The Different Faces of the Higgs

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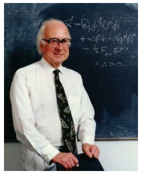
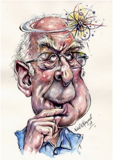
Plan



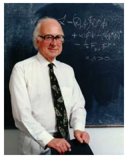
- electroweak symmetry breaking



- flavor puzzle

- key to the "dark" sector

- inflation

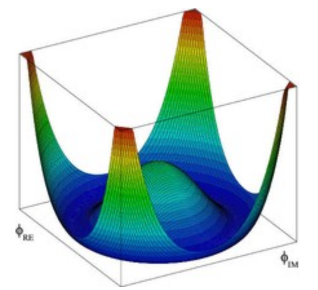


The Standard Higgs

H = spin-0 SU(2) doublet

$$V = \lambda\,(\bar{H}H - v^2)^2$$

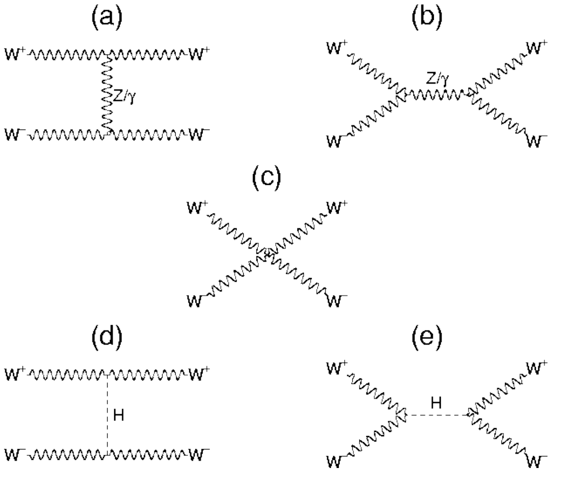
$$H \longrightarrow \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$



$$L_{mass} = -\,m_w^2\,WW \;-\; m_f\,\bar{f}\,f \;+\; \ldots$$

The Higgs particle required by unitarity :

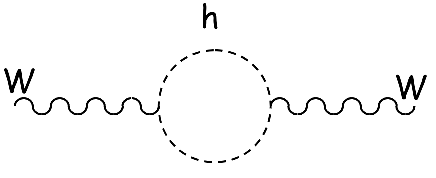
$$A\,(WW \rightarrow WW)\Big|_{\text{no Higgs}} \sim E^2$$



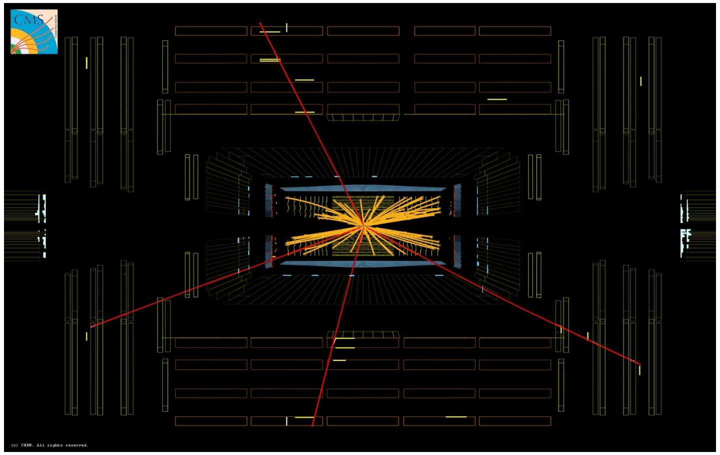
$m_h < 1$ TeV

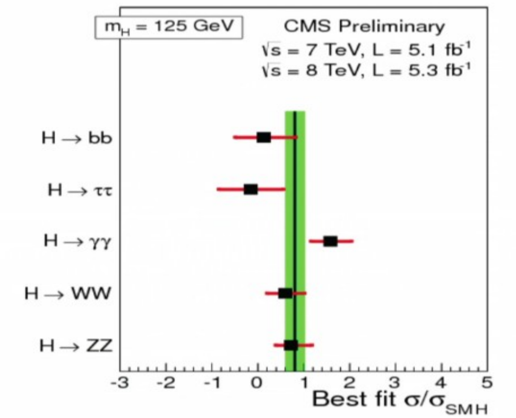
Electroweak precision measurements :

