

Searching for the Higgs boson at the LHC : the final hunt !

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Outline

- Gauge theories and origin of forces
- The problem of mass in gauge theories
- The Higgs mechanism
- Higgs boson physics at the LHC
- **Latest news** on Higgs boson searches
- A non-standard Higgs scenario
- Conclusions

Symmetries and origin of forces

- We observe 4 fundamental Forces in nature
- acting among matter constituents: from composed ones to fundamental elementary particles
- characterized by a range **R** of action, **strength**, and **sign** (attractive/repulsive (**A/R**), both (**AR**))

Gravity (A), EM (A/R), Strong (A/R), Weak (A/R)

- **Gravity** and **EM** have an infinity range of action, while **Strong** and **Weak** interactions are relevant only at subatomic distances
- Relative strength: **Strong >> EM > Weak >> Gravity**

Strong and Weak interactions

Range R of subatomic physics $R \sim 10^{-15} \text{ m}$ strong
 $R \sim 10^{-18} \text{ m}$ weak

Strong interactions: i.e. responsible of binding together protons and neutrons in atomic nuclei and their constituents (quarks)

Weak interactions: i.e. responsible of the beta decay
 $n \rightarrow p e^- \bar{\nu}$ → trigger nuclear reactions inside our Sun

Relative strength: strong = 1, EM = 10^{-2} , weak = 10^{-6}
gravity = 10^{-39}

Symmetries and origin of forces

- Symmetries play a crucial role in our modern understanding of forces or fundamental interactions. Forces are associated to “local” (space-time dependent) symmetries called gauge symmetries
- We know that in the case of Gravitational, EM, and Strong interactions the corresponding local symmetries are exact
- this is not the case for the Weak interactions → the associated gauge symmetry (the Electro-Weak symmetry) is broken
- In the standard model of electroweak interactions, the mechanism which generates the Electro-Weak symmetry breaking (EWSB) is responsible for the origin of mass of all fundamental particles
- it is called the Higgs mechanism (from P. Higgs) → it predicts a massive neutral scalar particle → Higgs boson

Why we are so concerned about Higgs boson

- ★ The **Standard Model** theory is not unitary and **renormalizable** without the Higgs boson (loses its predictivity)
- ★ it is the last missing piece to be discovered in **SM**
- ★ its 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 it very soon**) then a **New Physics** should show up at the TeV energy scale and it will be found at the **Large Hadron Collider (LHC)** !

Symmetries and origin of forces

Maxwell equations

$$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_0} \rho$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$

$$\vec{\nabla} \times \vec{B} - \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} = \mu_0 \vec{J}$$

Electric (E) and magnetic (B) fields unified in
4D space-time → **manifest relativistic invariance**

Four vector potential $A_\mu = (\Phi, \vec{A})$
time-like space-like

$$\vec{E} = -\vec{\nabla} \phi - \frac{\partial \vec{A}}{\partial t}, \quad \vec{B} = \vec{\nabla} \times \vec{A}$$

ϕ and $\vec{A}$ not uniquely determined at
fixed $\vec{E}$ and $\vec{B}$

→ **redundant degrees of freedom**

EM: as a U(1) gauge theory

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = \begin{pmatrix} 0 & B_y & E_x & B_x \\ E_x & 0 & E_z & B_z \\ E_z & B_z & 0 & E_y \\ E_y & B_y & E_x & 0 \end{pmatrix}$$

density and current $\rho, \vec{J} \rightarrow J_\mu = (\rho, \vec{J})$

Maxwell's eqs $\rightarrow \partial_\mu F^{\mu\nu} = J^\nu$

invariant under **gauge transformations**

hidden symmetry

$$\vec{A}' = \vec{A} + \vec{\nabla}\varepsilon \quad \phi' = \phi - \frac{\partial\varepsilon}{\partial t}$$

$$A'_\mu = A_\mu - \partial_\mu \varepsilon$$

space-time
dependent parameter

the heart of our modern understanding of all forces
Observables are gauge independent quantities !

Relativistic action of free fermions (Dirac)

$$S_{\text{Dirac}} = \int d^4x \, \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi$$

(spinorial field)

(Dirac 4x4 matrices)

Symmetry = invariance under global phase transformations

$$\psi \rightarrow e^{i\Lambda} \psi \quad \longrightarrow \quad \text{global phase } \Lambda \text{ is not observable}$$

When promoted to a local symmetry $\Lambda(x) \longrightarrow$ **EM interactions**

$$S_{\text{EM}} = \int d^4x \left[\bar{\psi} (i\gamma^\mu D_\mu - m) \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right]$$

$$D_\mu = \partial_\mu - \textcircled{iA_\mu}$$

local phase Λ is not observable

covariant derivative

EM interaction

$$\begin{cases} \psi \rightarrow e^{i\Lambda(x)} \psi \\ A_\mu \rightarrow A_\mu + \partial_\mu \Lambda(x) \end{cases}$$

SU(N) non-abelian gauge theories

(Yang, Mills '54)

Generalization of EM, with **charged interacting**
“photons”

$$\mathcal{L} = \frac{1}{4} \text{Tr}[\hat{F}_{\mu\nu} \hat{F}^{\mu\nu}]$$

Interaction term

$$\hat{F}_{\mu\nu} = \partial_\mu \hat{A}_\nu - \partial_\nu \hat{A}_\mu + ig [\hat{A}_\mu, \hat{A}_\nu]$$

$$\hat{A}_\mu = \sum_a A_\mu^a T^a \quad [T^a, T^b] = i \sum_c f_{abc} T^c$$

L is invariant under non-abelian gauge transformations

$$U(x) = \exp\left(i \sum_a \lambda^a(x) T^a\right) \longrightarrow$$

Elements of SU(N)
group → do not
commute
 $U(x)U(y) \neq U(y)U(x)$

$$\hat{A}_\mu \rightarrow \hat{A}_\mu + U^{-1} \partial_\mu U + U^{-1} \hat{A}_\mu U$$

Quantum Electrodynamics



Energy of EM field A_μ is quantized (Planck)



Quantum excitations of EM field A_μ described by an elementary massless particle of spin-1 : Photon (Einstein)



2 degrees of freedom



Infinity range of EM interactions are a consequence of the zero-mass of the Photon (γ)

massless photon $\longrightarrow$ protected by Gauge Invariance

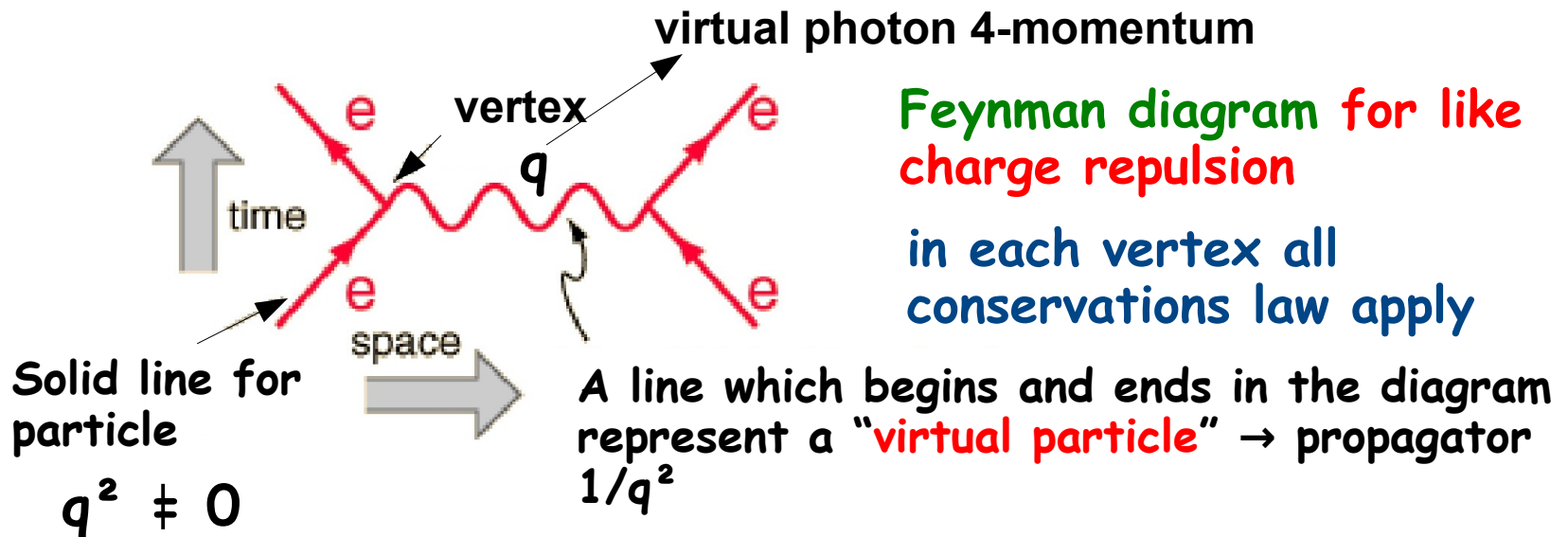
Relativistic equation of massive photon (m)

$$-\partial_\mu F^{\mu\nu} - \frac{m^2 c^2}{\hbar^2} A^\nu = 0 \quad \longrightarrow \quad 3 \text{ degrees of freedom}$$

is not invariant under gauge transformations $\longrightarrow A^\nu = A'^\nu - \partial^\nu \lambda$

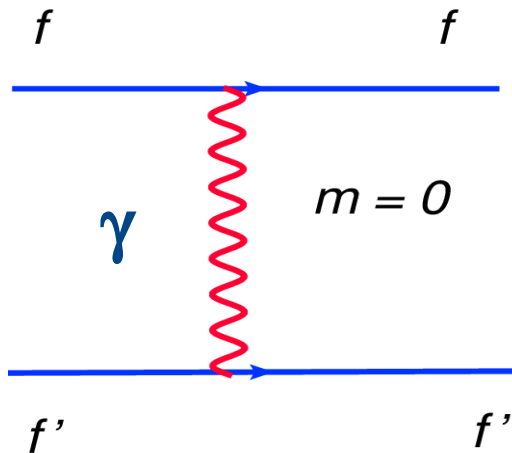
Tool: Feynman Diagrams

- ✱ $E = mc^2 \rightarrow$ In quantum relativistic theories **energy** and **momentum** are **conserved** but not particles' number
- ✱ Interactions $\rightarrow$ described in terms of exchange of **virtual particles** that can be created and destroyed from vacuum
- ✱ Feynman diagrams are graphical tools to calculate **probability amplitudes** in quantum field theory



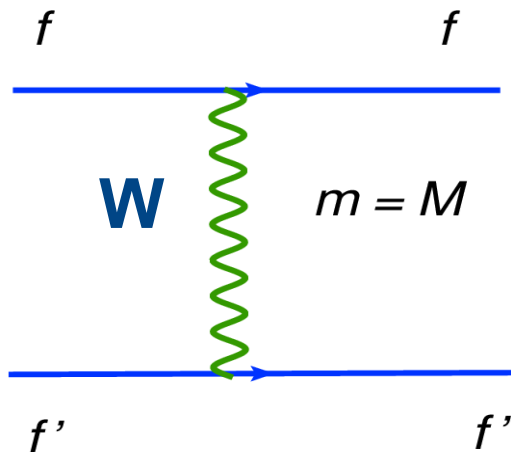
long- and short-distance interactions

If we look at the potential from the non relativistic limit of amplitude scatterings



$$V(r) \sim \frac{1}{r}$$

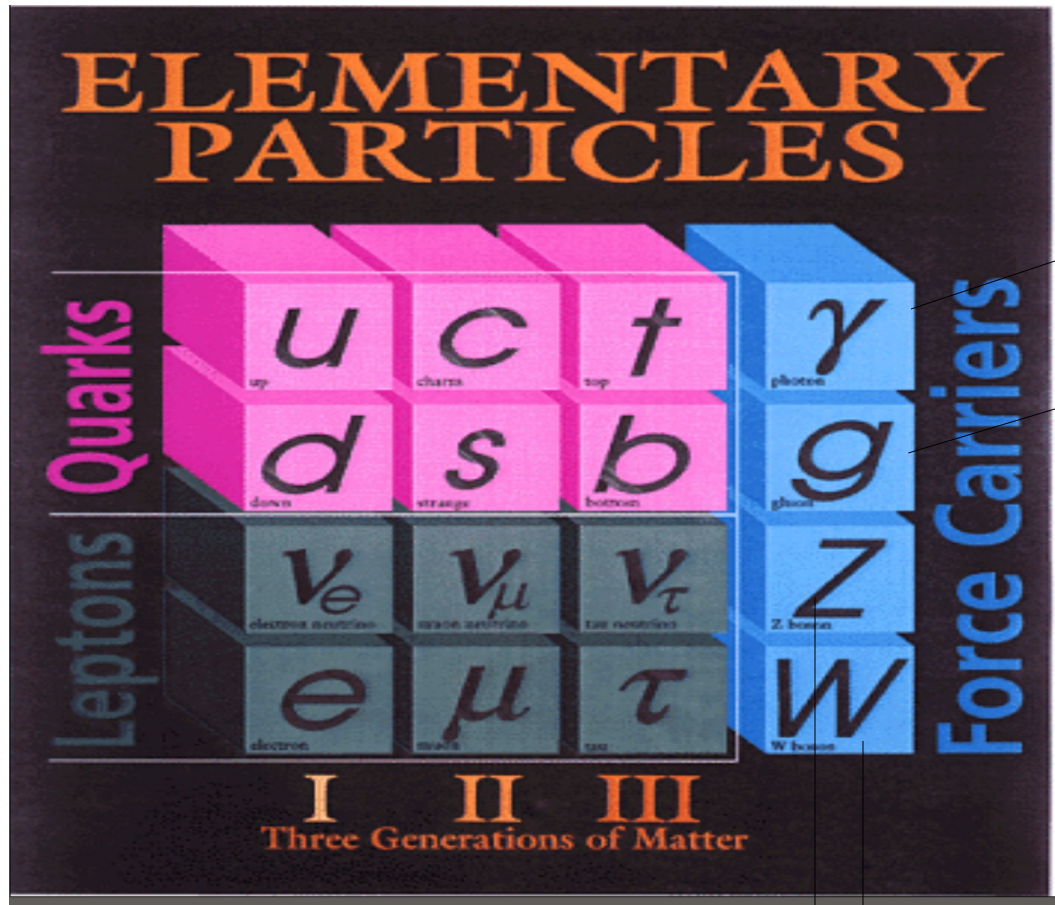
Massless gauge boson
(long-distance)



$$V(r) \sim \frac{1}{r} e^{-r/R}$$

Massive gauge boson (short-distance)
Yukawa-type potential, range $R \sim 1/M$

The building block of known elementary particles



Photon: EM

Gluons: Strong

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

$m_u \sim m_d \sim 5 - 8 \text{ MeV}$
 $m_s \sim 150 \text{ MeV}$
 $m_c \sim 1.5 \text{ GeV}$,
 $m_b \sim 3 \text{ GeV}$
 $m_t \sim 172 \text{ GeV}$

Electric charges
(in unity of e)

W,Z: Weak

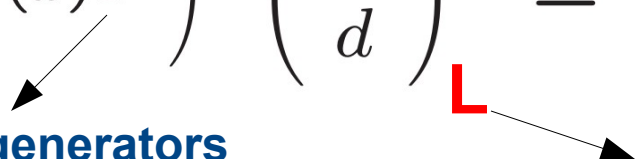
$\begin{cases} Q_v = 0 \\ Q_e = 1 \end{cases}$
 $\begin{cases} Q_U = 2/3 \\ Q_D = -1/3 \end{cases}$

$m_e \sim 0.5 \text{ MeV}$
 $m_\mu \sim 105 \text{ MeV}$
 $m_\tau \sim 1.77 \text{ GeV}$
 $m_\nu = 0$

Weak-interactions

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

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

 **SU(2) matrix generators** **Maximal Parity violation**

3 Quark families

Q = (u,d) (c,s) (t,b)

3 Lepton families

L = (ν_e,e) (ν_μ,μ) (ν_τ,τ)

SU(2) Broken → massive gauge-bosons (W , Z)



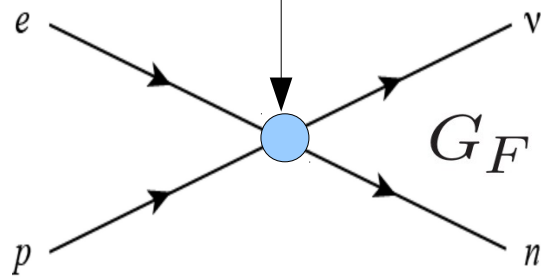
M_W = 80 GeV

M_Z = 91 GeV

Weak interactions

all started with Fermi theory for beta decay (1930)

4-fermions contact interaction: **G_F** coupling

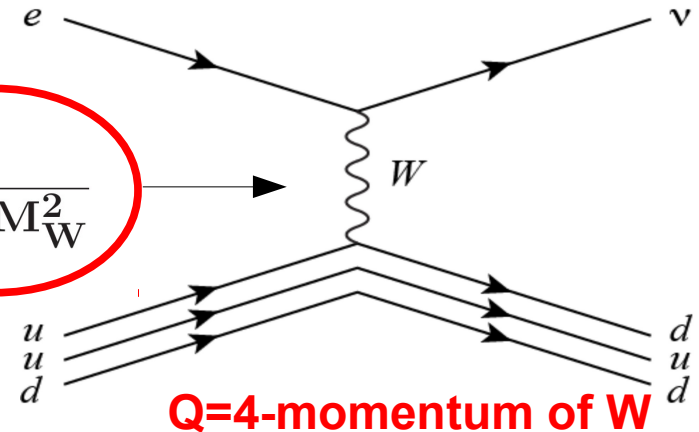


G_F

low energy

$$|Q^2| \ll M_W^2$$

$$\frac{1}{Q^2 - M_W^2}$$



$Q=4$ -momentum of W

- ★ **G_F** interpreted as an exchange of a heavy charged gauge bosons (W) → **$G_F \sim 1/M_W^2$** **$G_F \sim 10^{-5} / \text{GeV}^2$**
- ★ Weak interactions described by the gauge theory of non-abelian group **$SU(2) \times U(1)$** known as the **Standard Model**
(Glashow, Weinberg, Salam '68)
- ★ **Weak** and **EM** interactions embedded in $SU(2) \times U(1)$
- ★ SM predicts **weak neutral currents** → massive **Z boson**
- ★ **W and Z discovered at CERN** (1983-84 C. Rubbia, UA1, UA2)

**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 $SU(2) \times U(1)$**

- ✱ gauge invariance constraints the theory very tightly!

