# (B)SM and the LHC

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# V. Beyond the SM

# The Beautiful SM

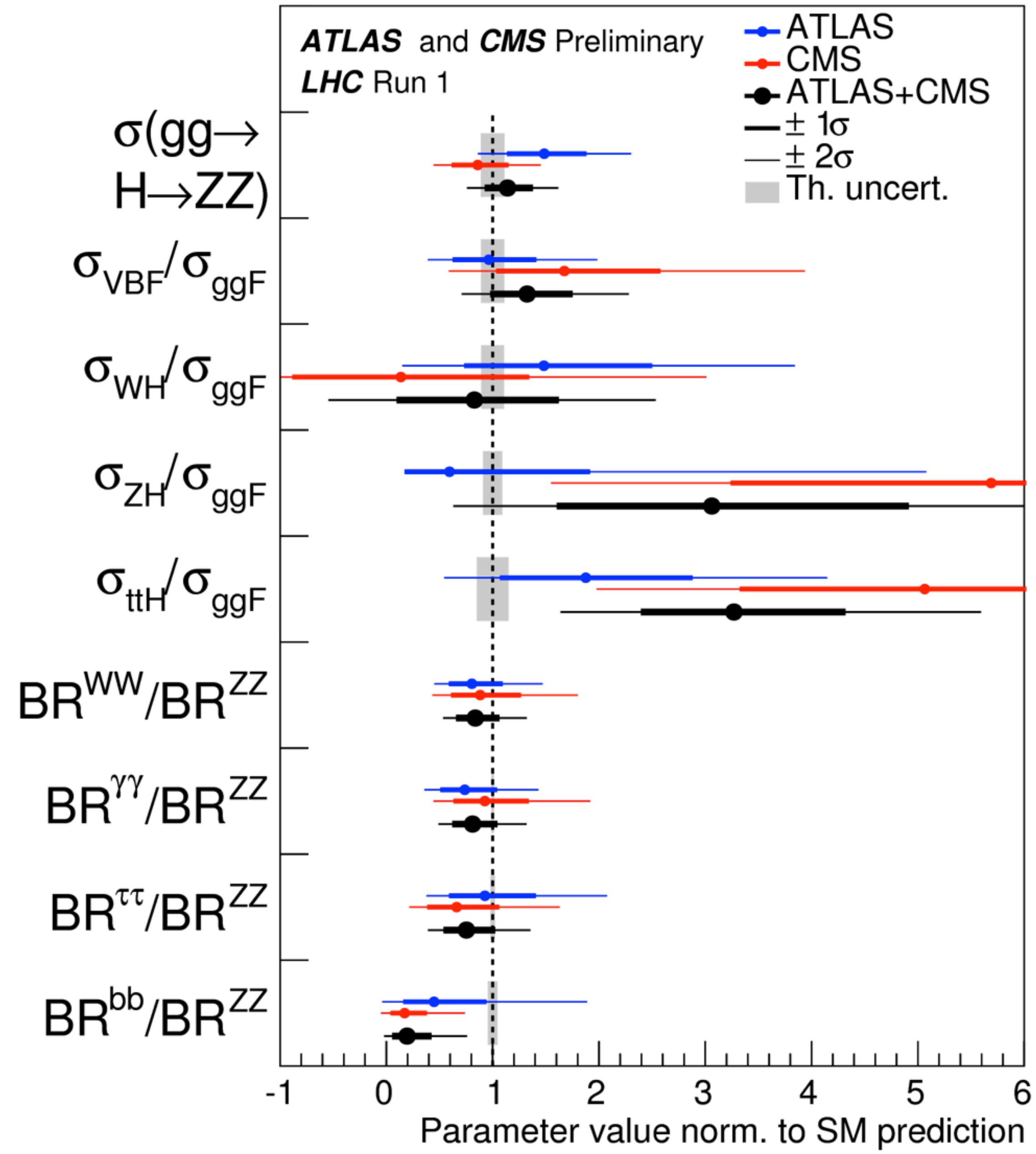
- **QFT = QM + SR**
- **Matter content: 3 generations of**
  - Quarks (u,d),(s,c),(b,t)
  - Leptons $(e,\nu_e),(\mu,\nu_\mu),(\tau,\nu_\tau)$
- **local gauge symmetry** $SU(3)_c \times SU(2)_L \times U(1)_Y$
  - 8 gluons, $W^+$, $W^-$, Z, Photon
- **Renormalizability**
- **Electroweak symmetry breaking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

# The Higgs boson

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

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

[ATLAS-CONF-2015-044]

