Journée nouveaux entrants du Pôle Théorie

Particle Physics

as of
1 December
2021

3. BSM & Higgs (4 + 1 + 4 + 2)

Asmâa ABADA (PR)
Adam FALKOWSKI (DR)
Yann MAMBRINI (DR)
Grégory MOREAU (MCF, HDR)
Ulrich ELLWANGER (PR)
Simon CLERY (fin 31/8/2024)
Giulia ISABELLA (fin 30/9/2022)
Ruifeng LENG (fin 29/9/2022)
Gioacchino PIAZZA (fin 30/09/2023)
Antonio RODRIGUEZ SANCHEZ (fin 30/06/2022)
Salvador ROSAURO ALCARAZ (fin 09/2024)

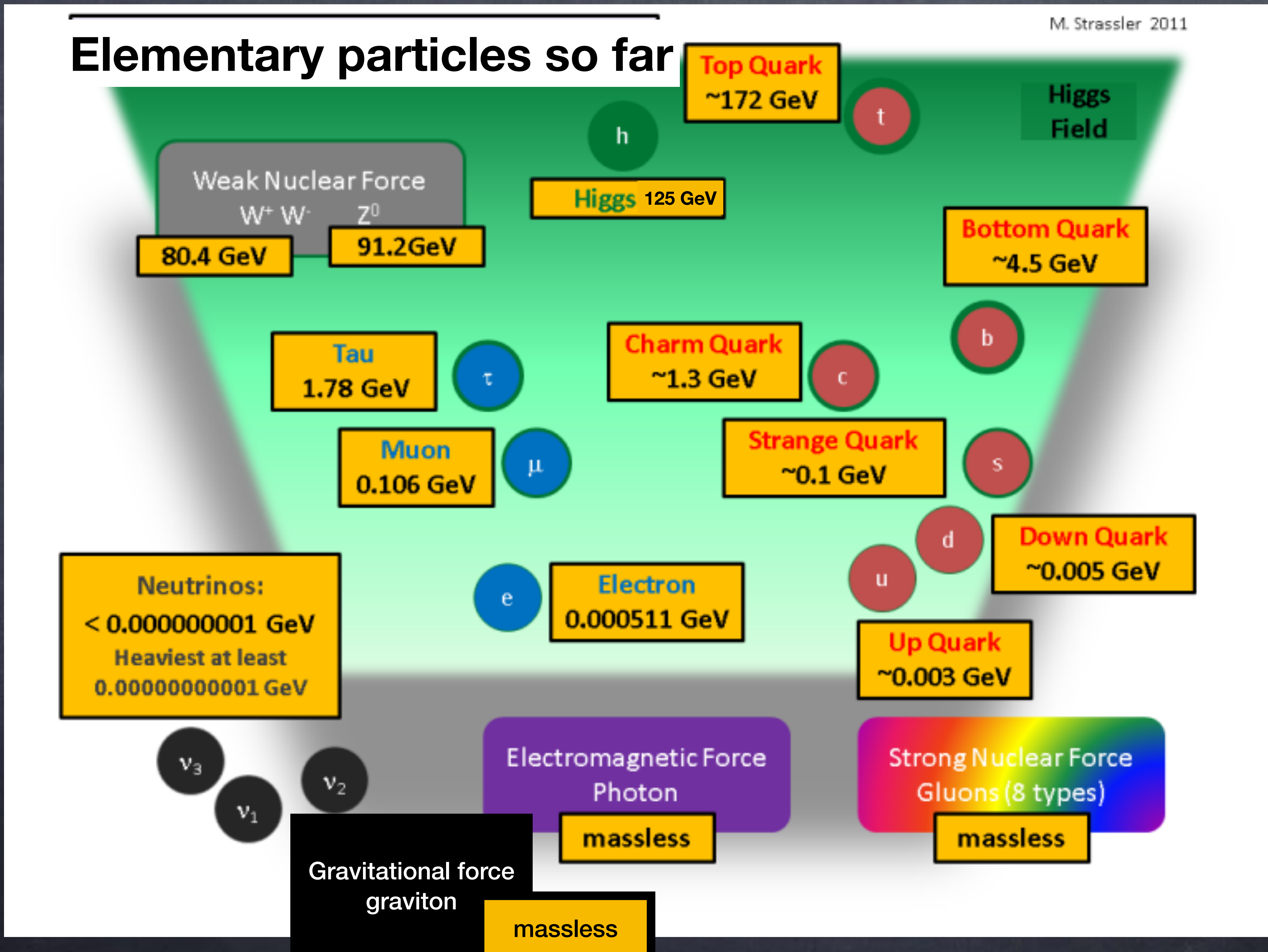
4. Phys. de la Saveur (5 + 1 + 4)

