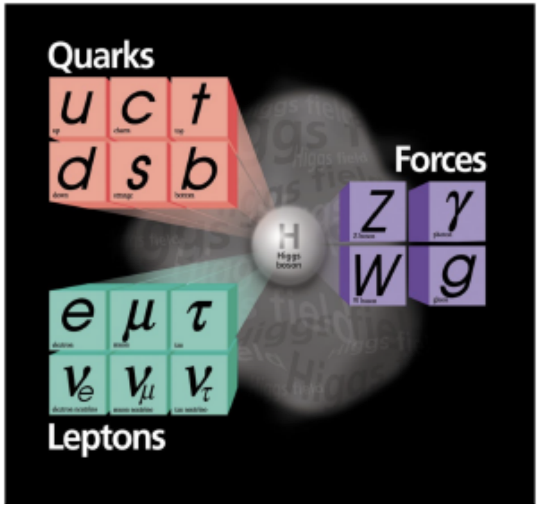
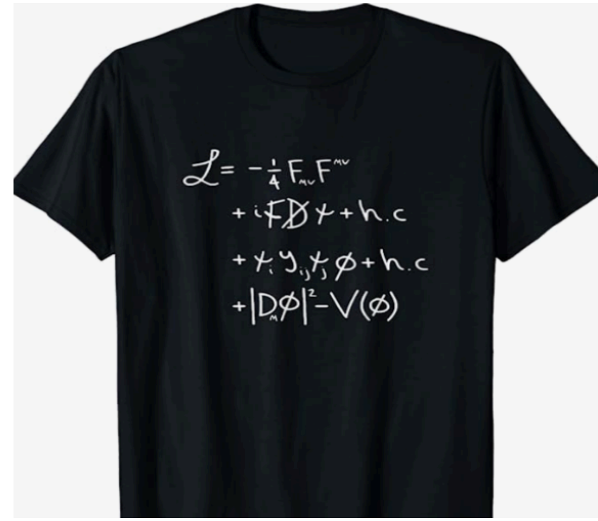
ISAPP2023: Neutrino physics , astrophysics and cosmology – SIF, Varenna, 26 June – 6 July 2023



MICRO-COSMOS



Basics on particle physics.

Structure of the

Standard Model of particle physics

Antonio Masiero

University of Padua and INFN

- By the end of the 20^{th} century … **we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]**

D. Gross 2007

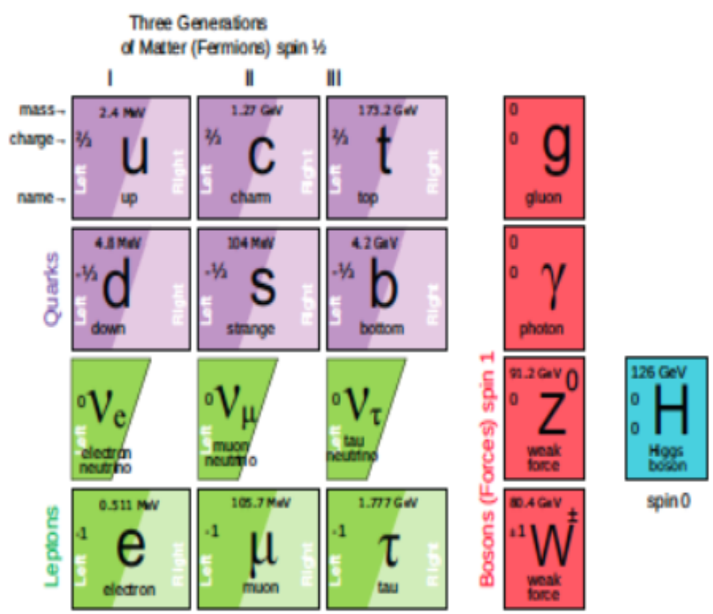
LECTURES I – II

- Where the **two infinities** touch each other: a bird's-eye view of the **Standard Models (SM) of particle physics and of cosmology**
- **Symmetries** and fundamental interactions
- The **QED** and **QCD** lessons
- **Spontaneous breaking** of a (gauge) symmetry and the **Higgs mechanism.** The appearance of the **electroweak energy scale**.
- The structure of the **SM of particle physics**.
- **Masses** and **mixings** of the SM **fermions**. **CP violation** in the SM
- The exceptional **points of strength** of the SM

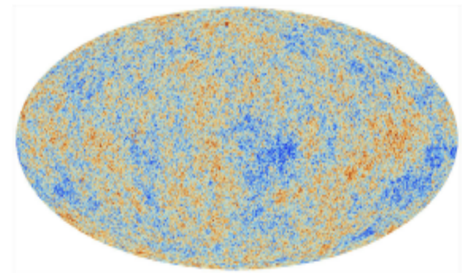
In this last decade → the triumph of the

