TESTING THE FUNDAMENTAL LAWS OF NATURE AT THE ENERGY FRONTIER

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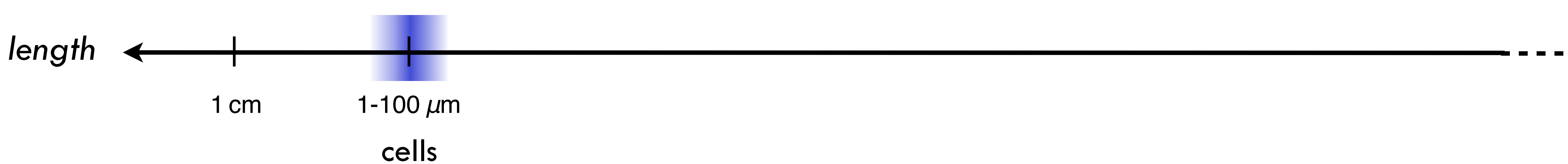
Much of the progress in Physics has been driven by the *quest of simplicity* (reductionism)

Several layers of structure in the microscopic description of matter have been uncovered at different length scales that are more and more fundamentals



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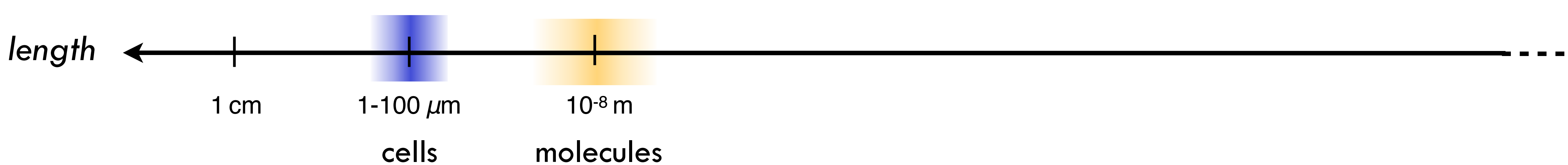

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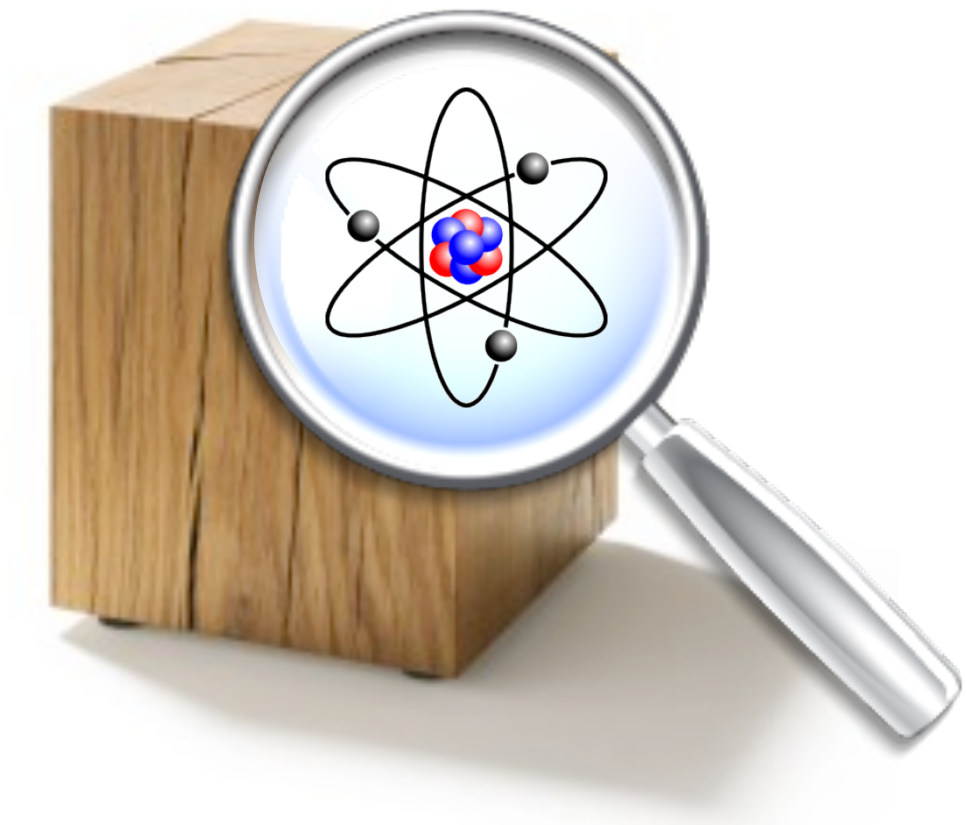

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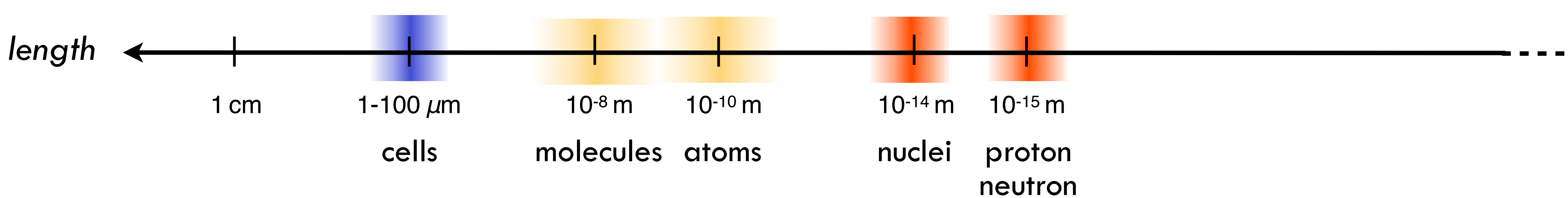

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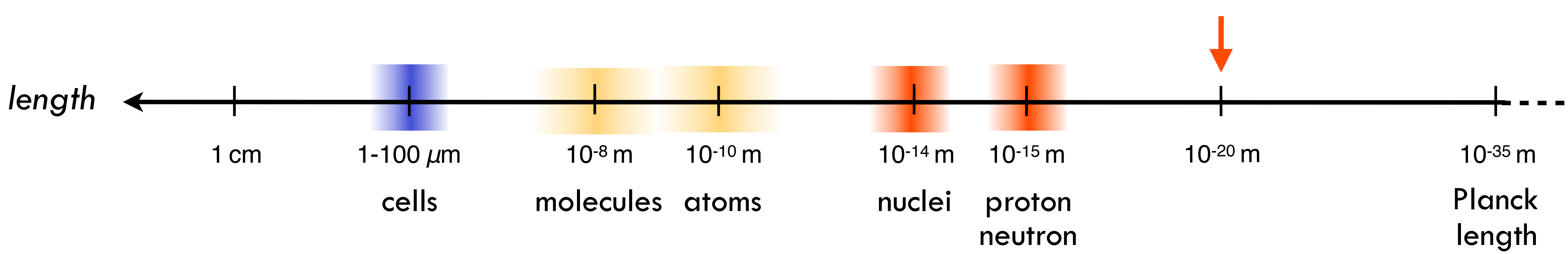
Several layers of structure in the microscopic description of matter have been uncovered at different length scales that are more and more fundamentals

Quarks and leptons appear point-like (i.e. fundamental) at the shortest scales probed so far (1 billionth of billionth of billionth of centimeter)



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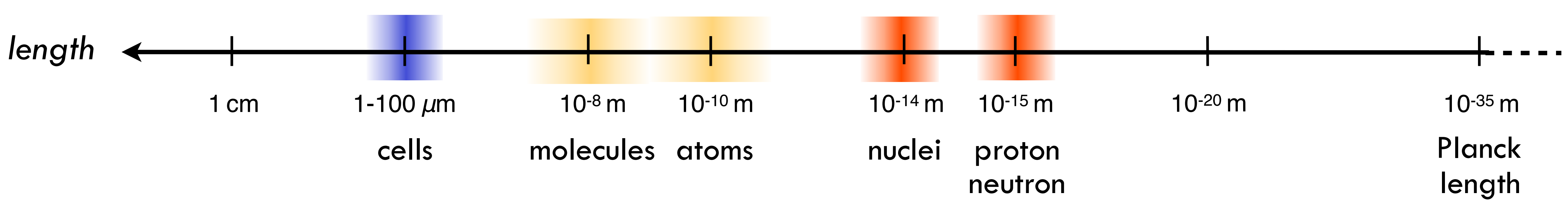
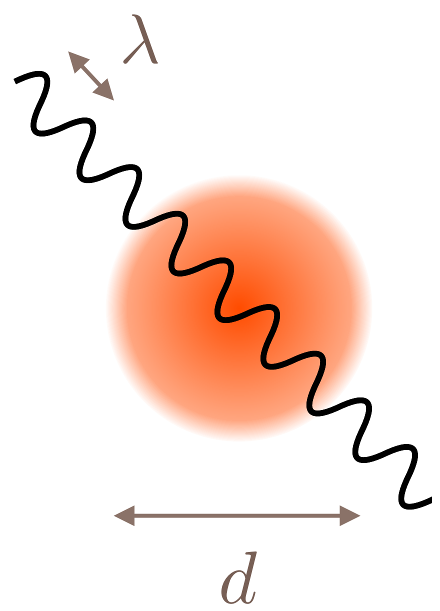
Reductionism in modern terms:

- *Theory with the fewest possible fundamental constituents (elementary particles)*
- *All (but one) length/energy scales dynamically generated*



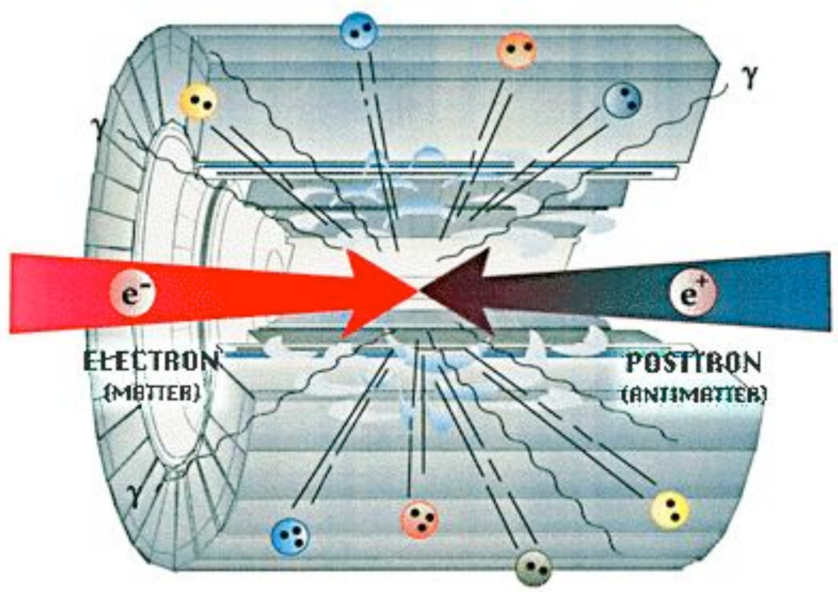
Particle Colliders: our most powerful microscopes

Exploring small distances requires probes with short wavelength, i.e. high momentum



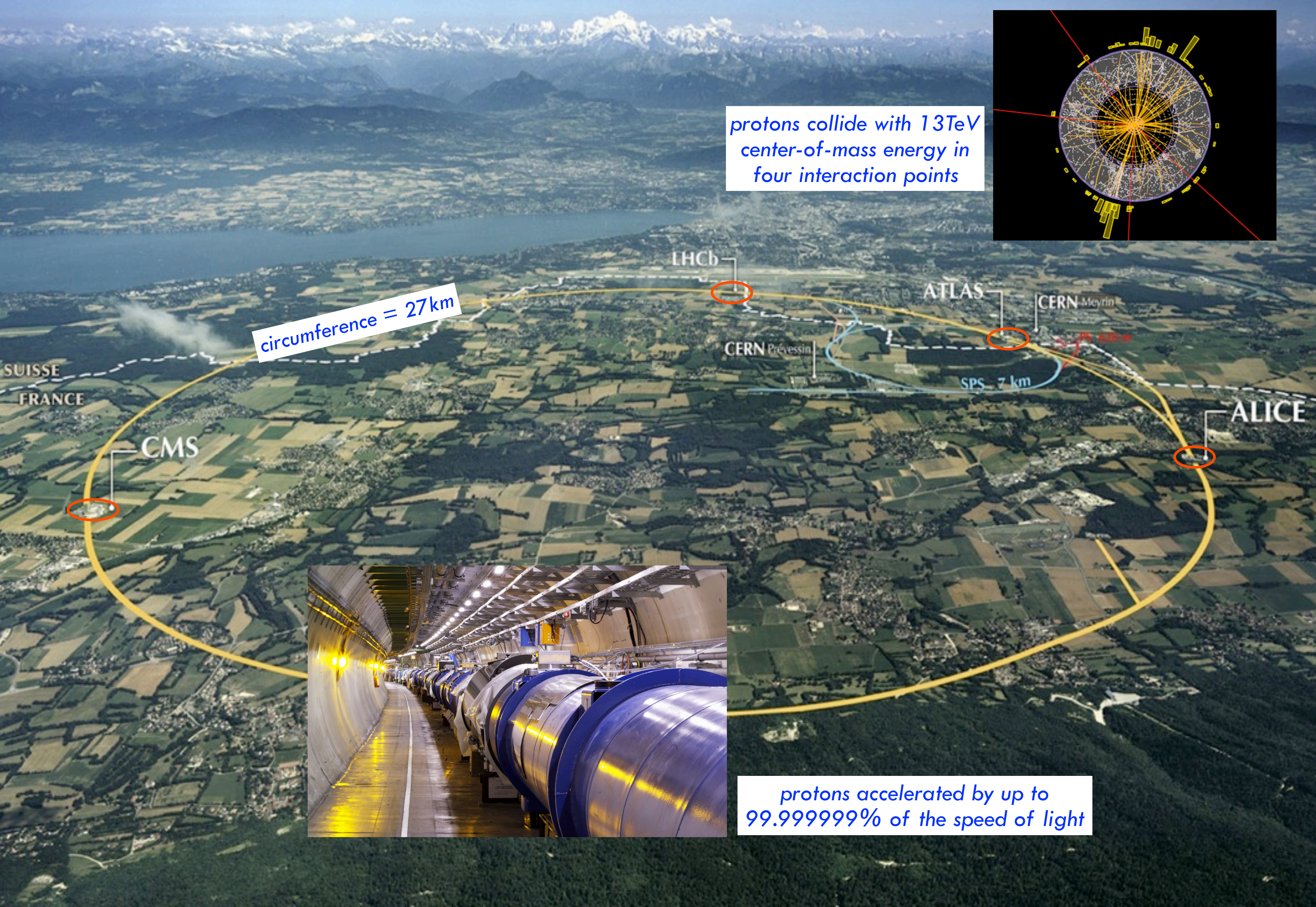
$$\lambda = \frac{h}{p}$$

To study their internal structure, particles are accelerated and made to collide



From the collision, new particles are created

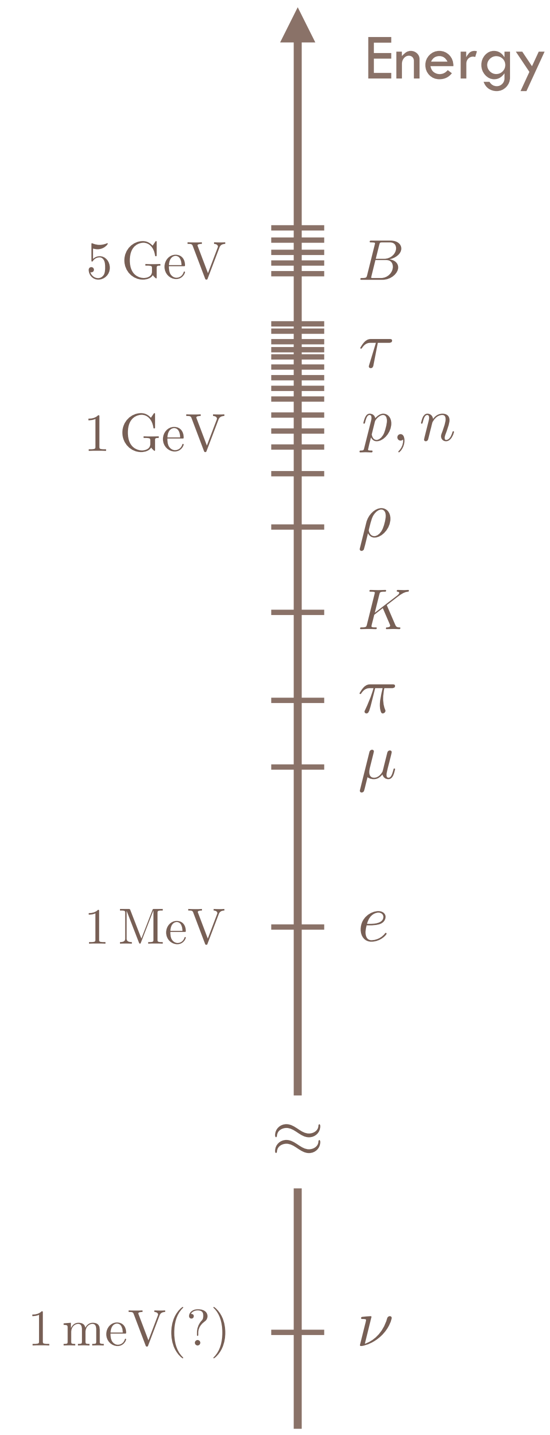
The Large Hadron Collider (LHC): the Lord of the collider rings