- ✱ stringent tests of predictions tested experimentally

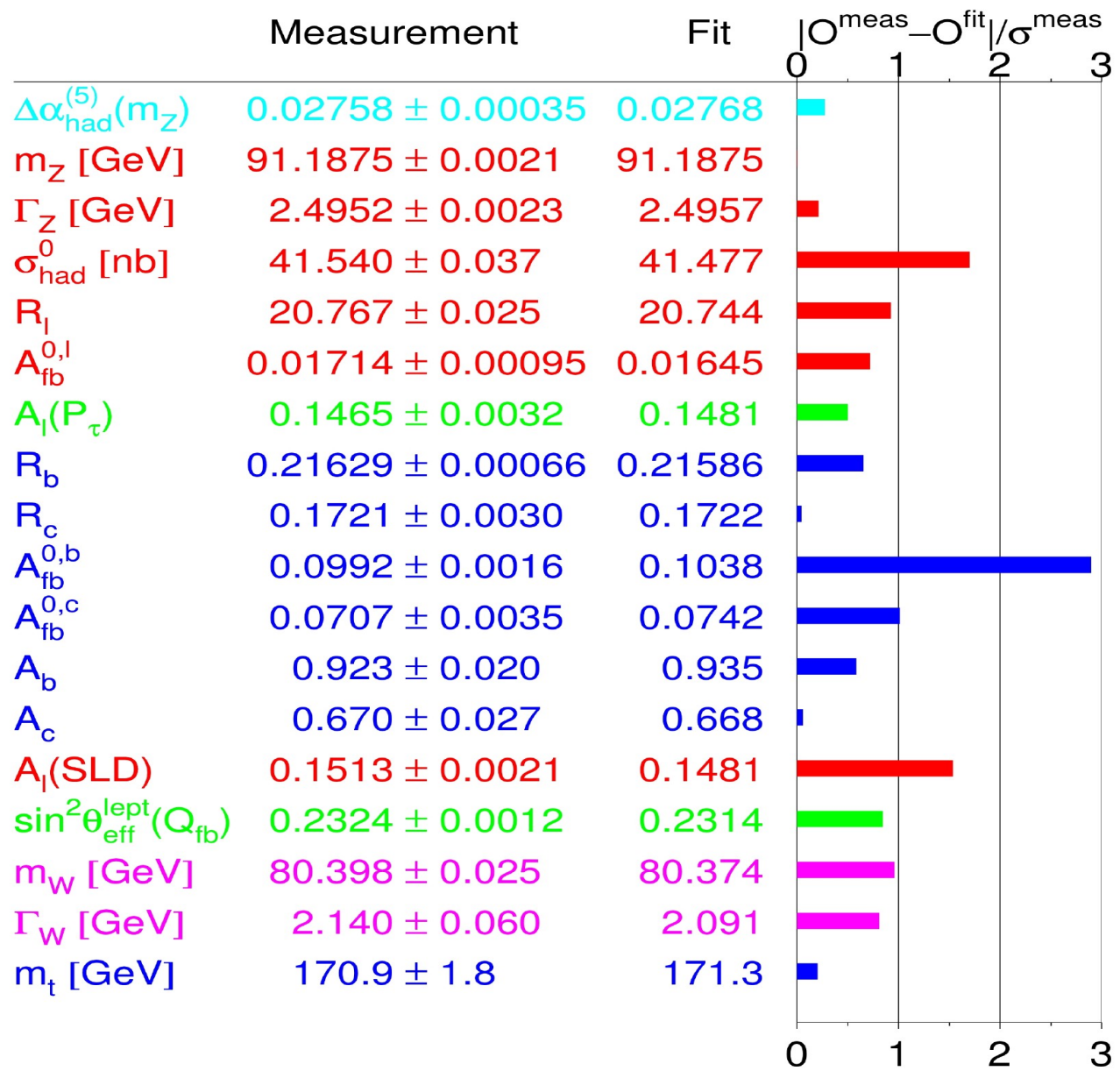
More than 20 years of precision tests of the SM

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) $E_{cm}=1.98$ 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 non-abelian gauge symmetry)

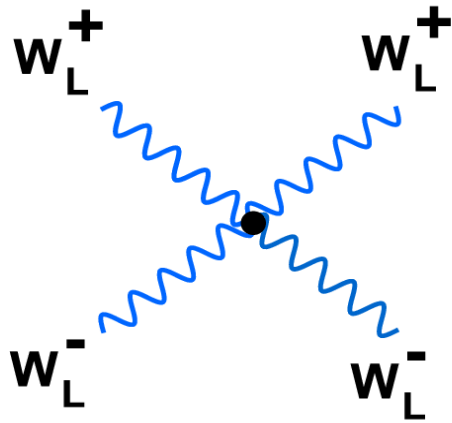
- **Problems:** bad high energy behavior for interacting gauge bosons
→ **W** and **Z** becomes strongly interacting at high energy
- polarization of **massive** gauge boson has 3 components
 - 2 **transverse** and 1 **longitudinal** (with respect to the 3-momentum)
- **Longitudinal** polarizations of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

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

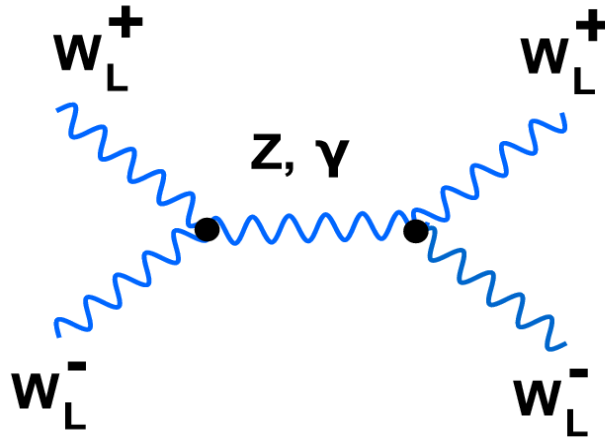
- at high energy $E > 1\text{-}2 \text{ TeV}$, scattering amplitudes for **W W** → **W W** **explode** → **unitarity violation** (**probability** > 1 → **makes no sense**)
- Problem absent in **U(1) gauge theory** due to the conservation of current $k_{\mu} J^{\mu} = 0$ → **U(1) longitudinal component are decoupled**

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

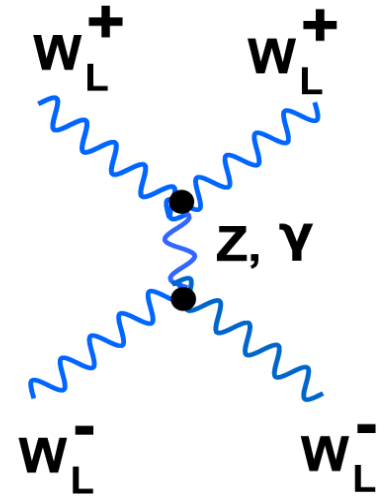
$W_L W_L \rightarrow W_L W_L$ (explicit symmetry breaking)



(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
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due to the gauge theory structure

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

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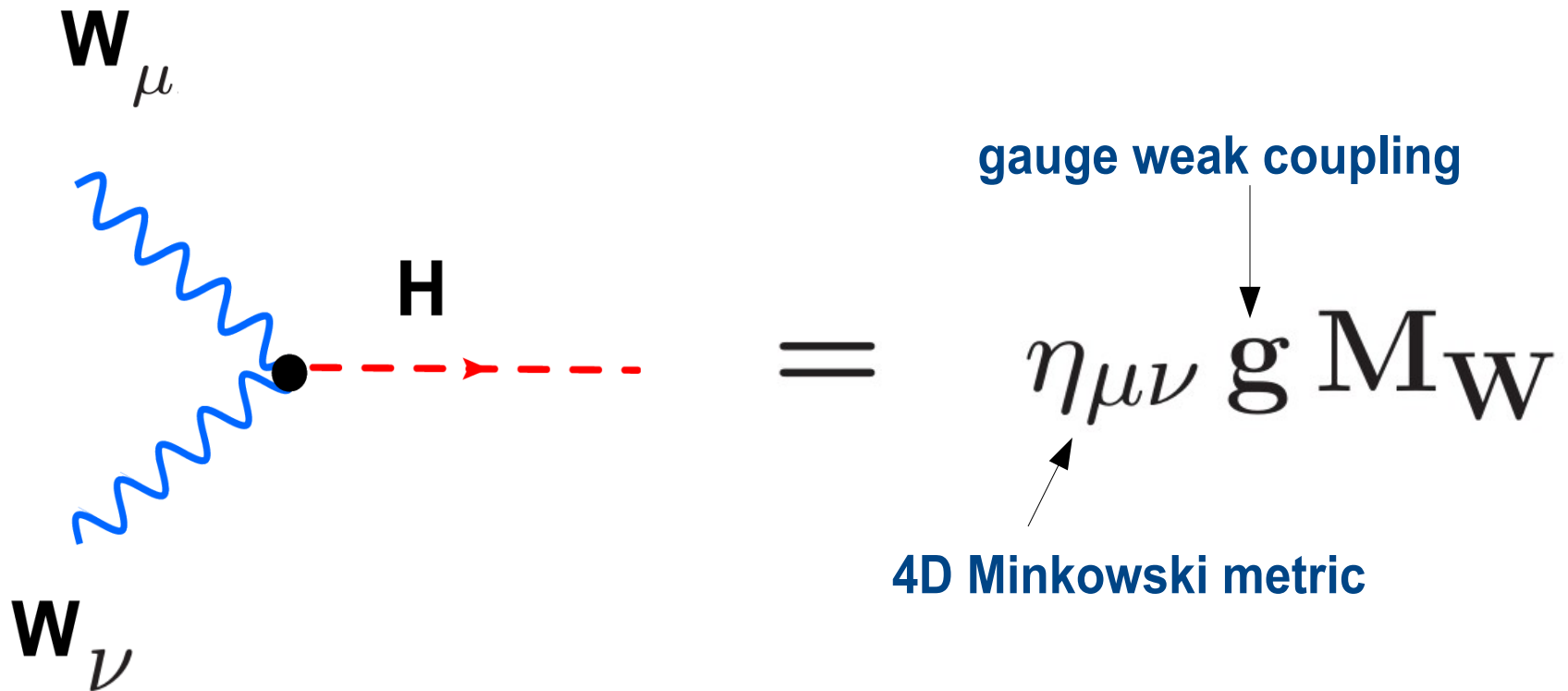
(b)	$-\cos \theta$
-----	----------------

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

Sum =	$\frac{1}{2} + \frac{1}{2} \cos \theta$
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new diagrams required !

Lets us add a new coupling term in the Lagrangian:
 due to a neutral scalar field **H** coupled to
W and **Z** with a coupling **proportional to W,Z masses**

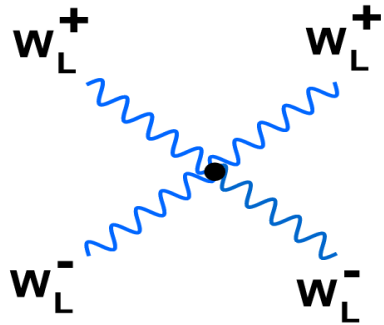


The diagram illustrates a vertex where a W_μ boson (represented by a blue wavy line) and a W_ν boson (represented by a blue wavy line) meet at a black dot. A red dashed line labeled H extends from this vertex to the right. This is equated to the mathematical expression $\eta_{\mu\nu} g M_W$.

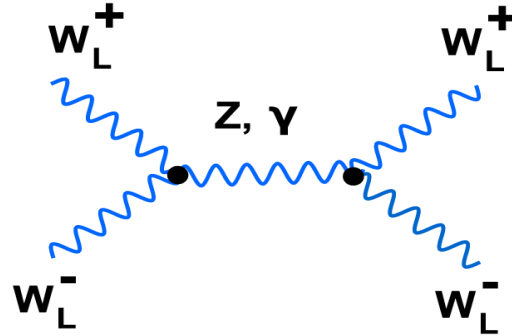
Annotations for the mathematical expression:

- $\eta_{\mu\nu}$ is labeled as the **4D Minkowski metric** with an arrow pointing to it.
- g is labeled as the **gauge weak coupling** with an arrow pointing to it.
- M_W is the mass of the W boson.

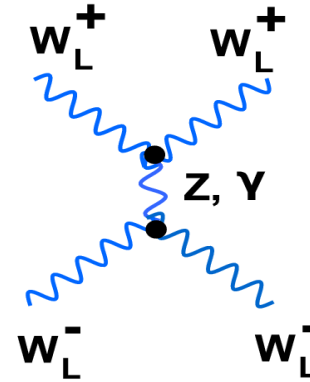
$W_L W_L \rightarrow W_L W_L @ E^2/M^2$



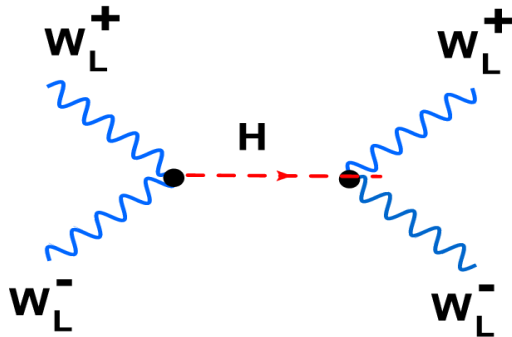
(a)



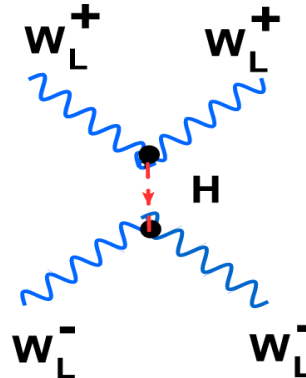
(b)



(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	$= 0$

● **cancellation not accidental !**

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

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

Spontaneous Symmetry Breaking:

Lagrangian $\mathcal{L}$ is symmetric but the vacuum $|0\rangle$ is **NOT**

Group generators

$U = \exp[i \lambda_n Q_n]$

$$U \mathcal{L} U^\dagger = \mathcal{L}$$

$$U|0\rangle = |0\rangle'$$

Goldstone theorem

- spontaneous breaking of a **continuous global symmetry**
→ **massless scalar particles** = N generators $Q_n|0\rangle \neq 0$
called **Nambu-Goldstone particles** (i.e. pions)

Higgs mechanism

(Higgs, Brout,
Englert, Guralnik,
Hagen, Kibble '64)

- SSB of a **gauge symmetry** → gauge bosons acquire a mass
massive gauge bosons = number n of generators $Q_n|0\rangle \neq 0$
- massless **gauge bosons combine with** Nambu-Goldstone
scalars and become **massive gauge bosons**:
Degrees of freedom conserved: $(2+1)*n = 3*n$

next is an example for $U(1)$ gauge theory



Higgs mechanism @ work in U(1) gauge theory

1 Goldstone in the spectrum

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

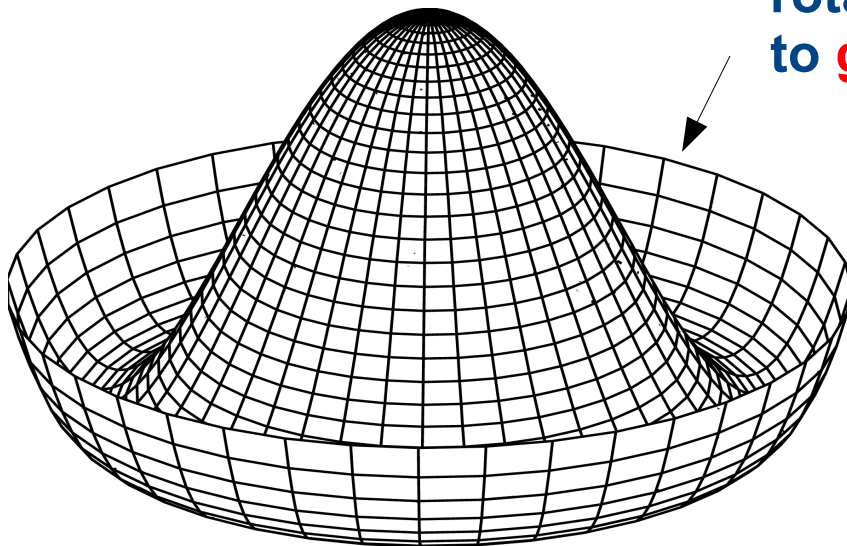
$\mathcal{L}$ is gauge invariant

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

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

Potential V

rotational symmetry corresponds to gauge symmetry



true minimum of V at

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

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

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

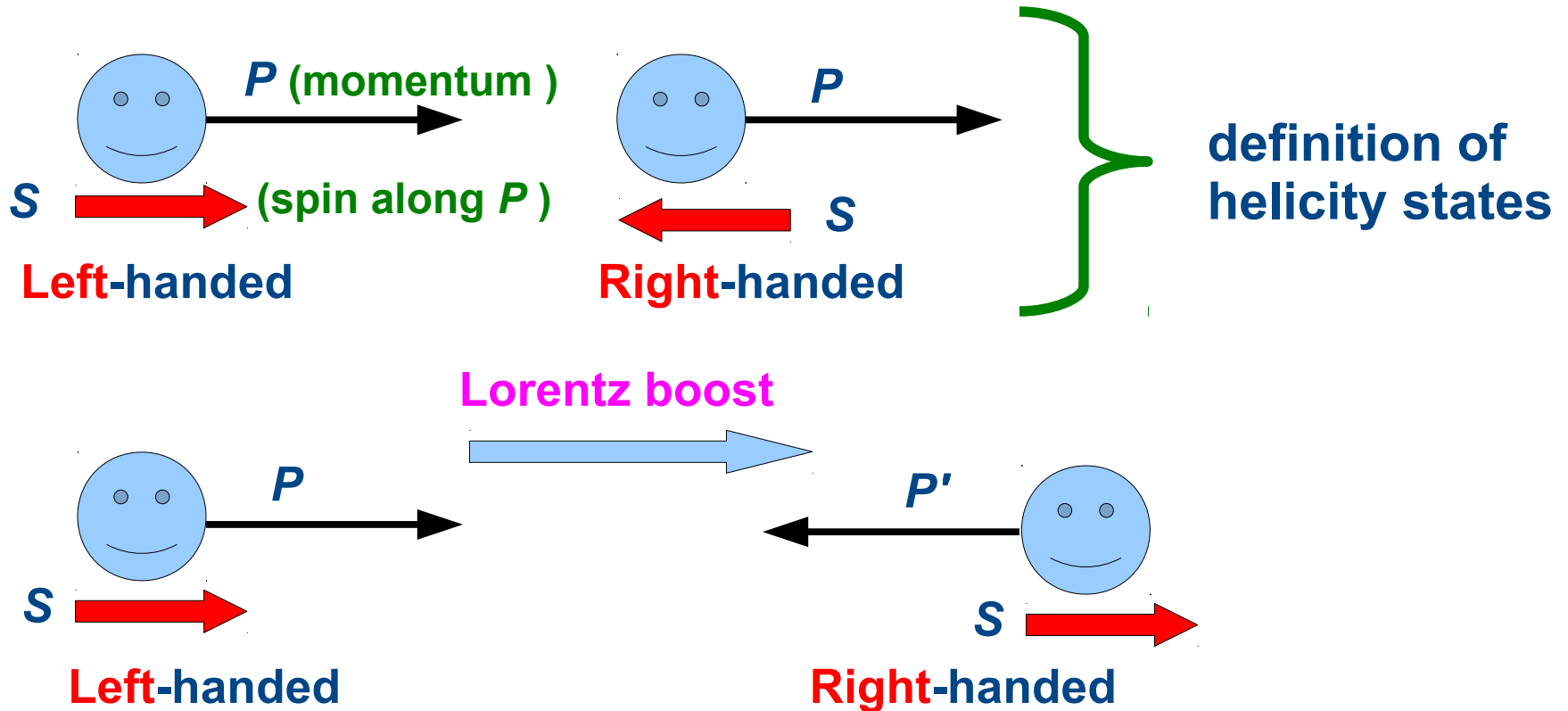
Mass term of A

Main advantages of Higgs mechanism

- massive gauge theory is still unitary and renormalizable!
(Veltman, t'Hooft, '75)
- renormalizable theories are predictive: number of UV divergencies is finite (absorbed in few free parameters)
- perturbation theory valid up to energies close to Planck scale 10^{19} GeV, but.... problems from Higgs potential!
- V in the SM is not stable under quantum corrections → main source of SM problems

