Introduction to the Standard Model of particle physics

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V. Beyond the SM

The beautiful SM

The Beautiful SM

- **QFT = QM + SR**
- **Matter content: 3 generations of**
  - Quarks (u,d),(s,c),(b,t)
  - Leptons $(e,\nu_e),(\mu,\nu_\mu),(\tau,\nu_\tau)$
- **local gauge symmetry** $SU(3)_c \times SU(2)_L \times U(1)_Y$
  - 8 gluons, W^+, W^-, Z, Photon
- **Renormalizability**
- **Electroweak symmetry breaking (EWSB)**
  - Higgs boson

The Higgs boson

$$m_h \simeq 125\ \text{GeV}$$

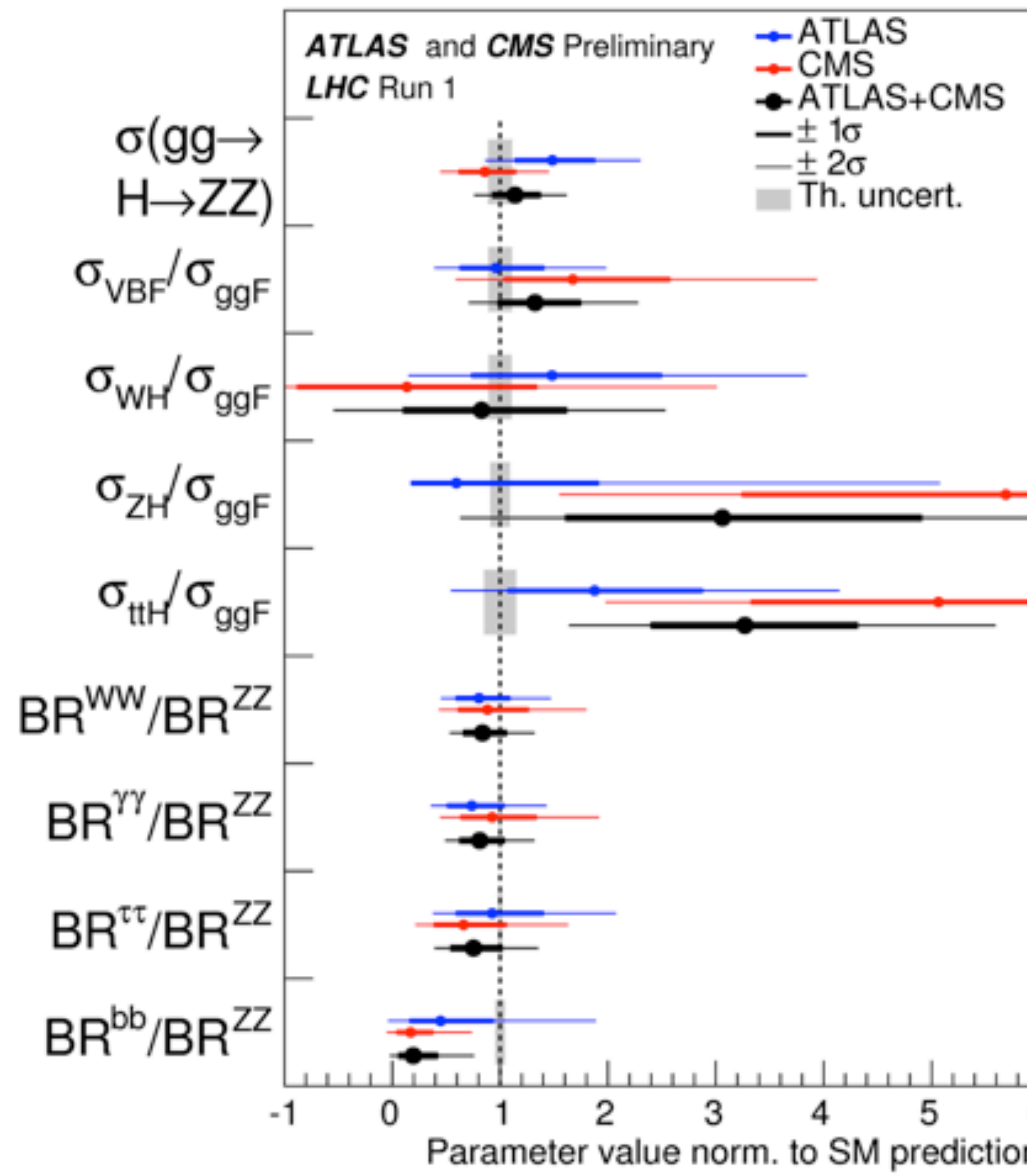
- The/A Higgs boson has been discovered at the LHC in 2012
  [ATLAS, PLB716(2012)1; CMS,PLB716(2012)716]

- All results are coherent with the expectations of the SM:
  - Spin = 0 [PLB726(2013)120]
  - P=+1, C=+1, CP = +1 [PRD92(2015)012004]
  - Couplings to the vector bosons (Z,W,γ,g) and to the fermions (t,b,τ) in agreement at ~30% precision

- Still to be measured are the self-couplings of the Higgs boson

Crucial to test the mecanism of EWSB!

[ATLAS-CONF-2015-044]



The weird SM

Input parameters

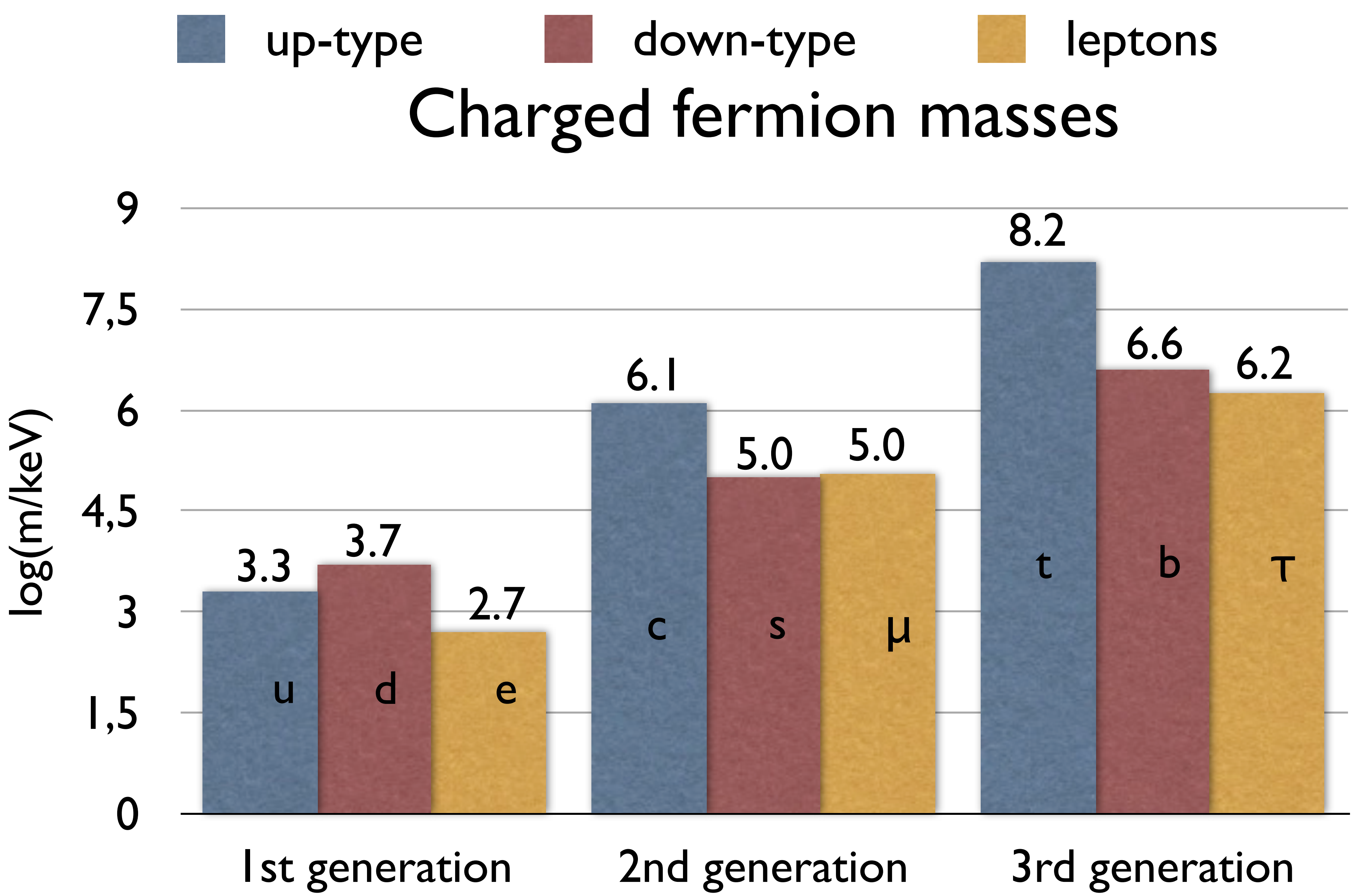
- The SM Lagrangian has **26 input parameters**
(of course not all are equally important)

