Beyond the Standard Model

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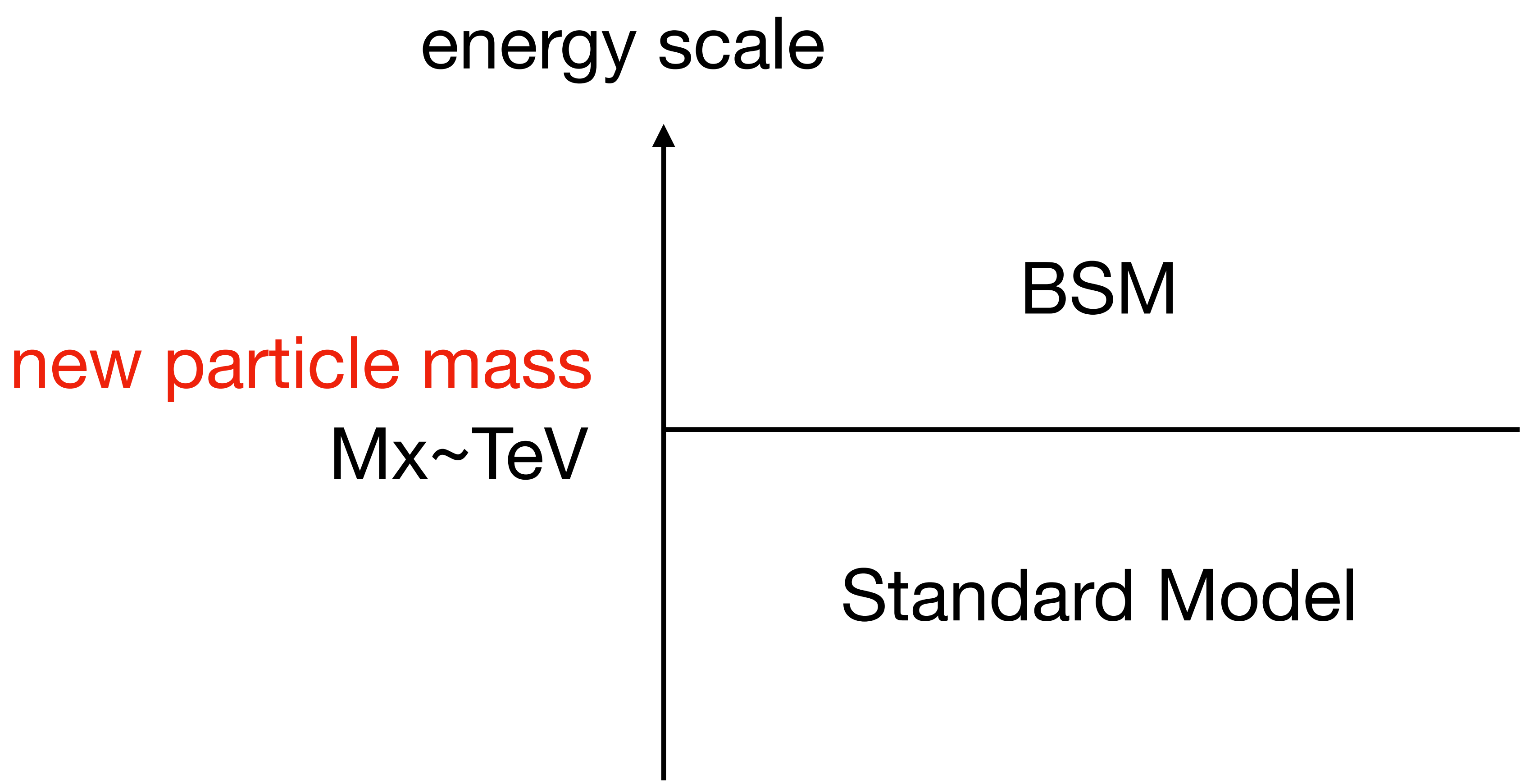
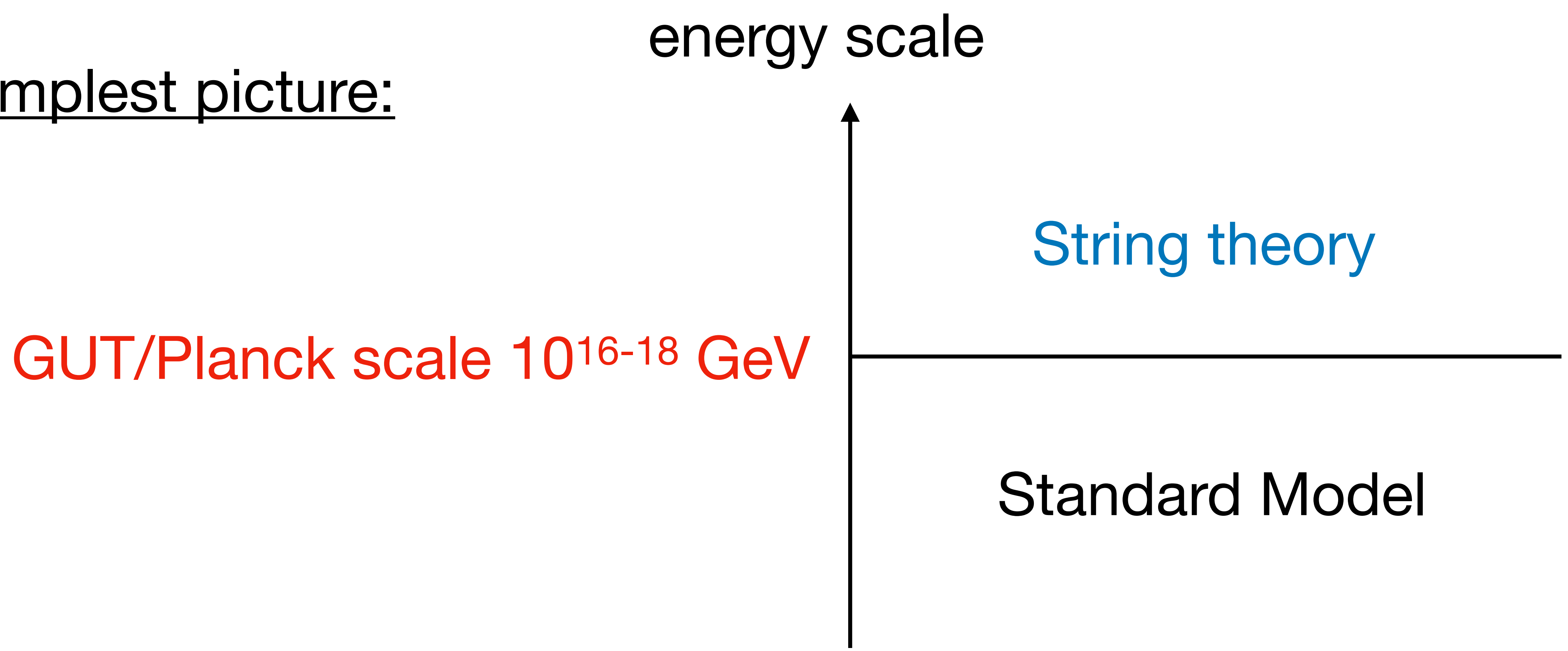
History of understanding particle physics gave us this (naturalness) picture:



This is not a theorem, but I think this is a well-educated guess.

simplest picture:



Either of them is wrong.

natural picture:

Higgs mass or VEV $(125\text{GeV})^2$ = (at most one-loop factors) * Mx^2

$\Rightarrow$ Mx ~ TeV or less.

energy scale

simplest picture:

String theory

GUT/Planck scale 10^{16-18} GeV

Standard Model

To me, this is too radical.

Either of them is wrong.

