# Multi Inert Doublet Models

Venus Keus

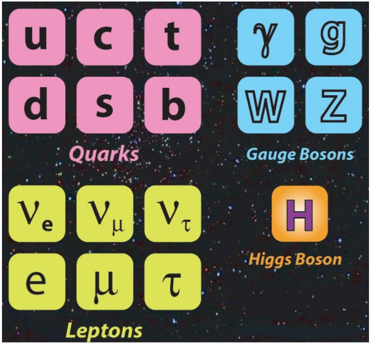
University of Southampton
The NExT Institute

In collaboration with S. King, S. Moretti and D. Sokolowska
(work in progress)
and based on JHEP 1401 (2014) 052

IOP Meeting, 8/4/14

# The Standard Model of particle physics

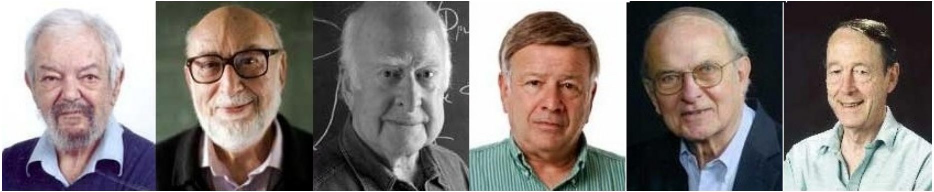
The gauge invariant model that was introduced by Glashow, Weinberg and Salam to describe the interactions between the fundamental particles in Nature.




[Glashow, Nucl.Phys.22,579 (1961)], [Salam, Weinberg, Phys.Rev.127,965 (1962)]

# Brout-Englert-Higgs-Guralnik-Hagen-Kibble Mechanism

The mechanism that ensures massive $W^{\pm}$ and $Z$ bosons and massless photons while preserving the gauge invariance.



[Englert, Brout, Phys.Rev.Lett.13,321 (1964)], [Higgs, Phys.Lett.12,132 (1964)], [Guralnik, Hagen, Kibble, Phys.Rev.Lett.13,585 (1964)]

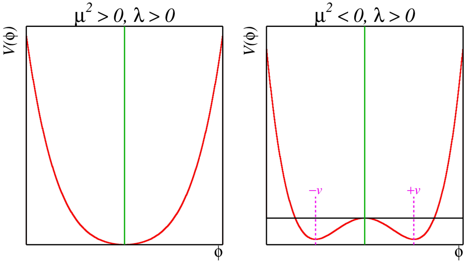
# EWSB in the Standard Model

The BEH mechanism postulates the existence of a doublet of complex scalar fields: $\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$ with the gauge invariant potential:

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

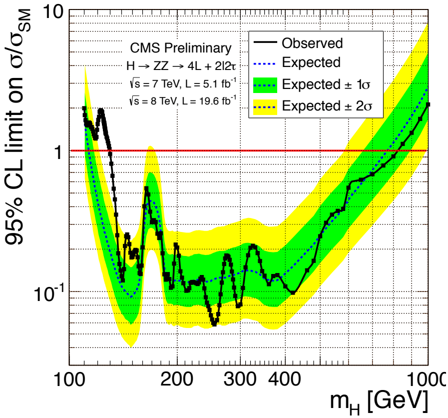
$\mu^2 > 0$ ; $\langle\phi\rangle = 0$ and the symmetry is explicit

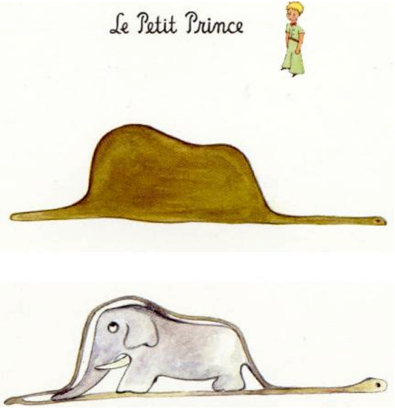
$\mu^2 < 0$ ; $\langle\phi\rangle = \pm\sqrt{\frac{-\mu^2}{2\lambda}}$ and the symmetry is broken