- They **need to be fixed** in order to make **predictions**

- The values and patterns of these parameters are quite **bizarre**!

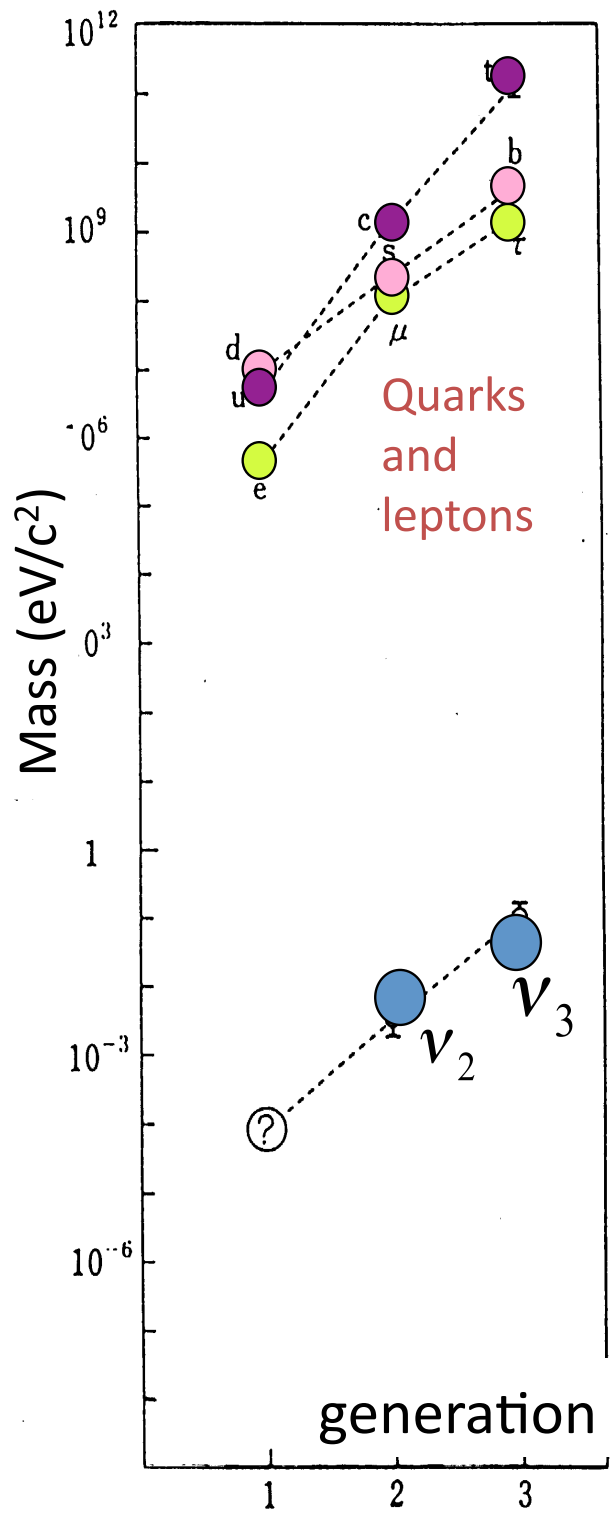
The Flavor Puzzle

The charged fermion masses are very hierarchical, extending over 5 orders of magnitude



The Flavor Puzzle

Things get even worse when we include neutrino masses!
12 ...14 orders of magnitude!



Why the neutrino mass is so small ?

$$\rightarrow \left(\frac{m(\nu_3)}{m(top\ quark)}\right) \approx \left(\frac{1}{3\times 10^{12}}\right)$$

See-saw mechanism

Minkowsky, Yanagida, Gell-mann, Ramond, Slansky

$$m_\nu \approx \frac{m_q^{\ 2}}{m_N}$$

If we input $m_{\nu 3}$ and m_q (m_{top} is used), we get $m_N = 10^{15}$ GeV

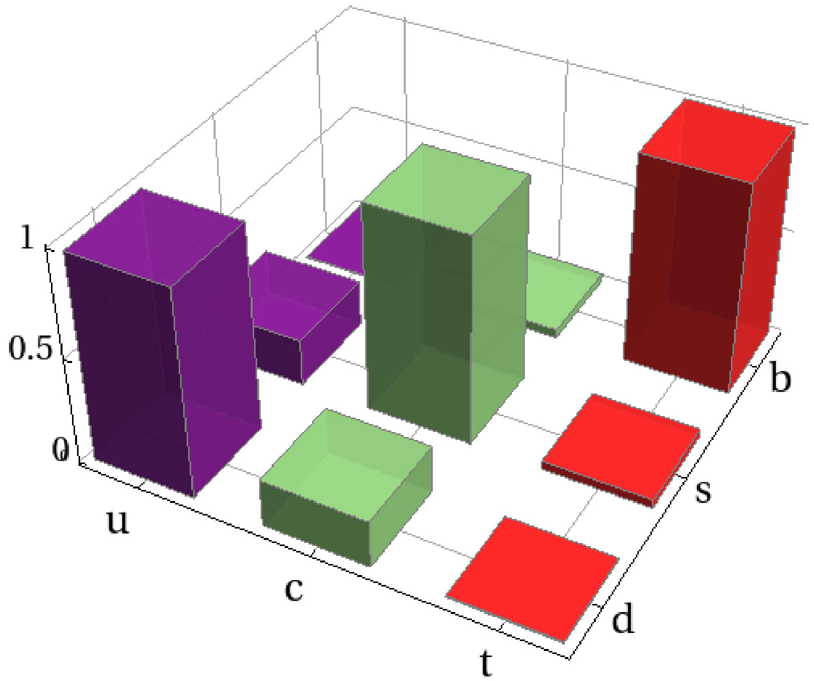
This suggests that physics of neutrino mass could be related to physics of Grand Unification!

The Flavor Puzzle

Quark and Lepton mixing parameters are quite different!

