

Implications of the present measurements on theoretical ideas

Emidio Gabrielli

NICPB, Tallinn, Estonia

University and INFN, Trieste, Italy

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French-Italian meeting on the b-Physics

Flavor physics in the light of the recent results at LHC

Outlook

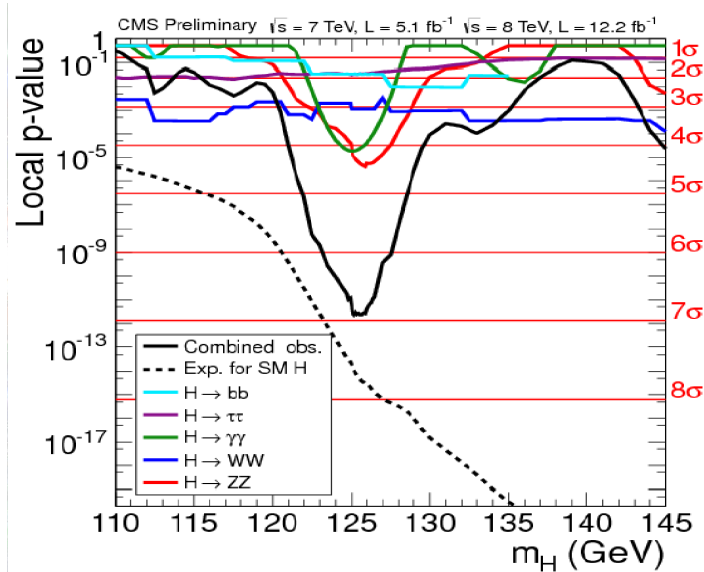
- **Anatomy of the Higgs-like resonance**
- **Impact on popular ideas on BSM Higgs scenarios**
- **Impact on Fermiophobic-like Higgs models**
- **Measuring the sign of top-Yukawa coupling**
- **Higgs-boson imposters**
- **Conclusions**

Where are we ?

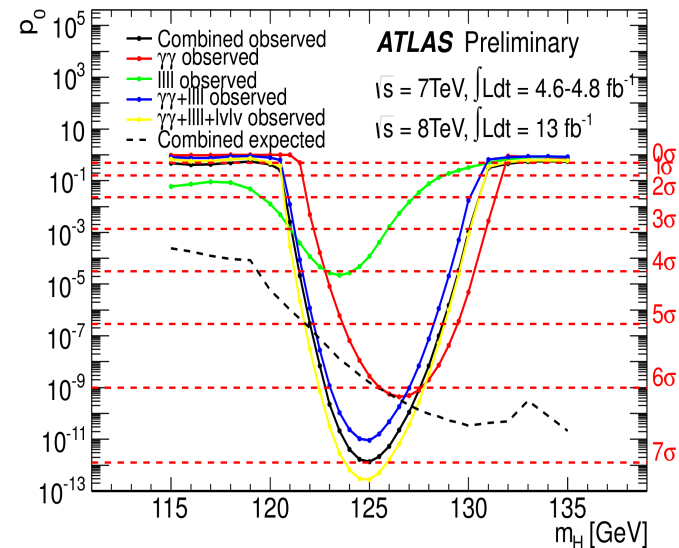
■ a new particle (resonance) has been discovered → consistent with the long-awaited **SM Higgs boson**

■ **fully confirmed in all its most sensitive channels**

CMS $m_H = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \text{ GeV}$



ATLAS $m_H = 126 \text{ GeV} \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \text{ GeV}$



■ Local probability p for a bckg-only experiment to be more signal like than the observation versus M_H

■ **Significance:** ATLAS **local 7.0** global 5.9 → in **122-131 GeV** ($p = 1.7 \times 10^{-9}$)
CMS **local 6.9**

■ **$H \rightarrow \gamma\gamma$ rules out spin-1. While spin-0 and spin-2 viable**

Anatomy of the 125 GeV resonance

■ assuming this is a SM Higgs-like boson

■ main production mechanisms are (in order of relevance)

● Gluon-gluon fusion $ggH \rightarrow \text{loop}$

● Vector Boson Fusion (VBF) $qqH \rightarrow \text{tree-level}$

● W,Z associated production $VH \rightarrow \text{tree-level}$

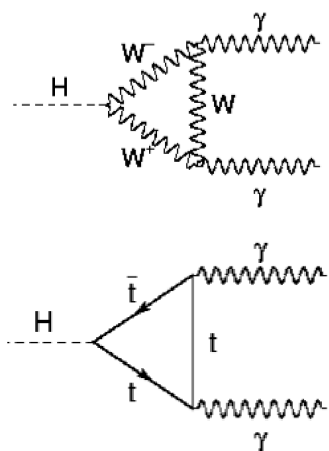
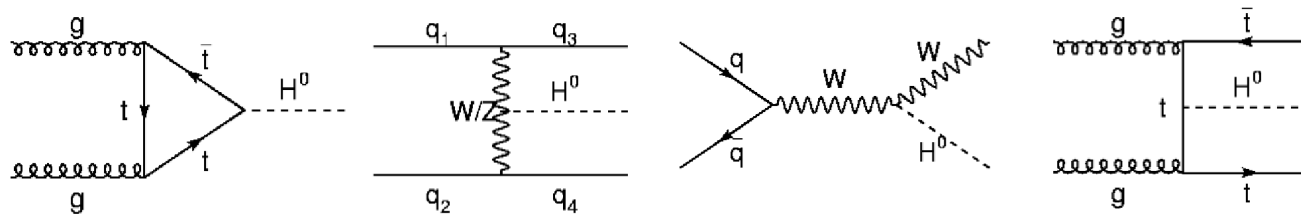
■ Crucial to measure Higgs couplings to W, Z, b, t, τ !

■ tags are needed to isolate the production mechanisms

● ggH → gives indirect informations on colored particles running in the loop, as well as on top-Yukawa coupling

● $VBF, VH, H \rightarrow VV$ → informations on Higgs coupling to W and Z

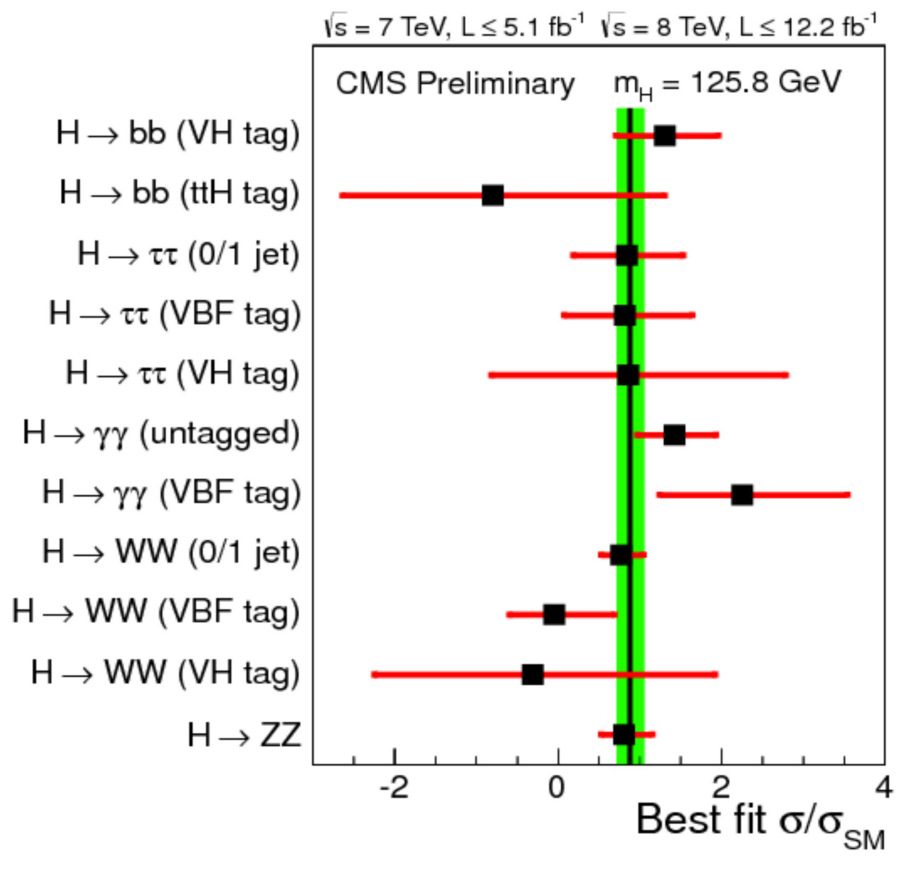
CMS tag analysis Nov 2012



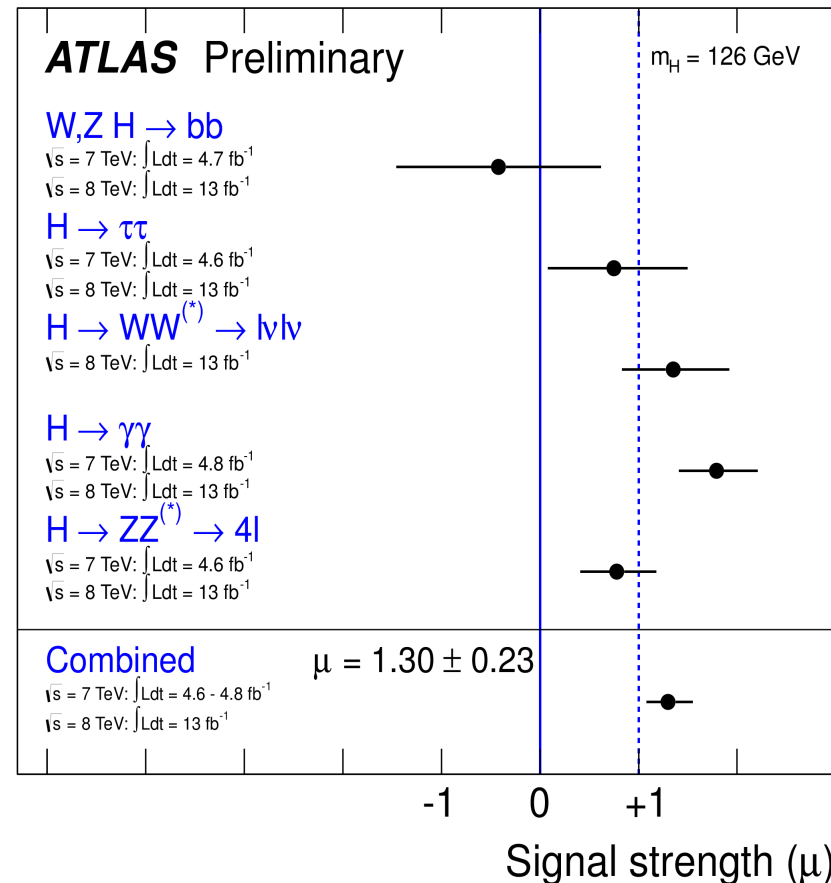
	Untag ged	VBF- tag	VH-tag	ttH- tag
$H \rightarrow \gamma\gamma$	✓	✓		
$H \rightarrow b\bar{b}$			✓	✓
$H \rightarrow \tau\tau$	✓	✓	✓	
$H \rightarrow WW$	✓	✓	✓	
$H \rightarrow ZZ$	✓			

Compatibility with SM Higgs hypothesis

CMS-HIG-12-045



ATLAS-CONF-2012-170



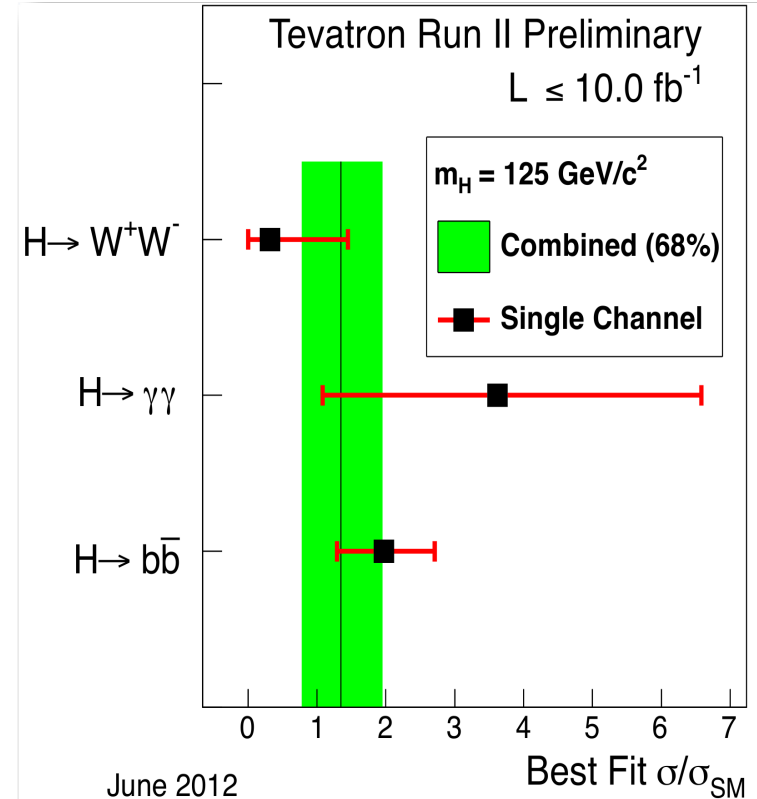
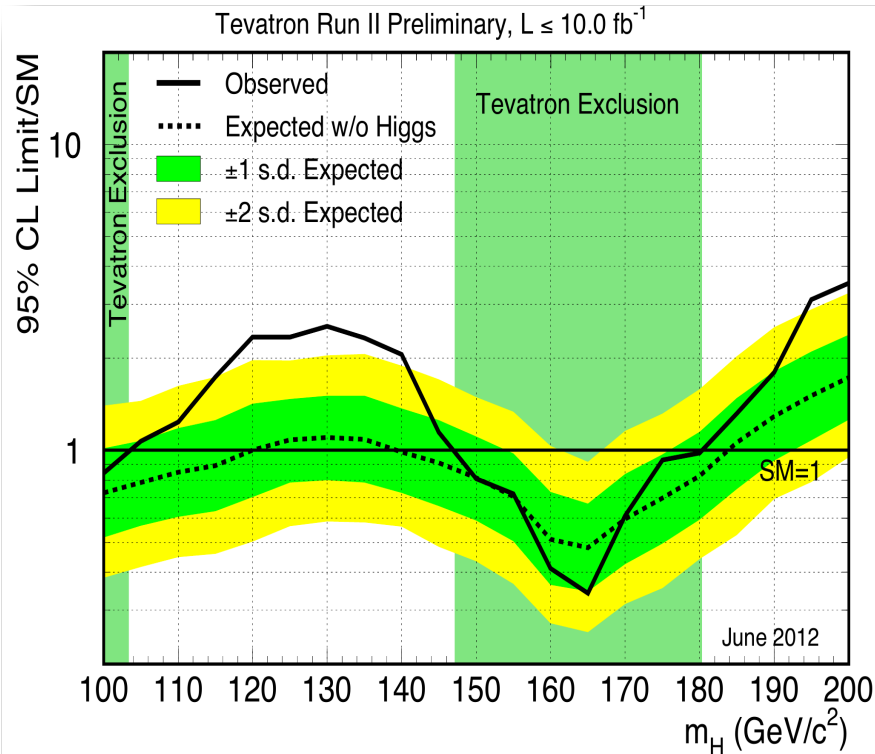
■ overall signal strength normalized to SM

CMS = 0.88 ± 0.21 ATLAS = 1.4 ± 0.23

■ di-photon rate enhancement is more pronounced in VBF

Higgs searches from Tevatron

Combination of searches for $H \rightarrow WW$ and $H \rightarrow bb$ shows a clear excess in the 115 GeV - 135 GeV mass region

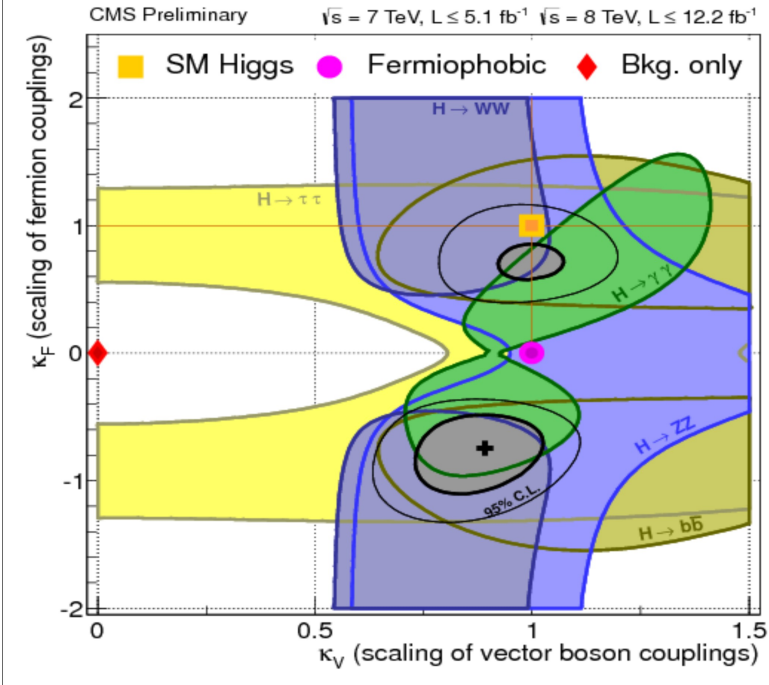


Combined production rates are consistent within 1σ with a Higgs mass of 125 GeV. However, bb and $\gamma\gamma$ rates appear enhanced !

