

Introduction to the Standard Model of particle physics

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V. Beyond the SM

The Beautiful SM

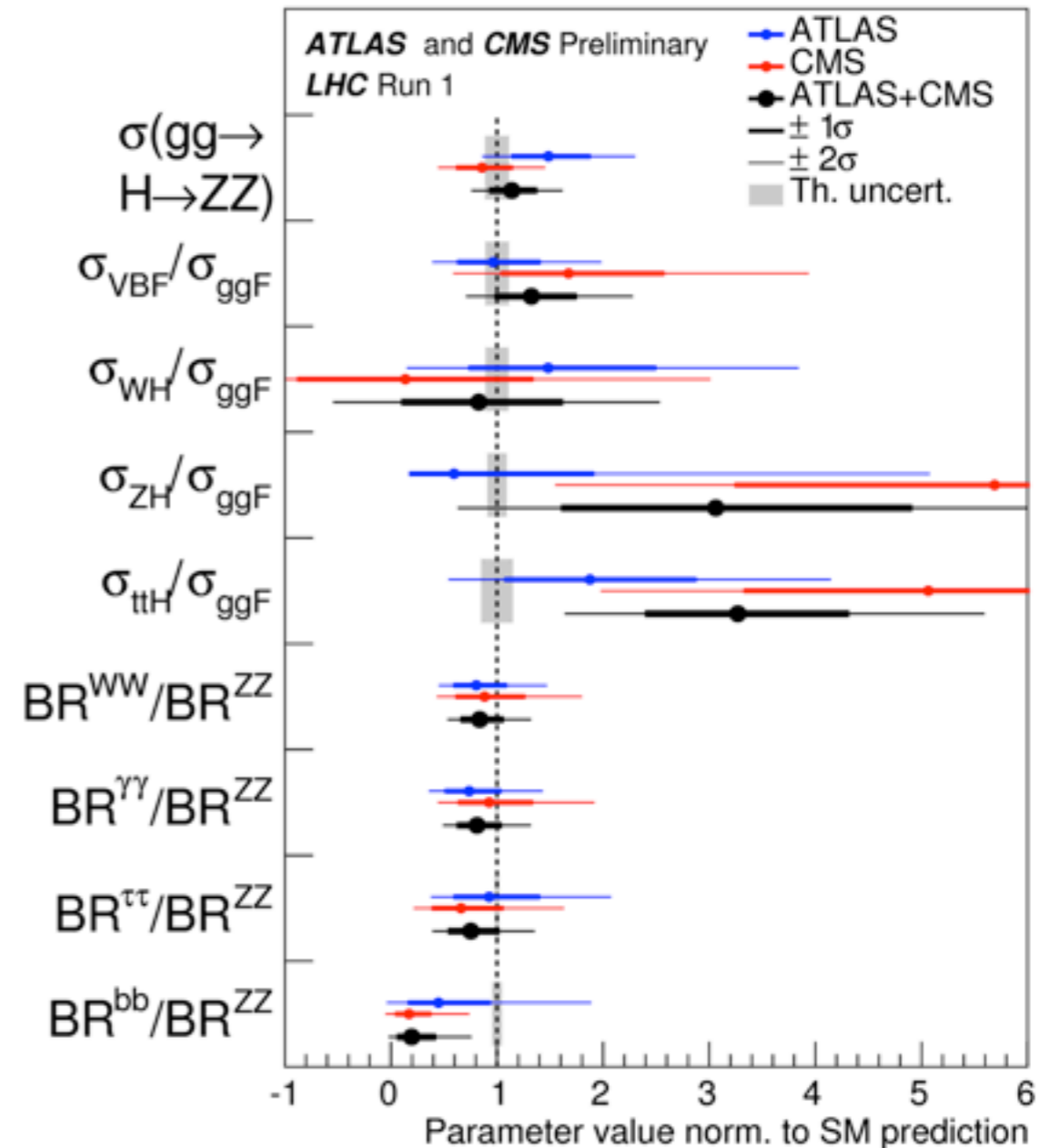
- **QFT = QM + SR**
- **Matter content: 3 generations of**
 - **Quarks** (u,d),(s,c),(b,t)
 - **Leptons** (e, ν_e),(μ , ν_μ),(τ , ν_τ)
- **local gauge symmetry** $SU(3)_c \times SU(2)_L \times U(1)_Y$
 - 8 gluons, W^+ , W^- , Z, Photon
- **Renormalizability**
- **Electroweak symmetry breaking (EWSB)**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

The Higgs boson

- 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

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

[ATLAS-CONF-2015-044]

