Fermiophobic Higgs scenarios at the LHC

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Outline

- SM Higgs boson searches at LHC
- Fermiophobic SM Higgs scenario
- Impact of radiative corrections
- Implications at LHC and linear colliders
- Fermiophobobia in supersymmetric models
- Conclusions
Why we care about Higgs boson

- **Standard Model** theory is not unitary and renormalizable without the Higgs boson

- It is the last missing piece to be discovered in **SM**

- Higgs discovery would be crucial since it would shed light on the mystery of **EWSB** and origin of masses of all fundamental particles

- If the SM Higgs boson does not exist (and we will know soon if this is the case) then a New Physics should show up at the TeV energy scale and it will be found at the **Large Hadron Collider (LHC)**!
... of SM Higgs mechanism
Properties of SM Higgs mechanism

The GOOD
- at high energy ($E \gg v$) the EW symmetry is restored
- cures unitary violation in $WW \rightarrow WW$ scatterings
- SM is renormalizable, unitary and perturbative
- $m_H < 1 \text{ TeV}$, EWPT favor a $m_H \lesssim 150 \text{ GeV}$

The BAD
- mass of the SM Higgs particle is not predicted, due to unknown parameters in the Higgs potential $V$
- couplings of the Higgs field to leptons and quarks, and to $W$ and $Z$ are proportional to their masses
- this makes Higgs discovery difficult

The UGLY
- Higgs potential unstable under quantum corrections: fine tuning problems $\rightarrow$ require New Physics:
- Supersymmetry, Technicolor, Extra-dimensions, etc.
$W_L W_L \rightarrow W_L W_L \text{ at } E^2/M^2$

\[ \cos \theta \equiv \frac{M_W}{M_Z} \]

- $E/M$ cancellation due to gauge-inv.
- $E^2/M^2$ cancellation not accidental!
- related to: spontaneous gauge symmetry breaking $\rightarrow$ the Higgs mechanism. Scalar $H$ is the Higgs boson field
- at $E^0$ order, unitarity requires $m_H \lesssim 1 \text{ TeV}$

\[
\begin{align*}
(a) & \quad 2 - 6 \cos \theta + \cos \theta^2 \\
(b) & \quad - \cos \theta \\
(c) & \quad \frac{3}{2} - \frac{15}{2} \cos \theta - \cos \theta^2 \\
(d + e) & \quad \frac{1}{2} - \frac{1}{2} \cos \theta
\end{align*}
\]

Sum $= 0$
Low mass Higgs: why is it important?

Corrections to the precision measurements depend on $\log(m_H)$

Best fit of EWPT

$$M_H^{\text{best}} = 96^{+31}_{-24} \text{ GeV}/c^2 \ (\text{No direct searches})$$
Status of Higgs searches before LHC

**Tevatron ('85 – 11):** proton-antiproton collider at Fermilab
- c.m. Energy \( \sim 2 \, \text{TeV} \)
- (several relevant processes)

exclusion regions on SM Higgs mass at 95% CL
- \([100 – 109] \, \text{GeV}\)
- \([156 – 177] \, \text{GeV}\)

**LEP ('90 – 00):** electron-positron collider at CERN
- c.m. Energy LEP1 \( \sim 91 \, \text{GeV} \) (Z pole)
- LEP2 \( \sim 200 \, \text{GeV} \)
- relevant process: \( e^+e^- \rightarrow H(\rightarrow bb)Z \)
- \( m_H > 114.4 \, \text{GeV} \)
Large Hadron Collider

proton-proton collisions

c.o.m. Energy = 7, 8, 14 (13 ?) TeV
LHC: where we are today

- LHC delivered in 2011 ~ 5.7 fb^-1 of Luminosity in pp collisions @ 7 TeV c.m. energy

- In 2012 LHC runs @ 8 TeV, already 4 fb^-1 of Luminosity collected! 20 fb^-1 expected by end of year

- In a few weeks we should be able to complete the SM-Higgs search-phase and find out whether:
  - there is a SM like Higgs signal at mH= 125-126 GeV (be tuned on new LHC results this summer at ICHEP) → start testing its properties
  - there is NOT a SM like Higgs signal → what is there instead?
    → this will take longer...