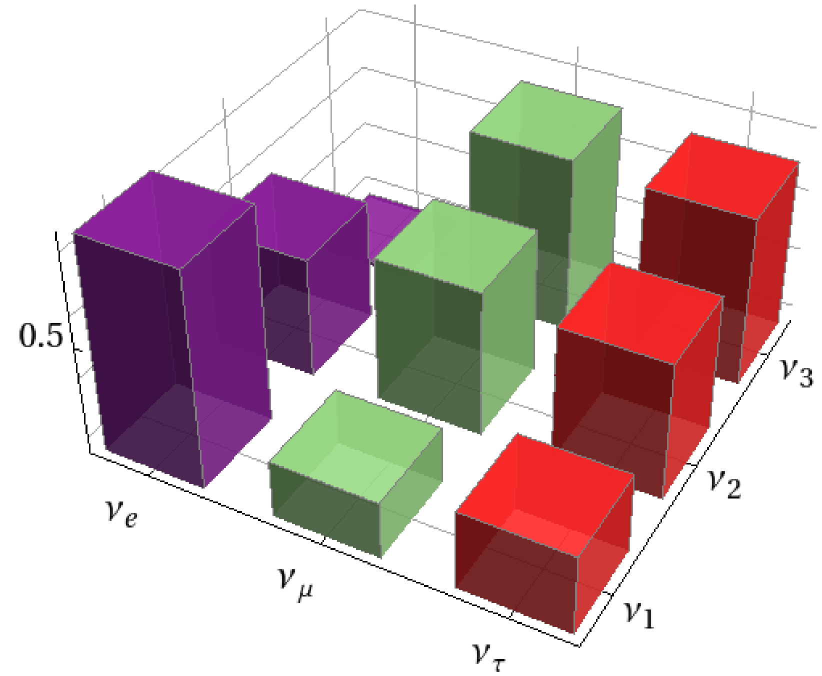
- **Quark Mixings**

$$V_{CKM} \sim \begin{bmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{bmatrix}$$



- **Leptonic Mixings**

$$U_{PMNS} \sim \begin{bmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{bmatrix}$$



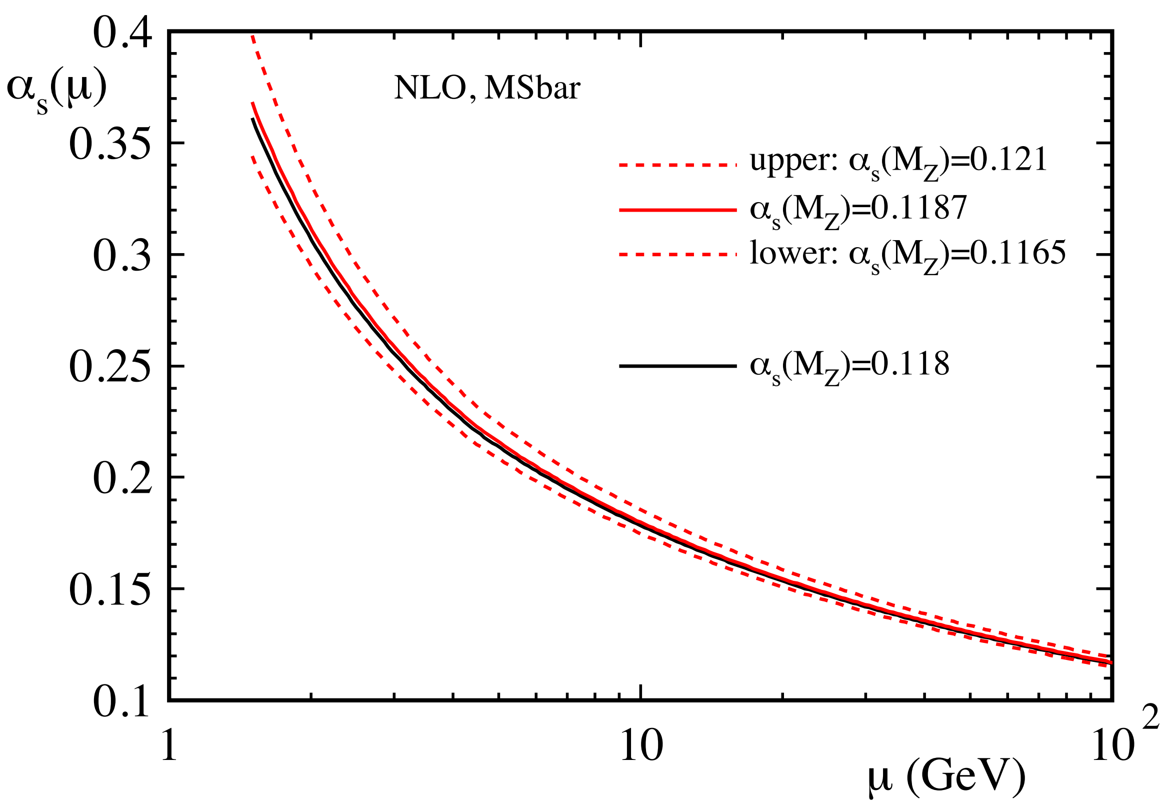
Quantum Corrections

- Quantum corrections have to be considered (otherwise some predictions very rough!)
- **UV** divergences appear
- **Renormalization** of Lagrangian parameters and fields
- This leads to **running parameters**
- Scale-dependence governed by **renormalization group equations** (RGEs)

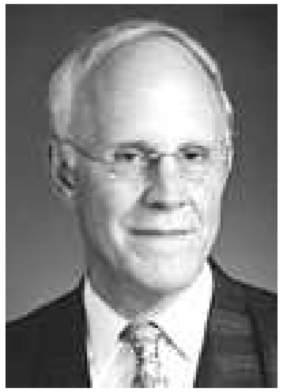
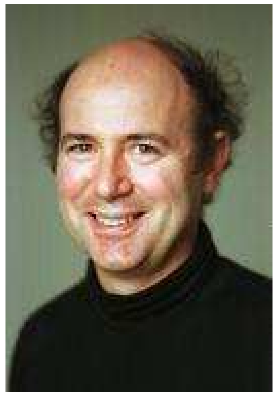
Asymptotic Freedom

Renormalization of UV-divergences:
Running coupling constant $a_s := \alpha_s/(4\pi)$

$$a_s(\mu) = \frac{1}{\beta_0 \ln(\mu^2/\Lambda^2)}$$



- Gross, Wilczek ('73); Politzer ('73)


Non-abelian gauge theories:
negative beta-functions

$$\frac{da_s}{d\ln\mu^2} = -\beta_0 a_s^2 + \ldots$$

where $\beta_0 = \frac{11}{3} C_A - \frac{2}{3} n_f$

$\Rightarrow$ asympt. freedom: $a_s \searrow$ for $\mu \nearrow$

- Nobel Prize 2004

The successful SM

The Succesful SM

- **All** the elementary matter particles (quarks, charged leptons, neutrinos) postulated by the SM have been discovered

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America first!

The fermions have been discovered in the USA

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Europe second!

