Running Masses at Various Energy Scales

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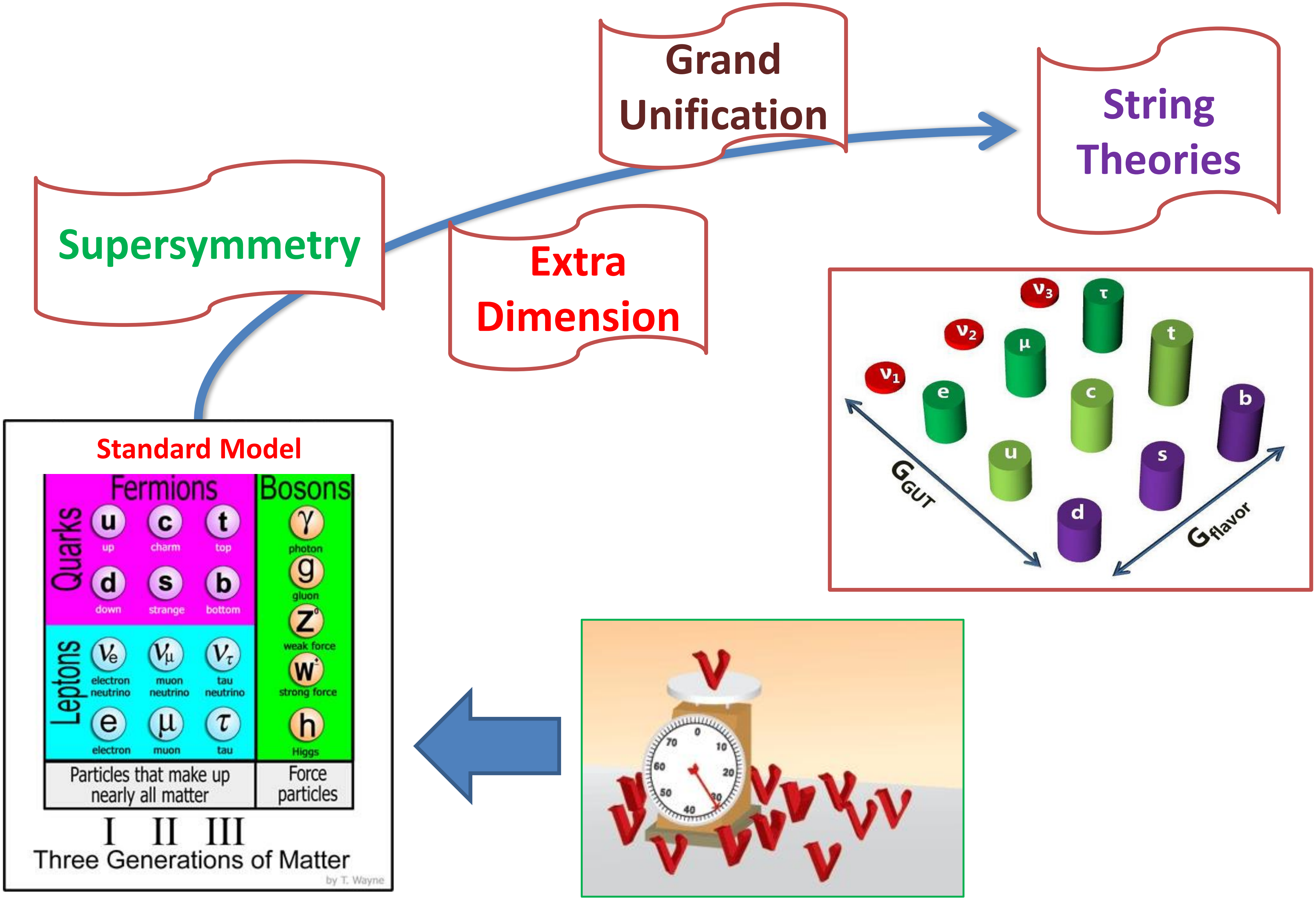
Contents:

- Motivations and PDG-fit parameters for the Standard Model
- Running fermion masses below and above the electroweak scale
- Introduction to **RUM**

Based on:

work in preparation with S. Zhou

Xing, Zhang, Zhou, PRD2008 [0712.1419]



Grand Unification
String Theories
Supersymmetry
Extra Dimension
Standard Model
Fermions
Bosons
Quarks
Leptons
u
up
c
charm
t
top
d
down
s
strange
b
bottom
γ
photon
g
gluon
Z
weak force
W
strong force
h
Higgs
electron neutrino
muon neutrino
tau neutrino
e
electron
μ
muon
τ
tau
Particles that make up nearly all matter
Force particles
I II III
Three Generations of Matter
by T. Wayne
ν_1
ν_2
ν_3
e
μ
τ
u
c
t
d
s
b
G_{GUT}
G_{flavor}

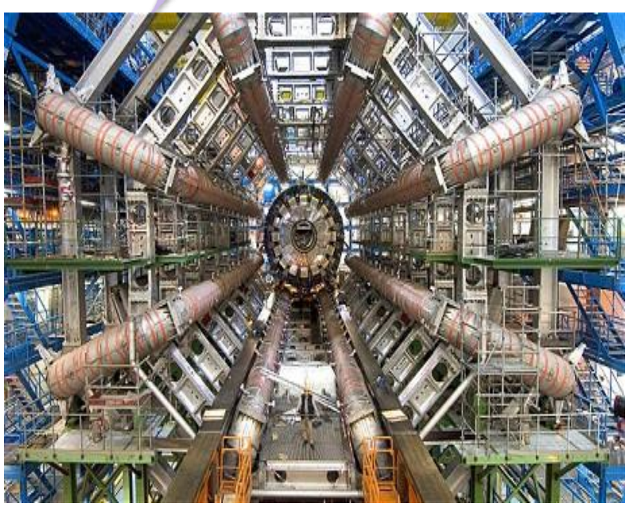
$$\mu \frac{d\alpha}{d\mu} = \frac{1}{16\pi^2} (\beta_1 \alpha^2 + \beta_2 \alpha^3 + \cdots)$$

GUT,
Supersymmetry,
Extra Dimension,
String, ...

High energy scale theories

RGE

Low-energy measurements



Reliable values of the running fermion masses, mixing parameters, gauge couplings, and Higgs quartic coupling are crucial for model building and phenomenological analysis. With these running variables at hand, it is convenient to compare the model predictions with the experimental data at a common energy scale (from M_Z to M_{GUT}).

❖ **How to evaluate these variables and uncertainties at an arbitrary scale?**

Conventions:

GRAND UNIFIED THEORY

Yukawa couplings y_f
$SU(3) \times SU(2) \times U(1)$ gauge couplings $g_3, \;\; g_2, \;\; g_1$
Higgs self-interaction λ
CKM parameters $\theta_{12}^q, \theta_{23}^q, \theta_{13}^q, \delta^q$
Neutrino mixing parameters and masses

EW scale $\qquad \mu = M_Z \sim 91.2\ \mathrm{GeV}$

Charged fermion running masses and pole masses
Strong coupling α_s
Electromagnetic coupling α
Fermi constant G_F

Light quark (u, d, s) masses are estimated using:

- **Lattice Gauge Theory ($\overline{\text{MS}}$)**

$$m_u = 2.15 \pm 0.15 \text{ MeV}$$

$$m_d = 4.70 \pm 0.20 \text{ MeV}$$

$$m_s = 93.5 \pm 2.5 \text{ MeV}$$

- **Chiral Perturbation Theory** $\bar{q}_L M q_R + \bar{q}_R M q_L \Rightarrow$ QCD ~~chiral symmetry~~

$$\frac{m_u}{m_d} = \frac{2m_{\pi^0}^2 - m_{\pi^+}^2 + m_{K^+}^2 - m_{K^0}^2}{m_{K^0}^2 - m_{K^+}^2 + m_{\pi^+}^2} = 0.56$$

- **Sum Rules**

$$\frac{\mathrm{d}R_\tau}{\mathrm{d}s} = \frac{\mathrm{d}\Gamma/\mathrm{d}s\left(\tau^- \to \text{hadrons} + \nu_\tau(\gamma)\right)}{\Gamma\left(\tau^- \to e^-\overline{\nu}_e\nu_\tau(\gamma)\right)}$$

PDG2013 summarizes the $\overline{\text{MS}}$ masses at the scale $\mu \cong 2$ GeV

$m_u = 2.3^{+0.7}_{-0.5}$ MeV $\quad$ $m_d = 4.8^{+0.5}_{-0.3}$ MeV $\quad$ $m_s = 95 \pm 5$ MeV

Heavy quark (c, b) masses:

- **heavy quark effective theory**
- **non-relativistic QCD**

$$m_c(m_c) = 1.275 \pm 0.025 \text{ GeV}$$

$$m_b(m_b) = 4.18 \pm 0.03 \text{ GeV}$$

Top quark pole mass:

