(B)SM and the LHC

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Summer School in Particle and Astroparticle physics
Annecy-le-Vieux, 23-28 August 2021

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]

- All results are coherent with the expectations of the SM:

  - Spin = 0 [PLB726(2013)120]

  - P=+1, C=+1, CP = +1 [PRD92(2015)012004]

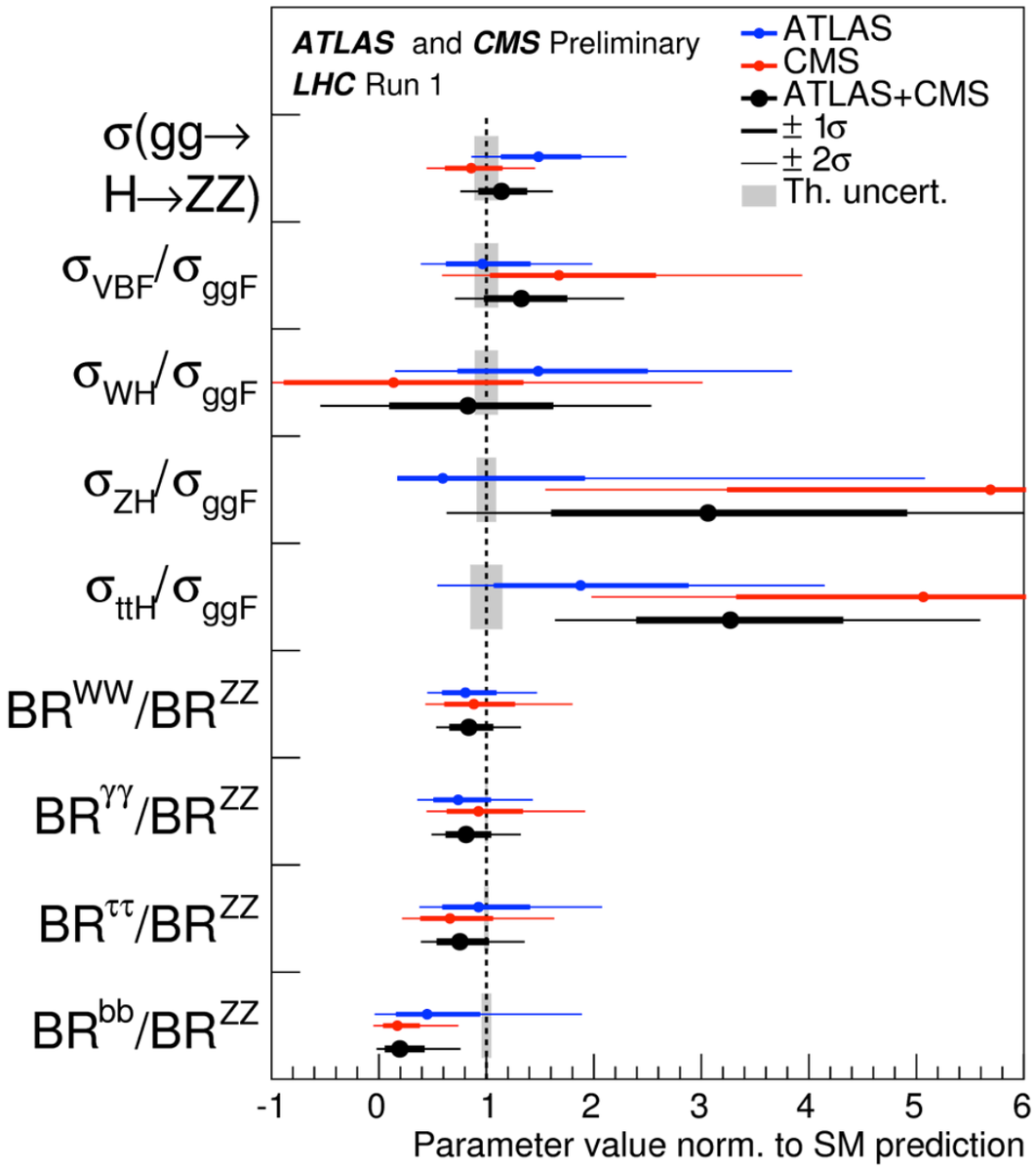
  - Couplings to the vector bosons (Z,W,γ,g) and to the fermions (t,b,τ) in agreement at ~30% precision

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

  Crucial to test the mecanism of EWSB!

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

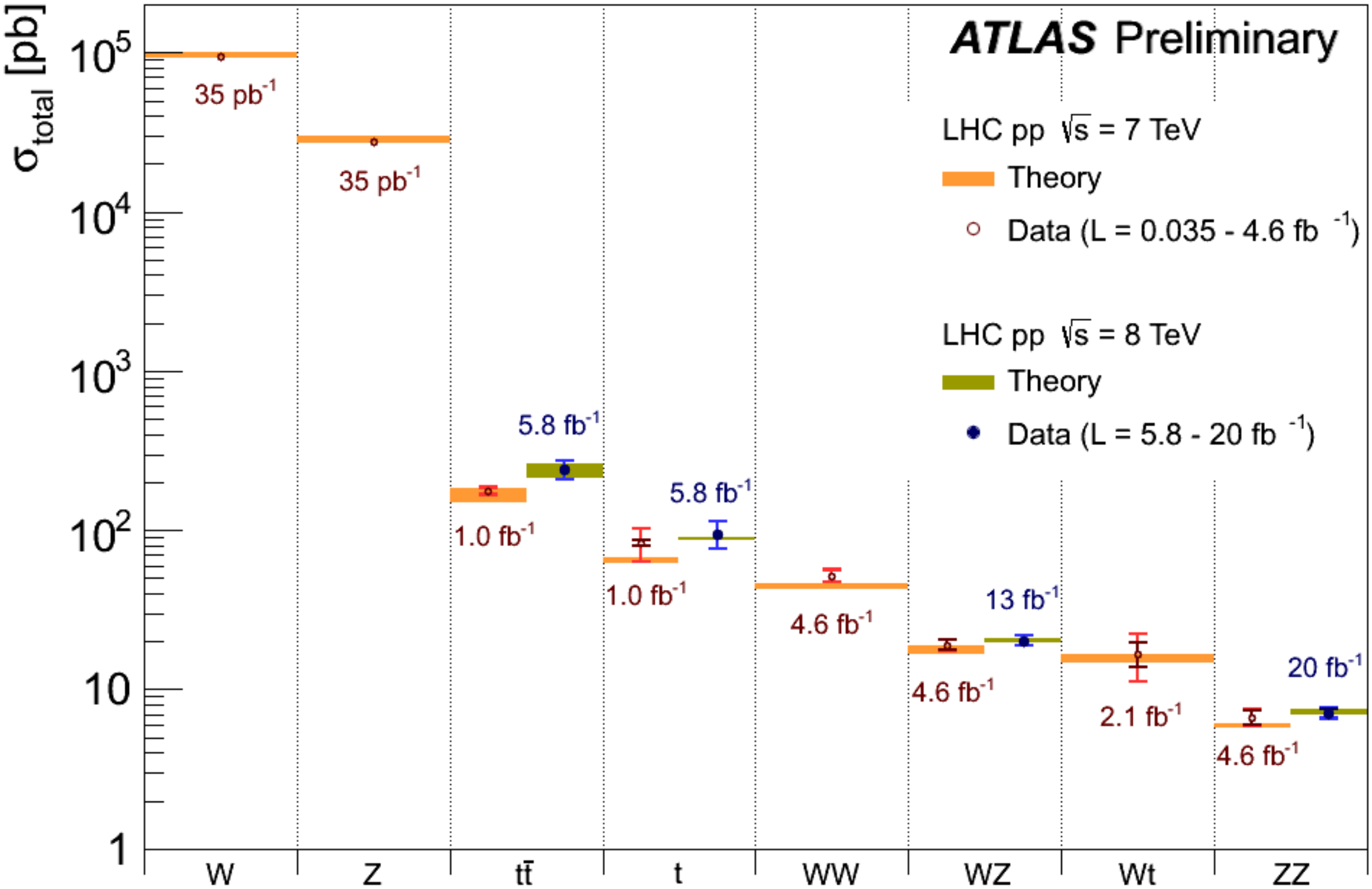
[ATLAS-CONF-2015-044]



