

Fermiophobic Higgs scenarios at the LHC

Emidio Gabrielli
NICPB, Tallinn

■ in collaboration with

B. Mele (INFN, Rome 1, Italy)

K. Kannike (NICPB & SNS and INFN Pisa, Italy)

A. Racioppi (NICPB)

M. Raidal (NICPB & Institute of Physics Tartu, Estonia, & CERN)

■ talk based on 1204.0080 [hep-ph], 1202.1796 [hep-ph]
PRD 83: 073009 (2011), PRD 82: 113014 (2010)

Department of Physics
University of Helsinki – June 19th 2012

Outline

- SM Higgs boson searches at LHC
- Fermiophobic SM Higgs scenario
- Impact of radiative corrections
- Implications at LHC and linear colliders
- Fermiophobia 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 a 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) !



THE GOOD THE BAD AND THE UGLY

... of SM Higgs mechanism

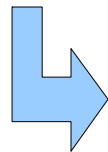
Properties of SM Higgs mechanism

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



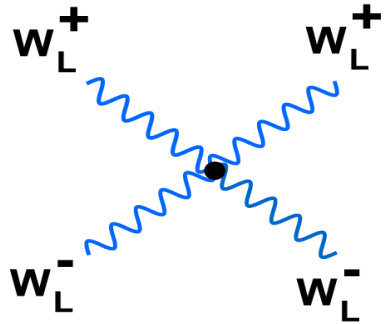
this makes Higgs discovery difficult

and The
UGLY

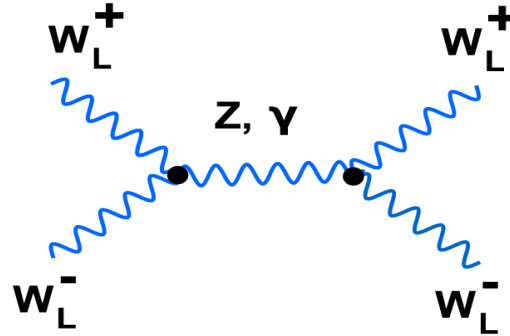
- Higgs potential unstable under quantum corrections: fine tuning problems → require New Physics:
- Supersymmetry, Technicolor, Extra-dimensions, etc.

$W_L W_L \rightarrow W_L W_L$ @ E^2/M^2

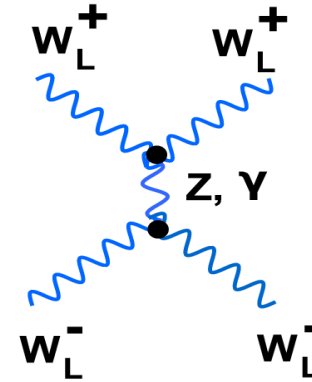
$$\cos \theta \equiv \frac{M_W}{M_Z}$$



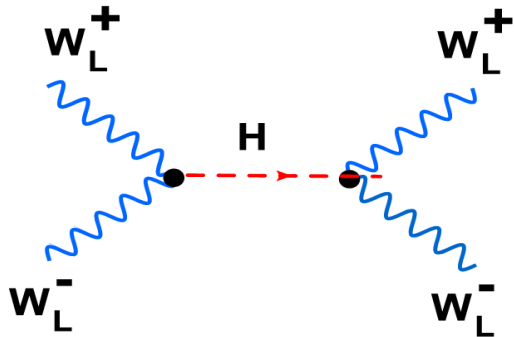
(a)



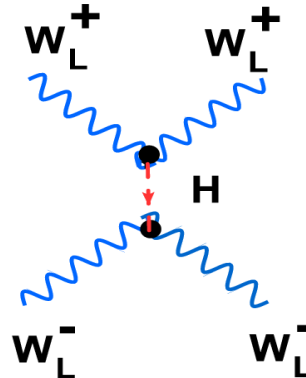
(b)



(c)



(d)



(e)

(a)	$2 - 6 \cos \theta + \cos^2 \theta$
(b)	$-\cos \theta$
(c)	$-\frac{3}{2} - \frac{15}{2} \cos \theta - \cos^2 \theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2} \cos \theta$
Sum	$= 0$

● E/M cancellation due to gauge-inv.

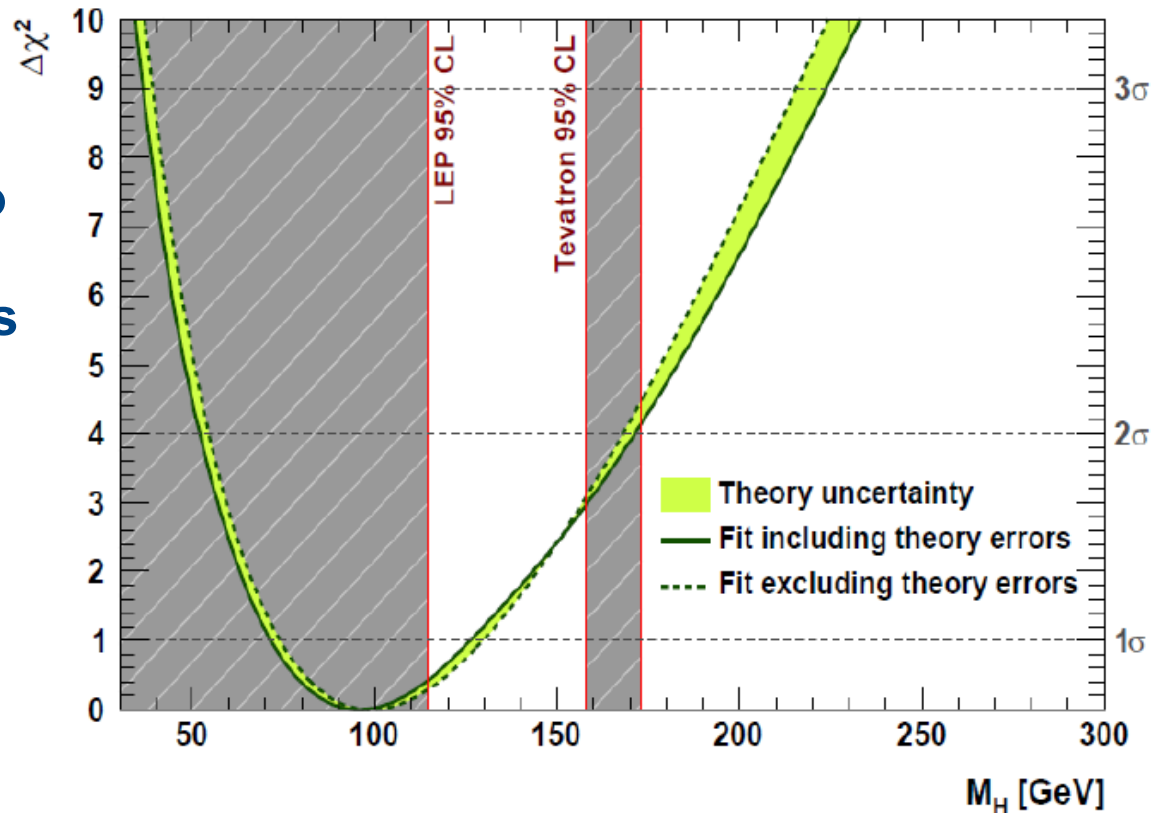
● E^2/M^2 cancellation not accidental !

● related to: **spontaneous gauge symmetry breaking** → the **Higgs mechanism**. Scalar **H** is the **Higgs boson field**

● at E^0 order, unitarity requires $m_H \lesssim 1 \text{ TeV}$

Low mass Higgs: why is it important ?

Corrections to the precision measurements depend on $\text{Log}(m_H)$



[GFitter Collaboration: arXiv:0811.0009]

Best fit of EWPT

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

Status of Higgs searches before LHC

LEP ('90 – 00): electron-positron collider at CERN
c.m. Energy LEP1 ~ **91 GeV** (Z pole)
LEP2 ~ **200 GeV**
relevant process: **$e^+e^- \rightarrow H(\rightarrow bb) Z$**

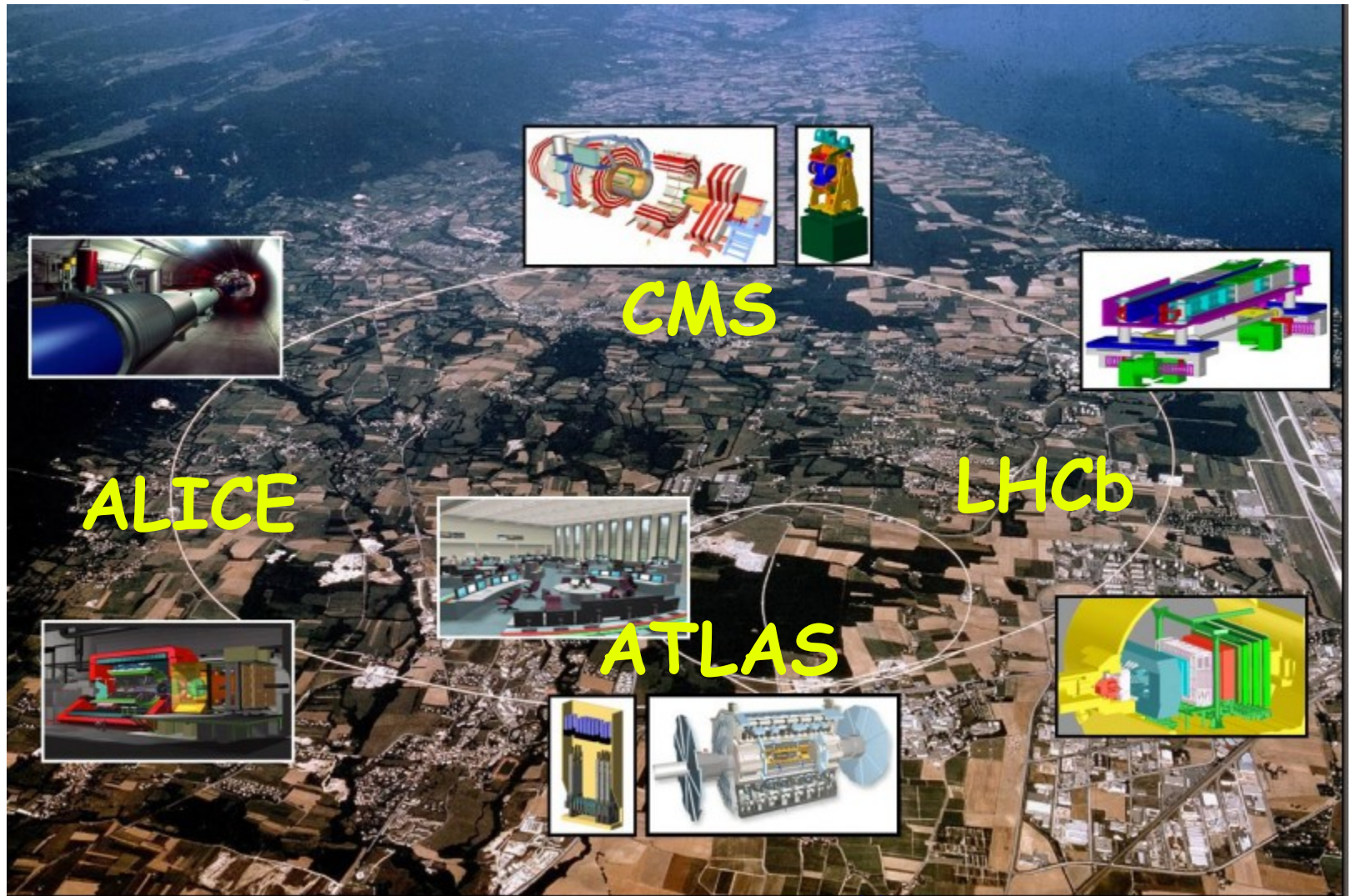
$m_H > 114.4 \text{ GeV}$

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

exclusion regions on SM Higgs mass at **95% CL**

$[100 - 109] \text{ GeV}$ and **$[156 - 177] \text{ GeV}$**

Large Hadron Collider



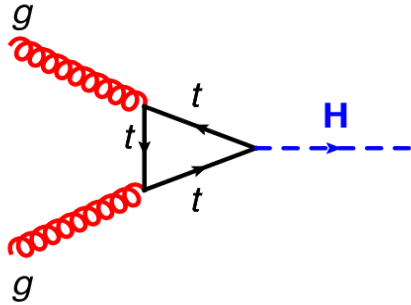
proton-proton collisions
c.o.m. Energy = 7, 8, 14 (13 ?) TeV

LHC: where we are today

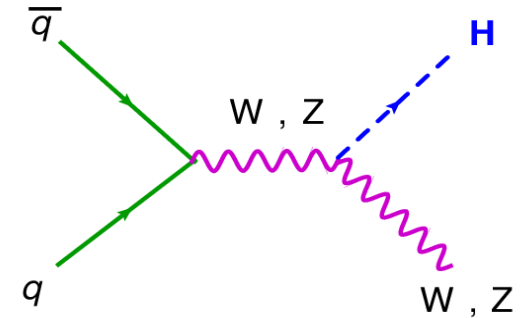
- LHC delivered in 2011 ~ 5.7 fb⁻¹ of Luminosity in pp collisions @ 7 TeV c.m. energy
- In 2012 LHC runs @ 8 TeV, already 4 fb⁻¹ of Luminosity collected ! 20 fb⁻¹ expected by end of year
- In a few weeks we should be able to complete the SM-Higgs search-phase and find out whether:
 - ◆ there is a SM like Higgs signal at $m_H = 125-126$ 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