Origin of fermion masses

Higgs mechanism not only give masses to **W** and **Z** but also to fermions, like **electrons** and **quarks**



helicity flip possible **only** if a particle has a mass
not possible for **massless particles** $\rightarrow$ **helicity states are physically distinct**

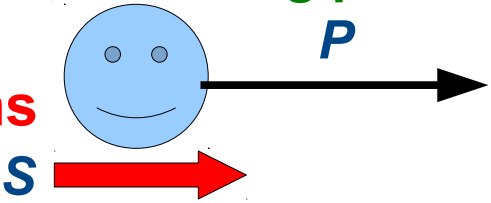
Strong and **EM** interactions do not distinguish between L- and R-handed interactions but **Weak interactions DO !**

→ **parity is broken** (discovered in 1957, Lee-Yang predicted it)

{

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

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



mass terms are not SU(2)_L gauge invariant

Right-handed **f** are singlet under SU(2)_L

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

Higgs mechanism solves this problem

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

$$\Phi = v + h \quad \longrightarrow \quad = -m \bar{f}_L f_R - m \bar{f}_R f_L - y h \bar{f}_L f_R - y h \bar{f}_R f_L$$

mass terms
Yukawa couplings

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 potential V

couplings of the Higgs field to leptons and quarks, and to W and Z are proportional to their masses

→ this makes its discovery very difficult

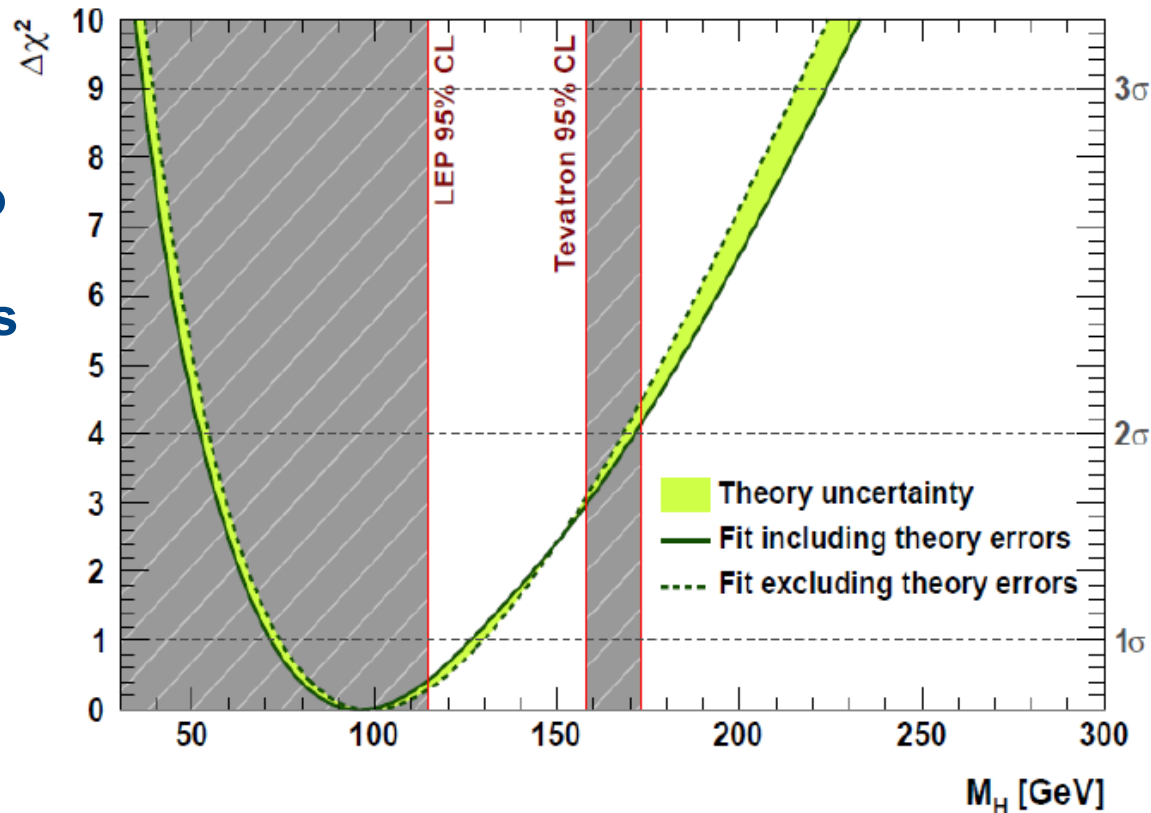
and The
UGLY

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

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

Why EWSB requires new phenomena at the TeV scale

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

Quantum corrections

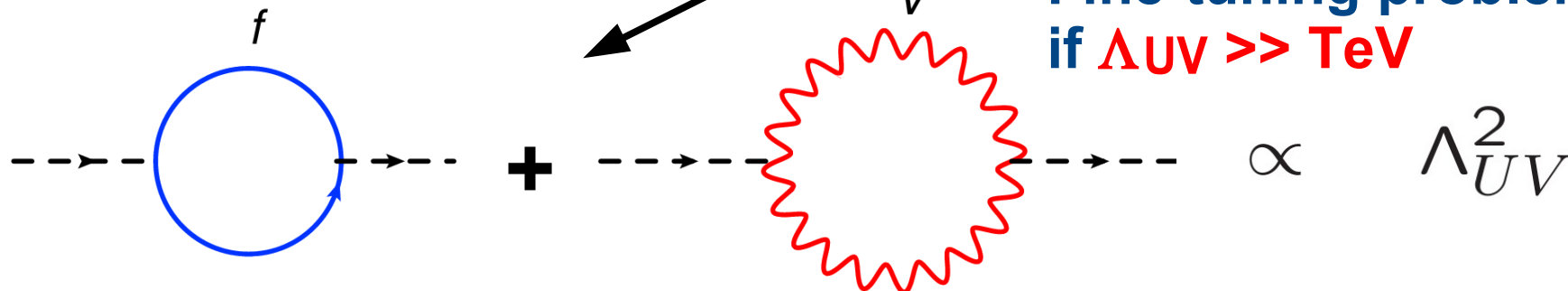
NP scale

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

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

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

Fine-tuning problem
if $\Lambda_{UV} \gg \text{TeV}$

 $\propto \Lambda_{UV}^2$

$\Lambda_{UV} = \max[m_f, m_V]$

$m_H + \delta m_H \lesssim 1 \text{ TeV}$

Alternative solutions to the SM Higgs mechanism

before late '90

Supersymmetry →

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

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

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 **Randal-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

Status of Higgs searches before LHC

LEP ('90 – 00): electron-positron collider at CERN
max c.o.m. Energy LEP1 = **91 GeV** (Z pole)
LEP2 = **200 GeV**
relevant process: $e^+e^- \rightarrow H(\rightarrow b\bar{b}) Z$

$m_H > 114.5 \text{ GeV}$

Tevatron ('85 – 11): **proton-antiproton** collider at Fermilab
c.o.m Energy = **1.98 TeV**
(several processes)

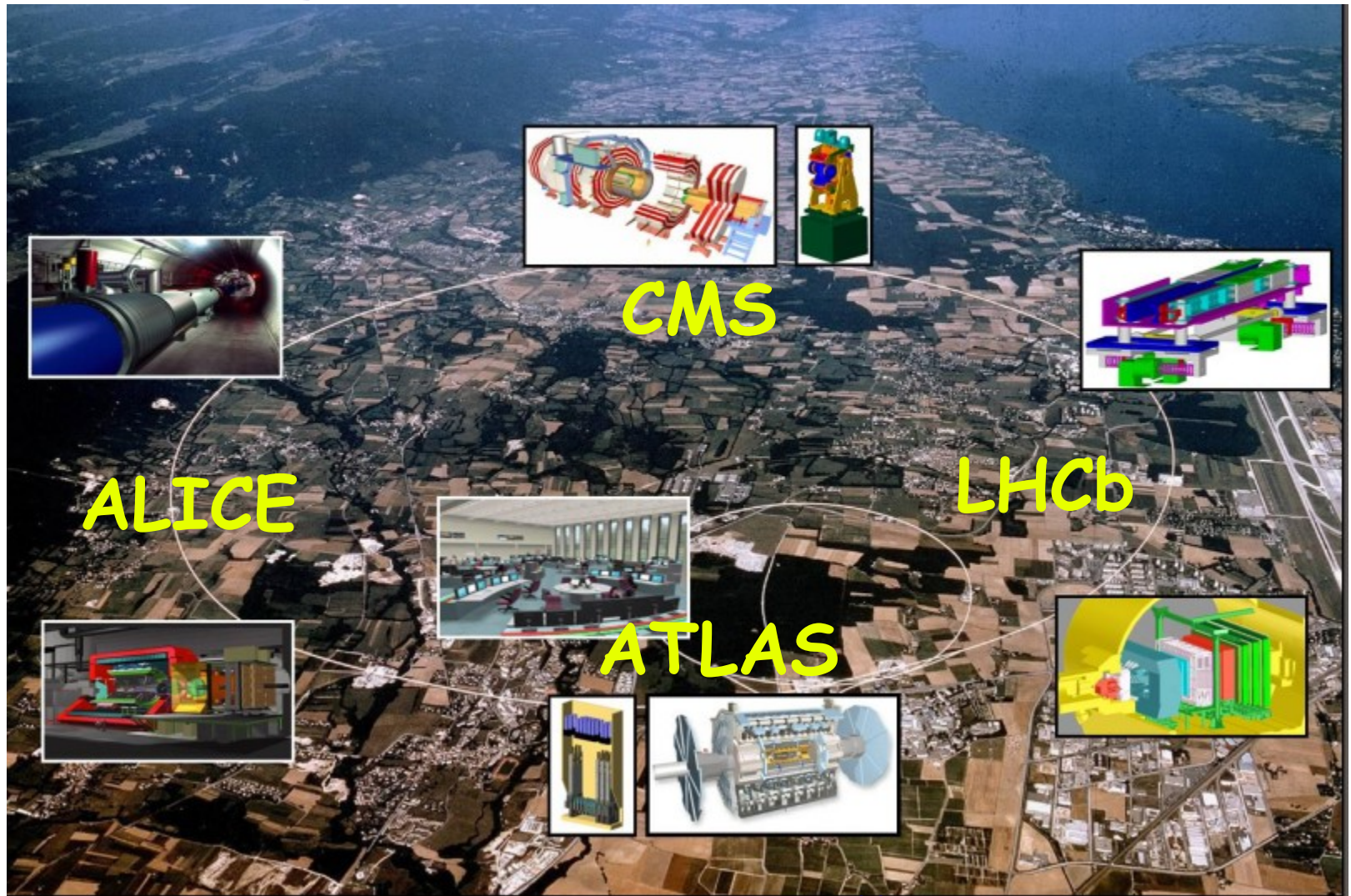
exclusion regions on SM Higgs mass at **95% CL**

[100 – 109] GeV

and

[156 – 177] GeV

Large Hadron Collider



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

LHC : an unprecedented enterprise

- **huge** technological (very high luminosity and energy), experimental (largest experiments in the world) and sociological (world scale collaborations) **challenge**
- with respect to energy → it will explore the TeV region
- a large number of different theoretical models to be tested (outcome of about 30 years of theoretical activities)

Physics motivations

- strong theoretical reasons to believe that the Beyond the SM (**BSM**) physics should show up at the TeV scale
- capability to uncover the mystery of **EWSB** and particle mass generation, origin of **Dark Matter**, existence of **supersymmetry**, extra-dimensions, etc.

LHC : where we are today

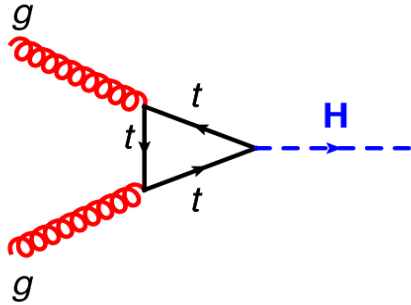
- In 2010 LHC delivered **45 pb⁻¹** of luminosity **L** in pp collisions at **E_{cm}=7 TeV**: **N(events)= L x cross-section**
- **ATLAS** and **CMS** could substantially improve bounds on direct signals from BSM models with respect to Tevatron limits by analyzing just the first **45 pb⁻¹** of L
- **New 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 ?)

Hot LHC data on Higgs boson

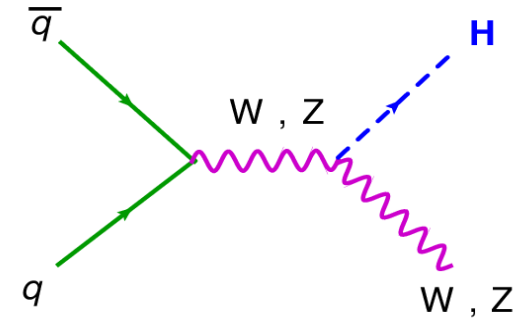
- In a few months we should be able to complete the **SM-Higgs search-phase** and find out whether:
 - ◆ there is a SM like Higgs signal
 - Start testing its properties
 - ◆ there is NOT a SM like Higgs signal
 - What is there instead ?
 - This will take longer...
- Results presented here are according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