- Results presented here are updated to Moriond 2012
SM Higgs production mechanisms

Gluon fusion

\[ \sigma(pp \rightarrow HX) = \sum_{ij} \int dx_1 \, dx_2 \, f_i(x_1) \, f_j(x_2) \, \hat{\sigma}(ij \rightarrow HX) \]

PDF

partonic cross-section

VH

VBF

ttH
SM Higgs production cross sections at LHC

Gluon fusion: leading production mechanism

VBF: next-to-leading production mechanism

$\sqrt{s} = 7 \text{ TeV}$
Relevant SM Higgs decay channels

**Tree-level decays**

\[ H \rightarrow \gamma \gamma, \tau \tau \] are relevant processes for Higgs discovery at low masses.

**One-loop decays**

- For high masses, the decay \( H \rightarrow \gamma \gamma, \gamma Z \) is very sensitive to new physics.
- The decay \( H \rightarrow \gamma Z \) is smaller but also quite sensitive to new physics.
$H \rightarrow bb$ dominant for $m_H < 140$ GeV → difficult to detect due to the huge QCD background. Possible to detect in VH production, but high luminosity required

$H \rightarrow \gamma\gamma$ golden discovery channel for $m_H < 130$ GeV
Weight of the individual channels

In the combination presented today \( \rightarrow \text{Nov. 2011} \)

\[ M_H(\text{GeV}/c^2) \]

\[ w_i = \frac{1}{\sum_j \frac{1}{\mu_{up,j}^2}} \frac{1}{\mu_{up,i}^2} \]

\( \mu_{up} \) expected upper limit on the signal strength modifier, \( \mu = \sigma/\sigma_{SM} \).

The \( w_i \) depend on the amount of integrated luminosity of each channel. They are computed in the asymptotic approximation.

Cowan, Cranmer, Gross, Vittels EPJC 71:155
ATLAS latest results

- Low-mass region

Planck 2012. Warsaw 28.05.2012

Regions excluded at 95% CL:
- $110 - 117.5$ GeV
- $118.5 - 122.5$ GeV
- $129 - 539$ GeV

Excess at $\sim 126$ GeV $\rightarrow$ local significance $2.5 \sigma$
**CMS latest results**

Planck 2012. Warsaw 28.05.2012

**Regions excluded**

- \([127.5 – 600] \text{ GeV} \) @ 95% CL ,  \([129 – 529] \text{ GeV} \) @ 99% CL

- a narrow range still allowed : \(114 – 127.5 \text{ GeV} \)

- At 125 GeV \(\rightarrow 2.1 \sigma \) of global significance in 110 – 145 GeV
Currently not a single channel has sensitivity to see Higgs at 125 GeV

$H \rightarrow \gamma\gamma$ and $H \rightarrow WW$ have same sensitivity in the region of interest

$H \rightarrow \gamma\gamma$ larger than SM $\rightarrow$ hint of a fermiophobic Higgs?
Prospects for 2012

- Gain from 7 $\rightarrow$ 8 TeV
  - corresponding to 20 % Luminosity
  - corresponding to 10 % significance

- Need 12 fb$^{-1}$ @ 8 TeV
  - for 5$\sigma$ significance in each experiment

- Combining data @ 7 TeV
  - we need $\sim$ 8 fb$^{-1}$ @ 8 TeV for discovery
  - by ICHEP 2012 we may have $\sim$ 5 fb$^{-1}$

- If Higgs exists with $m_H \sim 125$ GeV local significance increases from $3 \sigma \rightarrow 4 \sigma$

we will know more about it in a couple of weeks!

