Universität
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Vacuum stability in the Standard Model: Towards a four-loop precision analysis

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Outline

I. Introduction: Vacuum stability and the evolution of couplings

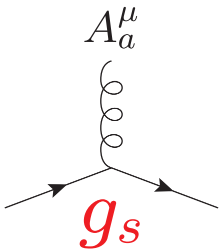
II. SM β-functions at 4 loops

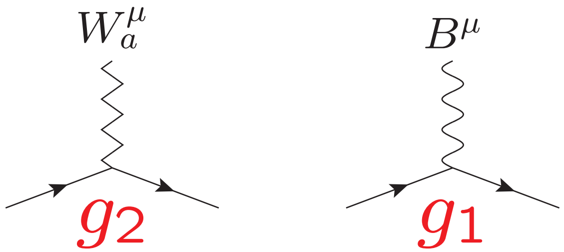
1. Conceptual challenge: γ_5-treatment
2. Leading 4 loop contributions to β_{g_s} [JHEP 1602 (2016) 095]
   and leading 4 loop contributions to β_{y_t} and β_λ [JHEP 06 (2016) 175]
3. 4 loop calculations beyond the SM [arXiv:1608.08982]

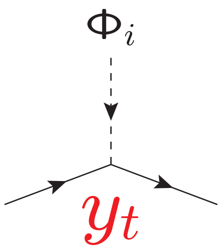
III. Current status of the the vacuum stability question in the SM

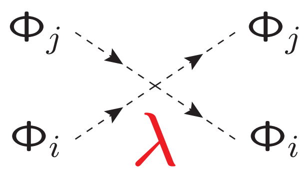
I. Vacuum stability and the evolution of couplings

Standard Model interactions:

- strong: 

electroweak: 

- Yukawa: 

Higgs self-interaction: 

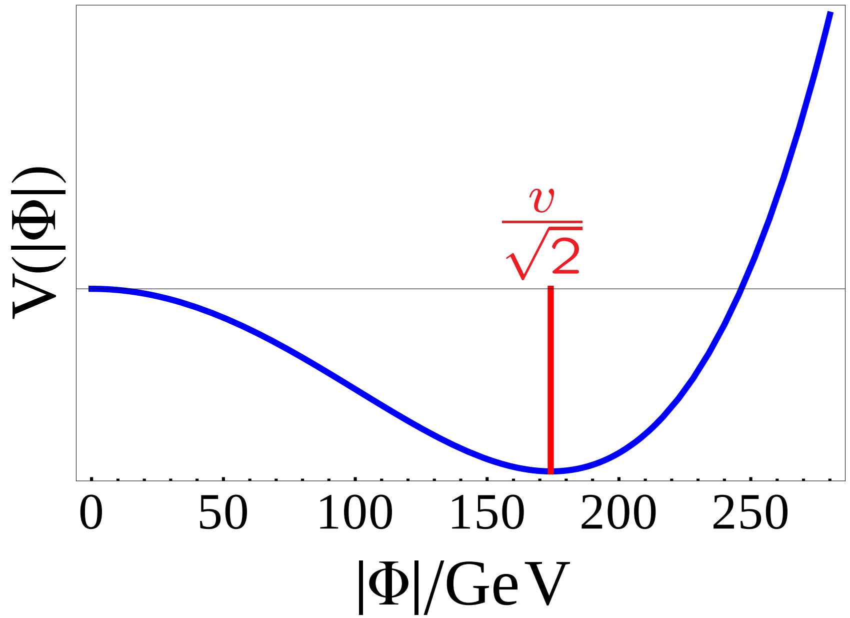
Classical Higgs potential:

$$V(\Phi) = m^2\, \Phi^\dagger\Phi + \lambda\, \left(\Phi^\dagger\Phi\right)^2$$

$$|\Phi(x)| \;=\; \frac{1}{\sqrt{2}}(v + H(x))$$

$$\Phi_{\rm cl}(x) \;\equiv\; \langle 0|\, \Phi(x)\, |0\rangle = \frac{v}{\sqrt{2}} \neq 0$$

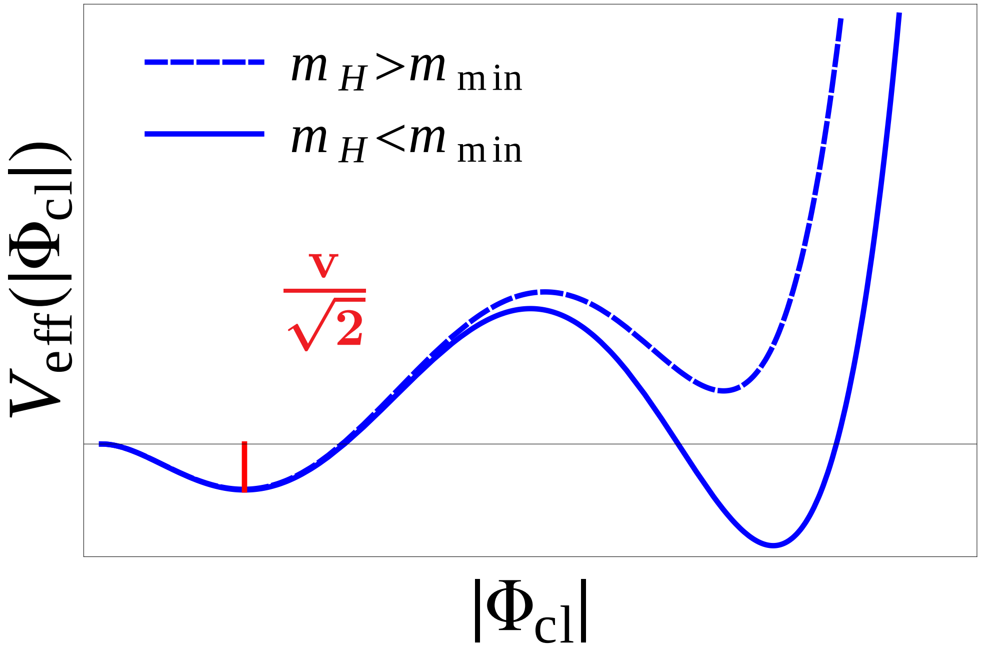
$v \approx 246$ GeV, $M_H^2 = -2m^2 = 2\lambda v^2$



The effective Potential

- Radiative corrections $\Rightarrow$ $\boxed{V_{\text{eff}}\left(\lambda(\Lambda), g_i(\Lambda), y_t(\Lambda), \ldots\right)[\Phi(\Lambda)]}$ [Coleman, Weinberg]

  (Λ: scale up to which the SM is valid)