$m_h < 148$ GeV



First glimpse of the Higgs :





m_h ~ 125 GeV

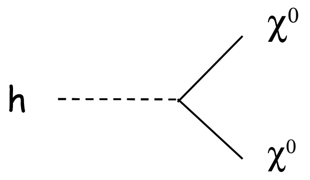
First constraints on BSM :

Giardino et al. '12
Espinosa et al. '12

$$Br_{inv} < 30\text{-}50\ \%$$

E.g. SUSY :

Dreiner, Kim, OL '12

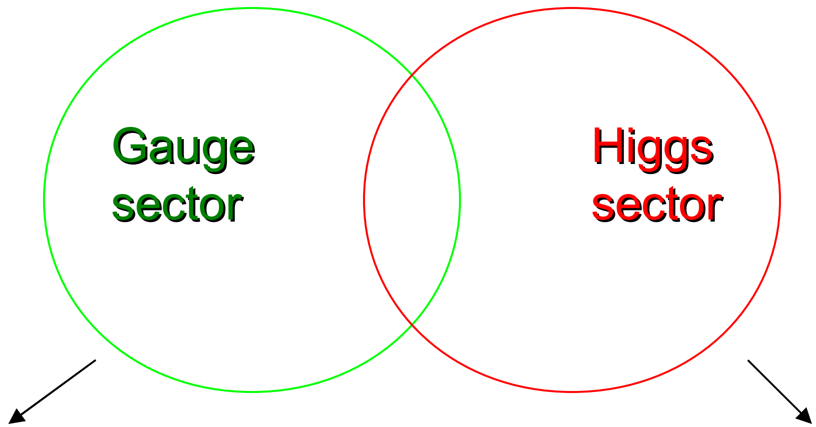


$\mu < 170$ GeV

$M_1 < 70$ GeV

⇒ *strongly disfavored*

The Higgs and the flavor puzzle



measured / understood

$A \bar{f} f$

NOT measured / understood

$h \bar{f} f$

In particular,

$m_u \sim 10^{-5}$, $m_d \sim 10^{-5}$, $m_s \sim 10^{-3}$

$m_c \sim 10^{-2}$, $m_b \sim 10^{-2}$, $m_t \sim 1$

Gauge couplings : 0.3 , 0.6 , 1

Yukawa couplings : 10^{-5} ... 1

⇒ ***FLAVOR PUZZLE***

Fermion mass in the SM :

$$y\, H\, \bar{f} f = y\, (v + h)\, \bar{f} f$$

$$= m\, \bar{f} f + y\, h\, \bar{f} f$$

Important relation :

$$y = m / v$$

Giudice, OL ' 08

Hypothesis :

$$y = y(H)$$

Then

$$y(H) = y^0 + y^1 \frac{\bar{H} H}{M^2} + \dots$$

M = "new physics" scale

Most interesting case :

$$y(H) = c \left(\frac{\bar{H} H}{M^2} \right)^n$$

(E.g. low order terms forbidden by symmetries)

⬇

No small couplings ! Small masses due to $M \gg v$

Simplest possible ``model of flavor'' ?

Prediction :

Since $(\bar{H} H)^n = (v + h)^{2n} = v^{2n} + 2n\, h\, v^{2n-1} + \ldots$,

the fermion – physical Higgs couplings increase :