STANDARD

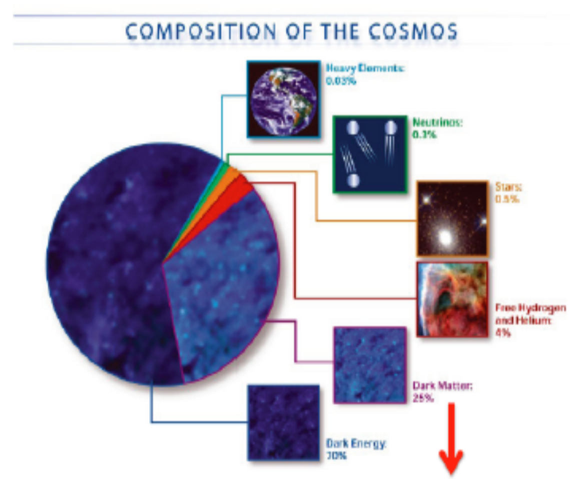
- PARTICLE STANDARD MODEL



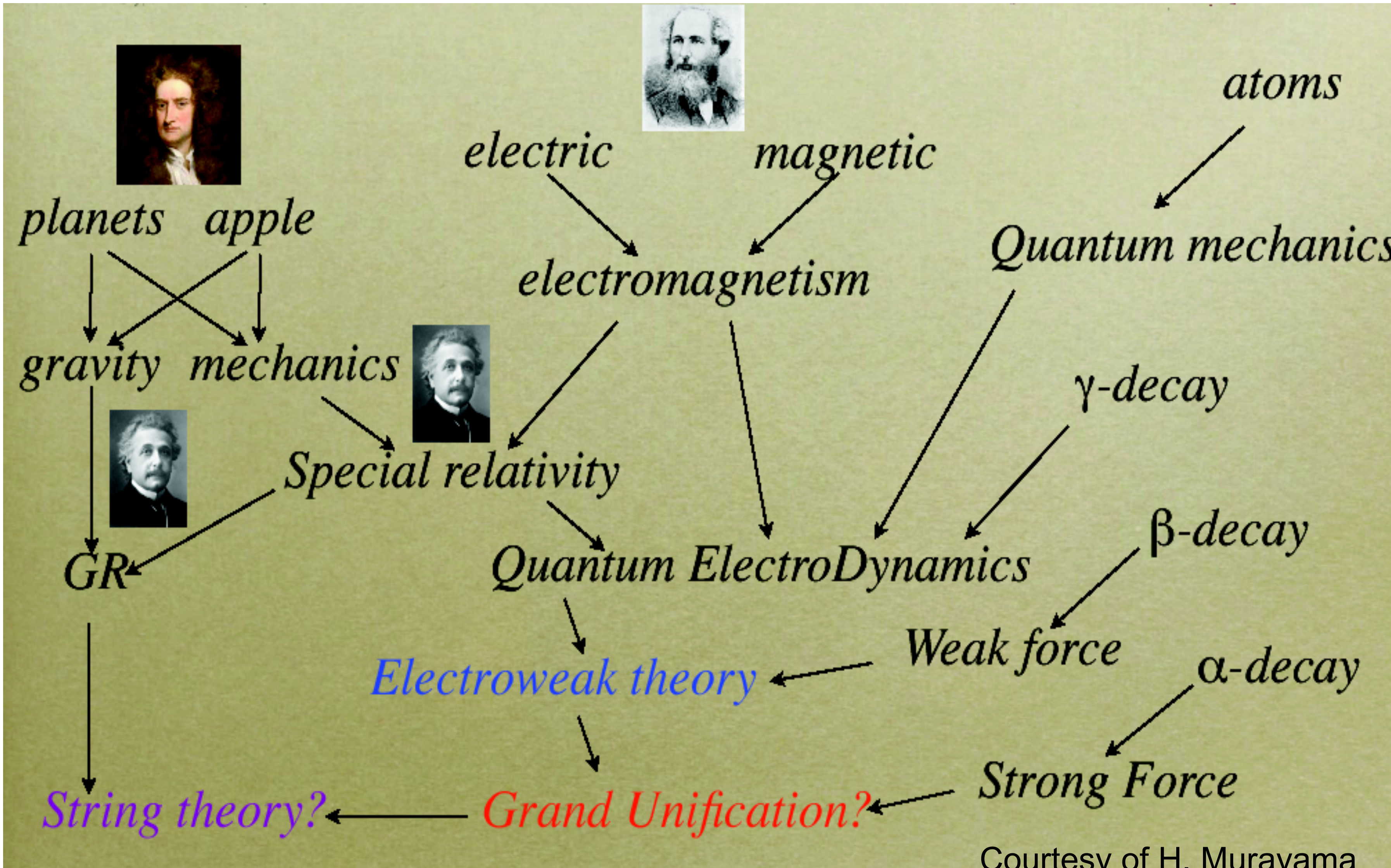
- COSMOLOGY STANDARD MODEL



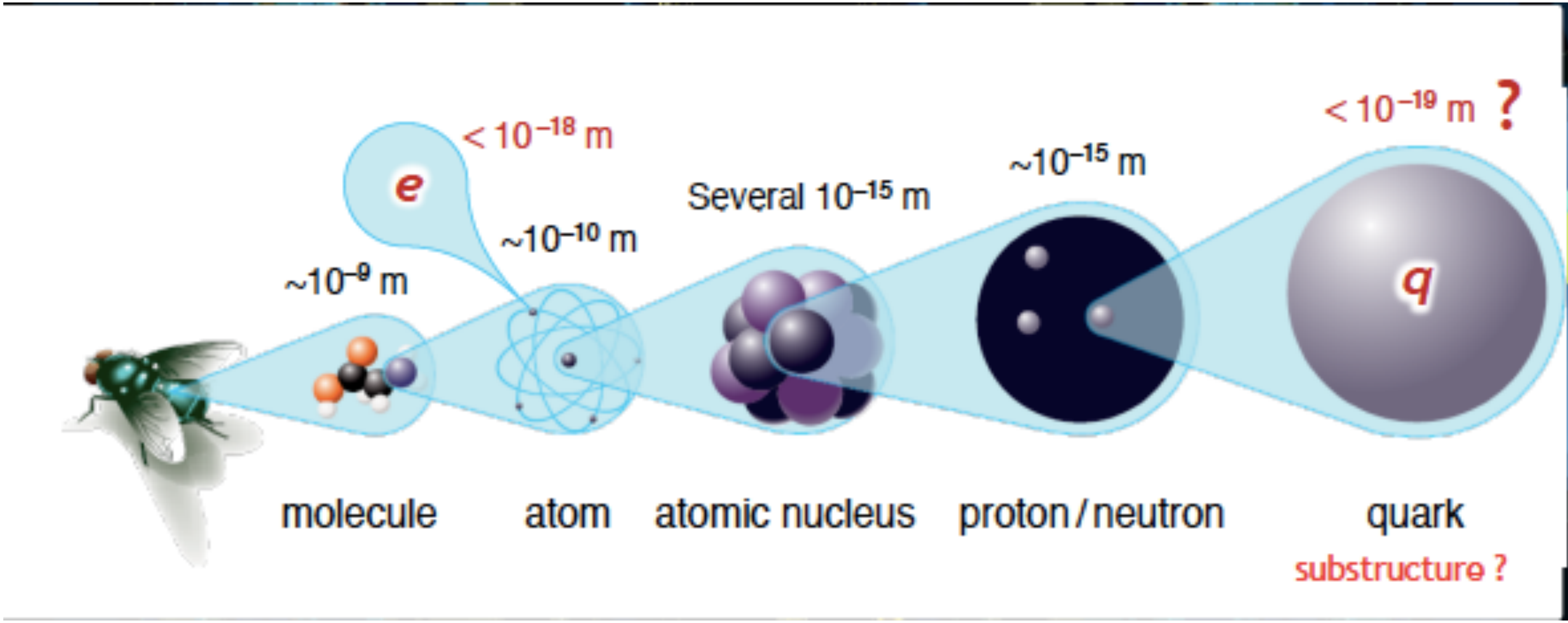
ΛCDM + "SIMPLE" INFLATION



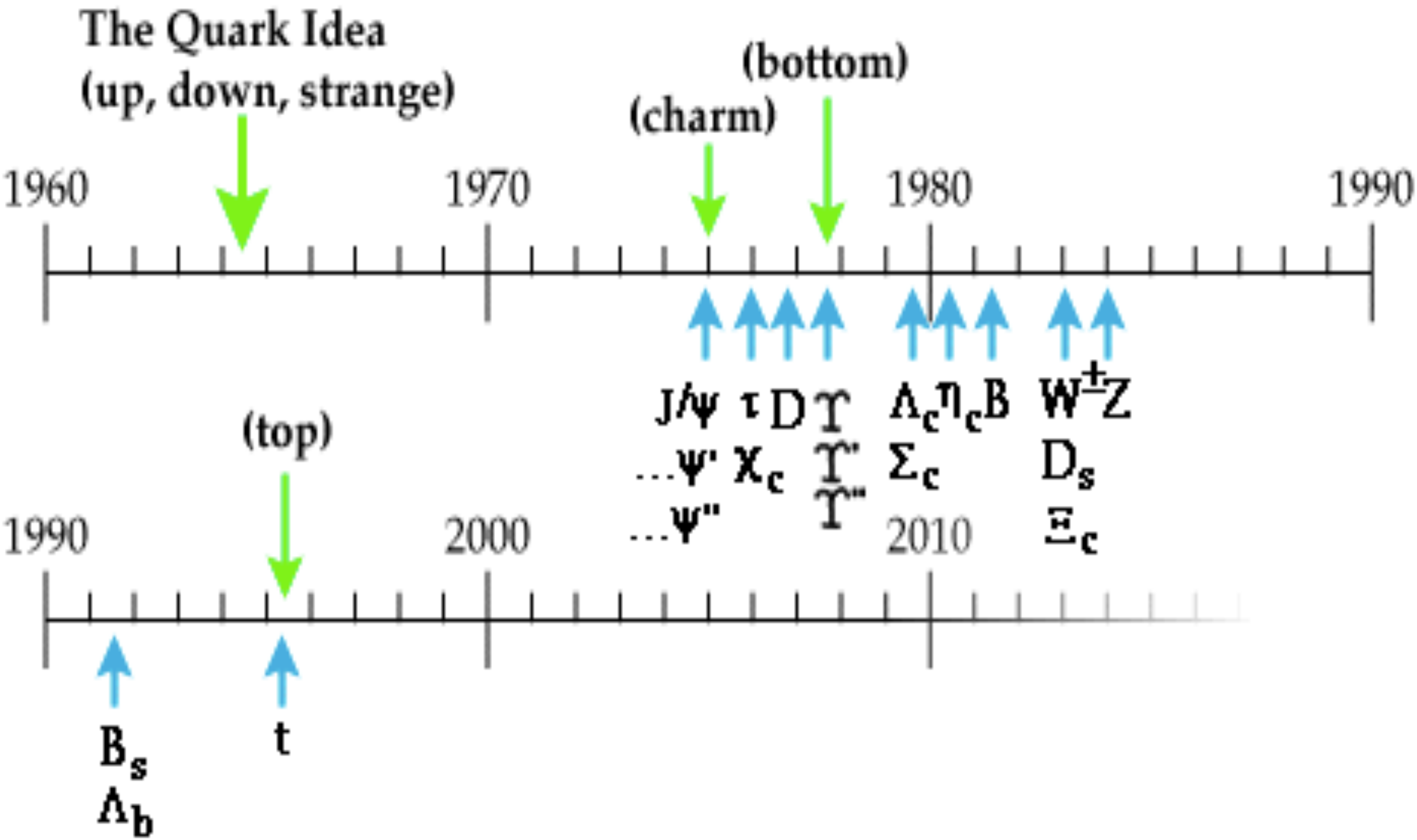
UNIFICATION of FUNDAMENTAL INTERACTIONS



MICRO-COSMOS



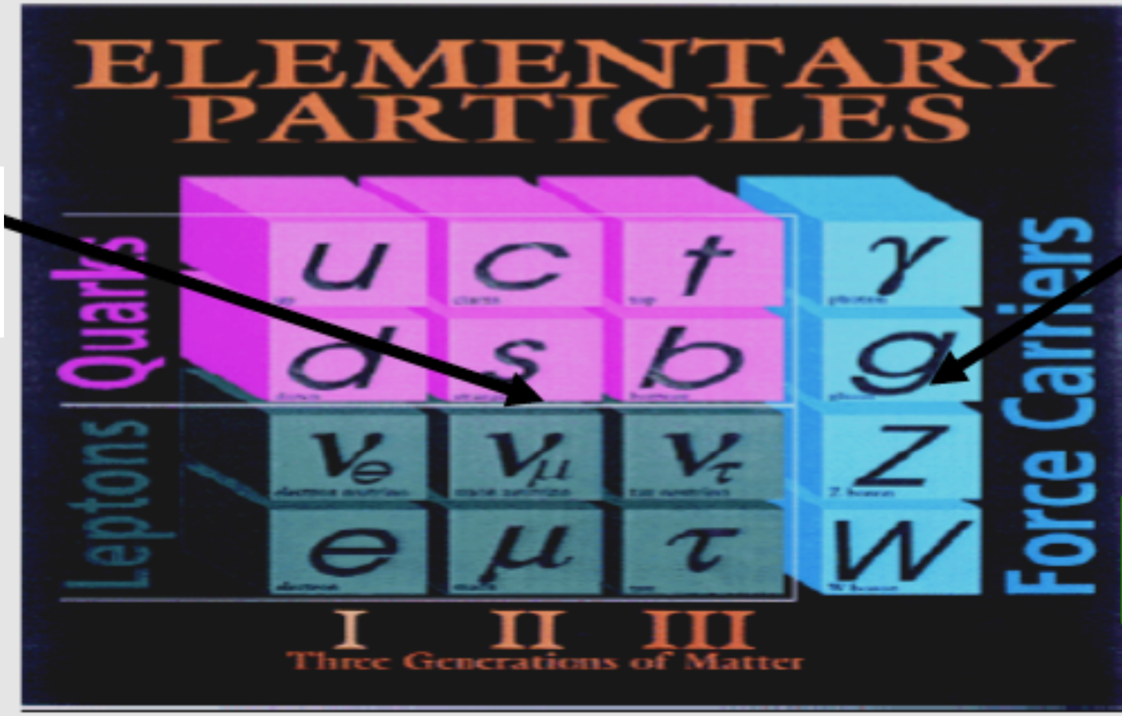
HUNTING FOR THE QUARKS



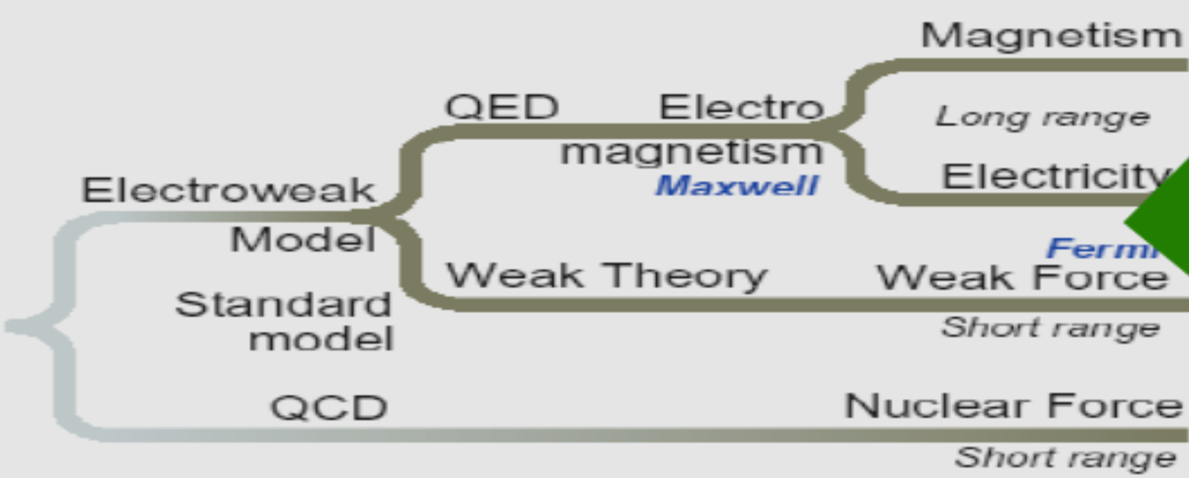
SM OF ELEMENTARY PARTICLES AND FUNDAMENTAL INTERACTIONS

MATTER

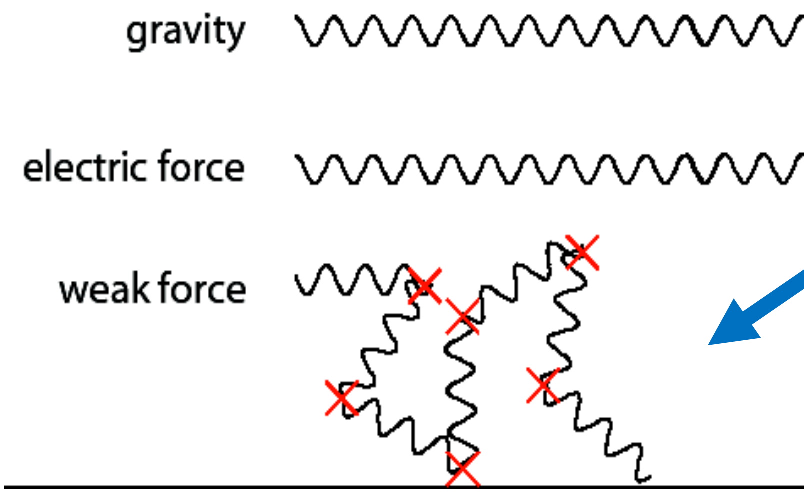
RADIATION

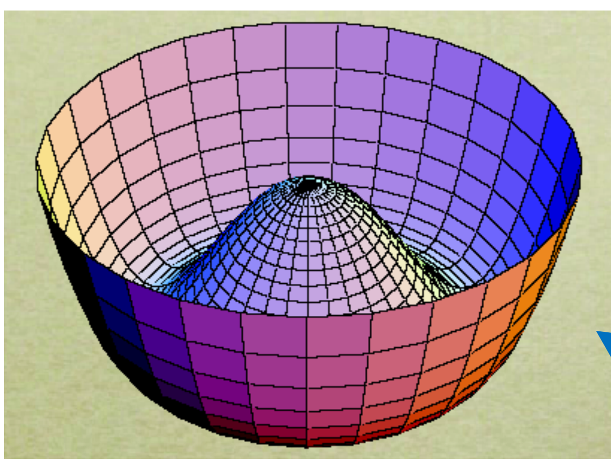


Grand
Unified
Theory
GUT



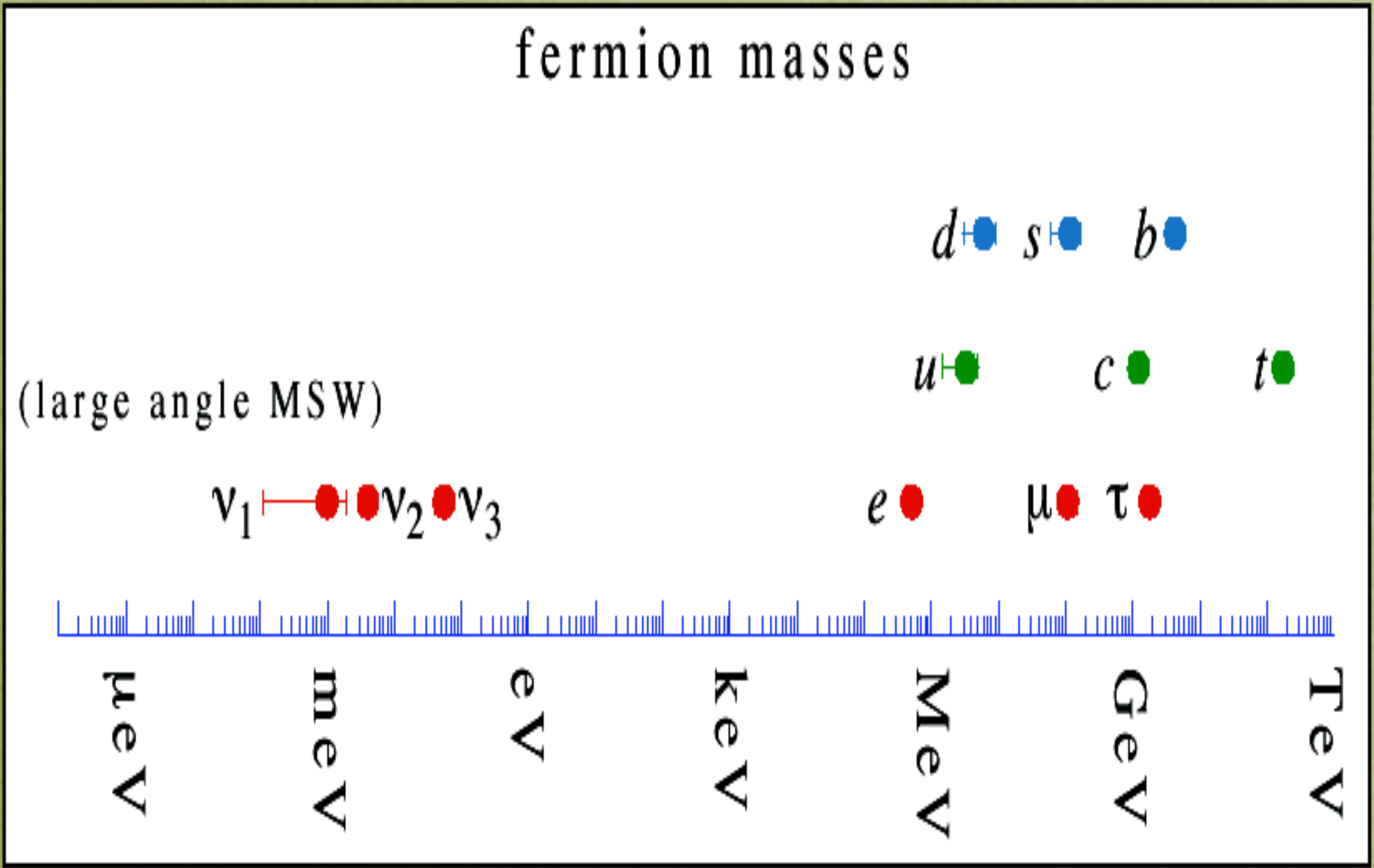
The HIGGS BOSON CONDENSATE





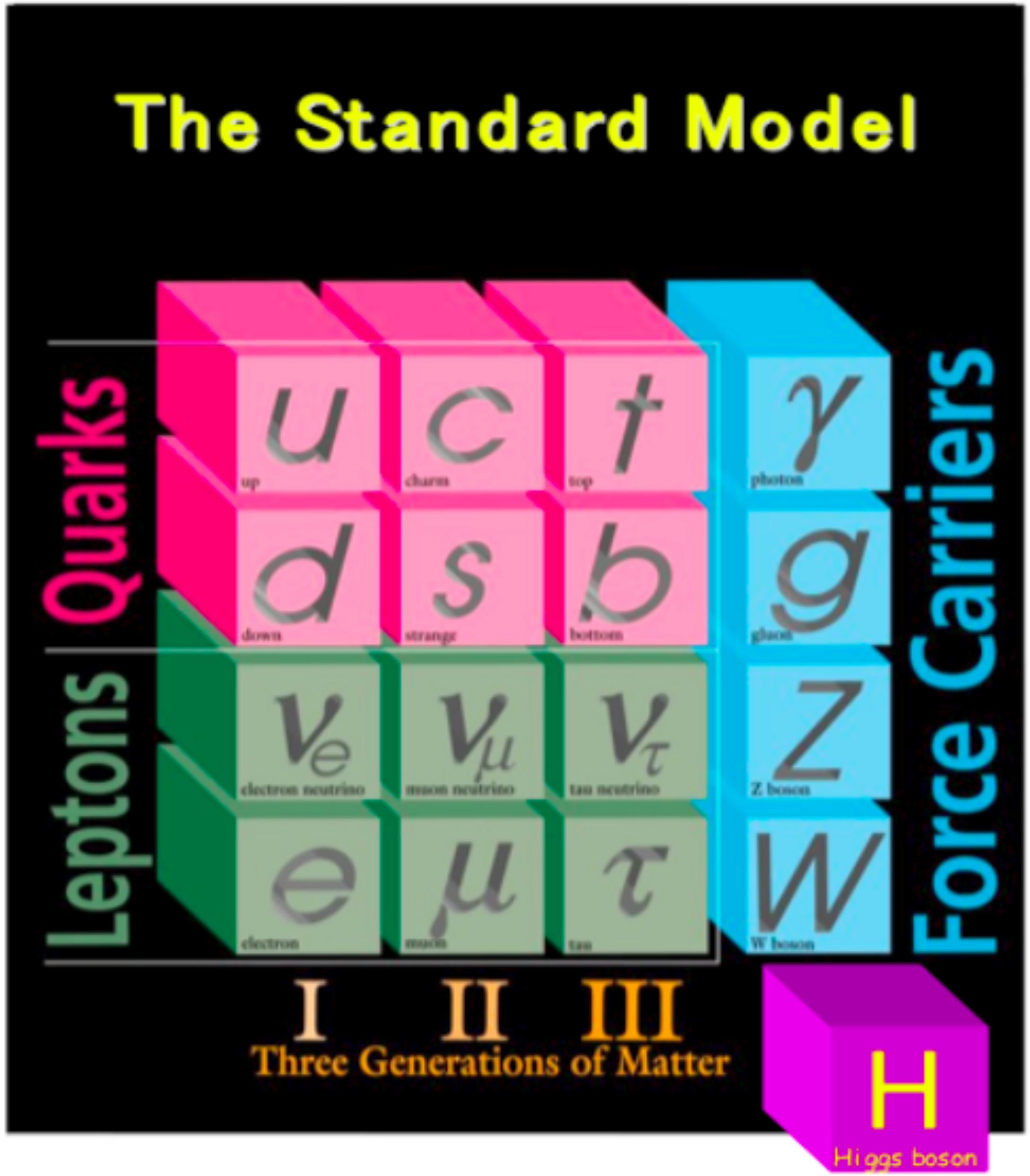
- "SOMETHING" fills the Universe: it "disturbs" **Weak interactions** making them **SHORT-RANGED,** while it does **NOT** affect **gravity** or **electromagnetism.**
- WHAT IS IT?
- Analogy with **SUPERCONDUCTIVITY**: in a superconductor the magnetic field gets repelled (**Meissner effect**) and penetrates only over the "penetration length", i.e. the magnetic field is short-ranged → source which disturbs are the **boson condensates**, **Cooper pairs.**
- We are "swimming" in **Higgs Boson Condensates** → its value at the minimum of its potential determines the masses of all particles!

THE FERMION MASS PUZZLE



Gravity

?



? → **EXP. 2012**

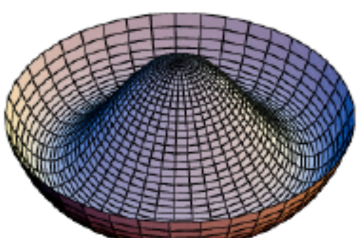
MICRO-COSMOS

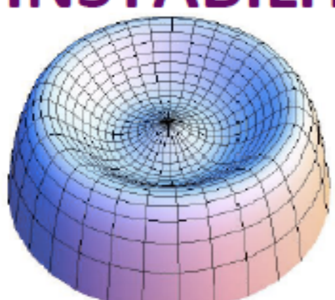
MACRO-COSMOS

- **PARTICLE STANDARD MODEL**

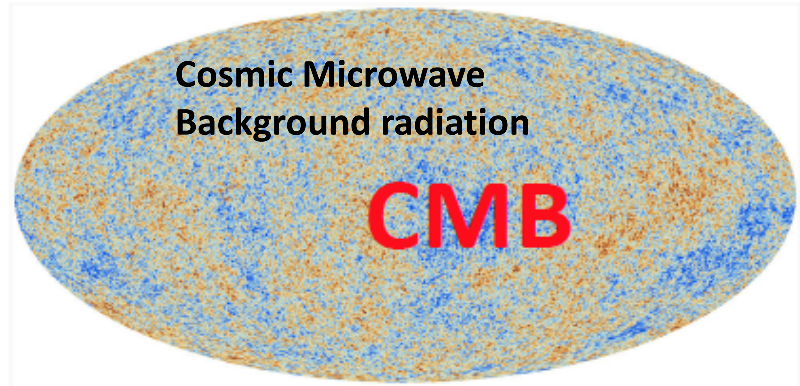
The Higgs boson and the destiny of the Universe