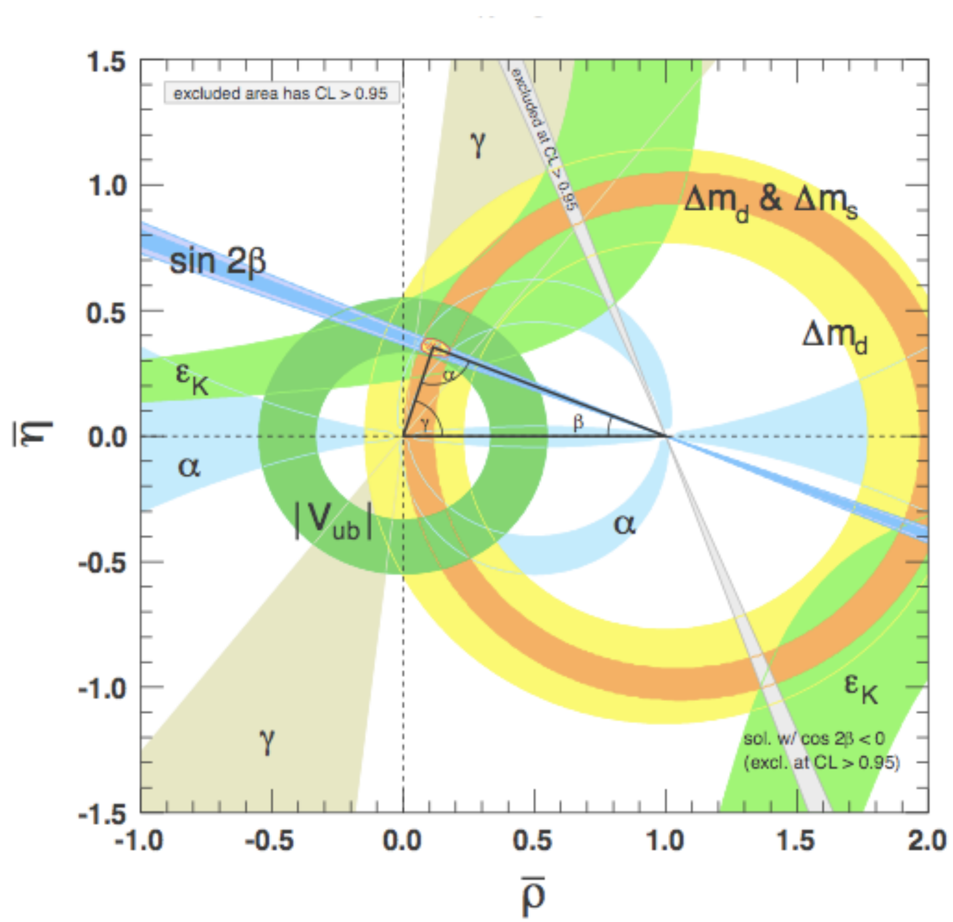
natural picture:

Higgs mass or VEV $(125\text{GeV})^2$ = (at most one-loop factors) * Mx^2

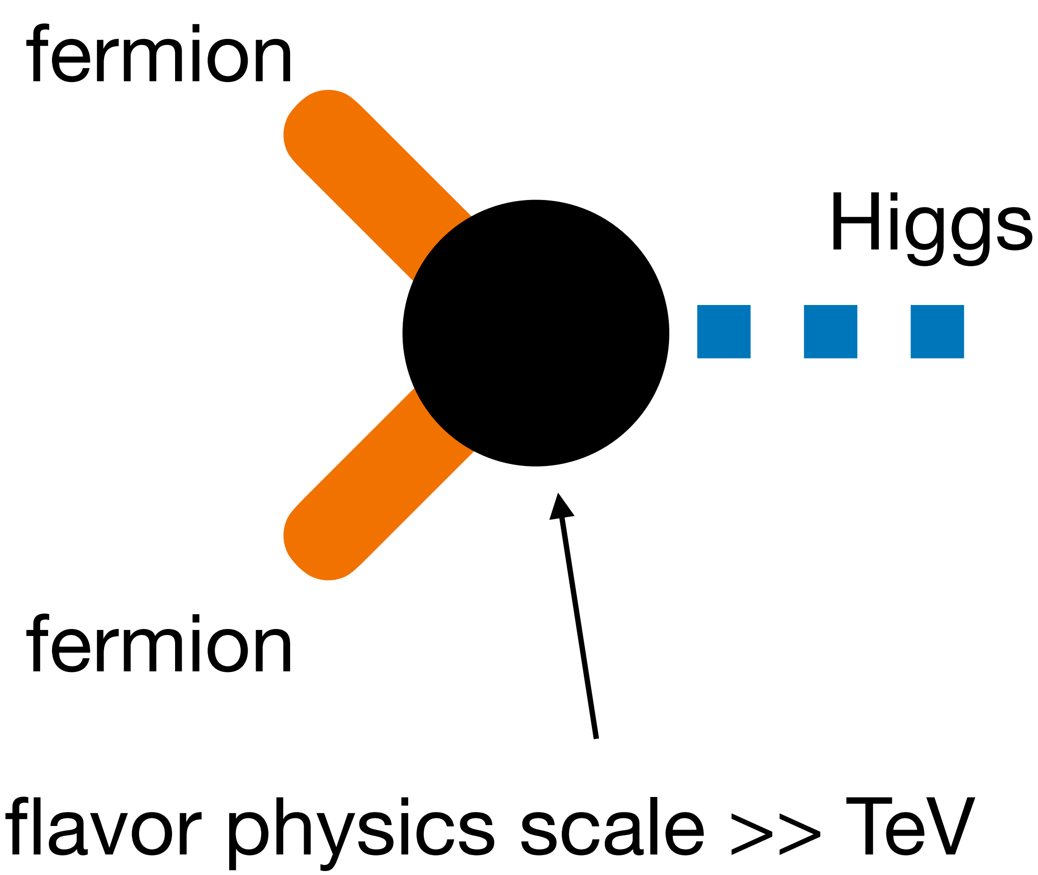
But this equation itself is not looking good. → Mx ~ TeV or less.

Flavor?

Very good agreement with the CKM paradigm.



gure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.



Roughly speaking, “don’t touch flavor” at TeV.

Confusing..

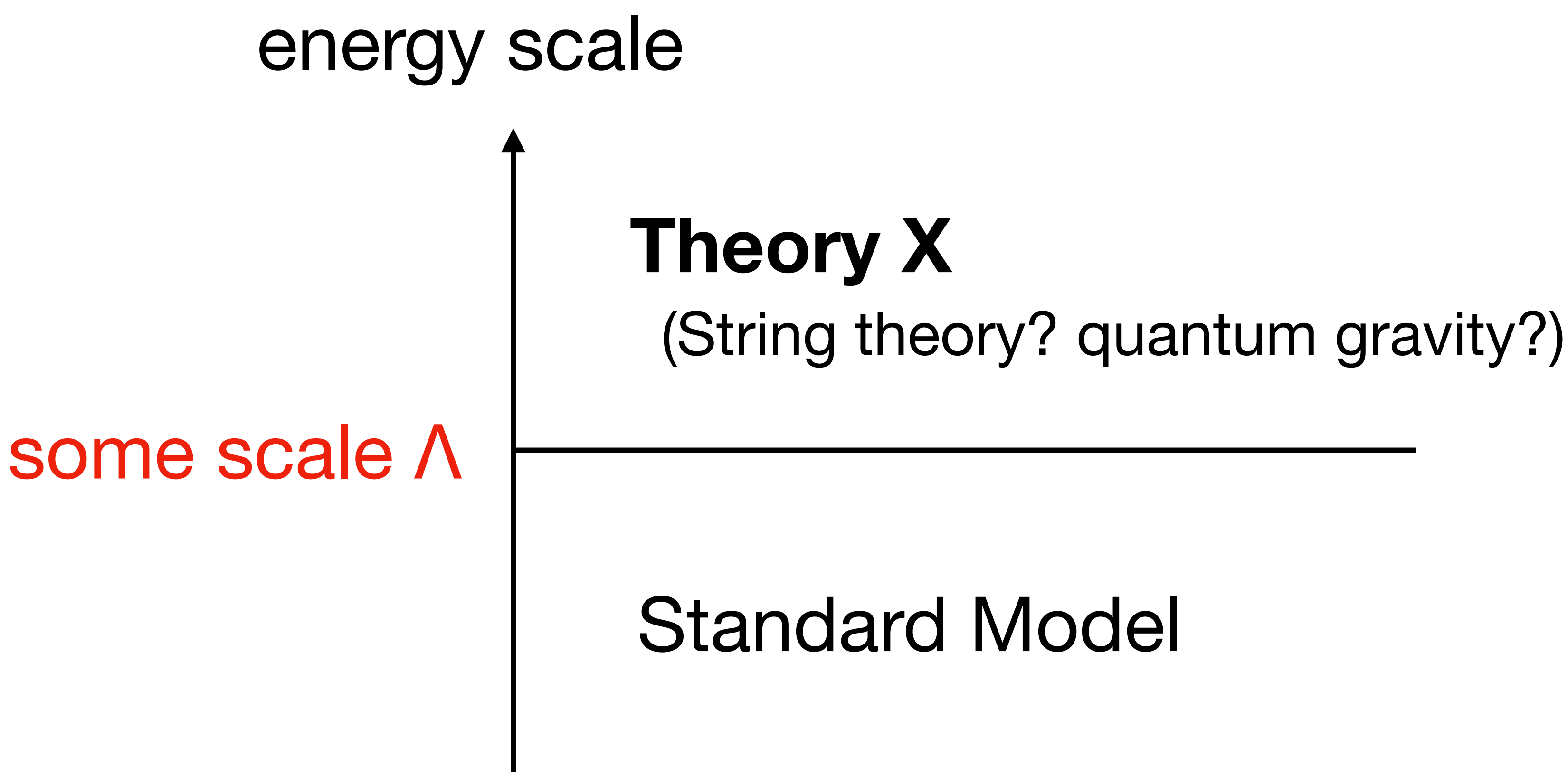
where to look for new physics?

I'll try to take the "**radical**" and "**optimistic**" attitudes today and discuss what to look for.

Sorry, I tried to review BSM, but I don't know what to talk now. Instead, I'll talk about something what I think is interesting now.