The bosons have been discovered in Europe

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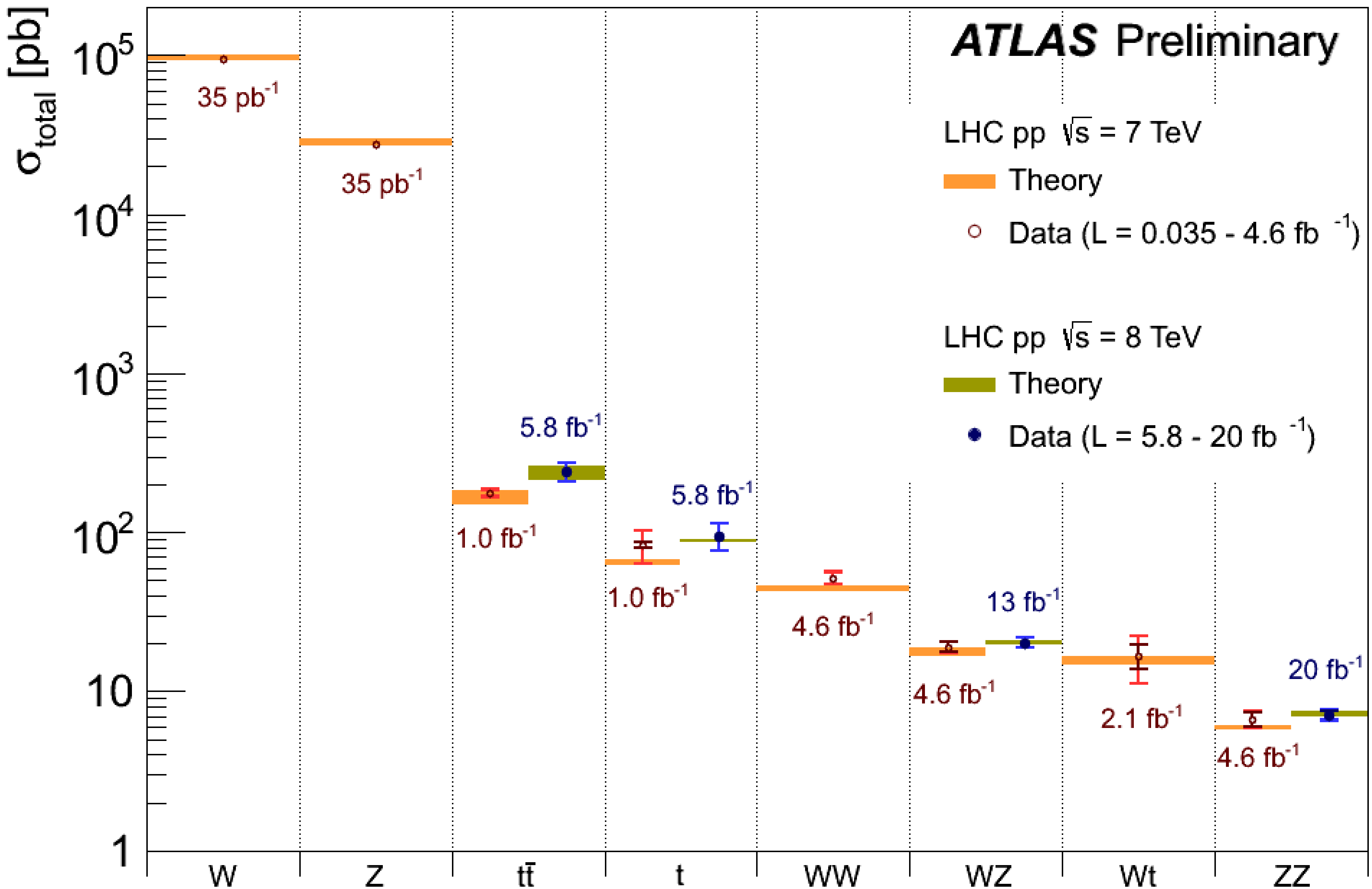
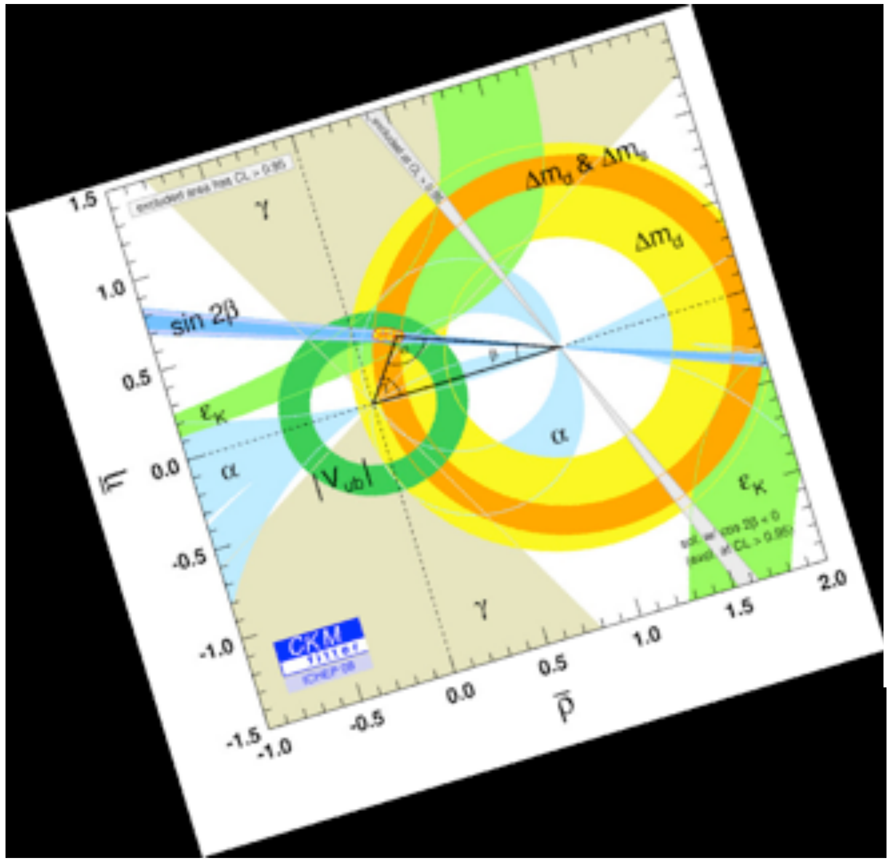
- **No other particles** have been found (so far)
- The SM is the **best-tested theory** in the history of science!

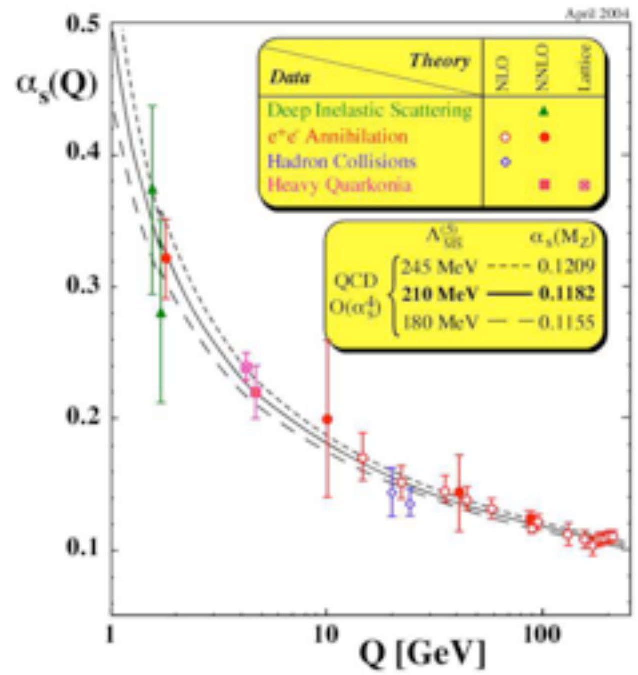
A very large number of precision measurements have been compared to SM computations at the ***(multi-)loop level*** *and* ***no solid evidence for BSM physics*** *has emerged (neither in direct searches nor indirectly due to loop effects)*