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 $SU(3)_c x SU(2)_L x U(1)_Y$ 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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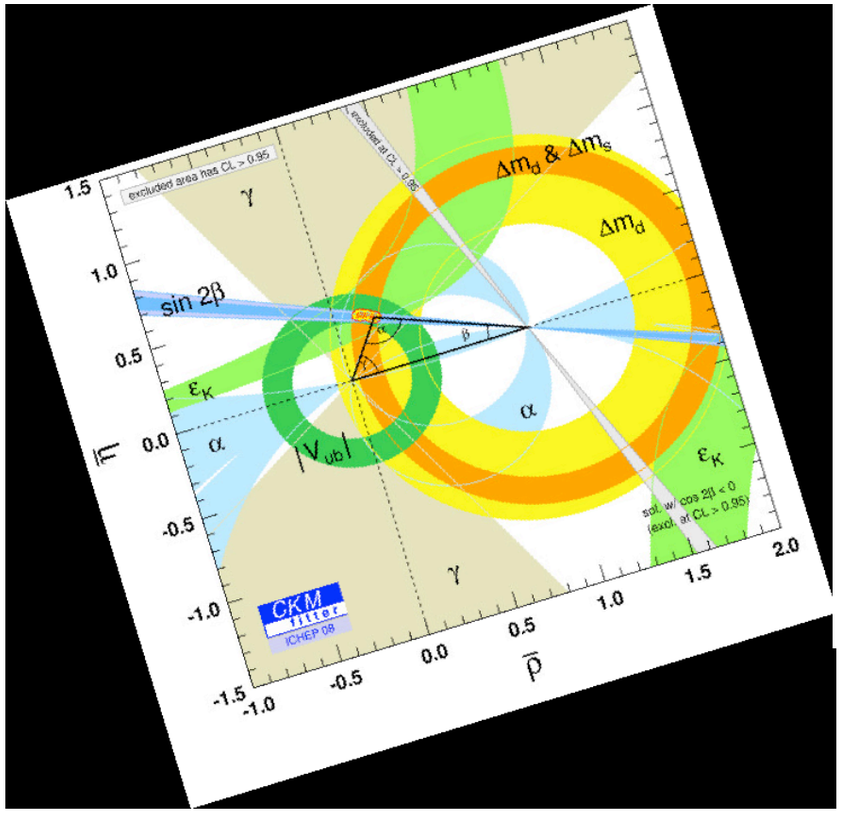
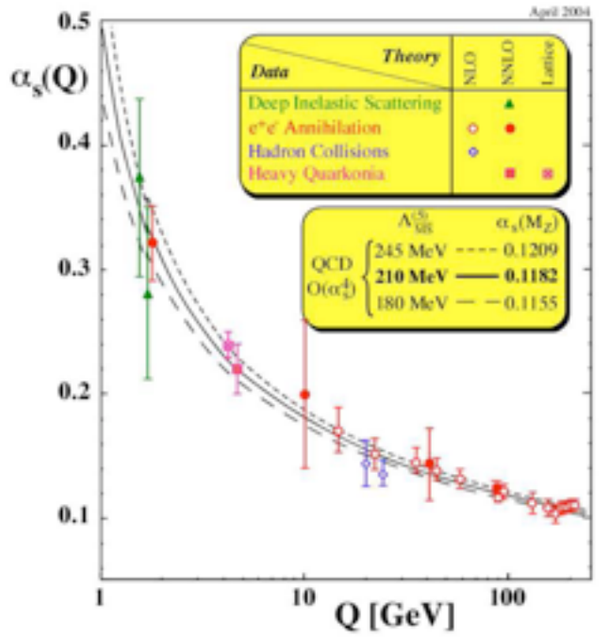
Z
tt̄
t
WW
WZ
Wt
ZZ