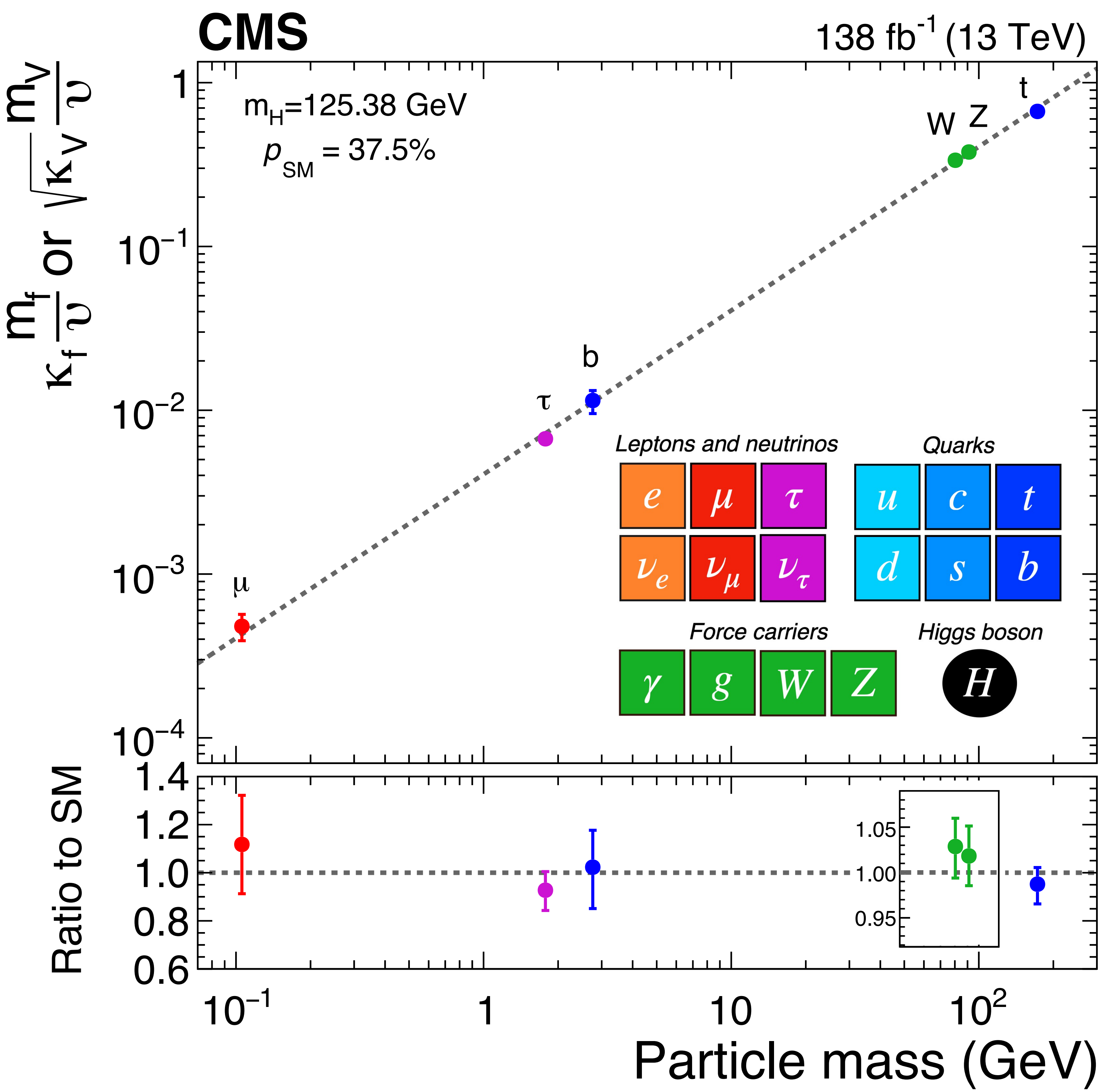



- All results are coherent with the expectations of the SM:
  - Spin = 0 [PLB726(2013)120]
  - P=+1, C=+1, CP = +1 [PRD92(2015)012004]
  - Couplings to the vector bosons (Z,W,γ,g) and to the fermions (t,b,τ) in agreement at ~30% precision

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

Crucial to test the mecanism of EWSB!

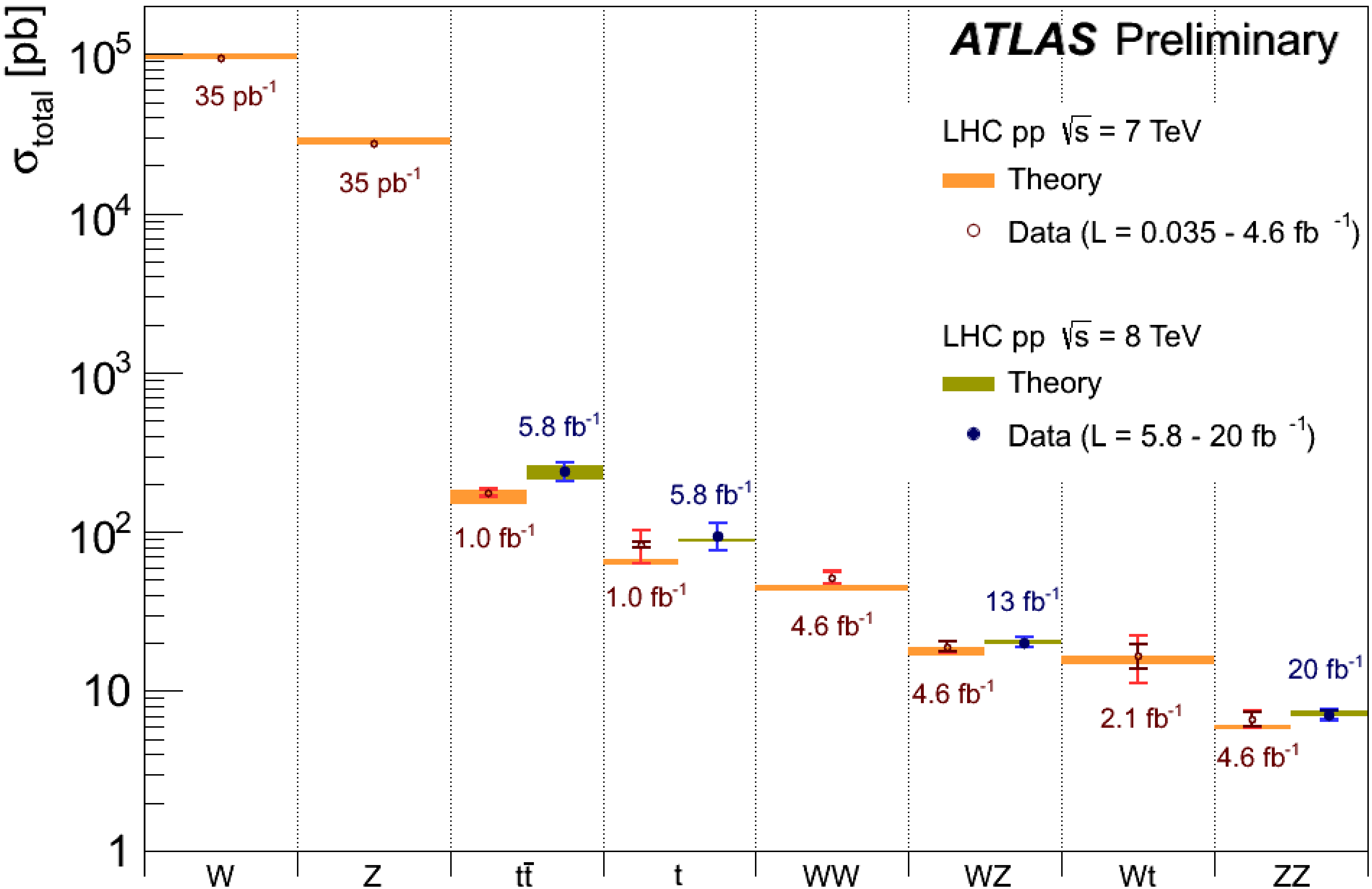
# The Higgs boson: 10 years after discovery



