The Standard Model of particle physics

The ultimate goal (for some at least...)

A consistent view of the world

AGE-OLD Questions

What are the fundamental constituents which comprise the universe?

AGE-OLD Questions

What are the fundamental constituents which comprise the universe?

How do they interact?

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What are the fundamental constituents which comprise the universe?

How do they interact?

What holds them together?

AGE-OLD Questions

What are the fundamental constituents which comprise the universe?

How do they interact?

What holds them together?

Periodic Table circa 425 BC

Earth

“The periodic table.”

Periodic Table circa 425 BC

Earth
Water

"The periodic table."

Periodic Table circa 425 BC

Earth
Water
Fire

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Periodic Table circa 425 BC

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Compact
Easy to remember
Fits on a T-shirt

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"Of course the elements are earth, water, fire and air. But what about chromium? Surely you can't ignore chromium."

Sidney Harris

Periodic Table circa 425 BC

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Physics Beyond the Standard Model?
The Higgs field?

Unification

Earth

Water

Fire

Air

"The periodic table."

Compact
Easy to remember
Fits on a T-shirt

Plato:
Since the four elements can transform into each other, it is reasonable to assume that there is only **one fundamental substance** and the four elements are just different manifestations of it!

Periodic Table circa 1900

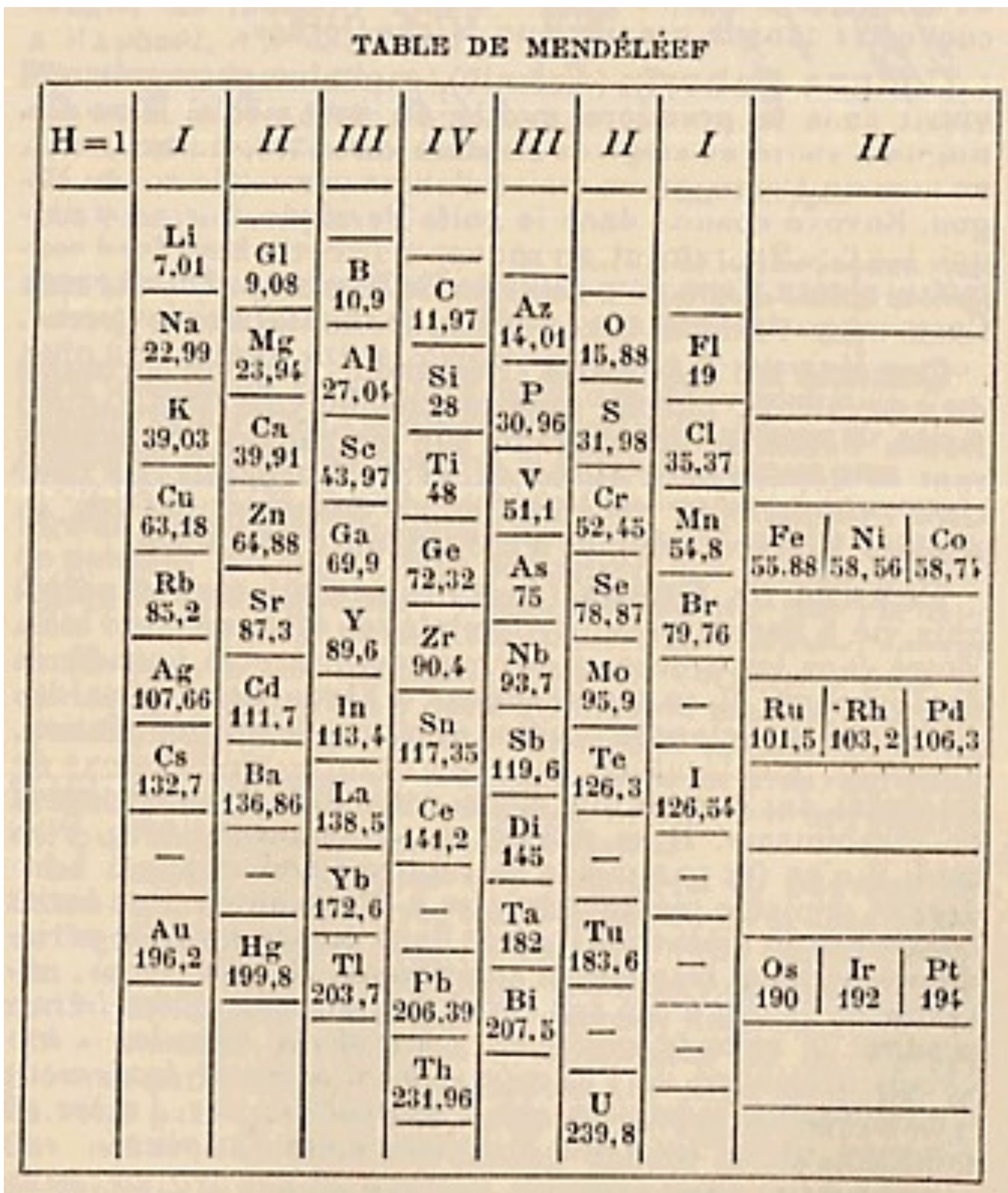

TABLE DE MENDÉLÉEF

H=1	I	II	III	IV	III	II	I	II		
	Li 7,01	Gl 9,08	B 10,9	C 11,97	Az 14,01	O 15,88	Fl 19			
	Na 22,99	Mg 23,94	Al 27,04	Si 28	P 30,96	S 31,98	Cl 35,37			
	K 39,03	Ca 39,91	Sc 43,97	Ti 48	V 51,1	Cr 52,45	Mn 54,8	Fe 55.88	Ni 58,56	Co 58,74
	Cu 63,18	Zn 64,88	Ga 69,9	Ge 72,32	As 75	Se 78,87	Br 79,76			
	Rb 85,2	Sr 87,3	Y 89,6	Zr 90.4	Nb 93,7	Mo 95,9	—	Ru 101,5	Rh 103,2	Pd 106,3
	Ag 107,66	Cd 111,7	In 113,4	Sn 117,35	Sb 119,6	Te 126,3	I 126,54			
	Cs 132,7	Ba 136,86	La 138,5	Ce 141,2	Di 145	—	—			
	—	—	Yb 172,6	—	Ta 182	Tu 183,6	—	Os 190	Ir 192	Pt 194
	Au 196,2	Hg 199,8	Tl 203,7	Pb 206.39	Bi 207.5	—	—			
				Th 231,96		U 239,8				

Dimitri Mendeleev (1834-1907)

Periodic Table circa 1900

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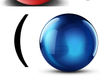
				Th 231,96		U 239,8	—	

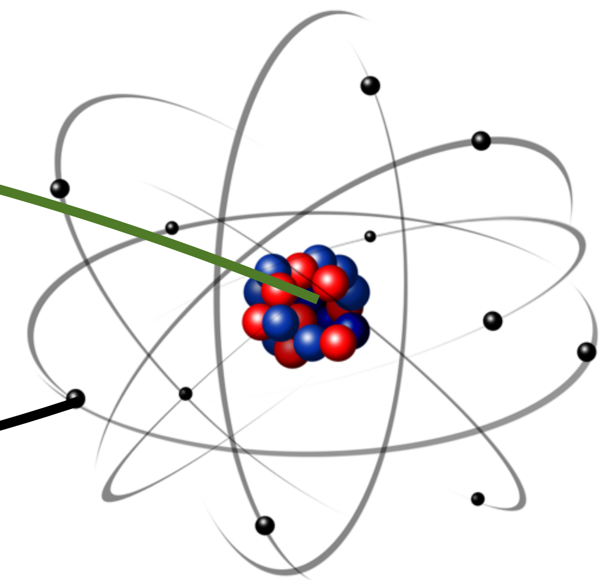
Dimitri Mendeleev (1834-1907)

66 elements!

Atoms

✦ At the atomic scale, matter is composed of <u>atoms:</u>

- ✤ A core: the nucleus, made of
  - ★ Protons ()
  - ★ Neutrons ()
- ✤ Peripheral **electrons** (•)



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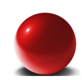
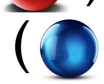
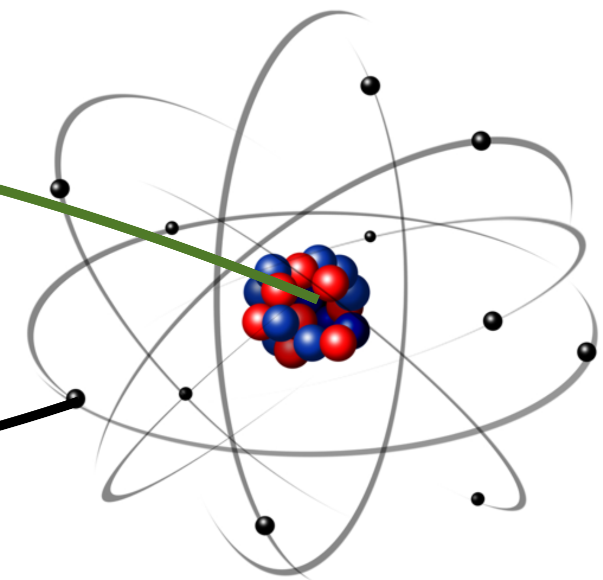
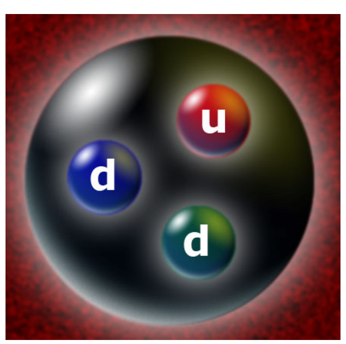
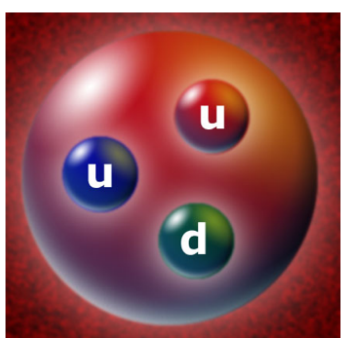
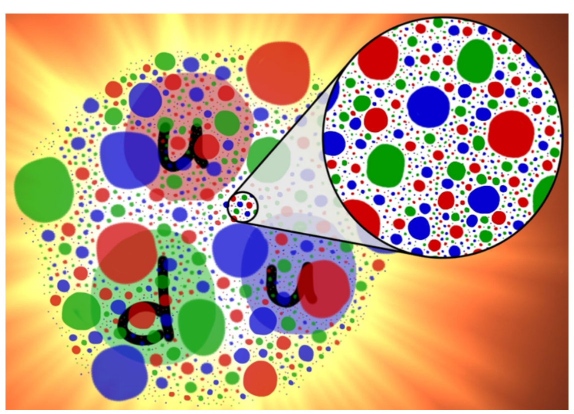
    - ★ Protons ()
    - ★ Neutrons ()
  - Peripheral electrons (•)







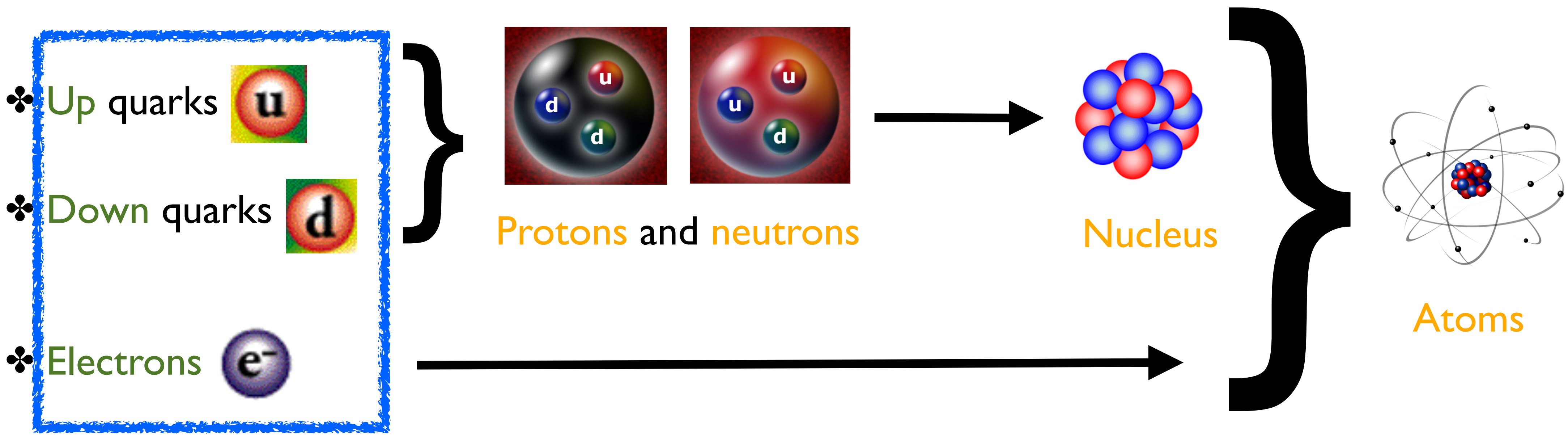


- Naively, protons and neutrons are <u>composed</u> objects:
  - Proton: two up quarks and one down quark
  - Neutron: one up quarks and two down quarks