[RK, Okawa in progress]

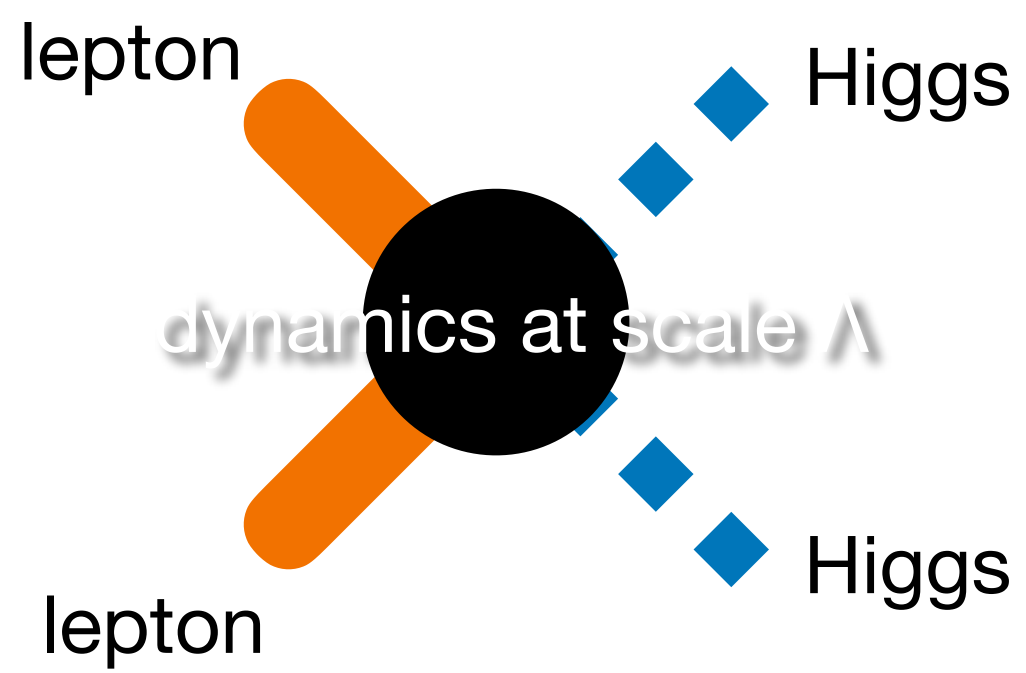
Radical view of BSM:
(Don’t care about naturalness)



* Theory X explains “neutrino masses.”
* Theory X explains “flavor structure.”
* don’t care about “EW hierarchy problem.”

neutrino masses can be very simply accommodated:

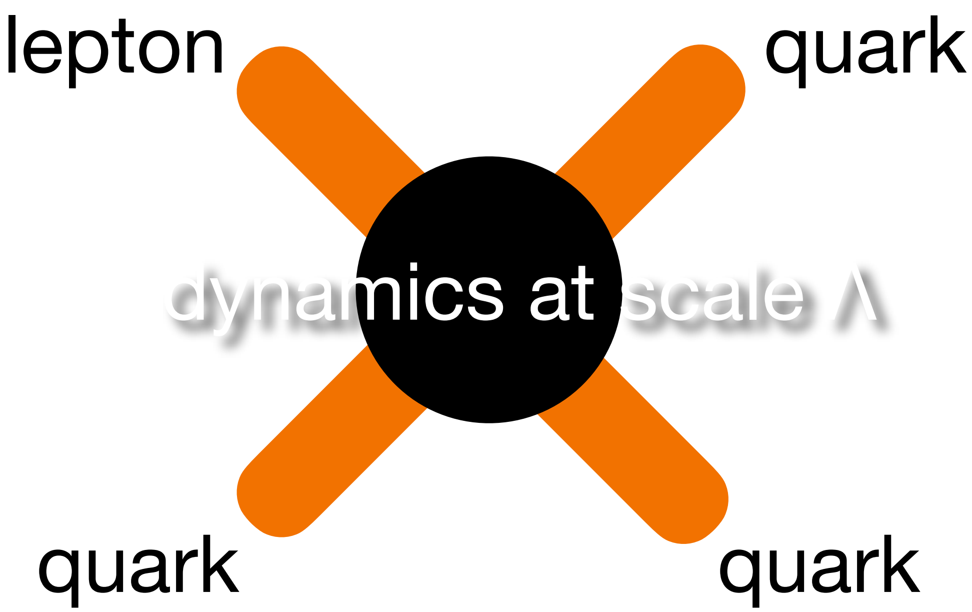
$$\frac{\lambda_{ij}^{(\nu)}}{\Lambda} l_i l_j H H$$



$$\Rightarrow \quad m_\nu^{ij} = \frac{\lambda_{ij}^{(\nu)} v^2}{\Lambda}$$

$$\frac{\lambda^{(\nu)}}{\Lambda} \sim \frac{1}{10^{15}\ \mathrm{GeV}}$$

at the same time, we expect to have this type of operators:

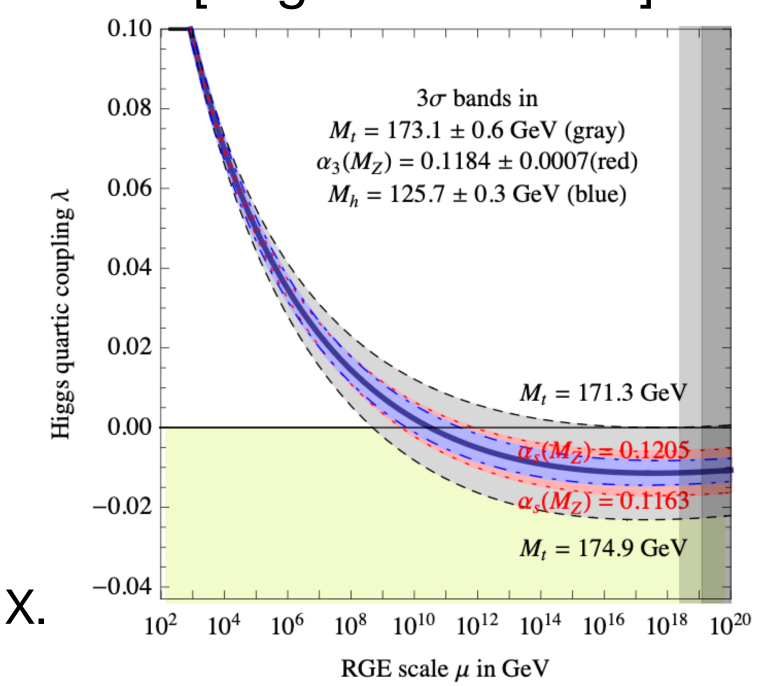


$$\frac{\lambda^{(B)}_{ijkl}}{\Lambda^2} q_i q_j q_k l_l$$

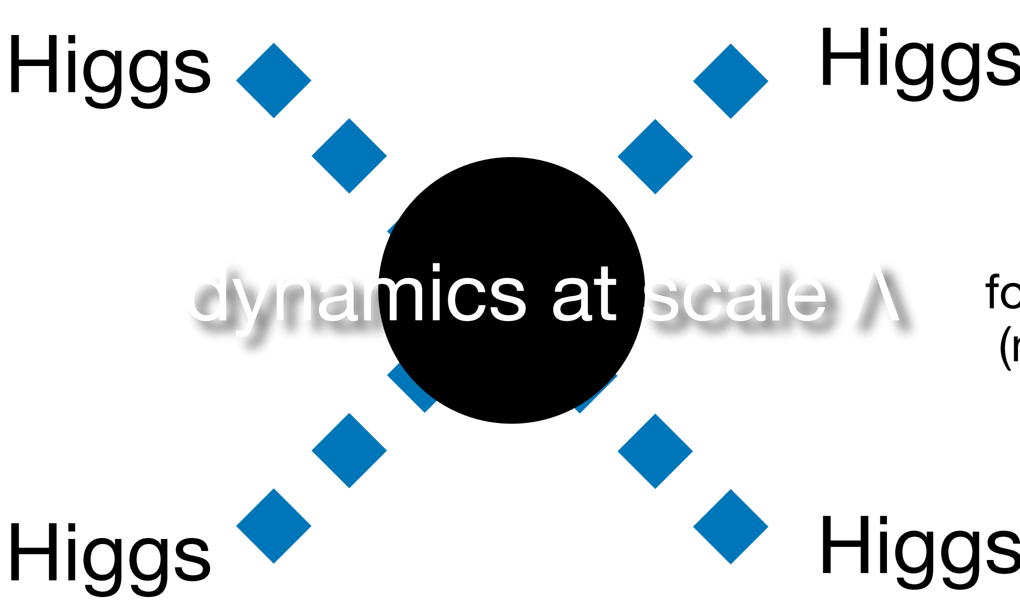
(There are four types of those.)

This will cause the proton decays!

[Degrassi et al ’12]



Also, we should assume



$$\lambda_H(\Lambda) > 0$$

for the stability of the vacuum in Theory X.
(not strict though.)