By the end of 2012 we should be able to discover the Higgs boson at @ 5 $\sigma$ for Higgs masses above 120 GeV!
Why fermiophobia?
Motivations

- hierarchy of fermion masses is still a puzzle!
- masses span almost over six order of magnitudes
- in SM, problem just shifted to the Yukawa sector
  \[ \mathcal{L} = Y_f \bar{\psi}_f \psi_f H \leadsto m_f = Y_f \langle H \rangle \]
- difficult to explain all fermion spectrum and CKM mixing by means of few parameters and in perturbation theory
- maybe the mechanisms of fermion (ChSB) and \( W, Z \) mass generation (EWSB) are different
- but EWPT favor a light Higgs mass below 150 GeV
...what if Higgs boson is only responsible for $M_W, M_Z$ but not of fermion masses?

fermion masses $m_f$ \Rightarrow ChSB

(Chiral Symmetry Breaking)

in SM, ChSB and EWSB ($M_W, M_Z$) generated by the Higgs mechanism at same scale $\sim \langle H \rangle$

not (yet) any experimental evidence supporting tree-level Yukawa couplings $Y_f$

EWPT not sensitive to Yukawa couplings: at 1-loop these depend on quark masses not on Yukawas.

ChSB and EWSB can have different mechanisms $\rightarrow$ compositeness, extra-dimensions, technicolor...
A non-standard scenario

Fermio-Phobic (FP) Higgs

- Higgs mechanism gives rise to EWSB and $M_W, M_Z$
  but is NOT responsible for ChSB $\rightarrow$ fermion masses

- Perturbative unitarity in WW scattering cured!

- NO Yukawa couplings at tree-level
Higgs decays: FP vs SM

\[ H \rightarrow WW, ZZ, \gamma\gamma, Z\gamma \]

SM Higgs

FP Higgs

for \( m_H \sim [100, 110, 120] \) GeV: \( BR(\gamma\gamma)_{FP} \sim [110, 30, 10] \times BR(\gamma\gamma)_{SM} \)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Fermiophobic
Fermio-Phobic Higgs production mechanisms at LHC

- **VBF**
- **VH**

- **NO** gluon-gluon fusion
- **VBF** fusion dominant mechanism
- harder $p_T$ spectrum $\rightarrow$ better $S/B$!
How to handle the problem of radiative corrections in the FP Higgs model?

- **FP Higgs model:** non-renormalizable $\rightarrow$ EFT
- **We need** Effective Field Theories tools (RGE)
- Radiative corrections depend in principle by UV completion of the theory
- but less sensitive if Yukawas vanish in the UV
FP Higgs is unstable under radiative corrections
Yukawa couplings radiatively generated

- Fermion mass put by hand → SM is not renormalizable
- SM → effective field theory valid up to some Λ scale
- FP model → Yukawas Yf vanish at the scale Λ
- due to explicit ChSB, the Yukawas are not protected under radiative corrections → Yf radiatively generated at low energy → large Log(Λ/mH) need to be summed up

Effective Field Theory approach allows to calculate the leading universal contributions
\[ [g^2 \text{Log}(\Lambda/M_H)]^n \]
universal → independent of UV completion of SM above Λ

EFT approach connects two scales $\Lambda$ and $m_H$

Assume $Y_f$'s vanishing at the scale $\Lambda \gg m_H$ (related to fermion-mass generation scale)

\[ Y_f(\Lambda) = 0 \]

Fermiophilia at scale $\Lambda$

Large logs $g_i^{2n} \log^n (\Lambda/m_H)$ can be summed up by

Renormalization Group Equation (RGE) technique

\[ Y_f(\Lambda) = 0 \rightarrow \text{RGE} \rightarrow Y_f(m_H) \]

(high energy) \hspace{2cm} \text{RGE} \hspace{2cm} (low energy)

Note! SM RGE (where $Y_f$'s and $m_f$ are related) not suitable here $\rightarrow$ new RGE's derived by keeping $Y_f$'s and $m_f$'s as independent parameters! Higgs field is assumed on-shell
Diagrams contributing to the $Y$'s beta-functions (Higgs on-shell)