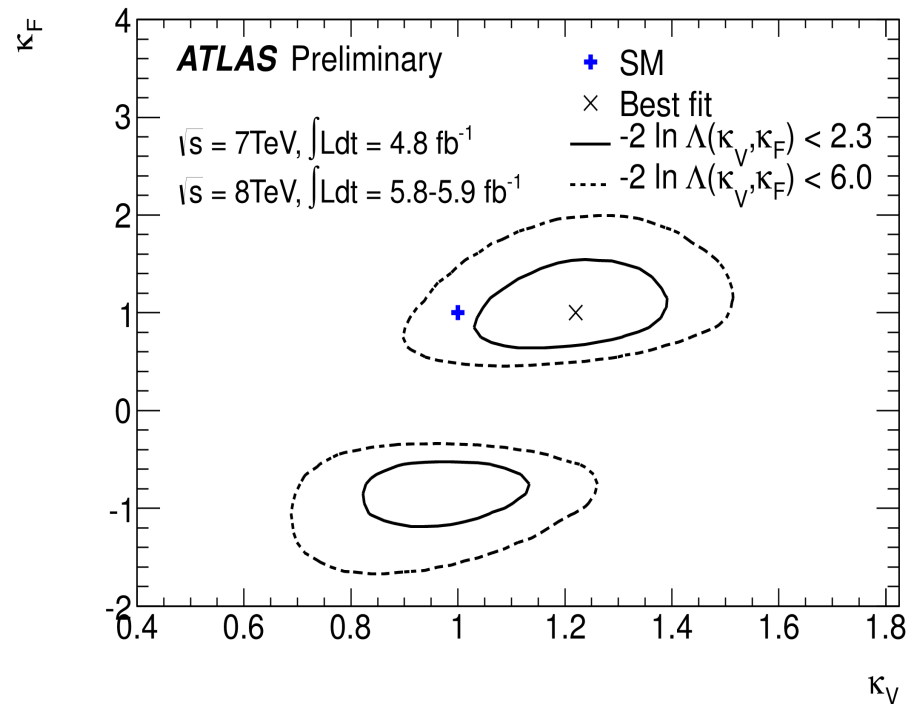
Combination of couplings

Assuming K_F scaling of all fermion couplings and K_V scaling of all vector boson couplings

CMS-HIG-12-045



ATLAS CONF-2012-127



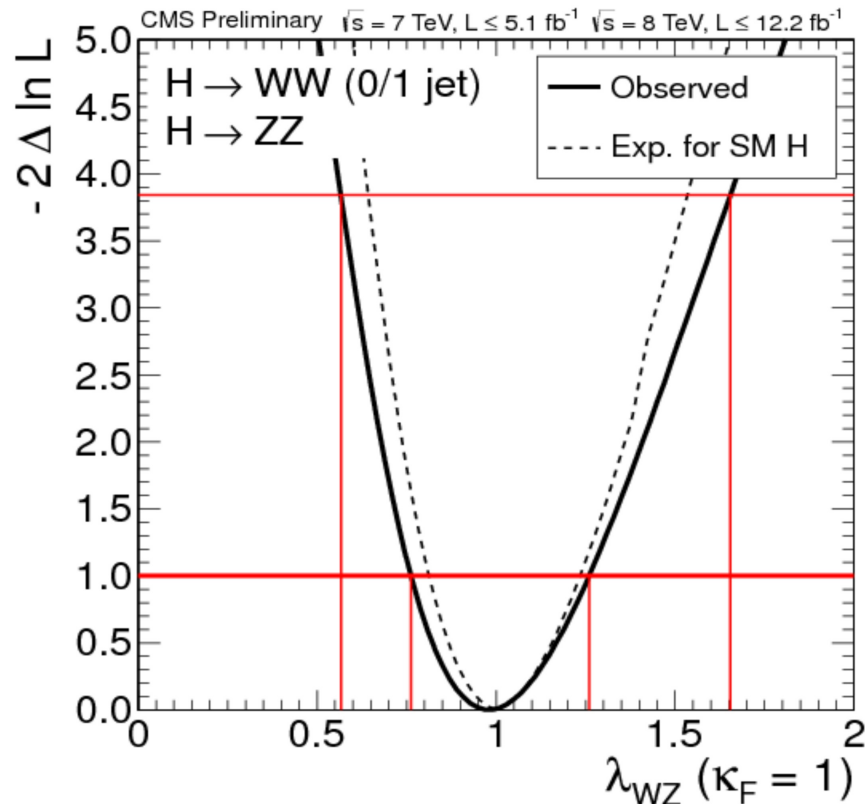
● **positive Yukawa** → **SM solution is out of 1σ region**

● **negative Yukawa** → **far from SM solution → dramatic implications for EWSB (see next slides)**

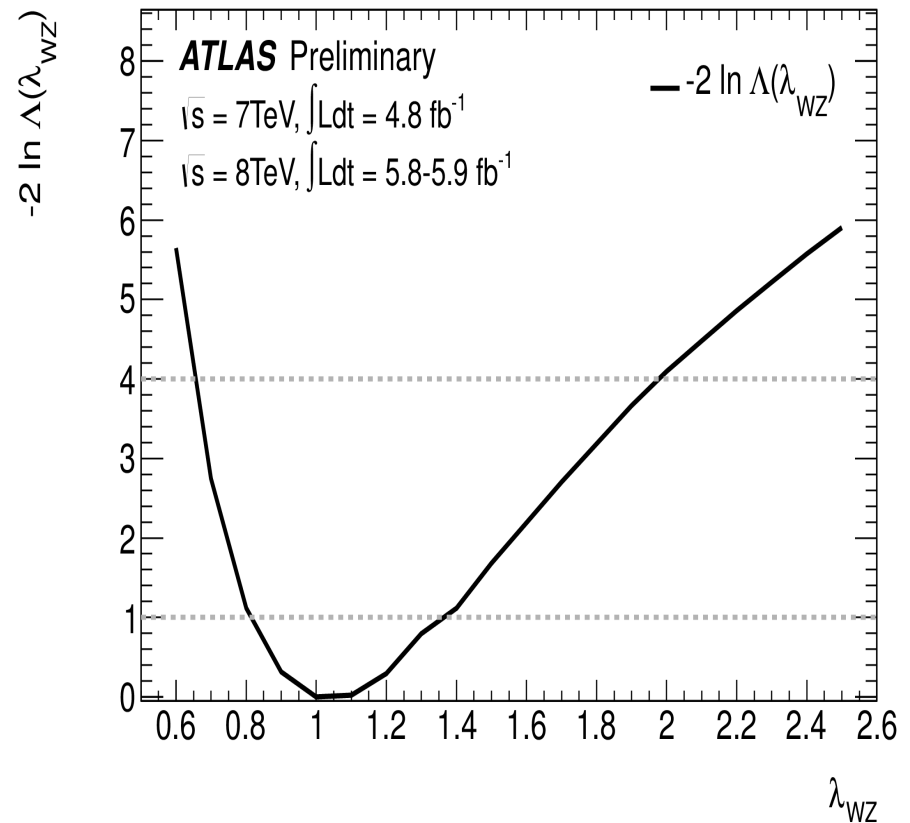
Test of Custodial Symmetry

- parametrization $\lambda_{WZ} = K_W / K_Z$ scaling of vector boson couplings
- results well consistent with SM
- $\lambda_{WZ} \in$ **CMS: [0.57 – 1.65]** **ATLAS: [0.65 – 2]** @ **95 % CL**

CMS-HIG-12-045



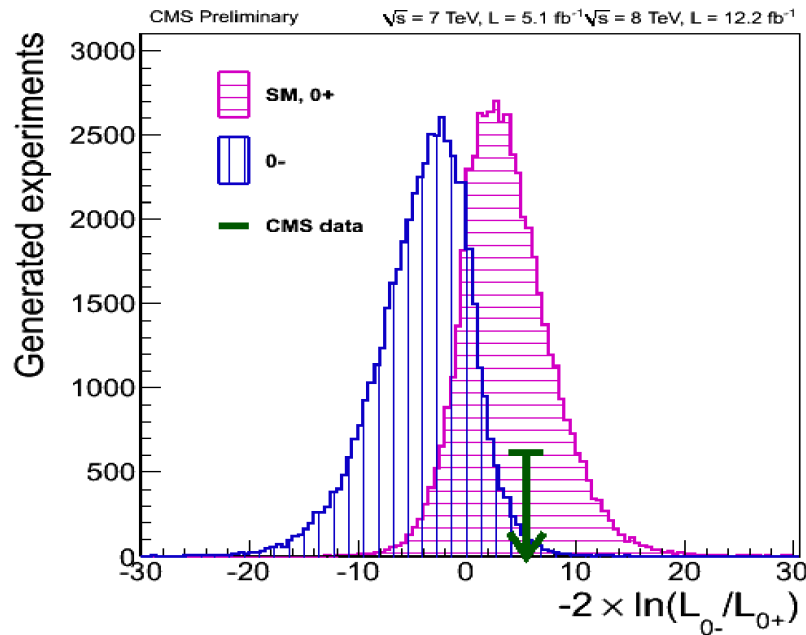
ATLAS CONF-2012-127



Main properties: spin and CP

■ couplings to photons → spin 0 or 2

■ leptons kinematic distributions in $H \rightarrow ZZ \rightarrow 4l$ decay used to discriminate $J^{PC} = 0^-$ and $J^{PC} = 2^+$ from $J^{PC} = 0^+$



CMS-HIG-12-045

◆ Expected distribution of the test statistics comparing the signal J^P hypotheses: 0^- vs 0^+
Observed value indicated by the arrow

◆ data disfavor pseudoscalar hypothesis (with a CL_s of 2.4 %)

What did we learn so far ?

- a new particle (elementary ?) with mass 125 GeV **exists**
- it is consistent with SM Higgs boson, considering its main decay channels $H \rightarrow WW$, $H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$
- observed decay $H \rightarrow \gamma\gamma$ rules out the **spin-1 hypothesis**
- spin 0 or 2 allowed $\rightarrow$ pseudoscalar disfavored
- decay $H \rightarrow \gamma\gamma$ looks higher than SM $\rightarrow$ **hint of new physics ?**
- more statistics is needed in order to assess a non-zero measurement of $H \rightarrow bb$ and $H \rightarrow \tau\tau$
- Tevatron sees a **2.9σ** excess in **bb production**, compatible with presence of $H \rightarrow bb$ with mass in the range **120 – 139 GeV**

Why not being happy with SM Higgs boson?

- mass is in the favored Higgs mass range of EWPT
- $\sigma \times \text{BRs}$ well consistent with SM predictions !!!
- SM is a renormalizable theory in principle valid up to Planck mass M_p

Theoretical arguments in favor of New Physics

- quantum instability of Higgs mass $\rightarrow$ sensitivity to $(\text{UV cutoff})^2$
(cutoff scale is identified with mass of heavy particles coupled to Higgs)
- this is at the origin of what we call the fine-tuning problem
- Cosmological constant problem is similar (but worst)
- Solving the fine-tuning problem has been the guide for BSM theories
- But...maybe the fine-tuning problem is a ill-defined problem ?

■ **Phenomenological arguments in favor of NP BSM:**

- huge hierarchy of fermion masses and mixing (origin of Yukawa couplings ?) → **flavor hierarchy problem**
- missing Dark matter candidate (as WIMP) in the SM
- not enough ~~CP~~ source for matter-antimatter asymmetry of Universe

■ **BSM theories aim to solve the Higgs fine-tuning problem**

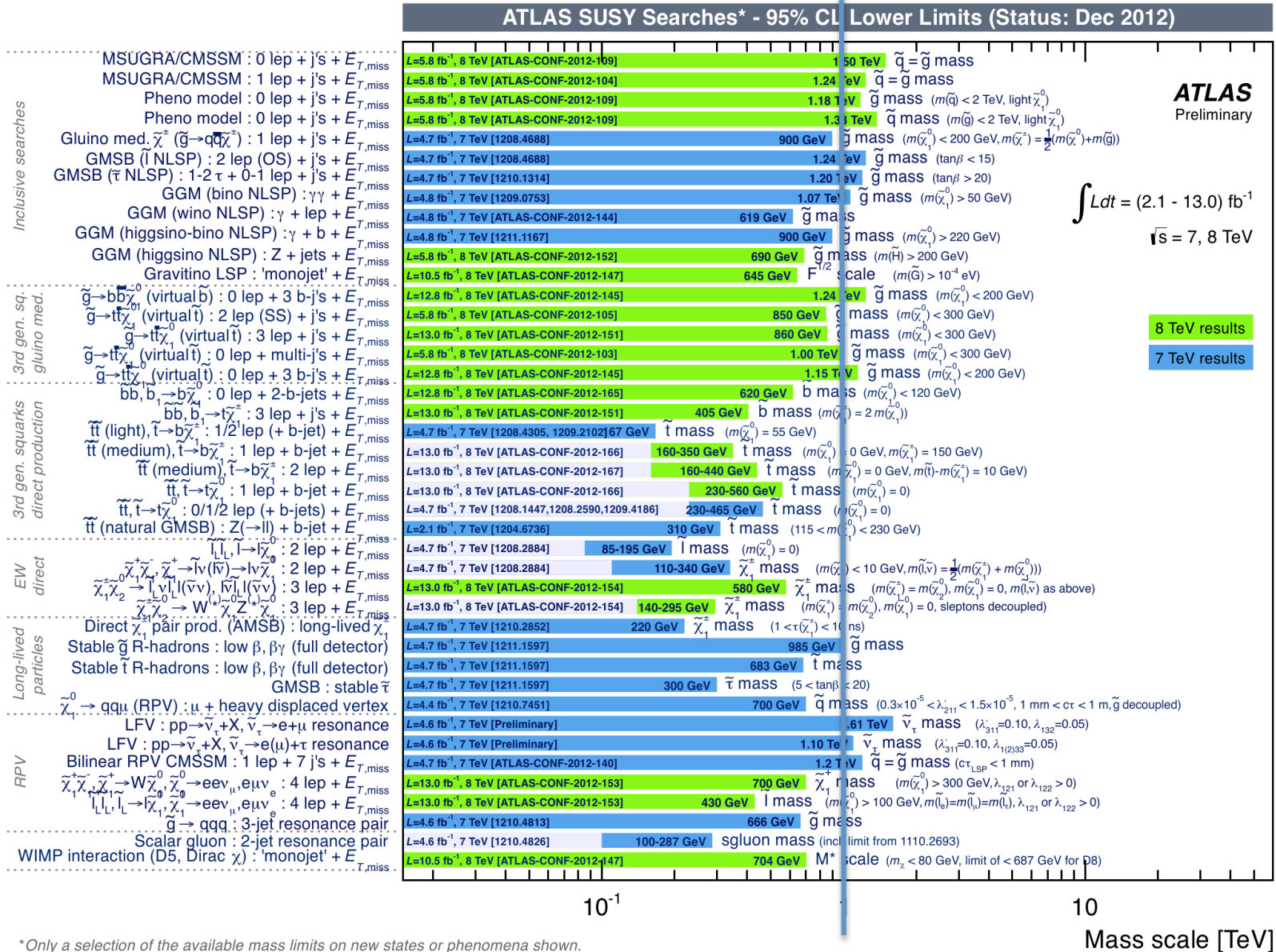
main approaches proposed so far:

- **Elementary Higgs boson** → **symmetry that cancels Λ^2 terms**
(SUSY models, Lee-Wick SM (SM replica with massive ghosts))
- **Elementary Higgs boson** → **UV scale lowered at TeV scale**
(quantum gravity models in large extra-dimensions)
- **Composite Higgs boson** → **strongly coupled NP sector,**
(Technicolor, composite Higgs boson as pNGB)

Current status of SUSY searches

1 TeV

squarks & gluinos
3rd gen squarks
EW direct
LL RP
Long-lived particles
RPV
Oth er



Higgs mass impact on SUSY models (MSSM)

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

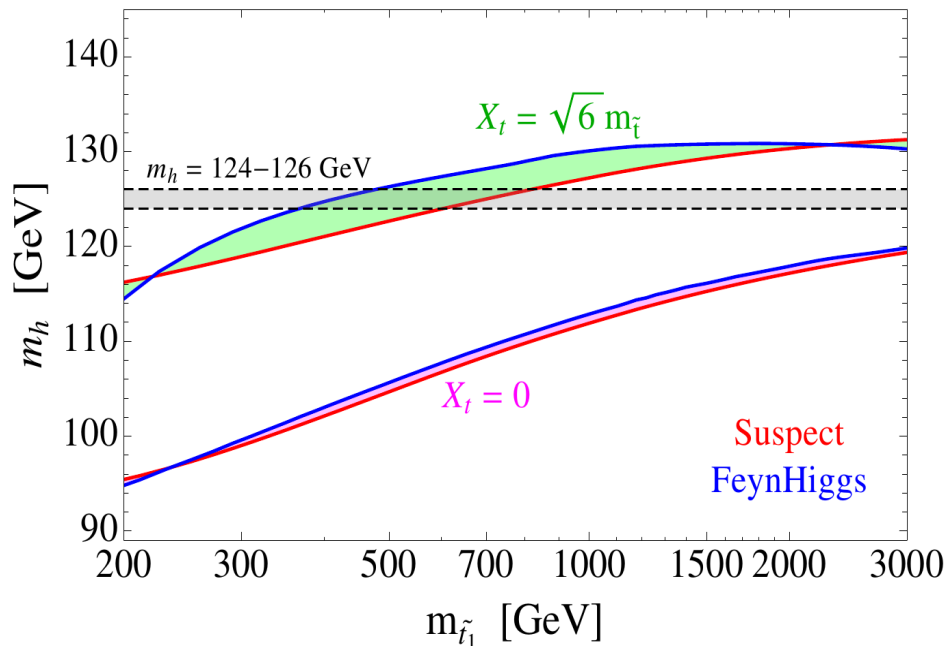
~ 85 GeV

large Higgs mass implies SUSY badly broken

at large $\tan\beta \rightarrow$
$$\delta_t \approx \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left[\ln \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12m_{\tilde{t}}^2} \right) \right]$$

$M_H=125$ GeV requires heavy squarks

MSSM Higgs Mass



Large mixing $\rightarrow$ heavy stops

$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700 \text{ GeV}$$

$\rightarrow$ fine-tuning O(1%) on EWSB condition

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

MSSM fine tuning

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2} (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \ln \left(\frac{\Lambda}{m_{\tilde{t}}} \right)$$

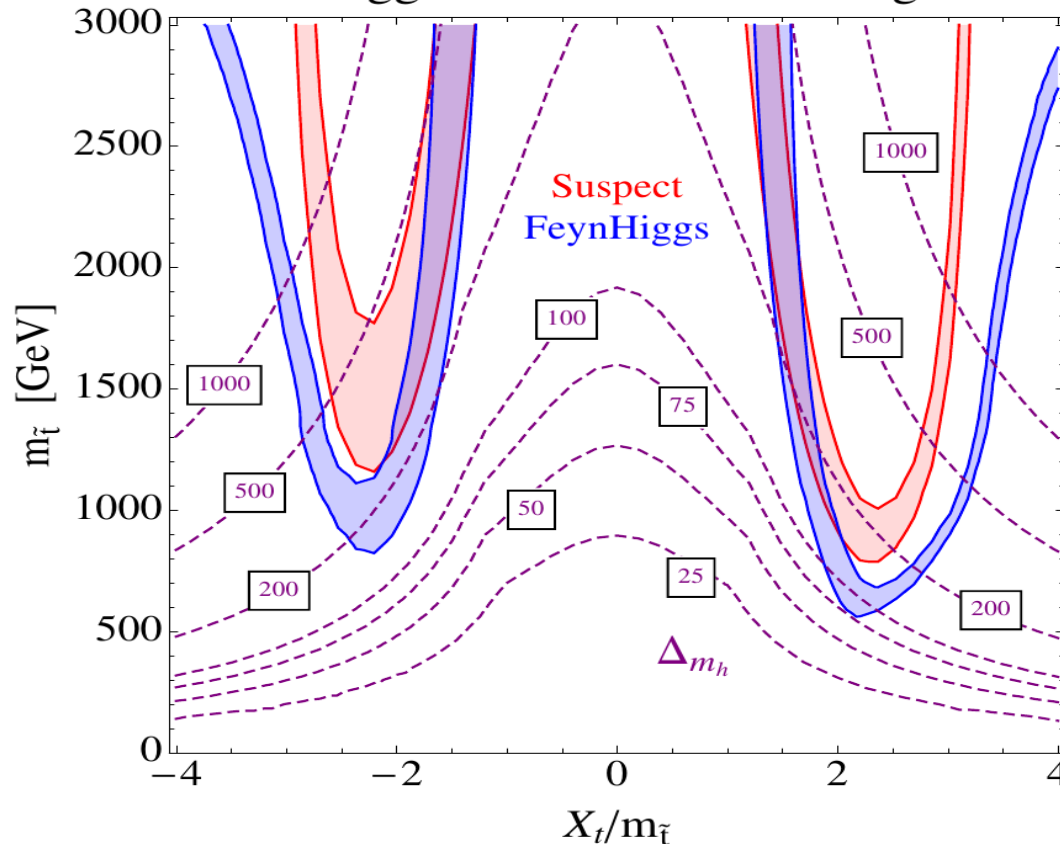
Λ scale of SUSY breaking

■ for large squarks $\delta m_{H_u}^2$ becomes too large

■ fine tuning is needed to achieve EWSB

$$\Delta_{m_h} = \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right|$$

Higgs Mass vs. Fine Tuning



■ maximal mixing required to avoid multi TeV stops

■ difficult to achieve in SUSY breaking scenarios

■ $\Delta_m > 75$ (100) in order to achieve $M_H = 124$ (126) GeV for $\Lambda = 10$ TeV

■ fine-tuning much worst for higher Λ scales

Natural SUSY with $M_H = 125$ GeV

Why SUSY should be simple MSSM ?

NMSSM → additional new singlet S → μ -term naturally generated by $\langle S \rangle$

$$\boxed{W \rightarrow \lambda S H_u H_d}$$

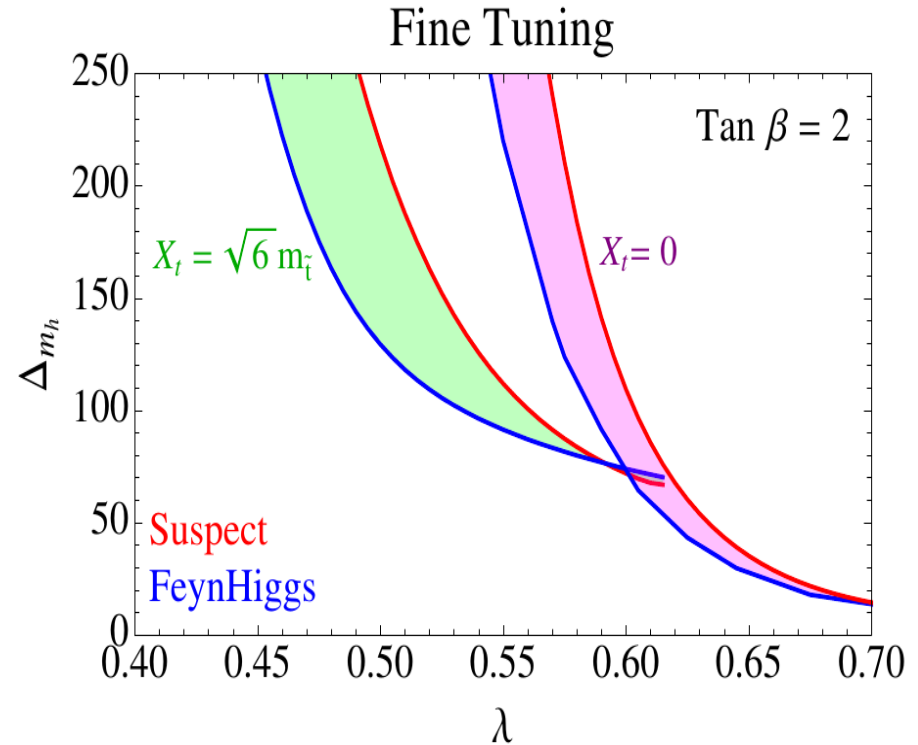
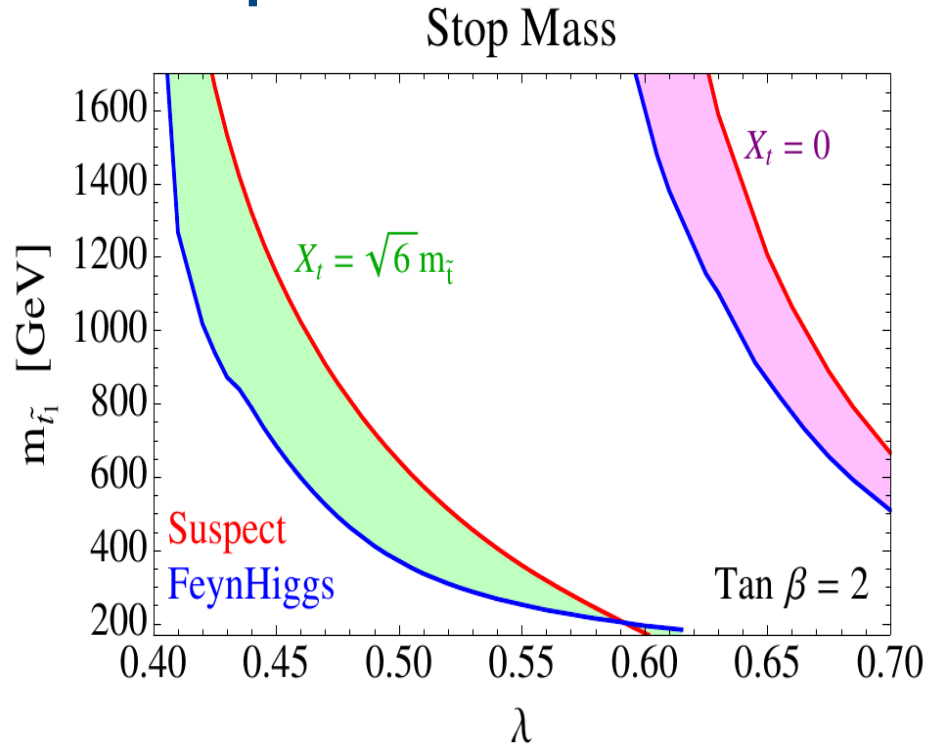
no dimensionfull terms
in the W superpotential

$$(m_h^2)_{\text{tree}} \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

- ◆ potentially reducing the fine-tuning problem
- ◆ however for large values of $\lambda > 0.7$ the theory becomes non-perturbative
- ◆ for $\lambda < 0.7$ theory is perturbative up to GUT scale

NMSSM perturbative

Hall, Pinner, Ruderman JHEP 1204 (2012)



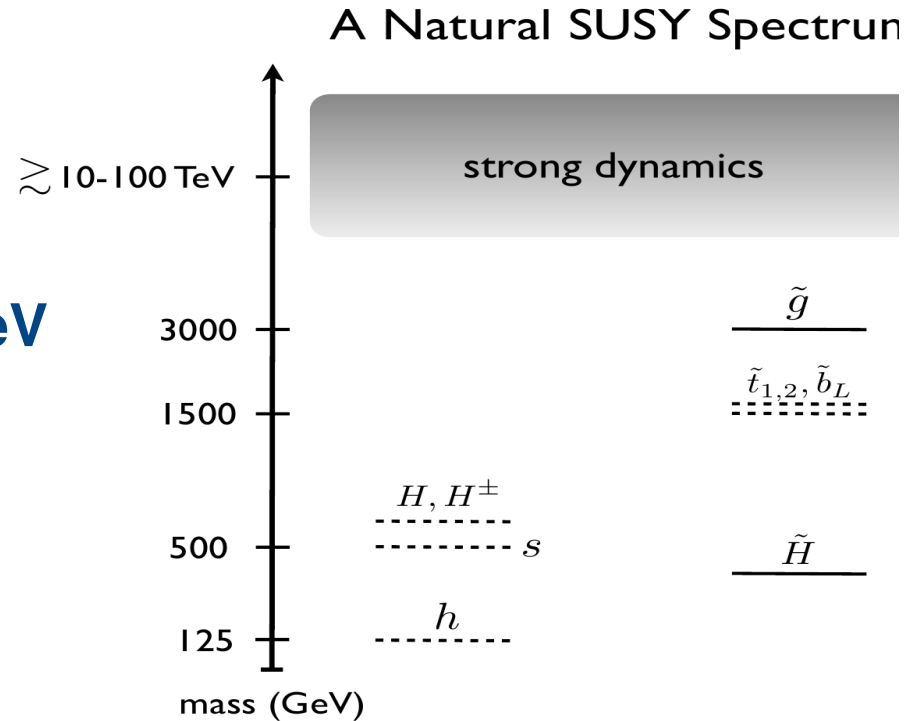
- ◆ large values of λ allow for lighter stops and much less fine tuning
- ◆ only 5 – 10 % tuning if mediation scale of SUSY breaking is low and stop mixing is non-maximal
- ◆ achieved with $\tan \beta \sim 2$ and $\lambda \sim 0.7$, but very close to the edge of perturbative regime

Naturalness in large λ -SUSY scenario

- Higgs mass can be still **125 GeV** with $\lambda > 2$ but strong dynamics expected at **10-100 TeV**

- stops mass can be ~ 1.5 TeV

- gluino as heavy as 3 TeV

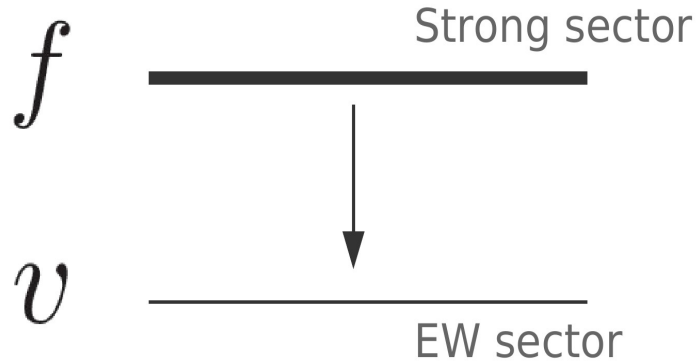


Hall, Pinner, Ruderman JHEP 1204 (2012)

- Interesting **non-decoupling effects** among Higgs-doublets:
 - suppresses the coupling of light Higgs to b-quarks
 - enhancing rates of $\gamma\gamma$ and WW and depleting rates of bb and $\tau\tau$

Composite Higgs models

$$\xi = \frac{v^2}{f^2} < 1$$



Higgs boson is a bound state of a new strongly interacting sector → Pseudo Nambu-Goldstone Boson

Mass protected by its PNGB nature

Strongly Interacting Light Higgs (SILH)

- ◆ Light composite Higgs as PNGB from strongly interacting sector (SIS)
- ◆ Higgs mass is acquired by interactions of SIS with SM fields
- ◆ Various realizations in specific models (Holographic Higgs as PNGB, Little Higgs, etc) Arkani-Hamed, Cohen, Georgi (2001), Arkani-Hamed, Cohen, Katz, Nelson (2002), Contino, Nomura, Pomarol (2003)
- ◆ Low energy effective Lagrangian parametrization in terms of two parameters: coupling g_ρ and mass m_ρ of the strongly interacting sector Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007)

$$m_\rho = g_\rho f$$

Characteristic parameters
f = scale of sigma-model

$$\xi \equiv \frac{v^2}{f^2}, \quad v = \left(\sqrt{2} G_F \right)^{-1/2} = 246 \text{ GeV}$$