# The Succesful 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)*



ATLAS Preliminary
LHC pp √s = 7 TeV
Theory
Data (L = 0.035 - 4.6 fb -1)
LHC pp √s = 8 TeV
Theory
Data (L = 5.8 - 20 fb -1)
σtotal [pb]
10^5
10^4
10^3
10^2
10
1
35 pb-1
35 pb-1
5.8 fb-1
1.0 fb-1
5.8 fb-1
1.0 fb-1
4.6 fb-1
13 fb-1
4.6 fb-1
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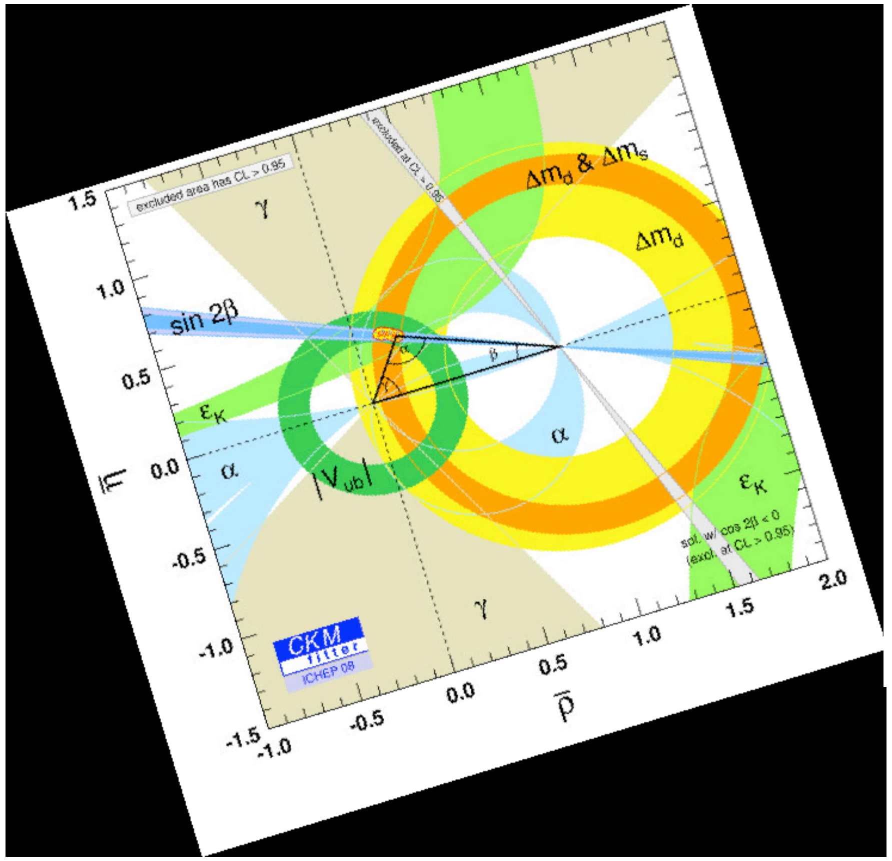
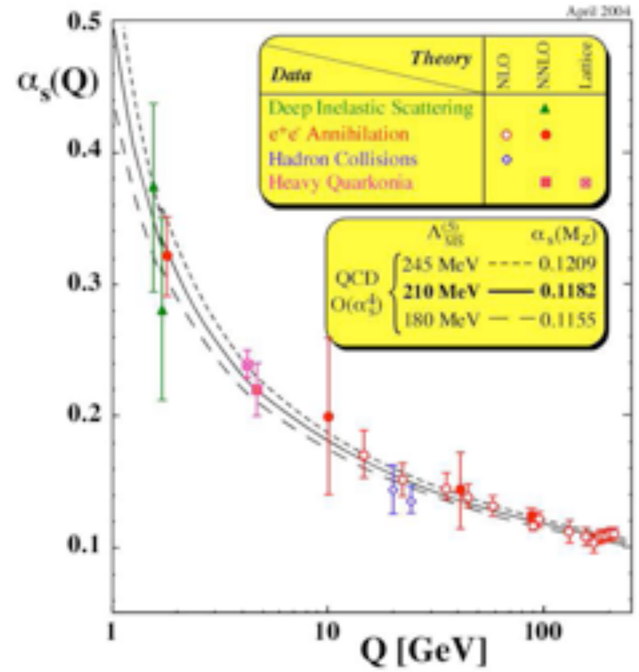
20 fb-1
4.6 fb-1
W
Z
tt̄
t
WW
WZ
Wt
ZZ

CKM angles

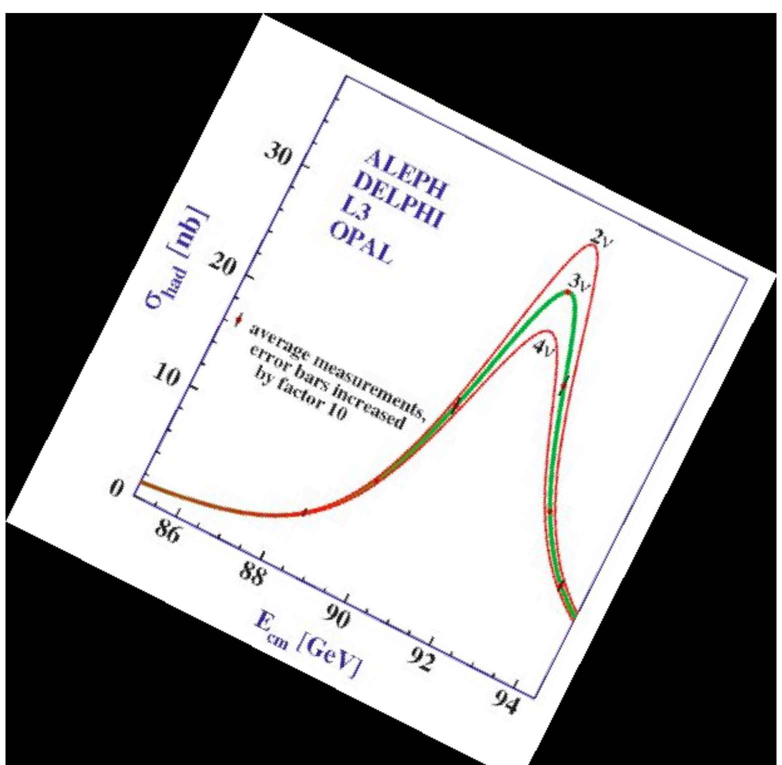


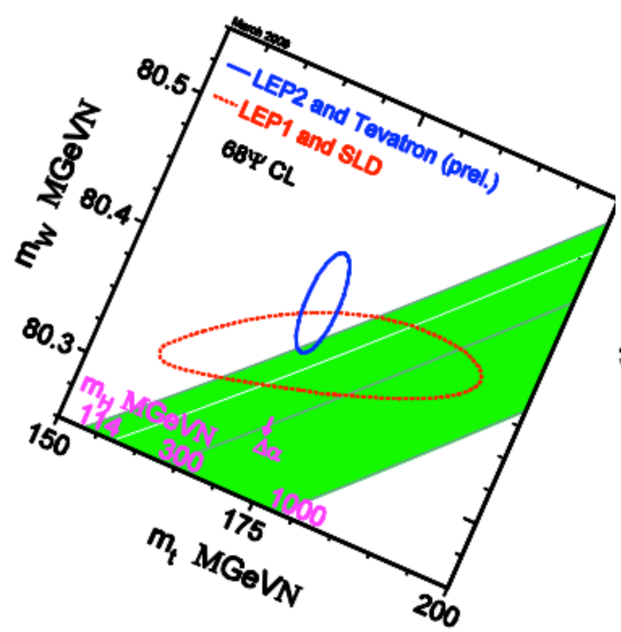

running $\alpha_s$

EW parameters

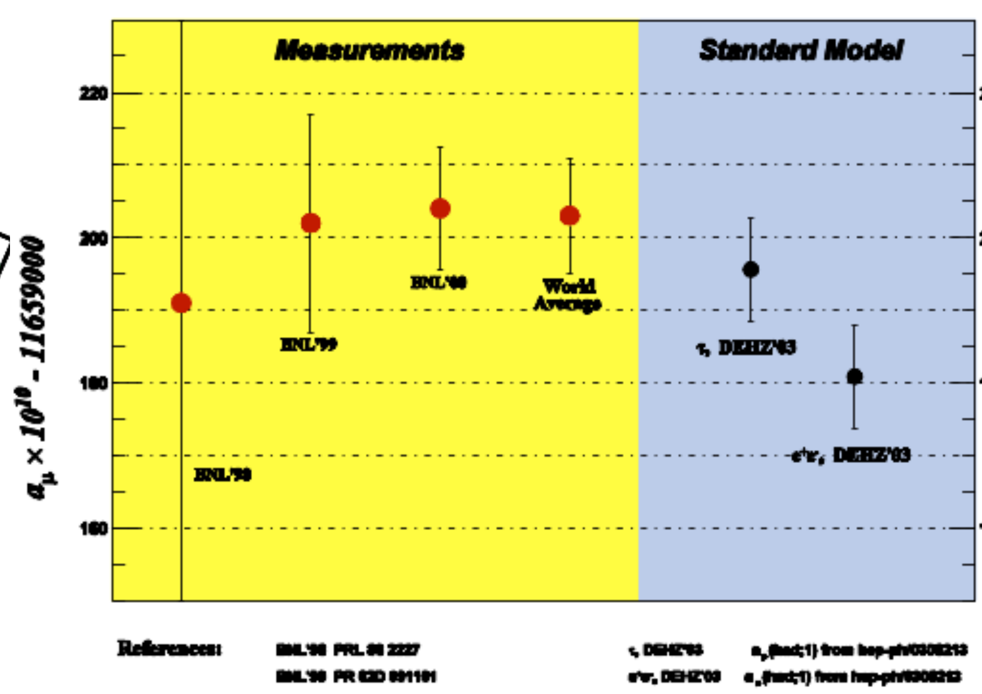

$Z^0$ width




top and W mass




anom. magnetic moment (g-2)