$$y = (2n + 1)\, y_{SM}$$

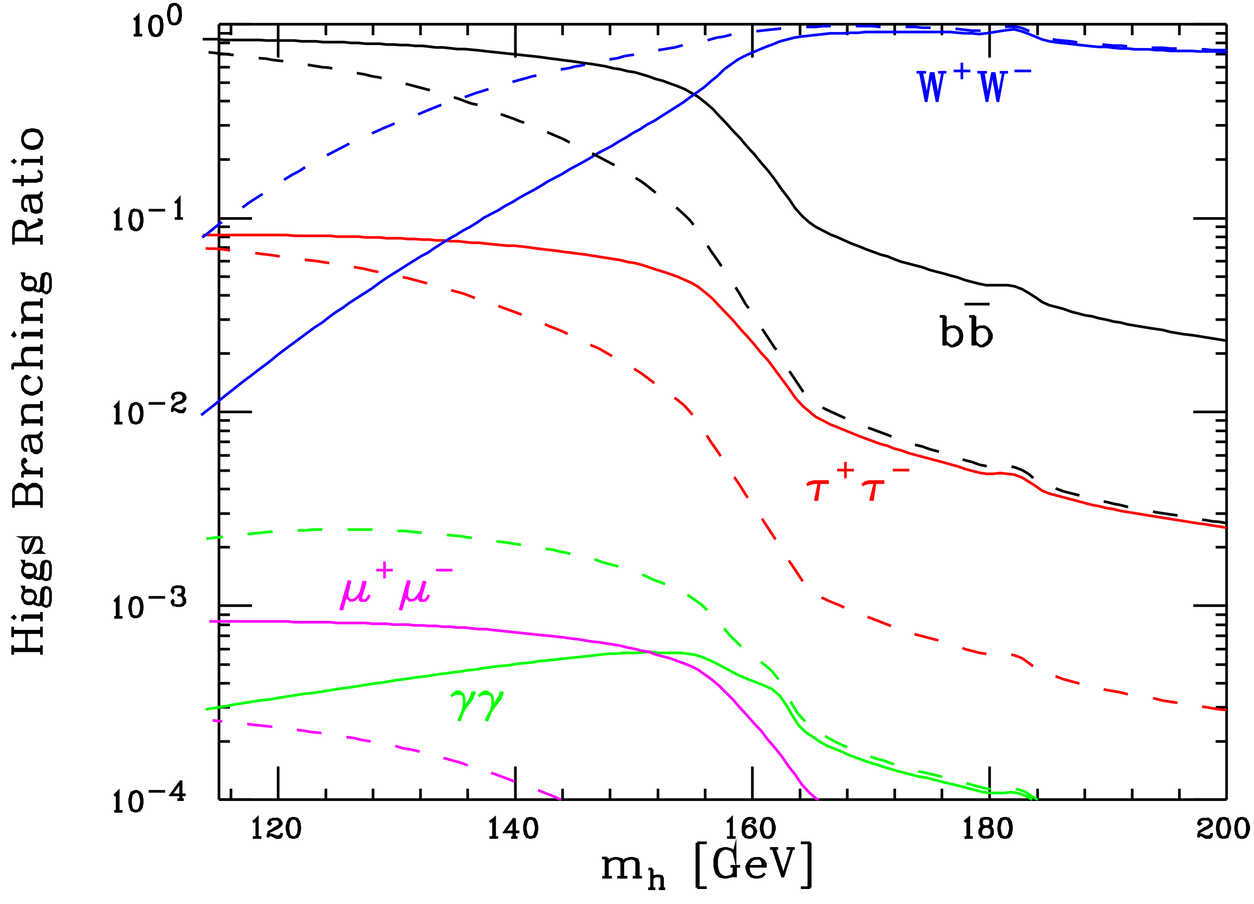
LHC :

Higgs decay rates into fermions increase ,

BR (h -> f f) increase !

(Here BR = decay rate (h -> X) / total decay rate)

LHC :



- - - - - = SM

——— = our model

- Extreme case disfavored by the 125 GeV Higgs

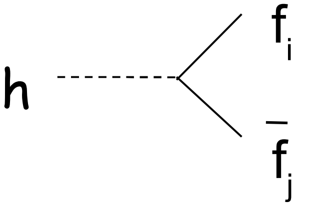
- General case Y=Y(H) viable → origin of masses

- Measure Higgs-fermion couplings with O(10%) precision

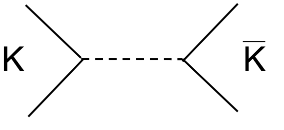
Also: Higgs-induced flavor violation

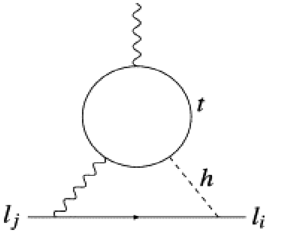
$$\begin{cases} M_{ij} = v\ Y_{ij} \\ y_{ij} = (2n_{ij}+1)\ Y_{ij} \end{cases}$$

⇨ *not diagonalizable simultaneously*



Constraints :

