Modified Higgs Couplings and Unitarity Violation

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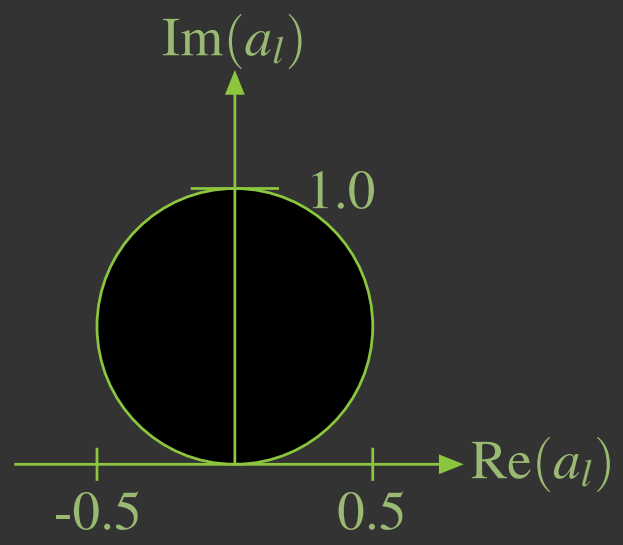
25th June, 2013

LHC Workshop at ICTP, Trieste, Italy

What Is Unitarity?

Every scattering amplitude can be expanded in terms of partial waves.

$$\mathcal{A}(\theta) = 16\pi \sum_{l=0}^{\infty} (2l+1) a_l P_l(\cos\theta) \tag{1}$$



Unitarity condition: $|a_l| \leq 1$.
If perturbative calculation is valid then unitarity must be obeyed at the tree level [1], i.e.,

$$|a_l^{tree}| \leq 1$$

Lesson : If the tree level amplitude grows with energy then we will have trouble with unitarity at high energies.

[1] M.S. Chanowitz et al, Nucl. Phys. B 153(1979) 402-430

$W_L W_L \to W_L W_L$ (SM)

Fig (a) Fig (b) Fig (c)

$$\mathcal{A}_{a,s}^{\gamma+Z} = -\frac{g^2E^4}{M_W^4}(4\cos\theta) - \frac{g^2E^2}{M_W^2}(\cos\theta) + \mathcal{O}(1) \quad (2)$$

$$\mathcal{A}_{a,t}^{\gamma+Z} = \frac{g^2E^4}{M_W^4}(3 - 2\cos\theta - \cos^2\theta) + \frac{g^2E^2}{2M_W^2}(15\cos\theta - 3) + \mathcal{O}(1) \quad (3)$$

$$\mathcal{A}_b = \frac{g^2E^4}{M_W^4}(6\cos\theta - 2 - \sin^2\theta) + \frac{g^2E^2}{M_W^2}(2 - 6\cos\theta) + \mathcal{O}(1) \quad (4)$$

$$\mathcal{A}_{\text{gauge}} = \frac{g^2E^2}{2M_W^2}(1 + \cos\theta) + \mathcal{O}(1) \quad (5)$$

$$\mathcal{A}_{c,h}^{s+t} = -\frac{g^2E^2}{2M_W^2}(1 + \cos\theta) - \frac{g^2M_H^2}{2M_W^2} + \mathcal{O}\left(\frac{1}{E^2}\right) \quad (6)$$

$e^-(p_1) + e^+(p_2) \to W_L^-(k_1) + W_L^+(k_2)$ (SM)