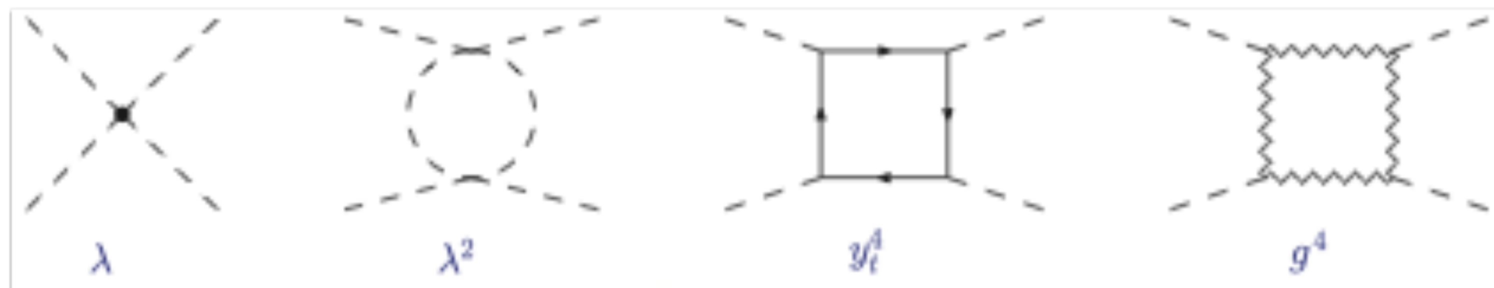


# Higgs effective potential

## 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:

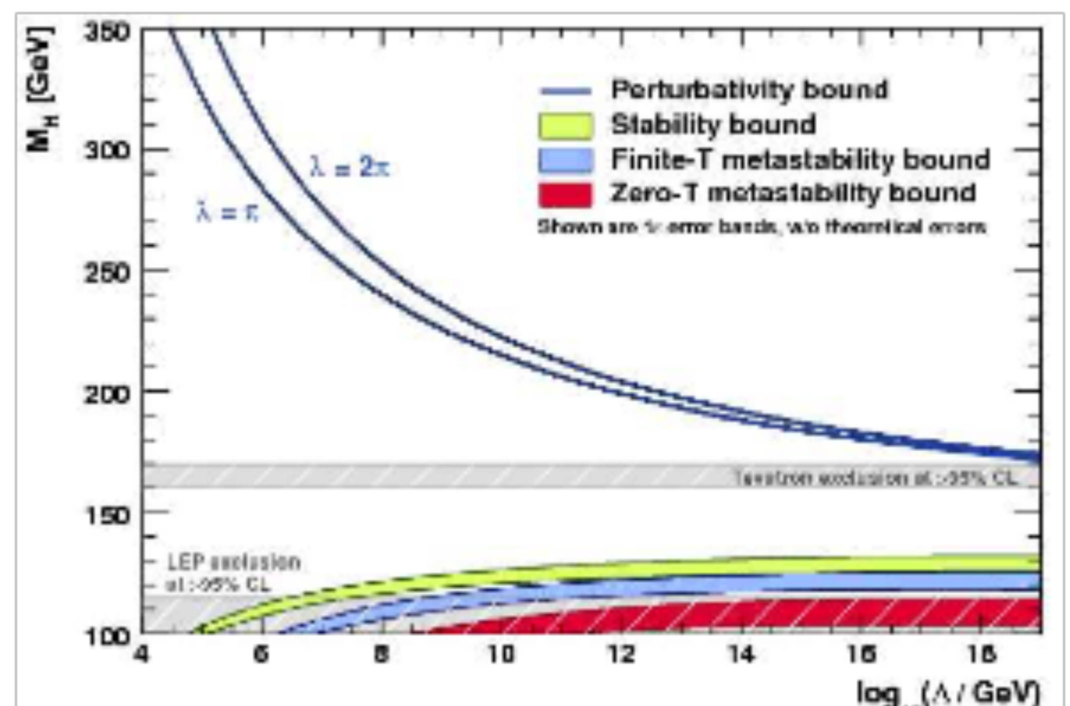
$$\frac{4\pi^2}{3}\frac{d\lambda(t)}{dt} = \lambda^2 - y_t^4 + \dots$$




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

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

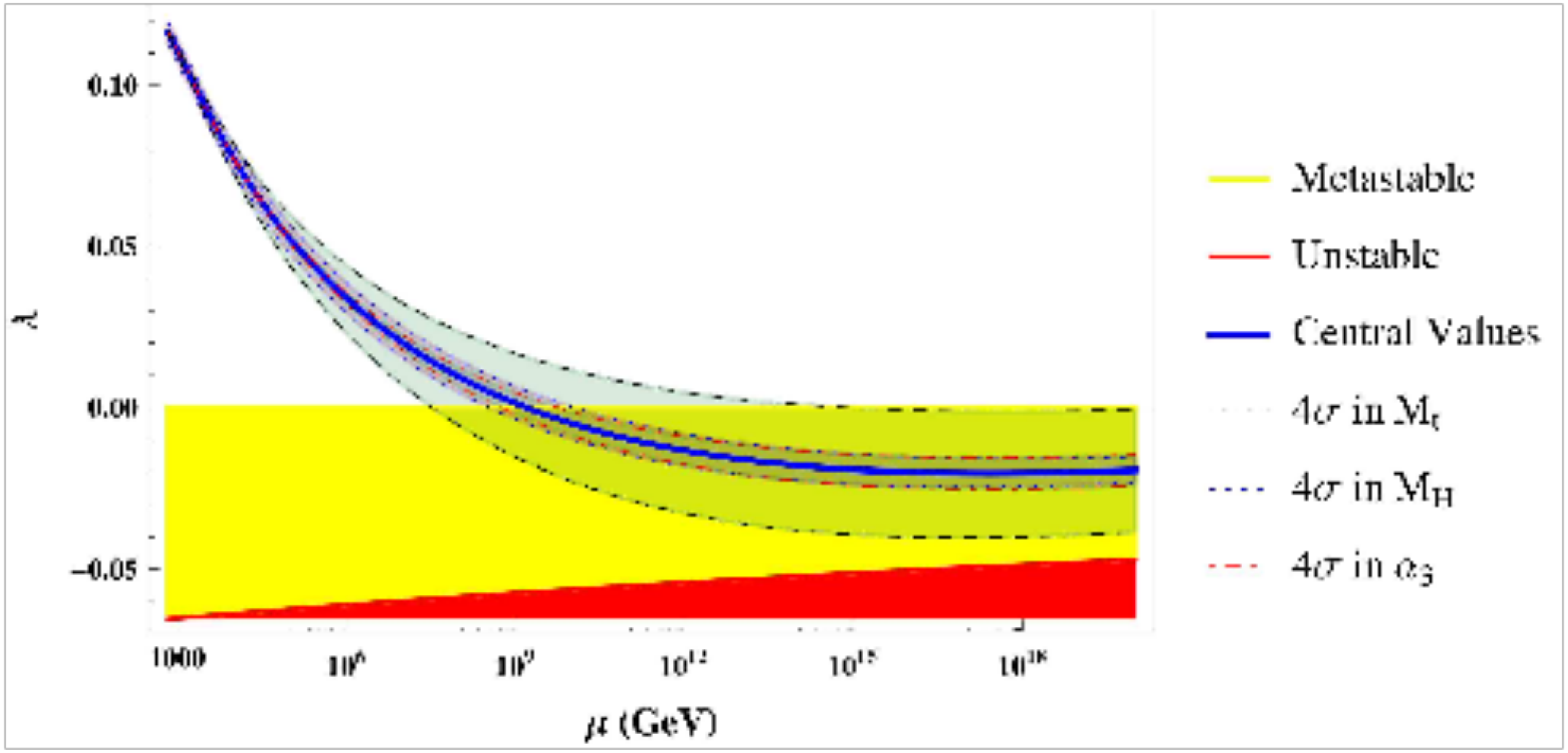
$$\Longrightarrow 2\lambda(v)v^2 = M_H^2 < \frac{8\pi^2 v^2}{3\ln(\Lambda^2/v^2)}$$



