Searches for New Physics

Beyond the Standard Model (BSM)

- Problems of the Standard Model
- Supersymmetry (SUSY)
- Extra Dimensions
- Further Alternatives

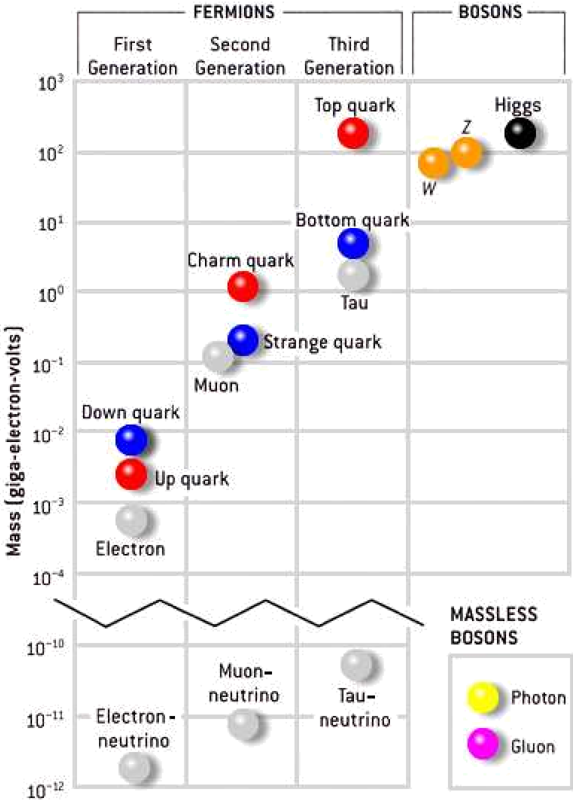
Standard Model Fermions

- Why 3 generations of quarks and leptons?
- Why so strange hypercharges?
  [$Y = 2(Q - T_3)$]
- Why flavour mixing for quarks (CKM) and neutrinos (MNS)?
- What to do with right-handed neutrinos?

$\begin{pmatrix} \nu'_e \\ e \end{pmatrix}_L^{-\frac{1}{2}}$	$\begin{pmatrix} \nu'_\mu \\ \mu \end{pmatrix}_L^{-\frac{1}{2}}$	$\begin{pmatrix} \nu'_\tau \\ \tau \end{pmatrix}_L^{-\frac{1}{2}}$	e_{R}^{-1}	μ_{R}^{-1}	τ_{R}^{-1}
$\begin{pmatrix} u \\ d' \end{pmatrix}_{\mathrm{L,r}}^{\frac{1}{6}}$	$\begin{pmatrix} c \\ s' \end{pmatrix}_{\mathrm{L,r}}^{\frac{1}{6}}$	$\begin{pmatrix} t \\ b' \end{pmatrix}_{\mathrm{L,r}}^{\frac{1}{6}}$	$u_{\mathrm{R,r}}^{\frac{2}{3}}$ $d_{\mathrm{R,r}}^{-\frac{1}{3}}$	$c_{\mathrm{R,r}}^{\frac{2}{3}}$ $s_{\mathrm{R,r}}^{-\frac{1}{3}}$	$t_{\mathrm{R,r}}^{\frac{2}{3}}$ $b_{\mathrm{R,r}}^{-\frac{1}{3}}$
$\begin{pmatrix} u \\ d' \end{pmatrix}_{\mathrm{L,g}}^{\frac{1}{6}}$	$\begin{pmatrix} c \\ s' \end{pmatrix}_{\mathrm{L,g}}^{\frac{1}{6}}$	$\begin{pmatrix} t \\ b' \end{pmatrix}_{\mathrm{L,g}}^{\frac{1}{6}}$	$u_{\mathrm{R,g}}^{\frac{2}{3}}$ $d_{\mathrm{R,g}}^{-\frac{1}{3}}$	$c_{\mathrm{R,g}}^{\frac{2}{3}}$ $d_{\mathrm{R,g}}^{-\frac{1}{3}}$	$t_{\mathrm{R,g}}^{\frac{2}{3}}$ $d_{\mathrm{R,g}}^{-\frac{1}{3}}$
$\begin{pmatrix} u \\ d' \end{pmatrix}_{\mathrm{L,b}}^{\frac{1}{6}}$	$\begin{pmatrix} c \\ s' \end{pmatrix}_{\mathrm{L,b}}^{\frac{1}{6}}$	$\begin{pmatrix} t \\ b' \end{pmatrix}_{\mathrm{L,b}}^{\frac{1}{6}}$	$u_{\mathrm{R,b}}^{\frac{2}{3}}$ $d_{\mathrm{R,b}}^{-\frac{1}{3}}$	$c_{\mathrm{R,b}}^{\frac{2}{3}}$ $d_{\mathrm{R,b}}^{-\frac{1}{3}}$	$t_{\mathrm{R,b}}^{\frac{2}{3}}$ $d_{\mathrm{R,b}}^{-\frac{1}{3}}$