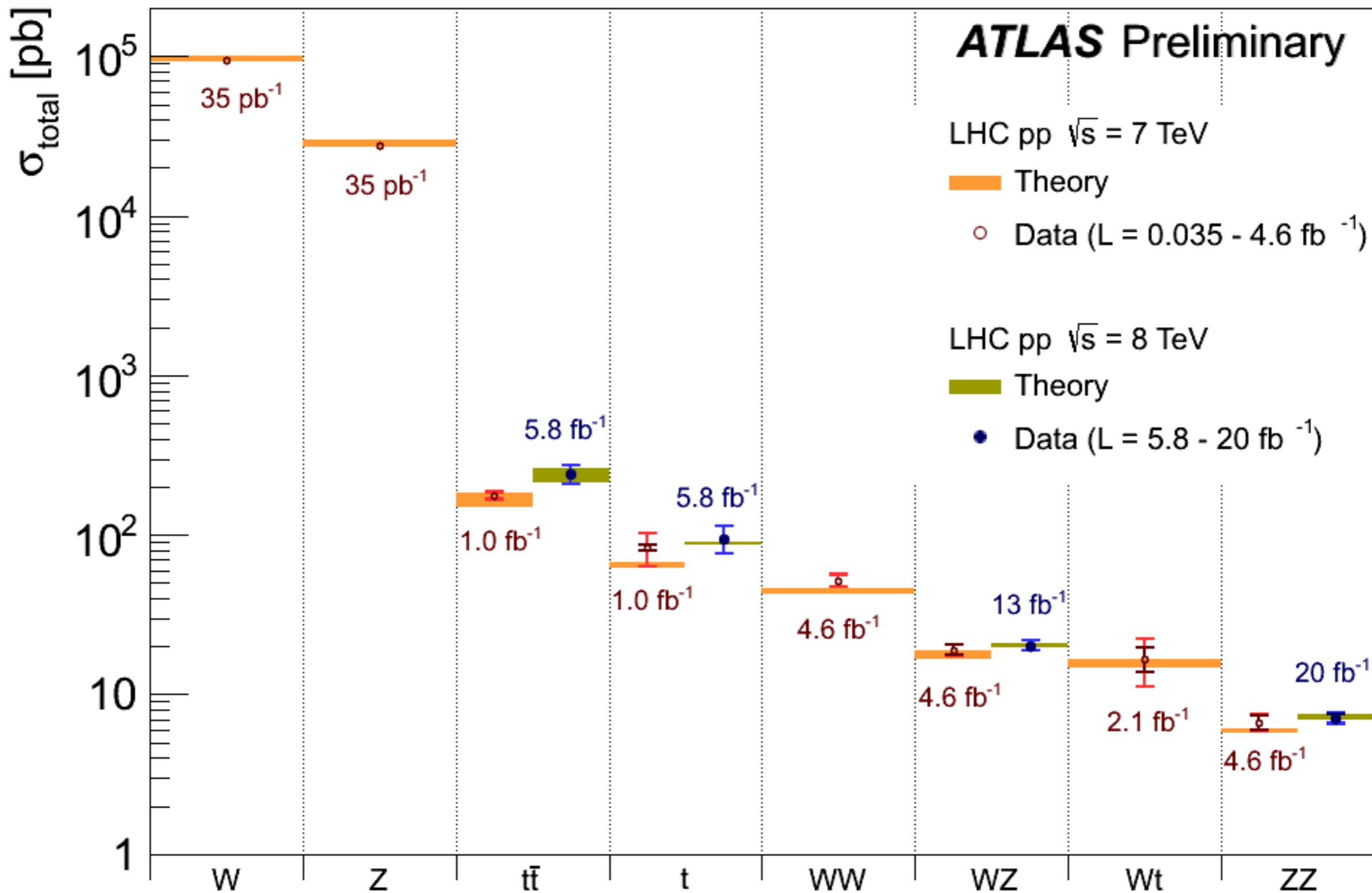


Crucial to test the mechanism of EWSB!

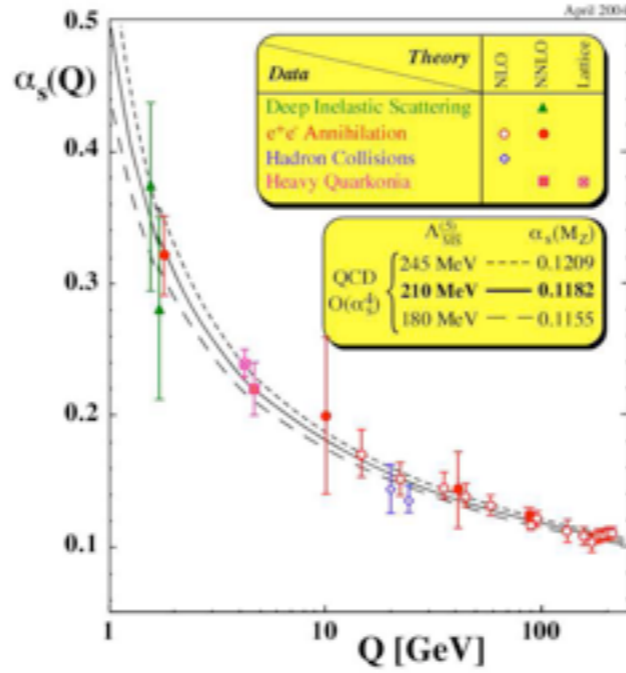
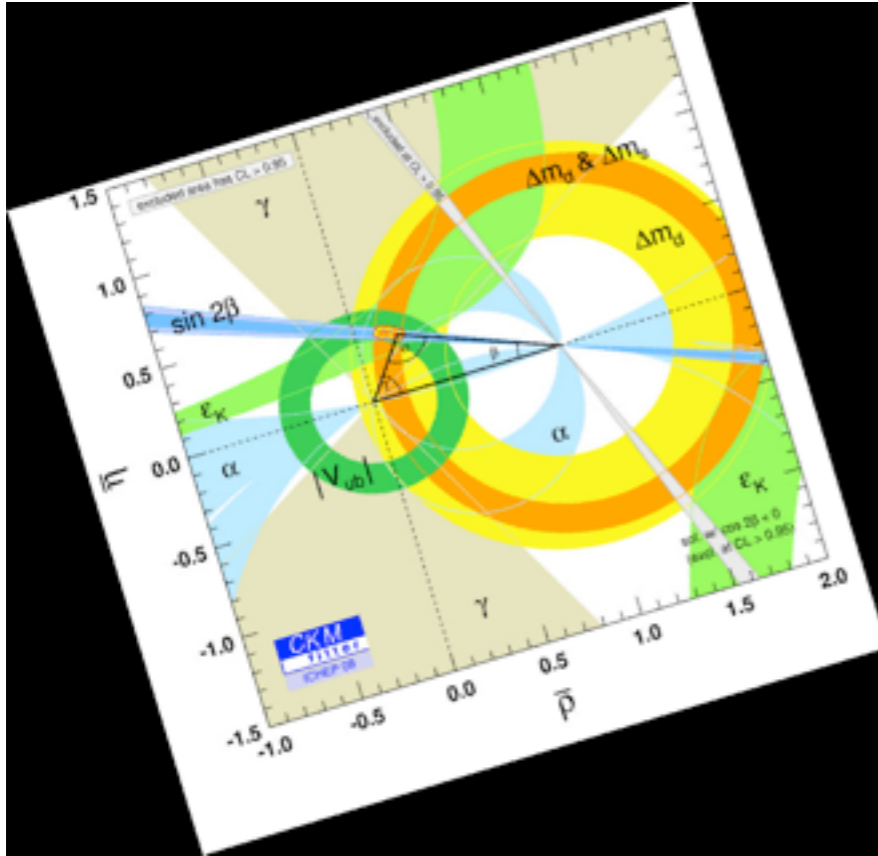
The Successful SM

- **All** the elementary matter particles (quarks, charged leptons, neutrinos) postulated by the SM have been discovered
- **All** the gauge bosons (gluons, W^+ , W^- , Z, photon) predicted by the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry have been discovered
- **A spin-0 particle** compatible with the SM Higgs boson has been discovered
- **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)*