Do we have a consistent picture?

flavor data:

$$m_u = 1.5 - 3.3\ \mathrm{MeV}, \quad m_d = 3.5 - 6.0\ \mathrm{MeV}, \quad m_s = 70 - 130\ \mathrm{MeV},$$

$$m_c = 1.3\ \mathrm{GeV}, \quad m_b = 4.2\ \mathrm{GeV}, \quad m_t = 171\ \mathrm{GeV},$$

$$V_{\mathrm{CKM}} \simeq \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ * & 0.96 & 0.04 \\ * & * & \sim 1 \end{pmatrix}$$

$$m_e = 0.5\ \mathrm{MeV}, \quad m_\mu = 106\ \mathrm{MeV}, \quad m_\tau = 1.78\ \mathrm{GeV},$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5}\ \mathrm{eV}^2, \quad \Delta m_{31}^2 \simeq \pm 2 \times 10^{-3}\ \mathrm{eV}^2$$

$$U \simeq \begin{pmatrix} 0.8 & 0.6 & 0.15 \\ * & 0.5 & 0.7 \\ * & * & 0.7 \end{pmatrix}$$

Interestingly, these can be beautifully explained by the ε scheme.

fun with ε's:

$$\mathcal{L}_{\rm mass} = -f_d^{ij}\bar{q}_i d_j H - f_u^{ij}\bar{q}_i u_j \widetilde{H} - f_e^{ij}\bar{\ell}_i e_j H - \frac{\lambda_{ij}}{\Lambda}(\bar{\ell}_i H)(\ell_i^c H) + \text{h.c.}$$

$$\boxed{f_u^{ij} \sim \lambda_{\rm yuk}^{ij}\,\epsilon_{q_i}\epsilon_{u_j}\,, \quad f_d^{ij} \sim \lambda_{\rm yuk}^{ij}\,\epsilon_{q_i}\epsilon_{d_j}\,, \quad f_e^{ij} \sim \lambda_{\rm yuk}^{ij}\,\epsilon_{\ell_i}\epsilon_{e_j}\,, \quad \lambda_{ij} \sim (\lambda_{\rm yuk}^2)^{ij}\,\epsilon_{\ell_i}\epsilon_{\ell_j}\,,}$$

O(4π) or less

suppression factors associated with each fields.

$$\epsilon_{q_i} \propto V_{i3} \simeq (0.004, 0.04, 1)\,,$$

(consistent with Cabibbo angle)

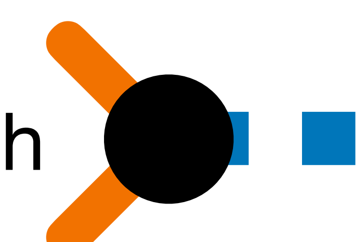
$$\epsilon_{u_i} \propto m_{u_i}/V_{i3} \propto (0.004, 0.2, 1)\,,$$

$$\epsilon_{d_i} \propto m_{d_i}/V_{i3} \propto (0.2, 0.6, 1)$$

$$\epsilon_{\ell_i} \propto U_{i3} \simeq (0.15, 0.7, 0.7)\,, \longrightarrow m_{\nu_i} \propto (\epsilon_{\ell_i})^2 \propto (0.04, 1, 1).$$

consistent with normal hierarchy.

$$\epsilon_{e_i} \propto m_{e_i}/\epsilon_{\ell_i} \propto (0.001, 0.06, 1)\,.$$

This is quite non-trivial and fits well with  this picture.

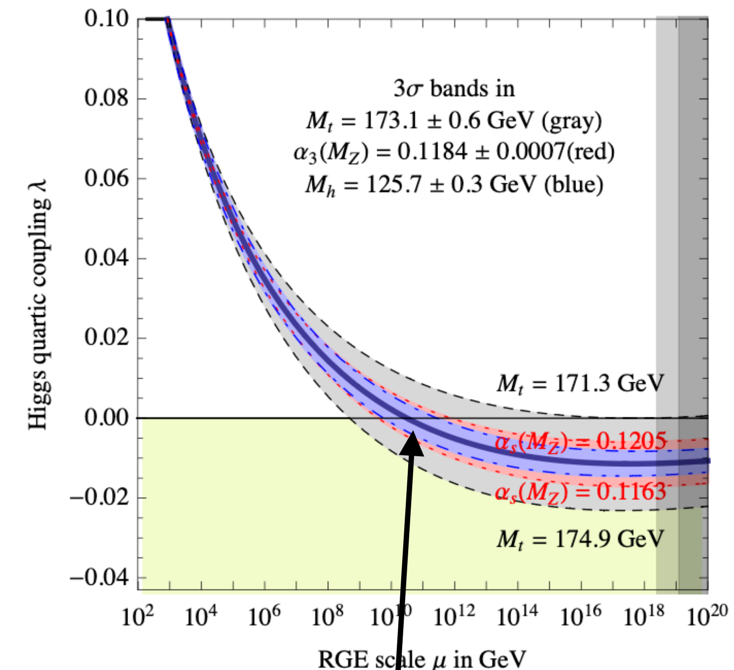
In order to reproduce the τ mass, and neutrino masses, one finds

$$\Lambda \gtrsim 1.3 \times 10^{11}\,\mathrm{GeV}$$

barely consistent with

$$\lambda_H(\Lambda) > 0$$

[Degrassi et al ’12]



for $\Lambda \sim 10^{11}$ GeV for which $\varepsilon_{e3}\sim 1$, $\lambda_{yuk}\sim 4\pi$.

Interesting. We may have something dramatic here.

Now, then

$$\mathcal{L}^{d=6}_{\mathrm{BNV}} = \sum_i C_{I,\,ijkl}\mathcal{O}_{I,\,ijkl}\,,$$

$$\mathcal{O}_{qqq\ell,\,ijkl} = (q_i^\alpha q_j^\beta)(q_k^\gamma \ell_l^\delta)\epsilon_{\alpha\gamma}\epsilon_{\beta\delta}$$
$$\mathcal{O}_{qque,\,ijkl} = (q_i^\alpha q_j^\beta)(\bar{u}_k^\dagger \bar{e}_l^\dagger)\epsilon_{\alpha\beta}$$
$$\mathcal{O}_{duue,\,ijkl} = (\bar{d}_i^\dagger \bar{u}_j^\dagger)(\bar{u}_k^\dagger \bar{e}_l^\dagger)$$
$$\mathcal{O}_{duq\ell,\,ijkl} = (\bar{d}_i^\dagger \bar{u}_j^\dagger)(q_k^\alpha \ell_l^\beta)\epsilon_{\alpha\beta}$$

$$C_{qqql,\,ijkl} = \lambda^2_{\mathrm{BNV}}\frac{c_{qqq\ell}}{\Lambda^2}\epsilon_{q_i}\epsilon_{q_j}\epsilon_{q_k}\epsilon_{\ell_l}\,, \qquad C_{qque,\,ijkl} = \lambda^2_{\mathrm{BNV}}\frac{c_{qque}}{\Lambda^2}\epsilon_{q_i}\epsilon_{q_j}\epsilon_{u_k}\epsilon_{e_l}\,,$$

$$C_{duue,\,ijkl} = \lambda^2_{\mathrm{BNV}}\frac{c_{qque}}{\Lambda^2}\epsilon_{d_i}\epsilon_{u_j}\epsilon_{u_k}\epsilon_{e_l}\,, \qquad C_{duql,\,ijkl} = \lambda^2_{\mathrm{BNV}}\frac{c_{duq\ell}}{\Lambda^2}\epsilon_{d_i}\epsilon_{u_j}\epsilon_{q_k}\epsilon_{\ell_l}\,,$$

$\lambda \sim 4\pi$, $\Lambda \sim 10^{11}$GeV gives

SK/HK can reach!?

$$\Gamma^{-1}(p\to\pi^0 e^+)_{\min} \simeq 7.1\times 10^{37}\,\mathrm{yrs}$$
$$\Gamma^{-1}(p\to K^0 e^+)_{\min} \simeq (1.0-6.6)\times 10^{37}\,\mathrm{yrs}$$
$$\Gamma^{-1}(p\to K^+ \bar{\nu}_e)_{\min} \simeq 1.4\times 10^{38}\,\mathrm{yrs}$$

