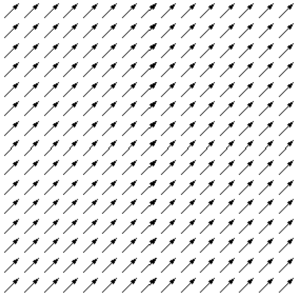
ニュートリノで探る標準模型を超える新しい物理

新学術領域「宇宙の歴史をひもとく地下素粒子原子核研究」研究会5/15-17/2015、神戸大学

Naoyuki Haba (Shimane U, Japan)

波 場



【理論的見地から】

TeV には標準模型を超える新しい物理があるだろう。

Hierarchy problem

量子補正を考慮すると，**Higgs**質量は**126GeV**にとどまらず，大きな質量を持ってしまう。

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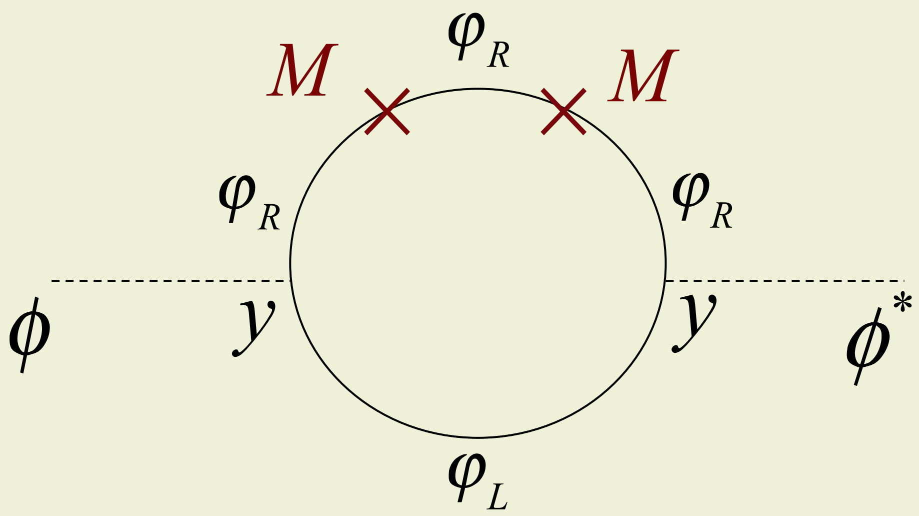

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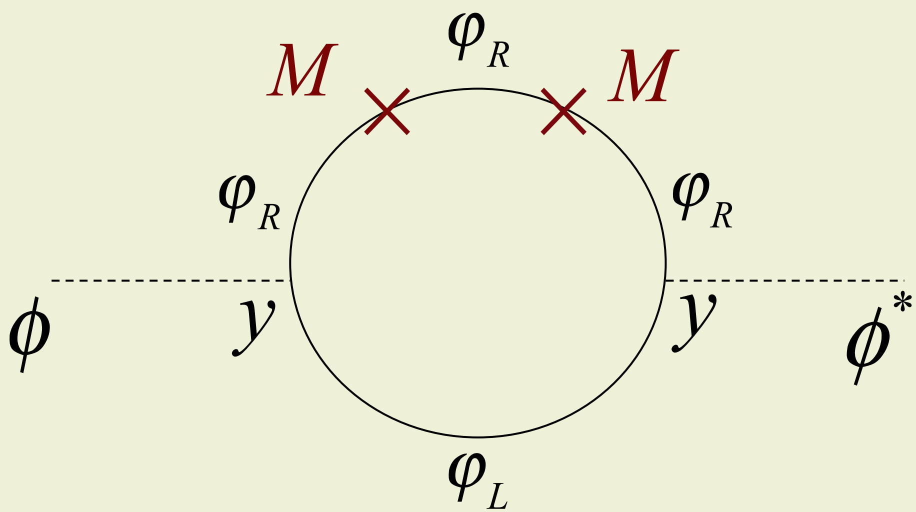

$$\int \frac{d^4 p}{16\pi^2}\left(\frac{i}{\not p}\right)^4 M_R^2$$

$$\sim -\frac{y^2}{16\pi^2} M^2 \log \Lambda$$

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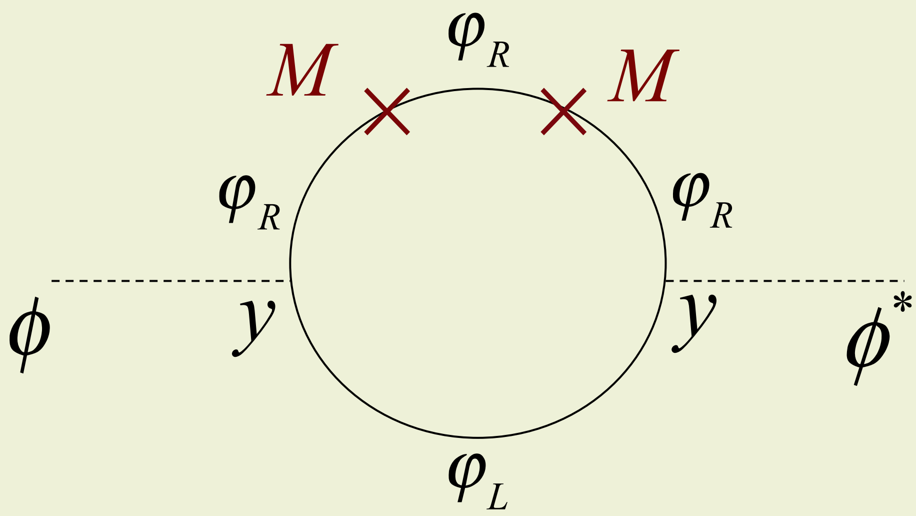

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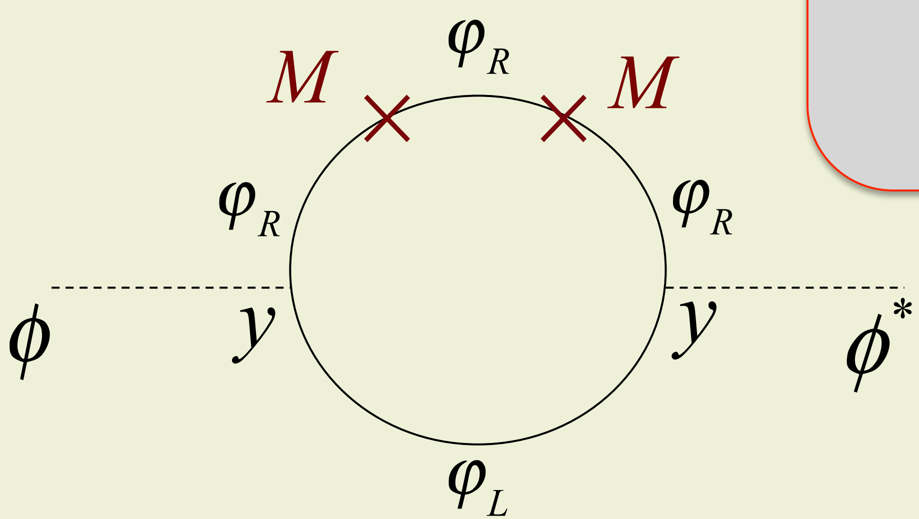
スキームに依らない物理量
（2次発散とは違う！）

↓

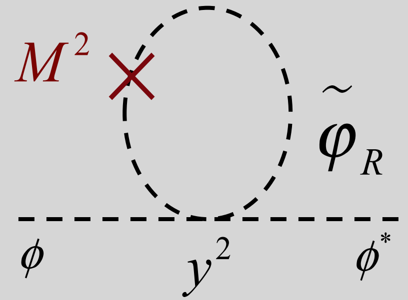
Higgs massは，Mの量子補正をどうしても受けてしまう！

Hierarchy problem



【解決法1】TeVに新しい理論 (new physics)

↙の量子補正はSUSYが有ればキャンセル



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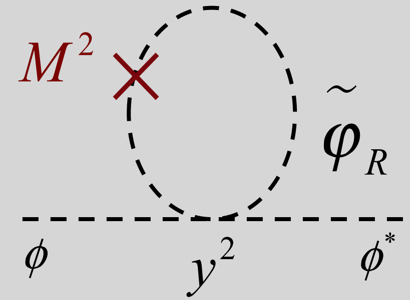

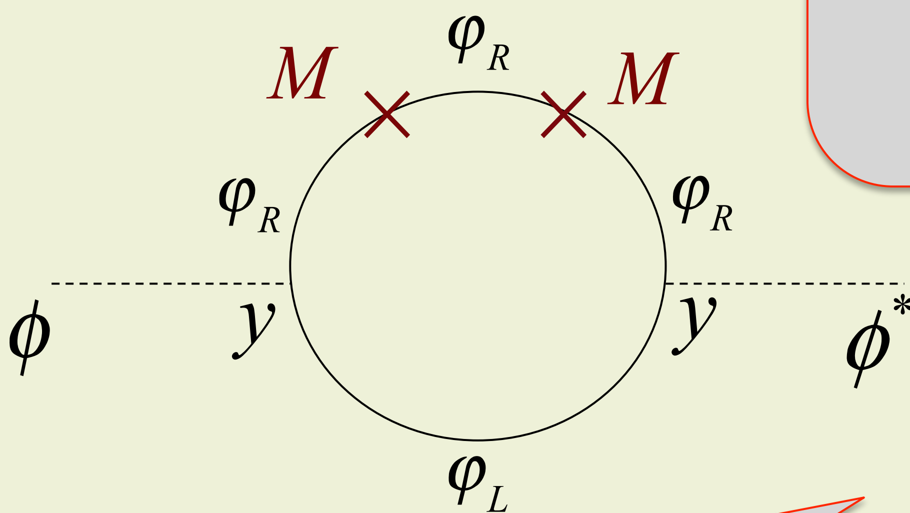

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classical conformal，かつ，中間スケールが（ダイナミカルにですら出てこ）ない理論

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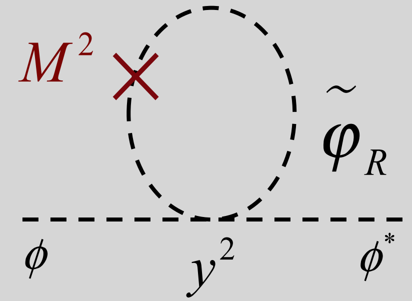

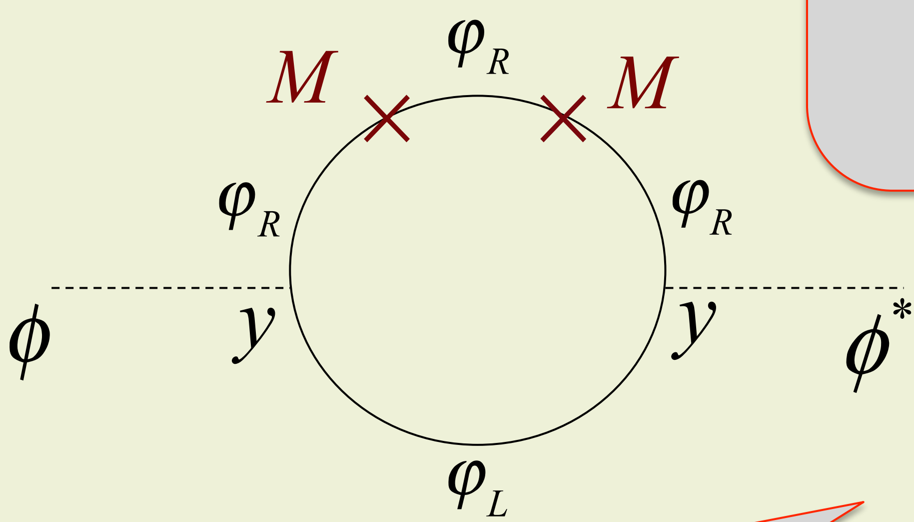

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どっちにせよ，TeVにnew physicsがあると考えるのが自然

【理論的見地から】

TeV 辺りに標準模型を超える新しい物理があると考えるのが自然

LHC results show…

An ongoing exciting matches (experiments) are facing a tough defense, and can't get a goal (see physics beyond the Standard Model) yet.

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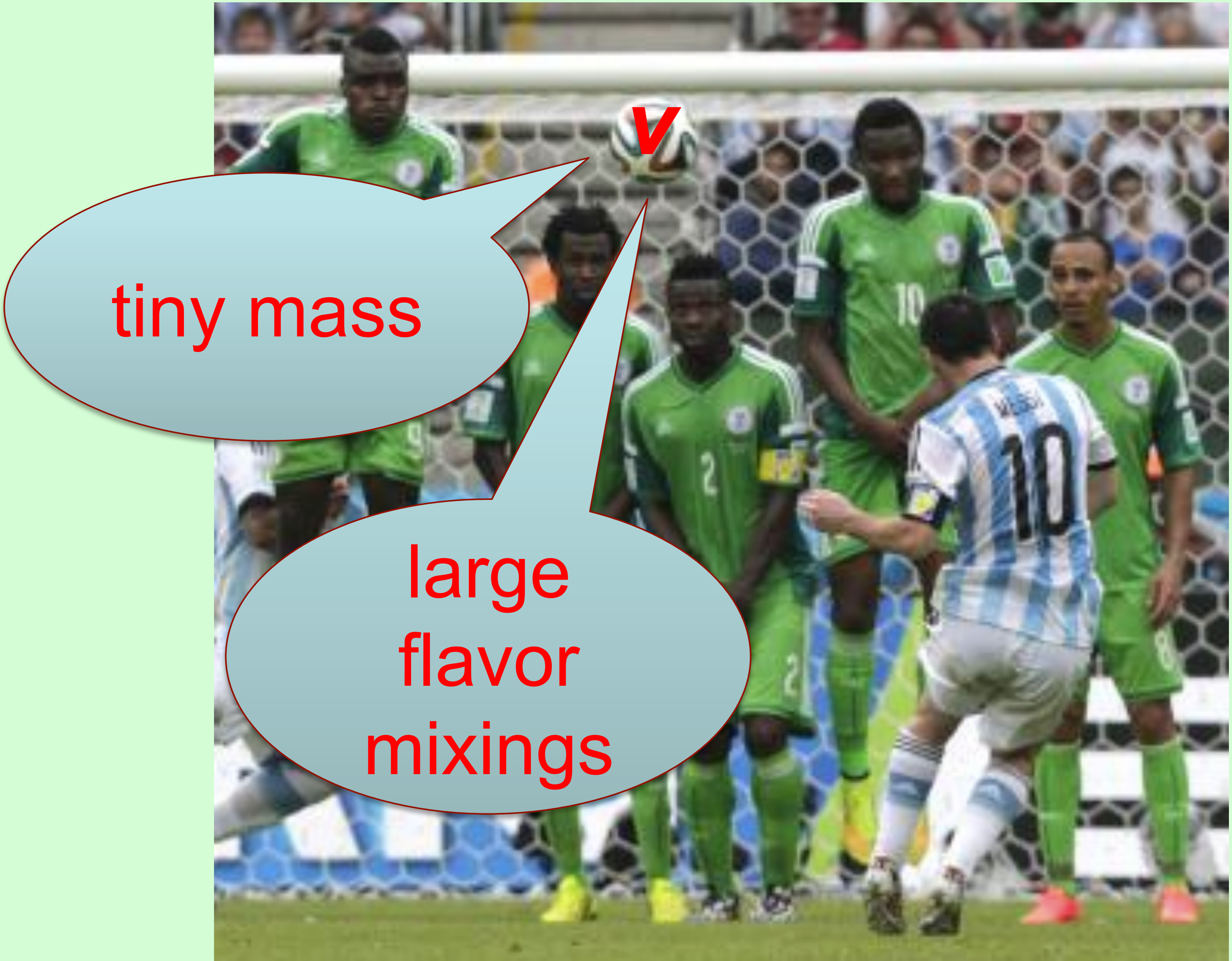

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Higgs mass が 126 GeV だった ことの衝撃