- **position of the pole in the quark propagator**

$$D(\not{p}) = \frac{i}{\not{p} - m_R - \Sigma(\not{p})}$$

Measurements from Tevatron and LHC

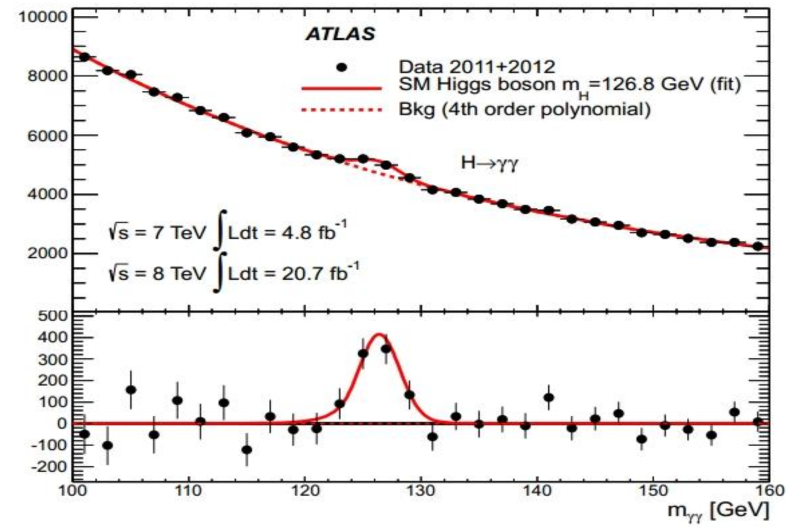
m_t (GeV/c^2)	Source	$\int \mathcal{L}dt$	Ref.	Channel
$175.1 \pm 0.8 \pm 1.3$	DØ Run I+II	≤ 5.4	[72]	ℓ+jets + $\ell\ell$
$172.5 \pm 1.4 \pm 1.5$	CDF Run II	5.8	[65]	All jets
$172.3 \pm 2.4 \pm 1.0$	CDF Run II	5.7	[66]	Missing E_T+jets
$172.3 \pm 3.4 \pm 2.1$	CDF Run II	2.0	[64]	$\ell\ell$
$172.7 \pm 9.3 \pm 3.7$	CDF Run II	2.2	[73]	τ+jets
$172.7 \pm 0.6 \pm 0.9$	CDF Run I+II	≤ 5.8	[74]	Multiple channels
$173.4 \pm 1.9 \pm 2.7$	CMS	0.036	[75]	ℓ+jets + $\ell\ell$
$175.9 \pm 0.9 \pm 2.7$	ATLAS	0.70	[53]	ℓ+jets
$173.5 \pm 0.6 \pm 0.8^{*}$	CDF,DØ CMS			publ. results, PDG best
$173.2 \pm 0.6 \pm 0.8^{**}$	CDF,DØ (I+II)	≤ 5.8	[76]	publ. or prelim. results

PDG 2013

$$M_t(\text{pole}) = 173.2 \pm 0.6 \pm 0.8 \text{ GeV}$$

Charged lepton masses (PDG):

$$M_e = 0.510998928 \pm 0.000000011\ \text{MeV}$$
$$M_\mu = 105.6583715 \pm 0.0000035\ \text{MeV}$$
$$M_\tau = 1776.82 \pm 0.16\ \text{MeV}$$



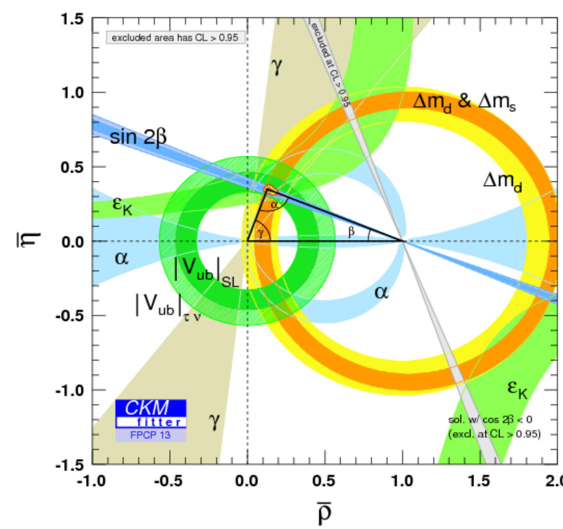
Gauge and Higgs bosons:

$$M_Z = 91.1876 \pm 0.0021\ \text{GeV}$$
$$M_W = 80.385 \pm 0.015\ \text{GeV}$$
$$M_H = 125.9 \pm 0.4\ \text{GeV}$$

The CKM quark mixing matrix

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.22535 \pm 0.00065 \qquad \bar{\rho} = 0.131^{+0.026}_{-0.013}$$
$$A = 0.811^{+0.022}_{-0.012} \qquad \bar{\eta} = 0.345^{+0.013}_{-0.014}$$



CKMfitter Group

Neutrino parameters

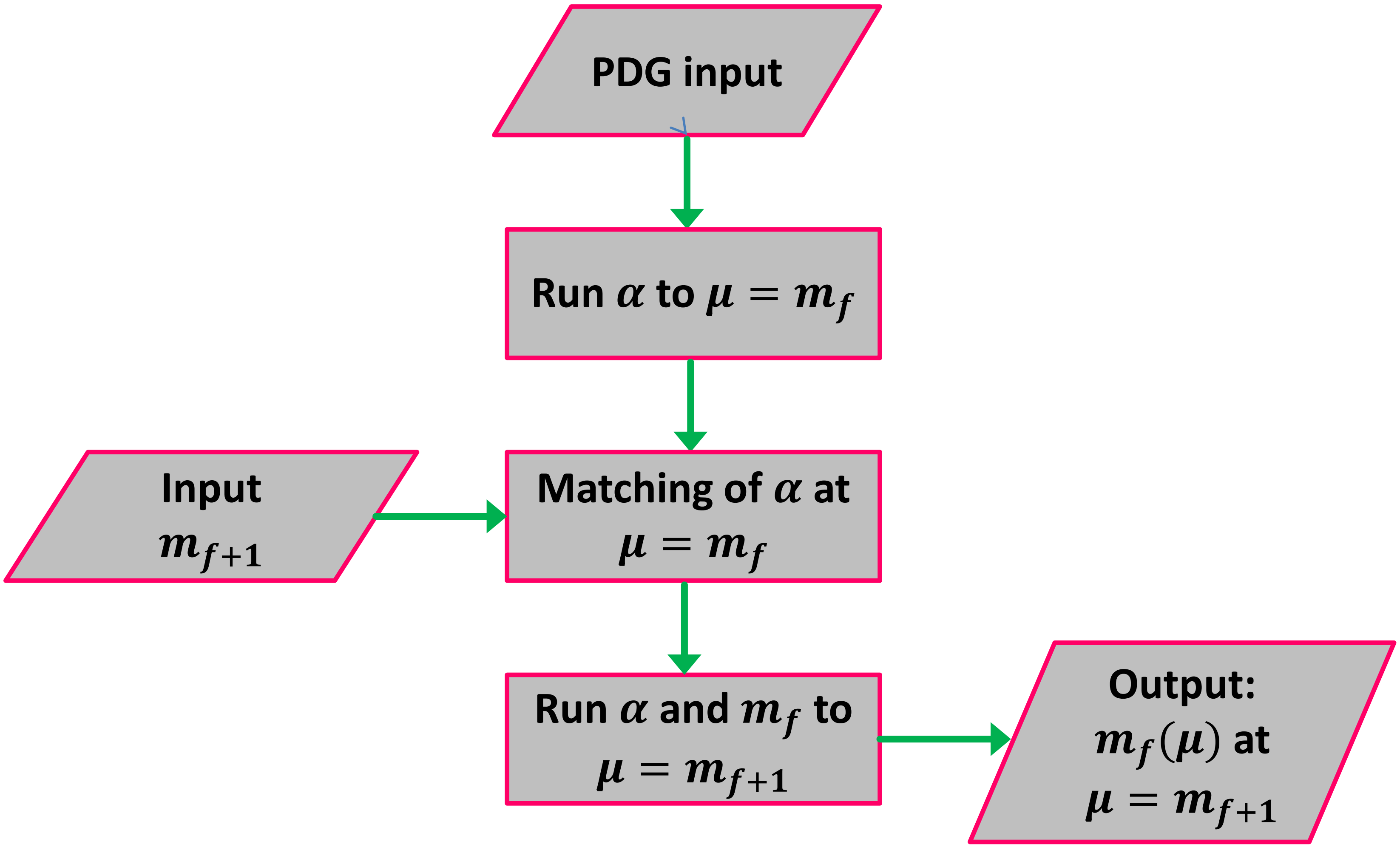
NuFIT 1.2 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \to 0.355$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.37 \to 36.01$	$34.02^{+0.79}_{-0.76}$	$31.78 \to 36.55$
$\sin^2\theta_{23}$	$0.446^{+0.008}_{-0.008} \oplus 0.593^{+0.027}_{-0.043}$	$0.366 \to 0.663$	$0.444^{+0.037}_{-0.031} \oplus 0.592^{+0.028}_{-0.042}$	$0.361 \to 0.665$
$\theta_{23}/^\circ$	$41.9^{+0.5}_{-0.4} \oplus 50.3^{+1.6}_{-2.5}$	$37.2 \to 54.5$	$41.8^{+2.1}_{-1.8} \oplus 50.3^{+1.6}_{-2.5}$	$36.9 \to 54.6$
$\sin^2\theta_{13}$	$0.0231^{+0.0019}_{-0.0019}$	$0.0173 \to 0.0288$	$0.0244^{+0.0019}_{-0.0019}$	$0.0187 \to 0.0303$
$\theta_{13}/^\circ$	$8.73^{+0.35}_{-0.36}$	$7.56 \to 9.77$	$9.00^{+0.35}_{-0.36}$	$7.85 \to 10.02$
$\delta_{CP}/^\circ$	266^{+55}_{-63}	$0 \to 360$	270^{+77}_{-67}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	$7.50^{+0.18}_{-0.17}$	$7.03 \to 8.08$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$+2.417^{+0.014}_{-0.014}$	$+2.247 \to +2.623$	$+2.429^{+0.055}_{-0.054}$	$+2.249 \to +2.639$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.411^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	$-2.422^{+0.063}_{-0.061}$	$-2.614 \to -2.235$

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, 13

How to evaluate these variables and uncertainties at an arbitrary energy scale?