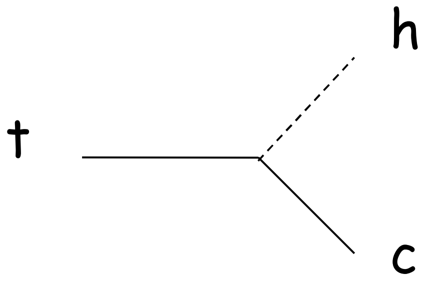




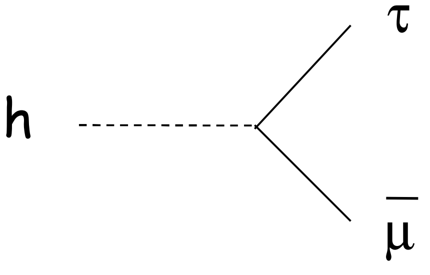
...

Giudice, OL '08
Goudelis, Park, OL '11

LHC :



BR ~ 10^{-3}



BR ~ 0.1

The Higgs key to the hidden sector

Motivation :

✓ E_8 X E_8 strings

observable hidden

✓ dark matter

✓ ...

Special role of the Higgs :

Silveira, Zee '85
Veltman, Yndurain '89
...

$|H|^2$ = the only gauge and Lorentz-inv. dim-2 operator

$$L = a\,|H|^2 S^2 + b\,|H|^2 S$$

(S = "hidden" scalar)

b=0 (S has hidden charge):

$$L = a\,|H|^2 S^2$$

"S" is stable and couples weakly to SM --> DARK MATTER (?)

Vector Higgs portal:

OL, Lee, Mambrini '11

$$L = a\,|H|^2\; V_\mu V^\mu \;+\; b\,(\,\bar{H} i D_\mu H\, V^\mu +\; h.c.)$$

(V_μ = "hidden" vector)

b=0 (V^μ <--> $-V^\mu$ symmetry):

$$L = a\,|H|^2\; V_\mu V^\mu$$

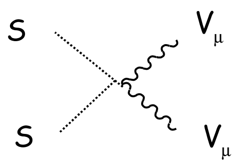
⇓

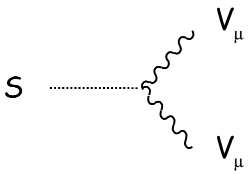
V^μ = DM (?)

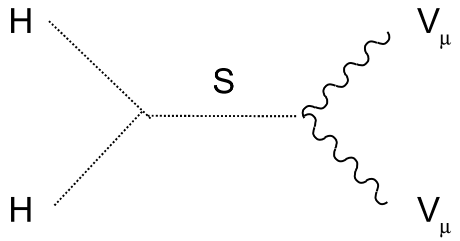
Higgs mechanism in the hidden sector :

$$L = -1/4\, F_{\mu\nu} F^{\mu\nu} + D_\mu S^* D^\mu S - V(S) + \lambda/4\; H^*H\, S^*S$$

S ⟶ VEV







$H^*H\, V_\mu V^\mu$ vertex

(Z_2 parity)

gauge invariance (+ minimal field content)

⇓

Z_2

OL, Lee, Mambrini '11

Stueckelberg DM :

$$L = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} + \tfrac{1}{2} m^2 V_\mu V^\mu$$

Here : $V_\nu \equiv V'_\nu + 1/\mu \, \partial_\nu \phi$

Gauge transform: $\begin{cases} \delta V'_\nu = \partial_\nu \varepsilon \\ \delta \phi = - \mu \varepsilon \end{cases}$

In general : $m^2 = \mu^2 (1 + c H^* H + \ldots)$

⇨ $H^* H V_\mu V^\mu$ coupling

OL, Lee, Mambrini '11

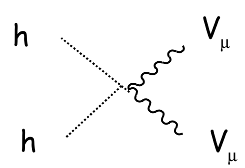
Unitarity:

$$L = \tfrac{1}{4}\lambda\, |H|^2\ V_\mu V^\mu + \tfrac{1}{2} m^2\, V_\mu V^\mu$$

Physical mass :

$$m^2_V = m^2 + \tfrac{1}{2}\lambda v^2$$

Cutoff :