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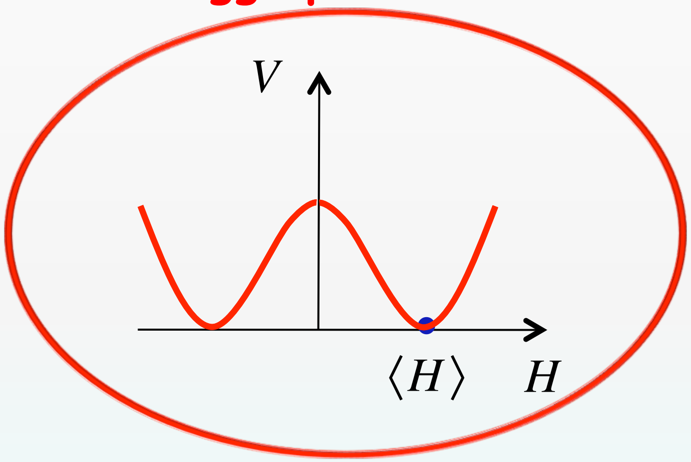
Higgs potential



$$V = \lambda(|H|^2 - v)^2$$

λ || **0.131@M_Z**

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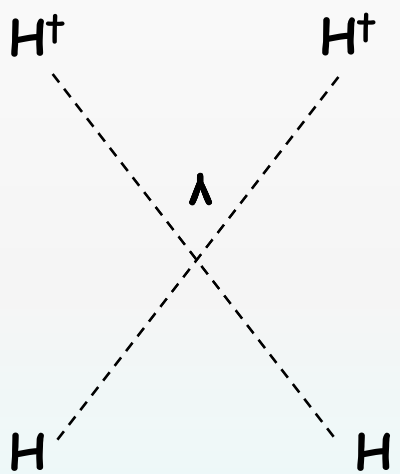

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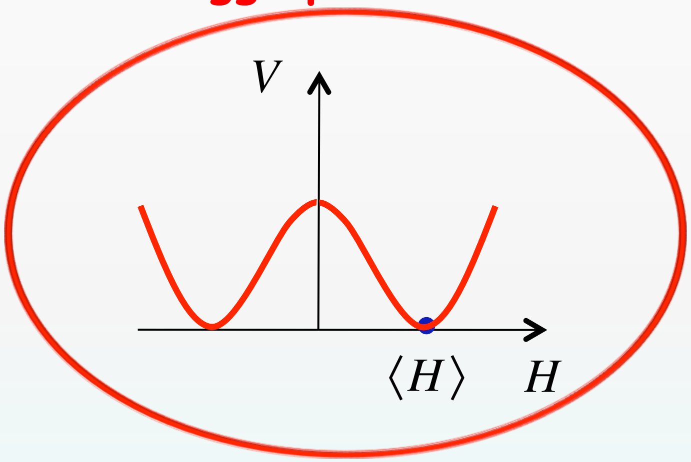

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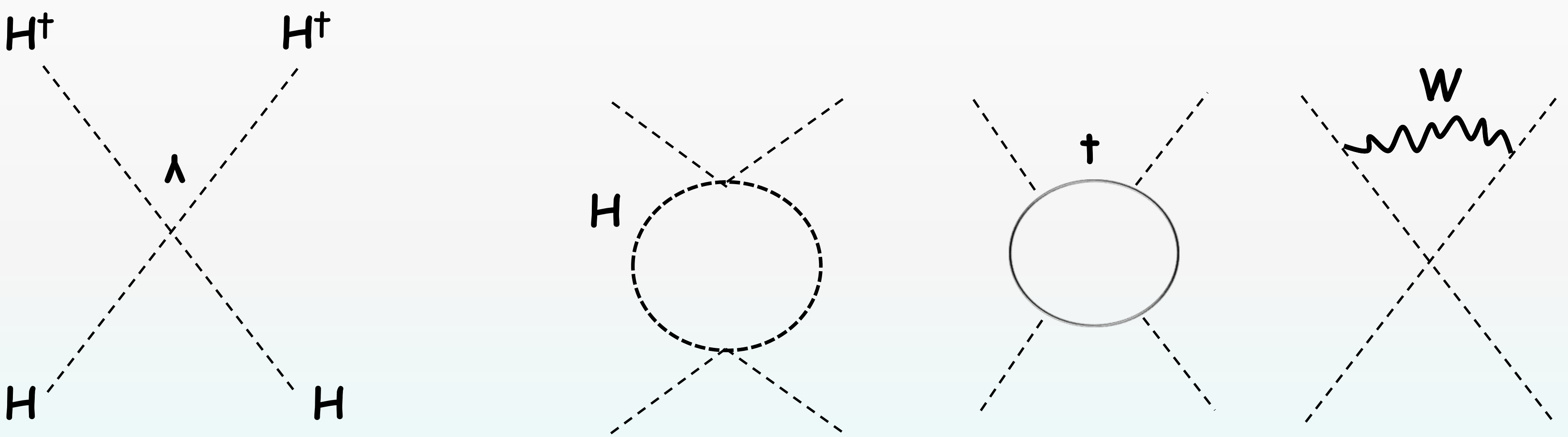
Quantum corrections



……….

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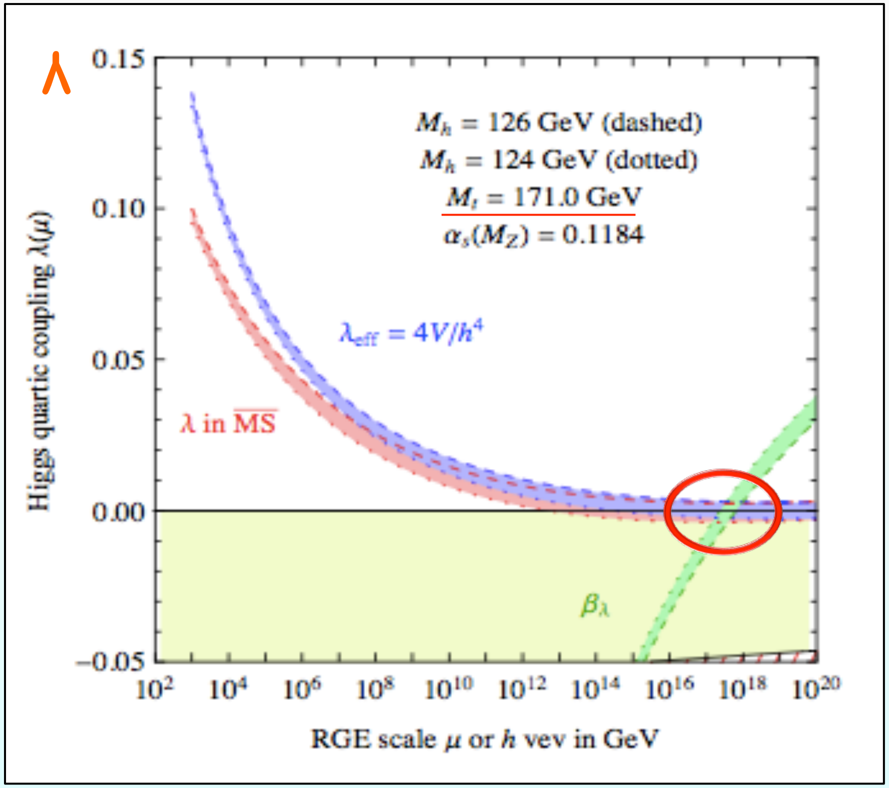
RGE of Higgs self coupling



G.Degrassi, S.Di Vita, J.Elias-Miro, J.R.Espinosa, G.F.Giudice, G.Isidori and A.Strumia, JHEP1208 (2012) 098

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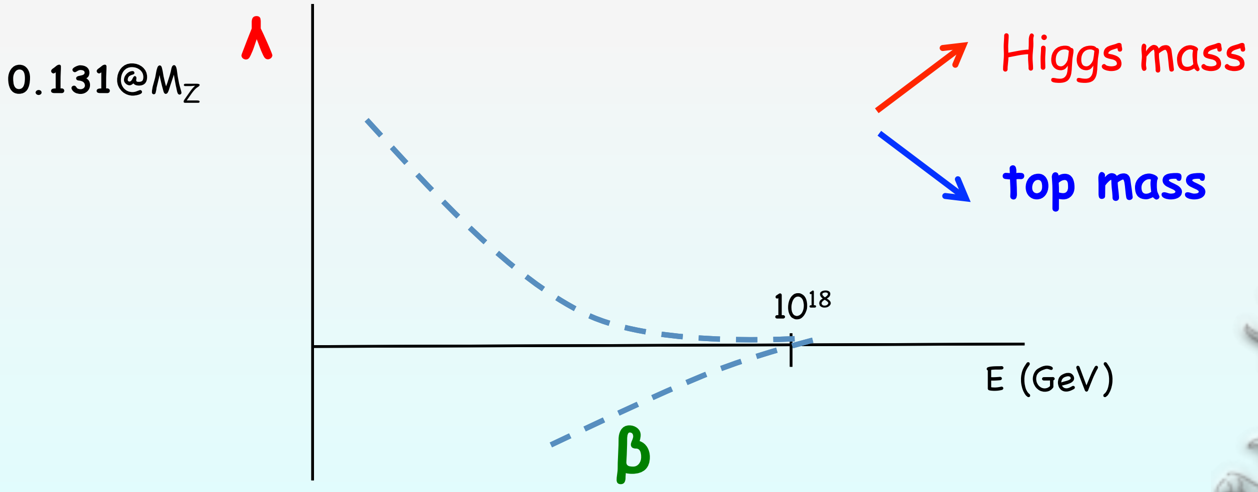
$$(4\pi)^2 \frac{d\lambda}{dt} = 24\lambda^2 + 12\lambda y_t^2 - 6y_t^4 - 3\lambda(g'^2 + 3g^2) + \frac{3}{8}[2g^4 + (g'^2 + g^2)^2]$$



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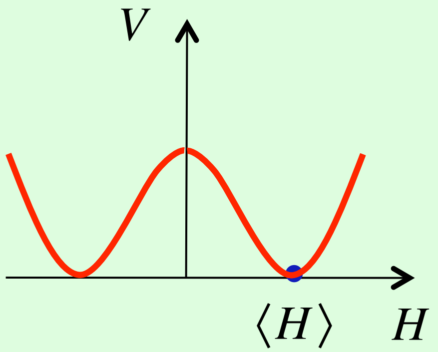

weak scale

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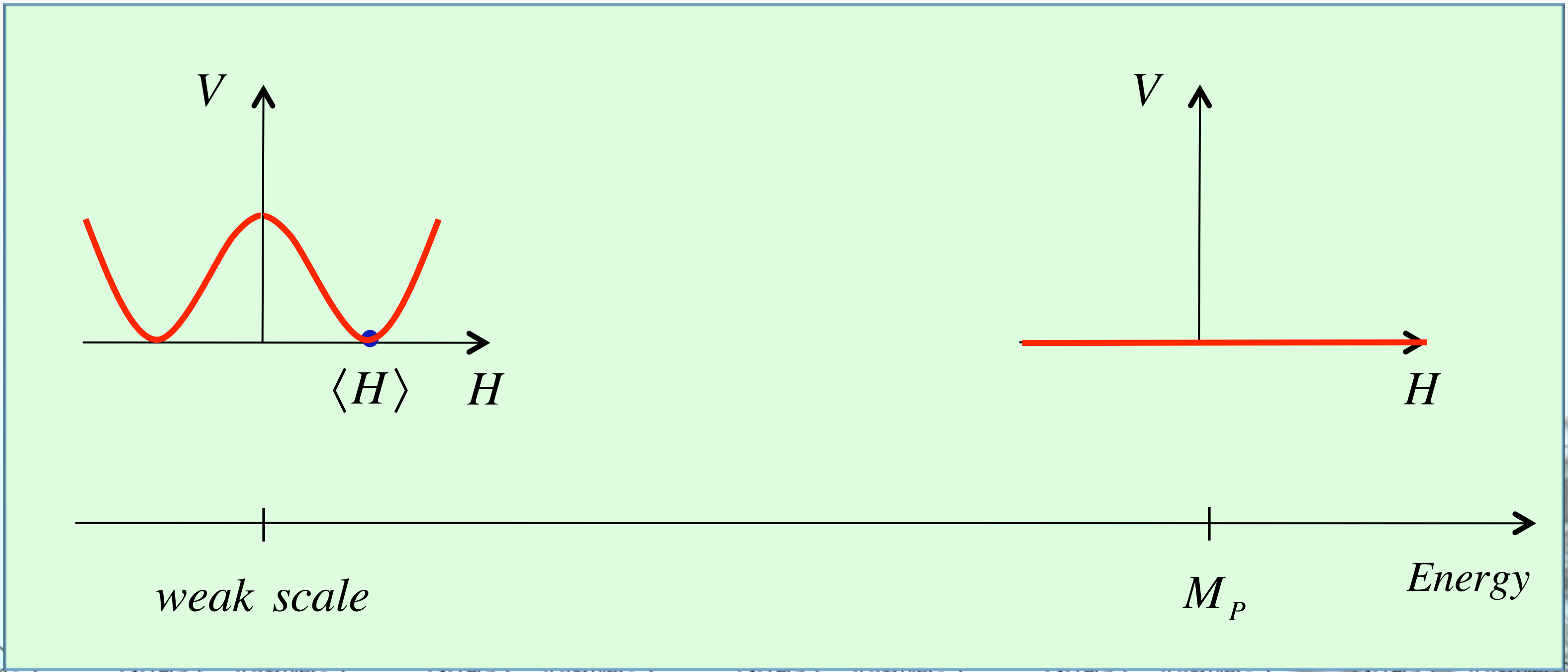

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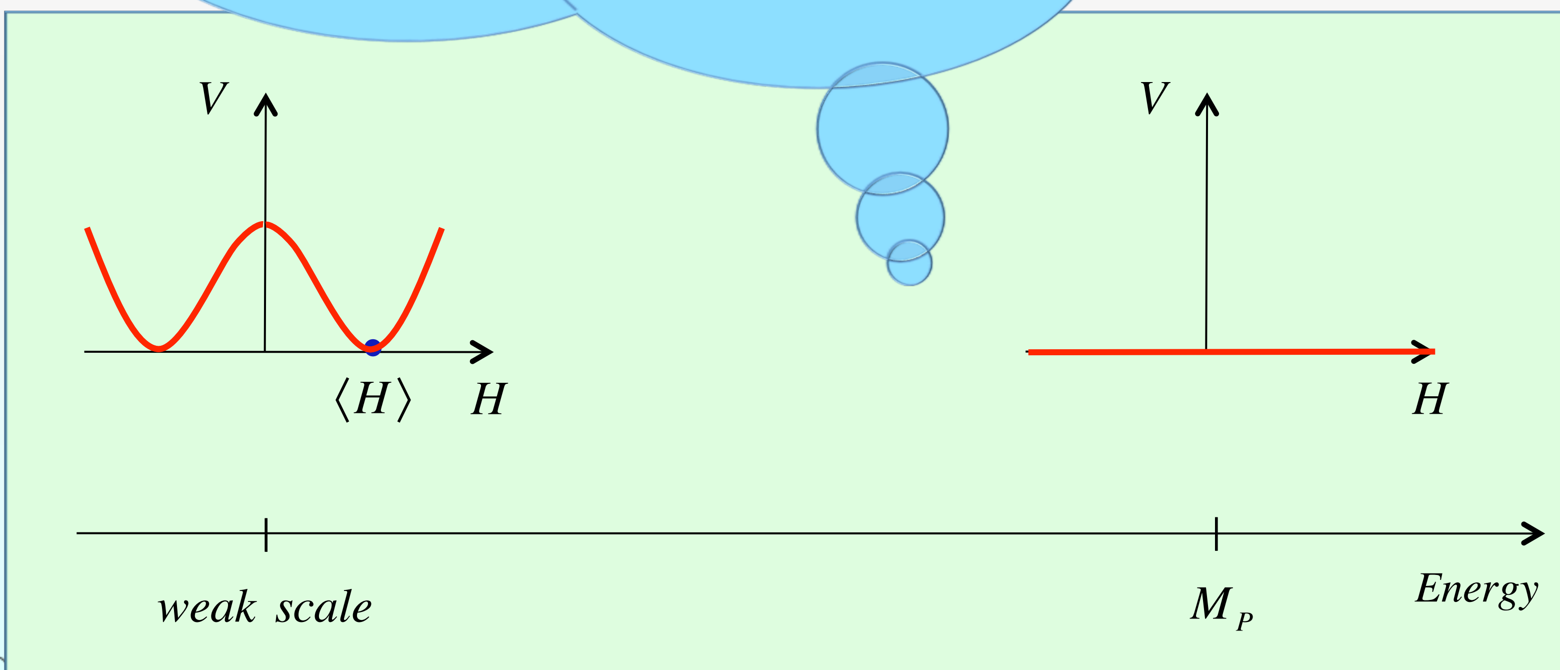
means SM -> Mp????