Damir BECIREVIC (DR)
Benoît BLOSSIER (CR, HDR)
Olcyr DE LIMA SUMENSARI (CR)
[Sébastien DESCOTES-GENON (DR)]
Emi KOU BOURHIS (DR)
Alain LE YAOUANC (DR)
Florentin JAFFREDO (fin 1/9/2022)
Tejhas KAPOOR (fin 30/09/2024)
Jan NEUENDORF (début 26/1/2021)
Ioannis PLAKIAS (fin 30/09/2024)
Martin NOVOA-BRUNET

5. QCD (2 + 4 + 5 + 2)

Jean-Philippe LANSBERG (CR, HDR)
Samuel WALLON (PR)
Véronique BERNARD (DR)
Michel FONTANNAZ (DR)
Bachir MOUSSALLAM (DR)
Hagop SAZDJIAN (PR)
Jelle BOR (fin 31/12/2023)
Michael FUCILLA (fin 31/10/2022)
Emilie LI (fin 30/10/2023)
Kate Lynch (fin 30/10/2025)
Yelyzaveta YEDELKINA (fin 12/2024)
Melih OZCELIK
Carlo FLORE (fin 30/11/2022)
Saad NABEEBACCUS (fin 31/08/2023)
Victor VILA

Elementary particles so far



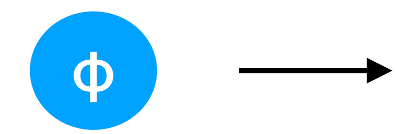
Borrowed from Matt Strassler's blog: http://profmattstrassler.com/

Recent and less recent history

Particle	Year	Collider	Energy	Place
Higgs boson	2012	LHC	8 TeV	Europe
Top quark	1995	Tevatron	1.8 TeV	USA
W/Z bosons	1984	SppS	630 GeV	Europe
Gluon	1979	PETRA	38 GeV	Europe
Bottom quark	1977	E288	20 GeV	USA
Tau lepton	1975	SPEAR	3 GeV	USA
Charm quark	1974	SLAC/BNL	3 GeV	USA
…				

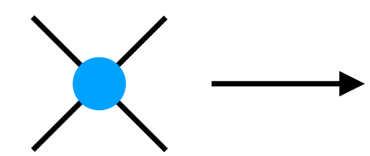
Relativistic quantum field theory (QFT):

- Particles (and their antiparticles) represented by fields with definite transformation properties under Lorentz transformations depending by particle's spin



$$\phi(x)$$

- Interactions between particles are encoded in a Lagrangian that is a local, hermitian and Lorentz-invariant function of the fields



$$\mathscr{L}(\phi)$$

- Each fundamental spin-1 (vector) particle comes with a corresponding local (gauge) symmetry that is strictly respected by the Lagrangian

$$\partial_\mu \phi \to D_\mu \phi \equiv \partial_\mu \phi - igT^a A^a_\mu \phi$$

- The fundamental spin-2 particle (graviton) comes with another local symmetry - general coordinate invariance

$$\partial_\mu V_\mu \to D_\mu V_\nu \equiv \partial_\mu V_\nu - \Gamma^\rho_{\mu\nu} V_\rho$$

- The gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ corresponding to the strong, weak, and electromagnetic forces

- Gauge symmetry spontaneously broken down to $SU(3)_C \times U(1)_{\text{em}}$ by vacuum expectation value of Higgs field H, implementing short range of the weak force (that is mass of W and Z bosons) and also allowing masses for matter fields

$$\langle H \rangle = \frac{1}{\sqrt{2}} \binom{0}{\text{v}}$$

Organizing principle: dimensional analysis

Organize the Lagrangian according to canonical dimensions of each term:

$$\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \ldots$$

This organizes the infinity of possible interactions according to their importance at low energies