Cross sections at the LHC in comparison to the SM



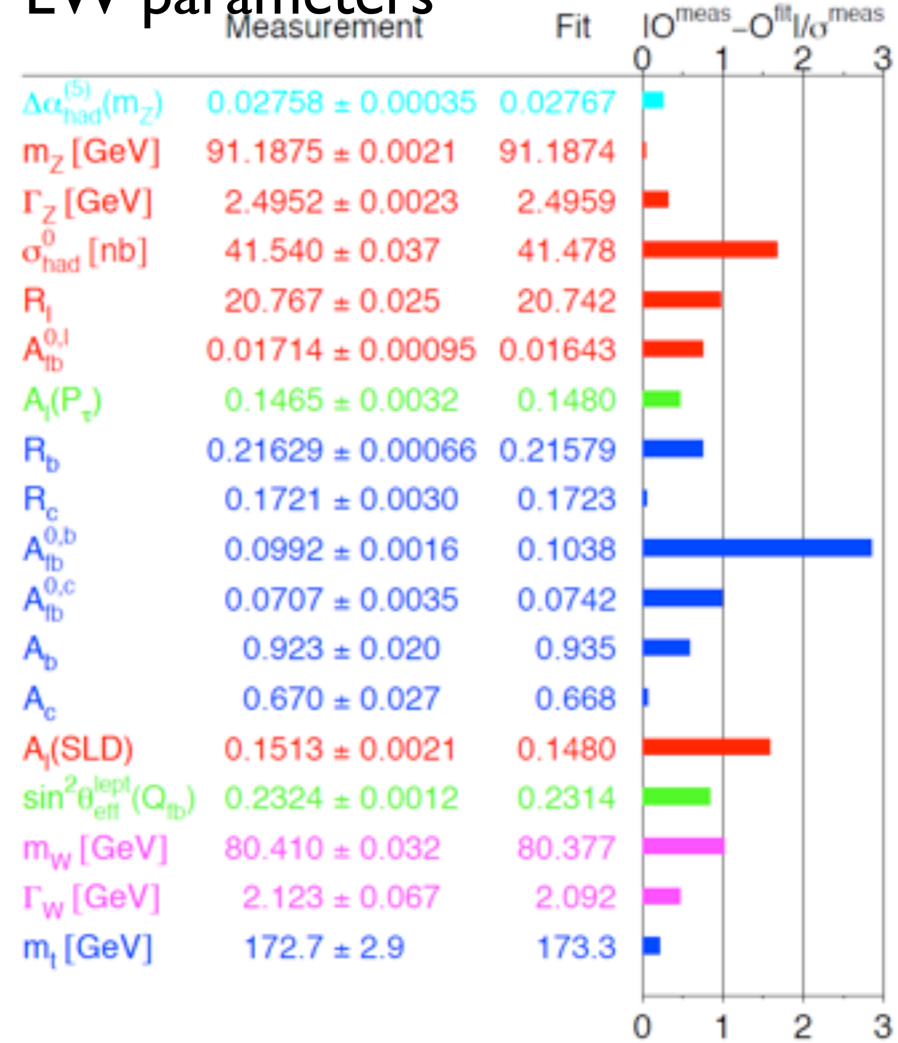
CKM angles



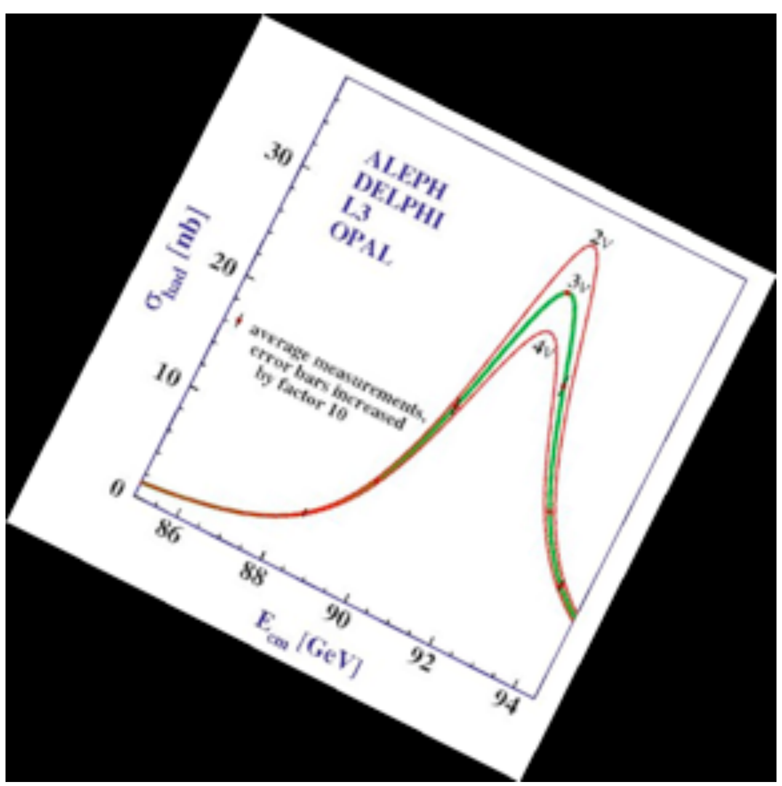


running α_S

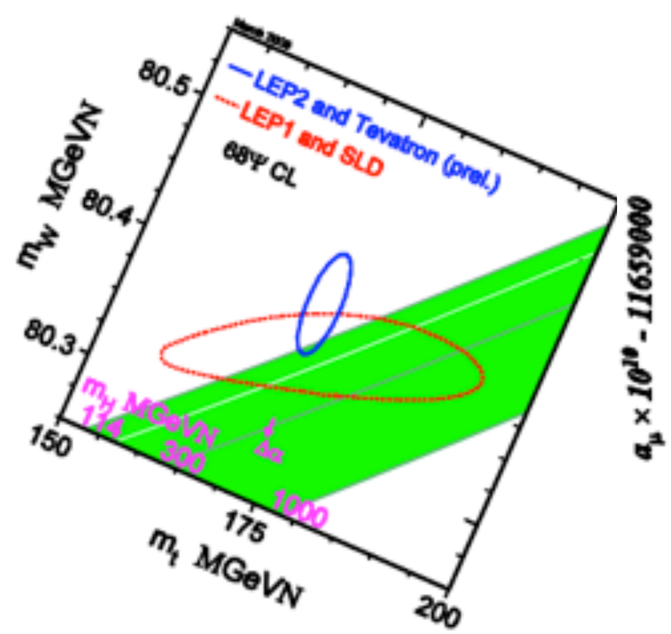
EW parameters



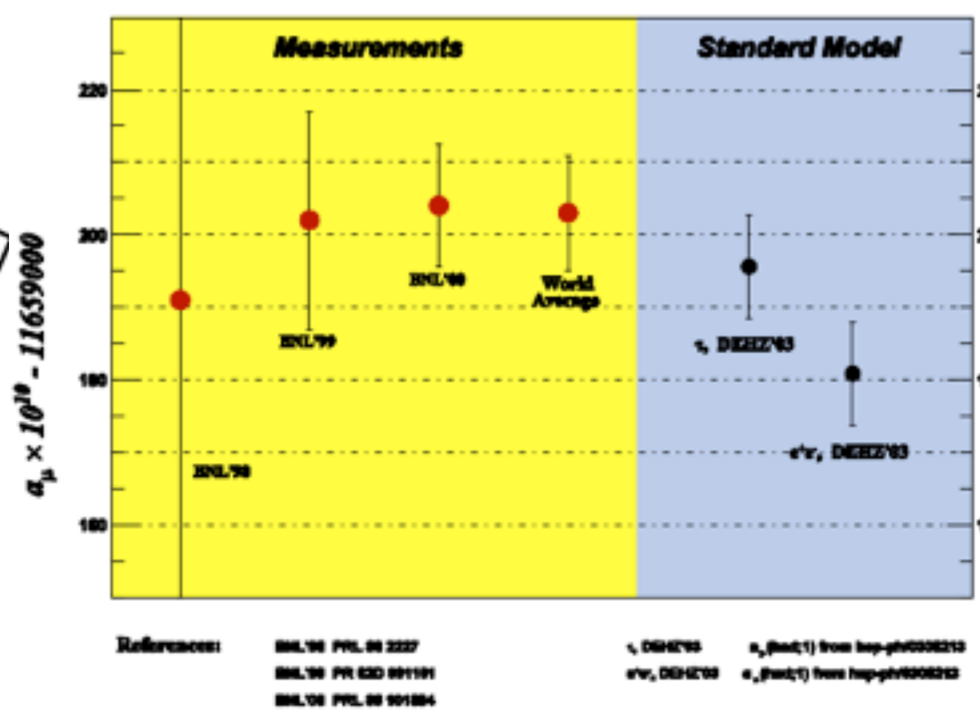
Z^0 width



top and W mass



anom. magnetic moment (g-2)