# Experimental evidence and deviations

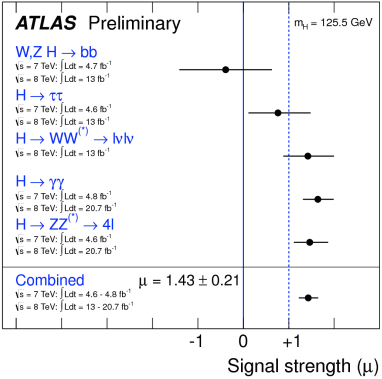
Evidence for a Higgs-like boson with mass 125 GeV:

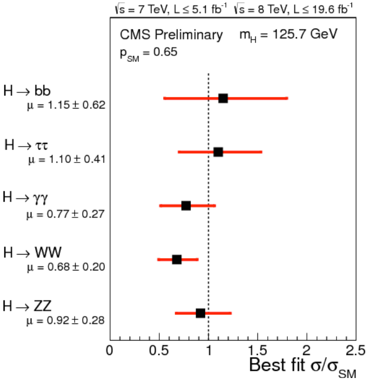


# Hints?

Deviations from the SM hint at a non-minimal Higgs sector.




Many non-minimal Higgs sectors have been studied:

[Accomando et al., arXiv:hep-ph/0608079]

# Non-minimal Higgs sectors

- Typically these sectors involve several Higgs fields:
  - Inert-doublet model (IDM); 2 Higgs doublets
  - Minimal Supersymmetric SM (MSSM); 2 Higgs doublets
  - $E_6$ Supersymmetric SM ($E_6$SSM); 6 Higgs doublets
- All BSM extensions have to abide to the existence of a Higgs boson at 125 GeV.
- Simplest BSM extensions: N-Higgs-doublet models (NHDMs)
- Extra doublets offer a richer particle spectrum with charged and neutral scalars.
- All neutral scalars could in principle be the scalar discovered at the LHC.

# Motivation for introducing more than one doublet

- No fundamental reason for a minimal scalar sector
- Hierarchy of the Yukawa couplings
- Sources of $CP$ violation (explicit and spontaneous)
- Baryon asymmetry of sufficient size
- Dark matter candidates
- Axion models with Peccei-Quinn symmetry

# 2 Higgs doublet models (2HDMs)

A second copy of the Higgs doublet:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}$$

The most general potential:

$$\begin{aligned} V &= {\mu^2}_{11}(\phi_1^\dagger\phi_1) + {\mu^2}_{22}(\phi_2^\dagger\phi_2) + {\mu^2}_{12}(\phi_1^\dagger\phi_2) \\ &+ \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ &+ \lambda_5(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + h.c. \end{aligned}$$

- $\mu^2_{11}, \mu^2_{22}, \lambda_1, \lambda_2, \lambda_3, \lambda_4$ are real
- $\mu^2_{12}, \lambda_5, \lambda_6, \lambda_7$ can be complex $\rightarrow$ Explicit CPV

# VEVs in 2HDM

In general, minimizing the potential gives

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u \\ v_2 e^{i\xi} \end{pmatrix}$$

- Non-zero $u$ $\rightarrow$ Charge-breaking vacuum $\rightarrow$ massive photon
- Non-zero $\xi$ $\rightarrow$ Spontaneous CPV

A common basis choice

$$\langle\phi_1\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 0 \\ \cos\beta \end{pmatrix}, \quad \langle\phi_2\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 0 \\ \sin\beta \end{pmatrix}, \qquad \tan_\beta = v_2/v_1$$

Physical states in 2HDM:

$$h^{SM}, H, A, H^\pm$$

# Inert Doublet Model (IDM)

A 2HDM with one inert doublet

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix}$$

Preventing FCNCs by imposing a $Z_2$ symmetry

$$g^{Z_2} = (+,-), \qquad \phi_1 \to +\phi_1 \qquad \phi_2 \to -\phi_2$$

The most general potential:

$$\begin{aligned} V &= -|\mu_1^2|(\phi_1^\dagger\phi_1) + \mu_2^2(\phi_2^\dagger\phi_2) + \lambda_1(\phi_1^\dagger\phi_1)^2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\ &\quad +\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda_5(\phi_1^\dagger\phi_2)^2 + h.c. \end{aligned}$$

with all real parameters.