# 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: $\lambda(\Lambda) = \lambda(Q_0) - \frac{3}{4\pi^2} y_t^4\, t \overset{!}{>} 0 \quad \Longrightarrow \quad M_H^2 > \frac{3\, v^4\, y_t^4}{2\pi^2 v^2} \ln \frac{\Lambda^2}{v^2}$




- 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…**

# 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…
  - There are **b-flavor anomalies** and **tensions** in the anomalous magnetic moment of the muon (D. Guadagnoli's lecture)
- 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
  $\Rightarrow$ 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 | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ |
|---|---|---|---|---|
| $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ | $\frac{1}{2}$ | $\mathbf{3}$ | $\mathbf{2}$ | $\frac{1}{3}$ |
| $u_R^c$ | $\frac{1}{2}$ | $\bar{\mathbf{3}}$ | $\mathbf{1}$ | $-\frac{4}{3}$ |
| $d_R^c$ | $\frac{1}{2}$ | $\bar{\mathbf{3}}$ | $\mathbf{1}$ | $\frac{2}{3}$ |
| $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\frac{1}{2}$ | $\mathbf{1}$ | $\mathbf{2}$ | -1 |
| $\nu_R^c$ | $\frac{1}{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | 0 |
| $e_R^c$ | $\frac{1}{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | 2 |
| $H = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$ | 0 | $\mathbf{1}$ | $\mathbf{2}$ | 1 |
| $G_\mu^\alpha$ | 1 | $\mathbf{8}$ | $\mathbf{1}$ | 0 |
| $W_\mu^a$ | 1 | $\mathbf{1}$ | $\mathbf{3}$ | 0 |
| $B_\mu$ | 1 | $\mathbf{1}$ | $\mathbf{1}$ | 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 $\gamma$, $Z^0$,$\pi^0$,$\eta$)
  - it's called Majorana-Neutrino ($\nu^M$) if it is its own anti-particle: $\nu^M=(\nu^M)^c$
  - **non-minimal** extension of the SM:
    - ★ mass term in $\mathscr{L}$ can be a gauge singlet
      ⇒ heavy mass term possible
      [not related to the Higgs mechanism]
    - ★ seesaw mechanism can explain tiny masses

| 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** | $\frac{1}{3}$ |
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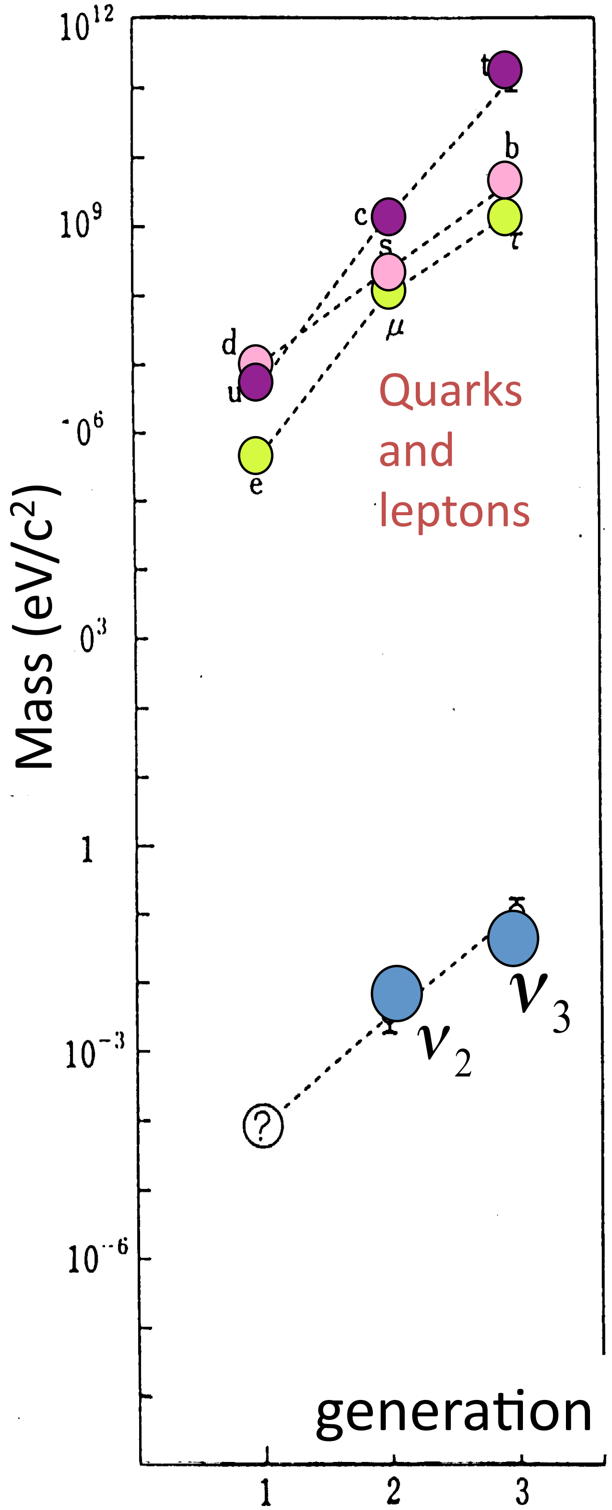
| $H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ | 0 | **1** | **2** | 1 |
| $G_\mu^\alpha$ | 1 | **8** | **1** | 0 |
| $W_\mu^a$ | 1 | **1** | **3** | 0 |
| $B_\mu$ | 1 | **1** | **1** | 0 |