CKM angles

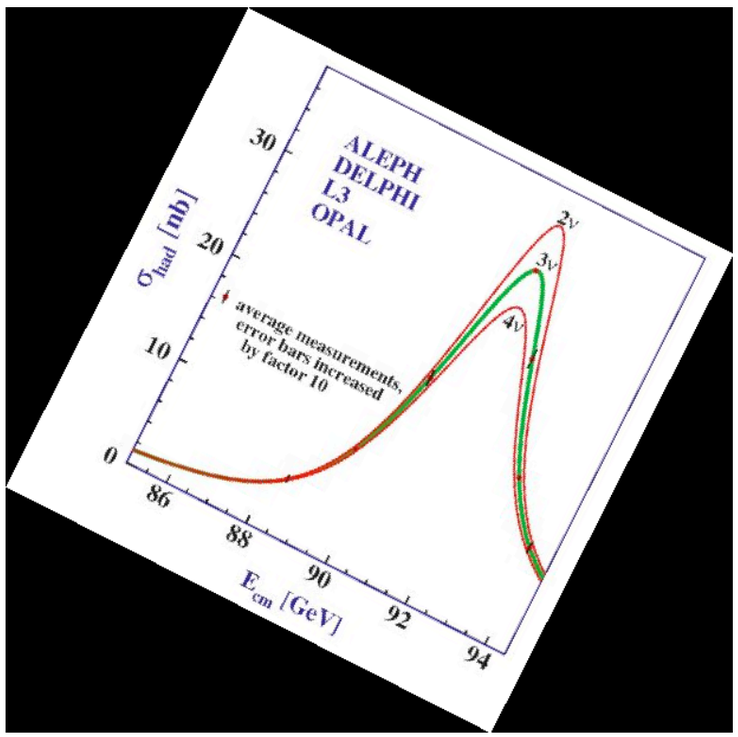




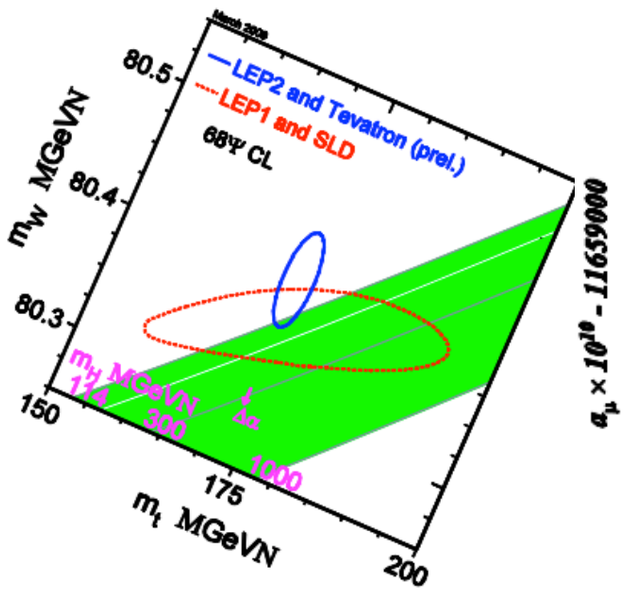
running α_S

EW parameters

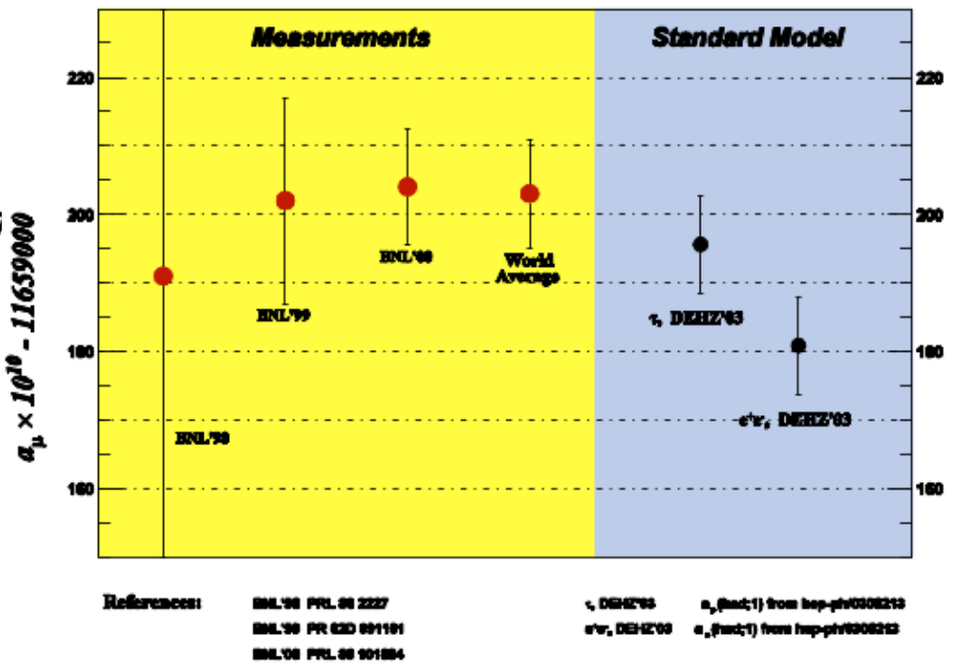
Z^0 width



top and W mass



anom. magnetic moment (g-2)

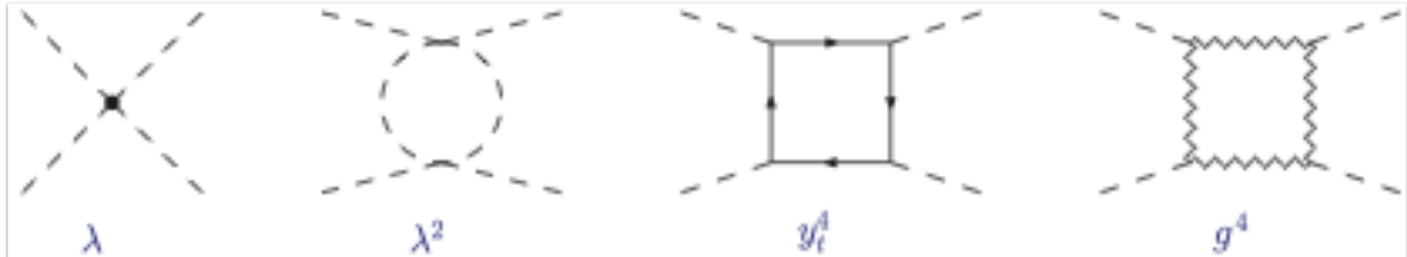


Higgs effective potential

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:

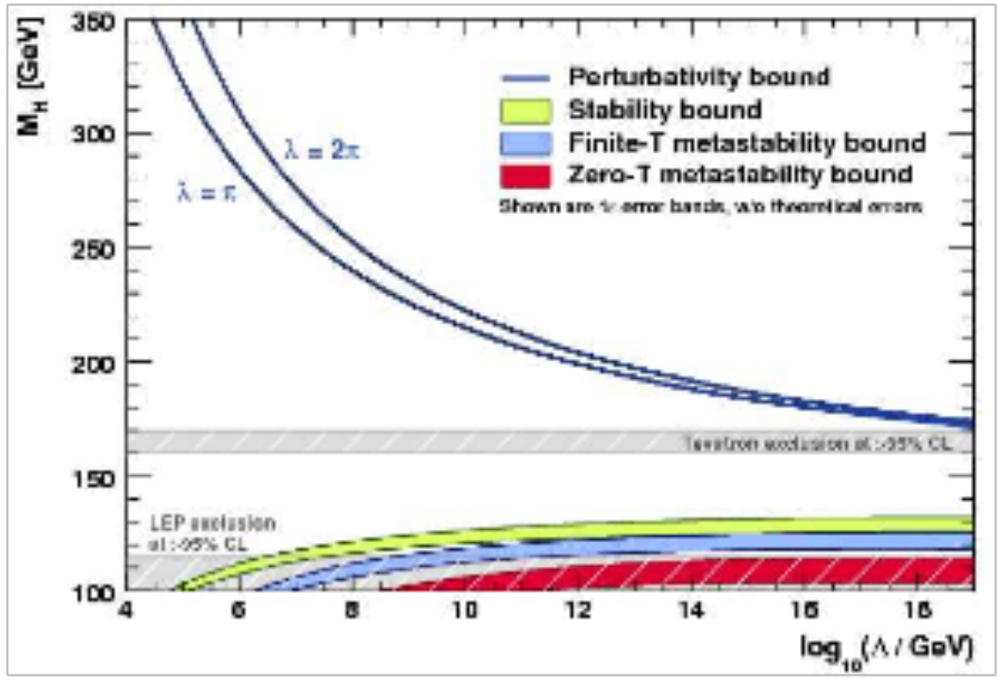
$$\frac{4\pi^2}{3}\frac{d\lambda(t)}{dt} = \lambda^2 - y_t^4 + \dots$$



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

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

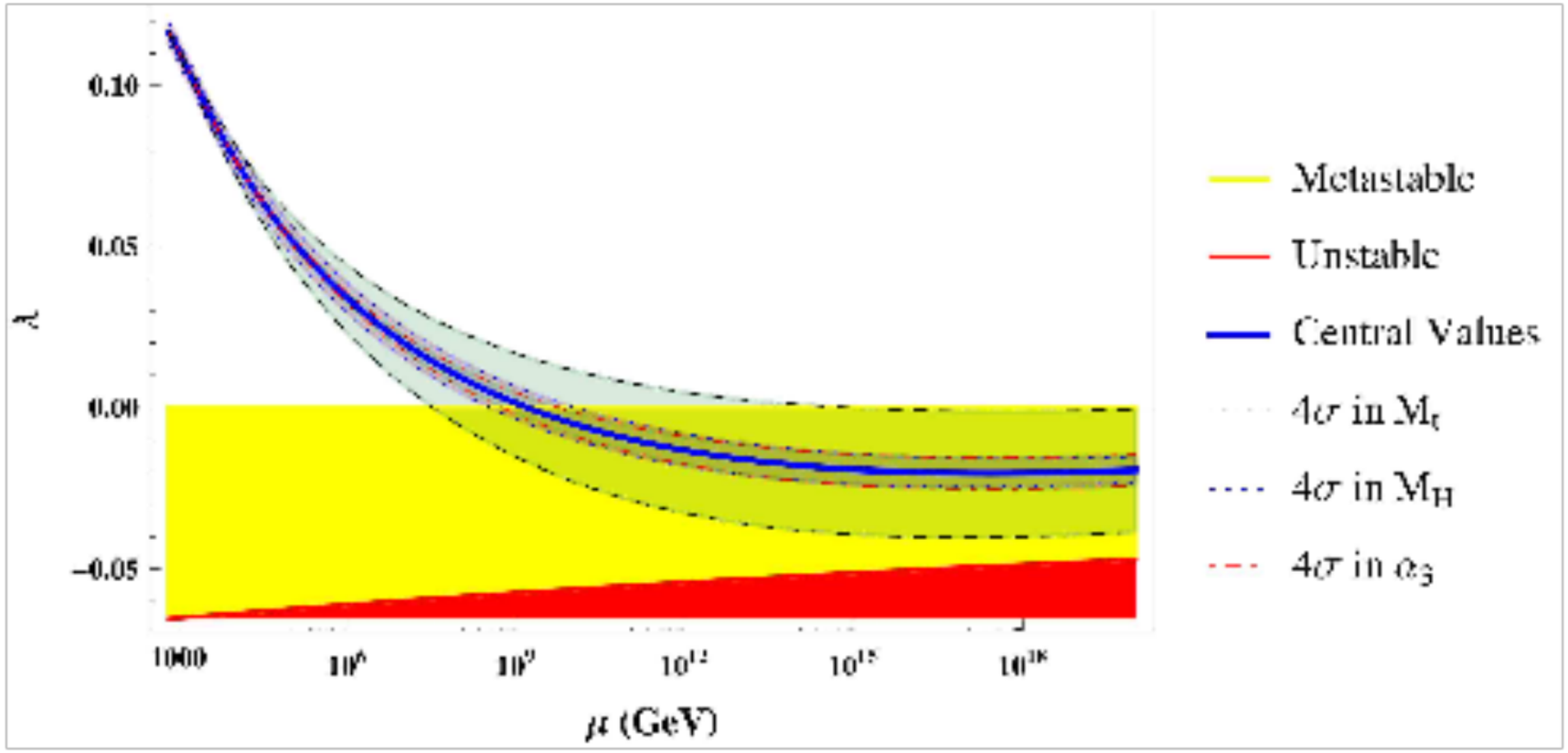
$$\Longrightarrow\ 2\lambda(v)v^2 = M_H^2 < \frac{8\pi^2 v^2}{3\ln(\Lambda^2/v^2)}$$



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...

