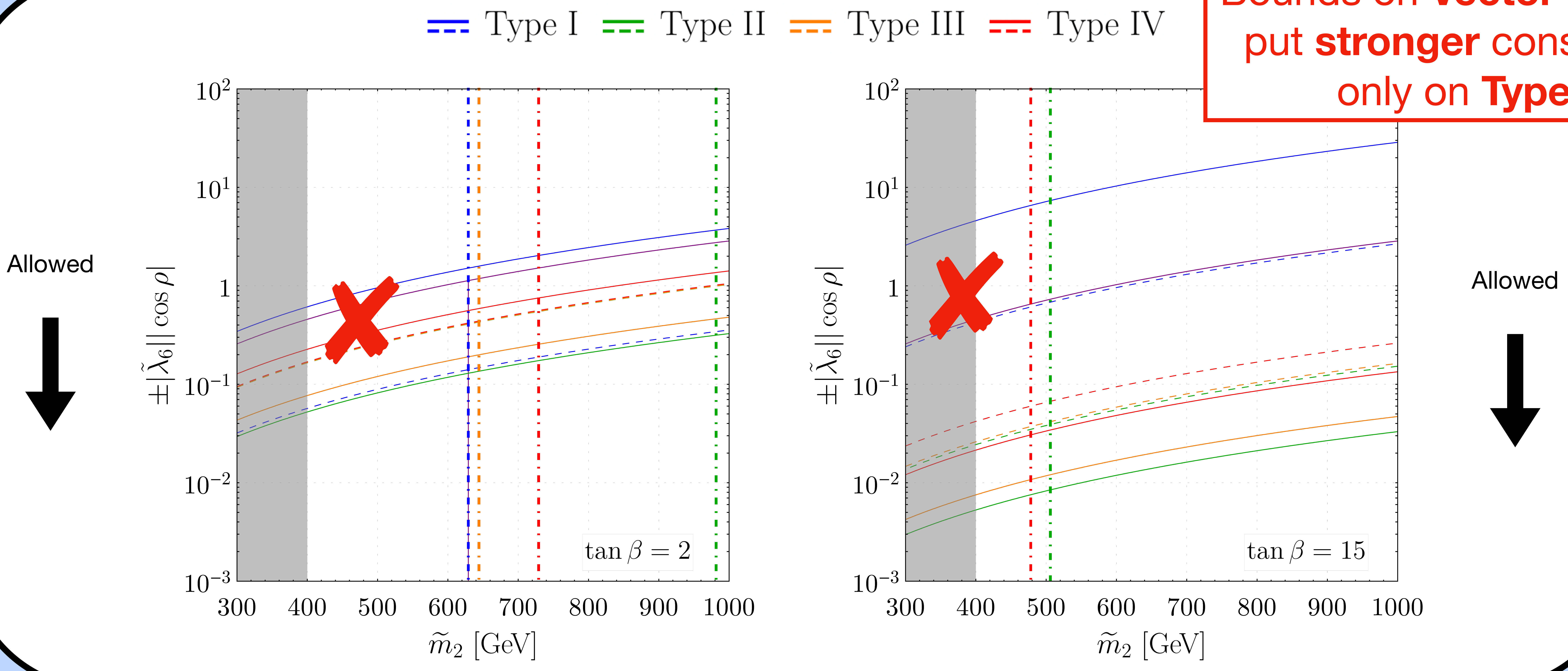


Arturo de Giorgi, arXiv: **2304.10560**

Bounds on the parameters

$$g_{hVV} = \frac{2\,m_V^2}{v^2}\left[1 - \frac{1}{2}\left|\widetilde{\lambda}_6\right|^2\left(\frac{v^2}{\widetilde{m}_2^2}\right)^2\right] \equiv \frac{2\,m_V^2}{v^2}\kappa_V \qquad \left|\widetilde{\lambda}_6\right|\left(\frac{v^2}{\widetilde{m}_2^2}\right) \le 0.17\,.$$