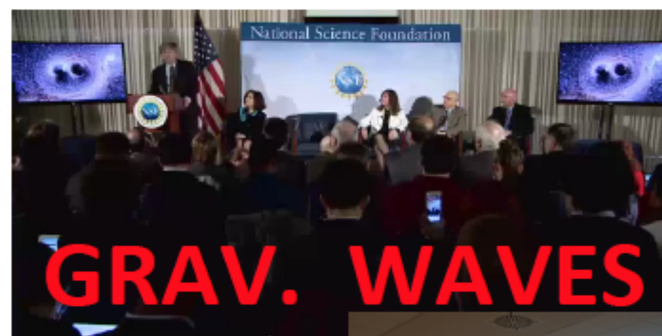
STABILITY ⟷ INSTABILITY

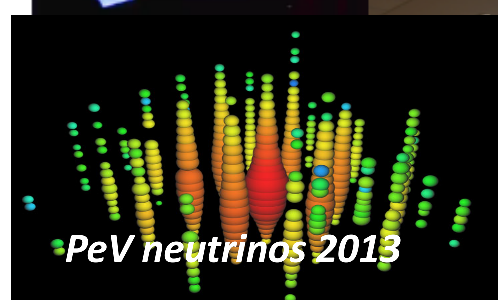


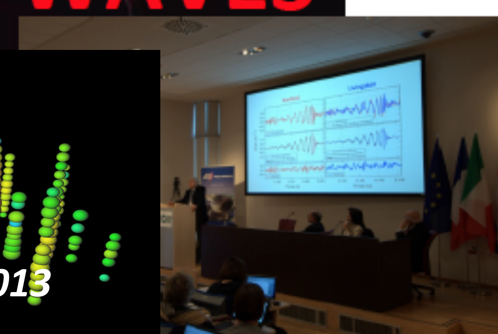


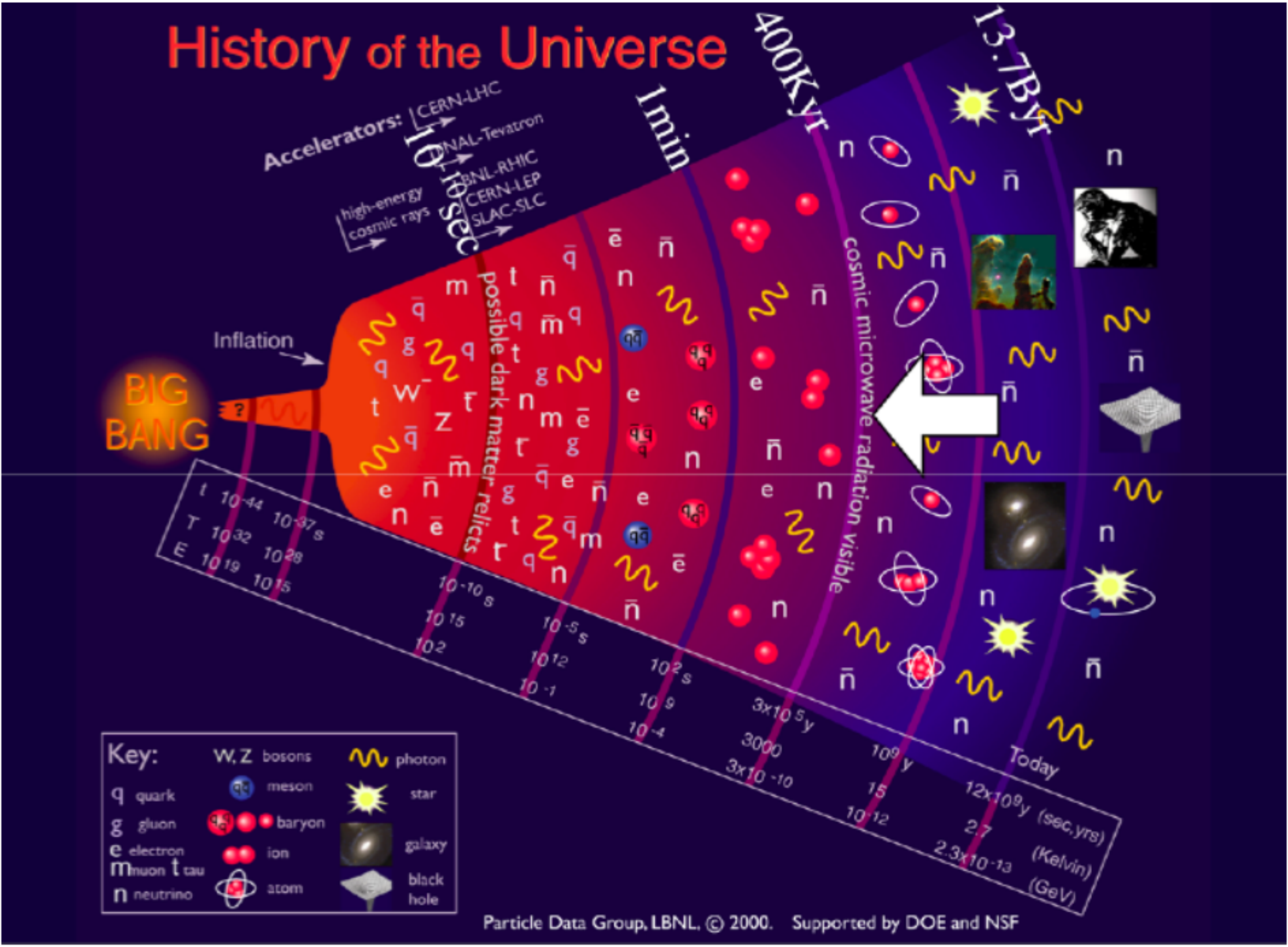
- **COSMOLOGY STANDARD MODEL**



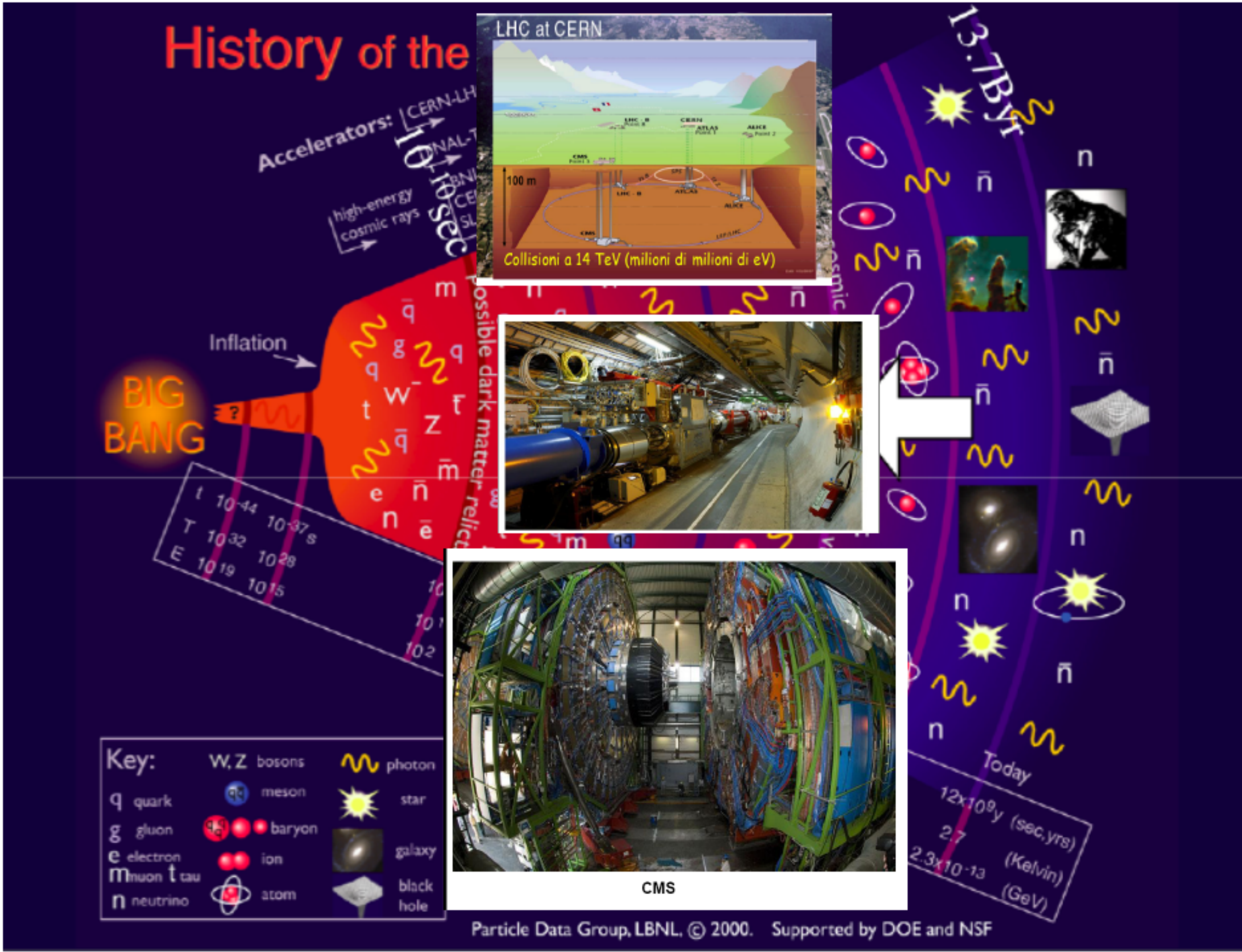


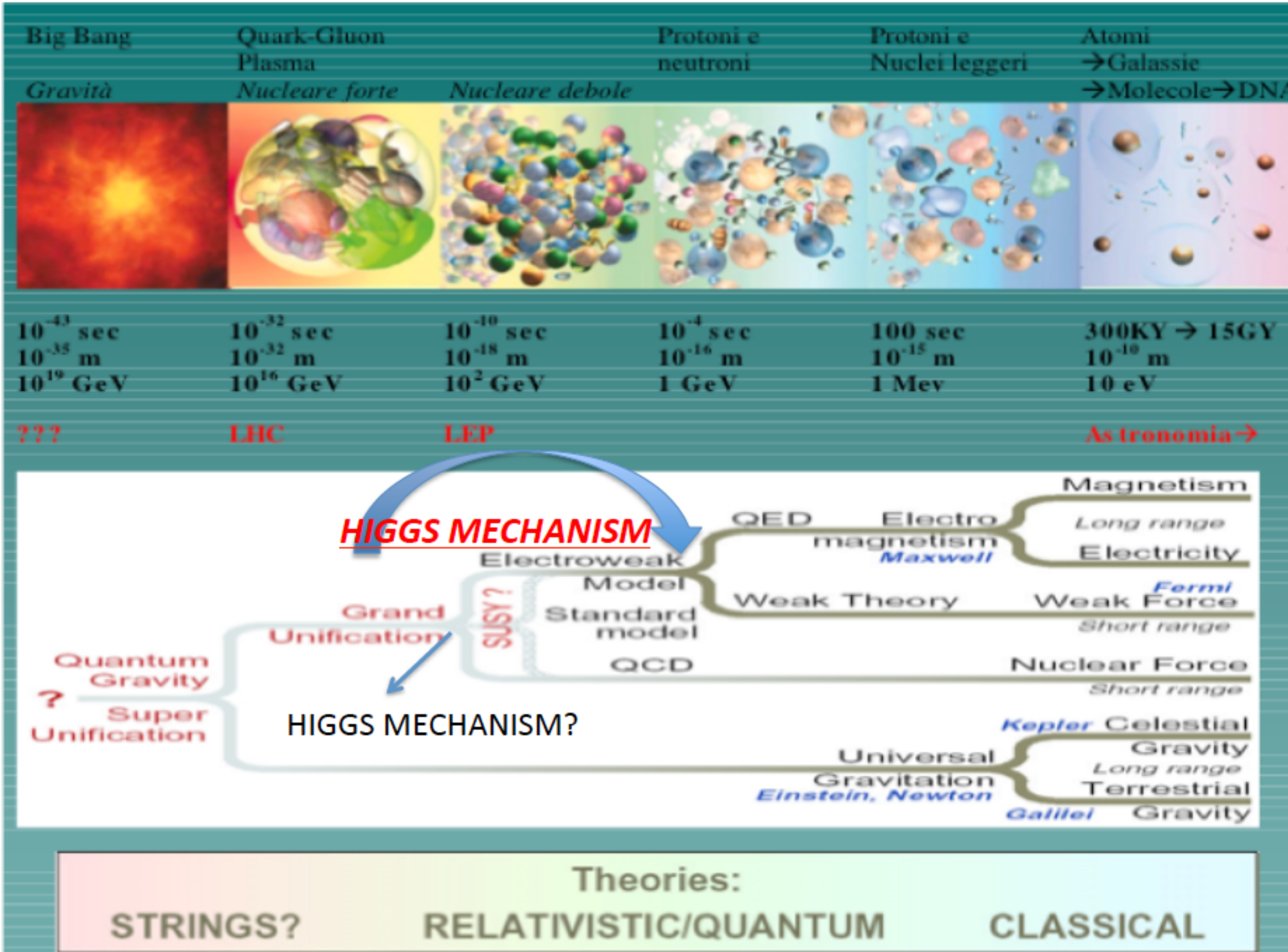




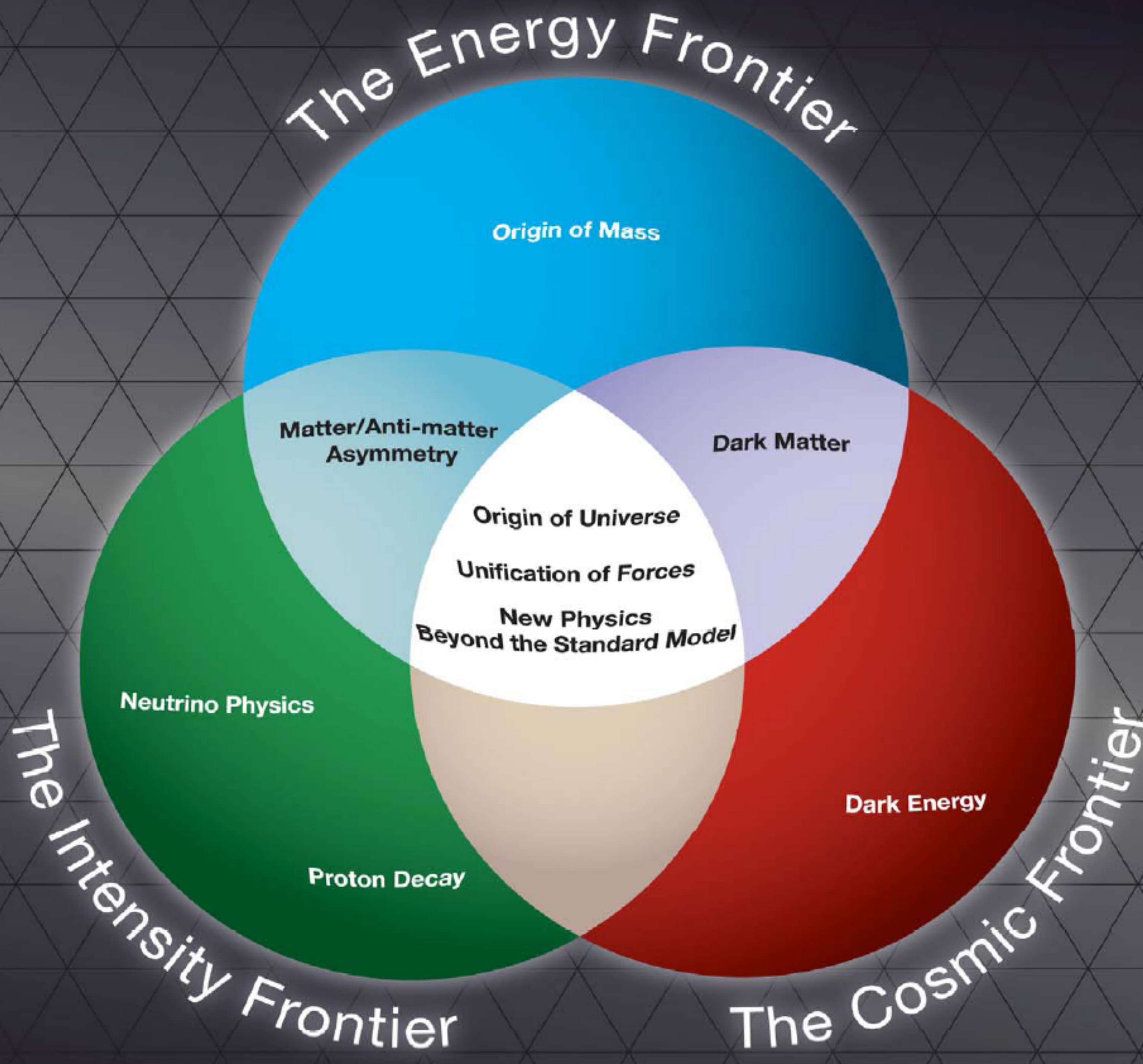


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
10^-10 sec
1 min
400K yr
13.7Byr
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s 10^15 10^2
10^-5 s 10^12 10^-1
10^2 s 10^9 10^-4
3x10^5 y 3000 3x10^-10
10^9 y 15 10^-12
Today 12x10^9 y (sec, yrs) 2.7 (Kelvin) 2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

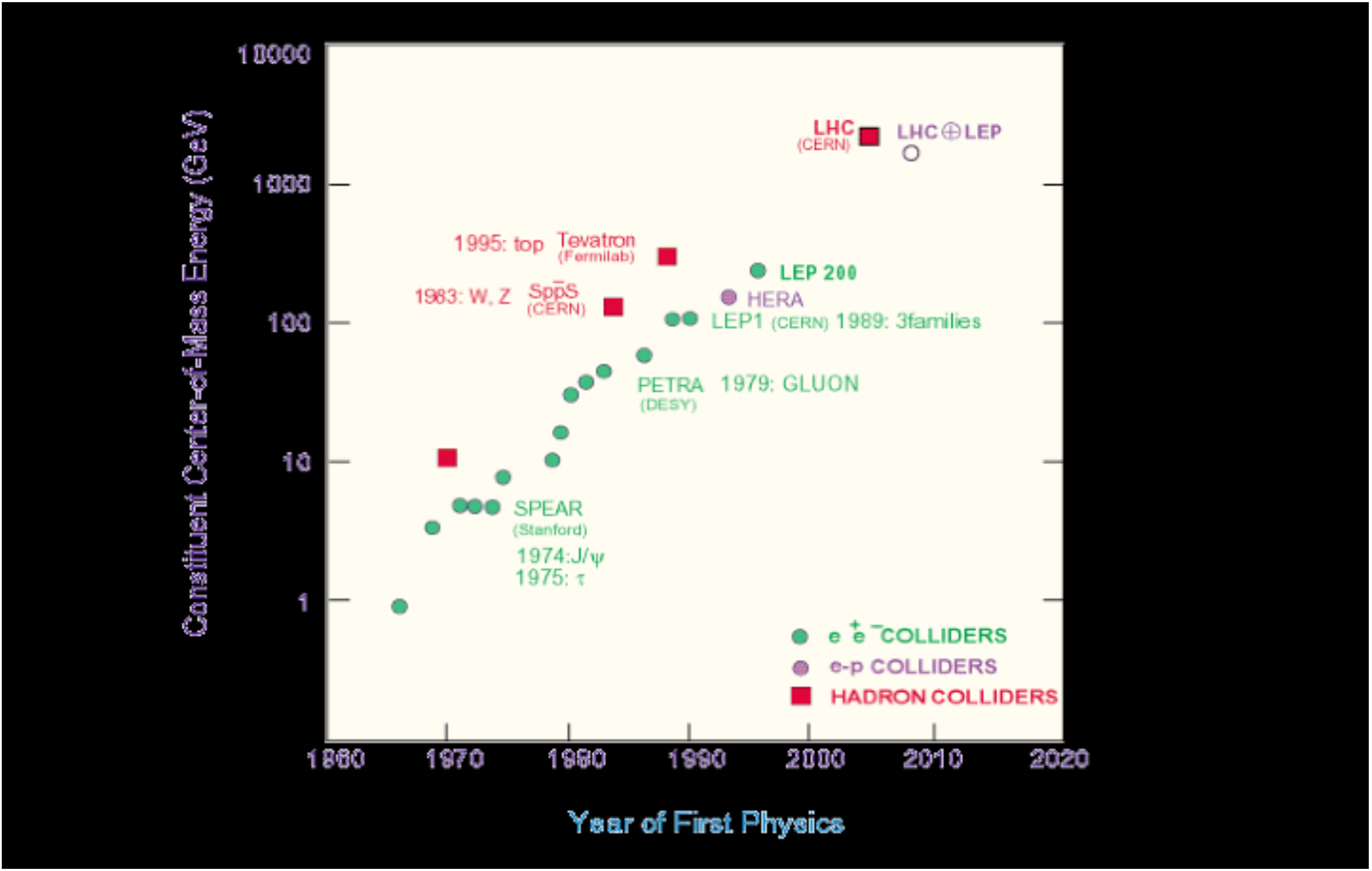

History of the
LHC at CERN
100 m
Collisioni a 14 TeV (milioni di milioni di eV)
13.7Byr
Accelerators:
high-energy cosmic rays
Inflation
BIG BANG
Possible dark matter relics
Key:
W, Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon t tau
n neutrino
atom
black hole
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
CMS
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



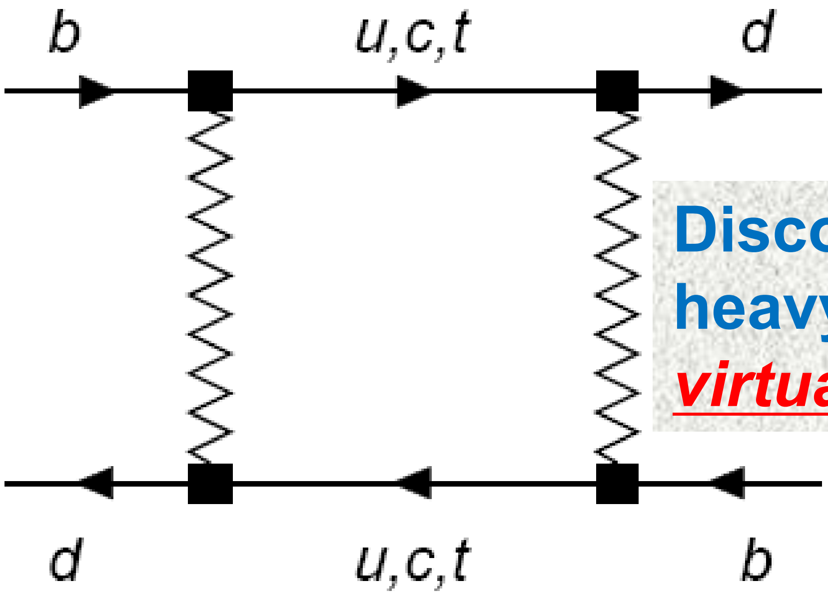
Big Bang
Gravità
Quark-Gluon Plasma
Nucleare forte
Nucleare debole
Protoni e neutroni
Protoni e Nuclei leggeri
Atomi →Galassie →Molecole→DNA
10^{-43} sec
10^{-35} m
10^{19} GeV
10^{-32} sec
10^{-32} m
10^{16} GeV
10^{-10} sec
10^{-18} m
10^{2} GeV
10^{-4} sec
10^{-16} m
1 GeV
100 sec
10^{-15} m
1 Mev
300KY → 15GY
10^{-10} m
10 eV
???
LHC
LEP
Astronomia→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak Model
Weak Theory
Fermi
Weak Force
Short range
Grand Unification
SUSY ?
Standard model
QCD
Nuclear Force
Short range
Quantum Gravity
?
Super Unification
HIGGS MECHANISM?
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
The Intensity Frontier
The Cosmic Frontier

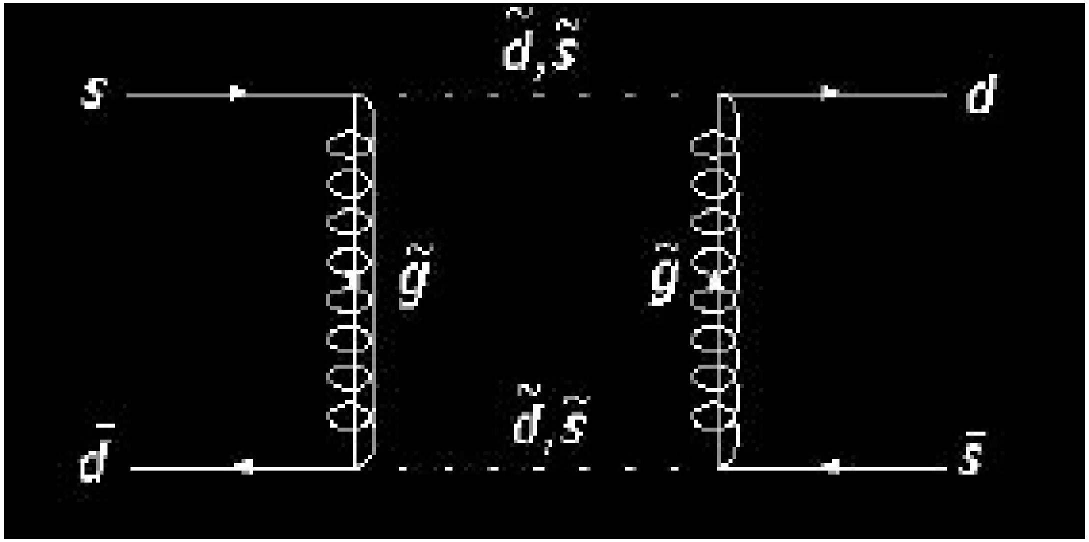
THE HIGH-ENERGY ROAD



THE HIGH-INTENSITY ROAD



Discovering the presence of the heavy up-type quarks through their ***virtual*** effects on physical processes

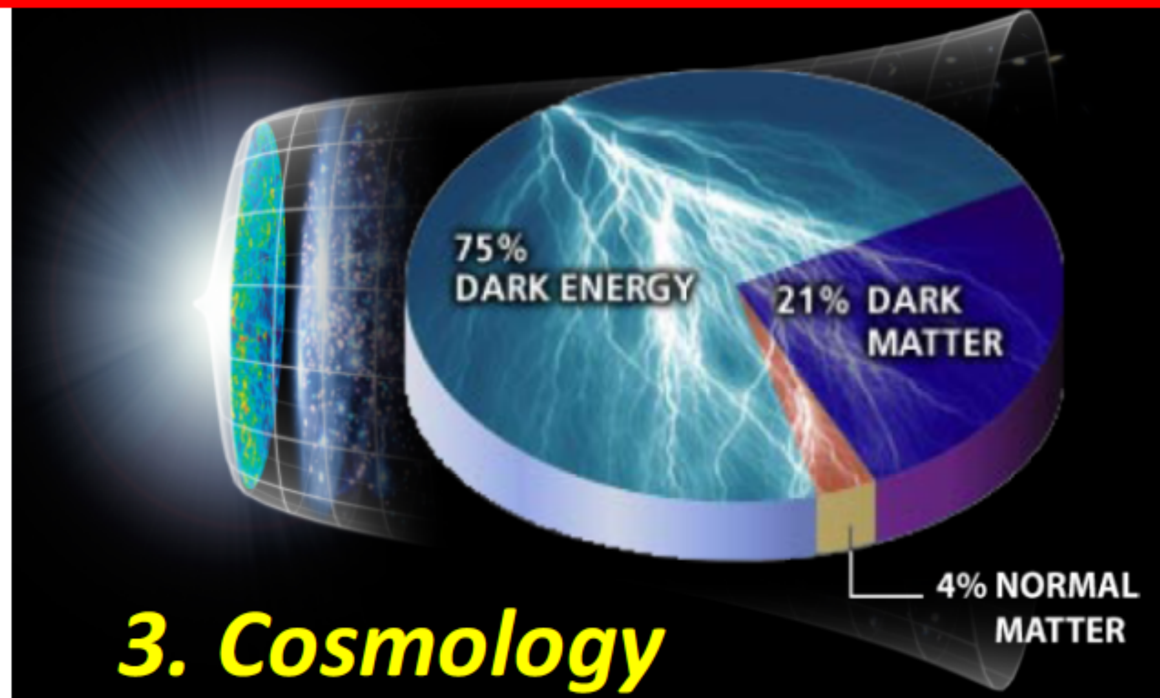


Looking for **NEW PARTICLES** through their virtual effects → **discrepancies** w.r.t. the **SM predictions**

THE ASTRO-PARTICLE PHYSICS ROAD

1. *High-energy Universe: multi-messengers*

2. *Neutrino's*



3. *Cosmology*

J. de Kleuver

1. STANDARD MODEL

SPONTANEOUSLY BROKEN GAUGE THEORY

~~SPON~~ SYMMETRIES : { CONTINUOUS { GLOBAL, LOCAL (GAUGE) }, DISCRETE (ex. PARITY) }

ex: $(i\not\partial - m)\,\psi(x) = 0 \qquad \not\partial \equiv \gamma^\mu \partial_\mu$

↳ DIRAC EQ. → free electron invariant under : $\psi(x) \to e^{i\alpha}\psi(x)$

α const. → $U(1)$ GLOBAL symm

$U(1)$ LOCAL (GAUGE) symm :

α const $\longrightarrow \alpha(x)$

↑ param. of the $U(1)$ rotation is a function of $x(t,\vec{x})$

to enforce the local $U(1)$ symm ;

$\partial_\mu \longrightarrow D_\mu \equiv \partial_\mu - ieA_\mu$

↳ covariant deriv. ; A_μ ⟶ "compensating" vector (gauge) field

$$A_\mu(x) \underset{U(1)}{\longrightarrow} A_\mu(x) - \frac{i}{e}\,\partial_\mu \alpha(x)$$

$(i\not D - m)\,\psi(x) = 0$ invar. under local $U(1)$

QUANTUM ELECTRODYNAMICS

$$\mathcal{L} = \bar{\psi}\,(i\gamma^\mu D_\mu - m)\,\psi$$
$$= \bar{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi \;-\; e\,Q\,A_\mu\,(\bar{\psi}\gamma^\mu\psi)$$

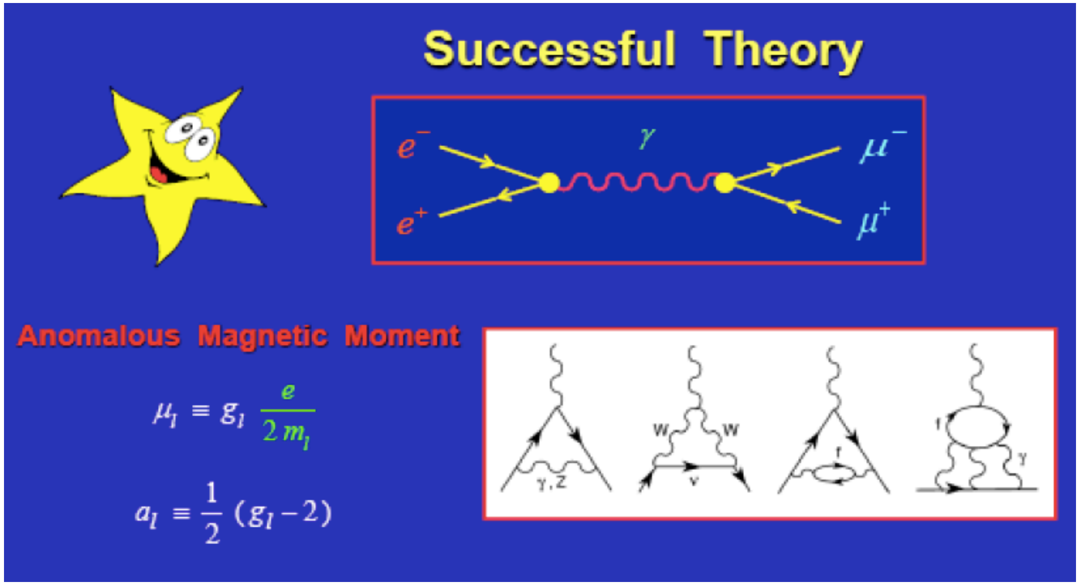
Kinetic term:

$$\mathcal{L}_K = -\frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} \quad \Longrightarrow \quad \partial_\mu F^{\mu\nu} = eQ\,(\bar{\psi}\gamma^\nu\psi)$$ Maxwell

Mass term: [exp: $m_\gamma < 1\cdot 10^{-18}$ eV]

$$\mathcal{L}_M = \frac{1}{2}\,m_\gamma^2\,A^\mu A_\mu$$ Not Gauge Invariant ⟹ $m_\gamma = 0$

Gauge Symmetry ⟹ QED Dynamics

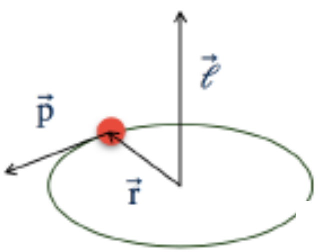


The motion of a classical particle of mass m and charge e with angular momentum

$$\vec{\ell} = \vec{r} \times \vec{p}$$

generates the (orbital) magnetic moment :

$$\vec{\mu}_\ell = \frac{e}{2m}\vec{\ell}$$



In 1925 Goudsmit & Uhlenbeck propose that the electron has an "internal rotation" characterised by a "spin" $\vec{s}$ and an associated magnetic moment, like a tiny bar magnet:

$$\vec{\mu}_s = g\frac{e}{2m}\vec{s}$$

with g = 2, not 1! Very strange, but worked.

- 1928: Dirac's equation unifies the two fields that revolutionized XX[th] century physics: special relativity and quantum mechanics.

The Dirac equation predicts that a unit of spin interacts with a magnetic field twice as much as a unit of orbital angular momentum: g=2!

Great triumph for the Dirac equation, but not the end of the story…

- 1948: With improvements in experimental techniques, Kusch & Foley measure g ≠ 2! The electron "magnetic moment anomaly" is:

a = (g-2)/2 = 0.00119(5)

What happened?? A relativistic quantum field theory of electromagnetism, ie Quantum ElectroDynamics (QED), is needed!

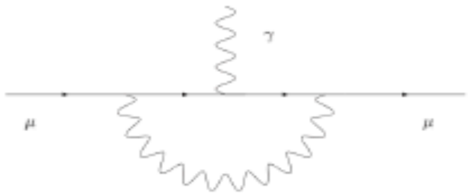
QED contribution

- 1948: Schwinger, using Quantum ElectroDynamics (QED), predicts

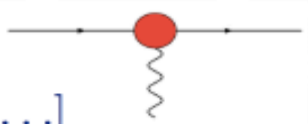
a = (g-2)/2 = α/(2π) = 0.00116

in perfect agreement with Kusch & Foley's measurement

a = (g-2)/2 = 0.00119(5)



- Tremendous quantitative triumph for relativistic QFT (QED).
- Today we keep studying the lepton-photon vertex:



$$\Gamma^\mu = ie[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m} F_2(q^2) + \ldots]$$

$$F_1(0) = 1 \qquad F_2(0) = a$$

"$g-2$ is not an experiment: it is a way of life."