- $\Phi_{\text{cl}} \sim \Lambda \gg v$: $\boxed{V_{\text{eff}}^{\text{RG}}[\Phi] = \lambda(\Lambda)\Phi^4(\Lambda) + \mathcal{O}(\lambda^2(\Lambda), g_i^2(\Lambda))}$ [Altarelli, Isidori; Ford, Jack, Jones]
- Stability of SM vacuum $\Leftrightarrow$ $\lambda(\Lambda) > 0$ [Cabibbo; Sher; Lindner; Ford]

Evolution of couplings $X \in \{\lambda, g_1, g_2, g_s, y_t, \ldots\}$

β-functions: $\boxed{\mu^2 \frac{d}{d\mu^2} X(\mu^2) = \beta_X[\lambda(\mu^2), y_t(\mu^2), g_i(\mu^2), \ldots]}$

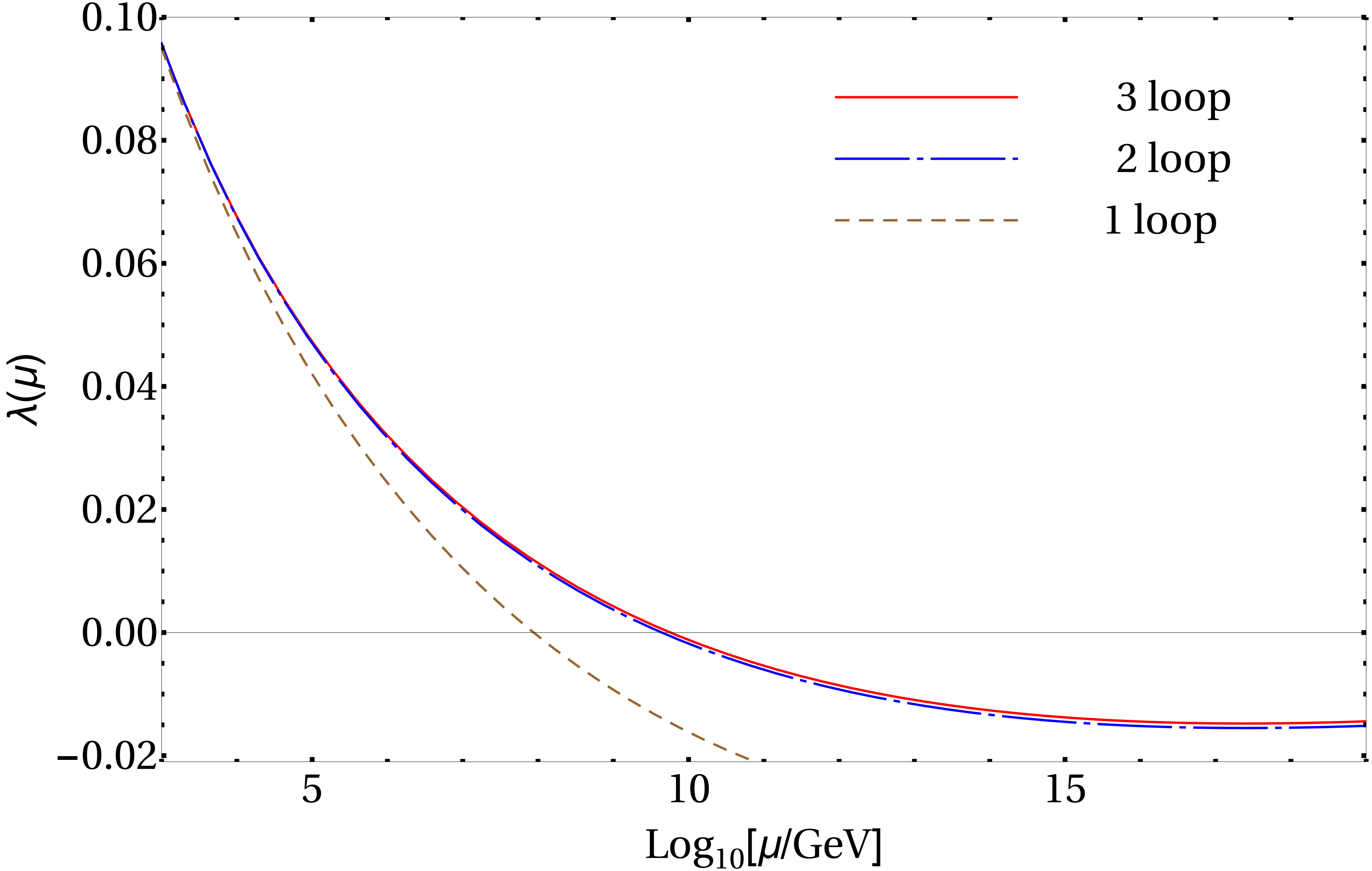
$\Rightarrow$ **Coupled system of differential equations with initial conditions:**

$$
\underbrace{
\begin{aligned}
\mu^2 \frac{d}{d\mu^2} \lambda(\mu^2) &= \beta_\lambda[\lambda(\mu^2), y_t(\mu^2), g_i(\mu^2)], \\
\mu^2 \frac{d}{d\mu^2} y_t(\mu^2) &= \beta_{y_t}[\lambda(\mu^2), y_t(\mu^2), g_i(\mu^2)], \\
\mu^2 \frac{d}{d\mu^2} g_s(\mu^2) &= \beta_{g_s}[\lambda(\mu^2), y_t(\mu^2), g_i(\mu^2)], \\
\mu^2 \frac{d}{d\mu^2} g_2(\mu^2) &= \beta_{g_2}[\lambda(\mu^2), y_t(\mu^2), g_i(\mu^2)], \\
\mu^2 \frac{d}{d\mu^2} g_1(\mu^2) &= \beta_{g_1}[\lambda(\mu^2), y_t(\mu^2), g_i(\mu^2)],
\end{aligned}
}
\qquad
\underbrace{
\begin{aligned}
\lambda(\mu_0^2) &= \lambda_0, \\
y_t(\mu_0^2) &= y_{t\,0}, \\
g_s(\mu_0^2) &= g_{s\,0}, \\
g_2(\mu_0^2) &= g_{2\,0}, \\
g_1(\mu_0^2) &= g_{1\,0}
\end{aligned}
}
$$

Calculated in $\overline{\text{MS}}$-scheme, power series in couplings

Experimental data matched to $\overline{\text{MS}}$-scheme

Evolution of $\lambda(\mu)$



II. Standard Model β-functions up to 4 loops

2 loop

[M. Fischler, C. Hill (1981); D. Jones (1982); M. Machacek, M. Vaughn (1983,1984,1985); I. Jack, H. Osborn (1984,1985)] [M. Fischler, J. Oliensis (1982); M. Machacek, M. Vaughn (1984); C. Ford, I. Jack, D. Jones (1992); M. Luo, Y. Xiao (2003)]