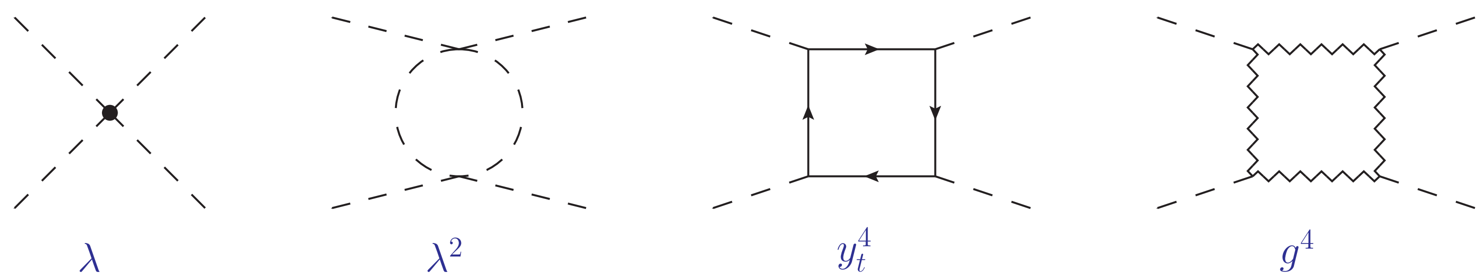


Higgs effective potential

self-consistency of SM: the Higgs-Top miracle

- consider self coupling of Higgs $\lambda(t)$ (from $\lambda/2(\varphi^\dagger\varphi)^2$) with $t = \ln \Lambda^2/Q_0^2$
- coupling runs:

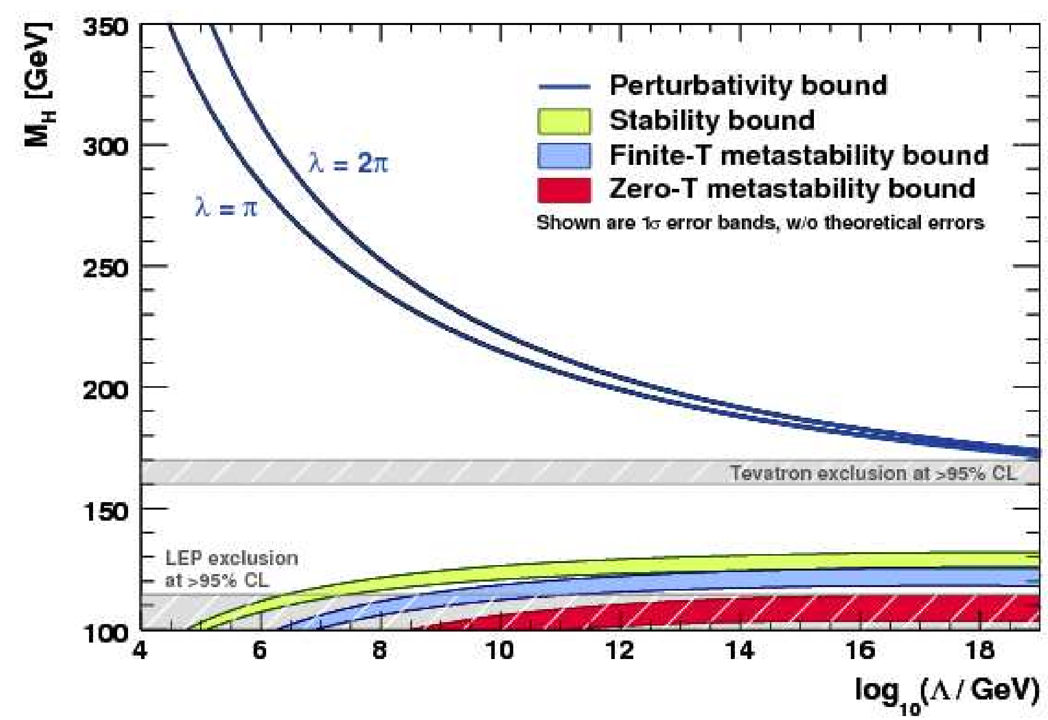
$$\frac{4\pi^2}{3}\frac{d\lambda(t)}{dt} = \lambda^2 - y_t^4 + \ldots$$



- if λ term dominant, i.e. large Higgs mass $\dot{\lambda} \sim \lambda^2$ $\rightarrow$ triviality/perturbativity bound:

$$\lambda(\Lambda) = \frac{\lambda(Q_0)}{1 - 3/(4\pi^2)\,\lambda(Q_0)\,t}$$

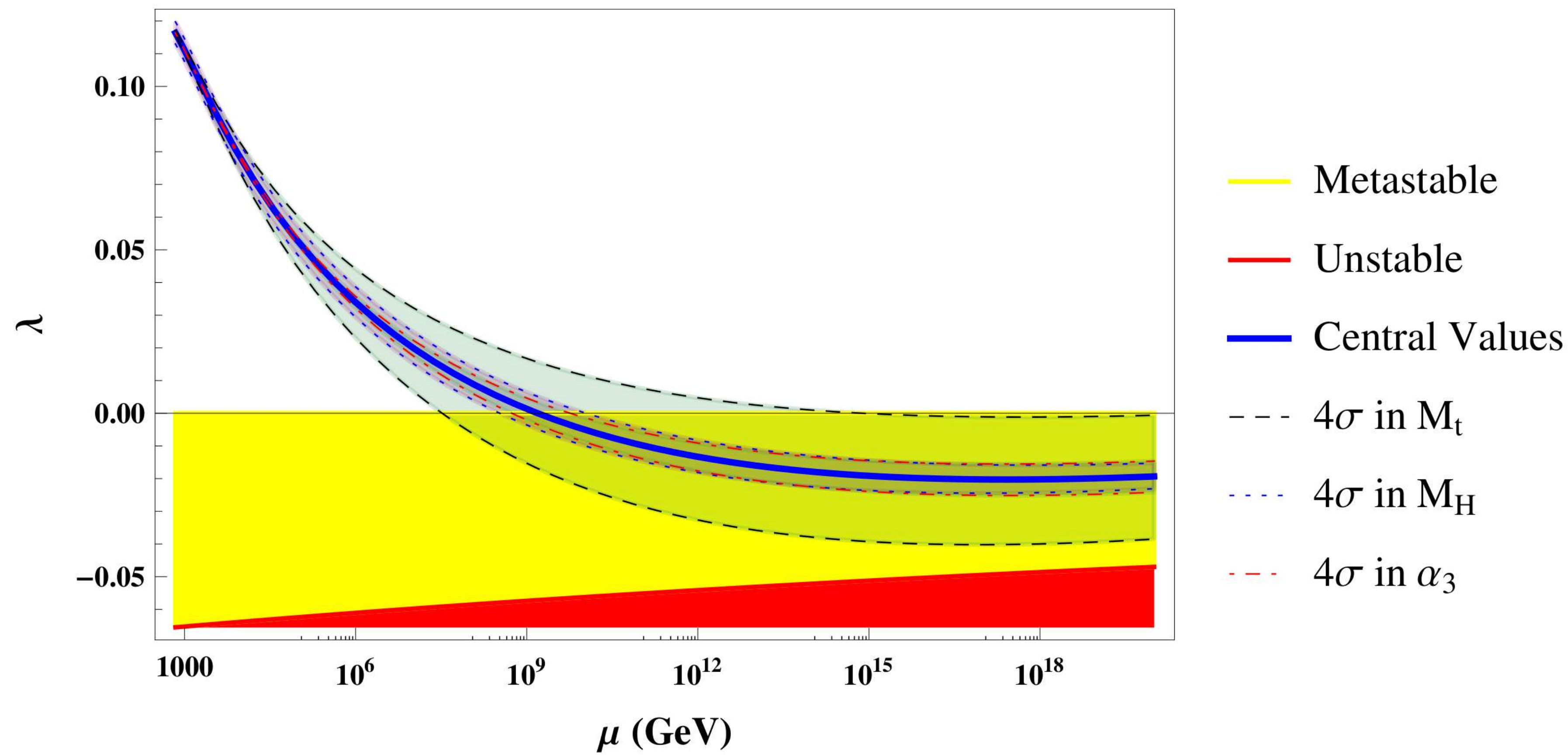
$$\Longrightarrow\ 2\lambda(v)v^2 = M_H^2 < \frac{8\pi^2\,v^2}{3\ln(\Lambda^2/v^2)}$$