SM Higgs production mechanisms

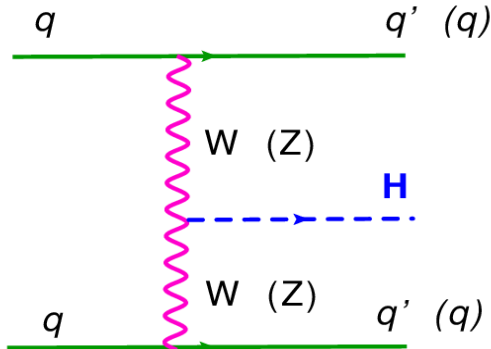
Gluon fusion



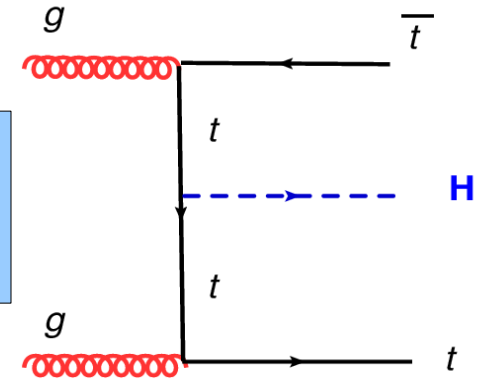
VH



VBF



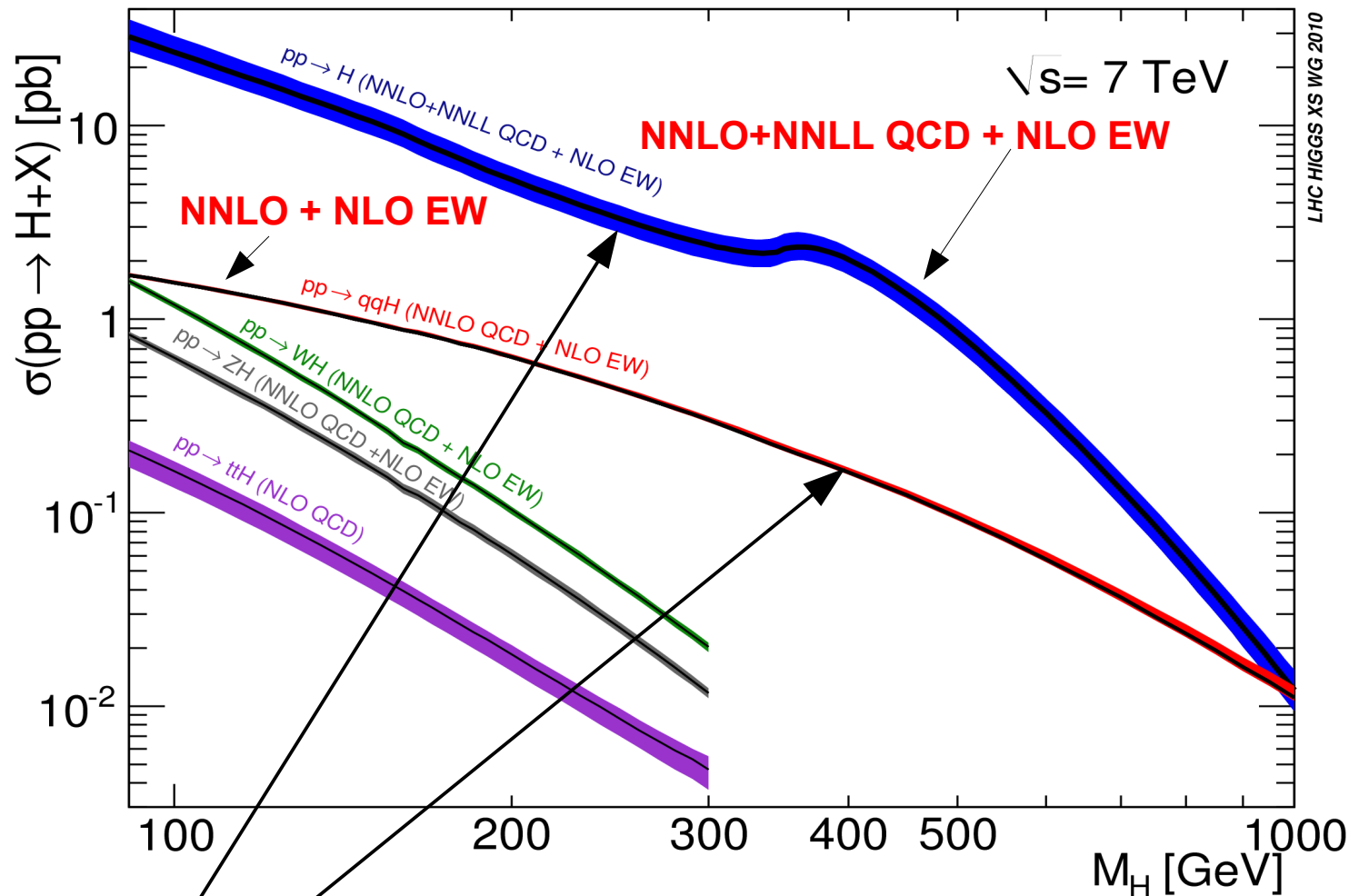
ttH



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

$(0 < x < 1)$ 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

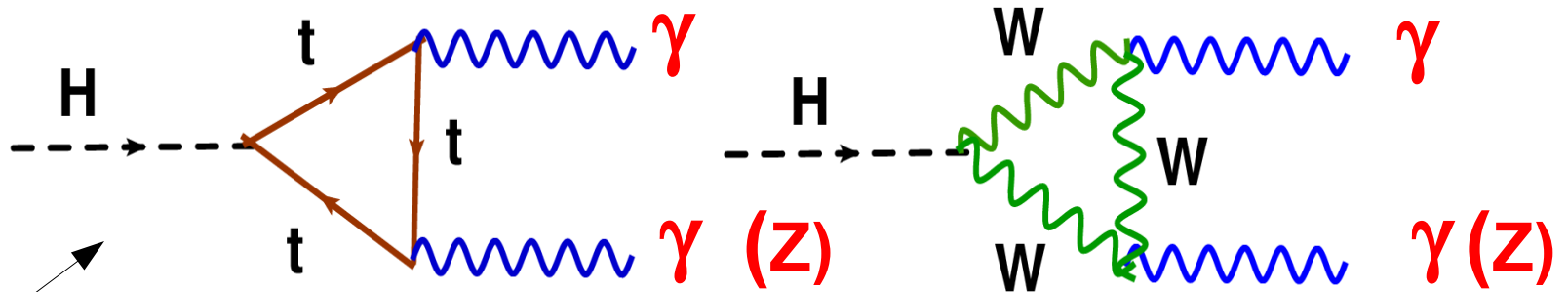
Tree - level decays



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

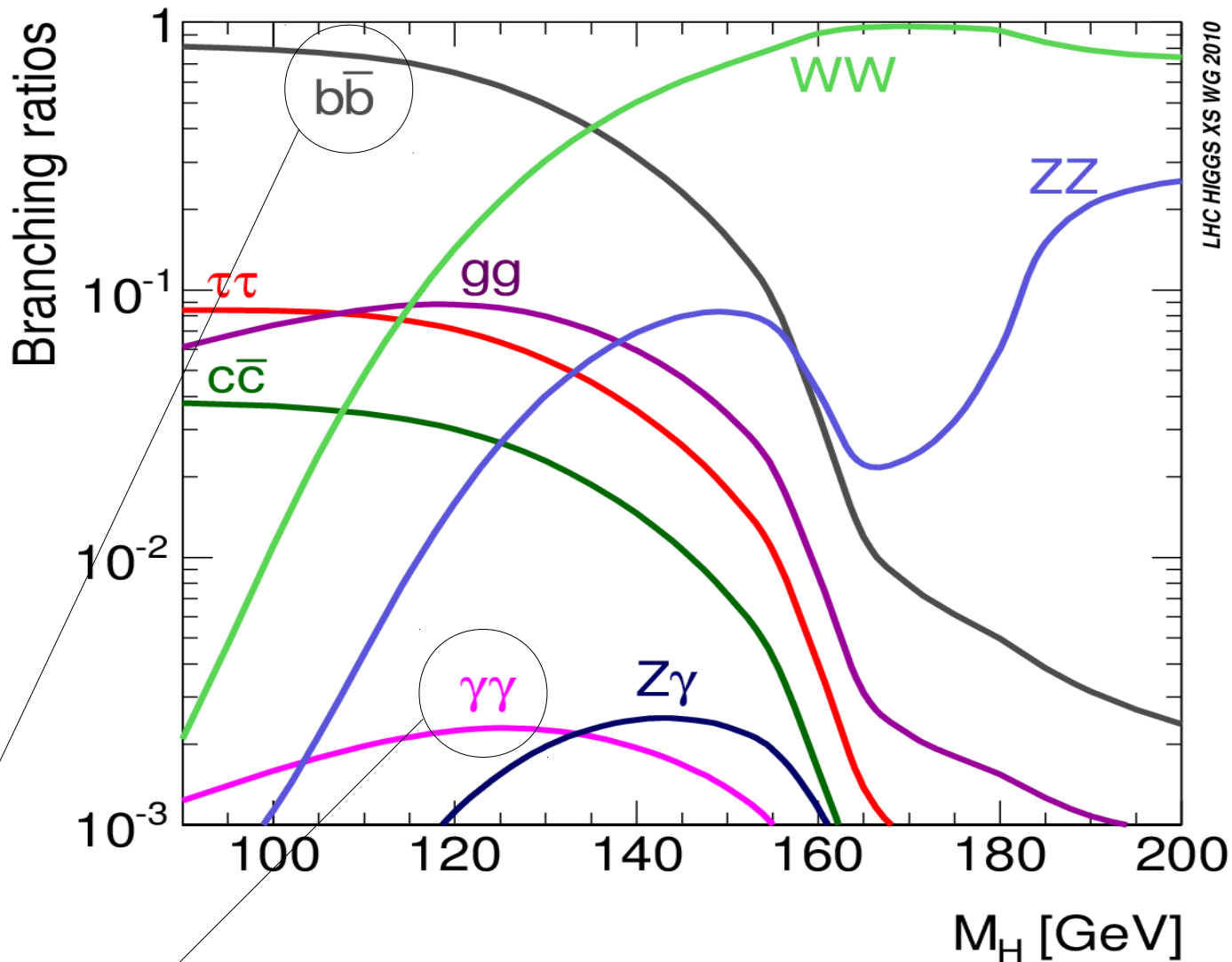
$L = e, \mu, \tau$

One-loop decay



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

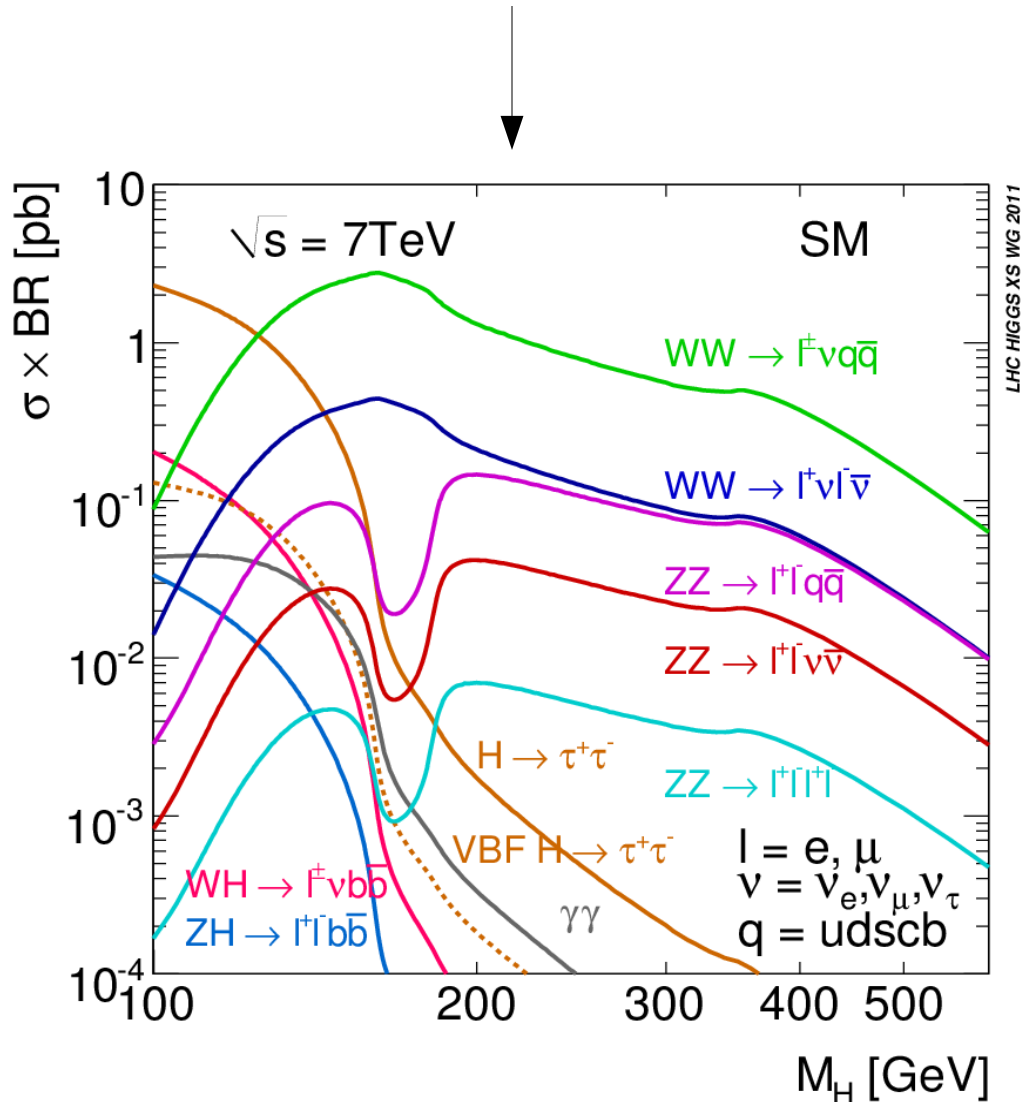
$H \rightarrow \gamma Z$ smaller, also quite sensitive to new physics



$H \rightarrow bb$ 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 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

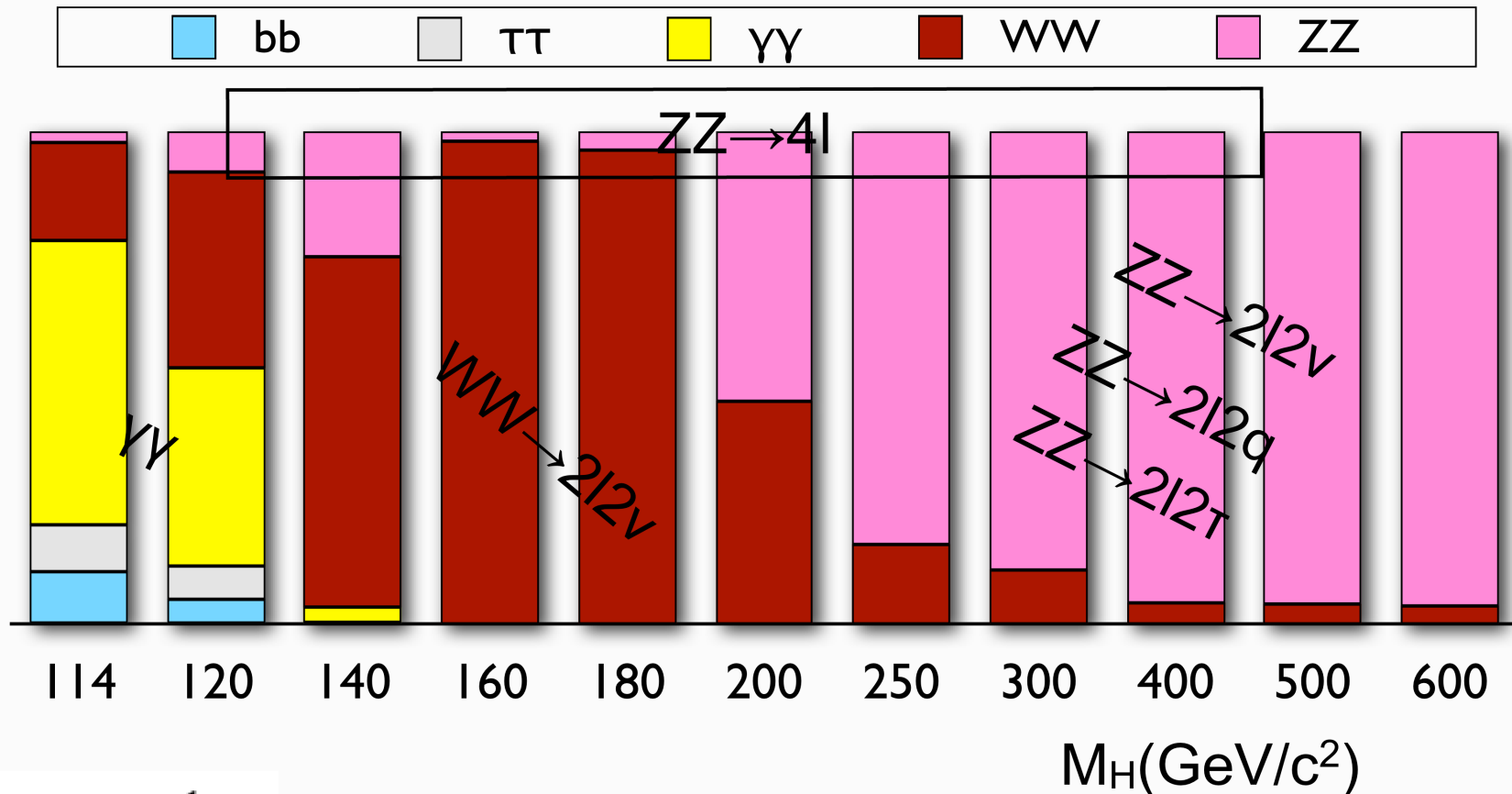
Dominant Backgrounds

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



Weight of the individual channels

In the combination presented today



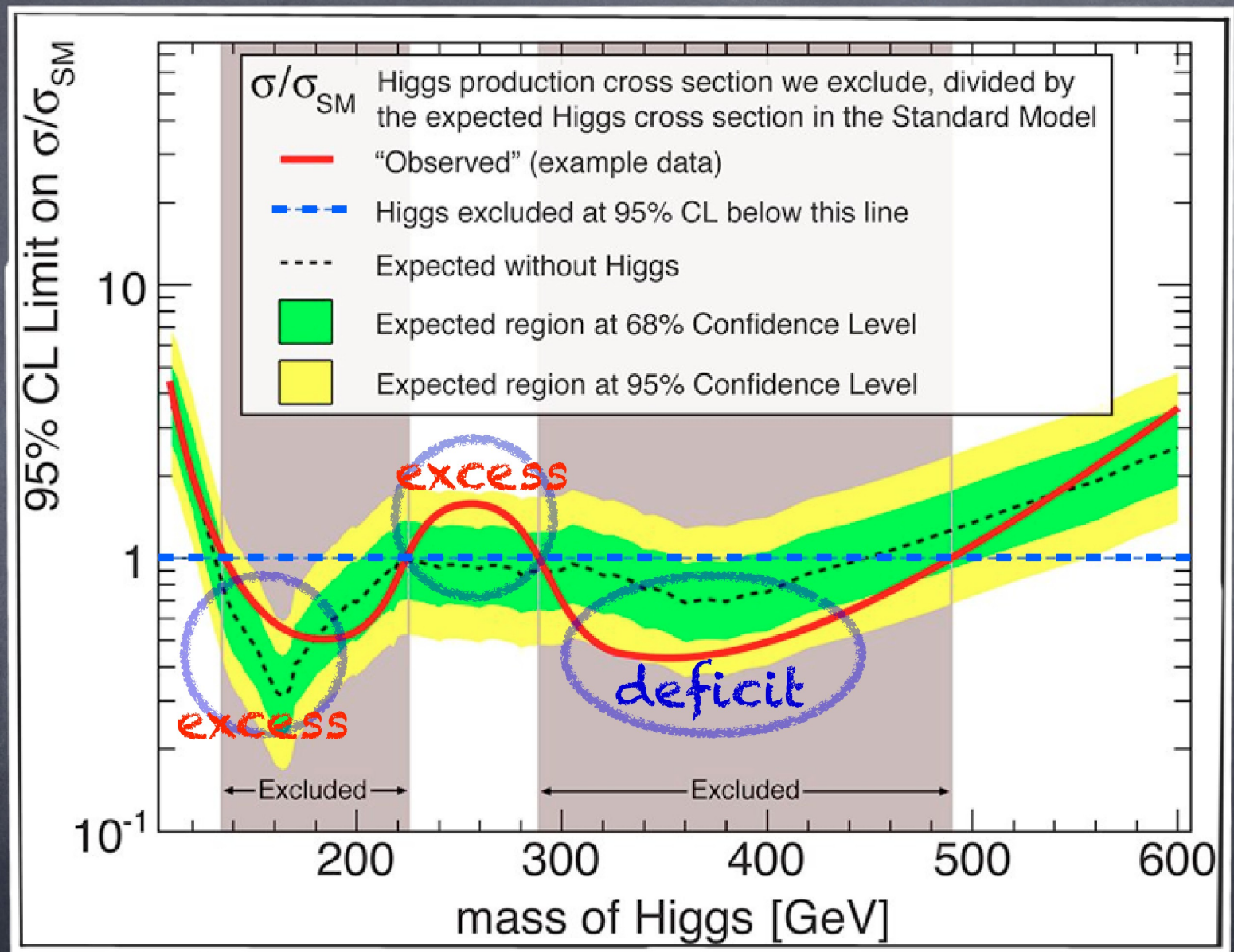
$$w_i = \frac{1}{\mu_{up,i}^2} \frac{1}{\sum_j \frac{1}{\mu_{up,j}^2}}$$

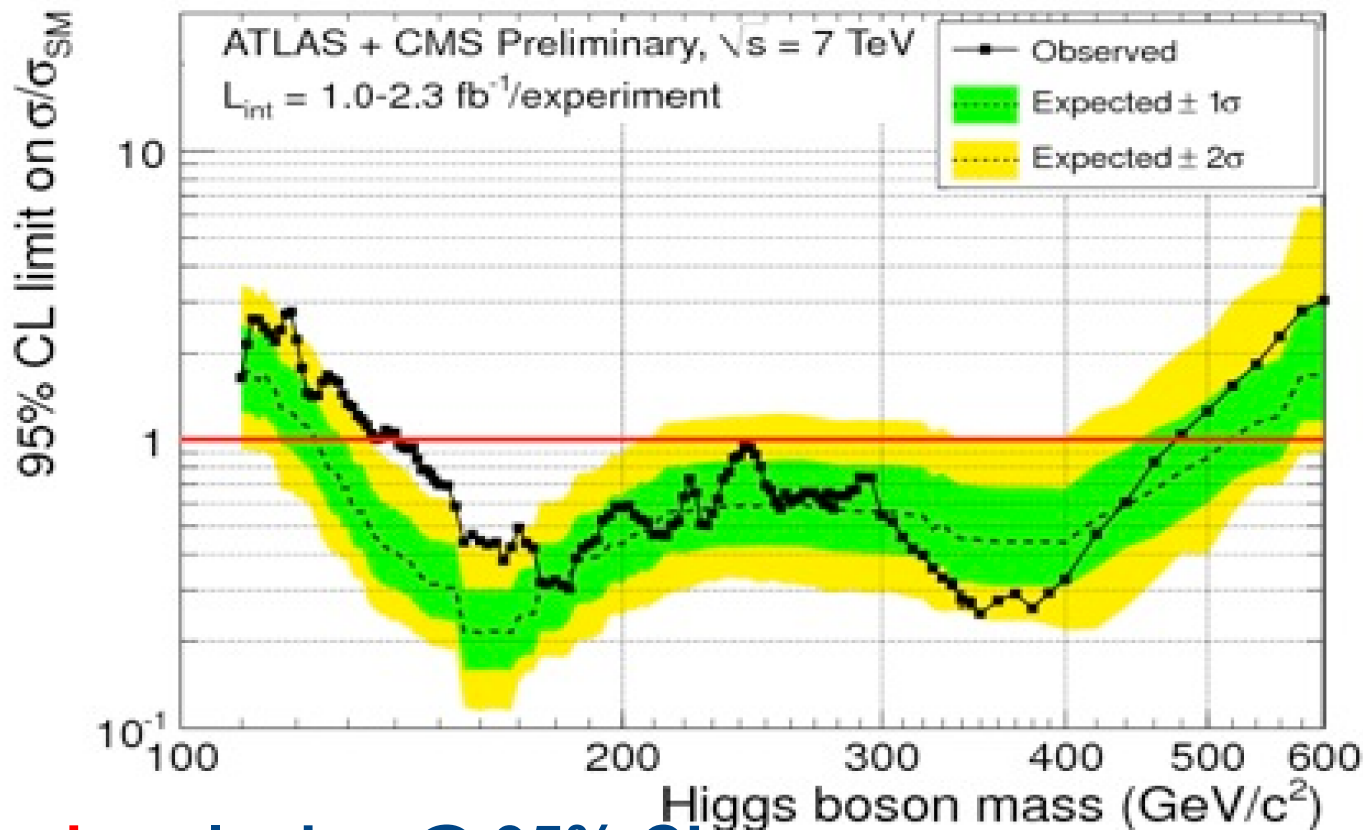
μ_{up} expected upper limit on the signal strength modifier, $\mu = \sigma/\sigma_{SM}$.