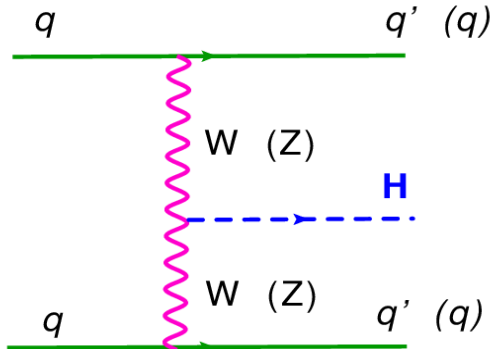
Gluon fusion



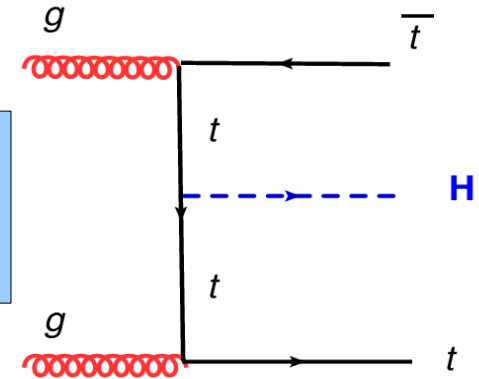
VH



VBF



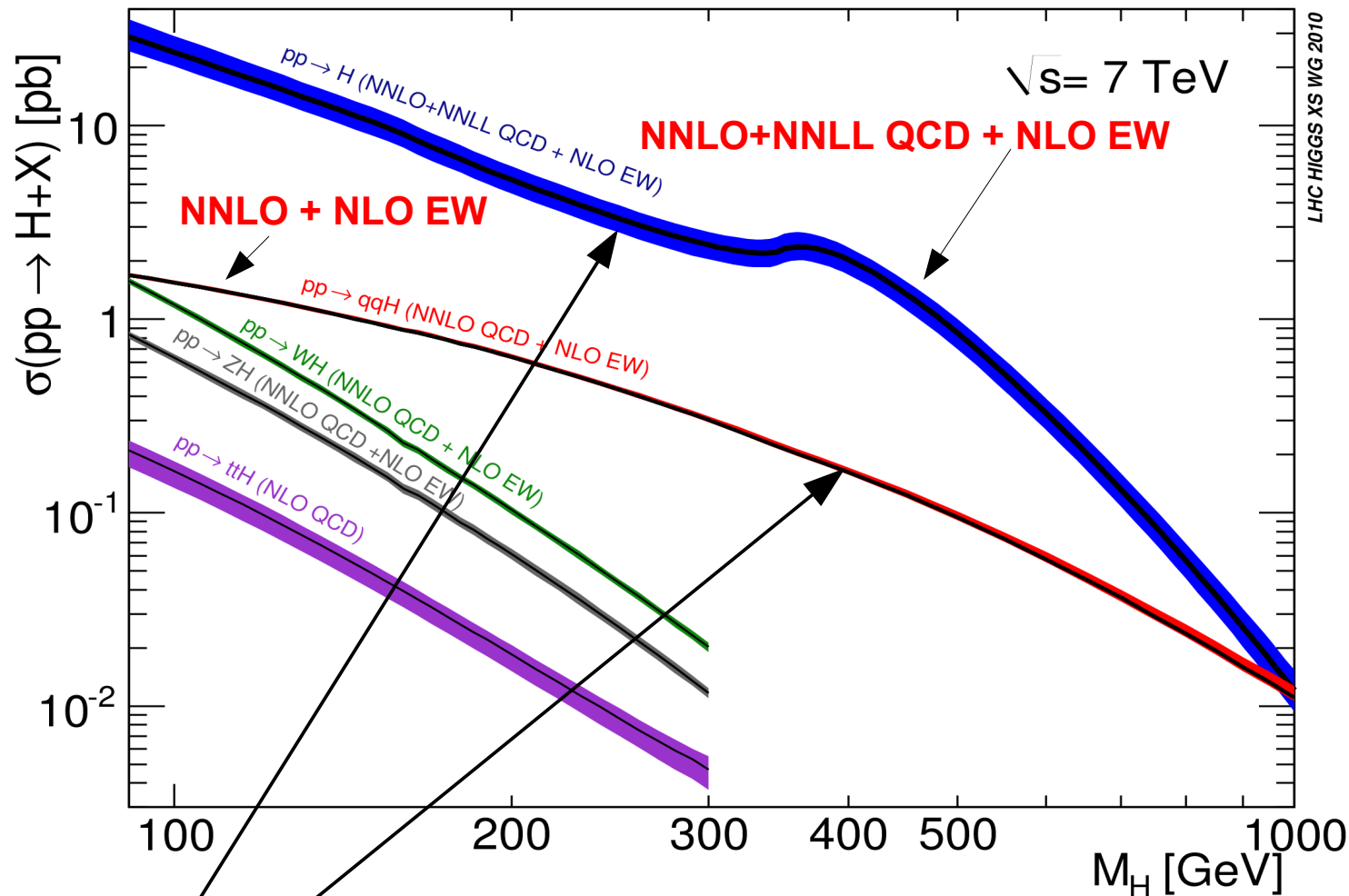
ttH



$$\sigma(pp \rightarrow HX) = \sum_{ij} \int_{(0 < x < 1)} dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}(ij \rightarrow HX)$$

$(0 < x < 1)$ PDF
 $f_i(x_1) f_j(x_2)$ PDF
 $\hat{\sigma}(ij \rightarrow HX)$ partonic cross-section

SM Higgs production cross sections at LHC

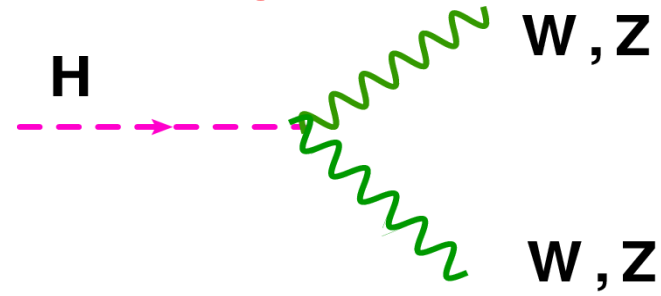
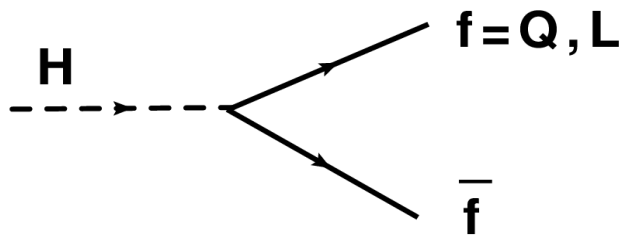


Gluon fusion : leading production mechanism

VBF : next-to-leading production mechanism

Relevant SM Higgs decay channels

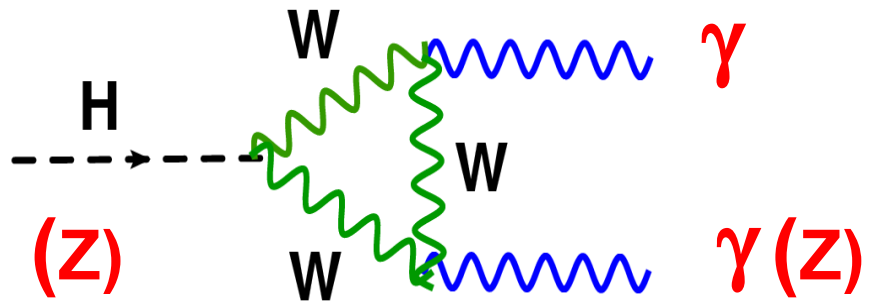
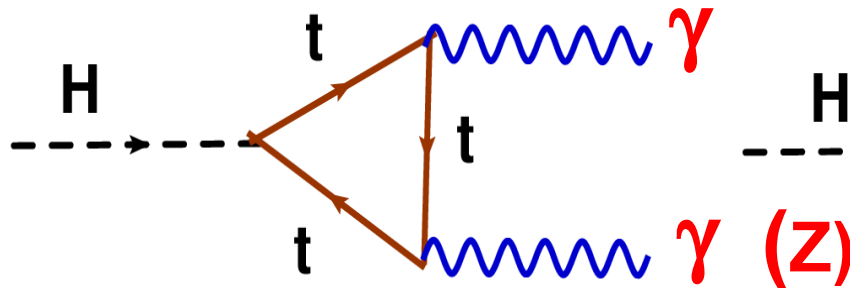
Tree - level decays



$Q = u, d, c, s, b$

$L = e, \mu, \tau$

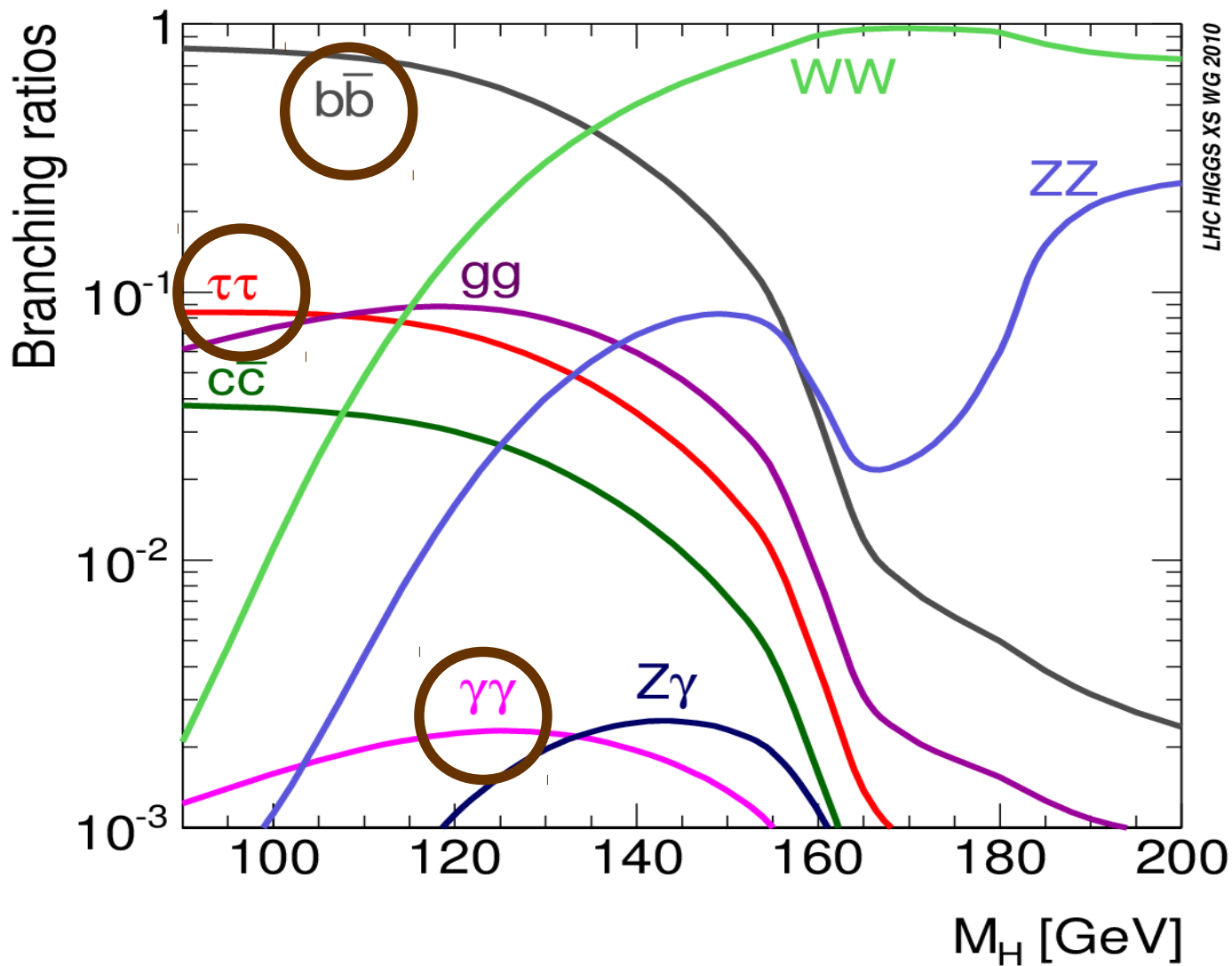
One-loop decays



$H \rightarrow \gamma\gamma, \tau\tau$ relevant processes for Higgs discovery at low masses

$H \rightarrow \gamma\gamma$ very sensitive probe of new physics

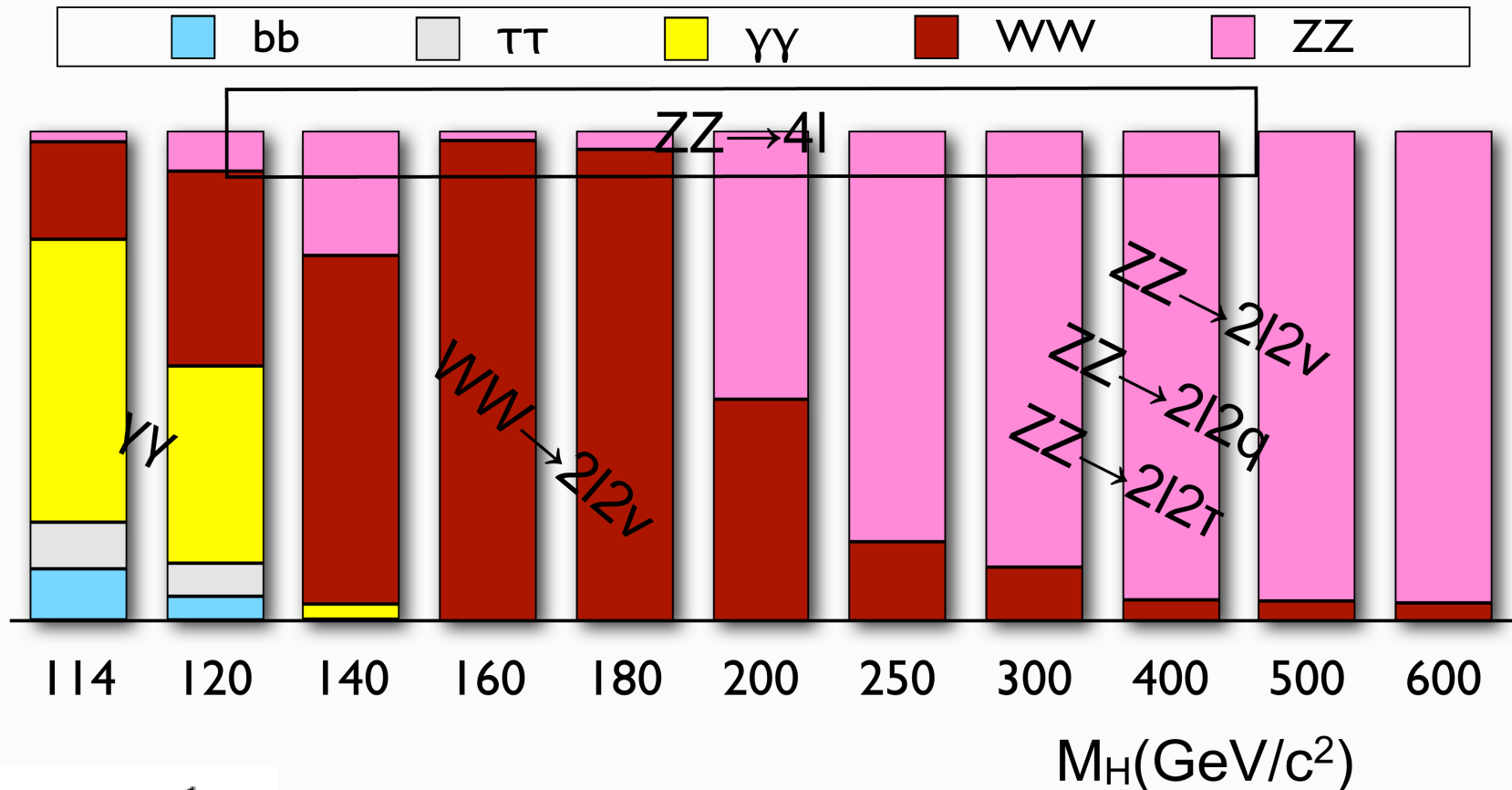
$H \rightarrow \gamma Z$ smaller, also quite sensitive to new physics



- $H \rightarrow bb$ dominant for $m_H < 140$ GeV $\rightarrow$ 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 → Nov. 2011



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

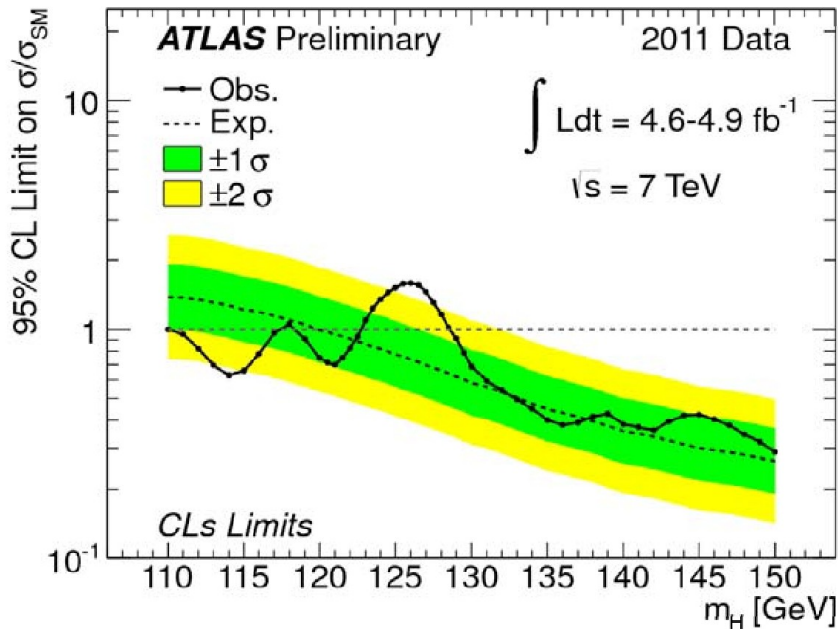
μ_{up} expected upper limit on the signal strength modifier, $\mu = \sigma/\sigma_{SM}$.

