

# Impact of radiative corrections to the Fermiophobic Higgs at the LHC and LC

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**Colloquium**

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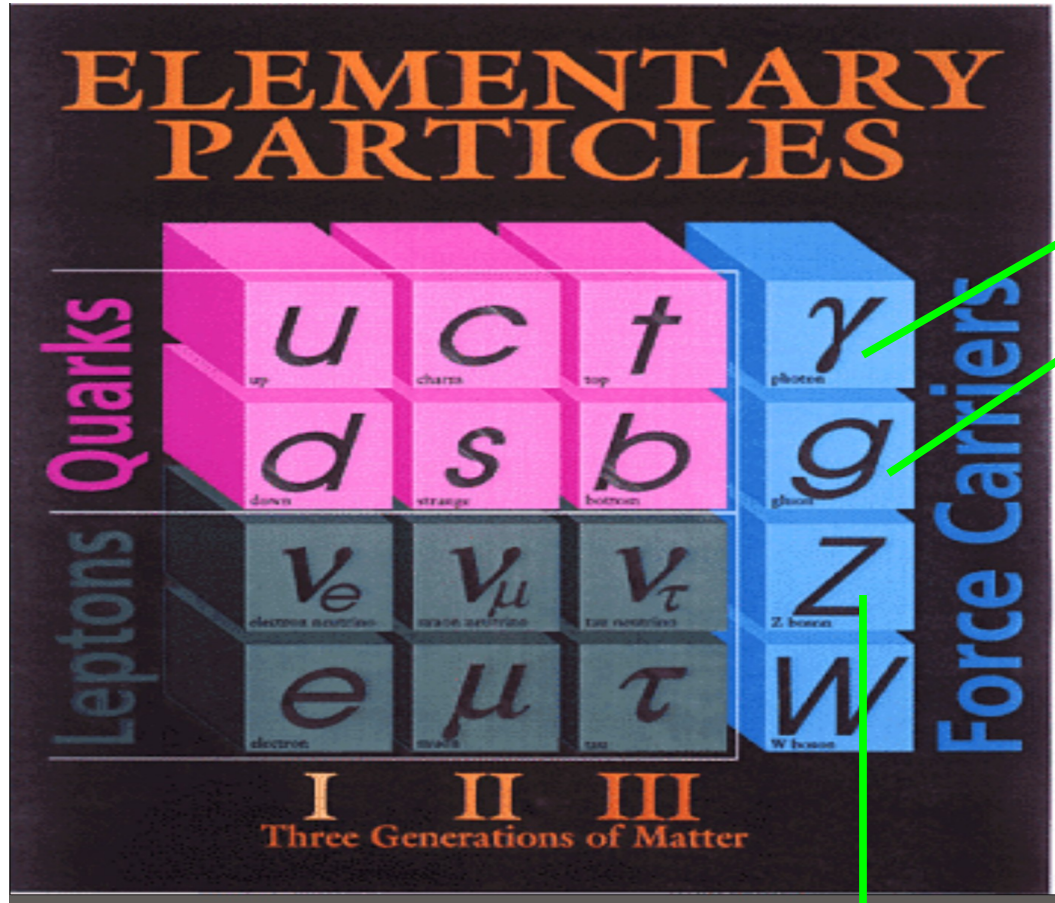
# Outline

- Higgs mechanism and origin of masses
- Higgs searches: where we are today
- **Fermiophobic** Higgs scenario
- Impact of radiative corrections
- Improved **Fermiophobic** Higgs scenario
- Implications at LHC and linear colliders
- Conclusions

# Why we are so concerned 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 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 building blocks of known elementary particles



**massless GB**

**Photon: EM**

U(1) gauge theory

**Gluons: Strong**  
SU(3)<sub>c</sub> gauge theory

**mass of quarks/leptons**  
(in unity of  $1/c^2$ )

$m_u \sim m_d \sim 5 - 8 \text{ MeV}$

$m_s \sim 150 \text{ MeV}$

$m_c \sim 1.5 \text{ GeV}$  ,

$m_b \sim 3 \text{ GeV}$

$m_t \sim 173 \text{ GeV}$

**Electric charges**  
(in unity of  $e$ )

$$Q_\nu = 0$$

$$Q_e = 1$$

$$Q_U = 2/3$$

$$Q_D = -1/3$$

**massive GB**

**Z, W : Weak**

Neutral    Charged Currents

$m_e \sim 0.5 \text{ MeV}$

$m_\mu \sim 105 \text{ MeV}$

$m_\tau \sim 1.77 \text{ GeV}$

$m_\nu < \text{eV}$

# Weak-interactions

Gauge theory **SU(2)** acting on Weak Isospin doublets

$$U(x) = \exp \left( i \sum_a \lambda^a(x) T^a \right) \left( \begin{array}{c} u \\ d \end{array} \right)'_L = U(x) \left( \begin{array}{c} u \\ d \end{array} \right)_L$$

$T^a \rightarrow$  SU(2) matrix generators

Maximal Parity violation

3 Quark families

$Q = (u,d) \quad (c,s) \quad (t,b)$

3 Lepton families

$L = (\nu_e, e) \quad (\nu_\mu, \mu) \quad (\nu_\tau, \tau)$

**SU(2)<sub>L</sub> x U(1)<sub>Y</sub>** broken to  $\rightarrow$  **U(1)<sub>EM</sub>**  $\rightarrow$  massive **W, Z**



$M_W = 80 \text{ GeV}$   
 $M_Z = 91 \text{ GeV}$

$$L \rightarrow (1 - \gamma_5)$$



Fermion mass terms  
are not gauge invariant

**But how to give masses to  
W and Z ?**

Before entering in this question one may wonder if the **SM** is a **gauge theory of  $SU(2)_L \times U(1)$**

- ✱ gauge invariance constraints the theory very tightly!

- ✱ stringent tests of predictions tested experimentally

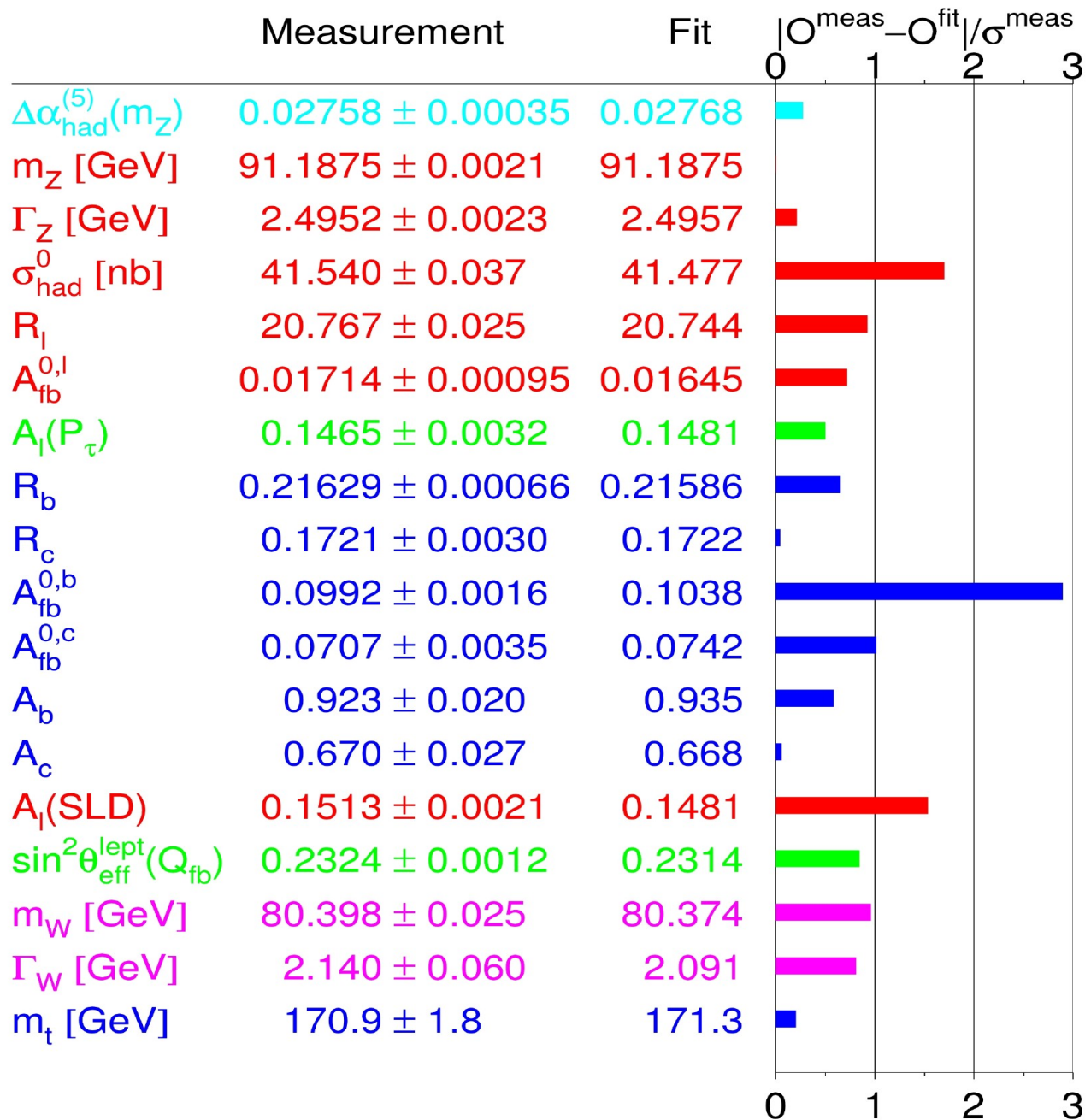
**More than 20 years of precision tests of the SM**

SM tested at the quantum level (one-loop radiative corrections)

- ✱ physics at the **Z pole** ('89-00) at LEP (CERN)  **$e^+e^- \rightarrow Z$**

- ✱ Tevatron physics (proton-antiproton)  $E_{cm} \sim 2 \text{ TeV}$  ('85-11)  
(top-quark discovery 1994)

- ✱ many low energy physics experiments: (meson rare decays, CP-violations,  **$g-2$  of muon**, etc.)



**All measurements in excellent agreement with SM !**

# What if we add W and Z mass terms by hand ? (explicit breaking of SU(2)<sub>L</sub> gauge symmetry)

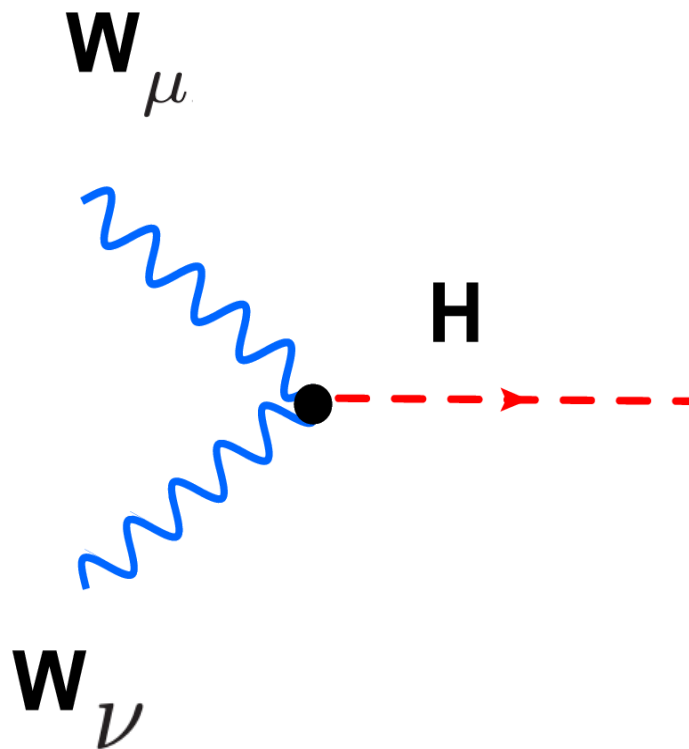
- **Problems:** bad high energy behavior for interacting gauge bosons  
→ **W** and **Z** becomes strongly interacting at high energy
- polarization of **massive** gauge boson has 3 components
  - 2 **transverse** and 1 **longitudinal** (with respect to the 3-momentum)
- **Longitudinal** polarizations of a spin-1 particle grows with energy

$$\varepsilon_{\mathbf{L}}^{\mu}(\mathbf{k}) \simeq \frac{\mathbf{k}_{\mu}}{M_{\mathbf{W}}}$$

- at high energy  $E > 1\text{-}2 \text{ TeV}$ , scattering amplitudes for **W W** → **W W** **explode** → **unitarity violation**
- Problem absent in **U(1) gauge theory** due to the conservation of current  $\mathbf{k}_{\mu} \mathbf{J}^{\mu} = 0 \rightarrow$  **U(1) longitudinal component are decoupled**

# How to discover the **Higgs mechanism** by requiring perturbative unitarity

In order to recover unitarity in perturbation theory we can add a neutral scalar field **H** coupled to **W** and **Z** with a coupling **proportional to W,Z masses**



The diagram shows a blue wavy line representing a  $W_\mu$  boson entering a vertex (black dot). From this vertex, a red dashed line with an arrow pointing right represents a Higgs boson ( $H$ ). Another blue wavy line representing a  $W_\nu$  boson exits the vertex. This represents a self-energy correction to the  $W$  boson propagator.

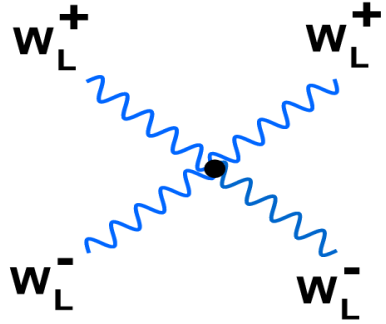
$$= \eta_{\mu\nu} g M_W$$

gauge weak coupling

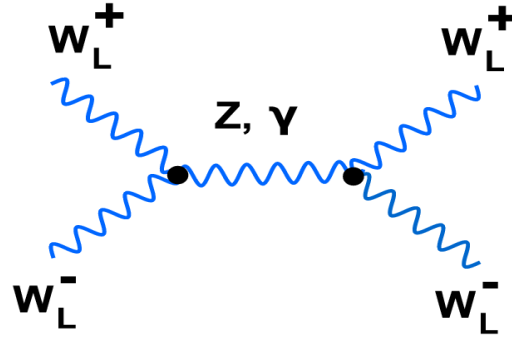
4D Minkowski metric

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

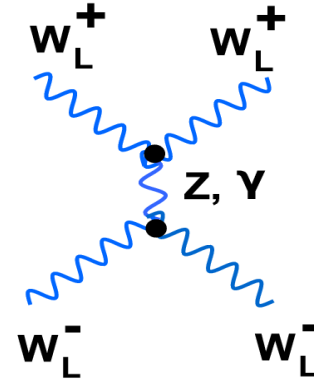
$$\cos \theta \equiv \frac{M_W}{M_Z}$$



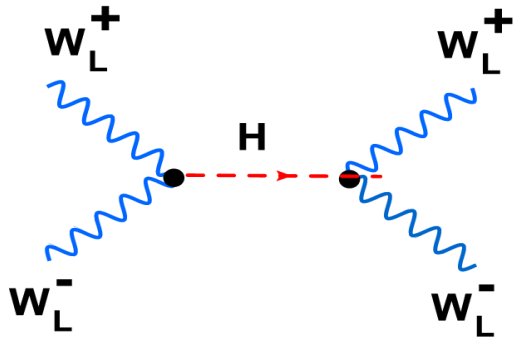
(a)



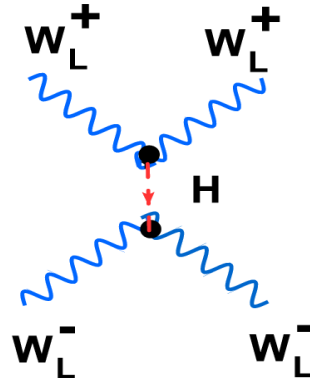
(b)



(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<sup>2</sup>/M<sup>2</sup>** cancellation not accidental !
- related to: **spontaneous gauge symmetry breaking** → the **Higgs mechanism**. Scalar **H** is the **Higgs boson field**
- at **E<sup>0</sup>** order, unitarity requires **m<sub>H</sub> ≲ 1 TeV**

# Higgs mechanism @ work in U(1) gauge theory

1 Goldstone in the spectrum

$$\mathcal{L} = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + \underbrace{\alpha \Phi^\dagger \Phi - \beta (\Phi^\dagger \Phi)^2}_{\text{Potential V}} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

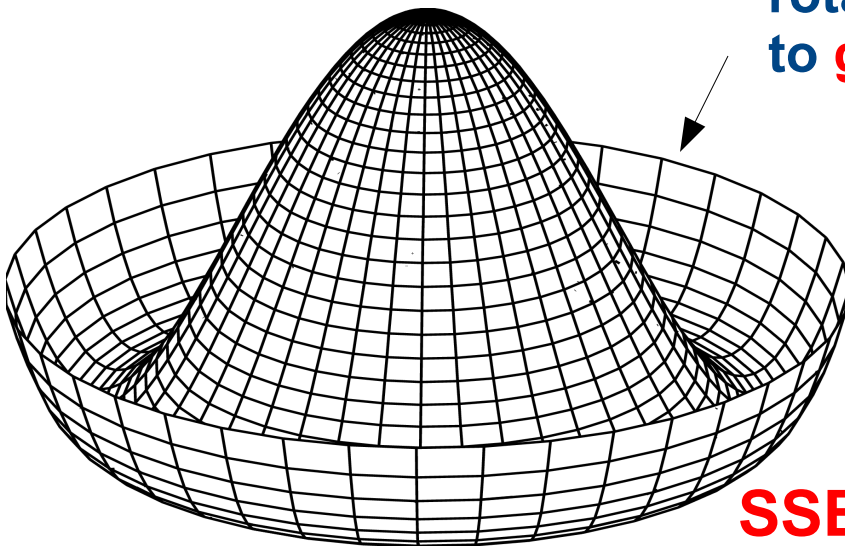
$\mathcal{L}$  is gauge invariant

$$\begin{cases} \Phi' = e^{i\lambda} \Phi \\ A'^\nu = A^\nu + \partial^\nu \lambda \end{cases}$$

$$\mathcal{D}^\mu = \partial^\mu - iA^\mu$$

Potential V

rotational symmetry corresponds to gauge symmetry



true minimum of V at

$$\langle |\Phi| \rangle = v = \sqrt{\alpha/2\beta}$$

**SSB** → Lagrangian is symmetric but the vacuum is not!

expanding  $L$  around the true minimum of  $V$

$$\Phi(x^\mu) = v + h(x^\mu)$$

Before (photon  $A$  is massless)

$$\begin{aligned}\mathcal{L} = & (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) \\ & + \alpha \Phi^\dagger \Phi - \beta (\Phi^\dagger \Phi)^2 \\ & - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}\end{aligned}$$

$\mathcal{L}$  is gauge invariant

After (photon  $A$  acquires a mass)

no Goldstone scalar in the spectrum, but one massive neutral scalar  $h$

Mass term for  $h$

interactions of  $h$  and  $A$

$$\begin{aligned}\mathcal{L} = & (\partial^\mu h)^2 - 4\beta v^2 h^2 \\ & - 4\beta v h^3 - \beta h^4 + 2v A^\mu A_\mu h + A^\mu A_\mu h^2 \\ & - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + v^2 A^\mu A_\mu\end{aligned}$$

Mass term of  $A$

# SM origin of fermion masses

**Strong** and **EM** interactions do not distinguish between **L-** and **R-handed** fermion components but **Weak interactions DO !**