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

Understanding The Yellow and Green Bands

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





Observed exclusion @ 95% CL

141 – 476 GeV

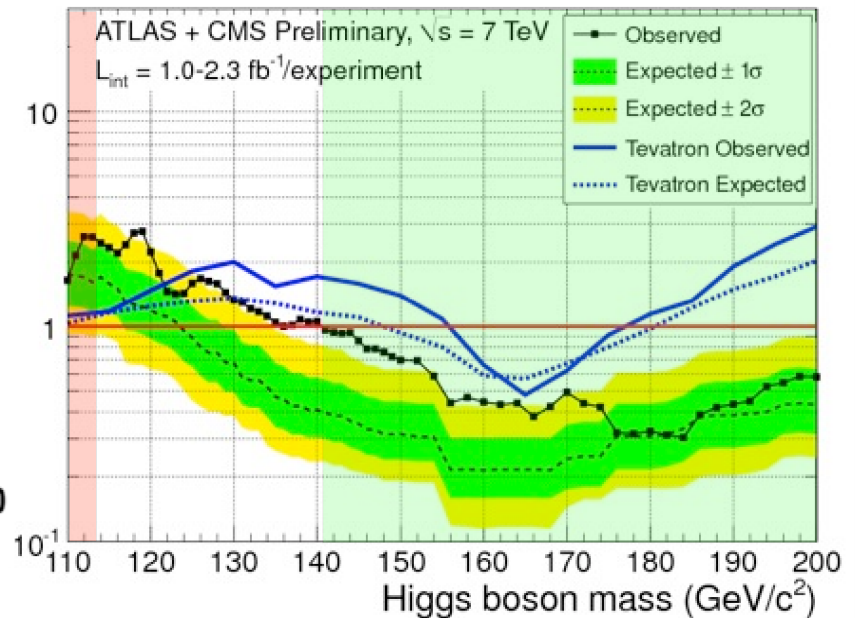
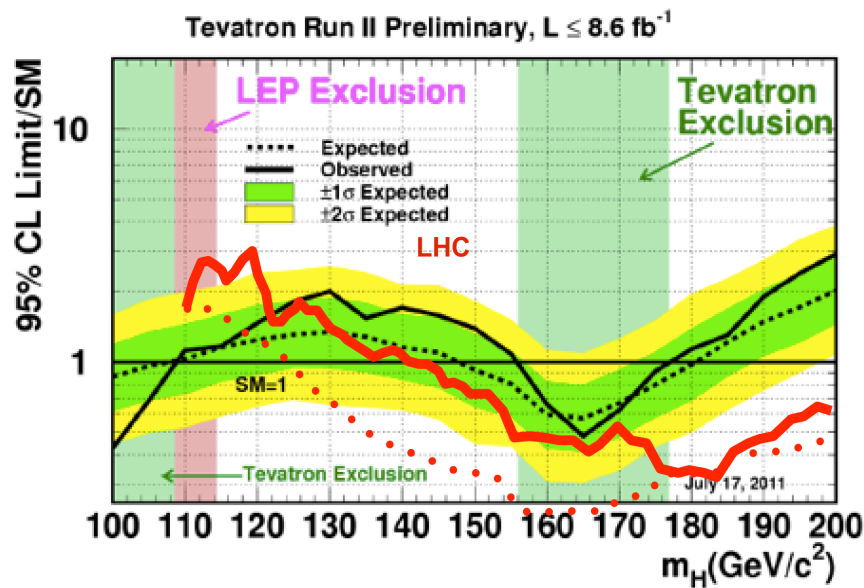
**Expected exclusion @ 95% CL
if no signal**

124 – 520 GeV

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

G. Rolandi (HCP Nov 2011)

Tevatron versus LHC



G. Rolandi (HCP Nov 2011)

In the non-excluded regions both colliders show an excess compared to the expectations

Every discovery starts with the inability to exclude regions...

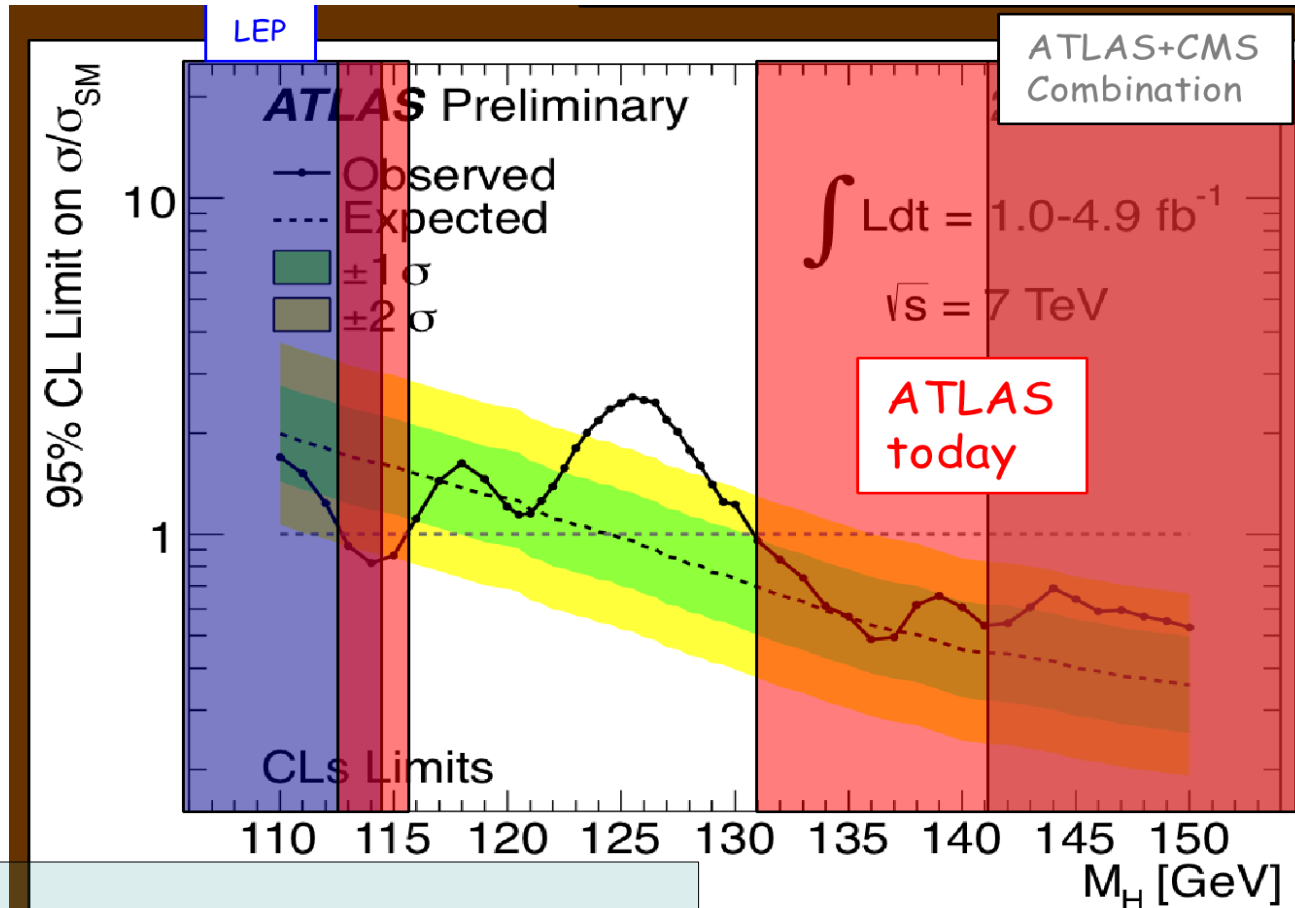
SM Higgs Search Prospects (Mass in GeV)

ATLAS + CMS $\approx 2 \times \text{CMS}$	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535



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

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 !

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

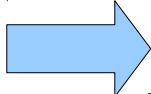
- but EWPT favor a light Higgs mass !

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

■ fermion masses m_f  ChSB

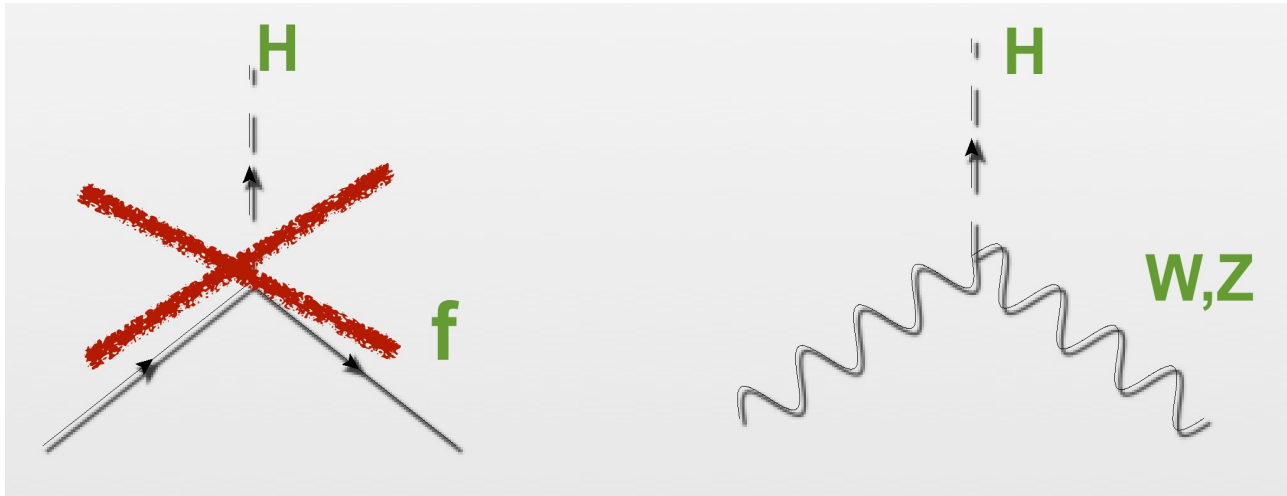
(Chiral Symmetry Breaking)

■ 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

■ ChSB and EWSB can have different mechanisms $\rightarrow$ compositeness, extra-dimensions, technicolor...

a non-standard scenario: a **F**ermio-**P**hobic (**FP**) Higgs



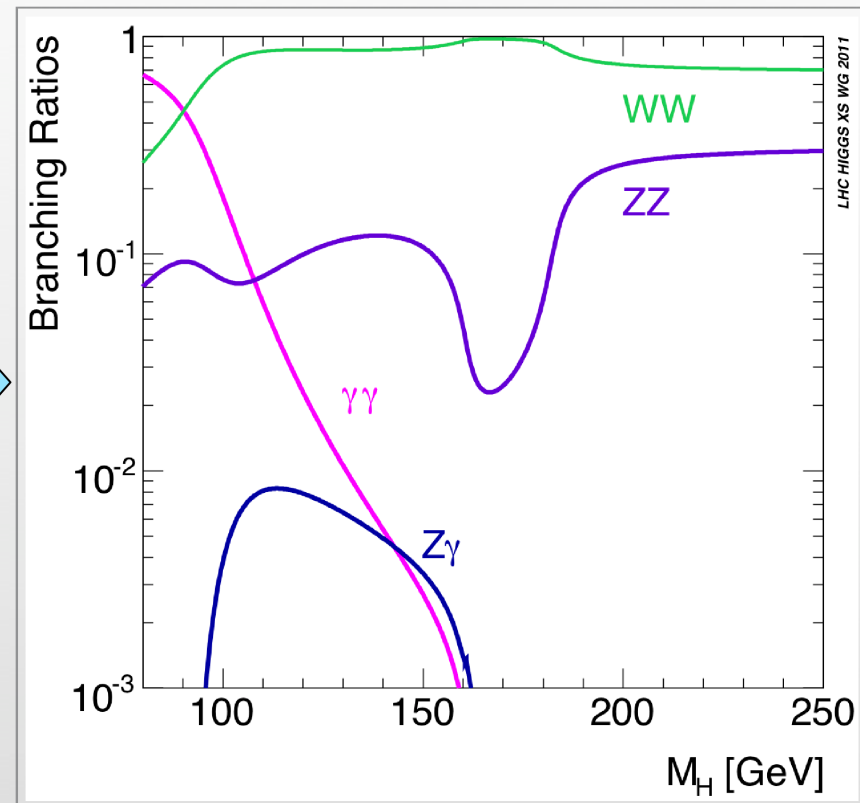
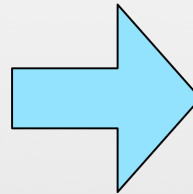
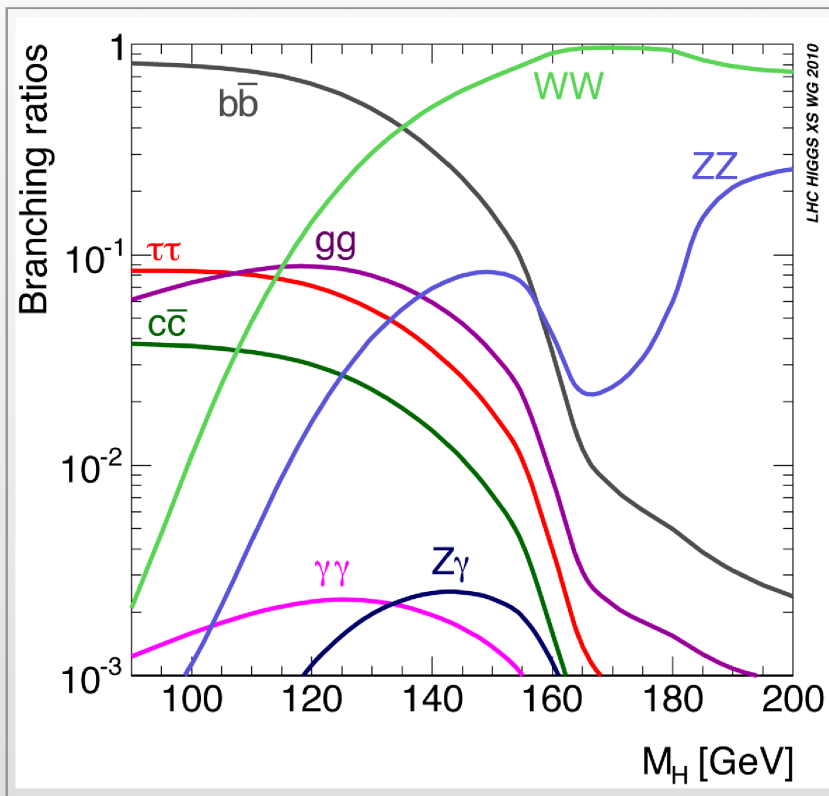
- **NO** Yukawa couplings at tree-level
- Higgs mechanism gives rise to **EWSB** and **M_W, M_Z** but is **not** responsible for **ChSB** and **fermion masses**

Higgs decays : FP vs SM

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

SM Higgs

FP Higgs

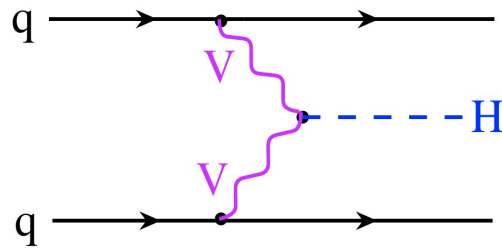


<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Fermiophobic>

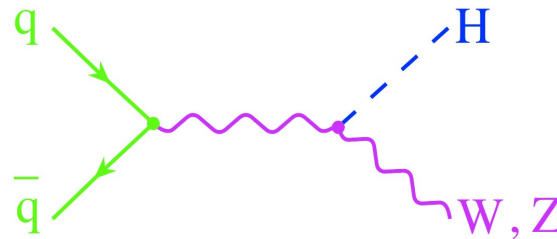
for $m_H \sim [100, 110, 120]$ GeV : $BR(\gamma\gamma)_{FP} \sim [110, 30, 10] \times BR(\gamma\gamma)_{SM}$

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** !