# Neutrinos and the Standard Model




Why the neutrino mass is so small ?

$$\left(\frac{m(\nu_3)}{m(top\ quark)}\right) \approx \left(\frac{1}{3\times10^{12}}\right)$$

See-saw mechanism

Minkowsky, Yanagida,
Gell-mann, Ramond, Slansky

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

If we input $m_{\nu3}$ 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 $\lambda$ and vev $v$ | 2 |
| $\theta$ 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

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

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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 $\Lambda_{UV}$
- 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 $n = 1,2,3,4,\ldots$ 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 $\varphi$

output: most general, Lorentz and gauge invariant Lagrangian

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

renormalizability requires (mass) dimension of operators 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 $\mathcal{L} \ni \frac{c^{(6)}}{\Lambda_{\rm UV}^2} O^{(6)}$ with $\Lambda_{\rm UV}$ 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 succesful. 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

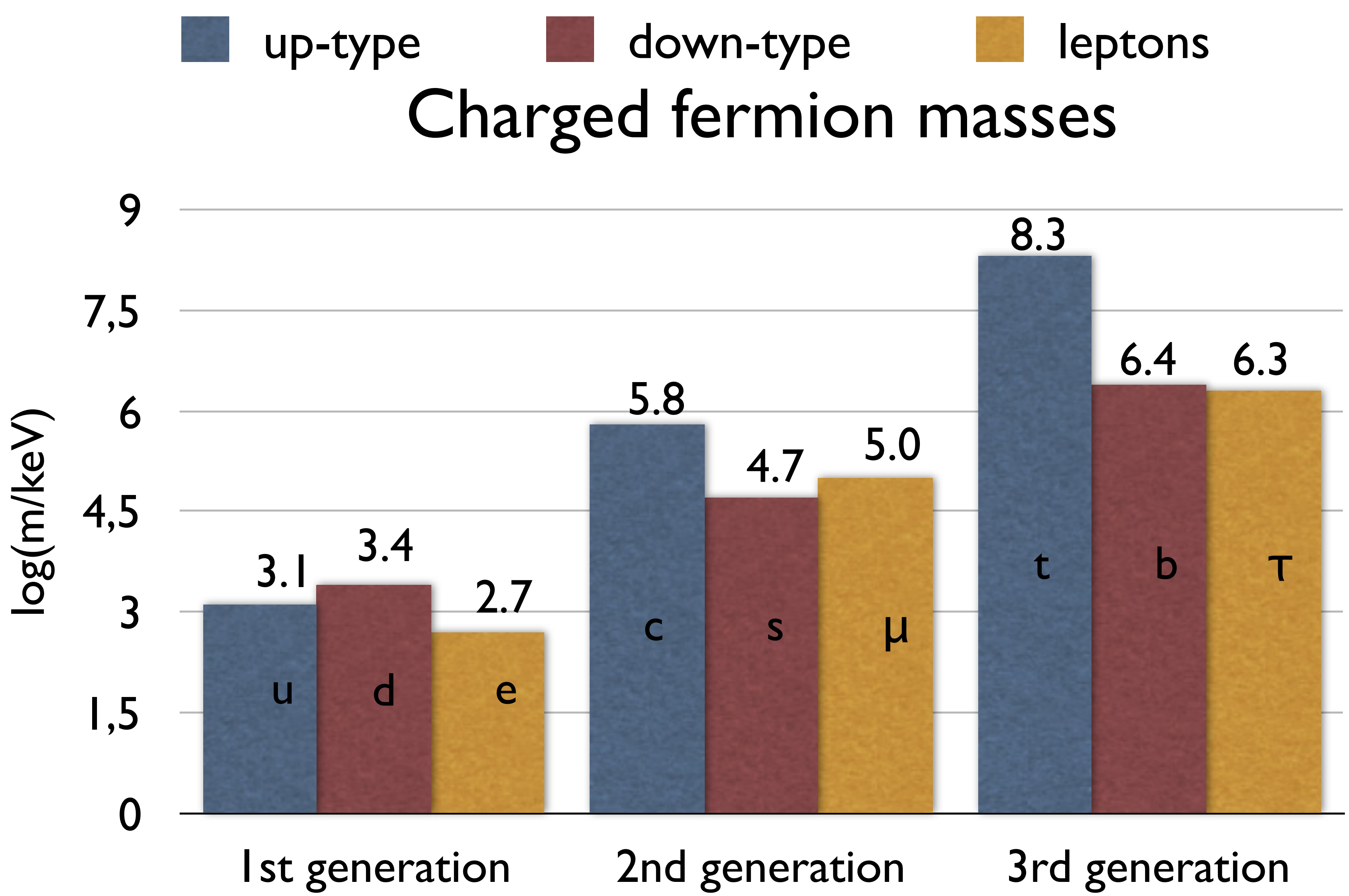
and

how different the mixing in the quark and lepton sector is

a few slides on the so called ‘flavor puzzle’

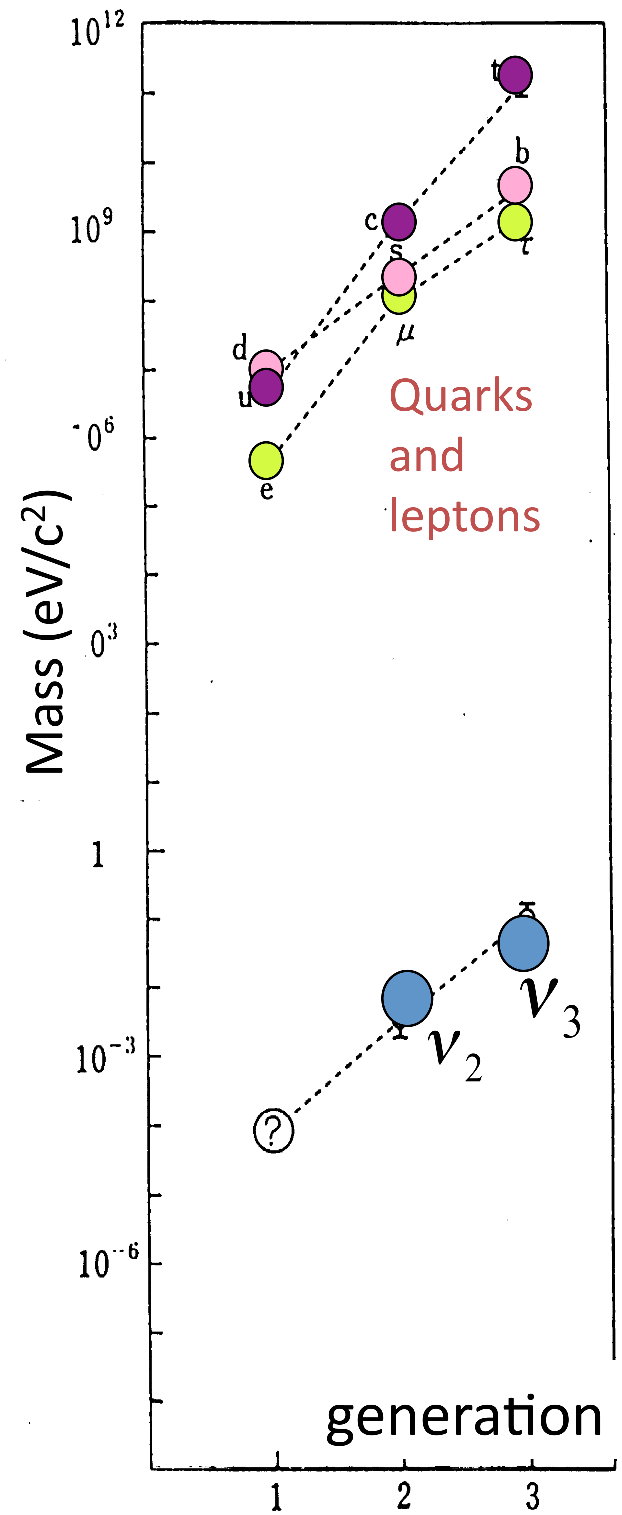
# The Flavor Puzzle

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!