→ **parity is broken**

**W** couples only to **L-handed fermions**

**Z** has both **L-** and **R-handed** couplings with different weights

mass terms are NOT **SU(2)<sub>L</sub>** gauge invariant

Right-handed **f** are singlet under **SU(2)<sub>L</sub>**

$$\mathcal{L} = \bar{f}_L \gamma^\mu \partial_\mu f_L + \bar{f}_R \gamma^\mu \partial_\mu f_R - m \bar{f}_L f_R - m \bar{f}_R f_L$$

**Higgs mechanism solves this problem**

$$\mathcal{L} = -y \bar{f}_L \Phi f_R - y \bar{f}_R \Phi^\dagger f_L \quad \text{gauge invariant} \quad \xrightarrow{\text{SSB}}$$

$$\begin{aligned} \Phi = v + h &\longrightarrow = -m \bar{f}_L f_R - m \bar{f}_R f_L - y h \bar{f}_L f_R - y h \bar{f}_R f_L \\ &\quad \text{mass terms} \qquad \qquad \qquad \text{Yukawa couplings} \end{aligned}$$

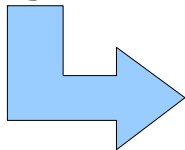
# Properties of SM Higgs mechanism

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



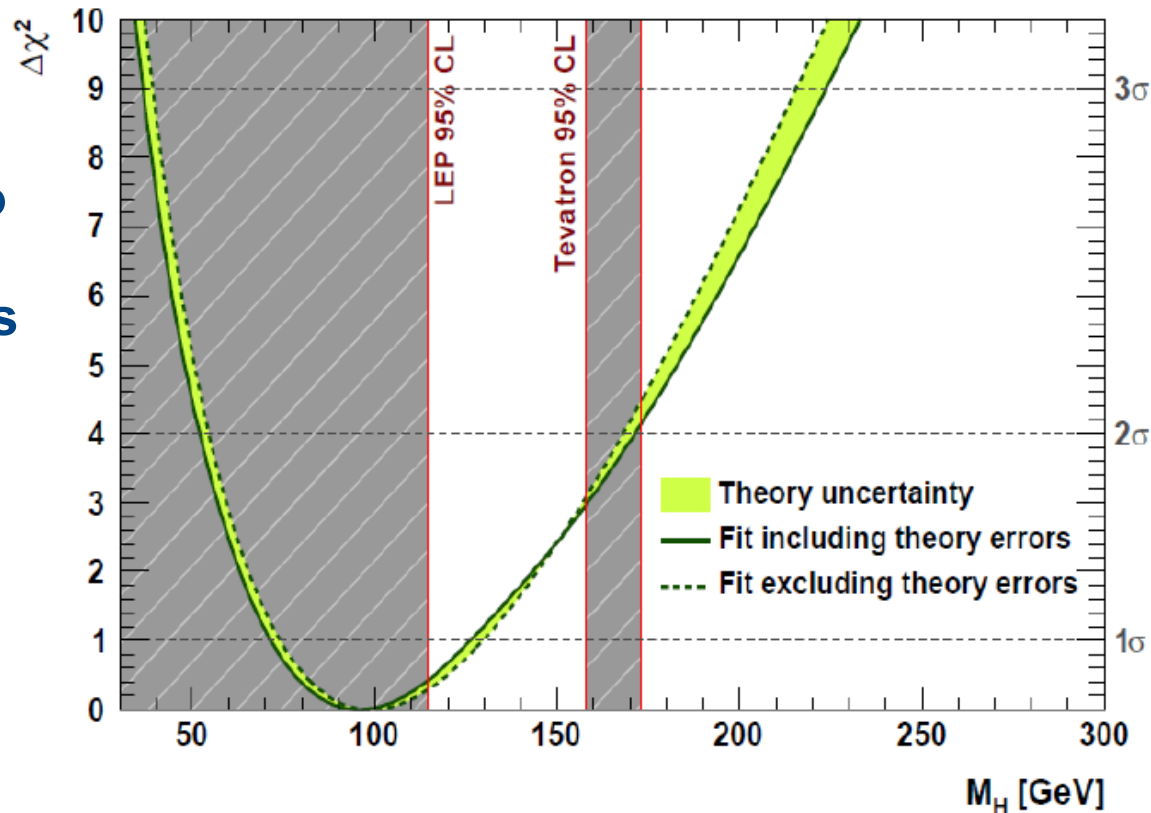
this makes Higgs discovery difficult

and The  
UGLY

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

# 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

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

# Why EWSB requires new phenomena at the TeV scale

**Perturbative unitarity at all energies**  $\rightarrow m_H \lesssim 1 \text{ TeV}$

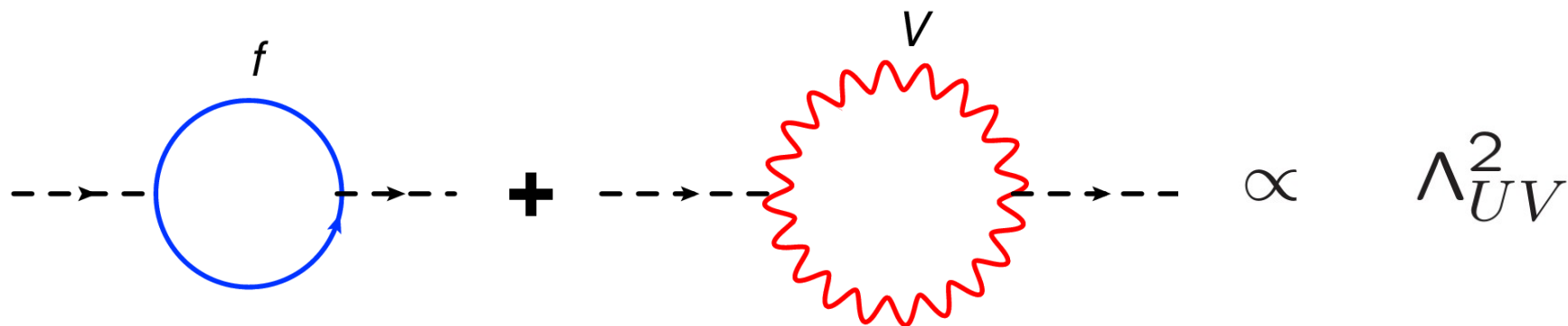
**Quantum corrections**

**NP scale**

$m_f \bar{\psi}\psi \xrightarrow{\text{chiral symmetry}} 0 \Rightarrow \delta m_f \sim m_f \ln \frac{\Lambda_{UV}}{m_f} \quad \text{OK}$

$m_W^2 W_\mu W^\mu \xrightarrow{\text{gauge symmetry}} 0 \Rightarrow \delta m_W^2 \sim m_W^2 \ln \frac{\Lambda_{UV}}{m_W} \quad \text{OK}$

$m_H^2 H^2 \xrightarrow{\text{no symmetry in SM}} \Rightarrow \delta m_H^2 \sim \Lambda_{UV}^2$



$m_H + \delta m_H \lesssim 1 \text{ TeV} \quad \rightarrow \quad \text{Fine-tuning if } \Lambda_{UV} \gg \text{TeV}$

# Alternative solutions to the SM Higgs mechanism

before late '90

## Supersymmetry →

Predicts a light Higgs boson  
 $m_H \simeq (100-140 \text{ GeV})$ ,

Favored by EWPT

Gauge coupling unification!

Dark matter candidate

◆ Global symmetry of **fermions** ↔ **bosons**



◆ replica of SM degrees of freedom with opposite statistics (**fermions** ↔ **bosons**)

◆ improve UV convergence and cure the problem of fine tuning of SM Higgs sector

◆ SUSY must be **(softly) broken** → expected superpartners mass below 1 TeV

## Technicolor →

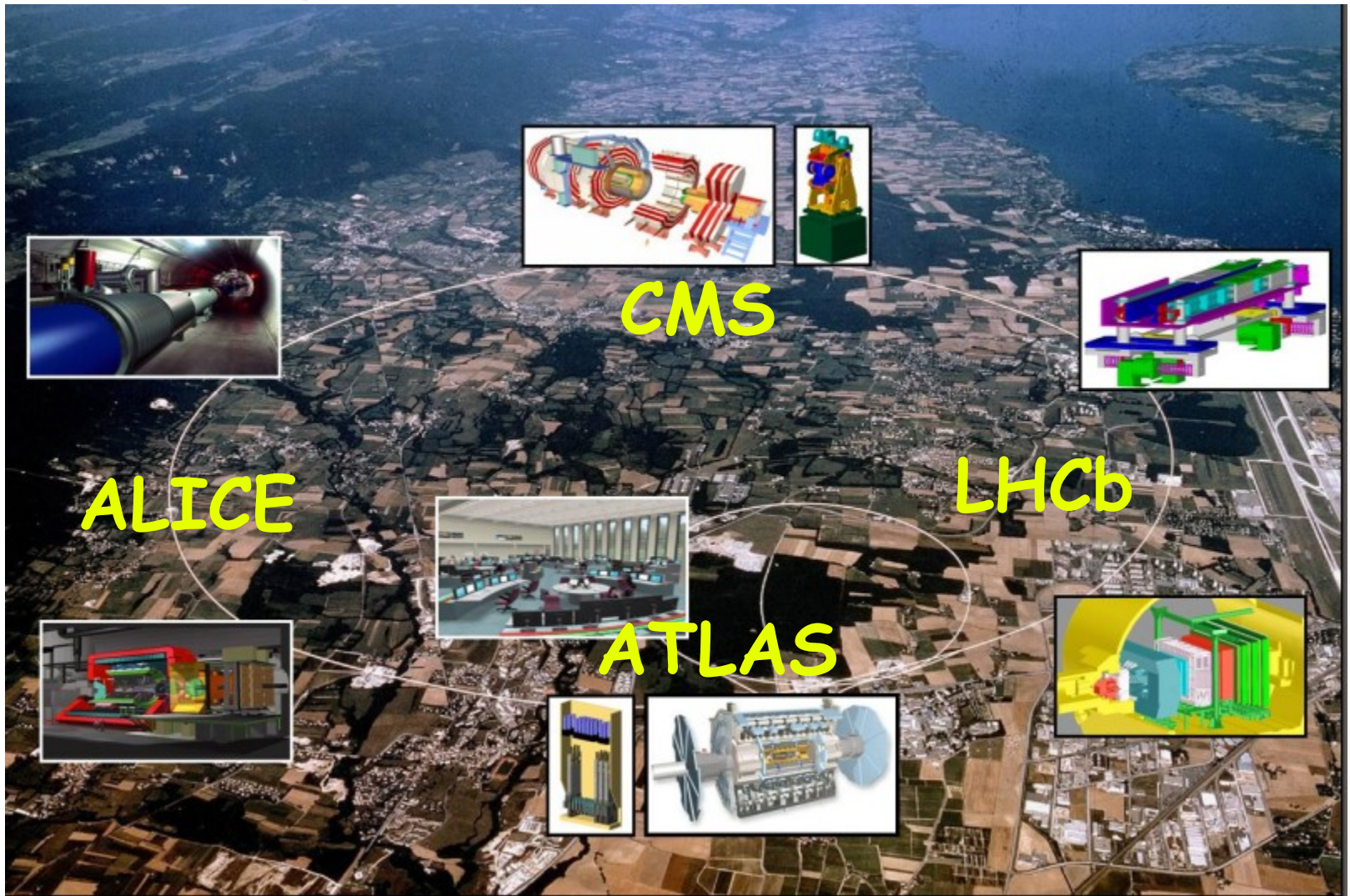
Problems with EWPT and FCNC processes

◆ Higgs field is a bound state of new fermions and antifermions as heavy as 1 TeV, bound by superstrong “**technicolor**” forces

◆ New force is  $10^3 \Lambda_{\text{QCD}}$

◆ New heavy particles expected at 1 TeV

# Large Hadron Collider



proton-proton collisions  
c.o.m. energy = 7 TeV → 14 TeV

# LHC : where we are today

- In 2010 LHC delivered **45 pb<sup>-1</sup>** of luminosity **L** in pp collisions at **E<sub>cm</sub>=7 TeV**: **N(events)= L x cross-section**
- **ATLAS** and **CMS** could substantially improve bounds on direct signals from BSM models with respect to Tevatron limits by analyzing just the first **45 pb<sup>-1</sup>** of L
- **New mass bounds** (by analyzing  $\lesssim 2 \text{ fb}^{-1}$  , Aug. 2011)
  - ◆ **SUSY** (constrained MSSM  $\rightarrow M_q=M_g$ ) **> 1 TeV**
  - ◆ **Gauge Bosons** (SSM) **> 2 TeV**
  - ◆ **Excited Quarks** **> 3 TeV**
  - ◆ **Scale of contact 4-fermion interactions** **> 9 TeV**
- LHC delivered up today  $\sim 5.7 \text{ fb}^{-1}$   $\rightarrow$  **set stronger constraints!**
- **further  $\sim 20 \text{ fb}^{-1}$**  expected by the end of 2012 (run at 8 TeV ? )

# 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:  **$e^+e^- \rightarrow H(\rightarrow b\bar{b}) Z$**

**$m_H > 114.4 \text{ GeV}$**

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**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**

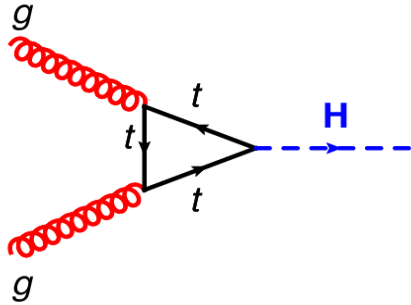
**$[100 - 109] \text{ GeV}$**  and  **$[156 - 177] \text{ GeV}$**

# Hot LHC data on Higgs boson

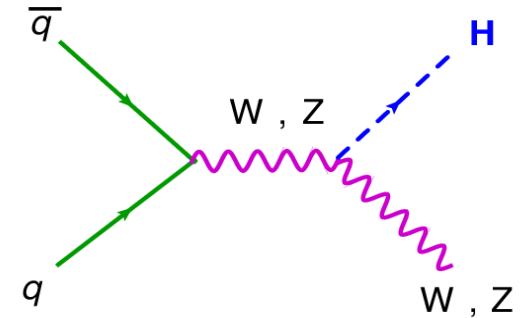
- In a few months we should be able to complete the **SM-Higgs search-phase** and find out whether:
  - ◆ there is a SM like Higgs signal
    - Start testing its properties
  - ◆ there is NOT a SM like Higgs signal
    - What is there instead ?
    - This will take longer...
- Results presented here are according to HPC (Nov 2011)
  - + update from ATLAS and CMS at 13 Dec CERN seminars

# SM Higgs production mechanisms

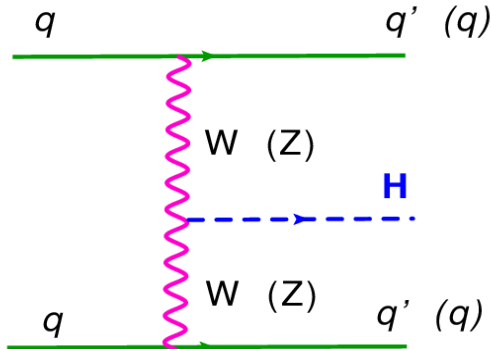
**Gluon fusion**



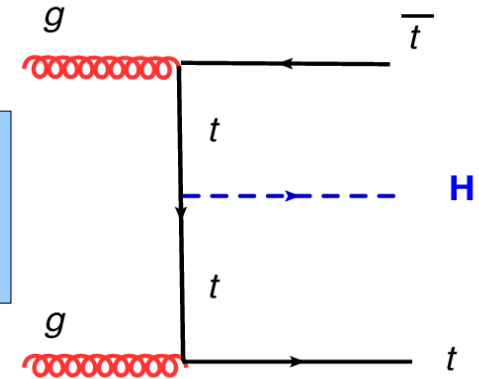
**VH**



**VBF**



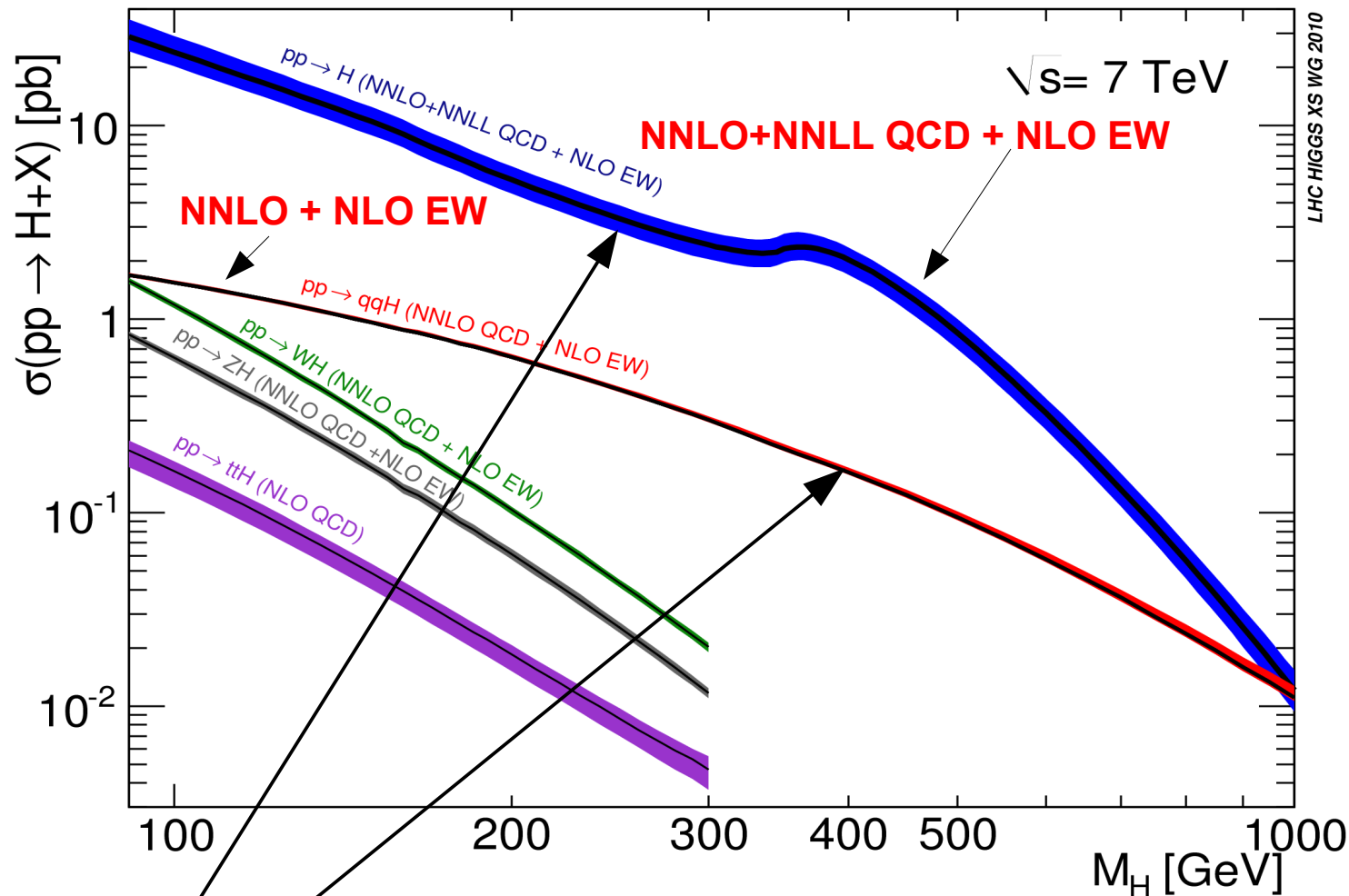
**ttH**



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

$(0 < x < 1)$  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

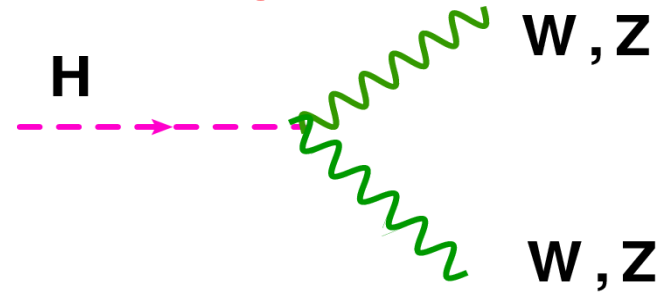
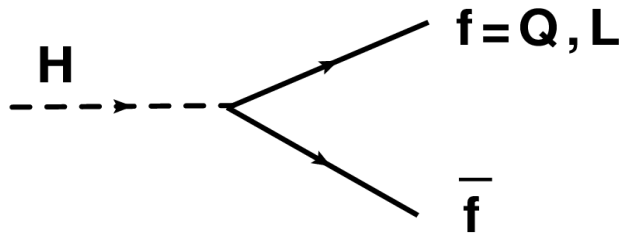