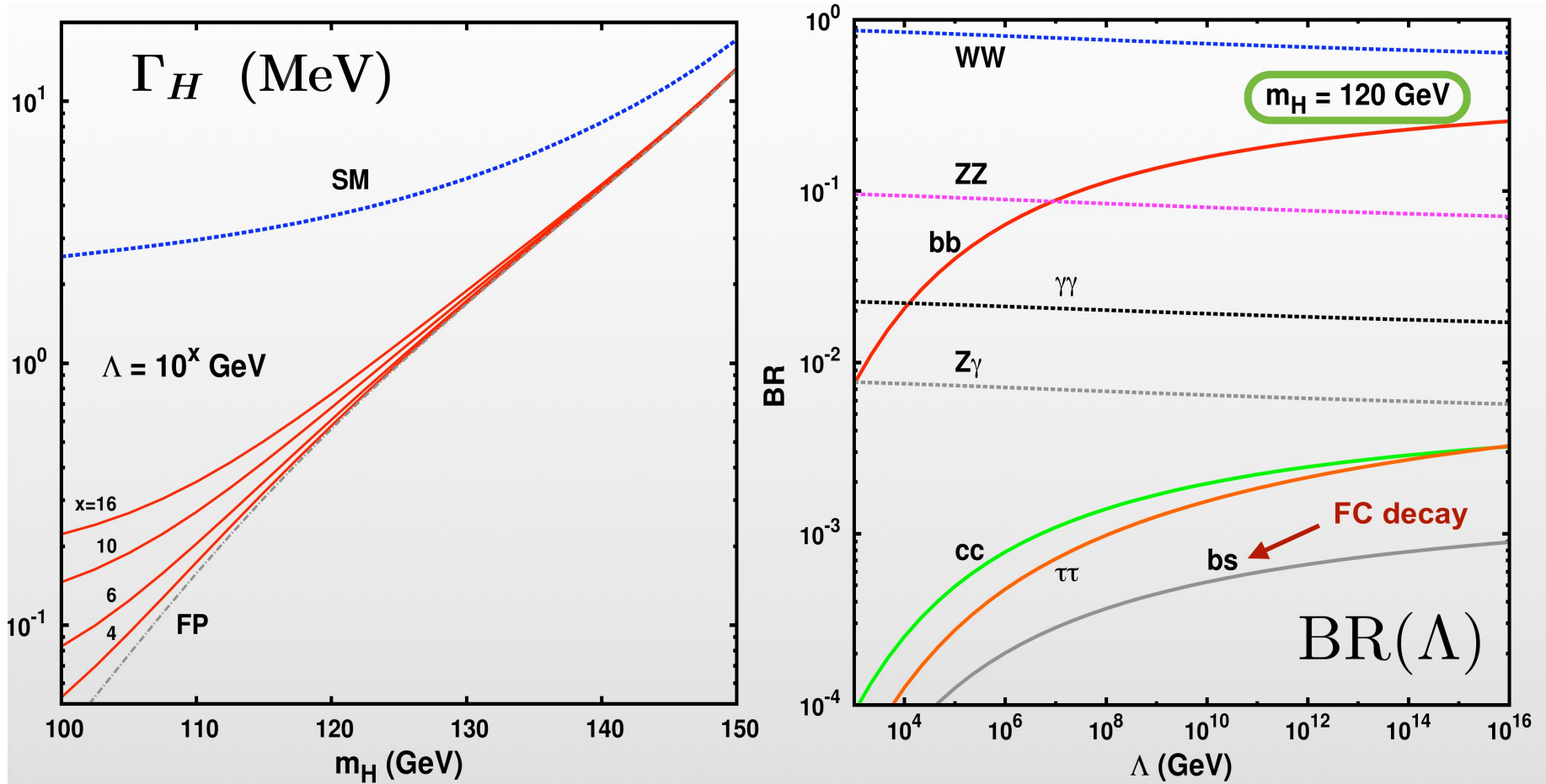
FP model is unstable under radiative corrections

Yukawa coupling are radiatively generated

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

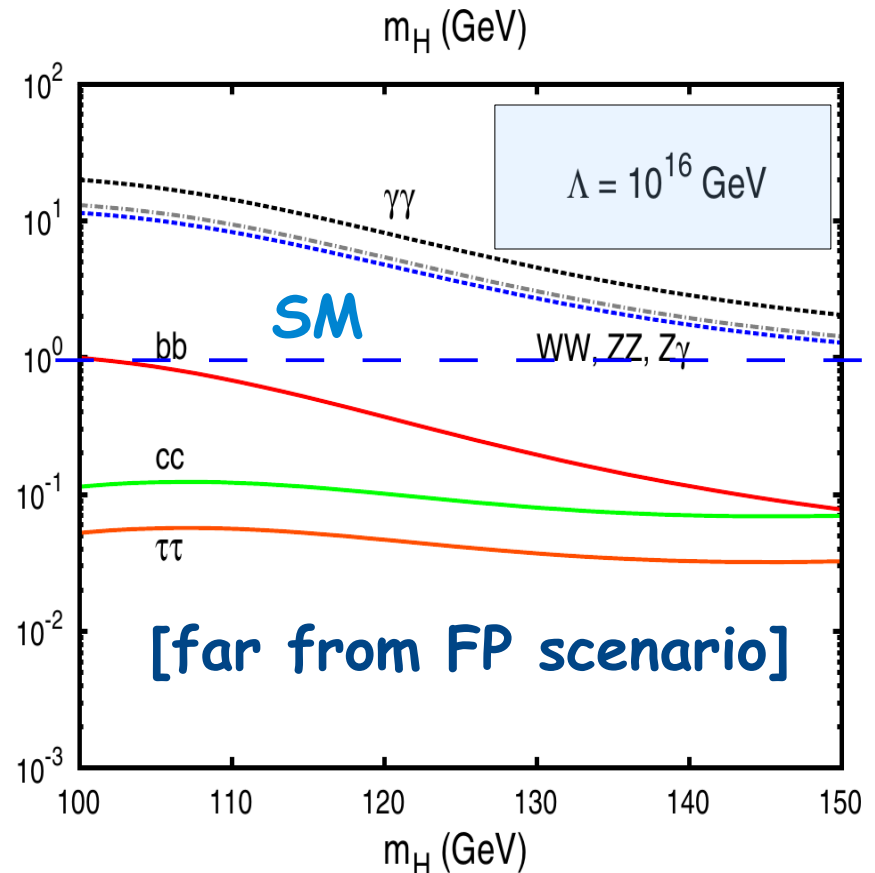
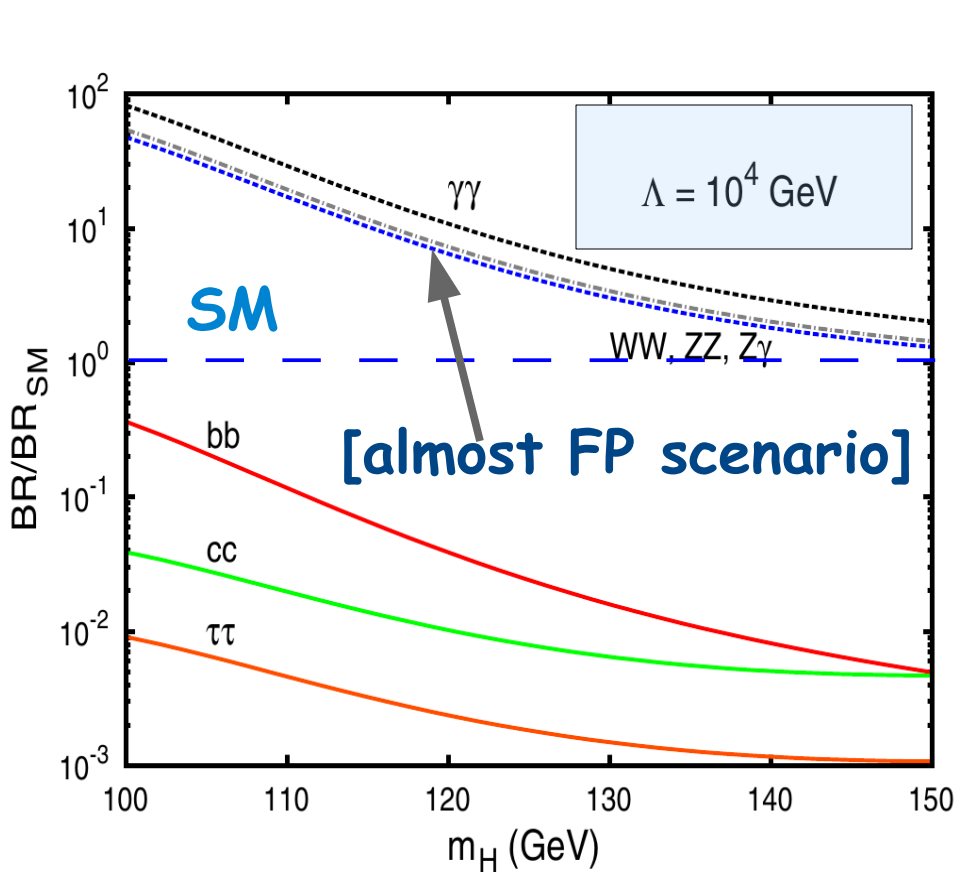
- if m_f 's are put by hand $\rightarrow$ SM is not renormalizable
- SM $\rightarrow$ effective field theory valid up to some Λ scale
- radiative corrections depend by the UV completion of the theory, but less sensitive if $Y(\Lambda) \rightarrow 0$
- due to $\text{ChsB} \sim m_f$, the Yukawas are not 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

Results for Γ_H and BR's versus Λ

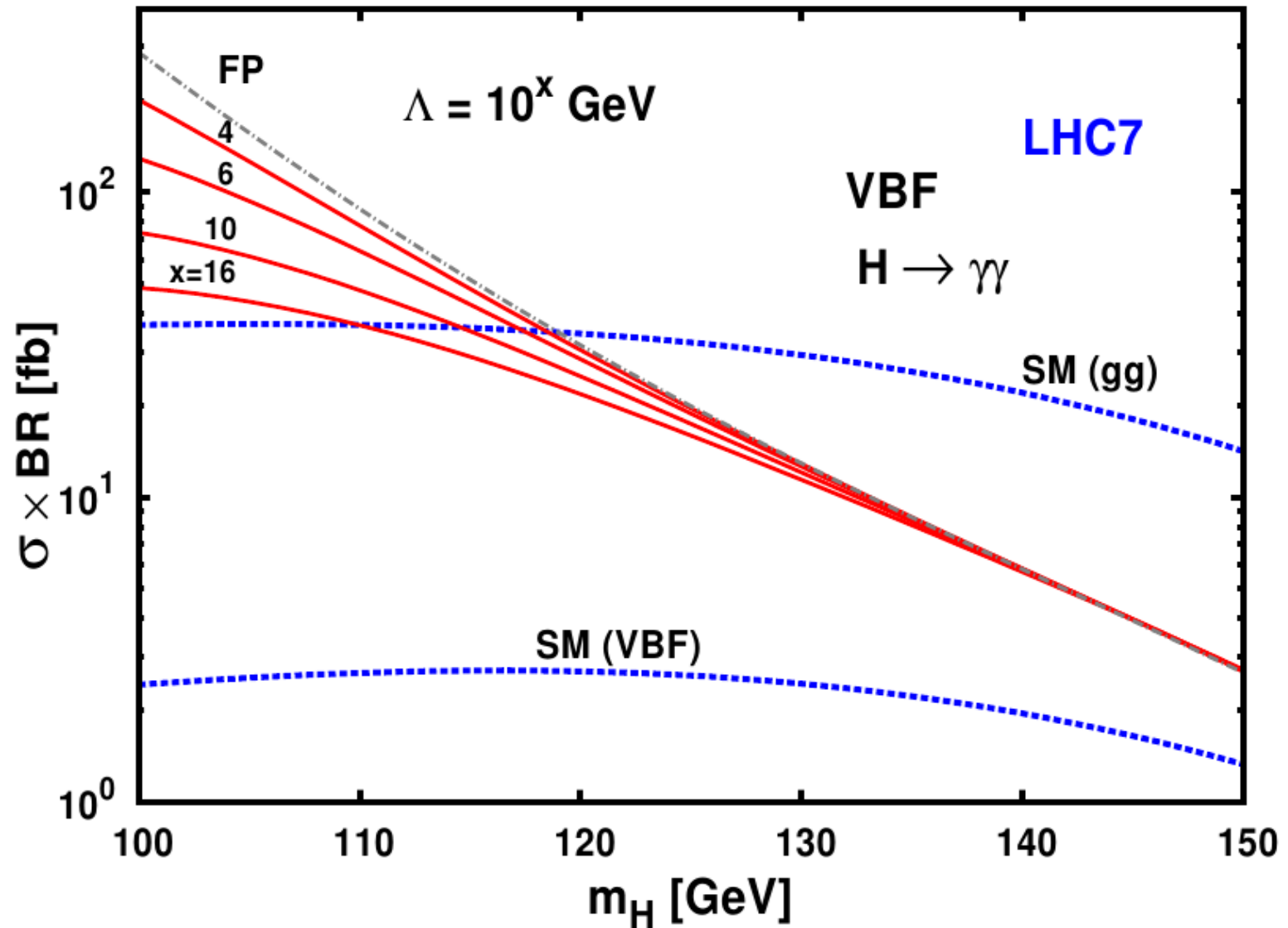


BR's enhanced by small total width

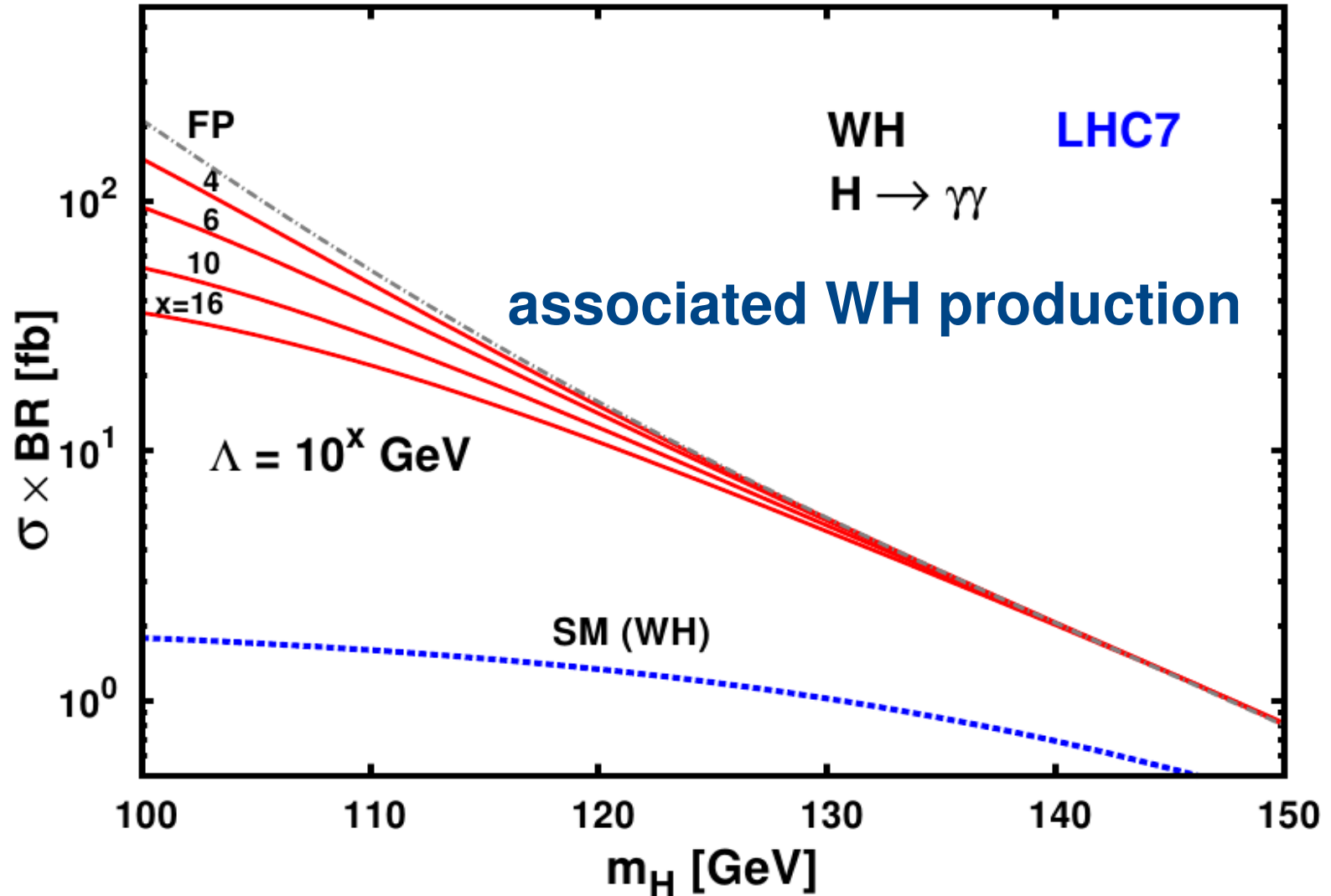
$BR / BR(SM): \Lambda \sim (10^4 \rightarrow 10^{16}) \text{ GeV}$



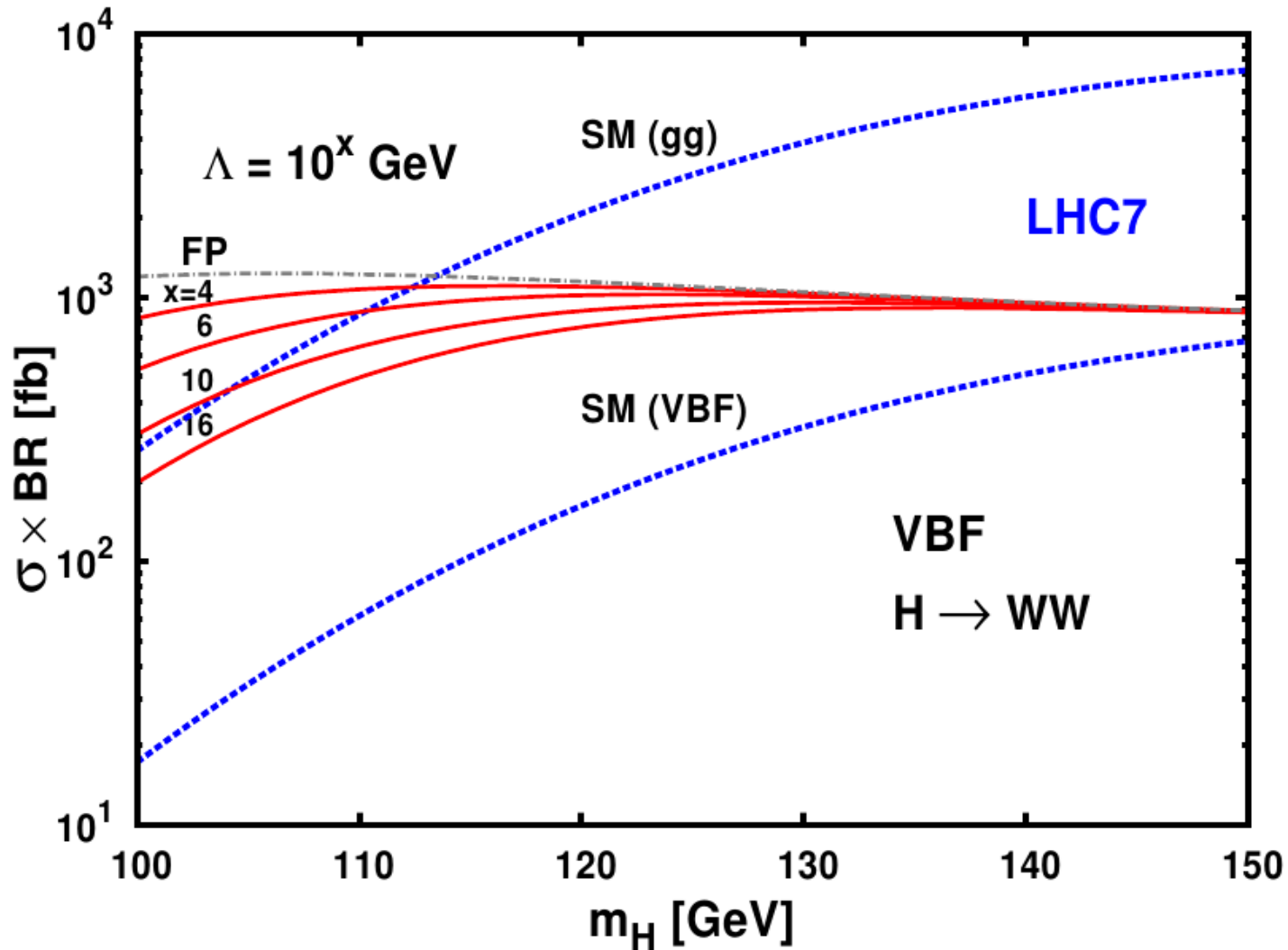
LHC (VBF) : $H \rightarrow \gamma\gamma$



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



LHC (VBF) : $H \rightarrow WW$



exp bounds on m_H (pure FP model)