SMはMpにある物理のダイレクトな窓口？

$+ g^2)^2]$



SM **MSSM**

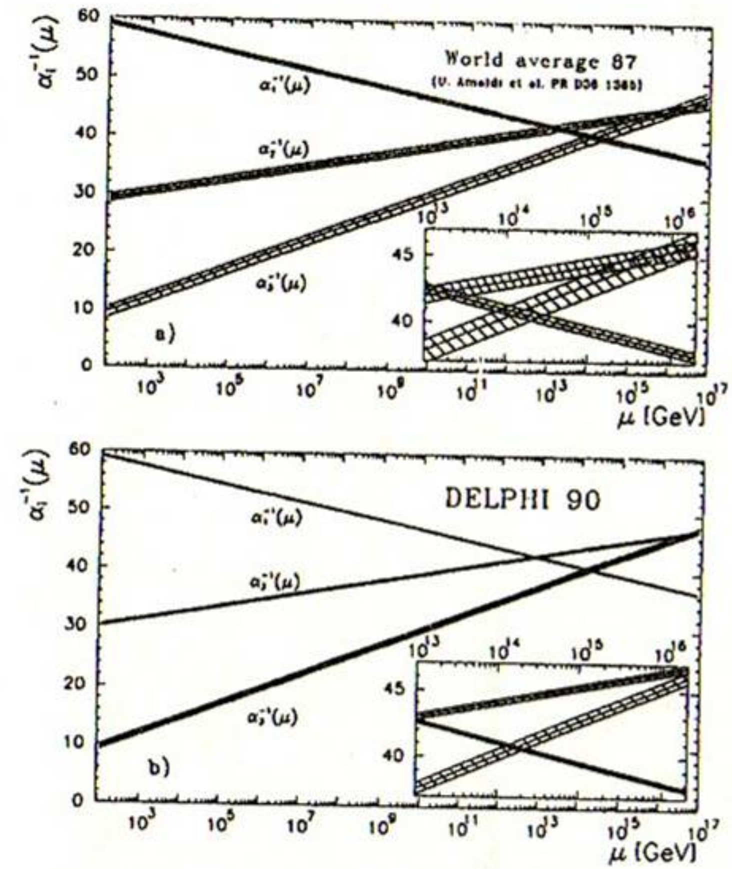


Fig. 1. (a) First order evolution of the three coupling constants in the minimal standard model (world average values in 1987 from ref. [1]). The small figure is a blow-up of the crossing area). (b) As above but using M_Z and $\alpha_s(M_Z)$ from DELPHI data. The three coupling constants disagree with a single unification point by more than 7 standard deviations.

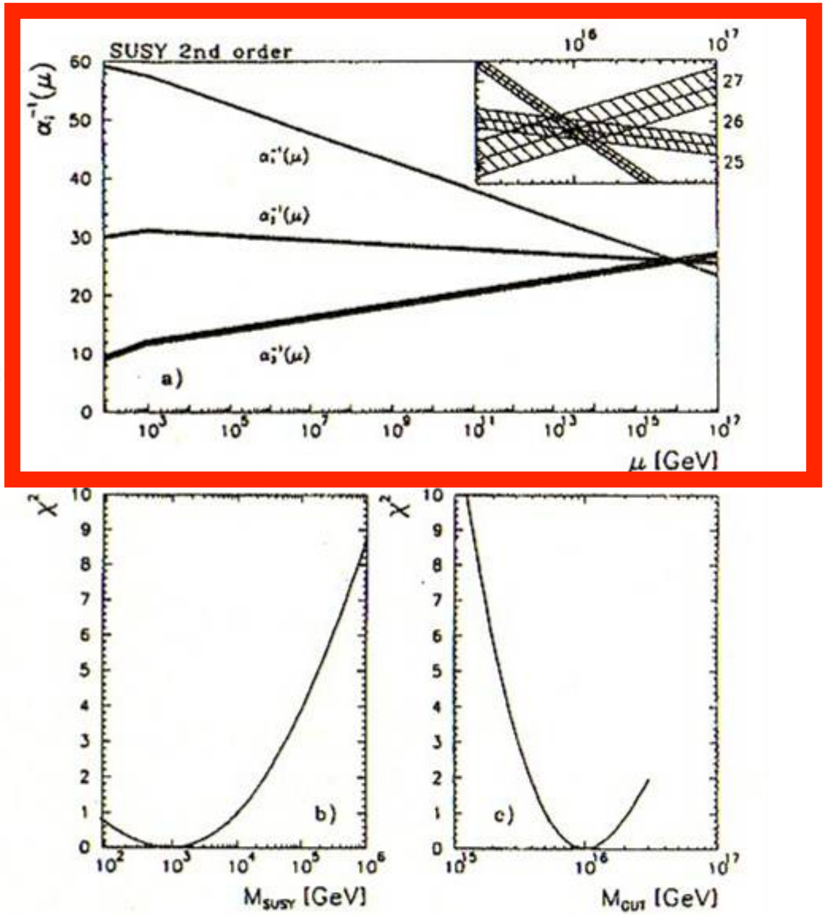


Fig. 2. (a) Second order evolution of the three coupling constants in the minimal SUSY model. M_{SUSY} has been fitted by requiring crossing of the couplings in a single point. The two lower plots show the χ^2 distribution for the SUSY scale M_{SUSY} (b) and for the unification scale M_{GUT} (c) taking into account their correlation.

(Amaldi, PLB260(1991)447)

Before this paper, SUSY is not so familiar than TC etc.

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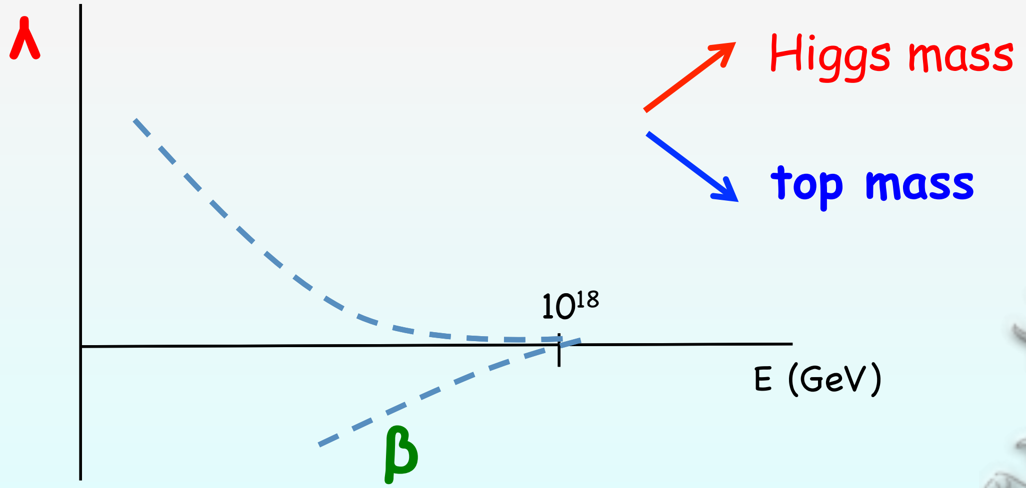

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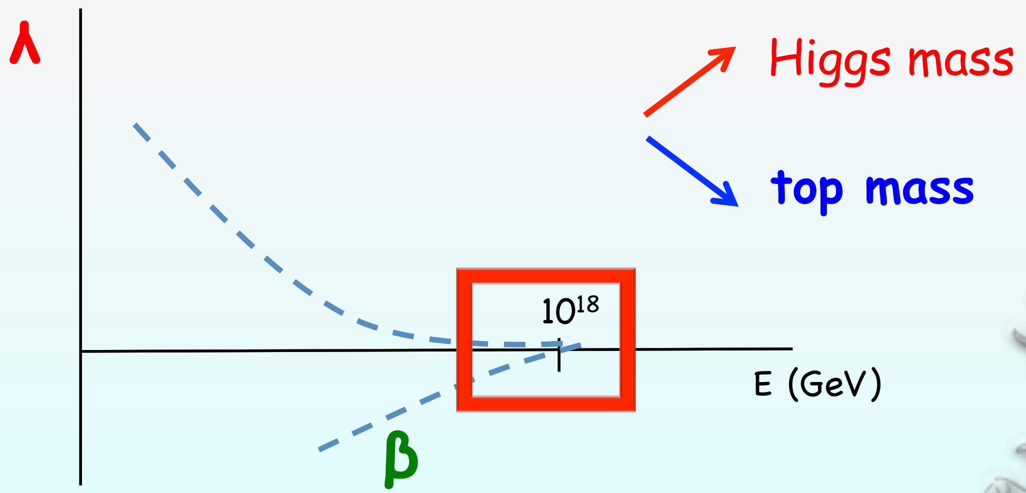

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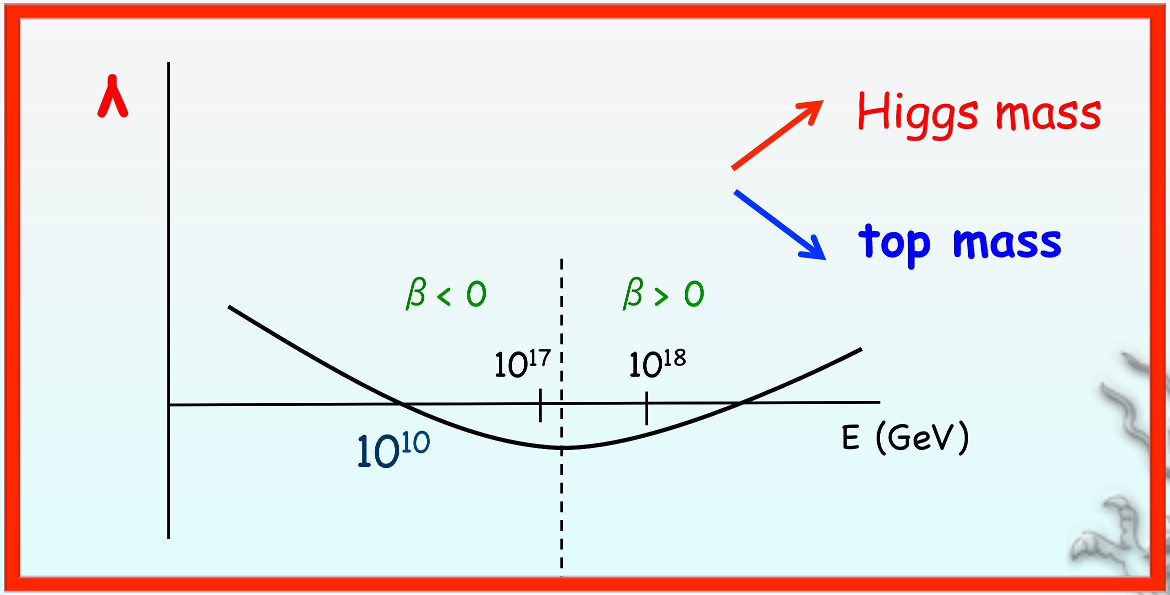

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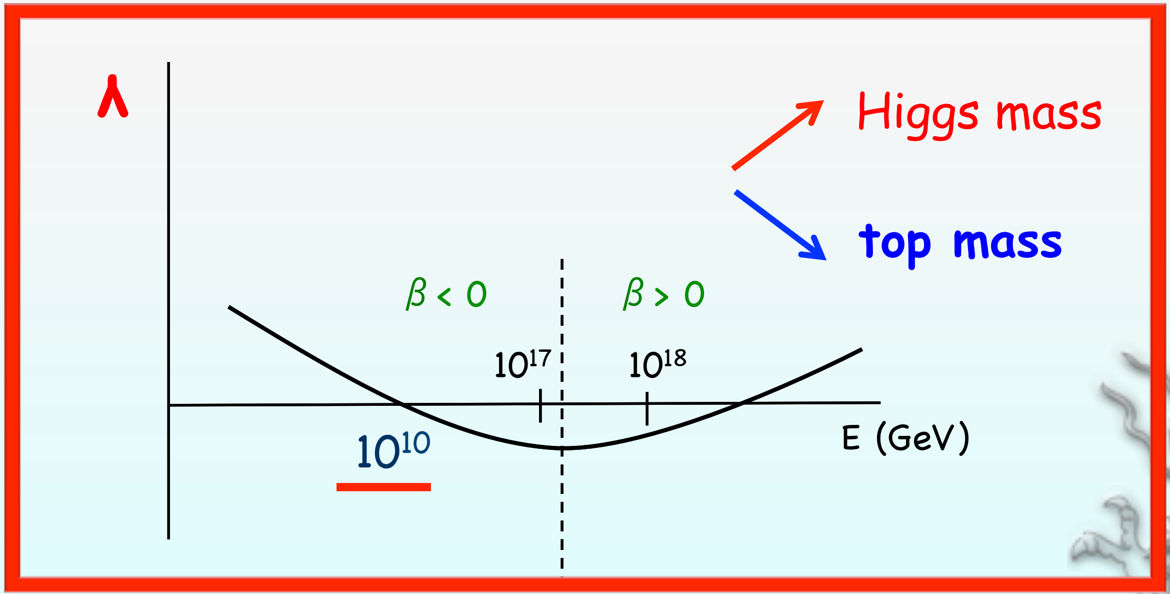

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171.081

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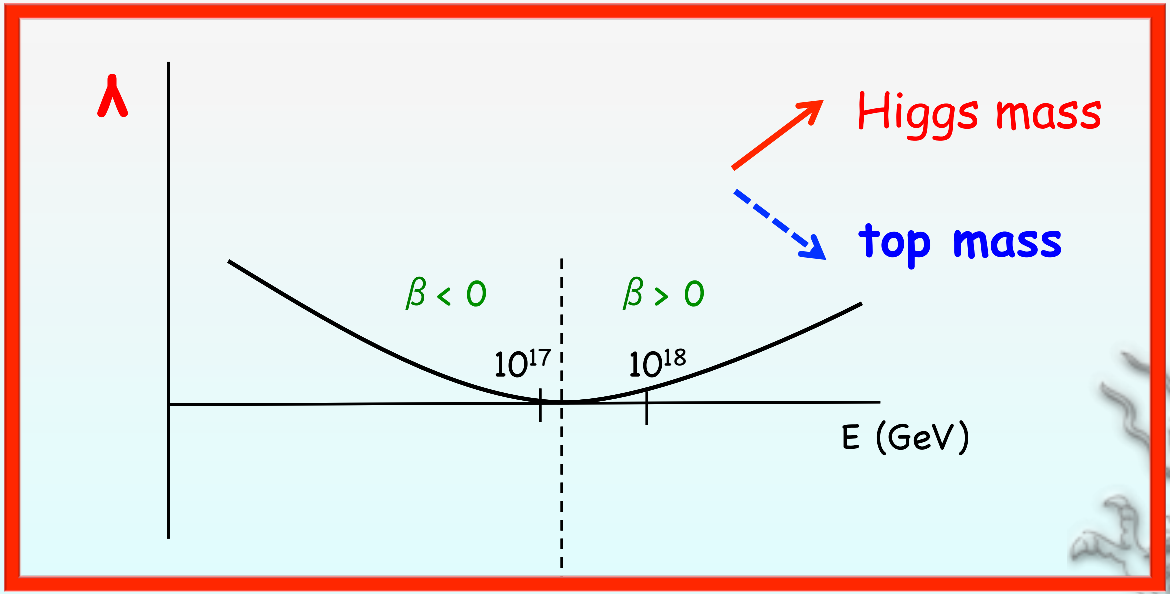

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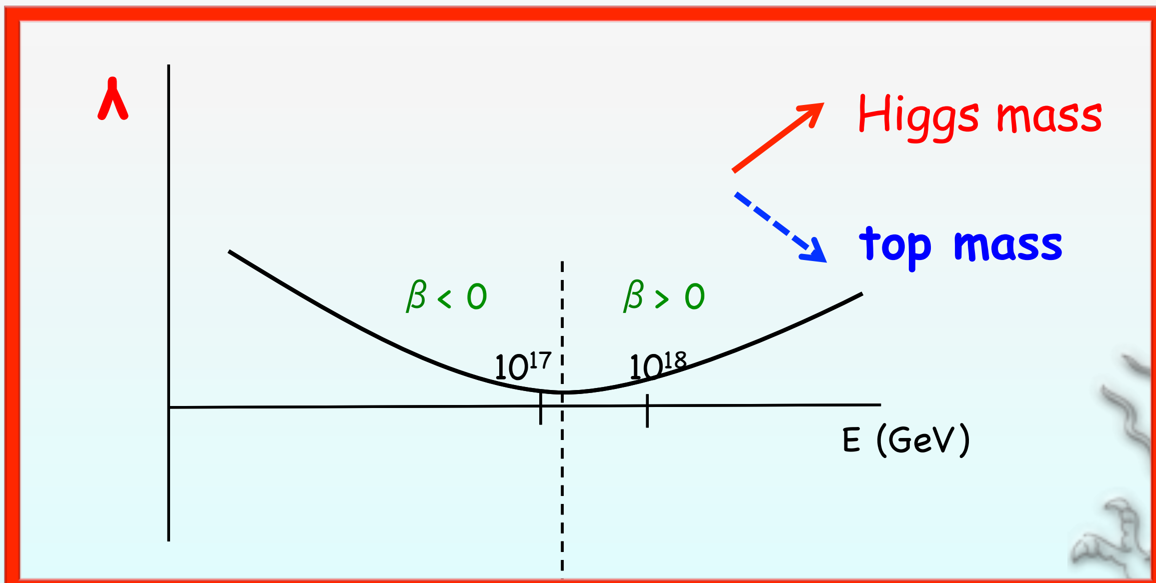

