DAMA:

→ Seasonal DM observed (?) in NaI crystal.

Reactor anomaly:

→ Deficit of $\bar{\nu}_e$ close to reactor cores
→ Could be explain by a 4th sterile neutrino

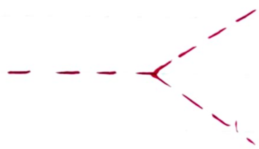
CH3 THEORETICAL LANDSCAPE

→ Standard Model = Effective field theory (EFT)
→ Scalar sector : least constraint, room for BSM physics

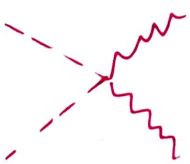
Scalar sector:

→ Higgs sector determined by only 1 free parameter: m_H
  → very predictive
  → coupling to vector boson exactly defined

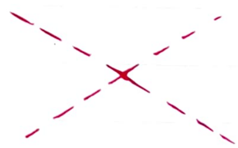
$\frac{2m_V^2}{v}$



$\frac{3m_h^2}{v}$



$\frac{2m_V^2}{v^2}$



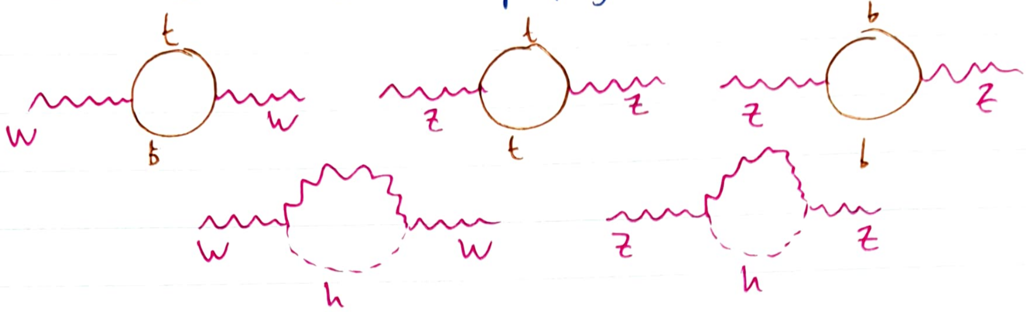
$\frac{3m_h^2}{v^2}$

→ After discovery (mass, spin), 1) coupling to bosons and fermions
  2) self coupling
→ All these measurement are test for BSM physics

ex of BSM: non-minimal Higgs scenarios
alternative to EWSB (ex: Higgs imposter)

⊙ Experimental contraints on m_h:

→ Radiative corrections on the propagators of bosons in the theory:



Since the higgs contributes to loops → constraints on m_H

⊙ The E-W fit: free parameters:

→ SM unifies e-m and weak interaction → only 2 coupling remain independant: 1) α
2) α_s

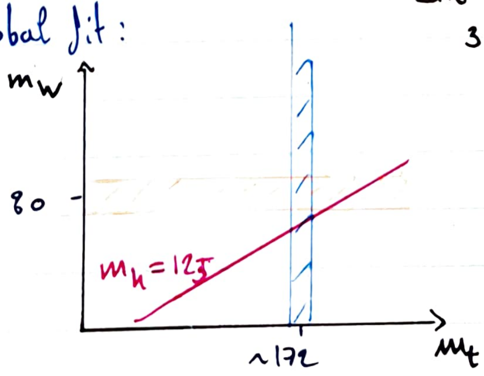
→ Only the top quark has $m_t \sim m_Z$, all the other fermions have $m_f \ll m_Z$

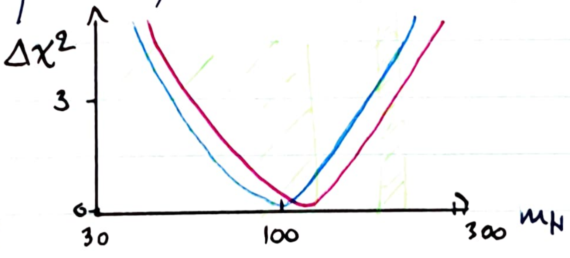
→ m_Z is precisly measured, but not m_W. Instead, we use G_F

→ The Higgs mass m_h

↳ The free parameters are $\{\alpha_s(m_Z^2), \alpha(m_Z^2), m_Z, m_t, m_H, G_F\}$

→ Global fit:





3.1 Theoretical constraints on m_H

⊙ Perturbativity and unitarity:

→ Scattering of VB at high energies is divergent due to their longitudinal polarization. Consider $k^\mu_{VB} = (E_k; 0, 0, \vec{k})$ with $E_k^2 = k^2 - m_V^2$
The 3 polarizations vectors are
1) right handed: $\varepsilon^\mu_+(\vec{k}) = \frac{1}{\sqrt{2}}(0; 1, i, 0)$

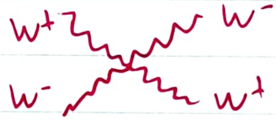
2) left handed: $\varepsilon^\mu_-(\vec{k}) = \frac{1}{\sqrt{2}}(0; 1, -i, 0)$