- In reality, they are <u>dynamical</u> objects:
  - Made of many interacting quarks and gluons (see later)

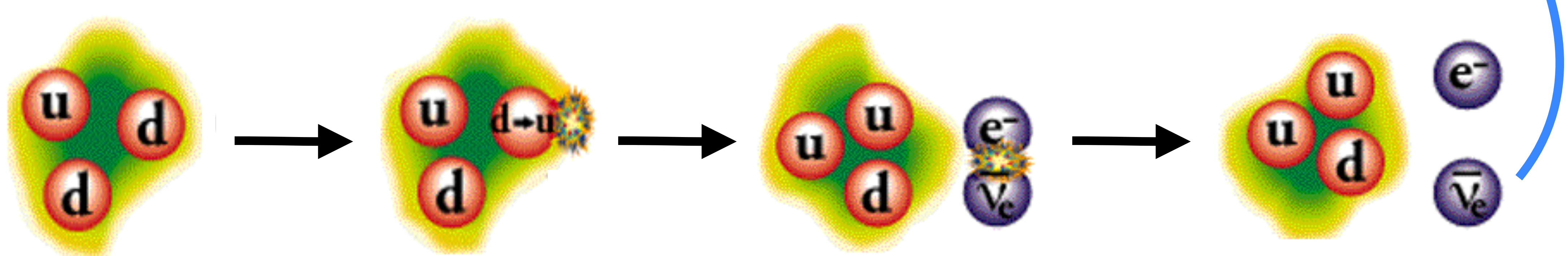
Elementary Matter Constituents I

- ✦ Elementary matter constituents



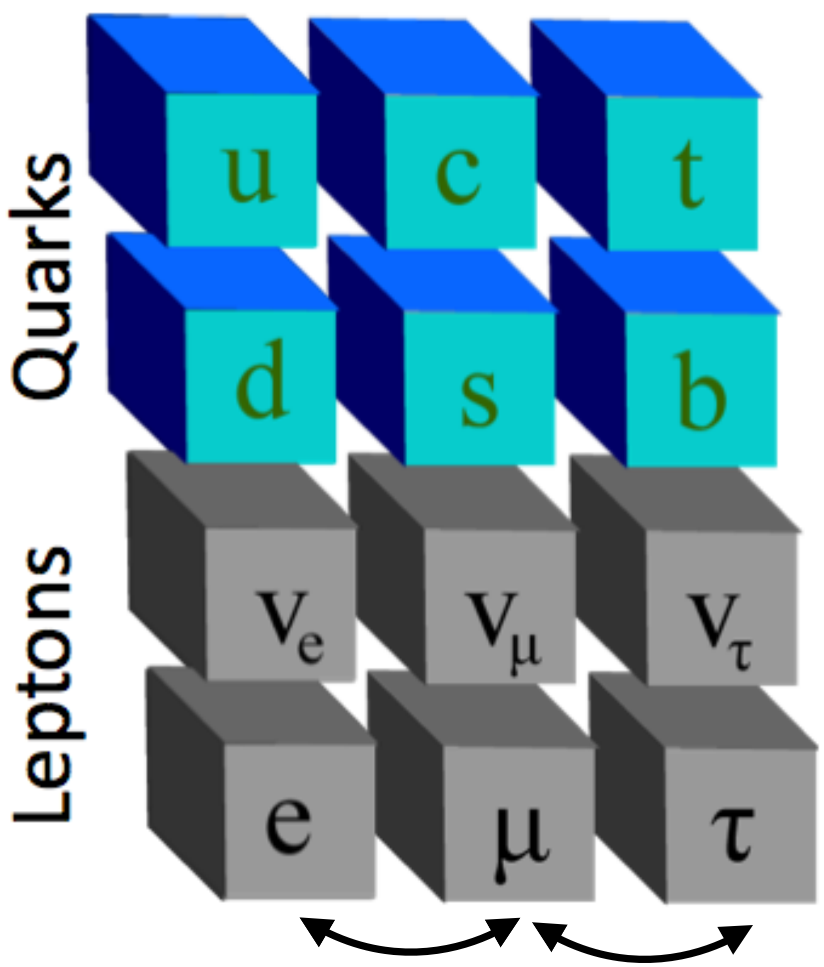
The neutrino

- ✦ Neutrons can be converted to protons: the beta decay



Elementary Matter Constituents II

✦ Elementary matter constituents: we have three families

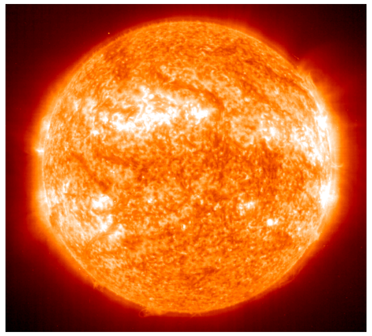


The only differences are the masses
All other properties are identical

- Three up-type quarks
  - ★ Up (u)
  - ★ Charm (c)
  - ★ Top (t)
- Three down-type quarks
  - ★ Down (d)
  - ★ Strange (s)
  - ★ Bottom (b)
- Three neutrinos
  - ★ Electron (ν_e)
  - ★ Muon (ν_μ)
  - ★ Tau (ν_τ)
- There charged leptons
  - ★ Electron (e)
  - ★ Muon (μ)
  - ★ Tau (τ)

Four fundamental Interactions

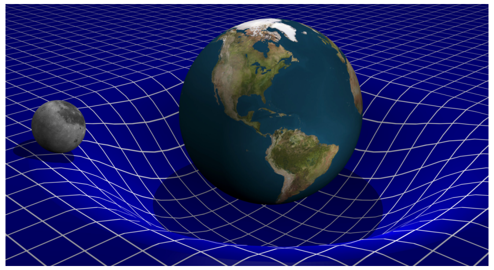
- ✦ Electromagnetism
  - Interactions between charged particles (quarks, charged leptons)
  - Mediated by massless photons γ



- ✦ Weak interactions
  - Interactions between all matter fields
  - Mediated by massive weak W-bosons and Z-bosons

- ✦ Strong interactions
  - Interactions between colored particles (quarks)
  - Mediated by massless gluons g
  - Responsible for binding protons and neutrons within the nucleus

- ✦ Gravity
  - Not included in the Standard Model



The Higgs boson

- The masses of the particles
  - Elegant mechanism to introduce them
  - Price to pay: a new particle, the so-called Higgs boson