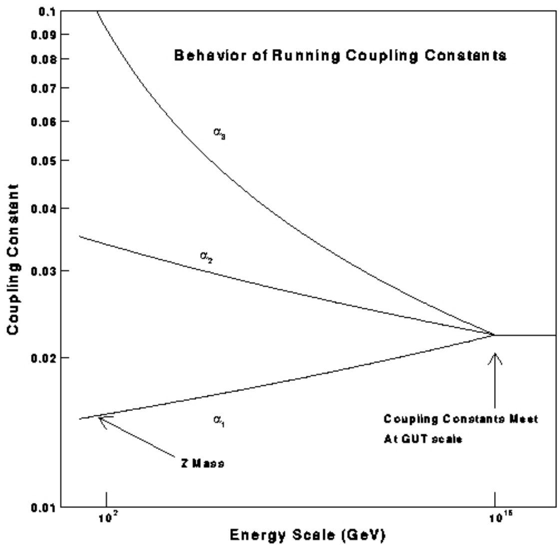
Standard Model Fermions

- Why 3 generations of quarks and leptons?
- Why so strange hypercharges?
  [$Y = 2(Q - T_3)$]
- Why flavour mixing for quarks (CKM) and neutrinos (MNS)?
- What to do with right-handed neutrinos?
- What is the origin of fermion masses?
  Why so huge fermion mass range?



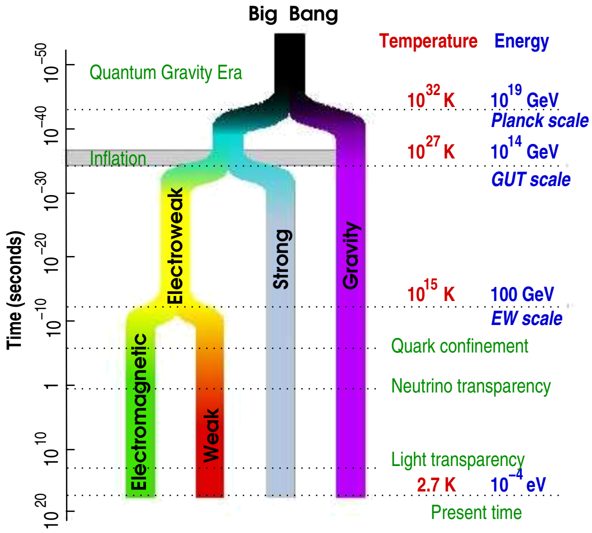
Standard Model Bosons

- Does SM Higgs exist?
- How can all gauge interactions be unified?



Standard Model Bosons

- Does SM Higgs exist?
- How can all gauge interactions be unified?
- Why such an hierarchy of gauge fields?



Cosmological Problems

- What is dark matter?
- What is dark energy?

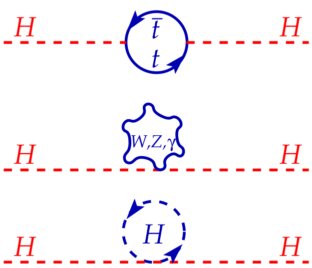
Attempts to Solve the Problems of the Standard Model

Many attemps going in different directions

- Extended gauge symmetries
- New mechanisms of symmetry breaking
- More fundamental fields
- Extra dimensions
- ...

Radiative Corrections to Higgs Mass

- Higgs Self-energy corrections in perturbation theory: $M_H^2 = M_{H,\text{bare}}^2 + \Delta M_H^2$
  Have to integrate over all particle momenta in loops
  $\Rightarrow$ Loop corrections to Higgs mass rise with UV cut-off Λ^2



$$\Delta M_{H,1}^2 = -\frac{3}{8\pi^2} g_f^2 \Lambda^2$$

$$\Delta M_{H,2}^2 = \frac{1}{16\pi^2} g^2 \Lambda^2$$

$$\Delta M_{H,3}^2 = \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \qquad V(\phi) = -\mu^2 |\phi^\dagger \phi| + \lambda |\phi^\dagger \phi|^2$$