We adopt the **running→matching→running** scheme



Running for the strong coupling

$$\mu^2 \frac{d\alpha_s}{d\mu^2} = (\beta_0 \alpha^2 + \beta_1 \alpha^3 + \beta_2 \alpha^4 + \cdots)$$

$$\beta_0 = \frac{1}{4}\left(11 - \frac{2}{3} n_f\right)$$

$$\beta_1 = \frac{1}{16}\left(102 - \frac{38}{3} n_f\right)$$

$$\beta_2 = \cdots$$

$$\beta_3 = \cdots$$

4-loop beta function in QCD
Ritbergen, Vermaseren & Larin, PLB400(1997)379

Running of the electromagnetic coupling α

Arason *et al.*, 1992

$$\mu^2 \frac{d\alpha}{d\mu^2} = -\frac{\alpha^2}{\pi}\left(\tilde{\beta}_0 + \tilde{\beta}_1 \left(\frac{\alpha}{\pi}\right) + \sum_i \rho_i \left(\frac{\alpha_s}{\pi}\right)^i + \cdots\right)$$

QCD corrections

$$\tilde{\beta}_0 = -\frac{1}{3}\sum_f Q_f^2 N_c^f \qquad \tilde{\beta}_1 = -\frac{1}{4}\sum_f Q_f^4 N_c^f$$

Current PDG global-fit data:

$$\alpha_s(M_Z) = 0.1185 \pm 0.0006$$

$$\alpha(M_Z)^{-1} = 127.944 \pm 0.014$$

Matching at each quark threshold

(n_f) flavor effective theory ⇦ ⇨ (n_f+1) flavor full theory

$E = 0$ $m_q(m_q)$ $E = \mu$

${\alpha_s}^{(n_f)}, \quad {m_q}^{(n_f)}$ ${\alpha_s}^{(n_f+1)}, \quad {m_q}^{(n_f+1)}$

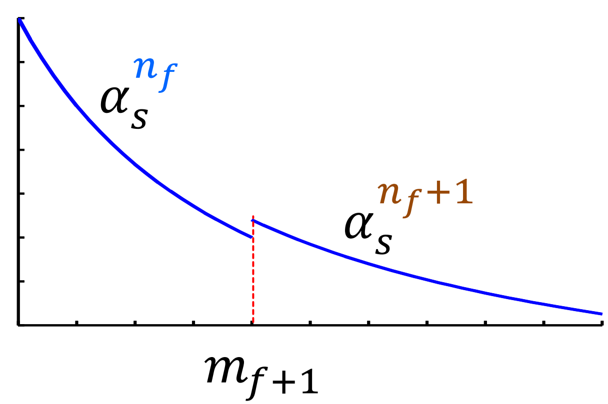
- The beta function coefficients are given in the effective theory in which n_f of the light quark flavors ($m_q \ll \mu$) are considered, and the remaining heavier quark flavors ($m_q \gg \mu$) decouple from the theory.
- $\alpha_s^{n_f}$ and $\alpha_s^{n_f+1}$ are related through the matching condition

$$\alpha_s^{n_f}(\mu) = \zeta_g^2 \alpha_s^{n_f+1}(\mu)$$

4-loop QCD decoupling

Chetyrkin, Kuhn & Sturm, NPB744(2006)121

$$\zeta_g^2 = 1 - \frac{\alpha_s^{n_f+1}(\mu)}{\pi}\left(\frac{1}{6}\ln\frac{\mu^2}{[m_{f+1}(m_{f+1})]^2}\right) + \cdots$$



RGEs for quark masses in the $\overline{\text{MS}}$ scheme

$$\mu^2 \frac{dm_q}{d\mu^2} = -\sum_{r=1}^{\infty} \gamma_r \left(\frac{\alpha_s}{4\pi}\right)^r m_q$$

$$\gamma_1 = 4$$
$$\gamma_2 = \frac{202}{3} - \frac{20}{9} n_f$$
$$\gamma_3 = \cdots$$

Chetyrkin, 97; Vermaseren, Larin & Ritbergen 97

$$m_q(\mu) = R(\alpha_s(\mu))\hat{m}_q \qquad \hat{m}_q = m_q(\mu_0)/R(\alpha_s(\mu_0))$$

$$R(\alpha_s) = \left(\frac{\alpha_s}{\pi}\right)^{\frac{\gamma_0}{\beta_0}} \left[1 + \frac{\alpha_s}{\pi} C_1 + \frac{\alpha_s^2}{2\pi^2}(C_1 + C_2) + \cdots\right]$$

$\overline{\text{MS}}$ mass $\Leftrightarrow$ Pole mass

$$M_q = m_q(m_q)\left\{1 + 1.333\left[\frac{\alpha_s^{n_f}(m_q)}{\pi}\right] + (13.44 - 1.041 n_l)\left[\frac{\alpha_s^{n_f}(m_q)}{\pi}\right]^2 + \cdots\right\}$$

Chetyrkin and Steinhauser, PRL83(1999)20

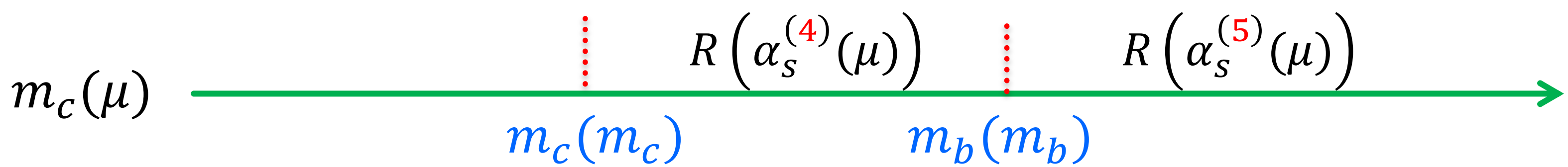
Matching at each quark threshold

Chetyrkin, Kniehl & Steinhauser, 98

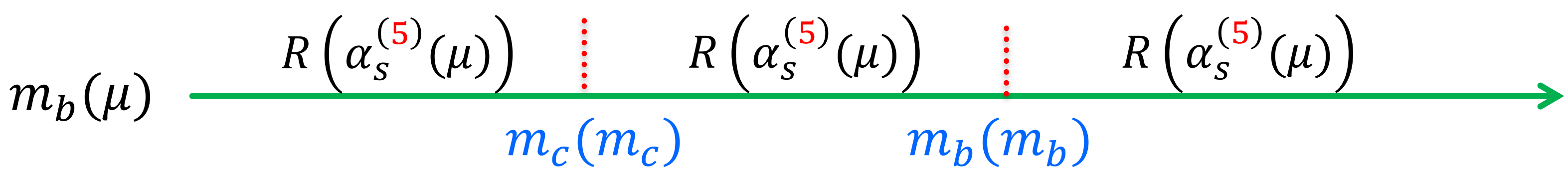
$$m_q^{(n_f-1)} = \zeta_m m_q^{(n_f)}$$

$$\zeta_m^{MS} = 1 + \left(\frac{\alpha_s^{(n_f)}(\mu)}{\pi}\right)^2 \left(\frac{89}{432} - \frac{5}{36}\ln\frac{\mu^2}{m_h^2} + \frac{1}{12}\ln^2\frac{\mu^2}{m_h^2}\right) + \left(\frac{\alpha_s^{(n_f)}(\mu)}{\pi}\right)^3 \left[\frac{2951}{2916} - \frac{407}{864}\zeta_3 + \frac{5}{4}\zeta_4 - \frac{1}{36}B_4 + \left(-\frac{311}{2592} - \frac{5}{6}\zeta_3\right)\ln\frac{\mu^2}{m_h^2} + \frac{175}{432}\ln^2\frac{\mu^2}{m_h^2} + \frac{29}{216}\ln^3\frac{\mu^2}{m_h^2} + n_l\left(\frac{1327}{11664} - \frac{2}{27}\zeta_3 - \frac{53}{432}\ln\frac{\mu^2}{m_h^2} - \frac{1}{108}\ln^3\frac{\mu^2}{m_h^2}\right)\right],$$

- For lighter quarks ($n_L < N$), the behavior of n-th quark between the N and $N+1$ quark thresholds should be evaluated by using $\alpha_s^{(N)}$.

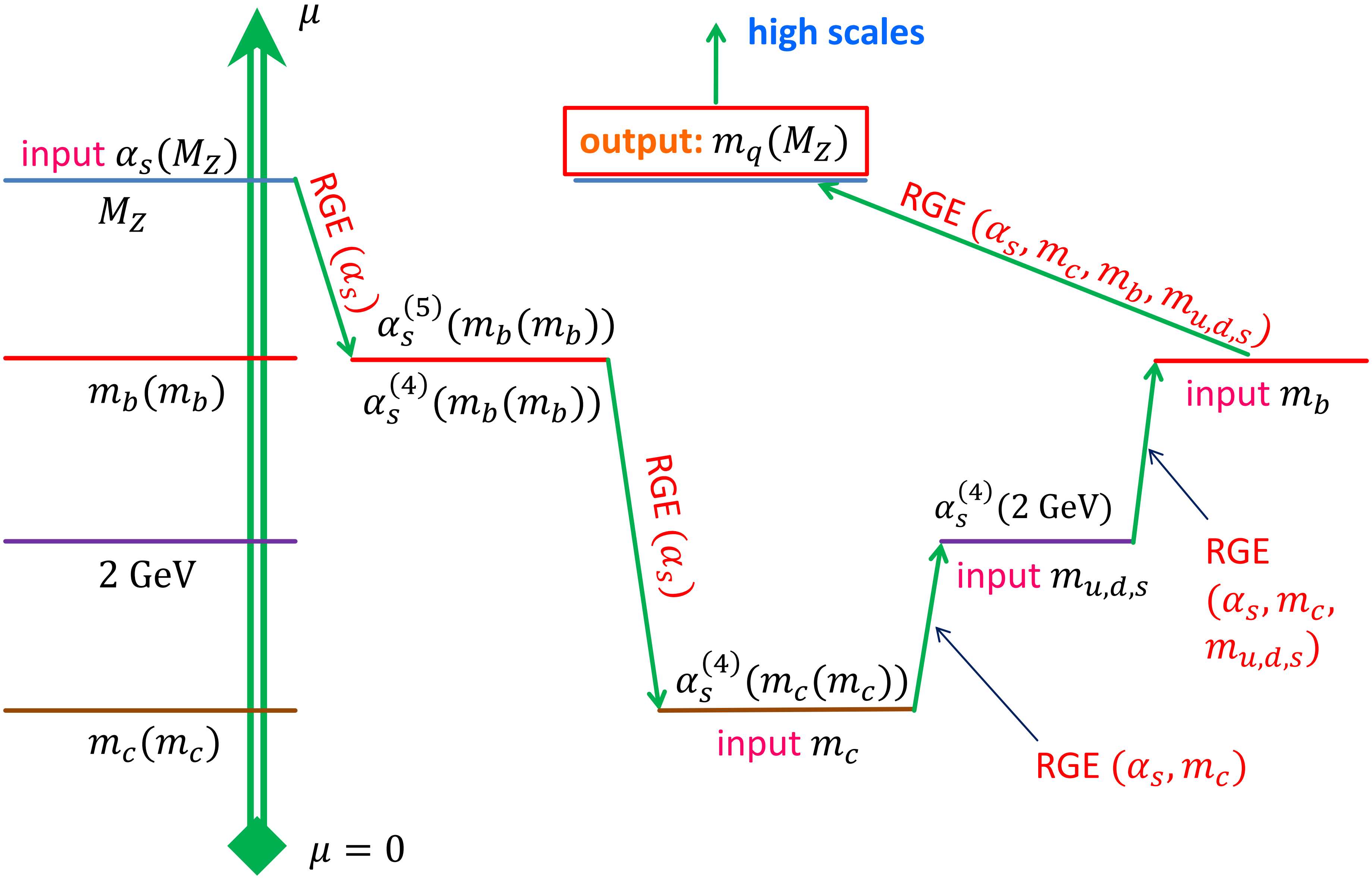


- For heavier quarks ($n_H < N$), the running between the N and $N+1$ quark thresholds should be evaluated by using $\alpha_s^{(n_H)}$.