[John Adams (Head of the Proton Synchrotron at CERN (1954-1961)]

This statement also applies to many theorists! [Nyffeler '16]

$$a_\mu^{\rm QED} = (1/2)\,(\alpha/\pi)$$ [Schwinger, 1948]

$$+\,0.765857426\,(16)\,(\alpha/\pi)^2$$

[Sommerfield; Petermann; Suura&Wichmann '57; Elend '66]

$$+\,24.05050988\,(28)\,(\alpha/\pi)^3$$

[Remiddi, Laporta, Barbieri...; Czarnecki, Skrzypek '99]

$$+\,130.8780\,(60)\,(\alpha/\pi)^4$$

[Kinoshita et al. '81-'15; Steinhauser et al. '13-'16; Laporta '17]

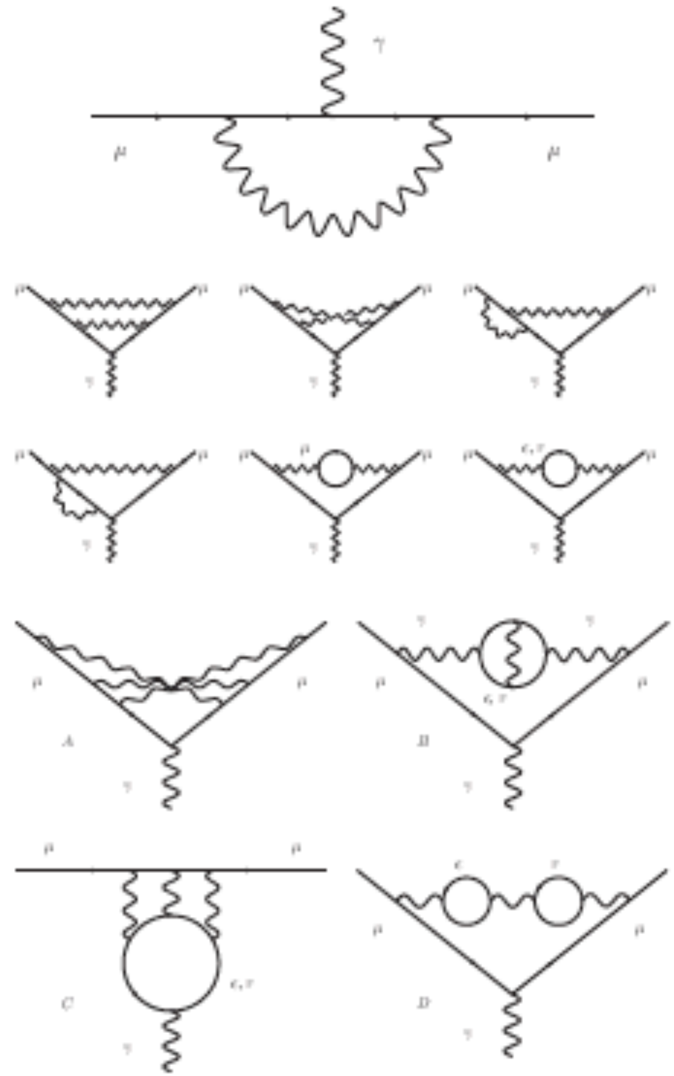
$$+\,750.86\,(88)\,(\alpha/\pi)^5$$ [Kinoshita et al. '90-'19]

$a_\mu^{\rm QED}$ = 116584718.931 (19)(100)(23) x 10^{-11}

mainly from 4-loop coeff. unc. ← 6-loop → from α(Cs)

α = 1/137.035999046(27) [0.2ppb] Parker et al 2018 WP20 value

[WP20 ≡ T. Aoyama *et al.*, Phys. Rept. '20]



NEW

arXiv:2209.13084v1 [physics.atom-ph] 27 Sep 2022

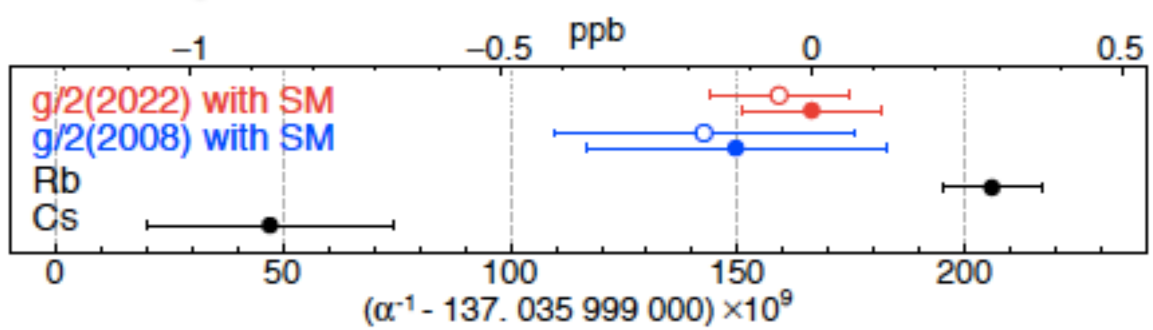
Measurement of the Electron Magnetic Moment

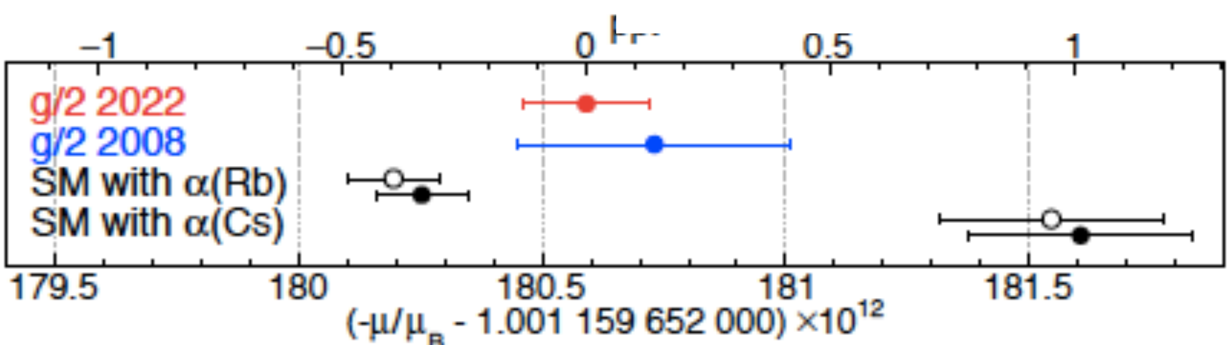
X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Center for Fundamental Physics, Northwestern University, Evanston, Illinois 60208, USA*

(Dated: September 28, 2022)

The electron magnetic moment in Bohr magnetons, $-\mu/\mu_B = 1.001\,159\,652\,180\,59\,(13)$ [0.13 ppt], is consistent with a 2008 measurement and is 2.2 times more precise. The most precisely measured property of an elementary particle agrees with the most precise prediction of the Standard Model (SM) to 1 part in 10^{12}, the most precise confrontation of all theory and experiment. The SM test will improve further when discrepant measurements of the fine structure constant α are resolved, since the prediction is a function of α. The magnetic moment measurement and SM theory together predict $\alpha^{-1} = 137.035\,999\,166\,(15)$ [0.11 ppb]





QUANTUM CHROMODYNAMICS

$$\mathbf{q} \equiv \begin{pmatrix} q \\ q \\ q \end{pmatrix}$$

FREE QUARKS: $\mathcal{L} = \bar{\mathbf{q}}\,[\,i\gamma^\mu \partial_\mu - m\,]\,\mathbf{q}$ $\qquad N_C = 3$

SU(3) Colour Symmetry: $\mathbf{q} \to \mathbf{U}\,\mathbf{q} \quad ; \quad \bar{\mathbf{q}} \to \bar{\mathbf{q}}\,\mathbf{U}^\dagger$

$$\mathbf{U}\,\mathbf{U}^\dagger = \mathbf{U}^\dagger\,\mathbf{U} = 1 \quad ; \quad \det \mathbf{U} = 1 \quad ; \quad \mathbf{U} = \exp\left\{ i\,\frac{\lambda^a}{2}\,\theta_a \right\}$$

Gauge Principle: Local Symmetry $\quad \theta_a = \theta_a(x)$

$$\mathbf{D}^\mu \mathbf{q} \equiv (\mathbf{I}_3\,\partial^\mu + i\,g_s\,\mathbf{G}^\mu)\,\mathbf{q} \;\to\; \mathbf{U}\;\mathbf{D}^\mu \mathbf{q}$$

$$\mathbf{D}^\mu \to \mathbf{U}\;\mathbf{D}^\mu\;\mathbf{U}^\dagger \quad ; \quad \mathbf{G}^\mu \to \mathbf{U}\,\mathbf{G}^\mu\,\mathbf{U}^\dagger + \frac{i}{g_s}\,(\partial^\mu \mathbf{U})\;\mathbf{U}^\dagger$$

$$[\mathbf{G}^\mu]_{\alpha\beta} \equiv \frac{1}{2}\,(\lambda^a)_{\alpha\beta}\;G_a^\mu(x)$$

8 Gluon Fields

Kinetic Term:

$$\mathbf{G}^{\mu\nu} \equiv -\frac{i}{g_s}\,[\mathbf{D}^\mu, \mathbf{D}^\nu] = \partial^\mu \mathbf{G}^\nu - \partial^\nu \mathbf{G}^\mu + i\, g_s\, [\mathbf{G}^\mu, \mathbf{G}^\nu] \quad \to \quad \mathbf{U}\ \mathbf{G}^{\mu\nu}\ \mathbf{U}^\dagger$$

$$\mathbf{G}^{\mu\nu} \equiv \frac{\lambda^a}{2} G_a^{\mu\nu} \quad ; \quad G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s\, f^{abc}\, G_b^\mu\, G_c^\nu$$

$$\mathcal{L}_K = -\frac{1}{2}\,\mathrm{Tr}\,(\mathbf{G}^{\mu\nu}\mathbf{G}_{\mu\nu}) = -\frac{1}{4}\, G_a^{\mu\nu}\, G_{\mu\nu}^a$$

Mass Term:

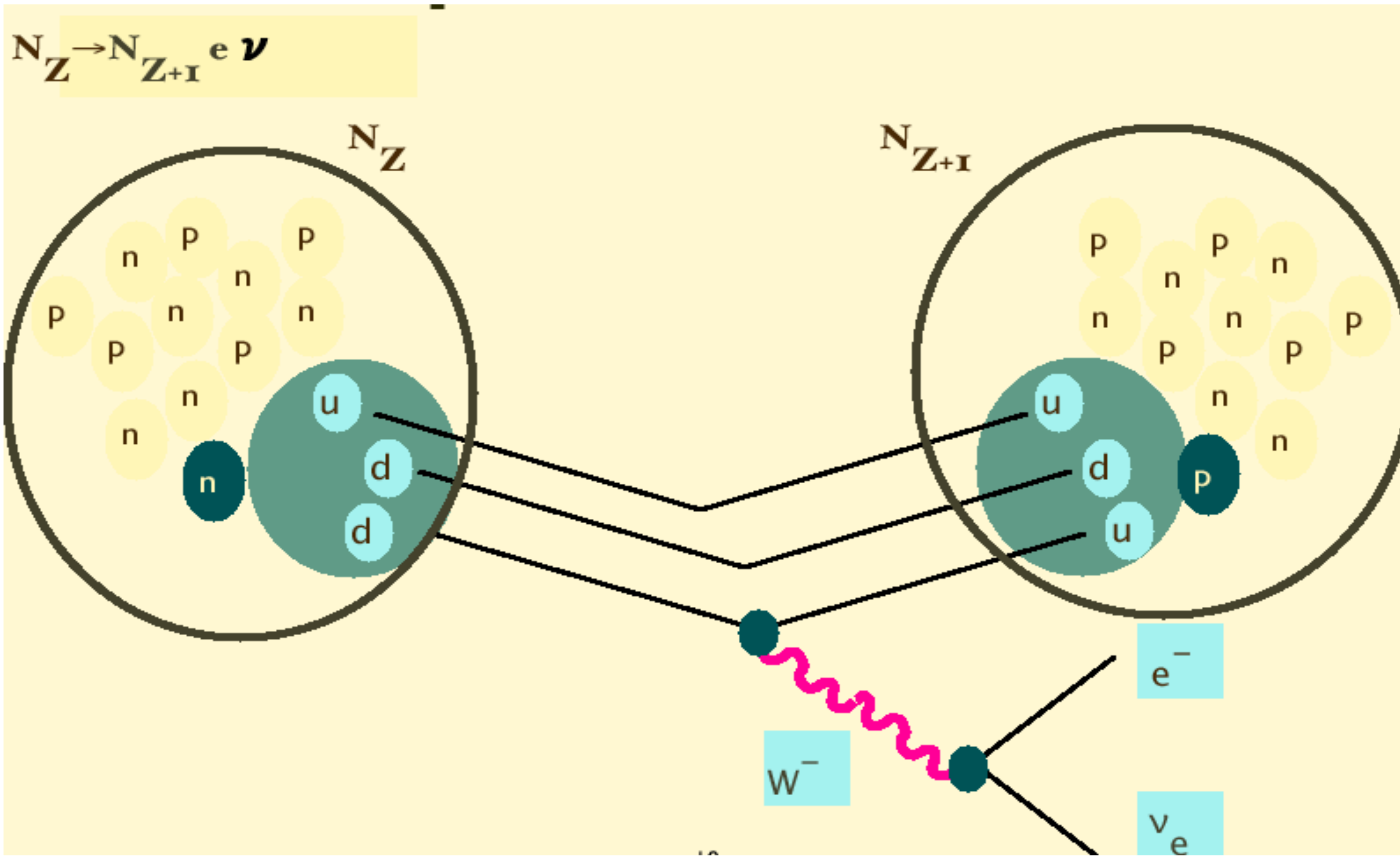
$$\mathcal{L}_M = \frac{1}{2}\, m_G^2\ G_a^\mu\, G_\mu^a$$

Not Gauge Invariant ➡ $m_G = 0$

Massless Gluons

NUCLEUS β-DECAY

(Nuclear) WEAK Interactions



EXPERIMENTAL FACTS

Three Families $\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix} \; , \; \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix} \; , \; \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix}$

Family Structure

$$\begin{bmatrix} \nu_l & q_u \\ l^- & q_d \end{bmatrix} \equiv \left\{ \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L , \; (\nu_l)_R \; , \; l_R^- \right\} \; ; \; \left\{ \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L , \; (q_u)_R \; , \; (q_d)_R \right\}$$

Charged Currents $W^\pm$
- Left–handed Fermions only
- Flavour Changing: $\nu_l \Leftrightarrow l \; , \; q_u \Leftrightarrow q_d$

Neutral currents $\gamma \, , \, Z$ Flavour Conserving

Universality (Family – Independent Couplings)

$(\nu_l)_R$?

$SU(2)_L \otimes U(1)_Y$

GAUGE THEORY

Fields	$\psi_1(x)$	$\psi_2(x)$	$\psi_3(x)$
Quarks	$\begin{pmatrix} q_u \\ q_d \end{pmatrix}_L$	$(q_u)_R$	$(q_d)_R$
Leptons	$\begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L$	$(\nu_l)_R$	$(l^-)_R$

Free Lagrangian for Massless Fermions:

$$\mathcal{L}_0 = \sum_j i\, \bar{\psi}_j \gamma^\mu \partial_\mu \psi_j$$

$SU(2)_L \otimes U(1)_Y$ **Flavour Symmetry:**

$$\mathrm{U_L} \equiv \exp\left\{ i \frac{\vec{\sigma}}{2} \vec{\alpha} \right\}$$

$$\psi_1 \to e^{i y_1 \beta}\, \mathrm{U_L}\, \psi_1 \quad ; \quad \psi_2 \to e^{i y_2 \beta}\, \psi_2 \quad ; \quad \psi_3 \to e^{i y_3 \beta}\, \psi_3$$

$$\bar{\psi}_1 \to \bar{\psi}_1\, \mathrm{U_L^\dagger}\, e^{-i y_1 \beta} \quad ; \quad \bar{\psi}_2 \to \bar{\psi}_2\, e^{-i y_2 \beta} \quad ; \quad \bar{\psi}_3 \to \bar{\psi}_3\, e^{-i y_3 \beta}$$

4 Massless Gauge Bosons $\quad W_\mu^\pm \,,\; W_\mu^3 \,,\; B_\mu^0$

CHARGED CURRENTS

$$\mathbf{W}_\mu \equiv \frac{\vec{\sigma}}{2}\cdot\vec{\mathrm{W}}_\mu = \frac{1}{2}\begin{pmatrix} W_\mu^3 & \sqrt{2}\,W_\mu^\dagger \\ \sqrt{2}\,W_\mu & -W_\mu^3 \end{pmatrix} \quad ; \quad W_\mu \equiv \frac{1}{\sqrt{2}}\left(W_\mu^1 + i\,W_\mu^2\right)$$

$$\mathcal{L}_{\mathrm{CC}} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\, \bar{q}_u\,\gamma^\mu\,(1-\gamma_5)\,q_d + \bar{\nu}_l\,\gamma^\mu\,(1-\gamma_5)\,l\,\right] + \text{h.c.}$$

Quark / Lepton Universality ; Left–Handed Interaction

NEUTRAL CURRENTS

$$\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

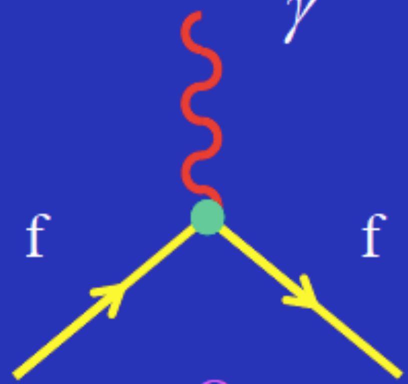
$$g\,\sin\theta_W = g'\cos\theta_W = e \quad ; \quad y_1 = Q_u - \frac{1}{2} = Q_d + \frac{1}{2} \quad ; \quad y_2 = Q_u \quad ; \quad y_3 = Q_d$$

$$\mathcal{L}_{\mathrm{NC}} = -e\,A_\mu \sum_j \bar{\psi}_j\,\gamma^\mu\,Q_j\,\psi_j + \mathcal{L}_{\mathrm{NC}}^{Z}$$

$$Q_1 = \begin{pmatrix} Q_u & 0 \\ 0 & Q_d \end{pmatrix} \quad ; \quad Q_2 = Q_u \quad ; \quad Q_3 = Q_d$$

→ **Electroweak Unification**

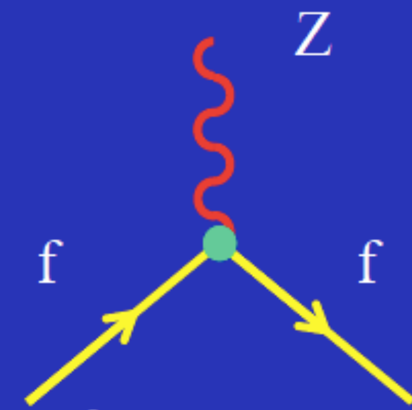
NEUTRAL CURRENTS



$e\, Q_f$

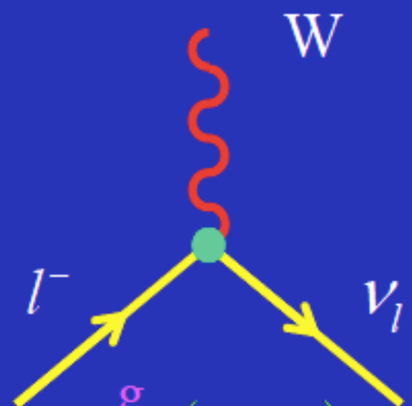
$$a_f = T_3^f = \pm\frac{1}{2}$$

$$v_f = T_3^f \left(1 - 4\,|Q_f|\,\sin^2\theta_W\right)$$

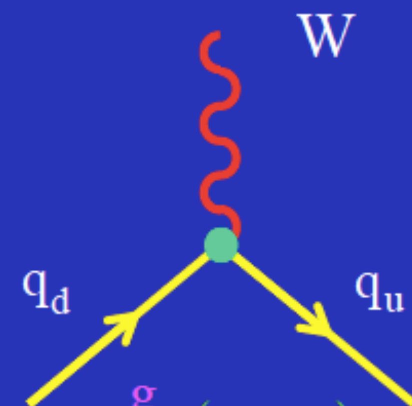


$$\frac{e}{2\, s_\theta c_\theta}\left(v_f - a_f\gamma_5\right)$$

CHARGED CURRENTS



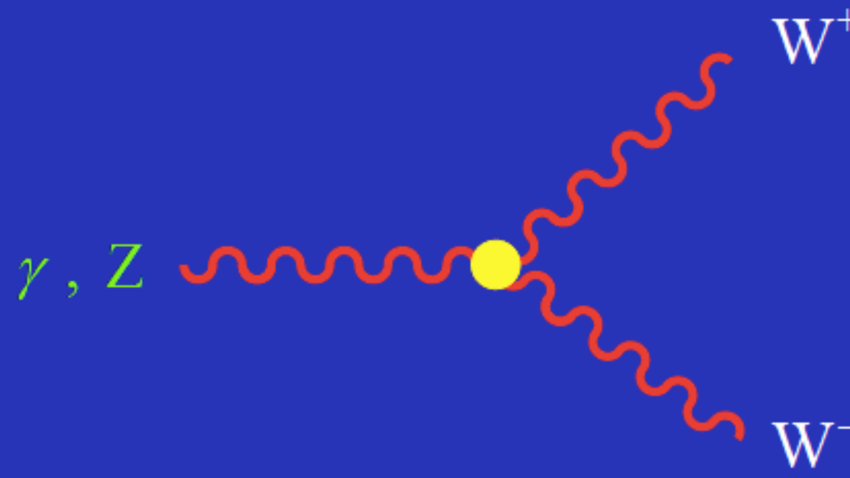
$$\frac{g}{2^{3/2}}\left(1-\gamma_5\right)$$

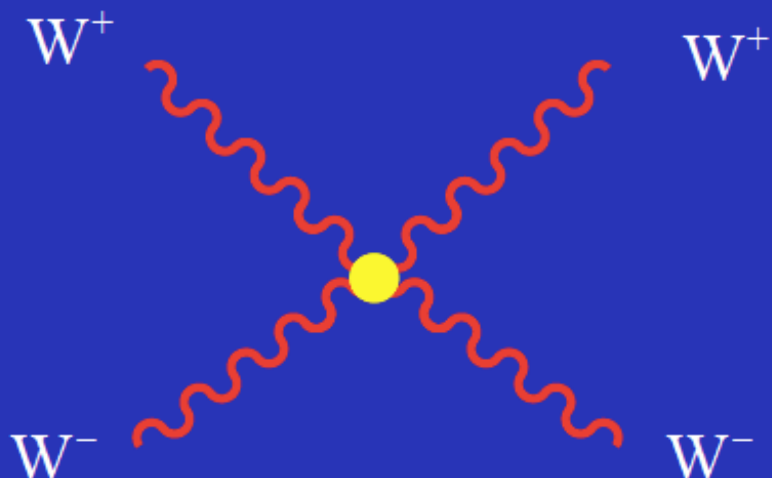


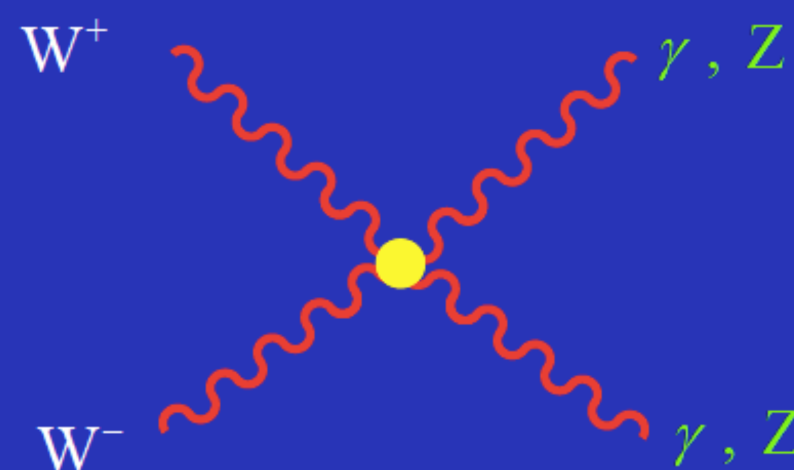
$$\frac{g}{2^{3/2}}\left(1-\gamma_5\right)$$