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
  ⇒ 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	$\frac{1}{2}$	$\overline{\mathbf{3}}$	**1**	$-\frac{4}{3}$
d_R^c	$\frac{1}{2}$	$\overline{\mathbf{3}}$	**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 $\mathscr{L}$ 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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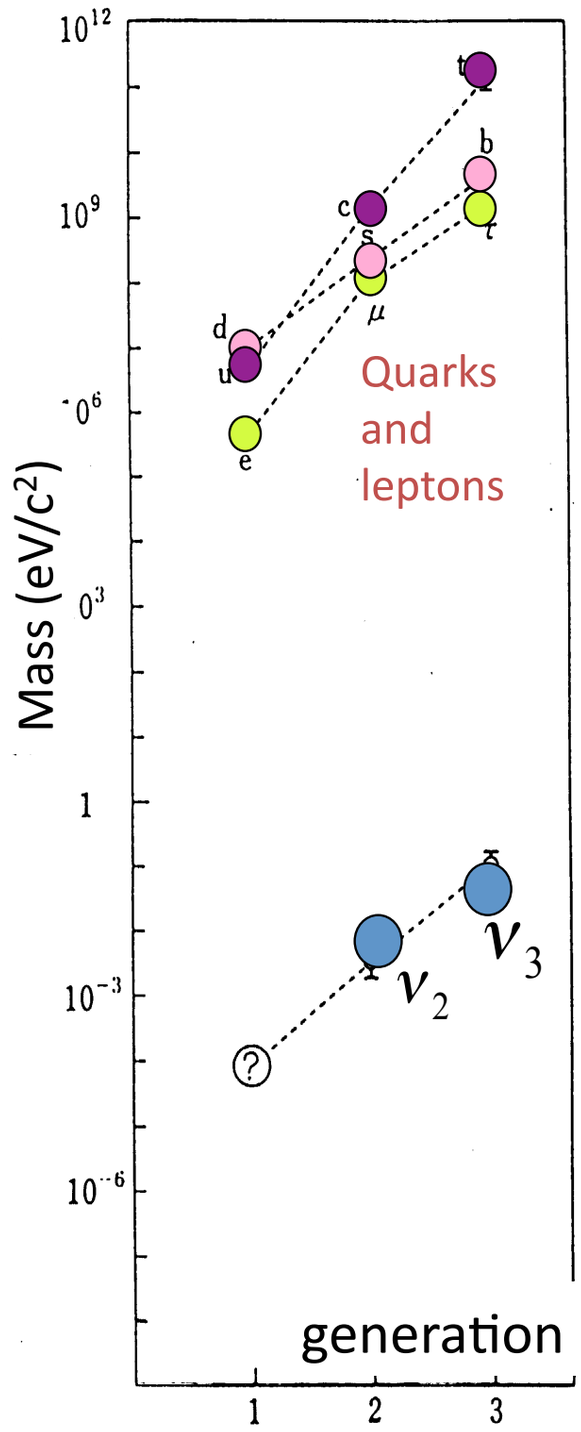
Neutrinos and the Standard Model



Why the neutrino mass is so small ?

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

See-saw mechanism

Minkowsky, Yanagida,
Gell-mann, Ramond, Slansky

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

If we input $m_{\nu 3}$ 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 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

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

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B_μ	1	**1**	**1**	0

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 $\Lambda_{UV} < M_{Pl} \sim 10^{19}$ 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 $\mathcal{L} \ni \frac{c^{(6)}}{\Lambda_{\rm UV}^2} O^{(6)}$ 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

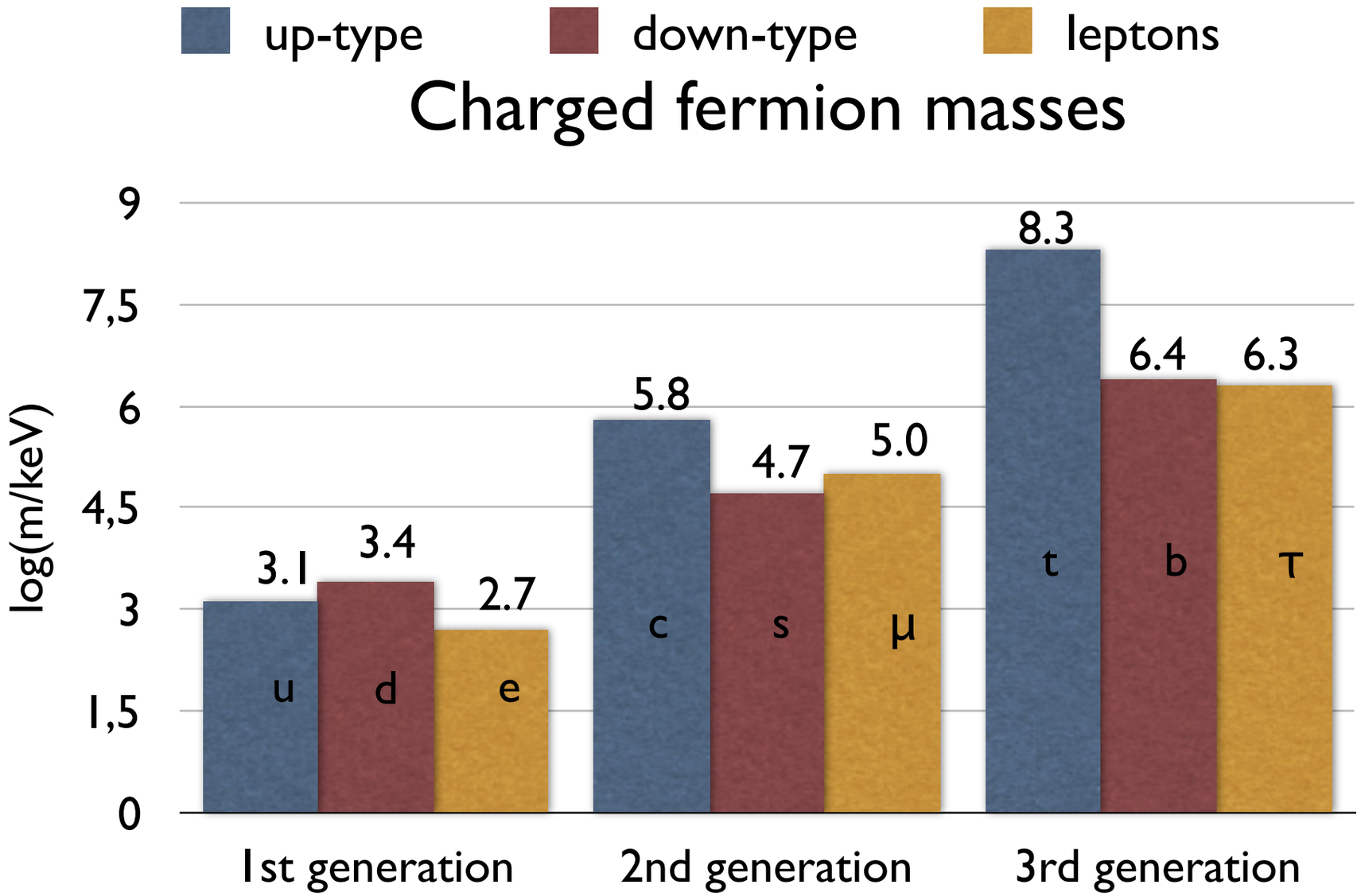
and

how different the mixing in the quark and lepton sector is

a few slides on the so called ‘flavor puzzle’