Each $\mathscr{L}_n$ contains all possible interactions terms allowed by Poincaré invariance, locality, hermiticity, and the SM gauge symmetry (totalitarian principle)

$$\mathscr{L}_1 = -\Lambda^4_{\text{cosmo}}(h/M_{\text{Planck}})$$

Experiment says: $\Lambda_{\text{cosmo}} \sim 10^{-11}\ \text{eV}$

$$\mathscr{L}_2 = \mu_H^2 H^\dagger H + \mathcal{O}(h^2)$$

Experiment says: $\mu_H \sim 100\ \text{GeV}$

$$\mathscr{L}_3 = -M\bar{f}f + \mathcal{O}(h^3, hH^\dagger H)$$

$$\mathscr{L}_4 = -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \sum_{f\in q,u,d,l,e} i\bar{f}\gamma^\mu D_\mu f$$

$$-\left(\bar{u}Y_u qH + \bar{d}Y_d H^\dagger q + \bar{e}Y_e H^\dagger l + \mathrm{h.c.}\right)$$

$$+D_\mu H^\dagger D^\mu H - \lambda(H^\dagger H)^2 + \tilde{\theta}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$+\mathcal{O}(h^4, h^2H^\dagger H, (\partial h)^2)$$

Experiment says: all the interactions have been observed, except for $\tilde{\theta}$ and λ

Organizing principle: dimensional analysis

Organise the Lagrangian according to canonical dimensions of each term:

$$\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \dots$$

$$\mathscr{L}_2 \supset \mu_H^2 H^\dagger H$$

]

$$\mathscr{L}_4 \supset -\frac{1}{4} \sum_{V \in B, W^i, G^a} V_{\mu\nu} V^{\mu\nu} + \tilde{\theta} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} + \sum_{f \in q,u,d,l,e} i\bar{f}\gamma^\mu D_\mu f$$
$$-\left(\bar{u} Y_u q H + \bar{d} Y_d H^\dagger q + \bar{e} Y_e H^\dagger l + \mathrm{h.c.}\right)$$
$$+ D_\mu H^\dagger D^\mu H - \lambda (H^\dagger H)^2$$

In principle, there is no reason to stop at dimension-4.
However, higher-dimensional terms, by dimensional analysis, come with inverse powers of explicit mass scale:

$$\mathscr{L}_5 = \frac{c_5}{\Lambda}(HL)(HL) - \frac{2}{M_{\text{Planck}}} h_{\mu\nu} D_\mu H^\dagger D_\nu H - \frac{2}{M_{\text{Planck}}} h_{\mu\nu} F_{\mu\rho} F_{\nu\rho} + \dots$$

$$\mathscr{L}_6 = \frac{c_6}{\Lambda^2} |H|^6 + \dots$$

Standard Model

Organise the Lagrangian according to canonical dimensions of each term:

$$\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \dots$$

$$\mathscr{L}_1 = -\Lambda^4_{\text{cosmo}}(h/M_{\text{Planck}})$$

$$\mathscr{L}_2 = \mu_H^2 H^\dagger H$$

$$\mathscr{L}_4 = -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \tilde{\theta} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \sum_{f\in q,u,d,l,e} i\bar{f}\gamma^\mu D_\mu f$$
$$-\left(\bar{u}Y_u qH + \bar{d}Y_d H^\dagger q + \bar{e}Y_e H^\dagger l + \text{h.c.}\right)$$
$$+D_\mu H^\dagger D^\mu H - \lambda(H^\dagger H)^2$$

$$\mathscr{L}_5 = \frac{c_5}{\Lambda}(HL)(HL) - \frac{2}{M_{\text{Planck}}} h_{\mu\nu} D_\mu H^\dagger D_\nu H - \frac{2}{M_{\text{Planck}}} h_{\mu\nu} F_{\mu\rho} F_{\nu\rho} \dots$$

$\mathscr{L}_6 = -$ [illegible] $|H|^6 + \dots$

The Standard Model is understood as the $\Lambda \to \infty$ and $M_{\text{Planck}} \to \infty$ limit of the Lagrangian allowed by the basic principles

Is Standard Model enough ?

Standard Model is a perfectly consistent theory, and it very well describes a wide range of phenomena in collider and many other experiments

However, it is certainly not the ultimate theory of nature

Why BSM?