$y(\nu_R) = Q_\nu = 0$ ➡ No ν_R Interactions **Sterile Neutrinos**

GAUGE SELF-INTERACTIONS







PROBLEM WITH MASS SCALES

Gauge Symmetry → $m_\gamma = 0$ **Good**

$M_W = M_Z = 0$ **Bad!**

$M_W = 80.40$ GeV

$M_Z = 91.19$ GeV

Moreover $\mathcal{L}_{m_f} \equiv -m_f \, \bar{f} f = -m_f \, (\bar{f}_L f_R + \bar{f}_R f_L)$

Also Forbidden by Gauge Symmetry → $m_f = 0 \quad \forall f$

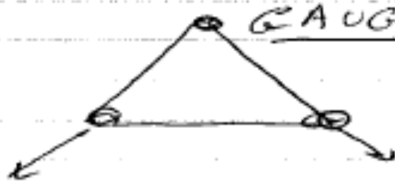
All Particles Massless

$\Rightarrow$ interaction term : $e\bar{\psi}\gamma^\mu\psi A_\mu$

→ interaction electron - photon fields

$F_{\mu\nu}F^{\mu\nu}$ → kinetic term for the photon

GAUGE SYMMETRY



MASSLESS GAUGE BOSONS

RENORMALIZABILITY → all infinities reabsorbable in a finite number of free parameters

SPONTANEOUS SYMMETRY BREAKING

↓ $\mathcal{L}$ (Lagrangian) respects a symm., but the vacuum of the theory does NOT respect it

ex: $V = \mu^2 \varphi\varphi^* + \lambda(\varphi\varphi^*)^2$

V invar. under $\varphi(x) \to e^{i\alpha}\varphi(x)$

if $\mu^2 < 0$ → $\langle 0|\varphi|0\rangle \neq 0$

↳ vacuum is NOT U(1) invariant

↓ order param. of the phase transition

$G \xrightarrow[\text{spont. break.}]{} G'$

if G global $\rightarrow$ generators of G/G'

↳ Goldstone bosons (massless scalars)

if **G LOCAL** $\rightarrow$ **HIGGS MECHANISM**

Goldstone bosons "eaten up" by the gauge bosons of G/G' to become their longitudinal components

$\Rightarrow$ gauge bosons of G/G' become MASSIVE, their mass being $\propto \langle 0|\varphi|0\rangle \equiv v$ and to their gauge coupl. const.

$G_{ST.\,MODEL} \equiv \underbrace{SU(3)_c}_{\text{8 gluons}} \otimes \underbrace{SU(2)_L}_{W_1^\mu, W_2^\mu, W_3^\mu} \otimes \underbrace{U(1)_Y}_{B^\mu}$

GAUGE SYMMETRY

B^μ: hypercharge gauge boson

MATTER FERMIONS

	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$(u^c)_L$	$(d^c)_L$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$(e^c)_L$
$SU(3)_c$	3	$\bar{3}$	$\bar{3}$	1	1
$SU(2)_L$	2	1	1	2	1
$U(1)_Y$	1/6	$-2/3$	$+1/3$	$-1/2$	$1/2$

$Q = T_3 + Y$

$$\mathcal{L}_{int} = g_1 J^\mu B_\mu + g_2 J_i^\mu W_{\mu i} + g_3 J_a^\mu A_{\mu a}$$

$i = 1, 2, 3 \qquad a = 1, \ldots, 8$

$$J_\mu^i = (\bar{u}\ \bar{d})_L \gamma_\mu \left(\frac{\tau_i}{2}\right)\begin{pmatrix} u \\ d \end{pmatrix}_L + (\bar{\nu}_e\ \bar{e})_L \gamma_\mu \left(\frac{\tau_i}{2}\right)\begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

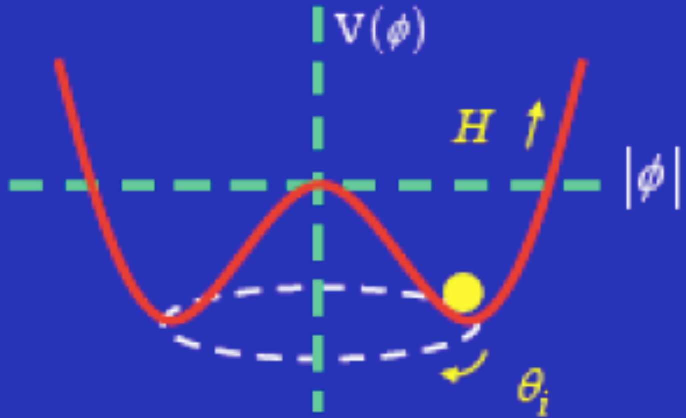
...

$$W_\pm^\mu = \frac{1}{\sqrt{2}}\left(W_1^\mu \mp i\, W_2^\mu\right)$$

As long as G_{SM} unbroken

$\Longrightarrow$ all gauge bosons + fermions are MASSLESS

Spontaneous Symmetry Breaking



$$\phi(x) \equiv \begin{pmatrix} \phi^{(+)}(x) \\ \phi^{(0)}(x) \end{pmatrix} = \exp\left\{ i \frac{\vec{\tau}}{2} \cdot \vec{\theta}(x) \right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$$\mathcal{L}(\phi) = (D_\mu \phi)^\dagger D^\mu \phi - \mu^2 \, \phi^\dagger \phi - h \, (\phi^\dagger \phi)^2 \qquad ; \qquad \mu^2 < 0$$

$$D^\mu \phi = \left[\partial^\mu - i\, g\, W^\mu - i\, g'\, y_\phi\, B^\mu \right] \phi \qquad ; \qquad W^\mu = \frac{\vec{\tau}}{2} \cdot \vec{W}^\mu$$

$$\left| \langle 0 | \phi^{(0)} | 0 \rangle \right| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}}$$

$$y_\phi = Q_\phi - T_3 = \frac{1}{2}$$

Unitary Gauge:

$$(D_\mu \phi)^\dagger D^\mu \phi \;\xrightarrow{\vec{\theta} = 0}\; \frac{1}{2} \partial_\mu H \, \partial^\mu H + \frac{g^2}{4} (v + H)^2 \left\{ W_\mu^\dagger W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right\}$$

$$\Rightarrow \quad M_Z \cos\theta_W = M_W = \frac{1}{2} v\, g$$

HIGGS MECHANISM

Bosonic Degrees of Freedom

Massless $W^{\pm}, Z$

3 x 2 polarizations = 6

+

3 Goldstones $\vec{\theta}$

SSB ↓

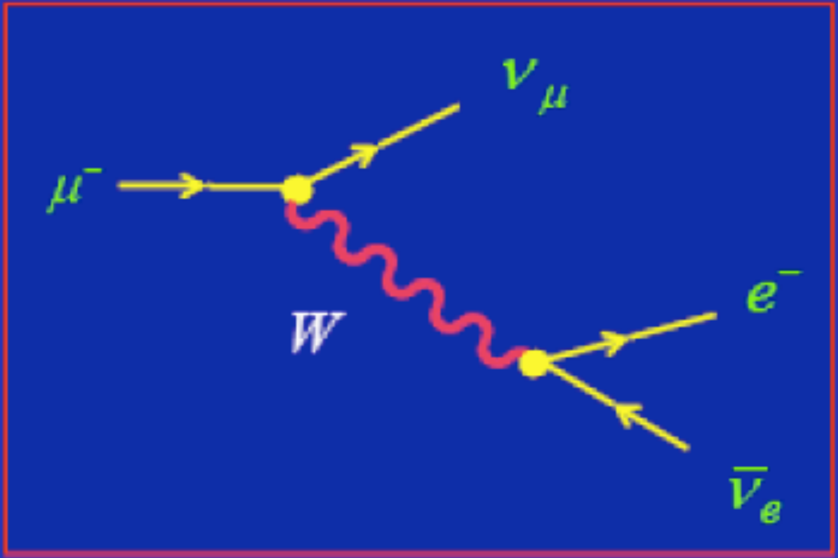
Massive $W^{\pm}, Z$

3 x 3 polarizations = 9

SAME PHYSICS

$$M_Z \cos\theta_W = M_W = \frac{1}{2}\, v\, g$$

$$M_Z = 91.1875\ \text{GeV} > M_W = 80.399\ \text{GeV} \Rightarrow \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.223$$



$$\frac{g^2}{M_W^2 - q^2} \approx \frac{g^2}{M_W^2} \equiv 4\sqrt{2}\, G_F$$

$$\frac{1}{\tau_\mu} \equiv \Gamma = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}$$

$$G_F = 1.16637 \times 10^{-5}\ \text{GeV}^{-2}$$

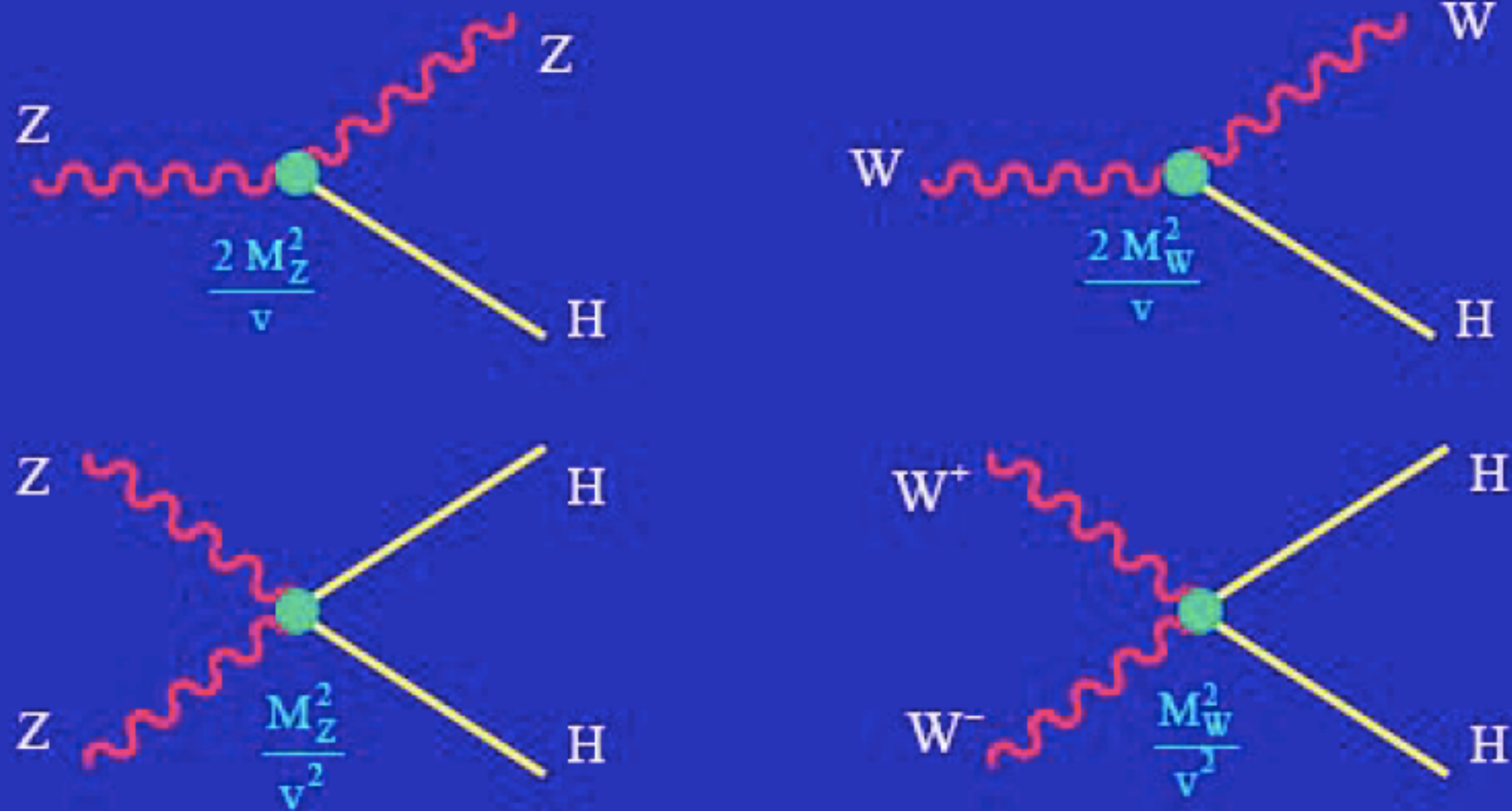
$$g = \frac{e}{\sin\theta_W}\ , \quad M_W$$

$\Rightarrow$

$$\sin^2\theta_W = 0.215$$

$$v = \left(\sqrt{2}\, G_F\right)^{-1/2} = 246\ \text{GeV}$$

Higgs Couplings $\propto$ Masses



$$v = \left(\sqrt{2}\, G_F\right)^{-1/2} = 246 \ \text{GeV}$$

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

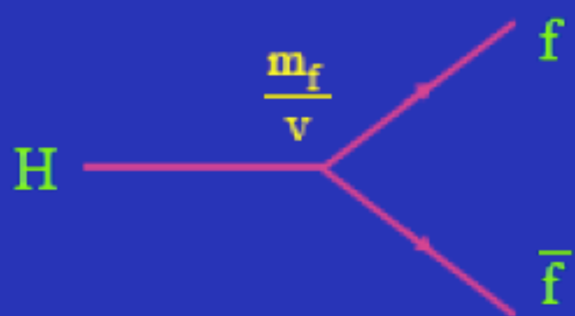
$$\mathcal{L}_Y = (\bar{q}_u, \bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] + (\bar{\nu}_l, \bar{l})_L \, c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_R + \text{h.c.}$$

↓ **SSB**

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\mathrm{v}}\right) \left\{ m_{q_d}\, \bar{q}_d\, q_d + m_{q_u}\, \bar{q}_u\, q_u + m_l\, \bar{l}\, l \right\}$$

Fermion Masses are New Free Parameters

$$\left[m_{q_d}, m_{q_u}, m_l \right] = -\left[c^{(d)}, c^{(u)}, c^{(l)} \right] \frac{\mathrm{v}}{\sqrt{2}}$$



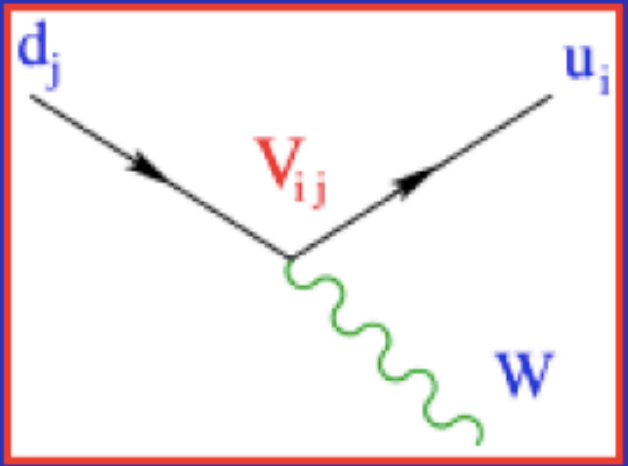
Couplings Fixed: $g_{Hf\bar{f}} = \frac{m_f}{\mathrm{v}}$

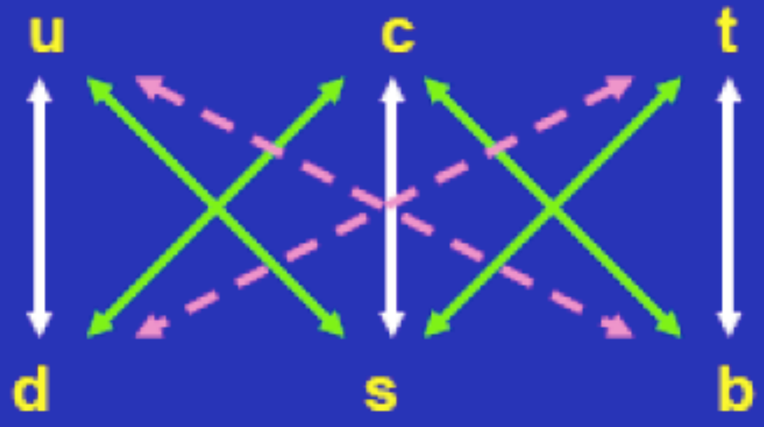
$$\mathcal{L}_{NC}^{Z} = -\frac{e}{2\sin\theta_W \cos\theta_W}\, Z_\mu \sum_f \bar{f}\,\gamma^\mu \left[v_f - a_f\,\gamma_5\right] f$$

Flavour Conserving Neutral Currents

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\sum_{ij} \bar{u}_i\,\gamma^\mu (1-\gamma_5)\, V_{ij}\, d_j + \sum_l \bar{\nu}_l\,\gamma^\mu (1-\gamma_5)\, l\right] + \text{h.c.}$$

Flavour Changing Charged Currents





QUARK MIXING MATRIX

- **Unitary** $N_G \times N_G$ **Matrix:** N_G^2 **parameters**

$$\mathbf{V} \cdot \mathbf{V}^\dagger = \mathbf{V}^\dagger \cdot \mathbf{V} = \mathbf{1}$$

- $2\,N_G - 1$ **arbitrary phases:**

$$u_i \to e^{i\phi_i}\, u_i \quad ; \quad d_j \to e^{i\theta_j}\, d_j \quad \Longrightarrow \quad \mathbf{V}_{ij} \to e^{i(\theta_j - \phi_i)}\, \mathbf{V}_{ij}$$

$\mathbf{V}_{ij}$ **Physical Parameters:**

$\frac{1}{2} N_G\,(N_G - 1)$ **Moduli** ; $\frac{1}{2} (N_G - 1)\,(N_G - 2)$ **phases**

- **$N_f = 2$:** 1 angle, 0 phases (Cabibbo)

$$\mathbf{V} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \quad \Rightarrow \quad \text{No } \not{CP}$$

- **$N_f = 3$:** 3 angles, 1 phase (CKM) $\qquad c_{ij} \equiv \cos\theta_{ij} \;\; ; \;\; s_{ij} \equiv \sin\theta_{ij}$

$$\mathbf{V} = \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix}$$

$$\approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}(\lambda^4)$$

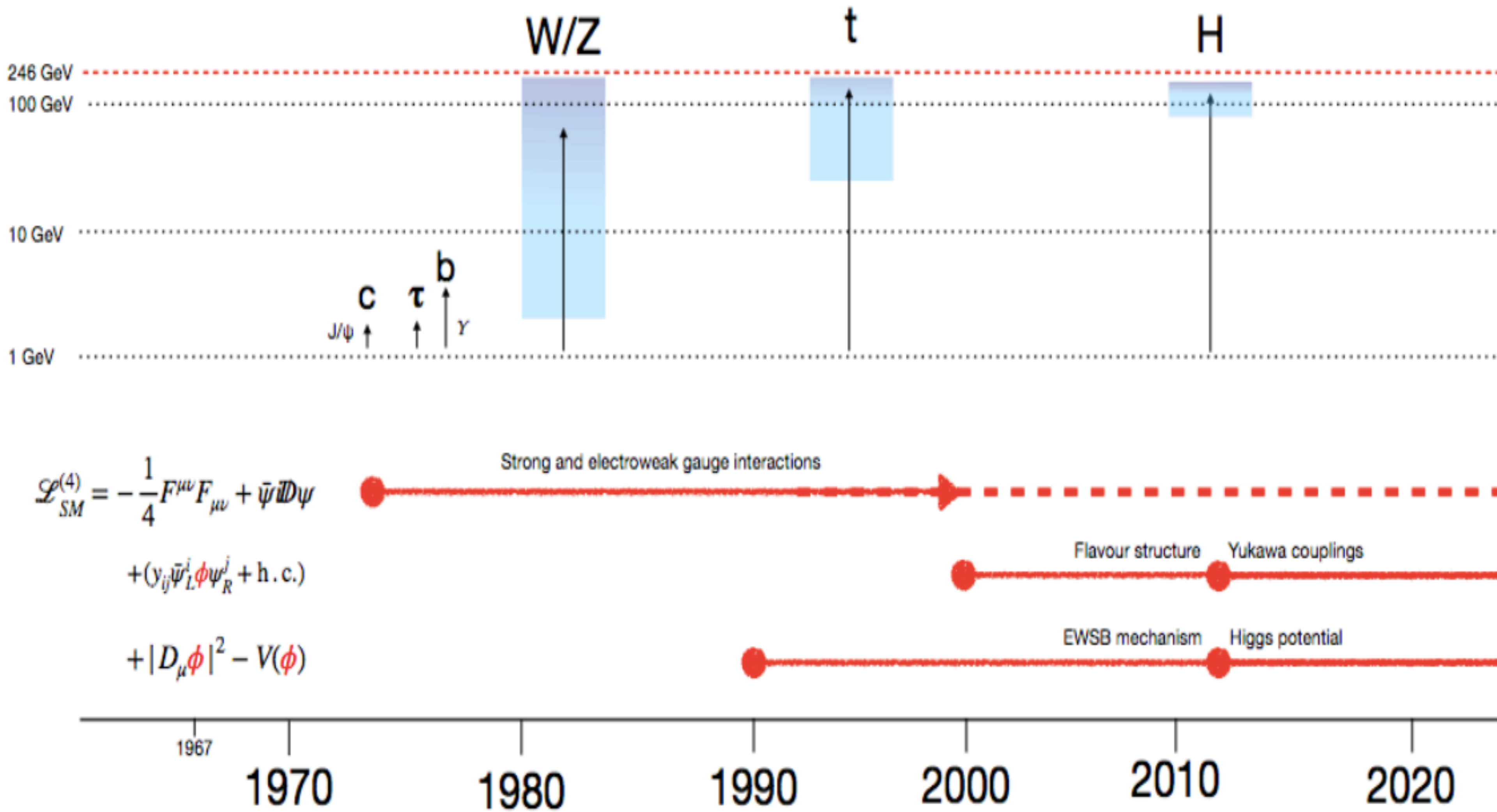
$\lambda \approx \sin\theta_C \approx 0.225 \;\; ; \;\; A \approx 0.81 \;\; ; \;\; \sqrt{\rho^2 + \eta^2} \approx 0.37 \qquad \delta_{13} \neq 0 \;\; (\eta \neq 0) \Rightarrow \not{CP}$