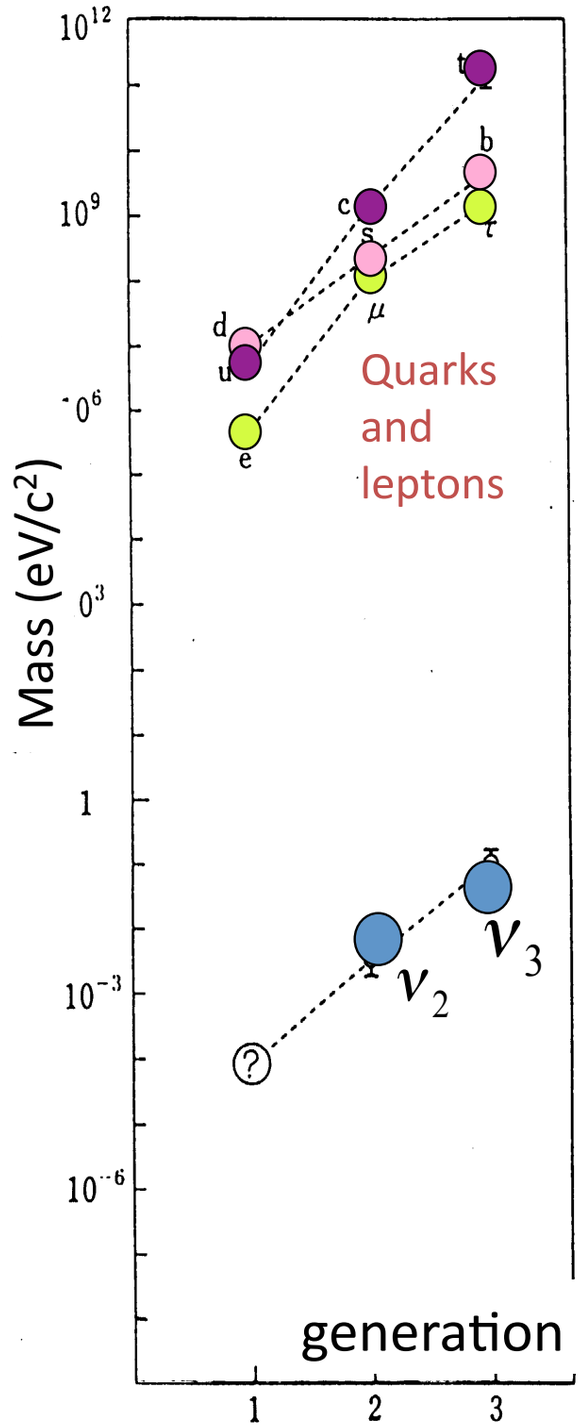
The Flavor Puzzle

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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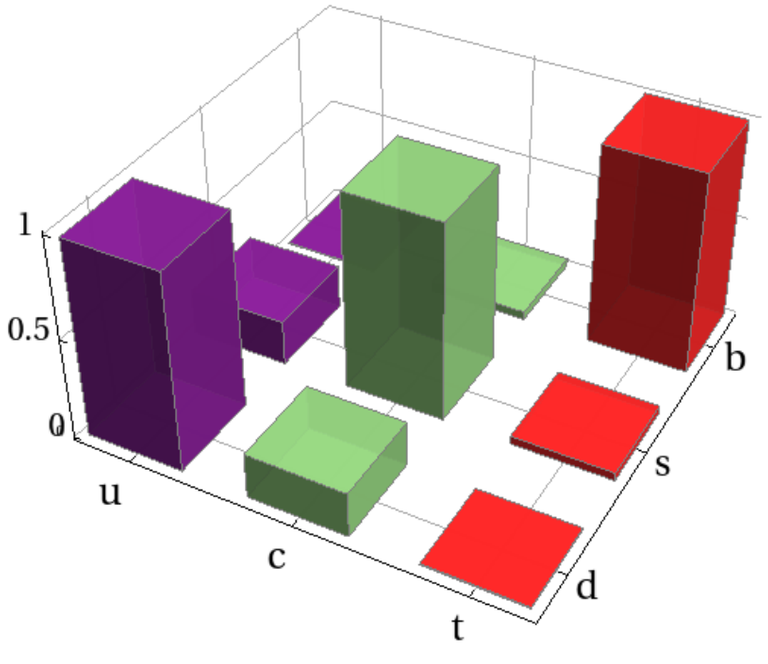
The Flavor Puzzle

Quark and Lepton mixing parameters are quite different!

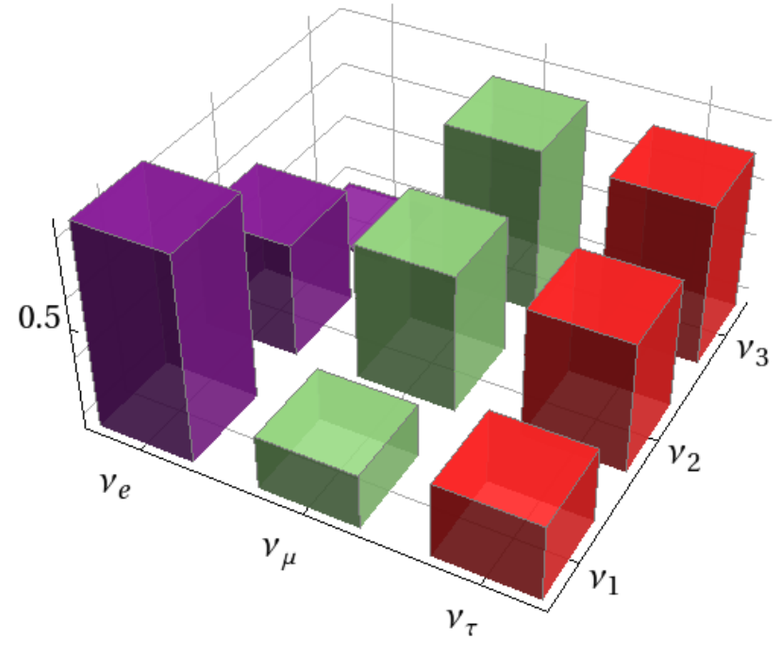
- **Quark Mixings**

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



- **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 Λ_{UV}?