- Expected small modifications to the SM Higgs couplings
- New operators in Higgs self-coupling suppressed by $1/m_\rho$

- Expected violation of unitarity in $VV \rightarrow VV$ scattering

$$\begin{aligned}
 g_{hWW} &= gm_W \left[1 - \frac{c_H}{2} \xi \right] , \\
 g_{hff} &= \frac{gm_f}{2m_W} \left[1 - \xi \left(\frac{c_H}{2} + c_y \right) \right] , \\
 g_{hhh} &= \frac{gm_H^2}{4m_W} \left[1 + \xi \left(c_6 - \frac{3c_H}{2} \right) \right]
 \end{aligned}$$

**C_i parameters of order $O(1)$
model dependent**

- Higgs does not balance completely the $VV \rightarrow VV$ amplitude**
- Scale of unitarity breaking higher than in no-Higgs**

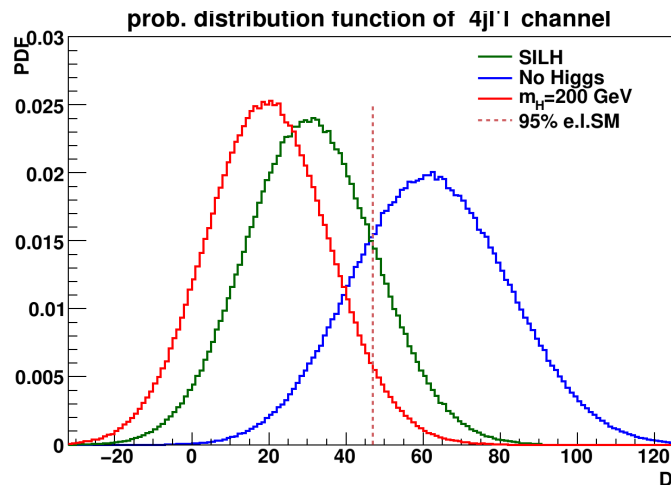
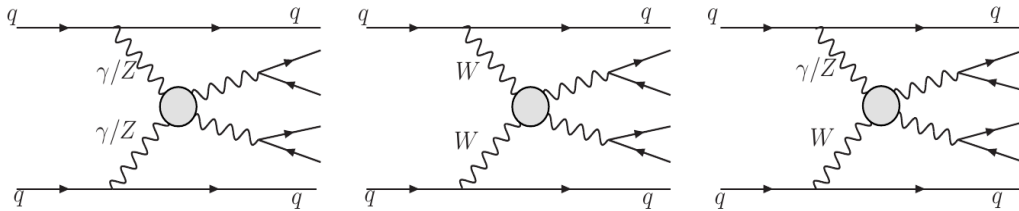
$$\sigma(pp \rightarrow V_L V'_L X)_{c_H} = (c_H \xi)^2 \sigma(pp \rightarrow V_L V'_L X)_H$$

- Unitarity recovered by exchange of heavy resonances**

◆ new resonances are predicted in Composite Higgs models → heavy vector-resonance ρ like in QCD, composite partners of top

◆ rich phenomenology expected at LHC

◆ Possible to distinguish SM Higgs from Higgsless and SILH via $VV \rightarrow VV$



$4j l^+ l^-$ channel

SILH with $c_H \xi = 1$

L=200/fb, LHC 14 TeV
sum over ee and $\mu\mu$ final states

D=actual number of events founds in the peak taking into account stat. fluct,

Ballestrero et al., JHEP 0911 (2009)

$$D = B + S - \overline{B}$$

Limits on Higgs compositeness

- Limits **from couplings measurement** of low mass Higgs h_{126}
 - > **LHC: $4\pi f > 5-7$ TeV** if no deviations observed
 - > **ILC: $4\pi f > 30$ TeV**
- Direct analysis of **VV scattering and double Higgs production at LHC:**
 - > $4\pi f > 4$ TeV (**direct probe of SILH scenarios**)
- **At LHC direct search of ρ** important at small g_ρ
 - > able to push m_ρ at 1 TeV-2 TeV, ie $4\pi f > 3-4$ TeV
but **less effective at high g_ρ**
- **At ILC the test of aTGC** can constraint $m_\rho > 7-8$ TeV

More exotic scenarios

...what if Higgs boson is only responsible for **M_w**, **M_z** but not of fermion masses ?

- fermion masses $\neq 0 \longrightarrow$ **Chiral Symmetry Breaking**
- in SM, **ChSB** and **EWSB** ($M_w, M_z \neq 0$) are generated by the Higgs mechanism at the same scale $\sim v_{\text{ev}} = \langle H \rangle$
- not (yet) any direct experimental evidence supporting the existence of **tree-level Yukawa couplings** Y_f
- present measurements of $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$ decays have large errors $\rightarrow$ still compatible with vanishing Yukawas
- a direct measurement of top quark coupling ($t\bar{t} H$) is missing
- **ChSB** and **EWSB** can have different mechanisms:
ChsB $\rightarrow$ compositeness, **extra-dimensions**, **technicolor...**

Naive **Fermio-P**hobic Higgs scenario



- **NO** Yukawa couplings at **tree-level**
- Higgs mechanism gives mainly rise to **EWSB** and M_W, M_Z
- but is **not** responsible for **ChSB** and fermion masses

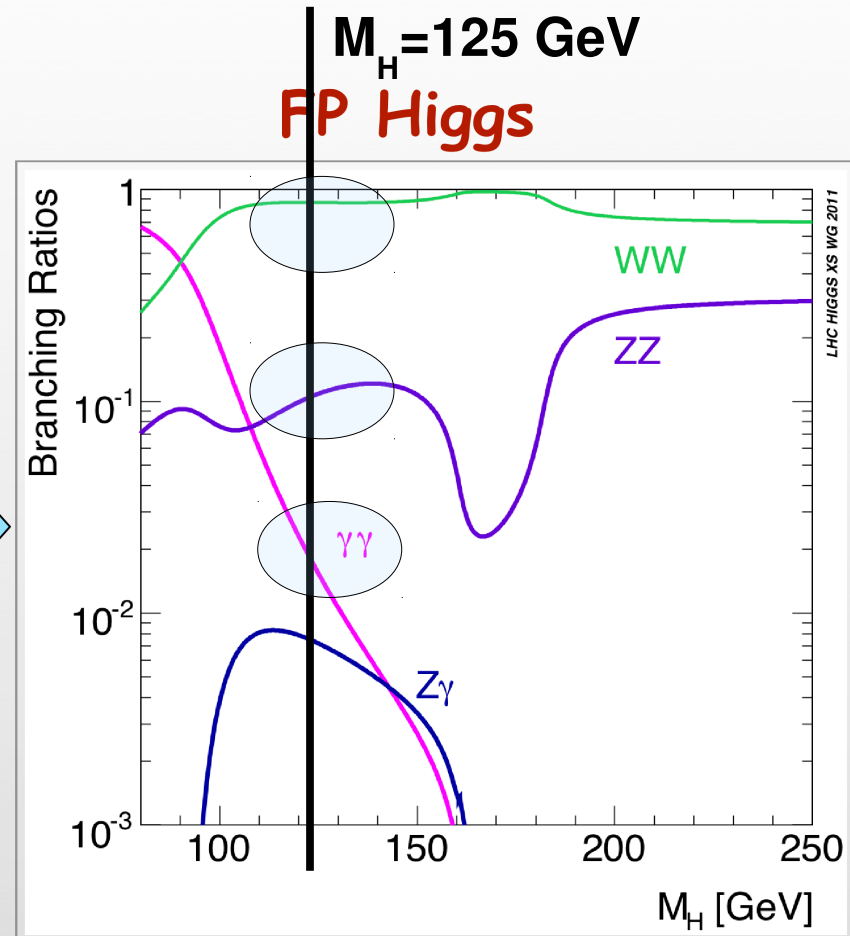
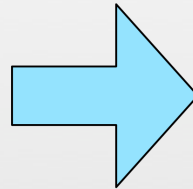
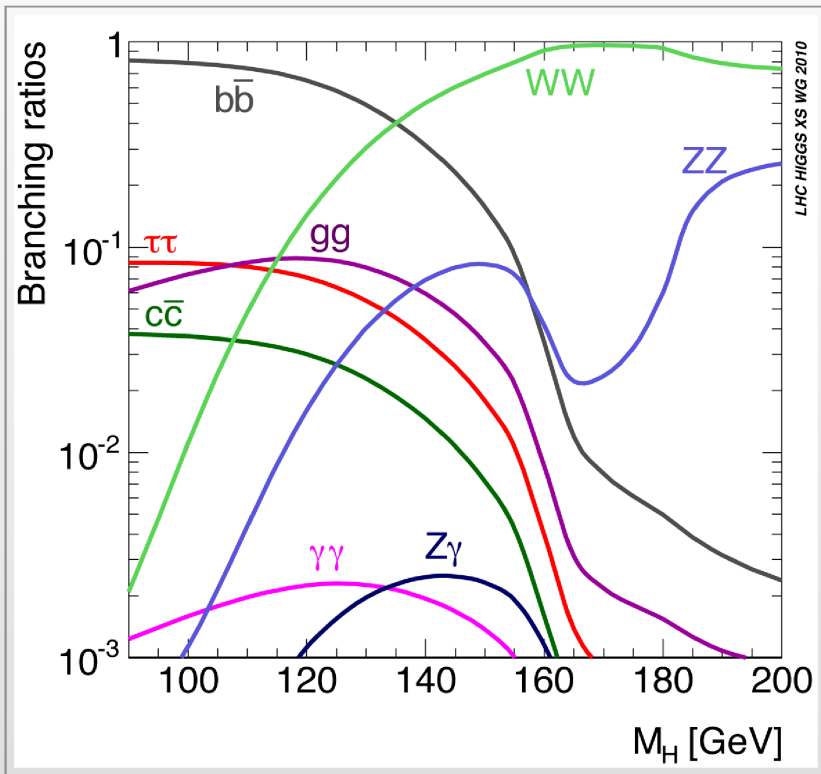
Advantages

- **Fermiophobia** lowers the vacuum stability bound on Higgs
- $M_H = 125$ GeV consistent with no NP below Planck scale

Higgs decays : FP vs SM

$H \rightarrow WW, ZZ, \gamma\gamma, Z\gamma$ [through W loops (no-top loops)]

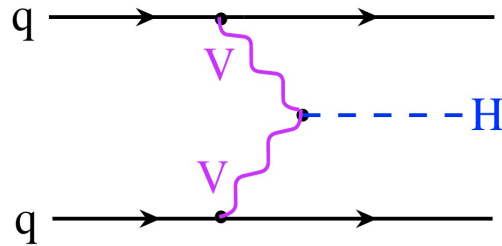
SM Higgs



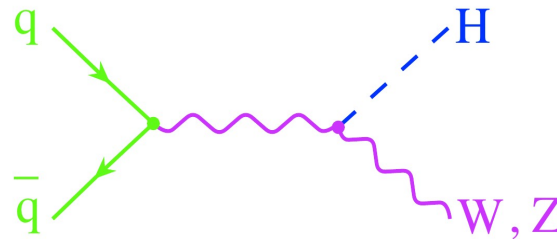
For $M_H \sim [100, 110, 125]$ GeV :
 $BR(\gamma\gamma)_{FP} \sim [110, 30, 7] \times BR(\gamma\gamma)_{SM}$

Naive Fermio-**P**hobic Higgs production mechanisms

VBF

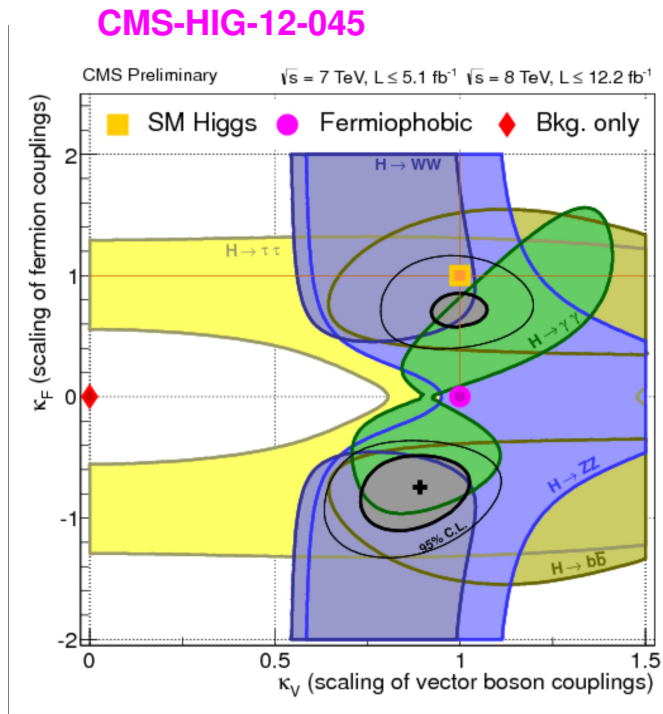


VH



- no gluon-gluon fusion
- **VBF** fusion dominant mechanism
- harder **pT** spectrum → better **S/B** !

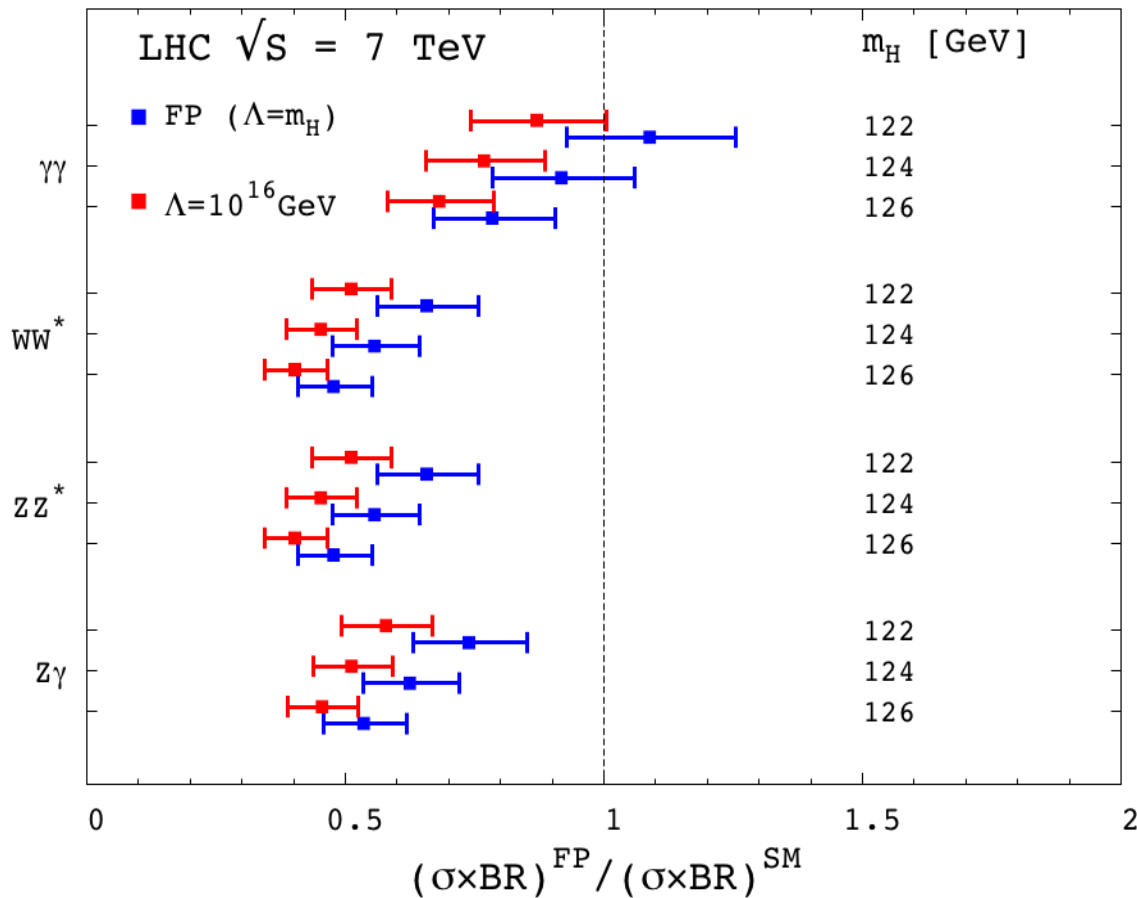
Naive FP Higgs with $M_H=125$ GeV excluded at 99 % CL



- NFP Higgs predicts $\mu=1$ @ $M_H=123$ GeV
- higher μ predicted in $WW, ZZ, \gamma\gamma$ when VBF and VH tagging are applied
- observed rates in VBF and VH are much smaller.