Bounds on **Vector-Bosons** put **stronger** constraints only on **Type-I**



Arturo de Giorgi, arXiv: **2304.10560**

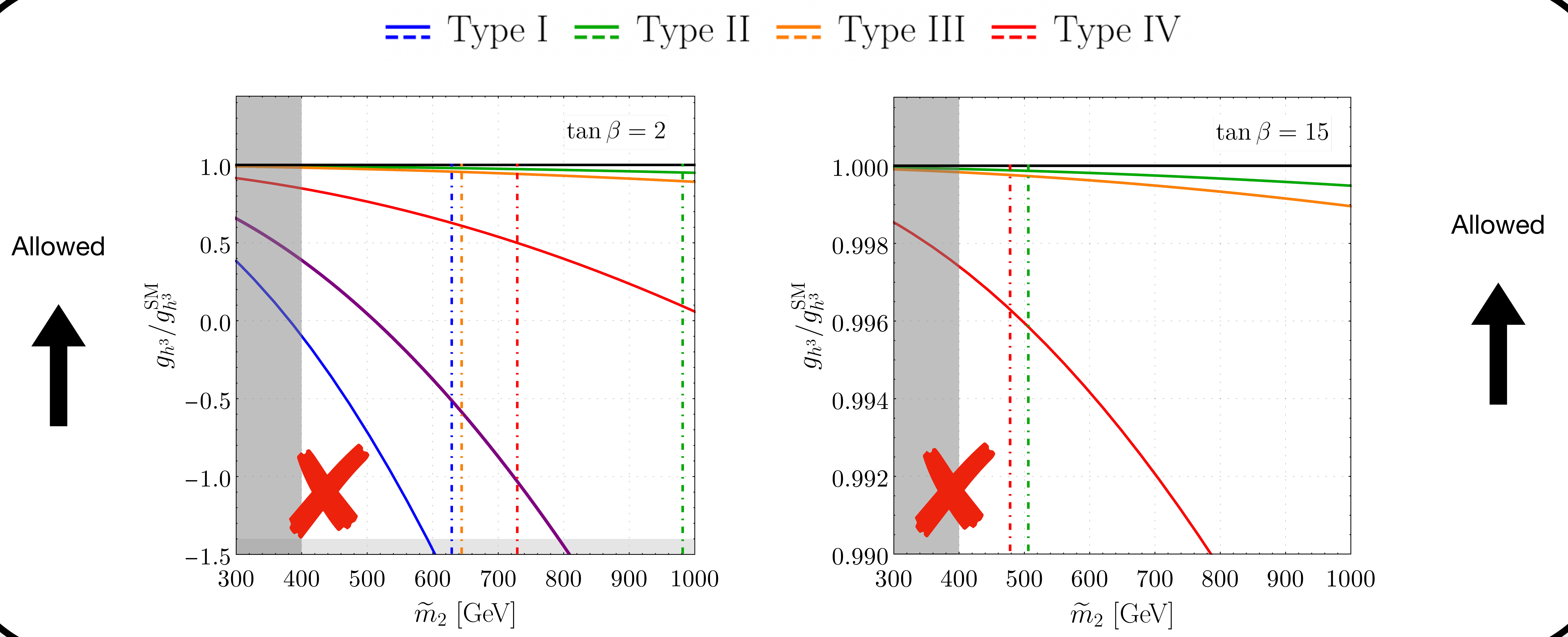
Triple Higgs Coupling

ATLAS Collaboration, arXiv:2211.01216

$$g_{h^3} = \frac{3\,m_h^2}{v^2} - 6\left|\widetilde{\lambda}_6\right|^2 \frac{v^2}{\widetilde{m}_2^2}$$

95% C.L.