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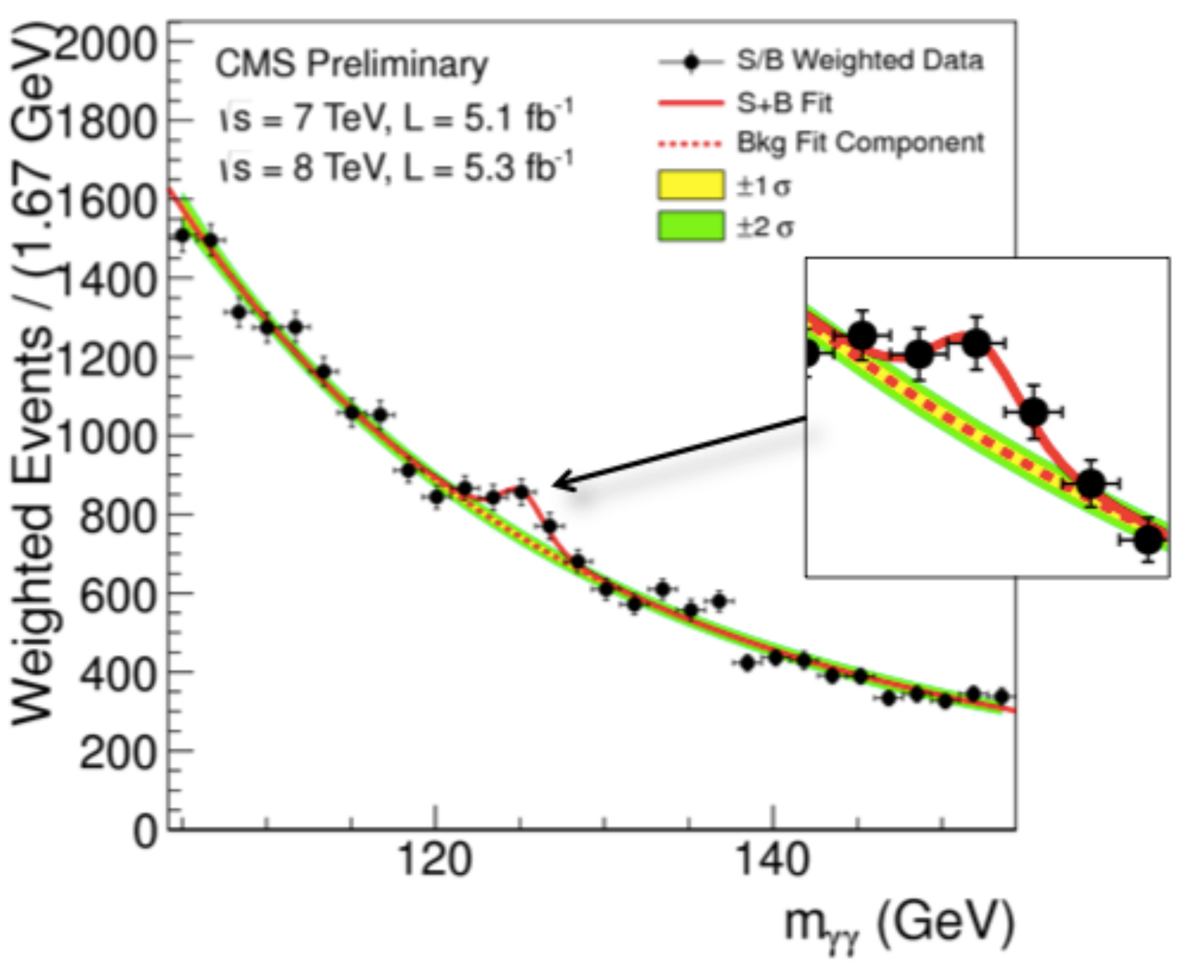
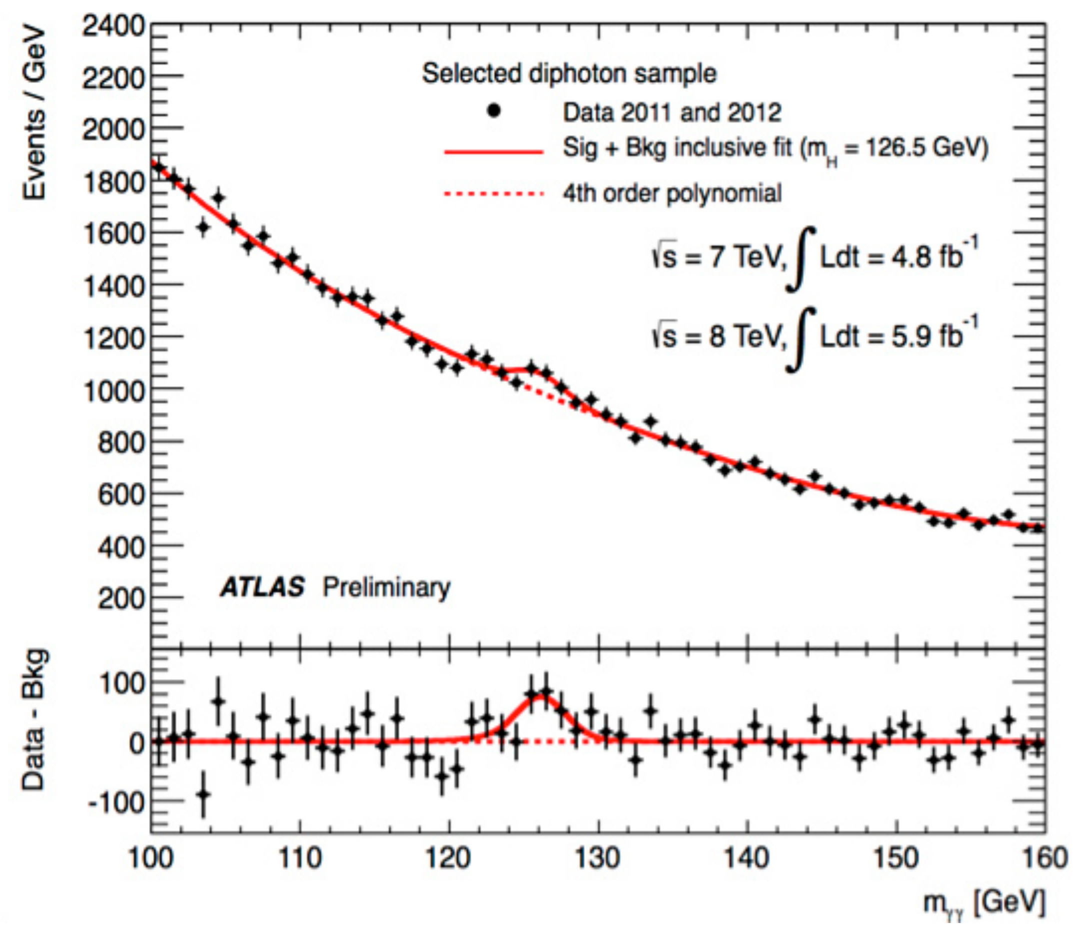
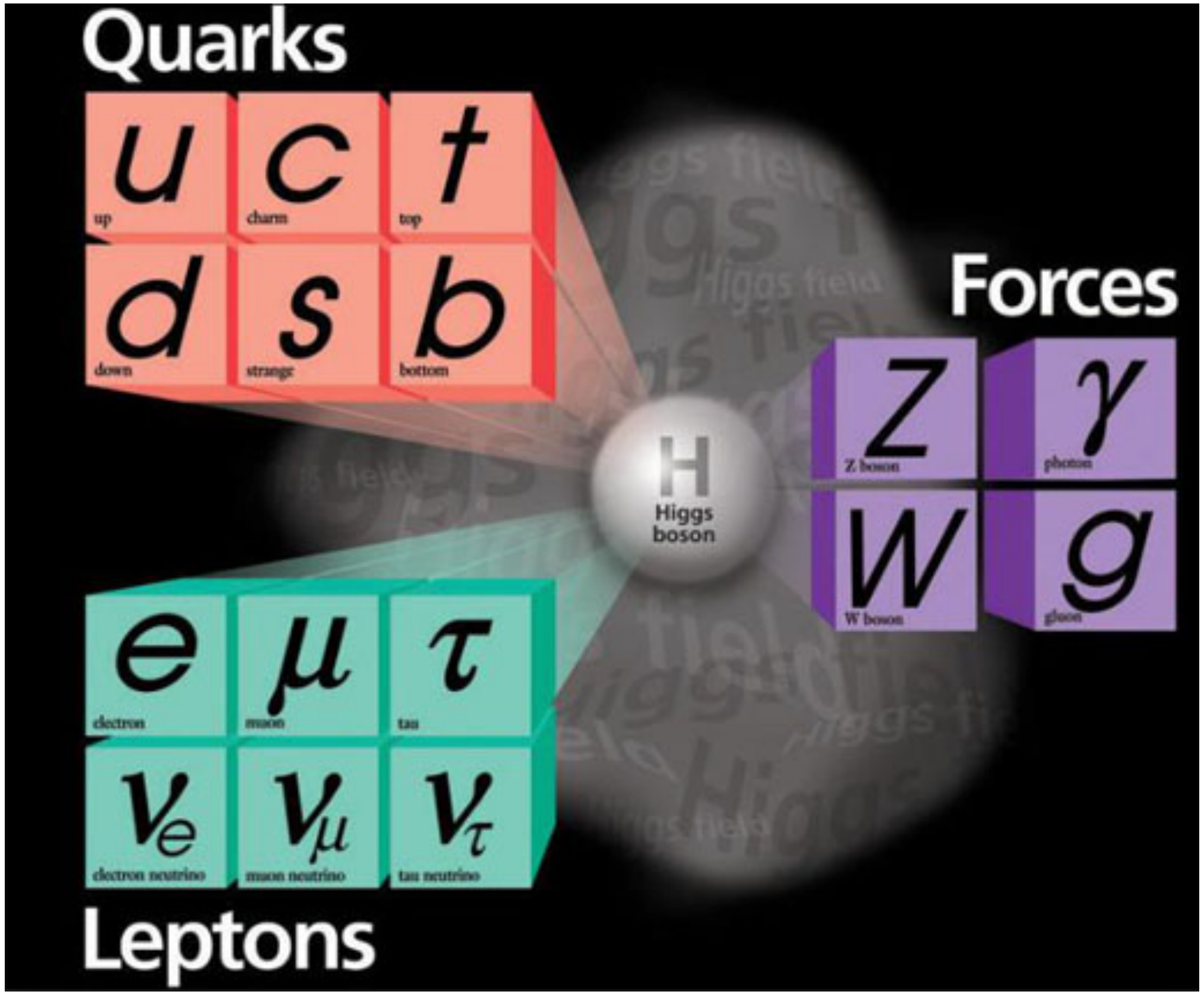
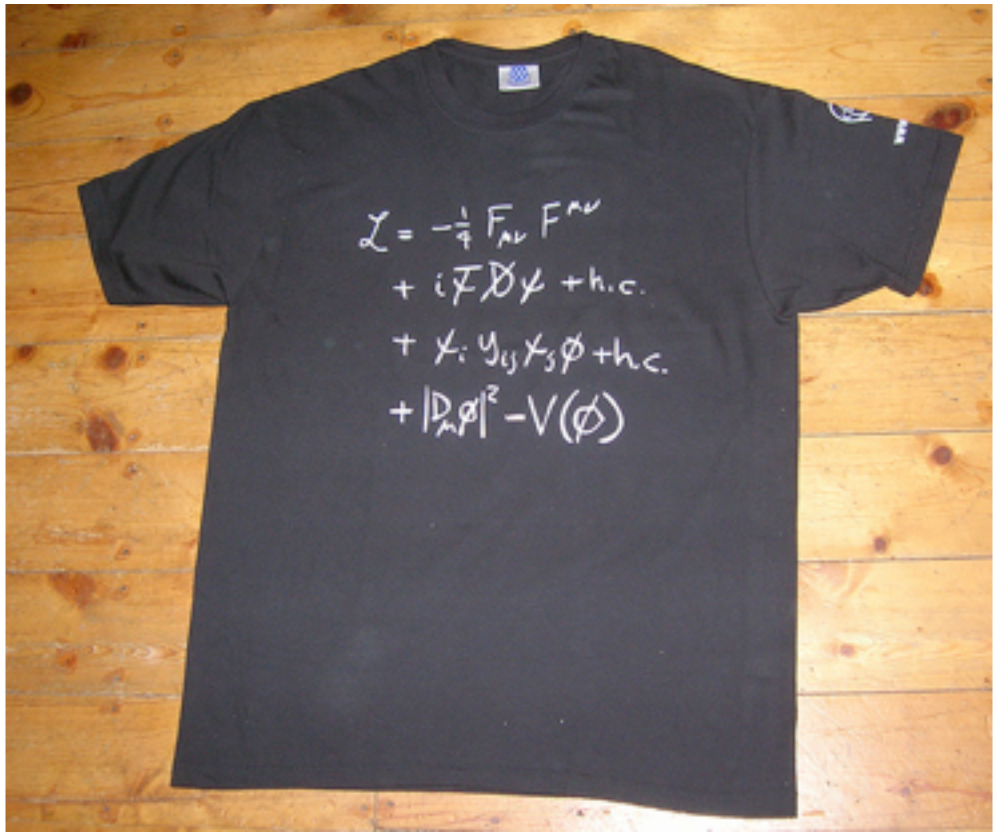
discovered in 2012





Periodic Table circa 2017 AD





Compact
Easy to remember
Fits on a T-shirt

The **Standard Model** (SM) for the strong, weak, and electromagnetic interactions

The Standard Model of particle physics (2nd round)

The Standard Model

- ... provides currently our best understanding of the world
- ... is a beautiful theory, based on a few principles
- ... has really weird input parameters
- ... is an extremly successful theory
- There are several reasons to look for theories beyond the SM
- We will now discuss some of these aspects to set the stage

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

One page summary of the world

Gauge group

$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

Particle content

MATTER				HIGGS		GAUGE	
$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$(\mathbf{3},\mathbf{2})_{1/3}$	$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$(\mathbf{1},\mathbf{2})_{-1}$	$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$	$(\mathbf{1},\mathbf{2})_{1}$	B	$(\mathbf{1},\mathbf{1})_0$
u_R^c	$(\overline{\mathbf{3}},\mathbf{1})_{-4/3}$	e_R^c	$(\mathbf{1},\mathbf{1})_{2}$			W	$(\mathbf{1},\mathbf{3})_0$
d_R^c	$(\overline{\mathbf{3}},\mathbf{1})_{2/3}$	ν_R^c	$(\mathbf{1},\mathbf{1})_{0}$			G	$(\mathbf{8},\mathbf{1})_0$

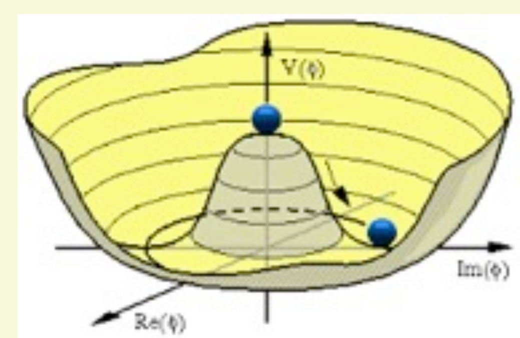
Lagrangian

(Lorentz + gauge + renormalizable)

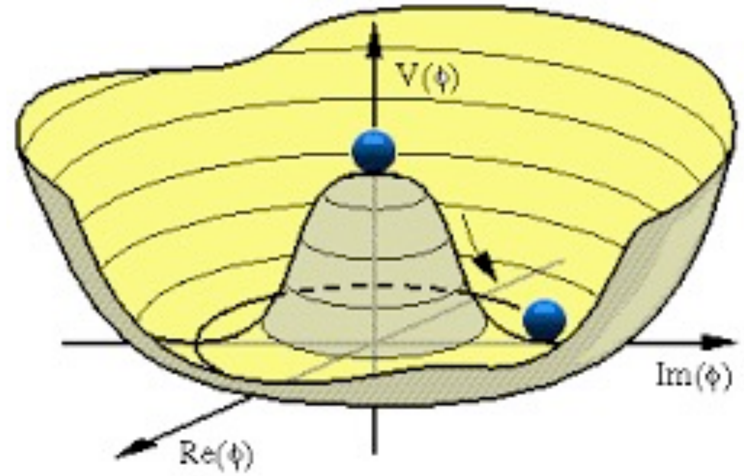
$$\mathcal{L} = -\frac{1}{4}G^{\alpha}_{\mu\nu}G^{\alpha\mu\nu} + \ldots \overline{Q}_k \not{D} Q_k + \ldots (D_\mu H)^\dagger (D^\mu H) - \mu^2 H^\dagger H - \frac{\lambda}{4!}(H^\dagger H)^2 + \ldots Y_{k\ell}\overline{Q}_k H (u_R)_\ell$$

SSB

- $H \to H' + \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$
- $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_Q$
- $B, W^3 \to \gamma, Z^0$ and $W^1_\mu, W^2_\mu \to W^+, W^-$
- Fermions acquire mass through Yukawa couplings to Higgs