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

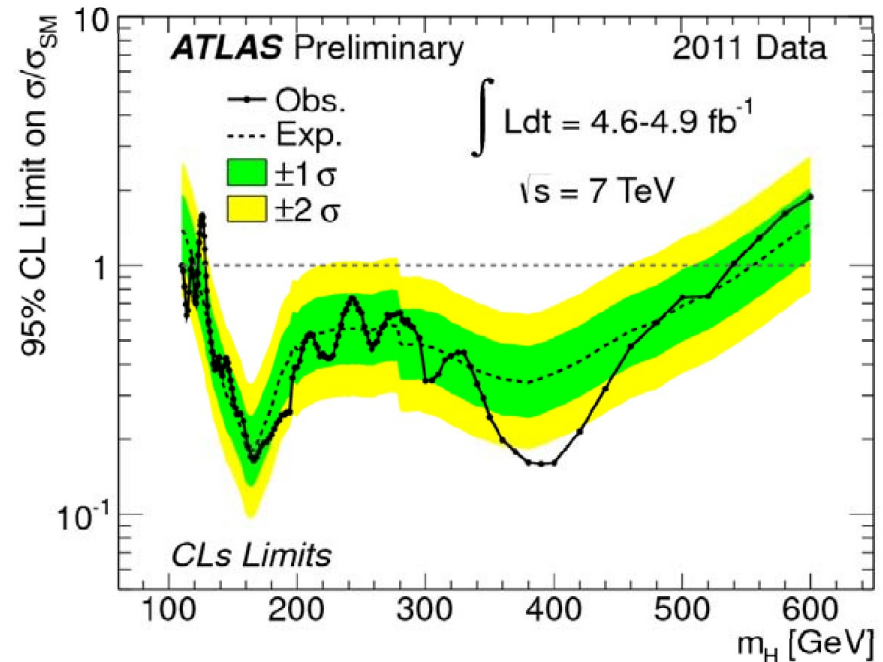
Cowan, Cranmer, Gross, Vittels EPJC 71:155

ATLAS latest results

❖ Low-mass region



❖ Complete region



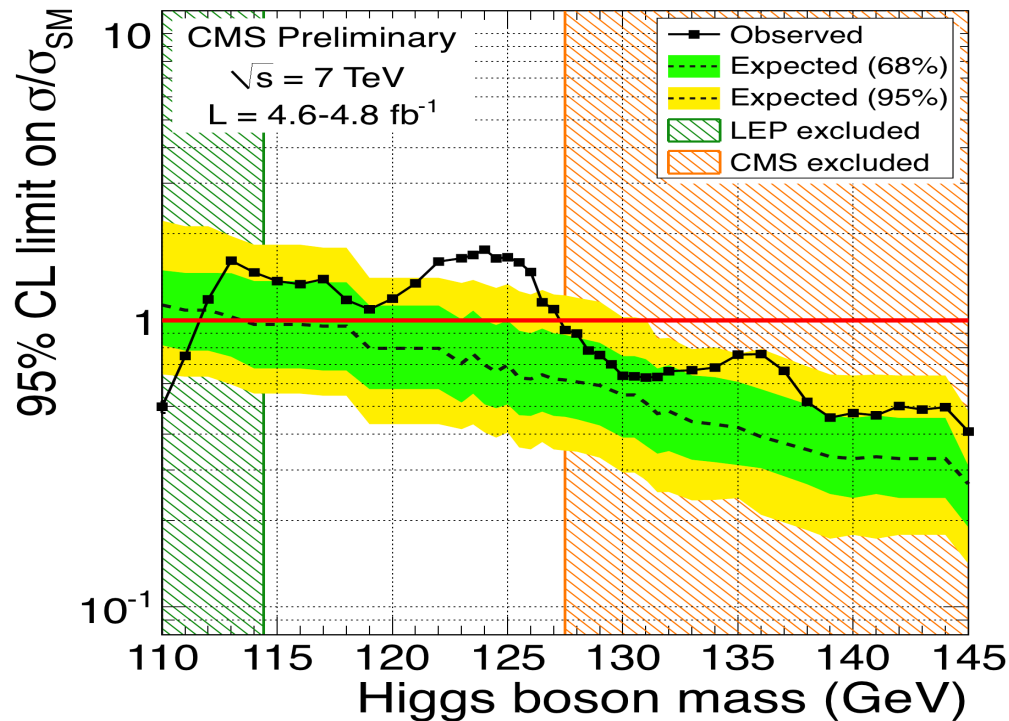
Planck 2012. Warsaw 28.05.2012

■ Regions excluded at 95% CL

110 – 117.5 GeV, **118.5 – 122.5 GeV**, **129 – 539 GeV**

■ **Excess at $\sim 126 \text{ GeV}$ $\rightarrow$ local significance 2.5σ**

CMS latest results



Planck 2012. Warsaw 28.05.2012

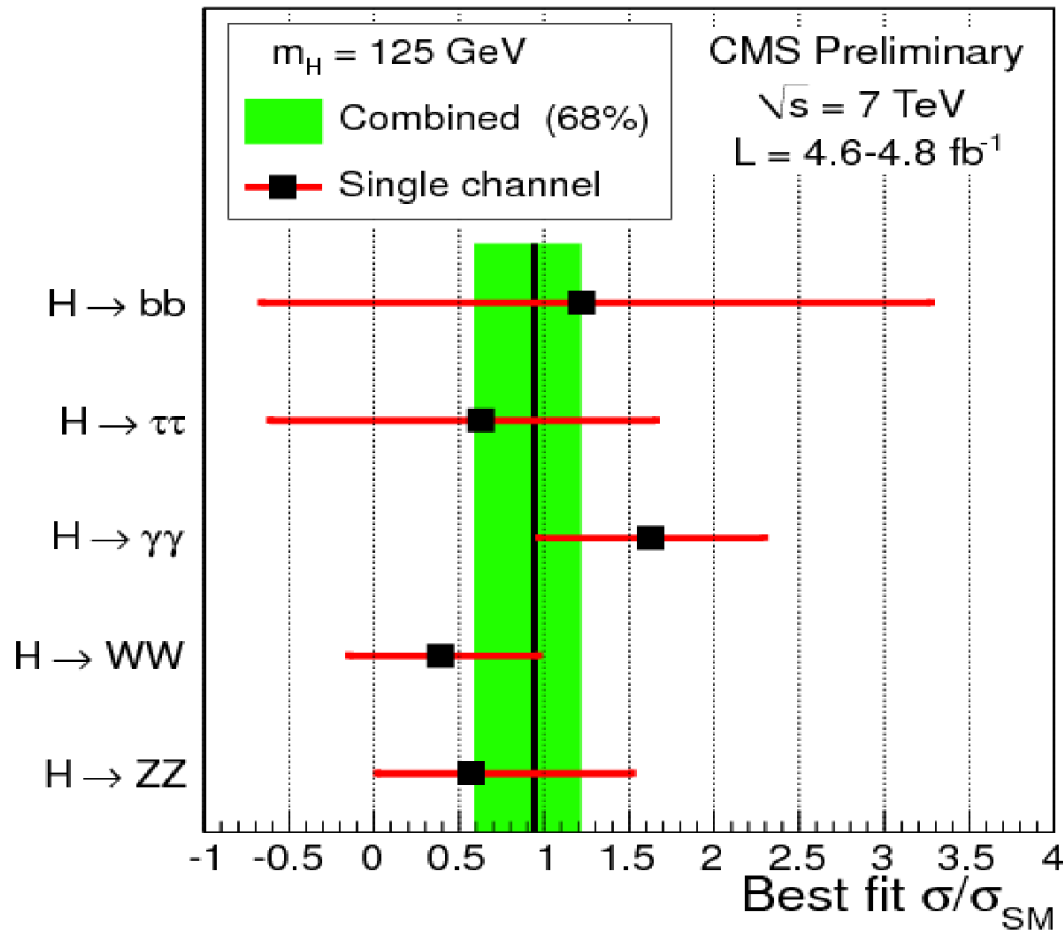
Regions excluded

[127.5 – 600] GeV @ 95% CL , [129 – 529] GeV @ 99% CL

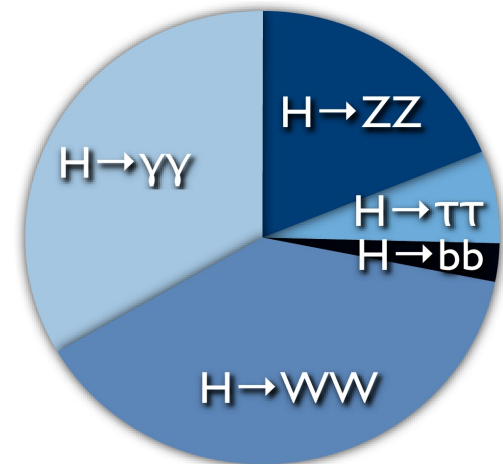
a narrow range still allowed : 114 – 127.5 GeV

At 125 GeV → 2.1 σ of global significance in 110 – 145 GeV

CMS latest results



Relative Contribution at 125 GeV



weight is defined as $1/\mu^2$, i.e. inverse expected signal strength squared

- 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 → hint of a fermiophobic Higgs ?

Prospects for 2012

- Gain from 7 → 8 TeV
 - corresponding to 20 % Luminosity
 - corresponding to 10 % significance
- Need 12 fb⁻¹ @ 8 TeV
 - for 5σ significance in each experiment
- Combining data @ 7 TeV
 - we need ~ 8 fb⁻¹ @ 8 TeV for discovery
 - by ICHEP 2012 we may have ~ 5 fb⁻¹
- If Higgs exists with m_H ~ 125 GeV local significance increases from 3 σ → 4 σ
- 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 σ 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

$$\mathcal{L} = Y_f \bar{\psi}_f \psi_f H \longrightarrow m_f = Y_f \langle H \rangle$$

- 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 ?