3) Longitudinal: $\varepsilon^\mu_L(\vec{k}) = \frac{1}{m_V}(k; 0, 0, E_k)$

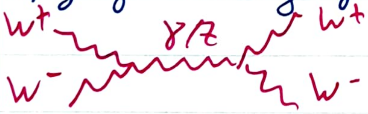
which satisfy for $a, b \in \{+, -, L\}$: $\quad k_\mu \varepsilon^\mu_a(\vec{k}) = 0$

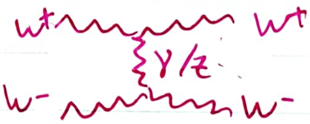
$$\varepsilon^\mu_a(\vec{k})\, \varepsilon^*_{b\mu}(\vec{k}) = -\delta_{ab}$$

→ When $E_k \gg m_V$, $|\varepsilon_L| \mapsto \infty$: diagram with external VB have divergent cross sections.
Consider $W_L^+ W_L^- \to W_L^+ W_L^-$:
1) 4-pt interaction:

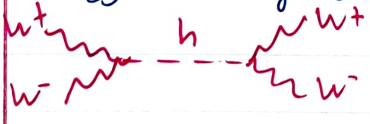


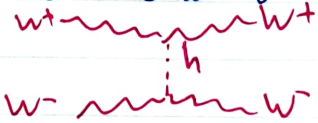
2) gauge exchange of γ/Z in the s-channel and t-channel





3) Higgs exchange in the s- and t- channel





→ The amplitude can be written as $\mathcal{A} = \mathcal{A}^{(2)} s^2 + \mathcal{A}^{(1)} s + \mathcal{A}^{(0)}$
When $s, t \gg m_V^2, m_h^2$, we have

$$\mathcal{A}^{(2)} \longrightarrow 0$$
$$\mathcal{A}^{(1)} \longrightarrow 0$$
$$\mathcal{A}^{(0)} \longrightarrow -\frac{2m_h^2}{v^2} \simeq -4\lambda$$

any deviation in scalar sector may spoil this → $W_L W_L$ scattering strong test of EWSB.

↳ If m_H too large → change $WW \to WW$ interaction
⇒ no looked situation at cern.

→ At loop level:

$\mathcal{A} \sim \frac{2\lambda^2}{16\pi^2}$

If $\lambda \sim 32\pi^2$, the E-W theory should break down when $m_H > 6$ TeV (not perturbative anymore)

When more carefull computation: upper bound $m_H < 710$ GeV

⊙ The triviality bound:

→ Another bound of the theory is the triviality bound.

→ To ensure the theory remains consistent at all scale Q, couplings like $g_i = (0{,}41 ; 0{,}64 ; 1{,}2)$, $y_t = \sqrt{2}\, m_t / v$, $\lambda = m_h^2 / 2v^2$ must stay finite at all Q.

→ Renormalization ⟹ running constants

ex: $\frac{dg_1}{dt} = \frac{41}{10}\frac{1}{16\pi^2}(g_1)^3$ $\quad\frac{dg_2}{dt} = -\frac{19}{6}\frac{1}{16\pi^2}(g_2)^3$

with $t = \ln(Q/Q_0)$

→ For large Higgs boson masses, $\frac{d\lambda}{dt} \simeq \frac{24}{16\pi^2}\lambda^2$. After integration, we obtain a Landau pole, the limit scale at which the theory stop being valid. Here, $Q_{LP} = m_h \exp\left\{\frac{4\pi^2 v^2}{3 m_h^2}\right\}$

PROP | To have the theory valid at all scales requires vanishing couplings. We call this the triviality condition.

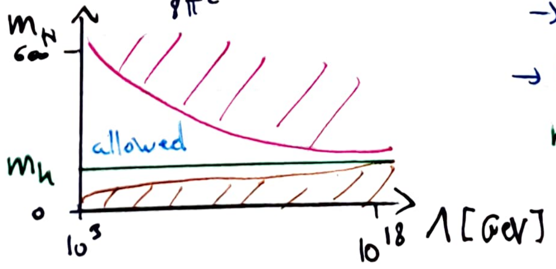
⊙ Vacuum stability bound:

→ For low Higgs boson mass, $\frac{d\lambda}{dt} \simeq \frac{-6}{16\pi^2} y_t^2$ so that for high Q, $\lambda < 0 \Rightarrow V < 0$.

