PHYSICS BEYOND THE STANDARD MODEL

http://ihp-lx2.ethz.ch/JenseitsSM/

I SM SUMMARY

Concepts and Results

II GUT

Unification of Couplings
SU(5)
Spontaneous Symmetry Breaking
Proton Decay

III SUPERSYMMETRY

SUSY Formalisms
Breaking of Supersymmetry
MSSM = Minimal Supersymmetric SM

IV HIDDEN VALLEYS

Mediator Barrier
Light Sector

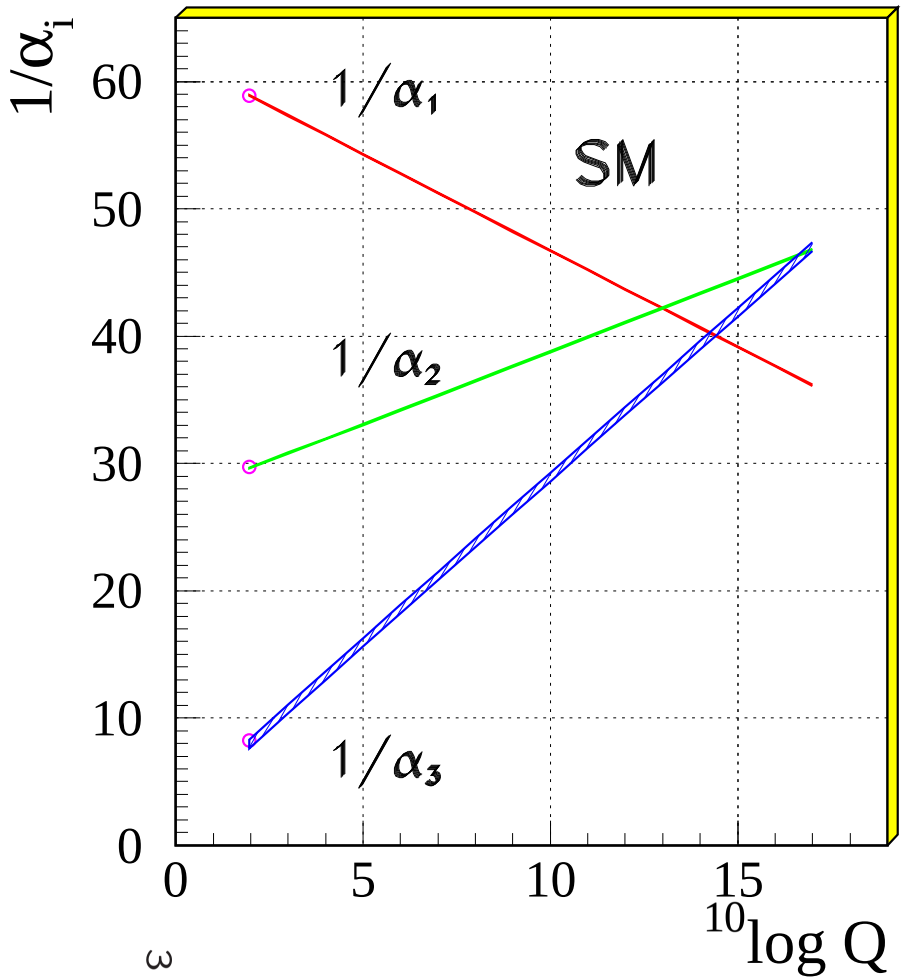
GUT

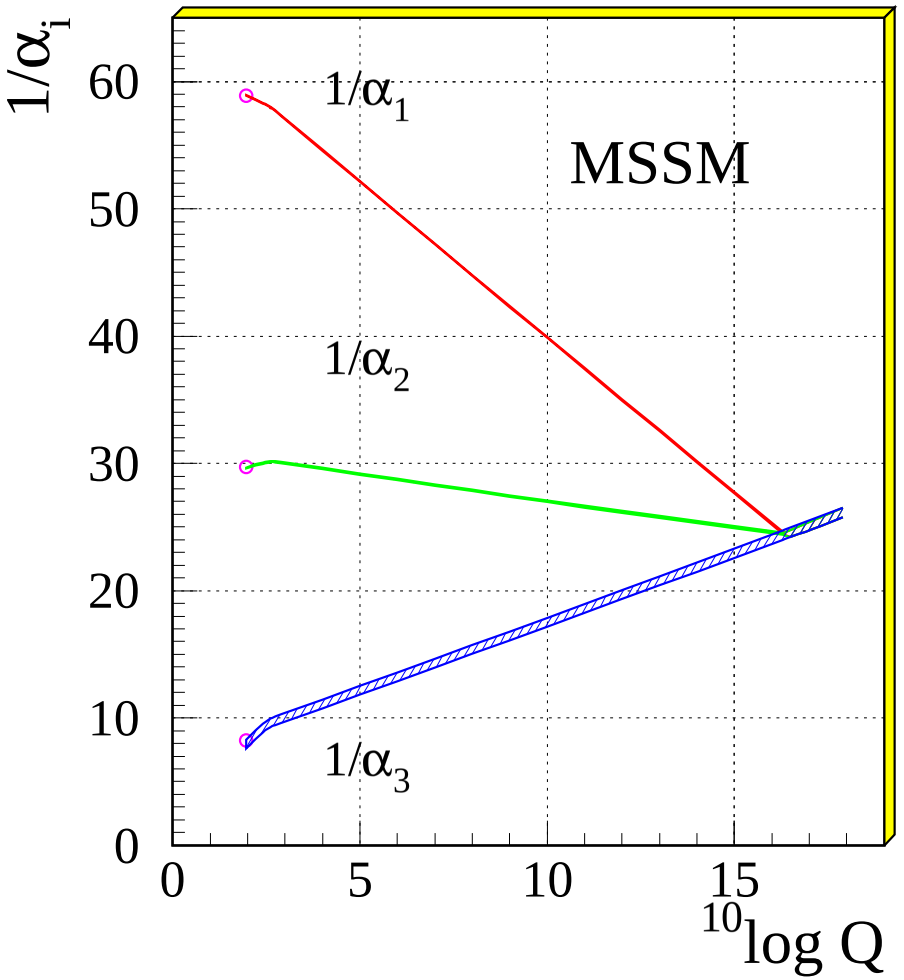
- Open Problems in SM:
  3 interactions + class. Gravity
  family structure
  multiplet structure of a family
  parameter number:

6	quark masses	
3	lepton masses	[6]
3	CKM rotation angles	[6]
1	$\mathcal{CP}$ phase	[2]
1	Higgs mass	
3	gauge couplings: $e, \sin^2\theta_W, g_s$	
1	electroweak Scale v	
1	θ parameter [strong $\mathcal{CP}$]	
19	parameter	[26]

- Partial Solution: Merging of interactions
  SU(3)×SU(2)×U(1) $\longrightarrow$ G
- Explanations:
  charge quantisation: $Q_{e^-} - 3Q_d = 0$
  multiplet structure in families: "15", "16"
- Predictions: $\sin^2\theta_W = 0.20 \ldots 0.25$
  stability problem [$\stackrel{?}{\rightarrow}$ SUSY]
  p decay [$\stackrel{?}{\leftarrow}$ SUSY]
  magnetic monopoles ?

Unification of the Coupling Constants in the SM and the minimal MSSM





SUPERSYMMETRY

Motivation:

(i) conjunction "bosons $\leftrightarrow$ fermions":

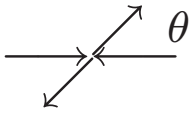
$$\left.\begin{array}{l} Q|F\rangle = |B\rangle \\ Q|B\rangle = |F\rangle \end{array}\right\} \text{1 multiplet}$$

(ii) maximal symmetry of $\mathcal{S}$–matrix:

Coleman–Mandula–theorem:

Bosonic operators cannot extend Poincaré–algebra:

— P_μ conserved:



$$\langle 1,2|P_\mu|1',2'\rangle = p_{1\mu} + p_{2\mu} = p'_{1\mu} + p'_{2\mu}$$

— $T_{\mu\nu} = \alpha p_\mu p_\nu + \beta g_{\mu\nu}$ conserved:



$$\begin{aligned}\langle 1,2|T_{\mu\nu}|1',2'\rangle &= p_{1\mu}p_{1\nu} + p_{2\mu}p_{2\nu} \\ &= p'_{1\mu}p'_{1\nu} + p'_{2\mu}p'_{2\nu} \ [\beta = 0]\end{aligned}$$

$\longrightarrow$ scattering only for $\theta = 0$!

fermionic operators:

$\langle|\tilde{Q}|\rangle = 0 \quad \tilde{Q} \sim \frac{1}{2}$ integer spin

$\tilde{Q} \neq 0$ conserved $\rightarrow$ possible:

$\Longrightarrow$ graded Lie algebra

$[Q_i, H] = 0 \Rightarrow [\{Q_i, Q_j\}, H] = 0$:

if $Q_i =$ spin $\frac{1}{2} \rightarrow \{Q_i, Q_j\} =$ spin 1 $\sim P_\mu$

$\longrightarrow$ possible

if $Q_i =$ spin $\frac{3}{2} \rightarrow \{Q_i, Q_j\} =$ spin 3

$\longrightarrow$ CM–forbidden

(iii) Hierarchy problem:

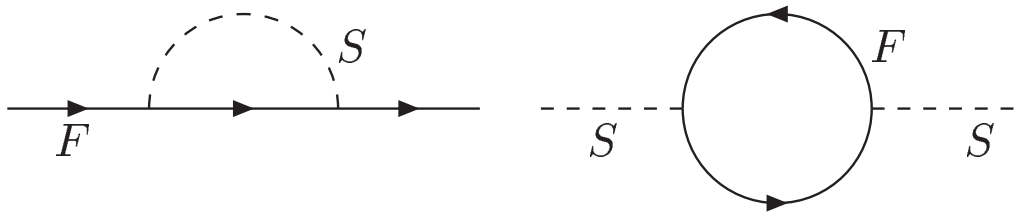
Standard Model: elw. scale $\sim 10^2$ GeV

GUT scale $\sim 10^{16}$ GeV

$\rightarrow$ fermion masses stable against radiative corrections

boson masses unstable:

$$\mathcal{L}_1 = \bar{\psi}(i\partial\!\!\!/ - m_F)\psi + \tfrac{1}{2}(\partial_\mu S)^2 - \tfrac{1}{2}m_S^2 S^2 - \frac{\lambda_F}{2}\bar{\psi}\psi S$$



$$\begin{aligned}
\delta m_F &= -\frac{3\lambda_F^2 m_F}{64\pi^2}\log\frac{\Lambda^2}{m_F^2} + \cdots \\
\delta m_S^2 &= -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 - m_F^2\log\frac{\Lambda^2}{m_F^2}\right] + \cdots
\end{aligned}$$

F: mild log. div.$\sim m_F \log\Lambda \to 0$ for $m_F \to 0$
(natural restriction: $m_F \to 0 \Rightarrow \gamma_5$–symmetry)

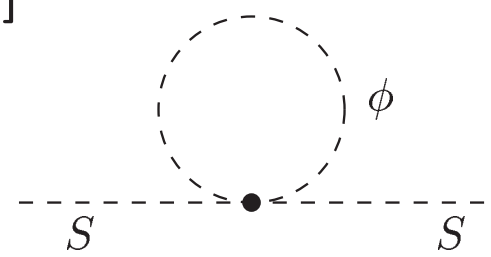
S: quadratic divergence $\sim \Lambda^2$
$\longrightarrow$ canceled only by fine–tuning of bare mass term

Boson masses cannot be kept small in a natural way in the context of high energy scales.