CKM angles

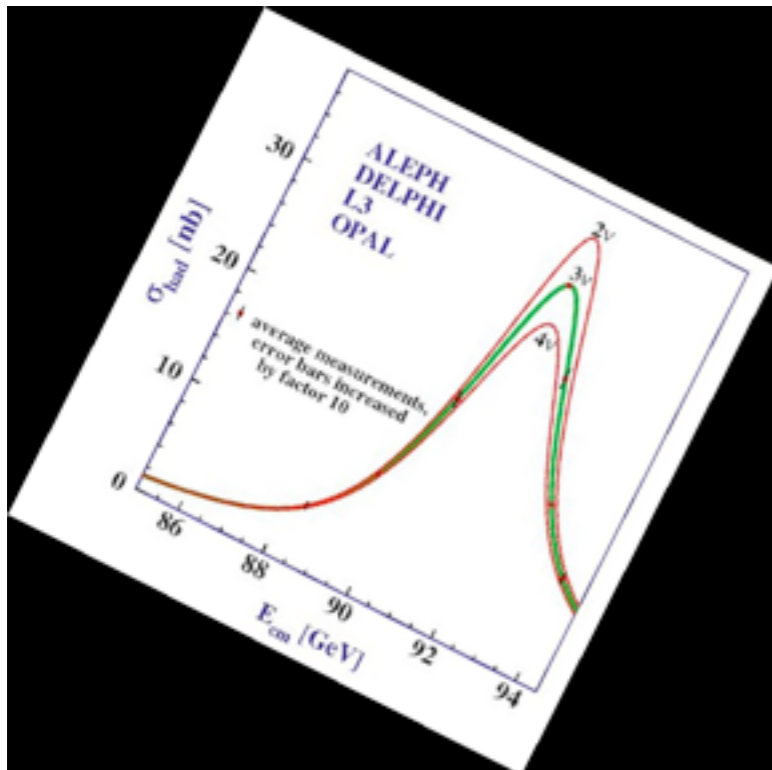


running α_s

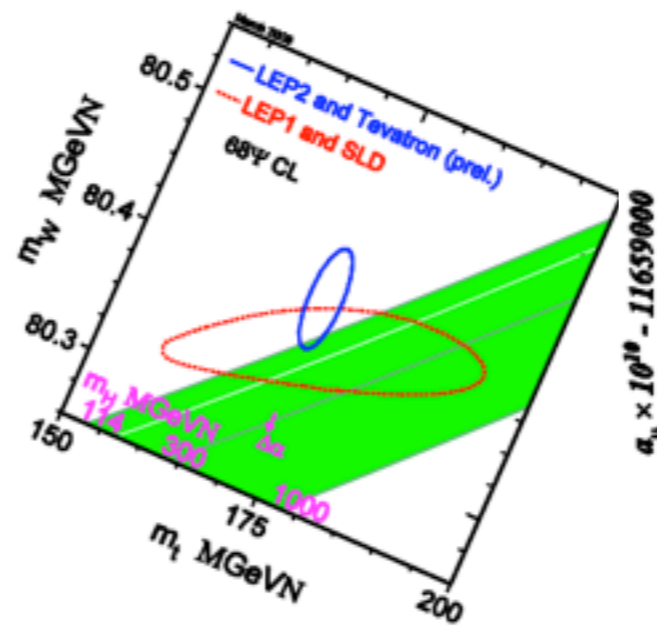
EW parameters

	Measurement	Fit	$10 \frac{\sigma_{meas} - \sigma_{fit}}{\sigma_{meas}}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767	0.3
m_Z [GeV]	91.1875 ± 0.0021	91.1874	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	0.3
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	1.5
R_l	20.767 ± 0.025	20.742	0.1
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643	0.5
$A_l(P_V)$	0.1465 ± 0.0032	0.1480	0.1
R_b	0.21629 ± 0.00066	0.21579	0.1
R_c	0.1721 ± 0.0030	0.1723	0.1
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	2.5
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	0.5
A_b	0.923 ± 0.020	0.935	0.1
A_c	0.670 ± 0.027	0.668	0.1
$A_l(\text{SLD})$	0.1513 ± 0.0021	0.1480	1.5
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	0.5
m_W [GeV]	80.410 ± 0.032	80.377	0.4
Γ_W [GeV]	2.123 ± 0.067	2.092	0.1
m_t [GeV]	172.7 ± 2.9	173.3	0.1

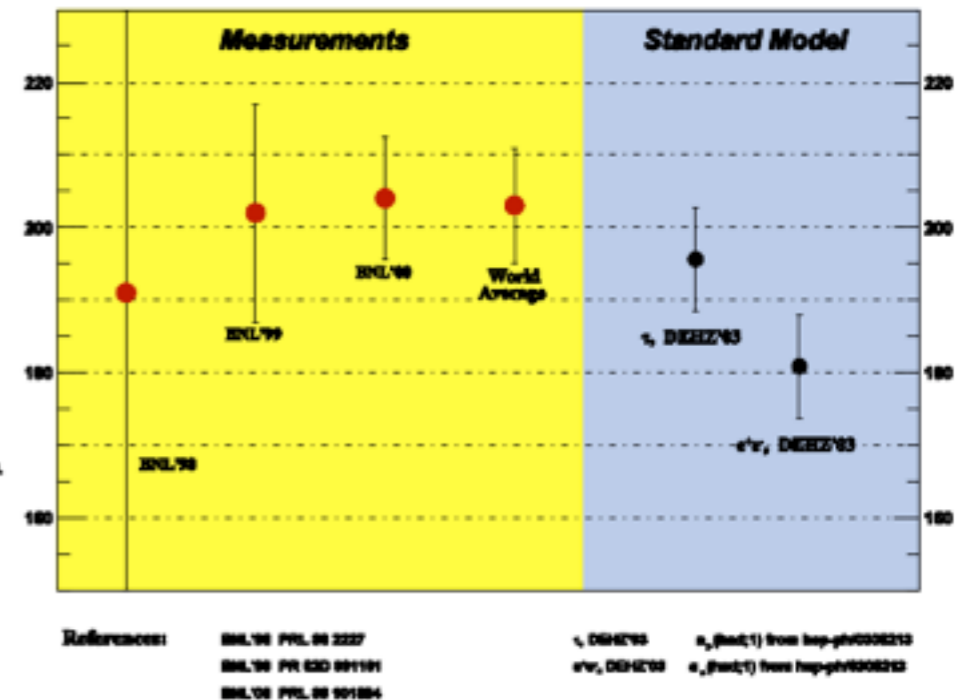
Z⁰ width



top and W mass



anom. magnetic moment (g-2)

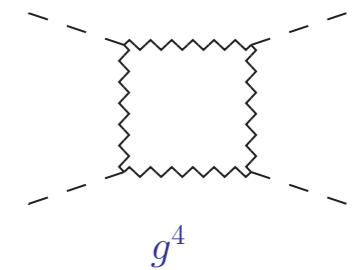
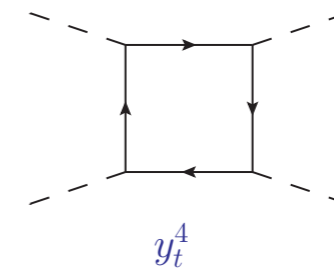
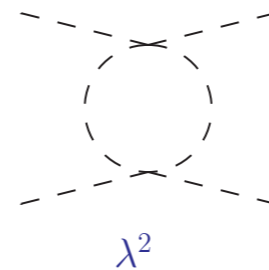
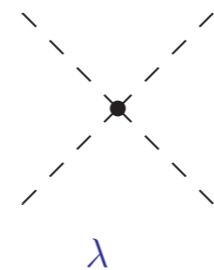