The Higgs mechanism



- The Higgs potential: $V = \mu^2 \phi^\dagger\phi + \lambda (\phi^\dagger\phi)^2$
- Vacuum = Ground state = Minimum of V:
- If $\mu^2>0$ (massive particle): $\phi_{min} = 0$ (no symmetry breaking)
- If $\mu^2<0$: $\phi_{min} = \pm v = \pm(-\mu^2/\lambda)^{1/2}$
  These two minima in one dimension correspond to a continuum of minimum values in SU(2).
  The point $\phi = 0$ is now unstable.
- Choosing the minimum (e.g. at $+v$) gives the vacuum a preferred direction in isospin space → spontaneous symmetry breaking
- Perform perturbation around the minimum

Higgs self-couplings

In the SM, the Higgs self-couplings are a consequence of the Higgs potential after expansion of the Higgs field H~(1,2)$_1$ around the vacuum expectation value which breaks the ew symmetry:

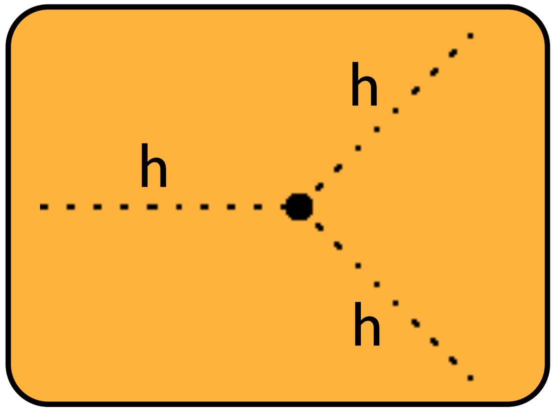
$$V_H = \mu^2 H^\dagger H + \eta (H^\dagger H)^2 \to \frac{1}{2} m_h^2 h^2 + \boxed{\sqrt{\frac{\eta}{2}} m_h h^3} + \boxed{\frac{\eta}{4} h^4}$$

with: $$m_h^2 = 2\eta v^2 \,,\; v^2 = -\mu^2/\eta$$

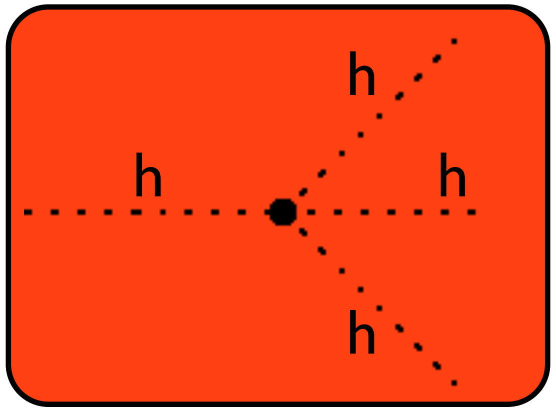
Note: v=246 GeV is fixed by the precision measures of G_F

In order to completely reconstruct the Higgs potential, on has to:

- Measure the 3h-vertex:
  via a measurement of Higgs pair production
  $$\lambda_{3h}^{\mathrm{SM}} = \sqrt{\frac{\eta}{2}} m_h$$



- Measure the 4h-vertex:
  more difficult, not accessible at the LHC in the high-lumi phase



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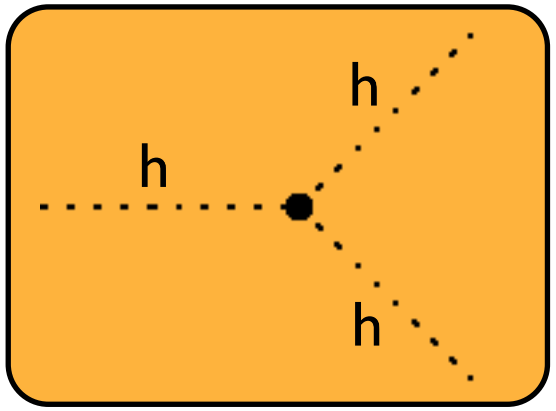

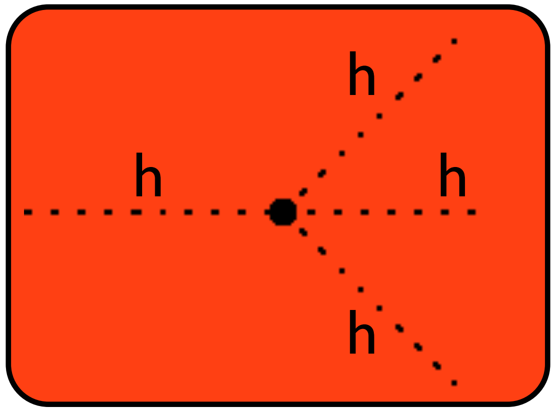

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with:

Note: v=246 GeV is fixed by the precision measures of G_F

Measuring the 3h-couplings:
major goal for the high-lumi phase at the LHC

The Higgs particle is just the messenger!

Need to reconstruct the potential

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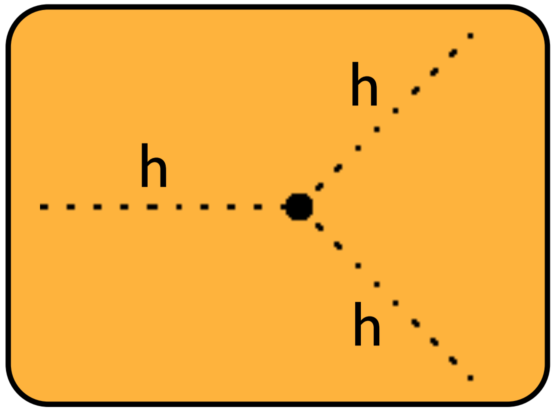

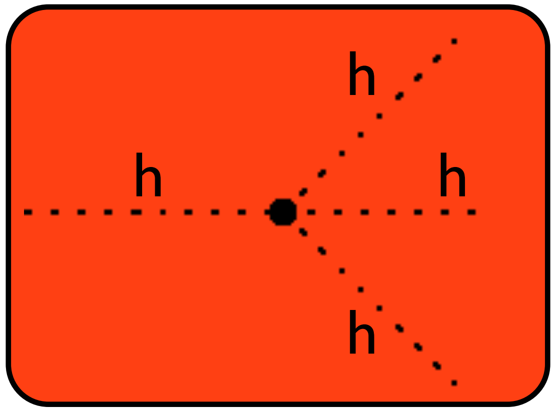

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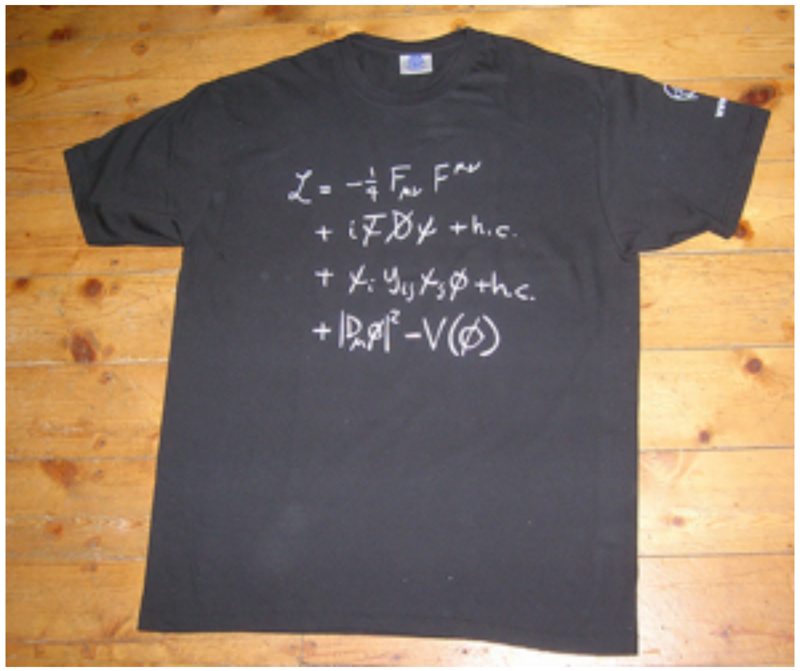
Not so compact anymore



Lagrangien du Modèle Standard

$$
\begin{aligned}
\mathcal{L}_{SM} = {} & \sum_{\ell=e,\mu,\tau} i\bar{\psi}_\ell\gamma^\mu\partial_\mu\psi_\ell + \sum_{\ell'=\nu_e,\nu_\mu,\nu_\tau} i\bar{\psi}_{\ell'}\gamma^\mu\partial_\mu\psi_{\ell'} + \sum_i^3\sum_{q=u,c,t} i\bar{\psi}_{q_i}\gamma^\mu\partial_\mu\psi_{q_i} + \sum_i^3\sum_{q'=d,s,b} i\bar{\psi}_{q'_i}\gamma^\mu\partial_\mu\psi_{q'_i} \\
& -\frac{1}{2}(\partial_\mu W^+_\nu - \partial_\nu W^+_\mu)(\partial^\mu W^{-\nu} - \partial^\nu W^{-\mu}) - \frac{1}{4}(\partial_\mu Z_\nu - \partial_\nu Z_\mu)(\partial^\mu Z^\nu - \partial^\nu Z^\mu) \\
& -\frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu) - \frac{1}{4}\sum_{a=1}^{8}(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu)(\partial^\mu G^{a\nu} - \partial^\nu G^{a\mu}) + \frac{1}{2}\partial_\mu h\partial^\mu h \\
& -\sum_{\ell=e,\mu,\tau}\frac{\lambda_\ell v}{\sqrt{2}}\bar{\psi}_\ell\psi_\ell - \sum_i^3\sum_{q=u,c,t}\frac{\lambda_q v}{\sqrt{2}}\bar{\psi}_{q_i}\psi_{q_i} - \sum_i^3\sum_{q'=d,s,b}\frac{\lambda_{q'} v}{\sqrt{2}}\bar{\psi}_{q'_i}\psi_{q'_i} \\
& -\left(\frac{gv}{2}\right)^2 W^+_\mu W^{-\mu} - \frac{1}{2}\left(\frac{gv}{2\cos\theta_W}\right)^2 Z_\mu Z^\mu - \frac{1}{2}\left(-2m^2\right)h^2 \\
& +\frac{g}{4\cos\theta_W}\left(\sum_{\ell=e,\mu,\tau}\bar{\psi}_\ell\gamma^\mu(4\sin^2\theta_W - 1 + \gamma^5)\psi_\ell Z_\mu + \sum_{\ell'=\nu_e,\nu_\mu,\nu_\tau}\bar{\psi}_{\ell'}\gamma^\mu(1-\gamma^5)\psi_{\ell'}Z_\mu\right) \\
& +\frac{g}{4\cos\theta_W}\left(\sum_i^3\sum_{q=u,c,t}\bar{\psi}_{q_i}\gamma^\mu(1 - \frac{8}{3}\sin^2\theta_W - \gamma^5)\psi_{q_i}Z_\mu + \sum_i^3\sum_{q'=b,s,b}\bar{\psi}_{q'_i}\gamma^\mu(\frac{4}{3}\sin^2\theta_W - 1 + \gamma^5)\psi_{q'_i}Z_\mu\right) \\
& +\frac{g}{2\sqrt{2}}\left(\sum_{\ell=e,\mu,\tau}\bar{\psi}_{\nu_\ell}\gamma^\mu(1-\gamma^5)\psi_\ell W^+_\mu + \sum_{\ell=e,\mu,\tau}\bar{\psi}_\ell\gamma^\mu(1-\gamma^5)\psi_{\nu_\ell}W^-_\mu\right) \\
& +\frac{g}{2\sqrt{2}}\left(\sum_i^3\sum_{\substack{q=u,c,t\\ q'=d,s,b}} V_{qq'}\bar{\psi}_q\gamma^\mu(1-\gamma^5)\psi_{q'_i}W^+_\mu + \sum_i^3\sum_{\substack{q=u,c,t\\ q'=d,s,b}} V^*_{qq'}\bar{\psi}_{q'_i}\gamma^\mu(1-\gamma^5)\psi_{q_i}W^-_\mu\right) \\
& +g_{em}\left(-\sum_{\ell=e,\mu,\tau}\bar{\psi}_\ell\gamma^\mu\psi_\ell A_\mu + \frac{2}{3}\sum_{q=u,c,t}\bar{\psi}_{q_i}\gamma^\mu\psi_{q_i}A_\mu - \frac{1}{3}\sum_{q'=d,s,b}\bar{\psi}_{q'_i}\gamma^\mu\psi_{q'_i}A_\mu\right) \\
& +g_s\left(\sum_{i,j}^3\sum_a^8\sum_{q=u,c,t}\bar{\psi}_{q_j}\gamma^\mu\psi_{q_i}G^a_\mu T^a_{ij} + \sum_{i,j}^3\sum_a^8\sum_{q'=d,s,b}\bar{\psi}_{q'_j}\gamma^\mu\psi_{q'_i}G^a_\mu T^a_{ij}\right) \\
& -\sum_{\ell=e,\mu,\tau}\frac{\lambda_\ell}{\sqrt{2}}\bar{\psi}_\ell\psi_\ell h - \sum_i^3\sum_{q=u,c,t}\frac{\lambda_q}{\sqrt{2}}\bar{\psi}_{q_i}\psi_{q_i}h - \sum_i^3\sum_{q'=d,s,b}\frac{\lambda_{q'}}{\sqrt{2}}\bar{\psi}_{q'_i}\psi_{q'_i}h \\
& +ig_{em}\left[\partial_\mu A_\nu W^{-\mu}W^{+\nu} + \partial_\mu W^+_\nu W^{-\nu}A^\mu + \partial_\mu W^-_\nu W^{+\mu}A^\nu - \partial_\mu A_\nu W^{-\nu}W^{+\mu}\right. \\
& \qquad \left. -\partial_\mu W^+_\nu W^{-\mu}A^\nu - \partial_\mu W^-_\nu W^{+\nu}A^\mu\right] \\
& +ig\cos\theta_W\left[\partial_\mu Z_\nu W^{-\mu}W^{+\nu} + \partial_\mu W^+_\nu W^{-\nu}Z^\mu + \partial_\mu W^-_\nu W^{+\mu}Z^\nu - \partial_\mu Z_\nu W^{-\nu}W^{+\mu}\right. \\
& \qquad \left. -\partial_\mu W^+_\nu W^{-\mu}Z^\nu - \partial_\mu W^-_\nu W^{+\nu}Z^\mu\right] + \frac{g^2 v}{2}W^+_\mu W^{-\mu}h + \frac{g^2 v}{4\cos^2\theta_W}Z_\mu Z^\mu h - \lambda v h^3 \\
& +g^2_{em}\left[W^+_\nu W^{-\mu}A_\nu A^\mu - W^+_\nu W^{-\mu}A_\mu A^\nu\right] + g^2\cos^2\theta_W\left[W^+_\nu W^{-\mu}Z_\nu Z^\mu - W^+_\nu W^{-\mu}Z_\mu Z^\nu\right] \\
& +g^2\cos\theta_W\sin\theta_W\left[2W^+_\mu W^{-\mu}Z_\nu A^\nu - W^+_\mu W^{-\nu}A_\nu Z^\mu - W^+_\mu W^{-\nu}A^\mu Z_\nu\right] \\
& +\frac{g^2}{2}\left[W^-_\mu W^{-\mu}W^+_\nu W^{+\nu} - W^-_\mu W^{+\mu}W^-_\nu W^{+\nu}\right] + \frac{g^2}{4}W^+_\mu W^{-\mu}h^2 + \frac{g^2}{8\cos^2\theta_W}Z_\mu Z^\mu h^2 - \frac{\lambda}{4}h^4 \\
& -\frac{g_s}{2}\sum_{a,b,c}^{8} f^{abc}(\partial_\mu G^{a\nu} - \partial_\nu G^a_\mu)G^{\mu b}G^{\nu c} - \frac{g_s^2}{4}\sum_{\substack{a,b,c\\ d,e,f}}^{8} f^{abc}f^{ade}G^b_\mu G^c_\nu G^{\mu d}G^{\nu e}
\end{aligned}
$$