SUPERSYMMETRY: Boson masses can be kept small in a natural way, if bosons are connected to fermions.

$$\mathcal{L}_2 = |\partial_\mu \phi_1|^2 + |\partial_\mu \phi_2|^2 + \frac{\lambda_S^2}{2} S^2 (|\phi_1|^2 + |\phi_2|^2)$$

$[\psi \leftrightarrow \phi_1, \phi_2]$ $\qquad -m_\phi^2 (|\phi_1|^2 + |\phi_2|^2)$



$$\delta m_S'^2 = +\frac{\lambda_S^2}{8\pi^2}\left[\Lambda^2 - m_\phi^2 \log \frac{\Lambda^2}{m_\phi^2}\right] + \cdots$$

$(\pm$ = Pauli–principle)

SUSY:

$$\left.\begin{array}{l}\text{d.o.f.: 2 ferm.} \leftrightarrow \text{2 bos.} \\ \lambda_F = \lambda_S\end{array}\right\} \delta m_S^2 \sim \frac{\lambda_S^2}{8\pi^2}(m_F^2 - m_\phi^2) \log \Lambda^2$$

Low-Energy Supersymmetry:

1.) doubling of spectrum

2.) Equality of coupling constants in ferm.$\sim$bos. coupling

3.) $m_{SM} \sim \mathcal{O}(100\,\text{GeV}) \Rightarrow m_\phi \equiv \tilde{m} \lesssim \mathcal{O}(1\,\text{TeV})$

$\uparrow$ Cancelation of quadratic divergences by increase of symmetries

Solution of hierarchy problem by low-energy SUSY masses $\lesssim \mathcal{O}(1\,\text{TeV})$.

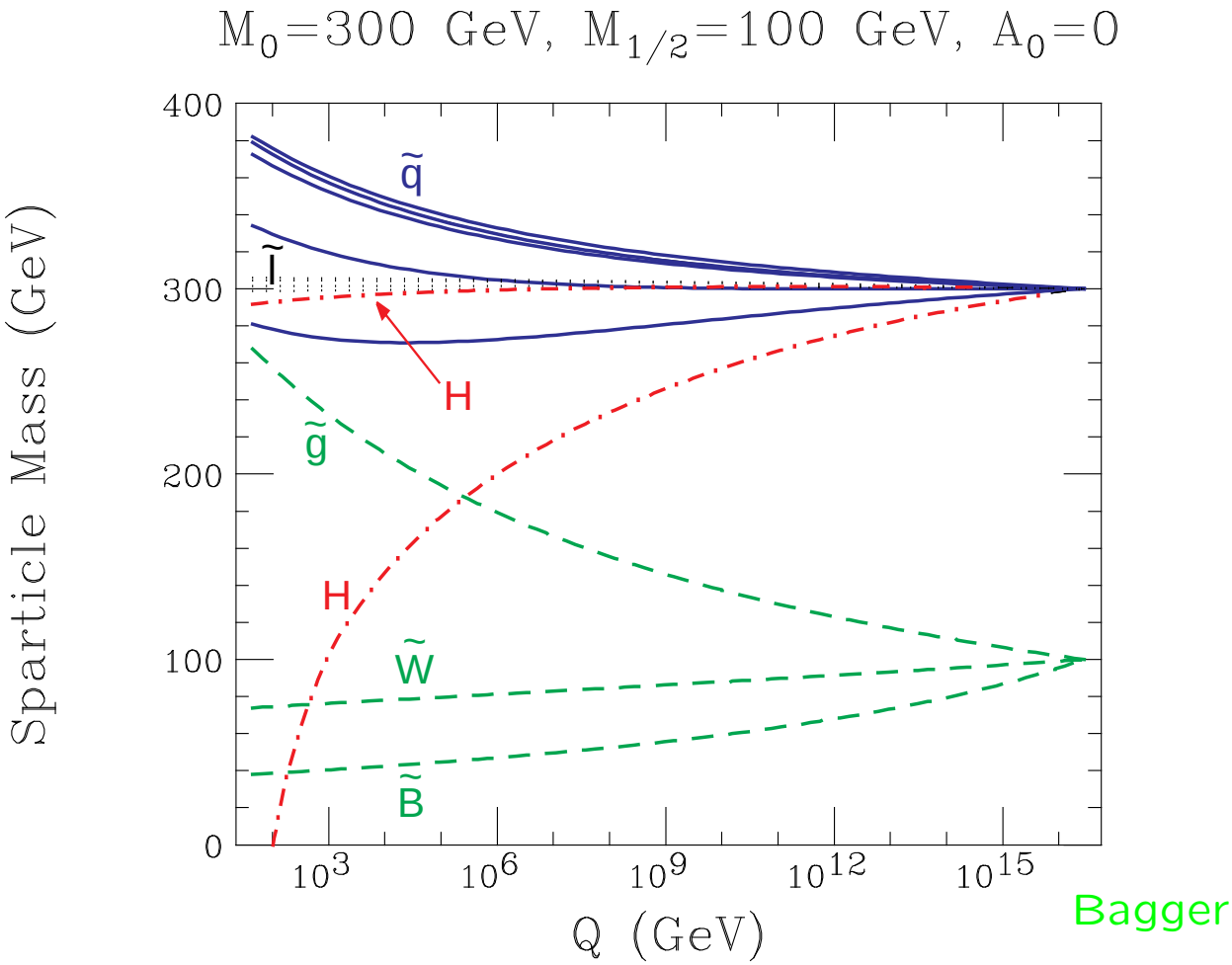
(iv) SUSY–GUT:

— elw. mixing angle:

$$\left.\begin{array}{rcl} \sin^2\theta_W & = & 0.2335 \pm 0.0017 \text{ th} \\ & = & 0.2316 \pm 0.0002 \text{ ex} \end{array}\right\} 2‰$$

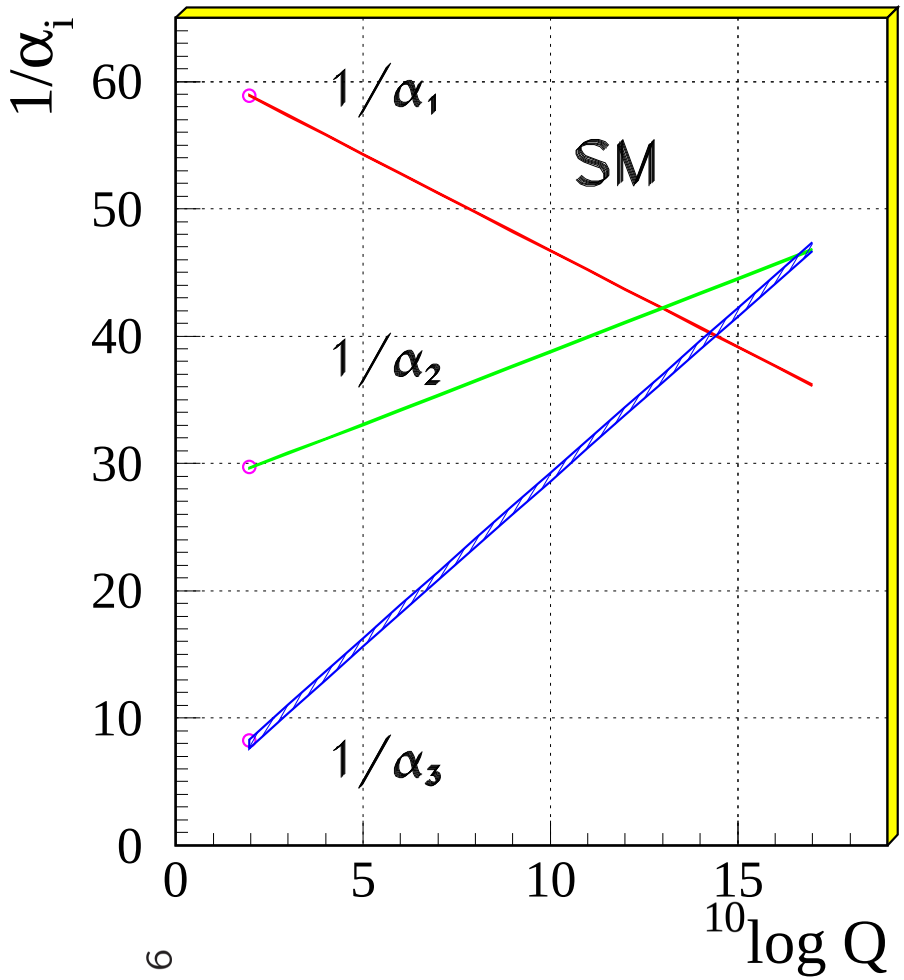
— proton decay suppressed:
$\Lambda_{\rm GUT} \sim 10^{15}$ GeV $\rightarrow 10^{16}$ GeV