Up-type quark couplings

Unitary gauge
Yukawas and fermion masses independent parameters
1-loop RGE's for Yukawa's

\[
\frac{dY_U}{dt} = \frac{1}{16\pi^2} \left\{ 3 \xi_H^2 (Y_U - Y_U^{SM}) - 3 Y_U^{SM} Y_D^{SM} (Y_D - Y_D^{SM}) + \frac{3}{2} Y_U (Y_U Y_U - Y_D^{SM} Y_D^{SM}) - Y_U \left( \frac{17}{20} g_1^2 + \frac{9}{4} g_2^2 + 8 g_3^2 - \text{Tr}(Y) \right) \right\},
\]

\[
\frac{dY_D}{dt} = \frac{1}{16\pi^2} \left\{ 3 \xi_H^2 (Y_D - Y_D^{SM}) - 3 Y_D^{SM} Y_U^{SM} (Y_U - Y_U^{SM}) + \frac{3}{2} Y_D (Y_D Y_D - Y_U^{SM} Y_U^{SM}) - Y_D \left( \frac{1}{4} g_1^2 + \frac{9}{4} g_2^2 + 8 g_3^2 - \text{Tr}(Y) \right) \right\},
\]

\[
\frac{dY_E}{dt} = \frac{1}{16\pi^2} \left\{ 3 \xi_H^2 (Y_E - Y_E^{SM}) + \frac{3}{2} Y_E Y_E Y_E - Y_E \left( \frac{9}{4} (g_1^2 + g_2^2) - \text{Tr}(Y) \right) \right\}
\]

\[\xi_H \equiv \frac{g_2 m_H}{2 M_W}\]

Back to the theory

W_L polarization

ChSB terms

\[Y_f^{SM} \equiv \frac{g_2}{\sqrt{2} M_W} \text{diag}[m_{f_1}, m_{f_2}, m_{f_3}]\]

\[Y \equiv N_c Y_U Y_U + N_c Y_D Y_D + Y_E Y_E\]

SM RGE's recovered for

\[Y_f^{SM} \rightarrow Y_f\]
Yukawas at low energy $E \sim m_H$

- only SM degrees of freedoms below $\Lambda$ assumed

- sign of Yukawas predicted $\rightarrow Y_t(m_H)$ is negative (dysfermiophilia)

- $|Y(m_H)| < 1$ satisfied for light Higgs masses

**top-Yukawa (mH)**

- $Y < 0$

**b-Yukawa (mH)**

- $Y < 0$
- $Y > 0$
Results for $\Gamma_H$ and BR's versus $\Lambda$

$\Gamma_H$ (MeV)

$\Lambda = 10^x$ GeV

$\langle x \rangle = 16, 10, 6, 4$

BR's enhanced by small total width

$\measured{m_H} = 120$ GeV
$\text{BR} / \text{BR(SM)}$: $\Lambda \sim (10^4 \rightarrow 10^{16})$ GeV

Higgs BR's in fermionic channels quite sensitive to the new physics scale $\Lambda$
accidental coincidence
For $m_H=124-126$ GeV, SM and FP Higgs predict a same inclusive production rate for $H \to \gamma\gamma$.
For $m_H=124-126$ GeV, FP Higgs has a smaller inclusive $WW^*$ production rate with respect to SM!
FP $H \rightarrow \gamma\gamma$ compatible with SM @ 125 GeV
but, **SM Higgs** and **FP Higgs** have different production mechanisms

to disentangle the two scenarios it is necessary to look at the **exclusive** production channels via VBF and HW, HZ $\rightarrow$ jj-tagging and V-tagging

in VBF and VH the signal is strongly enhanced with respect to the SM Higgs due to the enhanced Higgs BRs
In VBF, FP Higgs predicts a larger rate for $\gamma\gamma$ jj production with respect to SM (VBF)

At $m_H=125$ GeV for $H \rightarrow \gamma\gamma$ jj production, the rate for FP is approximately 7 times the rate of SM (VBF).
For $H \rightarrow WW^*jj$ at $m_H=125$ GeV

$\text{Rate}[\text{FP}] \sim 5 \times \text{Rate}[\text{SM(VBF)}]$
If LHC will confirm this scenario case for a linear collider advantages

- precise measurements of Yukawas
- LHC will constrain the scale $\Lambda$ of ChSB
- LC could provide a measurement of $\Lambda$
Excellent sensitivity to $\Lambda$
Correlations of $\frac{BR(H \rightarrow ff)}{BR(H \rightarrow bb)}$ is crucial to prove Effective Yf's scenario!
Previous exp bounds on FP Higgs