Higgs effective potential

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:

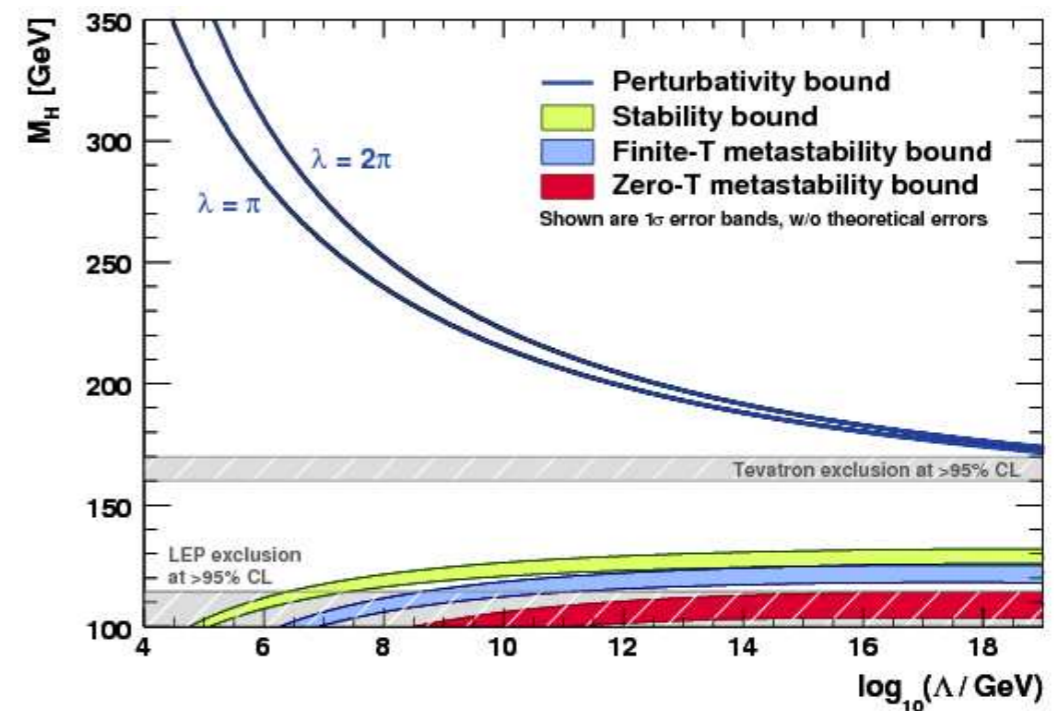
$$\frac{4\pi^2}{3} \frac{d\lambda(t)}{dt} = \lambda^2 - y_t^4 + \dots$$



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

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

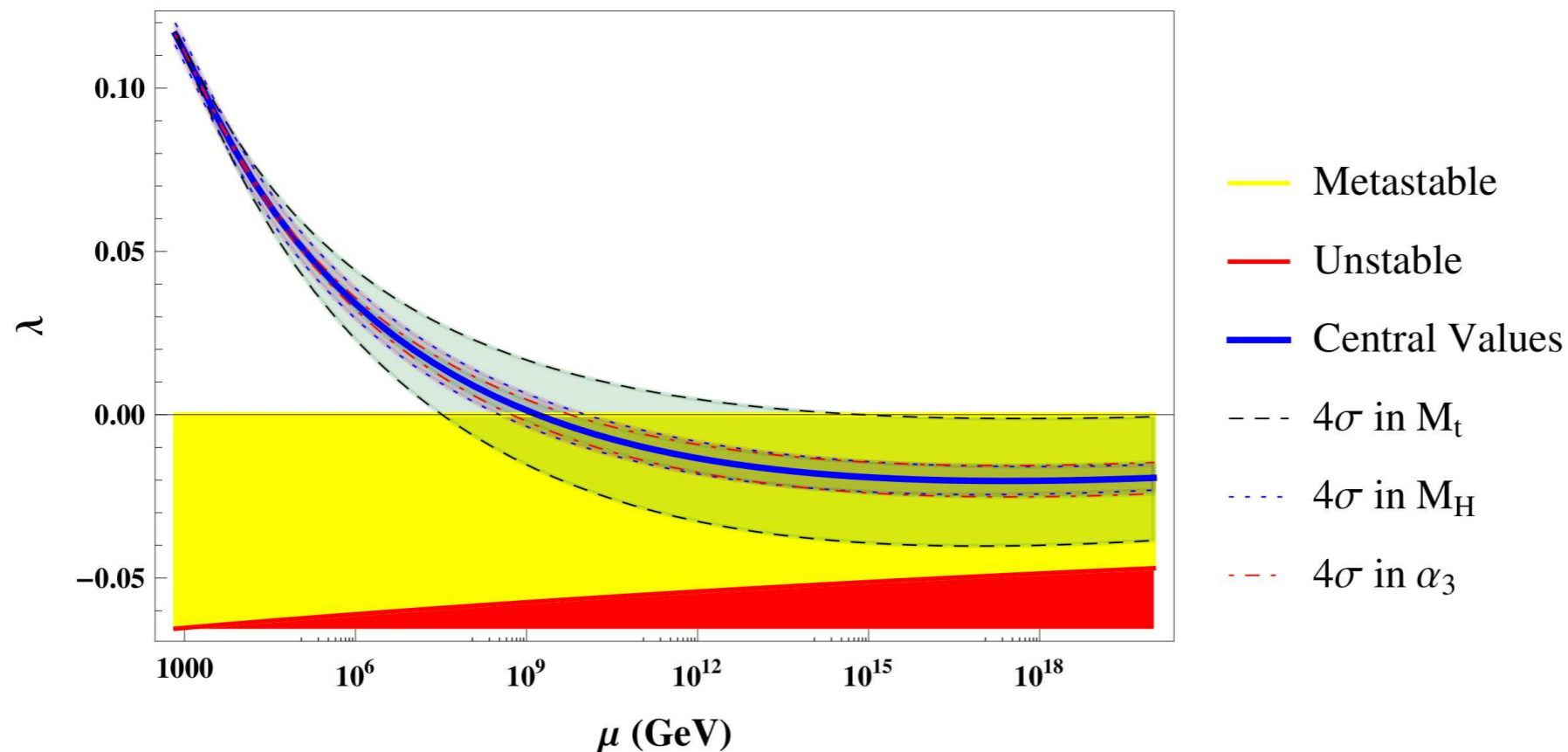
$$\Rightarrow 2\lambda(v)v^2 = M_H^2 < \frac{8\pi^2 v^2}{3 \ln(\Lambda^2/v^2)}$$



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:** $\lambda(\Lambda) = \lambda(Q_0) - \frac{3}{4\pi^2} y_t^4 t \stackrel{!}{>} 0 \implies M_H^2 > \frac{3 v^4 y_t^4}{2\pi^2 v^2} \ln \frac{\Lambda^2}{v^2}$



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

But there are also problems...