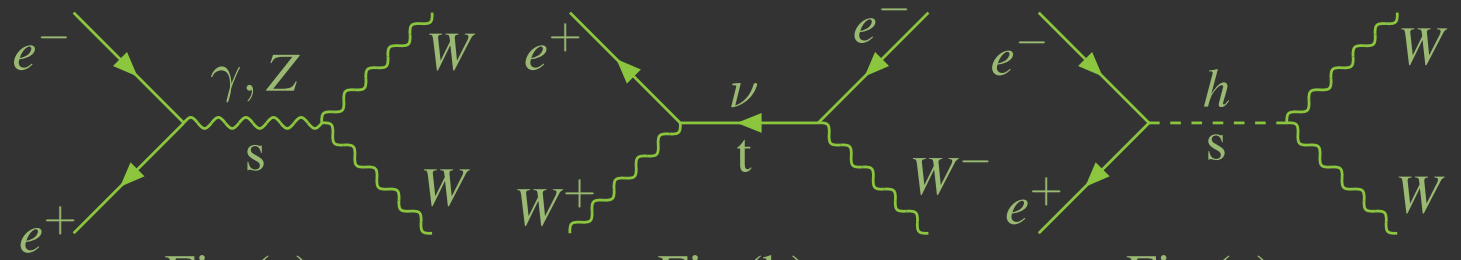


Fig (a) Fig (b) Fig (c)

$$\mathcal{A}_a^\gamma = \frac{e^2}{M_W^2}\bar{v}_2 \not{k}_1 u_1 + \mathcal{O}(1) \tag{7}$$

$$\mathcal{A}_a^Z = \frac{g\cos\theta_w}{2M_W^2}\left[\frac{g}{\cos\theta_w}(1/2 - \sin^2\theta_w)\bar{v}_2\not{k}_1 u_1 - \frac{g}{2\cos\theta_w}\bar{v}_2\not{k}_1\gamma^5 u_1 - m_e\frac{g}{2\cos\theta_w}\bar{v}_2\gamma^5 u_1\right] + \mathcal{O}(1) \tag{8}$$

$$\mathcal{A}_b = -\frac{g^2}{4M_W^2}\left[\bar{v}_2\not{k}_1(1-\gamma^5)u_1 + m_e\bar{v}_2(1-\gamma^5)u_1\right] + \mathcal{O}(1) \tag{9}$$

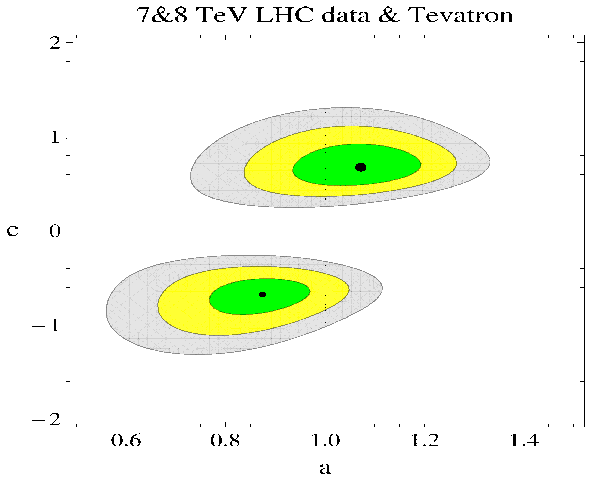
$$\mathcal{A}^{\text{without higgs}} = \mathcal{A}_a^\gamma + \mathcal{A}_a^Z + \mathcal{A}_b = -\frac{g^2}{4M_W^2}m_e\bar{v}_2 u_1 + \mathcal{O}(1) \tag{10}$$

$$\mathcal{A}_c = \frac{g^2 m_e}{4M_W^2}\bar{v}_2 u_1 + \mathcal{O}\left(\frac{1}{E}\right) \tag{11}$$