■ Quite a number of studies on pure FP scenario

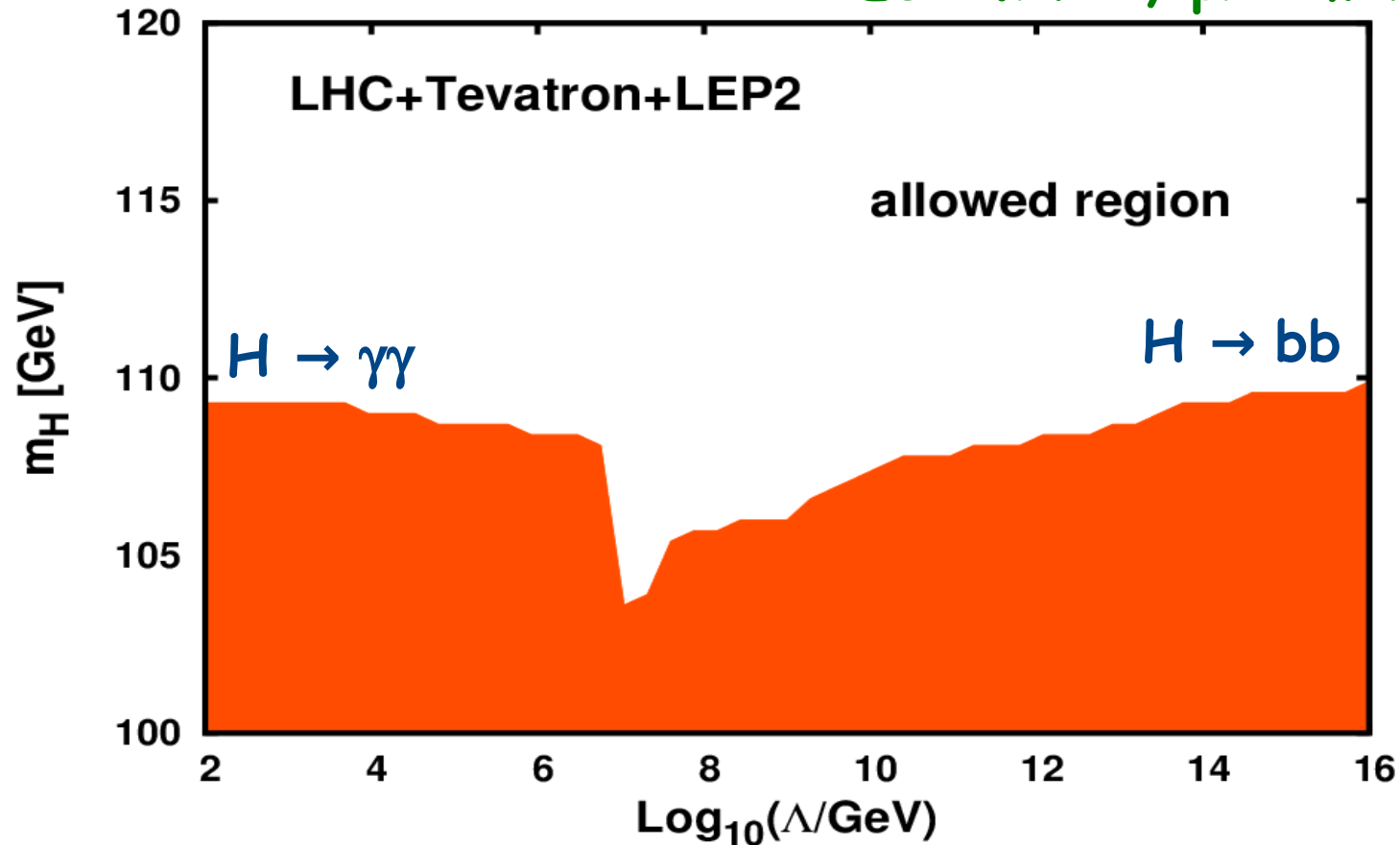
- * LEP $\rightarrow$ 109.7 GeV (comb. $\gamma\gamma$ data on 4 exps) ('02)
(108.3 GeV, comb. $\gamma\gamma+WW^*$ in L3)
- * Tevatron $\rightarrow$ (100-) 119 GeV 8.2 fb $^{-1}$ (Aug 2011)
- * ATLAS $\rightarrow$ [110-112] $\cup$ [113-118] GeV 1.08 fb $^{-1}$
(HCP2011)
- * CMS $\rightarrow$ (110-) 112 GeV 1.7 fb $^{-1}$ (LP2011)

■ bounds in “Effective Y_f ” scenarios needs dedicated studies

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

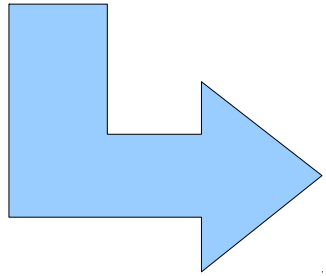
bounds on m_H (effective Y_f 's model)

EG B.Mele, preliminary



- 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 Λ of ChSB
- LC could provide a measurement of Λ

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 the Higgs boson...
- ...then a New Physics should show up at the TeV scale and **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

EFT approach connects two scales Λ and m_H

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

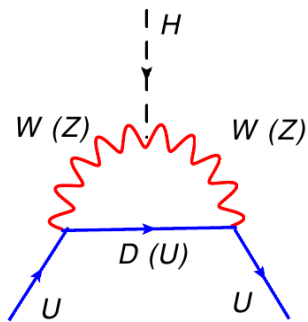
$$Y_f(\Lambda) = 0$$

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

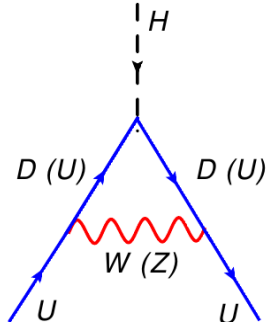
$$\begin{array}{ccc} Y_f(\Lambda) = 0 & \xrightarrow{\quad RGE \quad} & Y_f(m_H) \\ \text{(high energy)} & & \text{(low energy)} \end{array}$$

- **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!

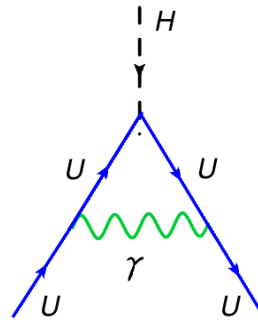
Diagrams contributing to the Y 's beta-functions



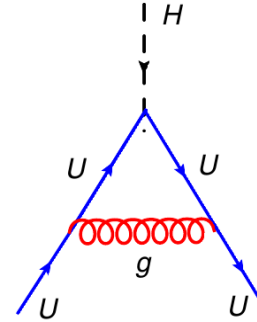
a)



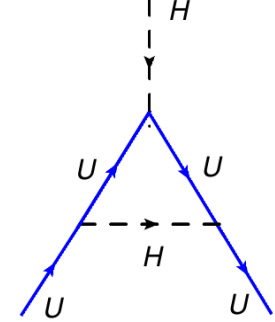
b)



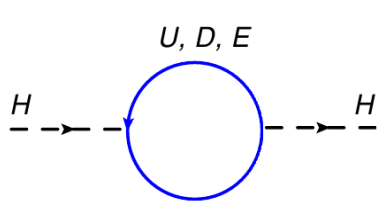
c)



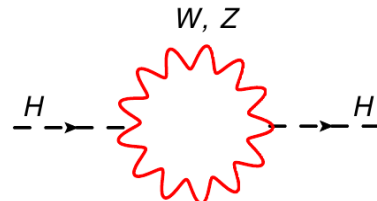
d)



e)

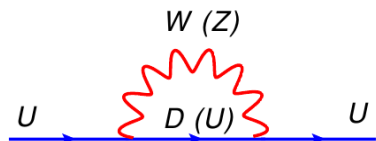


f)

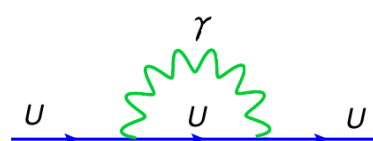


g)

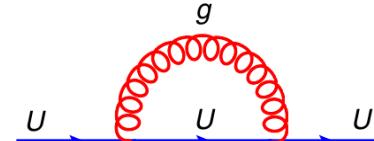
Up-type quark couplings



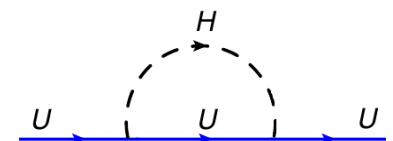
h)



i)



j)



k)

1-loop RGE's for Yukawa's

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

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

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

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

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

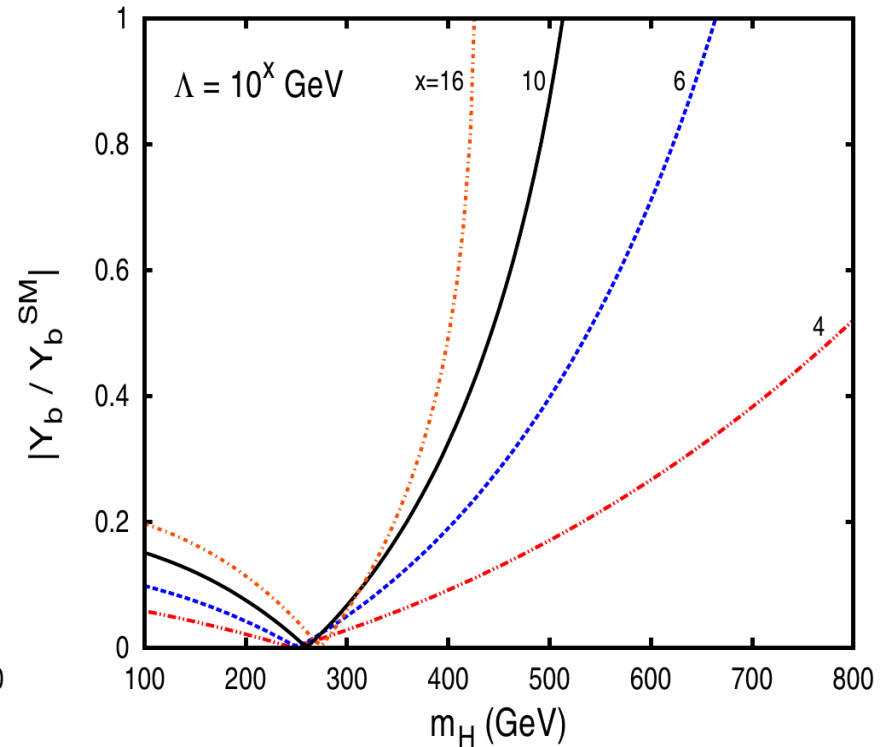
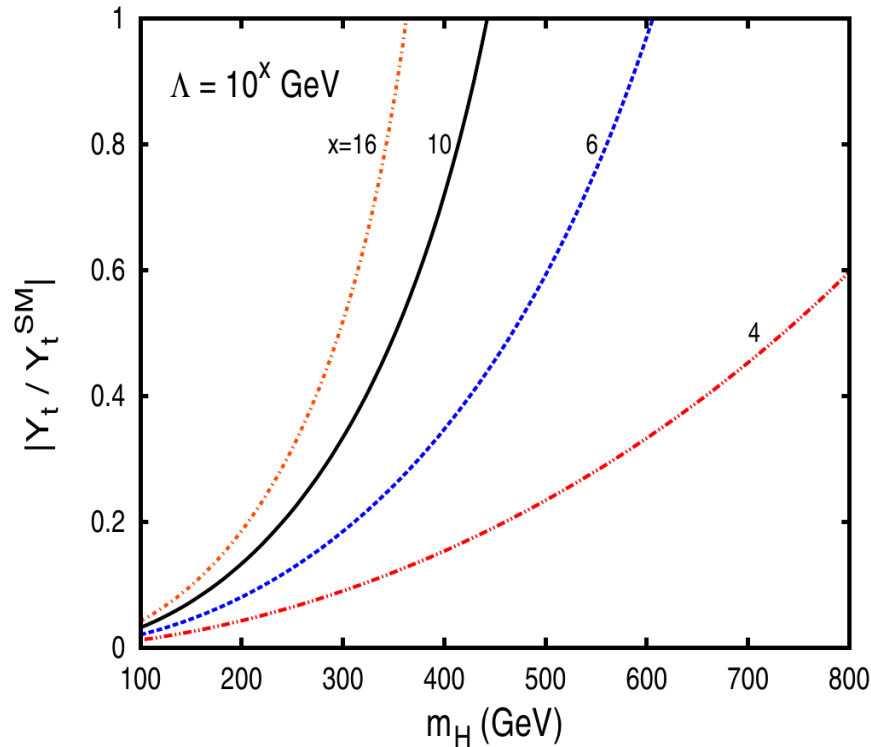
$$\mathbf{Y} \equiv N_c \mathbf{Y}_U \mathbf{Y}_U + N_c \mathbf{Y}_D \mathbf{Y}_D + \mathbf{Y}_E \mathbf{Y}_E$$

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

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)

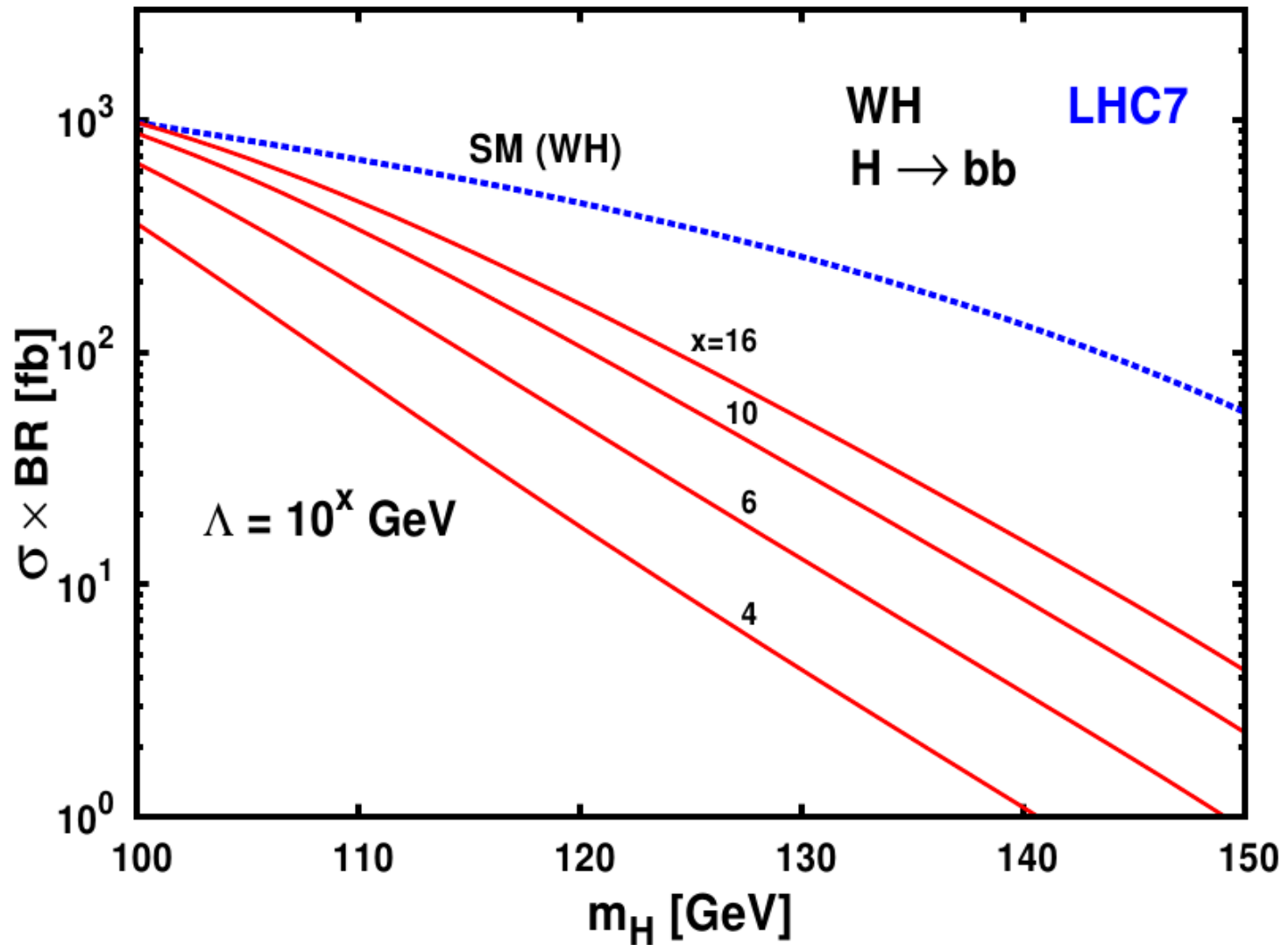


■ Λ varied between 10^4 and 10^{16} GeV

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

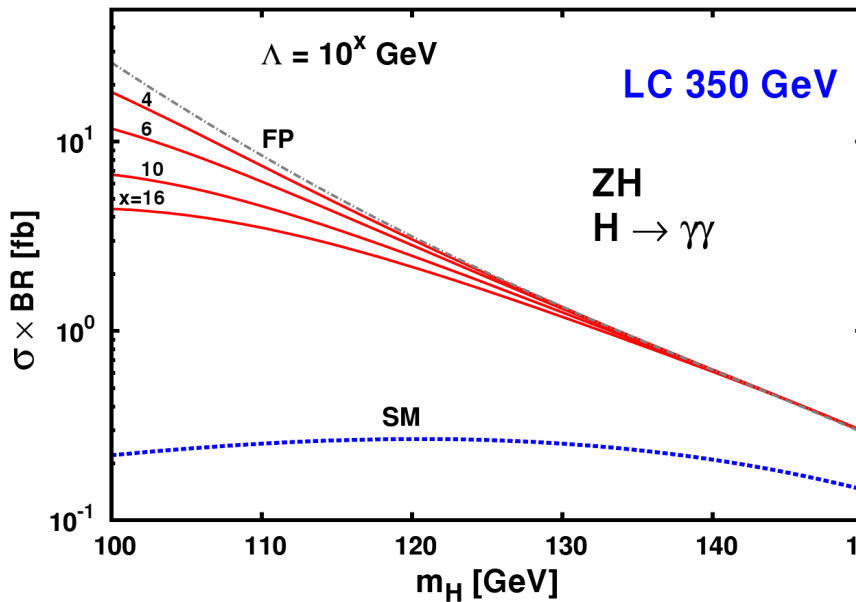
■ all Y_f 's perturbative for $m_H < \langle H \rangle \sim 246$ GeV