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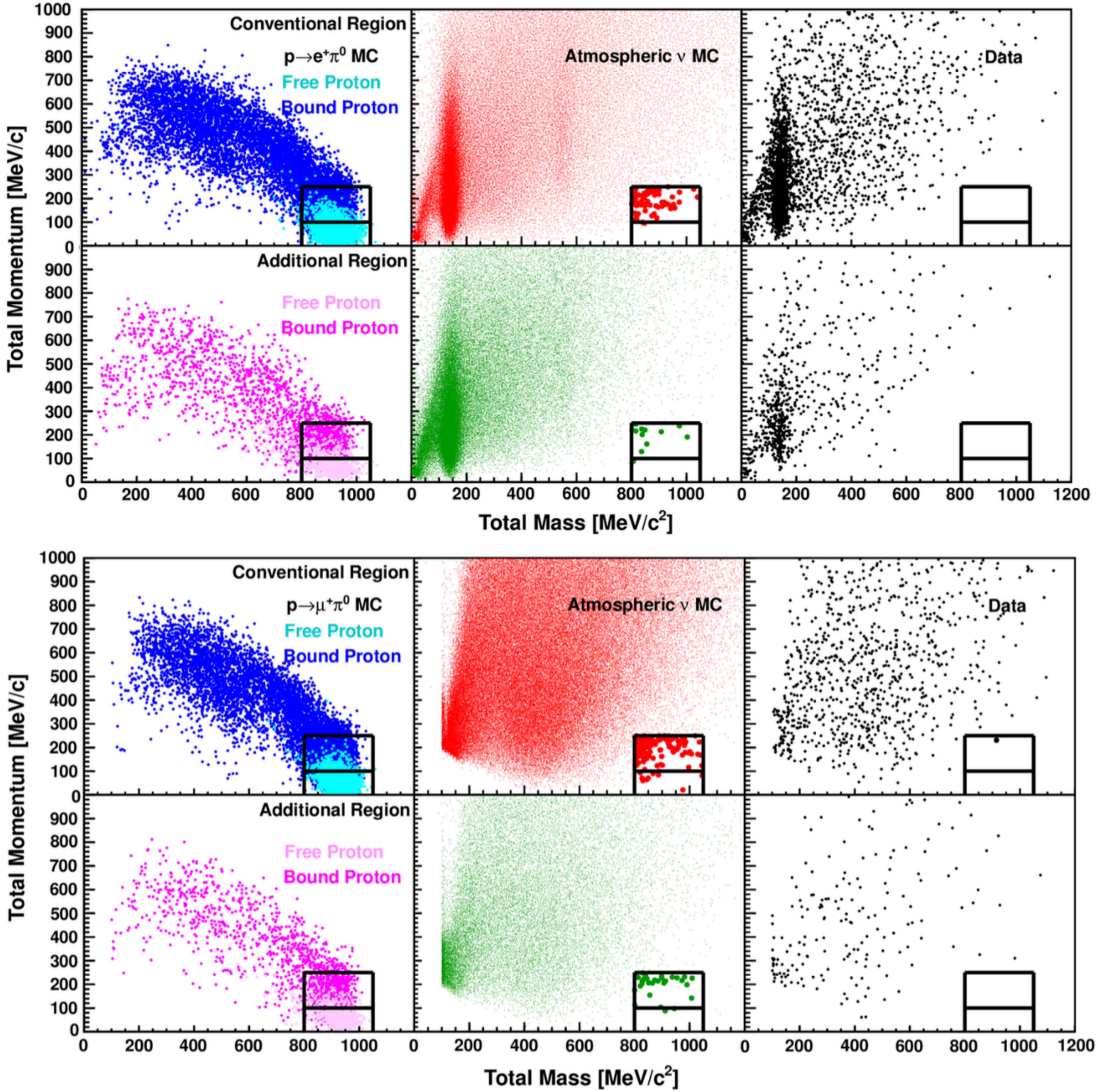
$$\boxed{\begin{aligned}\Gamma^{-1}(p\to\pi^0 \mu^+)_{\min} &\simeq 3.6\times 10^{34}\,\mathrm{yrs}\\ \Gamma^{-1}(p\to K^0 \mu^+)_{\min} &\simeq 0.51\times 10^{34}\,\mathrm{yrs}\\ \Gamma^{-1}(p\to \eta \mu^+)_{\min} &\simeq 6.1\times 10^{36}\,\mathrm{yrs}\end{aligned}}$$

$$\Gamma^{-1}(p\to\pi^0 e^+) \geq 2.4\times 10^{34}\,\mathrm{yrs}\ [15]$$
$$\Gamma^{-1}(p\to K^0 e^+) \geq 0.10\times 10^{34}\,\mathrm{yrs}\ [16]$$
$$\Gamma^{-1}(p\to K^+ \bar{\nu}_e) \geq 0.59\times 10^{34}\,\mathrm{yrs}\ [17]$$

$$\Gamma^{-1}(p\to\pi^0 \mu^+) \geq 1.6\times 10^{34}\,\mathrm{yrs}\ [15]$$
$$\Gamma^{-1}(p\to K^0 \mu^+) \geq 0.36\times 10^{34}\,\mathrm{yrs}\ [19]$$
$$\Gamma^{-1}(p\to \eta \mu^+) \geq 0.73\times 10^{34}\,\mathrm{yrs}\ [20]$$

already?

[SK ’20]



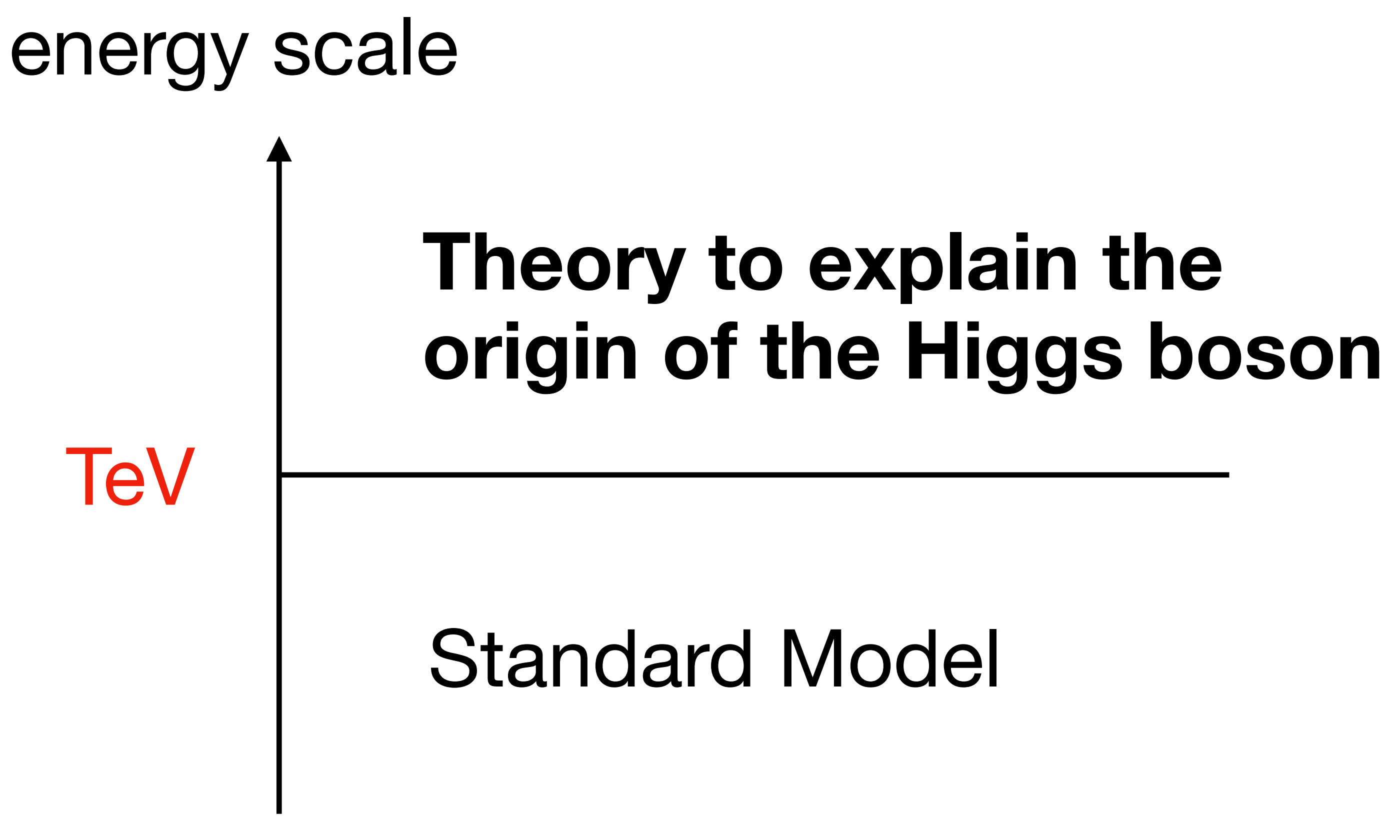
eπ mode

μπ mode

!

Optimistic view of BSM:

(The origin of Higgs will be revealed soon.)



