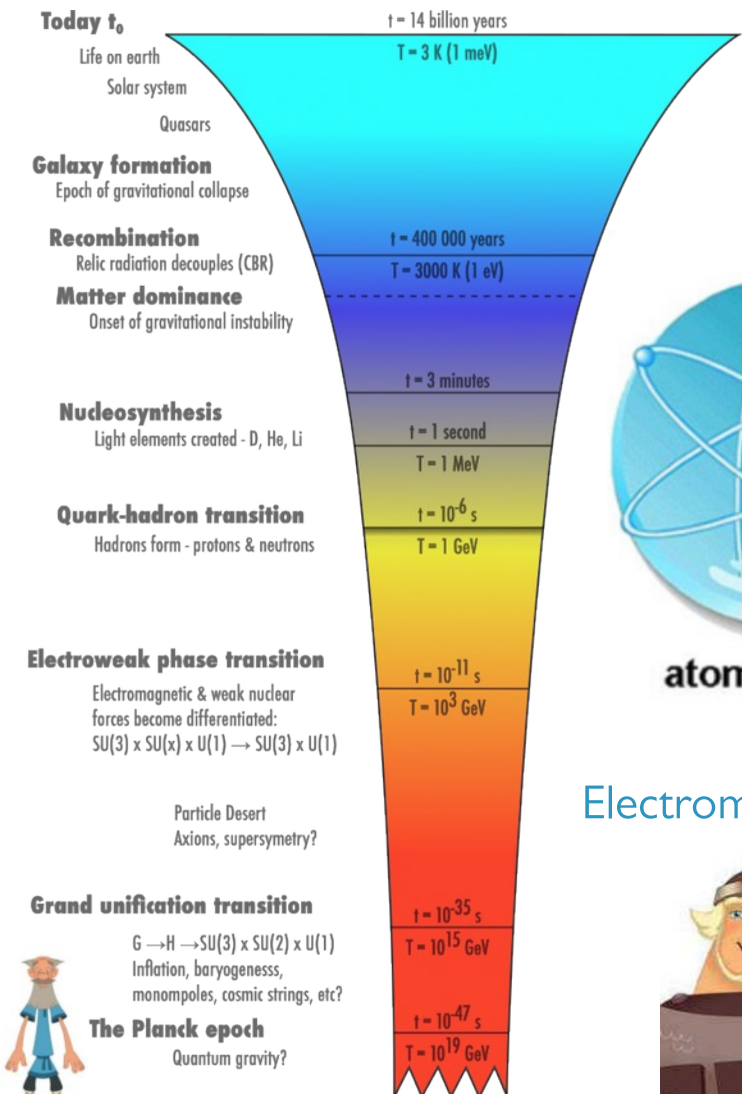
The Standard Model: Status and Perspectives

A.V. Bednyakov,
BLTP JINR

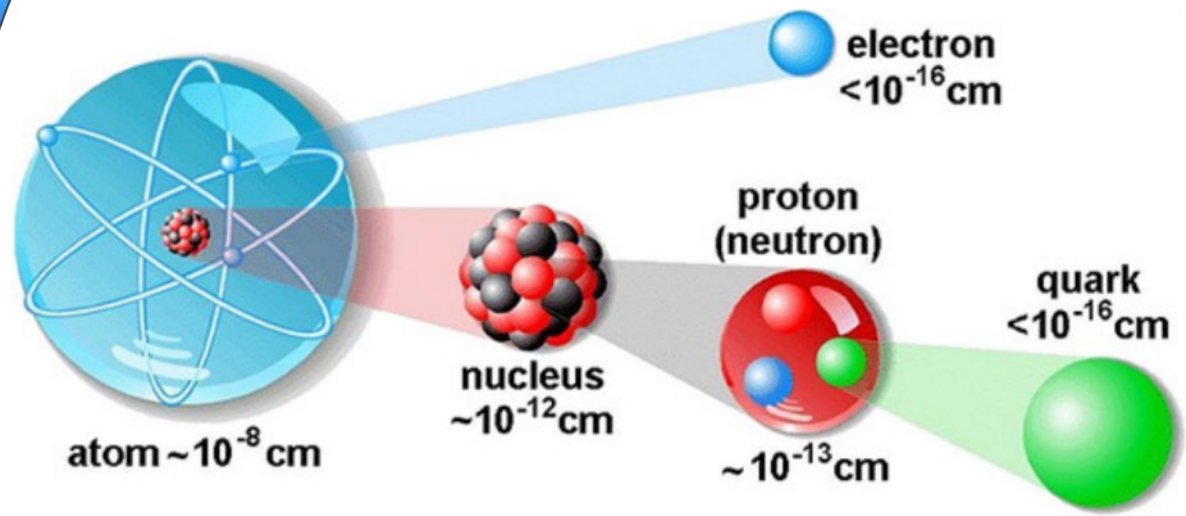
The XXVII International Scientific Conference of Young Scientists and Specialists (AYSS-2023) Dedicated to 110th anniversary of Bruno Pontecorvo

Fundamental questions…



Gravity?

- What is the world made of?
- What holds the world together?
- How did the world begin?

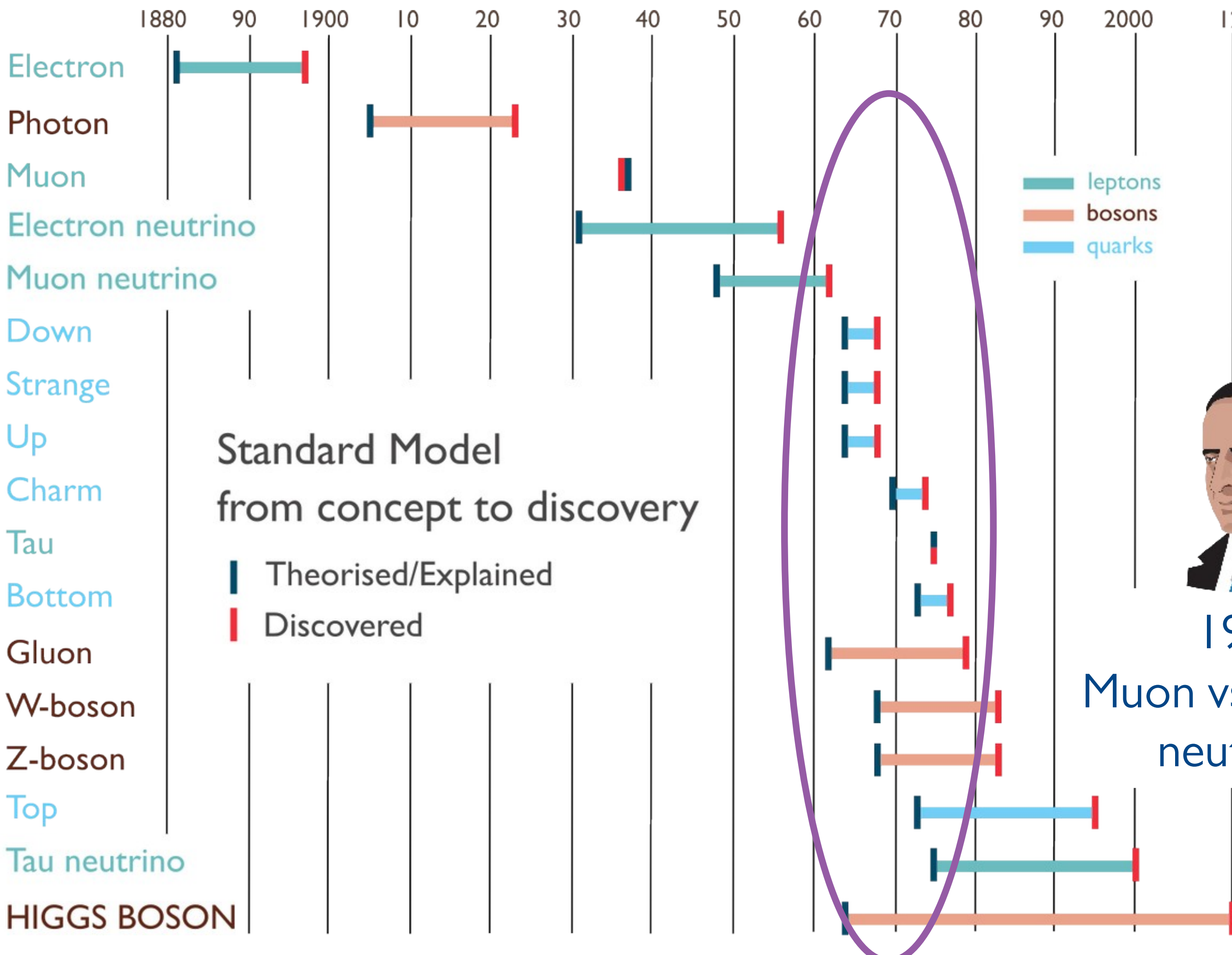


Electromagnetic

Weak

Strong

Brief History of Particle Physics



1959
Muon vs Electron neutrino

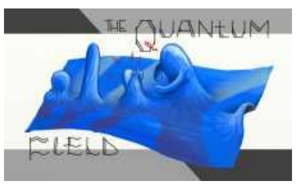
Courtesy to The Economist

What is the Standard Model?

Particle Zoo: (+ antiparticles!)

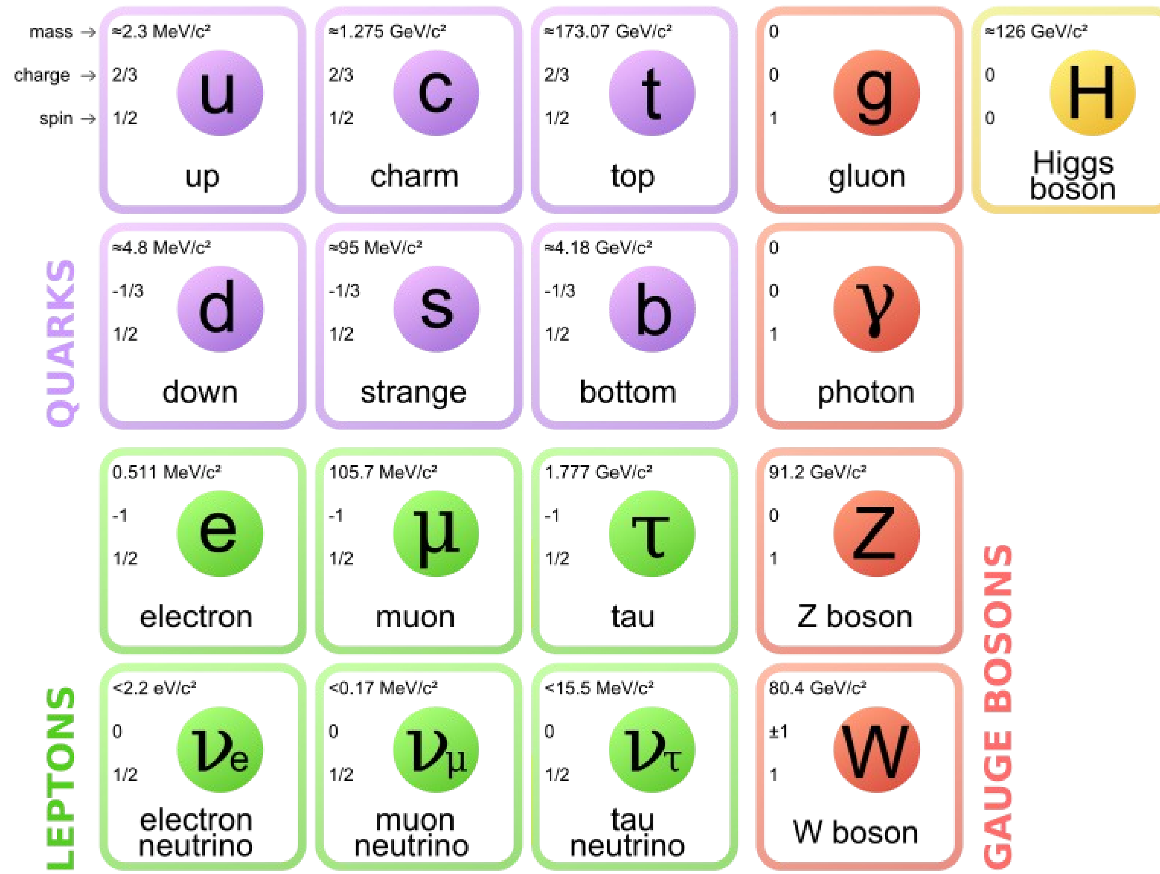
A Quantum-Field-Theory: which specify:

- particles
- interactions



Particles as quantum field excitations

Interactions are due particle exchange



Theory of Almost Everything, Robert Oerter

What is the Standard Model?

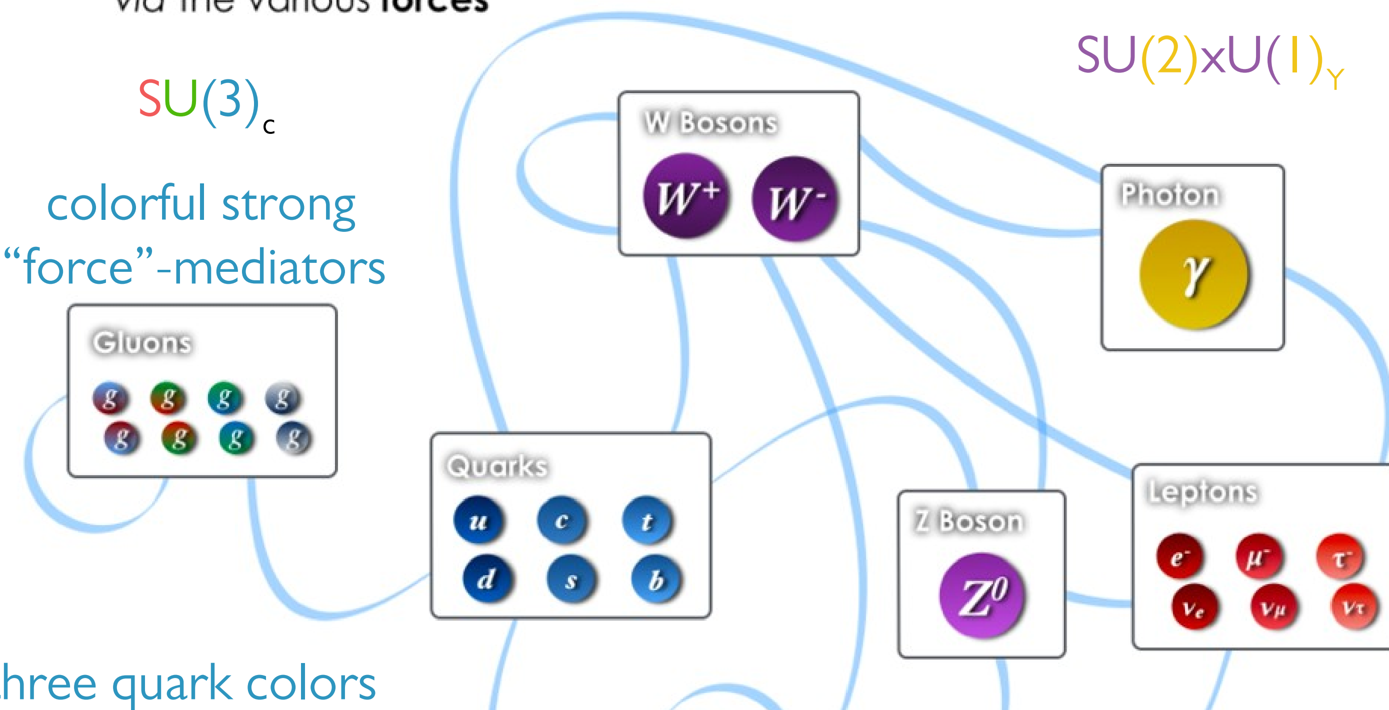
Crucially the **fundamental particles** are all **connected to one another** *via* the various **forces***

$SU(3)_c$

colorful strong "force"-mediators

Electromagnetic + Weak

$SU(2)xU(1)_Y$



three quark colors

Confinement...