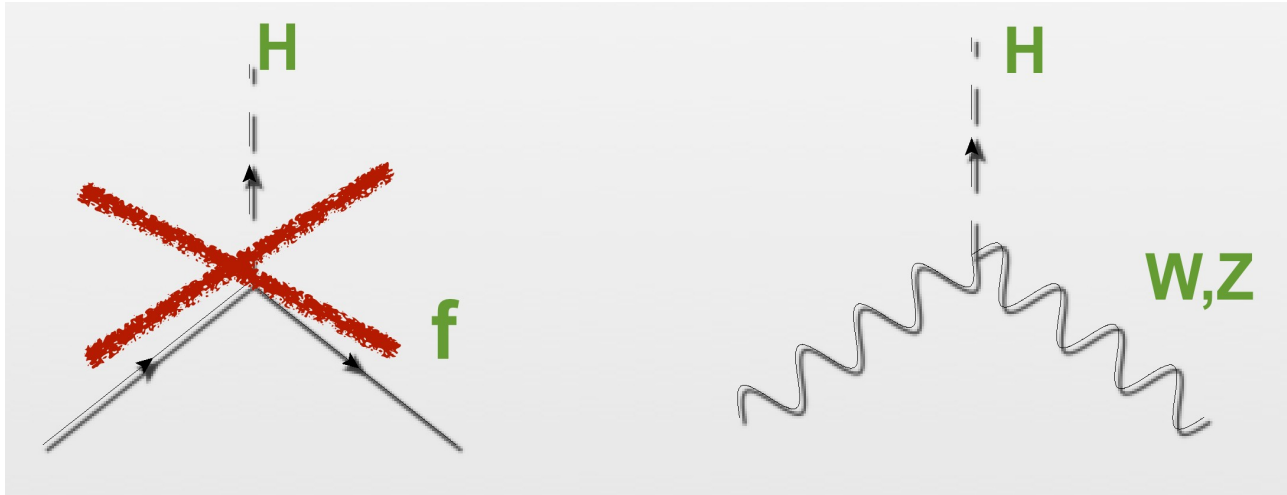
■ fermion masses m_f  ChSB

(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-**P**hobic (FP) Higgs



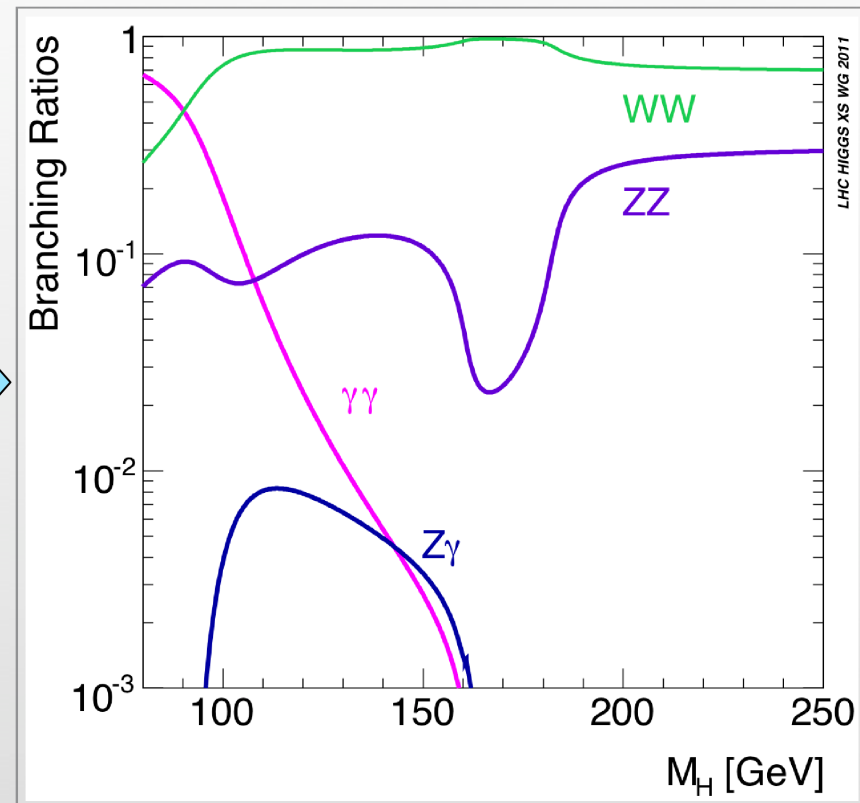
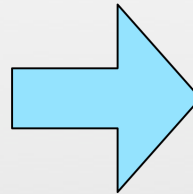
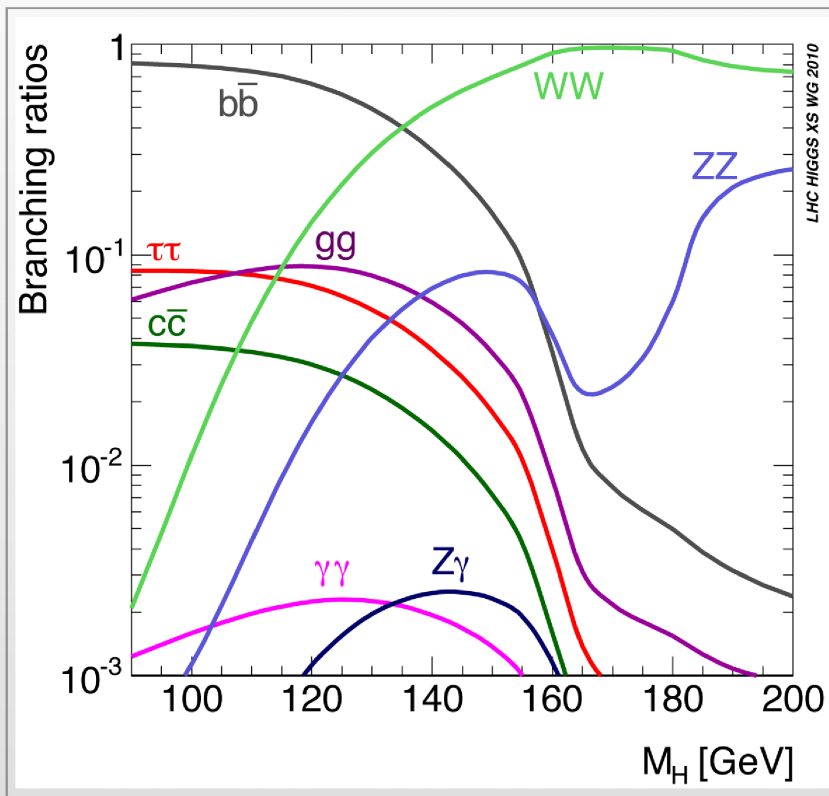
- Higgs mechanism gives rise to EWSB and M_W, M_Z but is **NOT** responsible for ChSB $\rightarrow$ fermion masses
- Perturbative unitarity in WW scattering cured !
- **NO** Yukawa couplings at tree-level

Higgs decays : FP vs SM

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

SM Higgs

FP Higgs

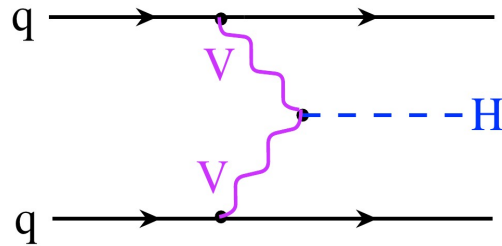


<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Fermiophobic>

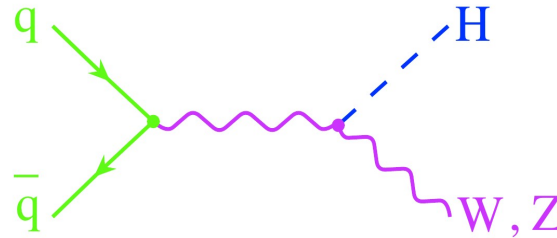
for $m_H \sim [100, 110, 120]$ GeV : $BR(\gamma\gamma)_{FP} \sim [110, 30, 10] \times BR(\gamma\gamma)_{SM}$

Fermio-**P**hobic Higgs production mechanisms at LHC

VBF



VH



- **NO** gluon-gluon fusion
- **VBF** fusion dominant mechanism
- harder **p_T** spectrum → better **S/B** !

How to handle the problem of radiative corrections in the FP Higgs model ?

- FP Higgs model: **non-renormalizable** → 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

E. Gabrielli and B. Mele, PRD 84 054017 (2011), PRD 83 073009 (2011)

- Fermion mass put by hand $\rightarrow$ SM is **not renormalizable**
- SM $\rightarrow$ effective field theory valid up to some Λ scale
- FP model $\rightarrow$ Yukawas Y_f vanish at the scale Λ
- due to explicit **ChSB**, the **Yukawas** are not protected under radiative corrections $\rightarrow Y_f$ **radiatively generated at low energy** $\rightarrow$ large **$\text{Log}(\Lambda/m_H)$** 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 $\rightarrow$ independent of UV completion of SM above Λ

EFT approach connects two scales Λ and m_H

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

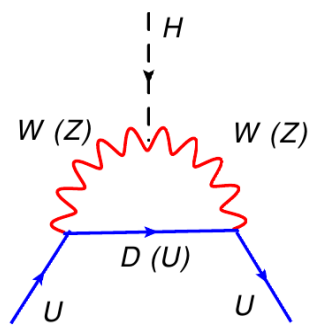
$$Y_f(\Lambda) = 0 \quad \text{Fermiophobia at scale } \Lambda$$

- large logs $g_i^{2n} \log^n(\Lambda/m_H)$ can be summed up by
Renormalization Group Equation (RGE) technique

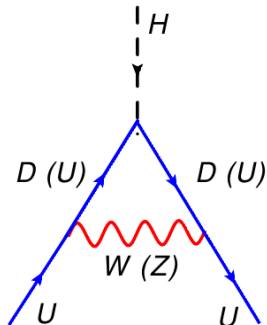
$$\begin{array}{ccc} Y_f(\Lambda) = 0 & \xrightarrow{\quad RGE \quad} & Y_f(m_H) \\ \text{(high energy)} & & \text{(low energy)} \end{array}$$

- 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

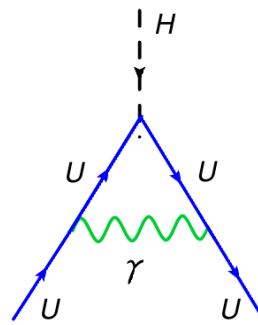
Diagrams contributing to the Y 's beta-functions (Higgs on-shell)



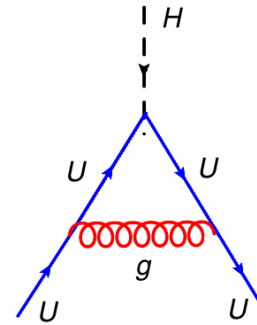
a)



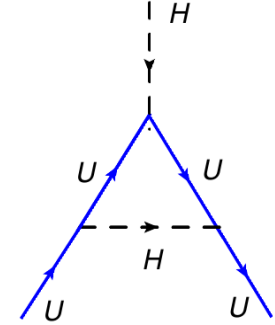
b)



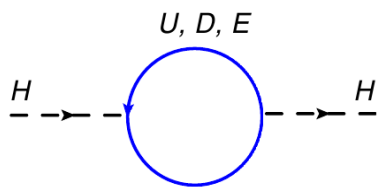
c)



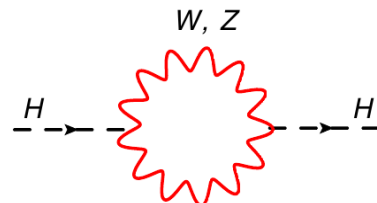
d)



e)

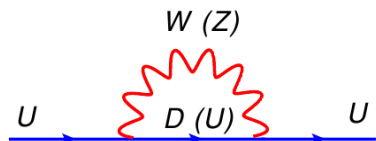


f)

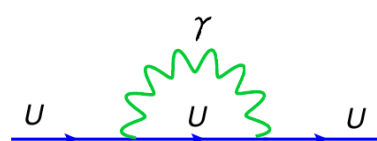


g)

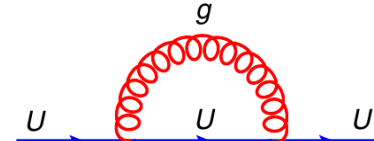
Up-type quark couplings



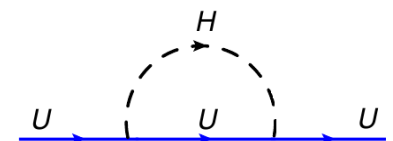
h)



i)



j)



k)

- Unitary gauge
- Yukawas and fermion masses independent parameters

1-loop RGE's for Yukawa's

(Higgs on-shell)

$$\frac{d\mathbf{Y}_U}{dt} = \frac{1}{16\pi^2} \left\{ \underline{3\xi_H^2} (\mathbf{Y}_U - \mathbf{Y}_U^{\text{SM}}) - 3\mathbf{Y}_U^{\text{SM}}\mathbf{Y}_D^{\text{SM}} (\mathbf{Y}_D - \mathbf{Y}_D^{\text{SM}}) + \frac{3}{2}\mathbf{Y}_U (\mathbf{Y}_U\mathbf{Y}_U - \mathbf{Y}_D^{\text{SM}}\mathbf{Y}_D^{\text{SM}}) \right. \\ \left. - \mathbf{Y}_U \left(\frac{17}{20}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2 - \text{Tr}(\mathbf{Y}) \right) \right\},$$

$$\frac{d\mathbf{Y}_D}{dt} = \frac{1}{16\pi^2} \left\{ \underline{3\xi_H^2} (\mathbf{Y}_D - \mathbf{Y}_D^{\text{SM}}) - 3\mathbf{Y}_D^{\text{SM}}\mathbf{Y}_U^{\text{SM}} (\mathbf{Y}_U - \mathbf{Y}_U^{\text{SM}}) + \frac{3}{2}\mathbf{Y}_D (\mathbf{Y}_D\mathbf{Y}_D - \mathbf{Y}_U^{\text{SM}}\mathbf{Y}_U^{\text{SM}}) \right. \\ \left. - \mathbf{Y}_D \left(\frac{1}{4}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2 - \text{Tr}(\mathbf{Y}) \right) \right\},$$

Back to the theory

$$\frac{d\mathbf{Y}_E}{dt} = \frac{1}{16\pi^2} \left\{ \underline{3\xi_H^2} (\mathbf{Y}_E - \mathbf{Y}_E^{\text{SM}}) + \frac{3}{2}\mathbf{Y}_E\mathbf{Y}_E\mathbf{Y}_E - \mathbf{Y}_E \left(\frac{9}{4}(g_1^2 + g_2^2) - \text{Tr}(\mathbf{Y}) \right) \right\}$$

$$\xi_H \equiv \frac{g_2 m_H}{2M_W}$$

W_L polarization

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

ChSB terms

$$\mathbf{Y} \equiv N_c \mathbf{Y}_U \mathbf{Y}_U + N_c \mathbf{Y}_D \mathbf{Y}_D + \mathbf{Y}_E \mathbf{Y}_E$$

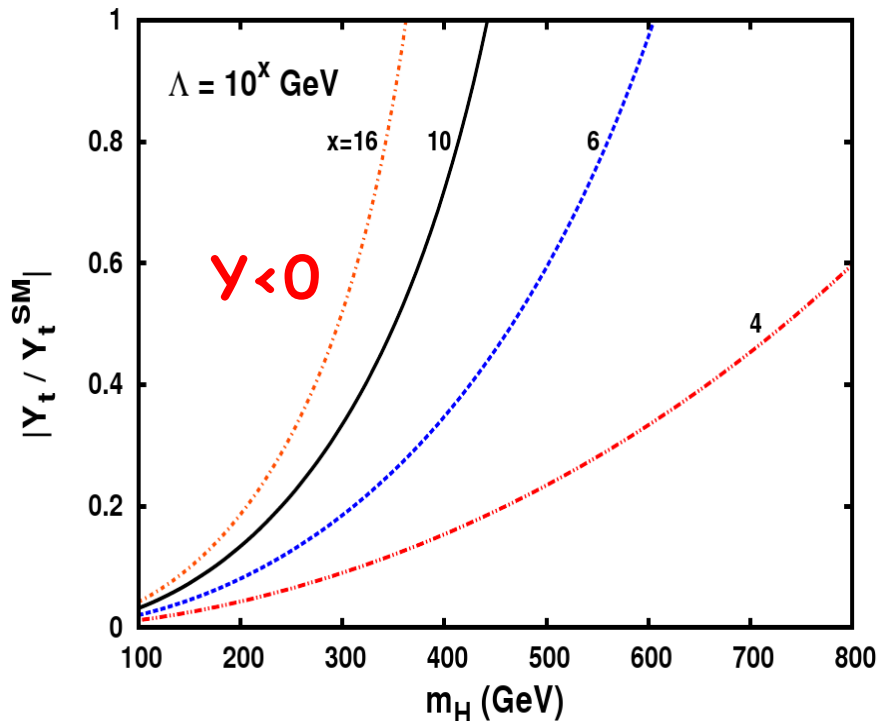
SM RGE's recovered for

$$\mathbf{Y}_f^{\text{SM}} \rightarrow \mathbf{Y}_f$$

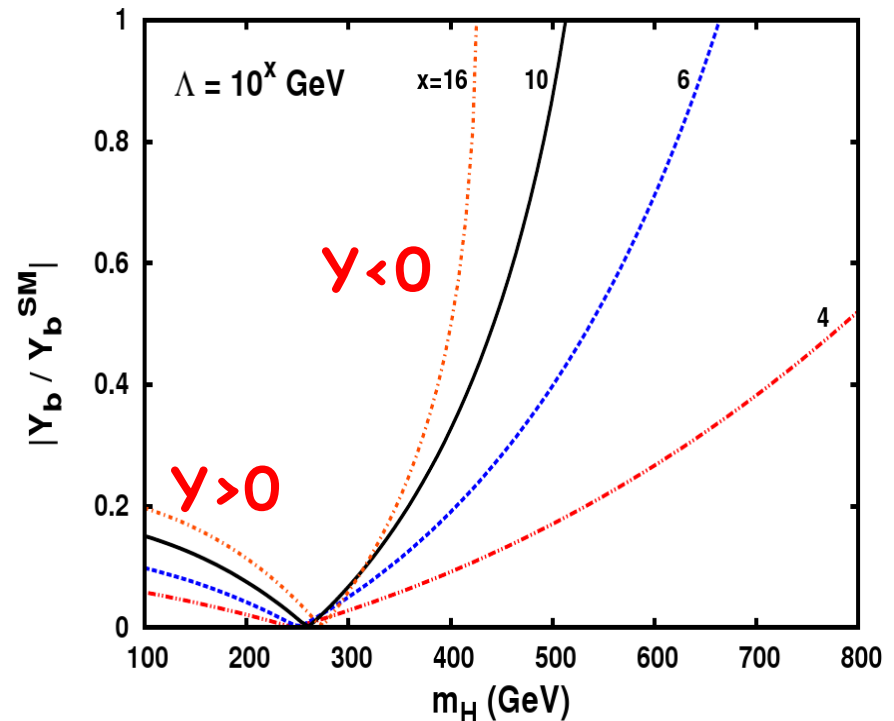
Yukawas at low energy $E \sim m_H$

- only SM degrees of freedom below Λ assumed
- sign of Yukawas predicted $\rightarrow Y_t(m_H)$ is negative
(dysfermiophilia)
- $|Y(m_H)| < 1 \rightarrow$ satisfied for light Higgs masses