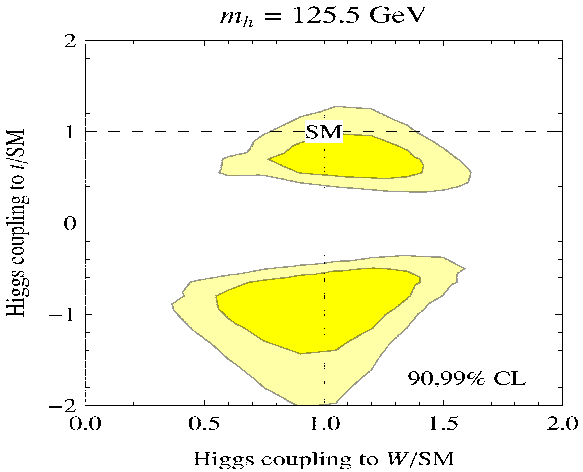
Non-Standard Couplings and Global Fits

$$g_{VVh} = (1-x) \times (g_{VVh})^{\rm SM} \quad (12)$$

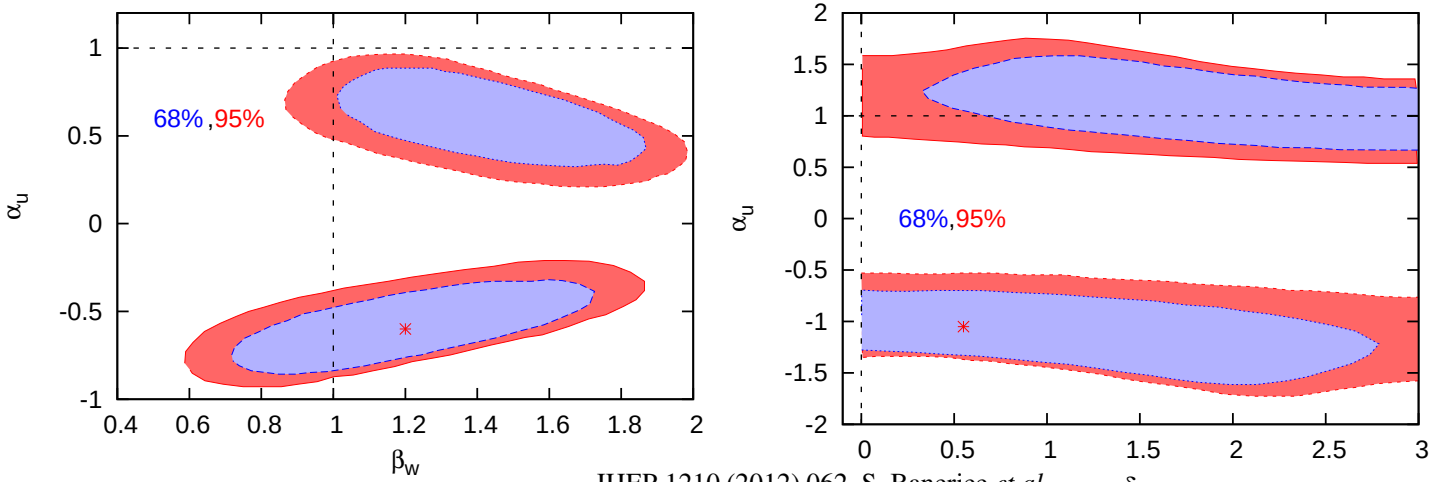
$$g_{tth} = (1-f)e^{-i\delta\gamma_5} \times (g_{tth})^{\rm SM} \quad (13)$$



JHEP 1212 (2012) 045
J. R. Espinosa *et al.*



Phys.Lett. B718 (2012) 469-474
P. P. Giardino *et al.*



JHEP 1210 (2012) 062, S. Banerjee *et al.*

Non-Standard Couplings and Unitarity

We have derived the following amplitudes at the leading order,

$$\mathcal{A}^{WW\to WW} = 2\sqrt{2}G_F E^2(2x - x^2)(1+\cos\theta) \quad (14)$$

$$\mathcal{A}^{\bar{t}t\to WW} = -2\sqrt{2}G_F m_t e^{-i\delta} Y(x,f,\delta)E \quad (15)$$