**Gluon fusion** : the leading production mechanism

**VBF** : the next-to-leading mechanism

# Relevant SM Higgs decay channels

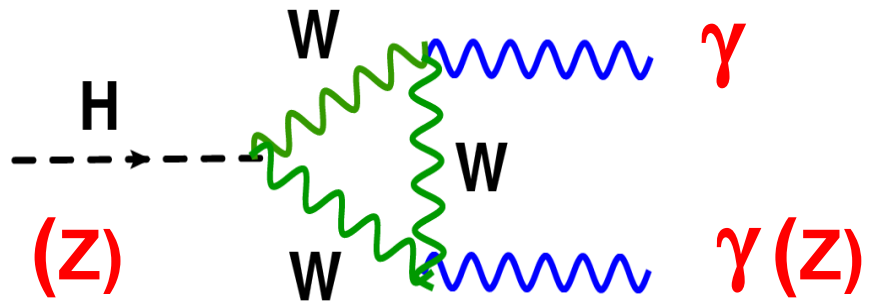
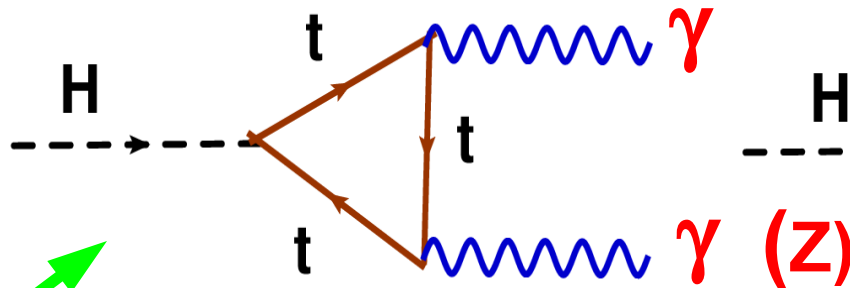
## Tree - level decays



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

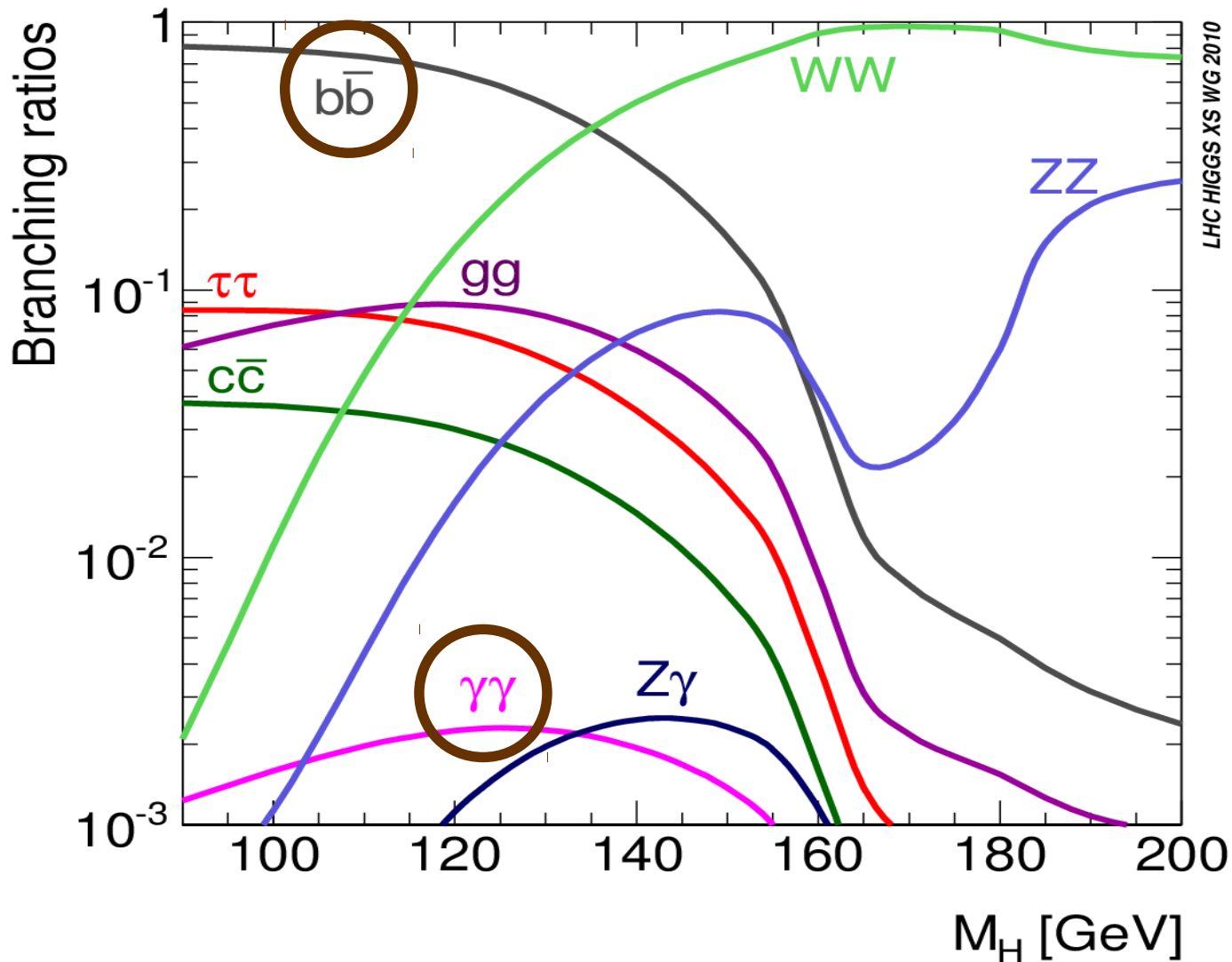
$L = e, \mu, \tau$

## One-loop decays



$H \rightarrow \gamma\gamma$  relevant process for Higgs discovery at low masses  
very sensitive probe of new physics

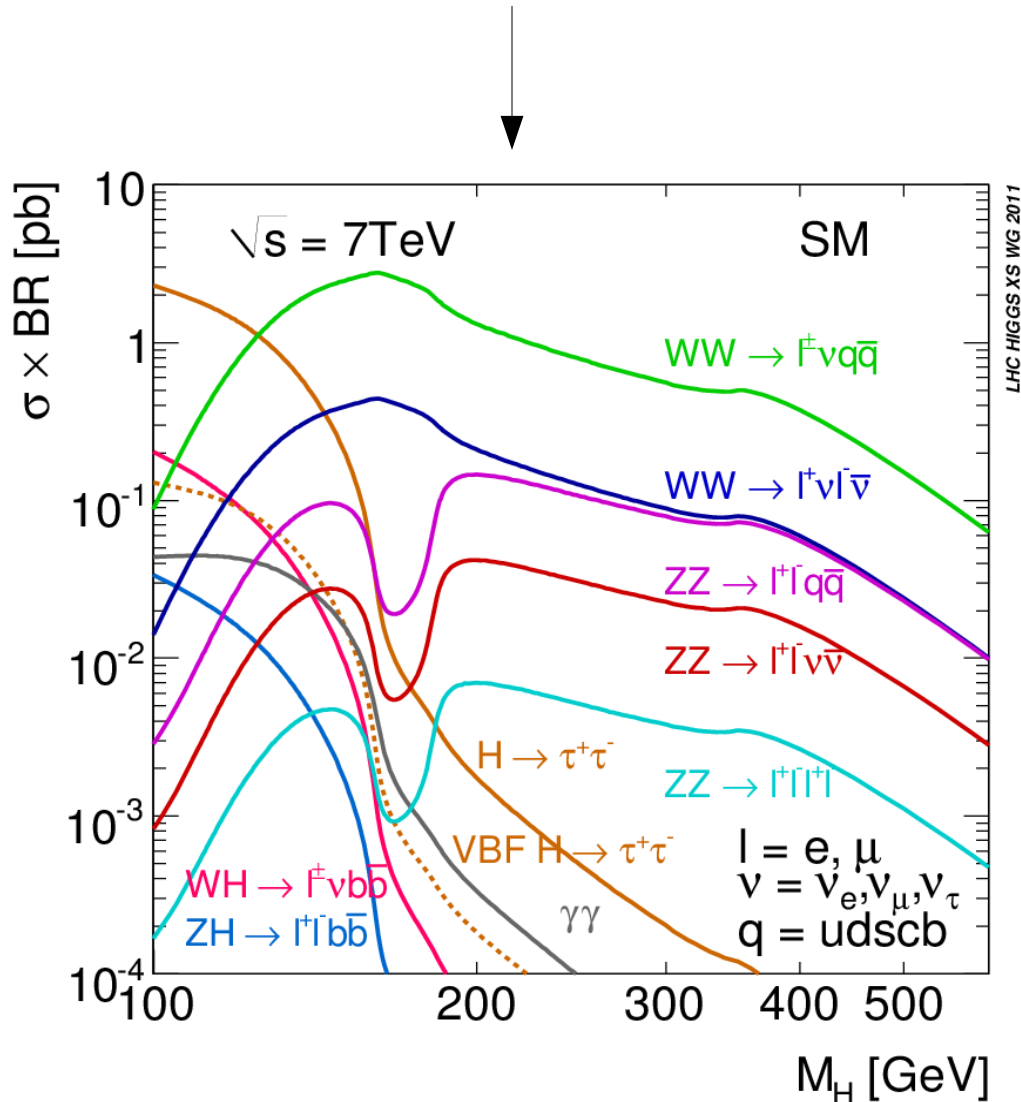
$H \rightarrow \gamma Z$  smaller, also quite sensitive to new physics



●  $H \rightarrow bb$  dominant for  $m_H < 140$  GeV, but signal difficult to detect due to the huge QCD background

●  $H \rightarrow \gamma\gamma$  golden discovery channel for  $m_H < 130$  GeV

# $\sigma \times \text{BR}$ (rate/signature)



Events produced in  $1 \text{ fb}^{-1}$

| $m_H$ , GeV | $WW \rightarrow 2l2\nu$ | $ZZ \rightarrow 4l$ | $\gamma\gamma$ |
|-------------|-------------------------|---------------------|----------------|
| 120         | 127                     | 1.5                 | 43             |
| 150         | 390                     | 4.6                 | 16             |
| 300         | 89                      | 3.8                 | 0.04           |

## Process

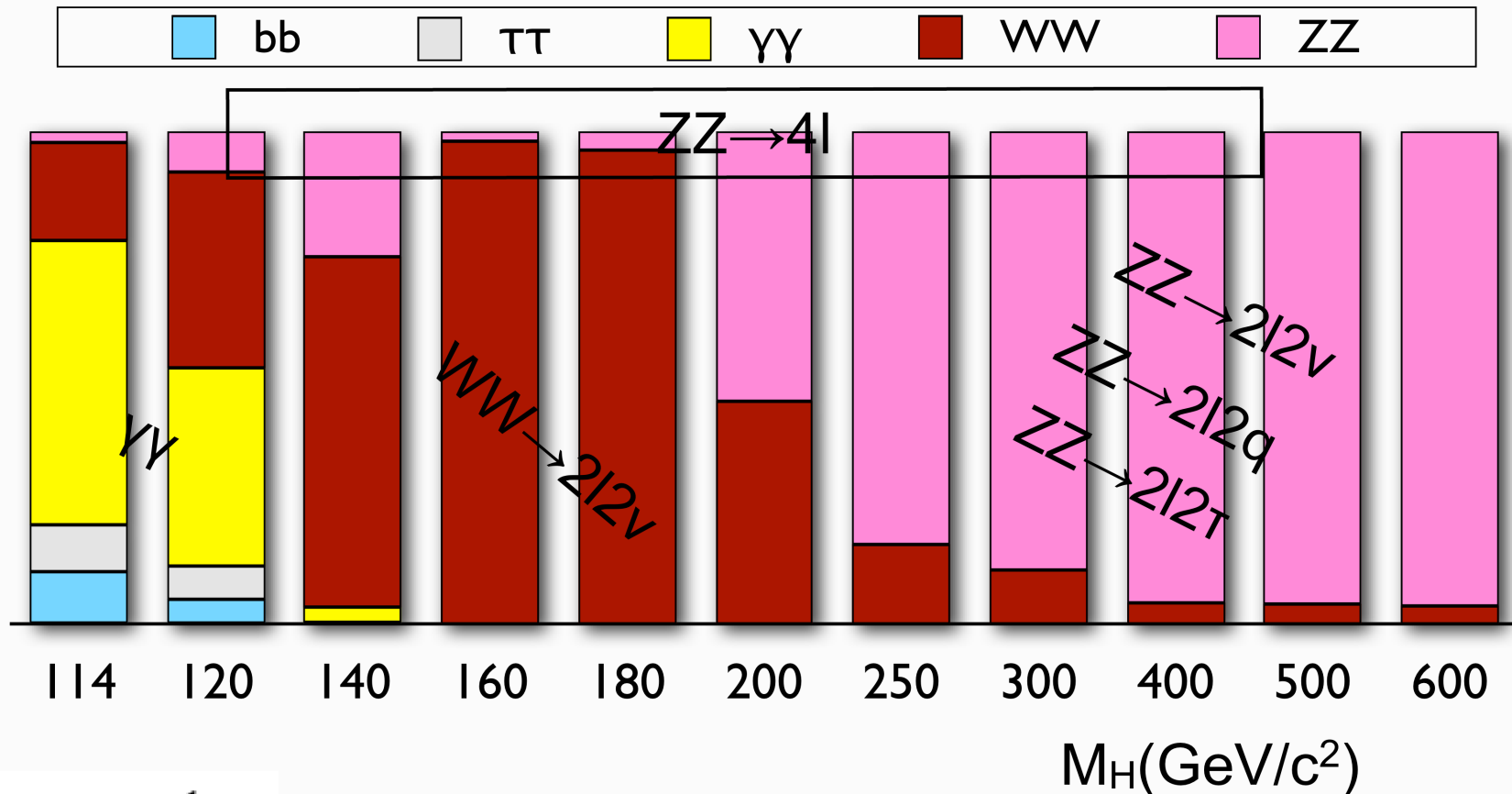
## Dominant Backgrounds

|                                              |                                         |
|----------------------------------------------|-----------------------------------------|
| $H \rightarrow \gamma\gamma$                 | $\gamma\gamma$ , $\gamma$ -jet          |
| $H \rightarrow \tau\tau$                     | $Z \rightarrow \tau\tau$ , top, EW, QCD |
| $H \rightarrow b\bar{b}$                     | $Vb\bar{b}$ , $V$ +jets, top            |
| $H \rightarrow WW \rightarrow l\nu l\nu$     | <b>WW</b> , $V$ +jets, top              |
| $H \rightarrow WW \rightarrow l\nu q\bar{q}$ | <b>WW</b> , $V$ +jets, top              |
| $H \rightarrow ZZ \rightarrow ll ll$         | <b>ZZ</b> , top, $Zb\bar{b}$            |
| $H \rightarrow ZZ \rightarrow ll \nu\nu$     | <b>ZZ</b> /WZ/WW, top, $Z$ +jets        |
| $H \rightarrow ZZ \rightarrow ll q\bar{q}$   | <b>ZZ</b> /WZ/WW, top, $Z$ +jets        |



# Weight of the individual channels

In the combination presented today



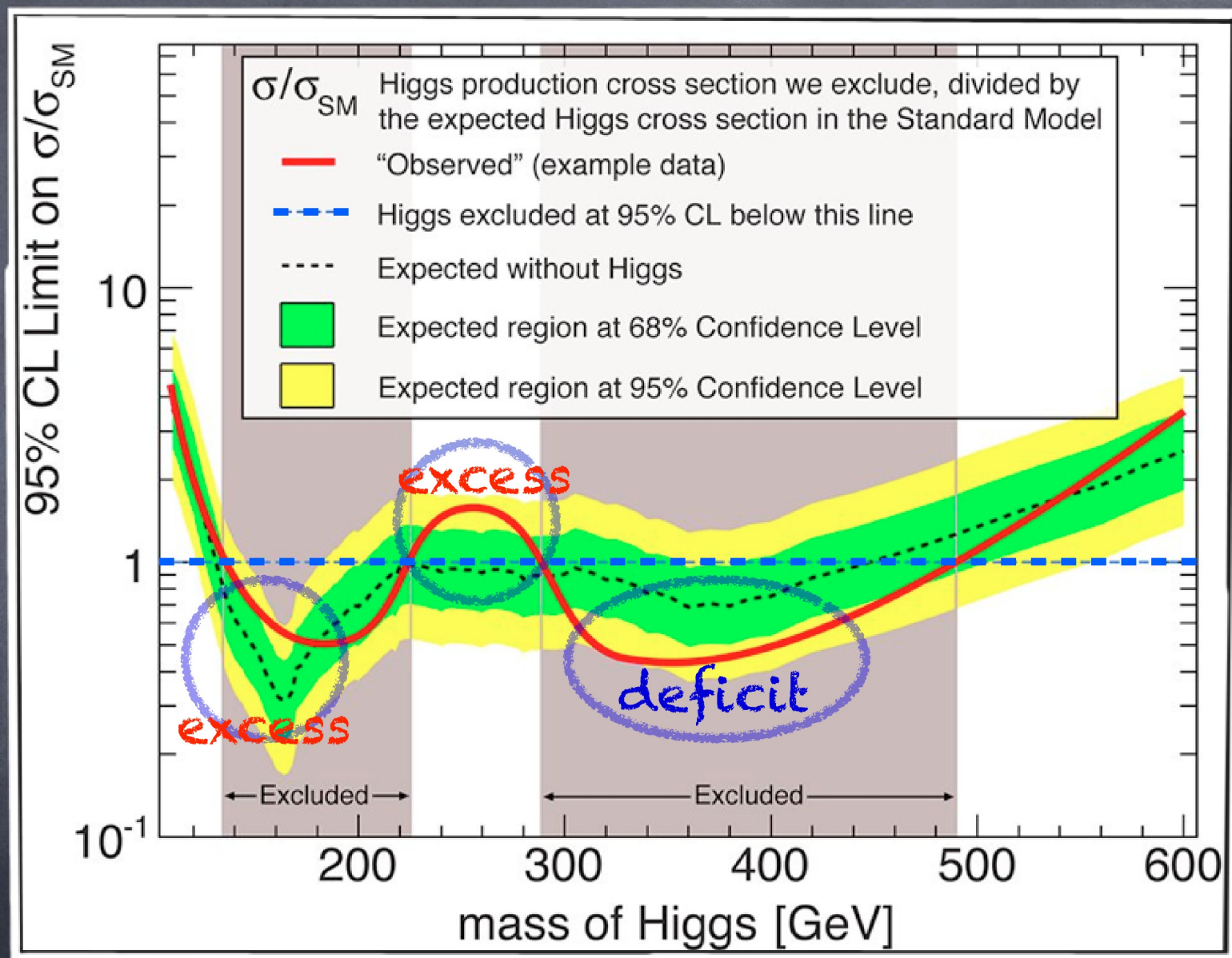
$$w_i = \frac{1}{\mu_{up,i}^2} \frac{1}{\sum_j \frac{1}{\mu_{up,j}^2}}$$