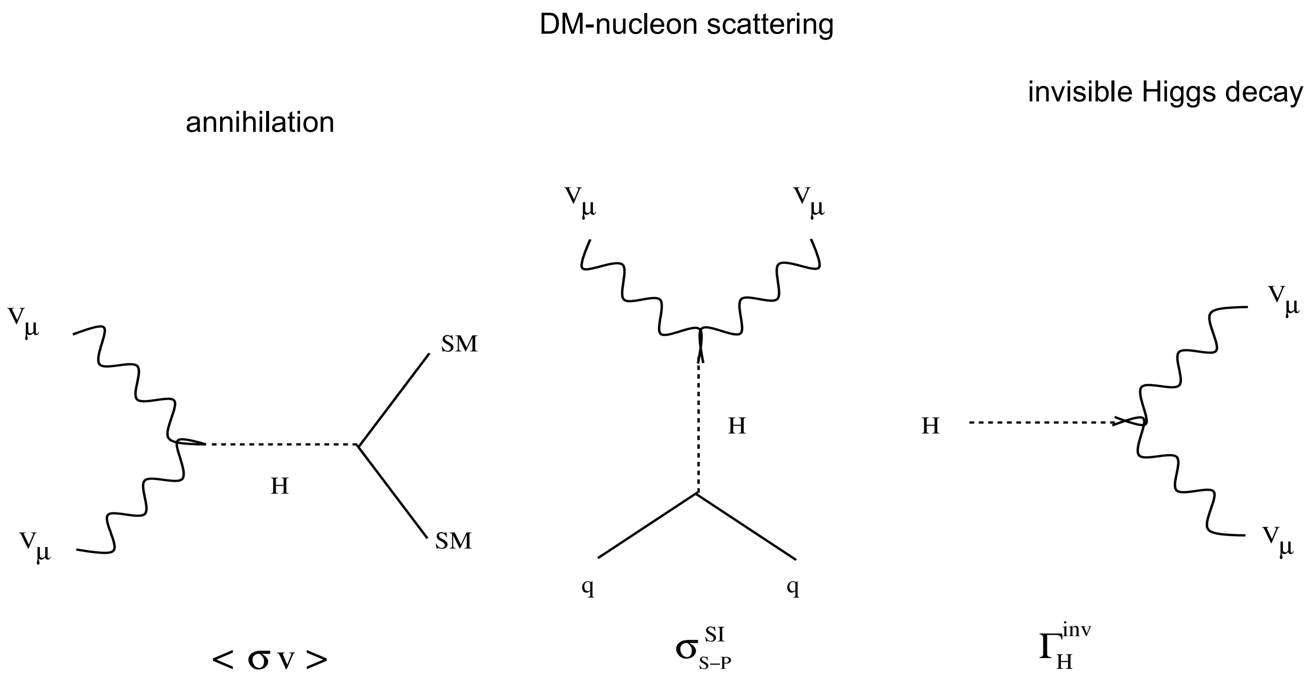


$$+ \quad \ldots \qquad \sim E^2$$

$$E \sim m^2_V / m$$

($\cdot \sqrt{16\pi / \lambda}$)

Important processes :