$g_{em} = g\sin\theta_W,\ v^2 = \frac{-m^2}{\lambda}\ (m^2 < 0, \lambda > 0),\ m_\ell = \frac{\lambda_\ell v}{\sqrt{2}},\ m_q = \frac{3\lambda_q v}{\sqrt{2}},\ m_W = \frac{gv}{2},\ m_Z = \frac{gv}{2\cos\theta_W},\ m_h = \sqrt{-2m^2}$

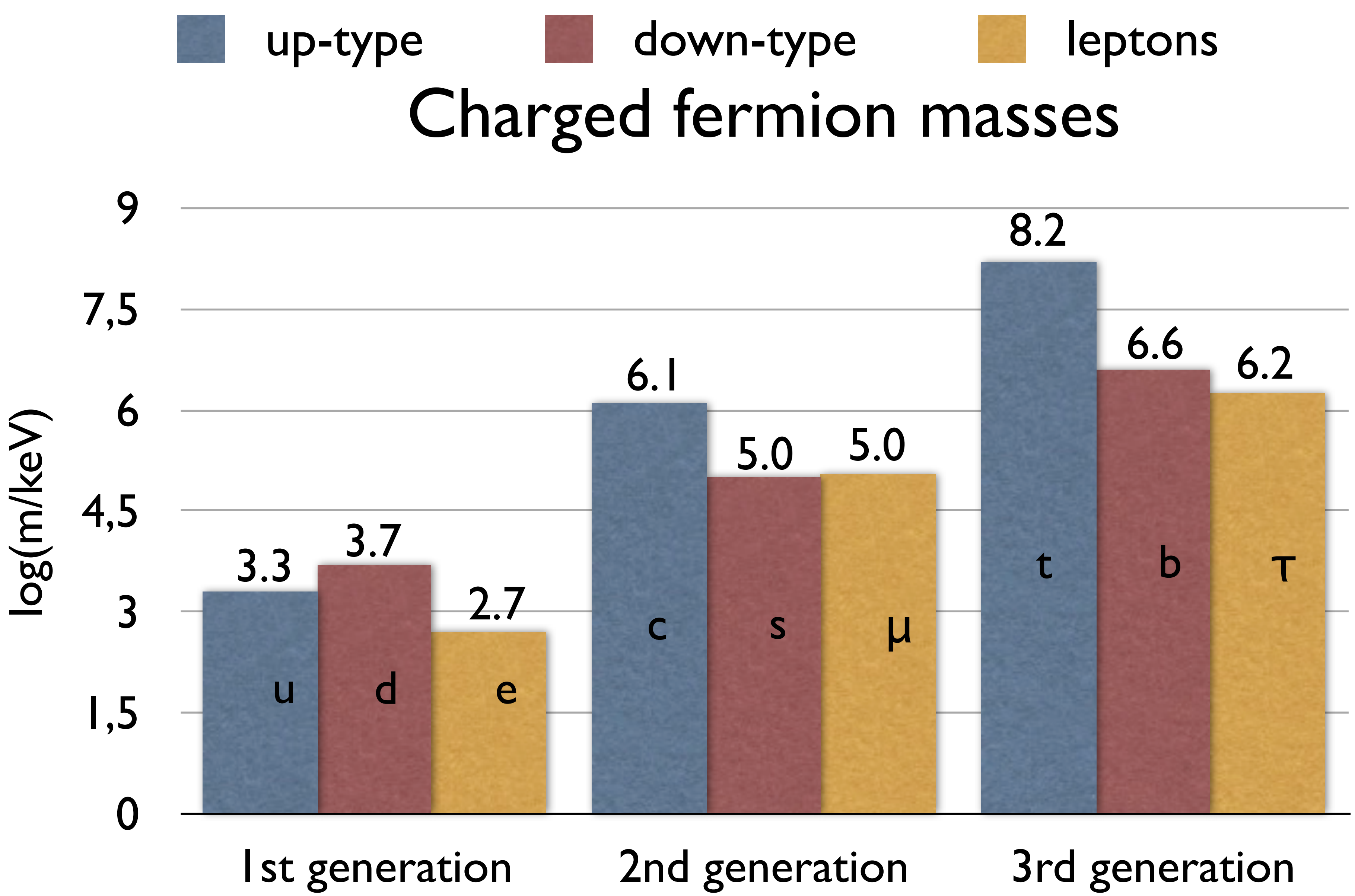
The weird SM

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**!

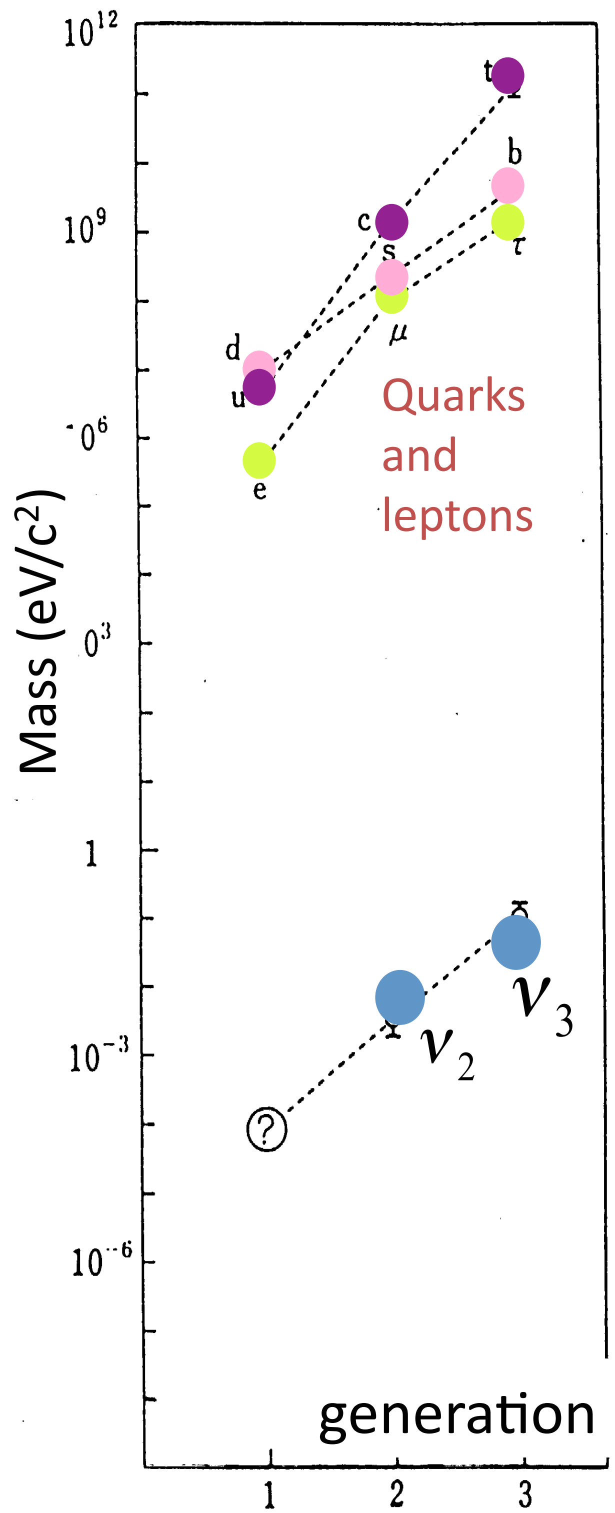
The Flavor Puzzle

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 ?

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

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

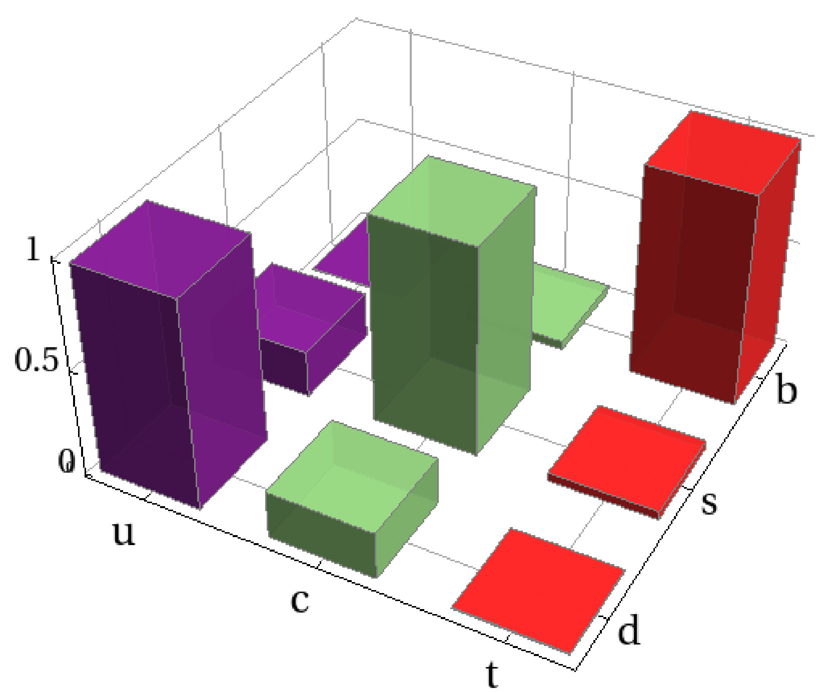
This suggests that physics of neutrino mass could be related to physics of Grand Unification!