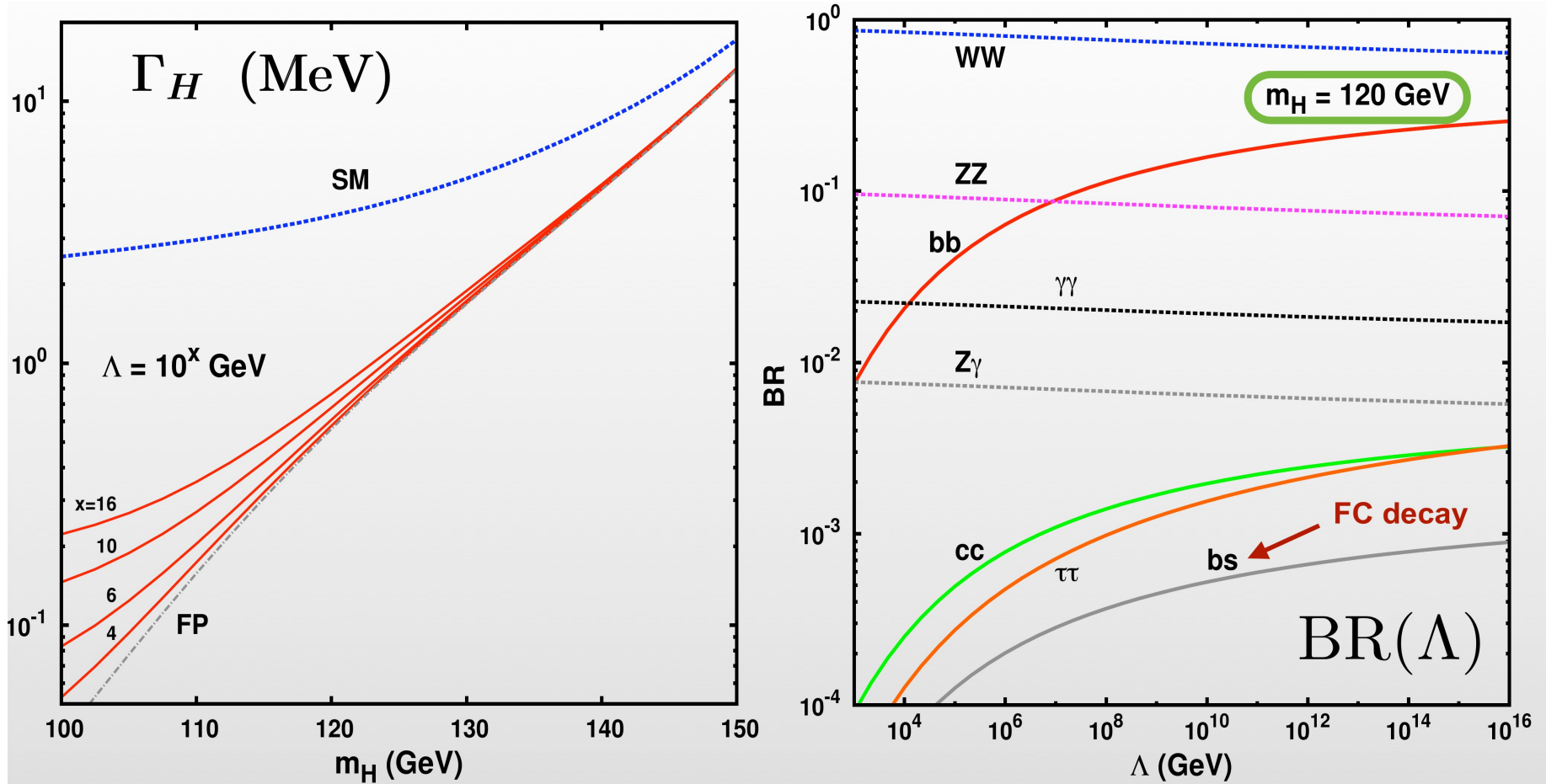
top-Yukawa (m_H)



b-Yukawa (m_H)

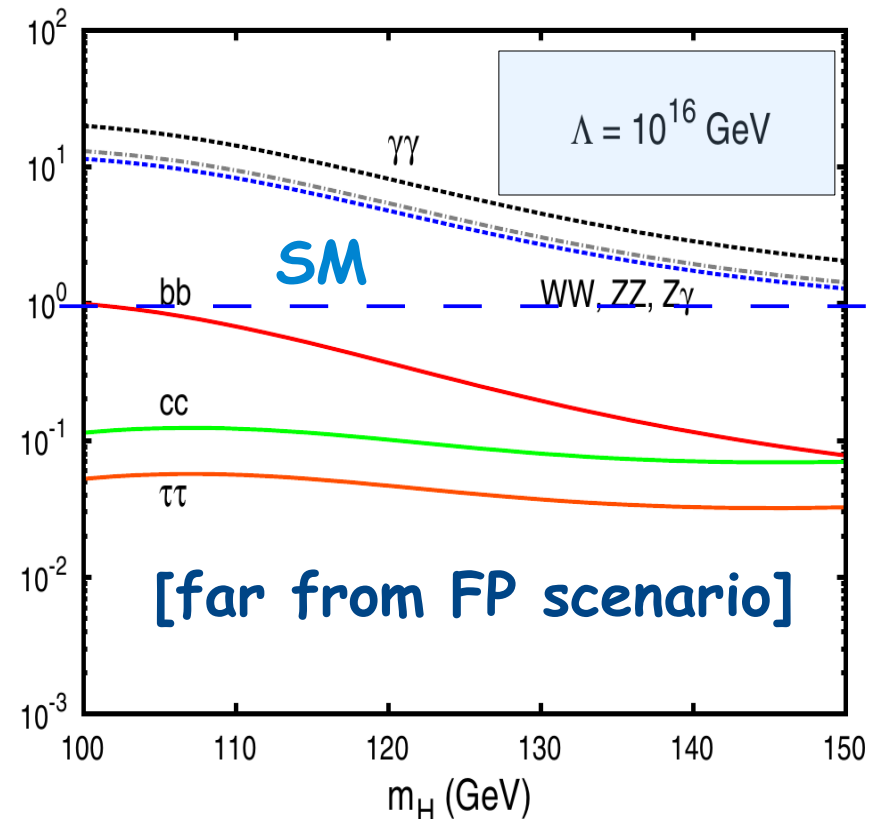
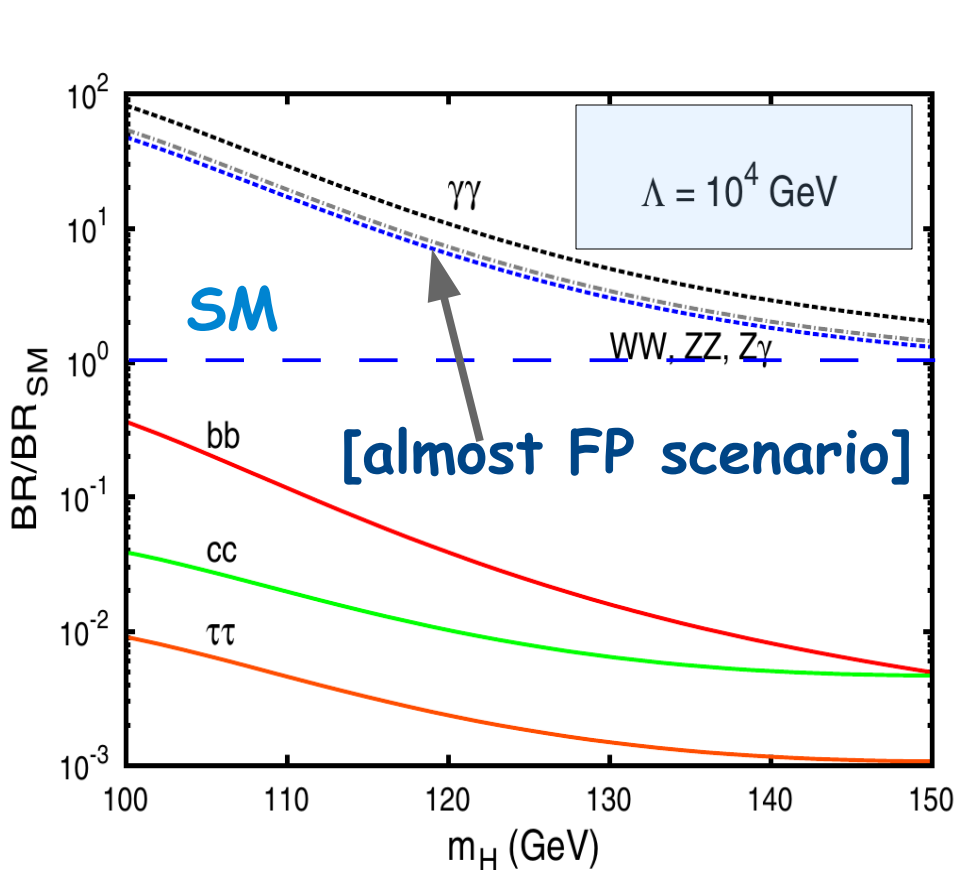


Results for Γ_H and BR's versus Λ



BR's enhanced by small total width

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

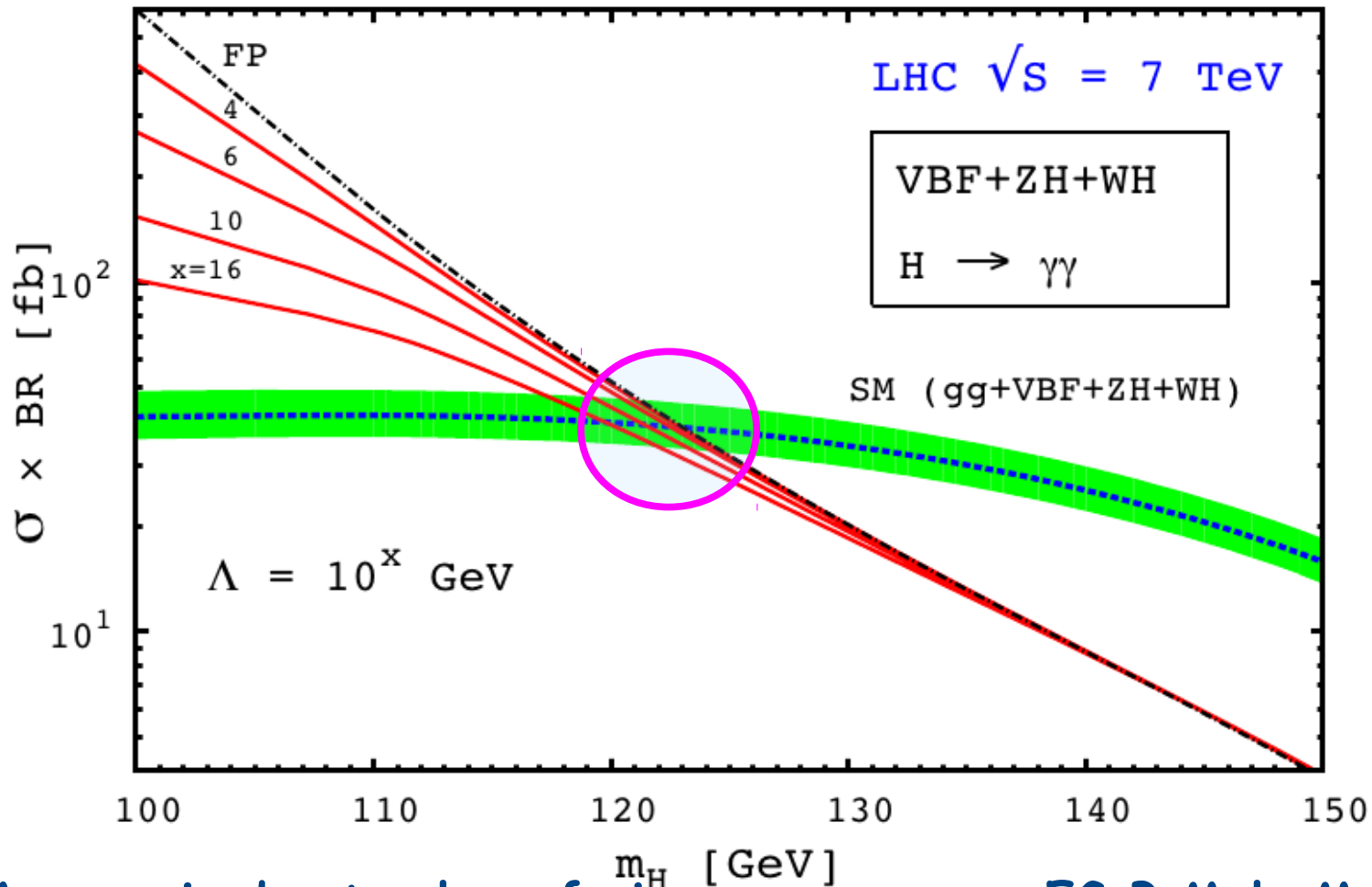


Higgs BR's in **fermionic channels** quite sensitive to the new physics scale Λ

accidental coincidence



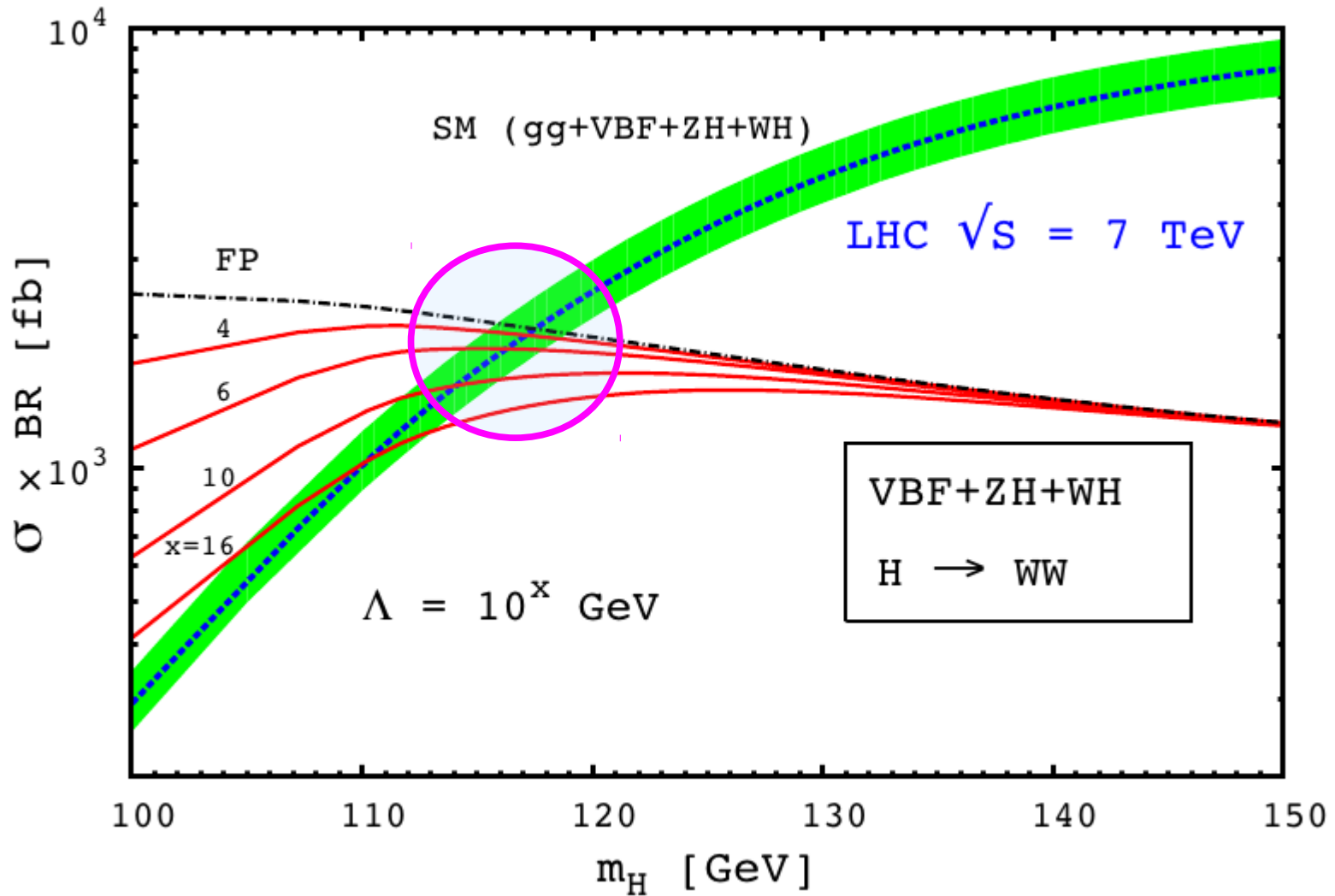
For $m_H=124-126$ GeV, SM and FP Higgs predict
 $\sim$ same inclusive production rate for $H \rightarrow \gamma\gamma$