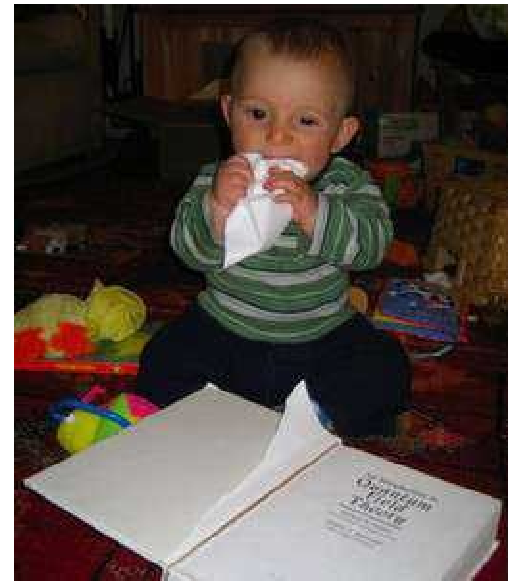
Gauge symmetries $SU(3) \times SU(2) \times U(1)$ dictate interaction pattern between particles

Theory of Almost Everything, Robert Oerter

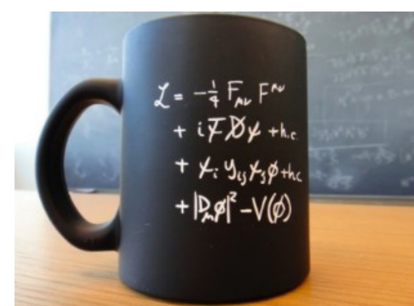
What is the Standard Model?

All this information is encoded in the SM Lagrangian

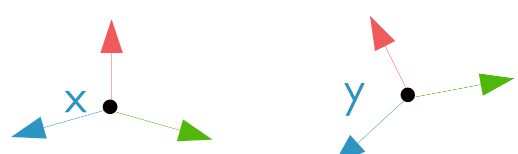
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$
$$+ \quad i\bar{\psi}\hat{D}\psi + (\bar{\psi}_i Y_{ij}\psi_j\phi + \text{h.c.})$$



ψ_i fermions (spin 1/2)
$F_{\mu\nu}$ vector bosons (spin 1)
ϕ scalar bosons (spin 0)



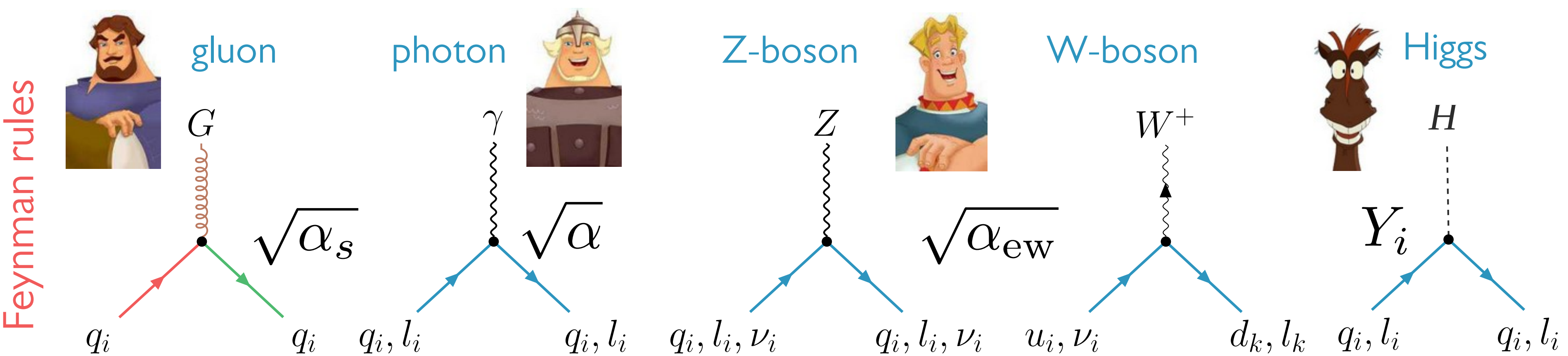
Gauge symmetries SU(3) x SU(2) x U(1) dictate interaction pattern between particles → Invariance under transformations of fields



Perturbation theory and Feynman Diagrams

$$
\begin{aligned}
\mathcal{L} \quad &= \quad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu \phi|^2 - V(\phi) \\
&+ \quad i\bar{\psi}\hat{D}\psi + (\bar{\psi}_i Y_{ij}\psi_j \phi + \text{h.c.})
\end{aligned}
$$

Every term in the Lagrangian with more than 2 fields corresponds to an interaction, e.g.,



Elementary interactions of vector (gauge) bosons with fermions,
the strength is characterized by the corresponding coupling “constant”,
details of interactions (e.g., of red and blue quarks) are due to postulated symmetries

Why do we need gauge symmetry breaking?

Gauge symmetry requires the gauge bosons* ("force-carriers")
to be massless (long-range).

* and all the SM fermions!

Ok, photon is massless

Gluon seems to be "ok"

Something wrong
with your theory..
Weak forces are short-range
and cannot be massless!

This is one of the problems that
Englert, Brout and Higgs were trying
to solve in sixties,
(do not forget about Guralnik, Hagen and Kibble!)

Forces from particle exchange

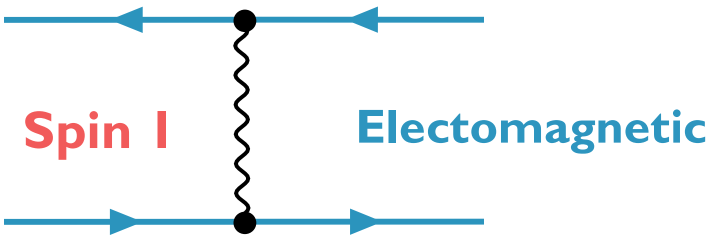
Gravity? due to graviton!

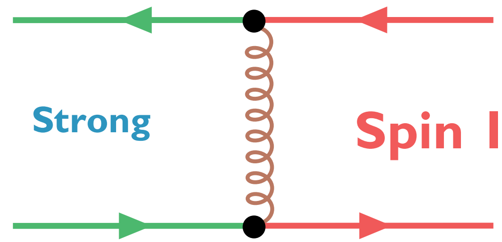
Spin 2

Spin 1

$$V(r) = -q_1 q_2 \frac{\alpha}{r}$$

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \lambda r$$

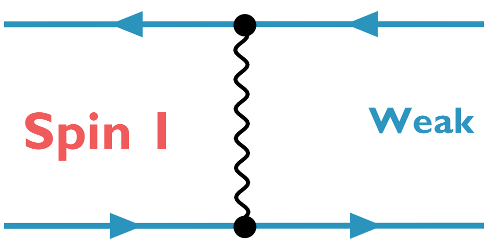




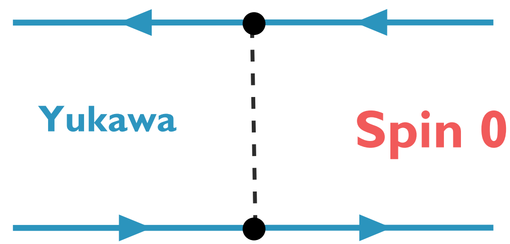
$$V(r) = -\frac{\alpha_W}{r} e^{-M_W r}$$

short-range

$$V(r) = -\frac{m_1 m_2}{M_W^2}\frac{\alpha_W}{r} e^{-M_H r}$$



$M_W \approx 91$ GeV



$M_H \approx 125$ GeV

Where are all Y_i?

Spontaneous Symmetry Breaking

~~in the SM~~

Laws(equations) of Nature are symmetric, but the states (solutions) are not.

Spontaneous Symmetry Breaking in the SM

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi)$$

Negative!

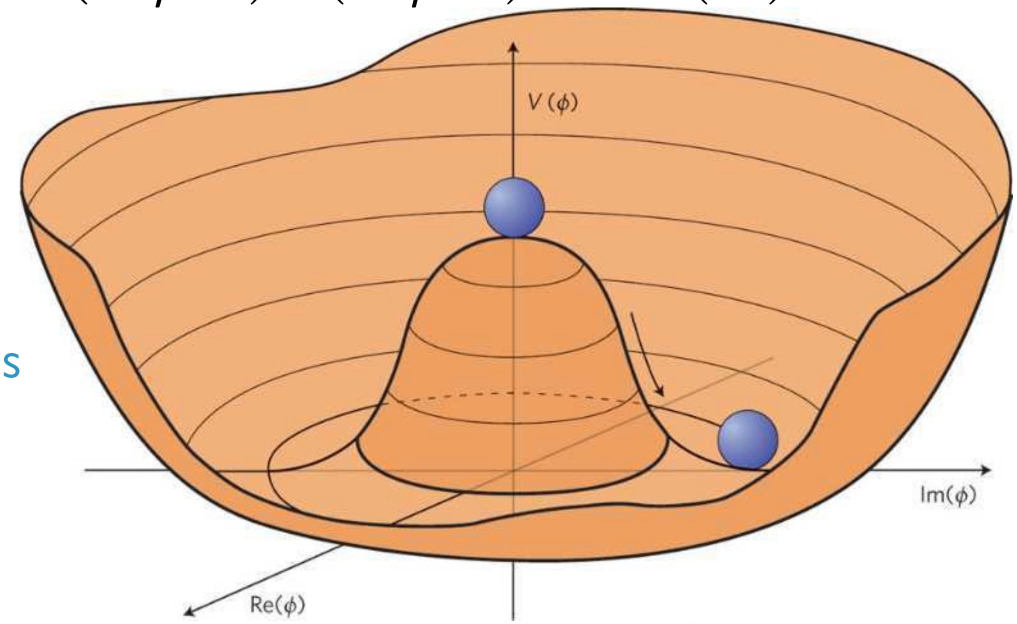
$$V(\Phi) = m^2 |\Phi|^2 + \lambda |\Phi|^4$$

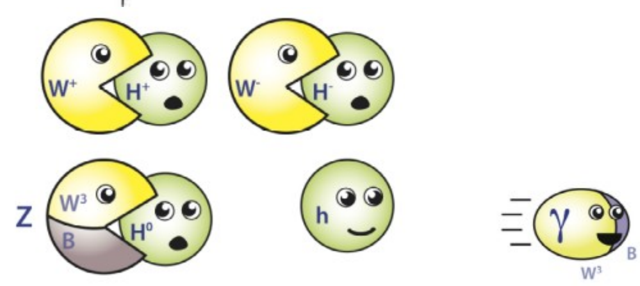
Would-be goldstone "eaten" by W-bosons

$$\Phi = \begin{pmatrix} \phi^+(x) \\ \frac{1}{\sqrt{2}}(\phi + i\chi) \end{pmatrix}$$

Neutral higgs field

"eaten" by Z-boson Would-be goldstone





Spontaneous Symmetry Breaking in the SM

$$\left.\frac{\partial V(\phi)}{\partial \phi}\right|_{\phi=v} = 0$$

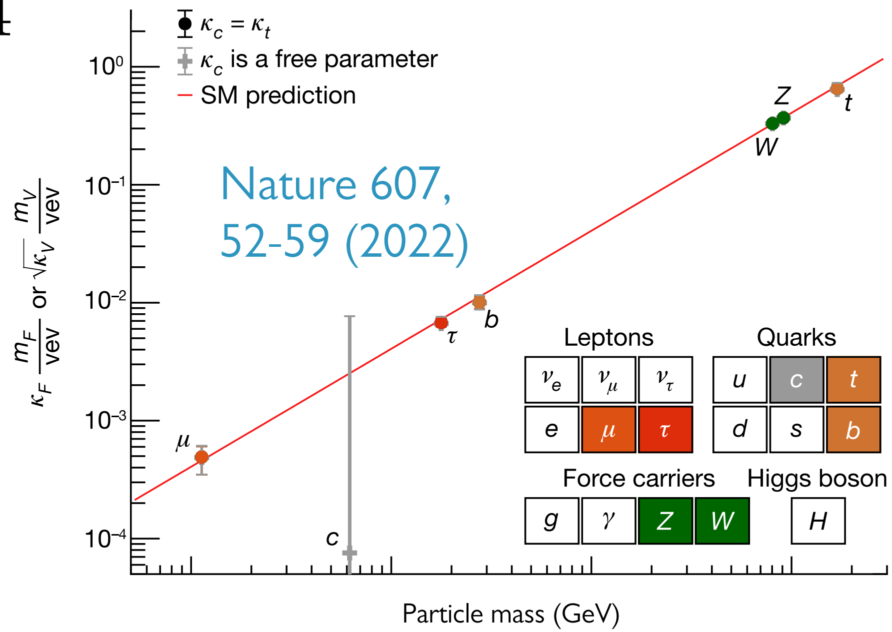
$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

The electroweak vacuum state is characterized by vacuum expectation value (vev)

$$\langle \phi \rangle = \sqrt{2}v \neq 0$$

with $v \simeq 174 \text{ GeV}$

at tree level $v = \sqrt{\frac{-m^2}{2\lambda}}$



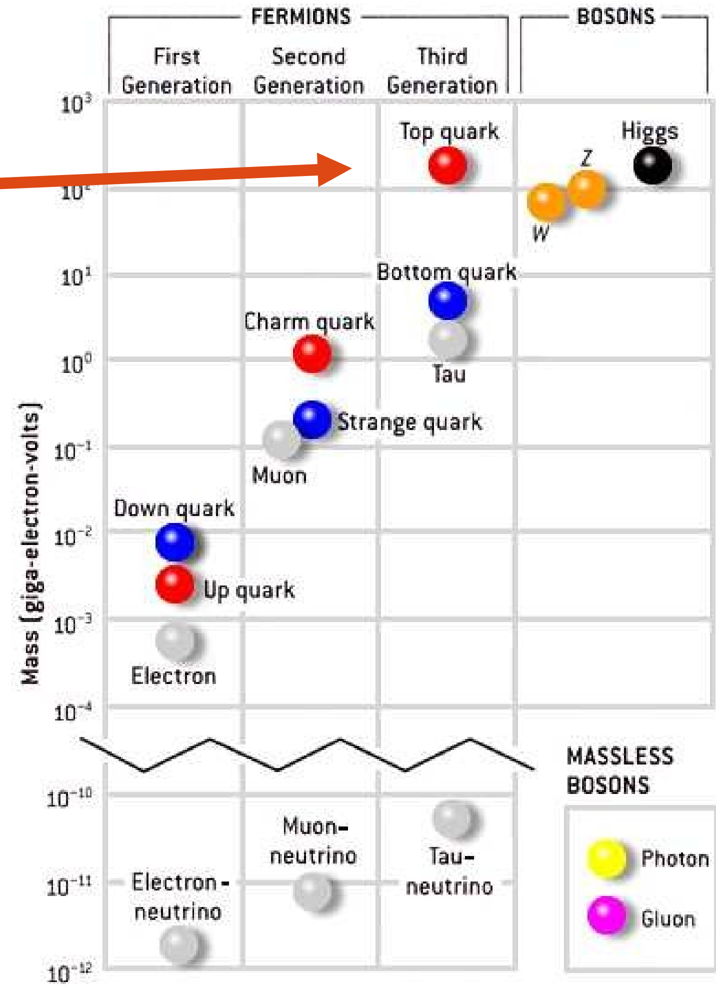
Nature 607, 52-59 (2022)

$$M_h = 2\sqrt{\lambda} \cdot v \qquad m_f = Y_f \cdot v \qquad M_{W,Z} = g_{W,Z} \cdot v$$

Fermions can also acquire their mass via coupling to the Higgs field

SSB and Fermion Masses

The heaviest elementary(?) fermion



Open Question: Why such a hierarchy?