- Fine tuning to precision $\sim M_H^2/\Lambda^2$ is needed
  For $\Lambda = M_{\text{Planck}}$, $M_H \sim 100\,\text{GeV}$: $(\Lambda/M_H)^2 \sim 10^{34}$ – gauge field scale hierarchy

$$M_H^2 = M_{H,\text{bare}}^2 + \underbrace{\frac{1}{16\pi^2}(-6g_t^2 + g^2 + \lambda^2) \cdot 10^{34} M_H^2}_{\text{SM}} - \underbrace{\ldots}_{\text{New Physics}} \simeq (130\,\text{GeV})^2$$

“Fine Tuning” Argument

- Current exp. limits on Higgs mass:

  $114.4 < M_H < 144\,\mathrm{GeV}$

  direct searches EW fits

- If SM is valid up to M_{Planck}, theor. limits:

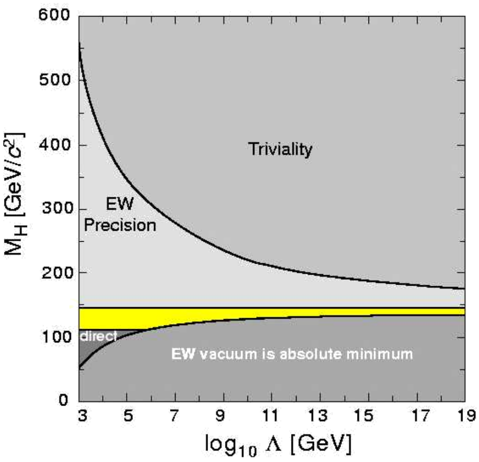
  $135 < M_H < 175\,\mathrm{GeV}$

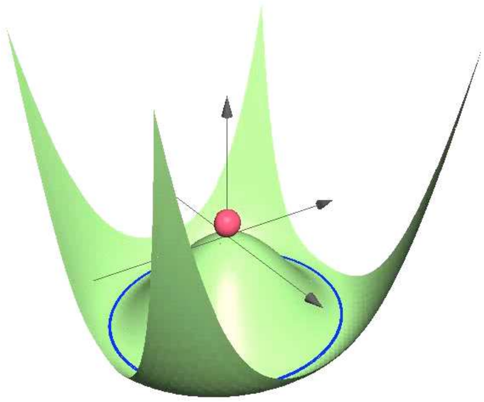
  EW vacuum Triviality

EW vacuum stability: Higgs mass cannot be too light or the potential will not have a Mexican hat shape and will turn negative at large values

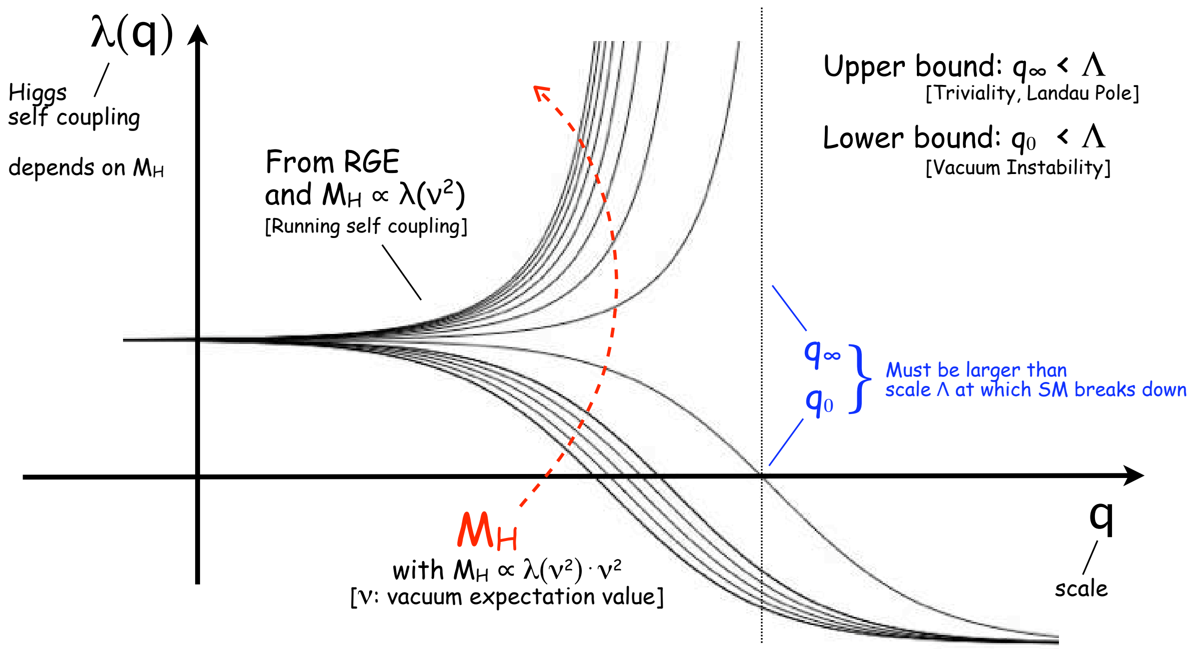
$$V(\phi) = -\mu^2|\phi^\dagger\phi| + \lambda|\phi^\dagger\phi|^2$$