The Flavor Puzzle

Quark and Lepton mixing parameters are quite different!

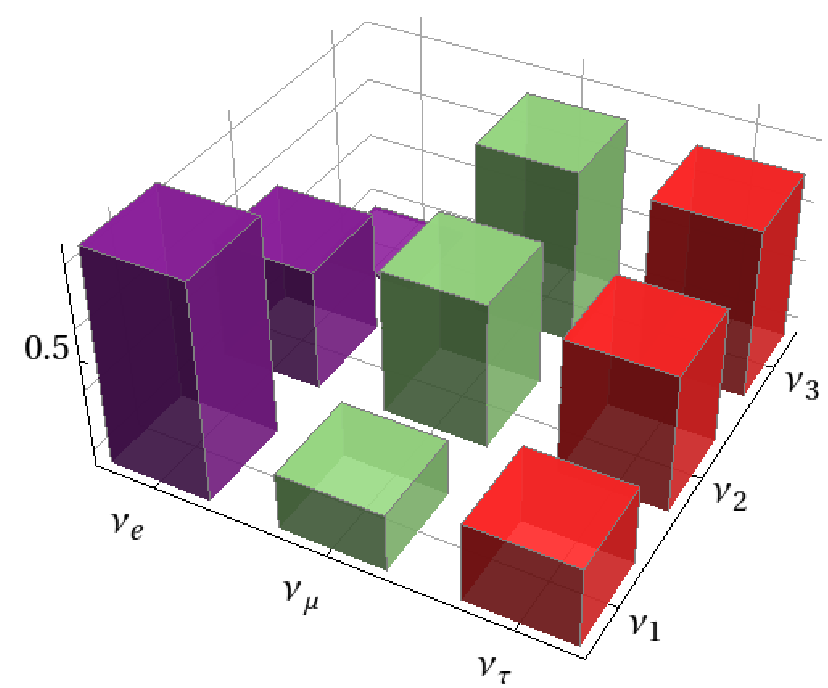
- **Quark Mixings**

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



- **Leptonic Mixings**

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



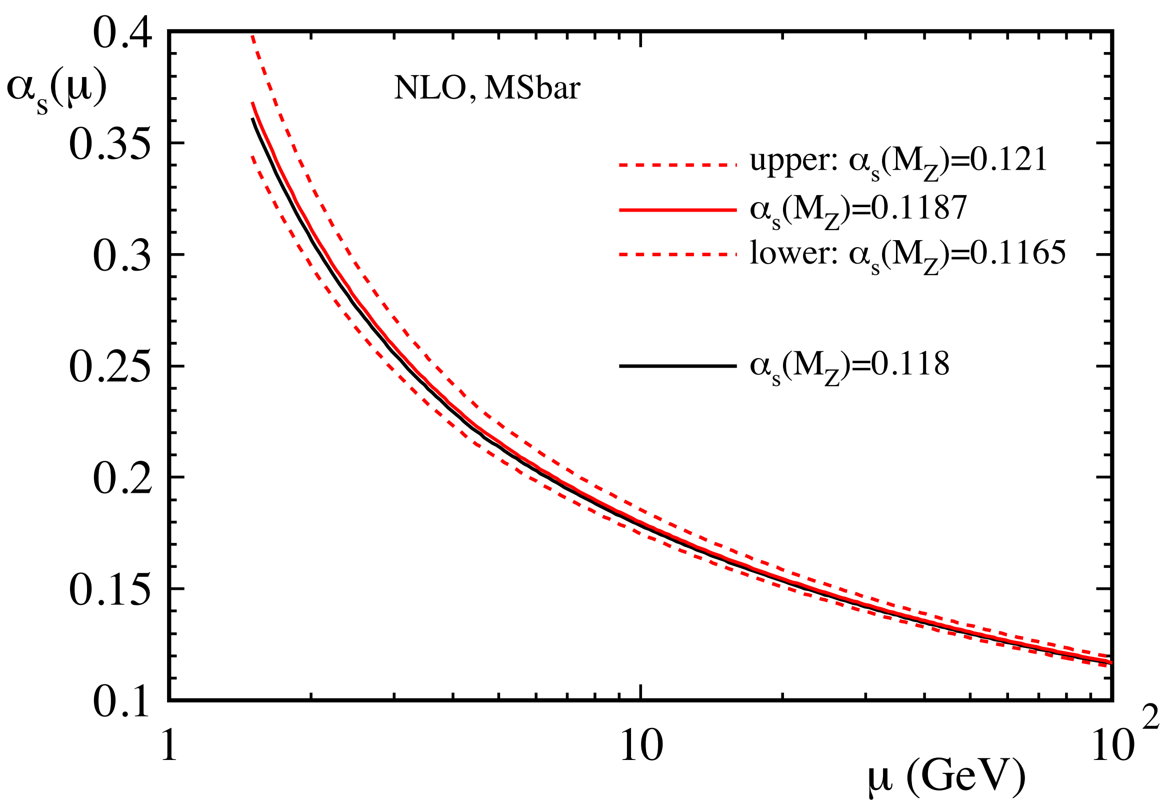
Quantum Corrections

- 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)

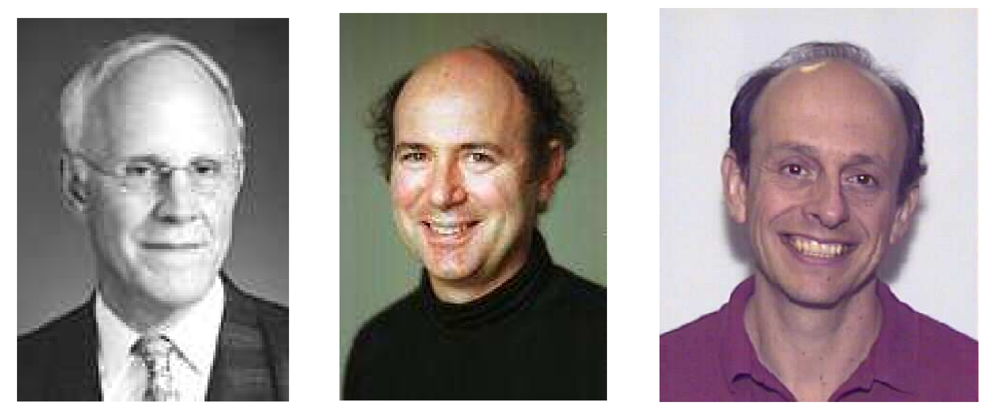
Asymptotic Freedom

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 $\mu \nearrow$

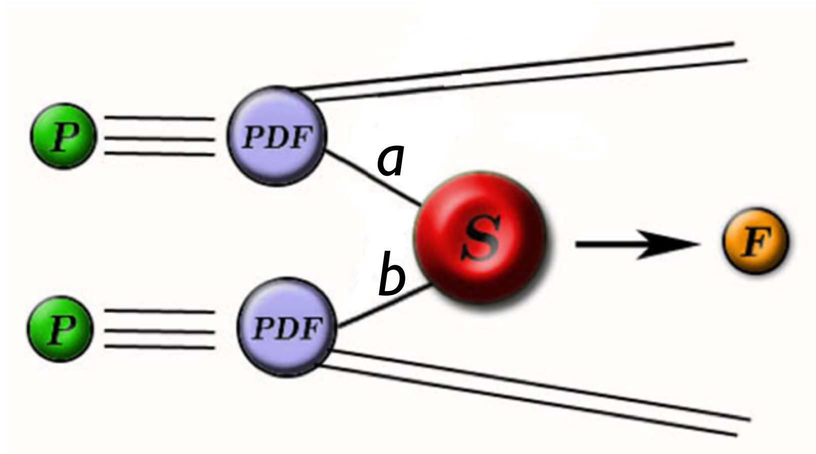
- Nobel Prize 2004

Proton-Proton collisions at the LHC

✦The master formula for hadron colliders

$$\sigma = \frac{1}{F}\sum_{ab}\int \mathrm{dPS}^{(n)}\mathrm{d}x_a\ \mathrm{d}x_b\ f_{a/p}(x_a)\ f_{b/p}(x_b)\overline{|M_{fi}|^2}$$

- ✤ We sum over all proton constituents (*a* and *b* here)
- ✤ We include the parton densities (the *f*-function)



They represent the probability of having a parton *a* inside the proton carrying a fraction x_a of the proton momentum

Also need parton densities as an input!
Can not (yet) be calculated in lattice QCD

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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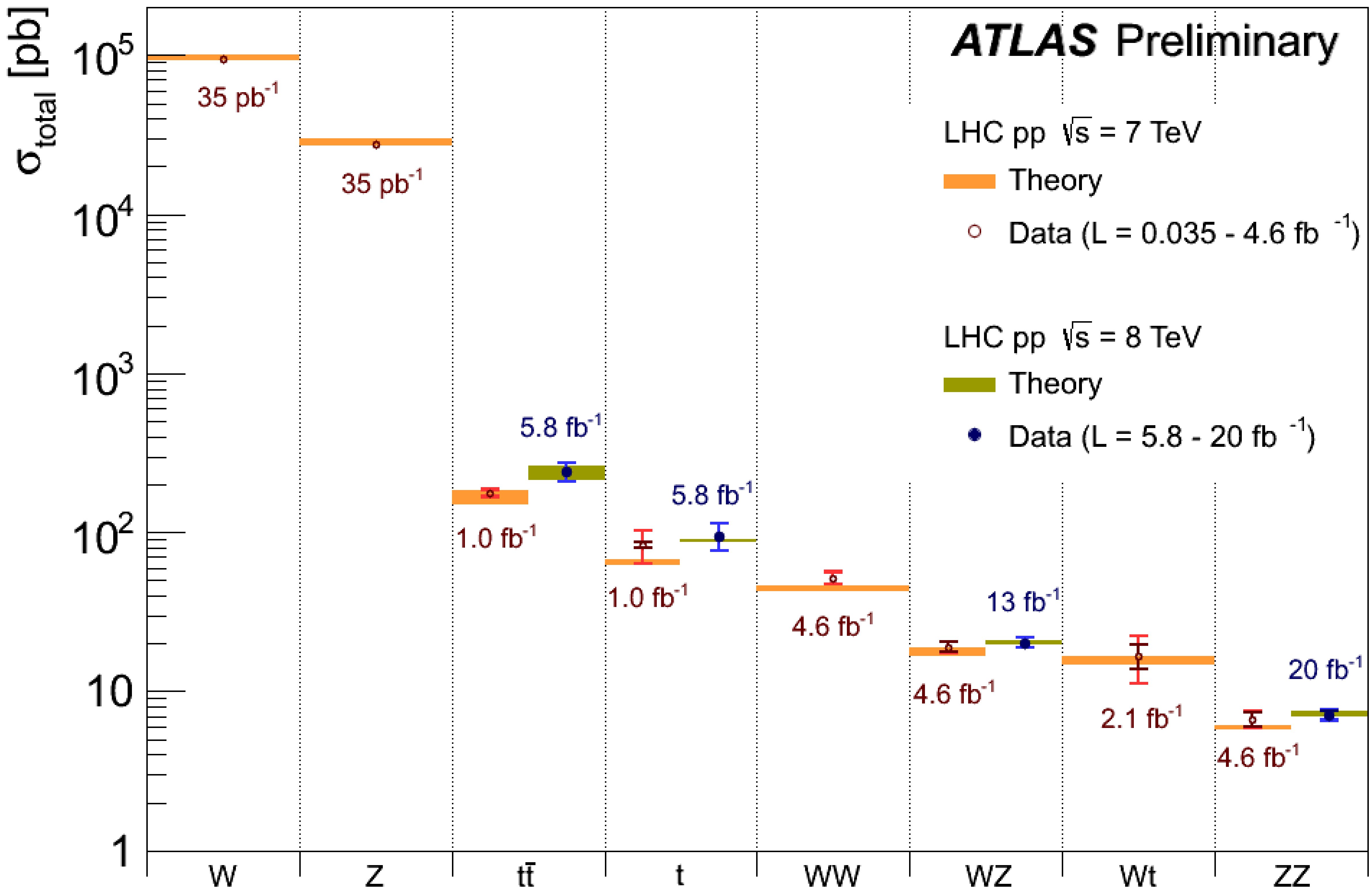
- **A spin-0 particle** compatible with the SM Higgs boson has been discovered
- **No other particles** have been found (so far)
- The SM is the **best-tested theory** in the history of science!