Higgs effective potential

self-consistency of SM: the Higgs-Top miracle plot: [Spencer-Smith. 1405.1975]

- if y_t term dominant i.e. large top mass $\dot{\lambda} \sim -y_t^4$
- vacuum stability: $\lambda(\Lambda) = \lambda(Q_0) - \frac{3}{4\pi^2} y_t^4 \, t \overset{!}{>} 0 \implies M_H^2 > \frac{3\, v^4\, y_t^4}{2\pi^2 v^2} \ln \frac{\Lambda^2}{v^2}$



- for $M_H \sim 125$ GeV and $M_t \sim 173$ GeV the SM seems to be consistent up to very high energies $\Lambda_{\rm UV} \sim 10^9 - 10^{14}$ GeV is this a coincidence ??

But there are also problems...

There are also problems...

- **Observational** problems Earth/Sky
- **Conceptional** problems
- **Theoretical** problems
- **Naive/Aesthetical/Religious** problems

Observational problems

Problems on "earth"

- Real problems with laboratory based experiments

- **Neutrino oscillations**

  It is by now well-established that neutrinos oscillate which is only possible if **at least two neutrinos are massive**. Now, in the original SM, neutrinos are massless particles...

The SM with massive neutrinos

(i) Too many free parameters

Gauge sector: 3 couplings g', g, g_3	3
Quark sector: 6 masses, 3 mixing angles, 1 CP phase	10
Lepton sector: 6 masses, 3 mixing angles and 1-3 phases	10
Higgs sector: Quartic coupling λ and vev v	2
θ parameter of QCD	1
	26

(ii) Structure of gauge symmetry

$$\mathrm{SU(3)}_c \times \mathrm{SU(2)}_L \times \mathrm{U(1)}_Y \overset{?}{\subset} \mathrm{SU(5)} \overset{?}{\subset} \mathrm{SO(10)} \overset{?}{\subset} \mathrm{E}_6 \overset{?}{\subset} \mathrm{E}_8$$

Why 3 different coupling constants g', g, g_3?

(iii) Structure of family multiplets

$$\underset{Q}{(\mathbf{3},\mathbf{2})_{1/3}} + \underset{\bar{u}}{(\bar{\mathbf{3}},\mathbf{1})_{-4/3}} + \underset{\bar{e}}{(\mathbf{1},\mathbf{1})_{-2}} + \underset{\bar{d}}{(\bar{\mathbf{3}},\mathbf{1})_{2/3}} + \underset{L}{(\mathbf{1},\mathbf{2})_{-1}} + \underset{\bar{\nu}}{(\mathbf{1},\mathbf{1})_{0}} \overset{?}{=} \mathbf{16}$$

Particles	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\frac{1}{2}$	**3**	**2**	$\frac{1}{3}$
u_R^c	$\frac{1}{2}$	$\bar{\mathbf{3}}$	**1**	$-\frac{4}{3}$
d_R^c	$\frac{1}{2}$	$\bar{\mathbf{3}}$	**1**	$\frac{2}{3}$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\frac{1}{2}$	**1**	**2**	-1
ν_R^c	$\frac{1}{2}$	**1**	**1**	0
e_R^c	$\frac{1}{2}$	**1**	**1**	2
$H = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$	0	**1**	**2**	1
G_μ^α	1	**8**	**1**	0
W_μ^a	1	**1**	**3**	0
B_μ	1	**1**	**1**	0

Fits nicely into the 16-plet of SO(10)

Problems on “earth”

- Real problems with laboratory based experiments

- **Neutrino oscillations**

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- Potentially problems in the flavour sector
  (see talk on flavour physics)

Problems in the "sky"

- The SM does not provide a candidate for **Dark Matter** (if DM is made of particles)
- **Dark Energy** is unexplained
- The amount of CP-violation in the SM is <u>not sufficient</u> to explain the **matter-antimatter asymmetry** in the universe/ baryon asymmetry of the universe (BAU)

Conceptual problems

Internal consistency

- Without the Higgs boson (or something equivalent) the SM would be internally inconsistent at the LHC scale!
- Without a Higgs the scattering of weak bosons would grow strongly with energy and **violate unitarity** (conservation of probability)
- The Higgs had to be there! (and was found)
- The **vacuum stability** of the Higgs potential is another necessary condition for the internal consistency of the SM

Internal consistency

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No internal inconsistencies so far!

Conceptual 'problems'

- The SM is 'only' an **effective theory**, it doesn't explain everything...
- effective theory means: the SM is valid up to a scale Λ_{UV}
- **Gravity** not included, therefore $\Lambda_{UV} < M_{Pl} \sim 10^{19}$ GeV because at the Planck scale gravity effects have to be included
- Error of predictions at **energy scale E**: $O[(E/\Lambda_{UV})^n]$ where $n = 1,2,3,4,...$ depending on the truncation of the effective theory
- **Renormalisability** is <u>not</u> considered a fundamental principle anymore, non-renormalisable operators of dimension 5,6,... can be included to reduce the theory error
- Systematic approach but <u>involved</u> due to a large number of possible operators (global analysis required)

Higher dimensional ops:

the Standard Model

input: Poincare symmetry

gauge symmetry, group $SU(3) \times SU(2) \times U(1)$: $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$

3 families of matter fields (in fundamental or trivial representation):

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \; q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; e_R, u_R, d_R$$

one scalar doublet φ

output: most general, Lorentz and gauge invariant Lagrangian

we have 1 operator of dim 2, a few (~ 15) of dim 4, 1 of dim 5,
quite a few (~ 60) of dim 6 and many of dim 8 and higher

renormalizability requires (mass) dimension of operators Dim ≤ 4

Note: we must have $[\mathcal{L}] = 4$ since $[\int d^4x\, \mathcal{L}] = 0$

Thus for a dim 6 operator $O^{(6)}$ we have $\mathcal{L} \ni \dfrac{c^{(6)}}{\Lambda_{\rm UV}^2} O^{(6)}$ with $\Lambda_{\rm UV}$ a scale (of BSM physics)

What is Λ_{UV}?

- Despite the phenomenal success of the SM, it is not the theory of everything (if this exists at all)
- The SM is 'only' an effective theory valid up to a scale Λ_{UV}
- What is Λ_{UV}?
  - gravity not part of SM: $\Lambda_{UV} < M_{Pl} \sim 10^{19}$ GeV
  - dark energy not part of SM: $\Lambda_{UV} = ??$
  - dark matter, matter-antimatter asymmetry: $\Lambda_{UV} = ??$
  - strong CP problem: $\Lambda_{UV} \sim 10^{10}$ GeV
  - neutrino masses (seesaw): $\Lambda_{UV} \sim 10^{10} \ldots 10^{15}$ GeV
  - hierarchy problem: $\Lambda_{UV} \sim \Lambda_{EW}$ (new physics at LHC)

Theoretical problems

Theorist's prejudice

- Everything that is not forbidden is allowed (realized in nature)!
  - Not forbidden (by symmetries) but not observed = problem!
- The only 'allowed' numbers are 0, 1, infinity
  (this is nonsense, of course!)
  - 0: forbidden because of symmetry
  - 1: natural number
  - infinity: to be redefined
  - small but non-zero couplings = problem ('unnatural')
  - large finite couplings (>>1) = non-perturbative

Naturalness problems I

- **Hierarchy problem**: Why $M_{ew} << \Lambda_{UV}$?