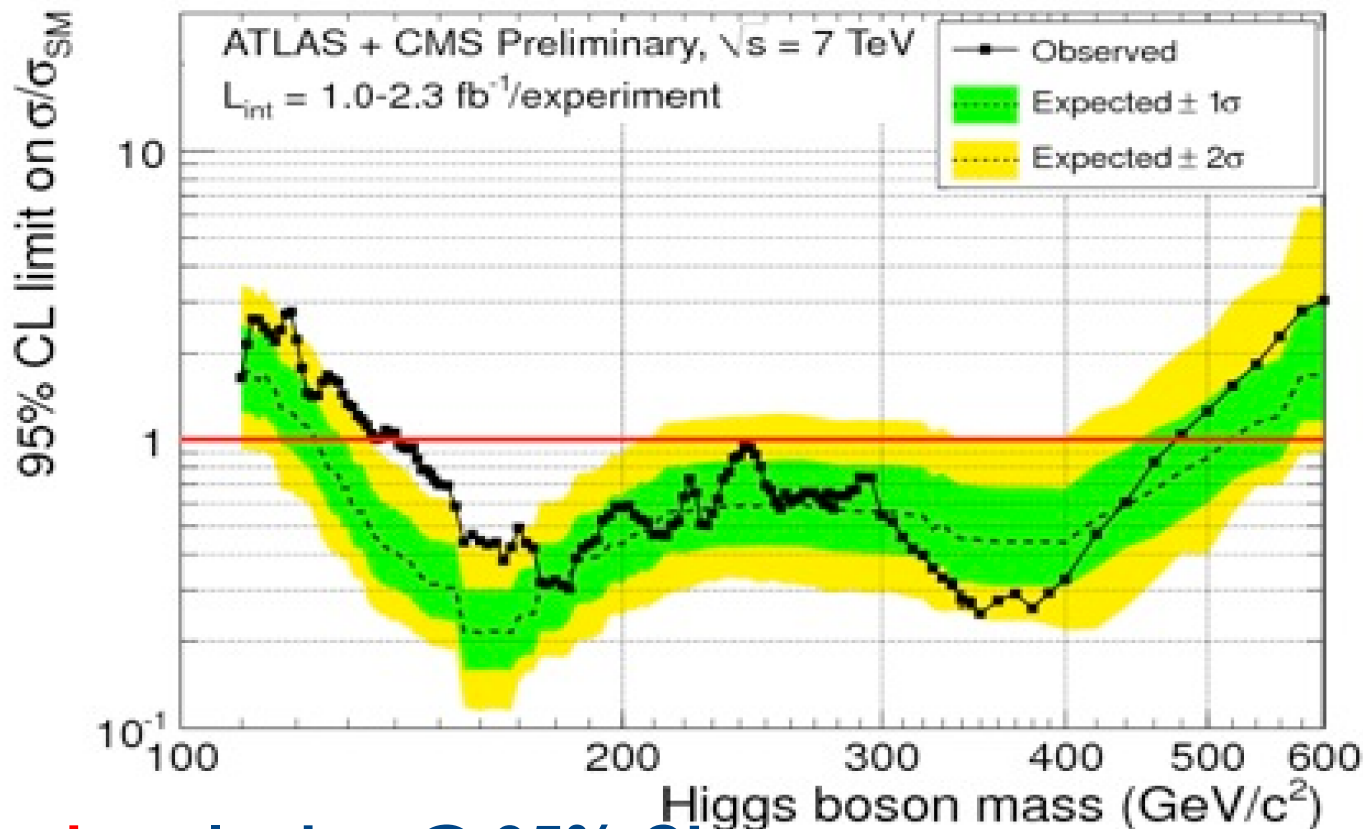
$\mu_{up}$  expected upper limit on the signal strength modifier,  $\mu = \sigma/\sigma_{SM}$ .

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

# Understanding The Yellow and Green Bands

$$\mu = \frac{\sigma}{\sigma_{SM}}$$





**Observed exclusion @ 95% CL**

**141 – 476 GeV**

**Expected exclusion @ 95% CL  
if no signal**

**124 – 520 GeV**

**Excess largely due to  
WW channel with a  
modulation induced  
by ZZ and  $\gamma\gamma$**

G. Rolandi (HCP Nov 2011)

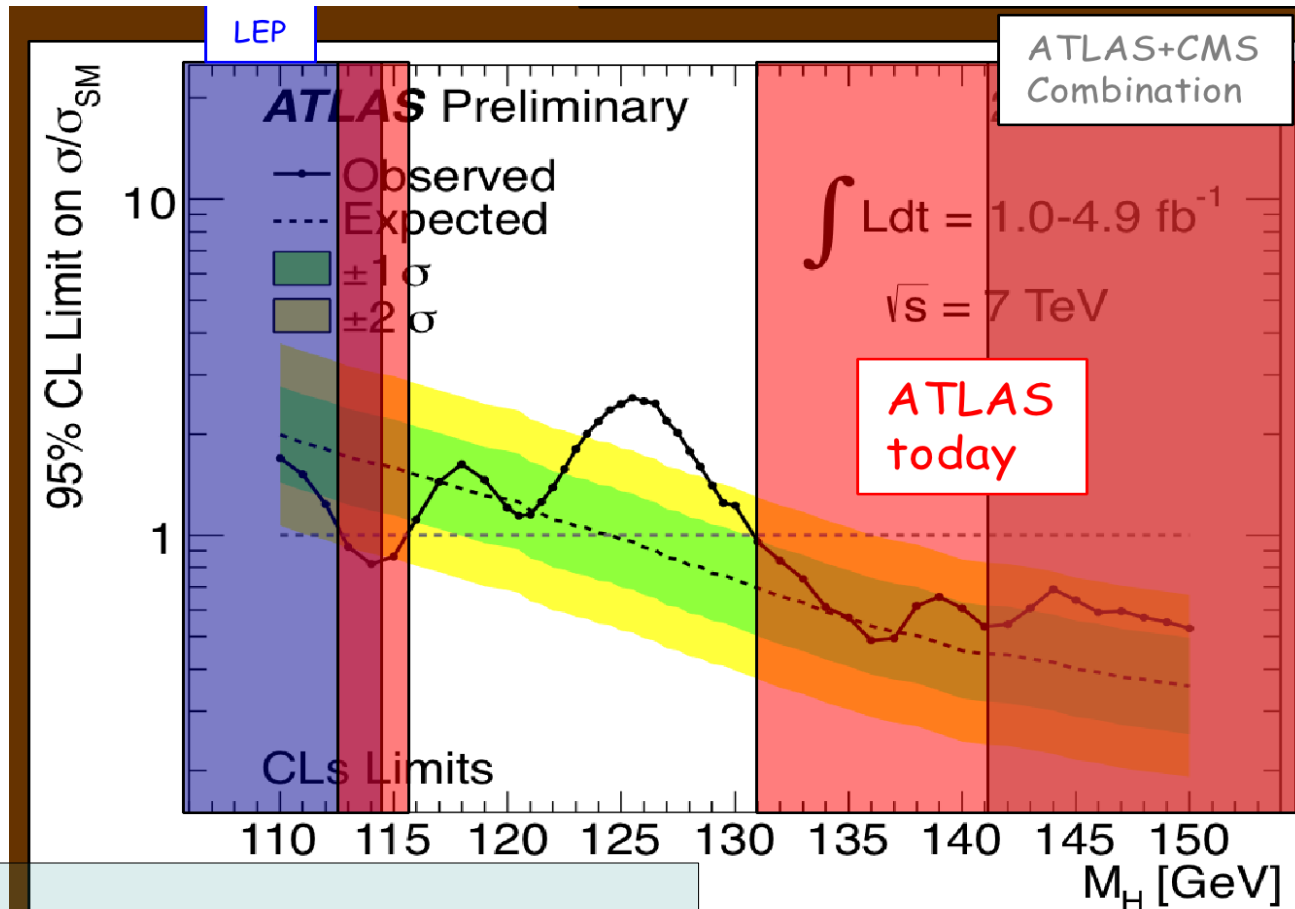
## SM Higgs Search Prospects (Mass in GeV)

| <b>ATLAS + CMS<br/><math>\approx 2 \times \text{CMS}</math></b> | <b>95% CL<br/>exclusion</b> | <b><math>3 \sigma</math> sensitivity</b> | <b><math>5 \sigma</math> sensitivity</b> |
|-----------------------------------------------------------------|-----------------------------|------------------------------------------|------------------------------------------|
| <b><math>1 \text{ fb}^{-1}</math></b>                           | <b>120 - 530</b>            | <b>135 - 475</b>                         | <b>152 - 175</b>                         |
| <b><math>2 \text{ fb}^{-1}</math></b>                           | <b>114 - 585</b>            | <b>120 - 545</b>                         | <b>140 - 200</b>                         |
| <b><math>5 \text{ fb}^{-1}</math></b>                           | <b>114 - 600</b>            | <b>114 - 600</b>                         | <b>128 - 482</b>                         |
| <b><math>10 \text{ fb}^{-1}</math></b>                          | <b>114 - 600</b>            | <b>114 - 600</b>                         | <b>117 - 535</b>                         |



**Higgs Boson, if it exists between masses of (114 - 600 GeV) will either be discovered or ruled out by the end 2012**

# Latest results 13 Dec 2011



Observed exclusion @ 95% CL

[112.7 – 115.5] GeV

[131 – 453] GeV

except [237 – 251] GeV

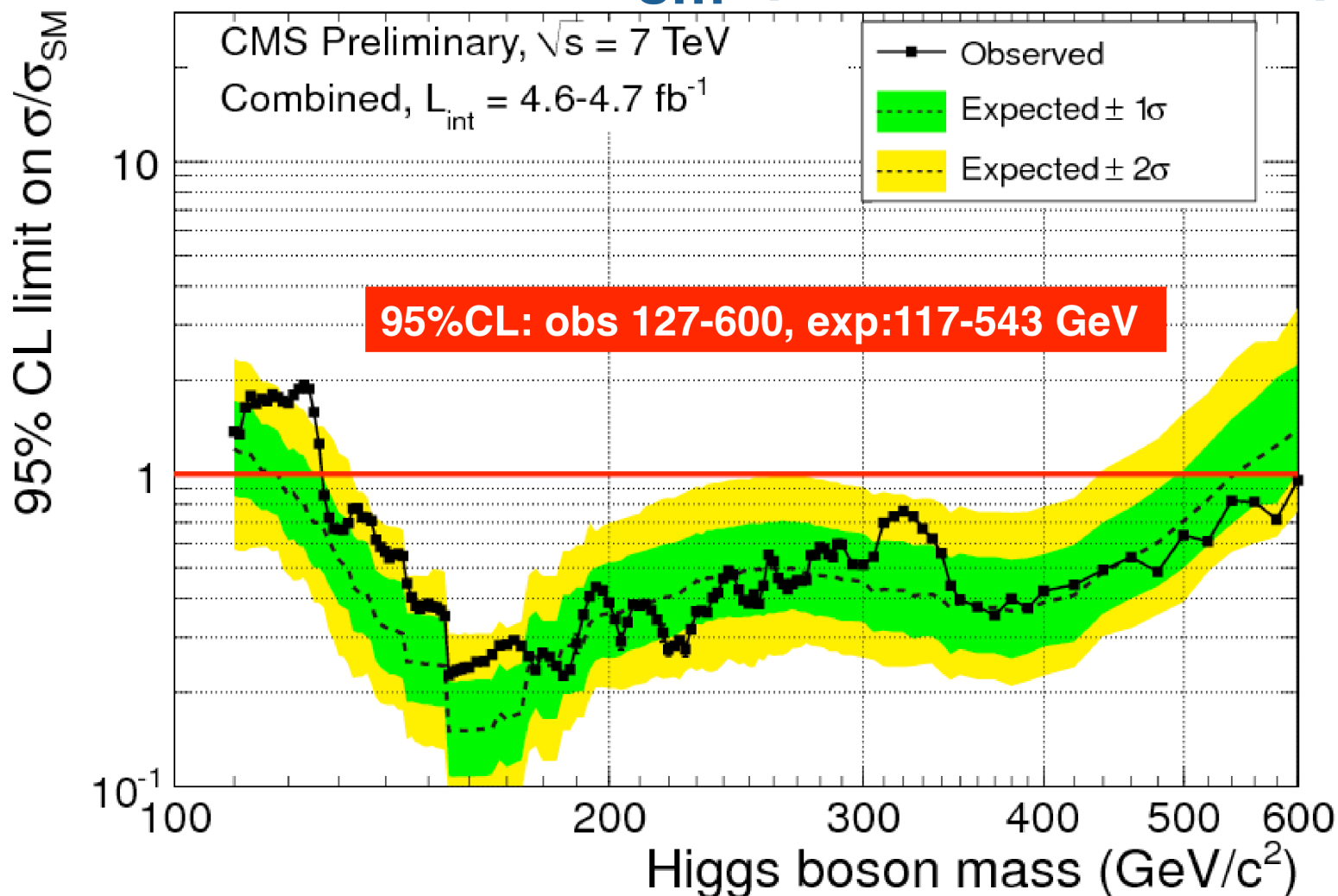
Excess in 124 – 128 GeV

Expected if no signal

[124.6 – 520] GeV



# Limits on $\sigma/\sigma_{\text{SM}}$ (CLs method)



# What if LHC will not find the SM Higgs ?

- Some New Physics should appear to account for unitarity in the  $WW \rightarrow WW$  scattering at TeV scale
- but higher luminosity needed to discover this New Physics
- Supersymmetry predicts a Higgs mass below 140 GeV
- finding no evidence for the SM Higgs boson in the range below 600 GeV, will dramatically affect SUSY models
- it could potentially rule out the CMSSM and strongly constrain all its various extensions
- Could the Higgs mechanism be completely ruled out in 2012 ?

**Not (yet) if the Higgs is fermiophobic !**  
limits on SM Higgs  $m_H > 127$  GeV do not hold !

# Origins of Yukawa couplings

- hierarchy of fermion masses is still a puzzle !

- 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

- maybe the mechanism of fermion and W, Z mass generation is different

- However, EWPT favor a light Higgs mass below  $m_H < 150$  GeV, so....

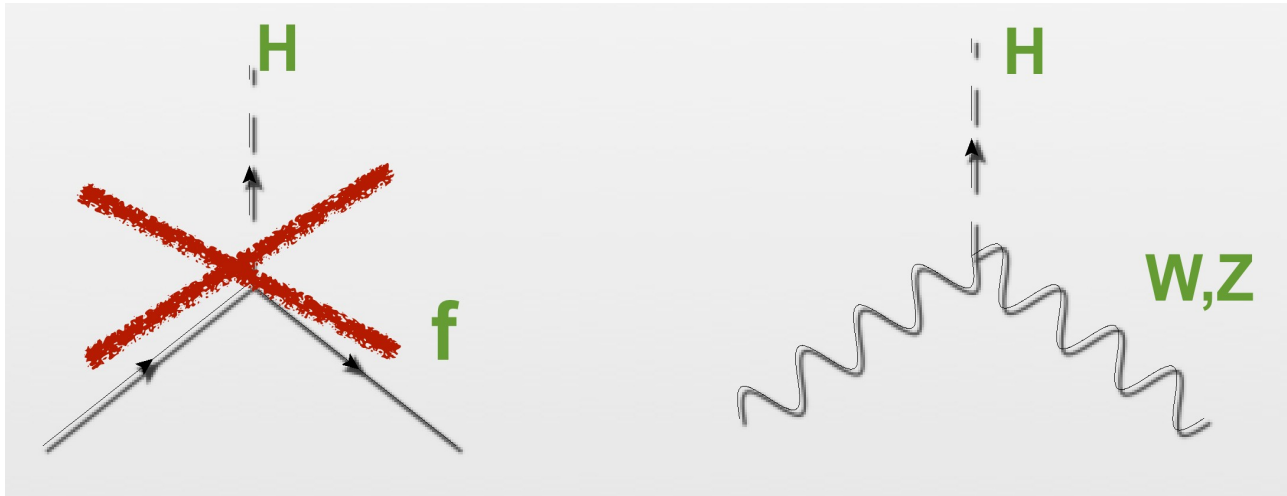
...what if Higgs boson is only responsible for  $M_W$ ,  $M_Z$  but not of fermion masses ?

