Beyond the SM physics - TH aspects

I Going beyond the SM

I.1. The SM of particle physics in a nutshell

The SM describes the dynamics of the fundamental particles

symmetry principles ↓ operations that leave the laws of Nature unchanged

- Matter sector → quarks and leptons
  ↳ particle types driven by spacetime symmetries (Poincaré)
- Fundamental interactions → gauge symmetries → $SU(3)_c \times SU(2)_L \times U(1)_Y$
  → EM, weak and strong interactions

+ Symmetry breaking and anomaly cancellation

Symmetry breaking ↳ masses of the gauge bosons + generation of the fermion masses

Anomaly cancellation ↳ quantum numbers of the particles

Lagrangian: $\mathcal{L}_{SM} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\Psi} i \not{D} \Psi + D_\mu \phi^\dagger D^\mu \phi - V(\phi) + \bar{\Psi} y \Psi \phi$

[all indices understood]

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- $F_{\mu\nu}F^{\mu\nu}$ and $\bar{\psi} i \not{D} \psi$ terms:

  * gauge interactions → fermion gauge couplings (eeγ, qqg, ...)
    multiple gauge interactions (WWW, γWW, ...)
  * established during the last 50 years (history started with Maxwell)
  * corresponds to the greatest success of the SM

  ⇒ KNOWLEDGE

- $D_\mu\phi^\dagger D^\mu\phi$:

  * gauge interactions of the Higgs field → HZZ, HWW, ...
  * gauge boson masses after EWSB
  * discovered and measured (more or less precisely) at the LHC

  ⇒ KNOWLEDGE

  (no new fundamental interaction)

- $\bar{\psi} y \psi \phi$: the Yukawa sector

  * masses for the fermions (after EWSB)
  * 9 free parameters (y_q, y_ℓ) → never measured before
  * the last 1-2 years: measurements of y_t, y_b and y_τ at the 5σ level by both ATLAS and CMS independently
    (uncertainties are large but this is now a FACT)

(Yukawa scalar interaction)

* Establishment of a new type of fundamental interaction at the LHC
  → CRUCIAL DISCOVERY

* Some consequences of the Yukawa coupling:
  . value of $m_n - m_p$ → stability of H ≡ y_u, y_d (still hypothetical)
  . size of atoms → y_e (still hypothetical) impacts the Bohr radius ($\propto \frac{1}{m_e}$ (→ y_e))
  . hierarchy of masses ⇒ hierarchy of couplings
    → maybe some dynamics behind it.

* The SM story is not over: y_μ, y_c, y_s ; y_u, y_d, y_e
  - y_μ ← HL-LHC
  - y_c, y_s: LHC? / future colliders
  - y_u, y_d: ?
  - y_e: future e^+e^- colliders?

• $V(\phi) = -\mu^2 |\phi|^2 + \lambda(\phi^\dagger \phi)^2$

* Higgs mass & Higgs self-interactions
  - Higgs mass: measured
  - self-interactions:
    . HHH @ HL-LHC + future colliders (HH+HHH-production)
    . HHHH @ future collider (HH + HHH production)

these three measurements will clearly establish the EWSB mechanism → no evidence (yet?) for SM-EWSB so far.

The SM is a success but it has not been firmly established
→ exciting times for particle physics as such: we want all terms being knowledge.

There is room for deviations from the SM. Moreover, there are conceptual issues and limitations of the SM that motivate BSM.

I.2. A critical review of the SM

Despite being extremely successful, the SM is plagued by many inherent issues.

I.2.1 The hierarchy problem

≡ the large difference between the EW scale and the Planck scale

EW scale ~ 100 GeV ↓ ~ M_W, M_Z → connected to the Higgs vev v

Planck scale: $M_P \sim \sqrt{\hbar c / G} \sim 10^{19}$ GeV

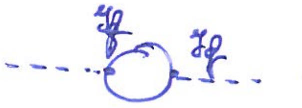
$$\Rightarrow \frac{M_P}{v} \sim 10^{17}$$

Natural values for v are 0 (there is a symmetry) or M_P (the SM breaks down → gravity must be included).