- **Because gravity exists!**

$$\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \ldots$$

$$\mathscr{L}_2 \supset \mu_H^2 H^\dagger H$$

$$\mathscr{L}_4 \supset -\frac{1}{4}\sum_{V\in B,W^i,G^a} V_{\mu\nu}V^{\mu\nu} + \tilde{\theta} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \sum_{f\in q,u,d,l,e} i\bar{f}\gamma^\mu D_\mu f$$
$$-\left(\bar{u}Y_u qH + \bar{d}Y_d H^\dagger q + \bar{e}Y_e H^\dagger l + \mathrm{h.c.}\right)$$
$$+D_\mu H^\dagger D^\mu H - \lambda(H^\dagger H)^2$$

$$\mathscr{L}_5 = \frac{c_5}{\Lambda}(HL)(HL) - \frac{2}{M_{\text{Planck}}} h_{\mu\nu} D_\mu H^\dagger D_\nu H - \frac{2}{M_{\text{Planck}}} h_{\mu\nu} F_{\mu\rho} F_{\nu\rho} \ldots$$

$$\mathscr{L}_6 = \cdots |H|^6 + \ldots$$

Interactions of graviton with matter and light have been observed and precisely measured

Why BSM?

Standard Model is a perfectly consistent theories at accessible energies, and it perfectly we describes wide range of phenomena in collider and many other experiments.

We know it's not a complete theory of nature, because gravity exists, and because U(1) of the SM has a Landau pole

Yet we have good reasons to think that it becomes invalid well below the Planck scale:

- **Phenomenological Reasons:**
  There exist experimental observations that require new physics below the Planck scale

- **Esthetic Reasons:**
  Certain puzzling aspects of the SM hint at a deeper explanation via new physics

Phenomenological Reasons
For Physics Beyond the Standard Model

- Neutrino Oscillations
- Dark Matter
- Baryon Asymmetry
- Inflation

All of them experimental facts!

Esthetic Arguments
For Physics Beyond the Standard Model

Certain features of the Standard Model appear ad-hoc or fine-tuned and we suspect that they have a deeper explanation

- Small cosmological constant
- Fermion generation structure and mass/mixing hierarchies
- Vacuum metastability
- Gauge coupling unification
- Strong CP problem
- Naturalness problem

Typical roads to BSM

Models addressing problems of the SM

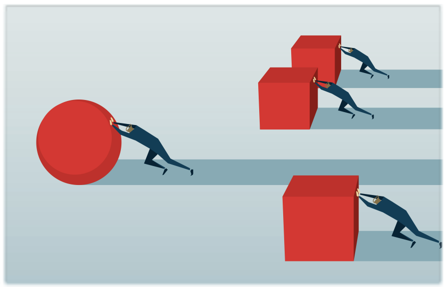
e.g supersymmetry
to address naturalness,
or axions to address
theta-problem of QCD

Ad-hoc models to explain experimental anomalies

e.g leptoquarks to address
B-meson anomalies
or milli-charged dark matter
to address 21cm absorption signal

Model-independent effective theory

explore all possible
higher-dimensional
effective interactions
added to the SM



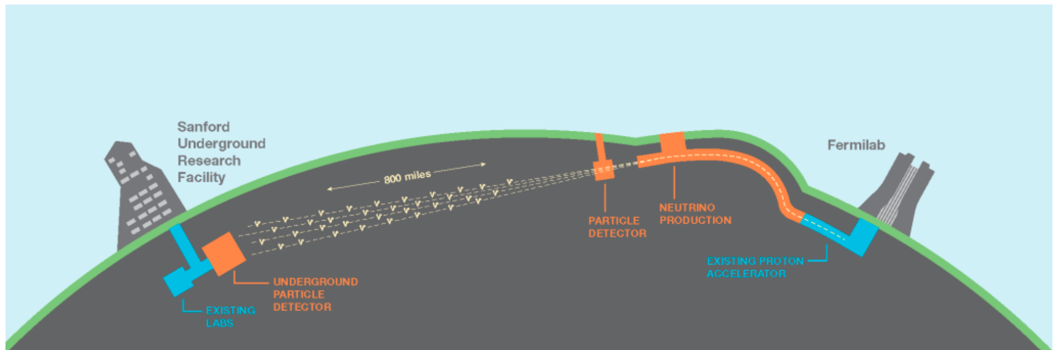
Biggest questions for particle physics

1 What are the parameters of dimension-5 extension of the SM?

$$\mathscr{L}_5 = \frac{1}{\Lambda_5}(HL)Y_\nu(HL)\ldots \to \frac{1}{2\Lambda_5}\nu Y_\nu \nu$$