- above results do not take into account effect of **Radiative Corrections**
- **RC** can suppress BRs of $H \rightarrow \gamma\gamma, WW, ZZ$ (depending on the NP scale Λ where Yukawa's are assumed to be vanishing)
- Yukawa couplings cannot be kept vanishing at any scale
- fermion masses $\longrightarrow$ Yukawa radiatively generated EG, Mele, PRD 82 (2010)

Inclusive production



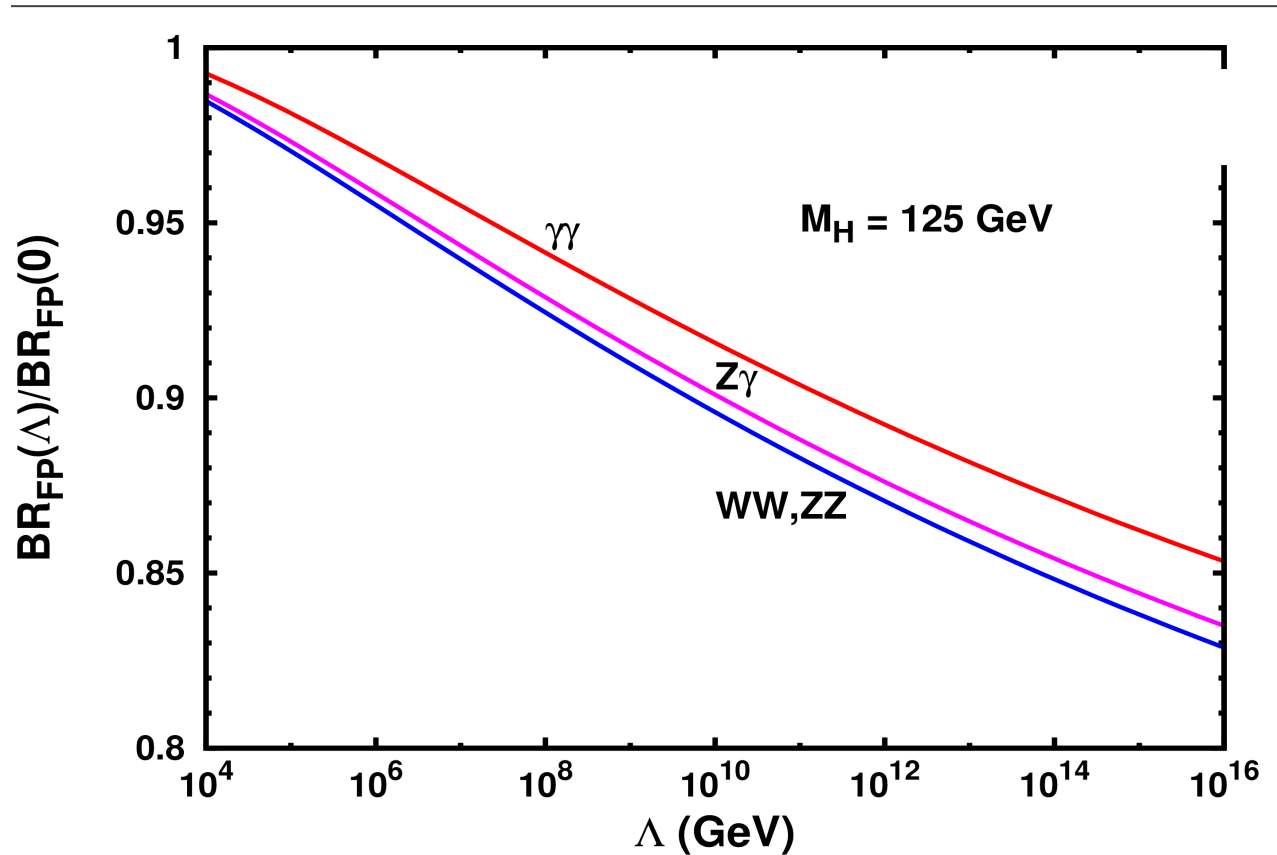
EG, B. Mele, M. Raidal PLB 716 (2012)

Naïve FP predicts $\mu = 1$ @ $M_H = 123$ GeV, while RC can reduce it

$\Lambda \rightarrow$ scale where Yukawa couplings are vanishing

Effects of radiative corrections on

$\text{BR}_{\text{FP}}(\Lambda) / \text{BR}_{\text{FP}}(0)$: $M_H = 125 \text{ GeV}$



reduction < 10 - 20% for $\Lambda \sim 10^{10} - 10^{16} \text{ GeV}$

Can SUSY be ruled out if we find that Yukawa couplings are vanishing at tree-level ?

■ Vanishing Yukawa's in MSSM

- impact on MSSM would be dramatic
- whole MSSM strongly disfavored !
vanishing Yukawas  $M_H < M_Z$

■ switching off Yukawa couplings in MSSM is not as smooth as in SM

■ supersymmetry as an effective low energy theory → NMSSM viable (but not renormalizable)

Failure of MSSM in the FP limit

Fermiophobic limit: $y_t \rightarrow 0$

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

- we cannot get $m_H > m_Z$ and even more ~ 125 GeV
- $m_H < m_Z \longrightarrow$ MSSM is ruled out
- FP Higgs if SUSY $\rightarrow$ cannot be just MSSM-like

Advantages of SUSY Fermiophobia

- **Fermiophobic Higgs** can cure some SUSY problems
- **fine-tuning problem** of SUSY induced only by gauge couplings → fine-tuning improved by a factor

$$N_c y_t^4 / g^4 \sim 25.$$

- removes **little SUSY hierarchy problem**
- squarks and sleptons masses of **2-3 TeV** become now completely Natural
- **FCNC** and **CP problems** automatically solved
- SUSY effects in FCNC processes much suppressed

Fermiophobic NMSSM viable

EG, Kannike, Mele, Racioppi, Raidal, PRD 86 (2012)

Z_3 symmetric FP NMSSM superpotential

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

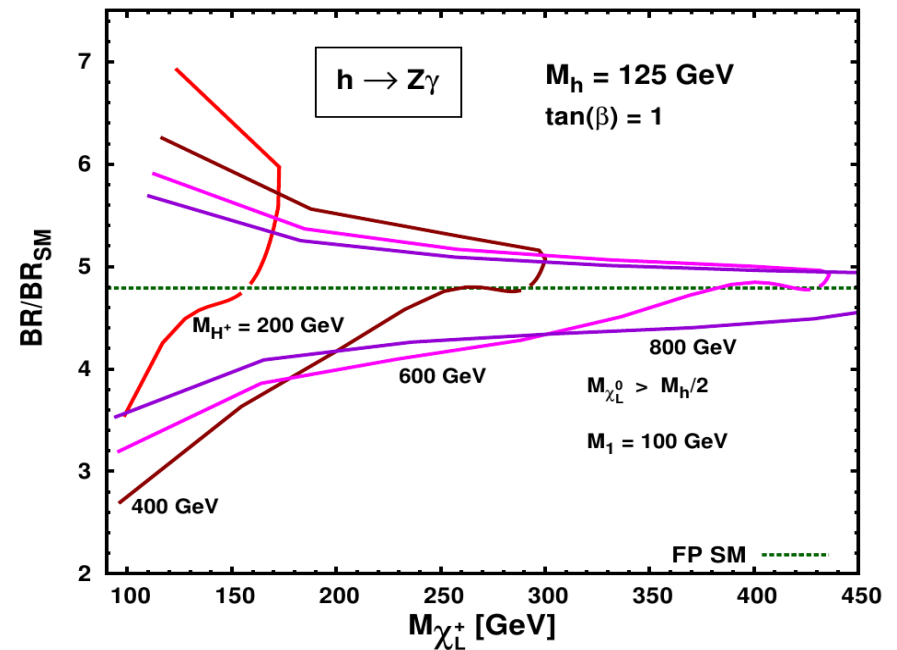
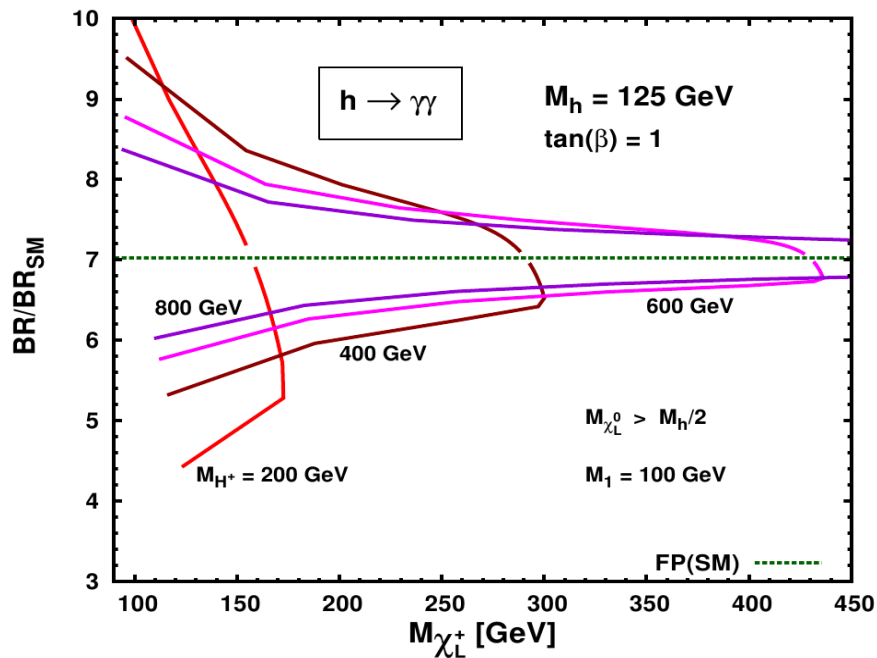
and S, H_u, H_d soft terms

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

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 $X_f = 0 \Rightarrow \boxed{y_f, a_f = 0}$

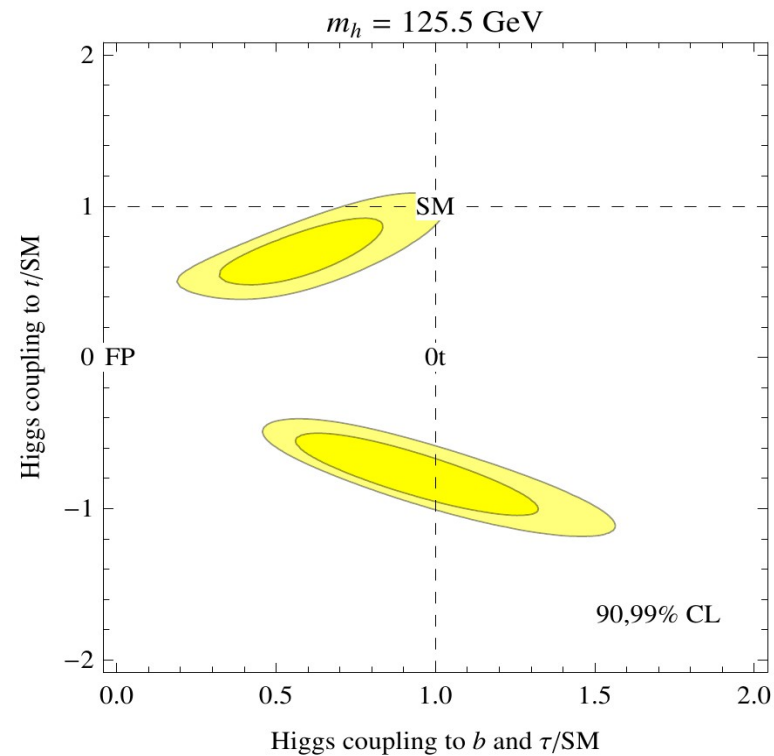
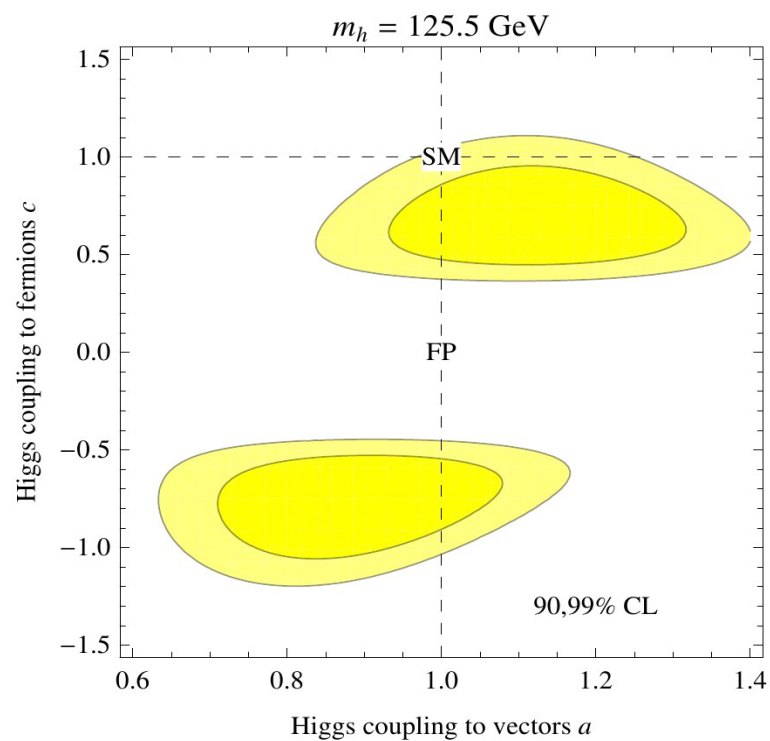
But also other possible configurations (see 1204.0080)



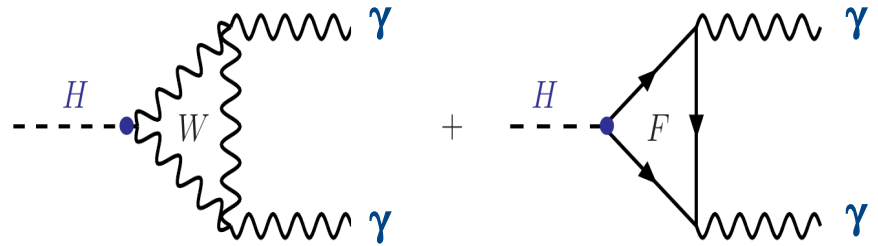
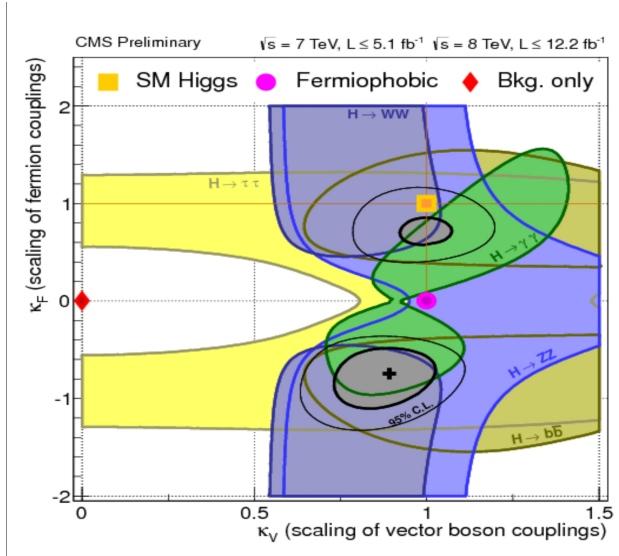
- BR($H \rightarrow \gamma\gamma$) can be decreased → reducing the tension in VBFxBR($\gamma\gamma$) rates
- but without **ggH coupling** the **FB NMSSM** is disfavored by observed inclusive production rates of $H \rightarrow \gamma\gamma$ (which requires a ggH coupling)
- but **ggH coupling** can be generated by loop of squarks alone !
- This requires large **A-terms** if Yukawa couplings are vanishing
(EG, Racioppi work in progress)
- FP NMSSM** would require a completely new strategy search at LHC

Wrong sign in Yukawa couplings: $Y_f \rightarrow -Y_f$
(suggested by the fits)

cure: requires new physics at TeV scale



Giardino, Kannike, Raidal, Strumia, PLB 718 (2012)



■ Negative solutions for K_F mainly comes from $H \rightarrow \gamma\gamma$

■ $\text{Sign}[A_{1/2}^H(\text{loop of top})] = -\text{Sign}[A_1^H(\text{loop of } W)]$