$$-1.4 < \frac{g_{h^3}}{g_{h^3}^{\rm SM}} < 6.1$$



Triple Higgs Coupling

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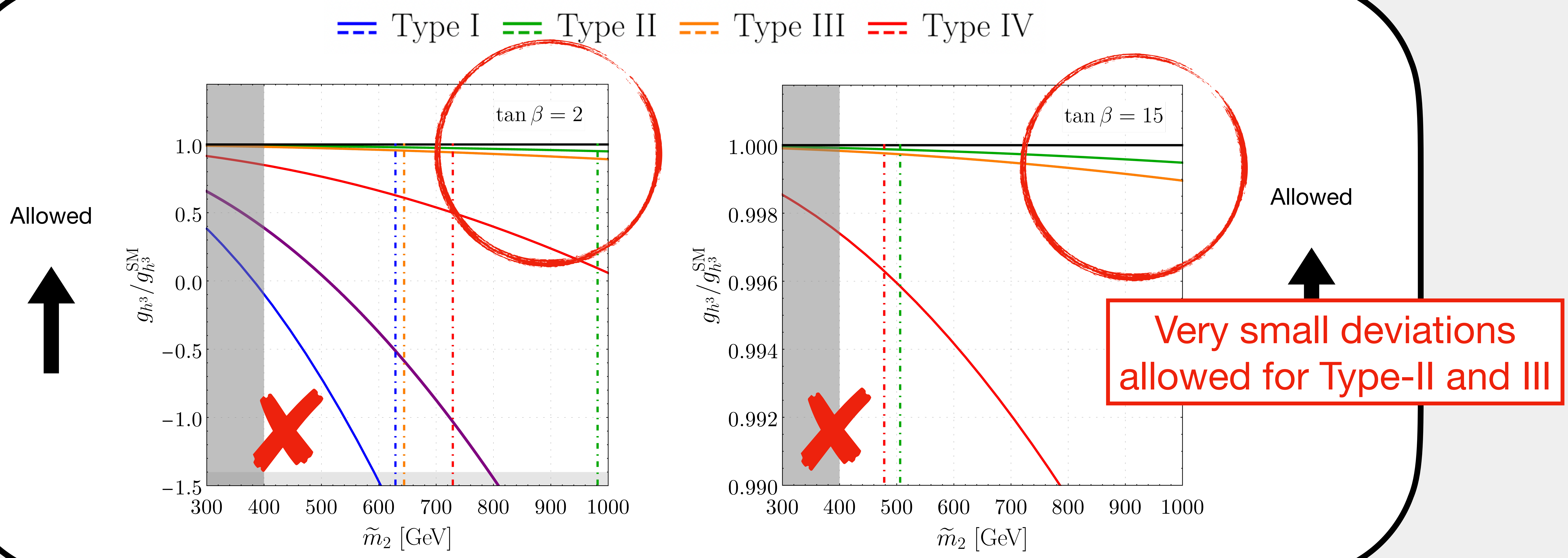

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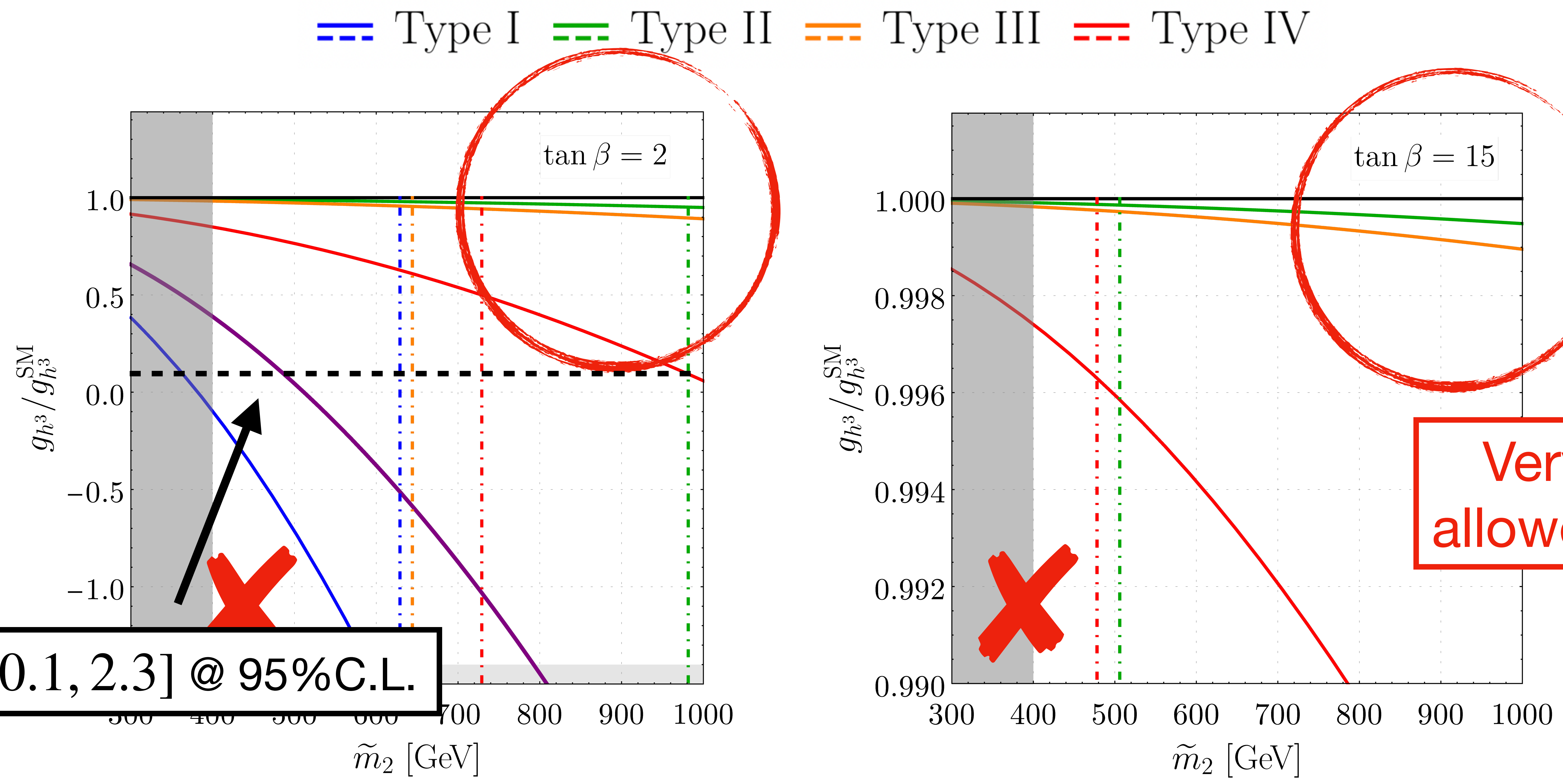
Allowed