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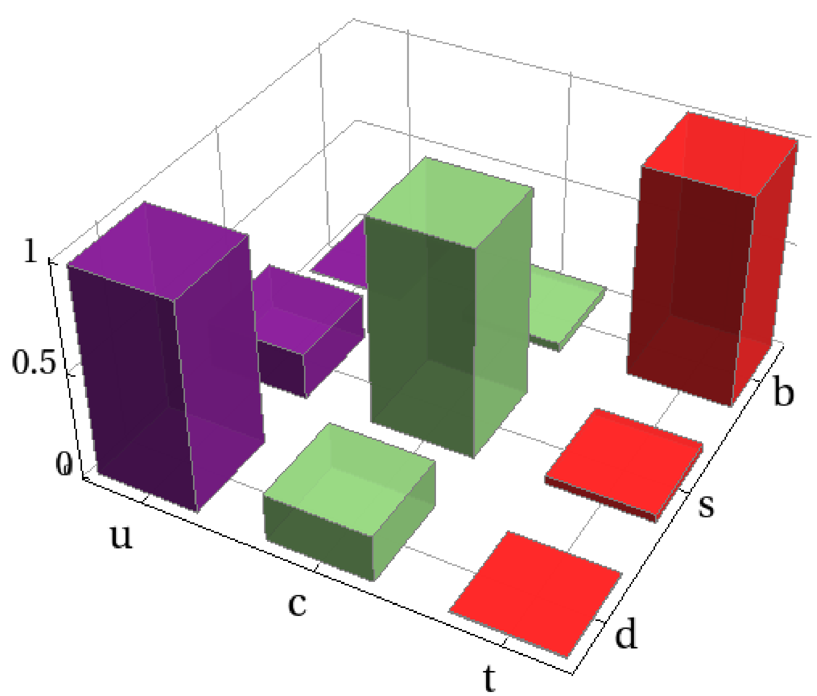
# The Flavor Puzzle

Quark and Lepton mixing parameters are quite different!

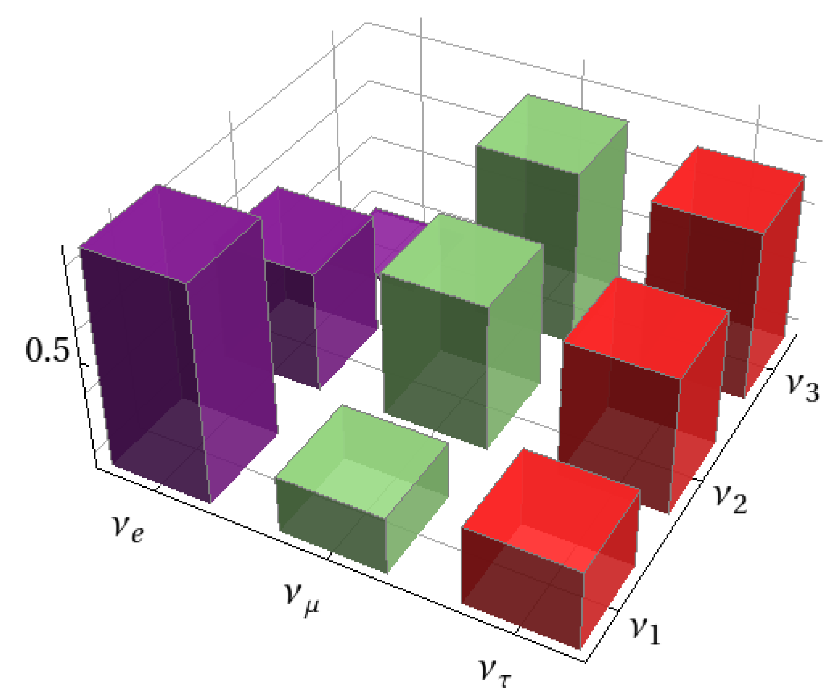
- **Quark Mixings**

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




- **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 $M_{ew} << \Lambda_{UV}$ ?
  - 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
  - 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 principles/laws of Nature (MPP, Asymptotic Safety)

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

# What is $\Lambda_{UV}$?

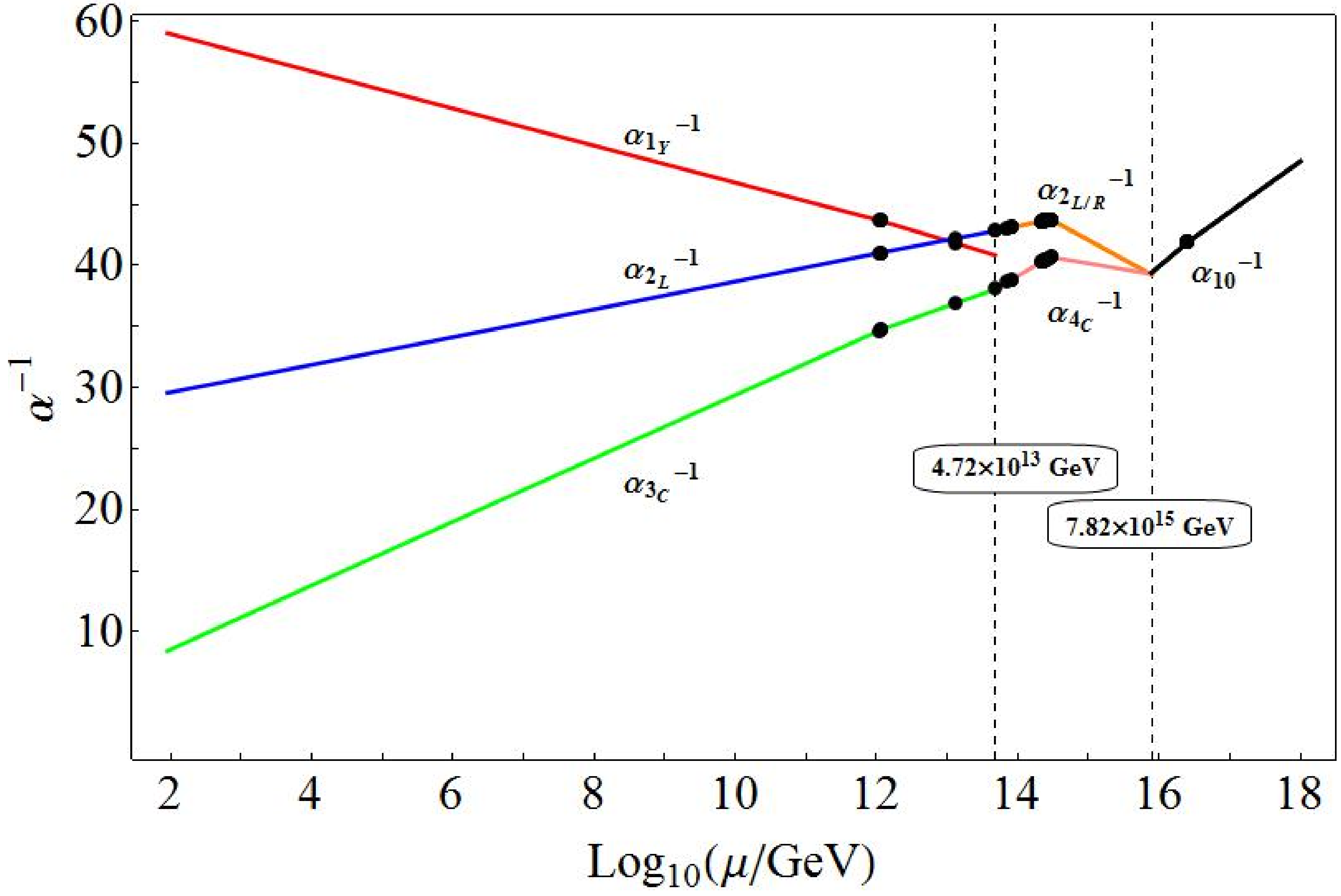
- Despite the phenomenal success of the SM, it is not the theory of everything (if this exists at all)
- The SM is 'only' an effective theory valid up to a scale $\Lambda_{UV}$
- What is $\Lambda_{UV?}$
  - gravity not part of SM: $\Lambda_{UV} < M_{Pl} \sim 10^{19}$ GeV
  - dark energy not part of SM: $\Lambda_{UV}$ = ??
  - 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)