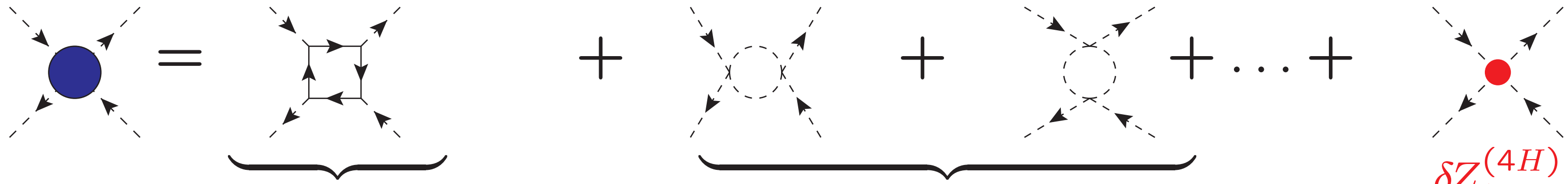
3 loop

- for gauge couplings g_1, g_2, g_s [L. Mihaila, J. Salomon, M. Steinhauser (2012); A. Bednyakov, A. Pikelner, Velizhanin (2012)]
- for Yukawa couplings y_t, y_b, y_τ, etc. [K. Chetyrkin, M.Z. (2012); A. Bednyakov, A. Pikelner, Velizhanin (2013)]
- for the Higgs self-coupling λ (and the mass parameter m^2) [K. Chetyrkin, M.Z. (2012 and 2013); A. Bednyakov, A. Pikelner, Velizhanin (2013)]

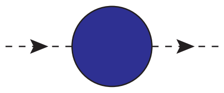
4 loop

- $\beta_{g_s}(g_s)$ [T. van Ritbergen, J. Vermaseren, S. Larin (1997); M. Czakon (2005)]
- $\beta_{g_s}(g_s, y_t, \lambda)$ [A. Bednyakov, A. Pikelner (2015); M.Z. (2015)]
- $\beta_\lambda \propto y_t^4 g_s^6$ [S. Martin (2016); K. Chetyrkin, M.Z. (2016)]
- $\beta_{y_t} \propto y_t g_s^8$ and $\beta_{m^2} \propto y_t^2 g_s^6$ [K. Chetyrkin, M.Z. (2016)]

Calculation of β-functions, e.g. $\beta_\lambda(\lambda, g_i)$



$\propto \frac{y_t^4}{(16\pi^2)}$ $\quad$ $\propto \frac{\lambda^2}{(16\pi^2)}$ $\quad$ $\delta Z_1^{(4H)}$

$\Big[$  $=$ finite $\Big]$ $\Rightarrow$ Field strength renormalization constant $Z_2^{(2H)}$

$$\lambda_B = \mu^{2\varepsilon}\,(\lambda + \delta Z_\lambda)\,; \qquad \delta Z_\lambda = (\lambda - \delta Z_1^{(4H)})\left(Z_2^{(2H)}\right)^{-2} = \sum_{n=1}^{\infty} \frac{a_n(\lambda,g_i)}{\varepsilon^n}$$

use $\mu^2 \frac{d}{d\mu^2}\lambda_B \equiv 0 \;\Rightarrow$ $\boxed{\beta_\lambda = \left[\lambda\frac{\partial}{\partial\lambda} + \frac{1}{2}\sum_i g_i \frac{\partial}{\partial g_i} - 1\right] a_1}$

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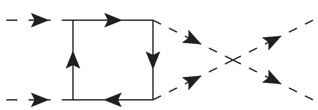
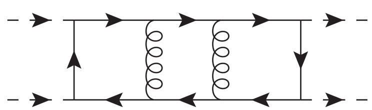
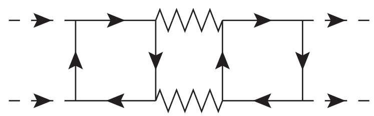
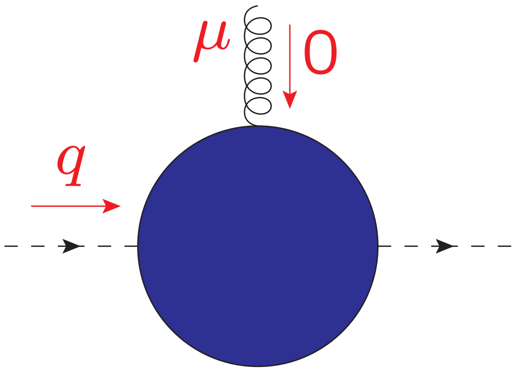
higher orders:

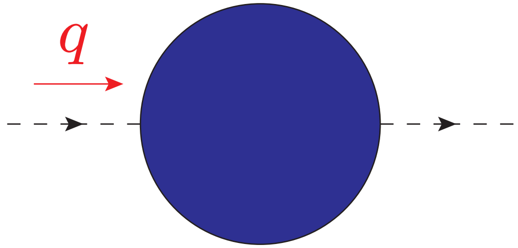
  

$\propto \frac{y_t^4\lambda}{(16\pi^2)^3}$ $\qquad$ $\propto \frac{y_t^4 g_s^4}{(16\pi^2)^3}$ $\qquad$ $\propto \frac{y_t^4 g_2^2}{(16\pi^2)^2}$

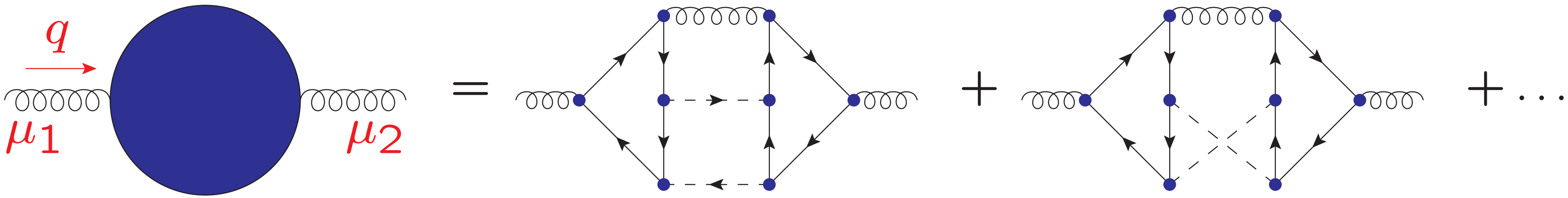
β_{g_s} at 4 loop from the ghost-gluon-vertex



projector: $\frac{q^\mu}{q^2}$



already scalar $\propto q^2$

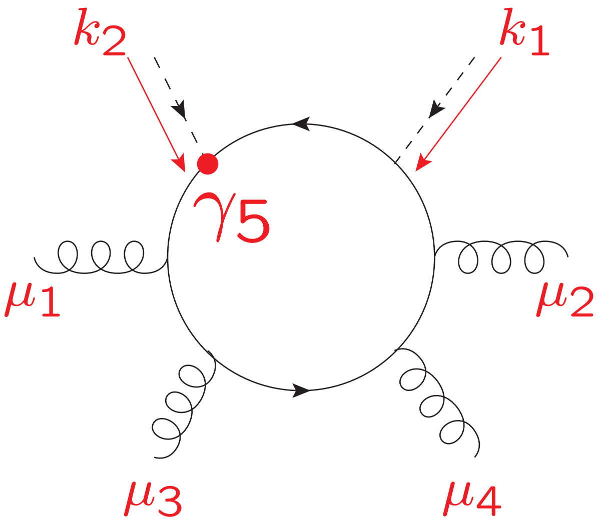


projector: $\frac{1}{D-1}\, g^{\mu_1\mu_2} \cdot \text{Ptr} + q^{\mu_1} q^{\mu_2} \cdot \text{Plong}$