Experimental landscape in the late 1970s

A zoo of particles described in terms of a few building blocks: quarks and leptons

The dynamics of quarks and leptons obeys the laws of QED+QCD, a quantum field theory based on $SU(3)_c \times U(1)_{em}$



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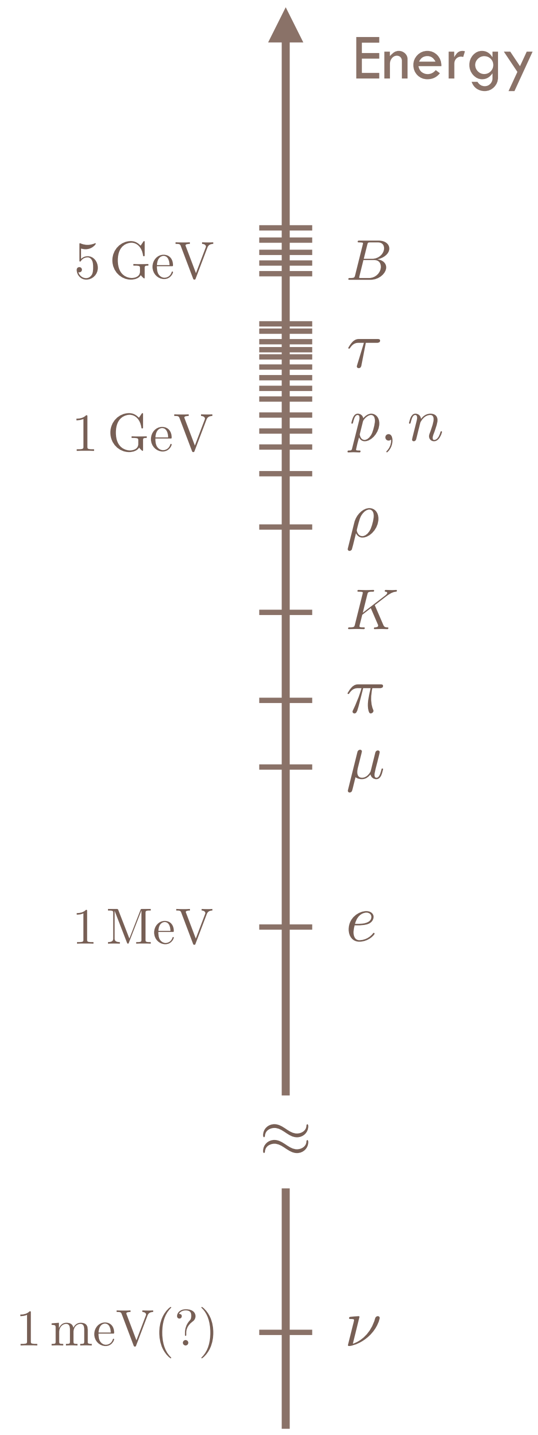
Hadronic mass scale explained *dynamically* by QCD but key properties of spectrum rely on arbitrary quark and lepton masses



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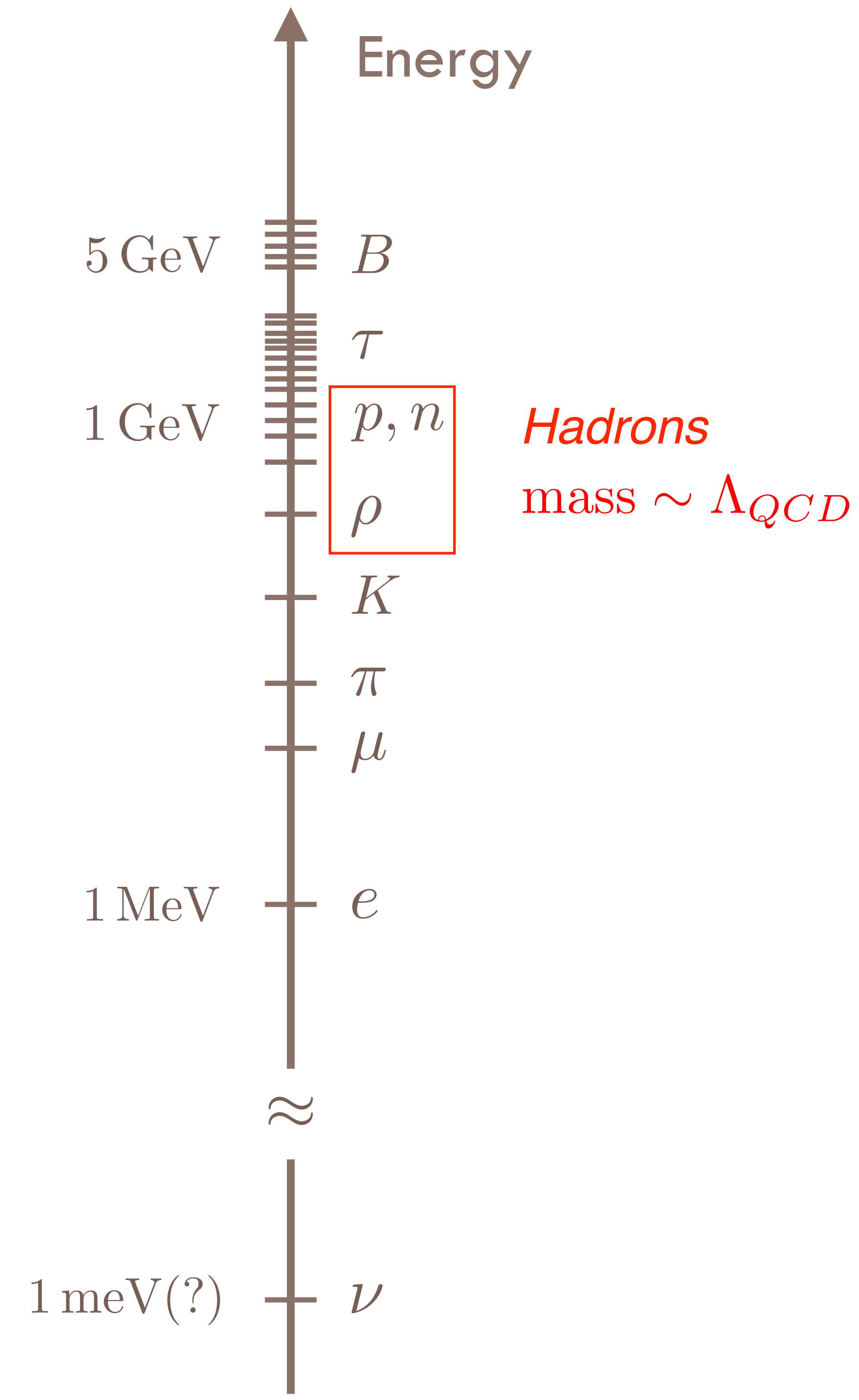

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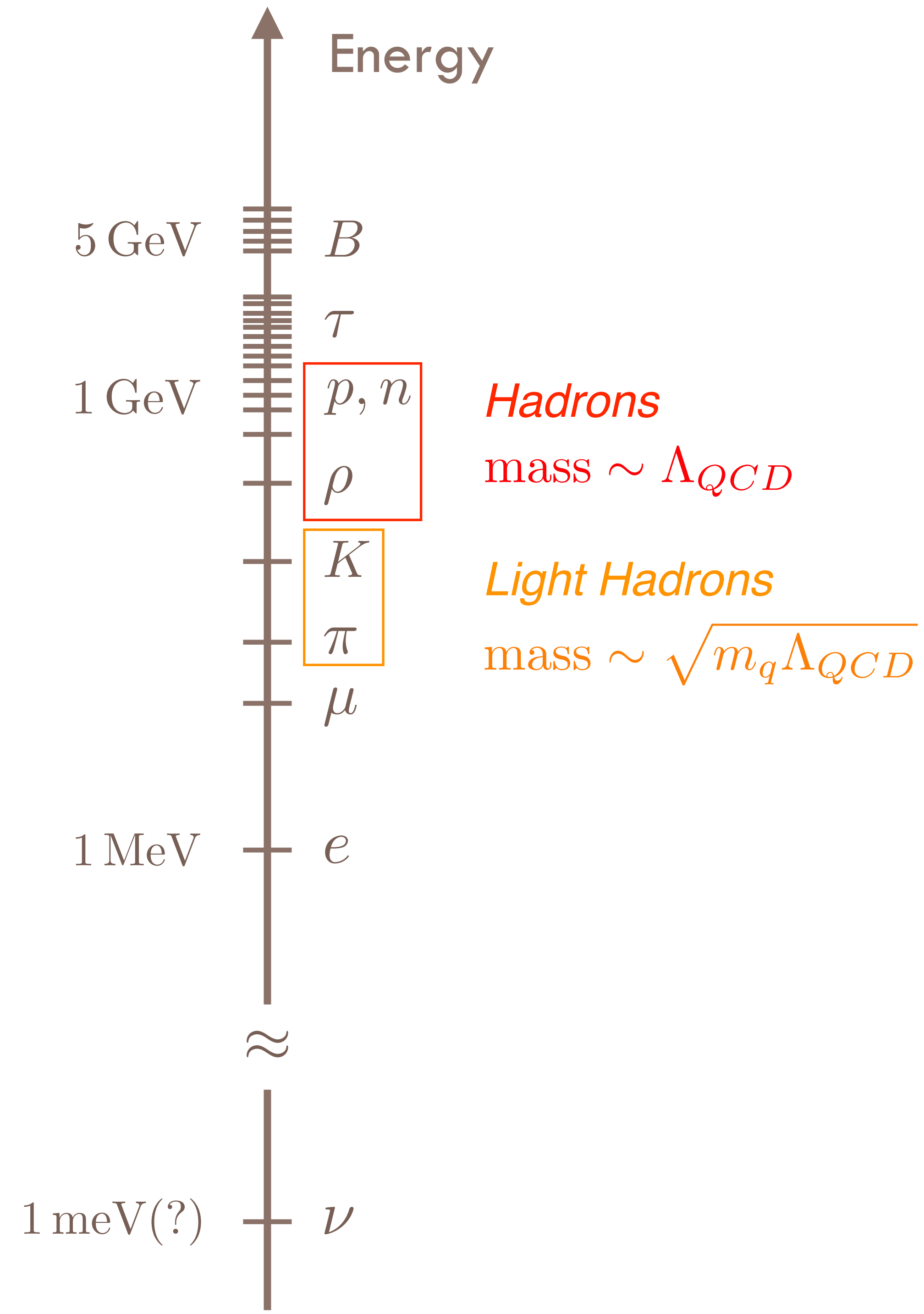

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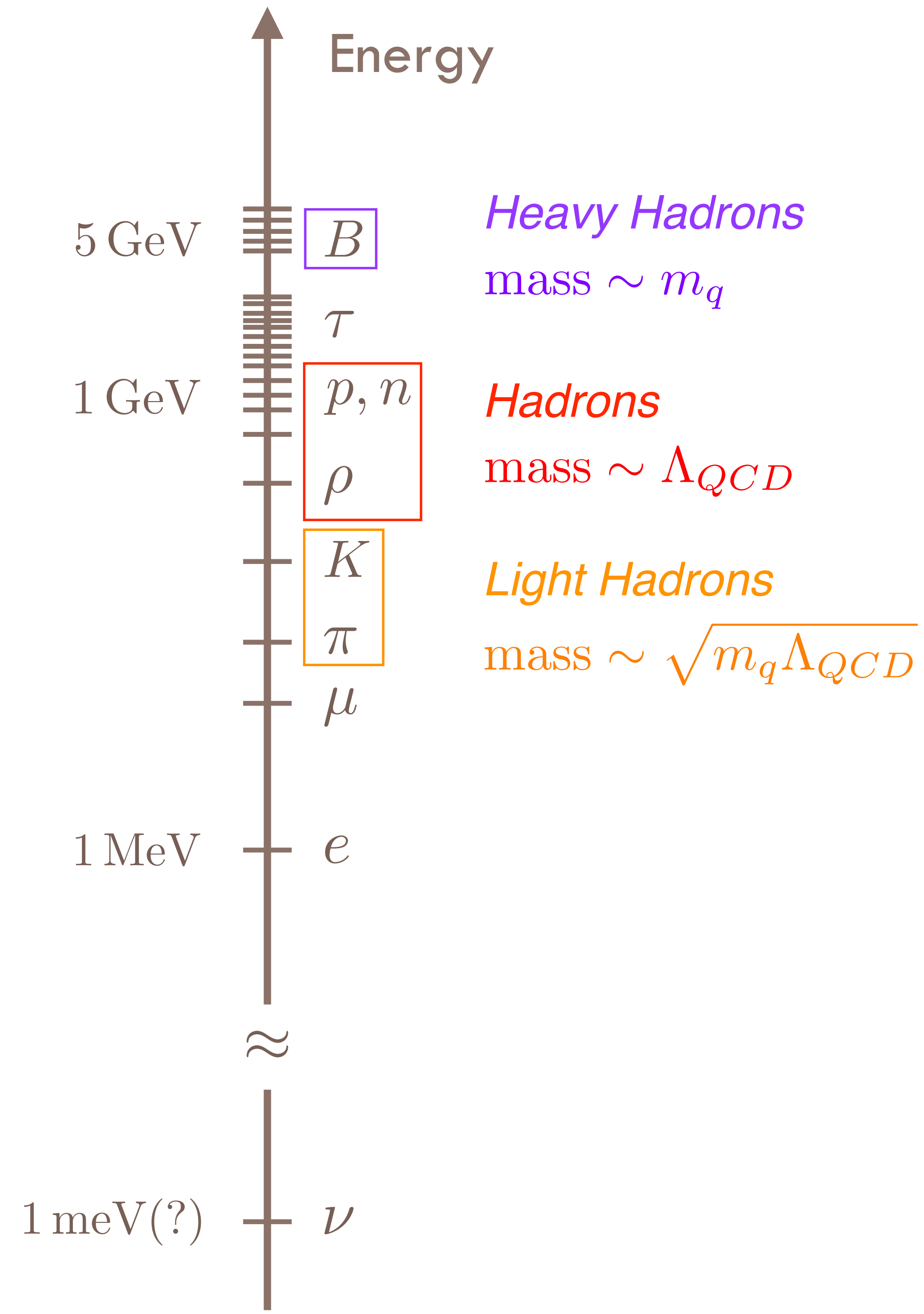