Strategy of running and decoupling (below M_Z)

running→matching→running scheme



Top quark Yukawa coupling ⟺ top quark pole mass M_t

Hemping & Kniehl, 95

$$y_t(\mu) = \frac{\sqrt{2}}{v} M_t\left(1 + \delta_t^{\mathrm{QCD}}(\mu) + \delta_t^{\mathrm{QED}}(\mu) + \delta_t^{\mathrm{W}}(\mu)\right)$$

$$\delta_t^{\mathrm{QCD}}(\mu) = \mathrm{C}_F \frac{\alpha_s(\mu)}{4\pi}\left(3\ln\frac{M_t^2}{\mu^2} - 4\right) + \cdots$$

Higgs mass ⟺ self-coupling λ

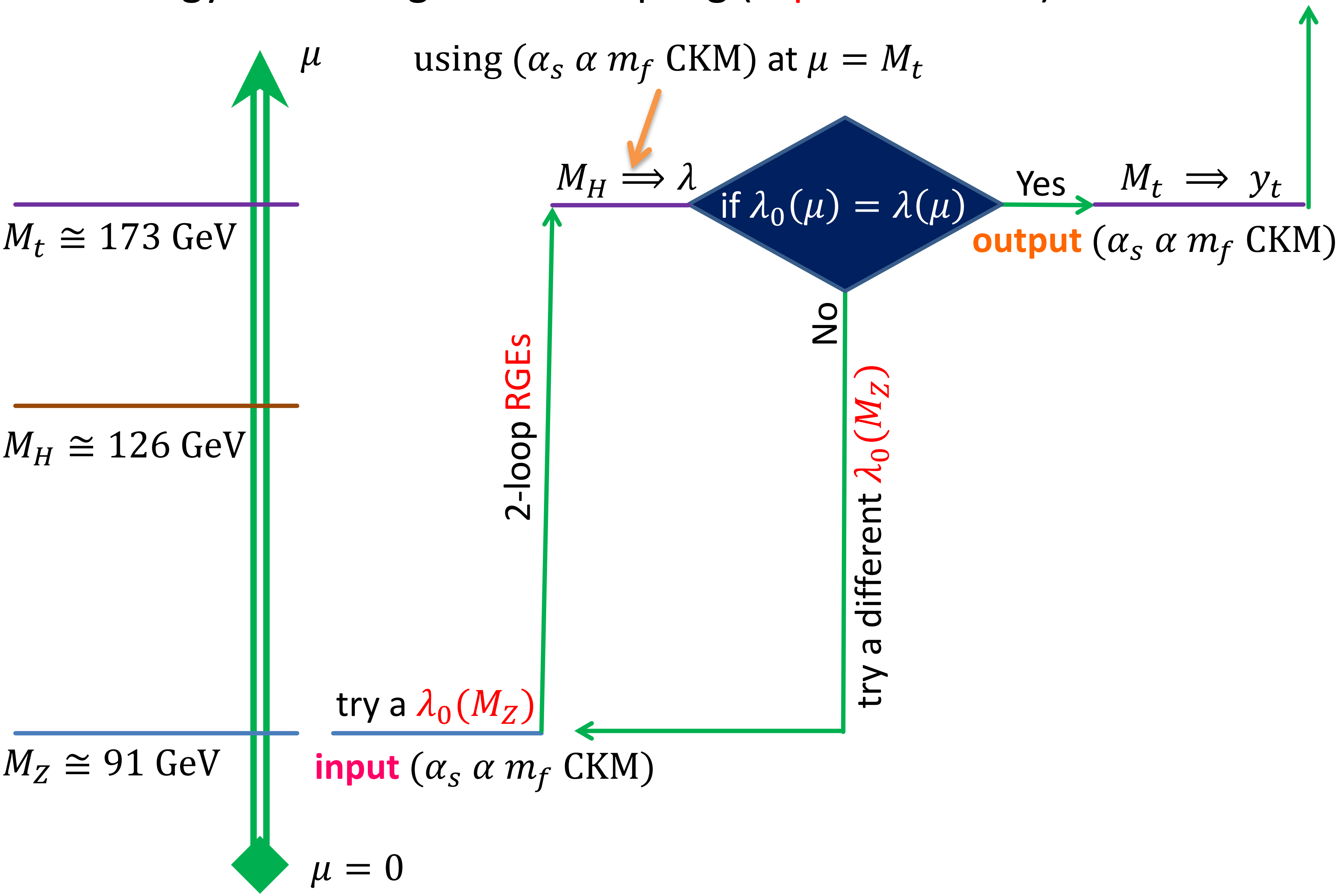
$$\lambda(\mu) = \frac{M_H}{v^2}(1 + \delta_H(\mu))$$

Sirlin & Zucchini, 86

$$\delta_H(M) = -\frac{1}{m_H^2}\mathrm{Re}[\Pi_{HH}(m_H^2)] - \frac{1}{m_H^2}\frac{T}{v} + \frac{1}{m_W^2}(A_{WW}^{\mathrm{bos}}(0) + A_{WW}^{\mathrm{had}}(0) + A_{WW}^{\mathrm{lep}}(0)) - E|_{\mathrm{finite}}$$

- In our calculation, we choose $\mu = M_t$

Strategy of running and decoupling (top mass and λ)



Running above the electroweak scale $\mu > M_Z$

- Gauge couplings

$$g_3^2 = 4\pi\alpha_s \qquad g_2^2 = \frac{4\pi\alpha}{\sin^2\theta_W} \qquad g_1^2 = \sqrt{5/3}\, g_2 \tan\theta_W$$

$$\frac{dg_i}{dt} = -b_i \frac{g_i^3}{16\pi^2} - \sum_k b_{ik} \frac{g_i^3 g_k^2}{(16\pi^2)^2} - \frac{g_i^3}{(16\pi^2)^2} \sum_a c_{ia} \mathrm{Tr} H_a$$

$$H_f = Y_f^\dagger Y_f$$

- Higgs self-coupling $$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\beta_\lambda^{(1)} + \frac{1}{(16\pi^2)^2}\beta_\lambda^{(2)}$$

$$\beta_\lambda^{(1)} = 12\lambda^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right)$$
$$+ 4\lambda \; \mathrm{Tr}(3H_u + 3H_d + H_e) - 4\mathrm{Tr}(3H_u^2 + 3H_d^2 + H_e^2)$$

- Yukawa couplings

$$\mu \frac{dY_f}{d\mu} = \left[\frac{1}{16\pi^2}\beta_f^{(1)} + \frac{1}{(16\pi^2)\text{^}2}\beta_f^{(2)} + \frac{1}{(16\pi^2)^3}\beta_f^{(3)} + \cdots\right] Y_f$$

Running above the electroweak scale $\mu > M_Z$

- Matching between SM and SUSY

  ✓ SM→ $\overline{\mathrm{MS}}$ scheme
  ✓ SUSY→ $\overline{\mathrm{DR}}$ scheme

$$\alpha_s^{\overline{\mathrm{MS}}} = \alpha_s^{\overline{\mathrm{DR}}}\left(1 - \frac{\alpha_s^{\overline{\mathrm{DR}}}}{4\pi}\right) \qquad m_f^{\overline{\mathrm{DR}}} = m_f^{\overline{\mathrm{MS}}}\left(1 - \frac{\alpha_s^{\overline{\mathrm{DR}}}}{4\pi}\right)$$

  ✓ We adopt the **common scale approach** with all the SUSY particles being roughly at a common scale $\mu = M_{\mathrm{SUSY}}$

  ✓ SUSY threshold correction

$$m_f^{\mathrm{SUSY}} = \frac{m_f^{\mathrm{SM}}}{1 + \epsilon_f \tan\beta}$$

⇨

- $f = d, s, b, e, \mu, \tau$
- ϵ_f could be as large as 1%
- $\tan\beta$ enhancement

Charged-lepton running mass $\Longleftrightarrow$ Pole mass

Chetyrkin & Steinhauser, 99
Melnikov & Ritbergen, 99
Baikov , Chetyrkin, Kühn & Sturm, 12

$$\frac{m_l(\mu)}{M_l} = \left\{1 + \frac{\alpha}{\pi}\left[-1 - \frac{3}{4}\ln\frac{\mu^2}{M_l^2}\right] + \left(\frac{\alpha}{\pi}\right)^2\left[\frac{7}{128} - \frac{3}{4}\zeta_3 + \cdots\right] + \cdots\right\}$$

Neutrino mass at one-loop

$$16\pi^2\,\frac{\mathrm{d}m_\nu}{\mathrm{d}t} = (C_e\,Y_e^\dagger Y_e + C_\nu\,Y_\nu^\dagger Y_\nu)^T\,m_\nu + m_\nu\,(C_e\,Y_e^\dagger Y_e + C_\nu\,Y_\nu^\dagger Y_\nu) + \bar{\alpha}\,m_\nu$$

$$\bar{\alpha}_{\mathrm{SM}} = -\frac{9}{10}g_1^2 - \frac{9}{2}g_2^2 + 2\,\mathrm{Tr}\left(Y_\nu^\dagger Y_\nu + Y_e^\dagger Y_e + 3Y_d^\dagger Y_d + 3Y_u^\dagger Y_u\right)$$