The SM fermions acquire their mass via **Yukawa** coupling to the Higgs field

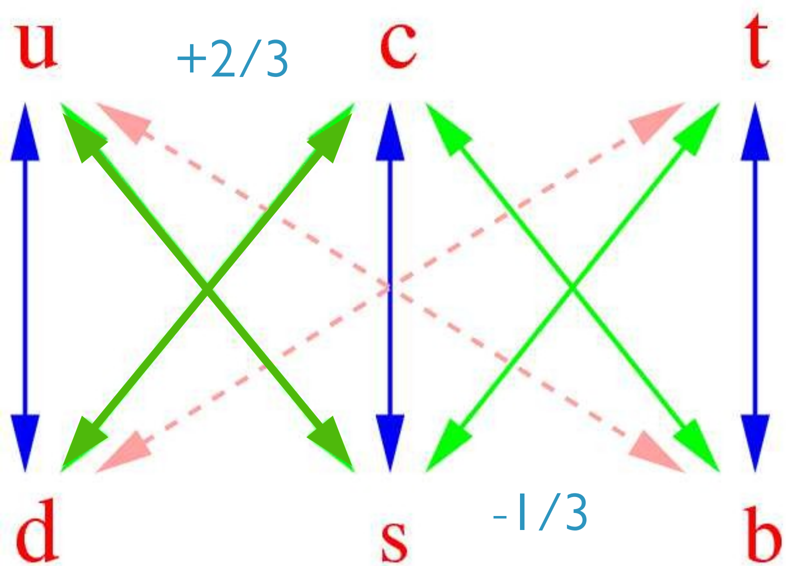
Flavor Physics: Beautiful yet Mysterious

$$\bar{\psi}_i Y_{ij} \psi_j \phi + \text{h.c.}$$

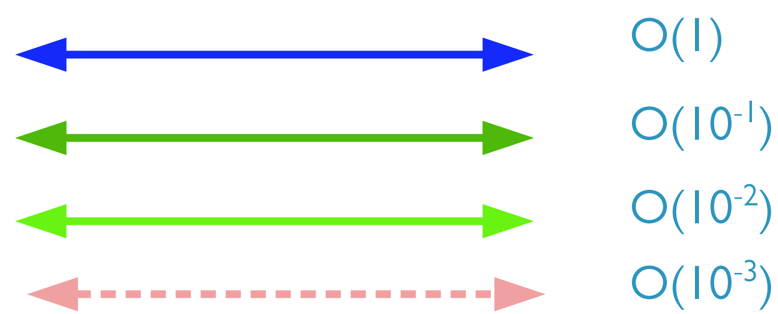
Flavor is about indices...
Flavor in the SM is due to non-trivial (matrix) **Yukawa couplings**

After diagonalization of the fermion mass matrices = (neutral higgs interactions in the SM) observable mixing appears only in charged-current interactions of the LH quarks* with W-bosons:

$$\Delta \mathcal{L}_W = \frac{g_2}{\sqrt{2}} \bar{u}_{Li} \gamma^\mu V^{ij}_{\text{CKM}} d_{Lj} W^+ + \text{h.c.}$$



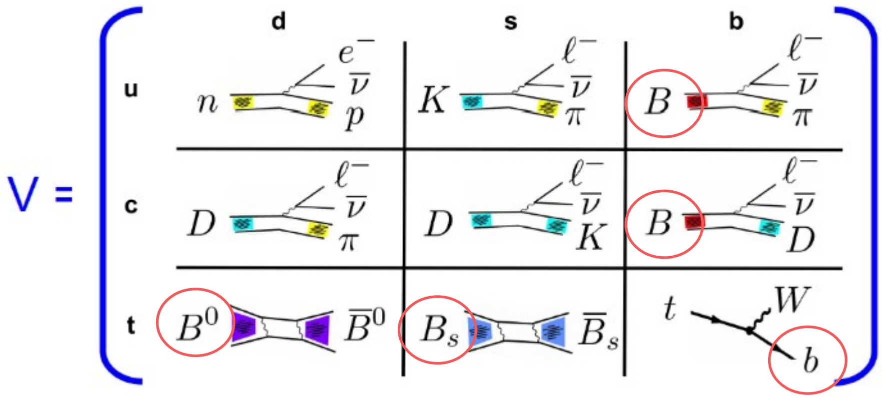
Cabbibo-Kobayashi-Maskawa



Open Question: Why such a pattern?

For neutrinos: Pontecorovo-Maki-Nakagawa-Sakata matrix

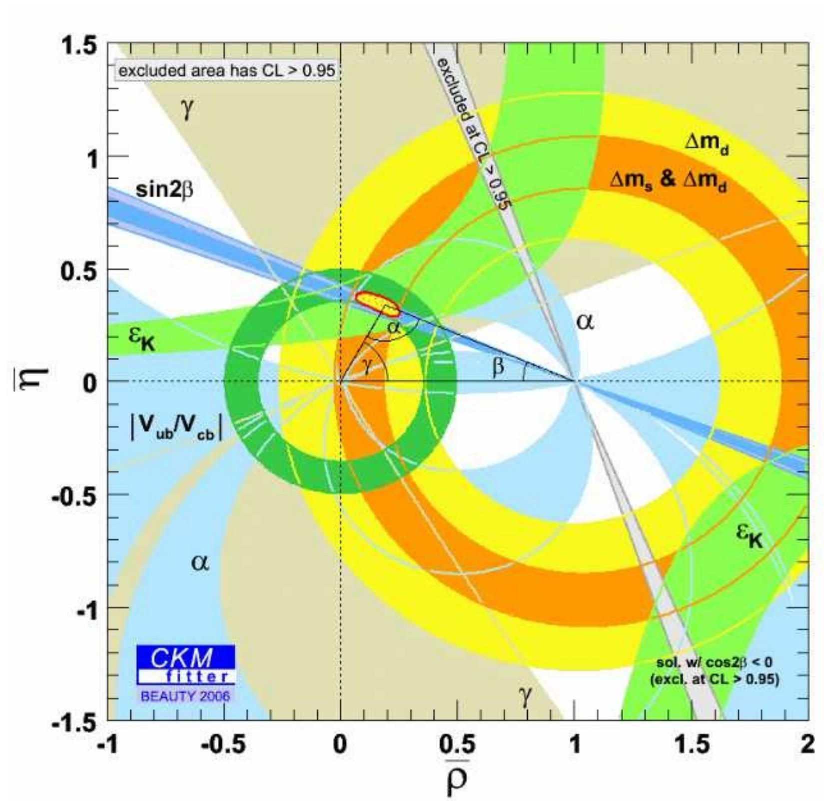
Flavor Physics: Beautiful yet Mysterious



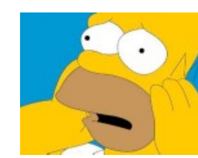
NB: a lot of B's here!

This picture survives stringent tests from different experiments!

The area of Unitarity triangle(s) is connected to amount of CP-violation: at least 3 sides (= generations) are required!



$$V^{\dagger}{}_{CKM} V_{CKM} = 1$$

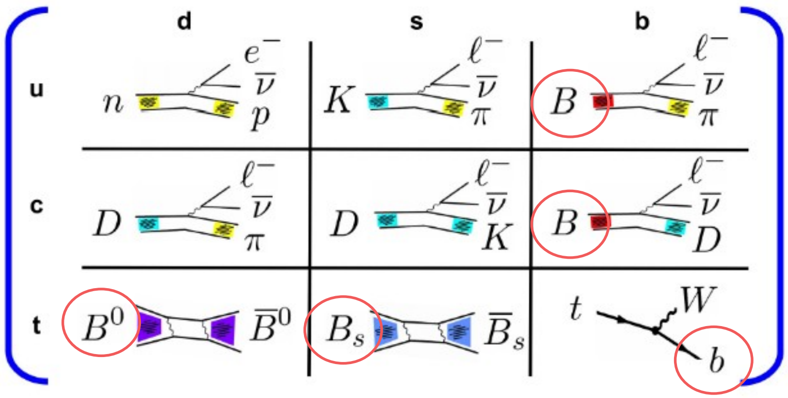


Not enough in the SM!

NB: CP-violation is crucial for generation of baryon asymmetry!

Flavor Physics: Beautiful yet Mysterious

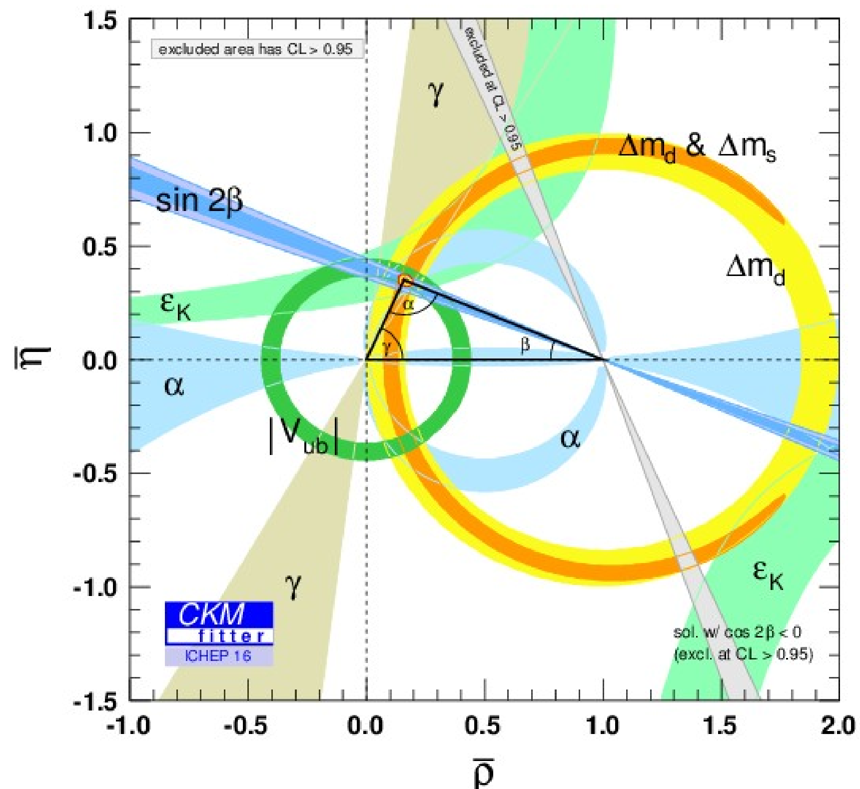
V =



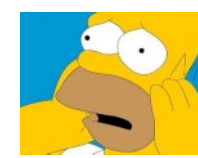
NB: a lot of B's here!

This picture survives stringent tests from different experiments!

The area of Unitarity triangle(s) is connected to amount of CP-violation: at least 3 sides (= generations) are required!



$$V^{\dagger}{}_{CKM} V_{CKM} = 1$$



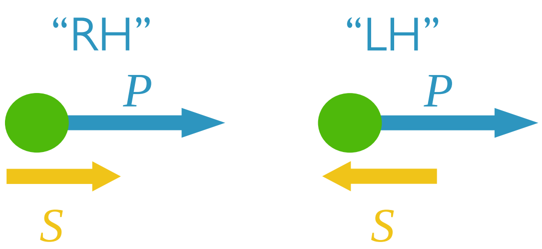
Not enough in the SM!

NB: CP-violation is crucial for generation of baryon asymmetry!

Distorted mirrors of electroweak interactions

P-transformation – reflection in a mirror.

C-transformation – replacement of particles with antiparticles.



Electroweak gauge bosons (Z,W) couple to left-handed (LH) particles – violation of P and C

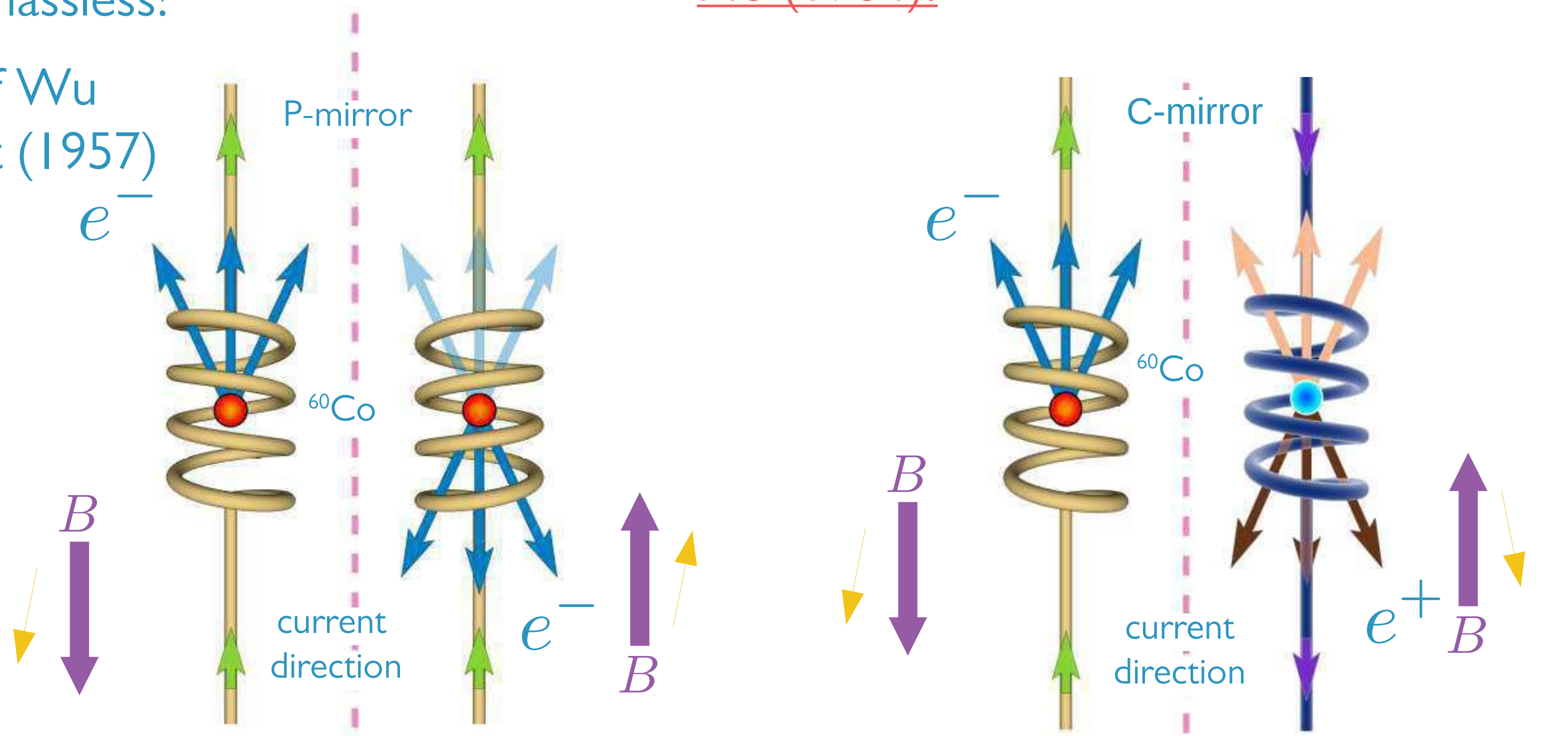
EW interactions are CP-symmetric?