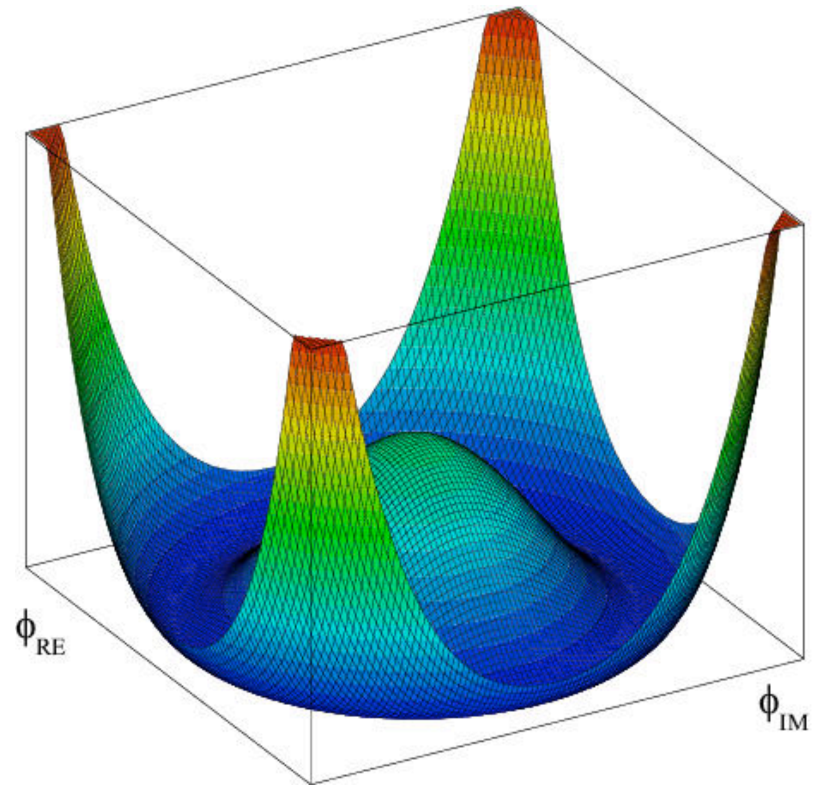
If this is the case, Higgs must be a bit away from the SM Higgs.

The central question would be “How Higgs is the Higgs?”

Of course,

the coupling measurements, especially, the hhh coupling are very important to see the nature of the Higgs boson/potential.

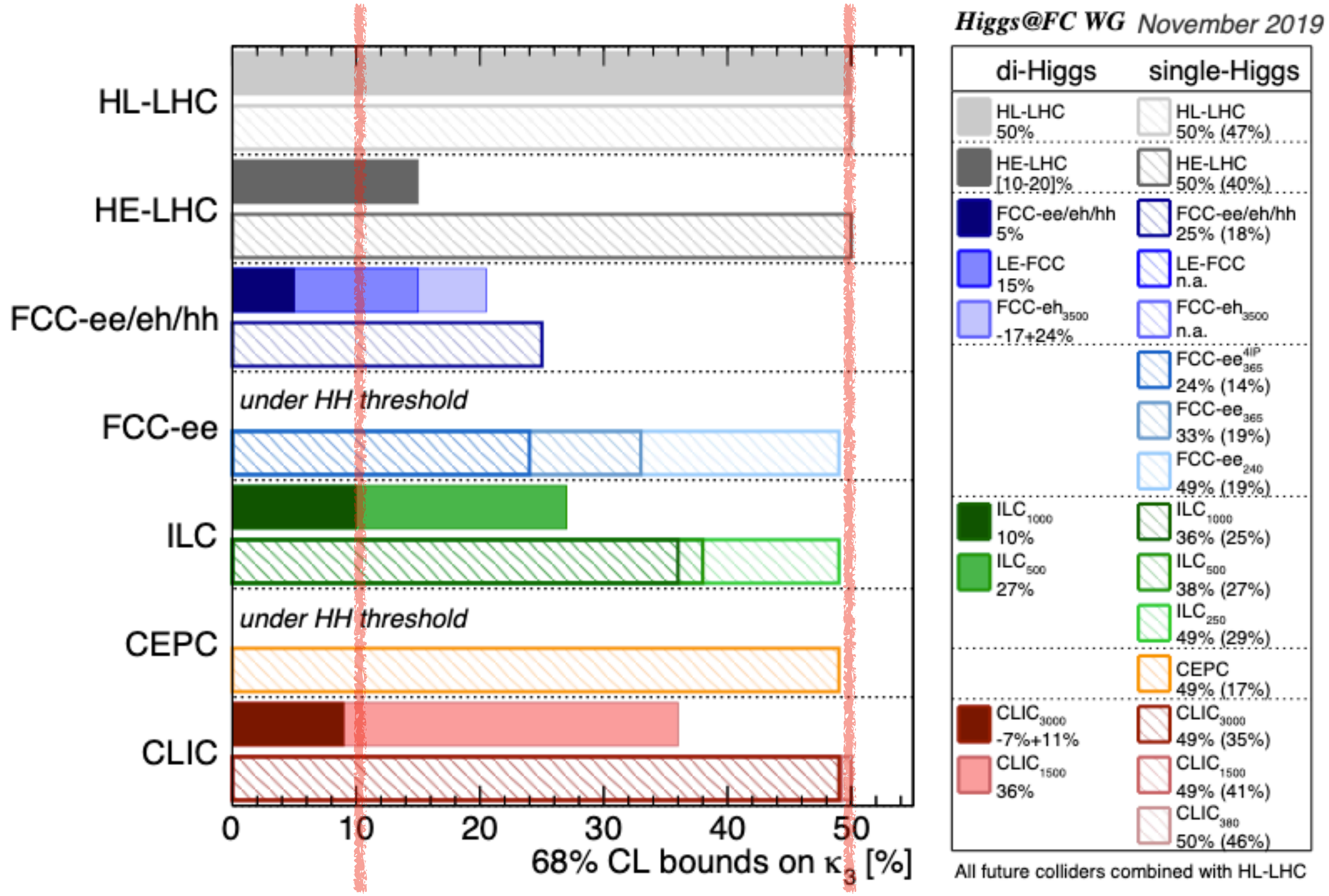
[from Wikipedia]



Is this really $-aH^2+bH^4$?

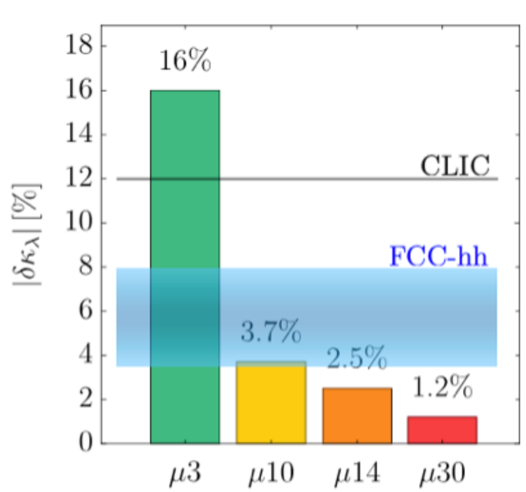
Which one do you want?

[Higgs boson potential at colliders: 1910.00012]



great if we can reach here.

50%. Already very important.



Muon collider

[Muon Collider Physics Summary: 2203.07256]

To me FCC-hh and/or Muon collider.