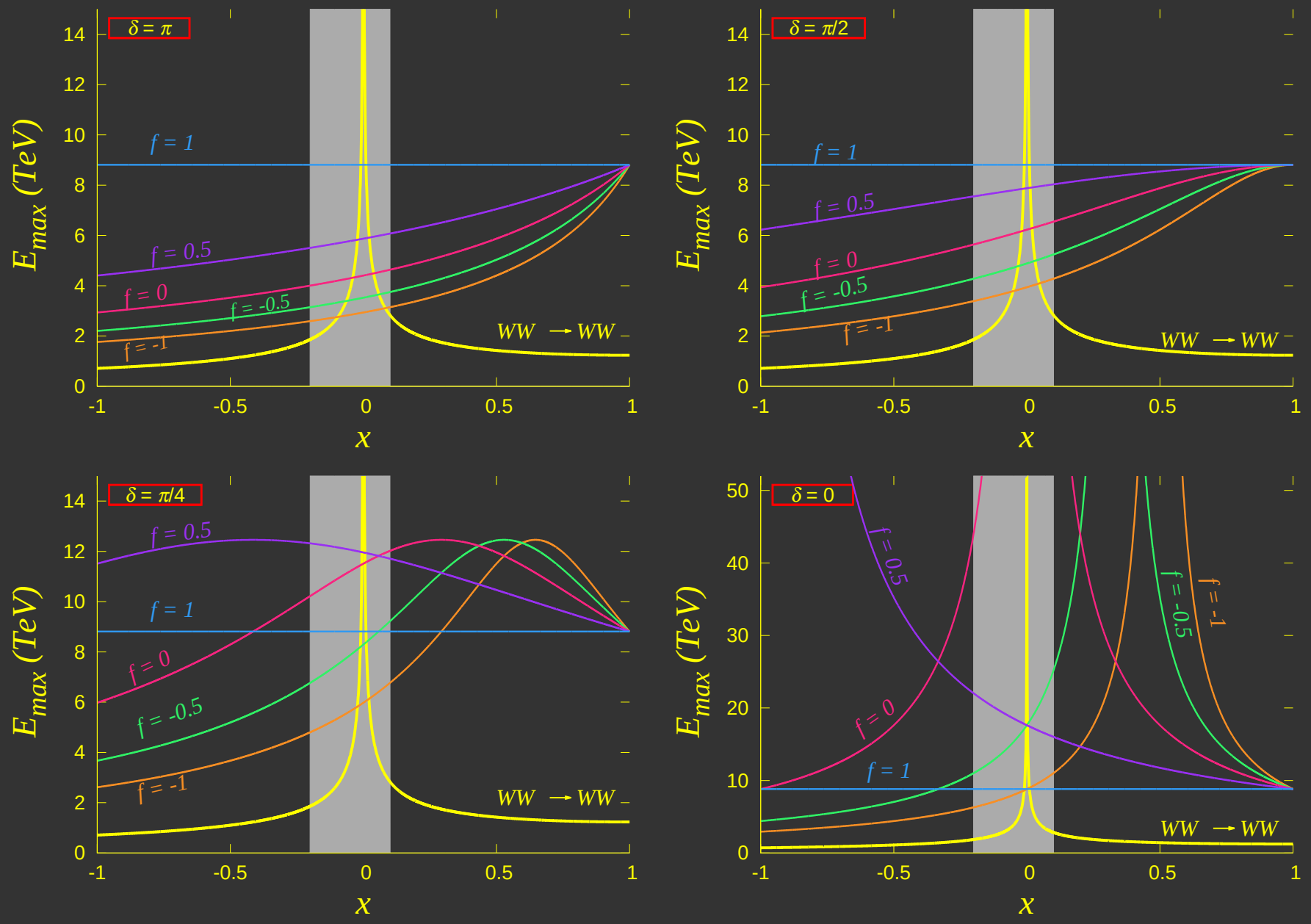
where, E is the CM energy, m_t is the top-quark mass, θ is the scattering angle, and

$$Y(x,f,\delta) = \left[e^{i\delta} - (1-f)(1-x)\right] \quad (16)$$

For Eq. (15) we have assumed the initial state fermions have the same helicities. The final energy growth in Eq. (15) will have the same structure for all SM fermions. The unitarity condition $|a_0| \leq 1$ puts the following limits on the CM energy :

$$E_{\max} \leq \left(\frac{4\sqrt{2}\pi}{G_F}\frac{1}{|(2x-x^2)|}\right)^{\frac{1}{2}} \quad [\text{from } WW \to WW] \quad (17)$$

$$E_{\max} \leq \frac{4\sqrt{2}\pi}{G_F m_t}\frac{1}{|Y(x,f,\delta)|} \quad [\text{from } \bar{t}t \to WW] \quad (18)$$