Neutrino masses and mixing show that $\Lambda_5 \sim 10^{15}$ GeV **for** $\mathcal{O}(1)$ Y_ν

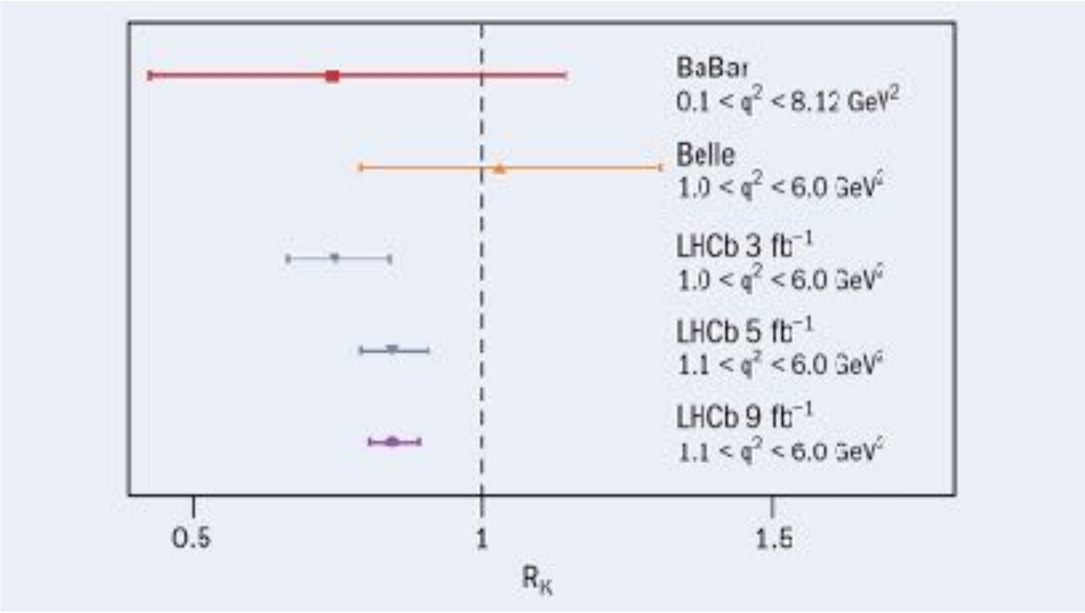
$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ &+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\ &+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2, \end{aligned}$$



2 What is the scale of dimension-6 extension of the SM ?

$$\mathscr{L}_6 \supset \frac{1}{\Lambda_6^2}(\bar{s}\gamma^\alpha P_L b)(\bar{\mu}\gamma_\alpha P_L \mu)$$

Lepton flavor universality violation tentatively observed in B-meson decays points to $\Lambda_6 \sim 30$ GeV