Above M_R

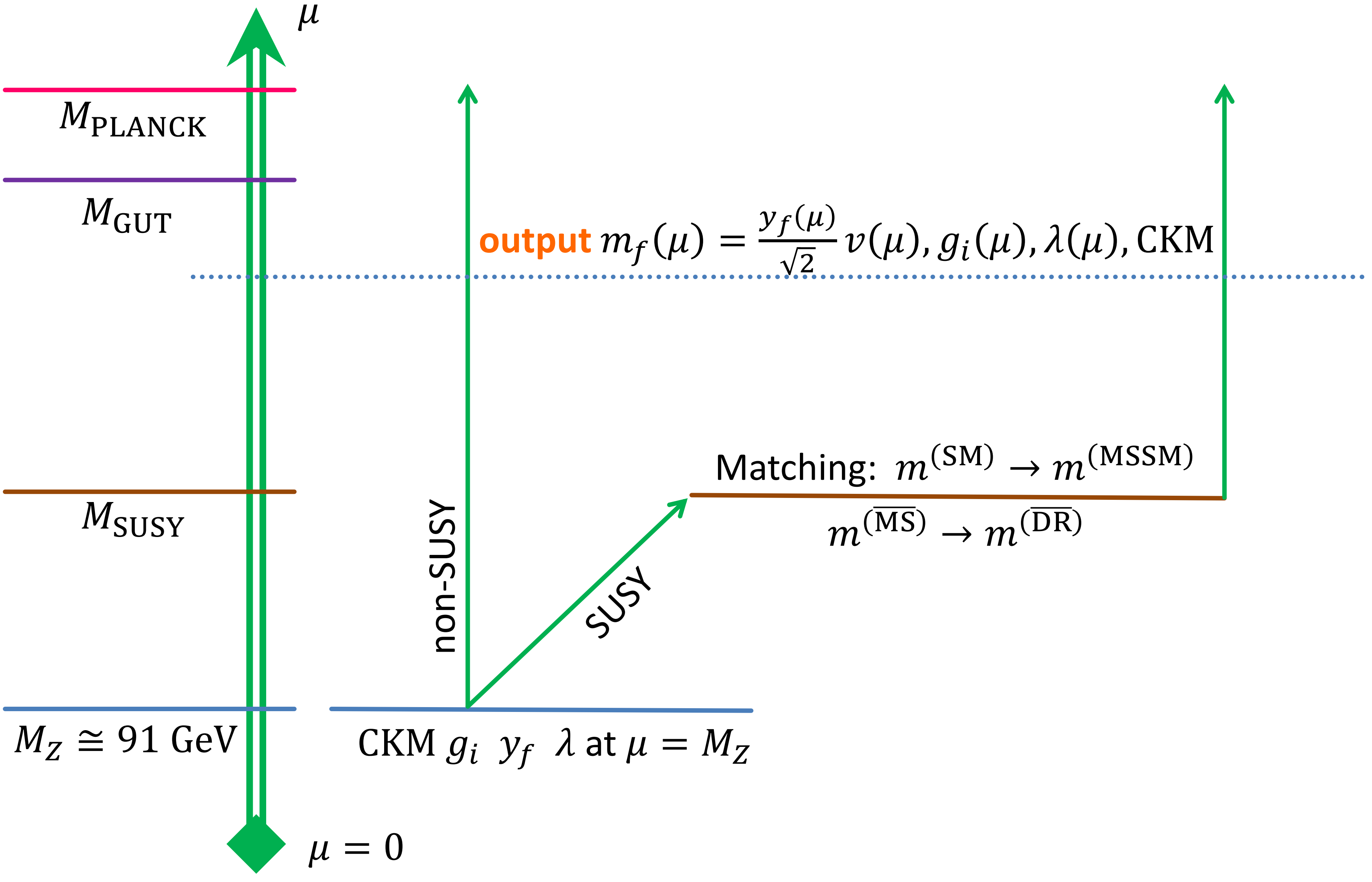
$\mu = M_R$

Below M_R

$$16\pi^2\,\frac{\mathrm{d}\kappa}{\mathrm{d}t} = C\,(Y_e^\dagger Y_e)^T\,\kappa + C\,\kappa\,(Y_e^\dagger Y_e) + \alpha\,\kappa$$

$$\alpha_{\mathrm{SM}} = -3g_2^2 + 2(y_\tau^2 + y_\mu^2 + y_e^2) + 6\left(y_t^2 + y_b^2 + y_c^2 + y_s^2 + y_d^2 + y_u^2\right) + \lambda$$

Strategy of running and decoupling (scale of new physics)



Uncertainty estimation

- Gaussian likelihoods assumed for the input quantities
- Monte Carlo sampling data: N points
- RGE running up to a scale μ
- Highest Posterior Density intervals: count how many points are located in certain interval:

68% points in the output $\rightarrow$ 1σ CL.

95% points in the output $\rightarrow$ 2σ CL.

Input parameter summary

$m_u(2\text{GeV}) = 2.3 \pm 0.61$

$m_d(2\text{GeV}) = 4.8 \pm 0.41$

$m_s(2\text{GeV}) = 95 \pm 5$

$m_c(m_c) = 1275 \pm 25$

$m_b(m_b) = 4180 \pm 30$

$M_t = 173070 \pm 890$

$M_e = 0.5109989 \pm 1.1\text{e-}08$

$M_\mu = 105.6583715 \pm 3.5\text{e-}06$

$M_\tau = 1776.82 \pm 0.16$

$M_W = 80385 \pm 15$

$M_Z = 91187.6 \pm 2.1$

$M_H = 125900 \pm 400$

$\lambda = 0.22535 \pm 0.00065$

$A = 0.811 \pm 0.018$

$\bar{\rho} = 0.131 \pm 0.021$

$\bar{\eta} = 0.345 \pm 0.014$

$\alpha_s(M_Z) = 0.1184 \pm 0.0007$

$\alpha(M_Z)^{-1} = 127.944 \pm 0.014$

$\sin^2\theta_W(M_Z) = 0.23116 \pm 0.00012$

RUM

RUnning **M**asses

RUM *is a standalone program for evaluation of fermion masses, gauge couplings, CKM matrix elements and the quartic Higgs coupling at energy scales between 1 GeV and the Planck scale 10^{19} GeV.*

Temporary webpage: http://www.mpi-hd.mpg.de/personalhomes/hzhang/RUM/

- Run α_s to each quark threshold and apply the matching condition
- Evaluate light quark masses m_f and match onto the full theory at $\mu = m_f$
- Conversion of charged-lepton pole masses to their $\overline{\mathrm{MS}}$ masses
- Top quark pole mass $\rightarrow$ $\overline{\mathrm{MS}}$ masses
- Higgs pole mass $\rightarrow$ quartic coupling λ_H (at $\mu = M_H$)
- Relation between $\overline{\mathrm{MS}}$ masses and Yukawa couplings
- 2-loop RGEs from M_Z to higher scales
- In SUSY, matching between SM and SUSY ($\tan\beta$ enhanced SUSY threshold effects)
- In SUSY, $\overline{\mathrm{MS}} \rightarrow \overline{\mathrm{DR}}$ conversion
- Uncertainties estimation: Highest Posterior Density

Temporary webpage: http://www.mpi-hd.mpg.de/personalhomes/hzhang/RUM/

RUM

RUnning Masses

RUM user manual

user manual

Contact us

Email

The running masses of quarks and leptons at a common energy scale are very useful for precise calculations in the Standard Model, model building of fermion mass hierarchies and flavor mixing patterns, and other new physics scenarios beyond the Standard Model. We provide a standalone program **RUM** for evaluating the running masses of quarks and leptons with uncertainties at any energy scales between the scale of dynamical chiral symmetry breaking $\Lambda_\chi \approx 1$ GeV and the Planck scale $\Lambda \approx 10^{19}$ GeV in the Standard Model and the Minimal Supersymmetric Standard Model. In the meanwhile, the quark flavor mixing parameters, the gauge coupling constants, and the quartic Higgs self-coupling constant are also evaluated. A user-friendly interface has been developed allowing the users to define and evaluate their own variables. The program can be used as a simple calculator with all the input parameters can be found from Particle Data Group.

Installation guide: We provide two optional methods for users to use RUM, **A)** installation together with MCR and **B)** installation without MCR.

A) ***Installation together with MCR.*** To run RUM, the MATLAB Complier Runtime (MCR) should be initialized in order to employ the MATLAB libraries, and it can be downloaded from the links below

For Linux OS: MCR(64-bit)

For MS Windows: MCR(32-bit)

Link to the MathWorks MCR installation page

After installation of MCR, download the RUM package (for Linux OS; for MS Windows) to your folder.