LHC (WH) : $H \rightarrow bb$



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

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



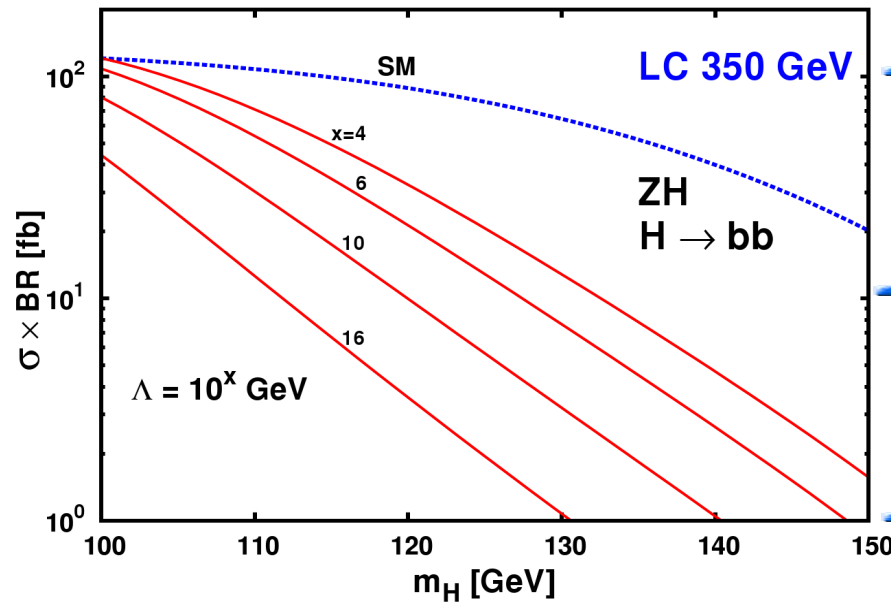
5000

500

50

LC 350

$H \rightarrow \gamma\gamma$



50000

5000

500

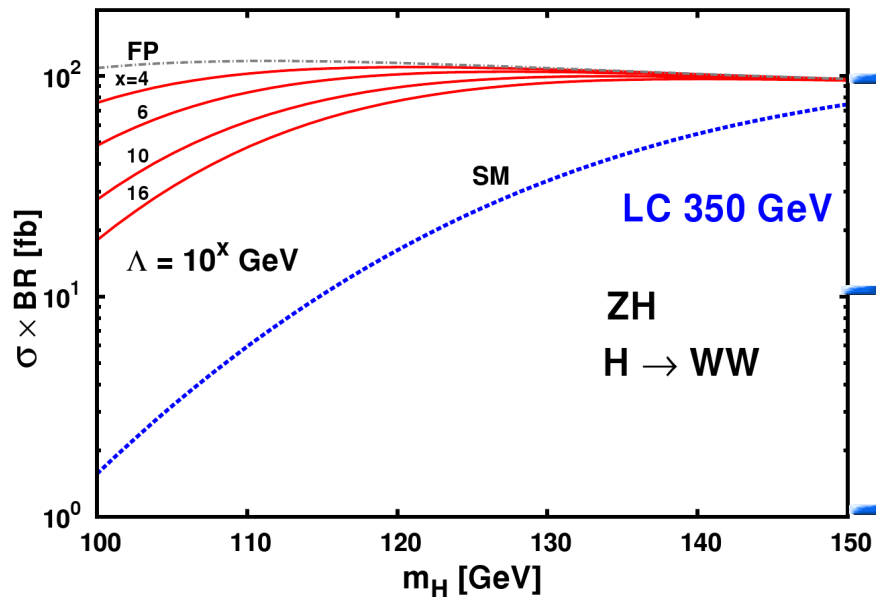
LC 350

$H \rightarrow b\bar{b}$

Excellent
sensitivity to Λ

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

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



50000

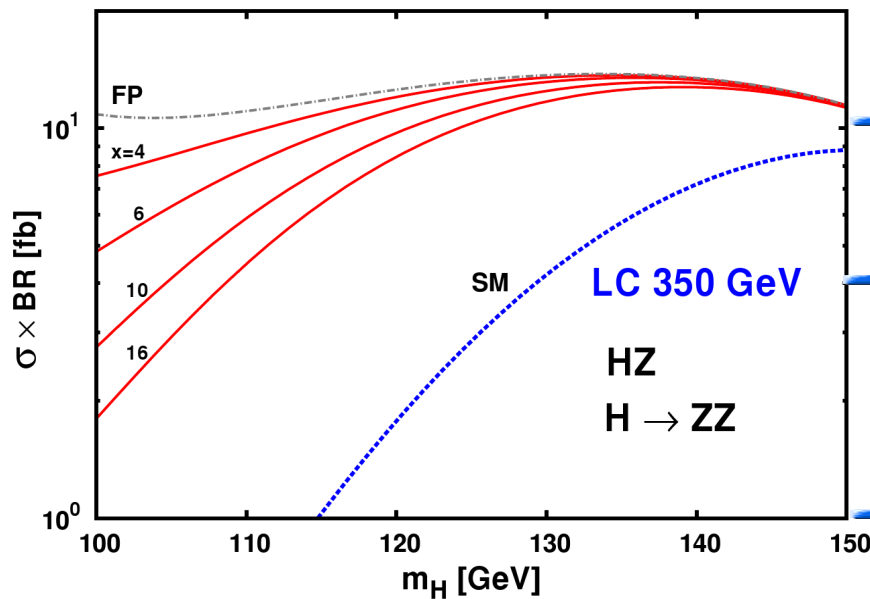
LC 350

5000

$H \rightarrow WW$

500

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



5000

LC 350

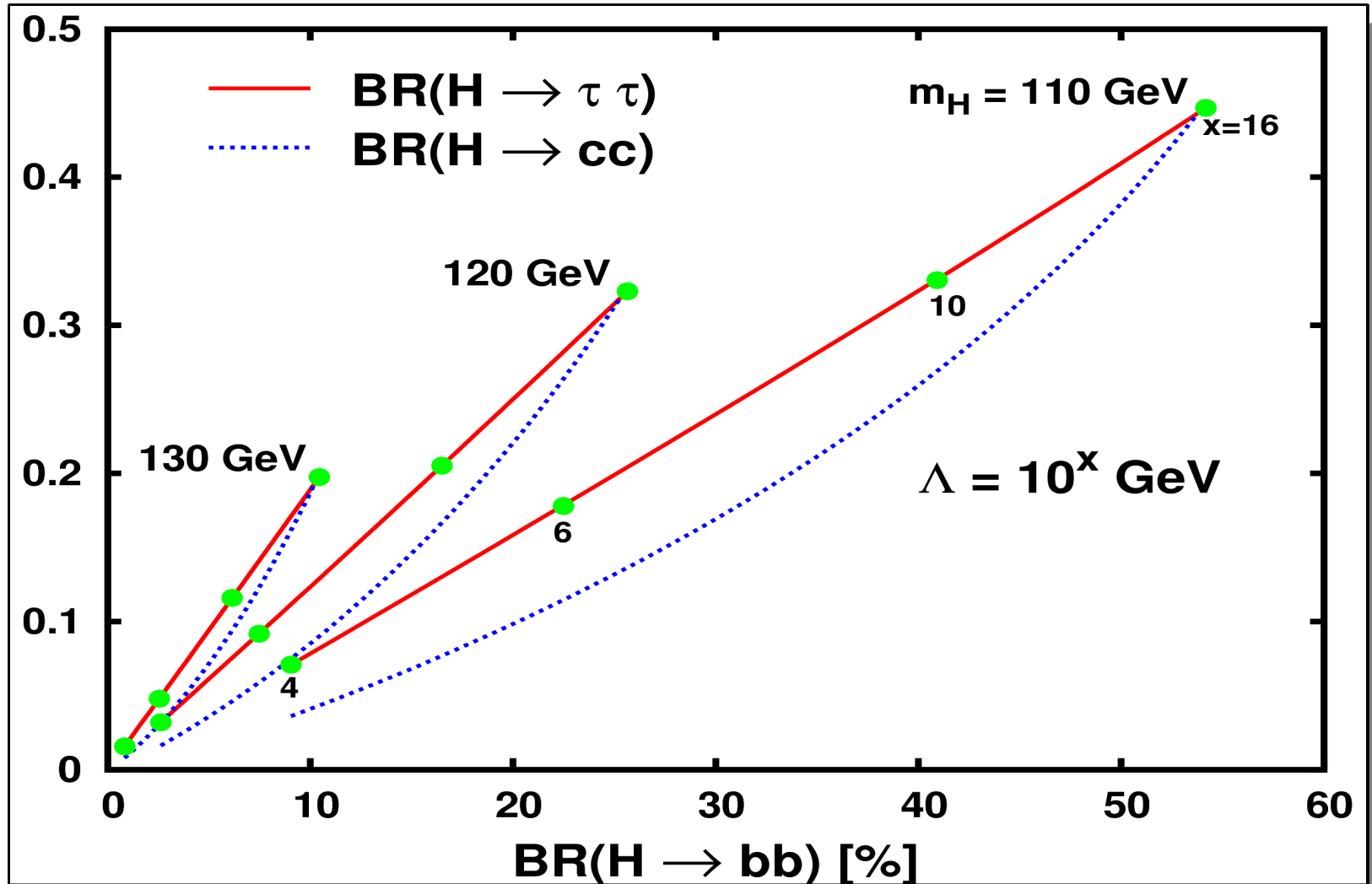
2000

$H \rightarrow ZZ$

500

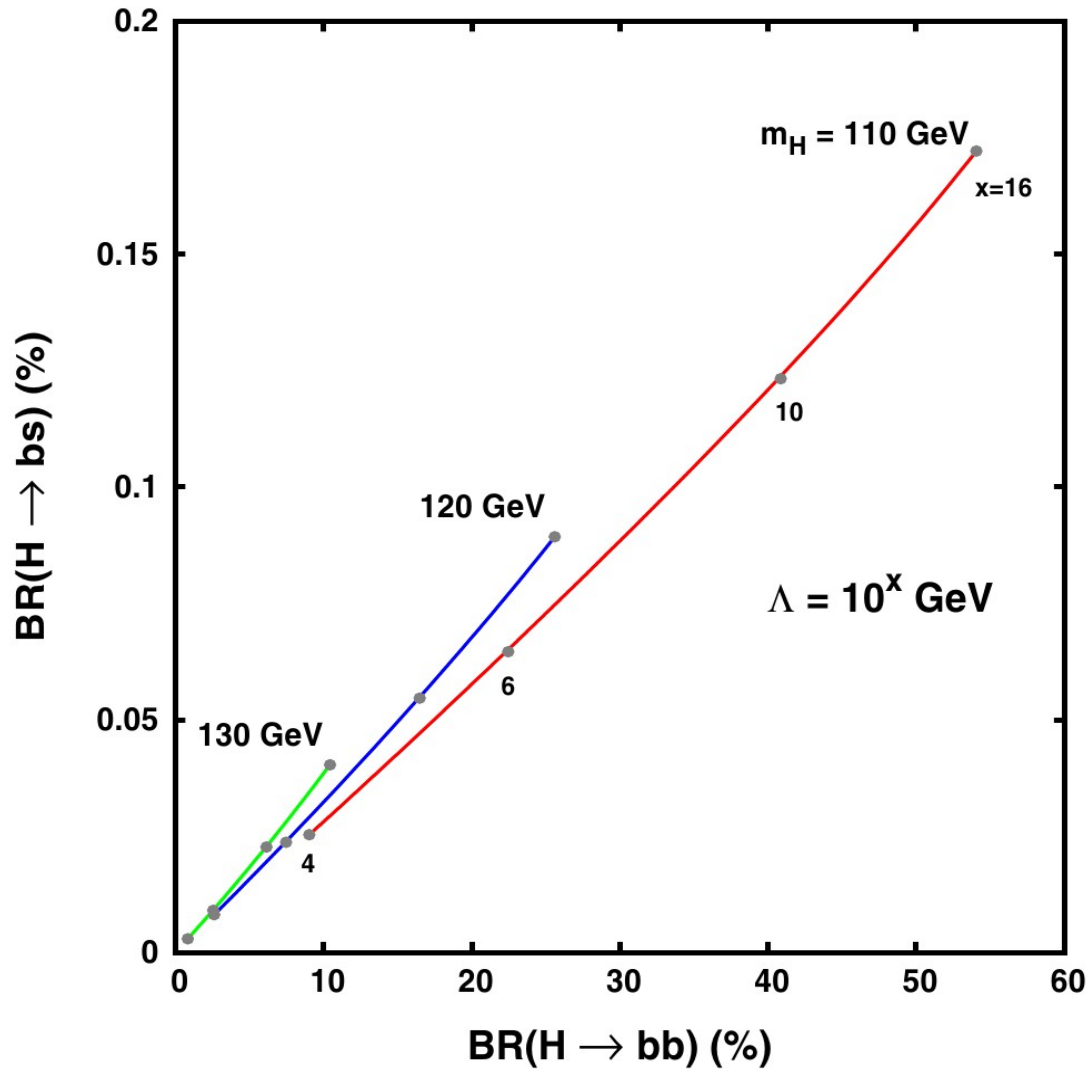
Correlations of $\text{BR}(H \rightarrow f\bar{f})/\text{BR}(H \rightarrow b\bar{b})$

BR[%]



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

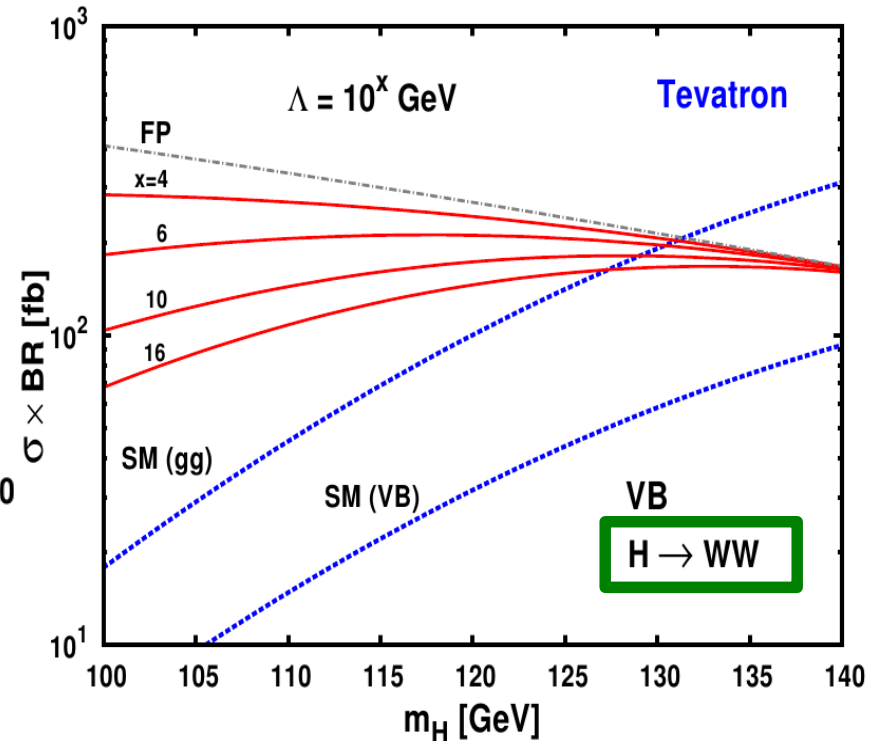
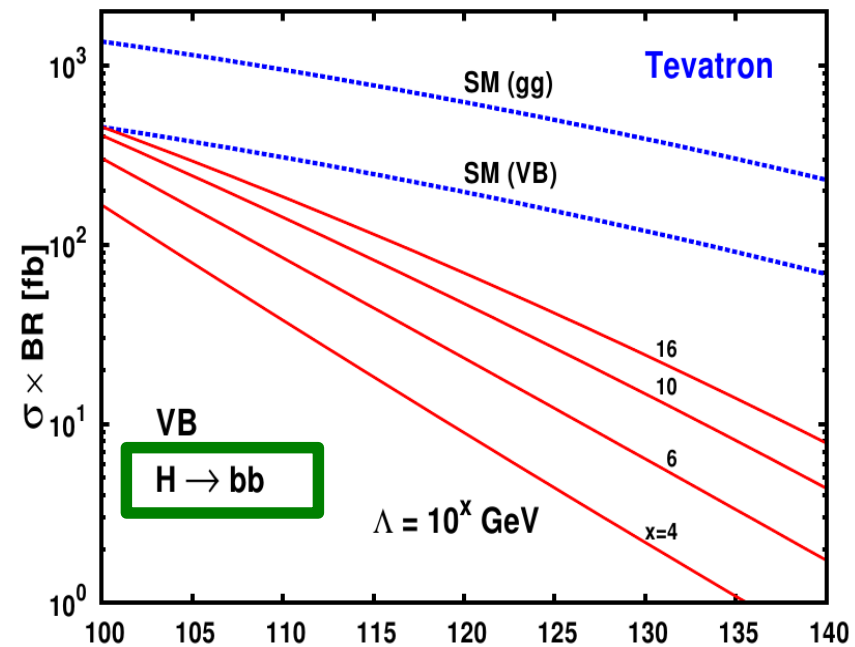
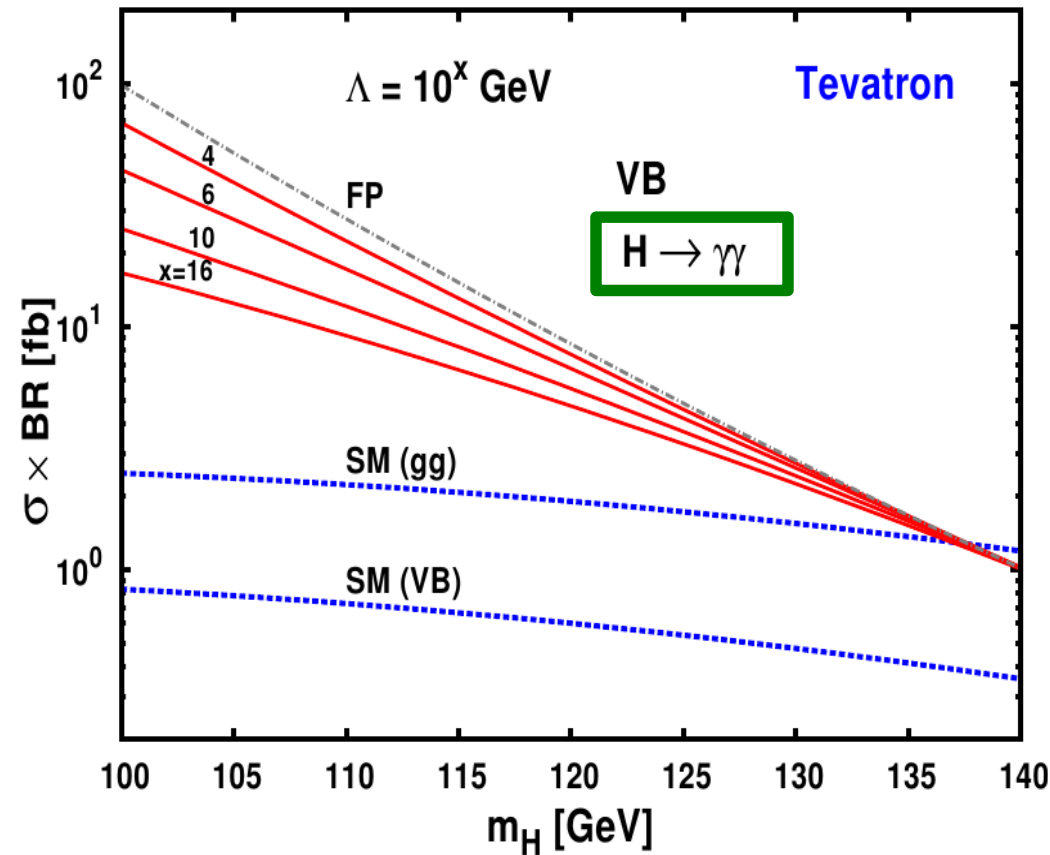
Correlations of FC $\text{BR}(H \rightarrow bs)/\text{BR}(H \rightarrow bb)$



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

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

VB = (WH+ZH+VBF)



 **Tevatron can constrain the model !**