■ 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: a **F**ermio-**P**hobic (**FP**) Higgs



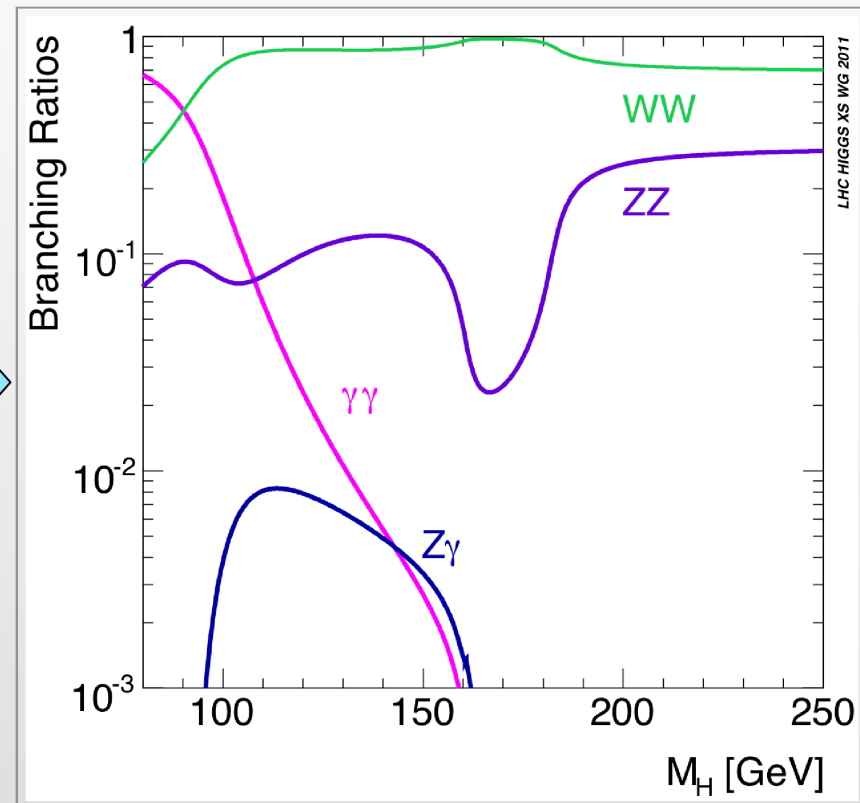
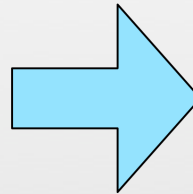
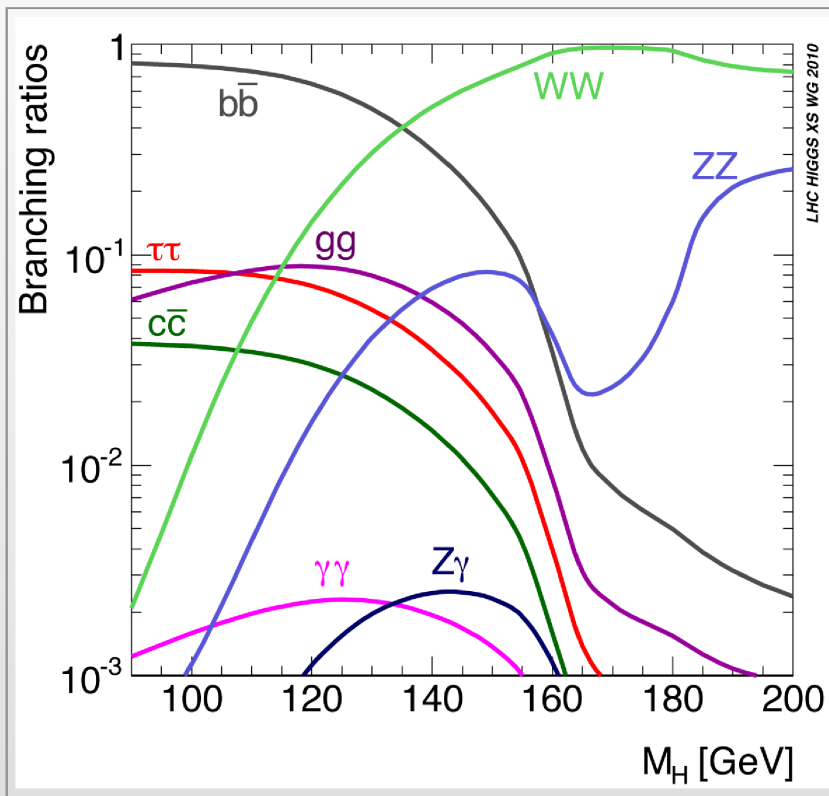
- **NO** Yukawa couplings at tree-level
- Higgs mechanism gives rise to **EWSB** and  **$M_W, M_Z$**  but is **not** responsible for **ChSB** and **fermion masses**

# Higgs decays : FP vs SM

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

SM Higgs

FP Higgs

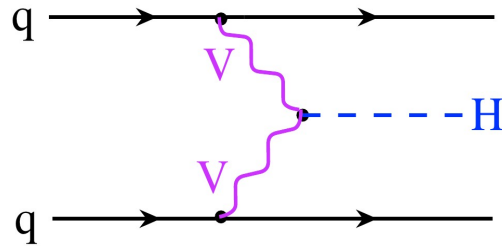


<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Fermiophobic>

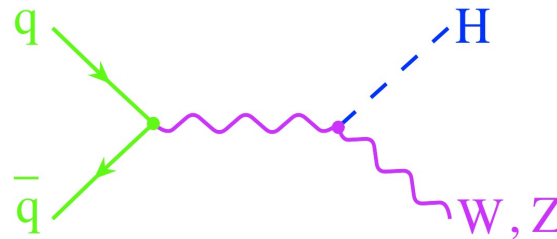
for  $m_H \sim [100, 110, 120]$  GeV :  $BR(\gamma\gamma)_{FP} \sim [110, 30, 10] \times BR(\gamma\gamma)_{SM}$

# Fermio-**P**hobic Higgs Production mechanisms

**VBF**



**VH**



- no gluon-gluon fusion
- **VBF** fusion dominant mechanism
- harder  $p_T$  spectrum of Higgs  $\rightarrow$  better **S/B** !

# FP model is unstable under radiative corrections

## Yukawa coupling are radiatively generated

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

- if  $m_f$ 's are put by hand  $\rightarrow$  SM is not renormalizable
- SM  $\rightarrow$  effective field theory valid up to some  $\Lambda$  scale
- radiative corrections depend by the UV completion of the theory, but less sensitive if  $Y(\Lambda) \rightarrow 0$
- due to  $\text{ChSB} \sim m_f$ , the Yukawas are not protected under radiative corrections  $\rightarrow$  radiatively generated  $\rightarrow$  large  $\text{Log}(\Lambda/m_H)$  need to be summed up
- Effective Field Theory approach allows to calculate the leading universal contributions  $\sim [g^2 \text{Log}(\Lambda/M_H)]^n$  which are independent of the UV completion of the theory

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

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

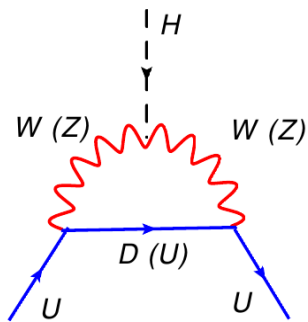
$$Y_f(\Lambda) = 0$$

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

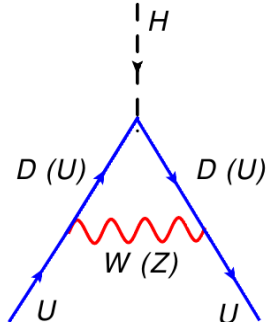
$$\begin{array}{ccc} Y_f(\Lambda) = 0 & \xrightarrow{\quad RGE \quad} & Y_f(m_H) \\ \text{(high energy)} & & \text{(low energy)} \end{array}$$

- **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 is taken on-shell

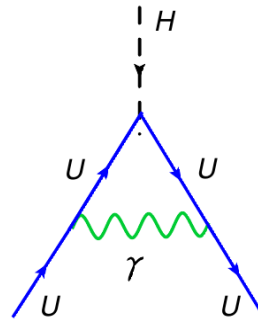
# Diagrams contributing to the $Y$ 's beta-functions



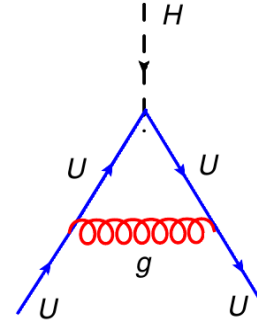
a)



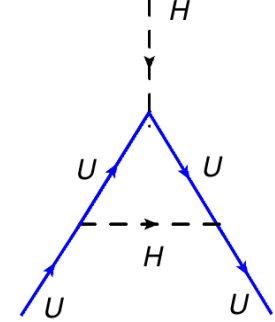
b)



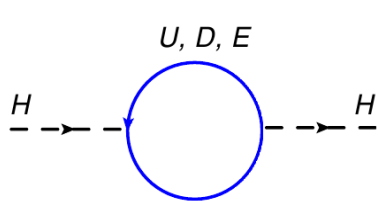
c)



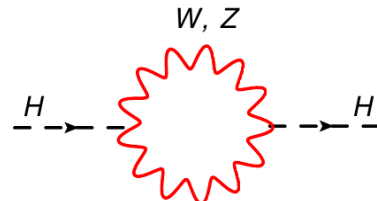
d)



e)

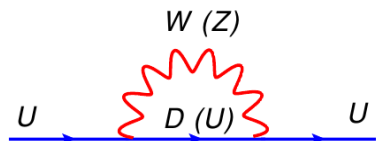


f)

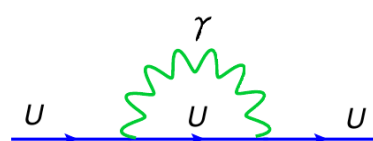


g)

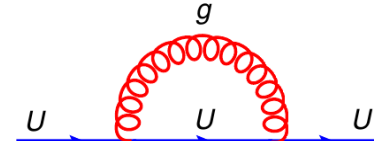
Up-type quark couplings



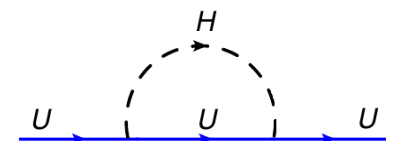
h)



i)



j)



k)

# 1-loop RGE's for Yukawa's

(Higgs on-shell)

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

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

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

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

$W_L$  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

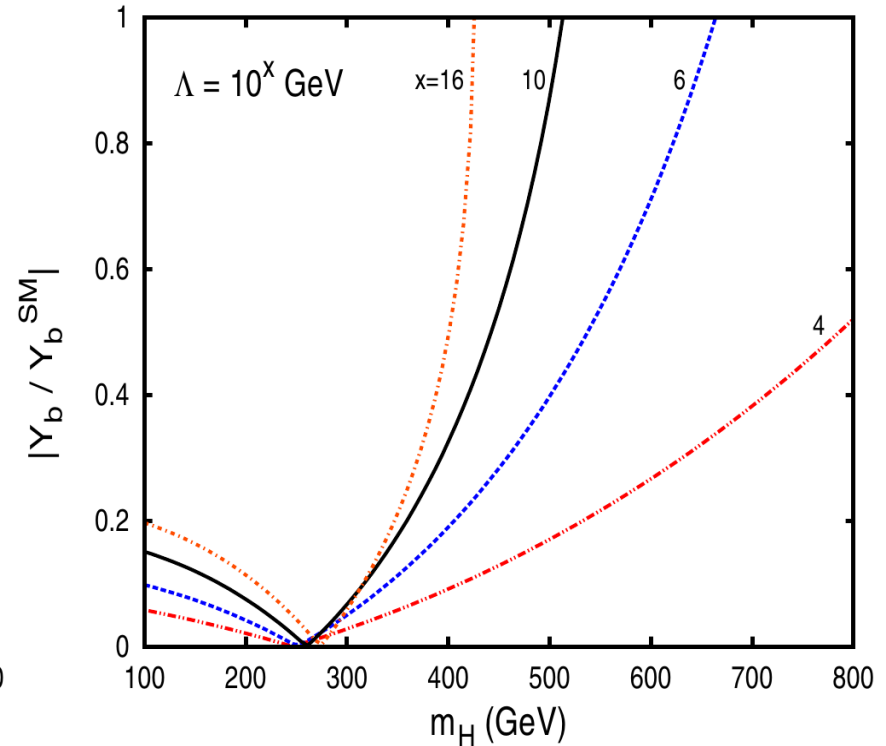
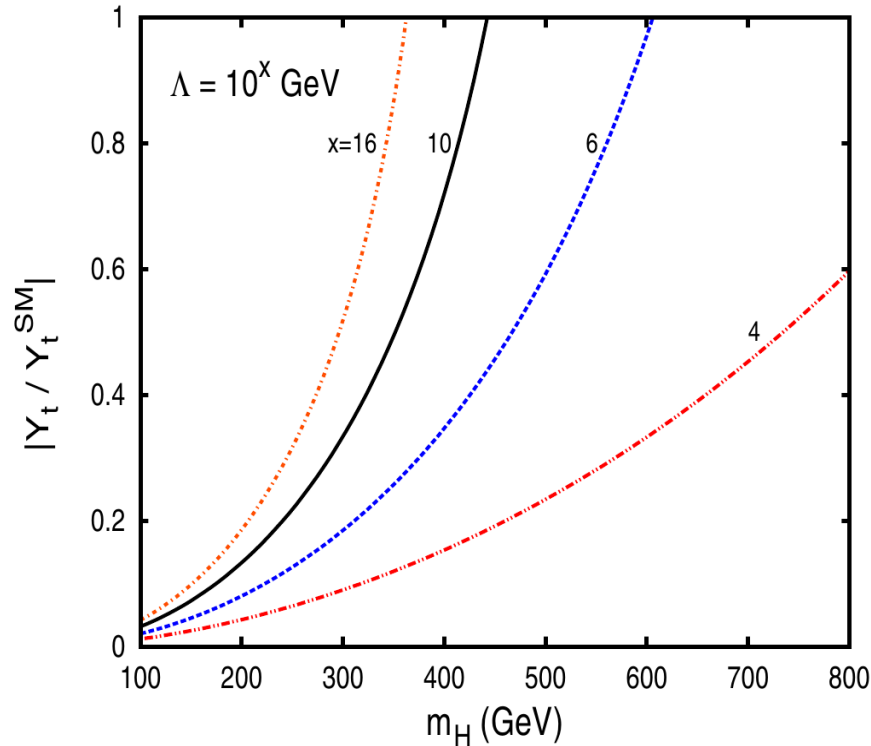
$$\mathbf{Y} \equiv N_c \mathbf{Y}_U \mathbf{Y}_U + N_c \mathbf{Y}_D \mathbf{Y}_D + \mathbf{Y}_E \mathbf{Y}_E$$

SM RGE's recovered for  $\rightarrow \mathbf{Y}_f^{\text{SM}} \rightarrow \mathbf{Y}_f$

# Results for $Y_t(m_H)/Y_t^{SM}$ and $Y_b(m_H)/Y_b^{SM}$

E. GABRIELLI AND B. MELE

PHYSICAL REVIEW D **82**, 113014 (2010)

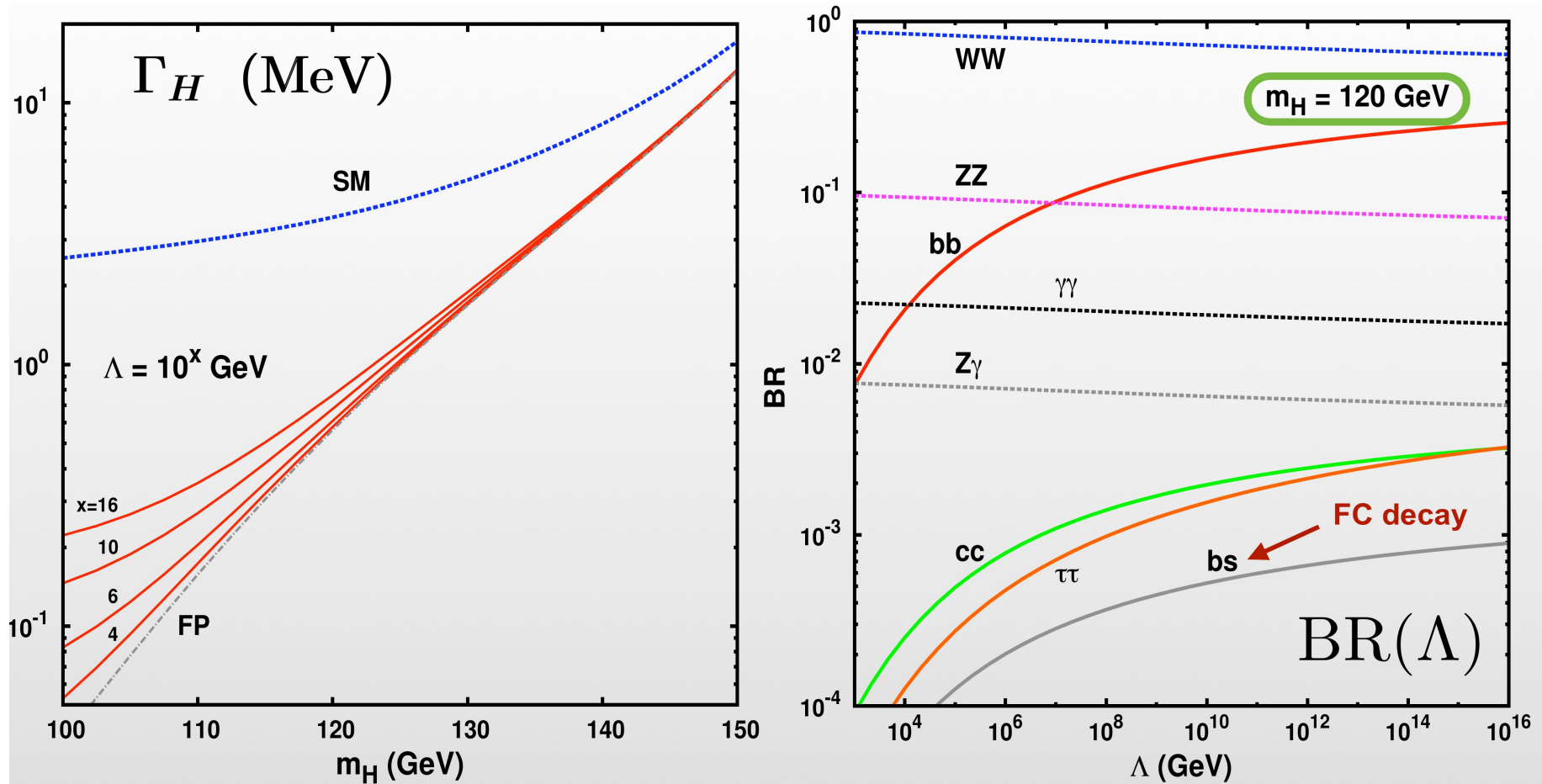


■  $\Lambda$  varied between  $10^4$  and  $10^{16}$  GeV

■ because of terms  $\xi_H \equiv \frac{g_2 m_H}{2M_W}$   $Y_f$  grows at large  $m_H$

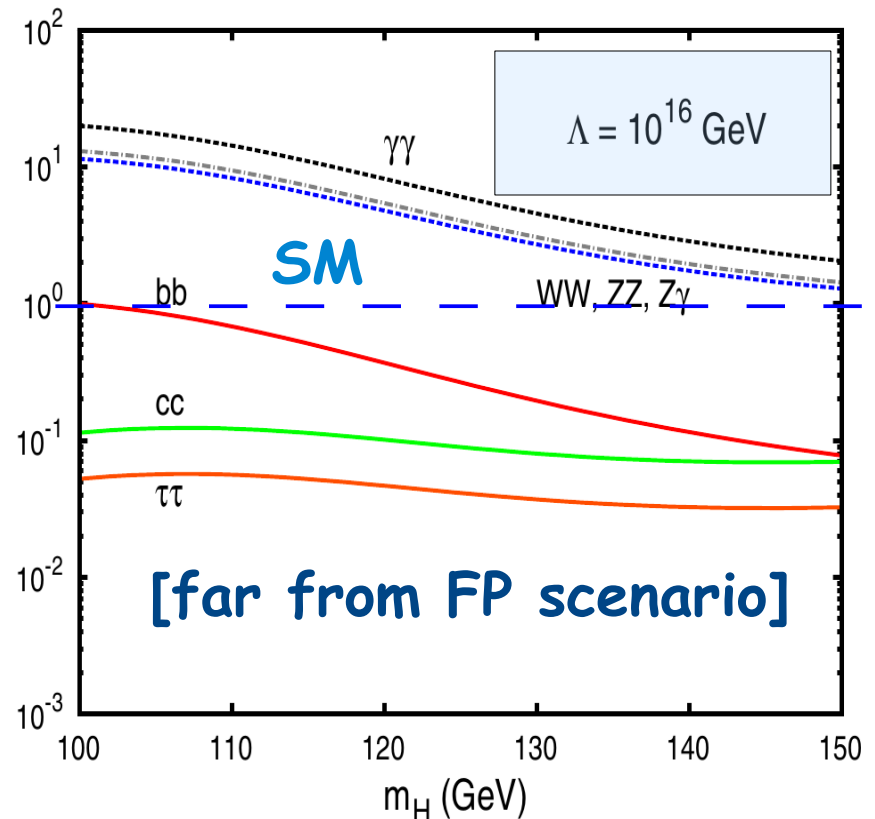
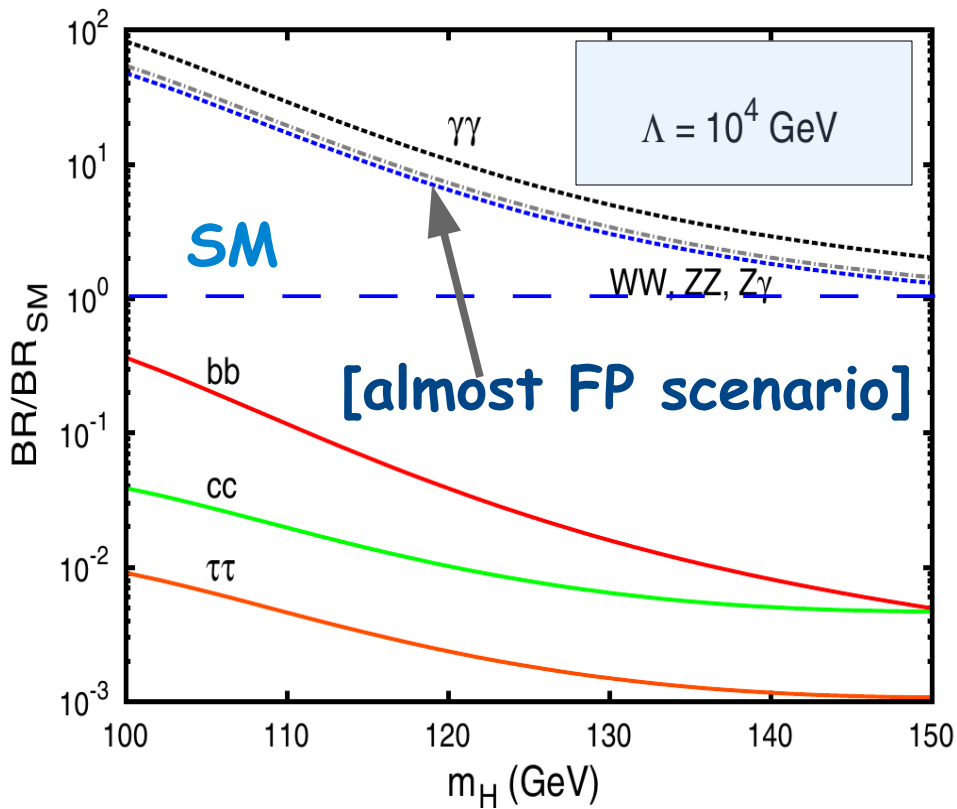
■ all  $Y_f$ 's perturbative for  $m_H < \langle H \rangle \sim 246$  GeV