For Linux users: extract the package by typing: "tar zxvf RUM.tar.gz"

then start the program by entering

`./run_RUM.sh /[MCRfolder]` **for example:** `./run_RUM.sh /packages/matlab/R2013b`

For MS Windows users: double click "RUM.exe"

B) ***Installation without MCR.*** For Linux users who do not wish to install MCR, we provide also a portable version with all the necessary lib files packed. You can download this RUM package from RUM full version for Linux OS, and extract it to your folder. Similarly, you can start RUM in the Linux terminal by using the command

`./run_RUM.sh ./MCR`

Download from here

- Read reliable input data directly from PDG
- Build-in functions for threshold matching, pole mass – $\overline{\mathrm{MS}}$ mass conversion, Higgs quartic coupling, RGE evolution, uncertainty estimation …
- User defined variables
- Friendly Graphic User Interface – can be easily used as a calculator
- Portable version provided – no need for installation

Fermion masses at $\mu = M_Z$

Snapshot from RUM

Variables below MZ — Scale [MeV] 91200 — Sample Size 5000 — C.L. [%] 68.27

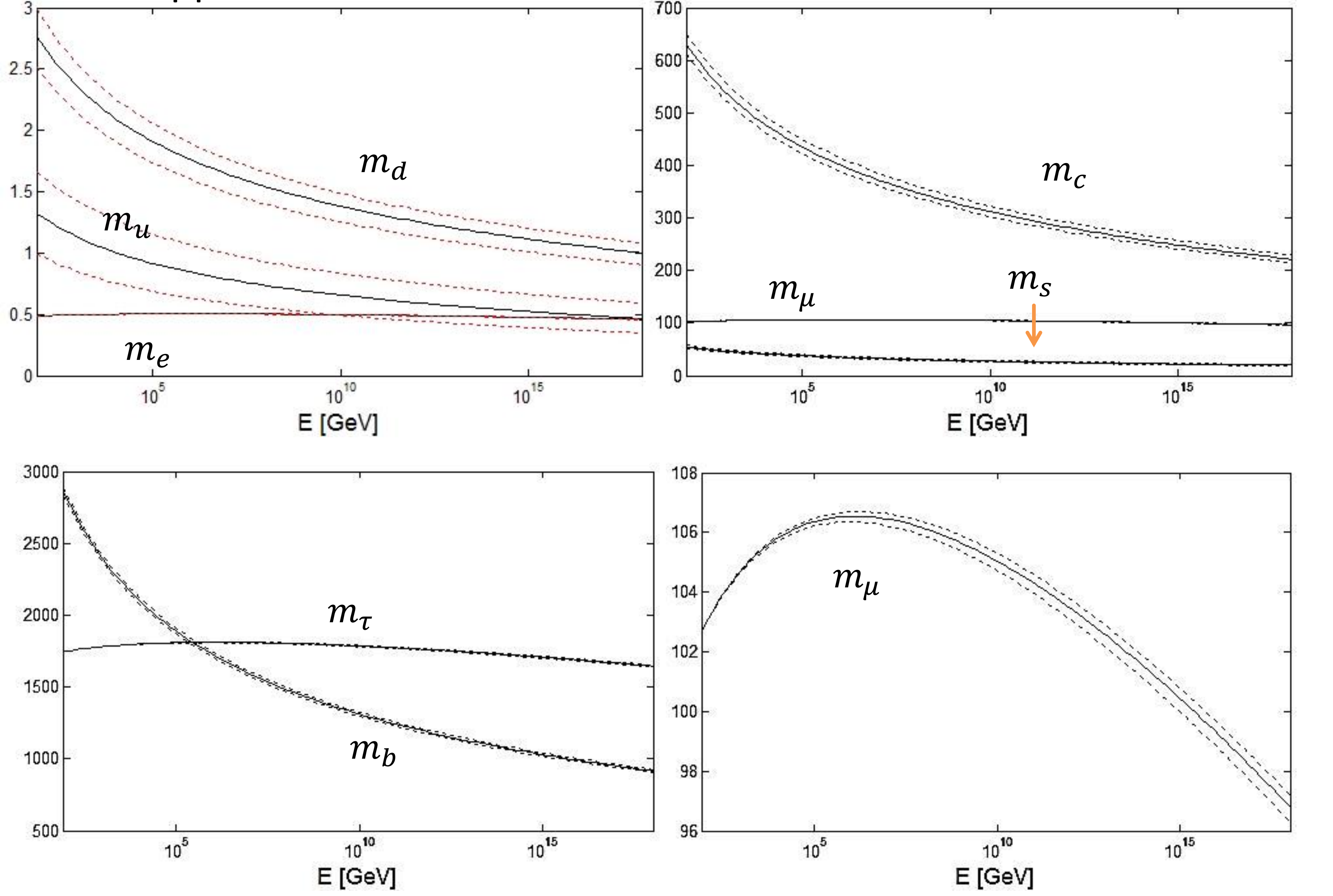
$m_u(\mu) =$	1.32	+0.35	-0.34
$m_d(\mu) =$	2.76	+0.24	-0.23
$m_s(\mu) =$	54.6	+2.8	-3
$m_c(\mu) =$	629	+19	-18
$m_b(\mu) =$	2.86e+03	+27	-27
$m_t(\mu) =$	1.71e+05	+9.5e+02	-9.7e+02
$m_e(\mu) =$	0.4865748	+2.6e-06	-2.7e-06
$m_\mu(\mu) =$	102.71874	+0.00032	-0.00033
$m_\tau(\mu) =$	1746.1699	+0.15	-0.16
$\alpha_s(\mu) =$	0.1184	+0.00069	-0.00071
$\alpha(\mu)^{-1} =$	127.944	+0.014	-0.014

Fermion masses and gauge couplings at $\mu = 1\ \mathrm{GeV}$

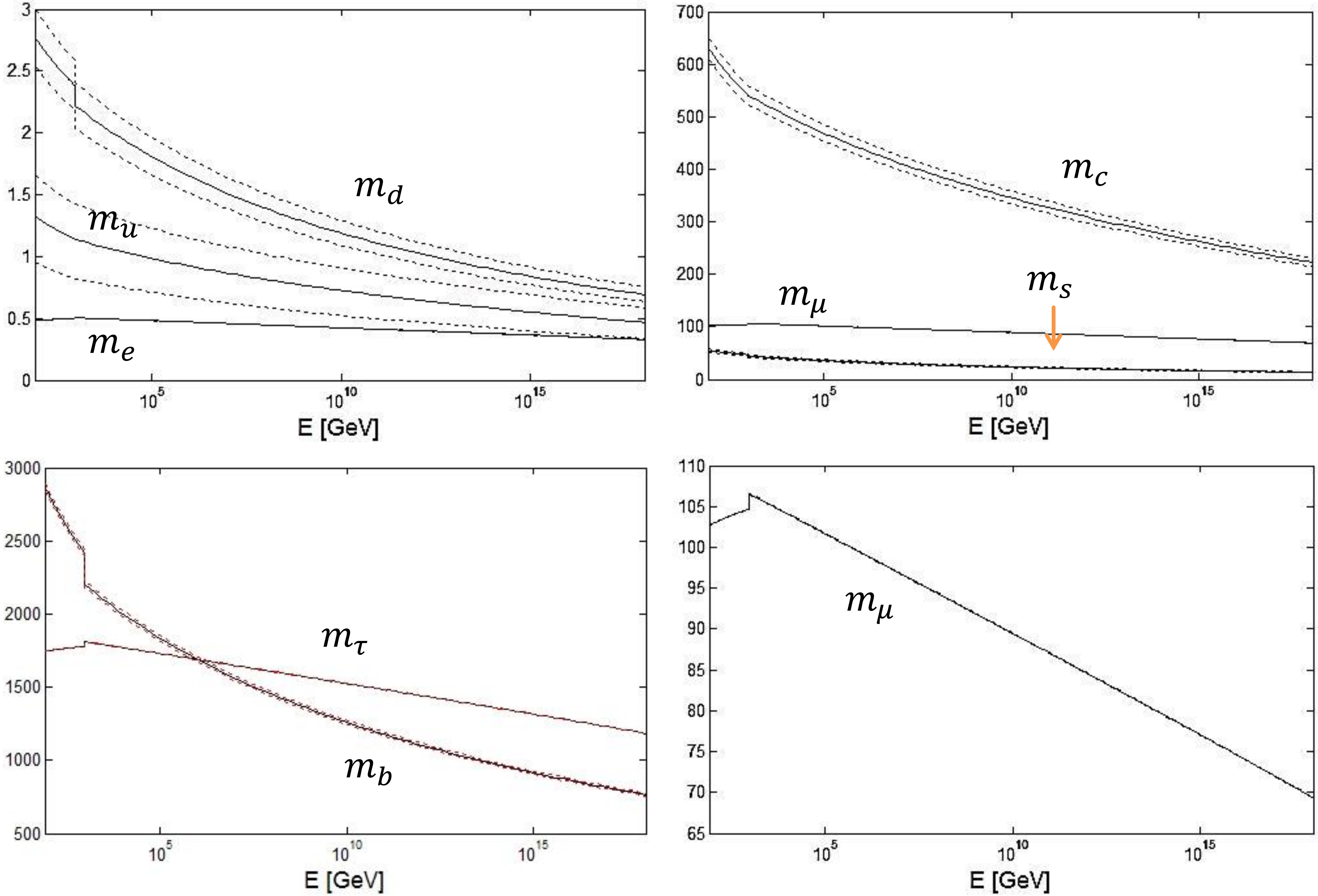
Variables below MZ — Scale [MeV] 1000 — Sample Size 5000 — C.L. [%] 68.27

$m_u(\mu) =$	3.07	+0.82	-0.86
$m_d(\mu) =$	6.41	+0.56	-0.55
$m_s(\mu) =$	127	+6.4	-7.1
$m_c(\mu) =$	1.43e+03	+39	-42
$m_b(\mu) =$	6.17e+03	+78	-77
$m_t(\mu) =$	4.01e+05	+6.3e+03	-6e+03
$m_e(\mu) =$	0.4959802	+1.7e-06	-1.6e-06
$m_\mu(\mu) =$	104.56089	+0.00012	-0.00012
$m_\tau(\mu) =$	1776.2383	+0.15	-0.16
$\alpha_s(\mu) =$	0.4848	+0.016	-0.014
$\alpha(\mu)^{-1} =$	134.442	+0.015	-0.014