- $\mathcal{C}$, $\mathcal{P}$: Violated maximally in weak interactions
- $\mathcal{CP}$: Symmetry of nearly all observed phenomena
- Slight (~ 0.2 %) $\not{\mathcal{C}}\not{\mathcal{P}}$ in K^0 decays (1964)
- Sizeable $\not{\mathcal{C}}\not{\mathcal{P}}$ in B^0 decays (2001)
- Huge Matter— Antimatter Asymmetry in our Universe → Baryogenesis

$\mathcal{CPT}$ Theorem: $\not{\mathcal{C}}\not{\mathcal{P}} \Leftrightarrow \not{\mathcal{T}}$

Thus, $\not{\mathcal{C}}\not{\mathcal{P}}$ requires:

- Complex Phases
- Interferences



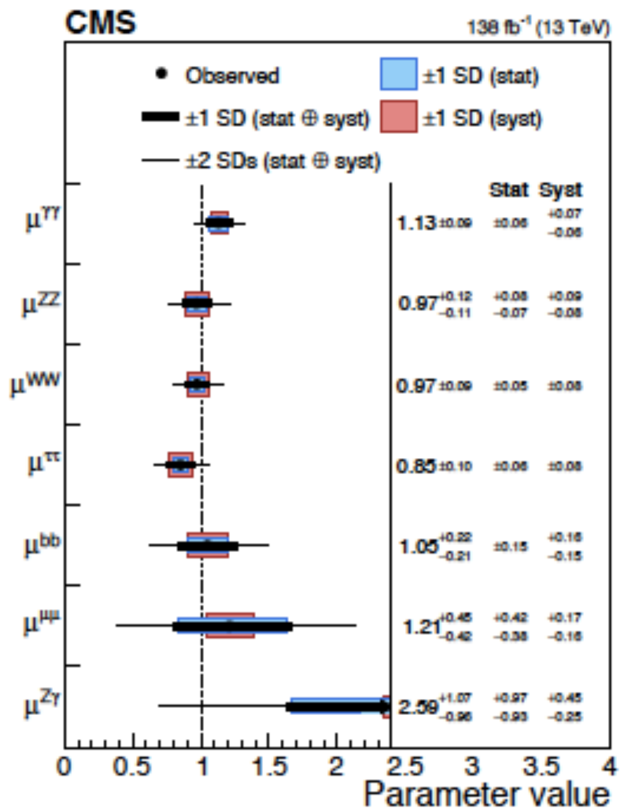
F. Maltoni, INFN -70 : Theory - Collider Physics, 2022

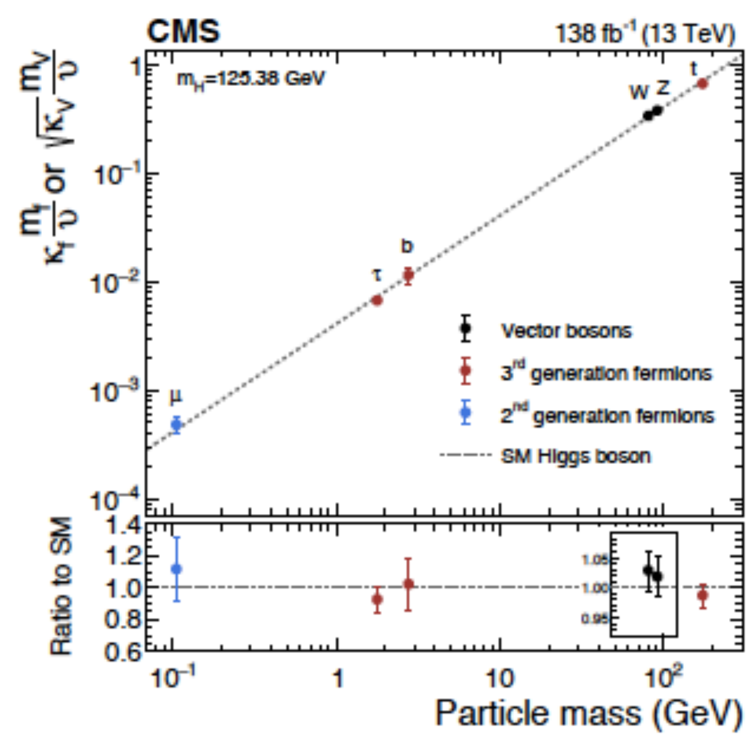
The LHC legacy (so far)

- **Higgs Boson mass** (combined LHC Run 1 + 2 results of ATLAS and CMS)

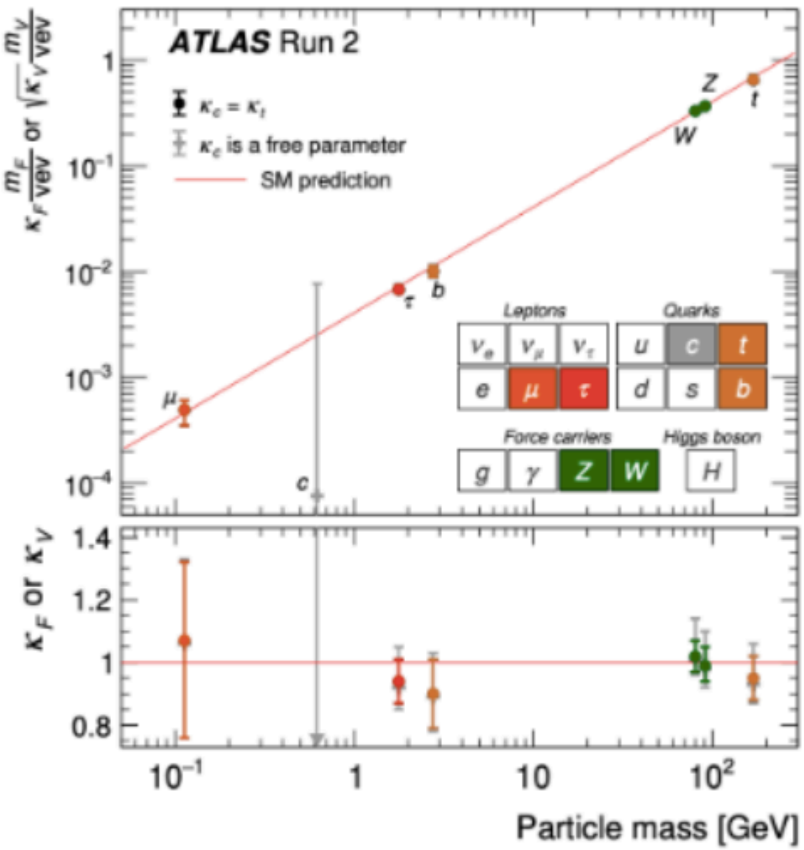
$$m_H \ = \ 124.94 \pm 0.17\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.})\ \mathrm{GeV}$$

- **Higgs Boson couplings** $\mu_i^f = \dfrac{\sigma_i \times BR^f}{(\sigma_i \times BR^f)_{SM}}$ (signal strengths)

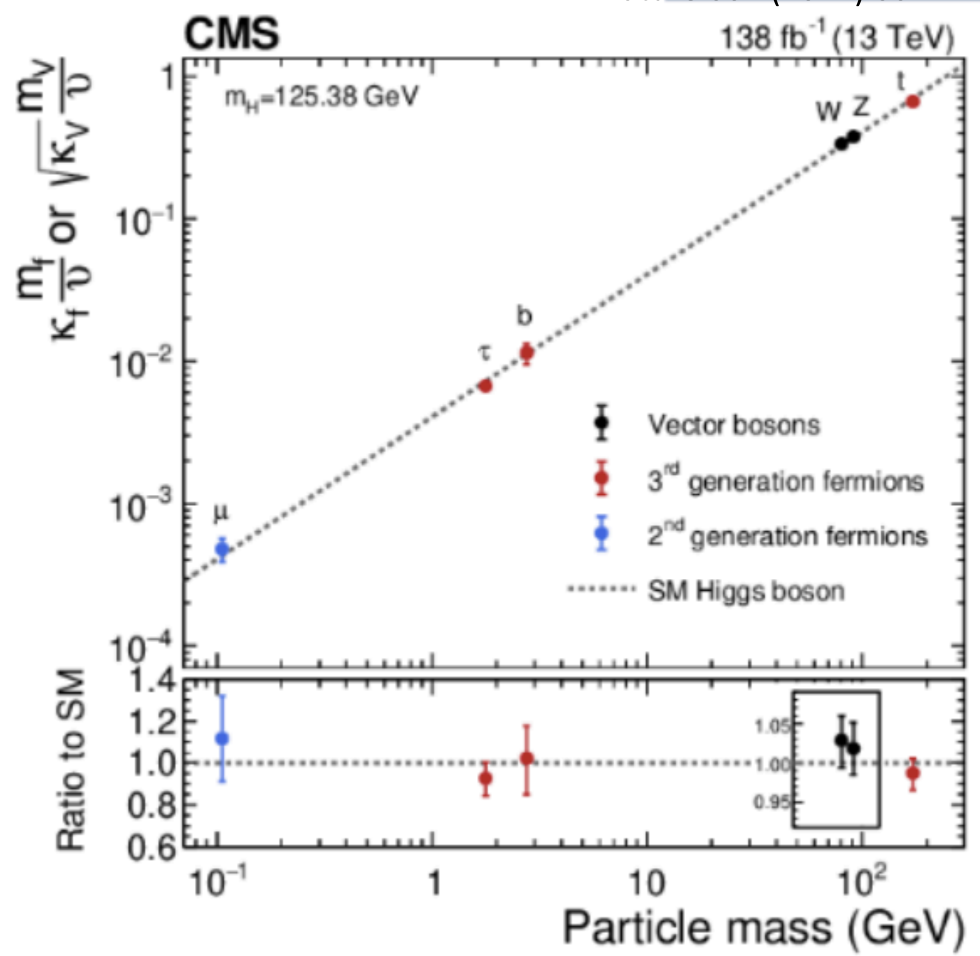




Nature 607 (2022) 52



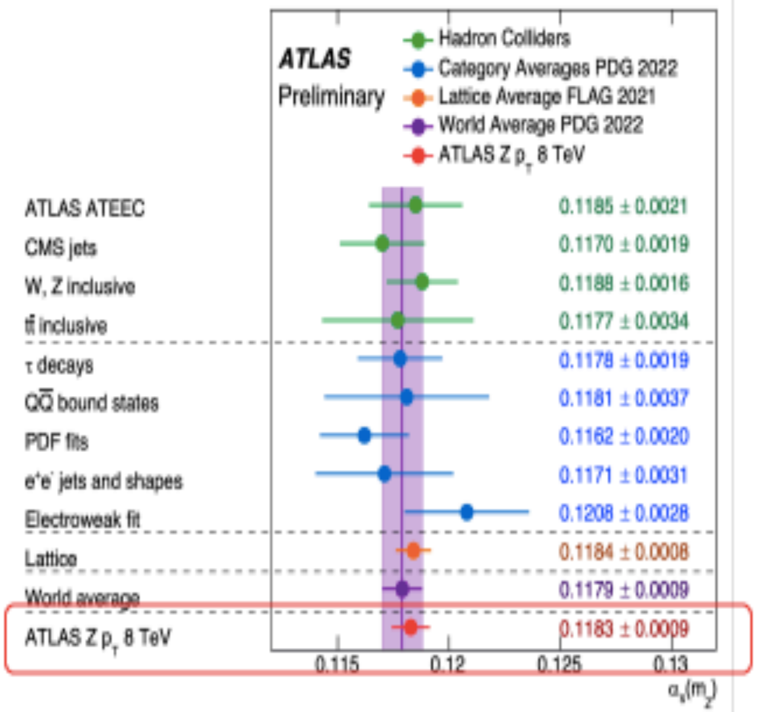
Nature 607 (2022) 60

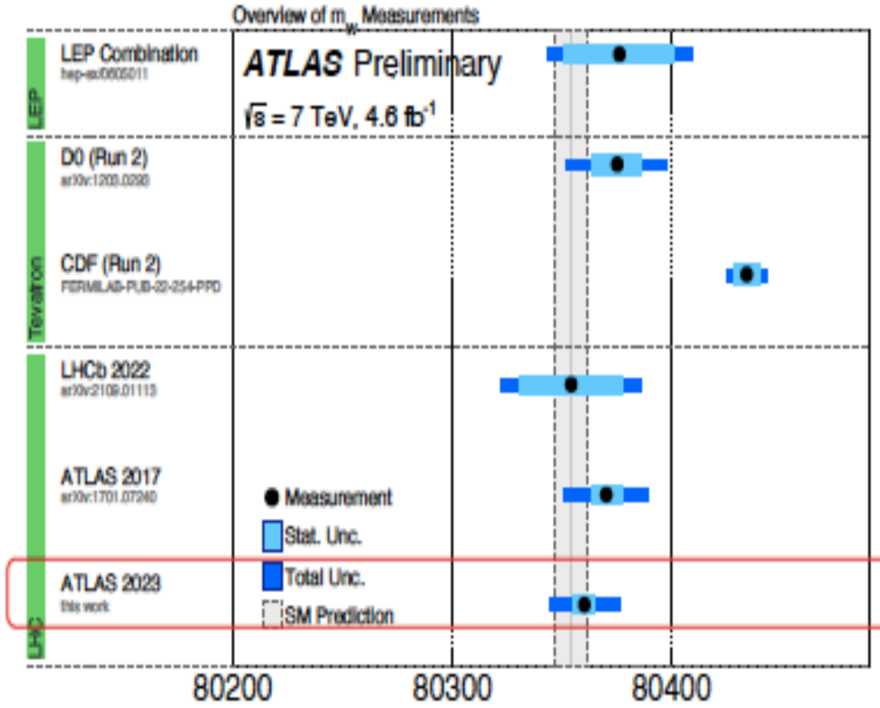


Hadron colliders are precision machines

New precise W mass measurement

New precise measurement of strong coupling strength



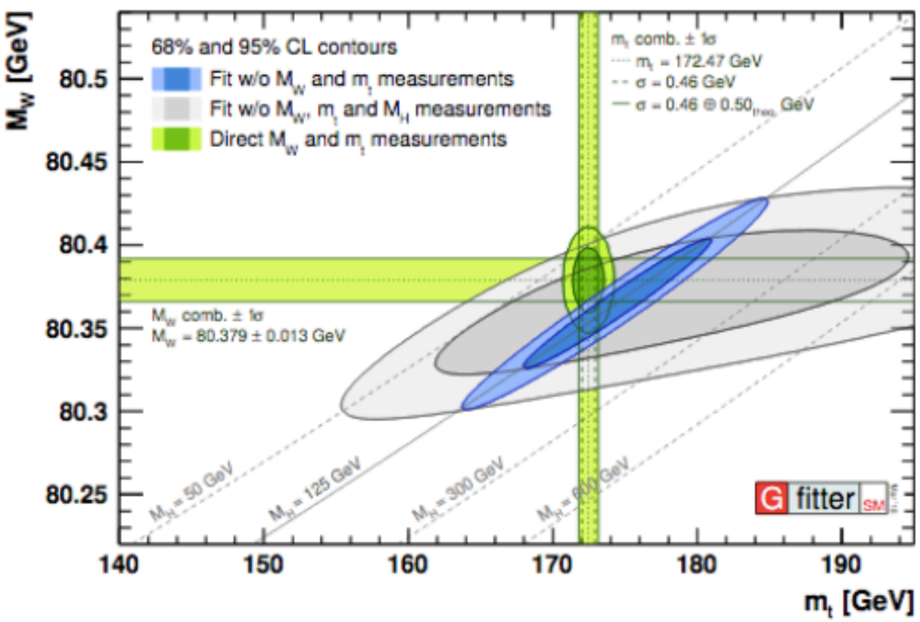


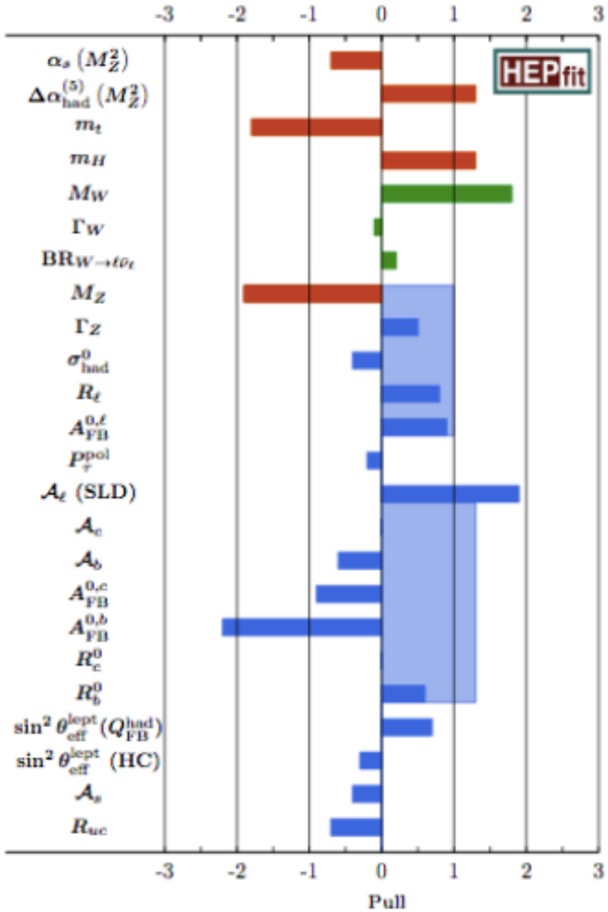
$\alpha_S(m_Z)$ = 0.1183 ± 0.0009 (0.76 %)

m_W = 80360 ± 16 MeV (0.02%)

Precision Observables

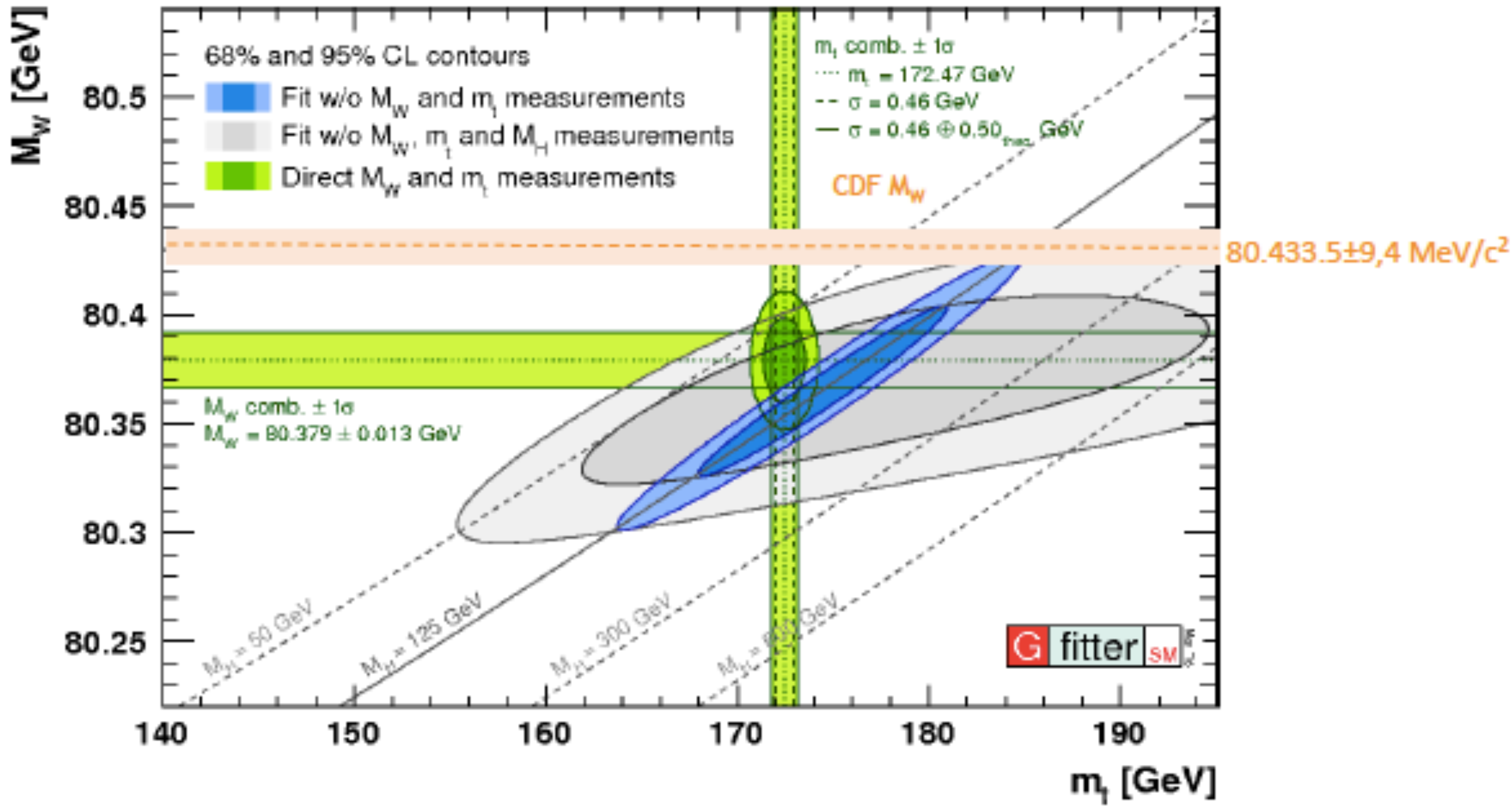
ELW. PRECISION PHYSICS





EPJC 78 (2018) 675 , arXiv:2112.07274

Standard Model Fit

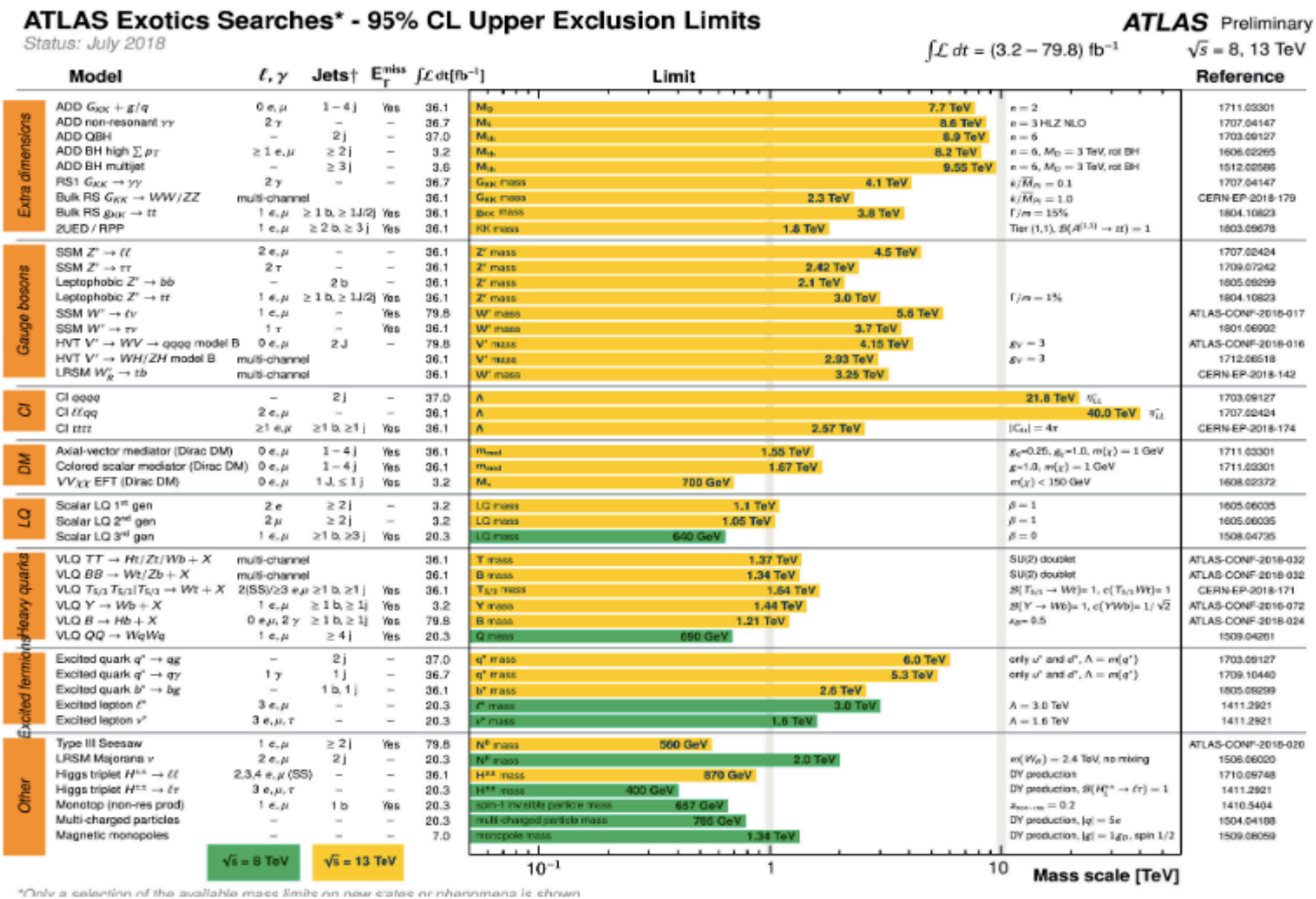


EW Precision fit from 2018

http://project-gfitter.web.cern.ch/project-gfitter/

BSM Direct Searches

High-Energy Frontier → produce and observe BSM new **heavy** particles



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018

ATLAS Preliminary
$\int \mathcal{L}\,dt = (3.2 - 79.8)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	Λ 40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	$\geq 1\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e, \mu$	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb) = 1$, $c(YWb) = 1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	$0\ e, \mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