λ(μ＜Mp)～0 をどうとらえるか？

$\lambda(\mu < Mp) \sim 0$ をどうとらえるか？

【その1】

SMはダイレクトにMpまでつながる。

（入れ忘れてる効果があって，本当は10^{10} GeVで負にはならない。）

（ex1）flat land scenario

Iso et al

Higgsポテンシャルは，Mpで消え失せるのだ〜！

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→ $U(1)_{B\text{-}L}$ゲージの破れ → νRのMajorana質量の起源

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$$V = \lambda |H|^4 + k|\phi|^2|H|^2 + \lambda_S |\phi|^4$$

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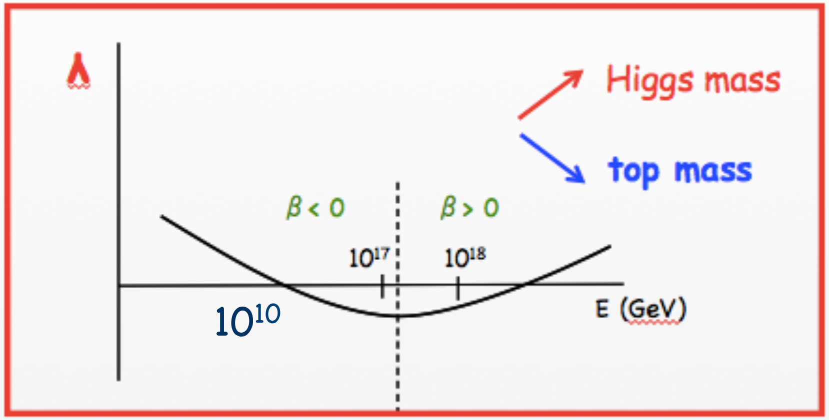

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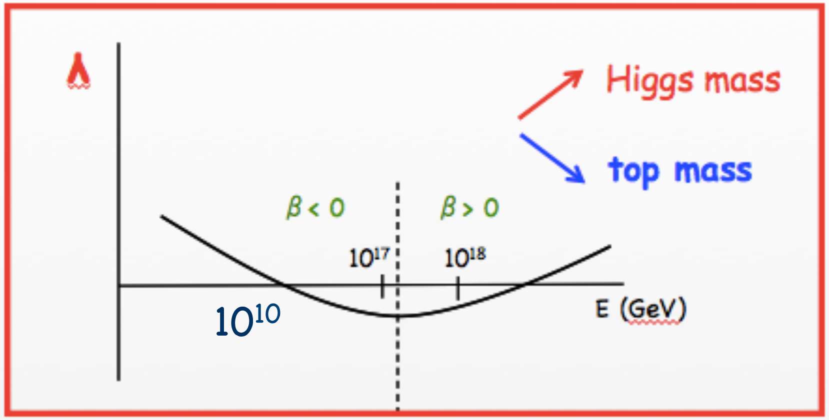

$$(4\pi)^2 \frac{dy_t}{dt} = y_t\left(\frac{9}{2}y_t^2 - \frac{17}{20}g_1^2 - \frac{9}{4}g_2^2 - 8g_3^2 - \square g_\square^2\right)$$

new gauge → 大 ⇒ Yt → 小

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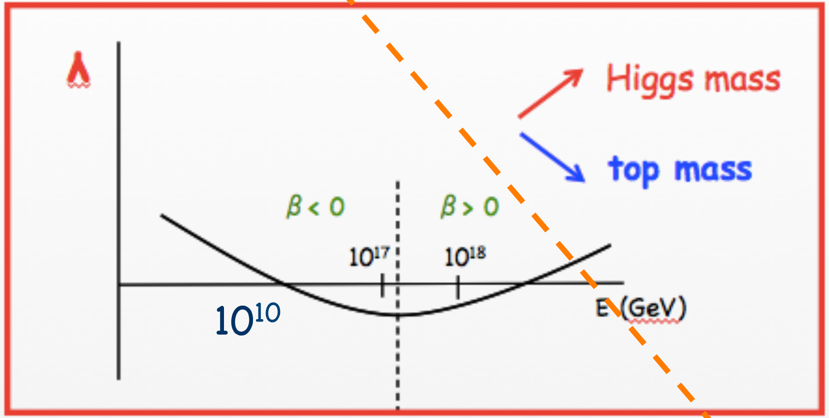

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⇒ λが持ち上がる！

（ex1）flat land scenario

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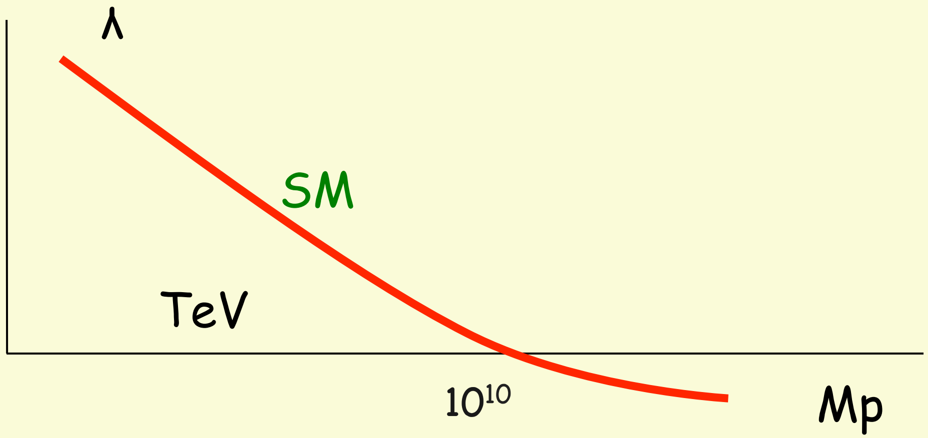
$$V=\lambda|H|^4+k|\phi|^2|H|^2+\lambda_S|\phi|^4$$

・SM + $U(1)_{B-L}$ゲージを導入。

・その結果



(ex1) flat land scenario

Iso et al

$$V = \lambda |H|^4 + k|\phi|^2|H|^2 + \lambda_S |\phi|^4$$

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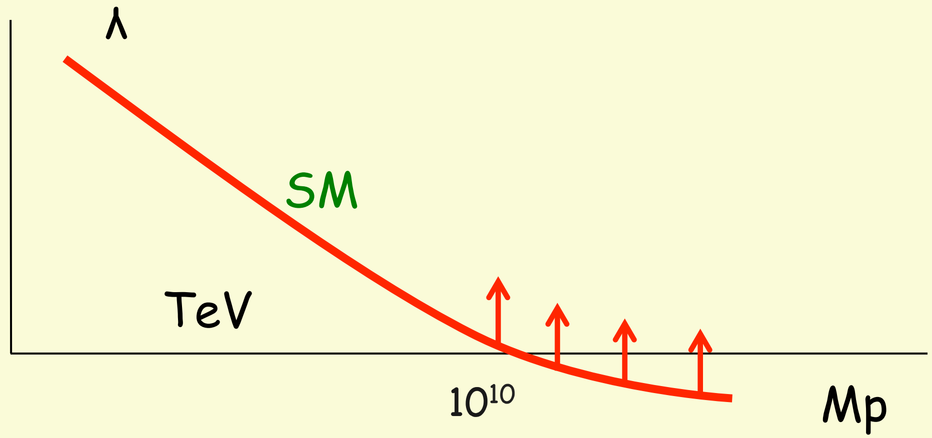

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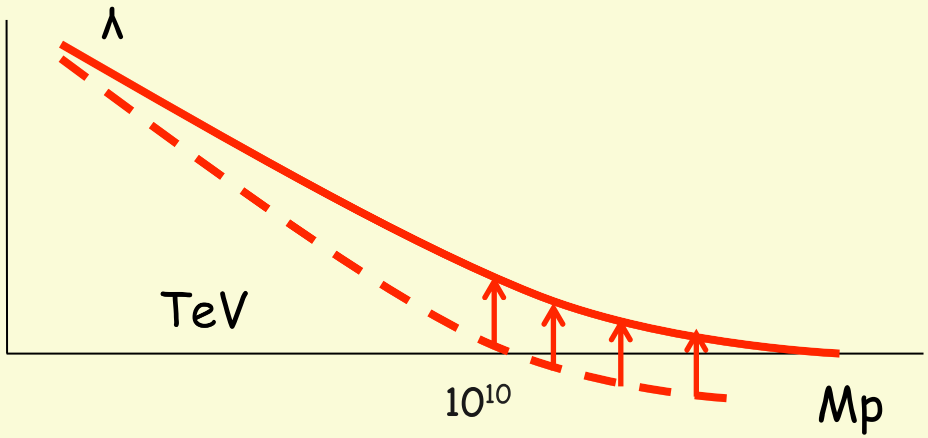

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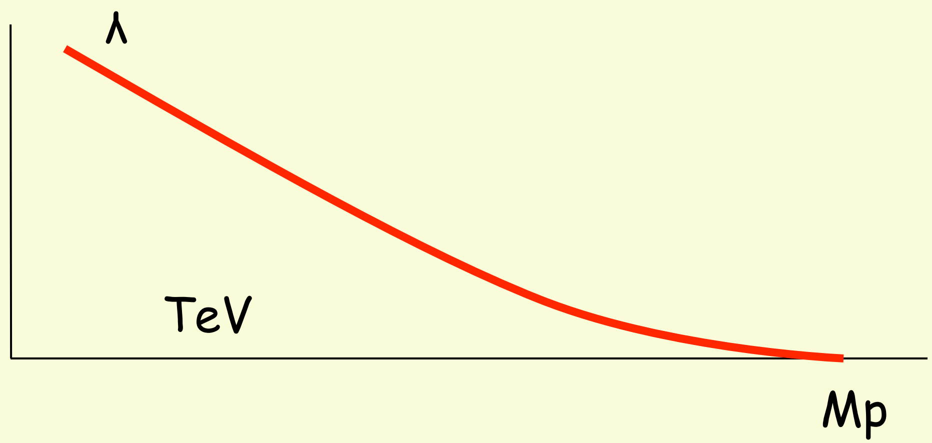

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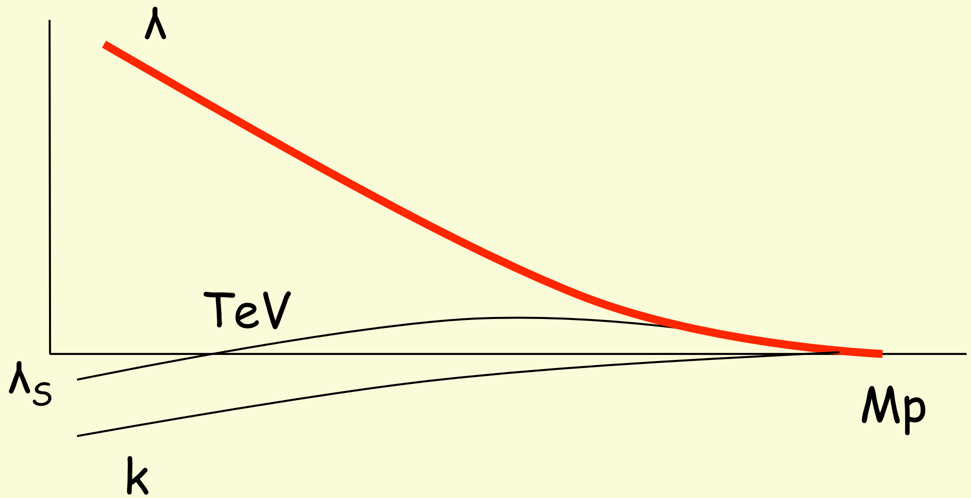

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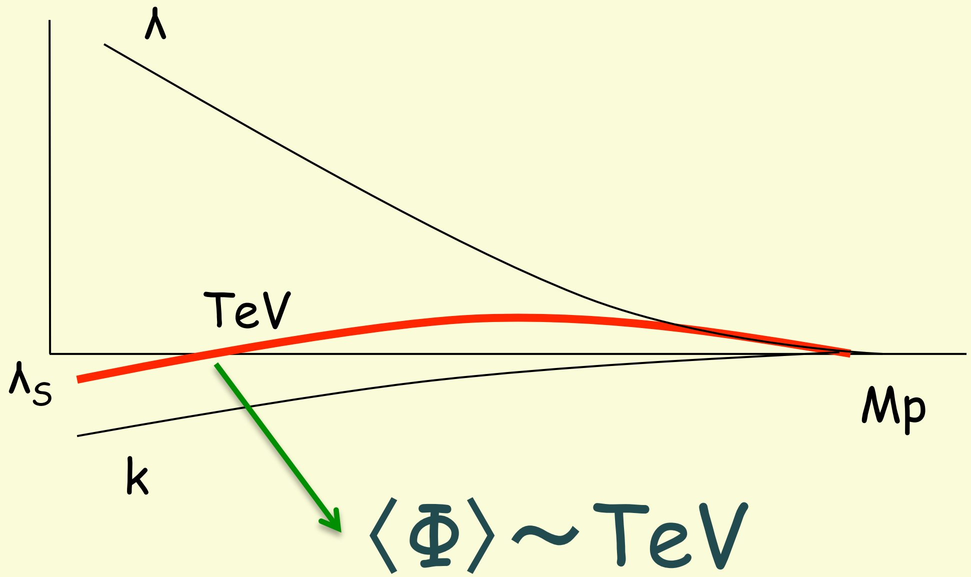

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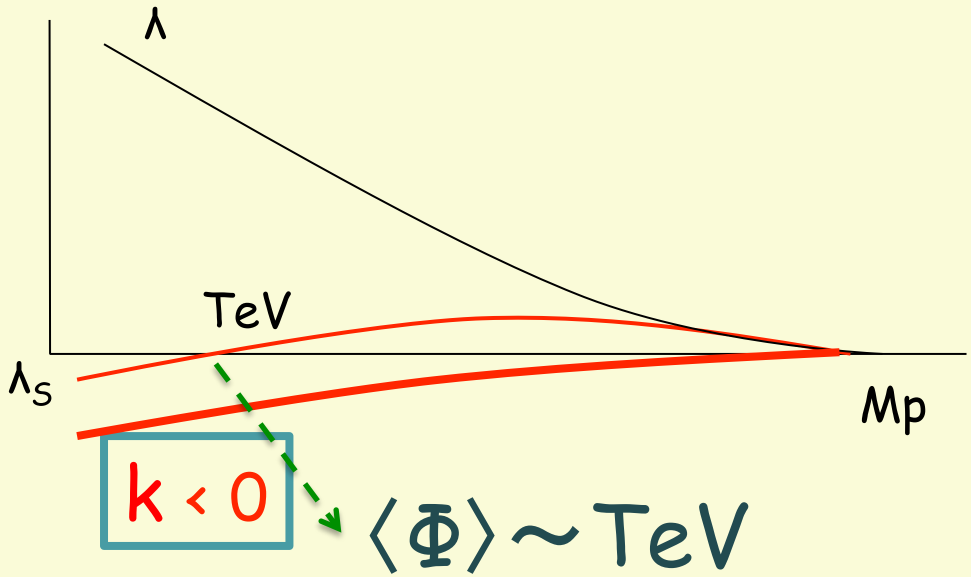

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$= -m^2$ (origin of the wine-bottle (EWB))

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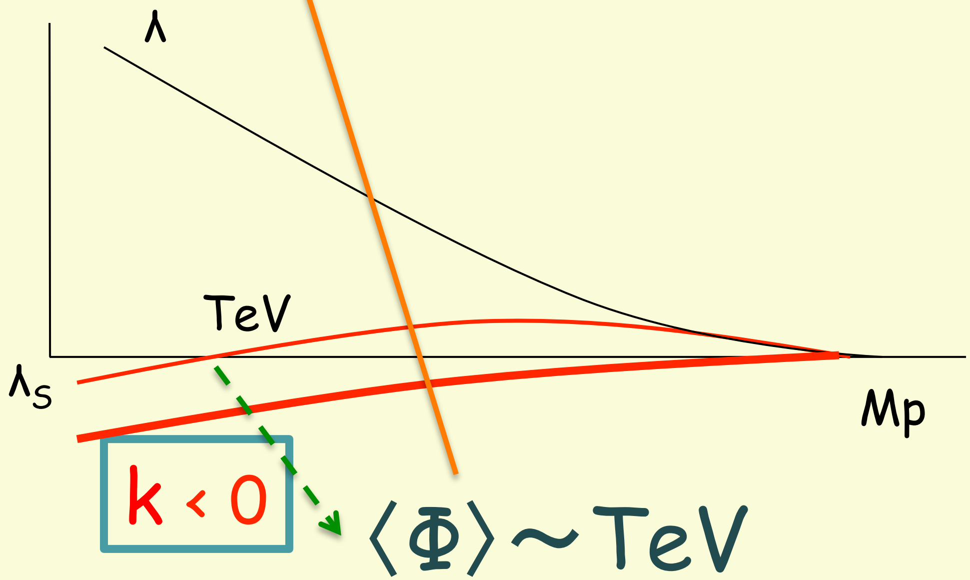