# Inert Higgs Doublet Model

A 2HDM with one inert doublet

$$\phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix}$$

Preventing FCNCs by imposing a $Z_2$ symmetry

$$g^{Z_2} = (+,-), \qquad \phi_1 \to +\phi_1 \qquad \phi_2 \to -\phi_2$$

- The VEV alignment $(v, 0)$ respects the $Z_2$ symmetry.
- All other SM fields have even $Z_2$ parity.
- The inert neutral states $H^0, A^0$, stabilised by the conserved $Z_2$ symmetry, are viable **DM candidates**.

# N-Higgs-doublet models

N copies of the SM Higgs doublet with identical quantum numbers:

$$\phi_\alpha = \begin{pmatrix} H_\alpha^+ \\ \frac{H_\alpha^0 + iA_\alpha^0}{\sqrt{2}} \end{pmatrix}, \qquad \alpha = 1, 2, \cdots N$$

The most general potential

$$V = Y_{ab}(\phi_a^\dagger \phi_b) + Z_{abcd}(\phi_a^\dagger \phi_b)(\phi_c^\dagger \phi_d)$$

All Abelian symmetries realisable in NHDM have been found.

[Ivanov, et al., J.Phys.A 45,215201 (2012)]

In 3HDMs, all symmetries are known:

$$U(1) \times U(1), \quad U(1), \quad U(1) \times Z_2$$

$$Z_2, \quad Z_3, \quad Z_4, \quad Z_2 \times Z_2, \quad D_6, \quad D_8, \quad A_4, \quad S_4, \quad \Delta(54)/Z_3, \quad \Sigma(36)$$

[Ivanov, et al., Eur.Phys.J.C 73,2309 (2013)]

# Multi Inert Doublet Models (NIDMs)

$Z_2$ symmetric 3HDM with 1 active doublet

(3-1) Inert Doublet Model

# (3-1) Inert Doublet Model

$Z_2$-symmetric potential with $g^{Z_2} = (-,-,+)$:

$$V = \sum_{i}^{3} \left[ -|\mu_i^2|(\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 \right] + \sum_{ij}^{3} \left[ \lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]$$
$$+ \left( -\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c. \right)$$

VEV alignment $(0, 0, v)$ respects the $Z_2$ symmetry:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} H_3^+ \\ \frac{v + H_3^0 + iA_3^0}{\sqrt{2}} \end{pmatrix}$$

- $\phi_3$ – SM-like doublet with SM-like Higgs $H_3^0$
- $\mu_{12}^2 \neq 0 \Rightarrow$ mixing between $\phi_1$ and $\phi_2$

$$H_1 = \cos\alpha H_1^0 + \sin\alpha H_2^0, \quad H_2 = \cos\alpha H_2^0 - \sin\alpha H_1^0$$

- $H_2$ – **DM candidate**, other dark particles heavier

# DM annihilation in (3-1)IDM

- Possible scenarios for $M_{H_2} < M_h/2$:

(A) no coannihilation effects: $M_{H_2} < M_{H_1,A_1,A_2,H_1^\pm,H_2^\pm}$

(B) coannihilation with $H_1$: $M_{H_2} \approx M_{H_1} < M_{A_1,A_2,H_1^\pm,H_2^\pm}$

(C) coannihilation with $A_2$: $M_{H_2} \approx M_{A_2} < M_{H_1,A_2,H_1^\pm,H_2^\pm}$

(D) coannihilation with $H_1, A_1, A_2$: $M_{H_2} \approx M_{A_2} \approx M_{H_1} \approx M_{A_2} < M_{H_1^\pm,H_2^\pm}$

- Constrained (3-1)IDM:

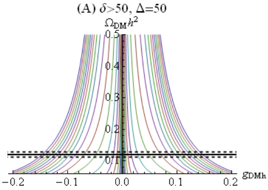
$$\mu_1^2 = k\mu_2^2, \quad \lambda_{13} = k\lambda_{23}, \quad \lambda'_{13} = k\lambda'_{23}, \quad \lambda_3 = k\lambda_2$$

Maximum mixing at $k = 1$:

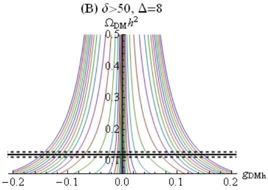
$$H_1 = \frac{1}{\sqrt{2}}(H_1^0 + H_2^0), \quad H_2 = \frac{1}{\sqrt{2}}(H_2^0 - H_1^0)$$