No (1964)!

NB: for massless!

Sketch of Wu experiment (1957)

What is Alien doing here?



CP-violation and Flavor Physics

Weak interactions exhibit tiny violation of CP-symmetry, e.g., in decays of long-lived heavy neutral kaon built from down and strange quarks (antiquarks)

$$K^0(d\bar{s}) \overset{CP}{\longleftrightarrow} \bar{K}^0(\bar{d}s)$$

$$K_L^0 \to \pi^+ e^- \bar{\nu}_e \qquad\qquad K_L^0 \to \pi^- e^+ \nu_e$$

Long-lived ($5 \cdot 10^{-8}$ s) **mixture**

$$K^0 - \bar{K}^0$$

Nature prefers this mode, but only slightly 10^{-3}

Common notion of matter-antimatter and left-right can be established across the Universe…

Once again: the very possibility to account for CP-violation in the SM is tightly connected with the existence of three generations (prediction of Kobayashi and Maskawa in 1973)

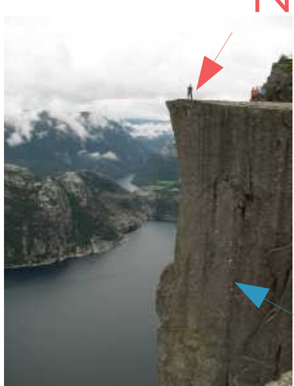
Flavor Physics: Beautiful yet Deadly(?)

Peculiar Feature of
Flavor transitions in the SM:

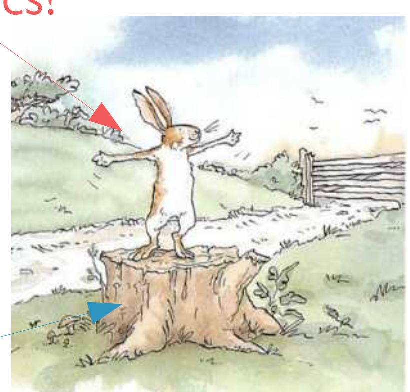
- No FCNC at tree-level: Flavor-Changing transitions between quarks of the same electric charge ("Neutral Current") are forbidden at the leading (no quantum **loops**) order.

Why is this important?

New Physics?



vs.



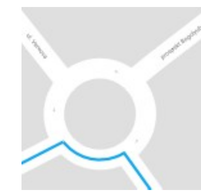
SM

Example:

$$K^+(u\bar{s}) \to \mu^+ \nu_\mu$$

64 out of 100 decay like this

$$K_L^0(d\bar{s}) \to \mu^+ \mu^-$$



7 out of 10^9 decay like this

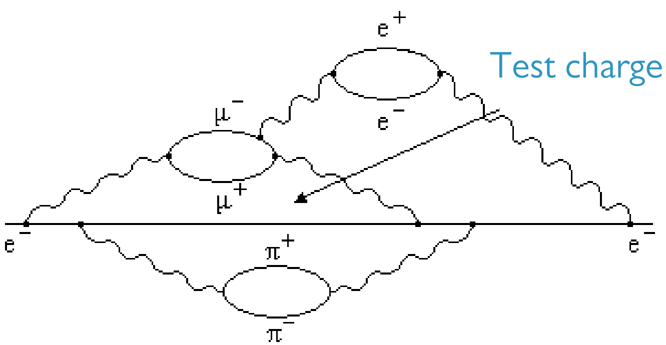
Rare FCNC processes impose very important constraint on possible New Physics ("New Physics killers")

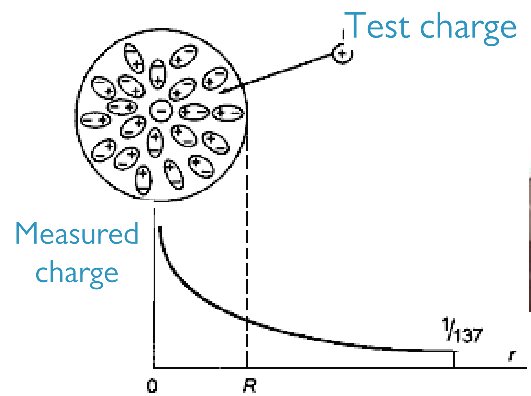
$$B_s(s\bar{b}) \to \mu^+ \mu^-$$

Again B's!

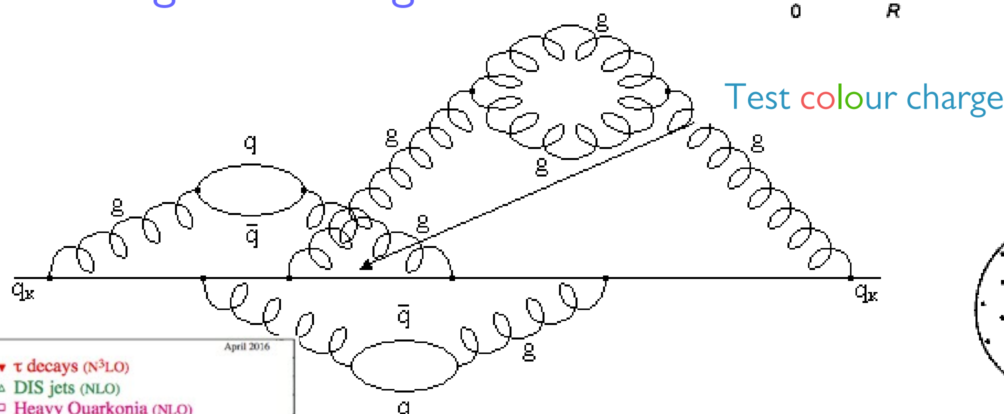
Loops (radiative corrections)...

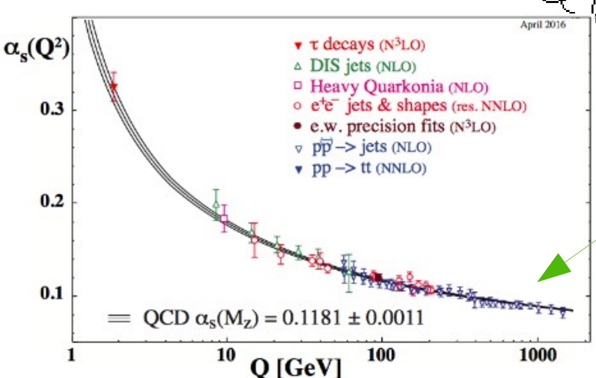
SM is a renormalizable QFT. Predicts scale-dependent (“running”) couplings



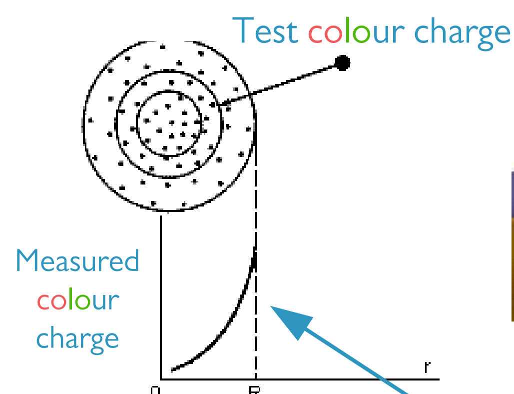


Electric charge screening





asymptotic freedom

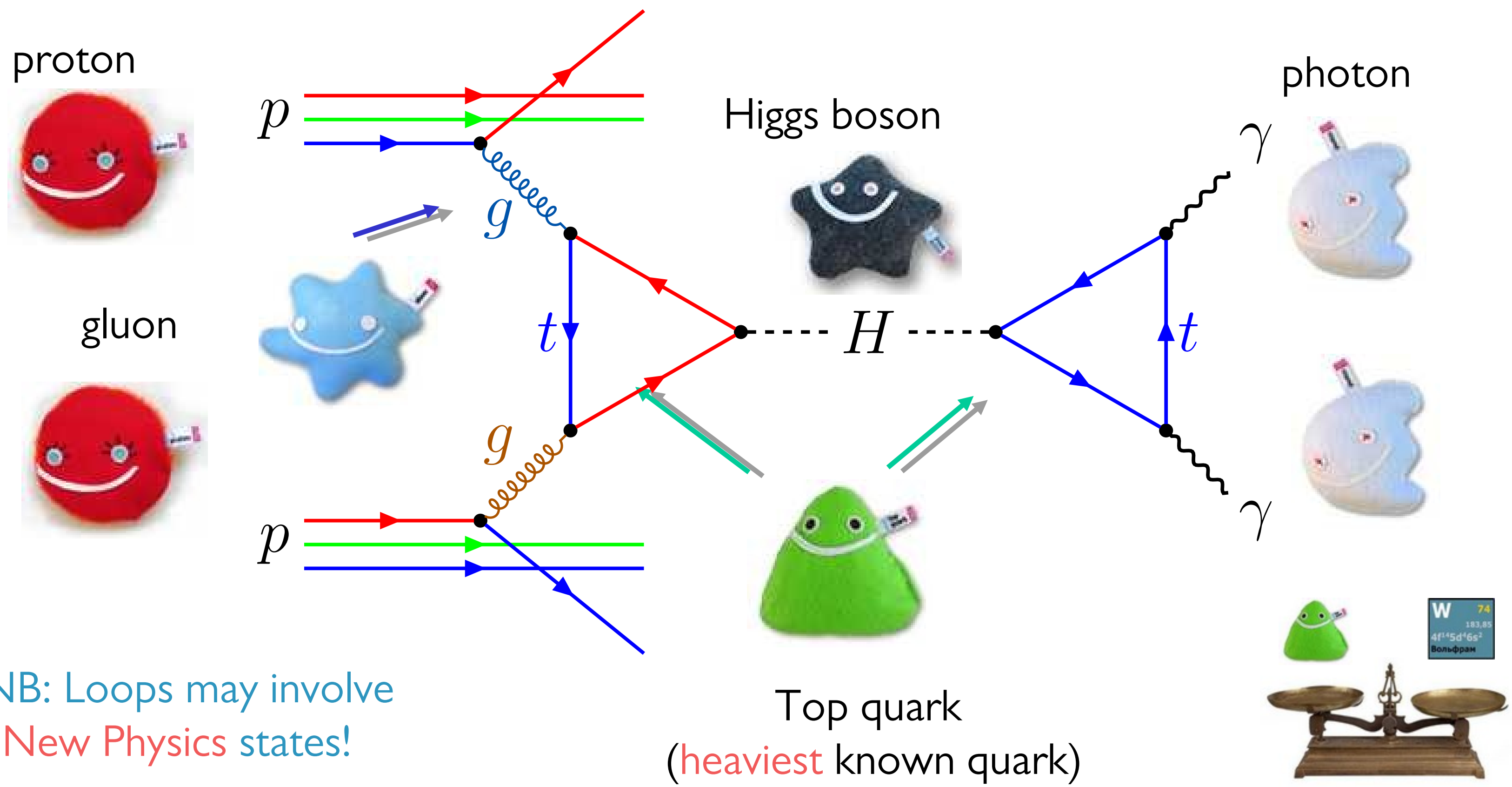


Anti-screening of colour charge

Confinement?

Radiative corrections are very important!

Radiative corrections are mandatory if one wants to relate physics at different scales. Moreover, some of the physical processes forbidden in the lowest order of perturbation theory are generated via loops, e.g.*

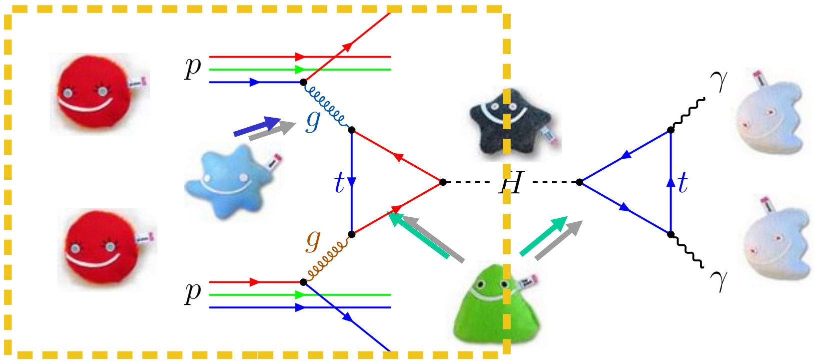


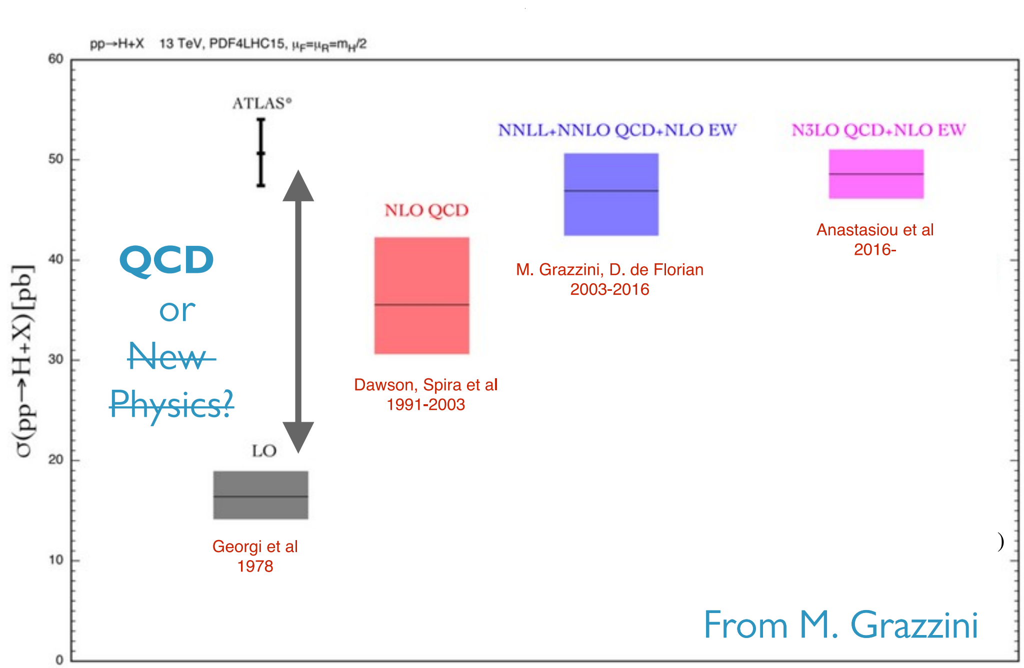
NB: Loops may involve
New Physics states!