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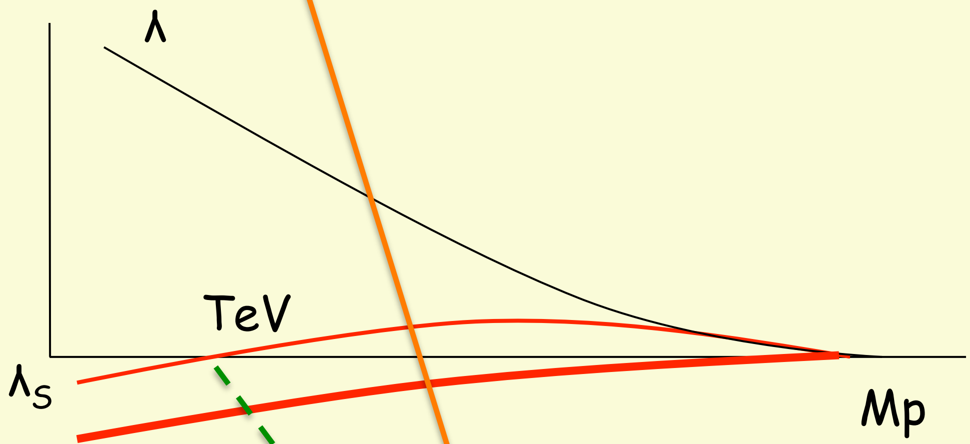

k<0

⟨Φ⟩～TeV

・L～⟨Φ⟩ν_R^2 → TeV Majorana mass of ν_R (Mayoron->縦波）。

g_{B-L}が大きいこと(~O(1))が必要，階層性問題の解決から⟨Φ⟩はTeV

→ νRのMajorana massもTeVじゃなくてはいけない！

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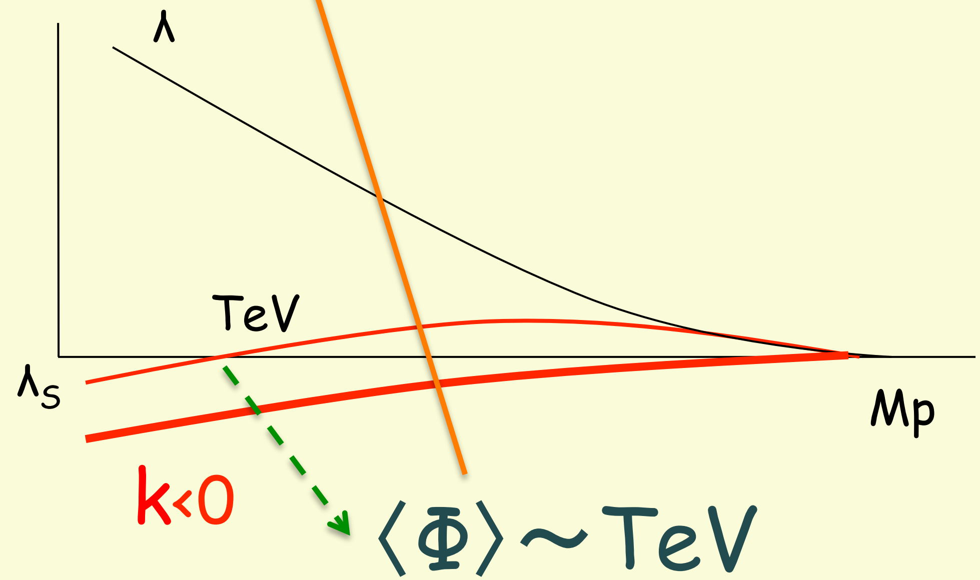

・$L \sim \langle\Phi\rangle v_R^2$ → TeV Majorana mass of v_R (Mayoron->縦波)。
→ TeV scale seesaw, (resonant) leptogenesis,
(anyhow, all phenomenology must be at TeV)

g_{B-L}が大きいこと(~O(1))が必要，階層性問題の解決から⟨Φ⟩はTeV

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(ex2) GUT @ Mp model

NH, Ishida, Takahashi, Yamaguchi
arXiv:1412.8230

- 中間スケールを導入できないので，GUT（＜Mp）はどうする？

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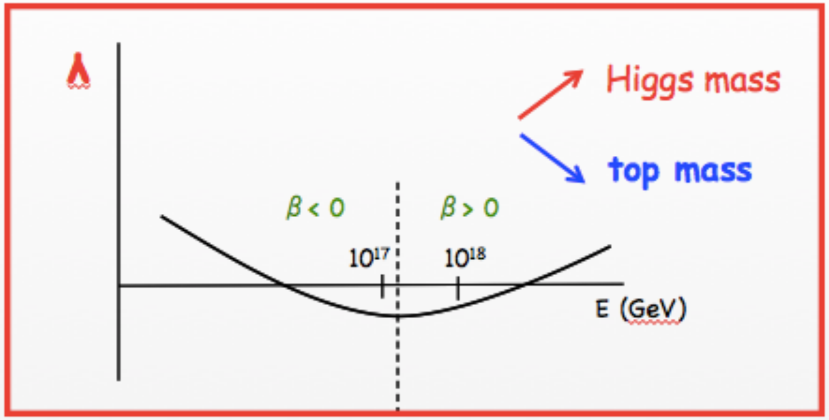
Extra fermions	(b'_1, b'_2, b'_3)	α_{GUT}^{-1}
$W \times 1\ (0.5) \oplus U\overline{U} \times 1\ (1) \oplus Q\overline{Q} \times 2\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{12}{5}, \frac{16}{3}, 6)$	19.1
$E\overline{E} \times 2\ (0.5) \oplus Q\overline{Q} \times 2\ (2) \oplus Q\overline{Q} \times 2\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{46}{15}, 6, \frac{20}{3})$	14.9
$L\overline{L} \times 1\ (0.5) \oplus E\overline{E} \times 1\ (0.5) \oplus Q\overline{Q} \times 1\ (1) \oplus U\overline{U} \times 1\ (1) \oplus Q\overline{Q} \times 2\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{56}{15}, \frac{20}{3}, \frac{22}{3})$	11.1
$E\overline{E} \times 1\ (0.5) \oplus W \times 1\ (0.5) \oplus U\overline{U} \times 2\ (4) \oplus Q\overline{Q} \times 3\ (10) \oplus D\overline{D} \times 4\ (10)$	$(\frac{22}{5}, \frac{22}{3}, 8)$	7.95

m_H=125.9±0.4 GeV, m_{top}=172.58~174.10 GeV in the SM

$$(4\pi)^2\frac{d\lambda}{dt}=\underline{24\lambda^2}+12\lambda y_t^2\underline{-6y_t^4}-3\lambda(g'^2+3g^2)+\frac{3}{8}[2g^4+(g'^2+g^2)^2]$$



一般的に，新粒子(GUCを実現するため)を入れるとgaugeは強くなる。

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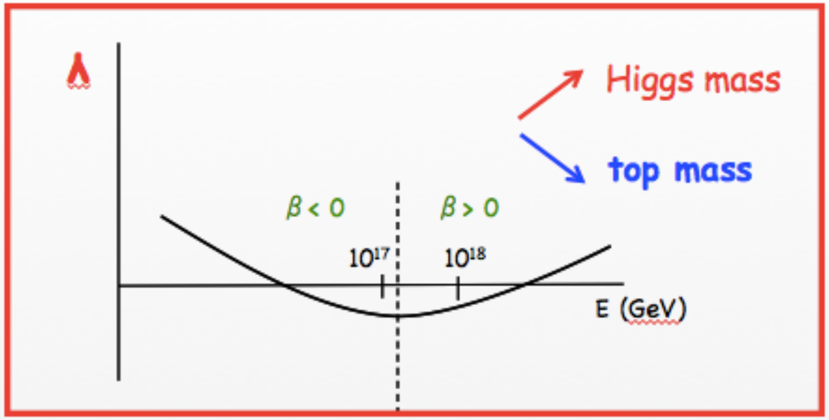

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Gauge → 大 ⇒ Yt → 小

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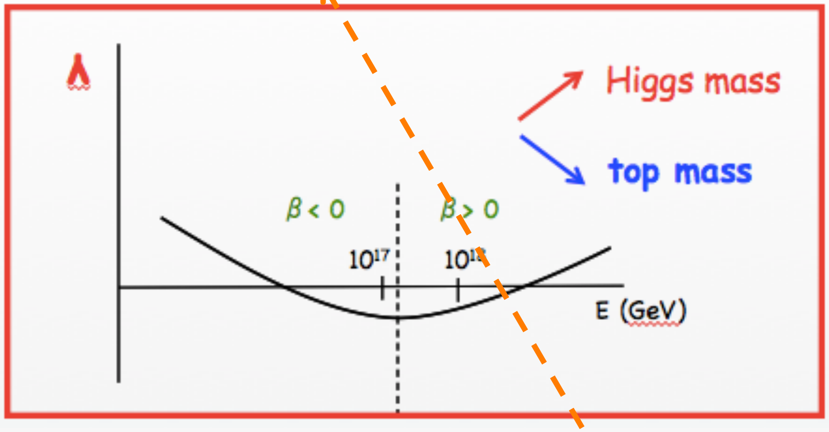

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⇒ λが持ち上がる！

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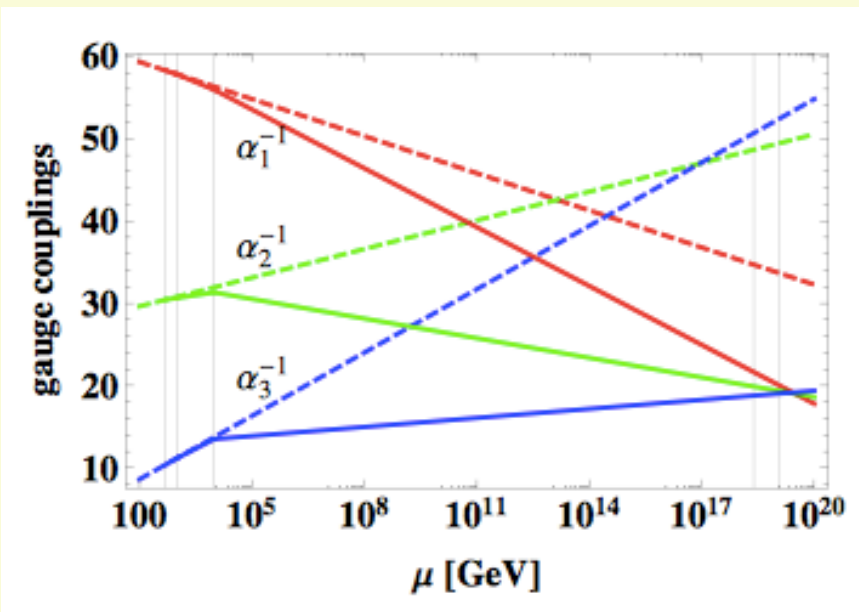

→ λ持ち上がる）

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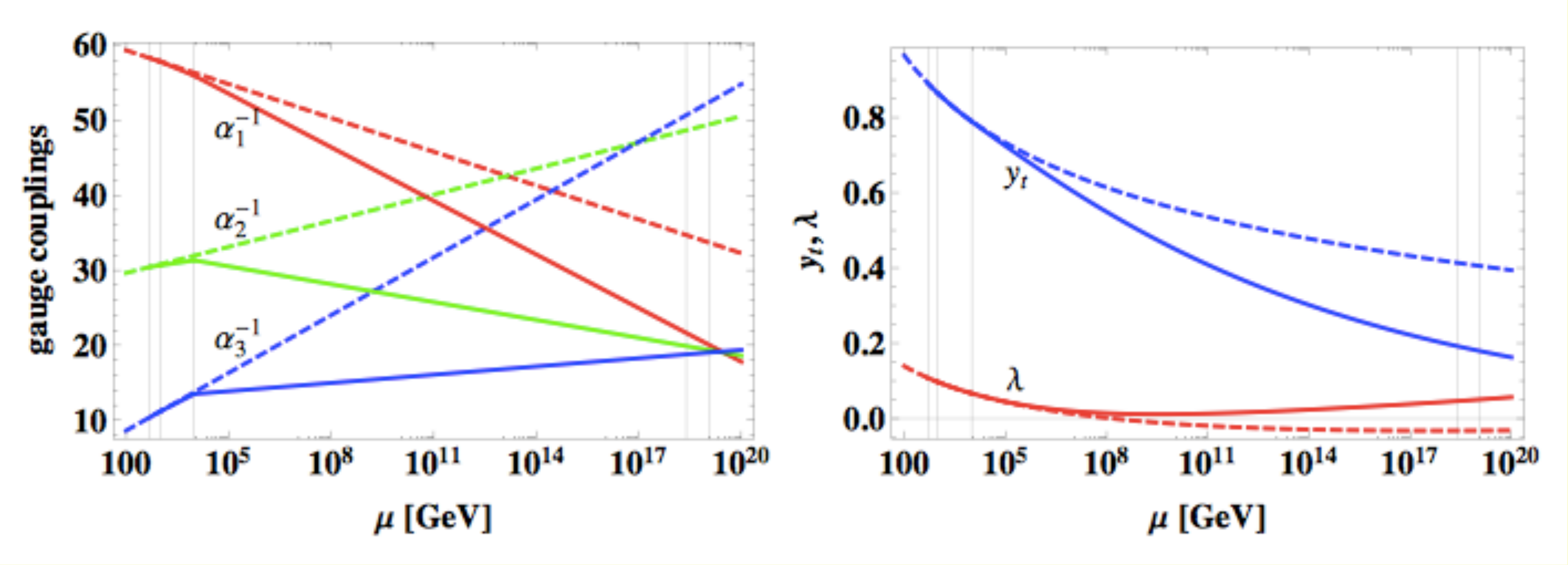
→ gauge->大　→ Yukawa->小　　→ λ持ち上がる）



→ vacuum becomes stable

LHC results show…

SMはMpにある物理のダイレクトな窓口？(no intermediate scale?)

【研究計画１】FlatLandシナリオの枠組みで,

→ ・TeV scale seesaw
(inverse seesaw? generation structure?
same sign di-lepton event? $0\nu\beta\beta$? other observations?)

→ ・leptogenesis/bariyogenesis?
(resonant leptogenesis? quantum effects? New mechanism・・・)

λ(μ＜Mp)～0 をどうとらえるか？

【その2】

μ～10^{10}GeVにBSMがある。

（例）余剰次元の大きさが，10^{10} GeV。Higgsはゲージ場に？

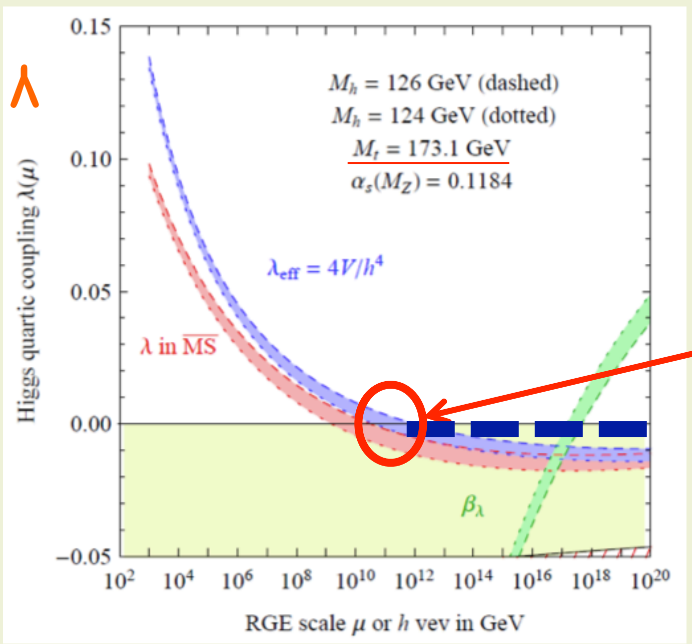
☆ Higgs=高次元gauge場の余剰次元成分 (Gauge-Higgs Unification)

$$A_M = A_\mu + A_5 \text{ (scalar @ 4D)}$$

・ゲージ場なので基本的にmassless。（短距離＝高エネルギーでゲージ場として復活）

mass＝余剰次元の境界を見る位のスケール（長距離＝低エネルギーでスカラー場）

× loop factor ($1/16\pi^2$)（treeでポテンシャルは無いから）←兎に角 finite



SM with top mass (173 GeV)

For this meta-stability, GHU says

$1/R \sim 10^{10}$ GeV!