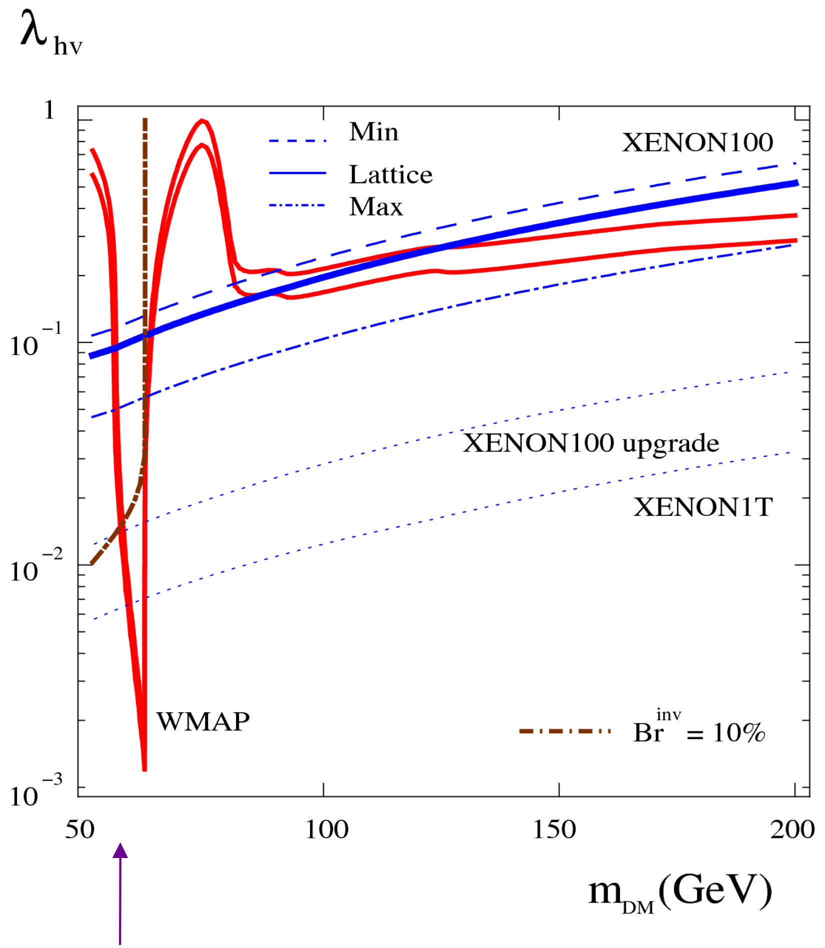


Constraints :

WMAP: annihilation cross section
XENON : DM-nucleon interaction
LHC : invisible Higgs decay

Djouadi, OL, Mambrini, Quevillon '11
OL , Lee , Mambrini '11

Higgs-vector coupling



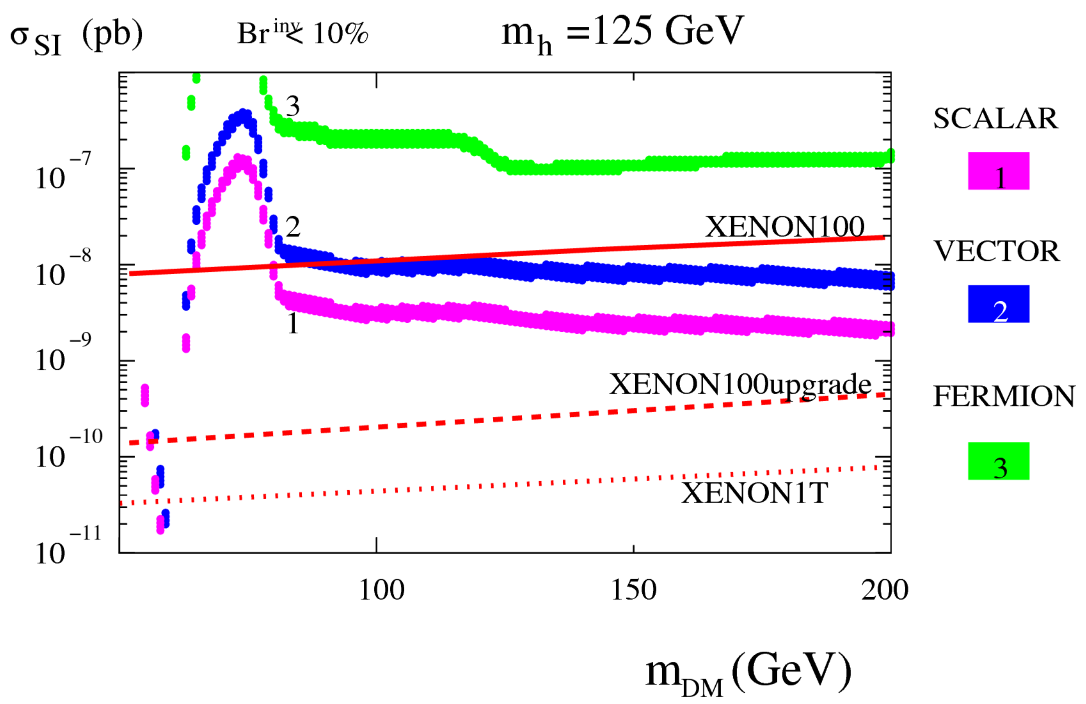
LHC: m_{DM} > 60 GeV

Scalar vs Vector DM :