δ = π
δ = π/2
δ = π/4
δ = 0
f = 1
f = 0.5
f = 0
f = -0.5
f = -1
WW → WW
E_max (TeV)
x

Enhanced Diphoton Rate and Unitarity

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 g^2}{2^{10}\pi^3}\frac{m_h^3}{M_W^2}\left[\left|(1-x)F_w + \frac{4}{3}(1-f)\cos\delta\, F_t\right|^2 + \left|\frac{4}{3}(1-f)\sin\delta\, P_t\right|^2\right]$$

where, SM corresponds to $x, f, \delta = 0$, and

$$F_w = 2 + 3\tau_w + 3\tau_w(2-\tau_w)f(\tau_w) \quad (19)$$

$$F_t = -2\tau_t\left[1 + (1-\tau_t)f(\tau_t)\right] \quad (20)$$

$$P_t = 2\tau_t f(\tau_t) \quad (21)$$

with $\tau_w = \left(\frac{2M_W}{m_h}\right)^2$ and $\tau_t = \left(\frac{2m_t}{m_h}\right)^2$. Since $m_h \approx 125$ GeV, both τ_w and τ_t are greater than 1. Hence,

$$f(\tau) = \left[\sin^{-1}\left(\sqrt{\frac{1}{\tau}}\right)\right]^2 \quad (22)$$

Partial decay width modification :

$$R_{\gamma\gamma} = \frac{|(1-x)F_w + \frac{4}{3}(1-f)\cos\delta\, F_t|^2 + +|\frac{4}{3}(1-f)\sin\delta\, P_t|^2}{|F_w + \frac{4}{3}F_t|^2} \quad (23)$$

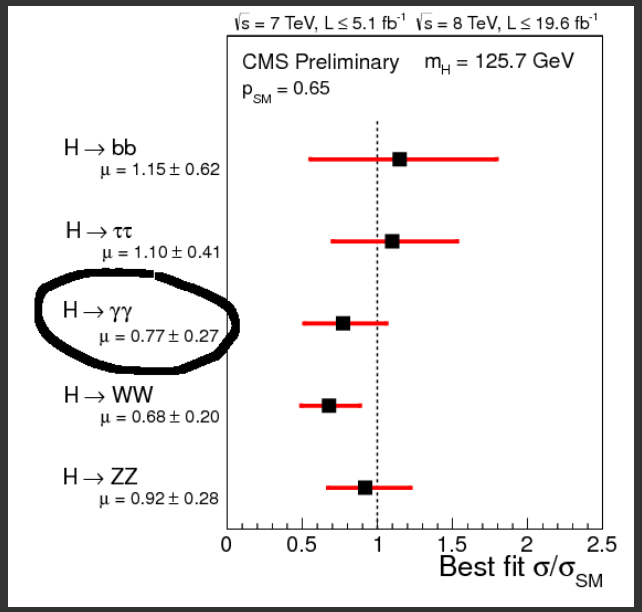
A 125 GeV Higgs decays mainly into, $b\bar{b}(58\%)$, $\tau^+\tau^-(7\%)$, $c\bar{c}(3\%)$, $VV^*(24\%)$ and $gg(8\%)$. Total decay width modification :

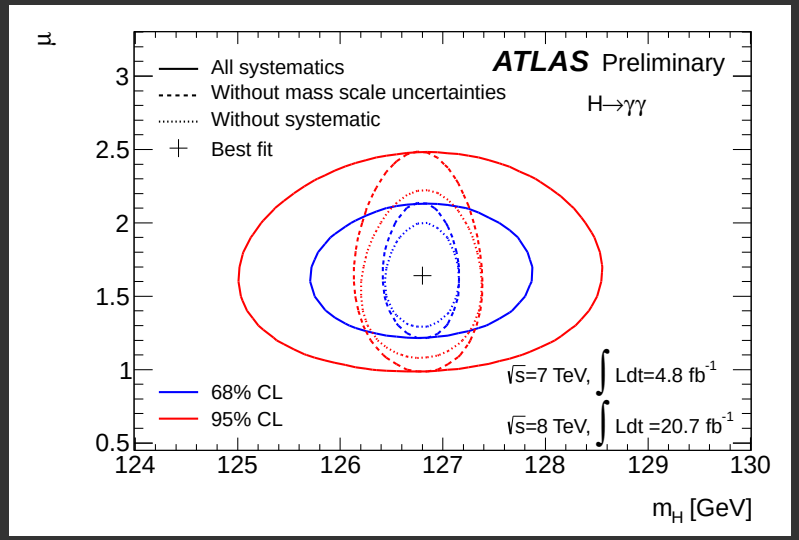
$$R_T = (58\% + 7\% + 3\%) + (1-x)^2 24\% + gl(f,\delta)8\% \tag{24}$$