N. Okada, Q. Shafi, et al

G.Degrassi, S.Di Vita, J.Elias-Miro, J.R.Espinosa, G.F.Giudice, G.Isidori and A.Strumia, JHEP1208 (2012) 098

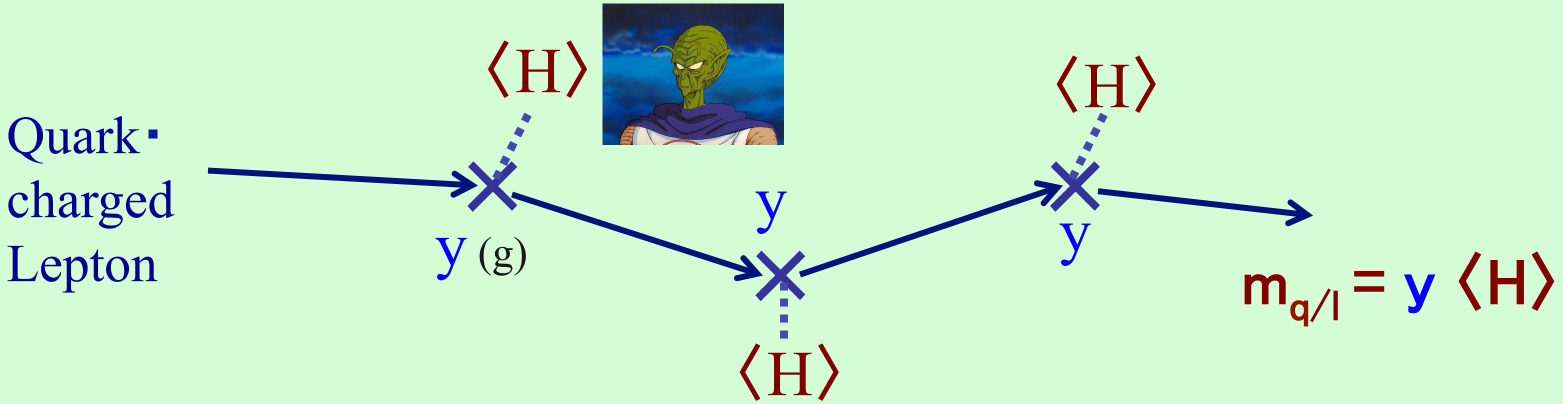
【理論的見地から】

TeV には標準模型を超える
新しい物理があると考えるの
が自然

他にも色々考えられないか？

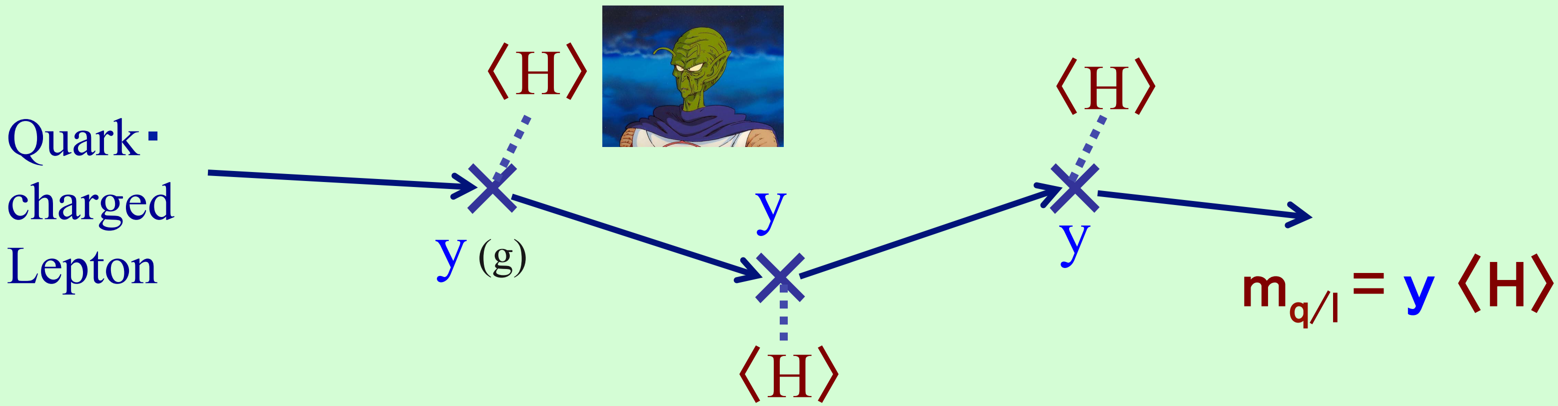
origin of tiny Dirac ν mass

mass hierarchy = Yukawa hierarchy ($y_t \sim 1$, $y_\nu \sim 10^{-12}$)



origin of tiny Dirac ν mass

another possibility: ***How about <u>tiny ⟨H⟩</u> only for ν?***



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neutrinophilic Higgs

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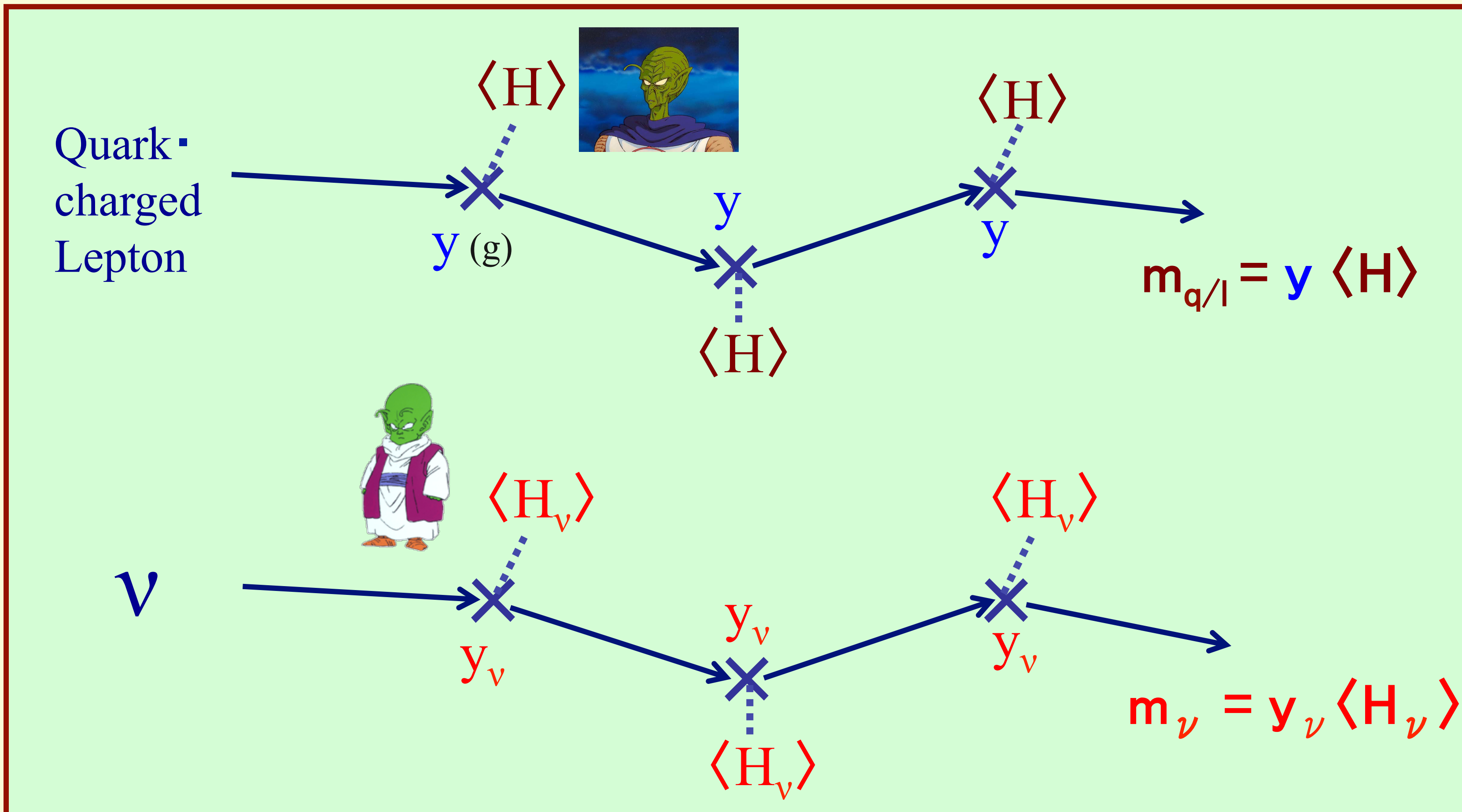

in of tiny Dirac ν mass

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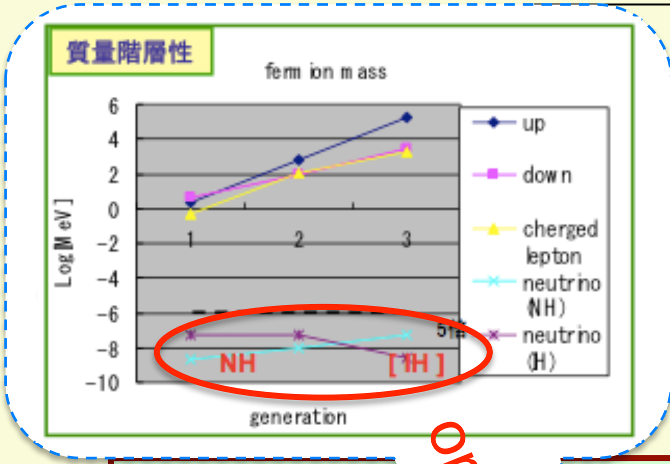

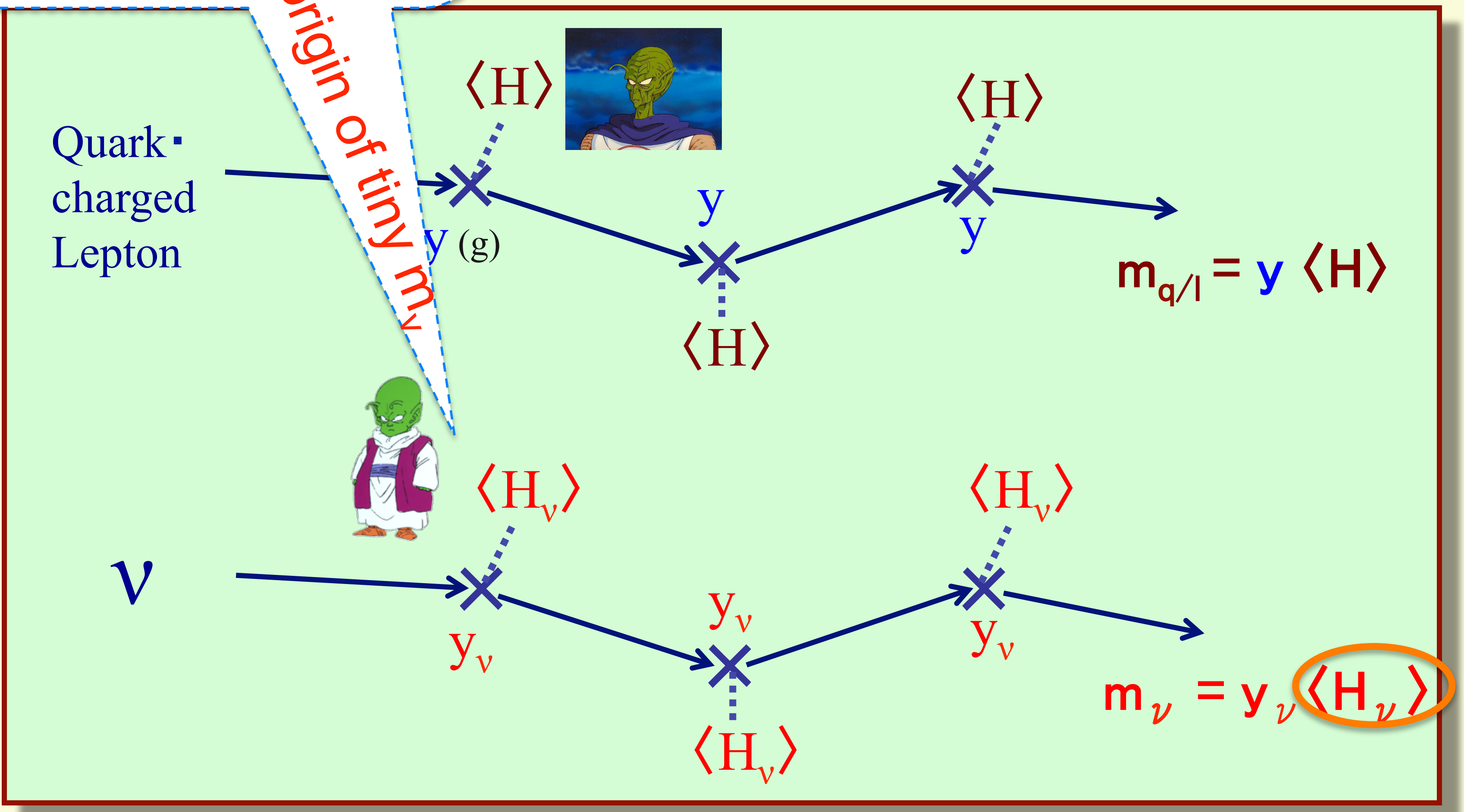

E. Ma (2001, 2006), E. Ma and M. Raidal (2001), N. H. and O. Seto (2010)
F. Wang, W. Wang and J. M. Yang (2006), S. Gabriel and S. Nandi (2007), G. Marshall, M. McCaskey, M. Sher (2010) ,

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$\langle H_\nu \rangle \sim 1$ eV

$$L = (\nu_L, e_L)$$

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fields	Z_2-charge
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ν_R	$-$
ν Higgs doublet: $\mathbf{H}_\nu$	$-$

distinguishes H_ν from H

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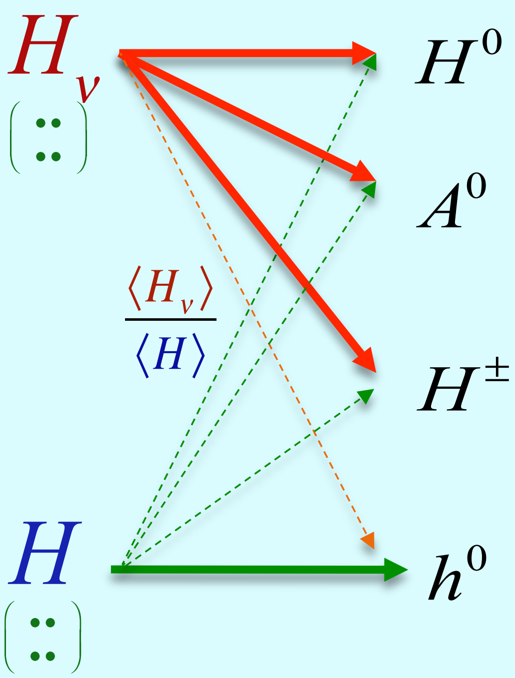

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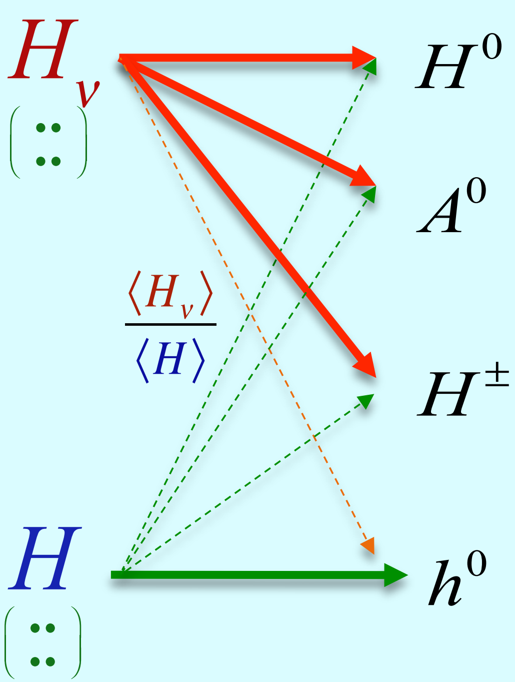

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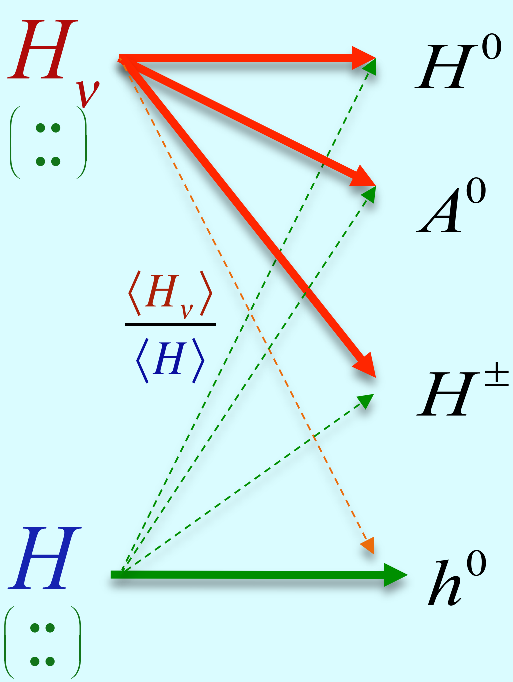

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⇒ non-small & only $(e, \mu, \tau)_L \times \nu_R$ Yukawa int.