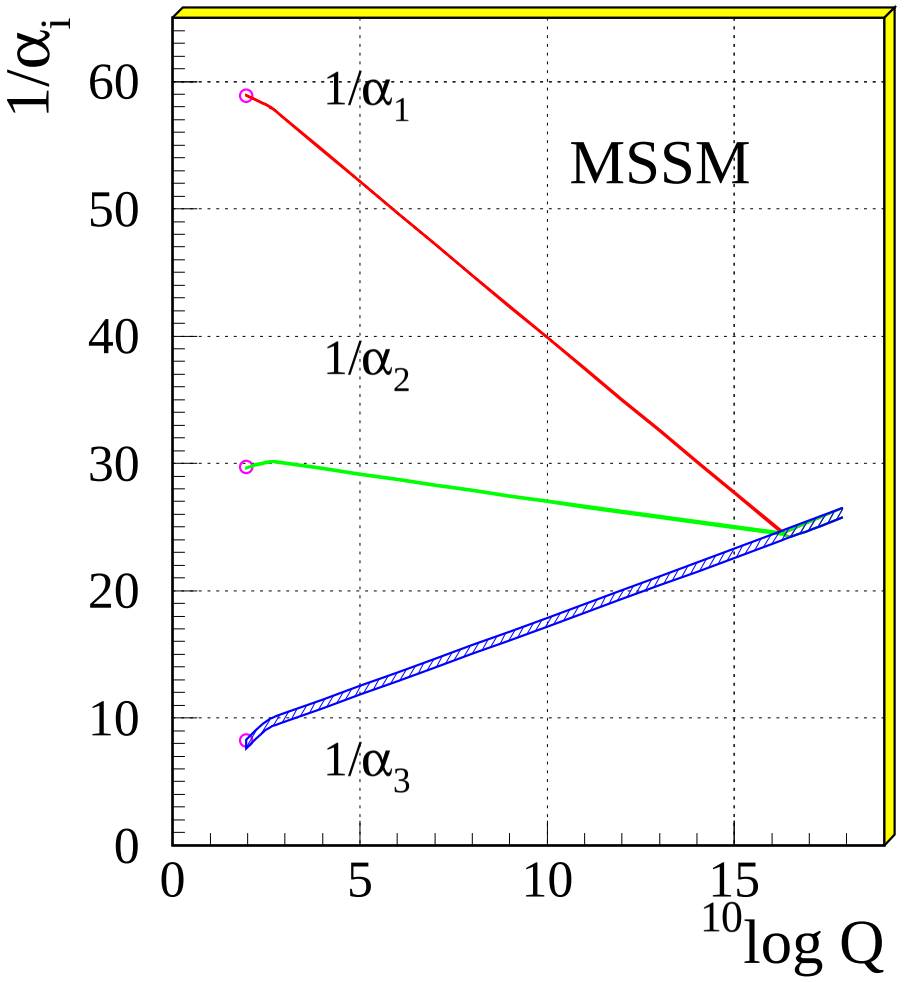
— Higgs mechanism generated through radiative corrections (for $m_t \sim 100 \ldots 200$ GeV)



Bagger

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(v) LSP stable: candidate for Dark Matter $\sim 25\%$ in the universe

(vi) local SUSY: enforces gravitational interactions