# Results for $\Gamma_H$ and BR's versus $\Lambda$

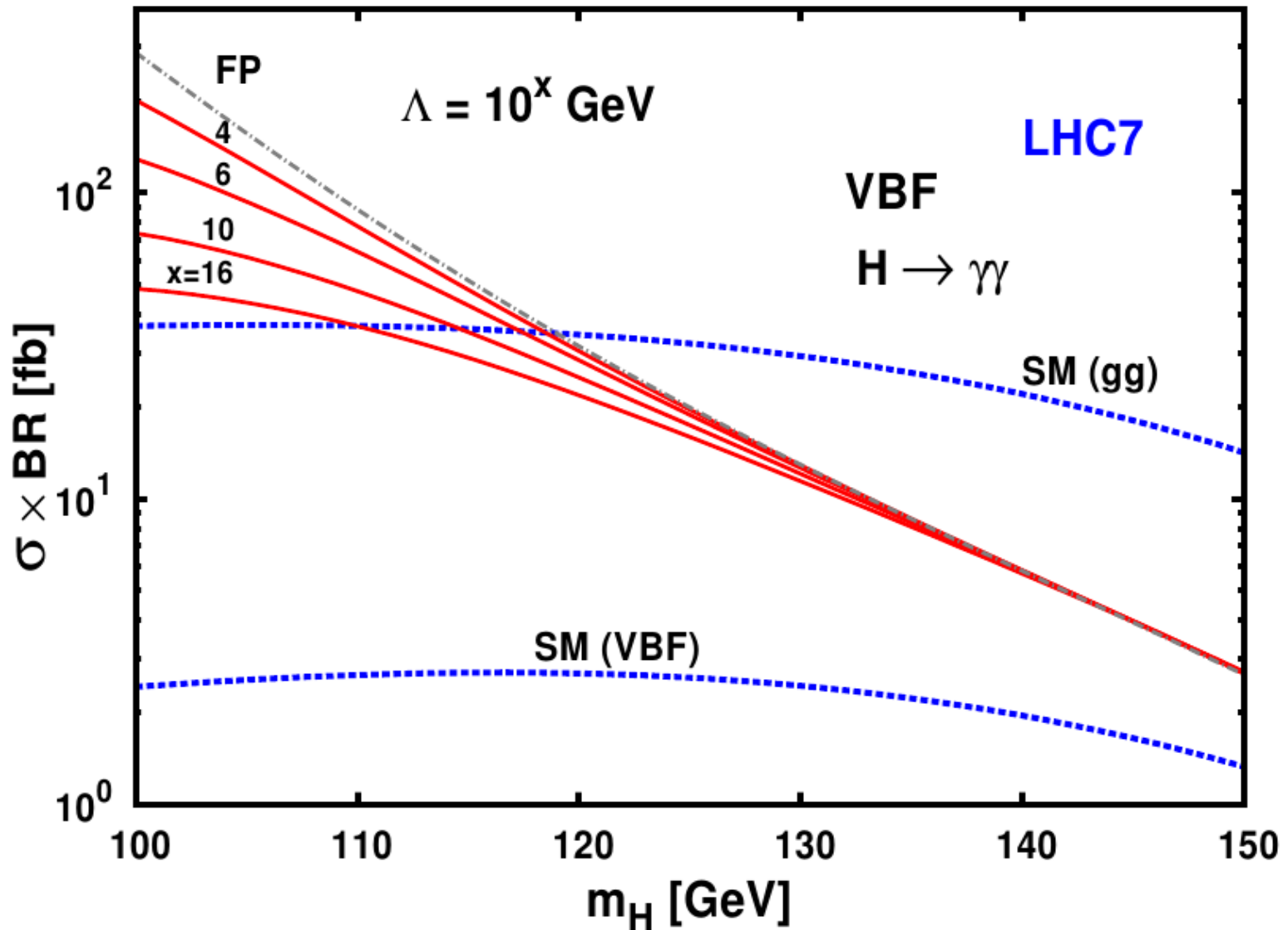


BR's enhanced by small total width

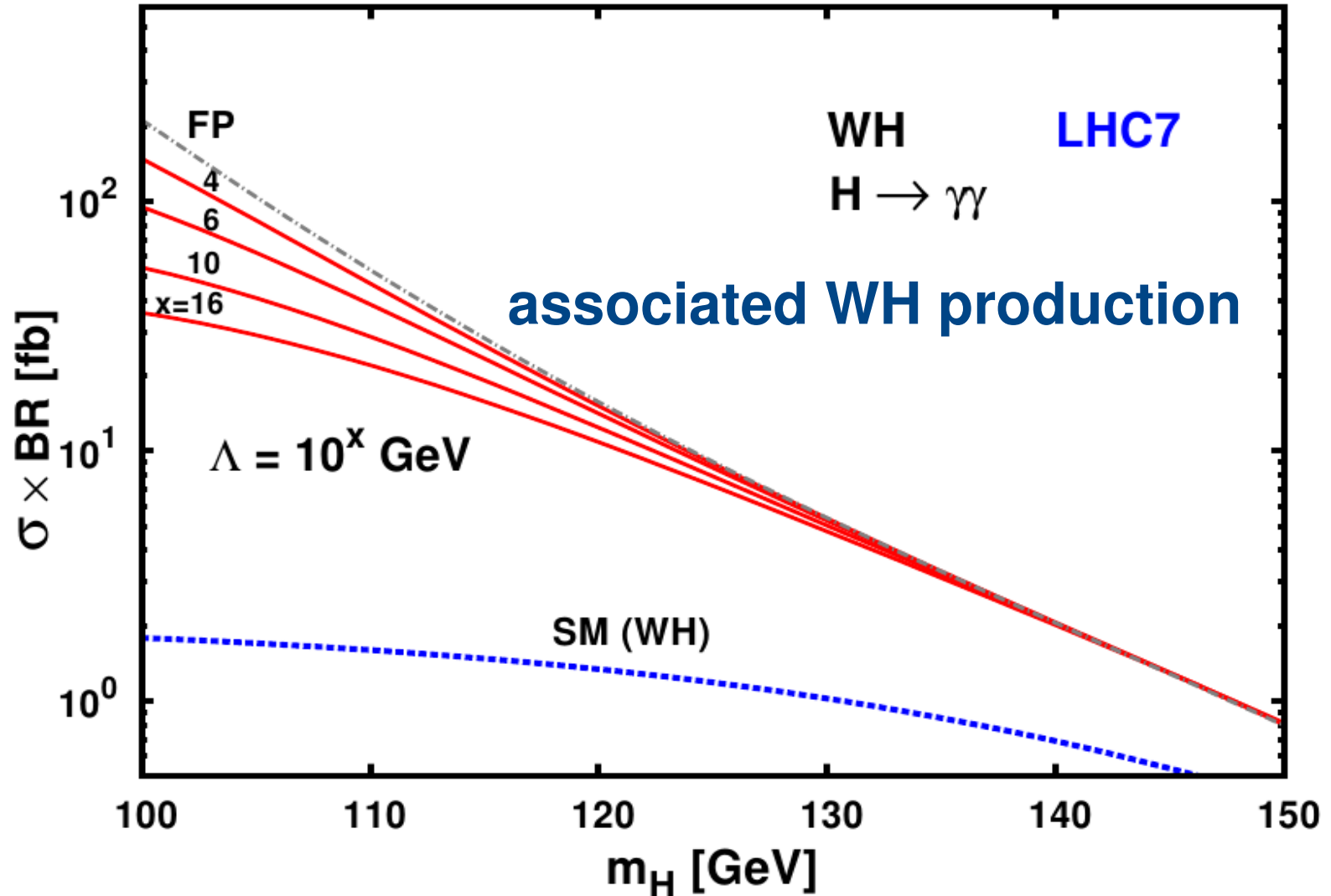
$BR / BR(SM): \Lambda \sim (10^4 \rightarrow 10^{16}) \text{ GeV}$



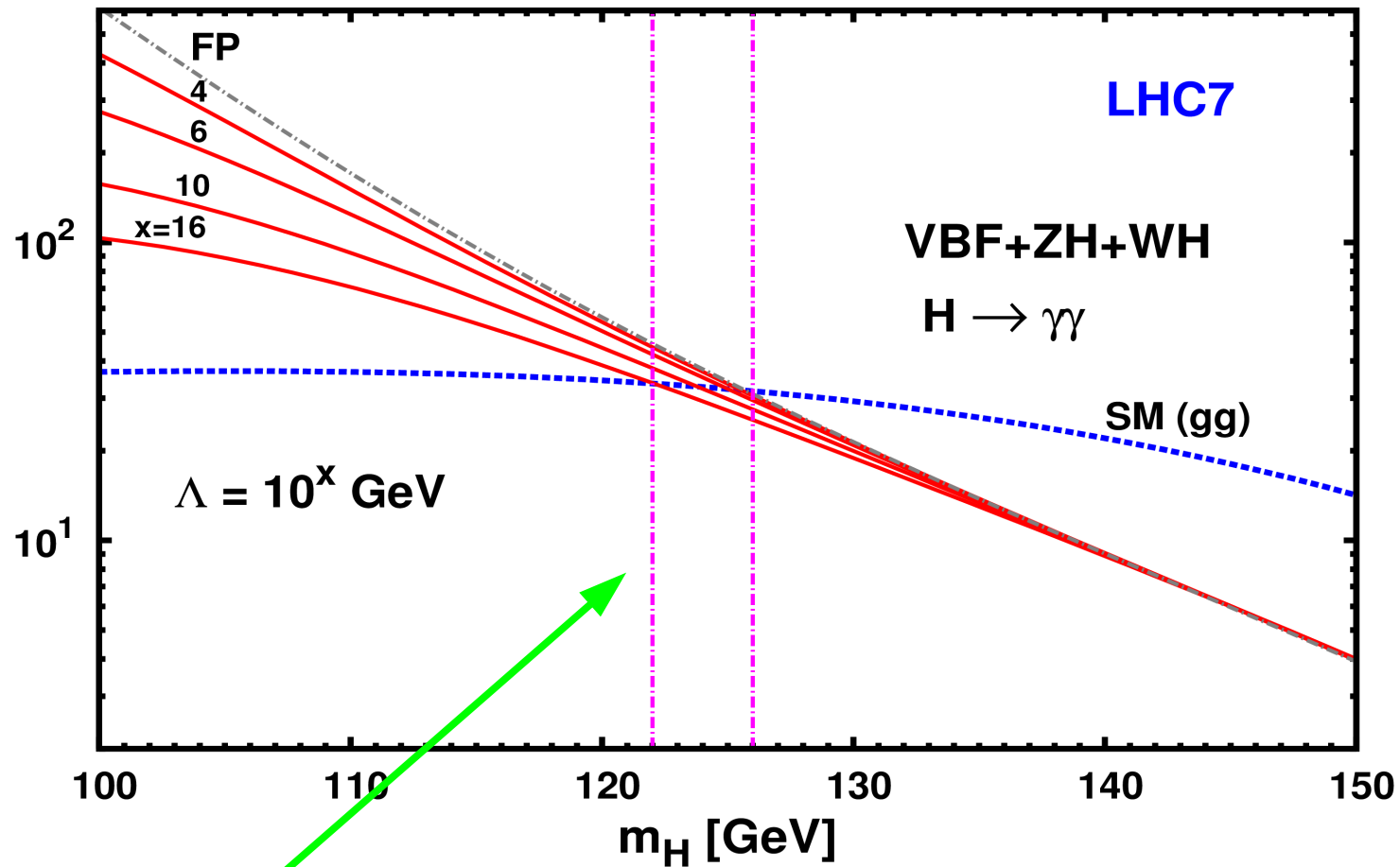
# LHC (VBF) : $H \rightarrow \gamma\gamma$



# LHC (WH) : $H \rightarrow \gamma\gamma$



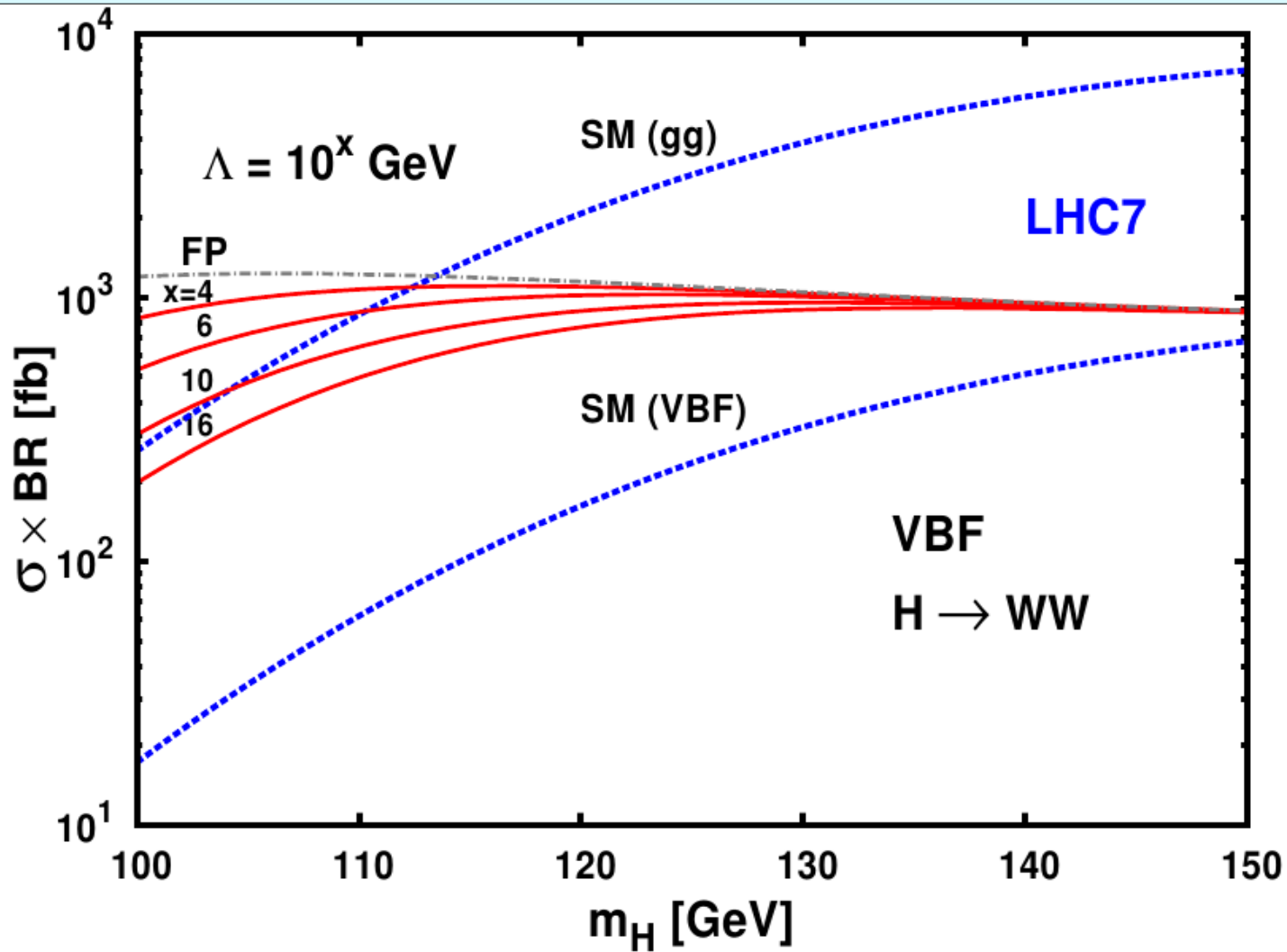
# LHC (VBF+WH+ZH) : $H \rightarrow \gamma\gamma$



For  $m_H = [122 - 126] \text{ GeV} \rightarrow$  same rate as SM Higgs

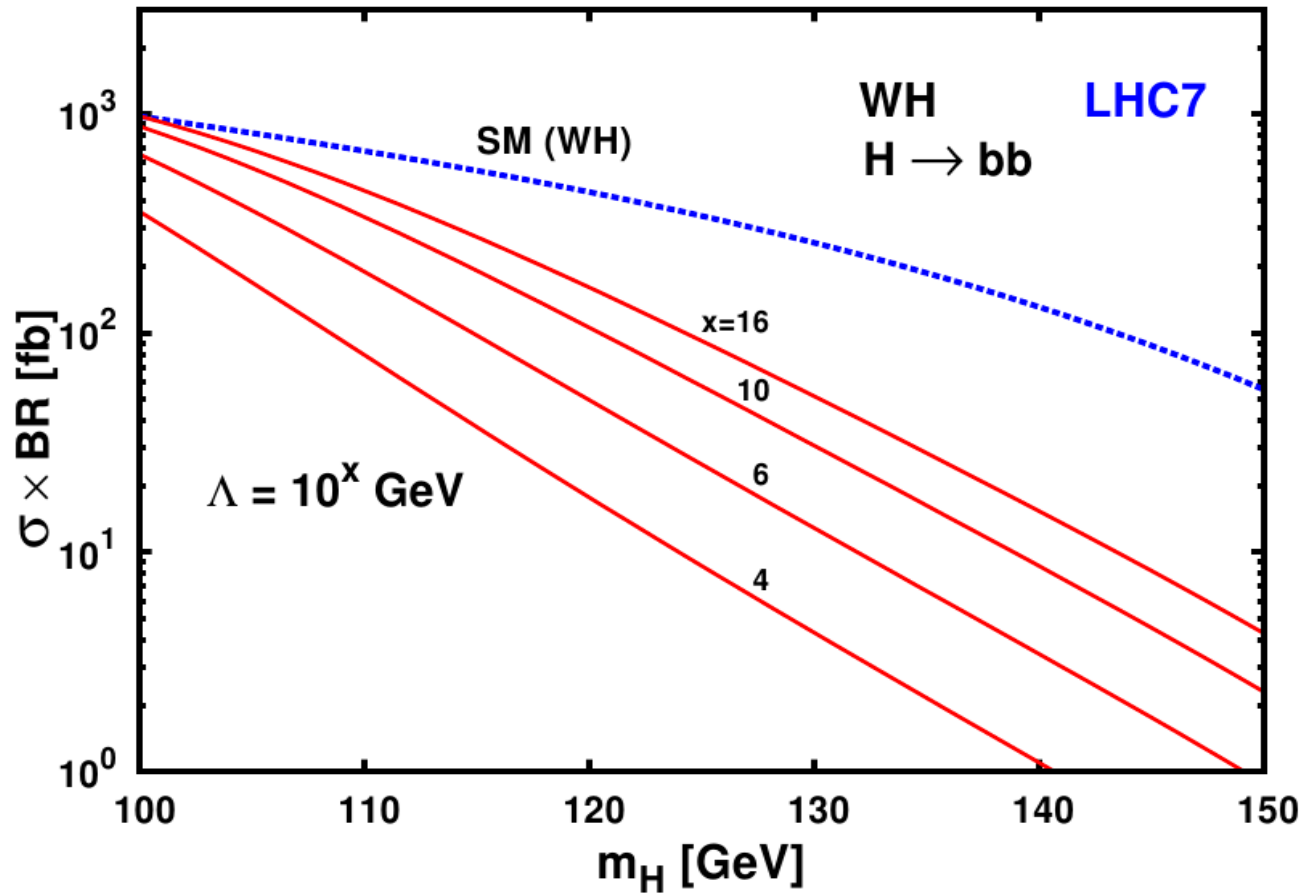
Signature of production mechanism is crucial for determining if there is a FP Higgs or SM one

# LHC (VBF) : $H \rightarrow WW$



SM limits on  $m_H > 127$  GeV do not hold if Higgs is fermiophobic !