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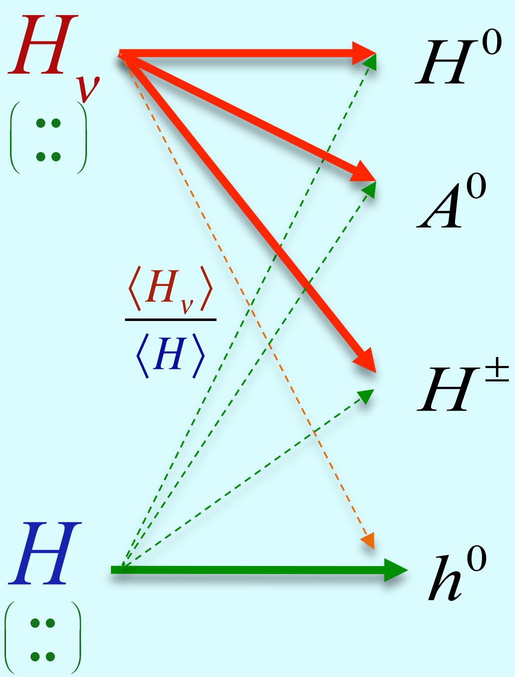

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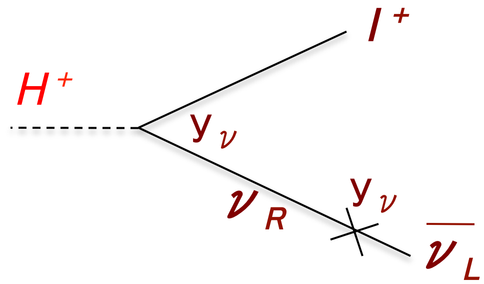
→ charged Higgs mainly decays into lepton, etc

(phenomenology @ LHC, ILC) S. M. Davidson and H. E. Logan (2009, 2010), N. H. and K. Tsumura (2010),

LHC, ILC phenomenology

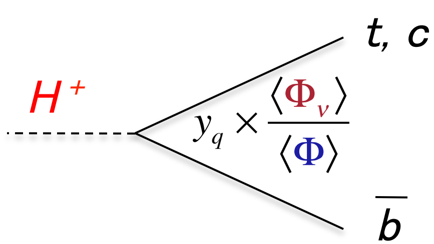
NH, K.Tsumura, JHEP 1106, 068 (2011).

$m_{H\pm} < m_{\nu R}$

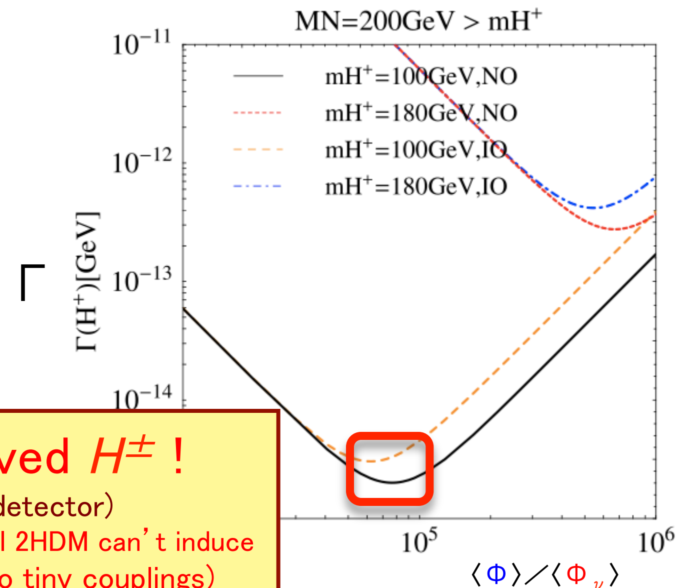


$$\Gamma(H^\pm \to l^\pm \nu_L) \sim G_F m_{H^\pm} m_\nu^2 \frac{\langle \Phi \rangle^2}{\langle \Phi_\nu \rangle^2}$$

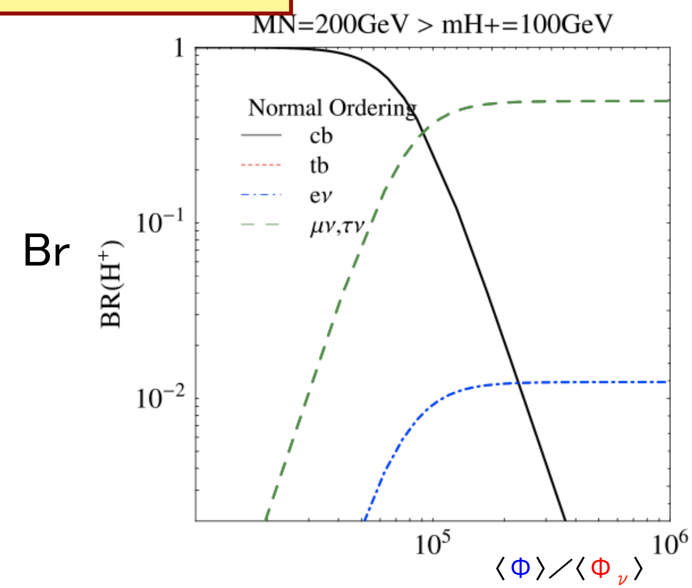
or



$$\Gamma(H^\pm \to q\bar{q}) \sim m_{H^\pm} y_q^2 \frac{\langle \Phi_\nu \rangle^2}{\langle \Phi \rangle^2}$$



long lived $H^\pm$!
(10cm in detector)
Conventional 2HDM can't induce
(due to no tiny couplings)



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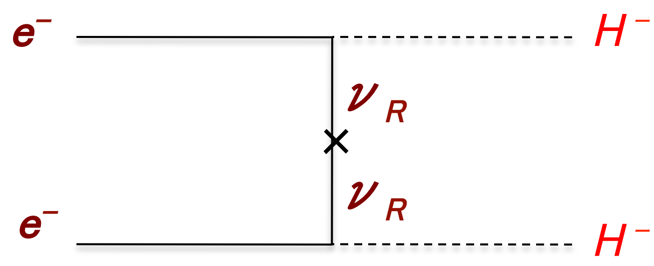
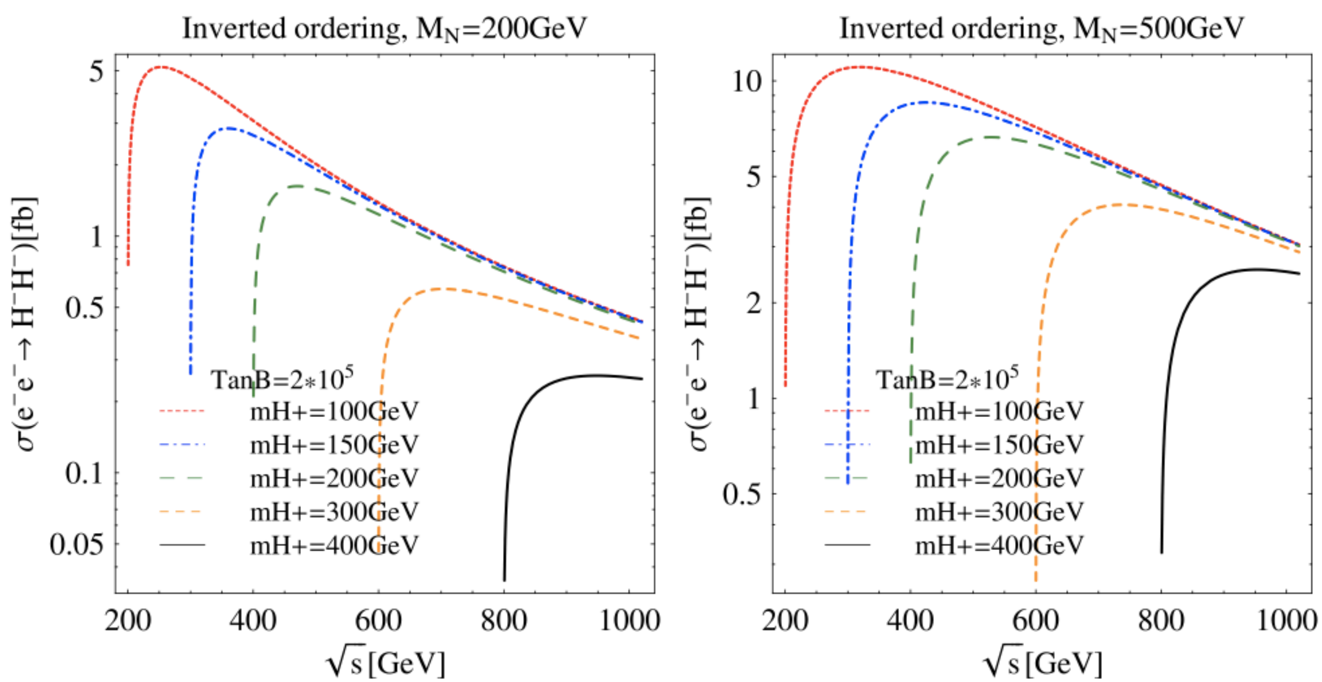
☆ILC: e^-e^- collider:



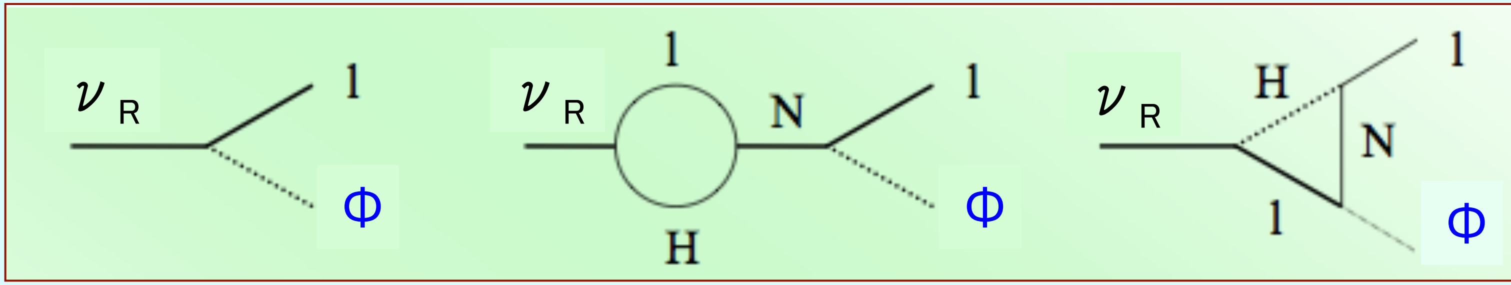


Total cross sections of $e^-e^- \to H^-H^-$ in νTHDM with ν_R, whose mass is $M_{\nu R}$ = 200 GeV and 500 GeV.

Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

leptogenesis: $\Gamma(\nu_R \to l + \Phi) \neq \Gamma(\overline{\nu}_R \to l + \Phi^*)$ ← CP violation



Conventional See-Saw (type-I)

$$\varepsilon \equiv \frac{\Gamma(\nu_{R1} \to \Phi + \overline{l}_j) - \Gamma(\nu_{R1} \to \Phi^* + l_j)}{\Gamma(\nu_{R1} \to \Phi + \overline{l}_j) + \Gamma(\nu_{R1} \to \Phi^* + l_j)}$$

$$\simeq -\frac{3}{8\pi}\frac{1}{(y_\nu y_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}(y_\nu y_\nu^\dagger)_{1i}^2 \frac{M_1}{M_i}, \ (M_i \gg M_1)$$

$$\simeq \frac{3}{8\pi}\frac{M_1 m_{\nu 3}}{\langle \Phi \rangle^2} \sin\delta \simeq 10^{-6}\left(\frac{M_1}{10^{10} GeV}\right)\left(\frac{m_{\nu 3}}{0.05 eV}\right)\sin\delta$$

$$\frac{n_b}{s} \simeq C\kappa \frac{\varepsilon}{g_*}$$

$\varepsilon \sim 10^{-7}$ for suitable n_b/s

thermal: $T_R > M_1$, ν_{R1} is produced in thermal

$M_1 > 10^9$ GeV : Davidson-Ibarra bound

S. Davidson and A. Ibarra, PLB 535, 25 (2002)

TeV-scale thermal leptogenesis is difficult !

Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

ν HDM: non−small y_ν with TeV−scale Majorana mass

$$\varepsilon \simeq -\frac{3}{8\pi}\frac{1}{(y_\nu y_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}(y_\nu y_\nu^\dagger)^2_{1i}\frac{M_1}{M_i} \simeq -\frac{3}{8\pi}\frac{M_1 m_{\nu 3}}{\langle\Phi_\nu\rangle^2}\sin\delta$$

$$\simeq -\frac{3}{16\pi}10^{-6}\left(\frac{0.1GeV}{\langle\Phi_\nu\rangle}\right)^2\left(\frac{M_1}{100GeV}\right)\left(\frac{m_\nu}{0.05eV}\right)\sin\delta$$

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$M_1 \geqq 5$ TeV is possible for thermal leptogenesis

$$0.1\ \mathrm{eV} \sim y^2\langle\Phi\rangle^2/M_R$$

↑ 大　　↓ 大

Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

ν HDM: non–small y_ν with TeV–scale Majorana mass

$$\varepsilon \simeq -\frac{3}{8\pi}\frac{1}{(y_\nu y_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}(y_\nu y_\nu^\dagger)_{1i}^2\frac{M_1}{M_i} \simeq -\frac{3}{8\pi}\frac{M_1 m_{\nu 3}}{\langle\Phi_\nu\rangle^2}\sin\delta$$

$$\simeq -\frac{3}{16\pi}10^{-6}\left(\frac{0.1GeV}{\langle\Phi_\nu\rangle}\right)^2\left(\frac{M_1}{100GeV}\right)\left(\frac{m_\nu}{0.05eV}\right)\sin\delta$$

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$M_1 \geqq 5$ TeV is possible for thermal leptogenesis

$$0.1\ \mathrm{eV} \sim y^2\langle\Phi_\nu\rangle^2/M_R$$

y^2 ↑ 大　$\langle\Phi_\nu\rangle$ ↑ 小　M_R ↓ 小

Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

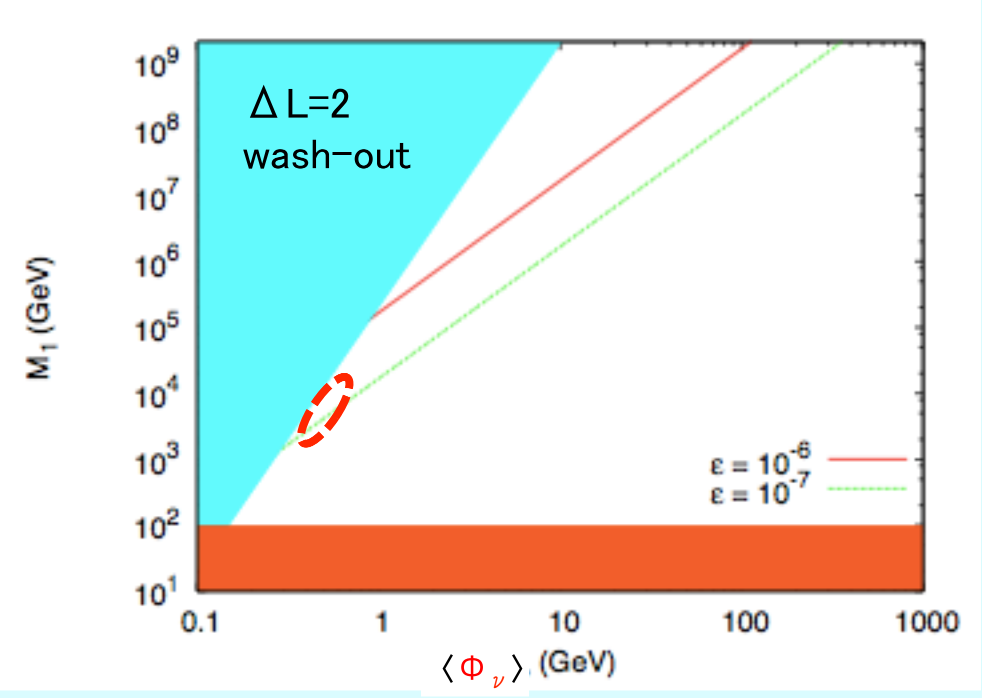
ν HDM: non-small y_ν with TeV-scale Majorana mass

$$\varepsilon \simeq -\frac{3}{8\pi}\frac{1}{(y_\nu y_\nu^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}(y_\nu y_\nu^\dagger)_{1i}^2\frac{M_1}{M_i} \simeq -\frac{3}{8\pi}\frac{M_1 m_{\nu 3}}{\langle\Phi_\nu\rangle^2}\sin\delta$$

$$\simeq -\frac{3}{16\pi}10^{-6}\left(\frac{0.1GeV}{\langle\Phi_\nu\rangle}\right)^2\left(\frac{M_1}{100GeV}\right)\left(\frac{m_\nu}{0.05eV}\right)\sin\delta$$

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$M_1 \geqq$ 5 TeV is possible for thermal leptogenesis



Low energy thermal leptogenesis

NH, O.Seto, Prog.Theor.Phys. 125, 1155 (2011); Phys. Rev. D84, 103524 (2011).