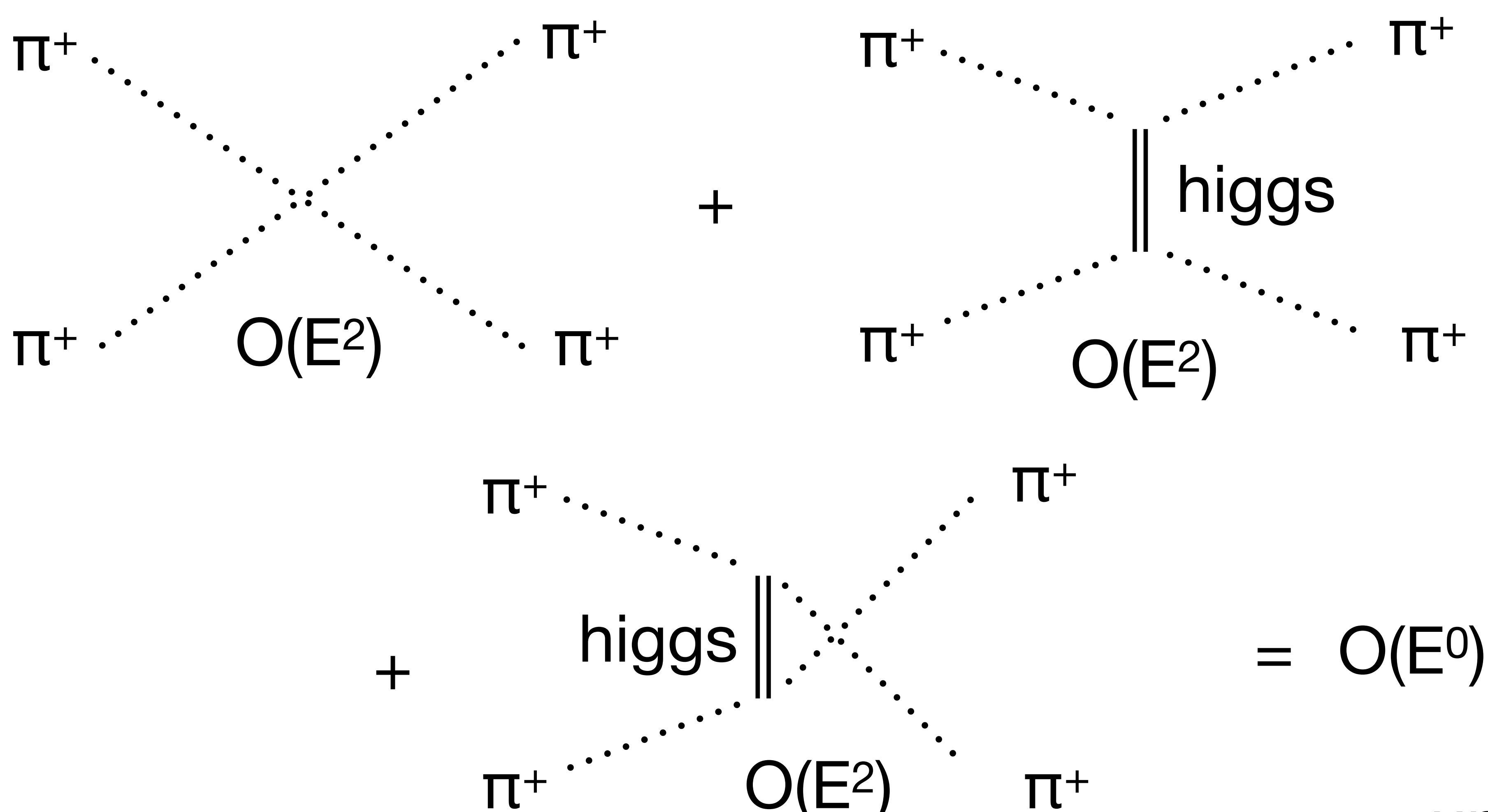
But I'll be dead before FCC-hh…

If we have 10TeV collider, one can ask more.

How Higgs is the Higgs?

Amplitudeology

scattering of longitudinal polarization of W

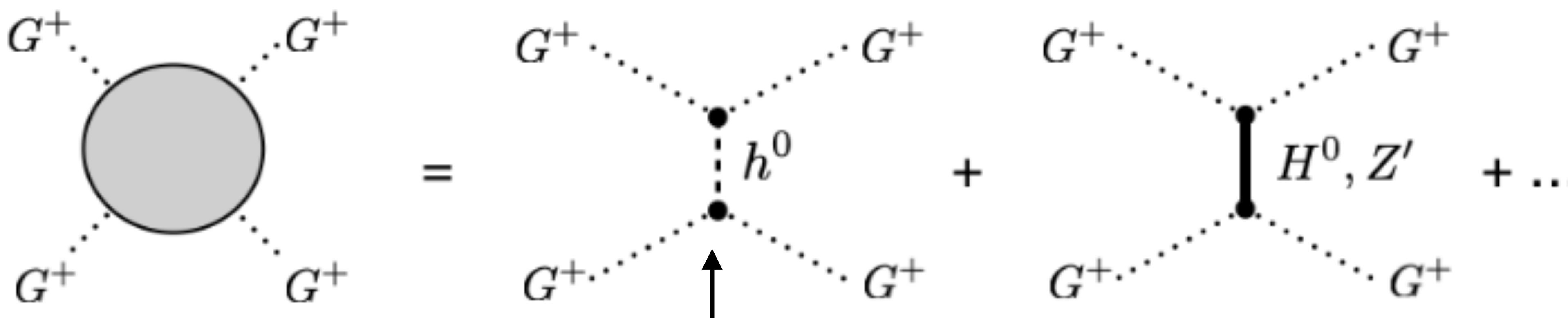


unitarize!

Is it really cancelled perfectly?

Unitarized scattering amplitudes:

some other unitarizers

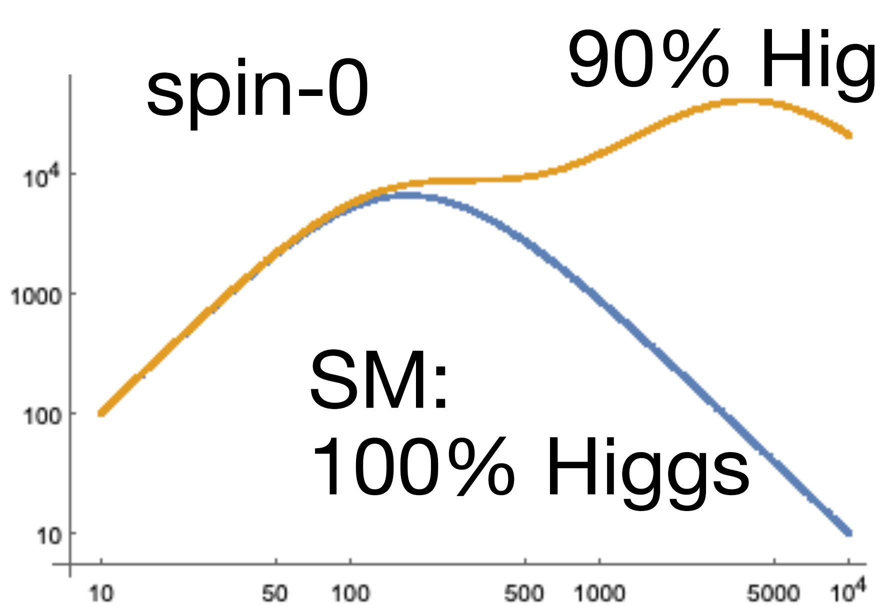


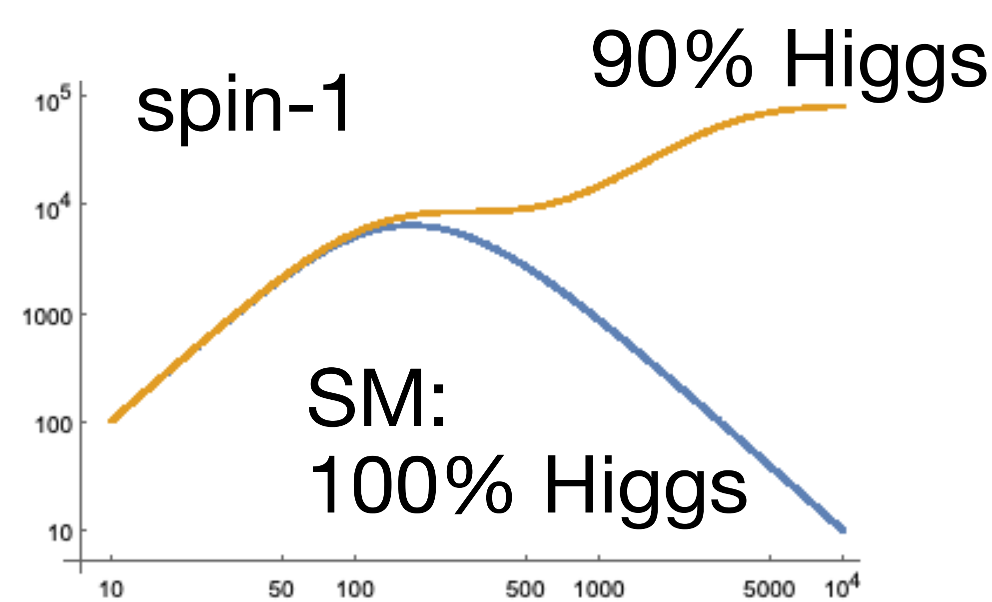
How much of this contribution? This measures how Higgs is Higgs.

$$\mathcal{M}(W_L^+W_L^+ \to W_L^+W_L^+) = \left[(1-\kappa_h)\frac{m_h^2}{v^2}\frac{t}{m_h^2-t} + \kappa_H\frac{m_H^2}{v^2}\frac{t}{m_H^2-t} + \kappa_V\frac{m_{Z'}^2}{3v^2}\frac{t+2u}{m_{Z'}^2-t} + (t\leftrightarrow u)\right] \times\left(1+\mathcal{O}\left(\frac{m_W^2}{s}\right)\right).$$