Around 85% of Higgs is produced via gluon-gluon fusion and 15% via vector boson fusion and vector boson associated production. Production cross section should be modified as,

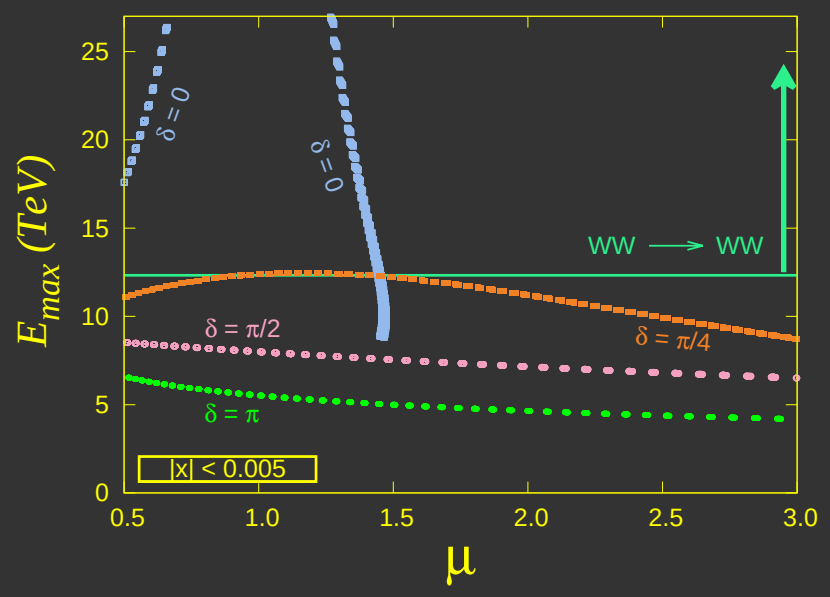
$$R_P = (1-x)^2 15\% + gl(f,\delta)85\% \tag{25}$$

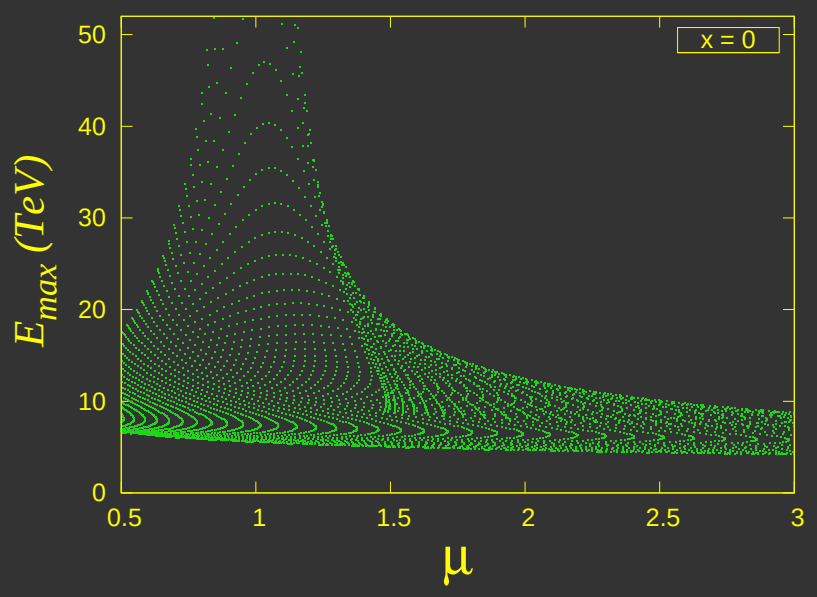
$$\mu = R_P \times \frac{R_{\gamma\gamma}}{R_T}\ ; \quad gl(f,\delta) = (1-f)^2 \frac{|\cos\delta\, F_t|^2 + |\sin\delta\, P_t|^2}{|F_t|^2} \tag{26}$$