Questions

3 *Are there additional light particles?*

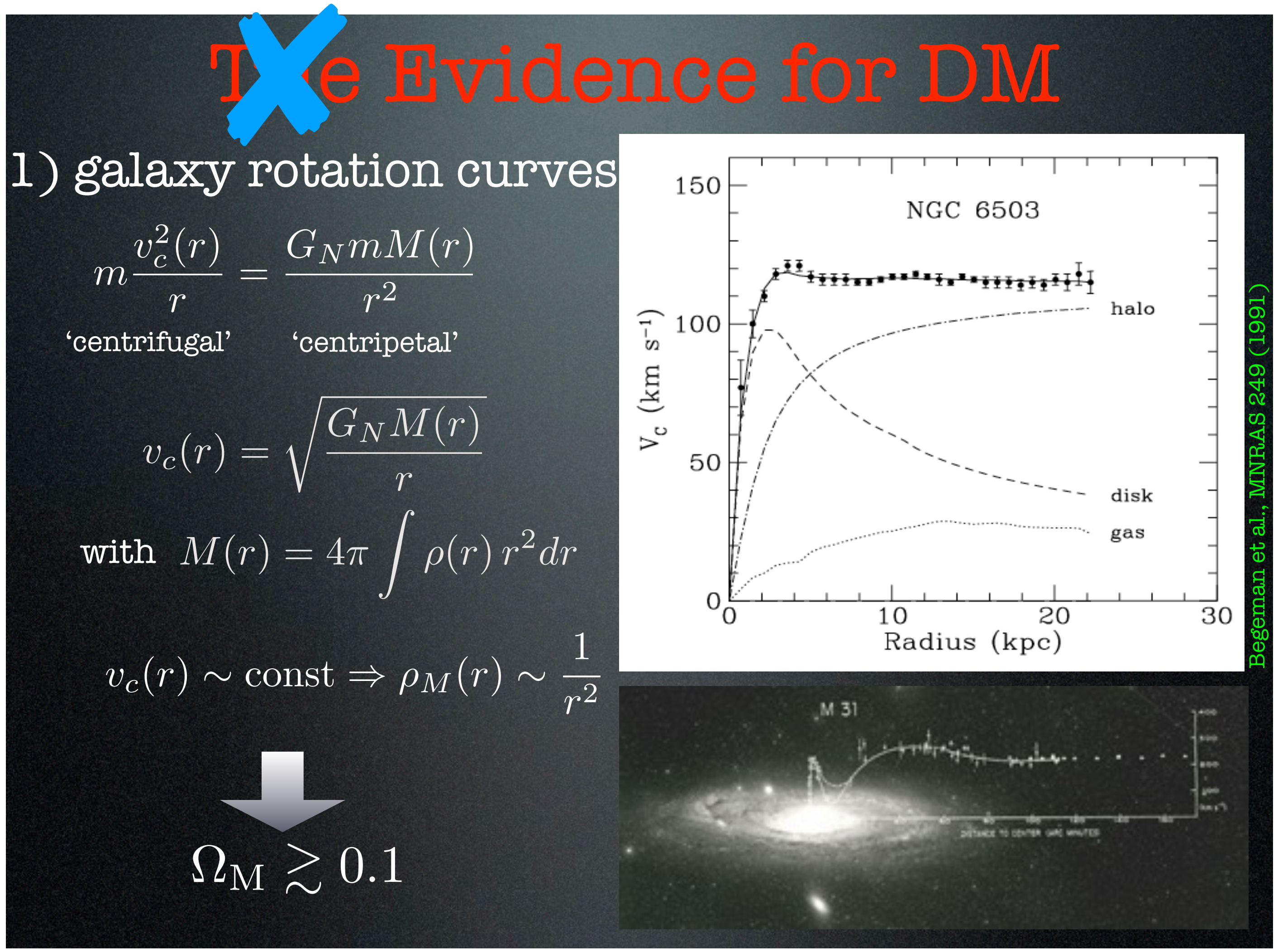
For example sterile neutrinos, or axions

If yes, that would imply a slight modification of the particle physics framework used to describe our experiments

$$\mathscr{L} = \mathscr{L}_1 + \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \ldots$$

add new terms with the new degrees of freedom

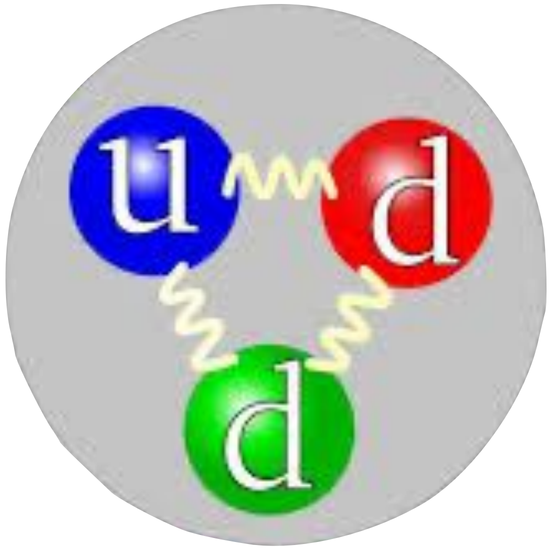
4 What is the nature of dark matter?