- Quite a number of studies on pure FP scenario

  * LEP → 109.7 GeV (comb. γγ data on 4 exps) ('02)
    (108.3 GeV, comb. γγ+WW* in L3)
  * Tevatron → (100-) 119 GeV 8.2 fb⁻¹ (Aug 2011)
  * CMS → (110-) 112 GeV 1.7 fb⁻¹ (LP2011)

- bounds in “Effective Yf” scenarios needs dedicated studies
  * in general weaker than in FP, and depending on Λ
ATLAS and CMS presented at Moriond 2012

new analyses based on same sample of data but selecting the VBF and VH Higgs production mechanisms
New ATLAS and CMS searches for FP Higgs $\rightarrow \gamma\gamma$
- ATLAS $\rightarrow$ 9 categories: both low and high $p_T(\gamma\gamma)$,
- CMS $\rightarrow$ jj-tagged (VBF), lepton-tagged (VH), 4 inclusive

Surprise: in $\gamma\gamma$ events the VBF component (high $p_T(H)$) is much larger than SM predictions $\rightarrow$ local significance for FP signal: $2.8\sigma$ (CMS) at 126 GeV, $3\sigma$ (ATLAS) at 125.5 GeV

A hint of FP Higgs? To confirm that, test $H \rightarrow VV^*$

A deficit in $WW^*jj$ channel is observed in both experiments with respect to FP Higgs expectations

Exclusion mass ranges for FP Higgs in $\gamma\gamma$ @ 95% CL
- CMS $\rightarrow$ [110-124], [128-136] GeV
- ATLAS $\rightarrow$ [110-118], [119.5-121] GeV

CMS combined results in all channels exclude FP Higgs 110-192 GeV @ 95% CL (hint at $m_H=126$ GeV)
Notice that FP Higgs at $m_H=125-126$ GeV is borderline to exclusion, but in same region as SM Higgs signal.

but for SM there is a hint of signal there, while bare FP Higgs is excluded $\rightarrow$ more conservative approach needed

including radiative corrections: FP Higgs mass @ 125 GeV with moderate/large $\Lambda$ is not yet excluded
After Moriond 2012, new fits seem to disfavor the SM and motivate for New Physics

\[ m_h = 125 \text{ GeV} \]

- red = no Higgs boson
- green = SM

P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254
a SM Higgs is not as favored as a partially FP Higgs

pure FP model (vanishing Yukawa) gives also good fit, but
best fit suggests partially FP Higgs (small negative $Y_t$)
radiative corrections to FP model go in the right direction
Fermiophobic Higgs and supersymmetry

What if the Higgs boson signal at 125 GeV will be confirmed to be fermiophobic-like?

Impact on MSSM would be dramatic

Whole MSSM would be ruled out!

Switching off Yukawa couplings in MSSM is not as smooth as in SM

Supersymmetry as an effective low energy theory, but not MSSM-like
Advantages

- Fermiophobic Higgs can cure SUSY problems
- Fine-tuning problem of SUSY induced only by gauge couplings $\rightarrow$ improving fine-tuning by a factor $\rightarrow \frac{N_c y_t^4}{g^4} \sim 25$.
- Removes little SUSY hierarchy problem
- Squarks and sleptons masses of 2-3 TeV become completely natural now.
- FCNC and CP problems automatically solved
- SUSY effects in FCNC processes very small.
Assume that the origin of fermion masses is not due to the Higgs mechanism (i.e. new strongly interacting dynamics above TeV scale)

adding fermion mass terms by hand breaks both chiral- and (softly) super-symmetry

SUSY model is non-renormalizable → effective theory valid up to some scale $\Lambda$

Higgs mass is strongly constrained in MSSM

how to get EWSB with $m_H = 125\,\text{GeV}$ if top-Yukawa is vanishing or very small?
In the MSSM $M^\text{tree}_h < M_Z$. But 1-loop corrections

$$\Delta M^2_h = 3y_t^4 \frac{v^2 \sin^2 \beta}{8\pi^2} \left[ \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{2M_S^2} \left( 1 - \frac{X_t^2}{6M_S^2} \right) \right]$$