SM error is due to gluon-fusion
cross-section

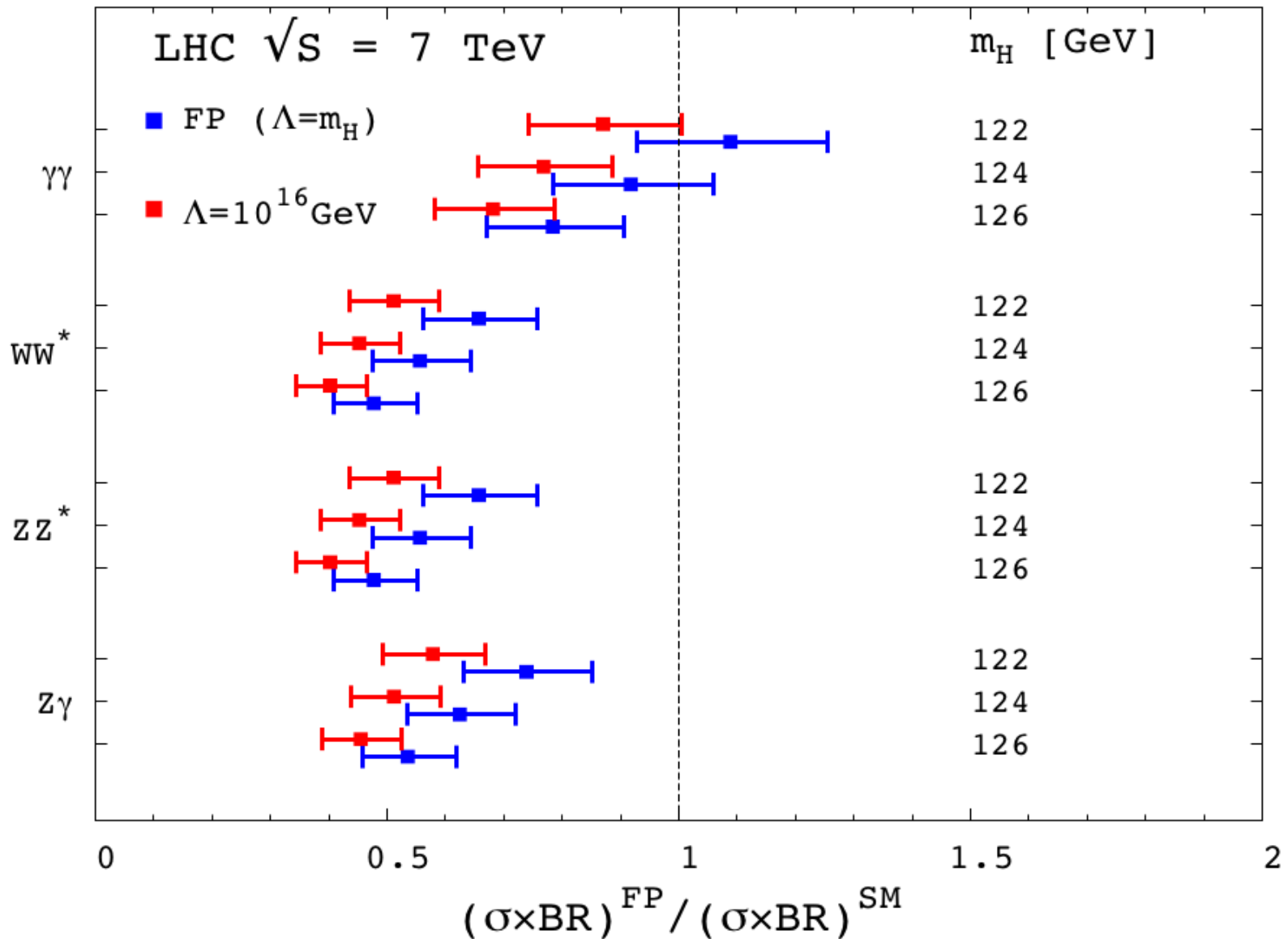
EG, B. Mele, M. Raidal
1202.1792 [hep-ph]

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



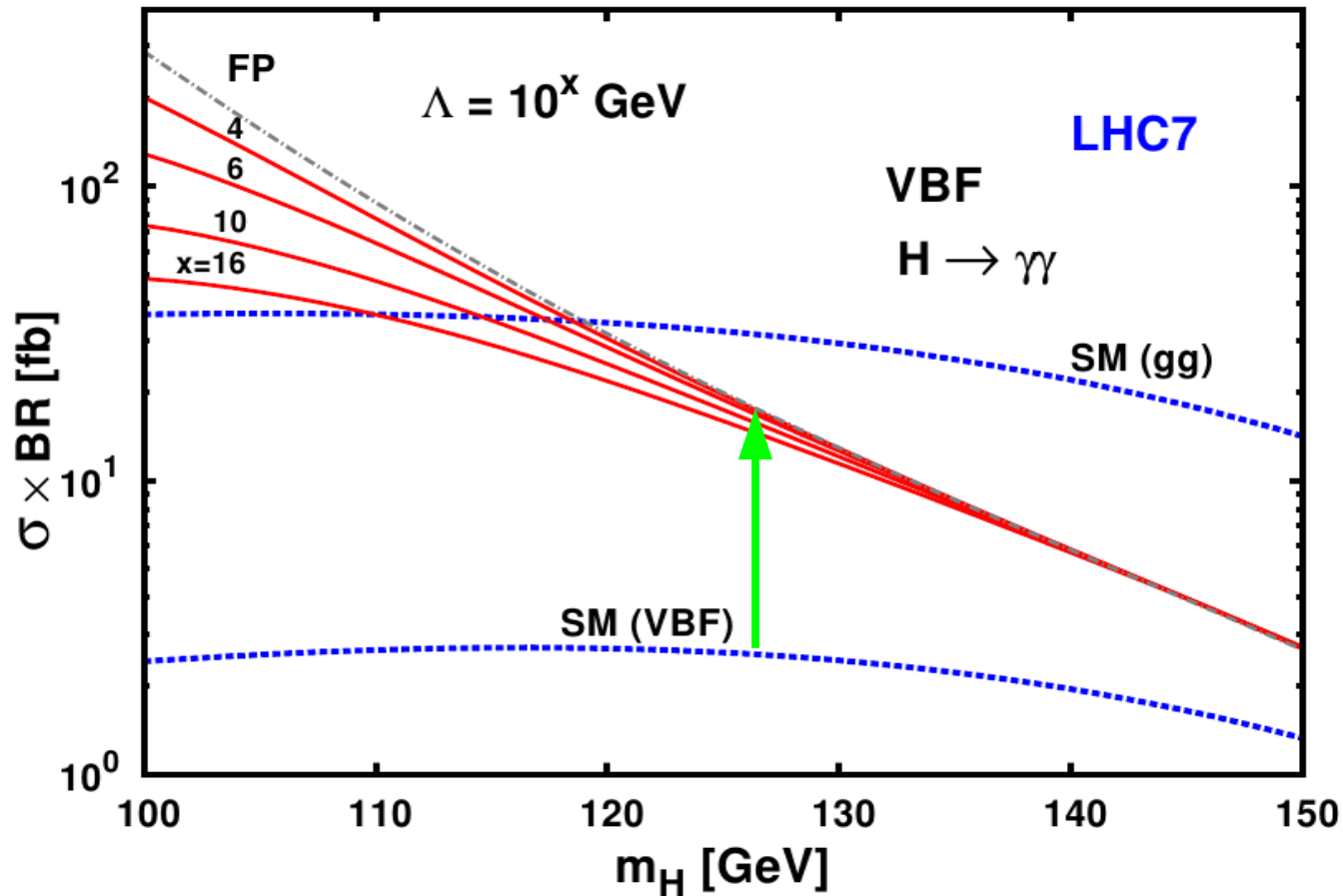
For $m_H=124-126 \text{ GeV}$, FP Higgs has a smaller inclusive WW^* production rate with respect to SM!

FP $H \rightarrow \gamma\gamma$ 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** → **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

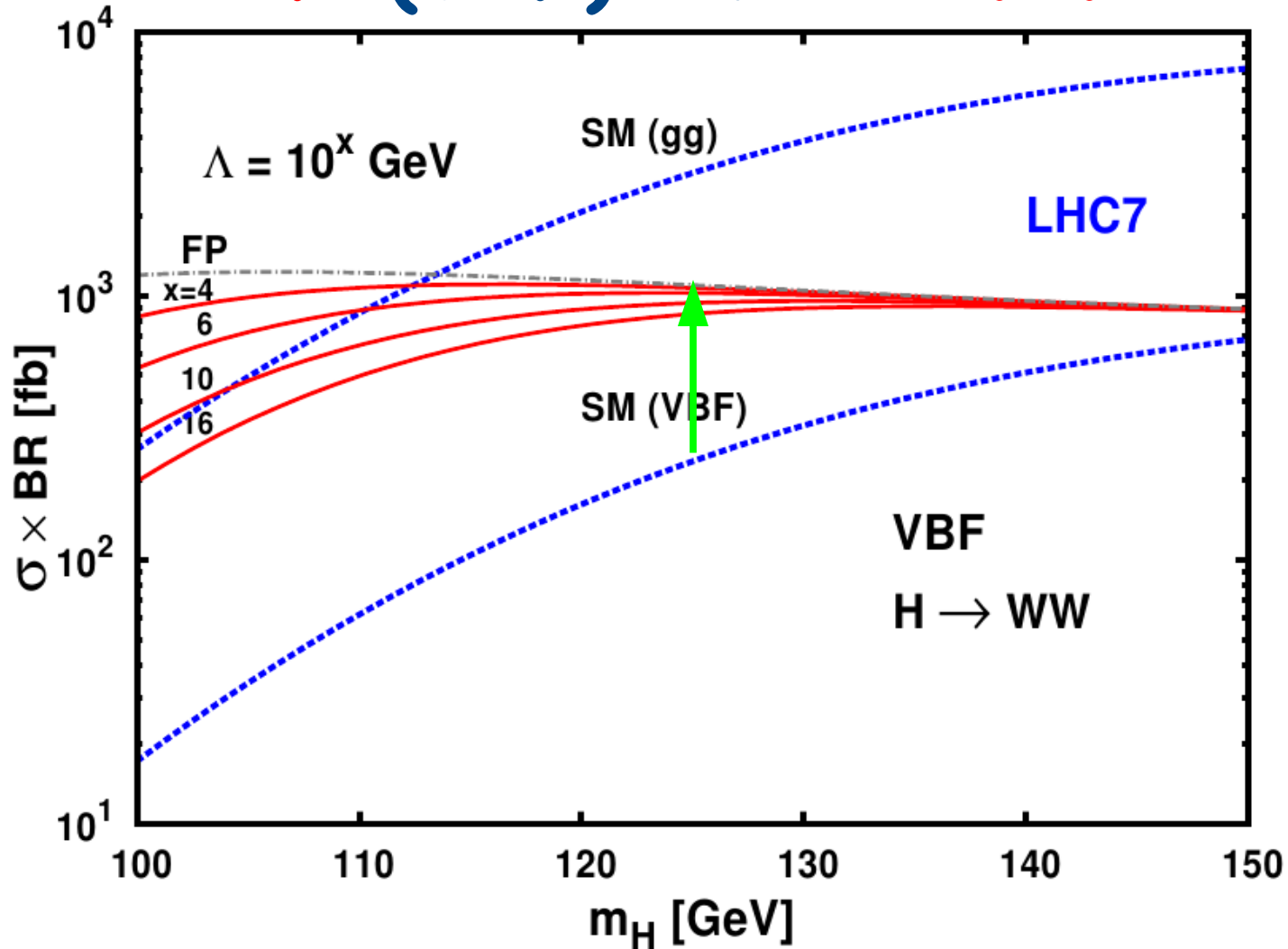
LHC (VBF) : $H \rightarrow \gamma\gamma$



◆ In VBF, FP Higgs predicts a **larger** rate for $\gamma\gamma jj$ production with respect to SM (VBF)

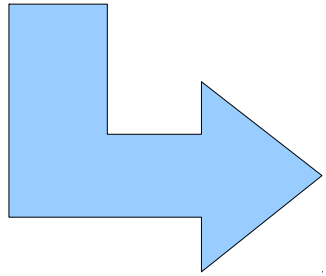
◆ At $m_H = 125$ GeV for $H \rightarrow \gamma\gamma jj$
 $\text{rate}[FP] \sim 7 \times \text{Rate}[SM(VBF)]$

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



For $H \rightarrow WW^*jj$ at $m_H = 125$ GeV
 Rate[FP] $\sim 5 \times$ Rate[SM(VBF)]

If LHC will confirm this scenario



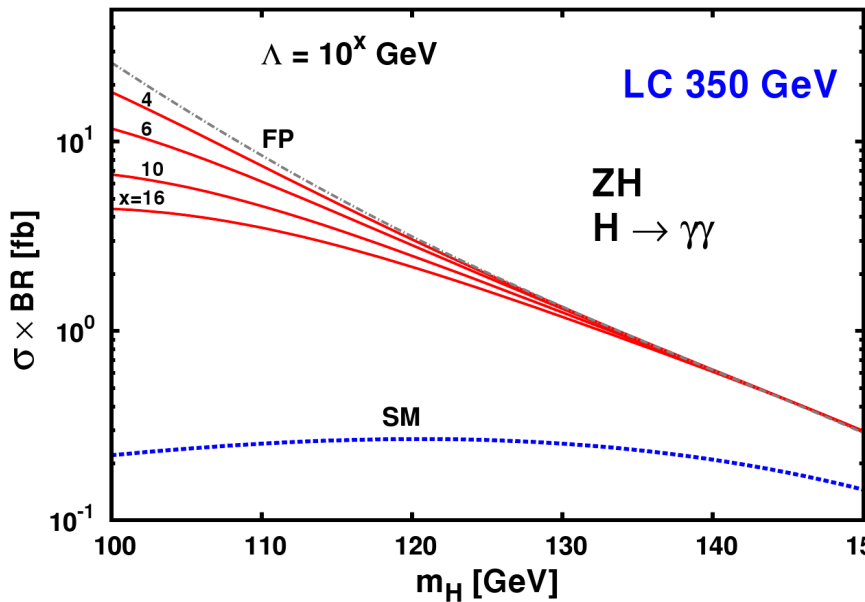
case for a linear collider

advantages

- precise measurements of Yukawas
- LHC will constrain the scale Λ of ChSB
- LC could provide a measurement of Λ