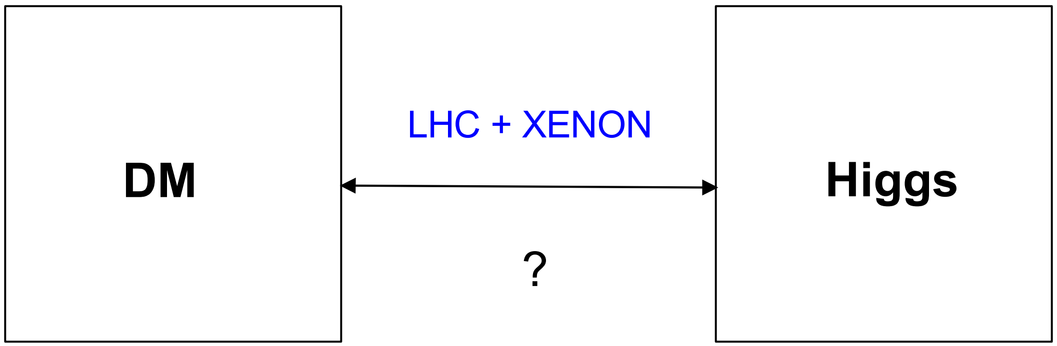
annihilation **:**	$g^2_{vector} = 3\, g^2_{scalar}$	(3 species)
direct detection **:**	same	(Higgs exchange)
Higgs decay **:**	$\Gamma_{vector} \sim \; m_h^4 / m_V^4 \; \Gamma_{scalar}$	(Goldstone production)

Prediction :

Djouadi, OL , Mambrini , Quevillon '11



DM direct detection with $\sigma \sim 10^{-8} - 10^{-9}$ pb


DM
LHC + XENON
?
Higgs

Higgs inflation

Bezrukov, Shaposhnikov '07

$$\Delta L = c\,|H|^2 R$$

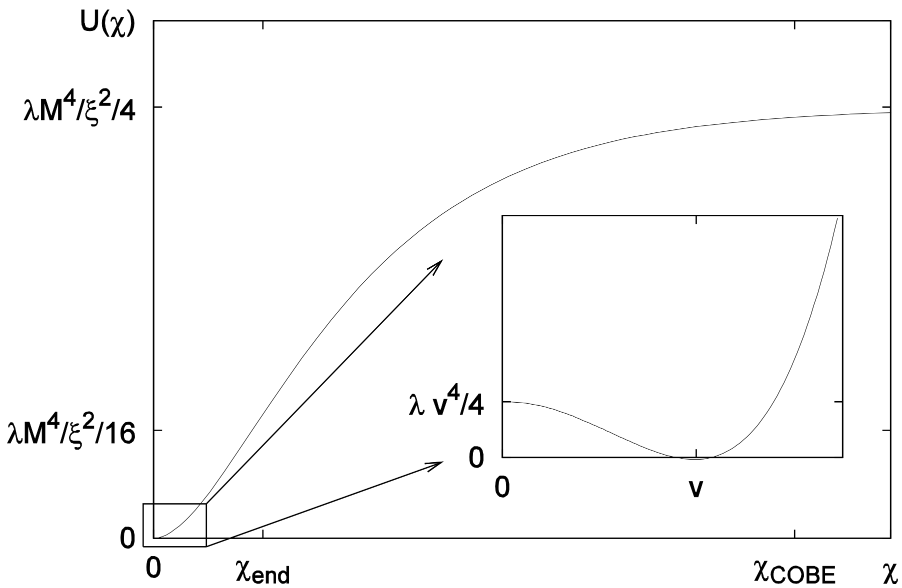
Conformal transformation to the Einstein frame :

$$g_{\mu\nu} \longrightarrow f(H)\, g_{\mu\nu} \quad , \quad f(H) = 1 + c|H|^2/M_{Pl}^2$$

Canonically normalized "Higgs" χ :

$$H = \text{const} \; \exp(\chi / M_{Pl})$$

$$V = \text{const} \; [\, 1 - 2 \exp(-2\chi / M_{Pl}) \,]$$



Inflation at $\chi \sim M_{Pl}$!

Preferred Higgs mass range 130 – 180 GeV

(problem ?)