Allowed

Very small deviations allowed for Type-II and III

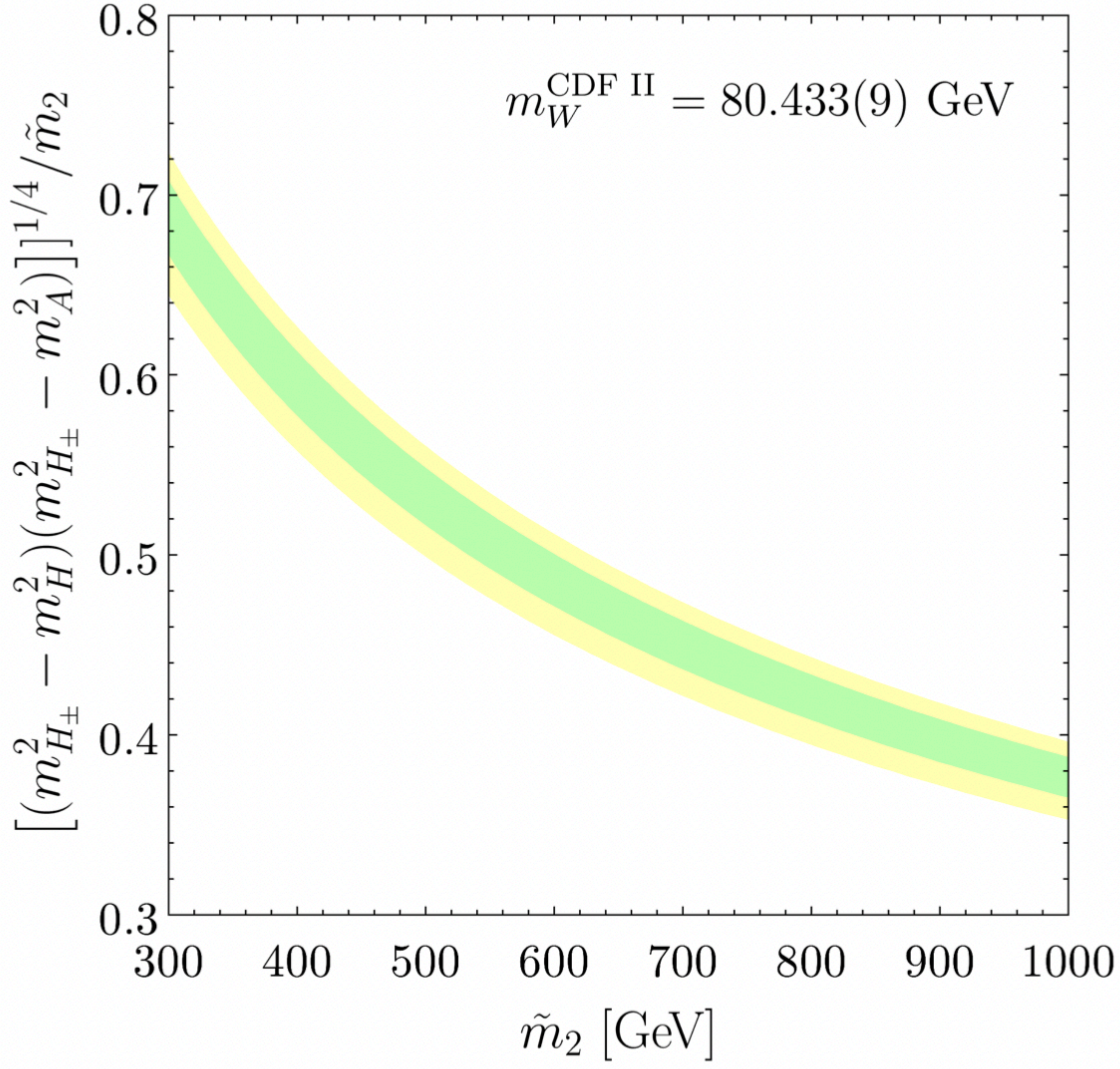
HL-LHC: $\kappa_\lambda \in [0.1, 2.3]$ @ 95%C.L.