# 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 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, 1507.06712




- Gauge coupling unification
- Explanation for quantization of electric charges

# (Some) GUT group candidates

- $G_{SM} = SU(3) \times SU(2) \times U(1)$
  - $\mathrm{rank}[G_{SM}] = \mathrm{rank}[SU(3)] + \mathrm{rank}[SU(2)] + \mathrm{rank}[U(1)] = 2 + 1 + 1 = 4$
  - $G_{SM} < G$, where $G$ is the gauge group of the GUT theory
  - $\mathrm{rank}[G_{SM}] \leq \mathrm{rank}[G]$
- Rank 4:
  - SU(5) unique rank 4 candidate: $\bar{5} + 10$
  - no $\nu_R$, 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:
  - $SU(5) \to G_{SM} \to SU(3)_c \times U(1)_{em}$
  - $SO(10) \to SU(5) \to G_{SM} \to SU(3)_c \times U(1)_{em}$
  - $SO(10) \to G(442) \to G_{SM} \to SU(3)_c \times U(1)_{em}$
  - $E_6 \to SO(10) \to \ldots$
  - 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 $SU(5) \to G_{SM}$ : $5 \to (3,1)_{2/5} + (1,2)_{-3/5}$

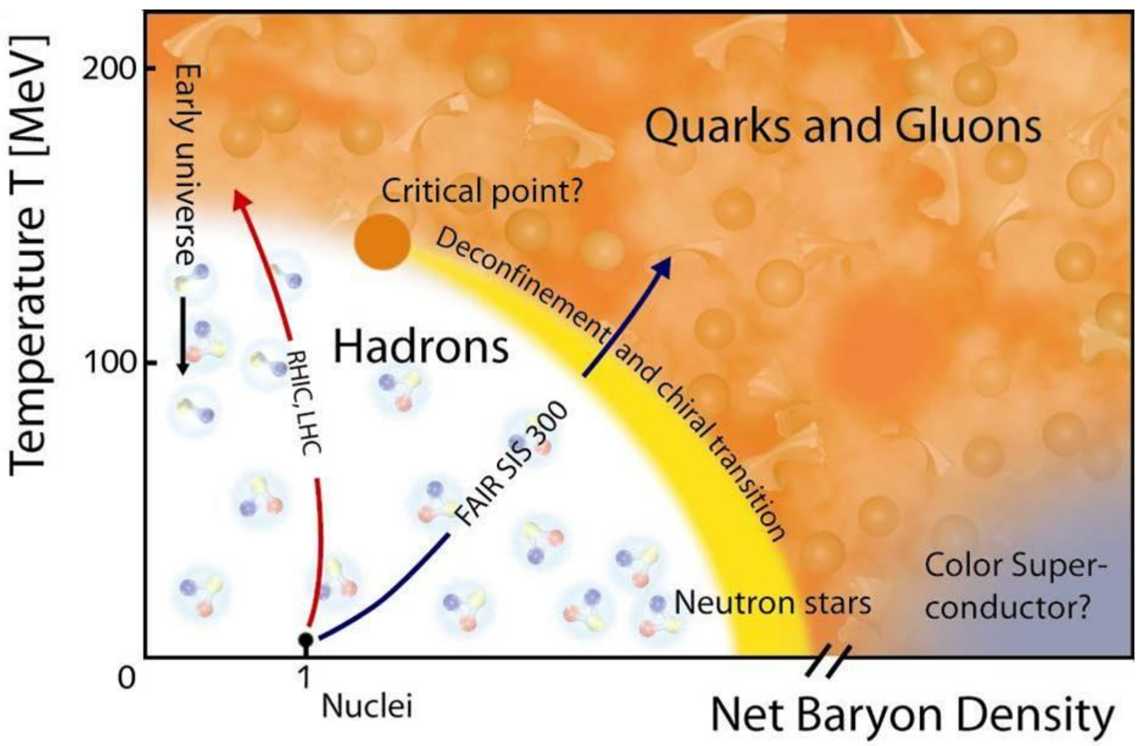
There are also open questions in QCD!
The frontier of particle physics is not just
Higgs and BSM physics…

# QCD under extreme conditions

**Understanding the dynamics of the strong interaction under extreme conditions of temperature and density**

**The QCD phase diagram connects to**

- Cosmology -> Evolution of the early universe
- Compact stars at high net-baryon density
- Strongly coupled quantum fluids




GSI Helmholtzzentrum für Schwerionenforschung

**Connect first principles QCD calculations with experimental observables via a realistic modeling of heavy ion collisions and astrophysical events**

# Key questions in QCD and hadronic physics

- **What is our degree of understanding of QCD?**
  - How precisely do we know the parameters of QCD?
  - What is the origin and the dynamics of confinement?
  - What is the origin and the dynamics of chiral symmetry breaking?
- **What is the structure of hadrons in terms of quarks and gluons?**
  - Which hadrons are there? How do they decay?
  - How does the hadron mass arise in terms of its constituents?
  - How are the quarks and gluons distributed inside the hadron?
  - How does the hadron spin arise in terms of its constituents?
- **What is the structure of nuclei in terms of quarks and gluons?**
- **What is the role of quarks and gluons in matter under extreme conditions?**
  - How does the QCD phase diagram look like? Existence of a phase transition with critical end point? Dof in the core of compact stars? Color super conductor phase?
  - What are the properties of the QGP?