Treatment of γ_5

$\boxed{\gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \frac{i}{4!}\varepsilon_{\mu\nu\rho\sigma}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma}$ in $D=4$: $\{\gamma_5,\gamma^\mu\}=0$ and $\gamma_5^2=1$

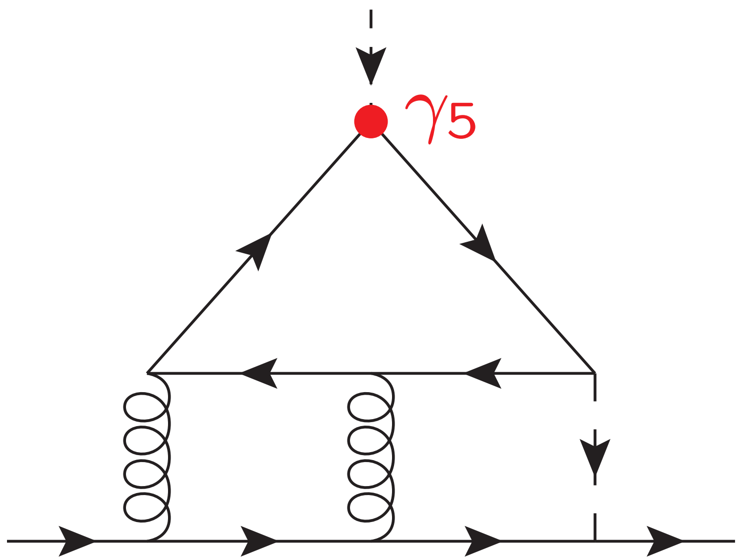
fermion loop:



$$\mathrm{Tr}(\ldots) \propto \#\,\varepsilon_{\mu_1\mu_2\mu_3\mu_4} + \#\,\varepsilon_{\mu_1\mu_2\alpha\beta}\,k_1^\alpha\,k_2^\beta + \ldots$$

$\Rightarrow$ At least 4 free Lorentz structures needed, else diagram=0

Treatment of γ_5 in the Z_{y_t} calculation



$\propto P_L = \frac{1}{2}(1-\gamma_5)$

use projector $\propto \gamma_5$ on external fermion line, apply

$$\gamma_5 = \frac{i}{4!}\varepsilon_{\mu\nu\rho\sigma}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma \text{ with } \varepsilon_{0123} = 1$$

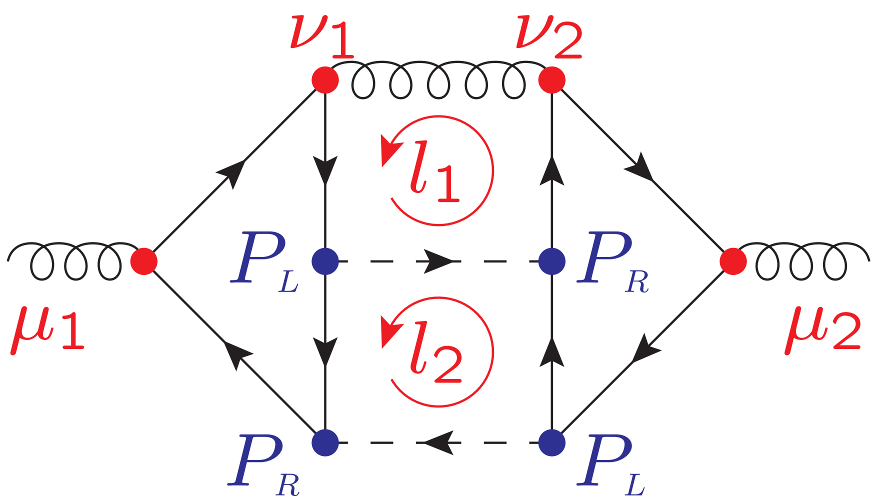
and use

$$\varepsilon^{\mu_1\mu_2\mu_3\mu_4}\varepsilon_{\nu_1\nu_2\nu_3\nu_4} = -g^{[\mu_1}_{\nu_1}g^{\mu_2}_{\nu_2}g^{\mu_3}_{\nu_3}g^{\mu_4]}_{\nu_4}$$

(error of $O(\varepsilon)$)

$\Rightarrow$ Pole part OK if Feynman integrals have only $\frac{1}{\varepsilon}$ poles. ($\surd$)

Treatment of γ_5 in the gluon propagator



- Use $\varepsilon^{\mu_1\mu_2\mu_3\mu_4}\varepsilon_{\nu_1\nu_2\nu_3\nu_4} = -g^{[\mu_1}_{\ \nu_1} g^{\mu_2}_{\ \nu_2} g^{\mu_3}_{\ \nu_3} g^{\mu_4]}_{\ \nu_4}\,(1 + \varepsilon \cdot \mathrm{LABEL})$
- Anticommuting γ_5 to different points in different diagrams changes result in this case! UV divergent part always transversal.
- Move γ_5 to external vertices $\rightarrow \frac{1}{\varepsilon} g_s^4 y_t^4 T_F^2 \left(\frac{4}{3} + 8\zeta_3\right)$
- Leave γ_5 at their original position $\rightarrow 3 \cdot \frac{1}{\varepsilon} g_s^4 y_t^4 T_F^2 \left(\frac{4}{3} + 8\zeta_3\right)$
  Only here also finite part of self-energy transversal [Bednyakov, Pikelner]

Automation

- Generation of diagrams $\rightarrow$ QGRAF [Noguira]
- SU(2) $\times$ U$_Y$(1) group factors $\rightarrow$ Form code [M.Z.]
- SU$_C$(3) group factors $\rightarrow$ COLOR [Van Ritbergen, Schellekens, Vermaseren]
- find topologies $\rightarrow$ GEFICOM [Chetyrkin, M.Z.] and
  Q2E, EXP [Seidesticker, Harlander, Steinhauser]
- Feynman rules, projectors, counterterms, fermion traces, expansion in external momenta $\rightarrow$ FORM [Vermaseren] code [Chetyrkin, M.Z.]
- massive tadpole integrals $\rightarrow$ up to 3 loop: MATAD [Steinhauser];
  Reduction at 4 loop: FIRE5 (C++ version) [Smirnov] (based on IBP)
  $\Rightarrow$ use 19 Master integrals [Czakon et al]