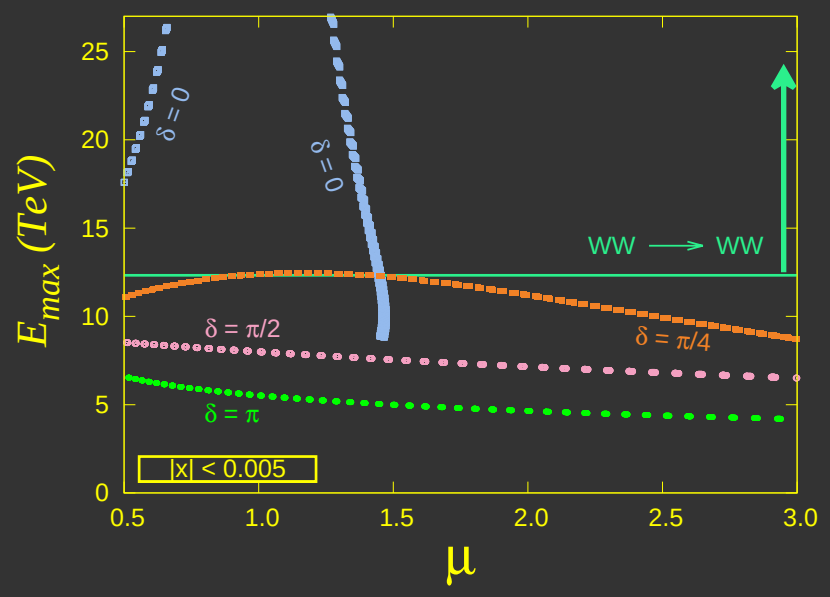
Results and Conclusion

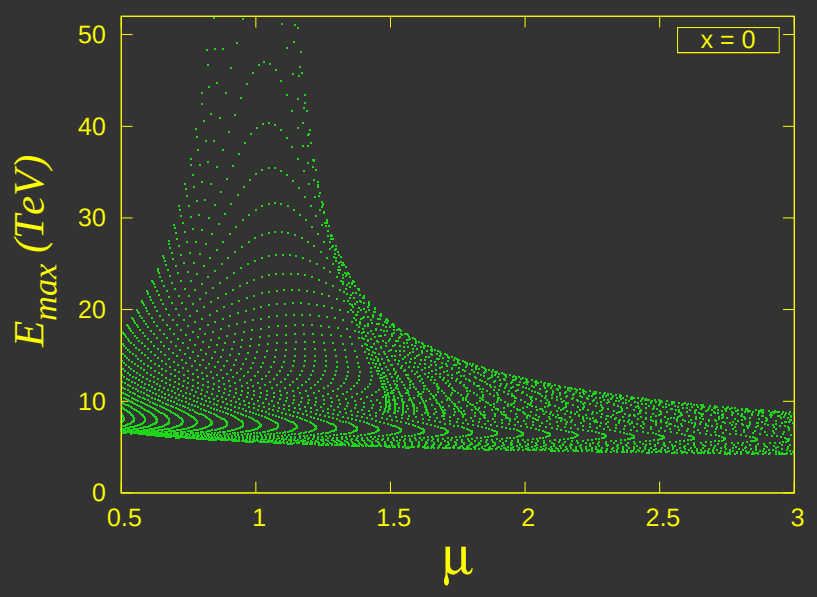




- We have done a quantitative analysis of how the unitarity violation scale depends on the non-standard parameters.
- If the Higgs couplings settle to non-standard values then above plots can be used to read the upper limit of the energy scale below which new physics must set in.

Results and Conclusion





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THANK YOU