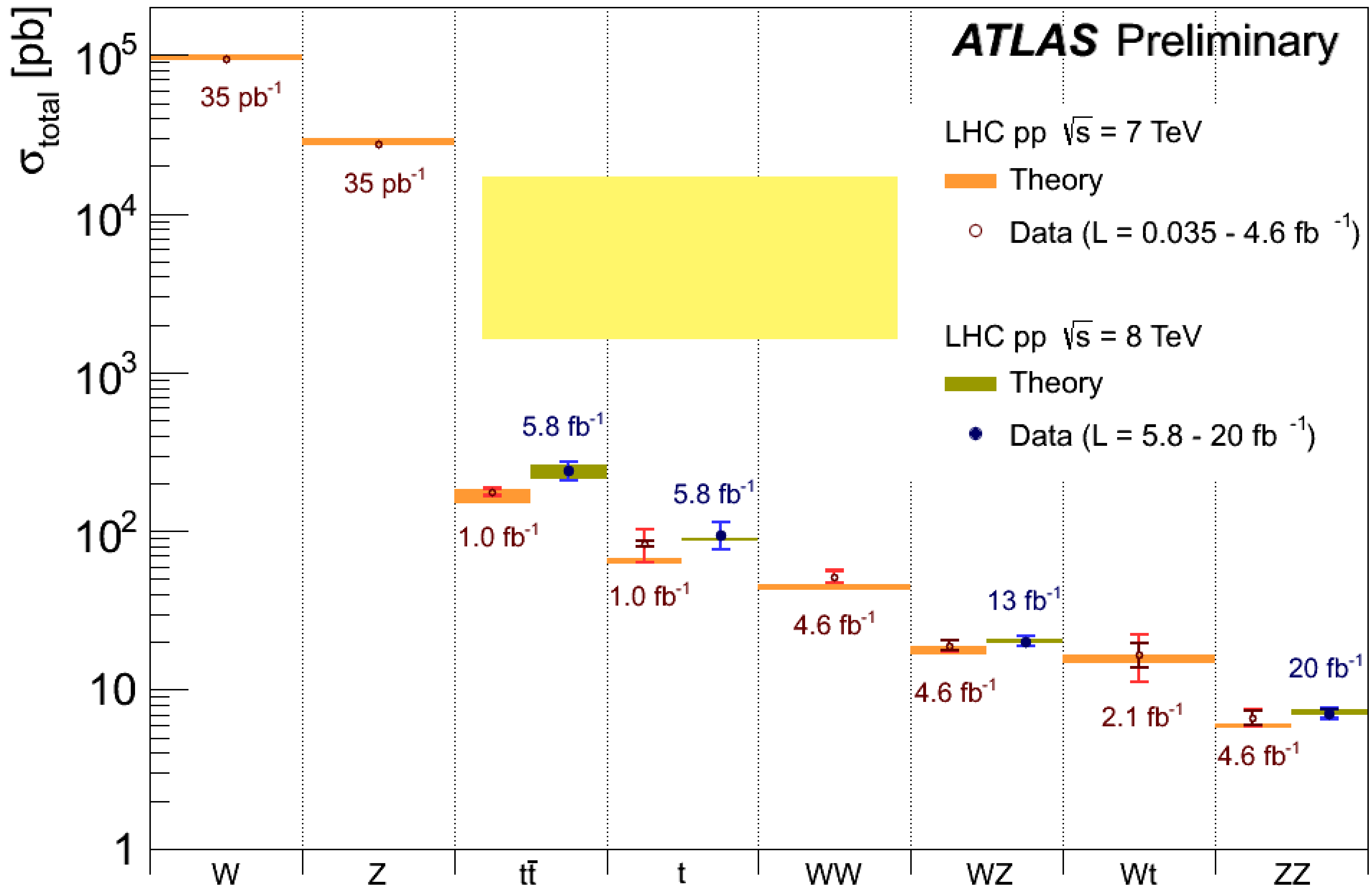
A very large number of precision measurements have been compared to SM computations at the ***(multi-)loop level*** *and* ***no solid evidence for BSM physics*** *has emerged (neither in direct searches nor indirectly due to loop effects)*

Cross sections at the LHC in comparison to the SM

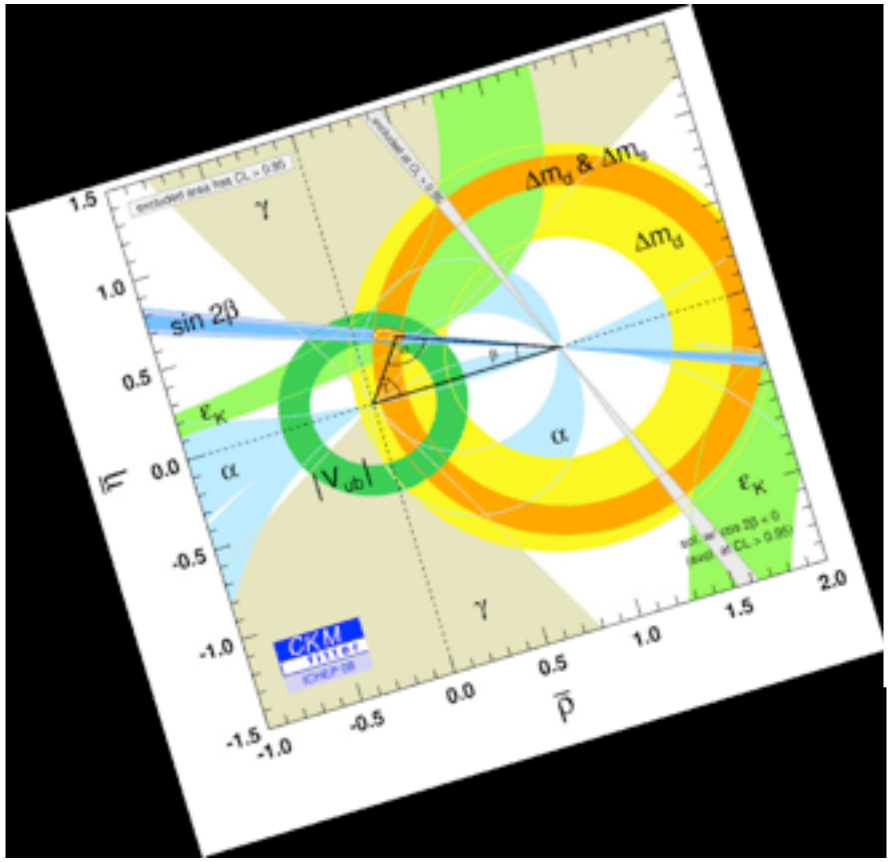


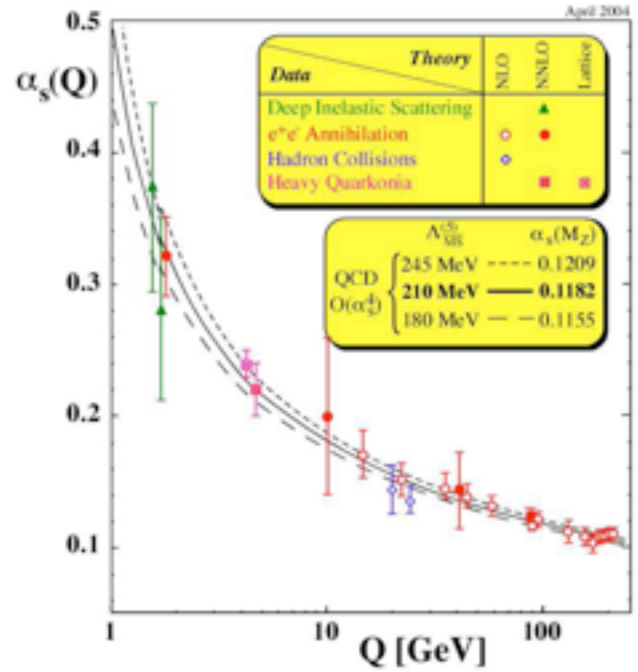
Cross sections at the LHC in comparison to the SM