Results

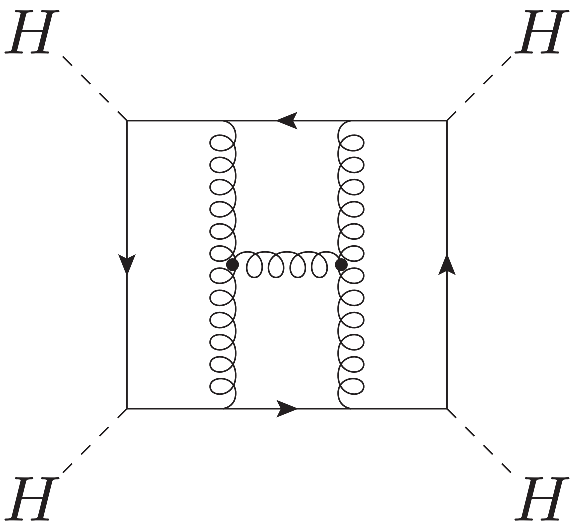
$$\mu^2 \frac{d}{d\mu^2} g_s(\mu) = \beta_{g_s} = \sum_{n=1}^{\infty} \frac{1}{(16\pi^2)^n} \beta_{g_s}^{(n)}$$ (in the $\overline{\text{MS}}$-scheme)

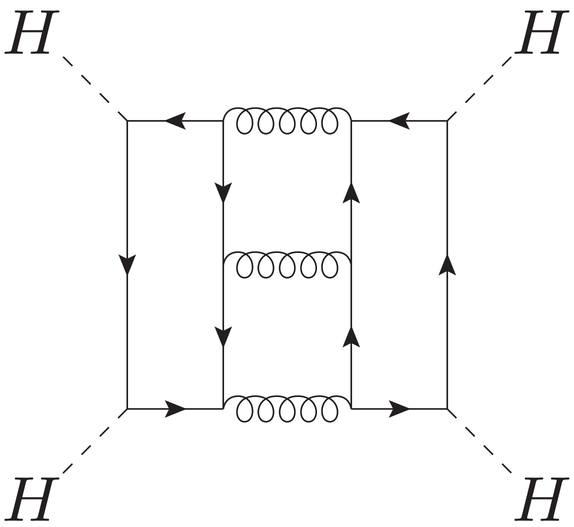
$$\begin{aligned}
\frac{\beta_{g_s}^{(4)}}{g_s} = &+ g_s^8 \Big(-\frac{149753}{12} + \frac{1078361}{324} n_f - \frac{50065}{324} n_f^2 - \frac{1093}{1458} n_f^3 \\
&-1782\zeta_3 + \frac{3254}{27}\zeta_3 n_f - \frac{3236}{81}\zeta_3 n_f^2 \Big) \\
&+ g_s^6 y_t^2 \Big(-\frac{9959}{18} + \frac{1625}{54} n_f + 136\zeta_3 \Big) \\
&+ g_s^4 y_t^4 \Big(\frac{423}{2} + 2 - 60\zeta_3 + 12\zeta_3 \Big) \qquad \leftarrow \text{non-naive part} \\
&+ g_s^2 y_t^6 \Big(-\frac{423}{8} - 3\zeta_3 \Big) - 15\, g_s^2 y_t^4 \lambda + 18\, g_s^2 y_t^2 \lambda^2
\end{aligned}$$

$$\begin{aligned}
\frac{\beta_{g_s}^{(4)}}{\beta_{g_s}^{(1)} (16\pi^2)^3} = &\underbrace{2.26 \times 10^{-4}}_{g_s^8} \underbrace{+2.47 \times 10^{-5}}_{g_s^6 y_t^2} \underbrace{-1.06 \times 10^{-5}}_{g_s^4 y_t^4 \text{(naive)}} \underbrace{+12.51 \times 10^{-7}}_{g_s^4 y_t^4 \text{(non-naive)}} \\
&\underbrace{+2.77 \times 10^{-6}}_{g_s^2 y_t^6} \underbrace{+1.06 \times 10^{-7}}_{g_s^2 y_t^4 \lambda} \underbrace{-1.82 \times 10^{-8}}_{g_s^2 y_t^2 \lambda^2}
\end{aligned}$$

Dominant contribution to β_λ at four loops

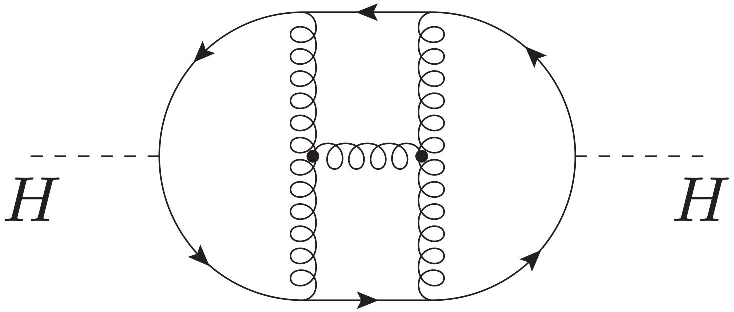
Four-Higgs-vertex:

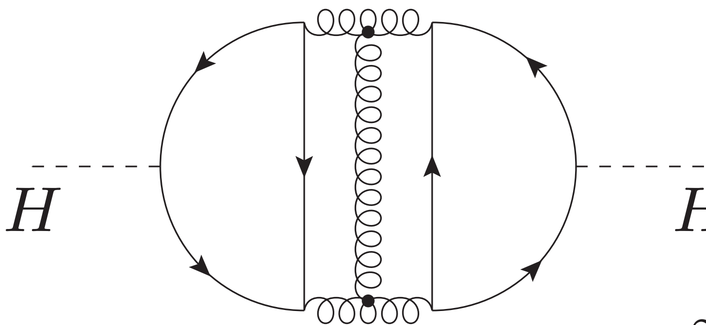




$$\propto \frac{y_t^4 g_s^6}{(16\pi^2)^4}$$

Higgs propagator:





$$\propto \frac{y_t^2 g_s^6}{(16\pi^2)^4}$$

Results

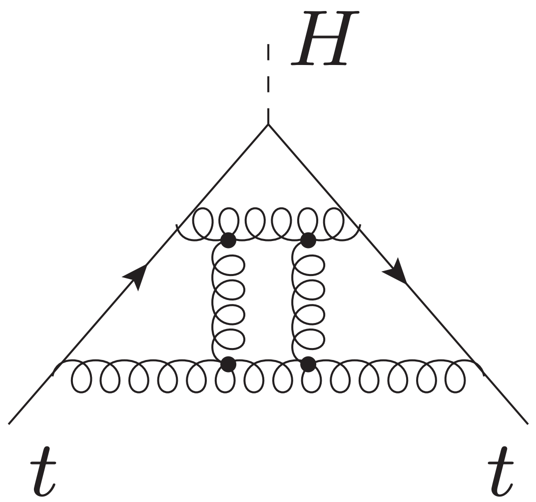
$$\mu^2 \frac{d}{d\mu^2}\lambda(\mu) = \beta_\lambda = \sum_{n=1}^{\infty} \frac{1}{(16\pi^2)^n} \beta_\lambda^{(n)}$$