- $M_S$ is the average stop mass
- $X_t$ is the stop mass mixing parameter, $X_t = \frac{a_t}{y_t} - \mu \cot \beta$
- $a_t$ is the trilinear coupling of the soft term $a_t \tilde{Q} H_u \tilde{u}^c$
Failure of MSSM in the FP limit

Fermiophobic limit: $y_t \to 0$

$$\Delta M^2_h = - \frac{3 v^2 \sin^2 \beta}{2 \pi^2} \frac{a_t^4}{48 M_S^4} < 0$$

- we cannot get $m_H > m_Z$ and even more $m_H \sim 125$ GeV
- $m_H < m_Z \implies$ MSSM is ruled out
- FP Higgs if SUSY, cannot be just MSSM-like
Fermiophobic NMSSM viable

$Z_3$ symmetric FP NMSSM superpotential

$$\mathcal{W} = \lambda S H_u H_d + \frac{k}{3} S^3$$

and $S, H_u, H_d$ soft terms

$$\mathcal{L}_{\text{soft}}^{S,H} = -\left(m_{h_u}^2 h_u^\dagger h_u + m_{h_d}^2 h_d^\dagger h_d + m_s^2 s^\dagger s\right) - \left(a_\lambda s h_u h_d + \frac{1}{3} a_k s^3 + h.c.\right)$$

where

- $s$ is the scalar component of $S$
- $Z_3$ is also used in order to get fermiophobia
- $X_{H_u} = X_{H_d} = X_S = 1$ and $X_f = 0 \Rightarrow y_f, a_f = 0$
  
  But also other possible configurations (see 1204.0080)
The scalar potential is given by:

\[ V = \left( m_{h_u}^2 + \lambda |s|^2 \right) \left( |h_u^0|^2 + |h_u^+|^2 \right) + \left( m_{h_d}^2 + \lambda |s|^2 \right) \left( |h_d^0|^2 + |h_d^-|^2 \right) + m_s^2 |s|^2 + \left( a_{\lambda} \left( h_u^+ h_d^- - h_u^0 h_d^0 \right) s + \frac{1}{3} a_{\kappa} s^3 + \text{h.c.} \right) + \left| \lambda \left( h_u^+ h_d^- - h_u^0 h_d^0 \right) + k s^2 \right|^2 + \frac{g_1^2 + g_2^2}{8} \left( |h_u^0|^2 + |h_u^+|^2 - |h_d^0|^2 - |h_d^-|^2 \right)^2 + \frac{g_2^2}{2} \left| h_u^+ h_d^{0*} + h_u^0 h_d^{-*} \right|^2 \]

Parametrization:

\[ h_d^0 = \frac{1}{\sqrt{2}} \left( v_d + h_{dR}^0 + i h_{dl}^0 \right) \quad v^2 = v_u^2 + v_d^2 \]

\[ h_u^0 = \frac{1}{\sqrt{2}} \left( v_u + h_{uR}^0 + i h_{ul}^0 \right) \quad \tan \beta = \frac{v_u}{v_d} \]

\[ s = \frac{1}{\sqrt{2}} \left( v_s + s_R + i s_l \right) \]
Minima of $V$: general case is quite complicated

there is a choice of parameters that allows no mixing between singlet $S$ and $h_u$, $h_d$

\[
\begin{align*}
a_\lambda &= 0 \\
k &= \lambda \\
tan \beta &= 1
\end{align*}
\]

tan$\beta=1$ is allowed since no low energy constraints come from Yukawa

we restrict our model to this special set of parameters $\rightarrow$ natural choice $\rightarrow$ more predictive
Spectrum of neutral CP even scalars