Triviality: if the Higgs mass is too large, the Higgs self-coupling drives the mass to infinity above certain scale

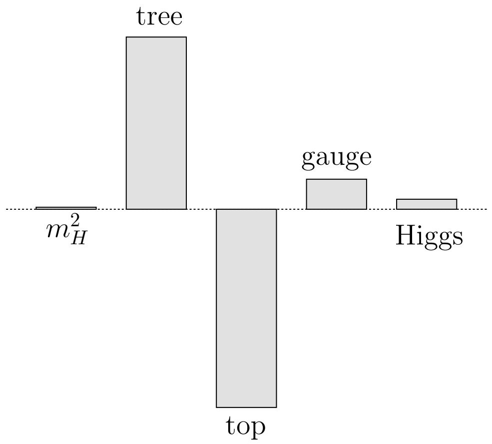


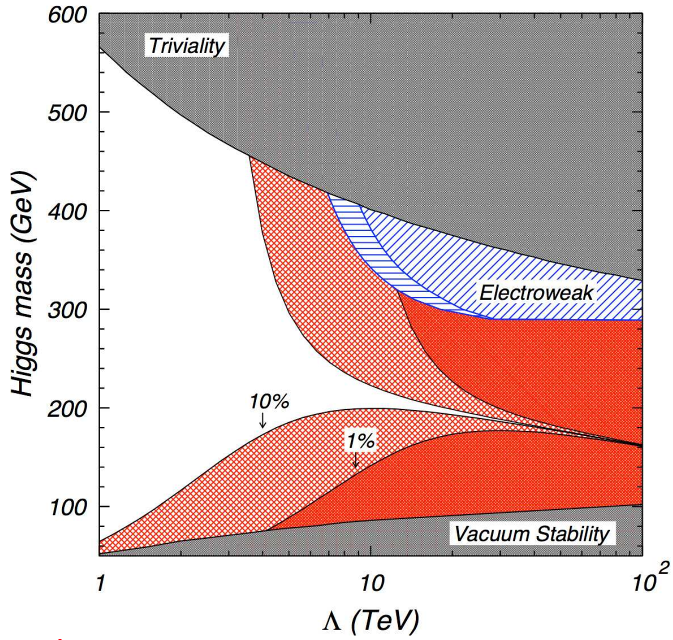


Triviality and Vacuum Instability



Even if new physics appears at
$\Lambda = 10\,\text{TeV}$, fine tuning is significant





However: SM can be valid up to the Plank scale!
Fine tuning is just a "stomach problem".

Anthropic principle: properties of the universe are so special because we happen to exist and be able to ask these very questions

Electron in Classical Electrodynamics

- E.m. self-energy

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e} \qquad r_e \text{ – "size"}$$

must be a part of the electron mass:

$$(m_e c^2)_{\text{observed}} = (m_e c^2)_{\text{bare}} + \Delta E_{\text{Coulomb}}$$

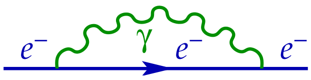
- From experiments: $r_e < 10^{-17}\,\text{cm} \implies \Delta E_{\text{Coulomb}} \gtrsim 10\,\text{GeV}$

$$0.511 = -9999.489 + 10000.000\,\text{MeV}$$

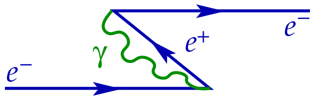
▶ Classical e.m. is not valid for scales where $\Delta E_{\text{Coulomb}} \gtrsim m_e c^2$:

$$d < \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.8 \cdot 10^{-13}\,\text{cm}$$