$\sigma \times \text{BR}$ [fb]

$N_{\text{ev}}/500 \text{ fb}^{-1}$



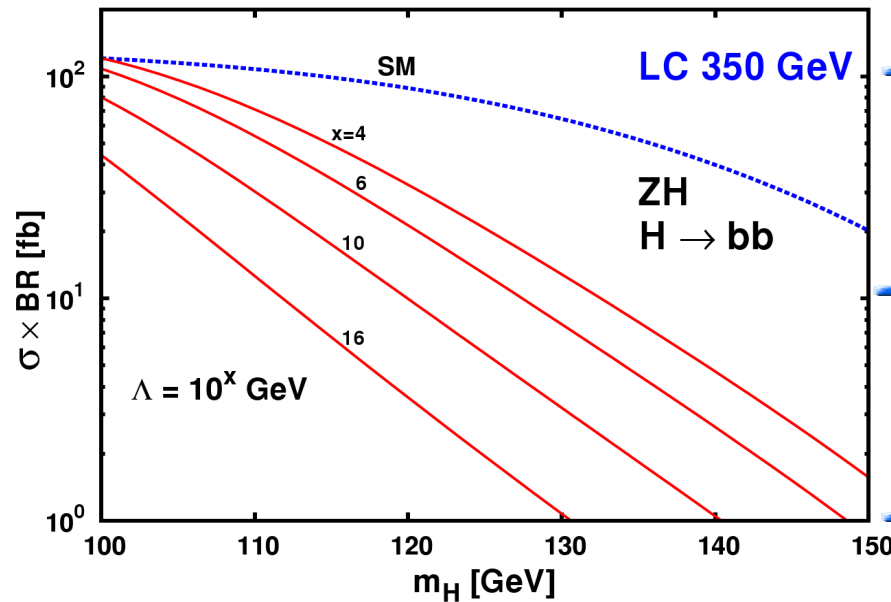
5000

500

50

LC 350

$H \rightarrow \gamma\gamma$



50000

5000

500

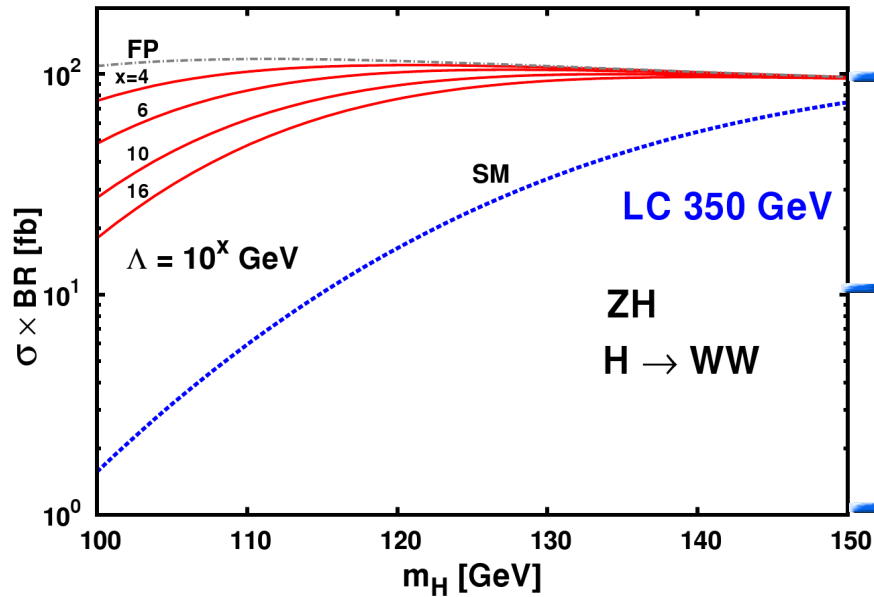
LC 350

$H \rightarrow b\bar{b}$

Excellent
sensitivity to Λ

$\sigma \times \text{BR}$ [fb]

$N_{\text{ev}}/500 \text{ fb}^{-1}$



50000

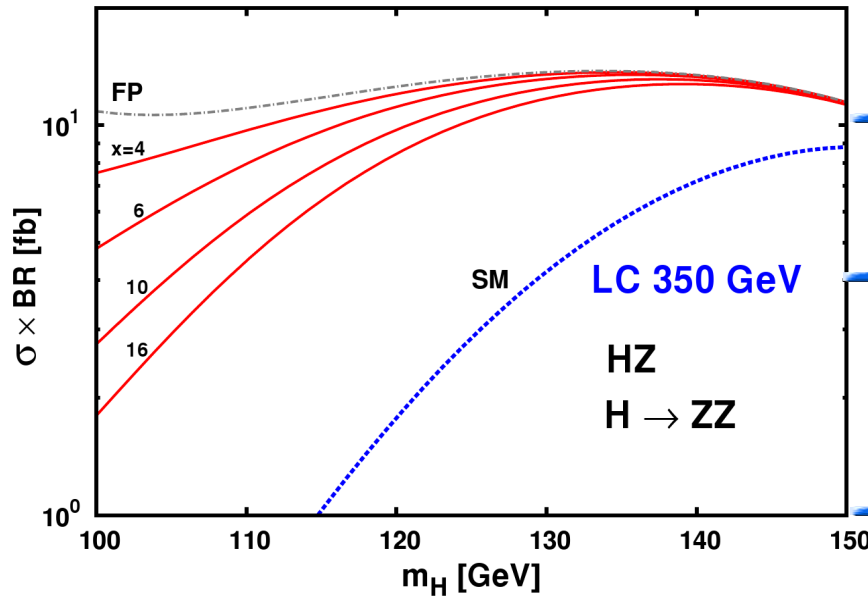
LC 350

5000

$H \rightarrow WW$

500

$\Lambda = 10^x \text{ GeV}$



5000

LC 350

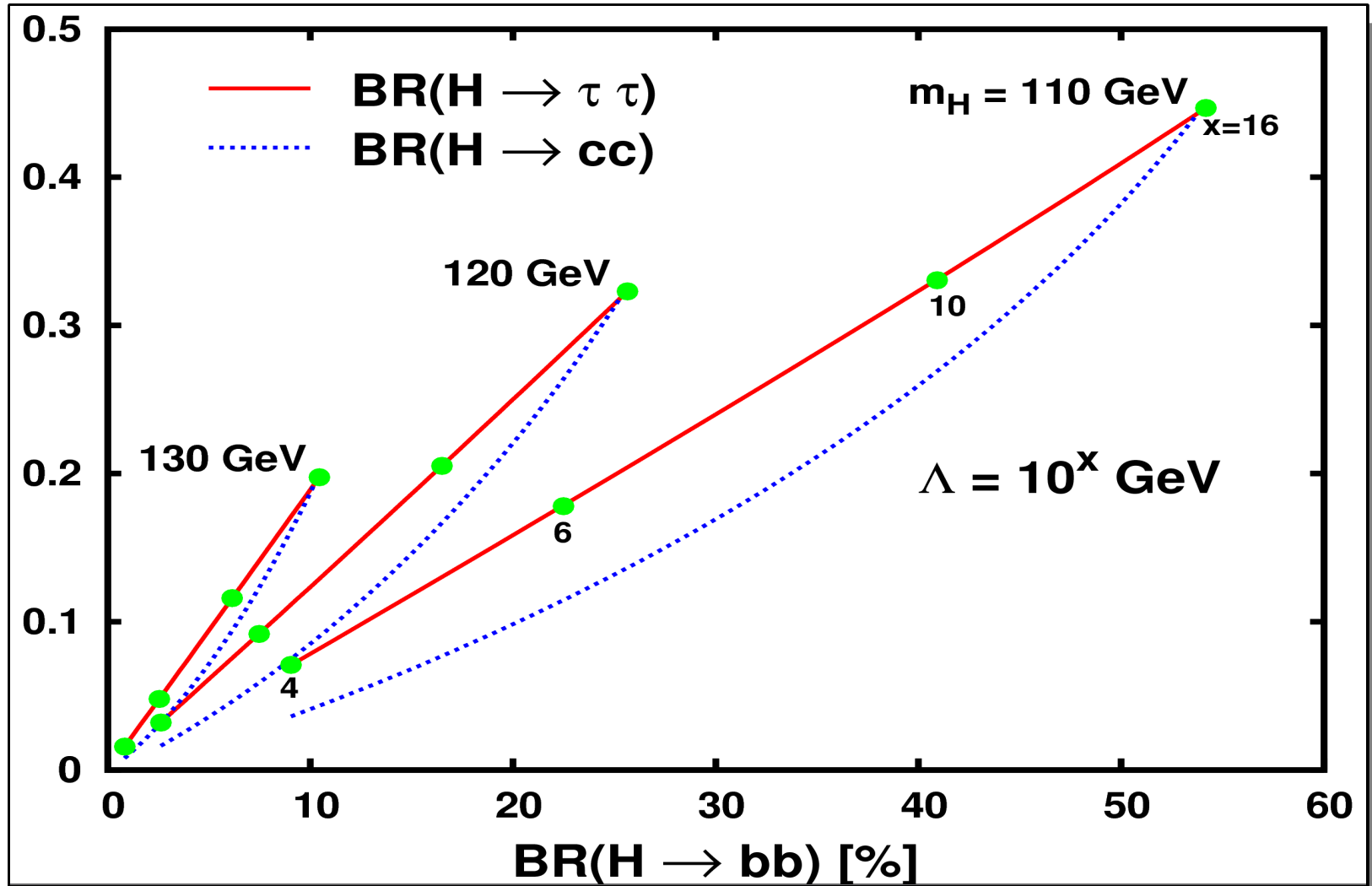
2000

$H \rightarrow ZZ$

500

Correlations of $\text{BR}(H \rightarrow f\bar{f})/\text{BR}(H \rightarrow b\bar{b})$

BR[%]



■ testing BR's correlations in fermion channels is crucial to prove Effective γf 's scenario !

Previous exp bounds on FP Higgs

■ Quite a number of studies on **pure FP** scenario

* LEP $\rightarrow$ 109.7 GeV (comb. $\gamma\gamma$ data on 4 exps) ('02)

(108.3 GeV, comb. $\gamma\gamma+WW^*$ in L3)

* Tevatron $\rightarrow$ (100-) 119 GeV 8.2 fb⁻¹ (Aug 2011)

* ATLAS $\rightarrow$ [110-112] $\cup$ [113-118] GeV 1.08 fb⁻¹
(HCP2011)

* CMS $\rightarrow$ (110-) 112 GeV 1.7 fb⁻¹ (LP2011)

■ bounds in “Effective Y_f ” scenarios needs dedicated studies

* in general weaker than in FP, and depending on Δ

ATLAS and CMS presented at Moriond 2012

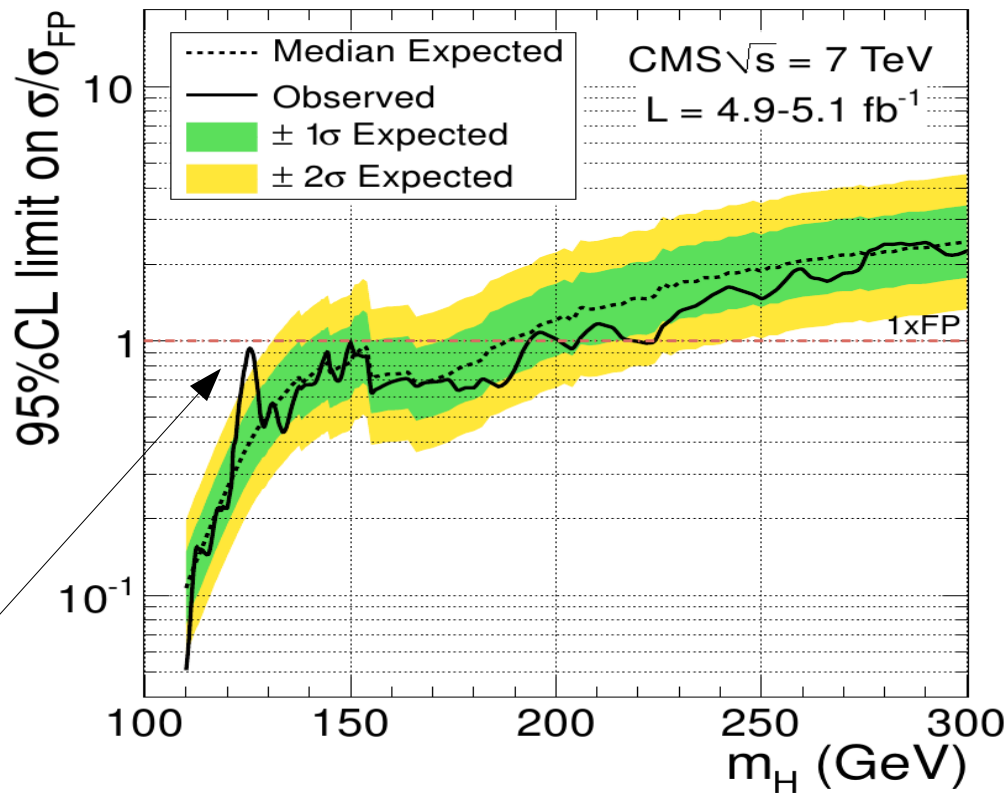
new analyses based on same sample
of data but selecting the **VBF** and
VH Higgs production mechanisms

Moriond 2012:

- **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: 2.8σ (CMS) at 126 GeV, 3σ (ATLAS) at 125.5 GeV