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2 \quad \tau_i = M_H^2 / 4M_i^2$$

■ Changing the sign of top-Yukawa coupling improves the fit in $H \rightarrow \gamma\gamma$: destructive interferences turn out to be constructive

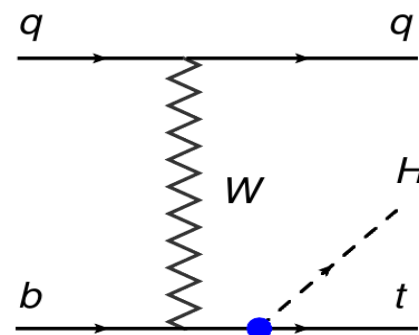
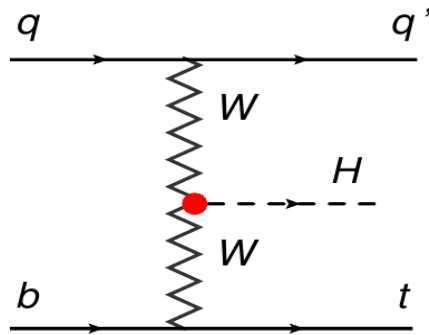
● Is any process allowing to directly constrain the sign of top-Yukawa coupling ? → **YES**

How to disentangle the sign of top Yukawa coupling

- Flipping the sign of Yukawa couplings has dramatic consequences for the EWSB
- relative sign of Hff and HWW couplings is physical
- unitarity and renormalizability are spoiled
- unitarity in $V_L V_L \rightarrow f f \rightarrow$ recovered by adding new weakly interacting resonances (Higgs-boson-like) or by infinite tower of strongly coupled resonances
- If the scale of unitarity violation is high enough then the low energy processes should be insensitive to UV-completion

Sensitive process to the sign of top-Yukawa

Biswas, EG, Mele JHEP 1301 (2013)



$q b \rightarrow t q' H \rightarrow t q' \gamma \gamma$ with signature of $H \rightarrow \gamma \gamma$

Two scenarios considered

- Universal Yukawa rescaling** that is assuming just one free parameter $C_f = C_t$ (and $C_V = 1$) both in production and decay amplitudes. $BR_{\gamma\gamma}$ is then a function of C_t , which enters both the $H \rightarrow \gamma\gamma$ width and the Higgs total width through C_f ;
- C_t and $BR(\gamma\gamma)$ as independent parameters** $C_V = 1$), with C_t affecting only production cross sections, and $BR_{\gamma\gamma}$ describing the overall effect of new physics on the Higgs decay rate.

SM total $\sigma \times \text{BR}(\gamma\gamma)$ is small

$$\sigma(q b \rightarrow t q' H)^{SM} \simeq 15.2 \text{ fb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$

$$\sigma(q b \rightarrow t q' H)^{SM} \simeq 71.8 \text{ fb} \quad \text{at } \sqrt{s} = 14 \text{ TeV}$$

$$\text{BR}_{\gamma\gamma}^{SM} \simeq 2.29 \cdot 10^{-3}$$

■ For $C_F < 0 \rightarrow \sigma$ expected to grow up due to unitarity breaking

■ $\text{BR}(\gamma\gamma)$ mostly sensitive to a reduction of magnitude $|C_F|$

$$\Lambda = 12\sqrt{2}\pi \frac{v^2}{m_t |c_F - c_V|} \sim 9.3 \text{ TeV}$$

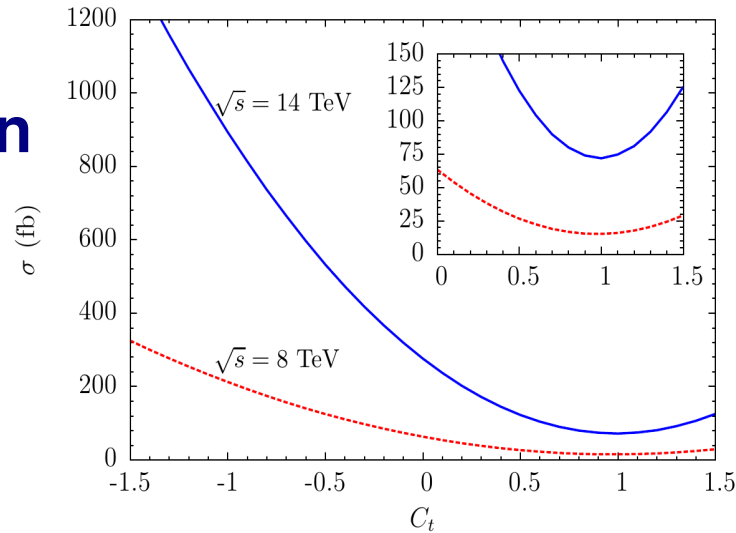
↓
scale of unitarity breaking

Farina, Grojean, Maltoni, Salvioni, Thamm 1211.3736

↙
same process but with $H \rightarrow b\bar{b}$ signature

Enhancement factors versus C_t

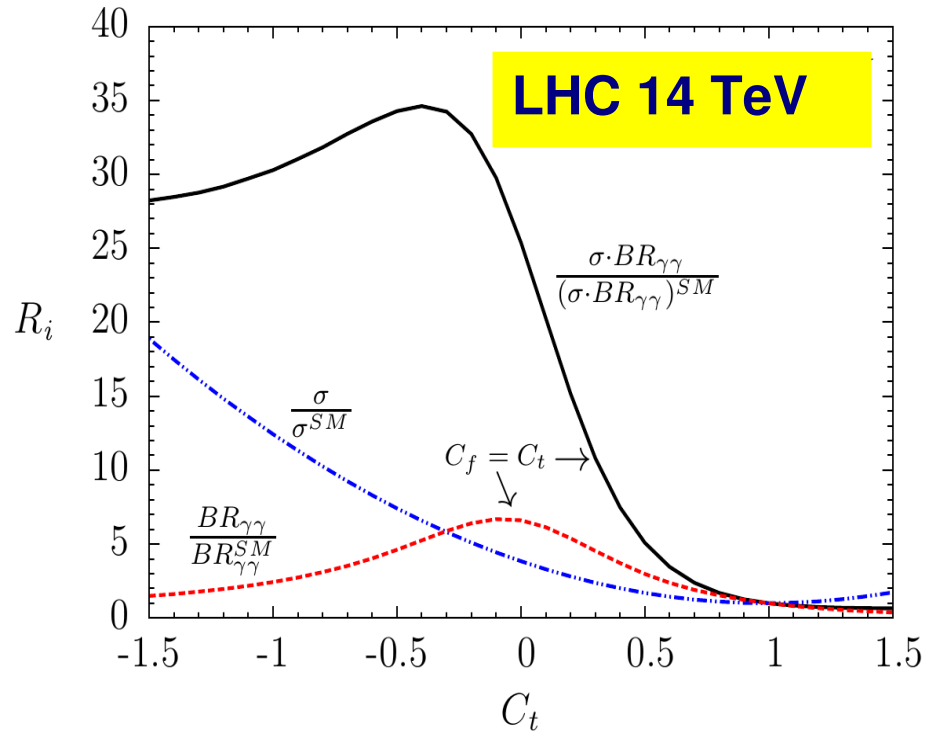
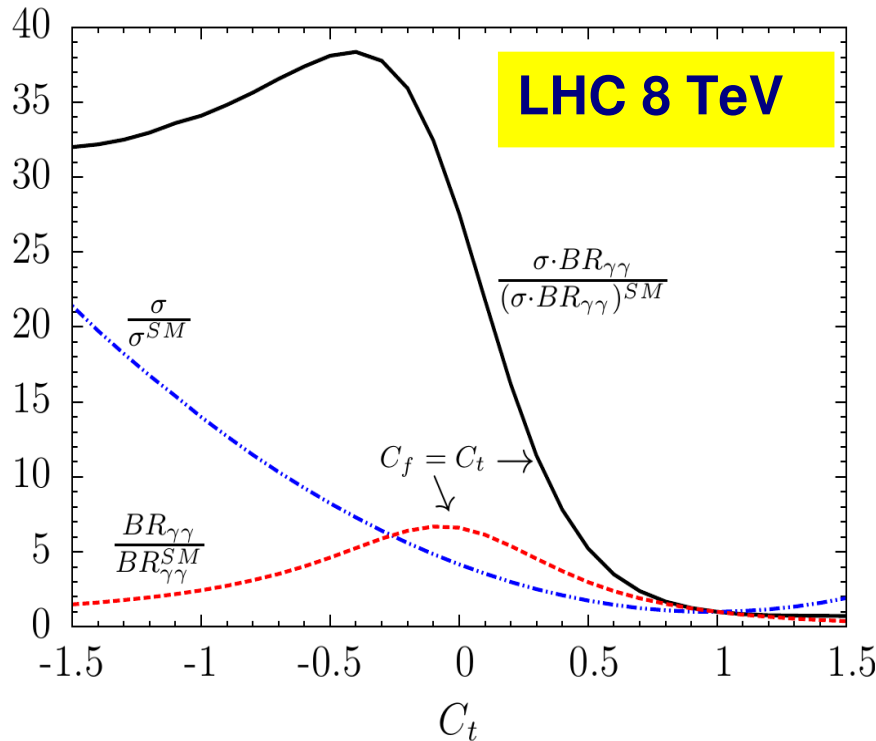
**Total cross section
 $pp \rightarrow t q H$**



SM $\rightarrow C_t = 1$

PDF = CTEQ6L1

R_i = Ratios



Irreducible backgrounds for $pp \rightarrow t \, q \, H (\rightarrow \gamma\gamma)$

■ we are looking for top decaying hadronically $t \rightarrow b \, q \, q'$

■ final state bckg consists of $\rightarrow 2 \, \gamma + b + (\geq 3 \, j)$

■ irreducibles bckg processes

$$pp \rightarrow 2 \, \gamma + t + j ,$$

$$pp \rightarrow 2 \, \gamma + \bar{t} t ,$$

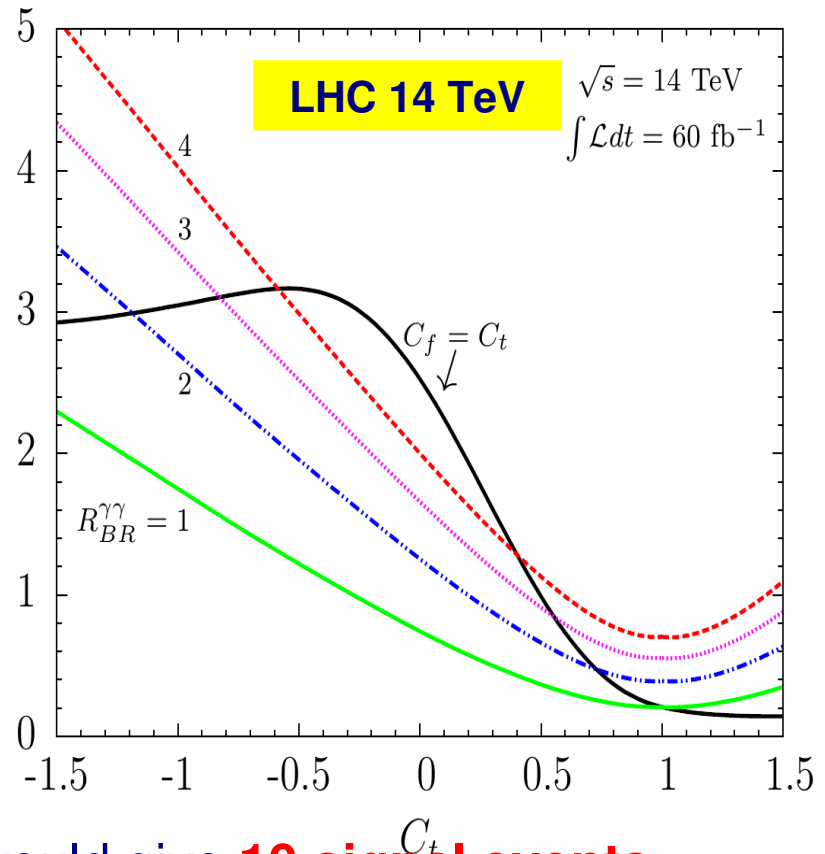
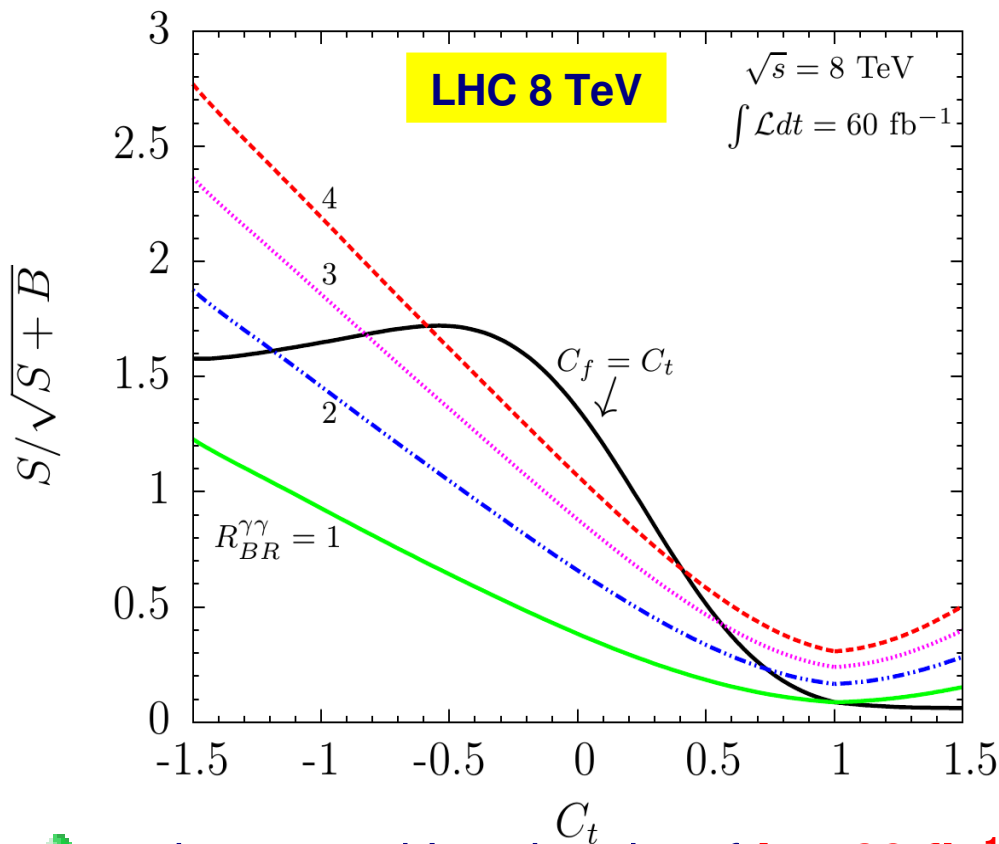
$$pp \rightarrow 2 \, \gamma + b + 3 \, j$$

■ optimized selection cuts

$$p_T^{\gamma_1} > 40 \, \text{GeV}, \quad p_T^{\gamma_2} > 30 \, \text{GeV}, \quad p_T^{j,b} > 25 \, \text{GeV}, \quad |\eta_{\gamma,b}| < 2.5, \quad |\eta_j| < 4.5$$

$$\Delta R_{i,j} = \sqrt{\Delta\eta_{i,j}^2 + \Delta\phi_{i,j}^2} > 0.4$$

◆ bckg well under control



- ◆ an integrated Luminosity of **$L = 60 \text{ fb}^{-1}$** would give **10 signal events** versus **0.3 of bckg** overall the negative range **$-1.5 < C_t < 0$**
- ◆ **SM would require HL-LHC to reach an observable event statistics**
- ◆ Including different decay channels can dramatically improve the significance already with data at 8 TeV (Biswas, Margaroli, Mele, work in progress)

**Can be the 125 GeV resonance an
Higgs-boson imposter?**

◆ **Spin-1 is ruled out** while **spin-2** case will be tested soon

◆ **Pseudoscalar case disfavored**

◆ **Let's focus on the case of a scalar-like imposter**

Low, Lykken, Shaughnessy PRD 86 (2012)

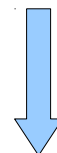
■ **EW singlet and a custodial singlet**



strongly disfavored



coupled to operator of dimension 4 (like dilaton, or graviscalar) i.e. to the trace of EMT $T_{\mu}^{\mu} \sim \text{masses}$