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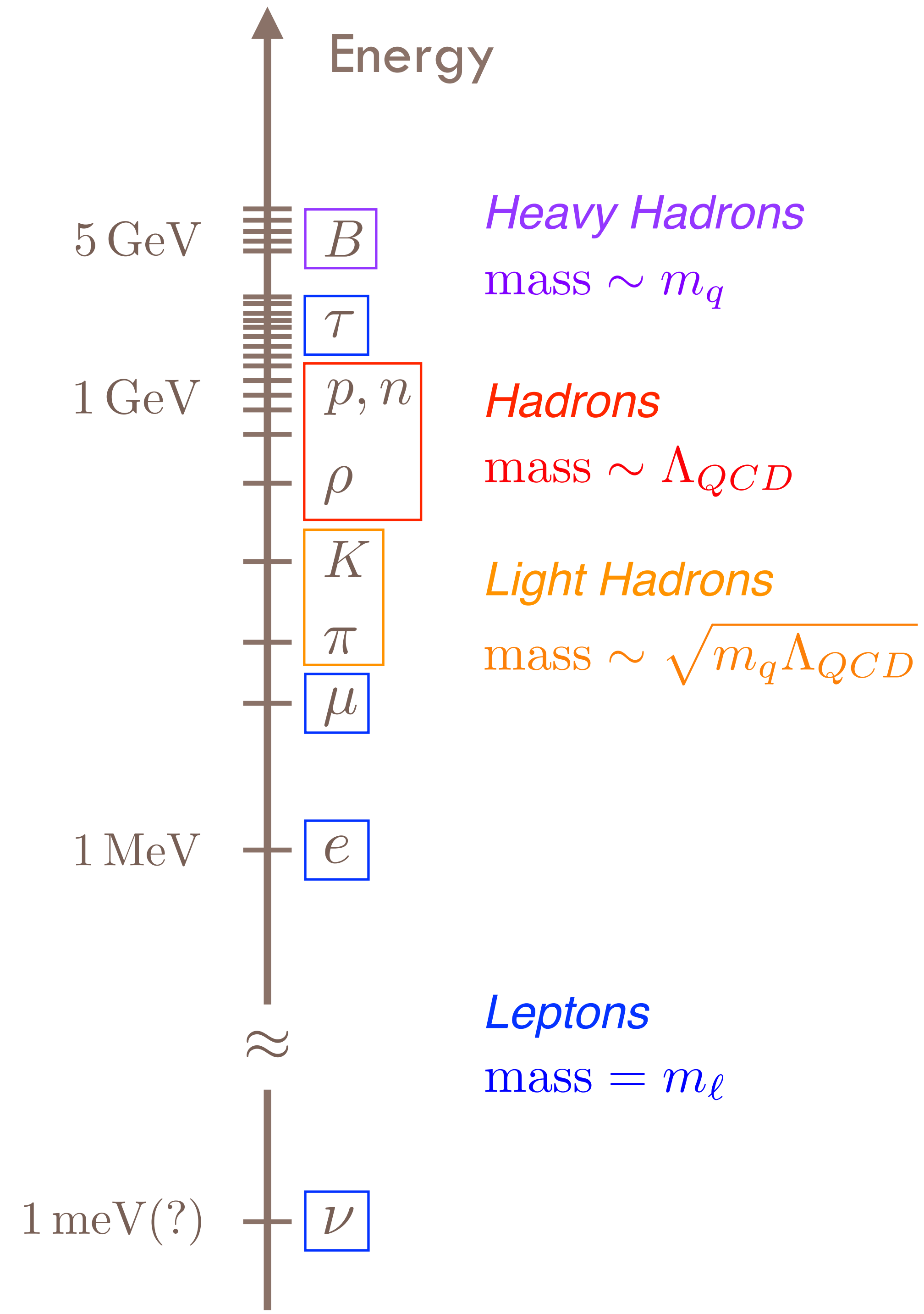

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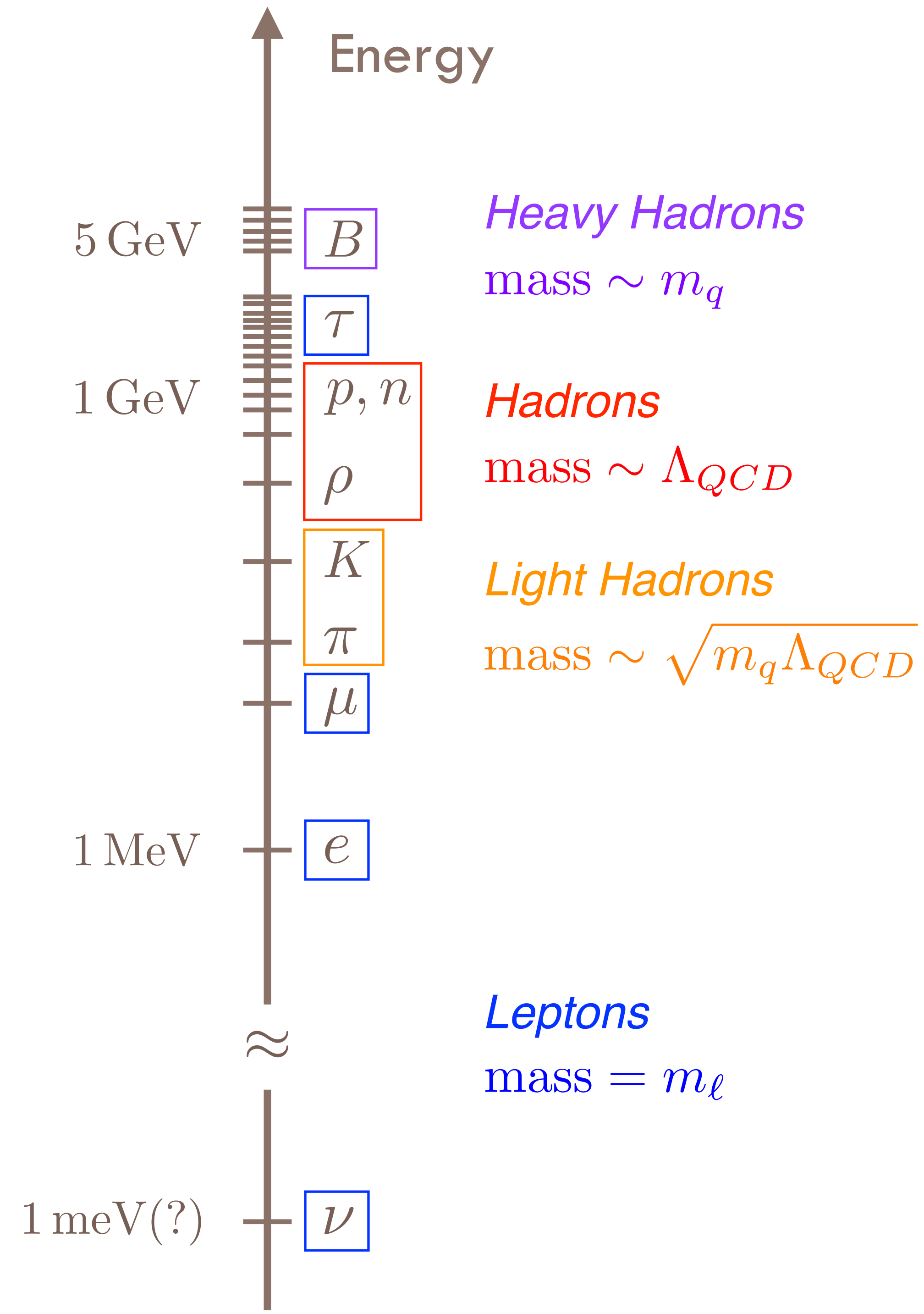
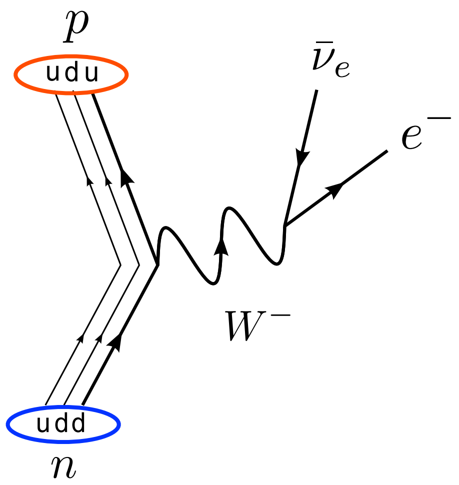
Q: *Can the whole spectrum be explained in terms of more fundamental scales ?*



A new symmetry and a new force emerging at high energies

In 1934 Fermi formulated a theory of weak interactions to explain nuclear beta decays



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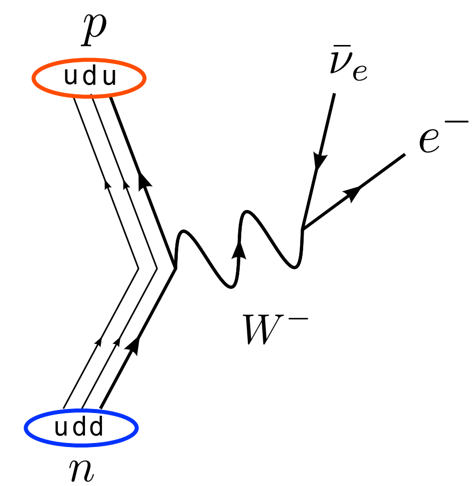

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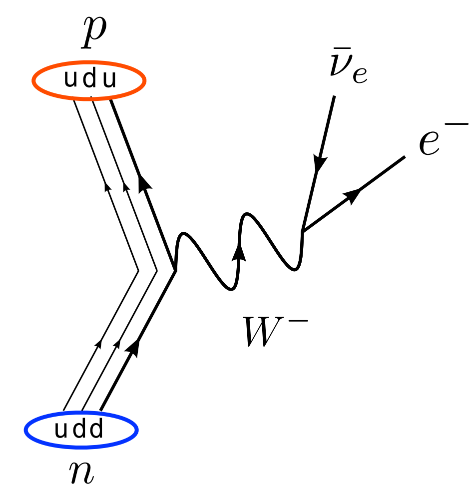

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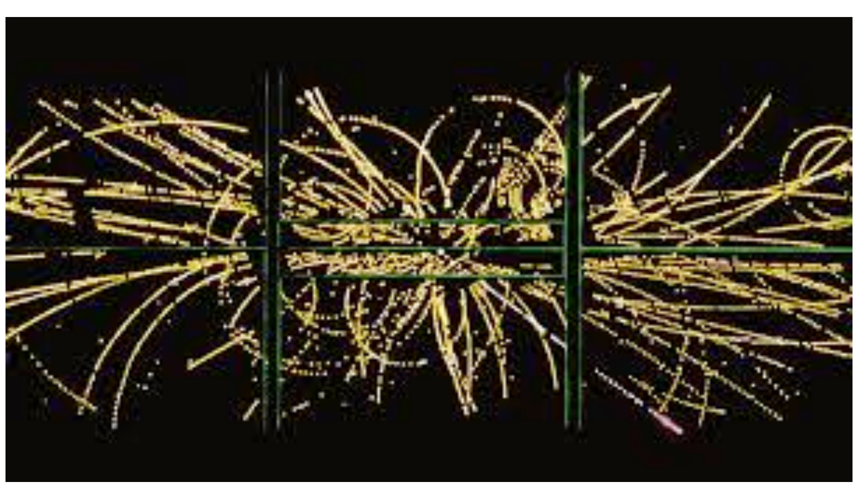
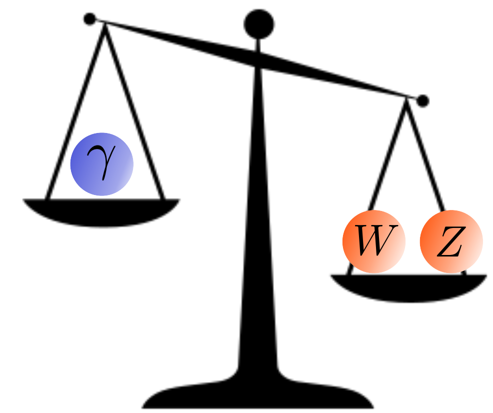


The carriers of the electroweak force, the W and Z bosons, were discovered at CERN in 1983 by an experimental collaboration led by C. Rubbia

- Electroweak symmetry “hidden” at distances larger than $1/m_W$



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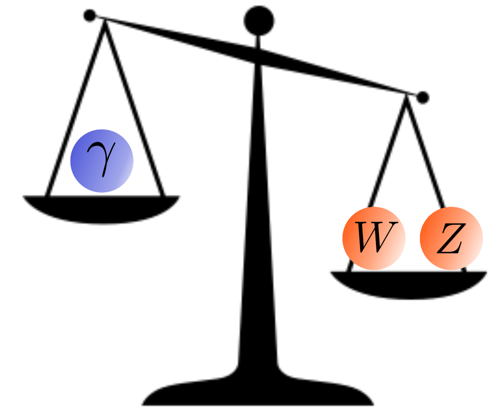

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- Example of spontaneous symmetry breaking:

> *i) Equations of motions are symmetric*
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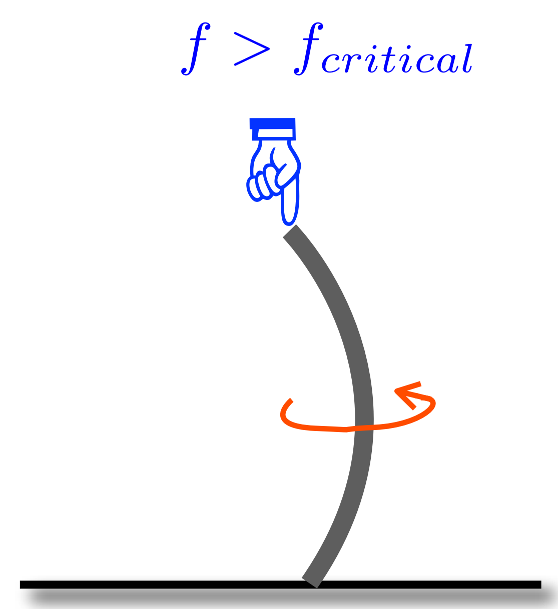
> *ii) Their solutions (including the vacuum) are not*