Degrassi et al.'12

SM stability bound: $m_h > 126$ GeV at 98% CL

(not settled : Alekhin et al. '12)

Higgs-portal inflation :

OL , Lee ' 11
OL '12

$$\Delta L = \lambda_{hs} |H|^2 S^2 + \lambda_s S^4 + \xi |H|^2 R + \zeta S^2 R$$

⇓

improved stability of the EW vacuum

Low energy states :

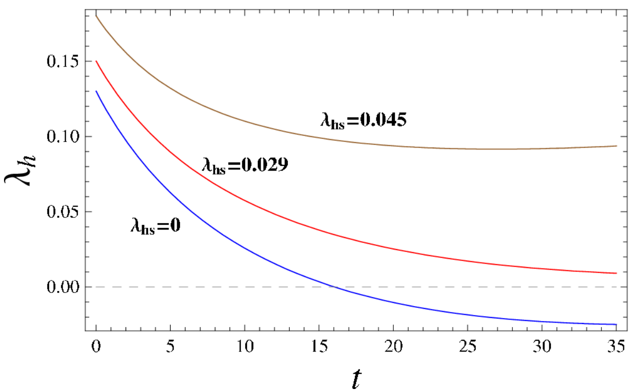
$$\begin{cases} H_1 = H\cos\theta + S\sin\theta \\ H_2 = H\sin\theta - S\cos\theta \end{cases}$$

OL '12
Elias-Miro et al. '12

If $\langle S\rangle \gg 246$ GeV ,

$$\begin{cases} \theta \to 0 \quad \text{(SM—like Higgs)} \\ m_h^{\,2} = 2\,v^2\,[\,\lambda_h - \lambda^2_{hs}/(4\lambda_s\,)] \end{cases}$$

Stability :

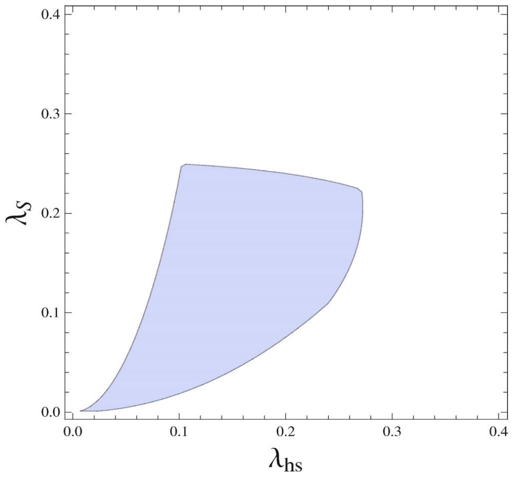


$\lambda_s = 0.01$
$t = \ln(\mu/m_t)$

a (very) weakly coupled singlet can stabilize the EW scale

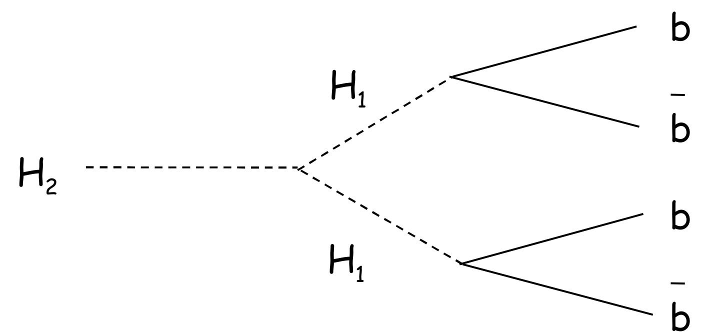
Higgs inflation constraints:

$$\begin{cases} \lambda_i\,(M_{INF}) > 0 \\ \lambda_i\,(M_{INF}) < O(1) \end{cases}$$



Possible low-energy signatures :

- 2 Higgs-like states
- suppressed couplings
- cascades



Higgs potential reconstruction :

Englert et al. '11

$m_1\ ,\ m_2\ ,\ \theta\ ,\ H_2 \rightarrow H_1 H_1$ ⇨ 4 parameters of the scalar potential

Conclusion

- Higgs sector is special
- origin of fermion masses / flavor puzzle
- key to the hidden sector / DM / inflation
- LHC is crucial