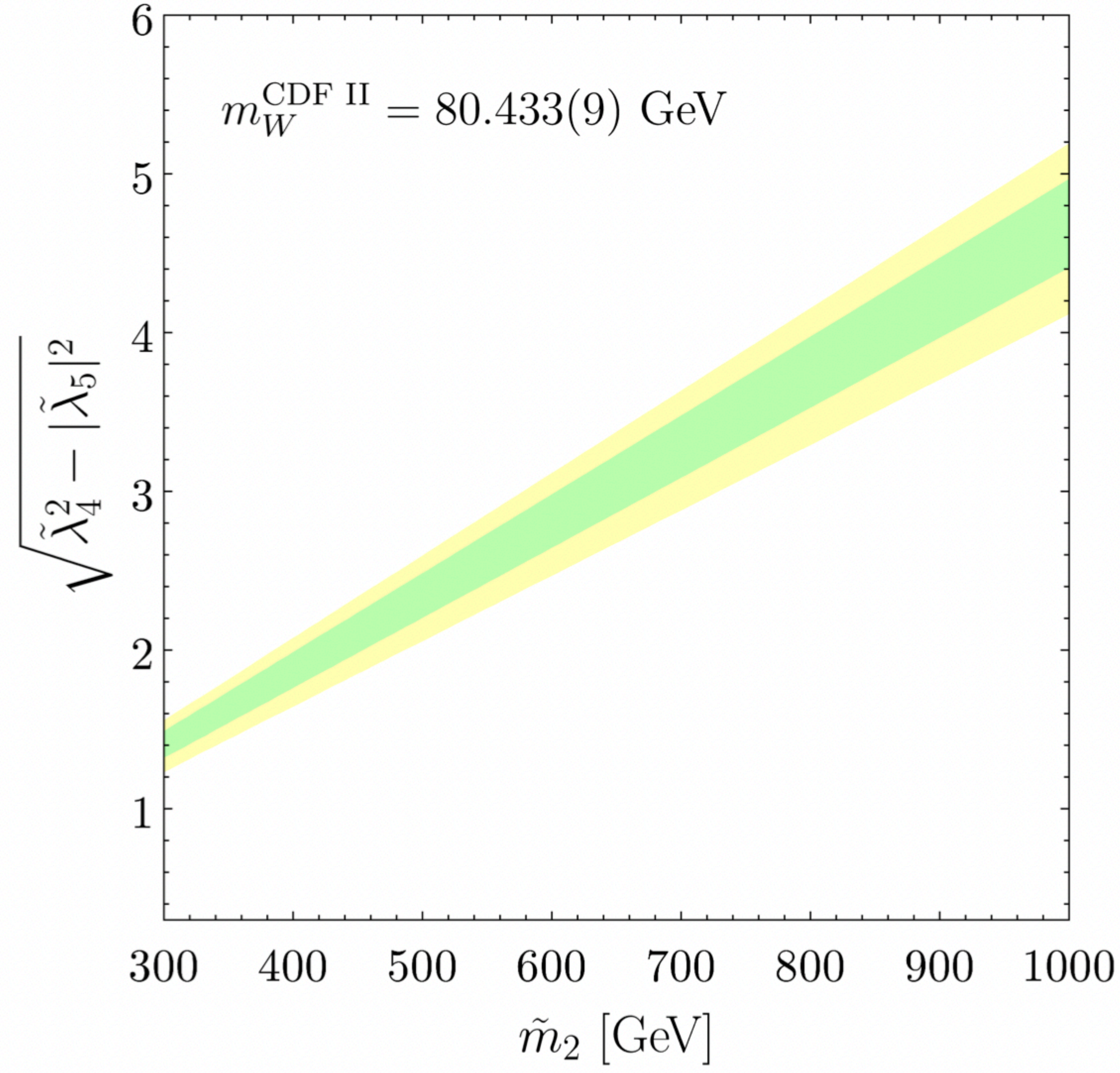
ATL-PHYS-PUB-2022-018

CDF II M_W

CDF Collaboration, C. Hays, PoS ICHEP2022 (2022) 898.

$$m_W^{\mathrm{SM}} = 80.354 \pm 0.007\ \mathrm{GeV} \qquad m_W^{\mathrm{CDF\ II}} = 80.4335 \pm 0.0094\ \mathrm{GeV}$$