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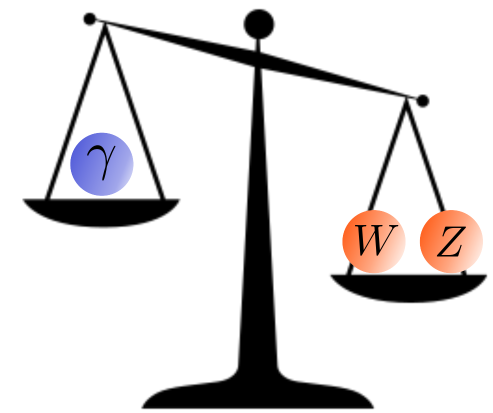

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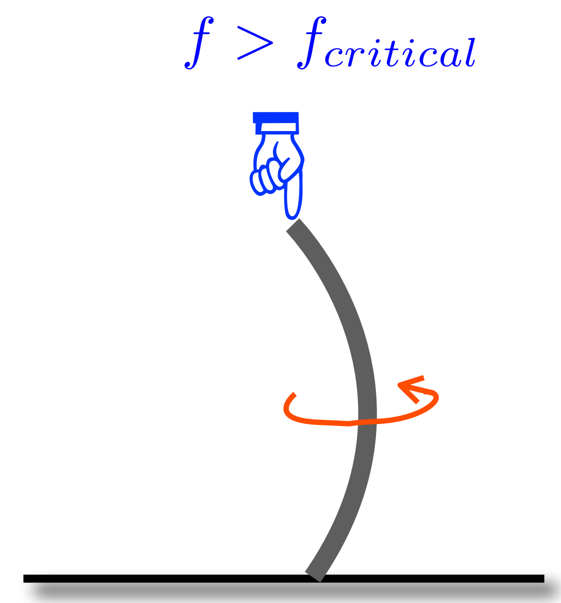

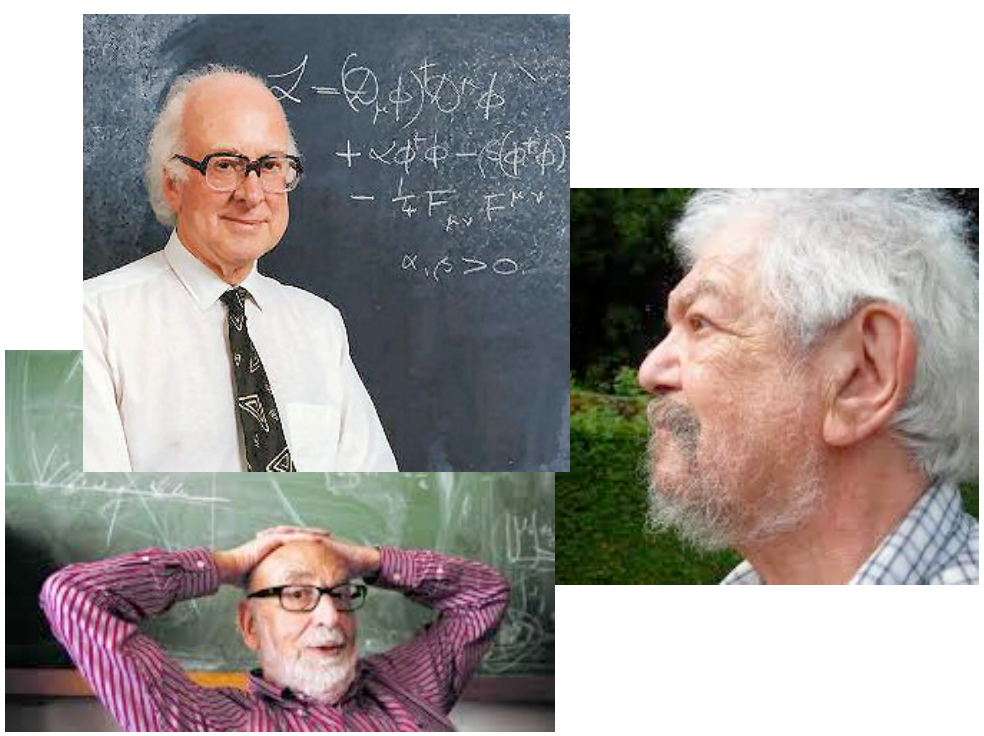

- The theoretical formulation of SSB of a gauge symmetry was given in a series of papers by Brout and Englert, by Higgs and by Guralnik, Hagen and Kibble in 1964.

Quarks and leptons are both charged under the $SU(2)_L \times U(1)_Y$ symmetry

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
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(1 family)

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charge conjugation $\dashrightarrow$

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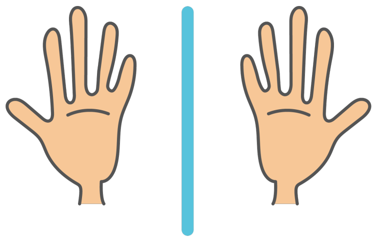
Not the same !

Chiral Representations



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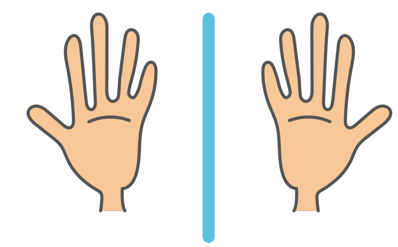

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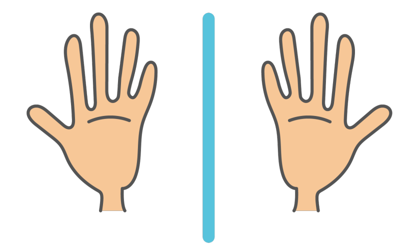

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☞ Chance to explain the particles' spectrum in terms of only dynamical scales

Charge quantization from anomaly cancellation

- Chiral representations are compatible with the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance only if some conditions on the hypercharges are satified (cancellation of gauge anomalies)

$$0 = \sum_{3,\bar{3}} y_\psi = 2y_q + y_{u^c} + y_{d^c}$$

$$0 = \sum_{doublets} y_\psi = 3y_q + y_\ell$$

$$0 = \sum_\psi y_\psi^3 = 6y_q^3 + 3y_{u^c}^3 + 3y_{d^c}^3 + 2y_\ell^3 + y_{e^c}^3$$

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$$\boxed{\begin{aligned} y_{u^c} &= -4y_q \\ y_{d^c} &= 2y_q \\ y_\ell &= -3y_q \\ y_{e^c} &= 6y_q \end{aligned}}$$

Nature's Choice

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Nature's Choice

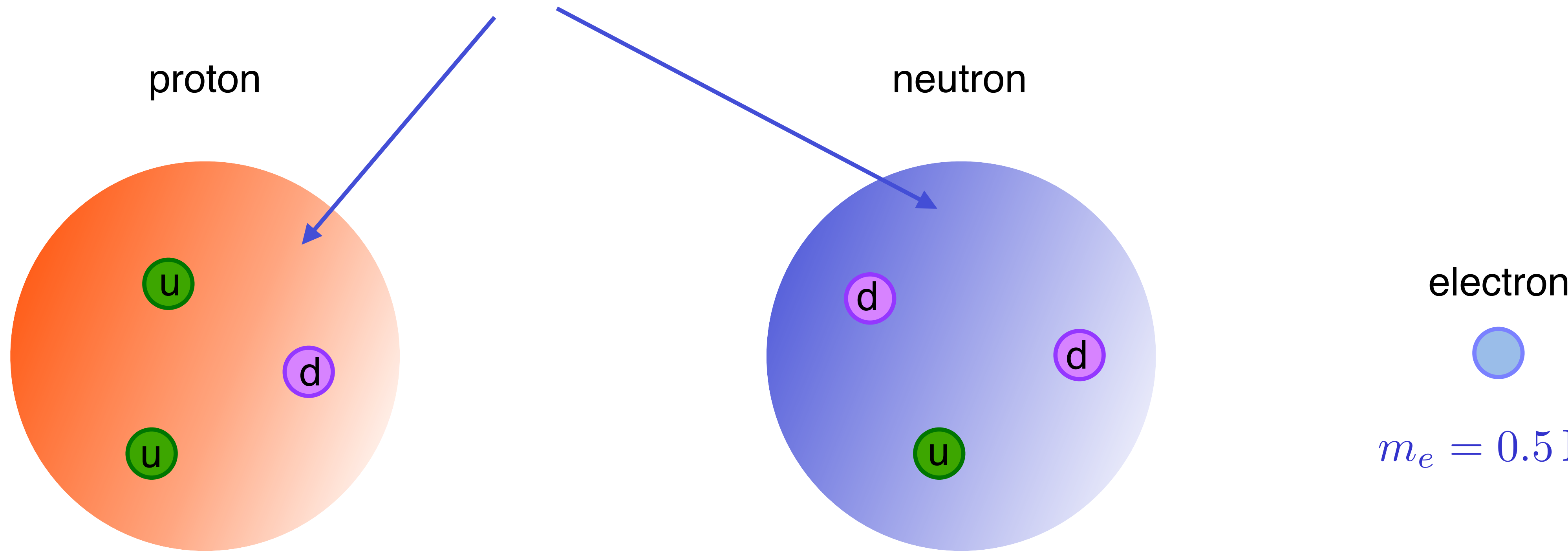
solution #2

$$\boxed{\begin{aligned} y_{u^c} &= -y_{d^c} \\ y_q = y_\ell &= y_{e^c} = 0 \end{aligned}}$$

Not our world

Importance of the EW correction to mass spectrum

the bulk of the proton and neutron mass
comes from the energy of the gluons



$$m_p = 0.9383 \times 10^3 \,\mathrm{MeV}$$

$$m_n = 0.9396 \times 10^3 \,\mathrm{MeV}$$

$$m_e = 0.5 \,\mathrm{MeV}$$

Contribution from the quark masses is tiny but
makes the neutron heavier than the proton:

$$\boxed{m_n - m_p = 1.29 \,\mathrm{MeV}}$$

The masses of the quarks and the electron are essential for the existence of the Universe as we know it

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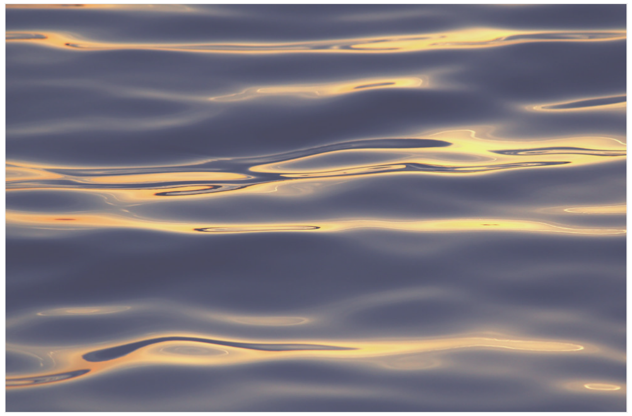

- *if the proton were heavier than the neutron, it would be unstable and the Universe would be made of a sea of neutrons without atoms*

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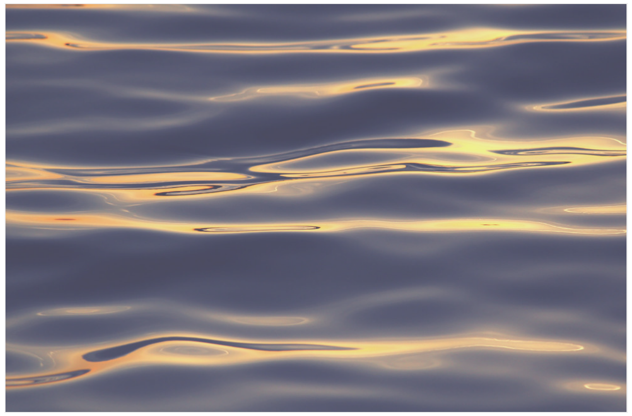

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- *if the neutron were a bit heavier, deuterium and other isotopes would be unstable and the formation of heavier elements (nucleosynthesis) would be altered. The Universe would be made of just hydrogen.*

$m_n - m_p > 2.7\,\mathrm{MeV}$ ➡ deuterium unstable: $d \to 2p + e^- + \bar{\nu}_e$

$m_n - m_p \gtrsim 10\,\mathrm{MeV}$ ➡ neutrons in nuclei unstable

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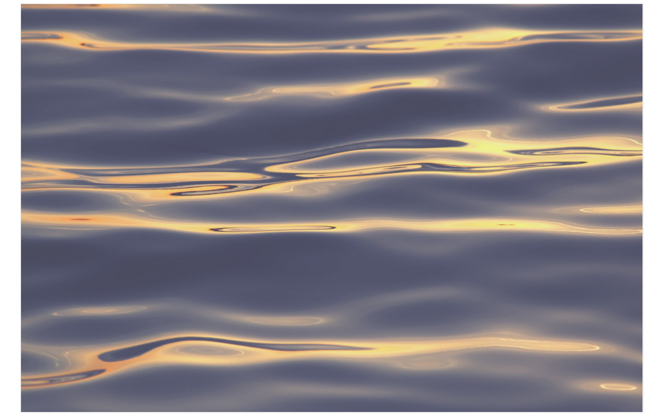

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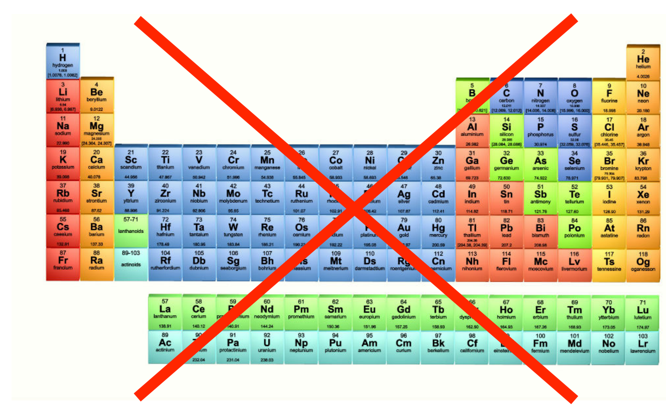


- *if the electron were heavier, atoms would be unstable and we would not have chemistry*

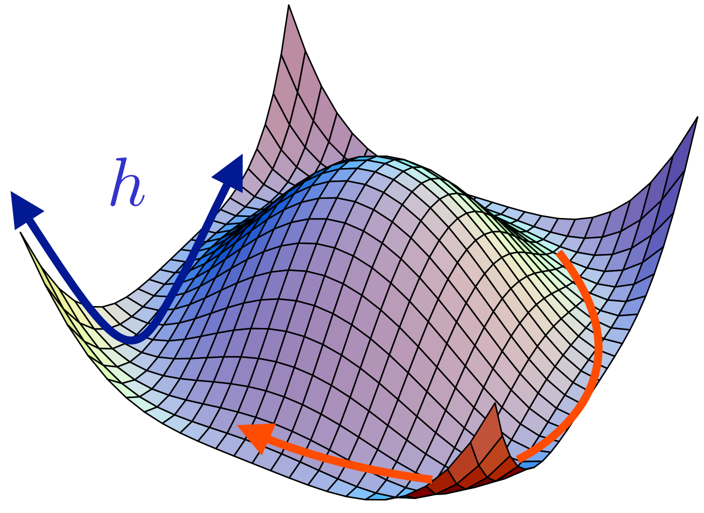
$m_e > m_n - m_p = 1.29\,\mathrm{MeV}$ → hydrogen atom unstable: ${}^1H \to n + \nu_e$

$m_e \gtrsim 10\,\mathrm{MeV}$ → all atoms unstable

Q: Do we have a dynamical model for Electroweak Symmetry Breaking ?