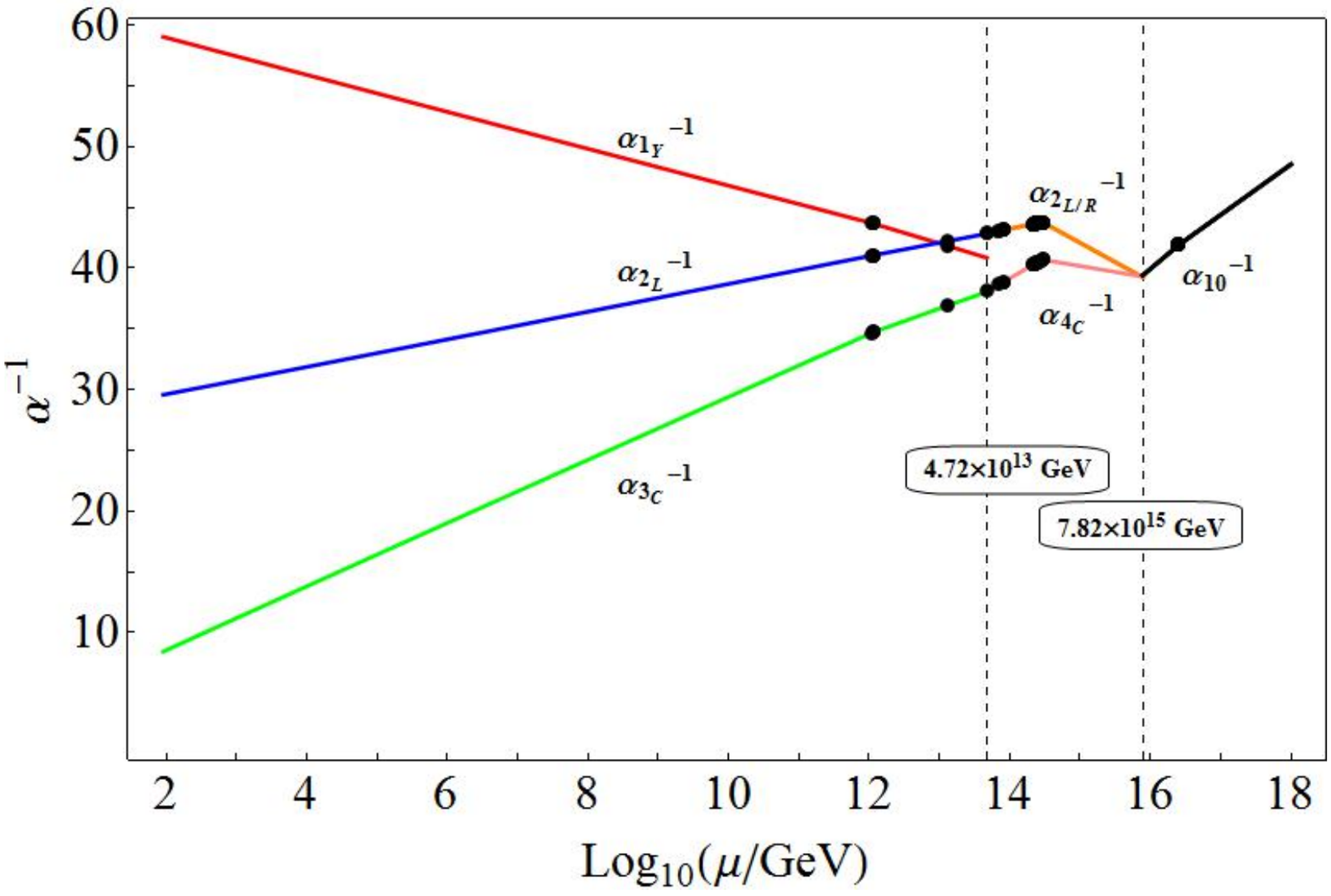
- Despite the phenomenal success of the SM, it is not the theory of everything (if this exists at all)
- The SM is 'only' an effective theory valid up to a scale Λ_{UV}
- What is Λ_{UV}?
  - gravity not part of SM: $\Lambda_{UV} < M_{Pl} \sim 10^{19}$ GeV
  - dark energy not part of SM: $\Lambda_{UV}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

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) 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}] ≤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:
  - $SU(5) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$
  - $SO(10) \rightarrow SU(5) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$
  - $SO(10) \rightarrow G(442) \rightarrow G_{SM} \rightarrow SU(3)_c \times U(1)_{em}$
  - $E_6 \rightarrow SO(10) \rightarrow$ ...
    - 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 $SU(5) \rightarrow G_{SM}$: $5 \rightarrow (3,1)_{2/5} + (1,2)_{-3/5}$

There are also open questions in QCD!

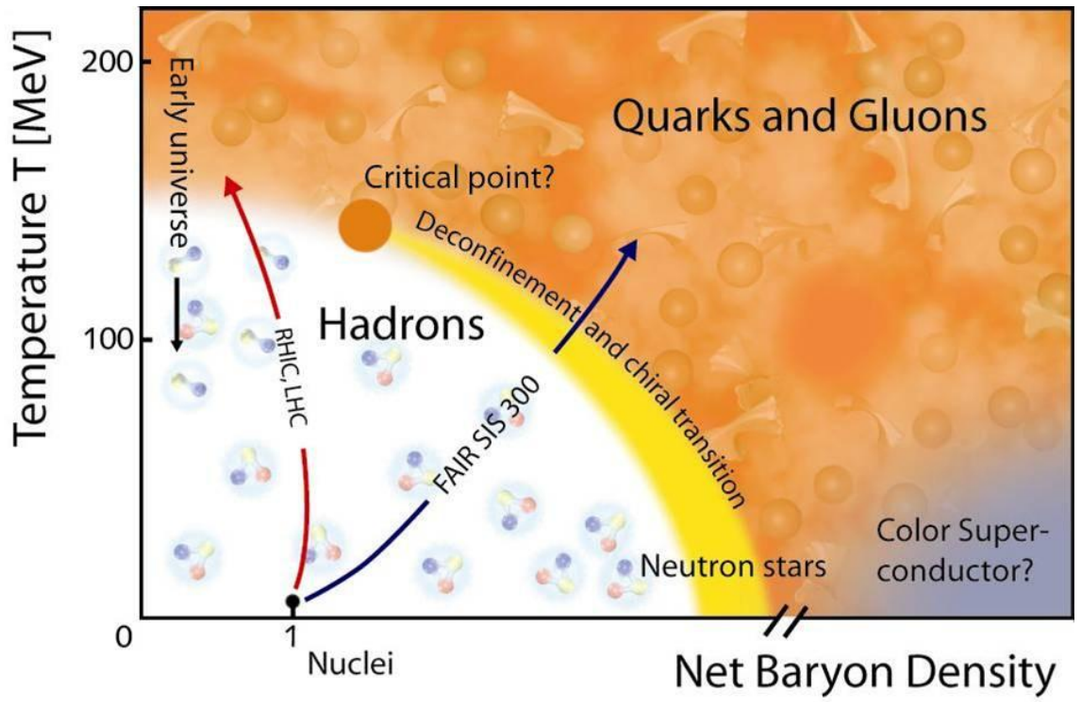
The frontier of particle physics is not just Higgs and BSM physics…

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?