Observational problems

- Problems on the ‘earth’
 - 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...
- Problems in the ‘sky’
 - The SM does not provide a candidate for **Dark Matter** (if DM is made of particles)
 - The amount of **CP**-violation in the SM is not sufficient to explain the **matter-antimatter asymmetry** in the universe/ baryon asymmetry of the universe (BAU)

Neutrinos and the Standard Model

- Neutrino oscillations:
 - ▶ at least two massive neutrino states
 - ▶ why should neutrinos be massless anyway? (no symmetry)
- In the **original** SM, neutrinos are massless
 ⇒ oscillation results = physics beyond the SM
- However, massive neutrinos possible by a **minimal** extension of the SM:
 - ▶ right-handed neutrino
 - ▶ gauge singlet (“sterile neutrino”)
 - ▶ can be a **Dirac fermion** like the electron
 - ★ mass term via Yukawa interaction with Higgs boson (Higgs mechanism)
 - ★ neutrino masses of order meV: tiny(!) Yukawa couplings

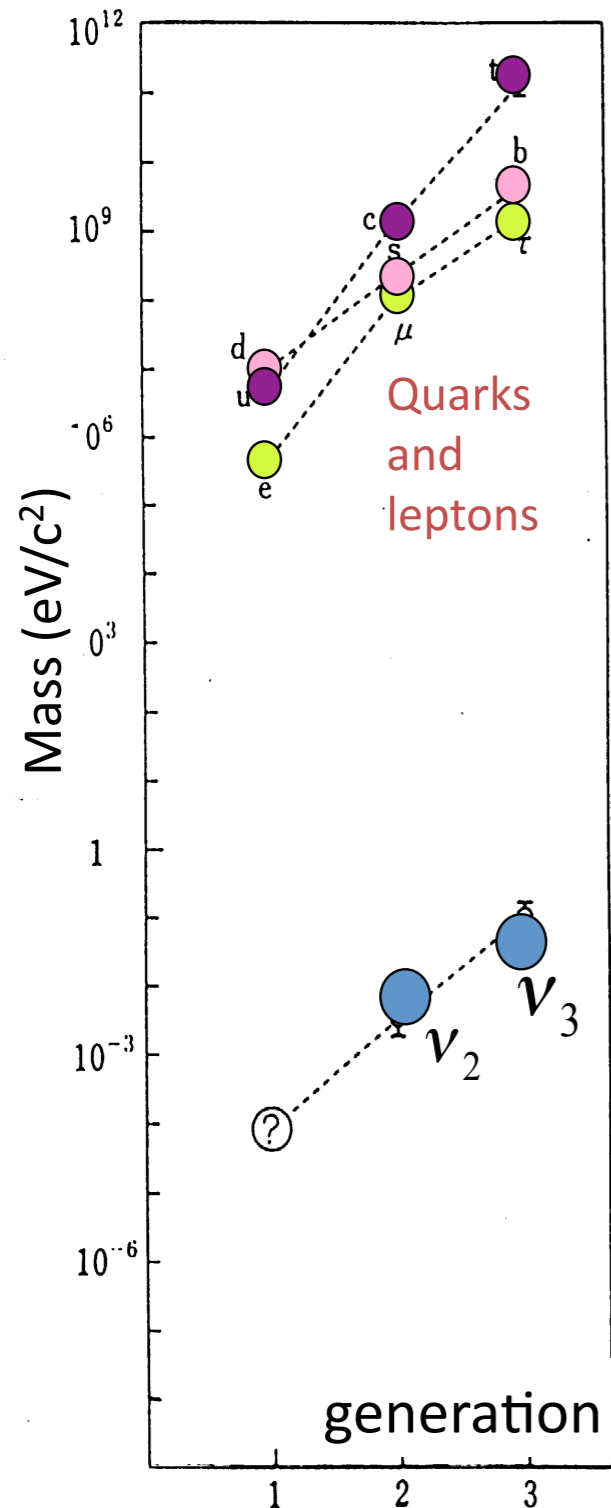
Particles	Spin	SU(3) _C	SU(2) _L	U(1) _Y
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\frac{1}{2}$	3	2	$\frac{1}{3}$
u_R^c	$\frac{1}{2}$	$\bar{\mathbf{3}}$	1	$-\frac{4}{3}$
d_R^c	$\frac{1}{2}$	$\bar{\mathbf{3}}$	1	$\frac{2}{3}$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\frac{1}{2}$	1	2	-1
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

Neutrinos and the Standard Model

- Neutrino oscillations:
 - ▶ at least two massive neutrino states
 - ▶ why should neutrinos be massless anyway? (no symmetry)
- In the **original** SM, neutrinos are massless
 ⇒ oscillation results = physics beyond the SM
- Conversely, neutrino only fermion in the SM without electric charge:
 - ▶ can be its own anti-particle (like γ, Z^0, π^0, η)
 - ▶ it's called **Majorana-Neutrino** (ν^M) if it is its own anti-particle: $\nu^M = (\nu^M)^c$
 - ▶ **non-minimal** extension of the SM:
 - ★ mass term in \mathcal{L} can be a **gauge singlet**
 ⇒ heavy mass term possible
 [not related to the Higgs mechanism]
 - ★ seesaw mechanism can explain tiny masses

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Neutrinos and the Standard Model



Why the neutrino mass is so small ?