Now, we know that $\lambda > 0$ ⟹ vacuum stability bound

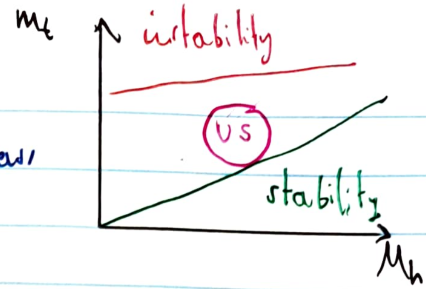
$$m_h^2 > \frac{v^2}{8\pi^2}(\ldots)\ln(Q/Q_0)$$

→



→ if $m_h = 60$ GeV ⟹ unstable vacuum

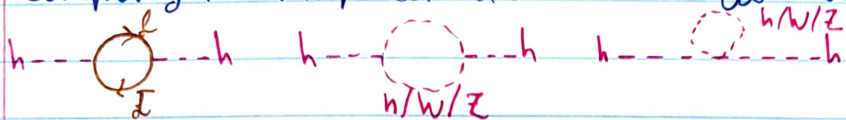
→ if 130 GeV $\lesssim m_h \lesssim 180$ GeV, metastable situation



→ Assuming only SM, one can compute the running of λ all the way to the Planck mass
→ The (méta) stability depends on m_t, α_s, m_h mostly.

⊙ Fine tuning constraints:

→ Computing the 1-loop correction to the higgs mass



, we get

$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda}{8\pi^2 v^2}\left(m_h^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)$$

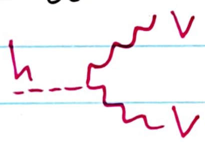
The cancellation between the bare mass m_h^0 and the other terms need to cancel up to 32 digit for a theory valid till $\Lambda \sim 10^{16}$ GeV, the GUT scale.

→ Specific to scalars

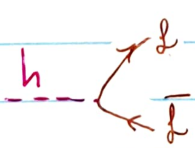
→ Fine-tuning makes the SM unnatural, even below ~ TeV.

3.2 Higgs properties

⊙ Higgs boson couplings:

→ 

$\mathcal{L}_{hVV} = \sqrt{\sqrt{2}G_F}\, m_V^2 \cdot h V^\mu V_\mu$ quadratic



$\mathcal{L}_{hf\bar{f}} \sim \frac{m_f}{v} = \sqrt{\sqrt{2}G_F}\, m_f$ linear

with $G_F = \frac{g^2}{\sqrt{32}\, m_W^2}$

→ Coupling proportional to the mass of the particle involved
↳ decay into the heaviest one allowed by phase-space.

Higgs decay into fermions:

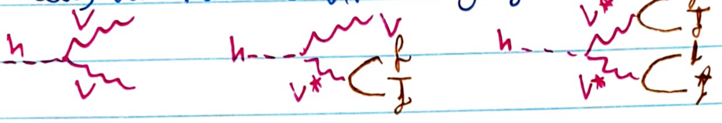
→ Born approximation:

$$\Gamma_{born}(h \to f\bar{f}) = \frac{G_F N_c}{4\sqrt{2}\pi} m_h m_f^2 \beta_f^3 \qquad \beta_f = (1 - 4m_f^2/m_h^2)^{1/2}$$

with N_c a color factor.

Higgs decays into W/Z bosons:

→ Decay into real and virtual gauge bosons:



→ When $m_h \gg m_V$, one has

$$\Gamma(h \to WW) \simeq 2 \cdot \Gamma(h \to ZZ)$$

and $\Gamma(h \to WW + h \to ZZ) \propto m_h^3$. At large mass, the Higgs boson becomes a broad resonance, losing its particle-like nature.

⇐ looze perturbativity

Higgs decays to massless particles:

→ Only at loop level

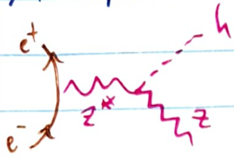
→ 

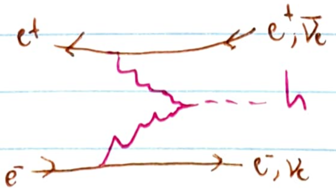
Summary:

→ Low mass: $b\bar{b}$ mostly
→ Discovery: $\gamma\gamma$-channel
→ High mass: heavy boson dominates, $+ t\bar{t}$.

⊙ Higgs production:

→ At lepton colliders:

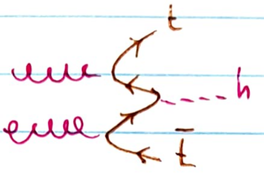


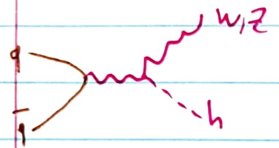


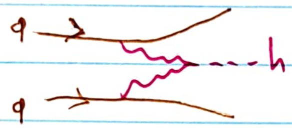
Higgsstrahlung

VBF

→ Hadron colliders:







VBF (E-W vertex)

⊙ Searching for the Higgs at LHC:

→ $h \to WW/ZZ$; $h \to \gamma\gamma$; $h \to b\bar{b}/\tau\tau$: need precise measurement of charged lepton, good calorimeter, determination of secondary vertex.

→ Some golden modes are mass dependents:
$h \to ZZ \to 4\ell$ $\quad h \to \gamma\gamma \quad$ $h \to WW \to 2\ell 2\nu$
but have low branching ratio.

→ Number of signal event $S \equiv N - B$, with statistical significance

$$\frac{S}{\sqrt{S+B}} \quad \text{(Poisson)}$$

↳ Goal in search: maximize $S/\sqrt{B}$

→ Knowing the decay channels help accelerate the detection of the Higgs in 2012.