*The sketch of the process with the SM Higgs boson, which lead to its discovery....

Radiative corrections are very important!

Radiative corrections are mandatory if one wants to relate physics at different scales. Moreover, some of the physical processes forbidden in the lowest order of perturbation theory are generated via loops, e.g.





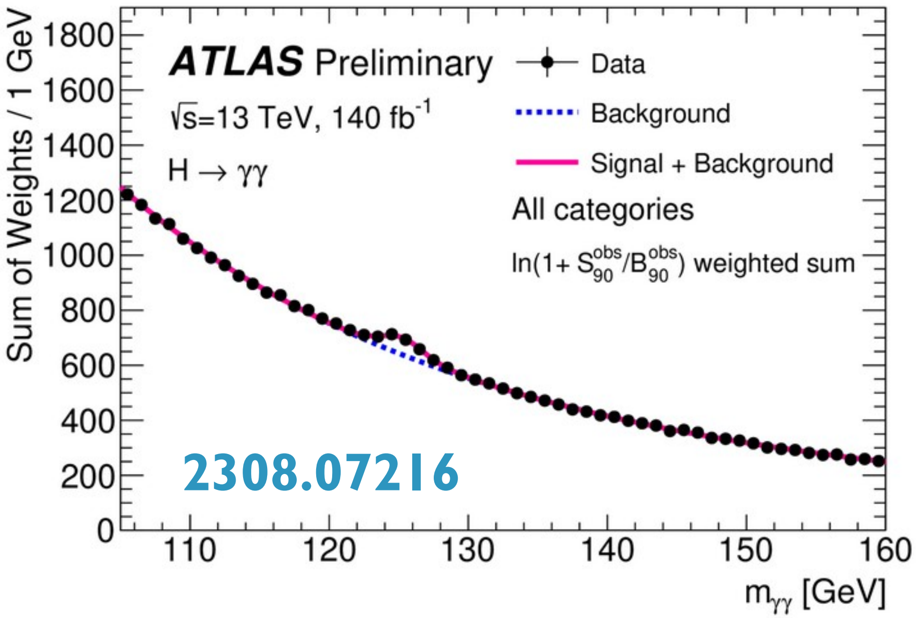
NB: Not the whole story!
QCD corrections to the process are known to be very important!

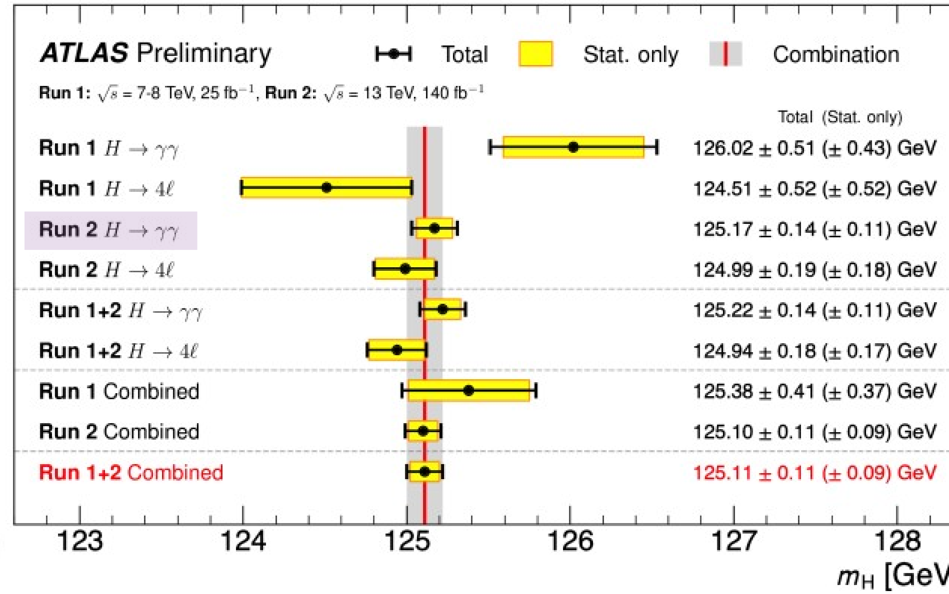
LO – leading order,
NLO – next-to-leading order
("one additional QCD loop"),
etc

Doubles the effect!

There will be other examples demonstrating crucial role of loop effects...

H → γγ at the LHC: evolution of precision





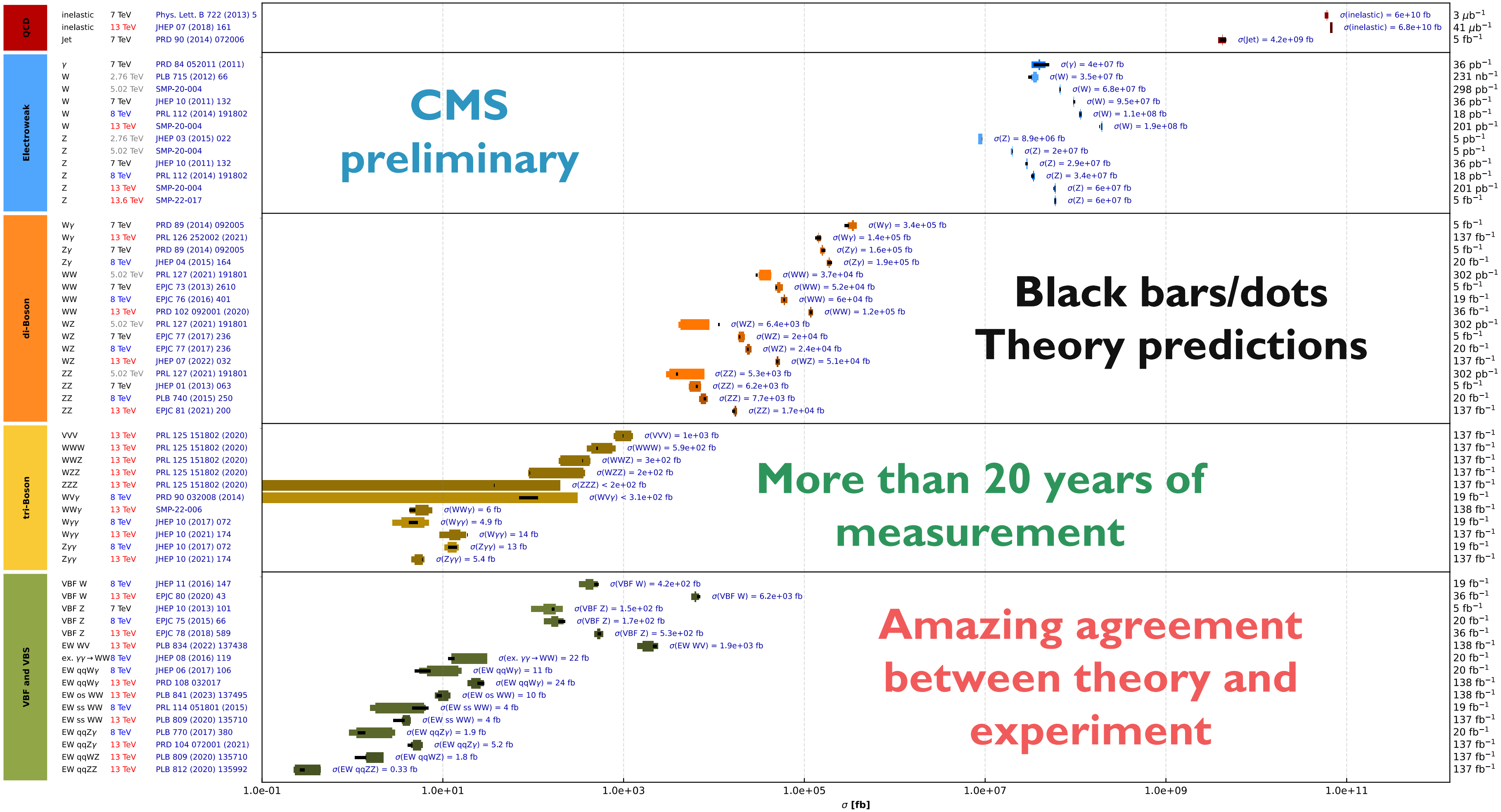
$$M_H^{\mathrm{ATLAS}} = 126.0 \pm 0.6 \;\mathrm{GeV}$$
$$M_H^{\mathrm{CMS}} = 125.3 \pm 0.6 \;\mathrm{GeV}$$

$$M_{H\to\gamma\gamma}^{\mathrm{ATLAS}} = 125.17 \pm 0.14 \;\mathrm{GeV}$$

2012
5 ‰ accuracy

2023
1 ‰ accuracy

Triumph of the SM at LHC



Measured/Computed cross-sections span about 10 orders of magnitude!

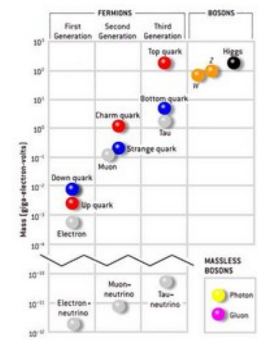
Mini-summary on nice features of the SM

- Minimalistic model describing (all?) known experimental data with (very) high precision
  - Involves only observed particles/antiparticles!
  - Based on symmetry principles!
  - Accounts for the properties of ~~three~~ four known forces (still w/o gravity)
  - Accounts for P,C, and CP-violation
  - Accounts for peculiarities in flavor transitions
  - Gives a hint on quark confinement
  - ….
- All the parameters* (18 + 1) are measured [+ PMNS matrix]
- Radiative corrections are mandatory to prove SM valid at different scales

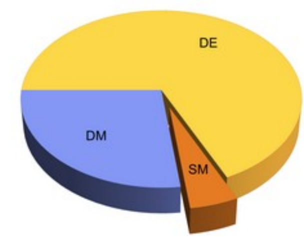
* assuming massless neutrino. See lectures on neutrino for more detail…

The SM Issues (Quest for New Physics)

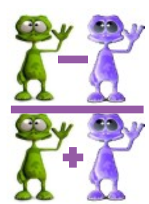
...since we have already mentioned New Physics several times,
let us briefly review main shortcomings of the ~~SM~~ Theory Of Almost Everything:



- Hierarchy problem(s)
  - Why is the Higgs boson so light (125 instead of 10^{19} GeV)?
  - Why are fermion masses/couplings to higgs so different?
- Lack of gauge-coupling unification at high energies
- No Dark Matter candidate (85 % of Matter is not explained!)



- Matter-Antimatter asymmetry



$\sim 10^{-9}$

  - No enough CP-violation
  - No strong first-order EW phase transition in Early Universe
- Neutrinos are assumed to be ~~massless~~. Mass scale? Nature of neutrinos?
- ...

Possible New Physics models aim to solve these problems...

Quest for New Physics…

Plenty of possibilities…

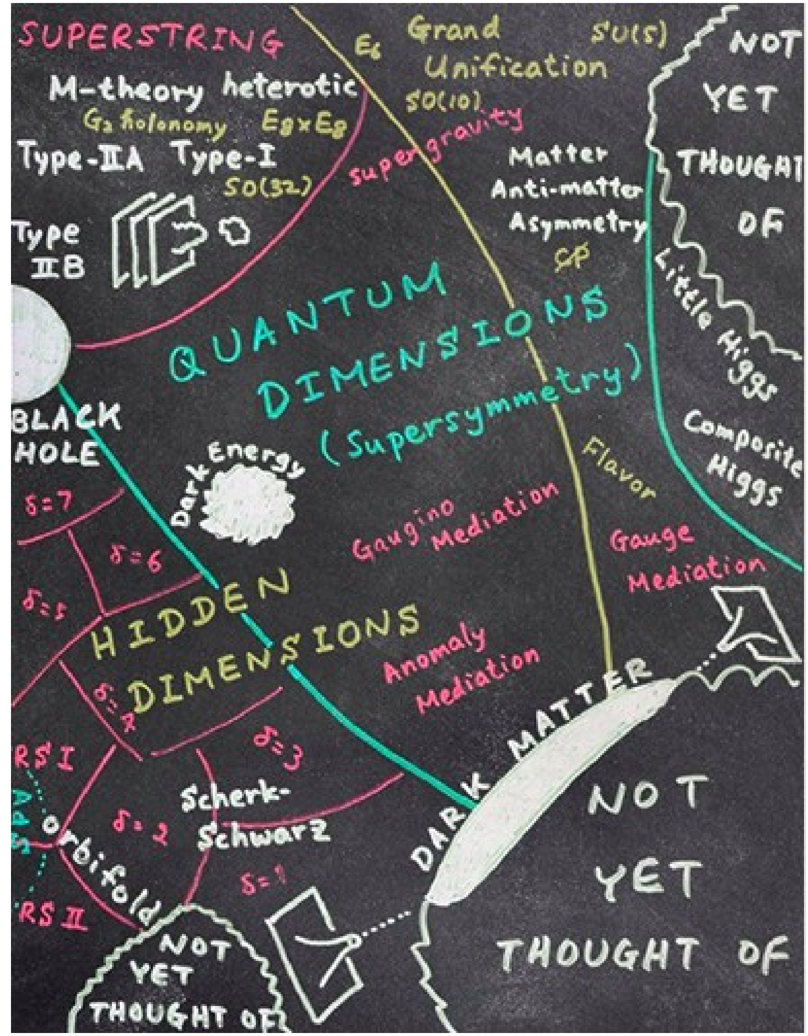
No roadmap…

Scale? TeV? 100 TeV?

No guaranteed discoveries in the near future?

Better to check every option…

Start by looking under lamp-post…

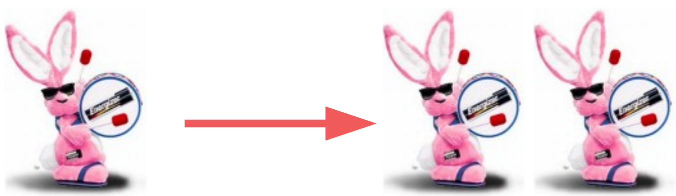


Courtesy to D. Dominguez and H. Murayama

Quest for New Physics...