$$(\kappa_h = \kappa_H + \kappa_V)$$

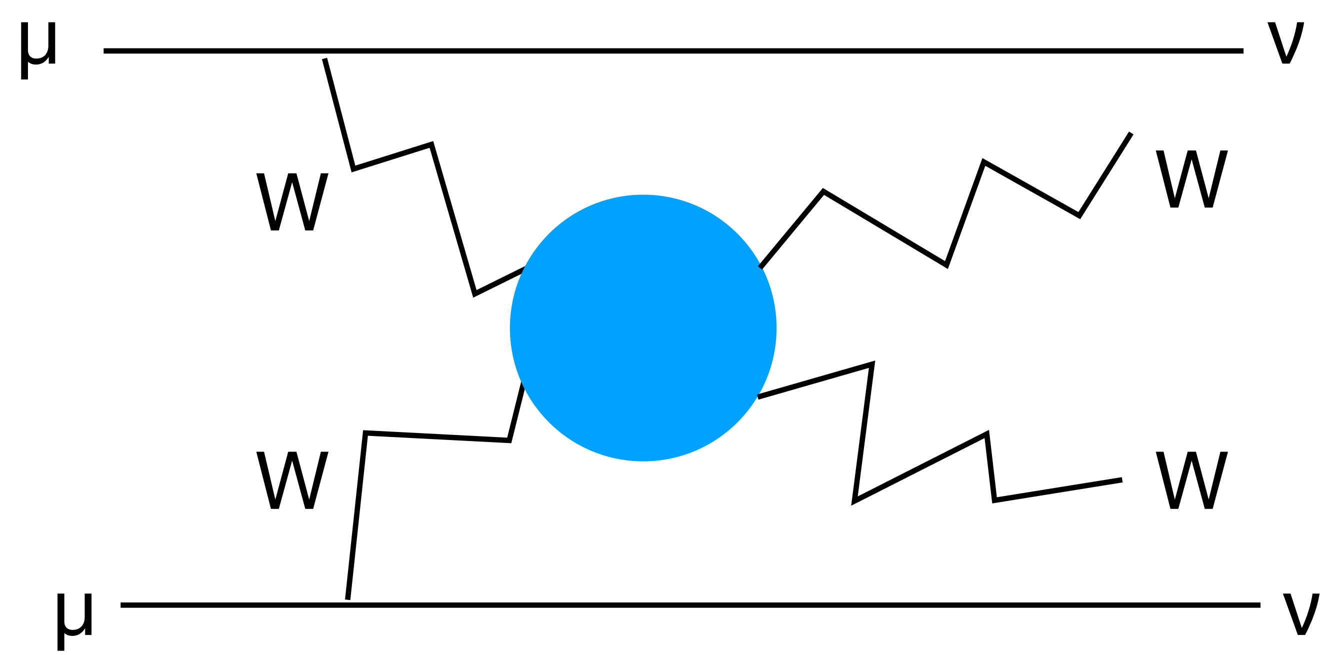
If we modify the coupling, the amplitude glows at high energy.
Very visible at high energy!





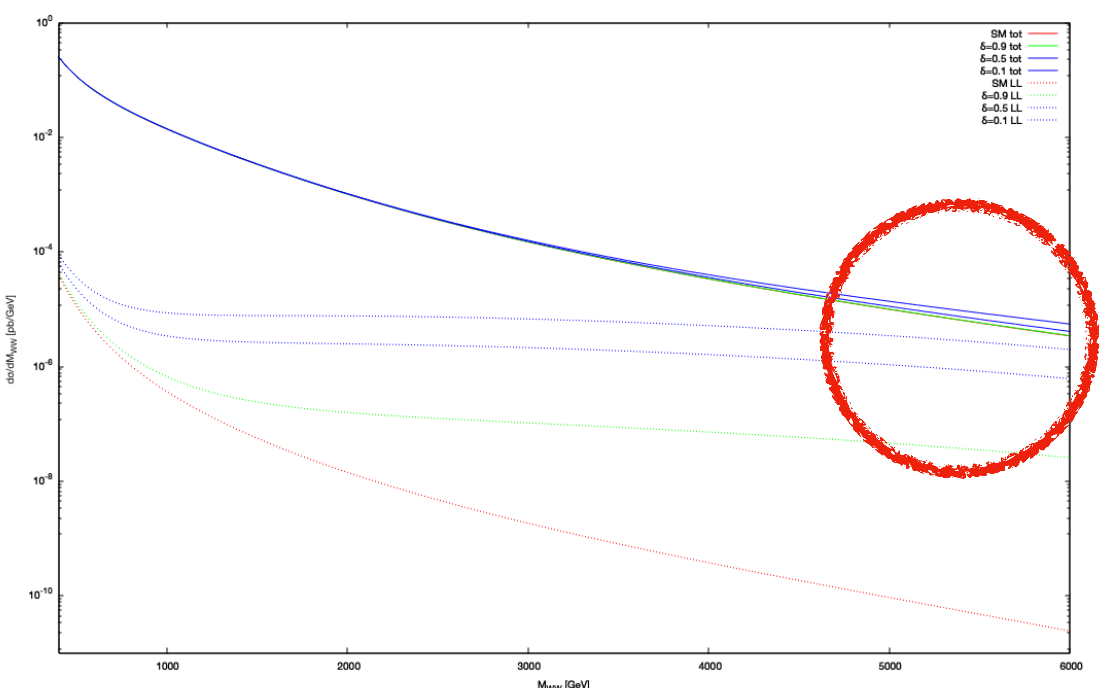
[RK, Okabe, Shirai in progress]

By WW scattering, one can check if Higgs is really Higgs!



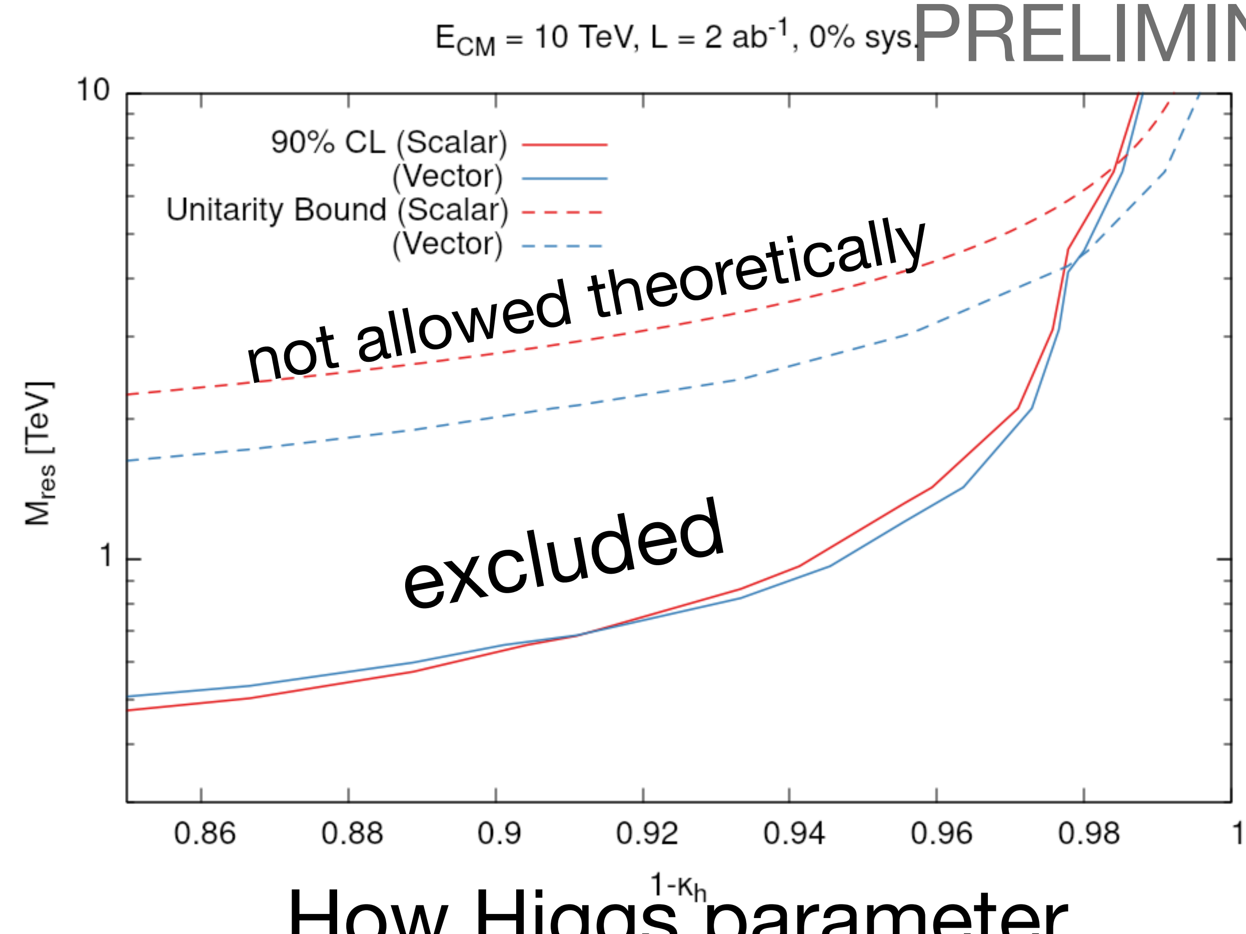
10TeV μ⁺μ⁺ collider

cross section



1TeV M_{WW} 5TeV

PRELIMINARY



How Higgs parameter

exciting.

Summary

Naturalness is still a very good guiding principle, but we do not yet know how "**natural**" nature is.

One may choose to abandon naturalness, but then we must supply new clues or predictions. Giving up naturalness without offering anything to look for is not an option.

(This is a message to myself.)

A 10 TeV collider would be wonderful. A real understanding of electroweak physics is waiting for us.

I love muon collider.