(in the $\overline{\text{MS}}$-scheme)

$$\begin{aligned}
\beta_{\lambda}^{(4)} = & y_t^4 g_s^6 d_R \Big\{ C_F^3 \left(-\frac{2942}{3} + 160\zeta_5 + 288\zeta_4 + 48\zeta_3 \right) \\
& + T_F C_F^2 \left(-64 + n_f \left(+\frac{562}{3} - 160\zeta_4 + \frac{32}{3}\zeta_3 \right) \right) \\
& + C_A C_F^2 \left(\frac{3584}{3} + 720\zeta_5 + 32\zeta_4 - \frac{3304}{3}\zeta_3 \right) \\
& + C_A T_F C_F \left(\frac{5888}{9} - 160\zeta_5 + 352\zeta_3 + n_f \left(-\frac{2644}{243} + 128\zeta_4 + 16\zeta_3 \right) \right) \\
& + C_A^2 C_F \left(-\frac{121547}{243} - 520\zeta_5 - 88\zeta_4 + \frac{1880}{3}\zeta_3 \right) \\
& + T_F^2 C_F \left(-\frac{256}{9} n_f + n_f^2 \left(-\frac{128}{3}\zeta_3 + \frac{10912}{243} \right) \right) \Big\} \\
& + \mathcal{O}(y_t^6) + \mathcal{O}(\lambda) + \mathcal{O}(g_2) + \mathcal{O}(g_1)
\end{aligned}$$

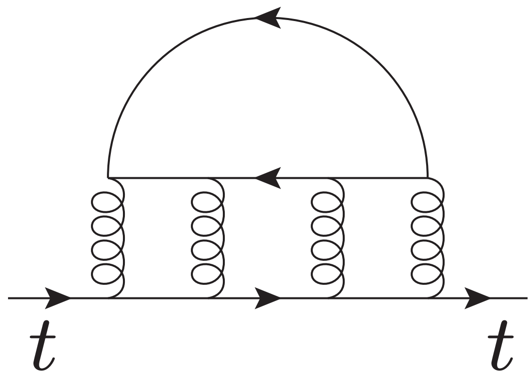
Dominant contribution to β_{y_t} at four loops:

Higgs-$t\bar{t}$-vertex:



$\propto \frac{y_t g_s^8}{(16\pi^2)^4}$

Top-propagator:



$\propto \frac{g_s^8}{(16\pi^2)^4}$

Results

$$\mu^2 \frac{d}{d\mu^2} y_t(\mu) = \beta_{y_t} = \sum_{n=1}^{\infty} \frac{1}{(16\pi^2)^n} \beta_{y_t}^{(n)}$$ (in the $\overline{\text{MS}}$-scheme)

$$\beta_{y_t}^{(4)} = y_t g_s^8 \Bigg\{ \frac{d_F^{abcd} d_A^{abcd}}{d_R} (32 - 240\zeta_3) + n_f \frac{d_F^{abcd} d_F^{abcd}}{d_R} (-64 + 480\zeta_3)$$
$$+ C_F^4 \left(\frac{1261}{8} + 336\zeta_3 \right) - C_A C_F^3 \left(\frac{15349}{12} + 316\zeta_3 \right)$$
$$+ C_A^2 C_F^2 \left(\frac{34045}{36} - 440\zeta_5 + 152\zeta_3 \right) + C_A^3 C_F \left(-\frac{70055}{72} + 440\zeta_5 - \frac{1418}{9}\zeta_3 \right)$$
$$+ n_f T_F C_F^3 \left(\frac{280}{3} + 480\zeta_5 - 552\zeta_3 \right) + n_f C_A T_F C_F^2 \left(\frac{8819}{27} - 80\zeta_5 + 264\zeta_4 - 368\zeta_3 \right)$$
$$+ n_f C_A^2 T_F C_F \left(\frac{65459}{162} - 400\zeta_5 - 264\zeta_4 + \frac{2684}{3}\zeta_3 \right)$$
$$+ n_f^2 T_F^2 C_F^2 \left(-\frac{304}{27} - 96\zeta_4 + 160\zeta_3 \right) + n_f^2 C_A T_F^2 C_F \left(-\frac{1342}{81} + 96\zeta_4 - 160\zeta_3 \right)$$
$$+ n_f^3 T_F^3 C_F \left(\frac{664}{81} - \frac{128}{9}\zeta_3 \right) \Bigg\} + \mathcal{O}(y_t^3) + \mathcal{O}(\lambda) + \mathcal{O}(g_2) + \mathcal{O}(g_1).$$

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with $d_F^{abcd} = \frac{1}{6} \text{Tr} \left(T^a T^b T^c T^d + T^a T^b T^d T^c + T^a T^c T^b T^d + T^a T^c T^d T^b + T^a T^d T^b T^c + T^a T^d T^c T^b \right)$

Beyond the SM: β_{α_s} with different fermion representations

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} - \frac{1}{2(1-\xi)} (\partial_\mu A^{a\,\mu})^2 + \partial_\mu \overline{c}^a \partial^\mu c^a + g_s f^{abc}\, \partial_\mu \overline{c}^a A^{b\,\mu} c^c$$
$$+ \sum_{r=1}^{N_{\text{rep}}} \sum_{q_r} \left\{ \frac{i}{2} \bar{q}_r \overleftrightarrow{\partial\!\!\!/}\, q_r + g_s \bar{q}_r A\!\!\!/^a T_r^a q_r \right\}$$

Gauge group factors:

$r = 1, \ldots, N_{\text{rep}}$ fermion representations of dimension $d_{F,i}$,
Adjoint representation with dimension N_A,
Casimirs: $C_{F,i}$ for fermion representation, C_A for adjoint

$$T_{F,i}\delta^{ab} = \mathbf{Tr}\left(T^{a,i}T^{b,i}\right)$$
$$d_i^{a_1 a_2 \ldots a_n} = \frac{1}{n!} \sum_{\text{perm } \pi} \text{Tr}\left\{T^{a_{\pi(1)},i} T^{a_{\pi(2)},i} \ldots T^{a_{\pi(n)},i}\right\},$$