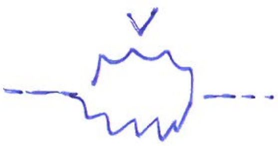
In the SM, quantum corrections to v send it to M_P ⇒ the hierarchy pb

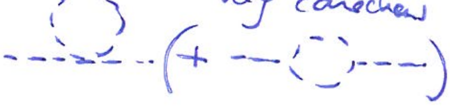
Inversely, to get the right value for $v \sim 246$ GeV, we need to tune the SM parameters to their 30th decimal to get miraculous cancellations.

Tree level:  M_h^2 is connected to v^2 $= \left(\frac{y_f v}{\sqrt{2}}\right)^2$

Quantum correction:  $\rightarrow \delta M_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2} \sum_f \left[-4 M_f^2\right] + \dots$

Λ is the scale at which the SM ceases to be valid

 $\delta M_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left[2M_W^2 + M_Z^2\right] + \dots$


log corrections

$= \frac{3\Lambda^2}{8\pi^2 v^2} M_h^2 + \dots$

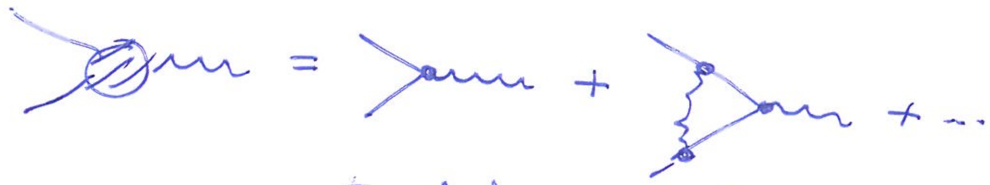
$\Rightarrow \delta M_h^2 \approx \frac{3\Lambda^2}{8\pi^2 v^2}\left[M_h^2 + 2M_W^2 + M_Z^2 - 4M_f^2\right]$

needs to be tiny

$\Rightarrow$ BSM: curing the issue

I.2.2 Unification

Gauge interaction strengths depend on the energy by virtue of quantum effects



tree-level one-loop

The energy behavior is embedded in the β-function:

$$\frac{d}{dt} g = \frac{1}{16\pi^2} \beta_g^{(1)} + \frac{1}{(16\pi^2)^2} \beta_g^{(2)} + \cdots$$

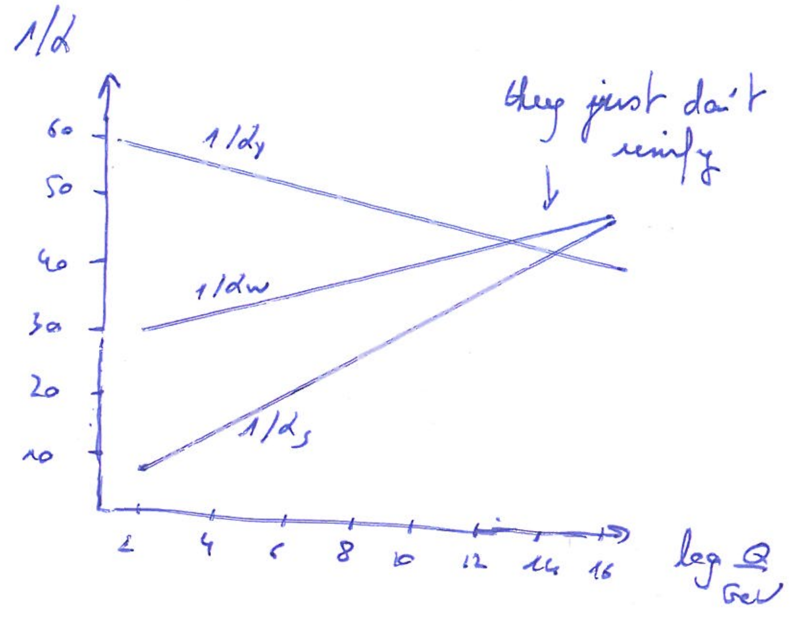
one-loop two-loop

Example @ one-loop:

$$\frac{d}{dt} g' = \frac{41}{160\pi^2} g'^3 \qquad U(1)_Y$$

$$\frac{d}{dt} g_w = -\frac{19}{96\pi^2} g_w^3 \qquad SU(2)_L$$

$$\frac{d}{dt} g_s = -\frac{7}{16\pi^2} g_s^3 \qquad SU(3)_c$$



$\alpha_Y = \frac{g'}{4\pi^2}$

$\alpha_W = \frac{g_W}{4\pi^2}$

$\alpha_S = \frac{g_S^2}{4\pi^2}$

Moreover, the gauge group pattern and representation choices is complicated.

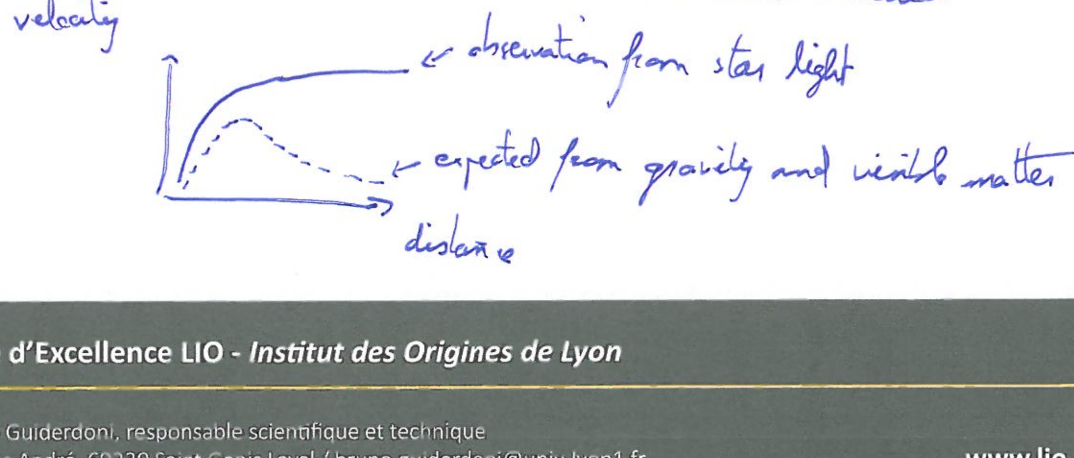
→ additional fields ↳ modified running
↳ grouped into 1-2 representations of a larger gauge group

could also explain why the electric charge is quantized

I.2.3 Dark matter

Many convincing evidence for DM

- flattening of the galaxy rotation curves at large distances
  ↳ extra invisible material needed



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- gravitational lensing : some matter density bends the light trajectory between an observer and a source

Einstein ring (≈ horseshoe) The image of a galaxy is distorted by another galaxy

Einstein cross (four images of the same distant quasar)

- Cosmic microwave background : EM radiation remnant of the early stage of the universe history (in standard cosmology). Dates from the recombination epoch: charged e^- and p^+ form H atoms → the universe becomes electrically neutral.

H is formed in higher-energy states → photon emission → CMB

$2s \to 1s + 2\gamma$

↖ $T \approx 4000K \xrightarrow{\text{redshift}} 2.75K$

The study of the CMB anisotropies gives insight on the cosmology → presence of DM. (Planck, WMAP, ...)

- structure formation : simulations of the formation of the galaxies show that a large amount of DM was necessary. Without DM, no galaxy / galaxy clusters formation.

⇒ there is no DM candidate in the SM.

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I.2.4 Other motivations for extending the SM

- Why 3 families ?
- Gravity ?
- Structure of spacetime (4D) ?
- The SM contains a large number of parameters.
- Origin of quark and lepton masses and mixing,
  ↳ neutrino physics (proof that we need BSM)
- Matter-antimatter asymmetry
- Strong CP problem.
- The SM is at best metastable at high energies
- etc.

⇒ There are many questions that require extending the SM.

Moreover: MiniBooNE/LSND, neutron lifetime, B-anomalies, $g-2_\mu$, ... ← data

These lectures: explaining the main paradigms investigated both theoretically and experimentally.