The French community working on QCD > PH is well organized within the GDR QCD

Close interaction EXP-THEO

https://gdrqcd.in2p3.fr/author/marquet/

French theorists Participating in the GDR QCD

IN2P3 labs are in bold

Lab	Name	Situation	Topics/Keywords
APC Paris	**J. Serreau**	University	IR QCD, QCD phase diagram, χSB
CPHT Palaiseau	**R. Boussarie**	CNRS	TMDs, Small-x, Saturation, CGC, Diffraction
	C. Lorcé	University	GPDs, TMDs, Nucleon spin and mass
	C. Marquet	CNRS	TMDs, Small-x, Saturation, CGC, Diffraction, Quarkonia
	S. Munier	CNRS	Diffraction, Quarkonia, Parton branching
	B. Pire	Emeritus	GPDs, DVCS, TCS, Diffraction
	U. Reinosa	CNRS	IR QCD, QCD phase diagram, χSB, QCD at finite T
CPT Marseille	**A. Bharucha**	CNRS	B and D decays, BSM: Flavor, Compositeness, DM, SUSY
	J. Charles	CNRS	Lattice QCD, $(g-2)_\mu$, B decays, Flavor, CKM, BSM
	E. De Rafael	Emeritus	Lattice QCD, $(g-2)_\mu$, hadronic vacuum polarization (HVP)
	A. Gérardin	University	Lattice QCD, $(g-2)_\mu$, HVP, B decays, HQET
	M. Knecht	CNRS	K decays, $(g-2)_\mu$, HVP, Compositeness, Higgs-ew chiral L
	L. Lellouch	CNRS	Lattice QCD, $(g-2)_\mu$, HVP, $m_{u,d,s}$, decay constants
	S. Zafeiropoulos	CNRS	Lattice QCD, pseudo-PDFs (nucleon, pion), $\alpha_s^{\overline{\rm MS}}(M_Z)$
DphN Saclay	**C. Mézrag**	CEA	GPDs, pion/kaon valence PDFs from DSE, $\alpha_s^{\rm eff}$
	H. Moutarde	CEA	GPDs, TMDs
IJCLab Orsay	**D. Becirevic**	CNRS	Lattice QCD (ETMC), B decays, Flavor physics, Leptoquarks
	B. Blossier	CNRS	Lattice QCD, B, D, Charmonia decays
	J. Carbonell	CNRS	Few body systems, relativistic bound states
	S. Decotes-Genon	CNRS	b-hadron decays, flavor physics, CKM, BSM
	S. Friot	University	K/π decay const., χPT, multi-loop, $(g-2)_\mu$, hypergeom. functions
	M. Fontannaz	Emeritus	last paper from 2017, prompt photons, photon-jet correlations
	E. Kou	CNRS	Flavor physics, B physics, hadronic τ decay
	J.-P. Lansberg	CNRS	Heavy quark(-onium) prod., PDFs, TMDs, CNM effects, DPS
	U. van Kolck	CNRS	Nuclear EFTs, χEFT, bound nucleon decay
	S. Wallon	University	GPDs, TMDs, Small-x, Diffractive exclusive processes, Saturation
IPhT Saclay	**J.-P. Blaizot**	Emeritus	QGP: fluid dynamics, heavy quark(-onia), $\hat{q}$, diffractive J/Ψ prod.
	F. Gelis	CEA	CGC, initial state of heavy ion collisions
	E. Iancu	CNRS	Small-x, CGC, non-linear evolution, Saturation, Jets in QGP
	G. Korchemsky	CNRS	Conformal theories, scatt. amplitudes, $\mathcal{N}=4$ SYM, $\mathcal{N}=2$ SYM
	D. Kosower	CEA	Conformal theories, scattering amplitudes, $\mathcal{N}=4$ SUGRA
	J.-Y. Ollitrault	CNRS	HI collisions: initial conditions, particle flow, hydrodynamic sim.
	G. Soyez	CNRS	Jets: substructure, in medium, small-x, BK evol., Parton Showers
IP2I Lyon	**H. Hansen**	University	Grav. waves, Dense matter, QCD phase diagram, χEFT
LAPTH Annecy	**J.-P. Guillet**	CNRS	Two-loop integrals, JetPHOX, FFs
	E. Pilon	CNRS	Two-loop integrals, Higgs
	E. Re	CNRS	Precision calc: NNLO+PS, N^{3}LL+NNLO, Higgs, VV, $t\bar{t}$, DY
L2C Montpellier	**J.-L. Kneur**	CNRS	RG improved QCD pressure, Higgs compositeness
LLR Palaiseau	**F. Arleo**	CNRS	Coherent energy loss in pA, R_{pA}: DY, J/Ψ, light hadrons, p_T-broad.
LPC Clermont	J.-F. Mathiot	CNRS	RGEs, TLRS regularization: axial anomaly
	V. Morenas	University	Lattice QCD, Heavy flavour mesons
LPSC Grenoble	**M. Mangin-Brinet**	CNRS	Lattice QCD (ETMC), $m_{u,d,s,c}$, $F_\pi(Q^2)$, $\langle r^2\rangle_\pi$
	I. Schienbein	University	PDFs, HQ production, FFs, BSM: NLO QCD+PS calc., RGE
LPTHE Paris	**M. Cacciari**	University	Higher order QCD/QED, Jets, HQ production, VBF Higgs at NNLO
	B. Fuks	University	BSM: VLQ, DM, Z', LR, Higgs, SUSY, Reinterpret.: MADAnalysis
	H.-S. Shao	CNRS	Heavy quark(-onium) prod., Higher orders, Automation, SM, BSM
Subatech Nantes	**J. Aichelin**	University	HI, QGP, transport models, PJNL: phase diagram, EPOS-HQ
	J. Ghiglieri	CNRS	QGP, shear viscosity/hydrodynam. at NLO QCD, pert. thermal QCD
	P.-B. Gossiaux	University	HI, QGP: energy loss, HQ/Jets, EPOS-HQ, EPOS3-Jet
	T. Gousset	University	HI, QGP: energy loss, jet-correlations, HQ
	M. Nahrgang	University	HI, QGP, HQ, HQ transport, QCD phase diagram
	S. Peigné	CNRS	Coherent energy loss in pA, R^h_{pA}, p_T-broadening
	T. Sami	University	HI, QGP, Critical fluctuations near QCD critical point, energy loss
	A. Smilga	University	Mathematical physics
	K. Werner	University	EPOS3, EPOS-HQ, EPOS-Jet, EPOS and Air Showers, HQ transport