Application: QCD + gluinos (Majorana fermions)

$$n_{f,1} = n_f, \qquad n_{f,2} = \frac{n_{\tilde{g}}}{2},$$
$$T_{F,1} = T_F, \qquad T_{F,2} = C_A,$$
$$C_{F,1} = C_F, \qquad C_{F,2} = C_A$$

β_{α_s} with different fermion representations

$$\beta^{(1)}_{\alpha_s} = -\frac{11}{3}C_A + \sum_i \frac{4}{3} n_{f,i} T_{F,i} \tag{1}$$

$$\vdots$$

$$\begin{aligned}
\beta^{(4)}_{\alpha_s} = & -\left(\frac{150653}{486} - \frac{44}{9}\zeta_3\right) C_A^4 + \left(\frac{80}{9} - \frac{704}{3}\zeta_3\right) \frac{d_A^{abcd} d_A^{abcd}}{N_A} \\
& + \sum_i n_{f,i} T_{F,i} \left[-46 C_{F,i}^3 + \left(\frac{4204}{27} - \frac{352}{9}\zeta_3\right) C_A C_{F,i}^2 - \left(\frac{7073}{243} - \frac{656}{9}\zeta_3\right) C_A^2 C_{F,i} \right. \\
& \left. + \left(\frac{39143}{81} - \frac{136}{3}\zeta_3\right) C_A^3 \right] - \sum_i n_{f,i} \left(\frac{512}{9} - \frac{1664}{3}\zeta_3\right) \frac{d_{F,i}^{abcd} d_A^{abcd}}{N_A} \\
& + \sum_{i,j} n_{f,i} n_{f,j} T_{F,i} T_{F,j} \left[-\left(\frac{184}{3} - 64\zeta_3\right) C_{F,i} C_{F,j} + \left(\frac{304}{27} + \frac{128}{9}\zeta_3\right) C_{F,i}^2 \right. \\
& \left. - \left(\frac{17152}{243} C_A C_{F,i} + \frac{448}{9}\zeta_3\right) C_A C_{F,i} - \left(\frac{7930}{81} + \frac{224}{9}\zeta_3\right) C_A^2 \right] \\
& + \sum_{i,j} n_{f,i} n_{f,j} \left(\frac{704}{9} - \frac{512}{3}\zeta_3\right) \frac{d_{F,i}^{abcd} d_{F,j}^{abcd}}{N_A} \\
& - \sum_{i,j,k} n_{f,i} n_{f,j} n_{f,k} T_{F,i} T_{F,j} T_{F,k} \left[\frac{1232}{243} C_{F,i} + \frac{424}{243} C_A\right]
\end{aligned} \tag{2}$$

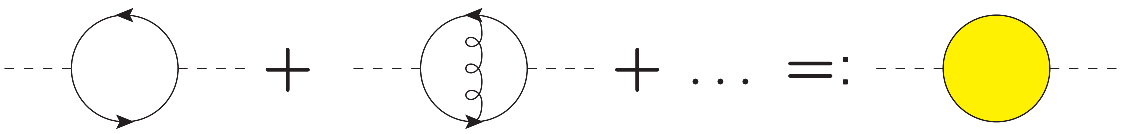
IV. Current status of vacuum stability

Starting values for SM couplings

[Sirlin, Zucchini; Hempfling, Kniehl; Jegerlehner et al; Bezrukov et al; Buttazzo et al; Kniehl, Veretin]

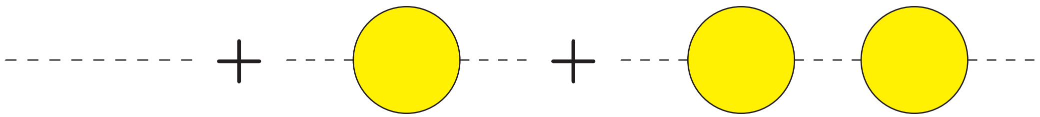
Example: The Higgs propagator

1 PI self energy:



$=: \Sigma(p^2, m_H, g_i)$

full propagator:



$\frac{i}{p^2 - m_H^2 - \Sigma(p^2, m_H, g_i)}$

Physical mass M_H $\Leftrightarrow$ pole of full propagator

For $\boxed{p^2 = M_H^2}$ $\Rightarrow$ $\boxed{m_H^2 - \Sigma(p^2, m_H, g_i) = M_H^2}$ with $\boxed{m_H = \sqrt{2\,\lambda}\,v}$

Same for M_t, M_W, M_Z, G_F $\Rightarrow$ Solve for λ, v, y_t, etc.

Starting values for SM couplings

Experimental input

$M_t^{\rm MC} \approx 173.34 \pm 0.76$ GeV $\Rightarrow$ $M_t = 173.39^{+1.12}_{-0.98}$ GeV

[Moch et al] via MSR mass [Hoang et al]