# LHC (WH) : $H \rightarrow bb$



Process very sensitive to the scale  $\Lambda$ , but difficult to measure at LHC

# exp bounds on $m_H$ (pure FP model)

■ 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)

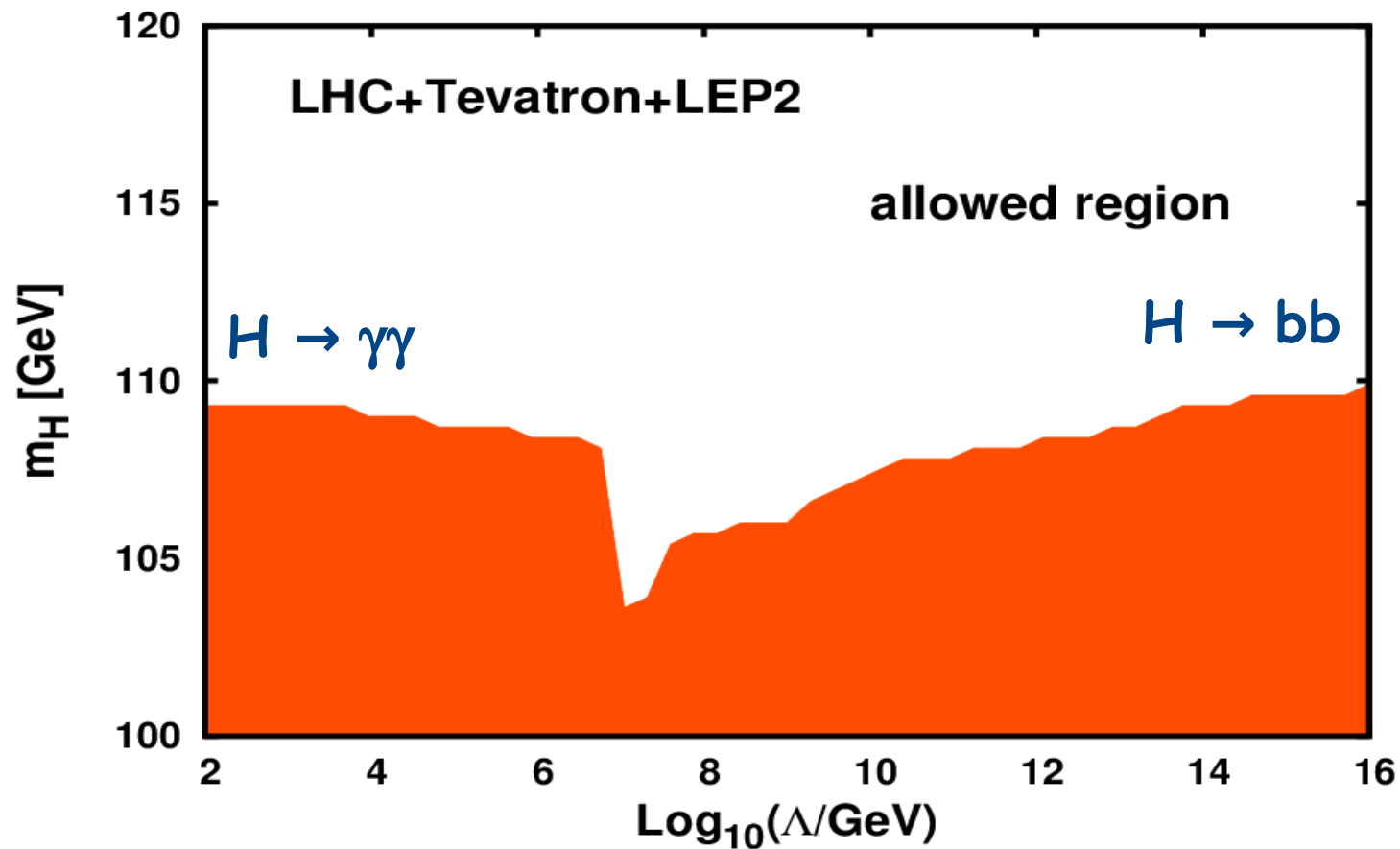
\* CMS  $\rightarrow$  (110-) 112 GeV 1.7 fb $^{-1}$  (LP2011)

■ bounds in “Effective  $Y_f$ ” scenarios needs dedicated studies

\* in general weaker than in FP, and depending on  $\Delta$

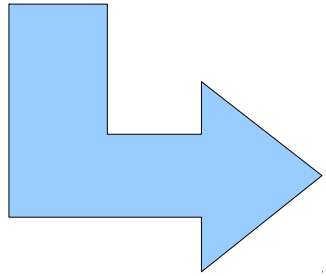
# bounds on $m_H$ (effective $Y_f$ 's model)

EG, B.Mele, 1112.5993 [hep-ph]



- bounds obtained with **Higgsbounds-3.4.0beta** (not updated with recent bounds on FP Higgs from LHC and CDF) **Comput.Phys.Comm.181:138 (2010)**

If LHC will confirm this scenario



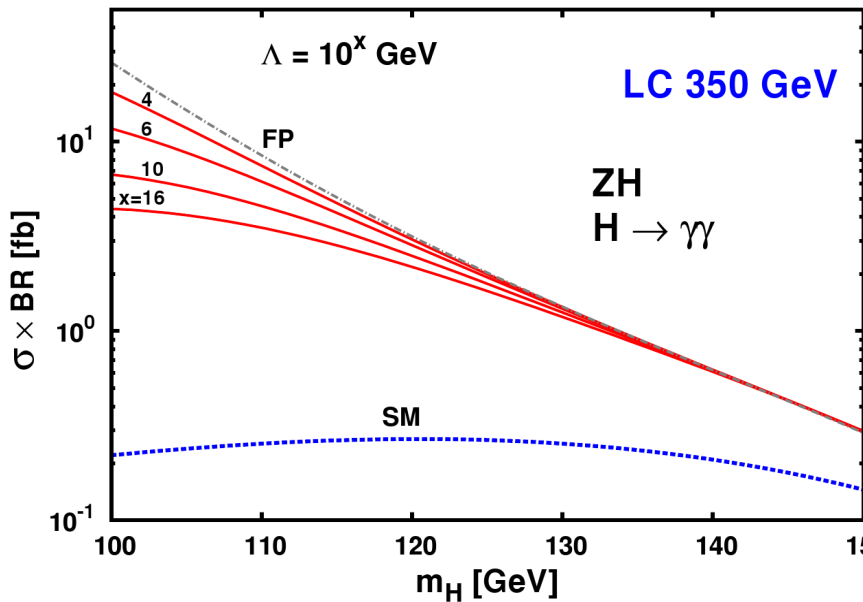
case for a linear collider

advantages

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

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

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



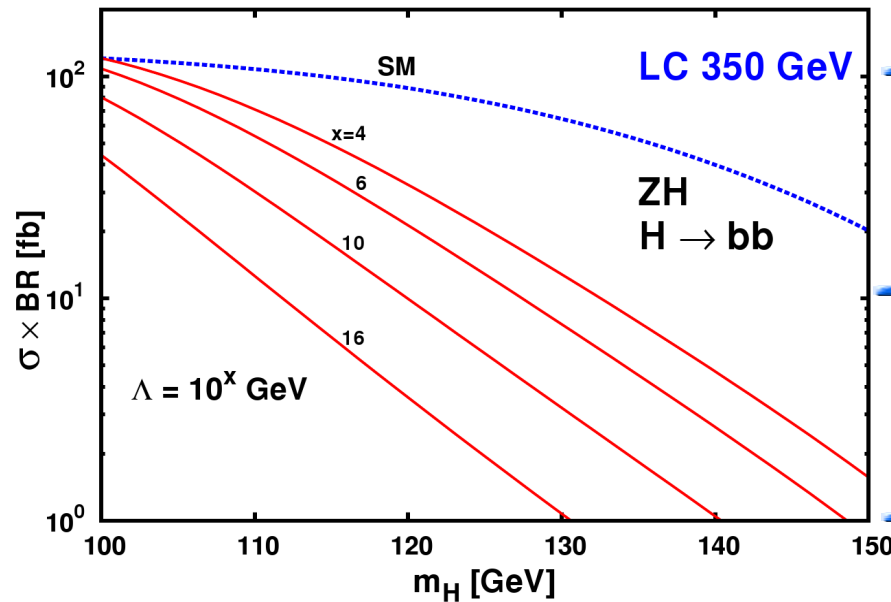
5000

500

50

LC 350

$H \rightarrow \gamma\gamma$



50000

5000

500

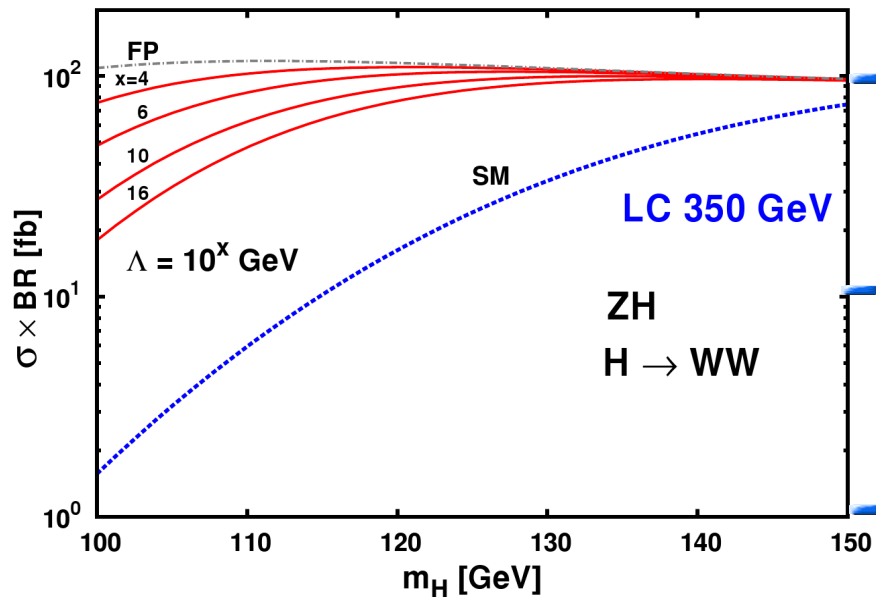
LC 350

$H \rightarrow b\bar{b}$

Excellent  
sensitivity to  $\Lambda$

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

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



50000

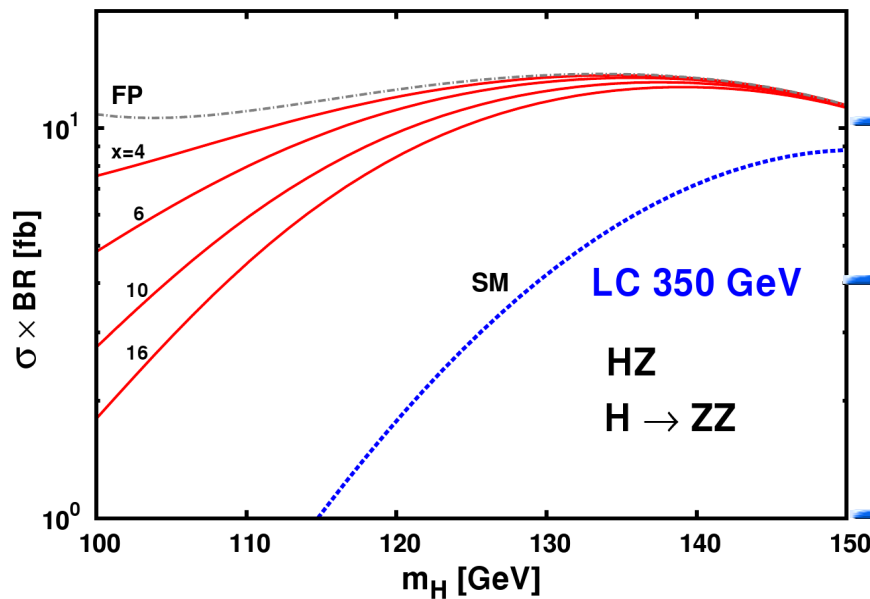
LC 350

5000

$H \rightarrow WW$

500

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



5000

LC 350

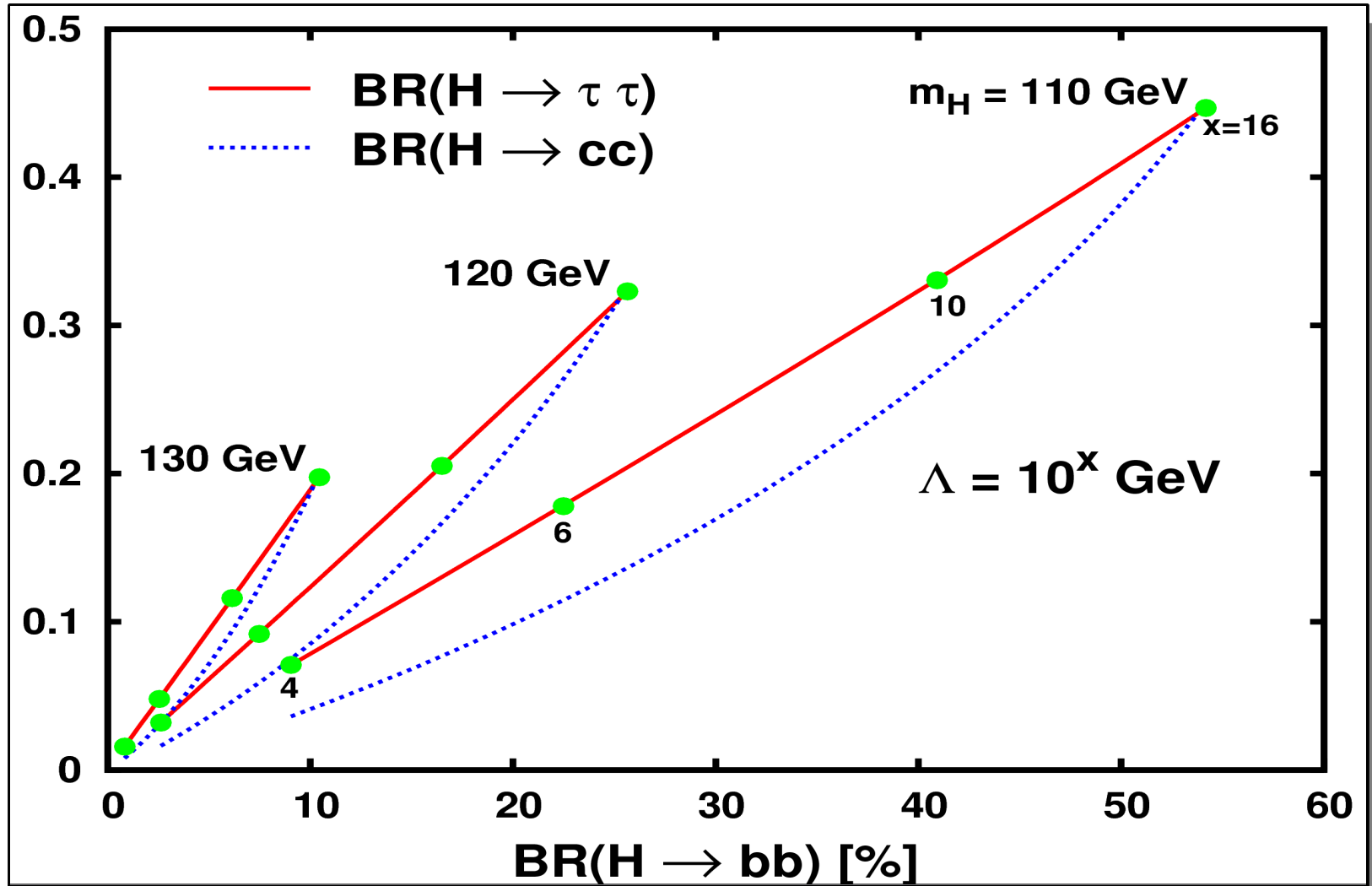
2000

$H \rightarrow ZZ$

500

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

BR[%]

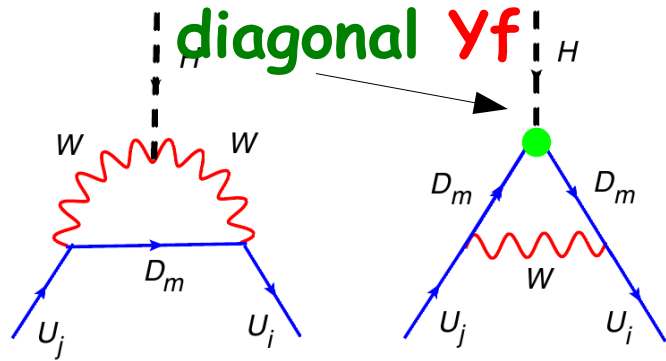


■ testing BR's correlations in fermion channels is crucial to prove Effective  $\gamma f$ 's scenario !