Standard model observables



CKM angles

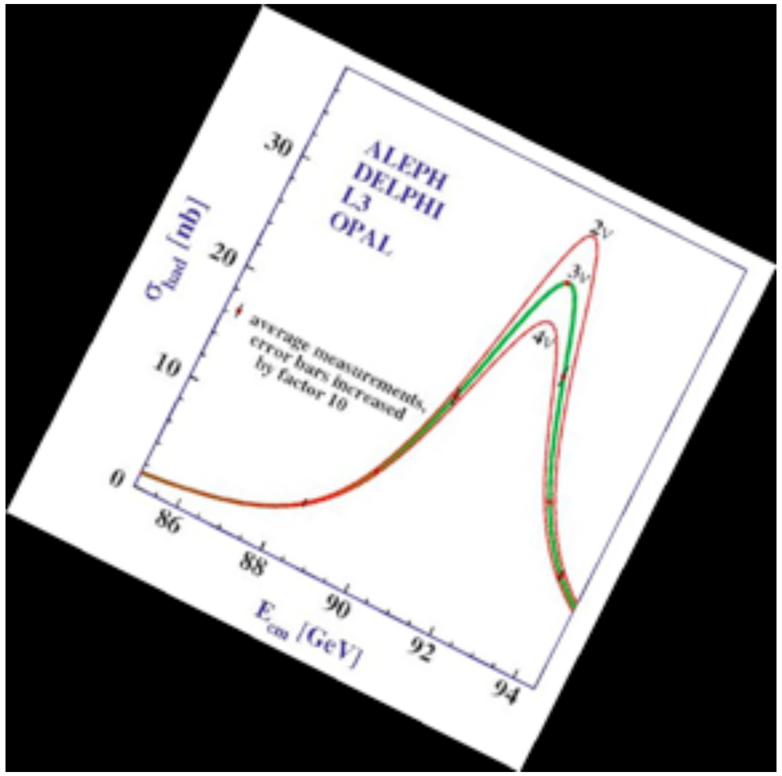




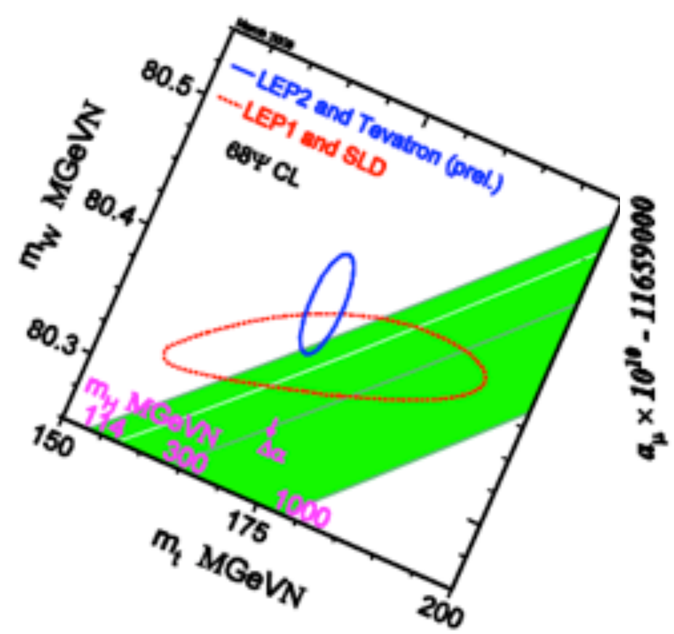
running α_S

EW parameters

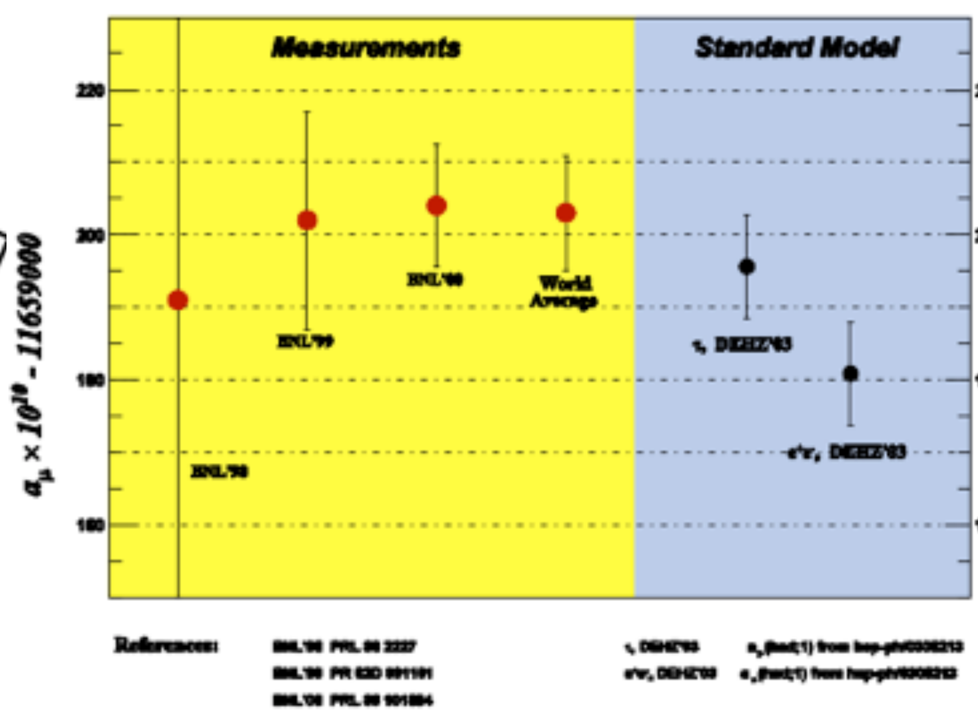
Z^0 width



top and W mass



anom. magnetic moment (g-2)

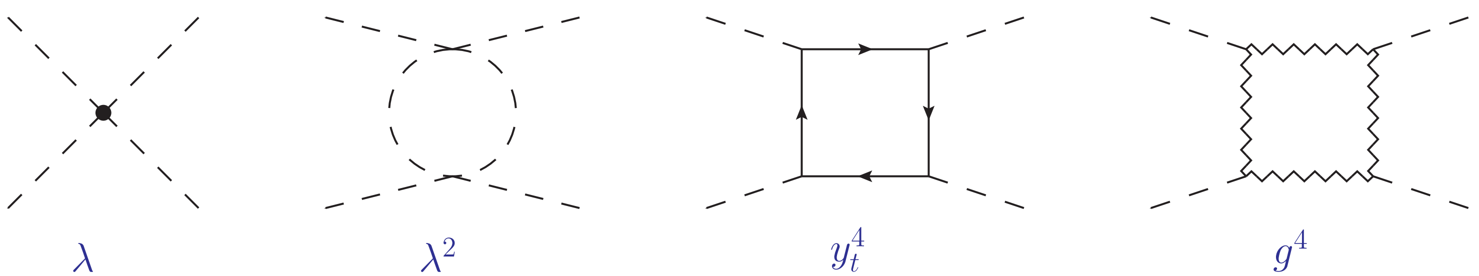


Higgs effective potential

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:

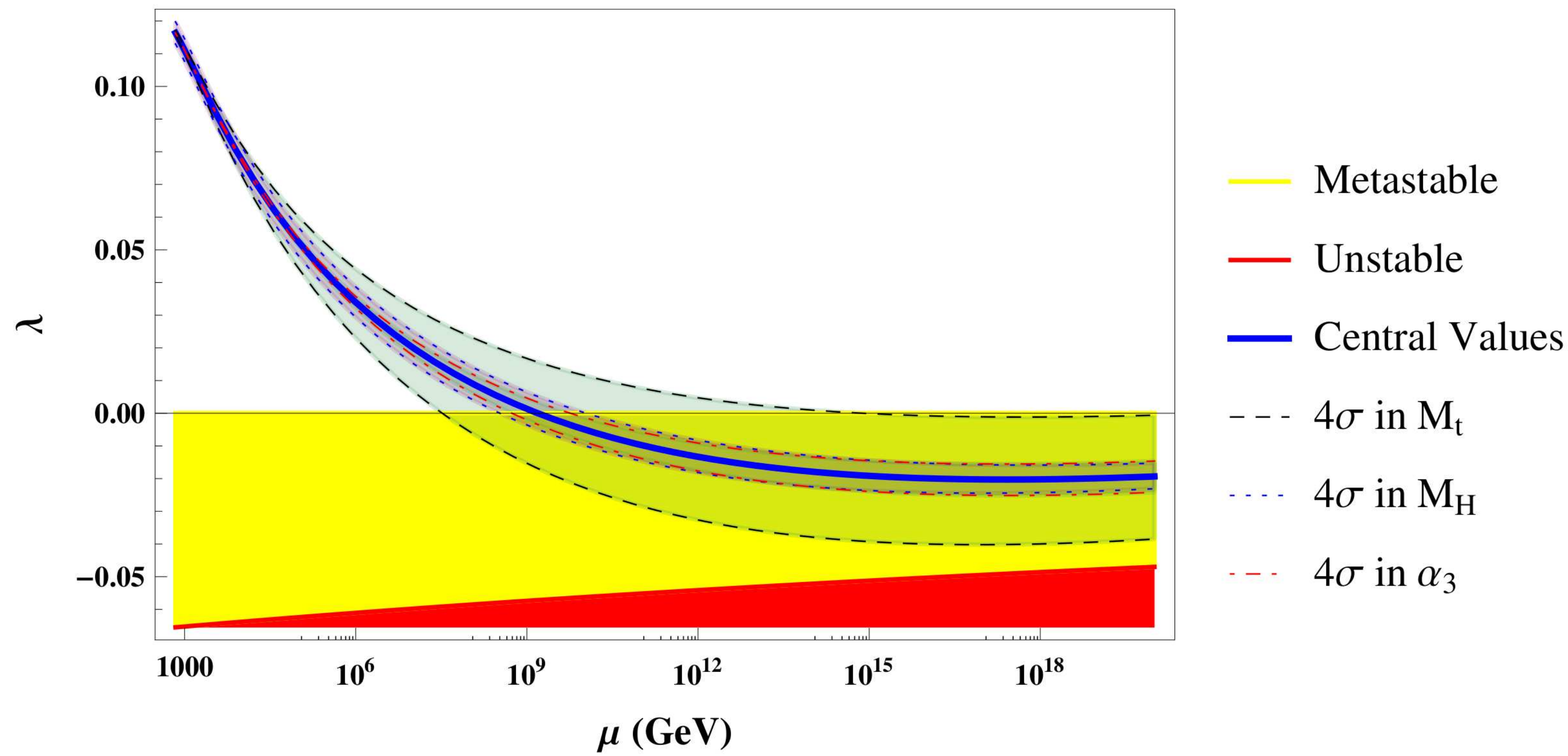
$$\frac{4\pi^2}{3}\frac{d\lambda(t)}{dt} = \lambda^2 - y_t^4 + \ldots$$



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 ??

Problems of the Standard Model

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 <u>original</u> 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

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

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

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
ν_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_μ^α	1	$\mathbf{8}$	$\mathbf{1}$	0
W_μ^a	1	$\mathbf{1}$	$\mathbf{3}$	0
B_μ	1	$\mathbf{1}$	$\mathbf{1}$	0

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 <u>necessary condition</u> for the internal consistency of the SM

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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)

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

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.

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

the physical Higgs boson mass is calculated to be

$$m_h^2 = 2\mu^2 + \delta m_h^2$$

where the quadratically divergent radiative correction is given by

$$\delta m_h^2 \simeq \frac{3}{4\pi^2}(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda)\Lambda^2$$

$\delta m_h^2 < m_h^2.$

$\Lambda < 1$ TeV.

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:** $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$

  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

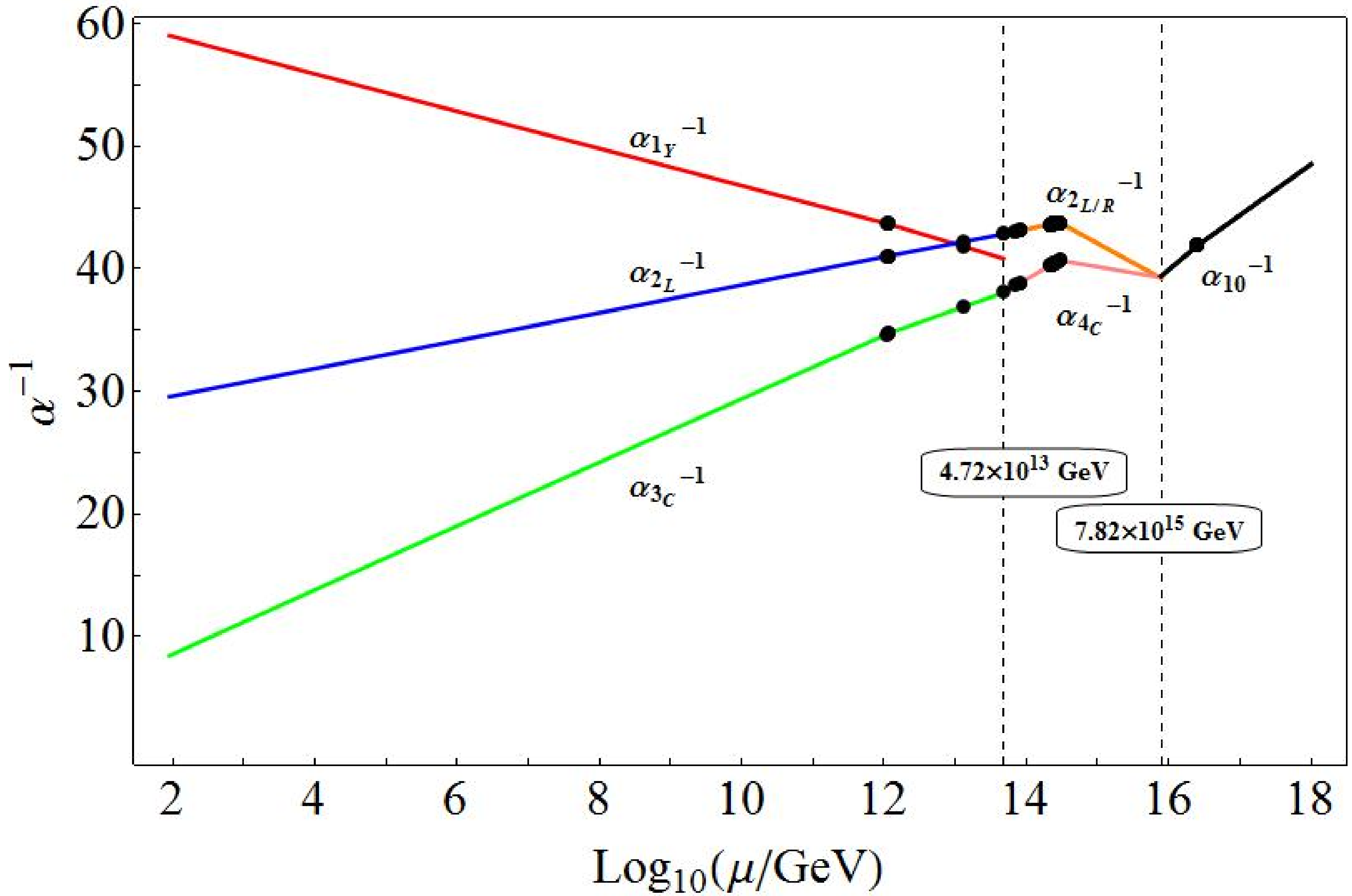
Aesthetics, Symmetry, Religion

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

Conclusions

Conclusions

- **The SM is still in excellent shape**
- **We need detailed understanding of electroweak symmetry breaking (LHC, Future Linear Collider)**
- **Important neutrino oscillation experiments**
- **Low energy experiments probing the SM**
- **DM searches**
- **Ongoing searches at LHC! Never give up!**
- **Theory:**

  It is time to revisit the naturalness problem!
  Alternative ideas/approaches/explanations needed!

  Maybe the SM is valid up to a very high scale. “The desert scenario”.