However, so far we only see gravitational effects of dark matter, and we know almost nothing about it's particle (or another) nature

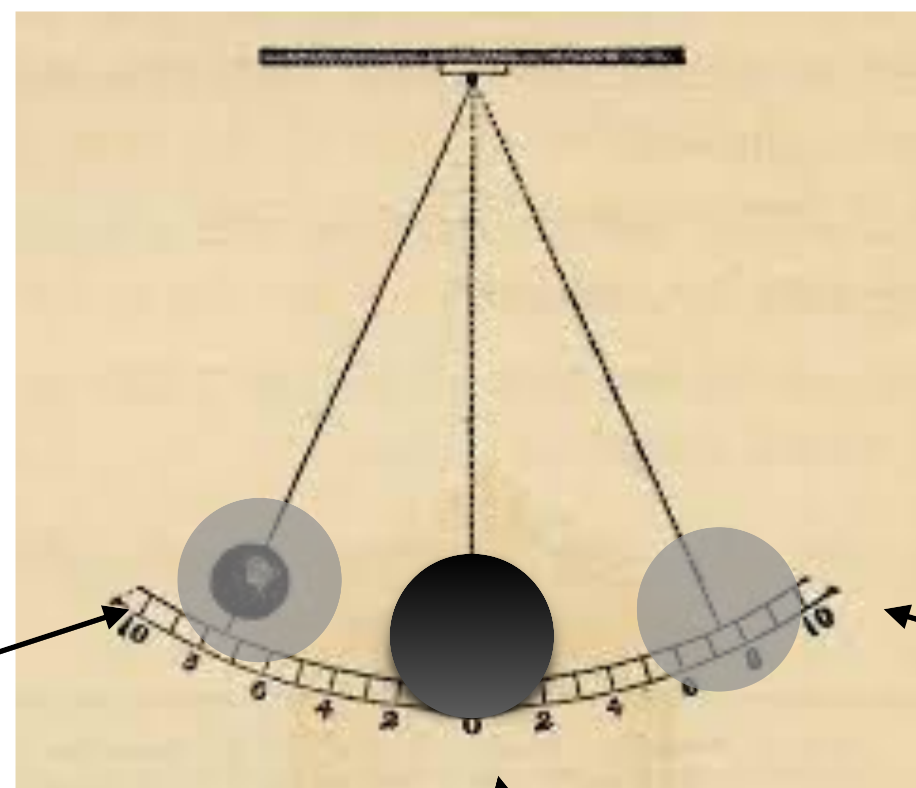
5

How to better understand strong interactions?



Many effective methods and tools:
lattice, chiral perturbation theory, dispersion relations, non-relativistic EFTs, PDFs, ...
but no silver bullet yet

6 *How rigid is quantum field theory?*

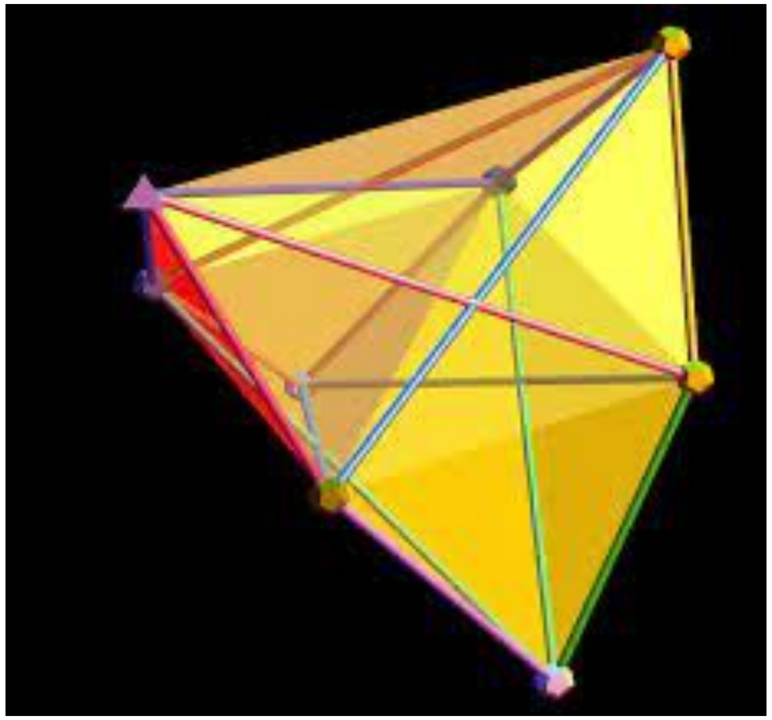


There is one ultimate fundamental theory

There is a landscape of 10^{500} fundamental theories

Unitarity, causality, locality, Lorentz invariance impose unexpected constraints on consistent quantum field theories

7 Is there another (better) formulation of quantum field theory?



Recent attempts at alternative formulations where spacetime is emergent rather than fundamental concept

Thank you