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

See-saw mechanism

Minkowsky, Yanagida,
Gell-mann, Ramond, Slansky

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

If we input m_{ν_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 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

$$SU(3)_c \times SU(2)_L \times U(1)_Y \stackrel{?}{\subset} SU(5) \stackrel{?}{\subset} SO(10) \stackrel{?}{\subset} E_6 \stackrel{?}{\subset} E_8$$

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

(iii) Structure of family multiplets

$$\begin{array}{cccccc}
 (3,2)_{1/3} & + & (\bar{3},1)_{-4/3} & + & (1,1)_{-2} & + & (\bar{3},1)_{2/3} & + & (1,2)_{-1} & + & (1,1)_0 & \stackrel{?}{=} & 16 \\
 Q & & \bar{u} & & \bar{e} & & \bar{d} & & L & & \bar{\nu} & &
 \end{array}$$

Particles	Spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
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Fits nicely into the 16-plet of $SO(10)$

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 $\Lambda_{UV} < M_{Pl} \sim 10^{19} \text{ GeV}$ because at the Planck scale gravity effects have to be included
- Error of predictions at **energy scale E**: $O[(E/\Lambda_{UV})^n]$ where $n = 1, 2, 3, 4, \dots$ depending on the truncation of the effective theory
- **Renormalisability** is not considered a fundamental principle anymore, non-renormalisable operators of dimension 5, 6, ... can be included to reduce the theory error
- Systematic approach but involved 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 $\text{Dim} \leq 4$

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

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

Philosophy corner:

- Do you think there exists something like a fundamental theory of everything?
(free of input parameters, explaining everything)
- Or is any theory “effective” valid in a given energy range?
- The principle of renormalisability was very predictive and successful. Maybe there is more to it? Or is this just an accident?
- Reminder: number of parameters and predictivity

No matter how you define what a physical theory is. It has to be something making **predictions** for **observables**!

Conceptual ‘problems’

- Any effective theory has **input parameters** which are **not explained** by it.
- To explain the input parameters one would need a more ‘fundamental/microscopic’ theory from which to derive the effective theory
- The SM has **19 input parameters/26 with massive neutrinos** (make a list!)
 - The masses of the SM fermions cover roughly **11(!) orders of magnitude**
 - The **mixing of quarks** is quite different from the **mixing of leptons**
 - This **bizarre** pattern of mass and mixing input parameters is called the **‘flavor puzzle’**.

It is not a problem (an effective theory doesn’t say anything about the input) but it is nevertheless a puzzle...

Just to illustrate how bizarre the spectrum of the SM fermion masses is

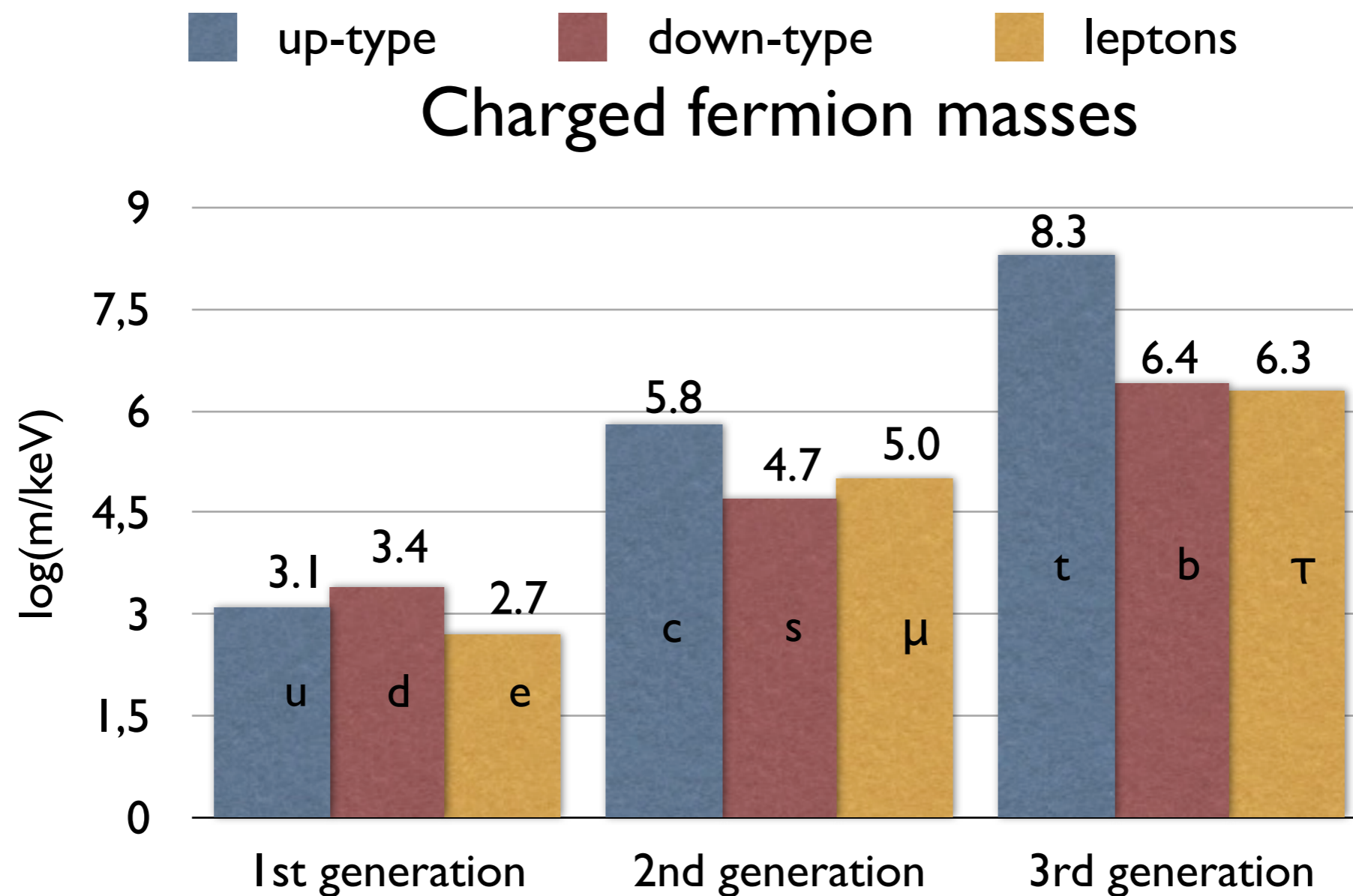
and

how different the mixing in the quark and lepton sector is

a few slides on the so called 'flavor puzzle'