Yes, we do: the Higgs model

$$\mathcal{L} = |D_\mu H|^2 + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2$$



$$\langle H \rangle \equiv \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{\lambda}}$$

$$H(x) = e^{iT^a \chi^a(x)} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

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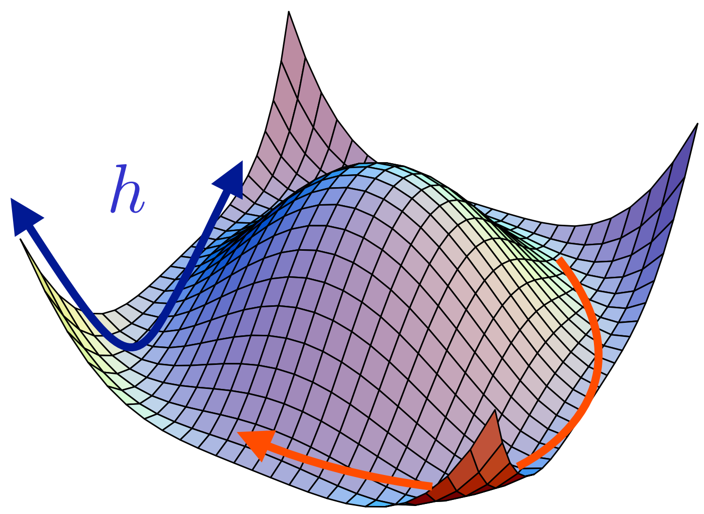

massless excitations:
NG bosons (χ^a)

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Predictions:

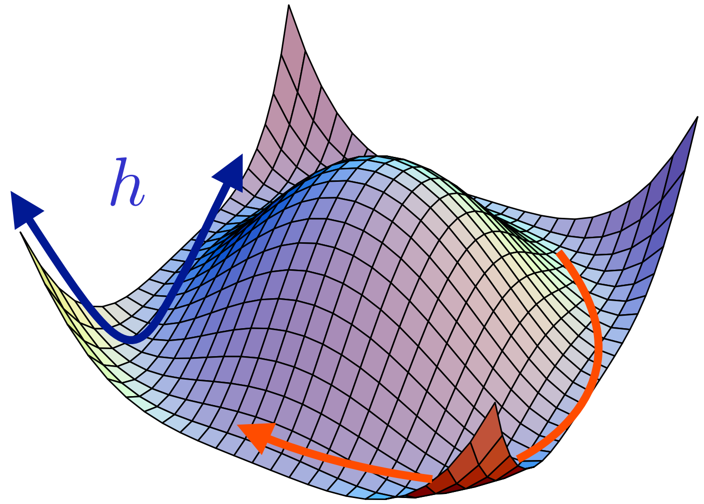
1. *Existence of an elementary (i.e. structure-less) spin-0 particle: the Higgs boson*
2. *Masses are proportional to the Higgs vev*

$$m_\psi = \frac{v}{\sqrt{2}} y_\psi$$
$$m_W = \frac{m_Z}{\cos\theta_W} = \frac{gv}{4}$$

3. *The Higgs boson itself is a force carrier (Yukawa and Higgs self interactions)*

Q: Do we have a dynamical model for Electroweak Symmetry Breaking ?

Yes, we do: the Higgs model



$$\mathcal{L} = |D_\mu H|^2 + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2$$

$$\langle H \rangle \equiv \frac{v}{\sqrt{2}} = \sqrt{\frac{\mu^2}{\lambda}}$$

$$H(x) = e^{iT^a \chi^a(x)} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \longleftarrow \text{'Higgs boson' (radial excitation)}$$

1. Existence of an elementary (i.e. structure-less) spin-0 particle: the Higgs boson

Predictions:

2. Masses are proportional to the Higgs vev

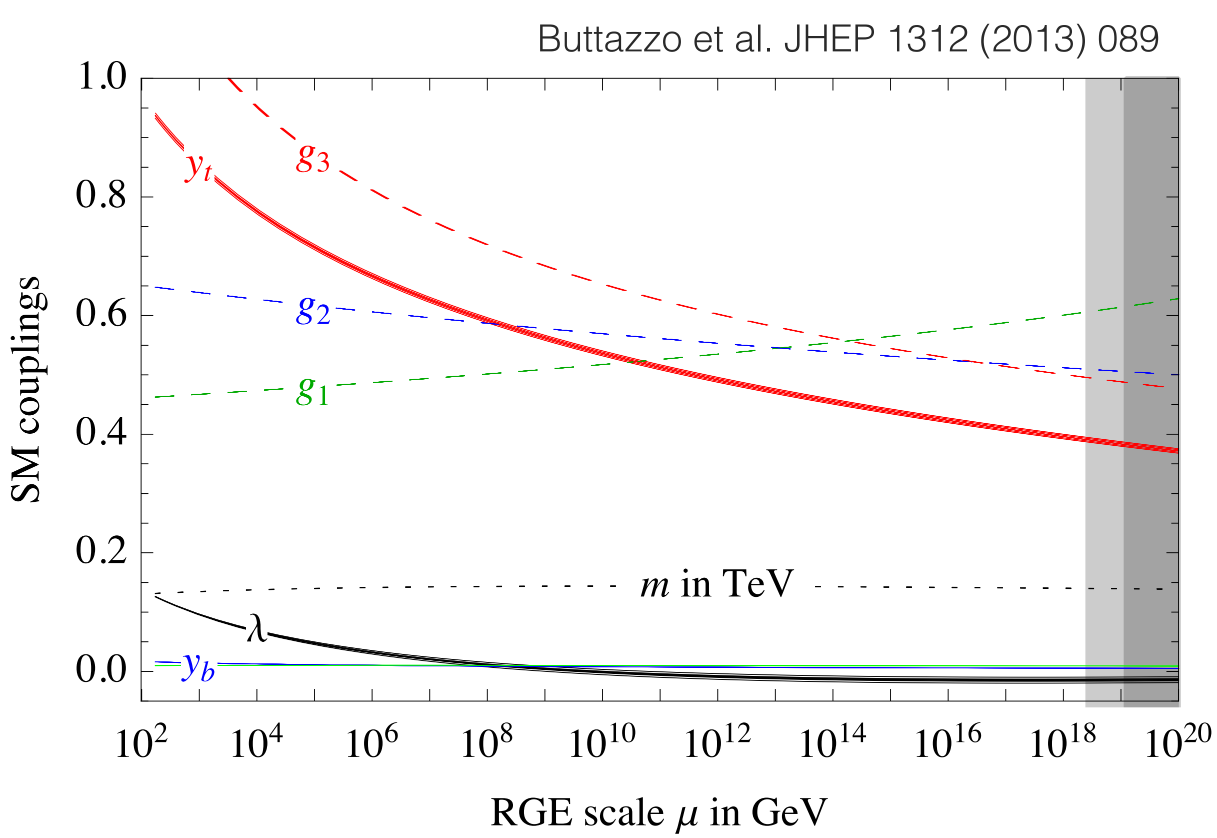
$$\boxed{\begin{aligned} m_\psi &= \frac{v}{\sqrt{2}} y_\psi \\ m_W &= \frac{m_Z}{\cos\theta_W} = \frac{gv}{4} \end{aligned}}$$

3. The Higgs boson itself is a force carrier (Yukawa and Higgs self interactions)

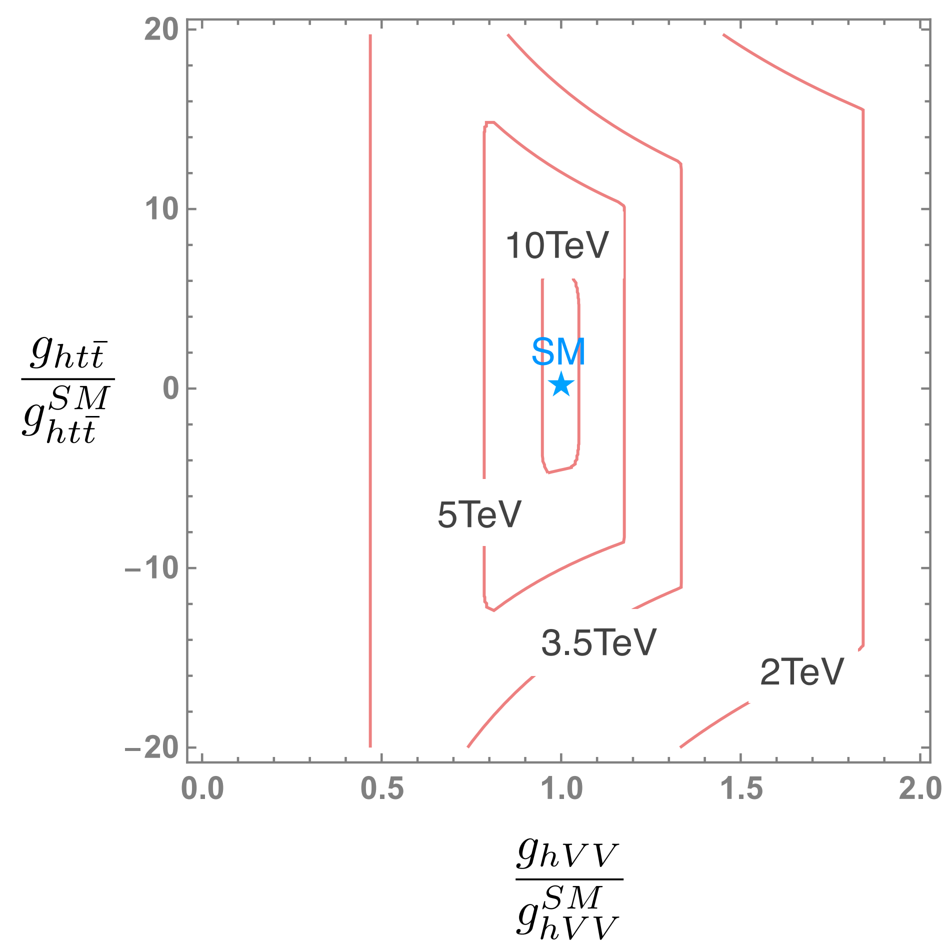
$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT $+$ Higgs Model $=$ The **Standard Model** of Fundamental Interactions

$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT + Higgs Model = The **Standard Model** of Fundamental Interactions

✔ *For the first time we have a theory that can be extrapolated up to extremely high energies (up to the Planck scale) and it's weakly coupled*



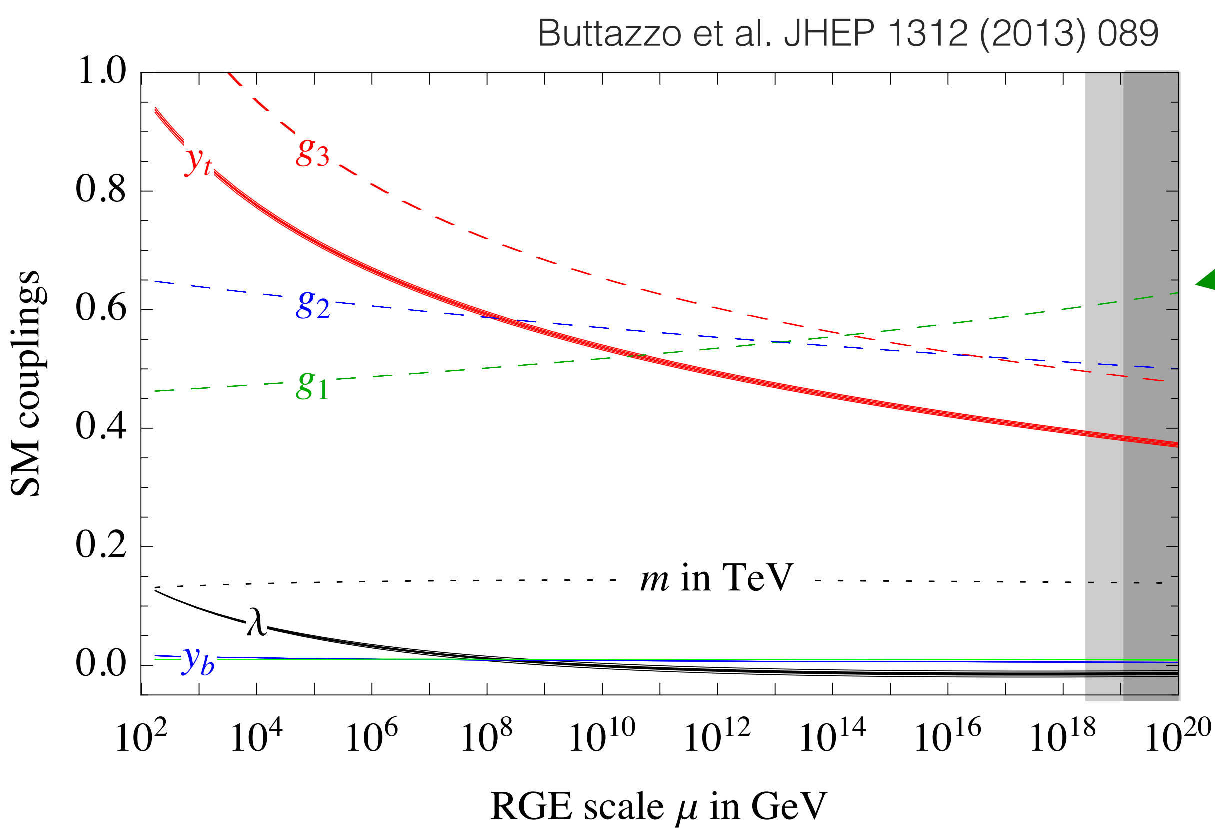
Couplings evolve logarithmically with the energy



Isocurves of max energy at which the theory can be extrapolated

$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT + Higgs Model = The **Standard Model** of Fundamental Interactions

✘ *The theory can<u>not</u> be extrapolated to <u>arbitrarily</u> high scales (due to hypercharge Landau pole + quantum gravity at Planck scale)*



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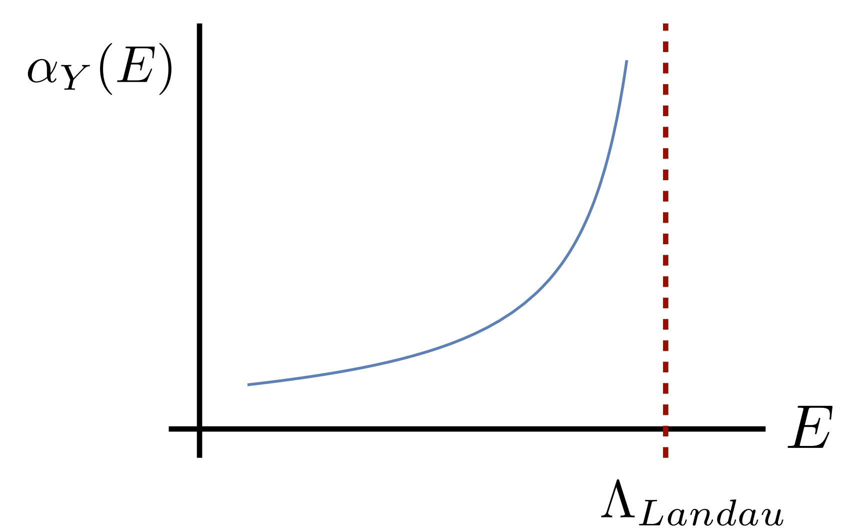