Coupled to operators of dim. 5, as $\phi F_{\mu\nu} F^{\mu\nu} / \Lambda$

■ **Not an EW singlet but a custodial singlet and neutral member of a custodial 5-plet**

→ could belong to an EW triplet of SU(2) (**triplet imposter**)

Dilaton imposter (χ) $\rightarrow$ same couplings as SM

$$\mathcal{L}_{\chi V_1 V_2} = c_{\chi V} \left(\frac{2m_W^2}{v} \chi W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v} \chi Z_\mu Z^\mu \right) \\ + c_{\chi g} \frac{\alpha_s}{12\pi v} \chi G_{\mu\nu}^a G^{a\mu\nu} + c_{\chi\gamma} \frac{\alpha}{8\pi v} \chi F_{\mu\nu} F^{\mu\nu} + c_{\chi Z\gamma} \frac{\alpha}{8\pi v s_w} \chi F_{\mu\nu} Z^{\mu\nu}$$

EW singlet imposter (s)

$$\mathcal{L}_{sV_1 V_2} = \kappa_W \frac{\alpha}{8\pi m_s s_w^2} s W_{\mu\nu}^+ W^{-\mu\nu} + \left(\kappa_W \frac{c_w^2}{s_w^2} + \kappa_B \frac{s_w^2}{c_w^2} \right) \frac{\alpha}{16\pi m_s} s Z_{\mu\nu} Z^{\mu\nu} \\ + \kappa_g \frac{\alpha_s}{16\pi m_s} s G_{\mu\nu}^a G^{a\mu\nu} + (\kappa_W + \kappa_B) \frac{\alpha}{16\pi m_s} s F_{\mu\nu} F^{\mu\nu} \\ + \left(\kappa_W \frac{c_w}{s_w} - \kappa_B \frac{s_w}{c_w} \right) \frac{\alpha}{8\pi m_s} s F_{\mu\nu} Z^{\mu\nu},$$

SZ γ coefficient of same order of **SZZ** and **SWW**

$$\Gamma_{gg} \gtrsim \Gamma_{\gamma\gamma} \gtrsim \Gamma_{Z\gamma} \gtrsim \Gamma_{WW} \gtrsim \Gamma_{ZZ}$$

$$\Gamma_{WW}^{(\text{SM})} > \Gamma_{gg}^{(\text{SM})} > \Gamma_{ZZ}^{(\text{SM})} > \Gamma_{\gamma\gamma}^{(\text{SM})} > \Gamma_{Z\gamma}^{(\text{SM})}$$

$\rightarrow$ @ $M_H = 125$ GeV

Model independent fits

Useful to consider the ratios

$$D_{W/Z} \equiv \frac{B\sigma_{gg}(WW)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \rightarrow WW)}{\Gamma(S \rightarrow ZZ)}$$

$$D_{\gamma/Z} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \rightarrow \gamma\gamma)}{\Gamma(S \rightarrow ZZ)},$$

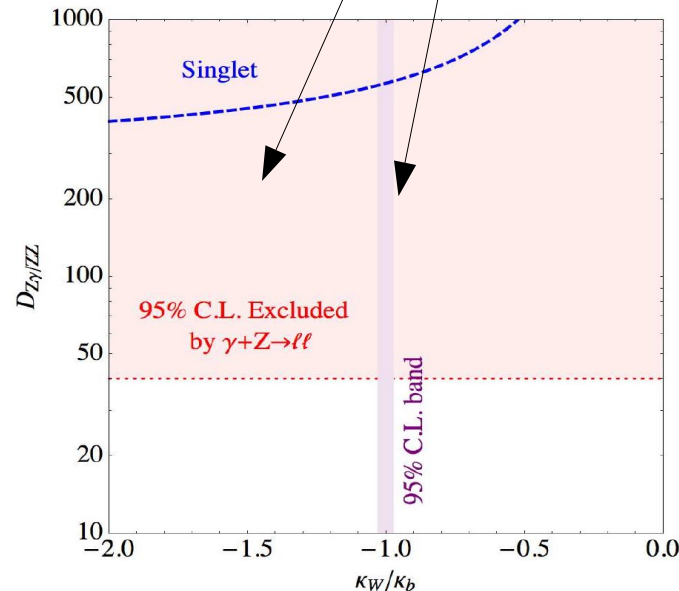
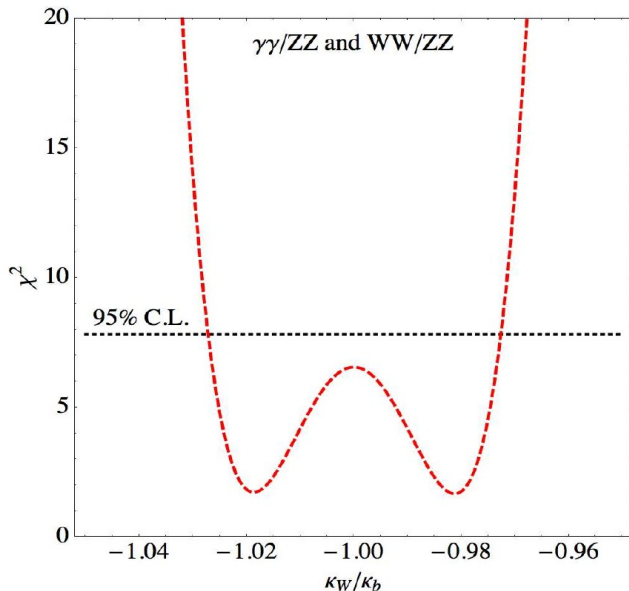
$$D_{Z\gamma/Z} \equiv \frac{B\sigma_{gg}(Z\gamma)}{B\sigma_{gg}(ZZ)} = \frac{\Gamma(S \rightarrow Z\gamma)}{\Gamma(S \rightarrow ZZ)}.$$

Predicted ratio

$$D_{Z\gamma/Z} \sim 500$$

95% CL excluded by $H \rightarrow Z\gamma$

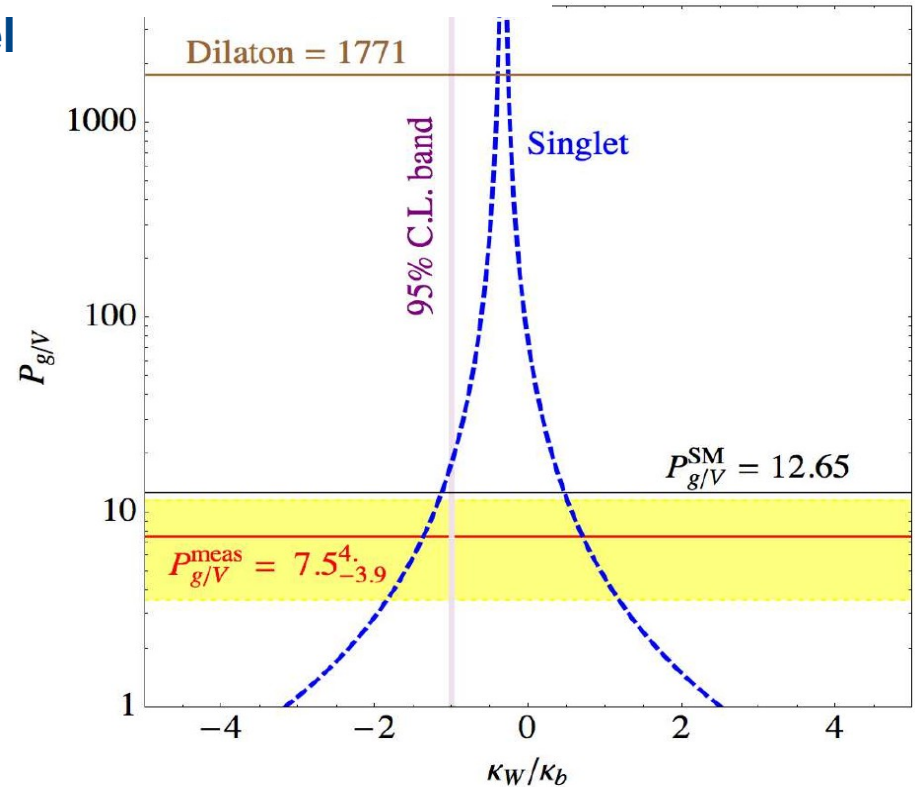
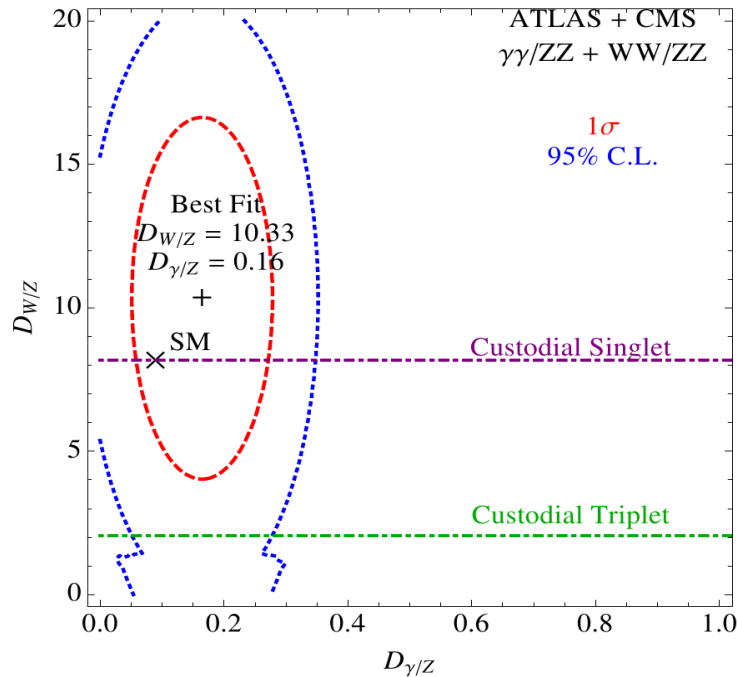
95%CL band comes from
best fit of χ^2



Predictions for **NOT EW-singlet** but a custodial singlet and 5-plet

$$D_{W/Z}^{(h)} = 8.16, \quad D_{W/Z}^{(h_5)} = \frac{1}{4} D_{W/Z}^{(h)} = 2.04$$

- custodial singlet consistent at 1σ level
- custodial triplet consistent at 2σ level



- **EW-singlet** like Dilaton (including RS radion) imposters are disfavored (observed $P_{g/V}$ is in agreement with SM)

$$P_{g/V} \equiv \frac{B\sigma_{gg}(\gamma\gamma)}{B\sigma_{\text{VBF}}(\gamma\gamma)}$$

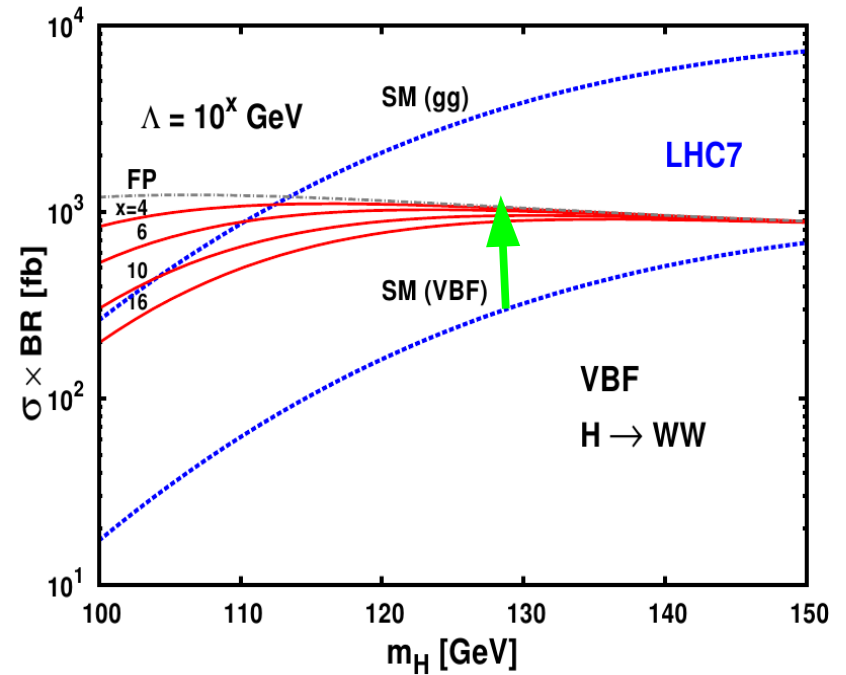
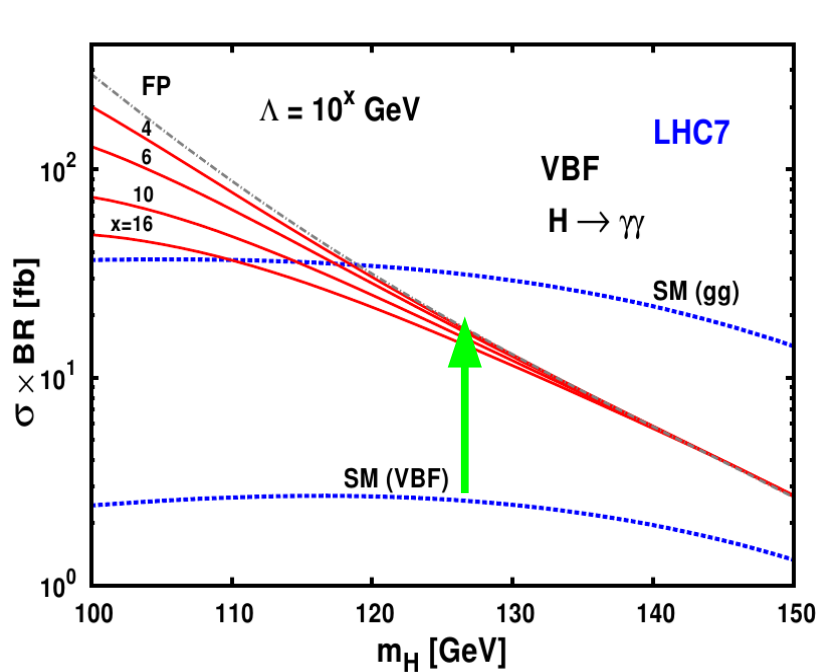
$$P_{g/V}^{(\text{D})} = 140 \times P_{g/V}^{(\text{SM})} \sim 1700$$

Conclusions

- A Higgs-like signal has been observed with 125 GeV mass
- Good consistency with SM Higgs → **dramatic implications for BSM scenarios**
- **MSSM is disfavored** → new scenarios like NMSSM seems viable, but large λ couplings needed to ameliorate the SUSY little fine-tuning problem
- A composite **PNGB Higgs** has almost same coupling as SM, more statistics is needed to test this scenario (HL- LHC) or ILC
- Precise measurements of Higgs couplings to fermions are crucial for understanding the origin of flavor problem and fermion masses
- **Fermiophobic naïve Higgs** is ruled out for $m_H=125$ GeV → **light NP is required to make it viable** → dramatic implications for flavor physics if confirmed
- sign of Yukawa coupling can be tested soon at LHC via **pp → H t q** process → dramatic implications for NP at TeV scale if wrong sign would be confirmed
- **EW singlet Higgs imposters** are ruled out, including dilaton and RS radion. **NOT-EW singlet Higgs imposters** are still viable → more statistics required

