What many Higgses can do for you

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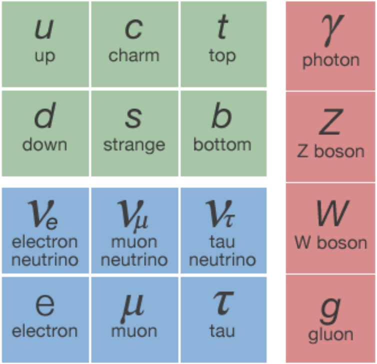
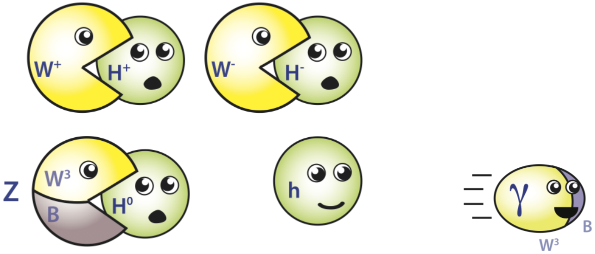
The Standard Model



The Standard Model

Brout-Englert-Higgs mechanism based on the Higgs doublet Φ $\to$ regrouping the bosons:



$$W_1,\ W_2,\ W_3,\ B,\ \Phi \to W^{\pm},\ Z,\ \gamma,\ h\,.$$

The Standard Model

The Standard Model:

- minimalistic, fully predictive theory,
- extremely efficient in describing collider data.

$N \times$ 

But there are several observations which the SM

- cannot accommodate (DM, baryon asymmetry of the Universe)
- can describe but not explain (fermion masses, mixing, CP violation, neutrinos).

Looking beyond the Standard Model

There must exist physics Beyond the Standard Model!

Theorists have proposed
$\sim$ 1000 models of New Physics!

We just don't know which one corresponds to reality!

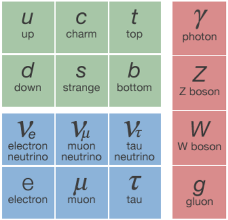
The main goal of the present-day experimental HEP is to find New Physics.

Non-minimal Higgs sectors

Non-minimal Higgs sectors

Non-minimal Higgs sectors: a conservative approach to New Physics.

SM



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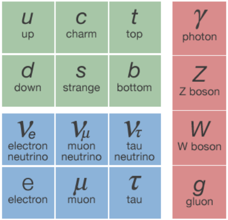
Multi-Higgs models



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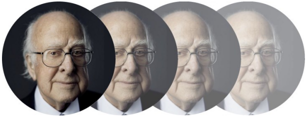


Several Higgs generations

Simple idea

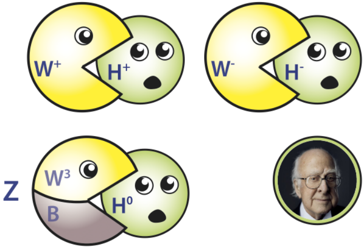
Higgses can come in generations → N-Higgs-doublet models (NHDMs).

- T.D. Lee, 1973: 2HDM as a new source of CP-violation (CPV);
- Weinberg, 1976: 3HDM with natural flavour conservation and CPV;
- 1990's: supersymmetry requires at least two Higgs doublets;
- ...
- Porto, Zee, 2008: "private" Higgs model, a separate Higgs doublet for each fermion flavour.

In total, $\mathcal{O}(10^4)$ papers over 40 years.

Counting Higgses

- SM: $\phi = (\phi^+, \phi^0)$; 4 real degrees of freedom.



3 bosons become W_L^+, W_L^-, Z_L; 1 Higgs boson remains.

Counting Higgses

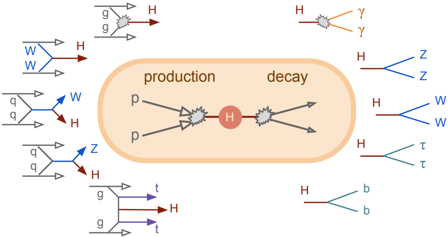
- 2HDM: ϕ_1, ϕ_2; $2 \times 4 = 8$ real degrees of freedom.