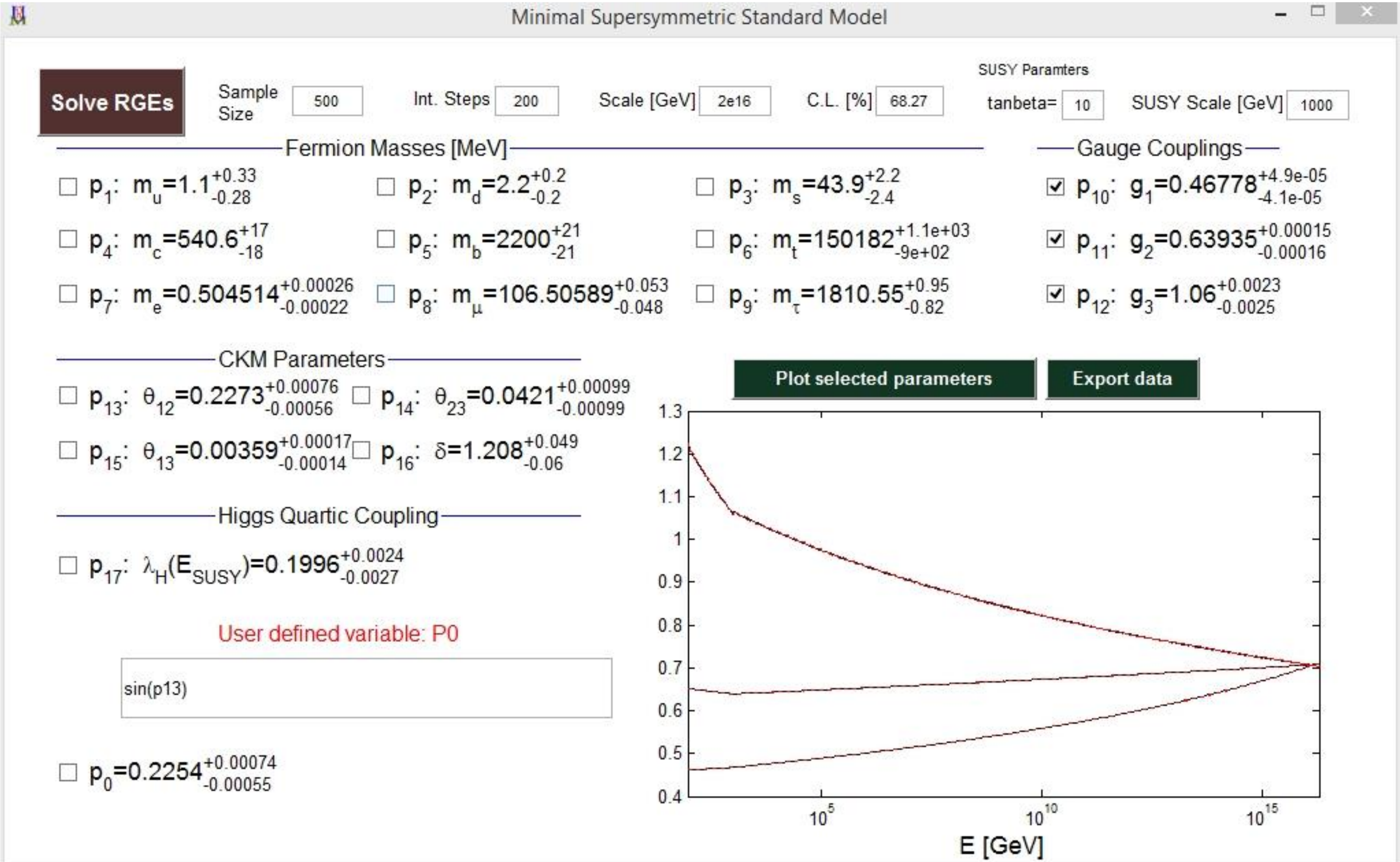
Applications: SM fermion masses



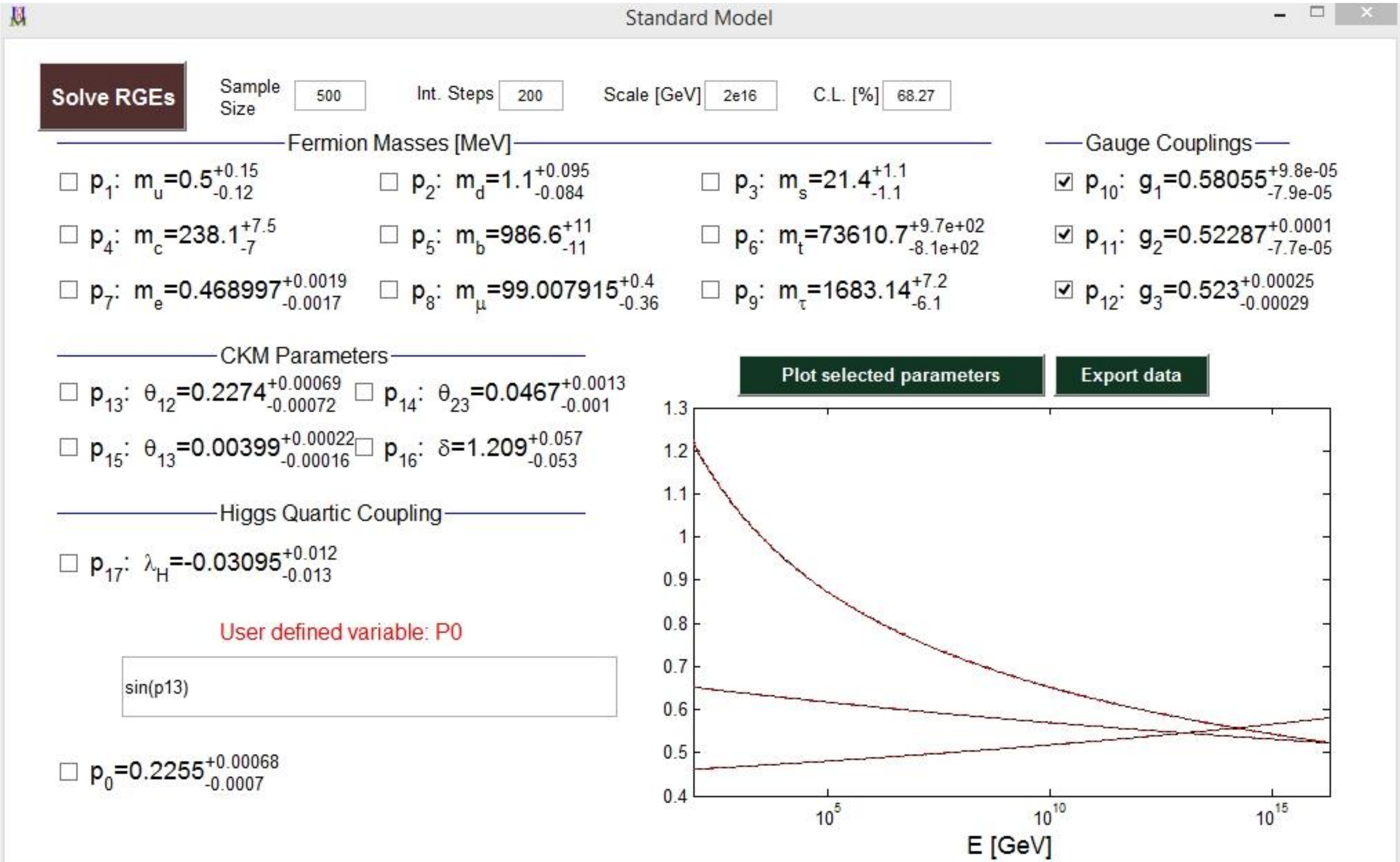
Applications: MSSM fermion masses: $\tan\beta = 10$, $M_{\mathrm{SUSY}} = 1\mathrm{TeV}$



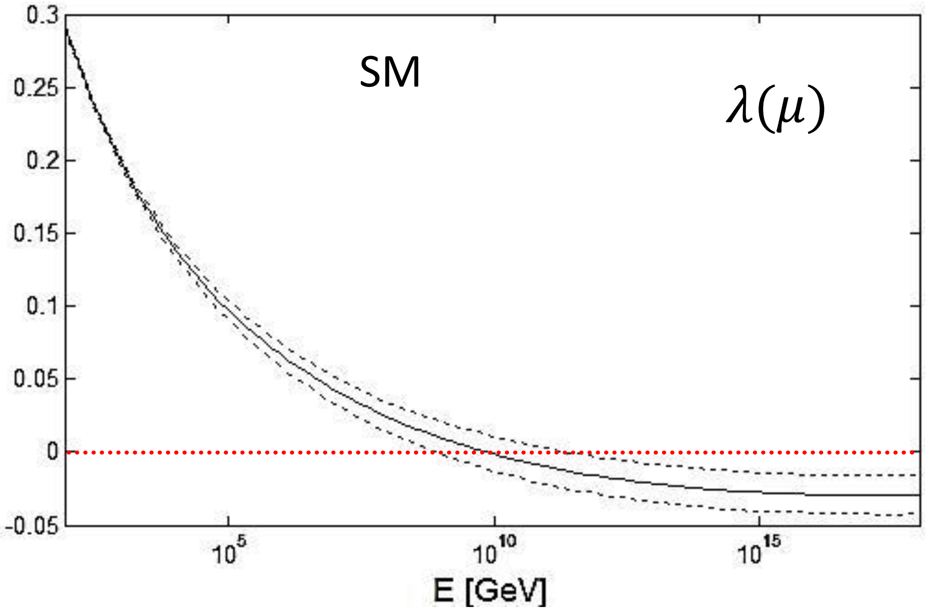
Output: $M_{\mathrm{GUT}} = 2 \times 10^{16}$ GeV for MSSM, $\tan\beta = 10$, $M_{\mathrm{SUSY}} = \mathrm{TeV}$