Backup slides

LHC (VBF) : $H \rightarrow \gamma\gamma, WW^*$



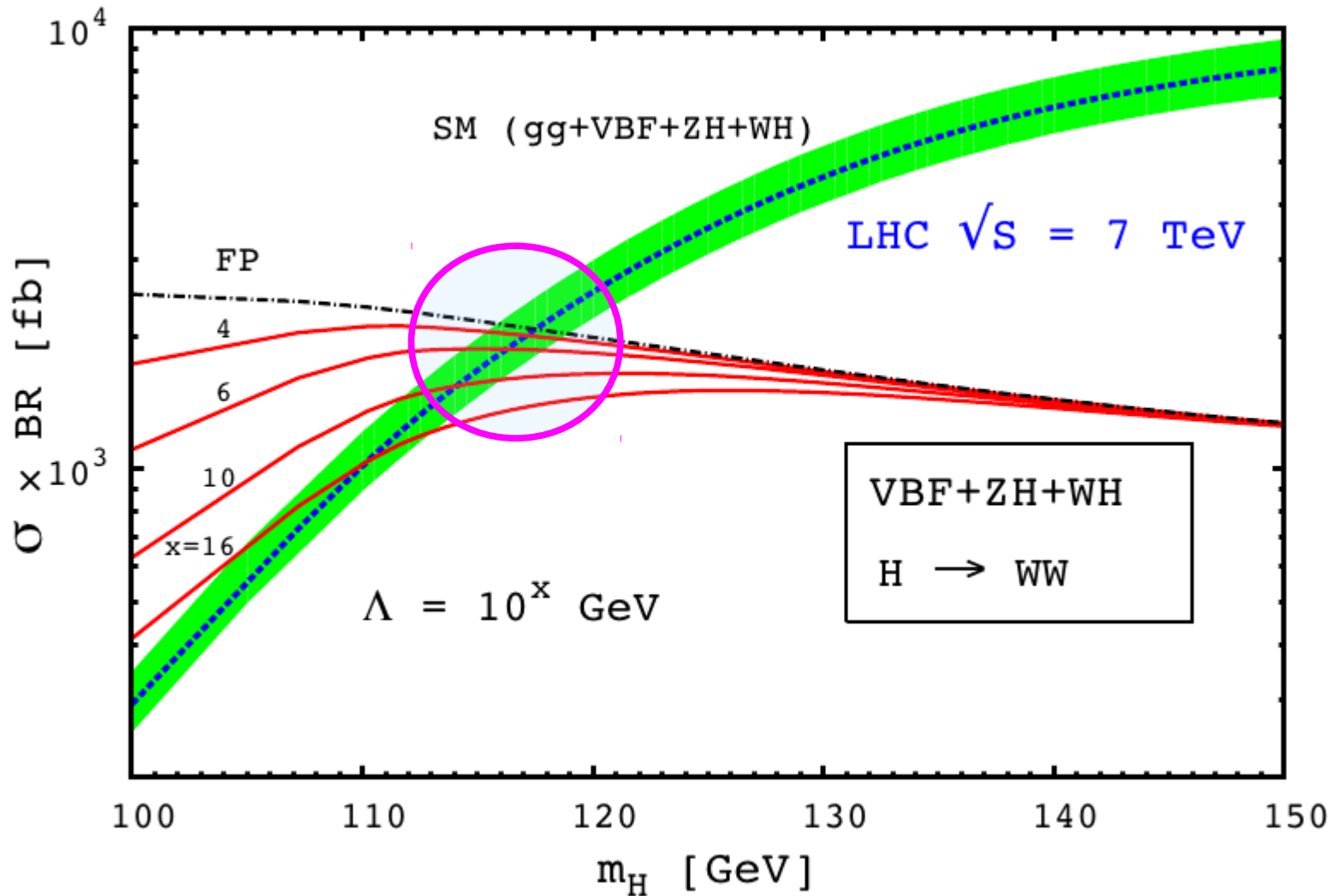
◆ rates of FP/VFB[SM] at $m_H=125$ GeV EG, Mele PRD 82 (2010)

→ $H \rightarrow gg$ rate[FP] ~ 7 x rate[SM(VBF)]

→ $H \rightarrow WW^*$ rate[FP] ~ 5 x rate[SM(VBF)]

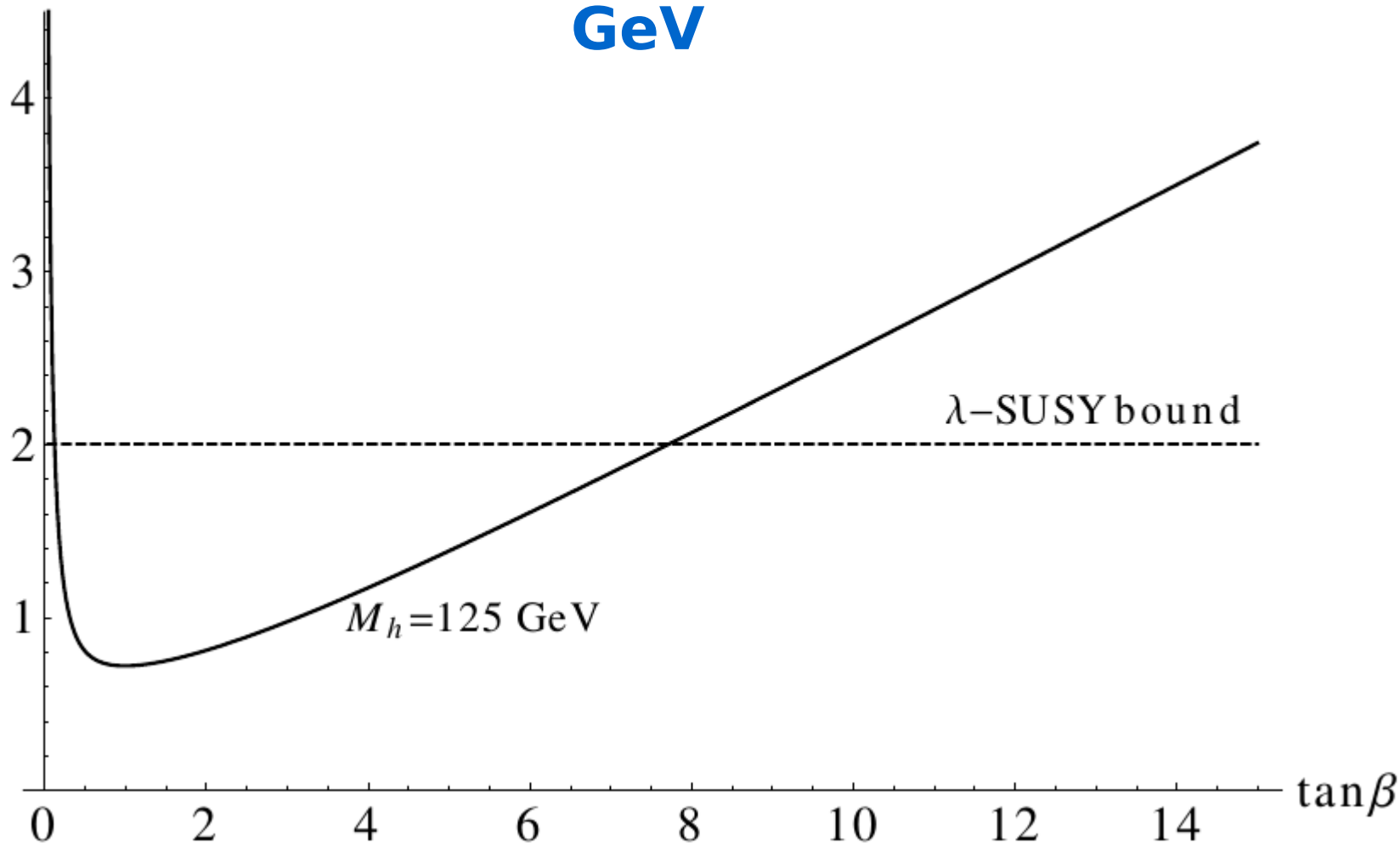
→ $H \rightarrow ZZ^*$ rate[FP] ~ 5 x rate[SM(VBF)]

FP(VBF+VH) : $H \rightarrow WW^*$



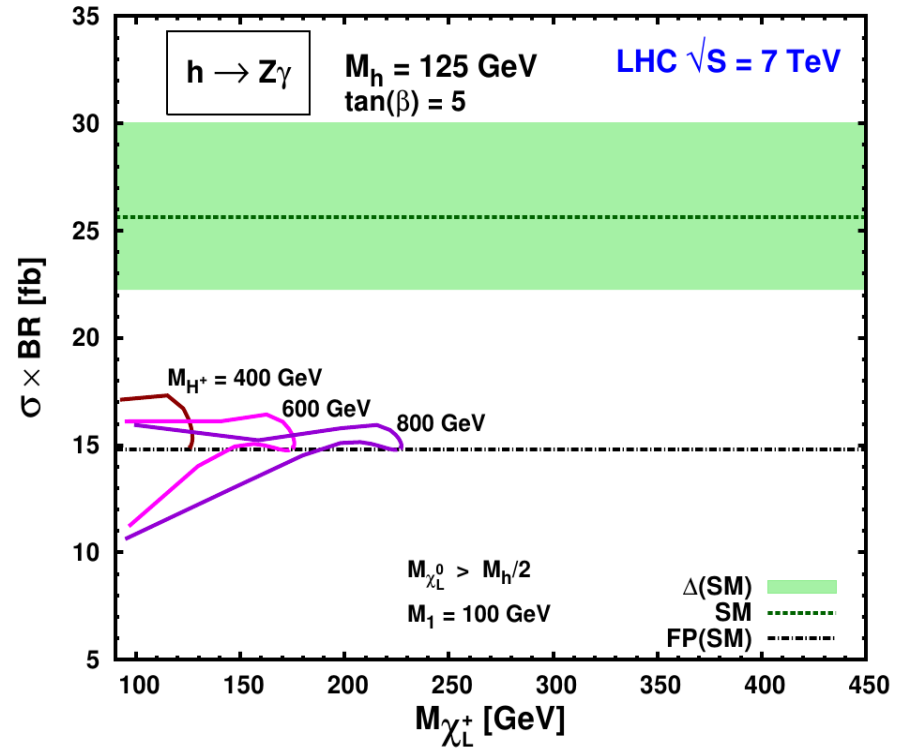
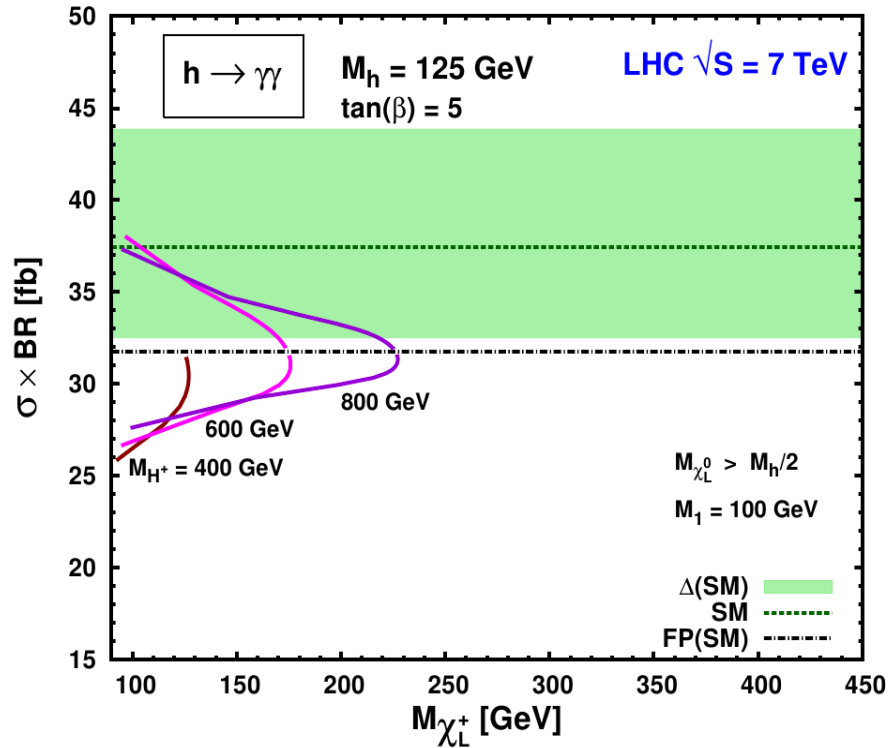
For $m_H=124-126 \text{ GeV}$, FP Higgs has a smaller inclusive WW^* production rate with respect to SM!

FP NMSSM, $\tan(\beta)$ versus λ for $M_H=125$ GeV



Upper bound on $\tan(\beta) < 8$

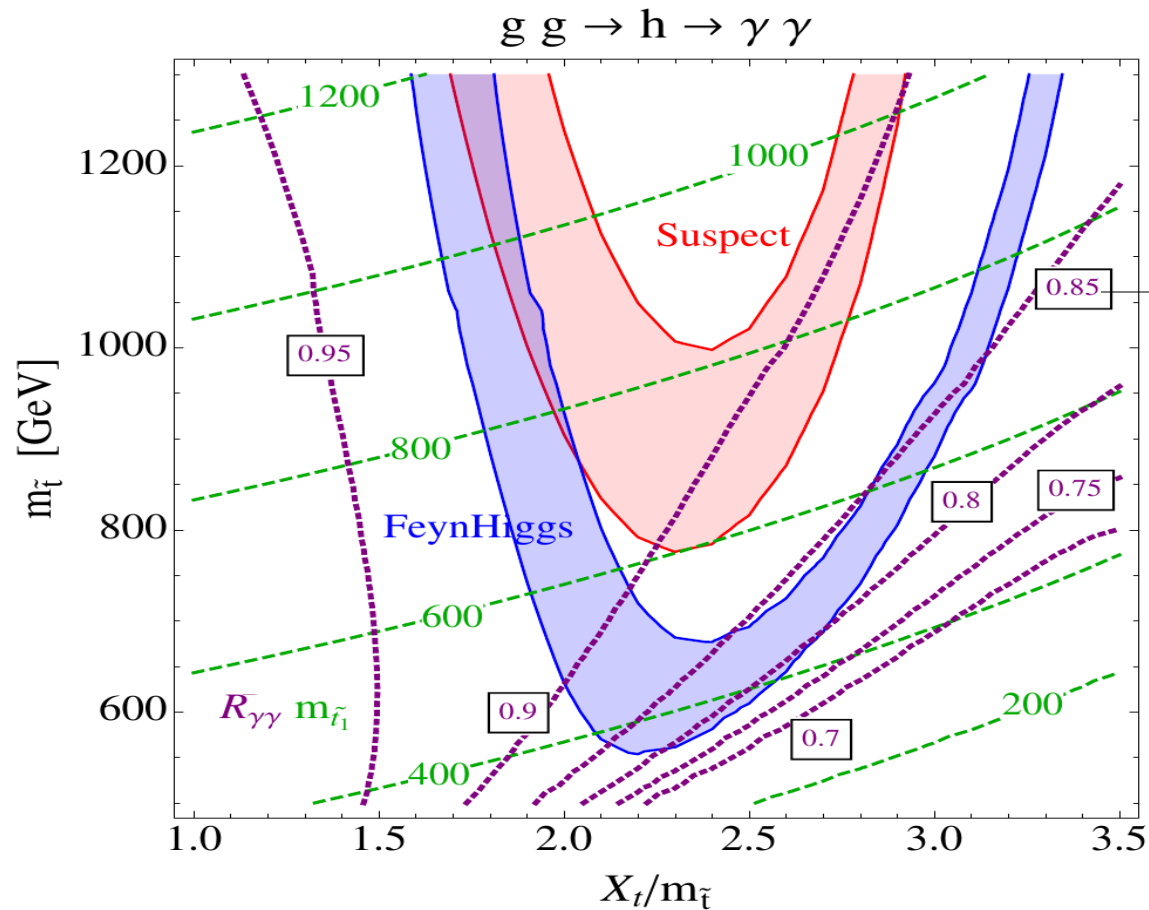
FP NMSSM with $\tan(\beta)=5$



Increasing $\tan(\beta) > 1$, deviations from FP SM on $\text{BR}(H \rightarrow \gamma\gamma)$ and $\text{BR}(H \rightarrow Z\gamma)$ are reduced

MSSM impact on couplings

Hall, Pinner, Ruderman '11



Contour plots at
 $M_H = 125$ GeV

BR X cross section
normalized to SM

Fermiophobic NMSSM

- 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

$$\begin{aligned} a_\lambda &= 0 \\ k &= \lambda \\ \tan \beta &= 1 \end{aligned}$$

- $\tan\beta=1$ is allowed since no low energy constraints come from Yukawa couplings
- we restrict our model to this special set of parameters
→ natural choice → more predictive

Strategy

- ▶ $M_h = \frac{|\lambda|v}{\sqrt{2}} = 125 \text{ GeV}$, $M_1 = 100 \text{ GeV}$ → **fixed-parameters**
- ▶ $(M_{H^\pm}, M_{\chi_L^+}) \rightarrow (|\mu|, M_2)$ → **free-parameters**
- ▶ $M_{\chi_L^0} > M_h/2 \Rightarrow h \nrightarrow \chi_i \chi_j$ → **to require neutralino LSP**
 $\Rightarrow R - \text{parity} \Rightarrow h \nrightarrow \chi_i^* \chi_j, \chi_i^* \chi_j^*$

FP SUSY contributions to $h \rightarrow \gamma\gamma, \gamma Z$