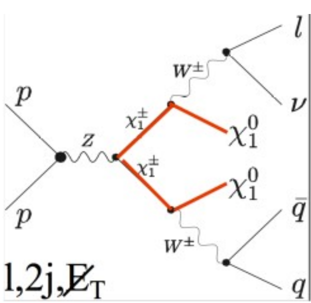
There seems to be two ways to discover something New:

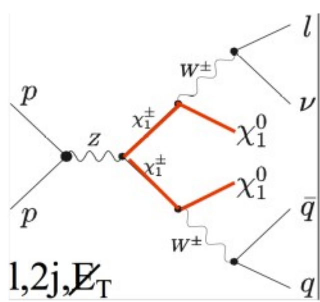
Energy frontier



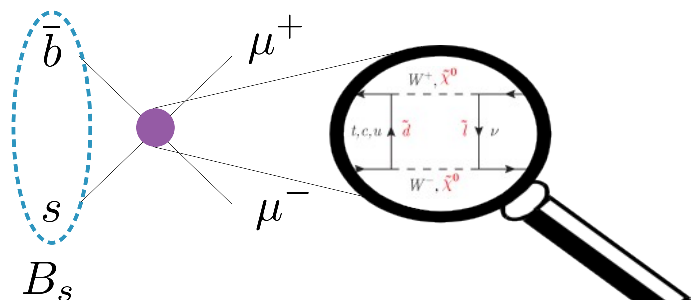
Produce real heavy particles(?)
and search for their signatures

The latter are usually model-dependent, e.g., in SUperSYmmetry





Precision frontier



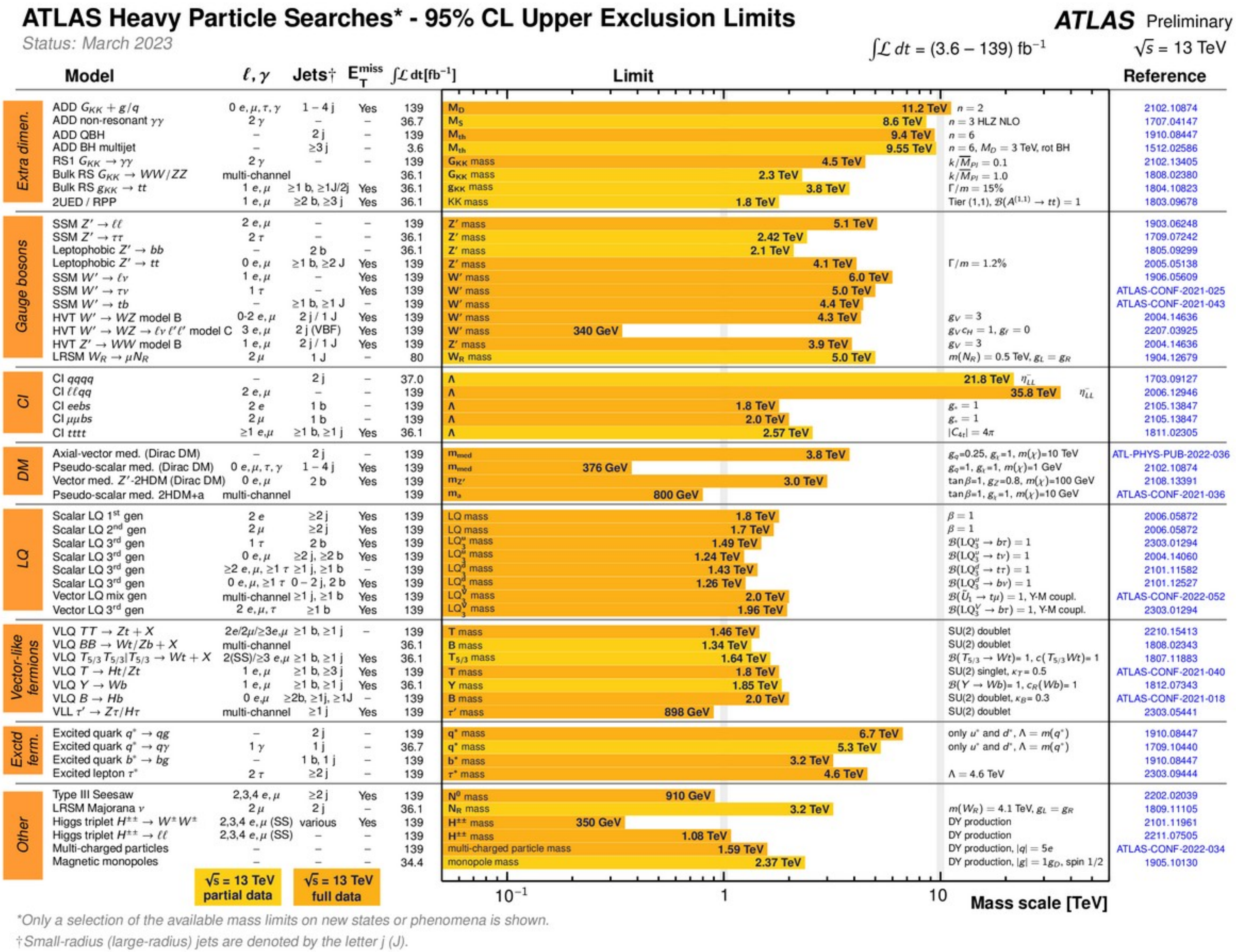
Study influence of virtual degrees of freedom on known phenomena

Higgs sector

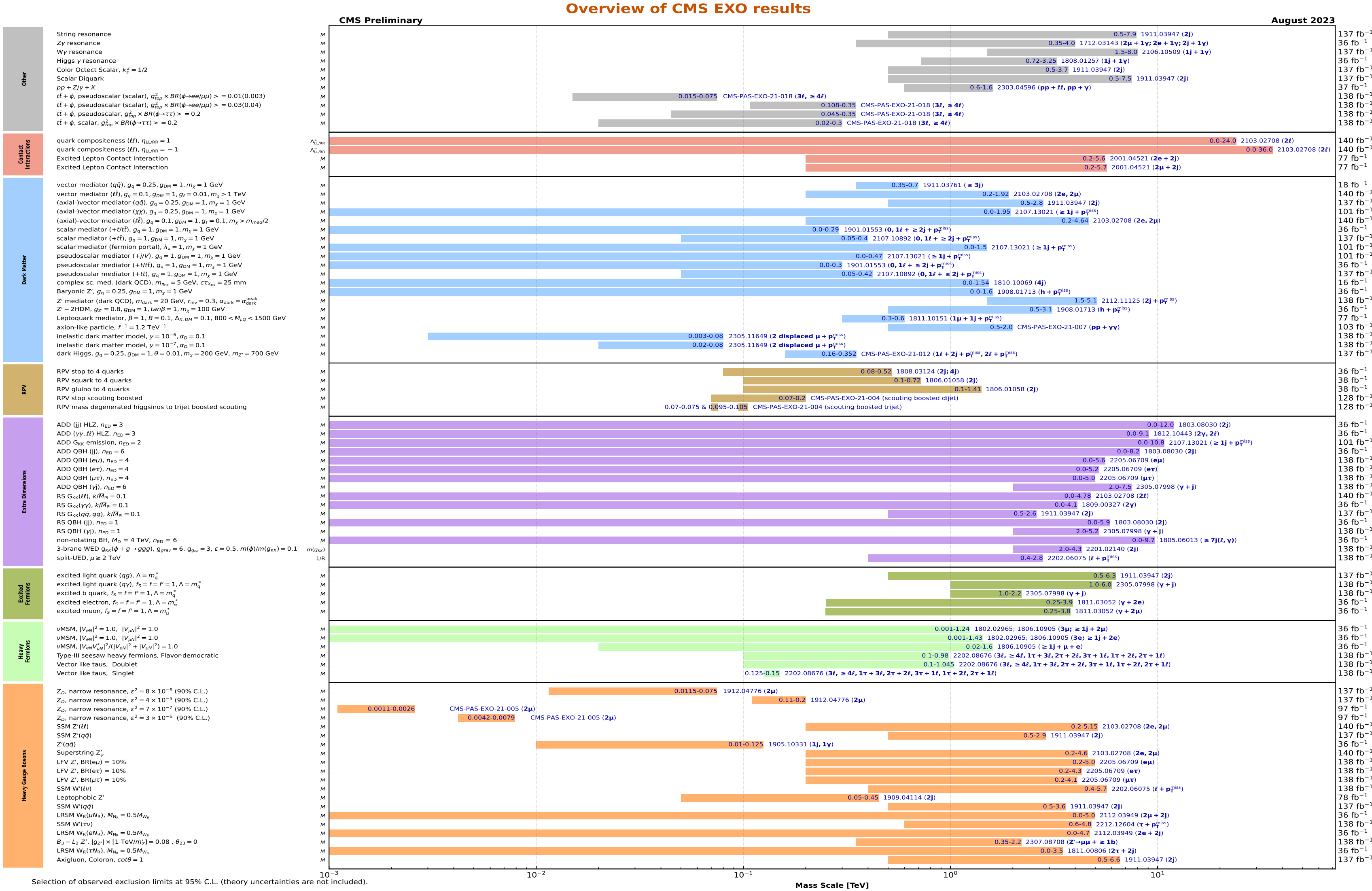
Flavor sector

Gauge sector

Result from LHC: Energy frontier



Result from LHC: Energy frontier



Precision frontier in Higgs sector

Test deviations from SM predictions...

Trees!

Z-boson

W-boson

top

bottom

tau

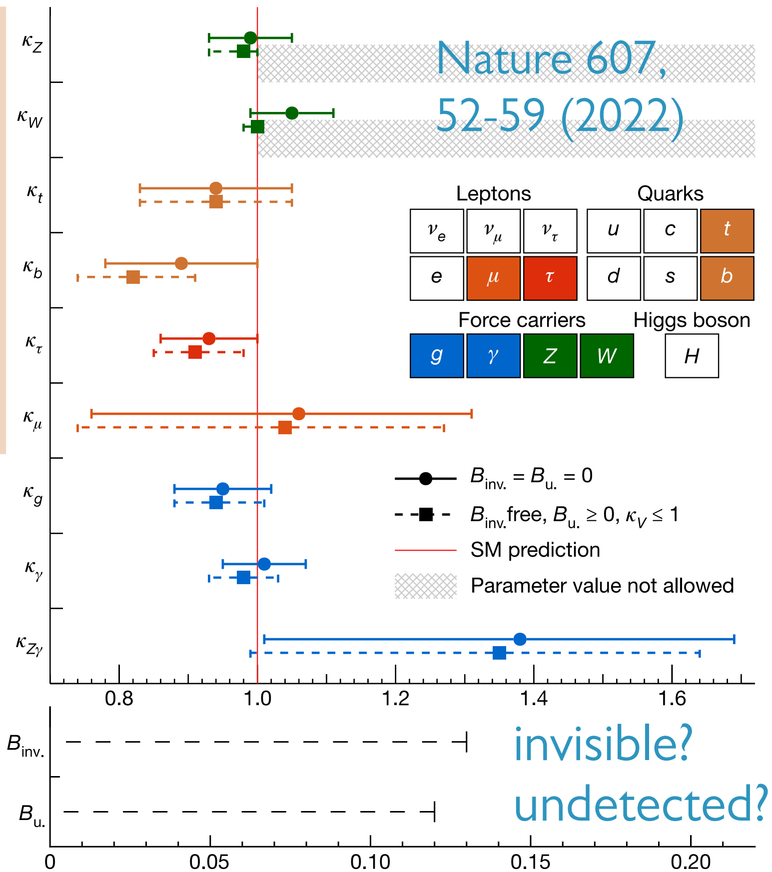
muon

Loops!

gluon

photon

Z-photon



Nature 607, 52-59 (2022)

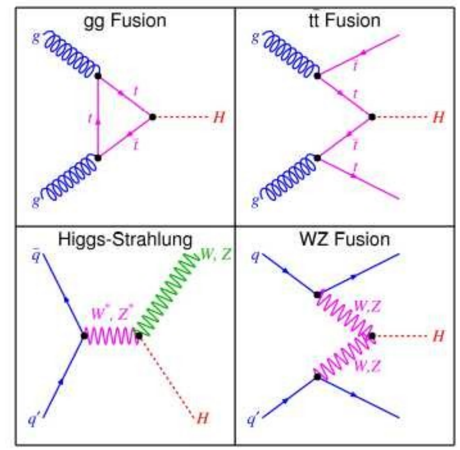
invisible?

undetected?

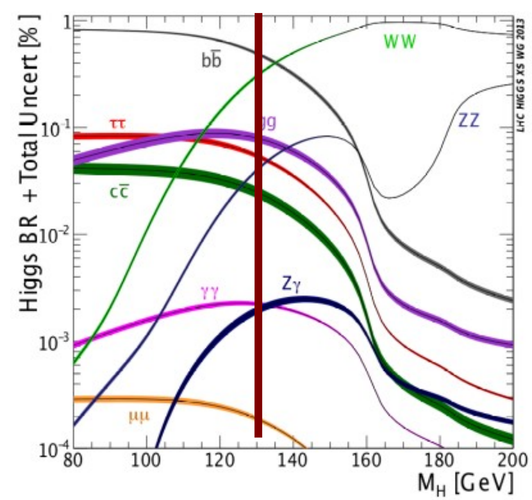
So far so good...

NB: higgs can be a **portal** to New Physics!