The SM is an Effective Theory, not a Theory of Everything

$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT $+$ Higgs Model $=$ The **Standard Model** of Fundamental Interactions

✔ *A large cutoff scale Λ_{UV} implies accidental symmetries at low energies*

Λ_{UV}

≈ $10^{15\text{-}16}$ GeV ⟵ Explain neutrino mass and oscillations

L violation @ dim-5 level $\dfrac{1}{\Lambda_{UV}}(H\ell)^2$

≈ 10^{11} GeV ⟵ Proton cosmologically stable ($\tau_p > 10^{10} yr$)

(B+L) violation @ dim-6 level $\dfrac{1}{\Lambda_{UV}^2}\, qqq\ell$

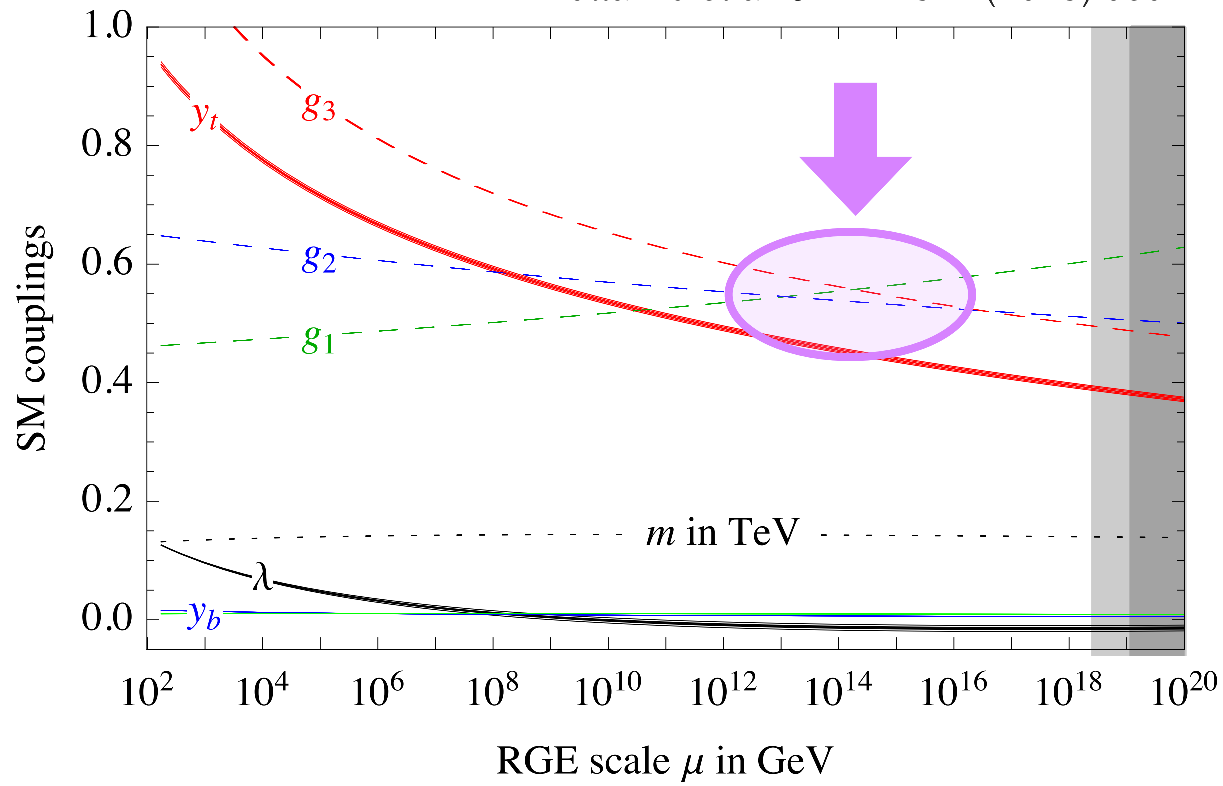
≈ 10^5 TeV ⟵ Explain absence of new flavor-violating effects

EW scale

$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT $+$ Higgs Model $=$ The **Standard Model** of Fundamental Interactions

✔ *When extrapolated at* $\sim 10^{14-15}\,\mathrm{GeV}$ *the gauge couplings seem to unify*

Buttazzo et al. JHEP 1312 (2013) 089



The SM may be embedded into a Grand Unified Theory with simple gauge group

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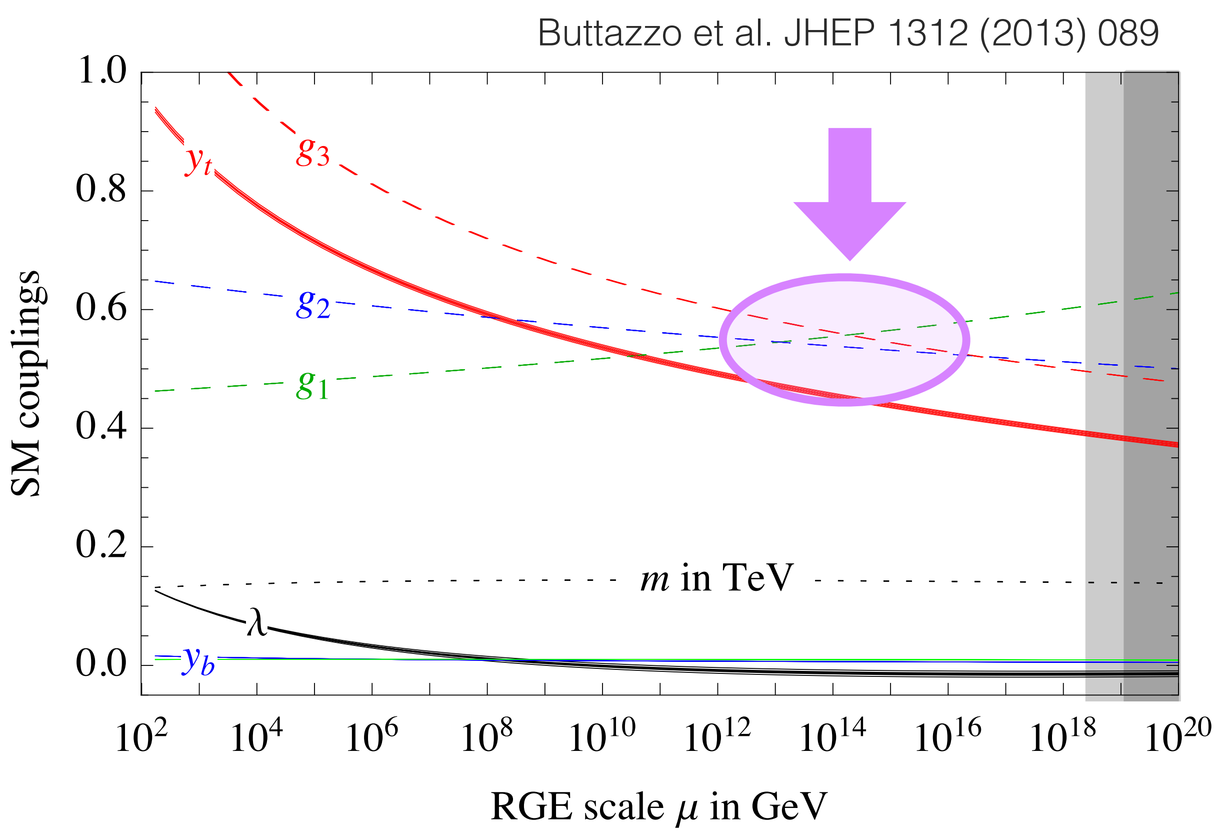


Couplings evolve logarithmically with the energy

The SM may be embedded into a Grand Unified Theory with simple gauge group

Ex: SU(5) GUT

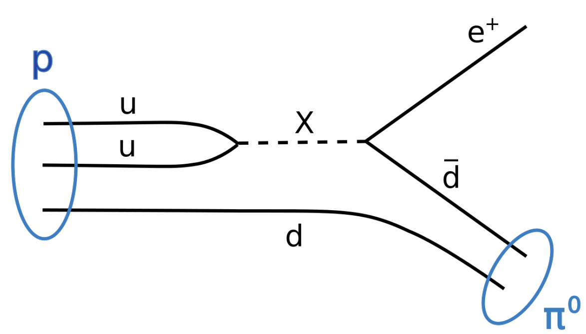
$$\bar{5} = \begin{pmatrix} d^c \\ \ell \end{pmatrix} \qquad 10 = \begin{pmatrix} u^c & q \\ & e^c \end{pmatrix}$$

SM fields fill two complete SU(5) multiplets

$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT $+$ Higgs Model $=$ The **Standard Model** of Fundamental Interactions

✔ *When extrapolated at* $\sim 10^{14-15}\,\mathrm{GeV}$ *the gauge couplings seem to unify*

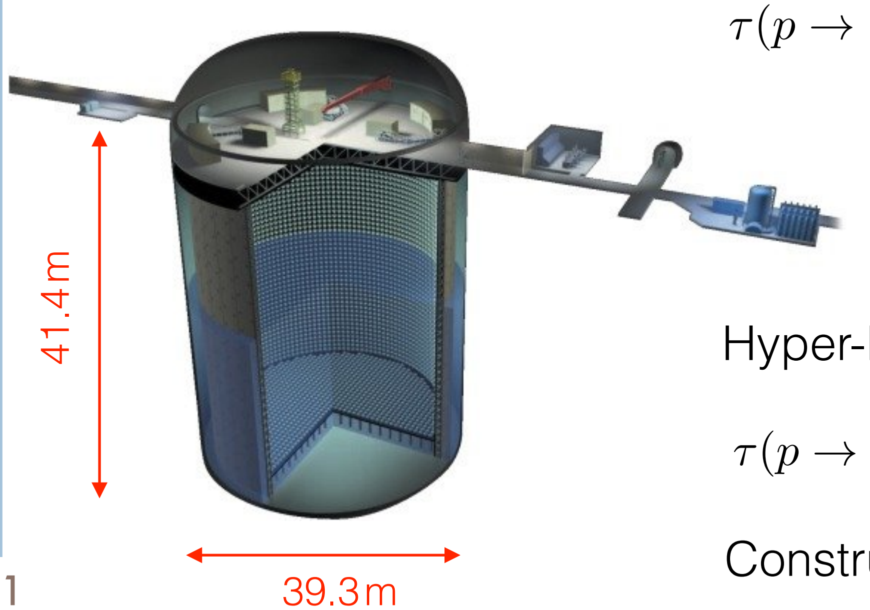
Prediction: proton must decay !



$$\tau_p \sim 10^{31} yr \left(\frac{M_{GUT}}{10^{16}\,\mathrm{GeV}} \right)^4$$

Super-Kamiokande (50k tons)

$$\tau(p \to e^+ \pi^0) > 1.67 \times 10^{34} yr$$



Hyper-Kamiokande (260k tons)

$$\tau(p \to e^+ \pi^0) \gtrsim 10^{35} yr$$

Construction begins April 2020

The SM may be embedded into a Grand Unified Theory with simple gauge group

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✔ *Thanks to chirality of gauge representations, physical spectrum explained in terms of just two fundamental scales*

1. *QCD scale* Λ_{QCD}

2. *Higgs Mass term* μ^2 *(EW scale)*

+ *the neutrino mass scale (dim-5 operator)*

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✔ *Thanks to chirality of gauge representations, physical spectrum explained in terms of just two fundamental scales*

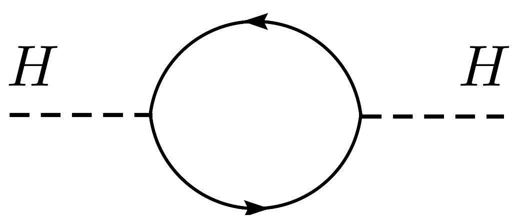
1. QCD scale Λ_{QCD} ⟵ *dynamical*

2. *Higgs Mass term* μ^2 *(EW scale)* ⟵ *NOT dynamical (i.e. arbitrary)* ✘

\+ *the neutrino mass scale (dim-5 operator)*

$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT + Higgs Model = The **Standard Model** of Fundamental Interactions

✘ *Furthermore: Higgs mass term unstable against radiative corrections*



$$\delta\mu^2 \sim \frac{g_{SM}^2}{16\pi^2}\Lambda_{UV}^2$$

Hierarchy Problem

[Wilson 1971]

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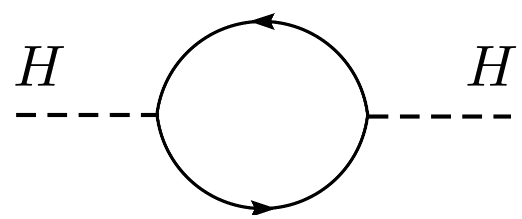

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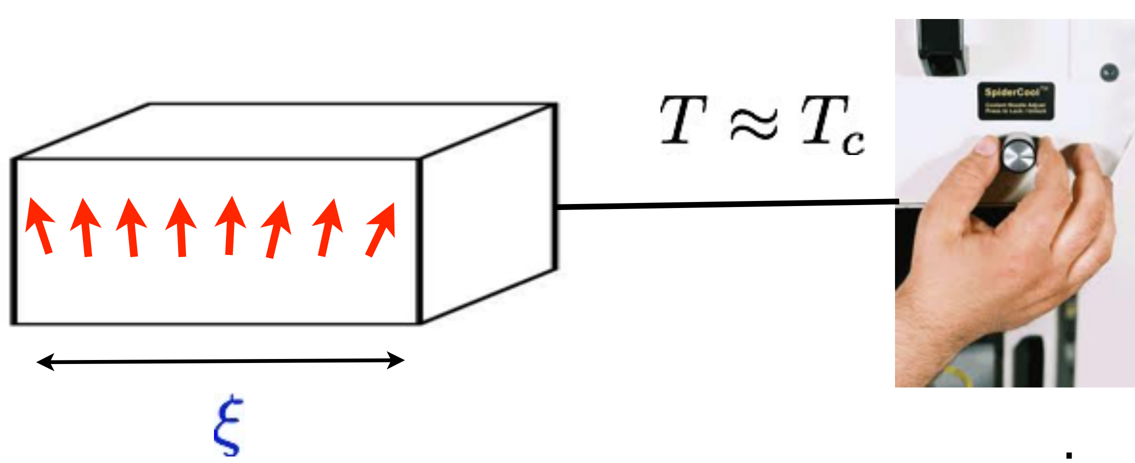
Hierarchy Problem

[Wilson 1971]

<u>Analogy</u>: statistical mechanical systems near critical point

T→ T_c requires to finetune the temperature:



experimenter

credit:
Slava Rychkov at EPS 2011

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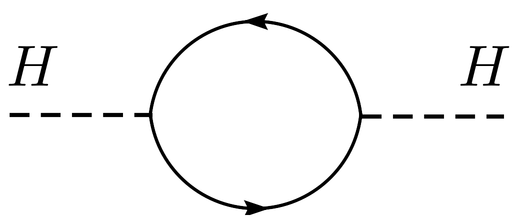