Arturo de Giorgi, arXiv: **2304.10560**

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CDF Collaboration, C. Hays, PoS ICHEP2022 (2022) 898.

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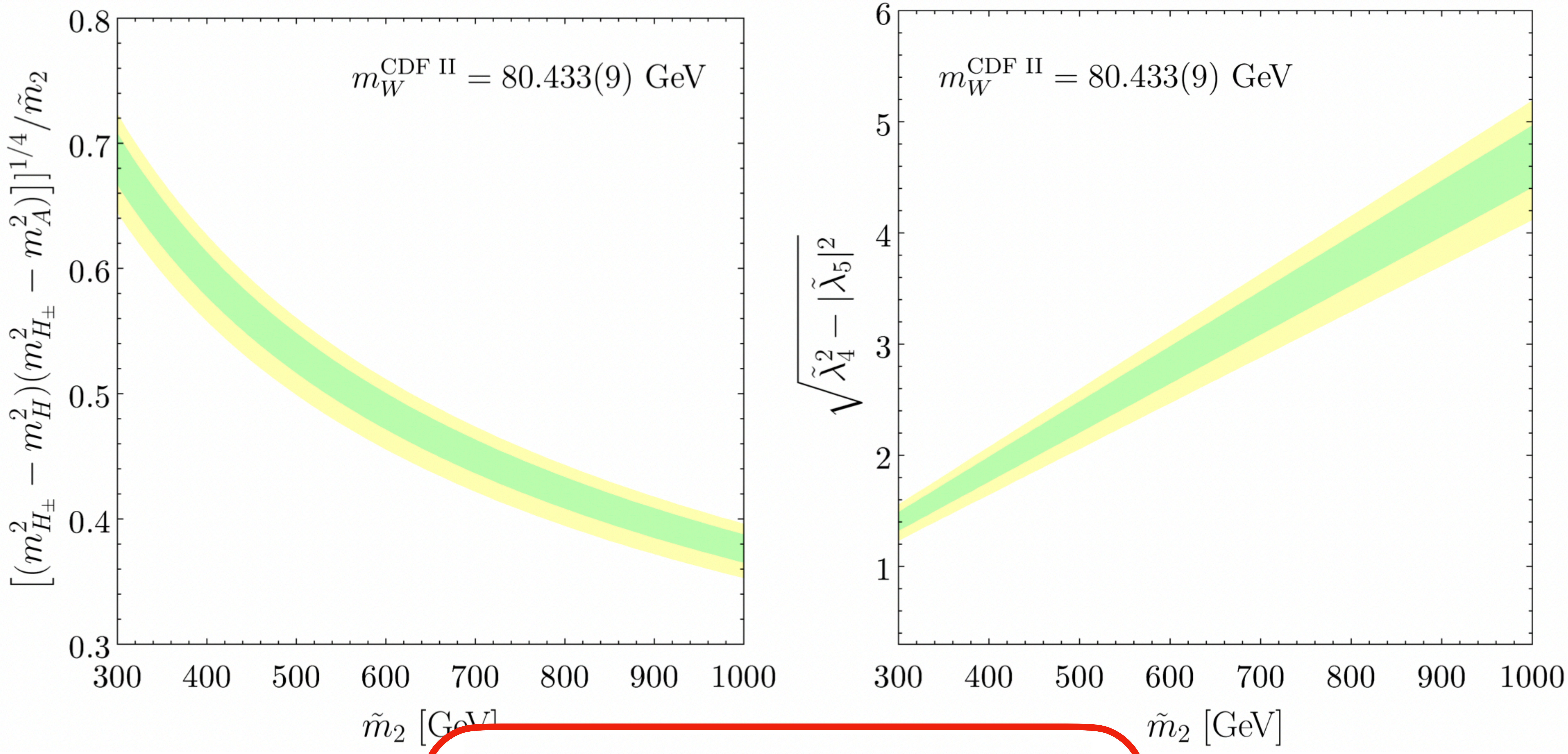