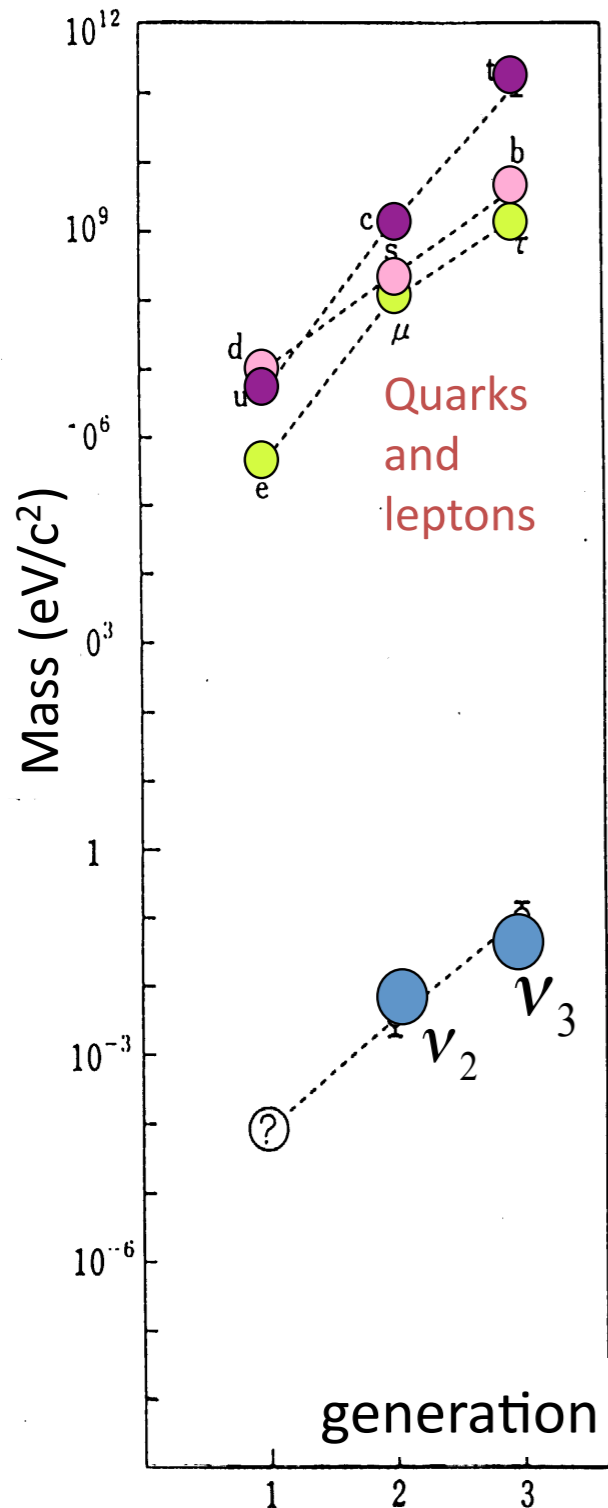
The Flavor Puzzle

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 ?

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

See-saw mechanism

Minkowsky, Yanagida, Gell-mann, Ramond, Slansky

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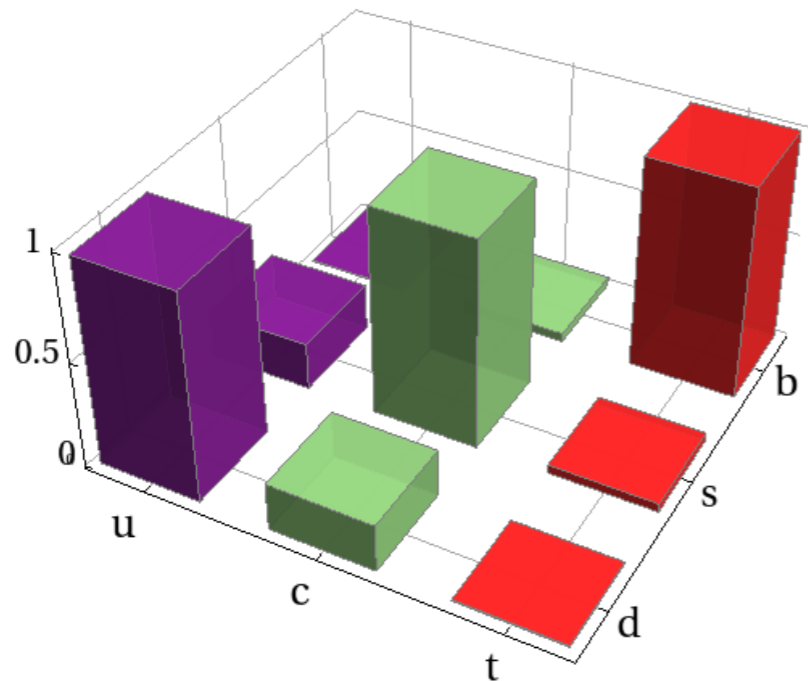
This suggests that physics of neutrino mass could be related to physics of Grand Unification!

The Flavor Puzzle

Quark and Lepton mixing parameters are quite different!

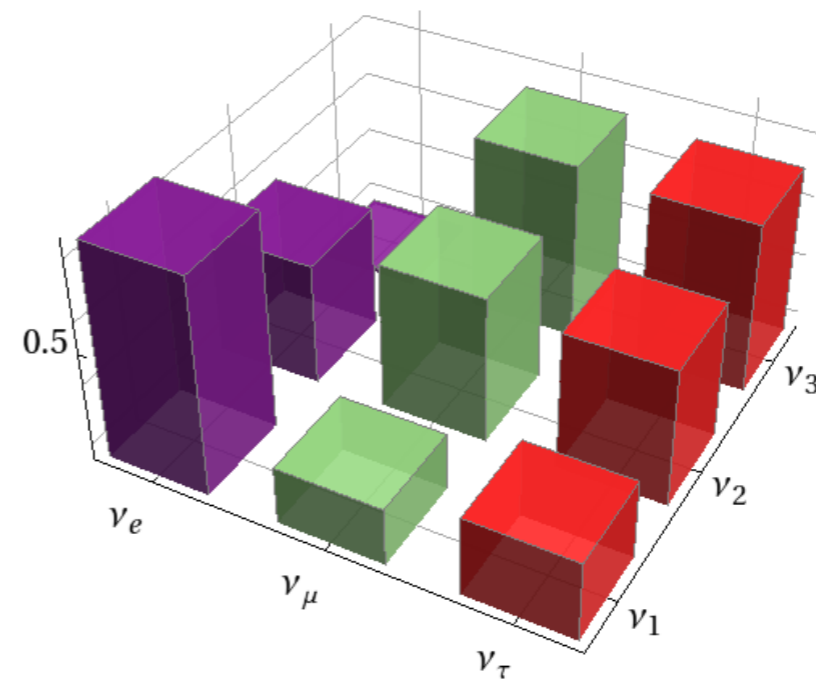
- **Quark Mixings**

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



- **Leptonic Mixings**

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



The Flavor Puzzle

Attempts to explain the flavor puzzle:

- Unified symmetries

$SU(5)$, $SO(10)$, E_6 , Pati-Salam symmetry, Left-right symmetry, $[SU(3)]^3$, ...

- Flavor symmetries

Frogatt–Nielsen mechanism, Anomalous $U(1)$, discrete Abelian or non-Abelian symmetries, continuous gauge symmetries, ..