  3 bosons become W_L^+, W_L^-, Z_L; 5 Higgs bosons remains:
  - 3 neutral h, H, A; 2 charged: $H^\pm$.

Exciting phenomenology at colliders, see review Branco et al, arXiv:1106.0034 ($\approx$ 1400 citations so far).

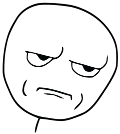
Higgs boson discovery

July 4th, 2012: Higgs searches → Higgs exploration



LHC Run 1 (20 fb^{-1}) + early Run 2 (80 fb^{-1}) statistics:

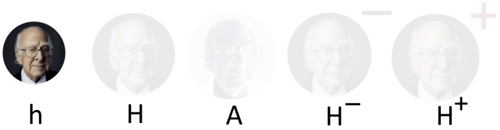
- no other Higgs bosons detected,
- very SM-like couplings of the 125 GeV Higgs.



2HDM phenomenology

This is not a blow to multi-Higgs models:

- One Higgs can be very similar to SM, the other Higgses are almost hidden → don't expect democracy among Higges!



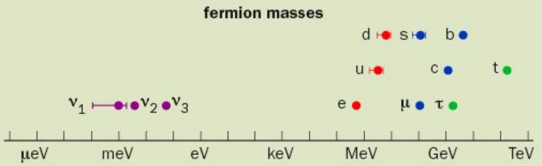
It arises naturally in many multi-Higgs models (Higgs alignment).

- Strategy: search for hints of non-standard Higgs interactions:
  - flavour-violating decays (e.g. $h \to \mu e$);
  - invisible Higgs decays;
  - deviations in rare decays ($h \to Z\gamma$, $h \to \mu\mu$, $h \to \Upsilon\gamma$, ...);
  - unusual *hh* production.

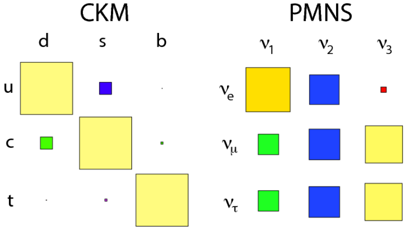
Attacking the flavour puzzle

Flavour puzzle

- highly hierarchical quark, lepton, and neutrino masses



- the patterns of the quark and neutrino mixing



Flavour puzzle

In the SM the poor single Higgs doublet does all the job:

$$\Gamma_{ij}\,\left(\text{right quarks}_i \times \underbrace{\text{Higgs}}_{v} \times \text{left quarks}_j\right), \quad i,j = 1,2,3$$

- masses to up-type quarks,
- masses to down-type quarks,
- mixing and CP violation for quarks.

But no resources left to explain anything...

Quark masses and mixing in NHDM

N generations of Higgses can do a lot!

$$\sum_a \Gamma^{(a)}{}_{ij}\ (\text{right quarks}_i \times \underbrace{\text{Higgs}_a}_{v_a} \times \text{ left quarks}_j)$$

- In general, $\Gamma^{(a)}_{ij}$ are unconstrained complex matrices $3 \times 3 \to$ too much freedom, complete mess.
- Suppose there is flavour symmetry group G which acts on quarks and Higgses $\to$ each $\Gamma^{(a)}_{ij}$ can be very simple, symmetry-constrained!
- Vacuum expectation values v_a break the flavour symmetry $\to$ relations among masses/mixing/CP-violation may remain.

Quark masses and mixing in NHDM

Lots of activity 70-80's: guess G, guess representations, arrange for symmetry breaking → deduce relations among masses/mixing/CP violation.

- permutation symmetry groups S_3 or S_4: [Pakvasa, Sugawara, 1978, 1979, + Yamanaka, 1982] → perfectly (for early 80's!) reproduced CKM;
- rephasing + permutations: $\Delta(54)$ which makes $\Gamma^{(a)}$ very simple [Segre, Weldon, Weyers, 1979]: mass hierarchy may come from $v_1 \ll v_2 \ll v_3$.
- typical prediction for top mass: 20–40 GeV; decline of activity in 90's;
- renewed interest in last years with many strong results, see review [Ivanov, arXiv:1702.03776].