# Relic density: 40 GeV $< M_{H_2} <$ 62 GeV

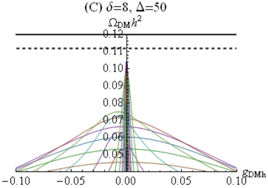
Let $\delta = M_{A_2} - M_{H_2}$ and $\Delta = M_{X_{\phi_1}} - M_{X_{\phi_2}}$



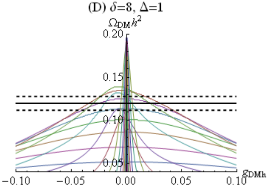

no coannhilation




coannhilation with $H_1$

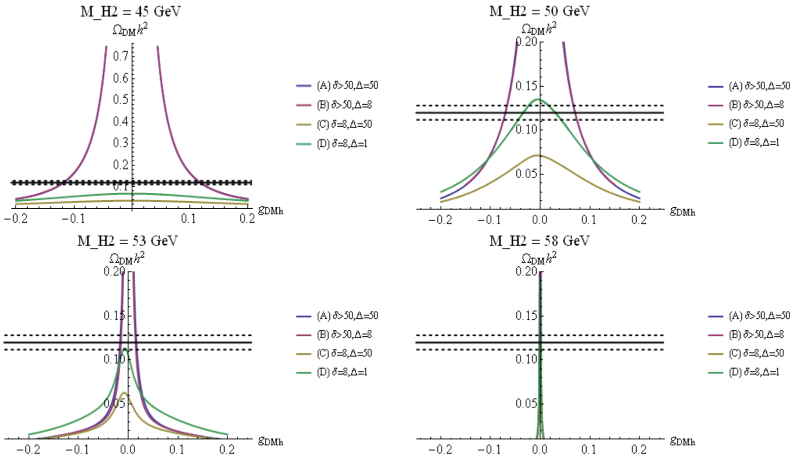



coannhilation with $A_2$

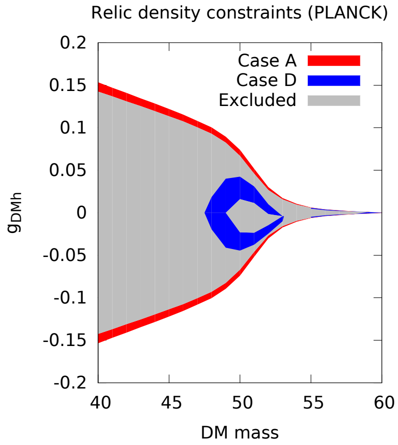



coannhilation with $H_1, A_1, A_2$

# Relic density – difference between cases

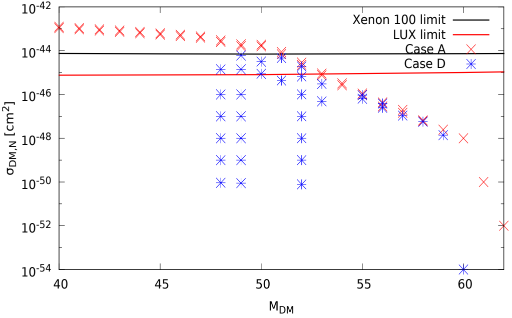


# Planck constraints




Case A (no coannhilation) – coupling generally bigger than in Case D (with coannihilation)

# Direct detection




Case D: new region in agreement with LUX with respect to Case A; coannhilation effects

# Summary

Multi-Higgs doublet models are good for you!

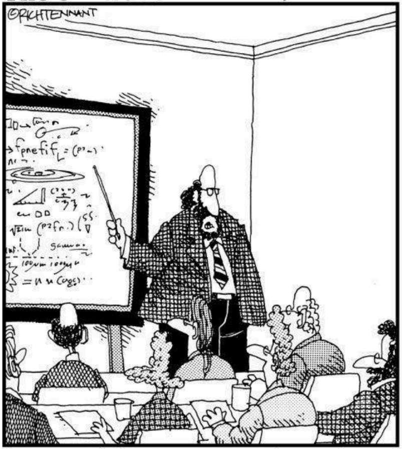
3HDMs are inspired by the SUSY and are very well motivated.

Multi-inert doublet models contain non-SM features which are testable at the LHC. Namely, a much larger invisible decay width with respect to the SM case.

These models contain viable dark matter candidates, leading to a relic abundance in agreement with the observed data. They could also provide inflaton candidates.

# Thank you for your attention!

The 5th Wave By Rich Tennant




"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."