The corresponding eigenvectors and eigenvalues

\[ h = \frac{1}{\sqrt{2}} \left( h_{dR}^0 + h_{uR}^0 \right) \]

\[ H = \frac{1}{\sqrt{2}} \left( h_{dR}^0 - h_{uR}^0 \right) \]

\[ M_h^2 = \frac{(\lambda v)^2}{2} \approx (125 \text{GeV})^2 \]

\[ M_H^2 = (\lambda v_S)^2 + M_Z^2 - M_h^2 \]

\[ M_{sR}^2 = \frac{a_k v_S}{\sqrt{2}} + 2(\lambda v_S)^2 \]

MSSM notation \[ \rightarrow \alpha = -\pi/4 \]

\[ \beta = \pi/4 \Rightarrow \text{no direct tree level coupling } HWW \text{ and } HZZ \]

OK with LHC seeing no other “resonance” but \( \approx 125 \text{GeV}. \)
Other relevant SUSY spectrum

Neutralino mass matrix 5x5

\[
M_0 = \begin{pmatrix}
M_1 & 0 & -M_Z \sin \theta_W & M_Z \sin \theta_W & 0 \\
\ldots & M_2 & M_Z \cos \theta_W & -M_Z \cos \theta_W & 0 \\
\ldots & \ldots & 0 & -\frac{1}{\sqrt{2}} \lambda v_S & -\frac{\lambda v}{2} \\
\ldots & \ldots & \ldots & 0 & -\frac{\lambda v}{2} \\
\ldots & \ldots & \ldots & \ldots & \sqrt{2} v_S
\end{pmatrix}
\]

Chargino mass matrix same as in MSSM

Charged-Higgs mass

\[
M_{H^\pm}^2 = (\lambda v_S)^2 + M_W^2 - M_h^2 \lesssim M_H^2 = (\lambda v_S)^2 + M_Z^2 - M_h^2
\]

relevant parameters:

\[M_1 > 0, \quad M_2 > 0, \quad |\lambda|, \quad |\mu| \equiv |\lambda v_S| / \sqrt{2}, \quad \text{sign}(\mu)\]
Strategy

- $M_h = \frac{|\lambda| \nu}{\sqrt{2}} = 125$ GeV, $M_1 = 100$ GeV $\rightarrow$ fixed-parameters

- $(M_{H^\pm}, M_{\chi_L^+}) \rightarrow (|\mu|, M_2)$ $\rightarrow$ free-parameters

- $M_{\chi_L^0} > M_h/2 \Rightarrow h \leftrightarrow \chi_i \chi_j$ $\rightarrow$ to require neutralino LSP
  $\Rightarrow R -$ parity $\Rightarrow h \leftrightarrow \chi_i^* \chi_j$, $\chi_i^* \chi_j^*$

FP SUSY contributions to $h \rightarrow \gamma \gamma$, $\gamma Z$
1. The lines above (below) the FP SM prediction for $h \rightarrow \gamma\gamma$ correspond to positive (negative) values the $\mu$. For $h \rightarrow Z\gamma$ is the opposite.

2. For fixed $M_{\chi_L^+}$ two non-degenerate values of $M_{\chi_H^+}$ are possible. So there are always two solutions for the one-loop SUSY contribution.

3. As in the MSSM, the dominant SUSY contribution comes from the $\chi^\pm$

4. The absence of points in the half-plane above (below) the FP(SM) line for $M_{H^+} = 200$ GeV in the case of $h \rightarrow \gamma\gamma$ ($h \rightarrow Z\gamma$), is due to the constraint $M_{\chi_L^0} > M_h/2$ and depends on our choice for $M_1 = 100$ GeV.
Conclusions

- FB Higgs scenario is unstable under radiative corrections → ChSB regenerates Yukawa couplings
- EFT approach to calculate radiative corrections → unified descriptions of a wide class of possibilities
- if the scale $\Lambda$ of ChSB is very large → $\text{BR}(H \rightarrow bb)$ at $m_H=125$ GeV can be as large as a few 10%
- FP Higgs scenario could be tested at Linear Colliders
- FP Higgs boson in MSSM is ruled out, but it is viable in NMSSM and could be discovered at the LHC
- However, all SUSY particle searches should be revised due to vanishing/suppressed top-Yukawa coupling
Thank you !
Backup slides
LHC (WH) : H → bb