$$m_{H_\pm}^2 > m_H^2,\ m_A^2\,,\quad m_{H_\pm}^2 < m_H^2,\ m_A^2$$

Arturo de Giorgi, arXiv: **2304.10560**

Summary and Conclusions

Z_2**-symmetric 2HDMs** in the **near decoupling limit**

3 parameters (LO)

$hb\bar{b}, h\tau\bar{\tau}$ **seem more promising** than $ht\bar{t}$

Deviations in g_{h^3} **?**

Stay Tuned!

Thanks!

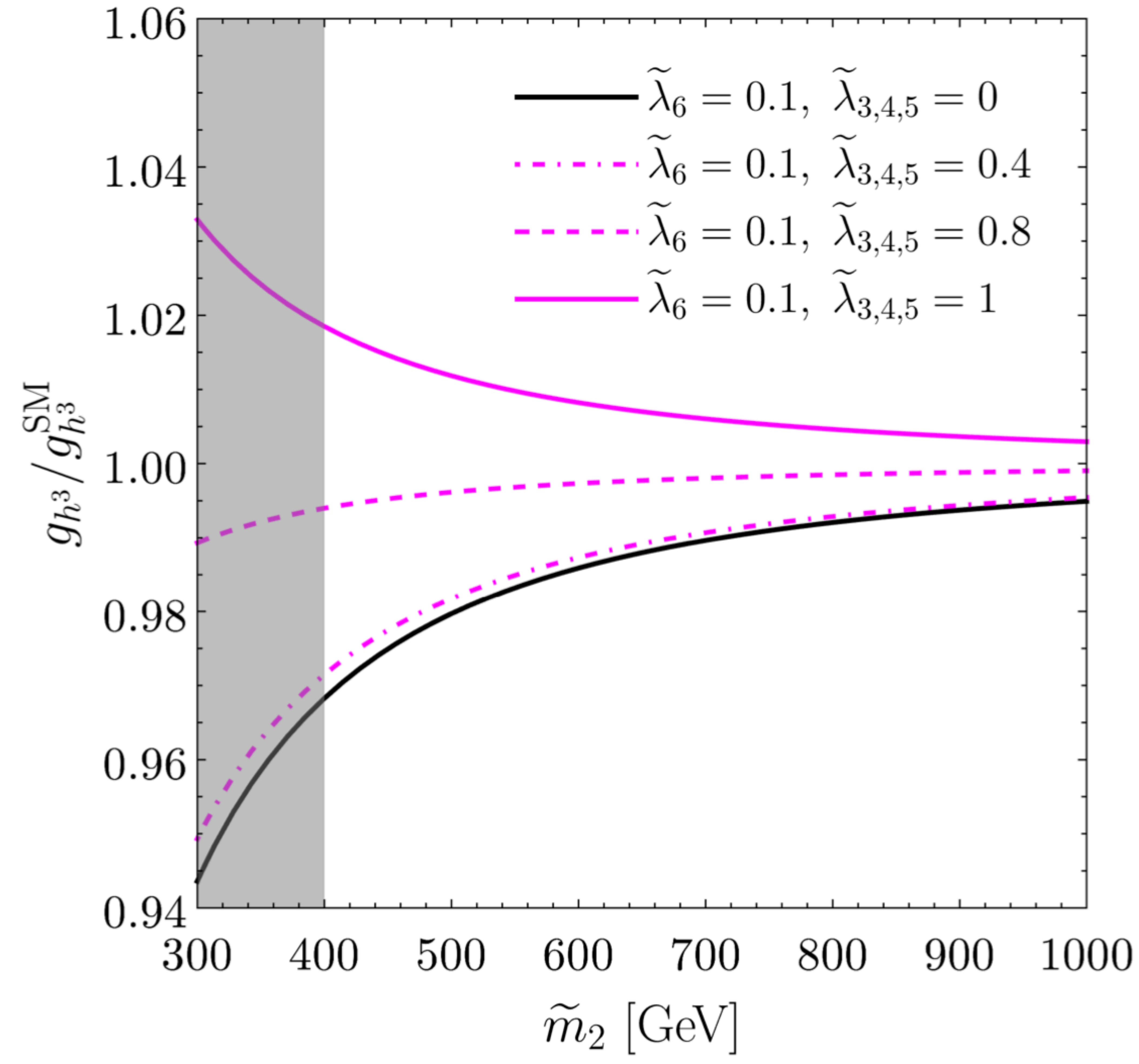
Arturo de Giorgi

arXiv: **2304.10560**

Triple Higgs Coupling: loops?