Quantum Effect – e^+e^- Pair Production

- Self-energy 

$\swarrow$ the same diagram in QED $\downarrow$



- Positron exists. e^+e^- pair production

  Vacuum fluctuations at $\Delta t \sim \dfrac{\hbar}{\Delta E} \sim \dfrac{\hbar}{2m_e c^2}$ (Heisenberg's uncertainty)

  modify physics at $d \sim c\Delta t \sim 200 \cdot 10^{-13}$ cm

$$\Delta E_{\rm pair} = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e} + \ldots \qquad \Longrightarrow \qquad \Delta E = \Delta E_{\rm Coulomb} + \Delta E_{\rm pair} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

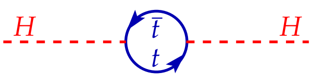
- Mass correction

$$(m_e c^2)_{\rm observed} = (m_e c^2)_{\rm bare}\left[1 + \frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

  Even for $r_e \sim 1/M_{\rm Plank} \sim 10^{-33}$ cm mass increases by 9%

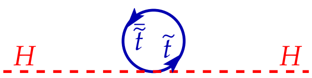
▶ Doubling d.o.f. + symmetry $\Longrightarrow$ divergency cancellation

Higgs Self-Energy



$$\Delta M^2_{H,{\rm top}} = -\frac{3}{8\pi^2} g_t^2 \Lambda^2 + \ldots$$

Bosons and fermions produce different signs in loops $\Longrightarrow$
Introduce "superpartner" for top = scalar top = "stop" = $\tilde{t}$



$$\Delta M^2_{H,{\rm stop}} = +\frac{3}{8\pi^2} g_t^2 \Lambda^2 + \ldots$$

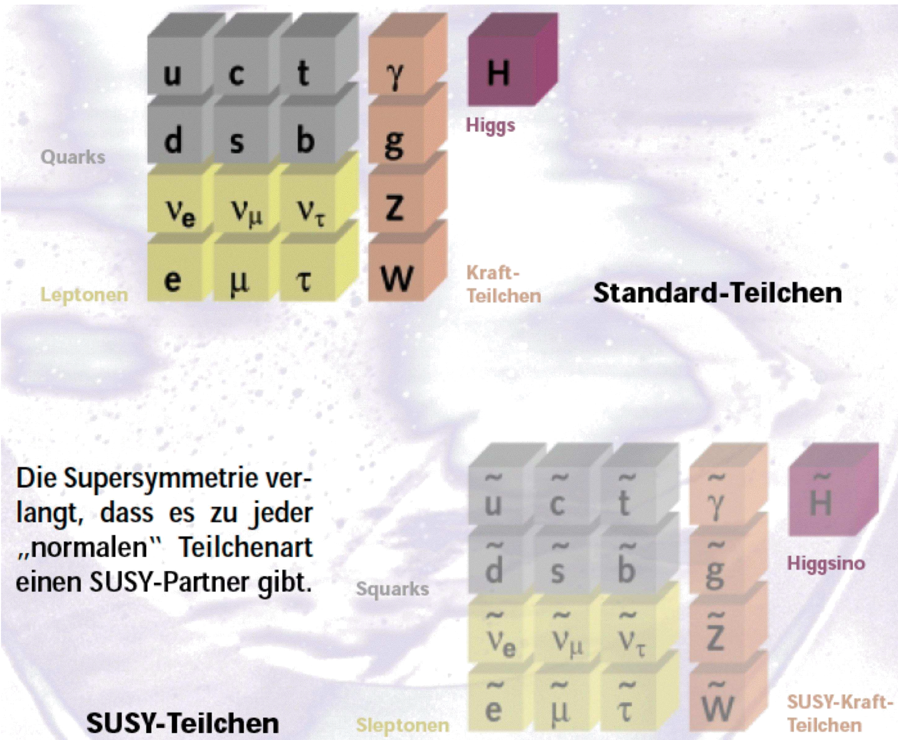
Total correction

$$\Delta M^2_{H,{\rm top}} + \Delta M^2_{H,{\rm stop}} = -\frac{3}{8\pi^2} g_t^2 (m_{\tilde{t}}^2 - m_t^2) \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$$

▶ "Naturalness" argument: $m_{\tilde{t}}$ should be not much larger than m_t $\qquad m_{\tilde{t}} \sim$ TeV???

Supersymmetry (SUSY)

SUSY Particles



sleptons, squarks = sfermions = bosons

. . . -inos = fermions
higgsinos, gauginos (photino, wino, . . .)
= neutralinos, charginos