- **Naturalness problem**: Why $M_h << \Lambda_{UV}$?

  A fundamental scalar is problematic!

  Its mass is not protected from large radiative corrections by any symmetry.

Possible solutions to the naturalness problem

- TeV-scale Supersymmetry
  (a symmetry protecting the scalar)

- TeV-scale Compositeness
  (the scalar is not fundamental)

- Large extra-dimensions at the TeV-scale
  (would also solve the hierarchy problem)

All these solutions require new physics at the LHC!

What if no new physics is found at the LHC?

- Would be a **M A J O R** (theoretical) problem!

- Fine-tuning, anthropic principle, multiverse?
- NEW classes of solutions?: Relaxion solutions, arXiv:1504.07551
- Non-LHC experiments:
  (nEDM, proton decay, lepton flavor violation, neutrinoless double-beta decay, ...)
- New crazy ideas?

Naturalness problems II

- All operators allowed by all symmetries should appear in the Lagrangian; if absent at tree level, these operators are generated at the loop level in any case
- Theorists prejudice: **naturally**, the coefficients of the operators are of O(1) unless there is
  - a (broken) symmetry
  - the operator is loop-suppressed
- **Strong CP problem:**

  There is an allowed term in the QCD Lagrangian (renormalisable, gauge invariant) which violates P,T, CP

  Its coefficient is extremly suppressed (or zero). There is only an upper limit... WHY?

Naturalness problems III

- The spectrum of fermion masses is not natural

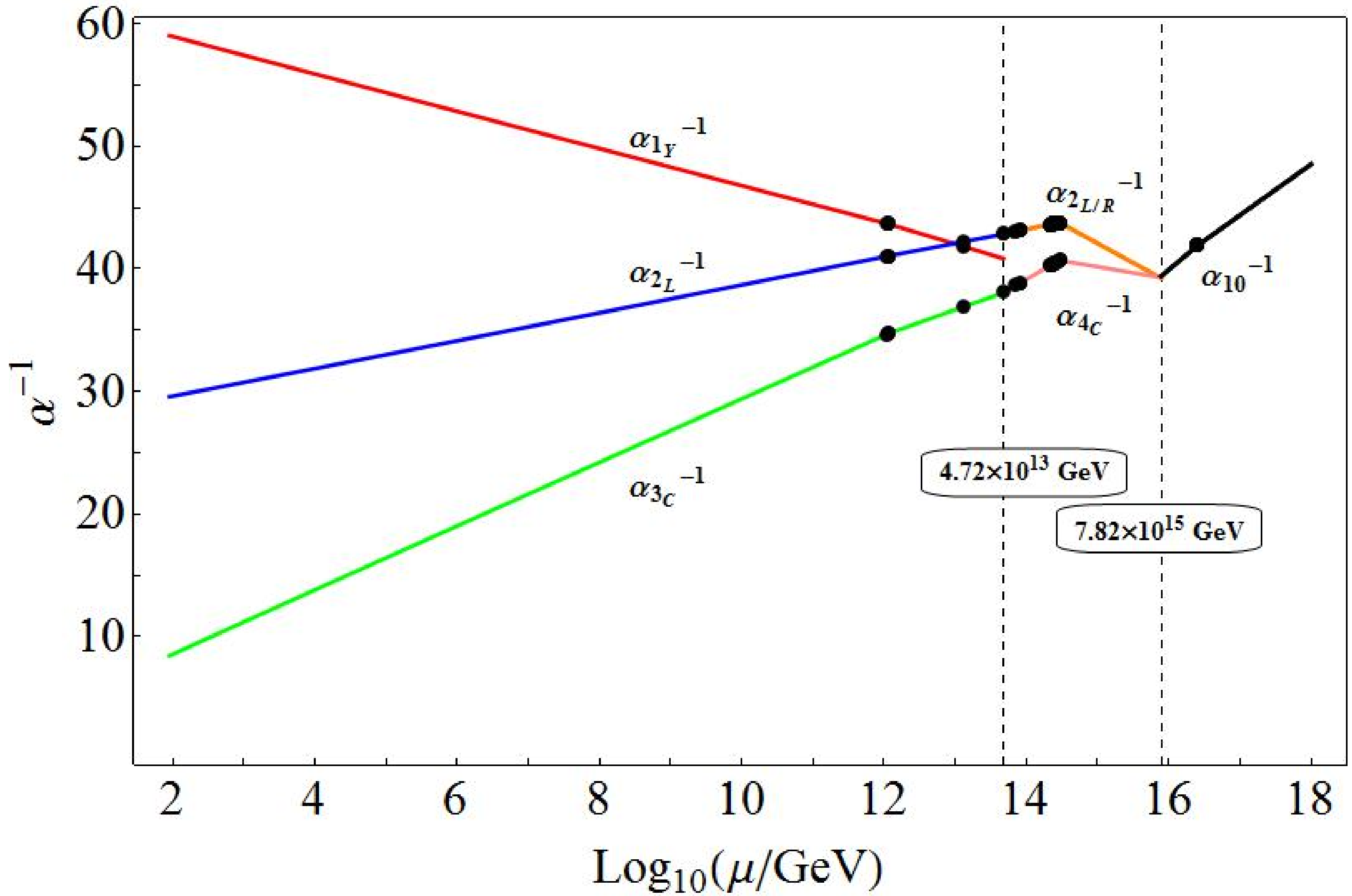
Aesthetics, Symmetry, Religion

Aestethics, Symmetry, Religion

- Gauge symmetry SU(3) x SU(2) x U(1)
  - not a simple group
  - left-right asymmetric (maximal parity violation)
- Matter content in different representations
  - left vs right, quarks vs leptons
- Why three generations? (Why three space dimensions?)
  (“Who ordered that?” I. I. Rabi after muon discovery)
- Wouldn’t it be a revelation to have complete **unification**?
  - one simple gauge group = one interaction
  - one representation for all matter = one matter type/one primary substance

Attractive features of GUTs

K. S. Babu, S. Khan, 1507.06712



- Gauge coupling unification
- Explanation for quantization of electric charges

(Some) GUT group candidates

- G_{SM} = SU(3) x SU(2) x U(1)
  - rank[G_{SM}] = rank[SU(3)] + rank[SU(2)] + rank[U(1)] = 2 +1 + 1 = 4
  - G_{SM} < G, where G is the gauge group of the GUT theory
  - rank[G_{SM}] $\leq$rank[G]
- Rank 4:
  - SU(5) unique rank 4 candidate: $\bar{5} + 10$
  - no ν_R, no B-L symmetry
- Rank 5:
  - SO(10): 16-plet
  - Pati-Salam group G(442) = $SU(4)_c$ x $SU(2)_L$ x SU(2)
- Rank 6:
  - E_6
  - Trinification $[SU(3)]^3$

Breaking patterns and branching rules

- Breaking patterns:
  - $SU(5) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$
  - $SO(10) \rightarrow SU(5) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$
  - $SO(10) \rightarrow G(442) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$
  - $E_6 \rightarrow SO(10) \rightarrow \ldots$
  - There are two aspects:
    - a) What are the subgroups of G with equal or lower rank?
    - b) Which Higgs fields are needed for the symmetry breaking?
- Branching rules:
  How does a multiplet of G split up into multiplets of G_{SM} after symmetry breaking?
  - Example $SU(5) \rightarrow G_{SM}$: $5 \rightarrow (3,1)_{2/5} + (1,2)_{-3/5}$