$$g_{h^3} = \frac{3\,m_h^2}{v^2} - 6\left|\widetilde{\lambda}_6\right|^2 \frac{v^2}{\widetilde{m}_2^2}$$

$$\delta g_{h^3}^{\rm NP} \approx \frac{1}{16\pi^2}\left(\frac{v}{\widetilde{m}_2}\right)^2 \Big[(\widetilde{\lambda}_3 + \widetilde{\lambda}_4 + \widetilde{\lambda}_5)^3 + \\ + (\widetilde{\lambda}_3 - 3\widetilde{\lambda}_5(\widetilde{\lambda}_3 + \widetilde{\lambda}_4)^2 - \widetilde{\lambda}_5^3)\Big]$$



M_W - Oblique Parameters

CDF Collaboration, C. Hays, PoS ICHEP2022 (2022) 898.

$$m_W^{\rm SM} = 80.354 \pm 0.007\ \text{GeV} \qquad m_W^{\rm CDF\ II} = 80.4335 \pm 0.0094\ \text{GeV}$$

$$i\Pi_{VV}^{\mu\nu} \equiv i\Pi_{VV}\eta^{\mu\nu} + i\Pi_{VV}^{pp}p^\mu p^\nu$$

$$T \equiv \frac{1}{\alpha_{\rm em}}\left(\frac{\Pi_{WW}^{\rm NP}(0)}{m_W^2} - \frac{\Pi_{ZZ}^{\rm NP}(0)}{m_Z^2}\right),$$

$$S \equiv \frac{4c_W^2 s_W^2}{\alpha_{\rm em}}\left[\frac{\Pi_{ZZ}^{\rm NP}(m_Z^2) - \Pi_{ZZ}^{\rm NP}(0)}{m_Z^2} - \frac{c_W^2 - s_W^2}{c_W s_W}\frac{\Pi_{Z\gamma}^{\rm NP}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}^{\rm NP}(m_Z^2)}{m_Z^2}\right],$$

$$U \equiv \frac{4s_W^2}{\alpha_{\rm em}}\left[\frac{\Pi_{WW}^{\rm NP}(m_W^2) - \Pi_{WW}^{\rm NP}(0)}{m_W^2} - \frac{c_W}{s_W}\frac{\Pi_{Z\gamma}^{\rm NP}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}^{\rm NP}(m_Z^2)}{m_Z^2}\right] - S,$$

$$S \approx \frac{1}{24\pi}\widetilde{\lambda}_4\frac{v^2}{\widetilde{m}_2^2},$$

$$T \approx \frac{1}{192\pi^2\alpha_{\rm em}}(\widetilde{\lambda}_4^2 - |\widetilde{\lambda}_5|^2)\frac{v^2}{\widetilde{m}_2^2}$$

$$m_W^2 = (m_W^{\rm SM})^2\left(1 + \frac{s_W^2}{c_W^2 - s_W^2}\Delta r'\right)$$

$$\Delta r' \equiv \frac{\alpha_{\rm em}}{s_W^2}\left(-\frac{1}{2}S + c_W^2 T + \frac{c_W^2 - s_W^2}{4s_W^2}U\right)$$

W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, Nucl. Phys. B 801 (2008) 81–96
W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, J. Phys. G 35 (2008) 075001
H. E. Haber and D. O'Neil, Phys. Rev. D 83 (Mar, 2011) 055017

$$\widetilde{\lambda}_4^2 - |\widetilde{\lambda}_5|^2 \approx \frac{4}{v^4}(m_{H_\pm}^2 - m_H^2)(m_{H_\pm}^2 - m_A^2)$$

M_W - Oblique Parameters

CDF Collaboration, C. Hays, PoS ICHEP2022 (2022) 898.

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W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, Nucl. Phys. B 801 (2008) 81–96
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