Leptogenesis in SUSY ν HDM: non-small y_ν with TeV-scale Majorana mass

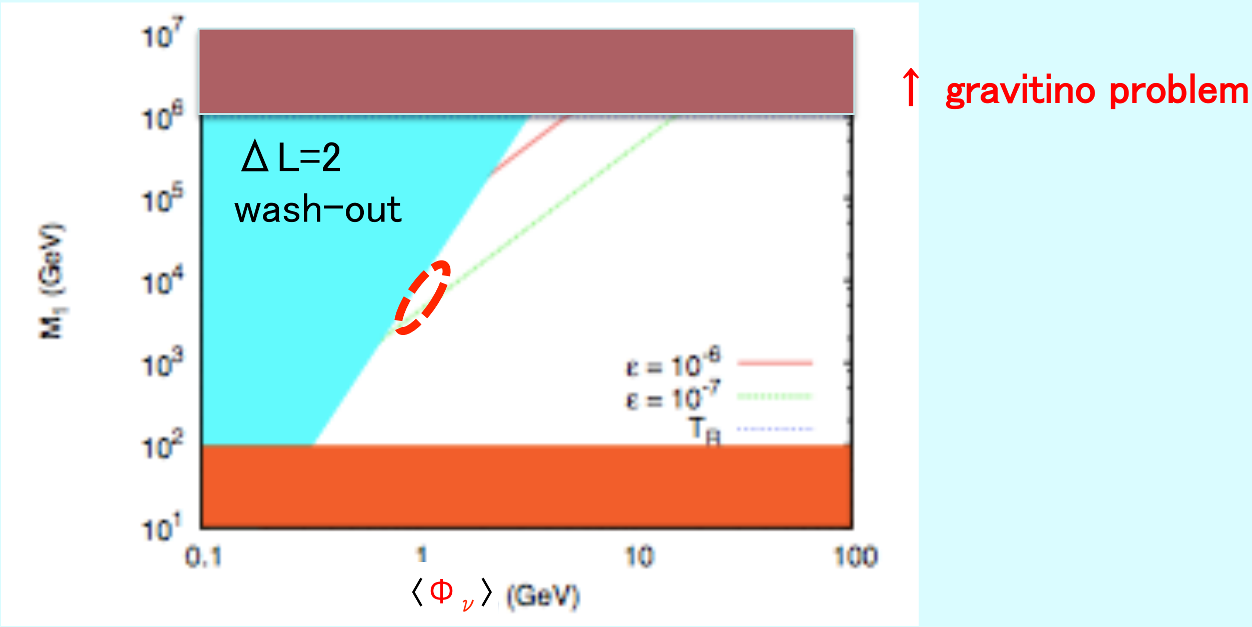
$$\varepsilon \equiv \varepsilon(\nu_R \to lH) + \varepsilon(\nu_R \to \tilde{l}\widetilde{H}) + \varepsilon(\widetilde{\nu_R} \to l\widetilde{H}) + \varepsilon(\widetilde{\nu_R} \to \tilde{l}H)$$

$$\simeq -\frac{3}{16\pi}10^{-5}\left(\frac{0.1GeV}{\langle\Phi_\nu\rangle}\right)^2\left(\frac{M_1}{10^3 GeV}\right)\left(\frac{m_\nu}{0.05eV}\right)\sin\delta$$

(NH, $m_1 \sim 0$, ($y_{i1} \ll y_{i2}, y_{i3}$))

$$\frac{n_b}{s} \simeq C\kappa\frac{\varepsilon}{g_*}$$

$M_1 \geqq 5$ TeV is possible for thermal leptogenesis



SUSY ν HDM is free from gravitino problem

- O(100) GeV gravitino with no-disturbing BBN needs $T_R < 10^6$ GeV.
- even this T_R, N_1 is thermally produced in our setup.

【研究計画２】

neutrinophiric Higgs は，FlatLand scenarioでうまくいくか？

【研究計画3】

・flavor symmetry:

tri-bi-maximal mixing [$\sin^2\theta_{12}$=1/3, $\sin^2\theta_{23}$=1/2] + deviation, seems good

-> find flavor symmetry (S_3, S_4, A_4, ・・・)

-> phenomenology

ex) ν mass sum rule

Sum Rule	Group
$\tilde m_1+\tilde m_2=\tilde m_3$	A_4 [167] ([175, 178–181]); S_4 ([182]); A_5 [69]*
$\tilde m_1+\tilde m_2=\tilde m_3$	$\Delta(54)$ [183]; S_4 ([163])
$\tilde m_1+2\tilde m_2=\tilde m_3$	S_4 [120]
$2\tilde m_2+\tilde m_3=\tilde m_1$	A_4 [165, 167] ([36, 37, 178–181, 188–194]) S_4 ([45, 124])†; T' [195, 196] ([46, 134, 197, 198]); T_7 ([199])
$2\tilde m_2+\tilde m_3=\tilde m_1$	A_4 ([200])
$\tilde m_1+\tilde m_2=2\tilde m_3$	S_4 [201]‡
$\tilde m_1+\tilde m_2=2\tilde m_3$	$L_e-L_\mu-L_\tau$ ([202])
$\tilde m_1+\frac{\sqrt{3}+1}{2}\tilde m_3=\frac{\sqrt{3}-1}{2}\tilde m_2$	A_5' ([203])
$\tilde m_1^{-1}+\tilde m_2^{-1}=\tilde m_3^{-1}$	A_4 [167]; S_4 ([163, 175]); A_5 [176, 177]
$\tilde m_1^{-1}+\tilde m_2^{-1}=\tilde m_3^{-1}$	S_4 ([163])
$2\tilde m_2^{-1}+\tilde m_3^{-1}=\tilde m_1^{-1}$	A_4 [135, 164, 165, 167, 204] ([37, 137, 145, 205–211]); T' [196]
$\tilde m_1^{-1}+\tilde m_3^{-1}=2\tilde m_2^{-1}$	A_4 ([212–214]); T' [215]
$\tilde m_3^{-1}\pm 2i\tilde m_2^{-1}=\tilde m_1^{-1}$	$\Delta(96)$ [66]
$\tilde m_1^{1/2}-\tilde m_3^{1/2}=2\tilde m_2^{1/2}$	A_4 ([162])
$\tilde m_1^{1/2}+\tilde m_3^{1/2}=2\tilde m_2^{1/2}$	A_4 ([216])
$\tilde m_1^{-1/2}+\tilde m_2^{-1/2}=2\tilde m_3^{-1/2}$	S_4 [217]

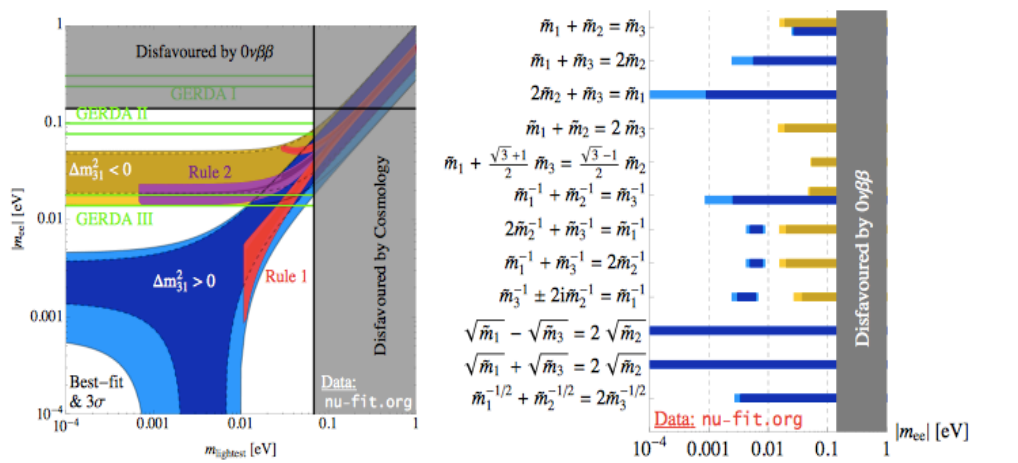


Figure 7: *Left panel:* Restrictions imposed on the allowed regions of $|m_{ee}|$ by two example sum rules (Rule 1: $\tilde m_1^{-1}+\tilde m_2^{-1}=\tilde m_3^{-1}$, Rule 2: $\tilde m_1+\tilde m_2=\tilde m_3$). The GERDA regions are displayed as examples for realistic experimentally accessible ranges. (Plot similar to Fig. 1 in Ref. [169].) *Right panel:* Derived ranges for the $|m_{ee}|$ from 12 different sum rules, covering more than 50 models in the literature. (Plot similar to Fig. 20 in Ref. [169].)

S. F. King, A. Merle, S. Morisi, Y. Shimizu and M. Tanimoto, New J. Phys.16 (2014) 045018

summary of research plan

【研究計画１】FlatLandシナリオの枠組みで,

→ ・TeV scale seesaw
(inverse seesaw? generation structure?
same sign di-lepton event? 0νββ? other observations?)

→ ・leptogenesis/bariyogenesis?
(resonant leptogenesis? quantum effects? New mechanism・・・)

【研究計画２】neutrinophiric Higgs in FlatLandシナリオ

【研究計画３】neutrinoからflavor symmetryを探る

For a goal
(discover BSM),

strong cooperation between experiment & theory is needed.

$\lambda(\mu < M_p) \sim 0$ をどうとらえるか？

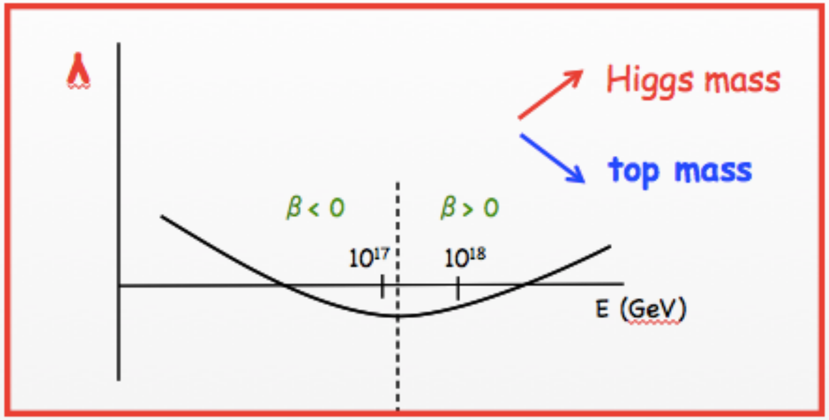
【その2】

EWの真空とMpの真空が縮退してる？

入れ忘れてる効果があって，本当は10^{10} GeVで負にはならないのだ。

m_H=125.9±0.4 GeV, m_{top}=172.58~174.10 GeV in the SM

$$(4\pi)^2\frac{d\lambda}{dt}=\underline{24\lambda^2}+12\lambda y_t^2\underline{-6y_t^4}-3\lambda(g'^2+3g^2)+\frac{3}{8}[2g^4+(g'^2+g^2)^2]$$

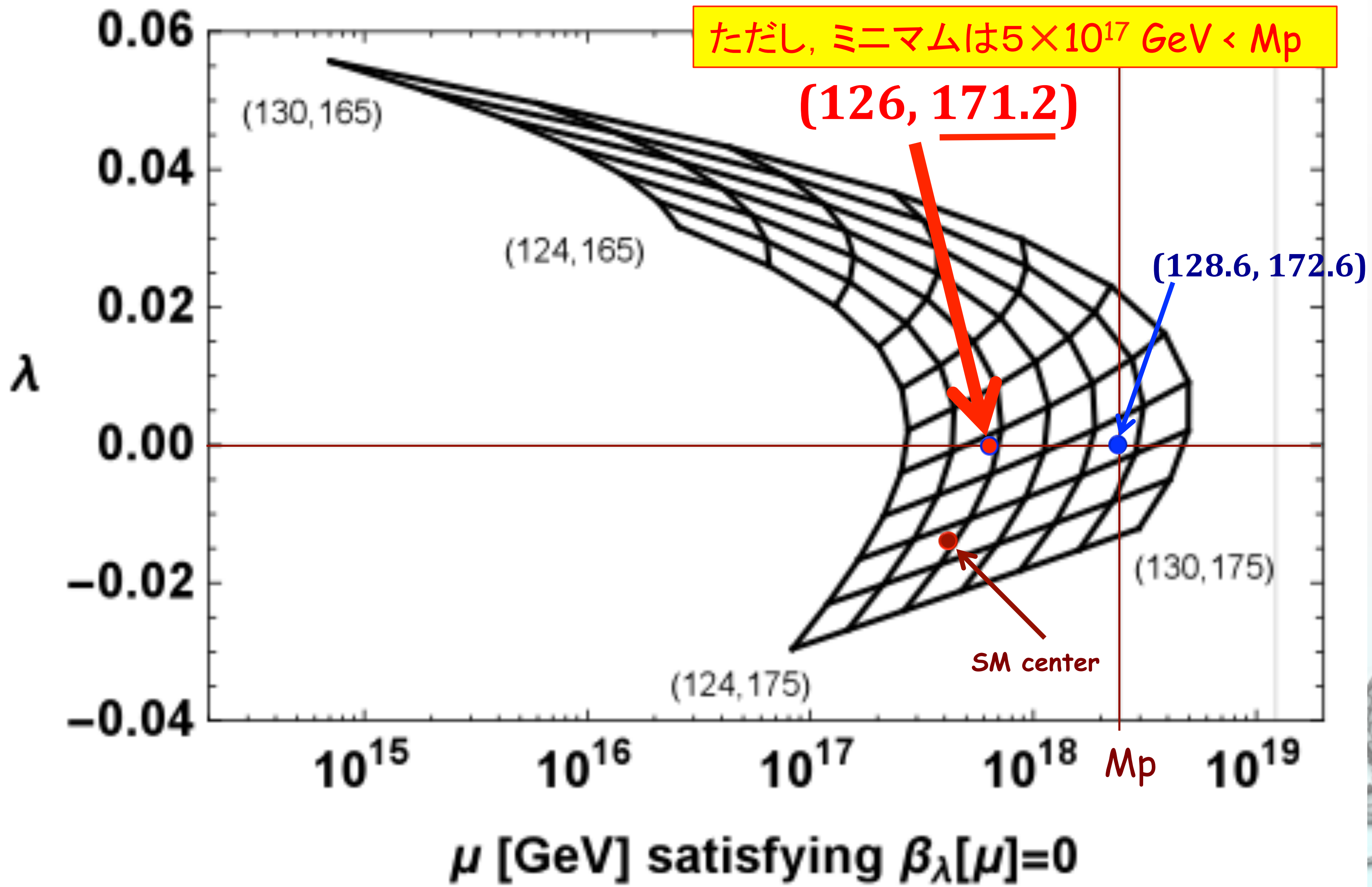


本当は，stable（持ち上がってるん）じゃない？
どういう時，持ち上がる（stableになる）か？

1. topが実はもう少し軽い？
2. scalarを入れる。
3. vectorを入れる。
4. gravityの効果？
5. gaugeのrunningがもっと強い？

…………

Higgs mass & top mass dependence for λ, β



Higgs mass & top mass are uniquely determined by MPCP @ Mp