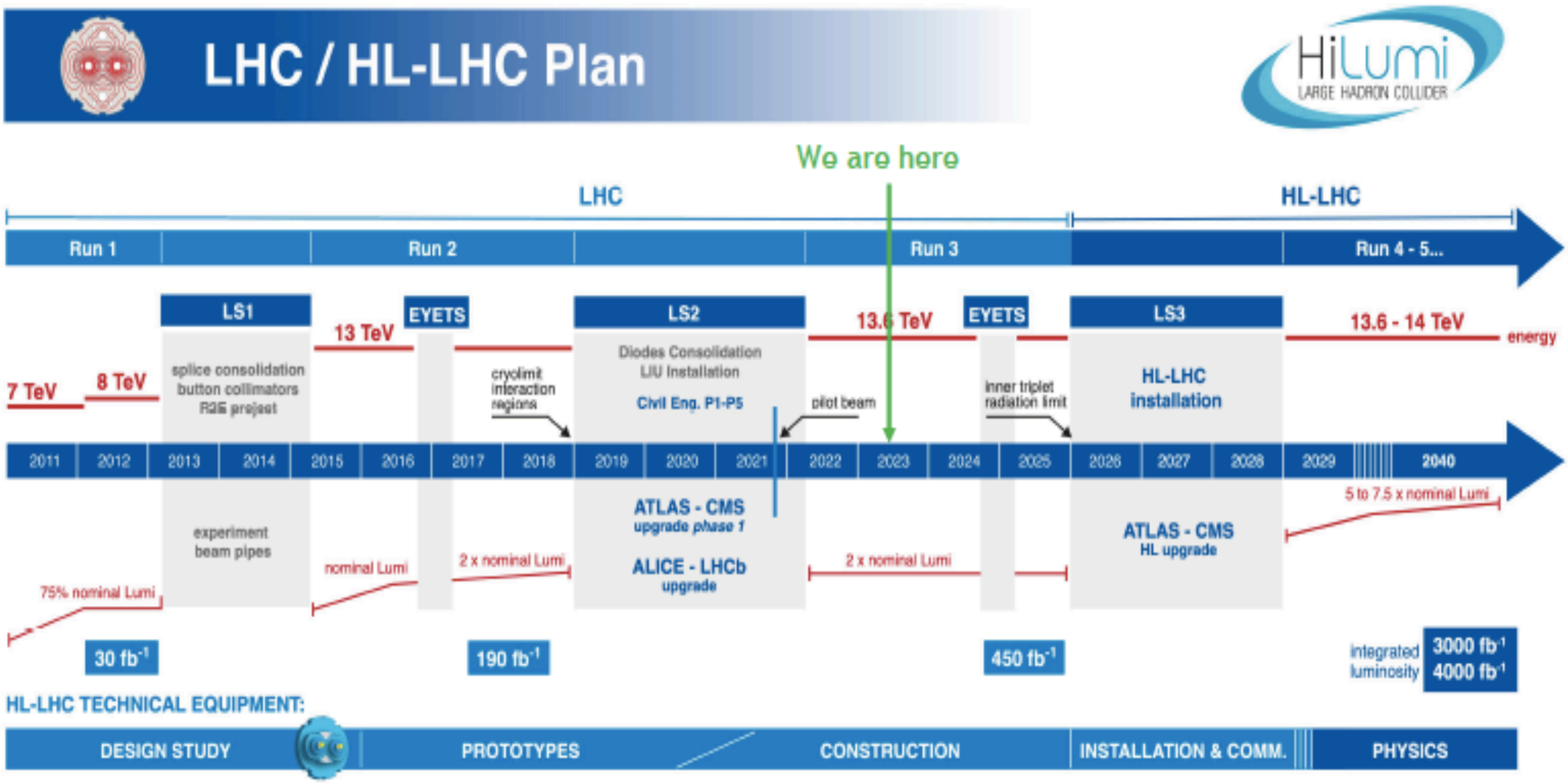
$\sqrt{s} = 8$ TeV $\sqrt{s} = 13$ TeV

Mass scale [TeV] (10^{-1}, 1, 10)

*Only a selection of the available mass limits on new states or phenomena is shown

Several EXOTIC models ruled out!

The LHC Schedule - Preparing for the future



HL-LHC CIVIL ENGINEERING:

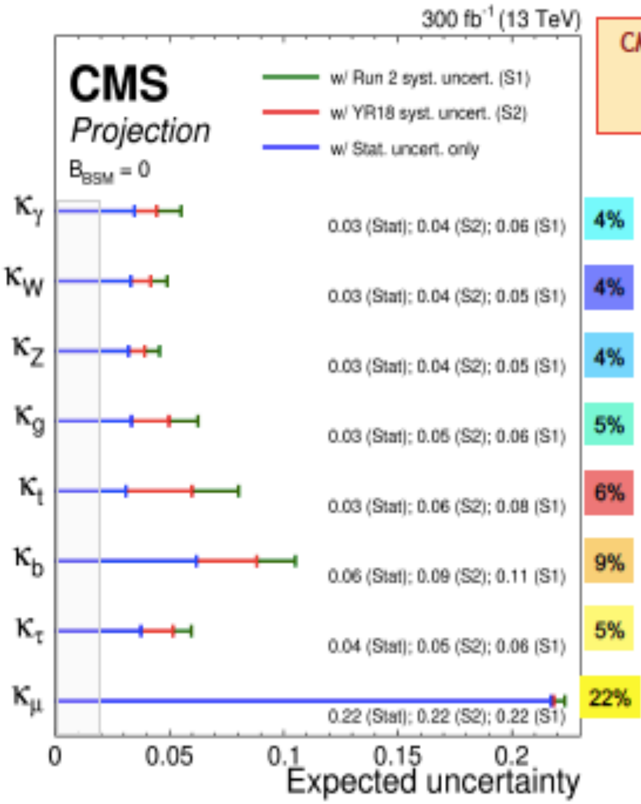
DEFINITION | EXCAVATION | BUILDINGS

New HL-LHC schedule updated to take into account current situation and delays in Run3 start.

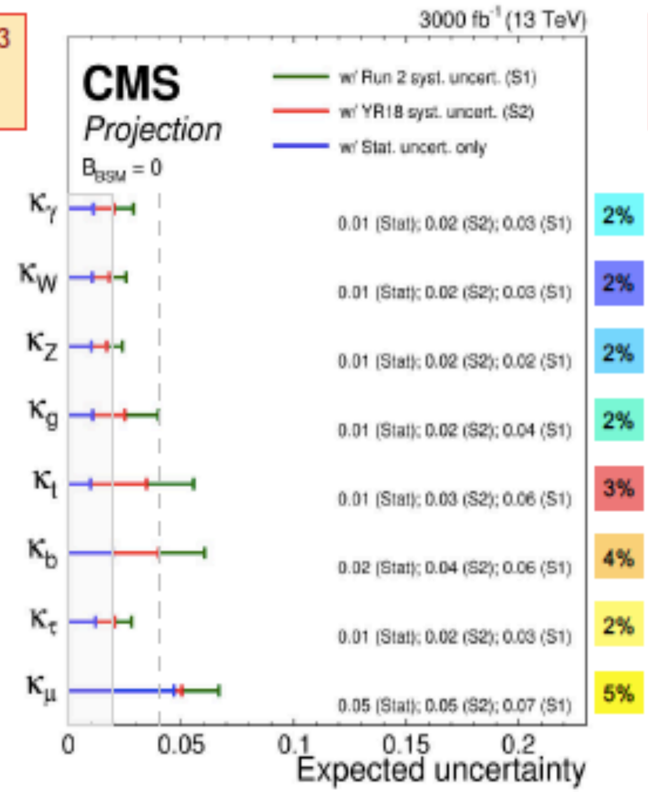
So far LHC has delivered ~ 6% of the total planned integrated luminosity!

HL-LHC: expectations on Higgs

CMS End of Run-3
13 TeV
300 fb^{-1}



CMS HL-LHC
13 TeV
3 ab^{-1}



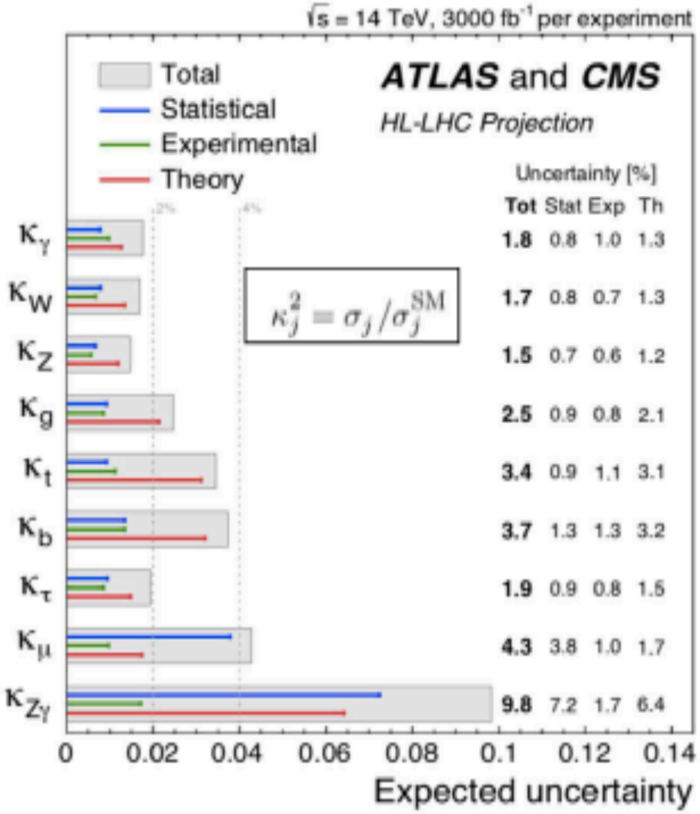
Most Higgs couplings known to better than 4%, dominated by systematic uncertainties

CMS-PAS-FTR-18-011

Physics potential of HL-LHC 1

Factor ~ 10 in data sample and improved detectors → significant increase in sensitivity for new physics and precise measurements

Higgs couplings measurements



Global fit assuming no BSM contributions to Γ_H

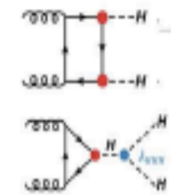
- 2-3 more precise than at end of LHC
- first 5σ observation of H→ Z

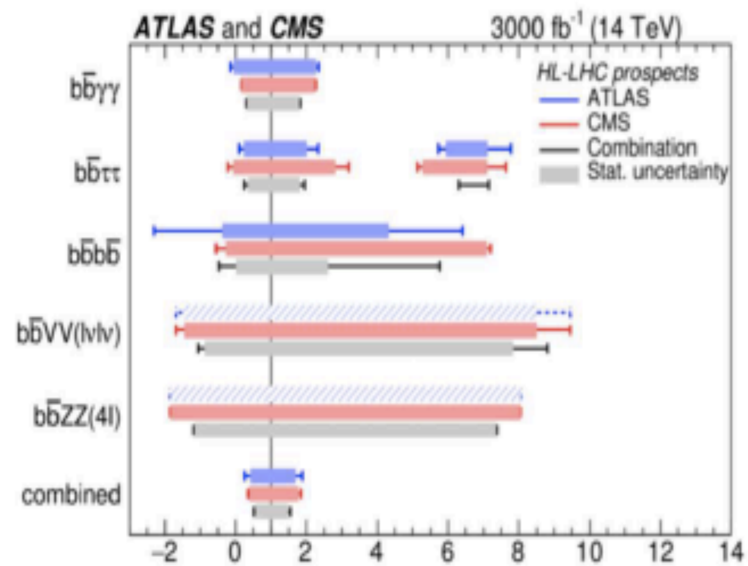
Experimental precision challenges theory!

First observation of HH production (~ 5σ level)

But only measure λ_3 to +/-50%

$$\mathcal{L}_h = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



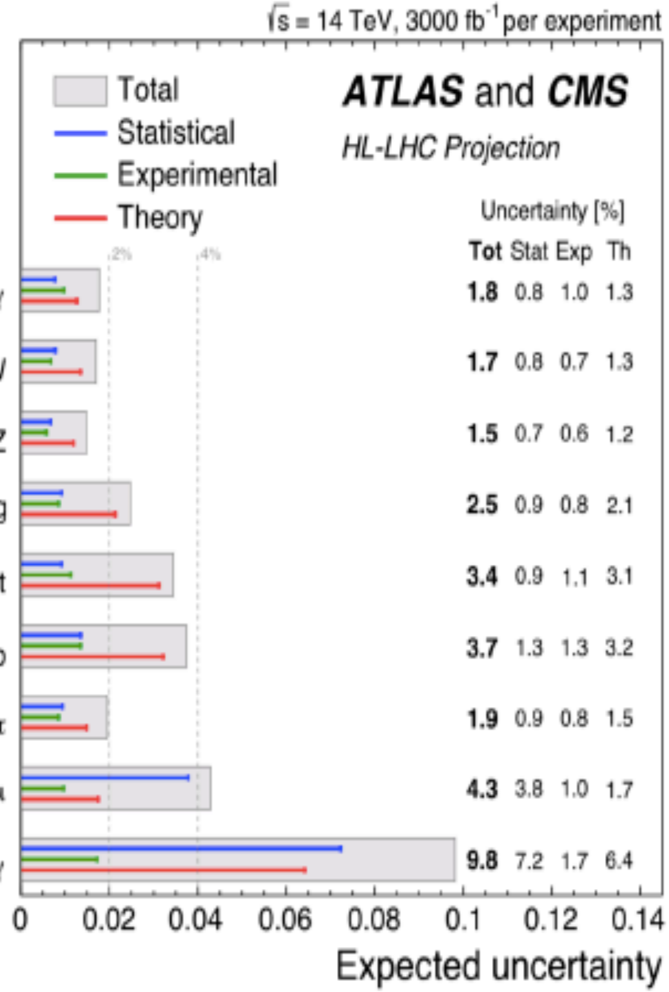


$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

0.52 < k_λ < 1.5 95% C.L.

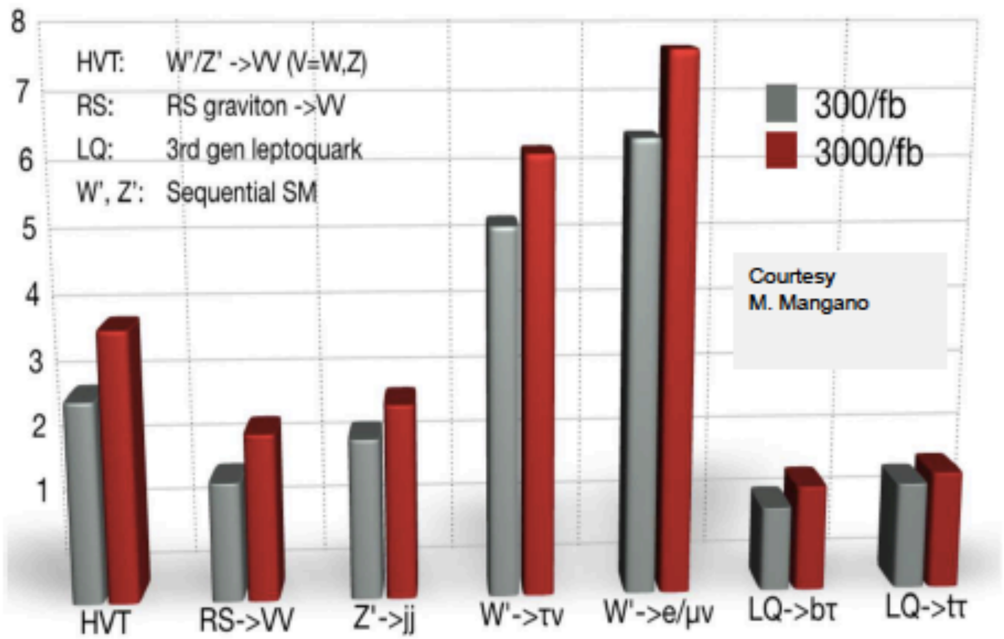
Higgs @ (HL)-LHC

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)

5σ discovery mass reach (TeV) for new particles:



Consistency tests of the CKM paradigm

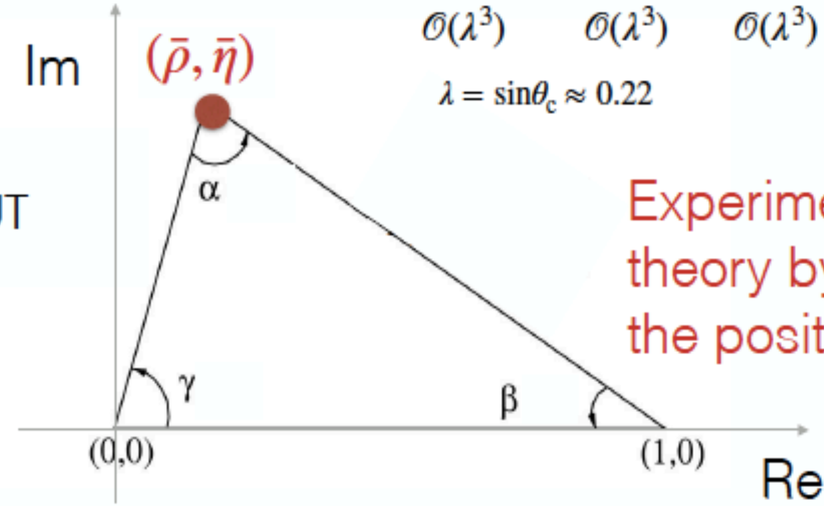
- Unitarity of CKM matrix implies relations of the form $\sum_i V_{ij} V^*_{ik} = \delta_{j,k}$, with $j \neq k$
- Each of these 6 unitarity constraints can be seen as the sum of 3 complex numbers closing a triangle in the complex plane

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

$\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$

$\lambda = \sin\theta_c \approx 0.22$

CP violation in the quark sector ($\bar{\eta} \neq 0$) is translated into a non flat UT



Experiments test the theory by constraining the position of the apex

M. Pepe-Altarelli, Erice School, June 2023

- **$N_f = 2$:** 1 angle, 0 phases (Cabibbo)

$$V = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \quad \Rightarrow \quad \text{No } \not{CP}$$

- **$N_f = 3$:** 3 angles, 1 phase (CKM) $\qquad c_{ij} \equiv \cos\theta_{ij} \; ; \; s_{ij} \equiv \sin\theta_{ij}$

$$V = \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix}$$

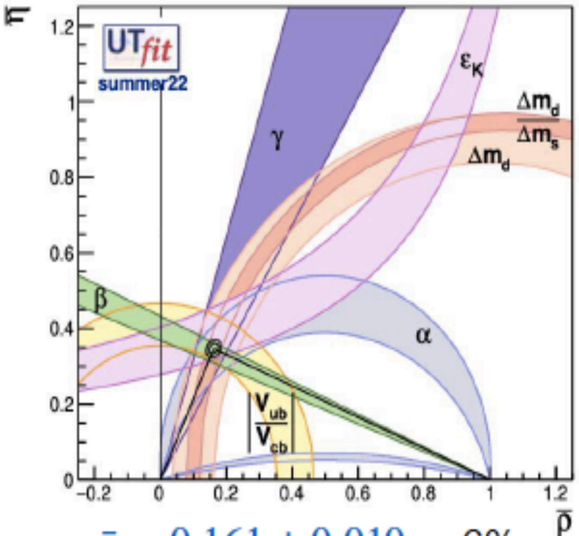
$$\Rightarrow \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\,(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\,(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

$\lambda \approx \sin\theta_C \approx 0.225 \; ; \; A \approx 0.81 \; ; \; \sqrt{\rho^2+\eta^2} \approx 0.37 \qquad \delta_{13} \neq 0 \;\; (\eta \neq 0) \Rightarrow \not{CP}$

Consistency tests of the CKM matrix

- At the current level of precision (~%), all measurements are consistent and intersect in the apex of the UT
- What is particularly noteworthy is the consistency of the tree-level determinations of CKM elements, with those obtained from meson-anti meson mixing