CP violation in NHDM

- Spontaneous CP-violation [T.D.Lee, 1973, Branco, 1979]:
  - lagrangian is CP-invariant, Γ's are real;
  - the position is minimum, v_a, is complex;
  - CKM becomes complex.

  Recent resurrection of the idea: [Nebot, Botella, Branco, 2018].
- Geometric CP-violation [Branco, Gerard, Grimus, 1984]: very stable, rigid prediction for the CP-violating phase;
- Higgs exchanges as a new source of CP-violation [Weinberg, 1976];
- new form of CP-symmetry (CP4 3HDM) [Ivanov, Silva, 2016] with peculiar phenomenology.

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Cosmological consequences

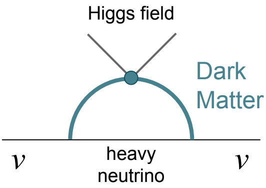
Scalar dark matter

Inert doublet model = 2HDM with new “parity” ($\mathbb{Z}_2$-symmetry) [Deshpande, Ma, 1978; Barbieri et al, 2006, Lopez Honorez et al, 2006]:

- all known particles are $\mathbb{Z}_2$-even; second Higgs doublet ϕ_2 is $\mathbb{Z}_2$-odd;
- $\mathbb{Z}_2$ parity is conserved $\to$ the lightest Higgs from ϕ_2 is automatically stable $\to$ dark matter candidate!

Constraints from colliders, cosmology and DM searches $\to$ a lot of interest.

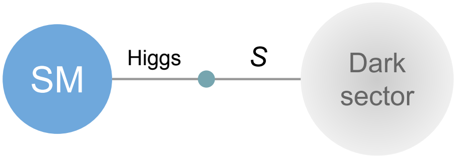
Dark matter can even help give tiny masses to neutrinos $\to$ scotogenic model [Ma, 2006].



Higgs portal models

Scalar DM arises in many other models beyond Higgs doublets.

Higgs portal framework: Higgs doublet ϕ and singlet scalar field S connect the (potentially rich) dark sector with the SM [Patt, Wilczek, 2006]:



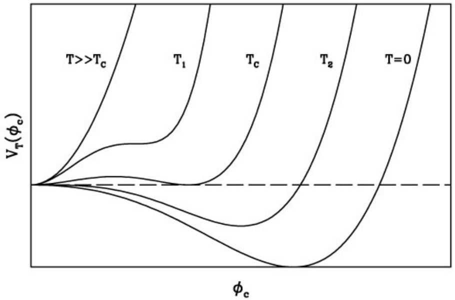
$$\mathcal{L}(\mathrm{SM}) + \lambda_{SM-D}(\phi^\dagger\phi)(S^\dagger S) + \mathcal{L}(\mathrm{dark})\,.$$

Testable through collider and astroparticle measurements.

Cosmological phase transition

Baryon asymmetry requires a strong first-order thermal electroweak phase transition in early Universe.

$$\frac{v(T_c)}{T_c} \gtrsim 1.$$

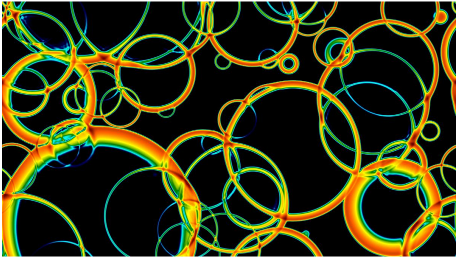


But it does not work in the SM!

We need to "additionally bend" the Higgs potential!

Cosmological phase transition

- Extra Higgses can produce strong phase transition!
- 2HDMs: from early works [Turok, Zadrozny, 1992] to the recent detailed studies [Dorsch, Huber, No, 2013].
- Several minima $\rightarrow$ a sequence of strong phase transitions.
- Can be probed with future GW observatories [Caprini et al, 1512.06239], a key item of the LISA scientific program.



Conclusions