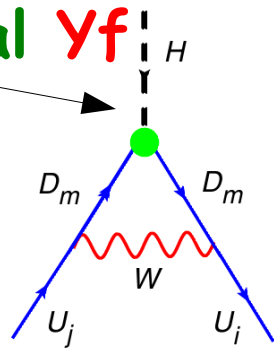
# Flavor-Changing Higgs decay $H \rightarrow bs$

- SM  $BR(H \rightarrow bs) < O(10^{-7})$  radiatively induced
- in FP Higgs scenario  $H \rightarrow bs$  also radiatively induced  $\rightarrow$  but BR enhanced since  $\Gamma_H$  depressed
- CKM matrix responsible of FC decay  $H \rightarrow bs$
- we computed RGE for the off-diagonal  $Y_f$ 's
- $BR(H \rightarrow bs)$  of order  $O(10^{-4} \rightarrow 10^{-3})$  for  $\Lambda \sim 10^4 \rightarrow 10^{16}$  GeV

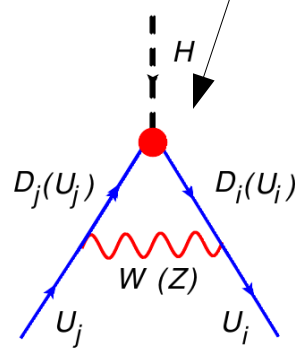
# Diagrams contributing to FC $\Upsilon f$ 's beta-functions



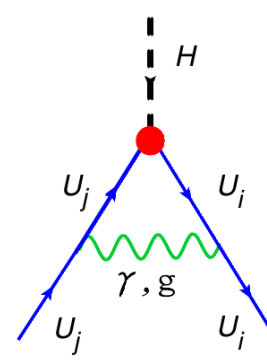
a)



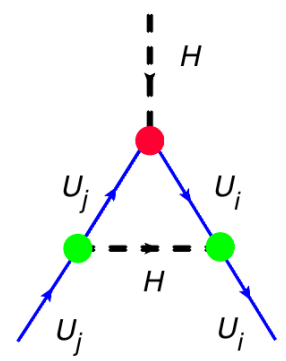
b)



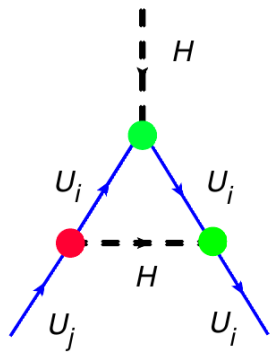
c)



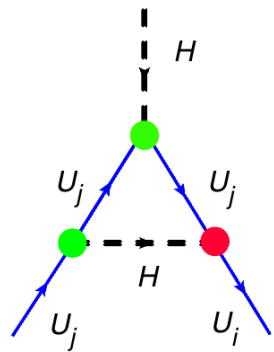
d)



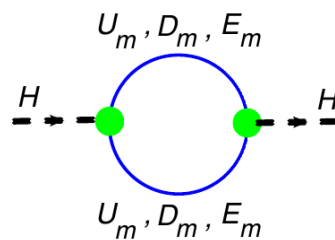
e)



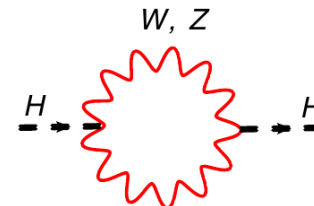
f)



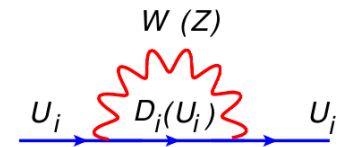
g)



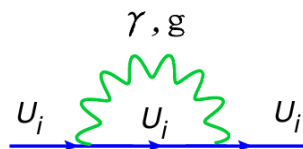
h)



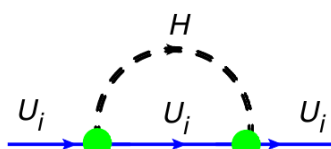
i)



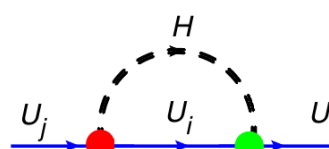
j)



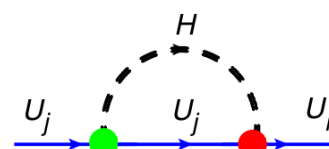
k)



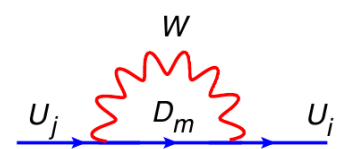
l)



m)



n)



o)

# FC Yukawas's beta-functions

E.G., B.Mele, PRD 84 054017 (2011)

Less sensitive to  $M_H$  due to  
unitarity of CKM

$$\frac{d[\mathbf{Y}_F^{\mathbf{L},\mathbf{R}}]_{ij}}{dt} = [\beta_F^{\mathbf{L},\mathbf{R}}]_{ij} ,$$

where the corresponding beta functions  $[\beta_F^{\mathbf{L},\mathbf{R}}]_{ij}$ , with  $\mathbf{F} = \{\mathbf{U}, \mathbf{D}\}$ , are given by

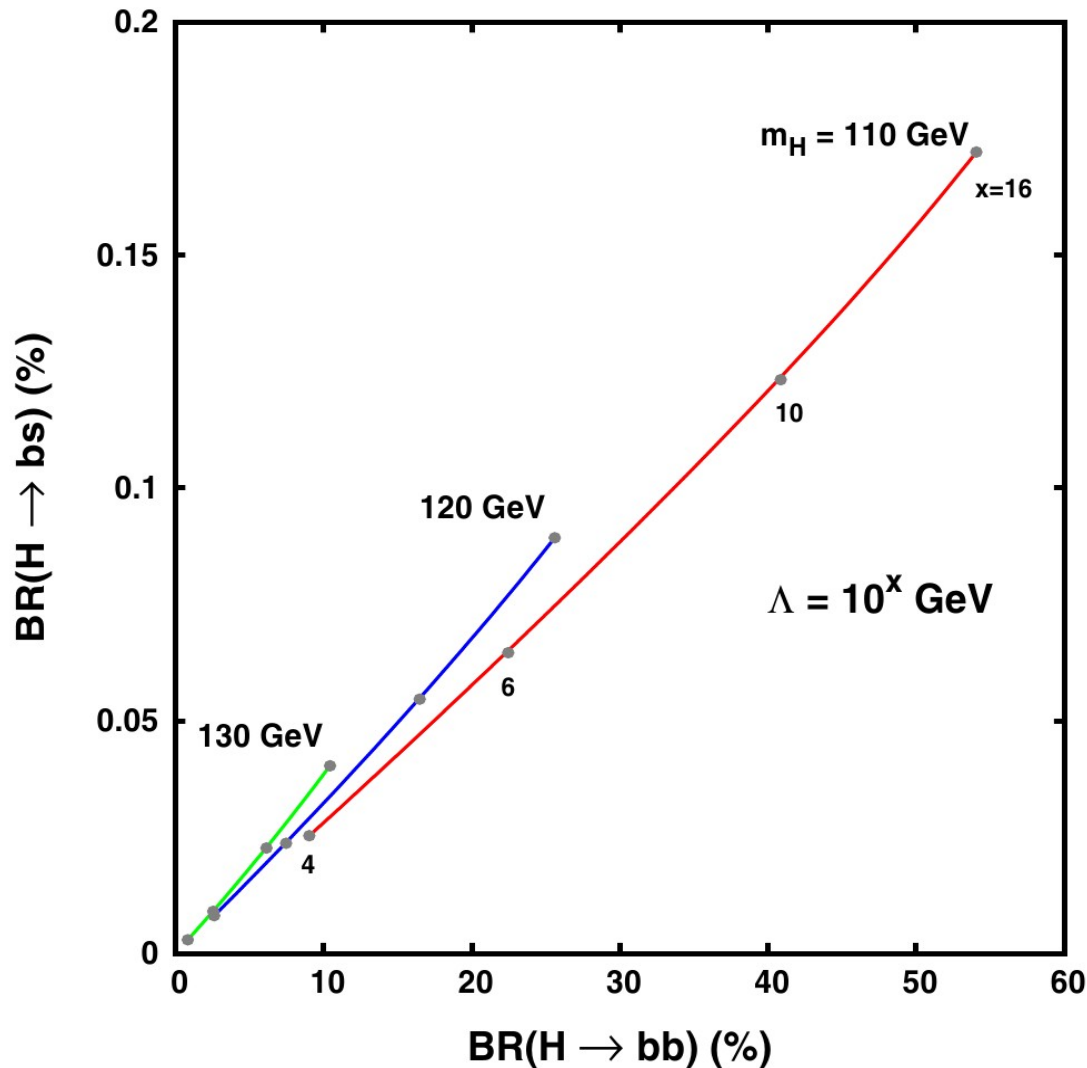
$$\begin{aligned} [\beta_{\mathbf{U}}^{\mathbf{L}}]_{ij} = & \frac{1}{16\pi^2} \left\{ 3 \sum_m \lambda_{D_m}^{ij} \left[ Y_{D_m}^{\text{SM}} Y_{U_i}^{\text{SM}} (Y_{D_m}^{\text{SM}} - Y_{D_m}) + \rho(u_i, u_j, D_m) Y_{U_j}^{\text{SM}} (Y_{U_i} Y_{U_j}^{\text{SM}} - Y_{U_j} Y_{U_i}^{\text{SM}}) \right] \right. \\ & + [\mathbf{Y}_{\mathbf{U}}^{\mathbf{L}}]_{ij} \left[ \underline{3\xi_H^2} - C_{\mathbf{U}} g_1^2 - \frac{9}{4} g_2^2 - 8g_3^2 + \text{Tr}(\mathbf{Y}) + \frac{1}{4} (Y_{U_i}^2 + Y_{U_j}^2) \right. \\ & + \frac{3}{2} (Y_{U_j}^2 \rho(u_i, u_j, u_i) - Y_{U_i}^2 \rho(u_i, u_j, u_j)) + (Y_{U_j}^{\text{SM}})^2 \left( \frac{3}{2} - \frac{2}{3} s_W^2 \right) \\ & + (Y_{U_i}^{\text{SM}})^2 \left( -\frac{1}{2} + \frac{2}{3} s_W^2 \right) - \frac{3}{2} (Y_{D_j}^{\text{SM}})^2 \left. \right] - 2[\mathbf{Y}_{\mathbf{D}}^{\mathbf{R}}]_{ij} Y_{U_i}^{\text{SM}} Y_{D_j}^{\text{SM}} - [\mathbf{Y}_{\mathbf{D}}^{\mathbf{L}}]_{ij} Y_{U_i}^{\text{SM}} Y_{D_i}^{\text{SM}} \\ & \left. + [\mathbf{Y}_{\mathbf{U}}^{\mathbf{R}}]_{ij} \left[ \frac{5}{2} Y_{U_i} Y_{U_j} - Y_{U_i}^{\text{SM}} Y_{U_j}^{\text{SM}} - \frac{3}{2} (Y_{U_i}^2 - Y_{U_j}^2) \eta(u_i, u_j) \right] \right\} , \end{aligned}$$

$$[\beta_{\mathbf{D}}^{\mathbf{L}}]_{ij} = [\beta_{\mathbf{U}}^{\mathbf{L}}]_{ij} \{(\mathbf{U}, \mathbf{D}) \rightarrow (\mathbf{D}, \mathbf{U})\} , \quad [\beta_{\mathbf{U}}^{\mathbf{R}}]_{ij} = [\beta_{\mathbf{U}}^{\mathbf{L}}]_{ji}^* , \quad [\beta_{\mathbf{D}}^{\mathbf{R}}]_{ij} = [\beta_{\mathbf{D}}^{\mathbf{L}}]_{ji}^* ,$$

where  $\rho(x, y, z) = m_z^2 / (m_x^2 - m_y^2)$ ,  $\eta(x, y) = m_x m_y / (m_x^2 - m_y^2)$ ,  $\lambda_{D_m}^{ij} = K_{im} K_{jm}^*$ ,  $\lambda_{U_m}^{ij} = K_{mi}^* K_{mj}$

**CKM** matrix elements

# Correlations of FC $\text{BR}(H \rightarrow bs)/\text{BR}(H \rightarrow bb)$



EG, B.Mele, Less sensitive to  $m_H$   
due to unitarity of CKM

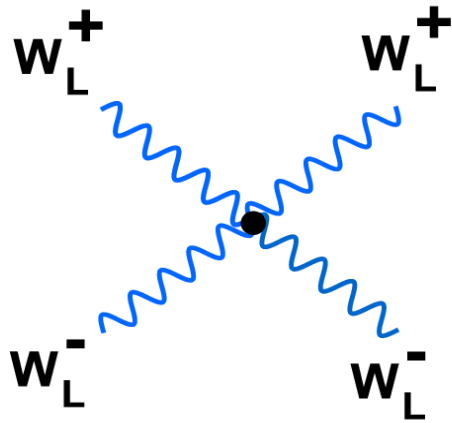
# Conclusions

- The Higgs mechanism plays a central role in the SM and its discovery will be crucial for particle physics
- LHC will be able to answer this question in a few months. But if there is not a SM Higgs boson...
- ...then a New Physics should show up at the TeV scale and a **new exciting era might start at the LHC !**
- However, there is no reason why the Higgs mechanism should be responsible of both  $W, Z$  and fermion masses
- A **Fermiophobic Higgs** scenario is a quite natural alternative and it could be tested at the LHC

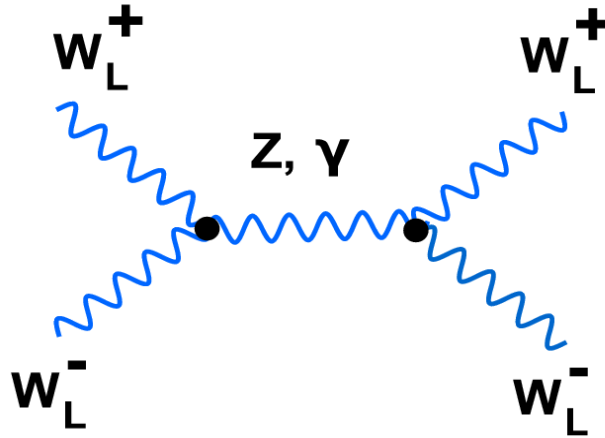
# Backup

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

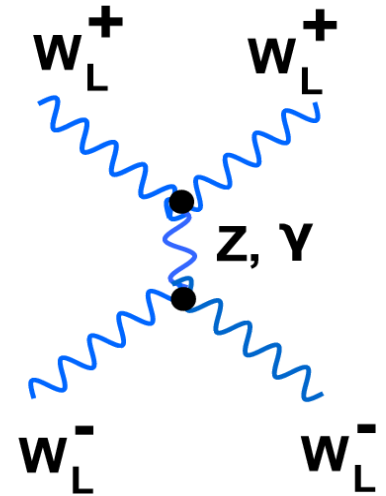
$W_L W_L \rightarrow W_L W_L$  (explicit symmetry breaking)



(a)



(b)



(c)

|        |                              |
|--------|------------------------------|
| Graphs | $\sim g^2 \frac{E^4}{M_W^4}$ |
|--------|------------------------------|

|     |                                      |
|-----|--------------------------------------|
| (a) | $-3 + 6 \cos \theta + \cos \theta^2$ |
|-----|--------------------------------------|

|     |                  |
|-----|------------------|
| (b) | $-4 \cos \theta$ |
|-----|------------------|

|     |                                      |
|-----|--------------------------------------|
| (c) | $-3 - 2 \cos \theta - \cos \theta^2$ |
|-----|--------------------------------------|

|       |   |
|-------|---|
| Sum = | 0 |
|-------|---|

due to the gauge theory structure

|        |                              |
|--------|------------------------------|
| Graphs | $\sim g^2 \frac{E^2}{M_W^2}$ |
|--------|------------------------------|

|     |                                     |
|-----|-------------------------------------|
| (a) | $2 - 6 \cos \theta + \cos \theta^2$ |
|-----|-------------------------------------|

|     |                |
|-----|----------------|
| (b) | $-\cos \theta$ |
|-----|----------------|

|     |                                                           |
|-----|-----------------------------------------------------------|
| (c) | $-\frac{3}{2} - \frac{15}{2} \cos \theta - \cos \theta^2$ |
|-----|-----------------------------------------------------------|

|       |                                         |
|-------|-----------------------------------------|
| Sum = | $\frac{1}{2} + \frac{1}{2} \cos \theta$ |
|-------|-----------------------------------------|

new diagrams required !

# Alternative solutions to the SM Higgs mechanism

after late '90

old proposals still very alive, but more constrained than before due to **EWPT**, FCNC, **light Higgs**, LHC

## Large extra-dimensions

Strongly constrained by astrophysics and LHC

no natural candidate for DM

pass all EW precision tests

- ◆ Gravity propagates in **extra-dimensions** (ADD and Randall-Sundrum scenarios)



- ◆ Fundamental Planck scale lowered to the TeV scale → hierarchy problem solved

- ◆ new phenomenology at TeV scale (**Kaluza-Klein excitations of graviton**, black holes)

## Little Higgs



Hierarchy problem only partially solved

- ◆ extra symmetries allow mH only at 2-loop

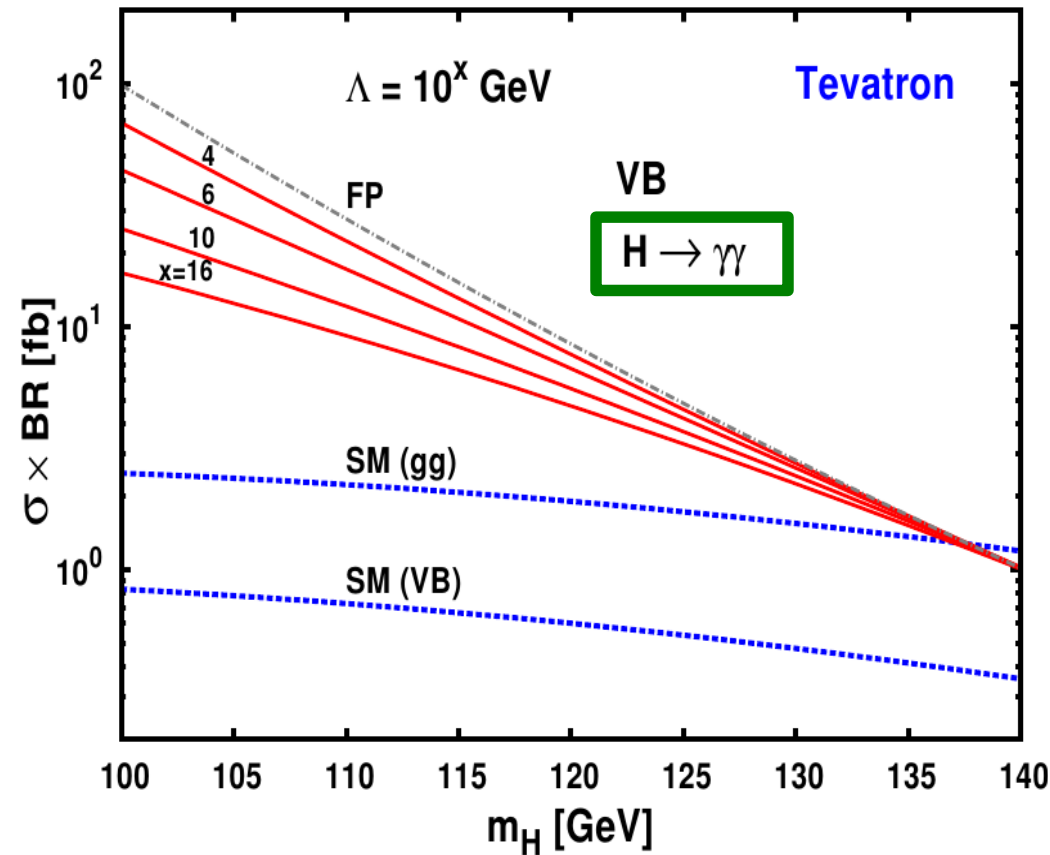
- ◆ non-perturbative regime starts at 10 TeV

## Light composite Higgs

- ◆ bound state of a strongly new interactively dynamics → SM Higgs as **pseudo-goldstone** of a larger symmetry

# Tevatron ( $p\bar{p} \rightarrow H X$ )

## VB = (WH+ZH+VBF)



 Tevatron can constrain the model !