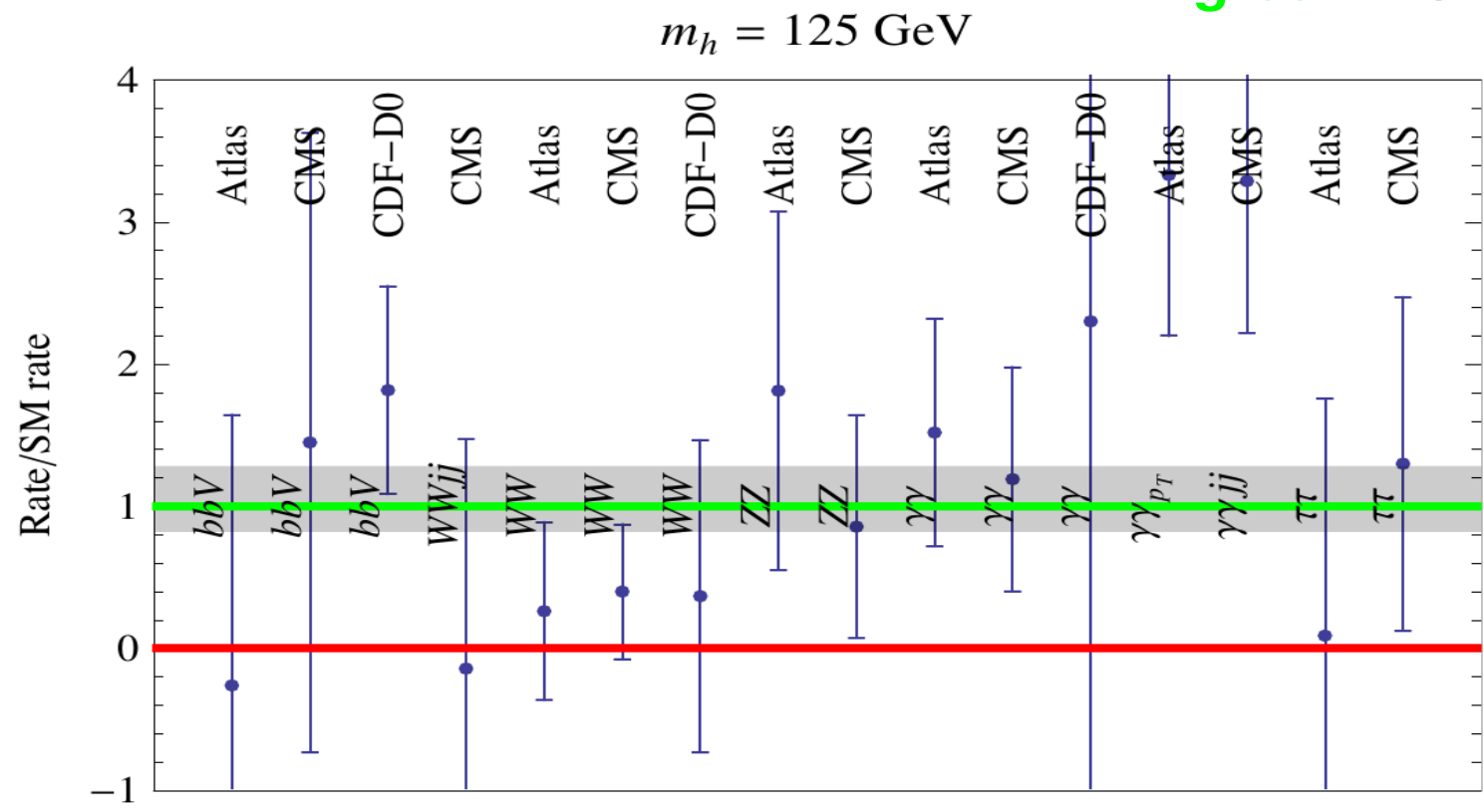
- **A hint of FP Higgs ? To confirm that, test $H \rightarrow VV^*$**
- **A deficit in WW^*jj channel is observed in both experiments with respect to FP Higgs expectations**
- **Exclusion mass ranges for FP Higgs in $\gamma\gamma$ @ 95% CL**
 - CMS $\rightarrow$ [110-124] , [128-136] GeV
 - ATLAS $\rightarrow$ [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 → more conservative approach needed
- including radiative corrections: FP Higgs mass @ 125 GeV with moderate/large Δ is not yet excluded

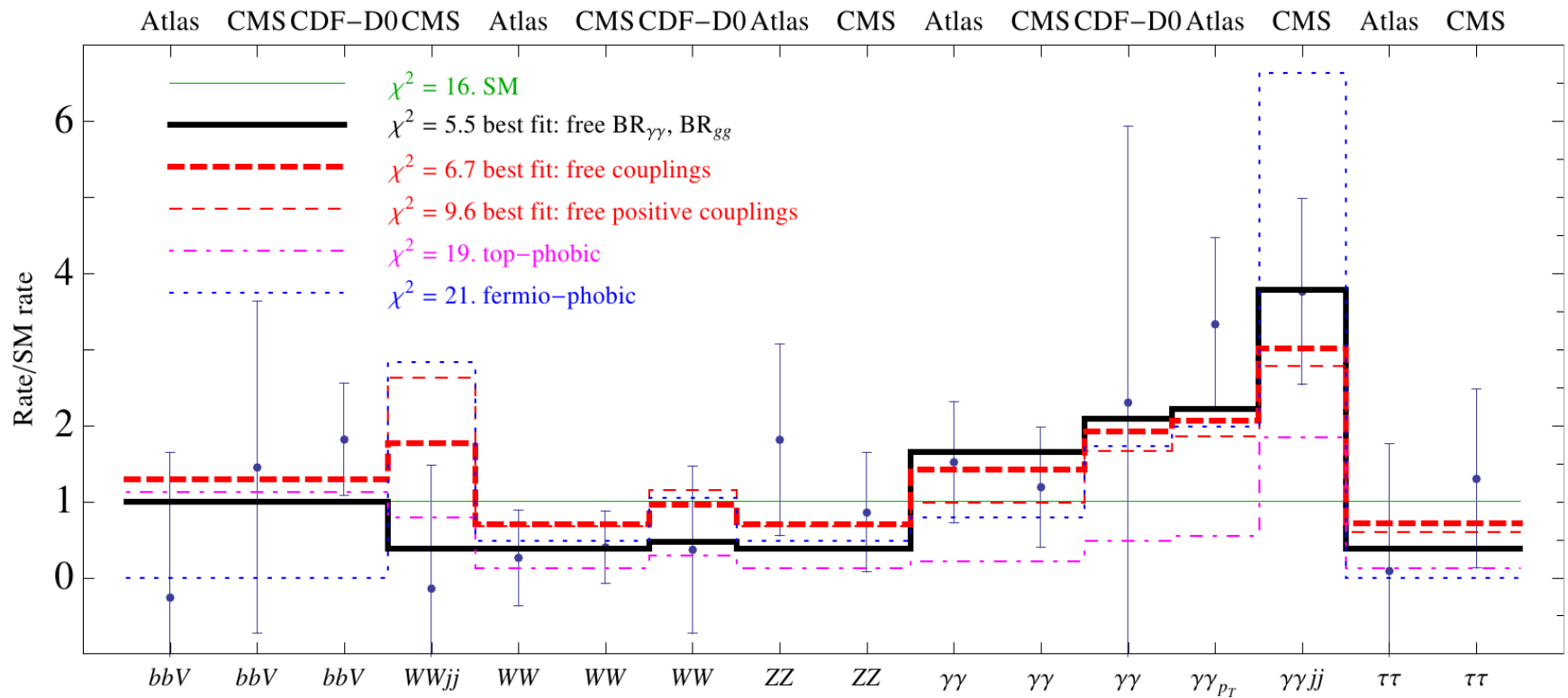
■ After Moriond 2012, new fits seem to disfavor the SM and motivate for New Physics

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



1203.4254

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 → improving fine-tuning 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 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 $\rightarrow$ effective theory valid up to some scale Λ
- 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 ?

MSSM & Higgs mass loop corrections

In the MSSM $M_h^{\text{tree}} < M_Z$. But **1-loop corrections**

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

- ▶ 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: $y_t \rightarrow 0$

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

- we cannot get $m_H > m_Z$ and even more $m_H \sim 125 \text{ GeV}$
- $m_H < m_Z \longrightarrow$ 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 $X_f = 0 \Rightarrow \boxed{y_f, a_f = 0}$

But also other possible configurations (see 1204.0080)

Scalar potential

$$\begin{aligned}
 V = & \left(m_{h_u}^2 + |\lambda s|^2 \right) \left(|h_u^0|^2 + |h_u^+|^2 \right) + \left(m_{h_d}^2 + |\lambda s|^2 \right) \left(|h_d^0|^2 + |h_d^-|^2 \right) \\
 & + m_s^2 |s|^2 + \left(a_\lambda \left(h_u^+ h_d^- - h_u^0 h_d^0 \right) s + \frac{1}{3} a_k s^3 + \text{h.c.} \right) \\
 & + \left| \lambda \left(h_u^+ h_d^- - h_u^0 h_d^0 \right) + k s^2 \right|^2 \\
 & + \frac{g_1^2 + g_2^2}{8} \left(|h_u^0|^2 + |h_u^+|^2 - |h_d^0|^2 - |h_d^-|^2 \right)^2 + \frac{g_2^2}{2} \left| h_u^+ h_d^{0*} + h_u^0 h_d^{-*} \right|^2
 \end{aligned}$$

Parametrization:

$$h_d^0 = \frac{1}{\sqrt{2}} \left(v_d + h_{dR}^0 + i h_{dI}^0 \right)$$

$$v^2 = v_u^2 + v_d^2$$

$$h_u^0 = \frac{1}{\sqrt{2}} \left(v_u + h_{uR}^0 + i h_{uI}^0 \right)$$

$$\tan \beta = \frac{v_u}{v_d}$$

$$s = \frac{1}{\sqrt{2}} \left(v_S + s_R + i s_I \right)$$

- 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

$$\begin{array}{l} a_\lambda = 0 \\ k = \lambda \\ \tan \beta = 1 \end{array}$$

- $\tan\beta=1$ 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

$$h = \frac{1}{\sqrt{2}} (h_{dR}^0 + h_{uR}^0)$$

$$H = \frac{1}{\sqrt{2}} (h_{dR}^0 - h_{uR}^0)$$

$$M_h^2 = \frac{(\lambda v)^2}{2} \simeq (125\text{GeV})^2$$

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

$$M_{SR}^2 = \frac{a_k v_S}{\sqrt{2}} + 2(\lambda v_S)^2$$

MSSM notation $\rightarrow \alpha = -\pi/4$



$\beta = \pi/4 \Rightarrow$ no direct tree level coupling HWW and HZZ



OK with LHC seeing no other “resonance” but $\simeq 125\text{GeV}$.

Other relevant SUSY spectrum

■ Neutralino mass matrix 5x5

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

■ Chargino mass matrix same as in MSSM

■ Charged-Higgs mass

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

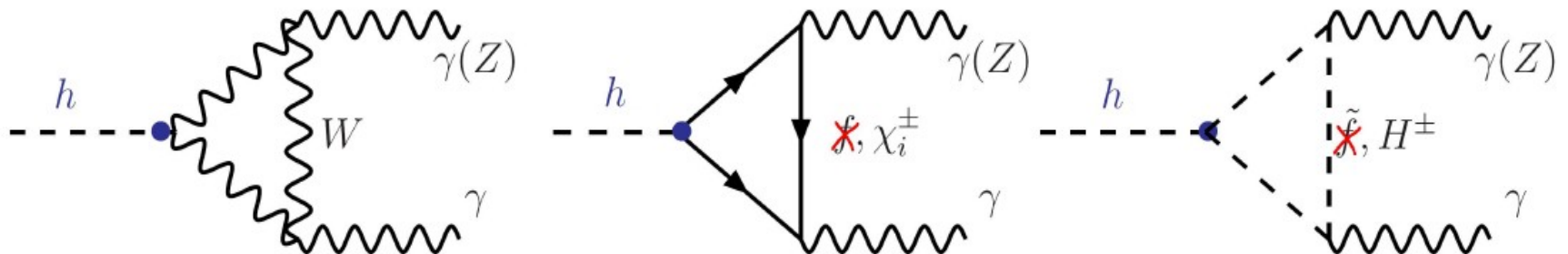
■ relevant parameters:

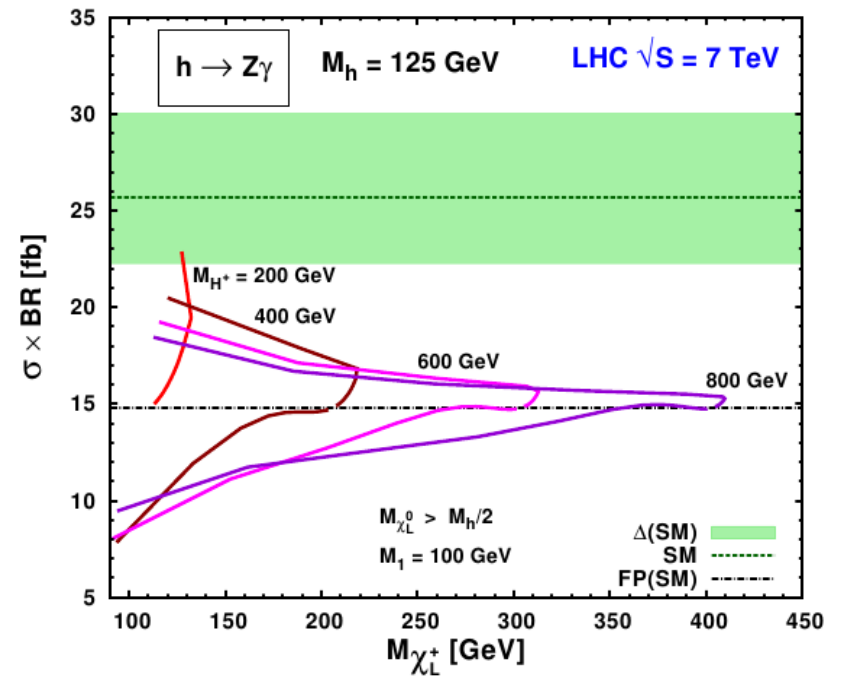
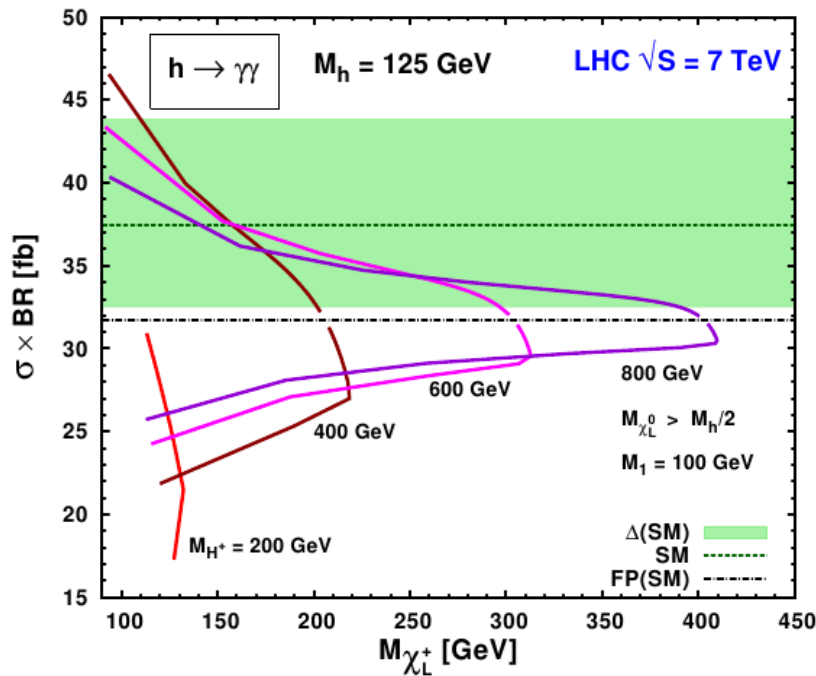
$$M_1 > 0, \quad M_2 > 0, \quad |\lambda|, \quad |\mu| \equiv |\lambda v_S| / \sqrt{2}, \quad \text{sign}(\mu)$$

Strategy

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

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





1. The lines above (below) the FP SM prediction for $h \rightarrow \gamma\gamma$ correspond to positive (negative) values the μ . For $h \rightarrow Z\gamma$ is the opposite.
2. For fixed $M_{\chi_L^+}$ two non-degenerates 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 Λ of **ChSB** is very large → **$BR(H \rightarrow bb)$** 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) : $H \rightarrow bb$