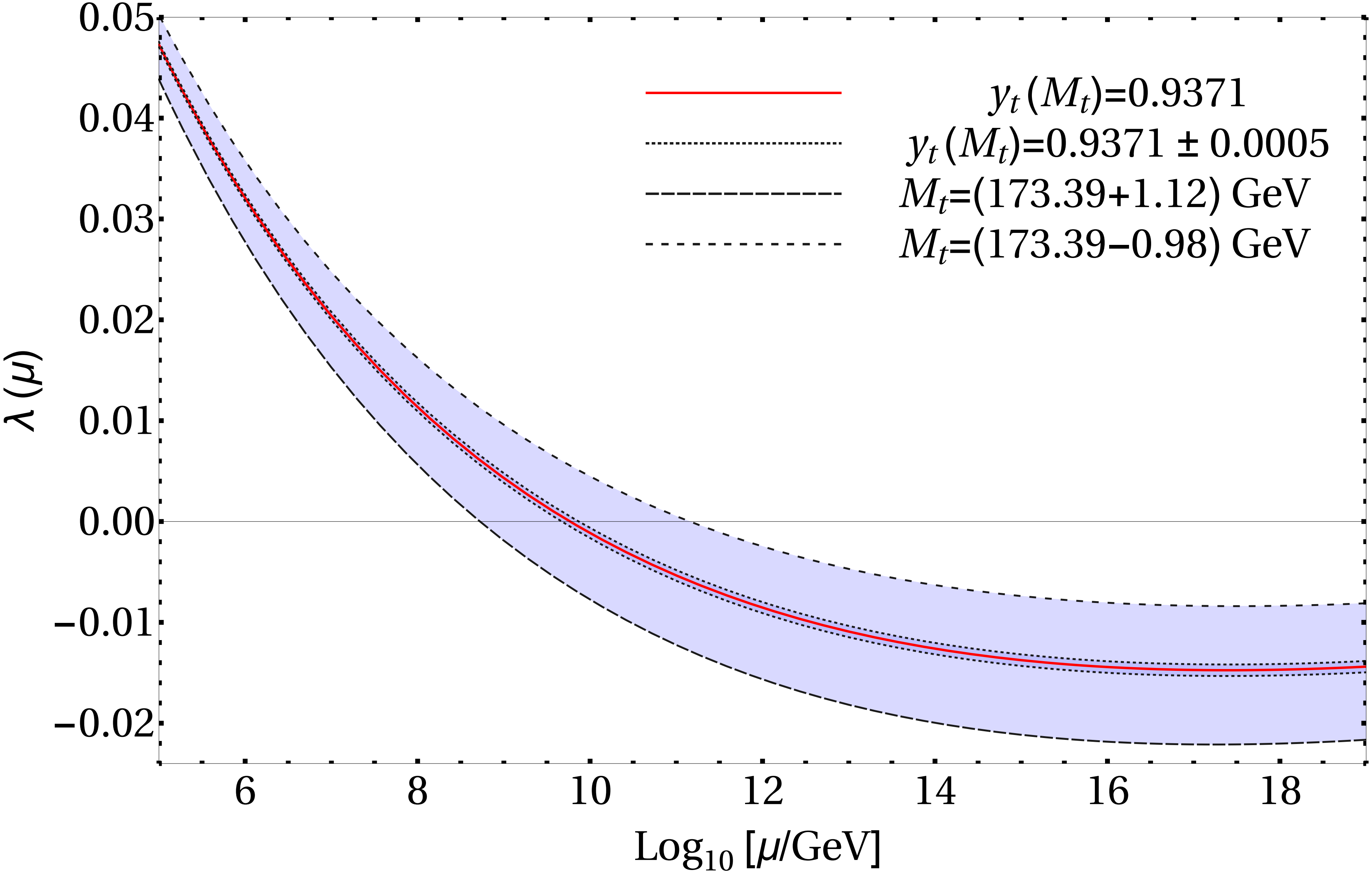
$M_H \approx 125.09 \pm 0.24$ GeV

$\alpha_s \approx 0.1185 \pm 0.0006$

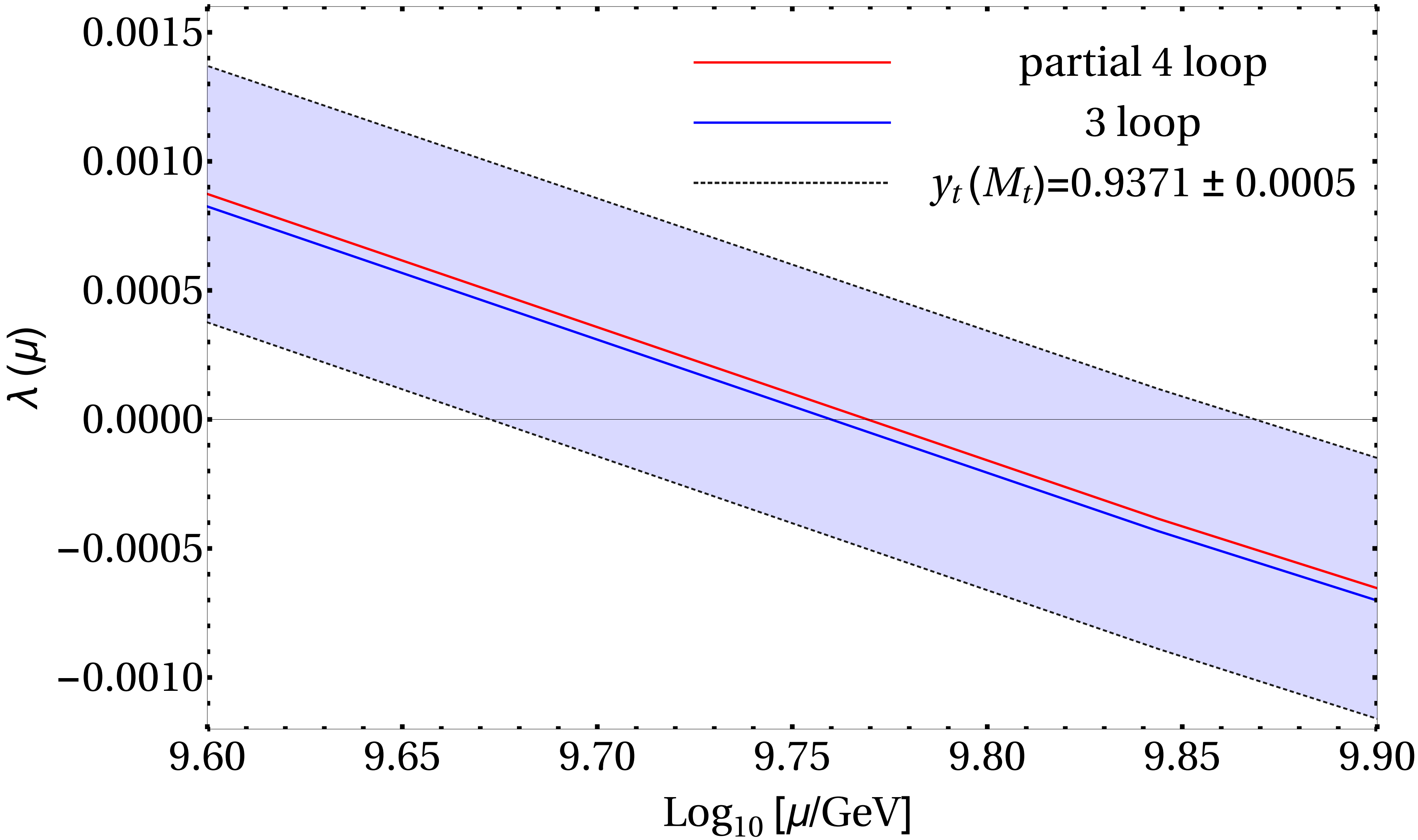
$\overline{\rm MS}$-couplings:

$$
\begin{aligned}
g_s(M_t) &= 1.1652 \pm 0.0035(\text{exp}), \\
y_t(M_t) &= 0.9374^{+0.0063}_{-0.0062}(\text{exp}) \pm 0.0005 \text{ (2 loop matching)}, \\
\lambda(M_t) &= 0.1259 \pm 0.0005(\text{exp}) \pm 0.0003 \text{ (2 loop matching)}, \\
g_2(M_t) &= 0.6483, \\
g_1(M_t) &= 0.3587
\end{aligned}
$$

Evolution of $\lambda(\mu)$



Evolution of $\lambda(\mu)$



Summary

- Stability of SM vacuum $\leftrightarrow$ $\boxed{\lambda > 0}$

- β-functions in full SM at 3 loop and now partial 4 loop

- Limiting problem for full 4 loop β-functions and 3 loop matching in the SM: γ_5

- SM vacuum looks not stable (metastable), M_t largest source of uncertainty

BACKUP

Evolution of $\lambda(\mu)$