SM Higgs Physics:



Production



Decay

Precision is the key: “anomalies”

5σ? | ≲2σ | 5σ? | ≈2σ | 3-4σ

a_μ | τ→μνν | b→sμμ | Z→bb | γγ, eμ(+b)

muon ≈0.1 GeV | nuclear ≈1GeV | B meson ≈10GeV | EW ≈100GeV | LHC ≈1TeV | FCC-hh ≈10TeV

CAA | b→cτν | m_W | jj(-jj) | pp→ee

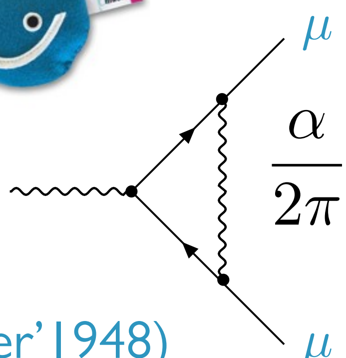
≲3σ | ≳3σ | 7σ? | ≈3σ | ≈3σ

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$$

From Crivellin, Mellado,2023

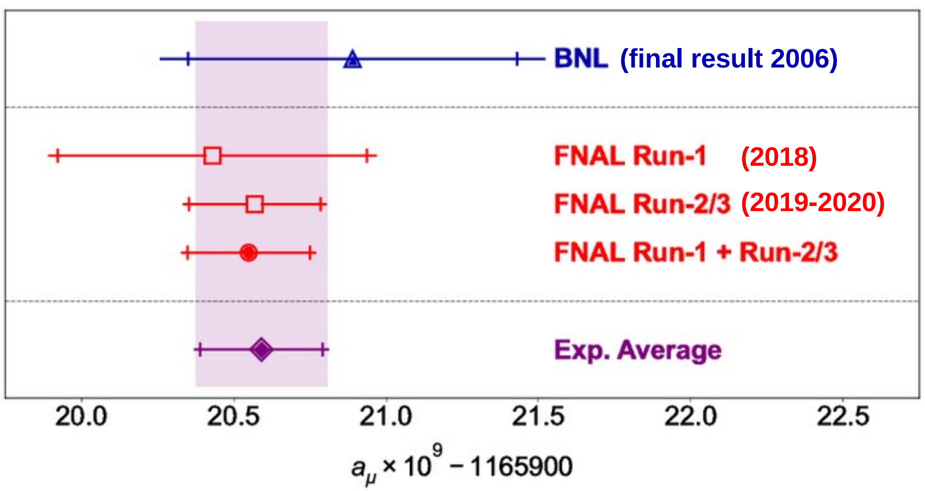
Muon anomalous magnetic moment, a.k.a a_μ

$$\vec{\mu}_f = g_f \cdot \frac{e}{2m}\vec{s} = (1 + a_f)\cdot\frac{e}{m}\vec{s}$$

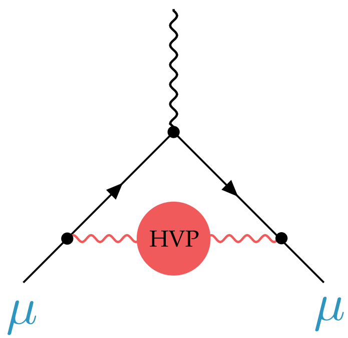


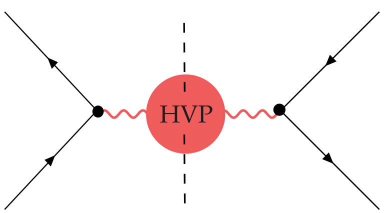
- Dirac equation predicts $g_f = 2$, and $a_f = 0$
- Quantum corrections lead to $a_f \approx 0.1\,\%$

(Schwinger'1948)



Magnet traveled from
Brookhaven to Fermilab





$e^- e^+ \to$ hadrons

non-perturbative (hadrons)

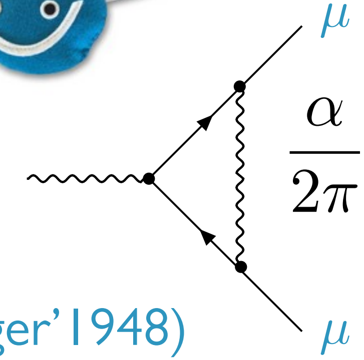
$$a_\mu^{\mathrm{FNAL}} = 116592055(24)\cdot 10^{-11}$$

(0.20 ppm)

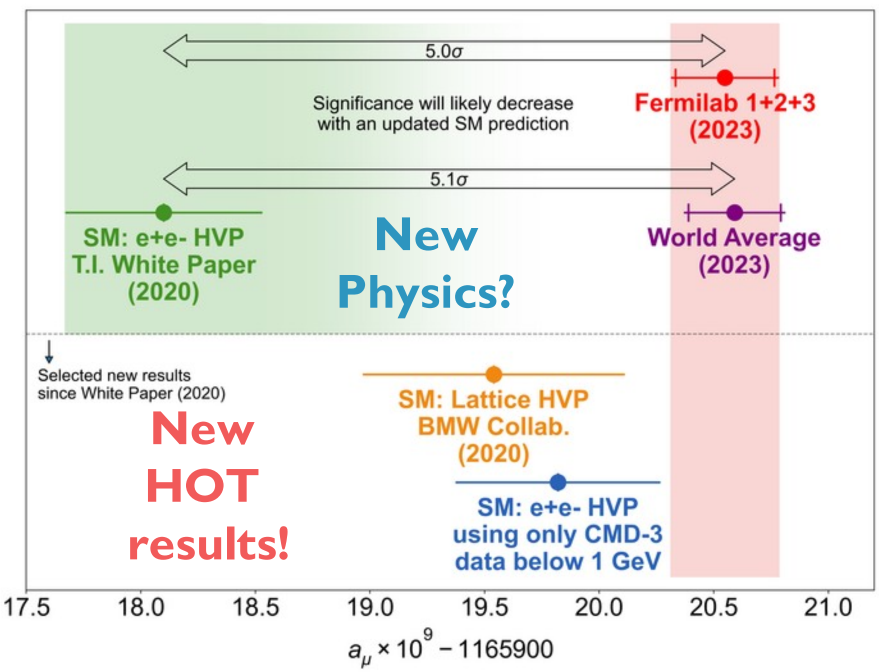
Muon anomalous magnetic moment, a.k.a a_μ

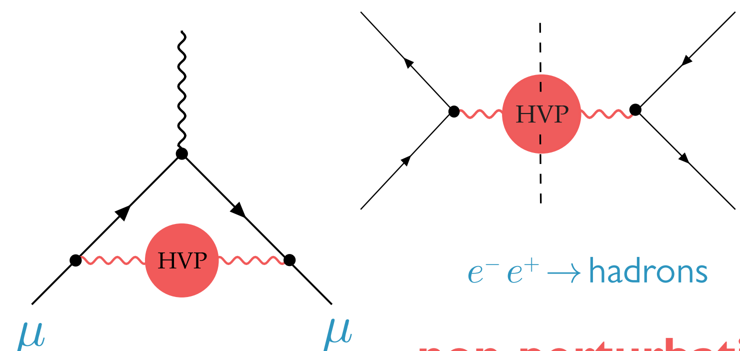
$$\vec{\mu}_f = g_f \cdot \frac{e}{2m}\vec{s} = (1 + a_f) \cdot \frac{e}{m}\vec{s}$$

- Dirac equation predicts $g_f = 2$, and $a_f = 0$
- Quantum corrections lead to $a_f \approx 0.1\,\%$



(Schwinger'1948)





$e^- e^+ \to$ hadrons

non-perturbative (hadrons)

$$a_\mu^{\mathrm{FNAL}} = 116592055(24) \cdot 10^{-11}$$

(0.20 ppm)

Long-standing discrepancy ... still no full understanding....

Mass of the W-boson: theory vs experiment

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2(1 - M_W^2/M_Z^2)}\left[1 + \Delta r(M_H, m_t, \ldots)\right]$$

quantum corrections from virtual SM & possible New Physics!

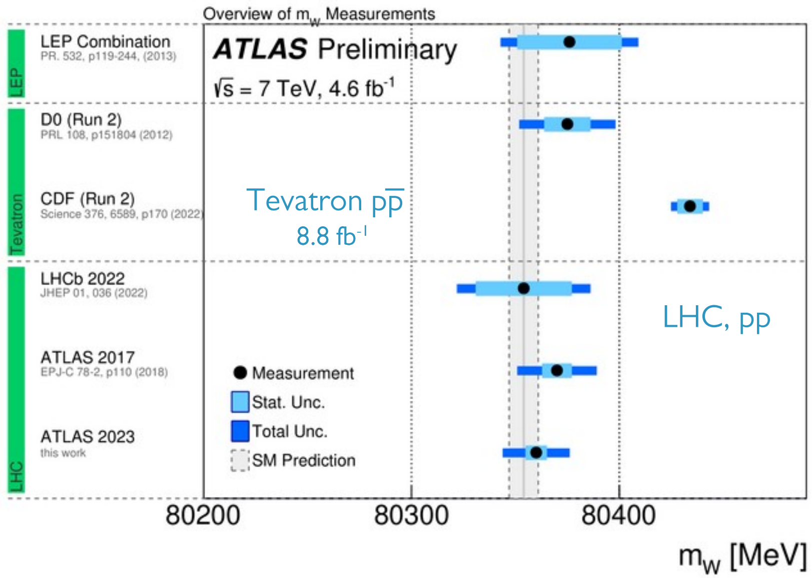
Given **measured** values of Fermi constant G_F, fine-structure constant α, and the Z-boson mass M_Z one **predicts** M_W.

(90 ppm) $$M_W^{\rm SM} = 80354 \pm 7\ {\rm MeV}$$

$$M_W^{\rm CDF} = 80433.5 \pm 9.4\ {\rm MeV}$$

7 sigma deviation? New Physics?

$$M_W^{\rm ATLAS} = 80360 \pm 16\ {\rm MeV}$$



CDF 2022 result is the most precise one …

An independent confirmation from LHC is still missing…

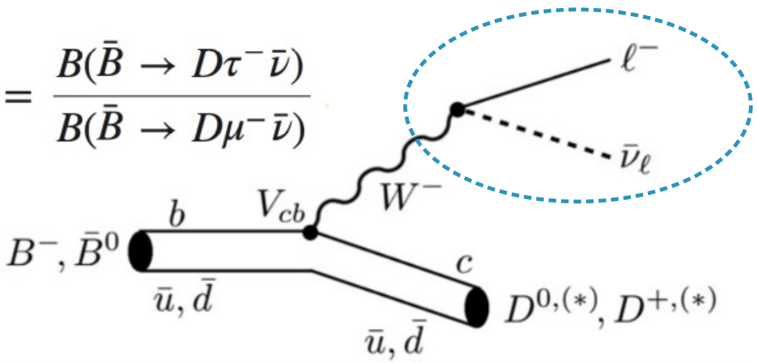
Precision frontier in flavour physics

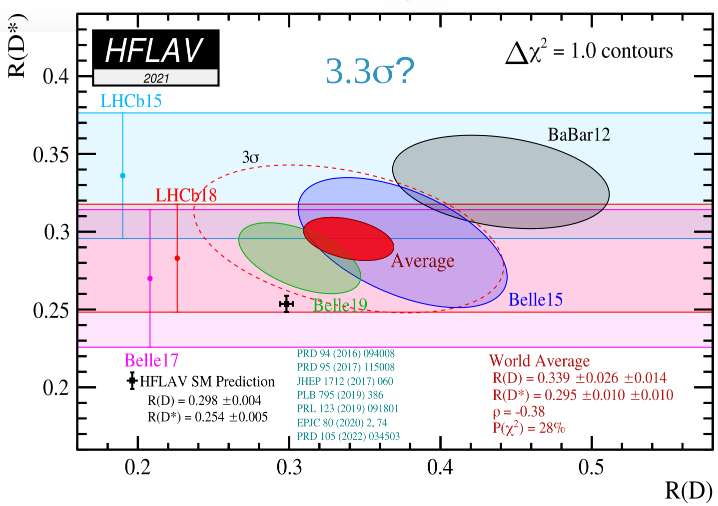
B-physics: (LHCb, Belle 2,...)

Some examples:

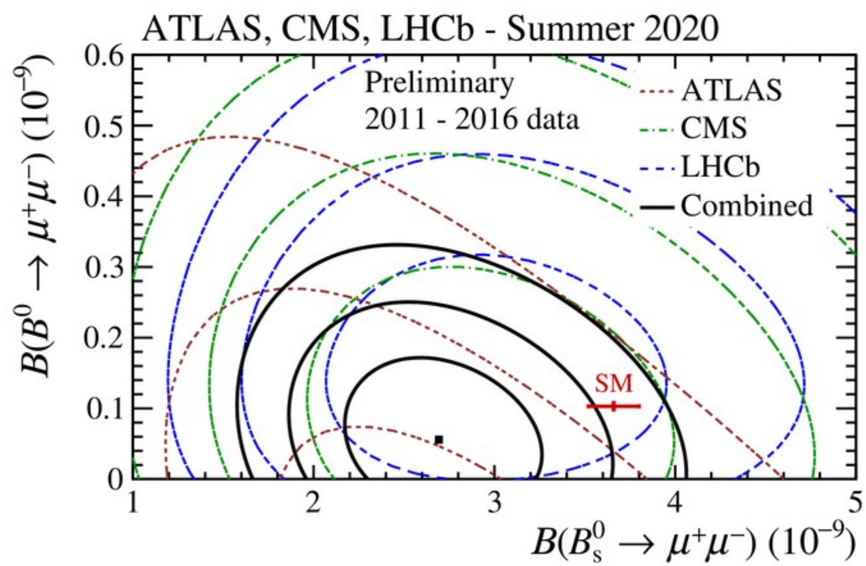
A Challenge to SM Lepton Universality in B-meson Decays

$$R = \frac{B(\bar{B} \to D\tau^-\bar{\nu})}{B(\bar{B} \to D\mu^-\bar{\nu})}$$





Measurement of extremely rare B-meson decays:



$$\mathrm{Br}_{\mathrm{th}}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \cdot 10^{-9}$$

$$\mathrm{Br}_{2020}(B_s \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \cdot 10^{-9}$$

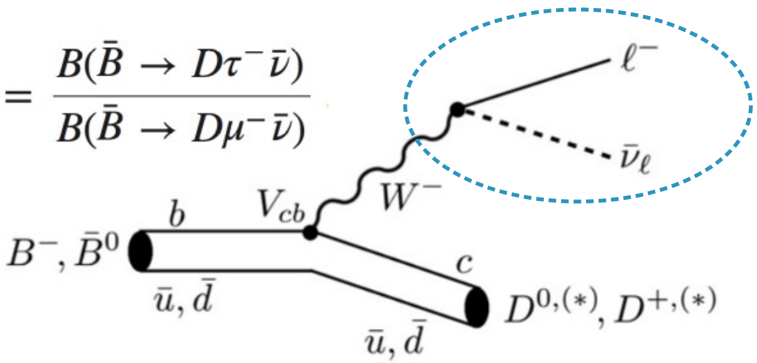
Precision frontier in flavour physics

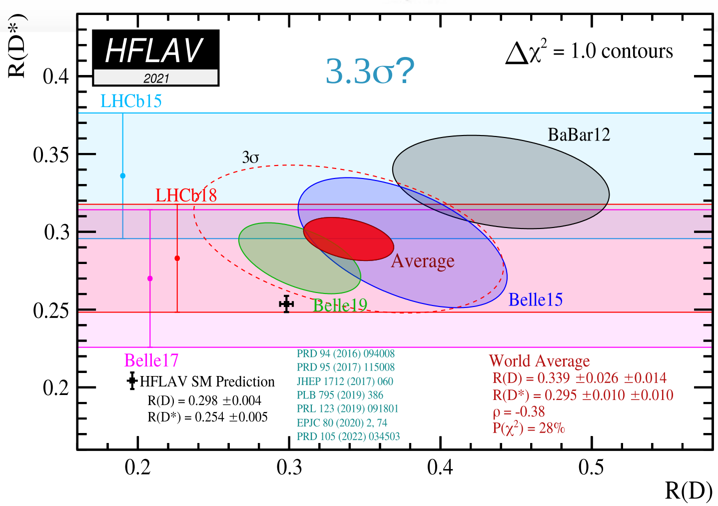
B-physics: (LHCb, Belle 2,...)