Output: $M_{\mathrm{GUT}} = 2 \times 10^{16}$ GeV for SM



Applications

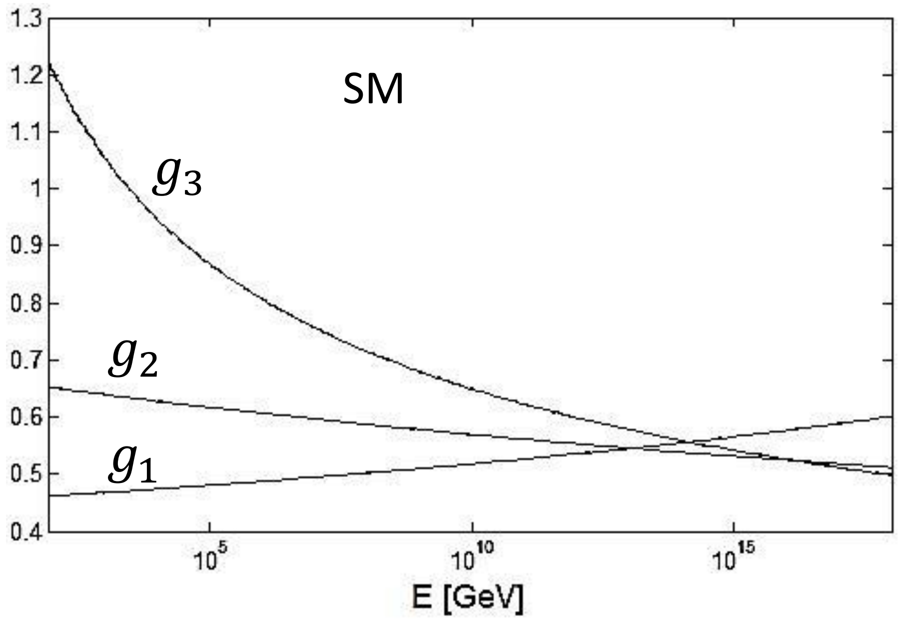


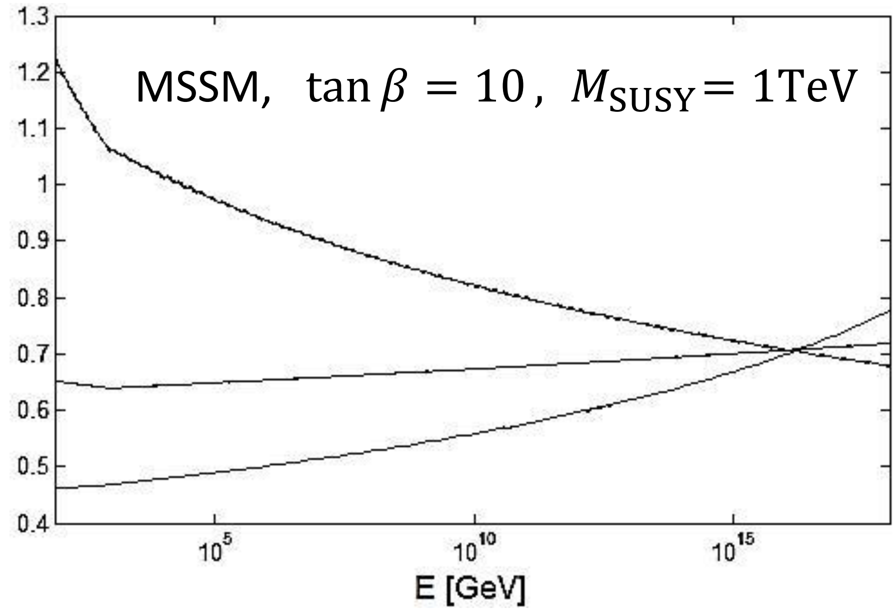
- Higgs vacuum stability

$\lambda(\mu) = 0$ around $\mu \sim 10^{10}\mathrm{GeV}$
$\lambda < 0$ at $M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$

- Running gauge couplings

NO gauge unification in the SM





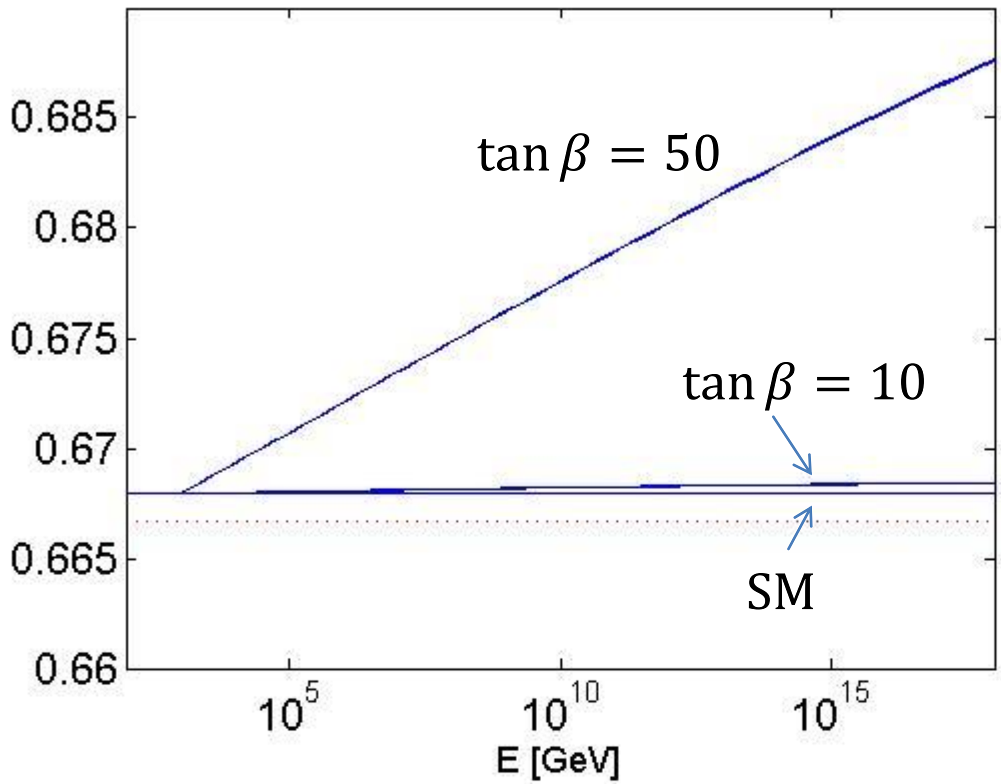
Applications: Koide's mass relation

$$Q = \frac{m_e + m_\mu + m_\tau}{\left(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau}\right)^2} \approx \frac{\mathbf{2}}{\mathbf{3}}$$

Koide, 82

May be realized in $\mathbf{U(3)} \times \mathbf{SU(2)}$ family gauge symmetry

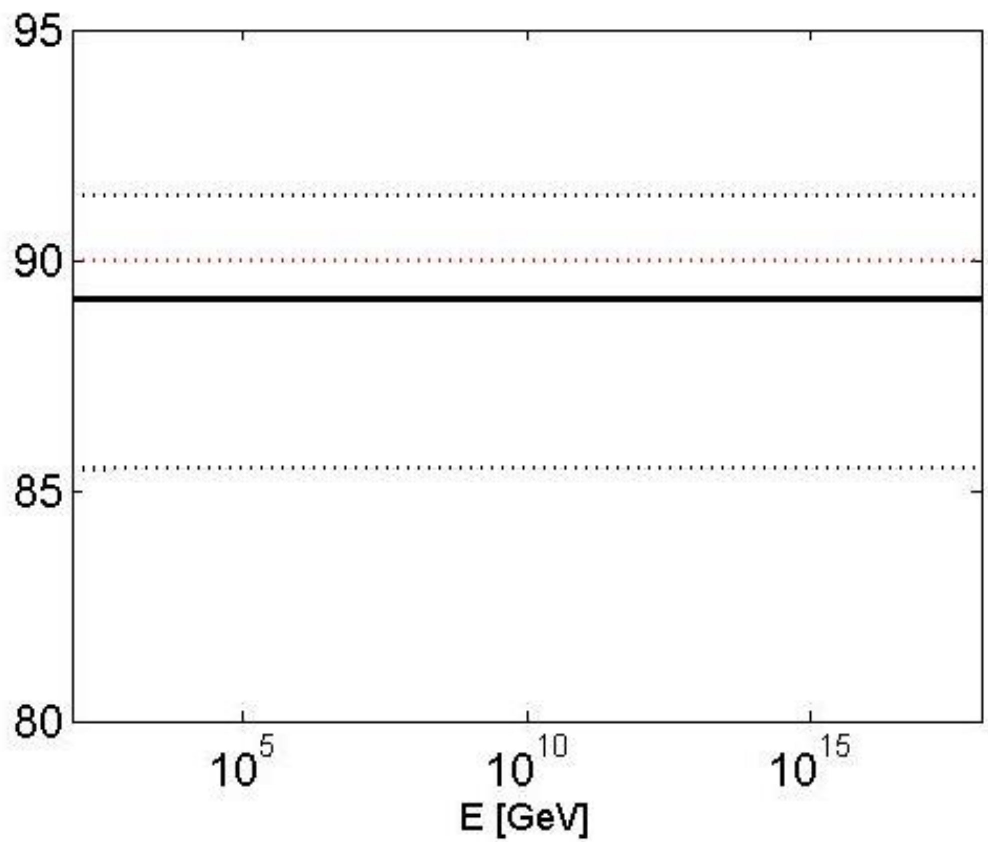
Sumino, 08

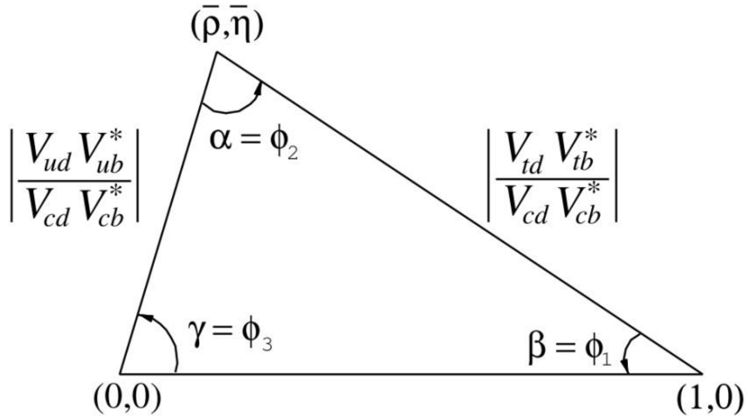


Applications: Is the Unitarity Triangle Right?

Harrison, Roythorne, Scott, 09; Xing, 09;
Antusch, King, Malinsky, Spinrath, 09

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) = \arg\left(-\frac{(s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta})c_{23}c_{13}}{c_{12}c_{13}s_{13}e^{i\delta}}\right)$$





- $\alpha \cong 90^\circ$ is rather stable against radiative corrections

Current status of RUM:

- Manual writing
- Beta testing

Future plans:

- Include 3-loop beta functions (available now in the literature).
- Add neutrino masses.
- Rewrite the source codes using C++ or Java.
- Add more popular modes, e.g. extra dimension models.
- Develop web-based application: Webserver configuration and Java programming

Welcome to join us

Summary

- Reliable values of fermion masses, mixing parameters and gauge parameters are very useful for model constructions.

- Knowledge on fermion masses and mixing parameters has been improved in recent years.

- Starting with the latest values given by PDG, we have evaluated the running fermion masses, gauge couplings, and flavor mixing parameters at various energy scales.

- An easy-to-use package RUM is provided for the evolutions of physical parameters below and above the EW scale.

Thank you for your attention