- Radiative generation of fermion masses

Georgi, Glashow (1973), Barr, Zee (1977); Zee (1980), Balakrishna, Kagan, Mohapatra (1987), Babu, Mohapatra (1990), Ma (1990), Nilles, Olechowski, Pokorski (1990), He, Volkas, Wu (1990), Dobrescu, Fox (2008), Kowanacki, Ma (2016), ...

- Extra dimensional geography

Arkani-Hamed, Schmaltz (2000), Agashe, Okui, Sundrum (2009), ...

Conceptual 'problems'

- Electroweak Symmetry Breaking (EWSB)

- SM Higgs mechanism 'ad hoc'
- Hierarchy problem: Why $M_{ew} \ll \Lambda_{UV}$?
- Naturalness problem: Why $M_h \ll \Lambda_{UV}$?

A **fundamental** scalar is problematic! Its mass is not protected from large radiative corrections by any symmetry.

- Possible solutions

- Fine-tuning, anthropic principle, multiverse
- A symmetry protecting the scalar: Supersymmetry at the TeV-scale
- The scalar is not fundamental: Compositeness at the TeV-scale
- Large extra-dimensions at the TeV-scale
- **NEW** class: Relaxion solutions, [arXiv:1504.07551](#)

Conceptual 'problems'

- 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 extremely suppressed (or zero). There is only an upper limit... WHY?

What is Λ_{UV} ?

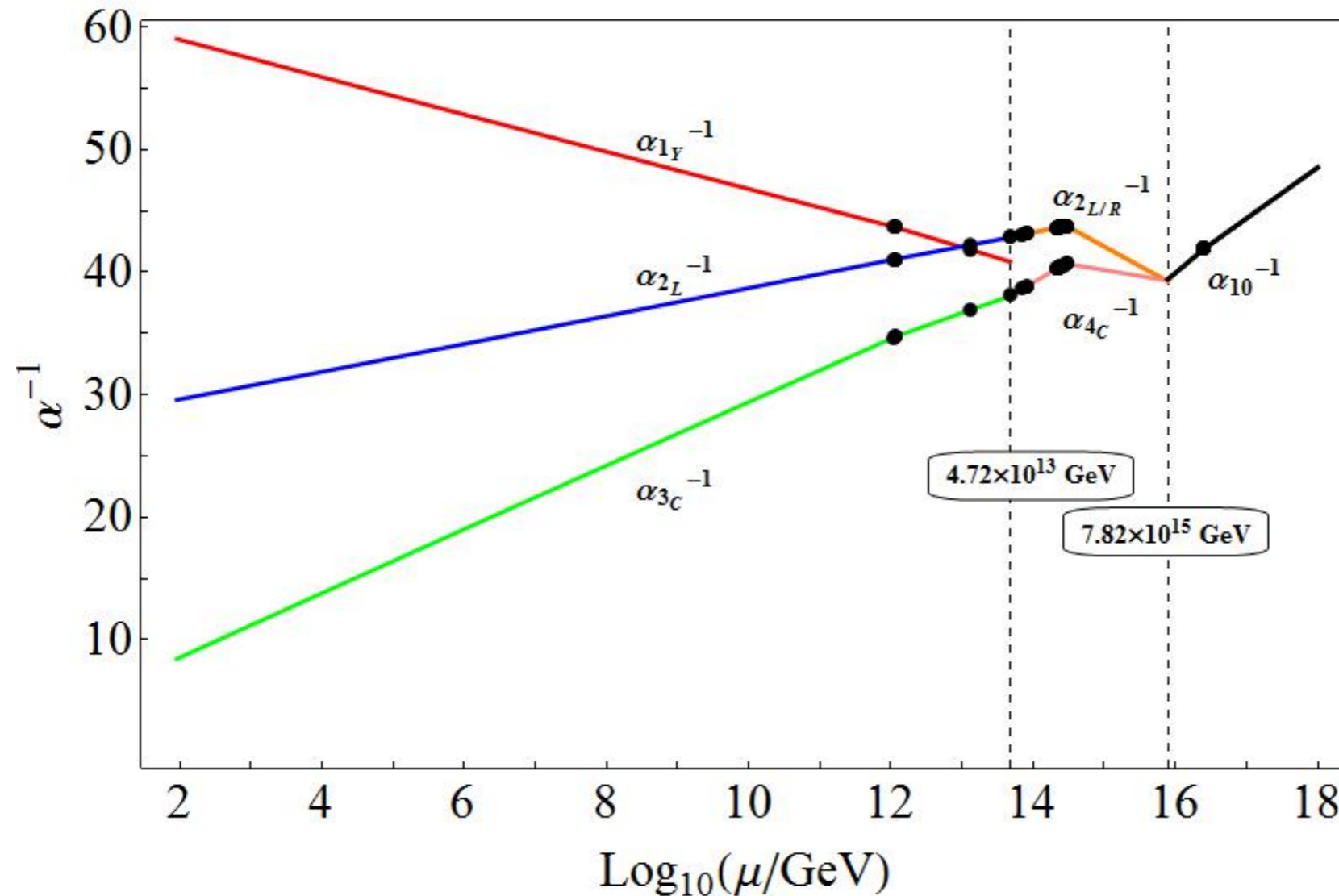
- Despite the phenomenal success of the SM, it is not the theory of everything (if this exists at all)
- The SM is ‘only’ an effective theory valid up to a scale Λ_{UV}
- What is Λ_{UV} ?
 - gravity not part of SM: $\Lambda_{UV} < M_{Pl} \sim 10^{19}$ GeV
 - dark energy not part of SM: $\Lambda_{UV}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

Aesthetics, Symmetry, Religion

- Gauge symmetry $SU(3) \times SU(2) \times U(1)$
 - 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 has ordered this?” 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, I507.06712



- Gauge coupling unification
- Explanation for quantization of electric charges

(Some) GUT group candidates

- $G_{SM} = SU(3) \times SU(2) \times U(1)$
 - $\text{rank}[G_{SM}] = \text{rank}[SU(3)] + \text{rank}[SU(2)] + \text{rank}[U(1)] = 2 + 1 + 1 = 4$
 - $G_{SM} < G$, where G is the gauge group of the GUT theory
 - $\text{rank}[G_{SM}] \leq \text{rank}[G]$
- 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 $G(442) = SU(4)_c \times SU(2)_L \times SU(2)$
- Rank 6:
 - E_6
 - Trinification $[SU(3)]^3$

Breaking patterns and branching rules

- **Breaking patterns:**

- $SU(5) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$

- $SO(10) \rightarrow SU(5) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$

- $SO(10) \rightarrow G(442) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$

- $E_6 \rightarrow SO(10) \rightarrow \dots$

- 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 $SU(5) \rightarrow G_{SM} : 5 \rightarrow (3, 1)_{2/5} + (1, 2)_{-3/5}$