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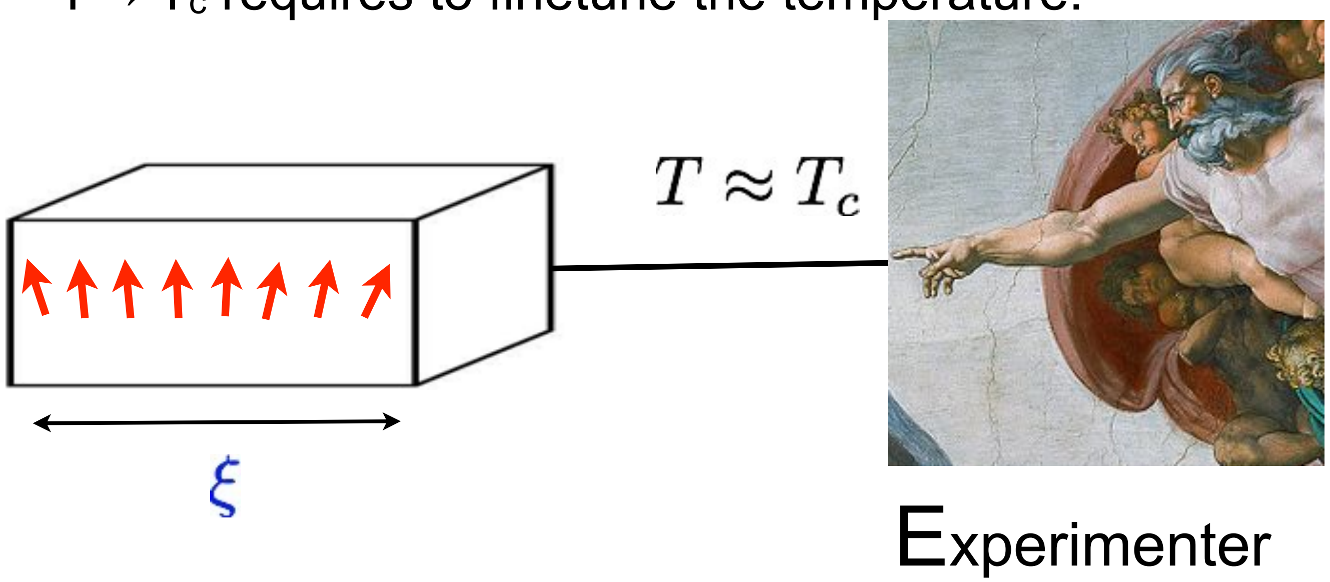

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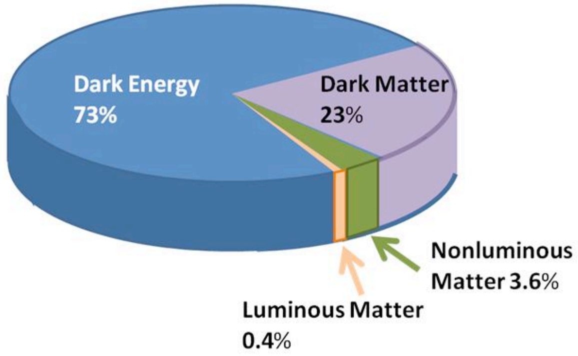
$SU(3)_c \times SU(2)_L \times U(1)_Y$ QFT + Higgs Model = The **Standard Model** of Fundamental Interactions

✘ *SM + GR fails to explain some basic features of our Universe*

1. *Dark Matter* and Dark Energy*

   * *Primordial Black Holes can reproduce the DM abundance but the mechanism of their production is beyond the SM*



2. *Matter anti-Matter asymmetry*

3. *Inflation*

What laboratory data say on the EWSB dynamics

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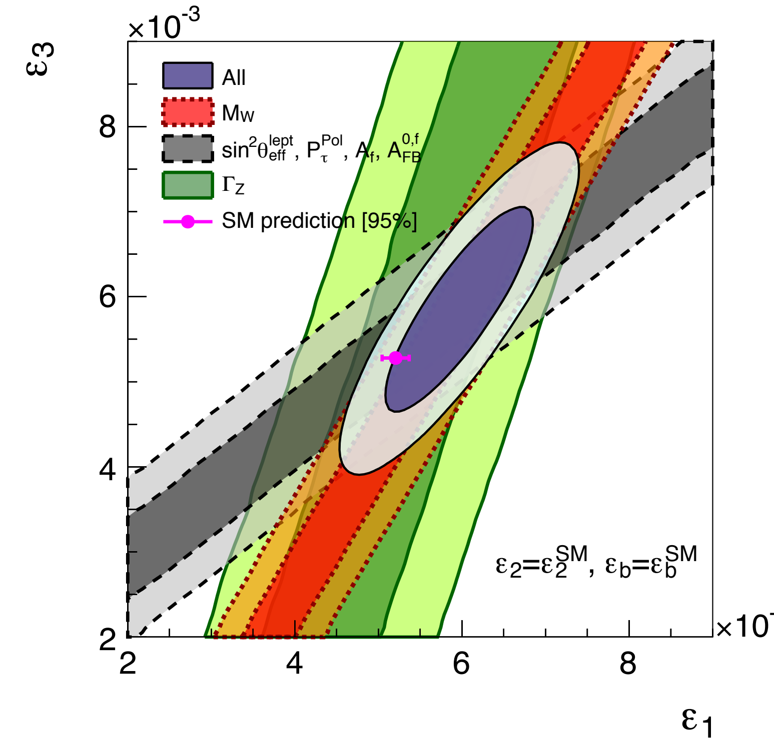
- LEP + Tevatron

  Precision Tests on EW observables have tested SM loop corrections at the 10^{-3} level with $\sim 10\,\%$ precision. Excellent agreement with SM predictions.

Ciuchini et al. JHEP 1308 (2013) 106



$$\epsilon_1 = (6.0 \pm 0.6) \times 10^{-3}$$
$$\epsilon_3 = (5.9 \pm 0.8) \times 10^{-3}$$

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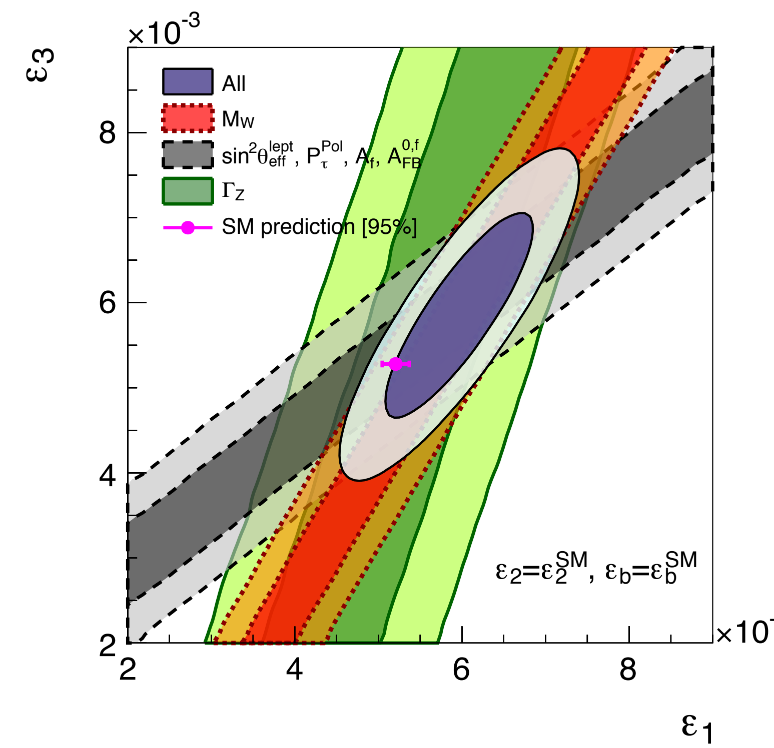

$$\epsilon_1 = (6.0 \pm 0.6) \times 10^{-3}$$
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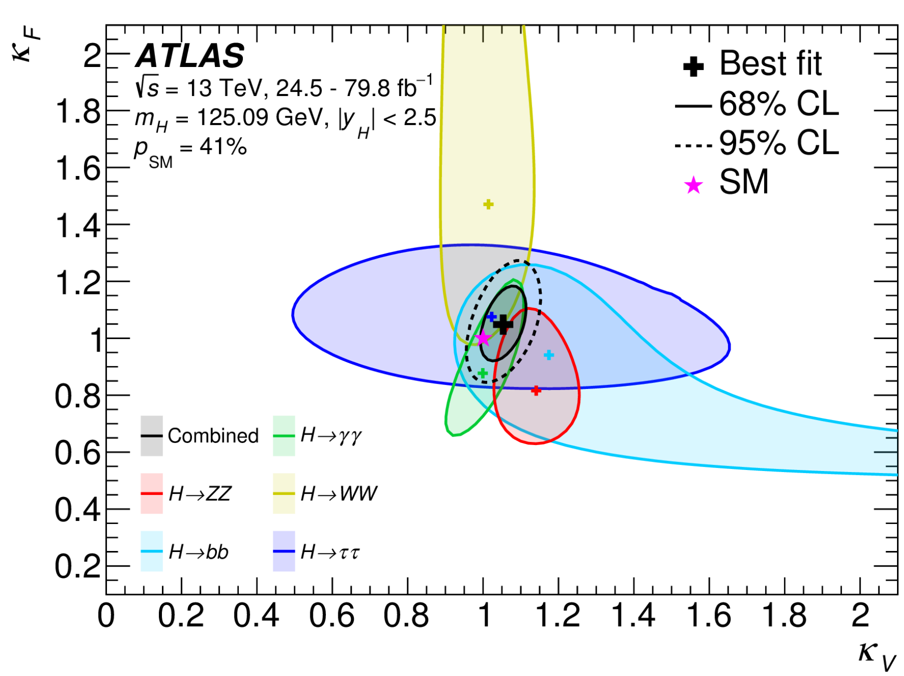
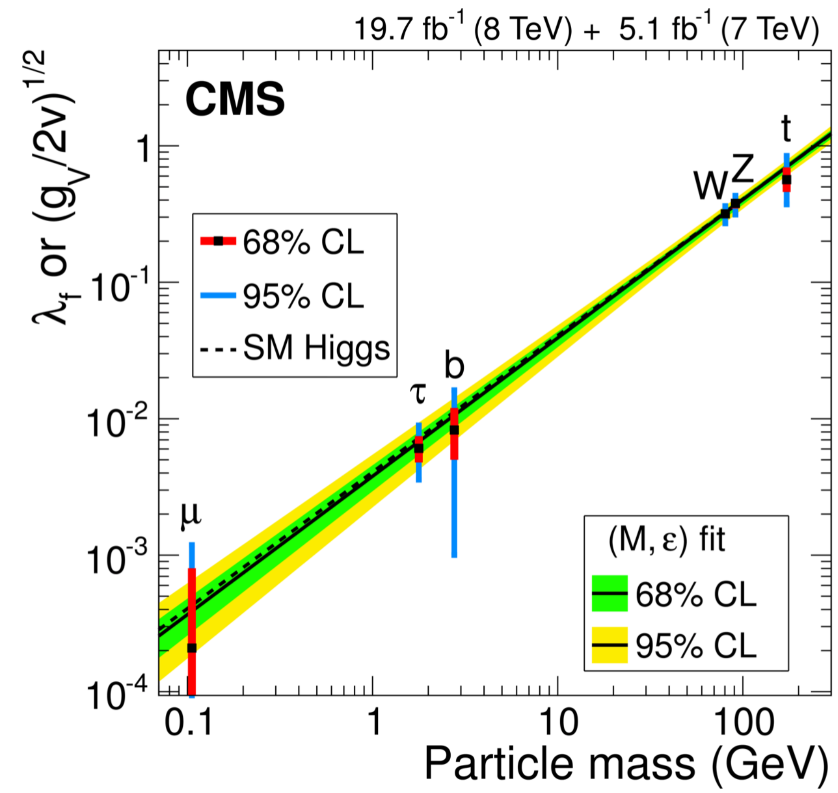
- LHC

  Higgs boson has right quantum numbers (spin/CP) and its couplings are SM-like with $\lesssim 10\%$ precision





- Furthermore: No new particles discovered at LHC (or other colliders) so far

What lies beyond the SM ?

Where to look for New Physics ?

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☞ New Physics can be of two kinds:

i) charged under SM and heavy ($m \gtrsim 0.5-4\,\mathrm{TeV}$)

ii) neutral under SM and possibly very light

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What lies beyond the SM ?

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☞ New Physics can be of two kinds:

i) charged under SM and heavy ($m \gtrsim 0.5 - 4\,\mathrm{TeV}$) ⇨ Energy Frontier

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☞ New Physics can be of two kinds:

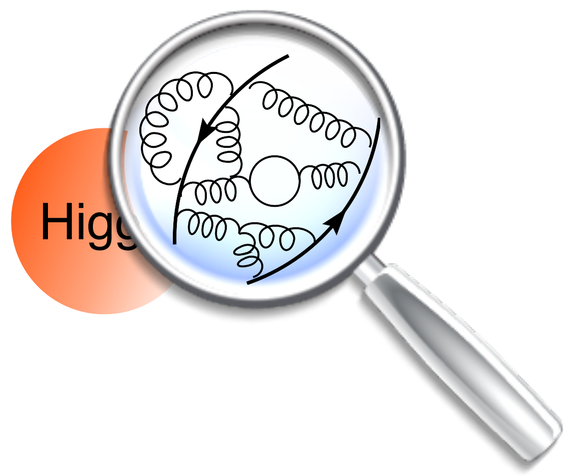
i) charged under SM and heavy ($m \gtrsim 0.5 - 4\,\mathrm{TeV}$) ⇨ Energy Frontier

ii) neutral under SM and possibly very light ⇨ Intensity Frontier

Motivated Scenarios: my personal viewpoint

1 Theories with dynamical EW scale: Composite Higgs Theories [Georgi-Kaplan 1980's]

The Higgs boson is not elementary, but a bound state of new dynamics above the TeV scale



Generic predictions:

1. *Modified Higgs couplings*
2. *Top partners (fermionic resonances with top quantum numbers)*
3. *Additional SM-singlet pNGB*

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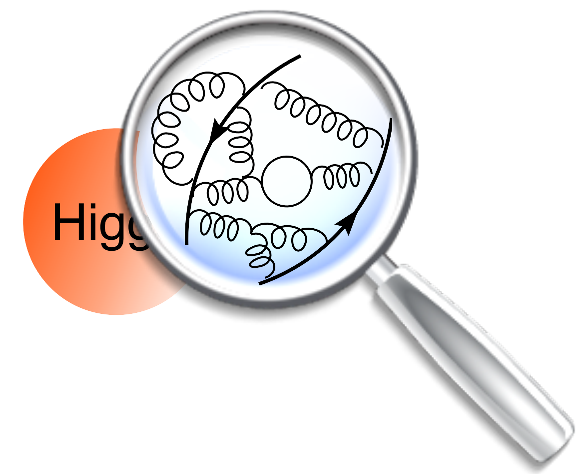

Generic predictions:

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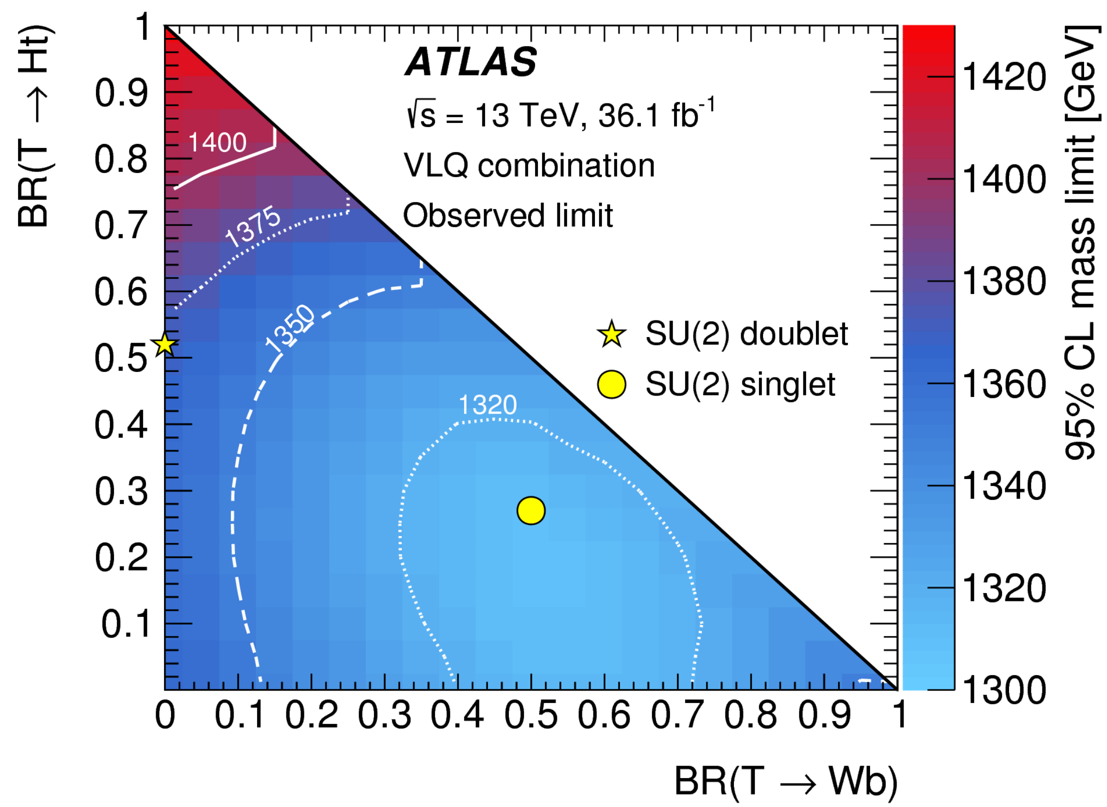
Current bounds on top partners:

$$M_T, M_B \gtrsim 1.1 - 1.3\,\mathrm{TeV}$$

Associated fine tuning

$$\mathrm{FT} \approx \frac{3y_t^2}{4\pi^2}\frac{M^2}{m_h^2} \simeq \left(\frac{M}{0.45\,\mathrm{TeV}}\right)^2 \simeq 10$$



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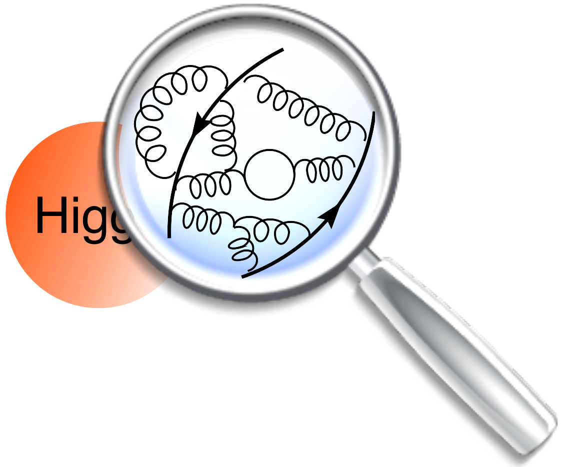

Generic predictions:

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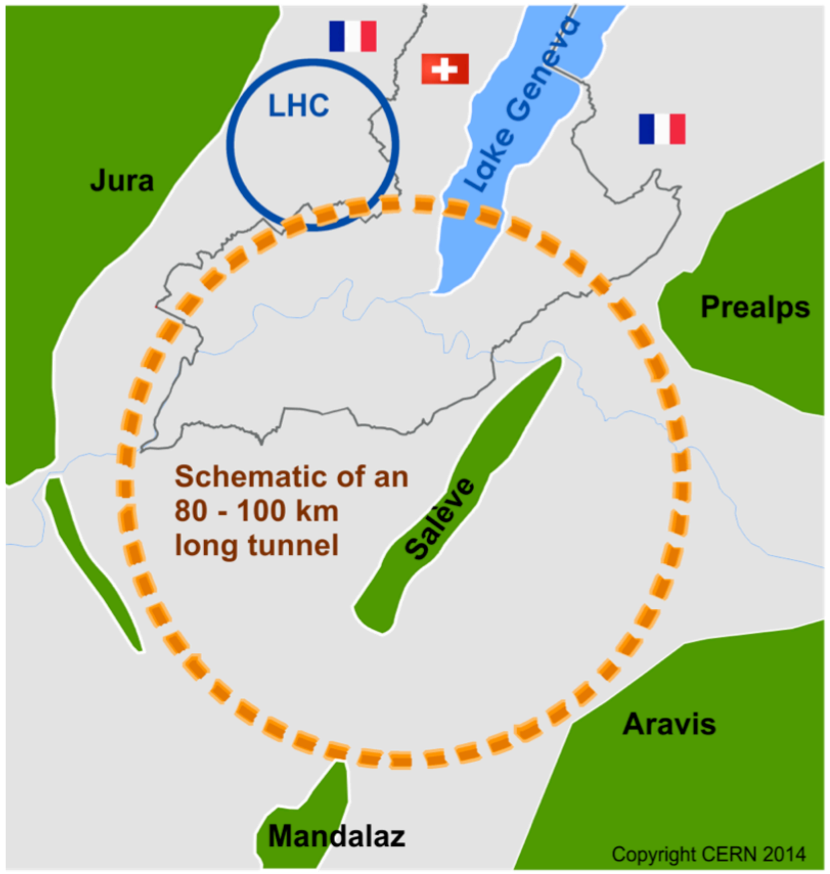
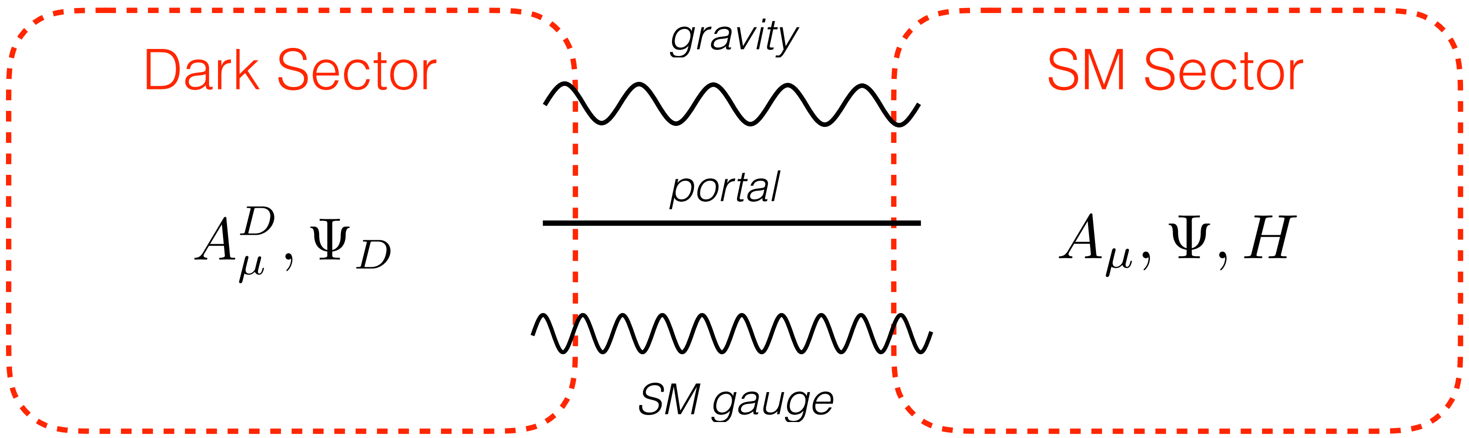
Best discovery opportunities from a future 100km circular colliders:

- Higgs Precision Tests at e^+e^- phase (FCC-ee)
- Top partners searches at pp phase (FCC-hh)



Motivated Scenarios: my personal viewpoint

2 Theories with dynamical DM scale: Composite DM Theories



Dark Matter might be a bound state of new strongly-coupled dynamics.

DM stability might be the consequence of an accidental symmetry (in analogy with proton stability in the SM)

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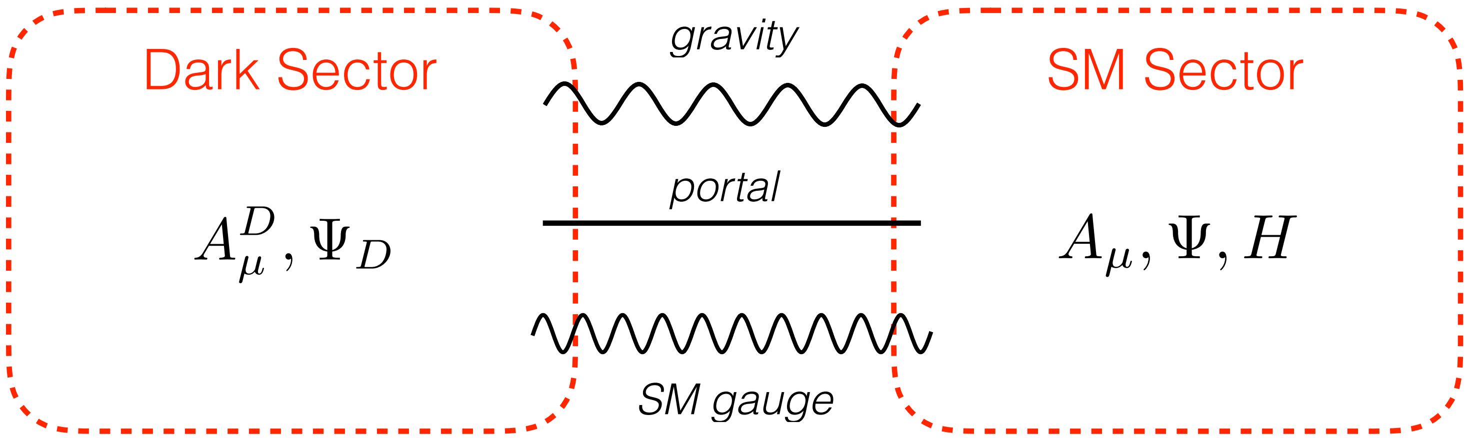

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Types of accidental DM candidates:

Dark baryons

Dark mesons (pions and quarkonia)

Gluequarks (Qg bound states with adjoint dark quarks)

Dark nuclei

⋮

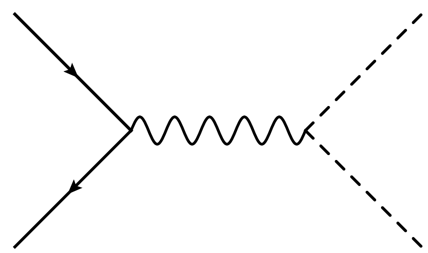
Motivated Scenarios: my personal viewpoint

2 Theories with dynamical DM scale: Composite DM Theories

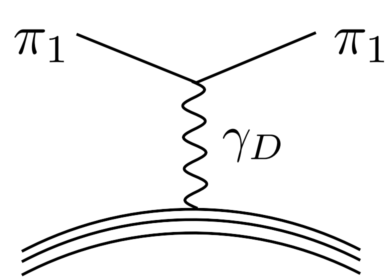
Most interesting (and most difficult to build) theories are those with chiral gauge representations and only dynamical scales

Signatures:

- Collider production of SM-charged partners

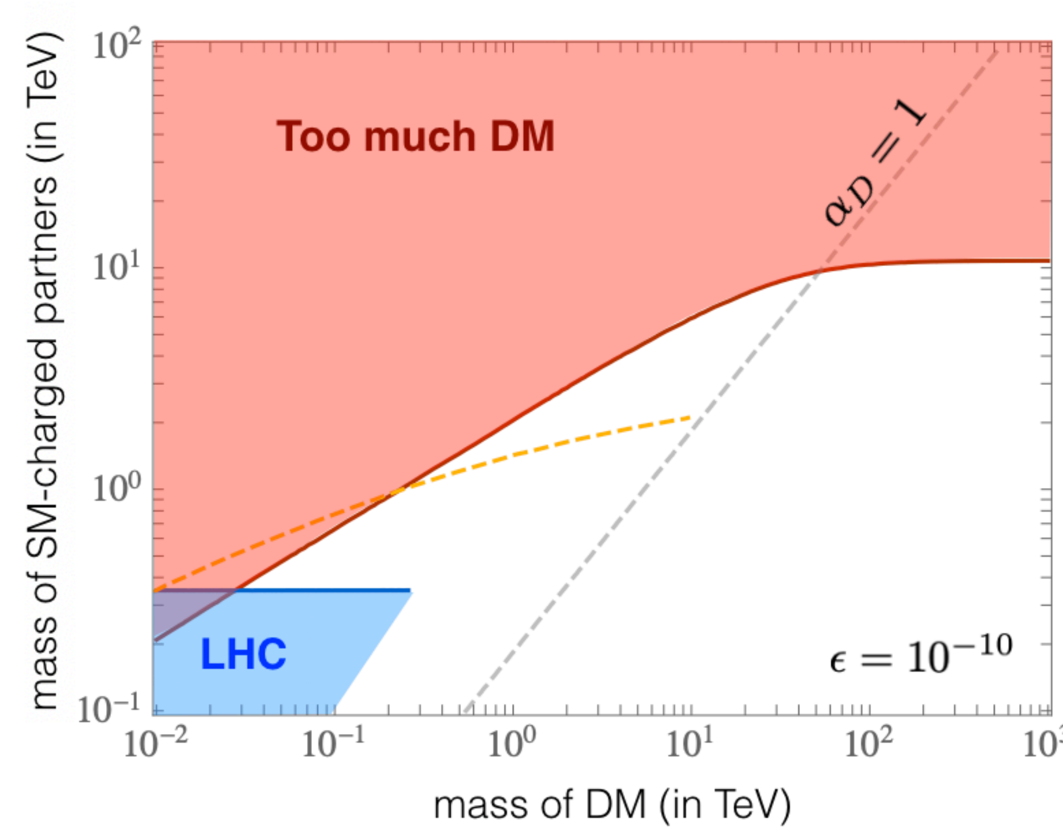


- DM direct detection



- DM indirect detection

Ex: model with chiral $U(1)_D$
[RC, Podo, Revello, work in progress]



Conclusions

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- We have a mathematical model (the '*Standard Model*') which explains all laboratory data collected so far, but leaves some important theoretical and experimental issues unanswered

  - what is the origin of the EW scale and why the Higgs boson is light ?

  - what is Dark Matter made of ?

  - what is the mechanism of Baryogenesis ?

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  - *what is the origin of the EW scale and why the Higgs boson is light ?*

  - *what is Dark Matter made of ?*

  - *what is the mechanism of Baryogenesis ?*

- Next generation colliders will be tremendous enterprises with gigantic size. Advance in our understanding of fundamental interactions might come in the near future from 'unconventional' experiments (Dark Matter detection, cosmology)