Some examples:

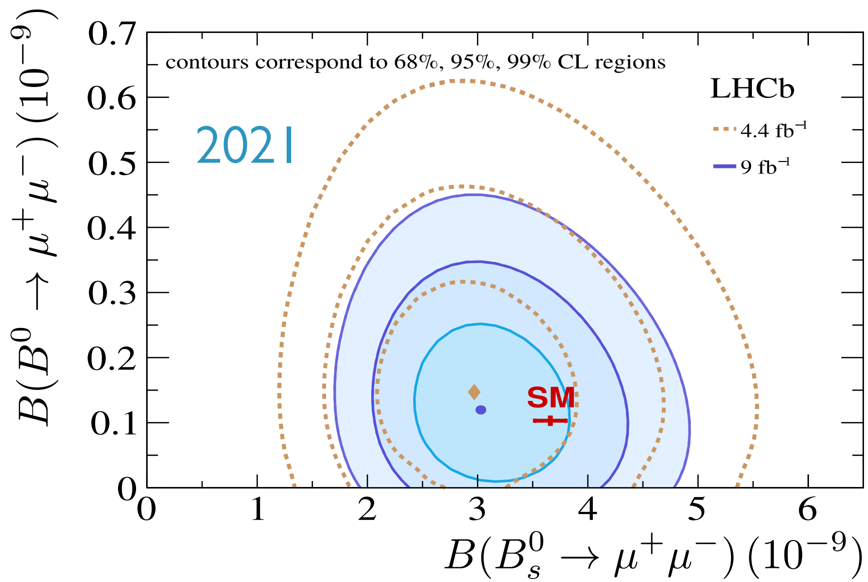
A Challenge to SM Lepton Universality in B-meson Decays

$$R = \frac{B(\bar{B} \to D\tau^- \bar{\nu})}{B(\bar{B} \to D\mu^- \bar{\nu})}$$





Measurement of extremely rare B-meson decays:



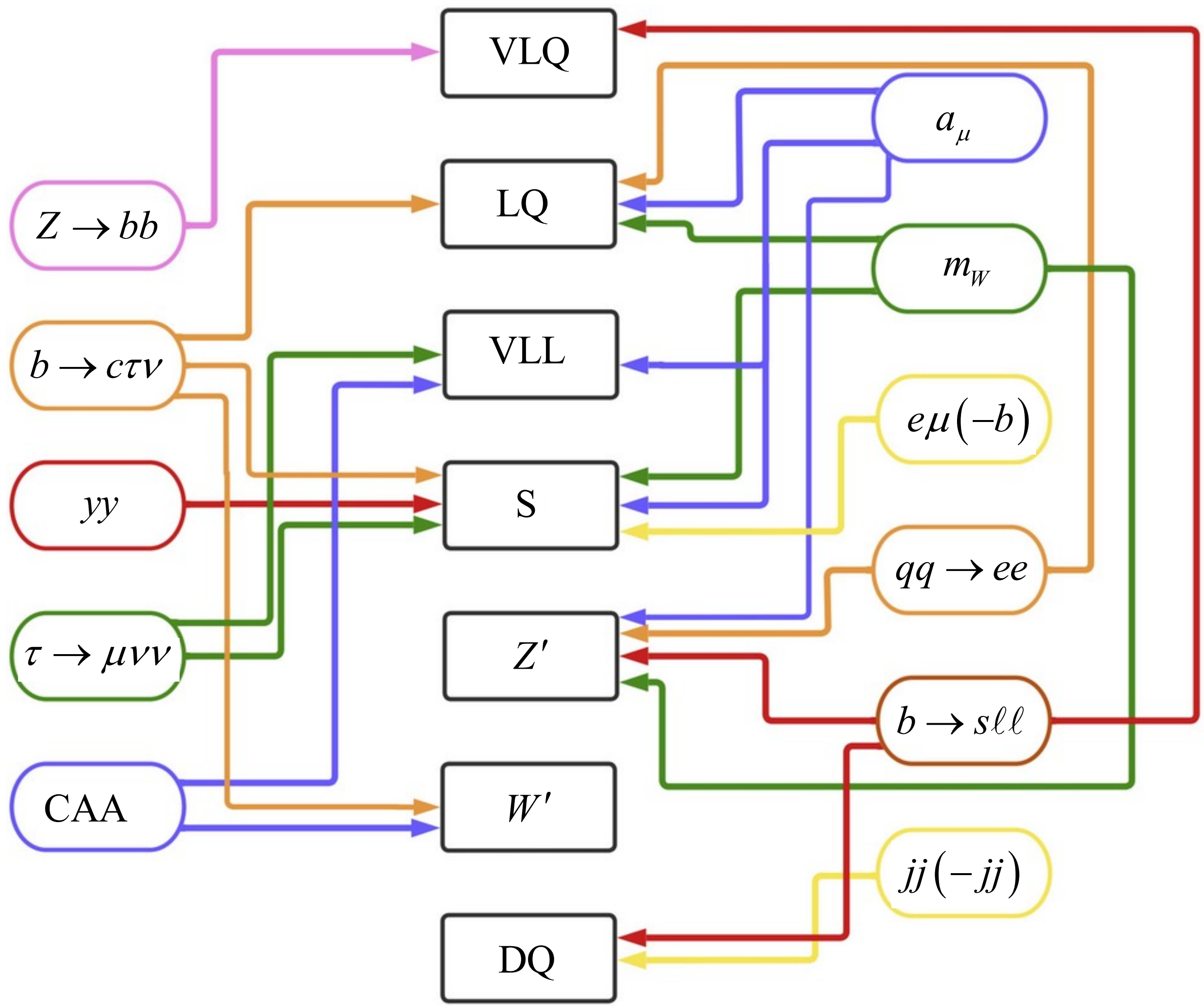
$$\mathrm{Br}_{\mathrm{th}}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \cdot 10^{-9}$$

$$\mathrm{Br}_{\mathrm{LHCb}}(B_s \to \mu^+\mu^-) = (3.09^{+0.48}_{-0.44}) \cdot 10^{-9}$$

Not much room for New Physics...

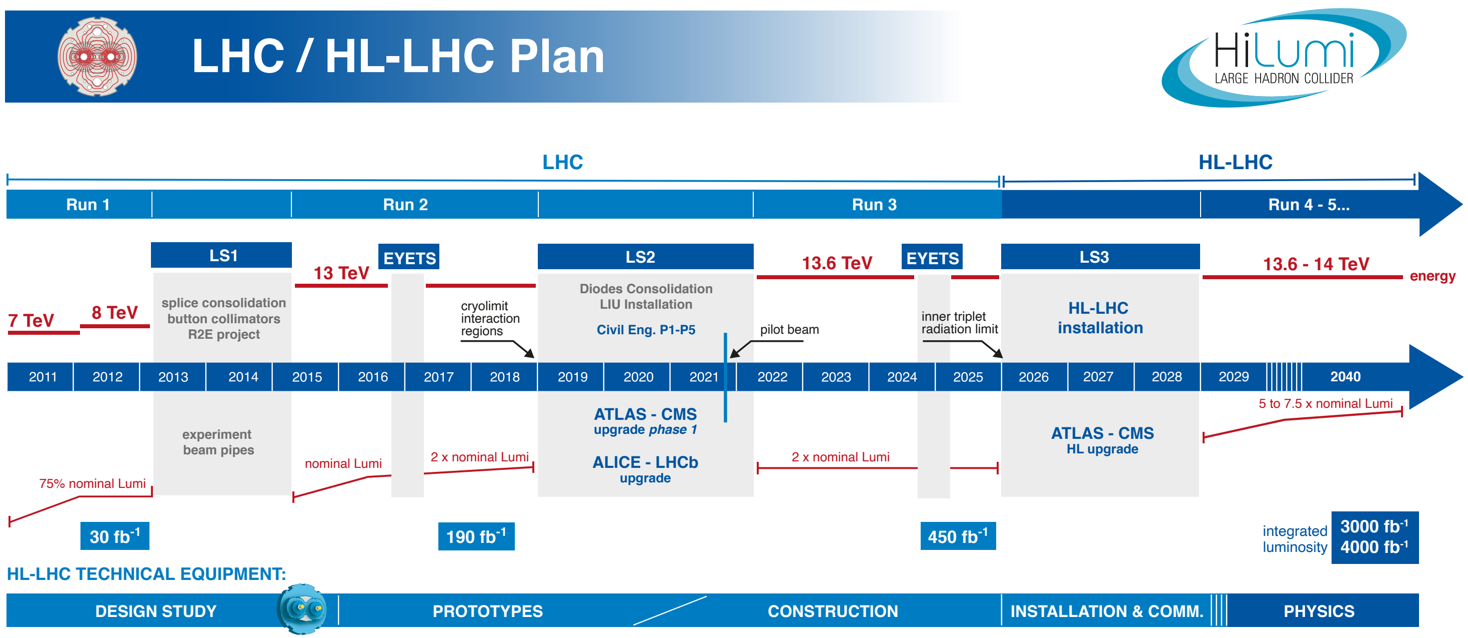
Anomalies and New Physics?

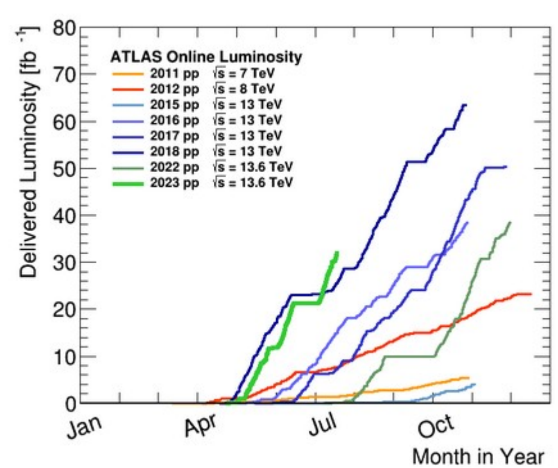
- Vector-Like Quarks (VLQ)
- Leptoquarks (LQ)
- Vector-Like Leptons (LLQ)
- New Scalars (S)
- Z'-bosons (neutrai)
- W'-bosons (charged)
- Scalar Diquarks (DQ)



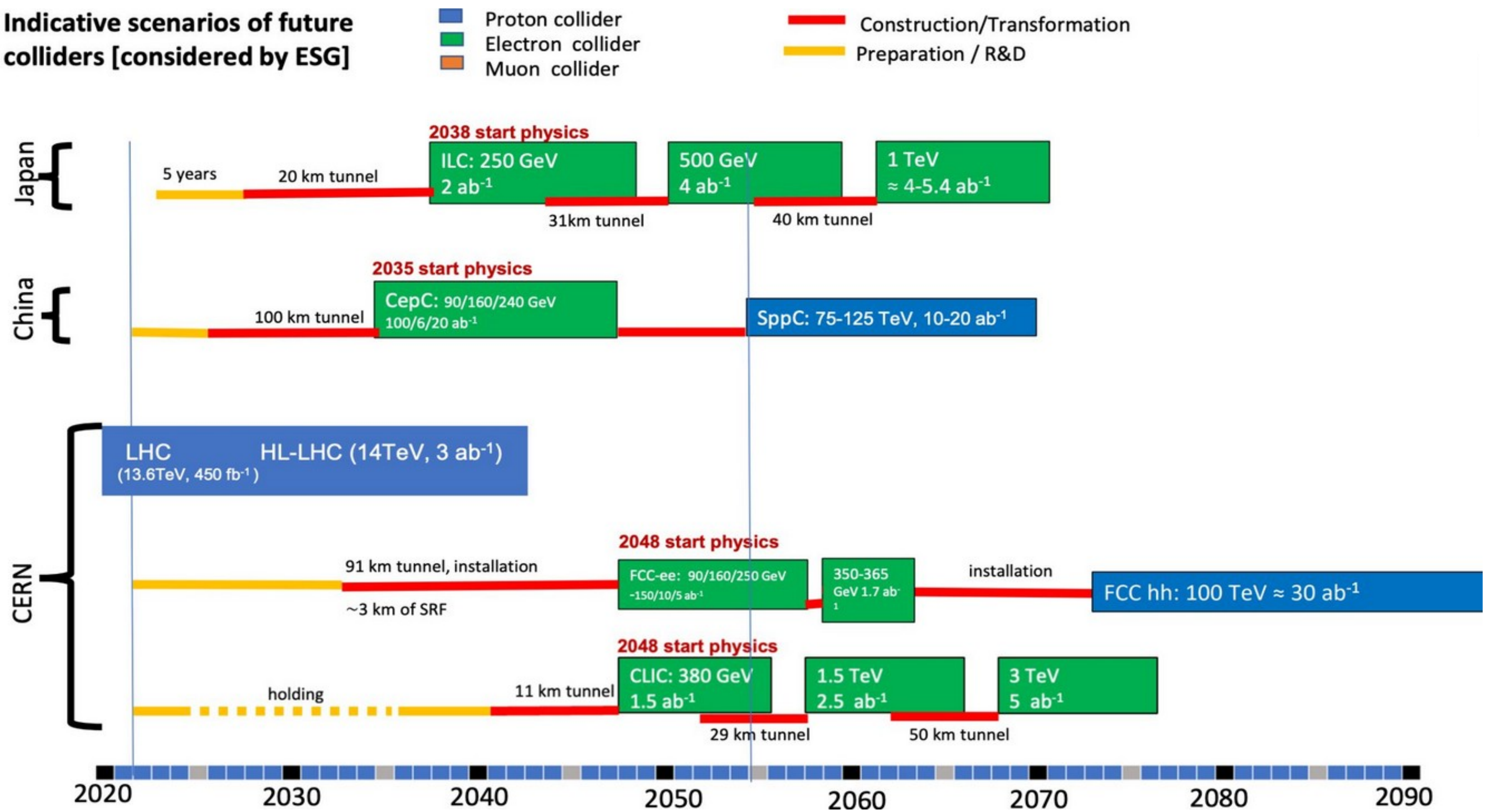
From Crivellin, Mellado,2023

Large Hadron Collider: Past, Present and Future of the World's largest microscope





Beyond the LHC...

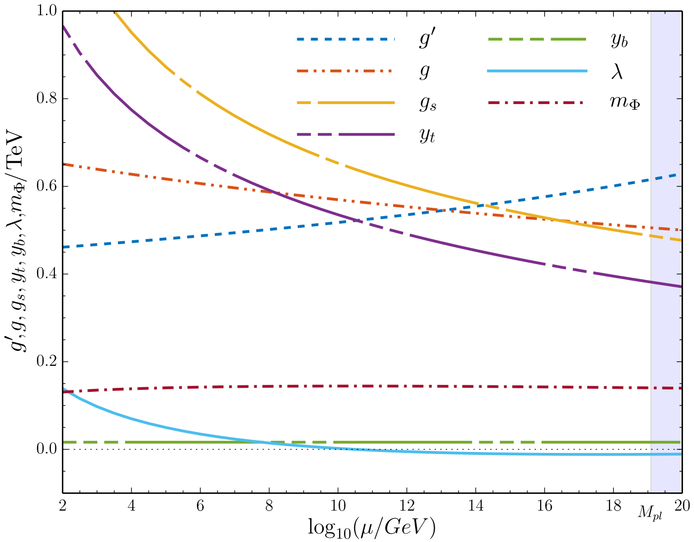


F. Zimmermann - Future Circular Colliders

Conclusions and Outlook

- The SM is a beautiful particle physics model.
- We believe it is not the ultimate theory.
- But it is very hard to find a hint (from Mother Nature) for New Physics scale! A lot of NP variants are on the market!
- LHC (and not only LHC!) works hard to discover New Physics, have to wait and test different possibilities.
- An upgrade to High-Luminosity LHC is planned after the ongoing Run 3 (pushing forward Precision frontier) and even to High-Energy LHC (Energy frontier).
- Complimentary machines (ILC, CLIC, FCC,...) are considered for construction.

Thank you for your attention!



Special thanks go

to Melnitsa Animation for nice cartoon characters

to Particle Zoo for nice subatomic plush