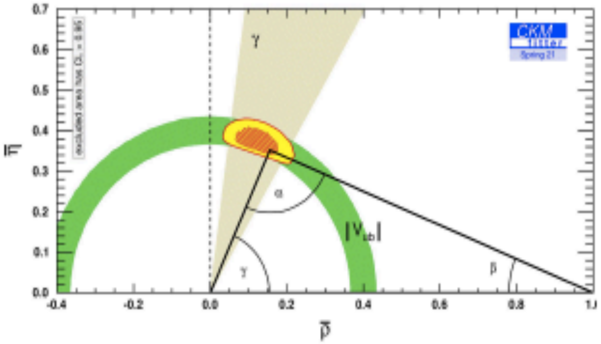
arXiv:2212.03894 UTfit,



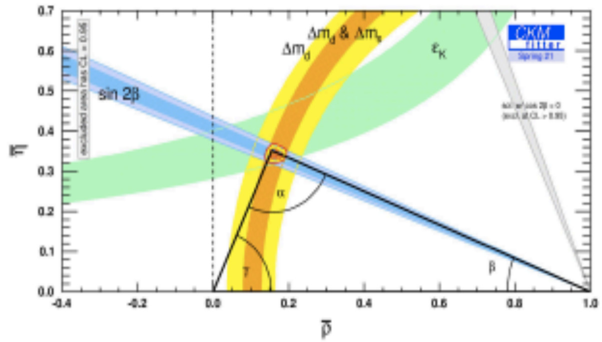
$\bar{\rho} = 0.161 \pm 0.010$ ~6%

$\bar{\eta} = 0.347 \pm 0.010$ ~3%

Tree-level observables



Loop observables



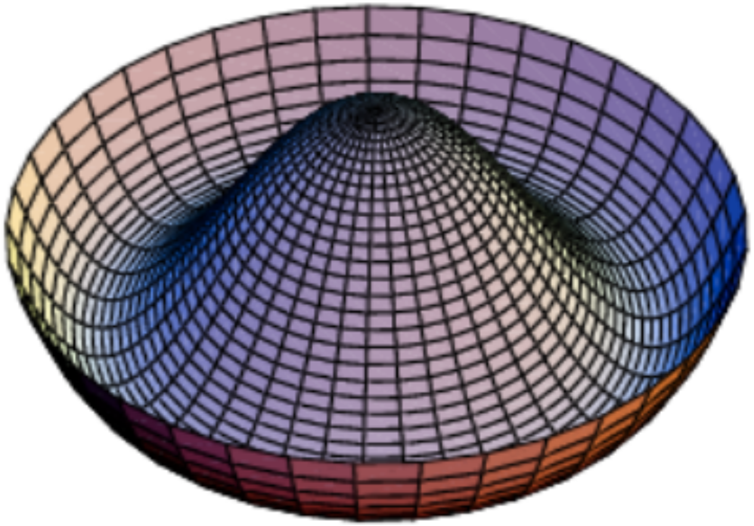
- New Physics effects (if there) are small!
- But… past examples show that it is unwise to think that few % is good enough

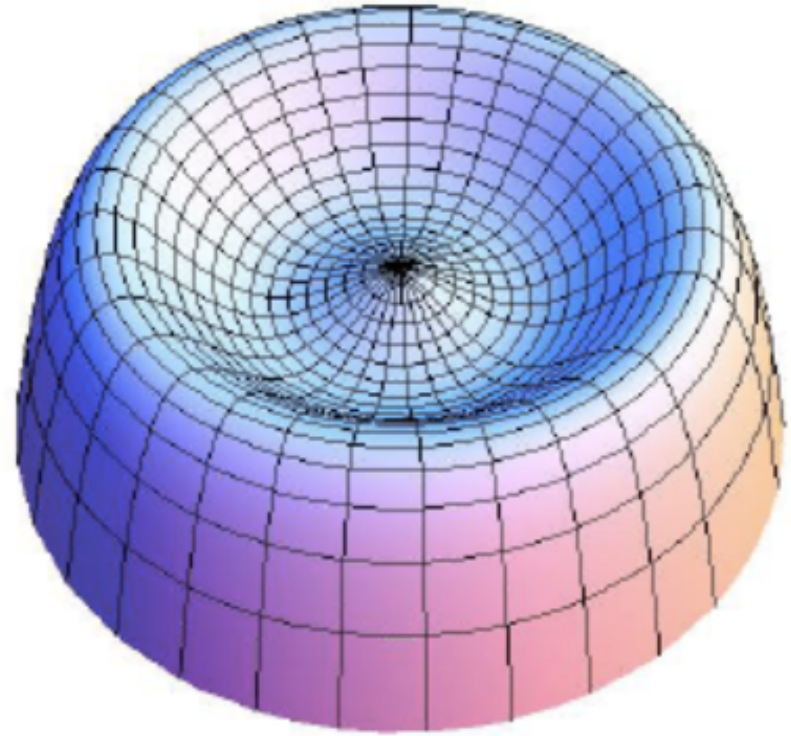
M. Pepe-Altarelli, Erice School, June 2023

On the peculiar value of M_H

- **For the SM to survive up to a very large scale, M_{GUT} or M_{Planck} : M_H in the fork 125 – 180 GeV, with ~ 125 GeV just on the verge between stability and instability of the vacuum state where the SM sits**
- For the existence of a **(minimal) supersymmetric extension of the SM** at the elw. scale, the lightest SUSY Higgs must have **M_h < 130 GeV** (for M_h >120 GeV, the radiative correction to M_h is ~ 50% of the tree-level value)

STABILITY ↔ **INSTABILITY**

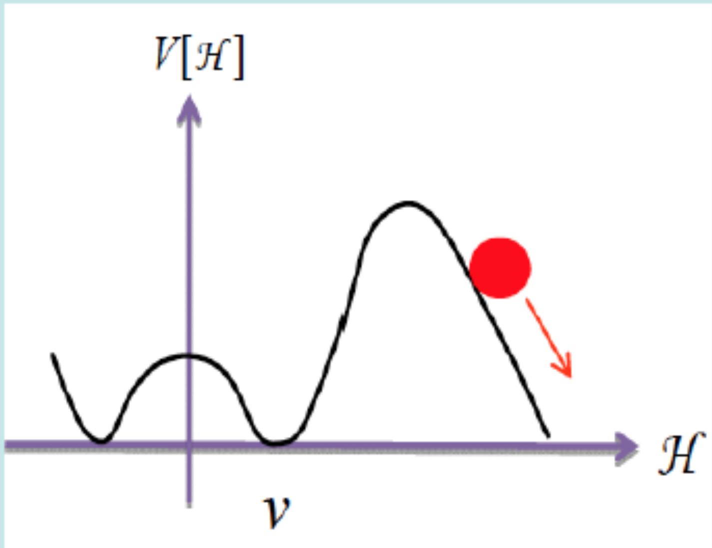




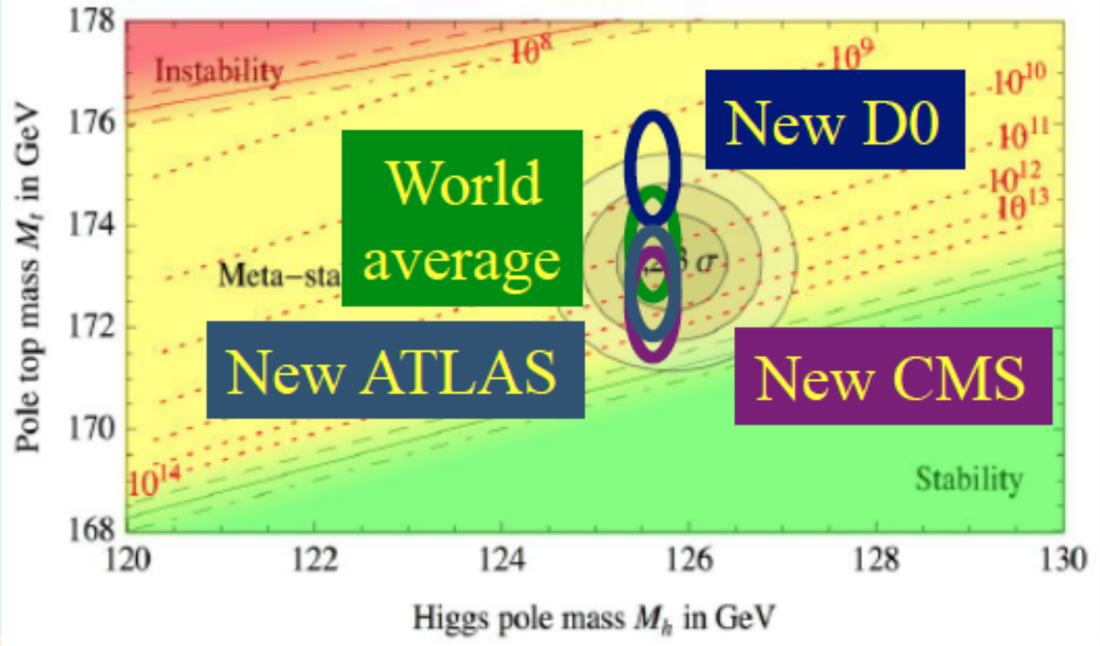
ON THE IMPORTANCE OF PRECISELY MEASURING HIGGS and TOP MASSES

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



J. Ellis, LP 2015

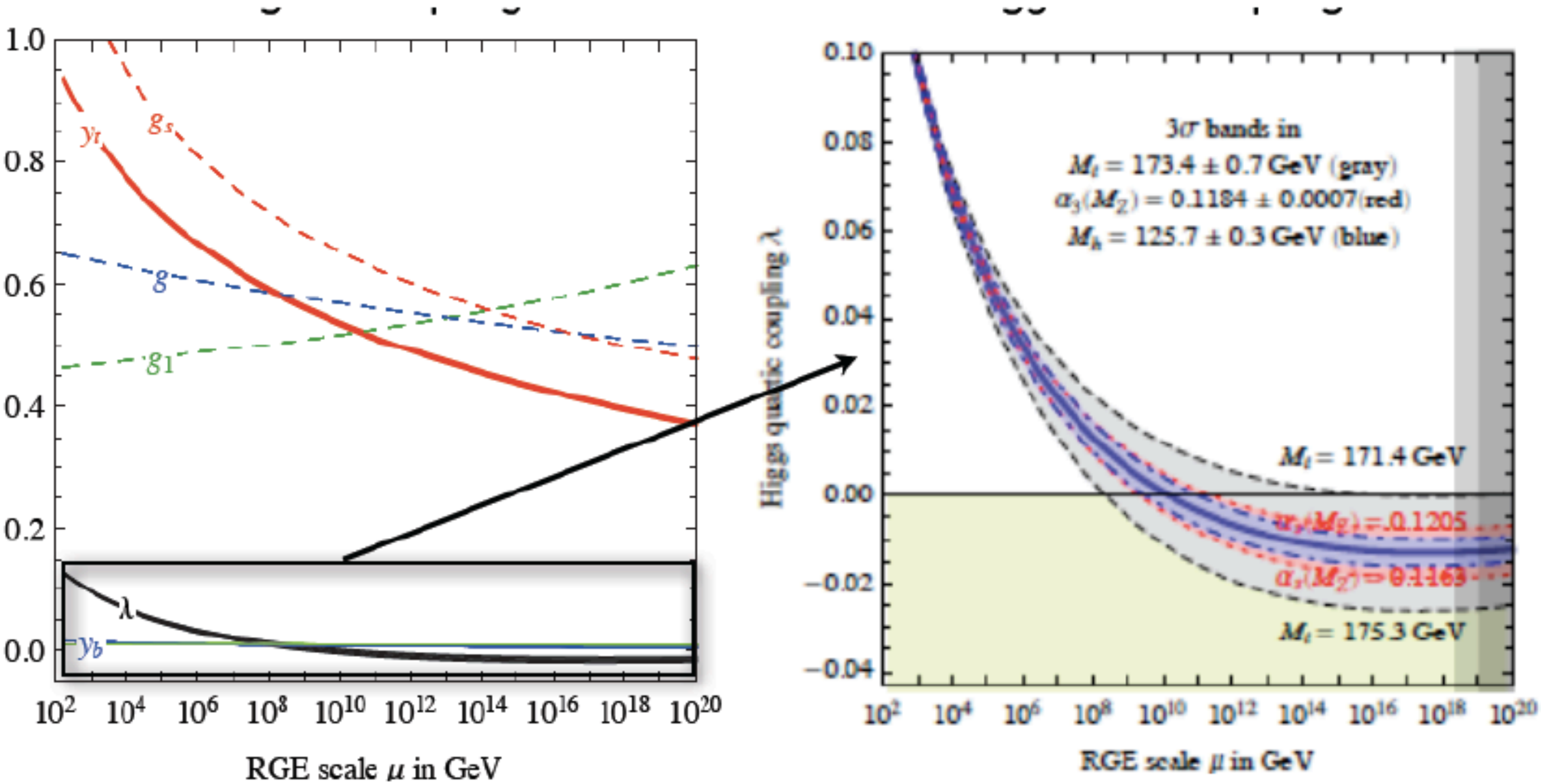


Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Instability scale:

$$\log_{10}\frac{\Lambda_I}{\mathrm{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\mathrm{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\mathrm{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

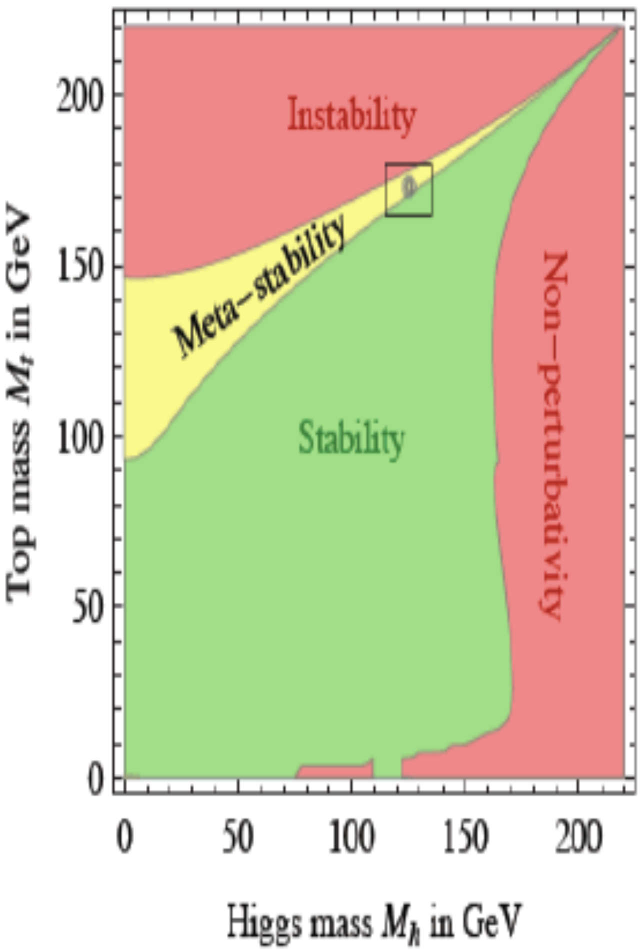
$m_t = 173.3 \pm 1.0$ GeV → $\log_{10}(\Lambda/\mathrm{GeV}) = 11.1 \pm 1.3$

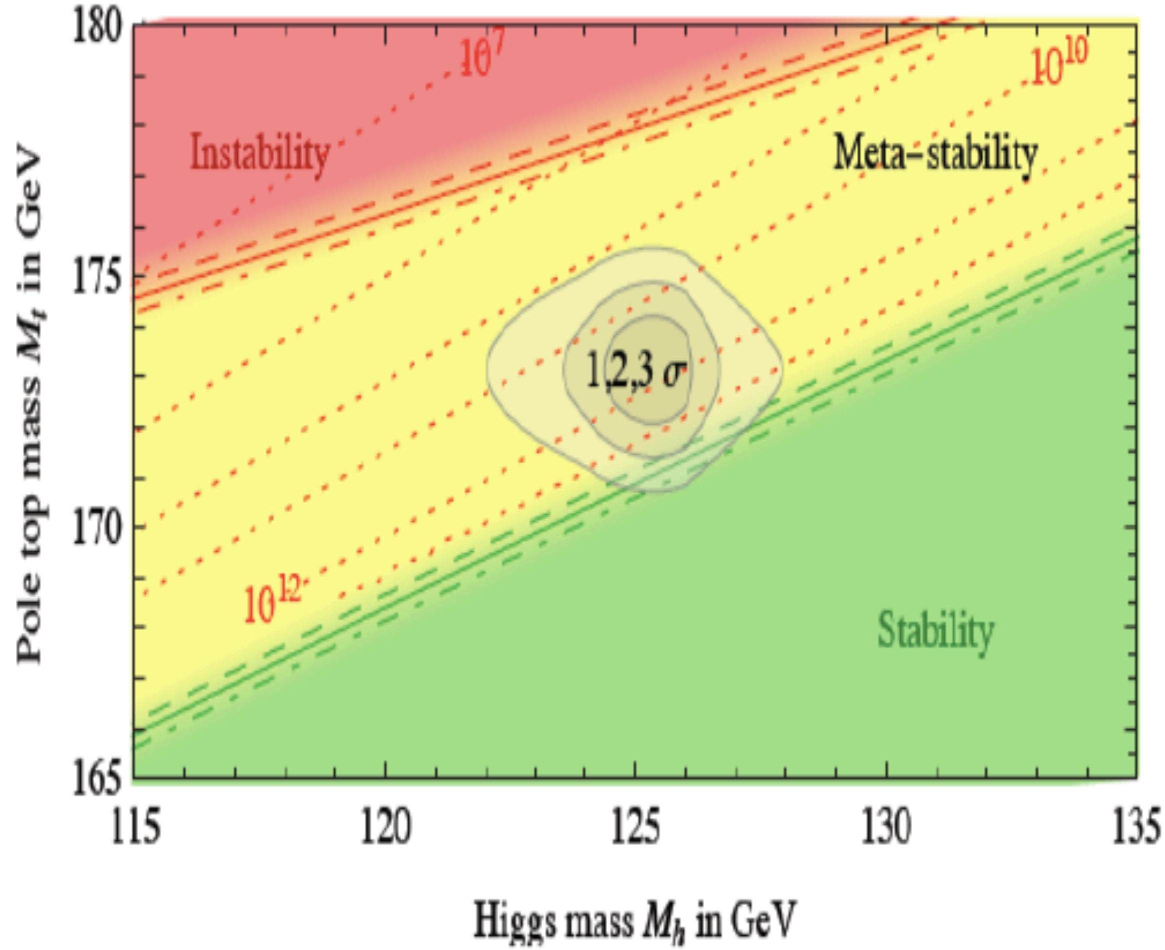


Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia 2013

For previous works: Krive, Linde '76; Krasnikov '78; Maiani, Parisi, Petronzio '78; Cabibbo et al '79; Lindner '86; Altarelli, Isisdori '96; Ellis et al 2009; Shaposhnikov et al '12; Elias-Miro' 'et a ''12; …..
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

LIVING DANGEREOUSLY IN A "PROBABLE" METASTABLE UNIVERSE

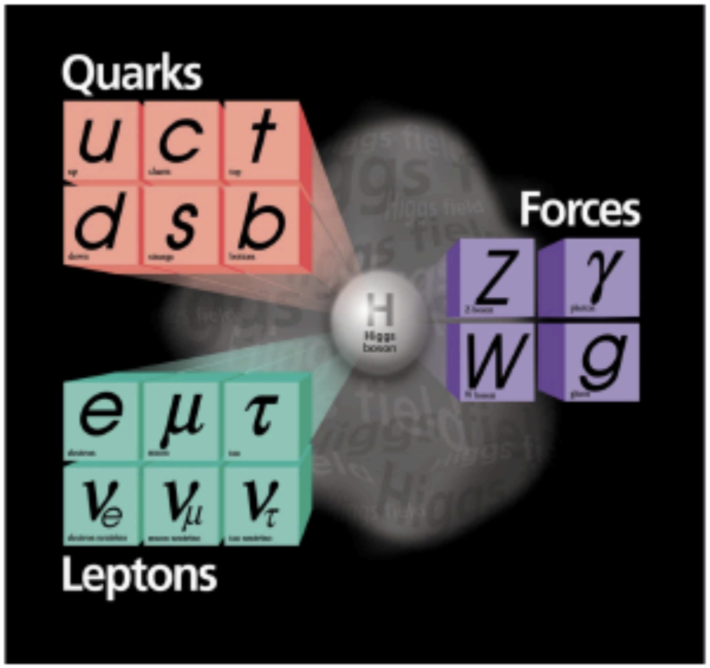


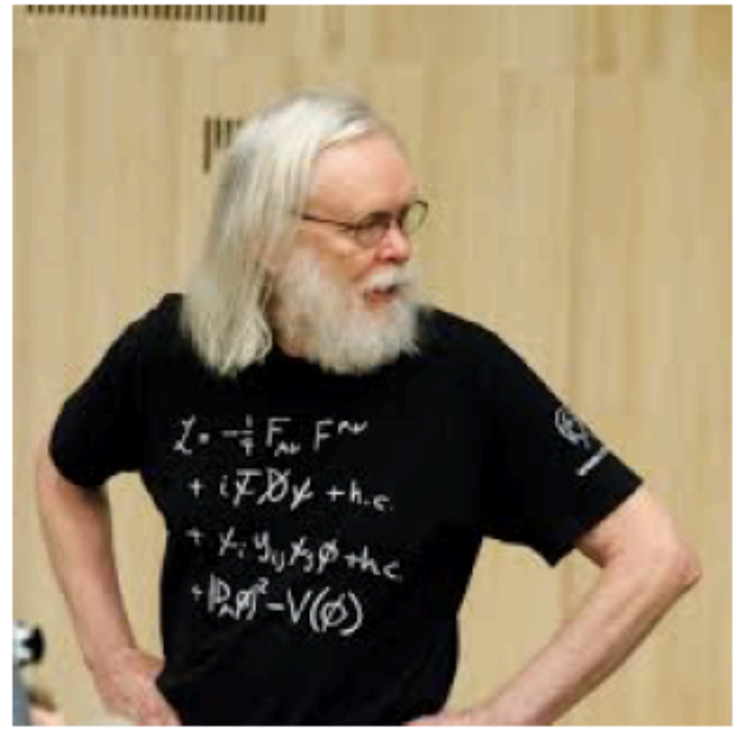


BEZRUKOV, KALMIKOV, KNIEHL, SHAPOSHNIKOV 2012;
DEGRASSI, DI VITA, ELIAS-MIRO', ESPINOSA, GIUDICE, ISIDORI, STRUMIA 2012

FIRST COMPLETE ANALYSIS NNLO OF THE SM HIGGS POTENTIAL

The Standard Model (SM) is a remarkably simple Quantum Field Theory (QFT) that describes well all microscopic phenomena that we observe in Nature





The SM describes fundamental interactions among elementary particles

“This is short enough to write on a T-shirt!”

[John Ellis]