LNF, 26 - 27 June 2012

Summer Institute on QCD, Heavy Flavours and Higgs Physics

Searches for the Higgs boson : what if it is fermiophobic ?

Barbara Mele

INFN Istituto Nazionale di Fisica Nucleare

Sezione di Roma

LNF, 27 June 2012

Outline

- why "Today" is so special for HEP:
  - historical prologue
  - LHC : where we stand today
- status of SM Higgs boson searches
- a fermiophobic Higgs scenario

from NY Times, 19 June 2012

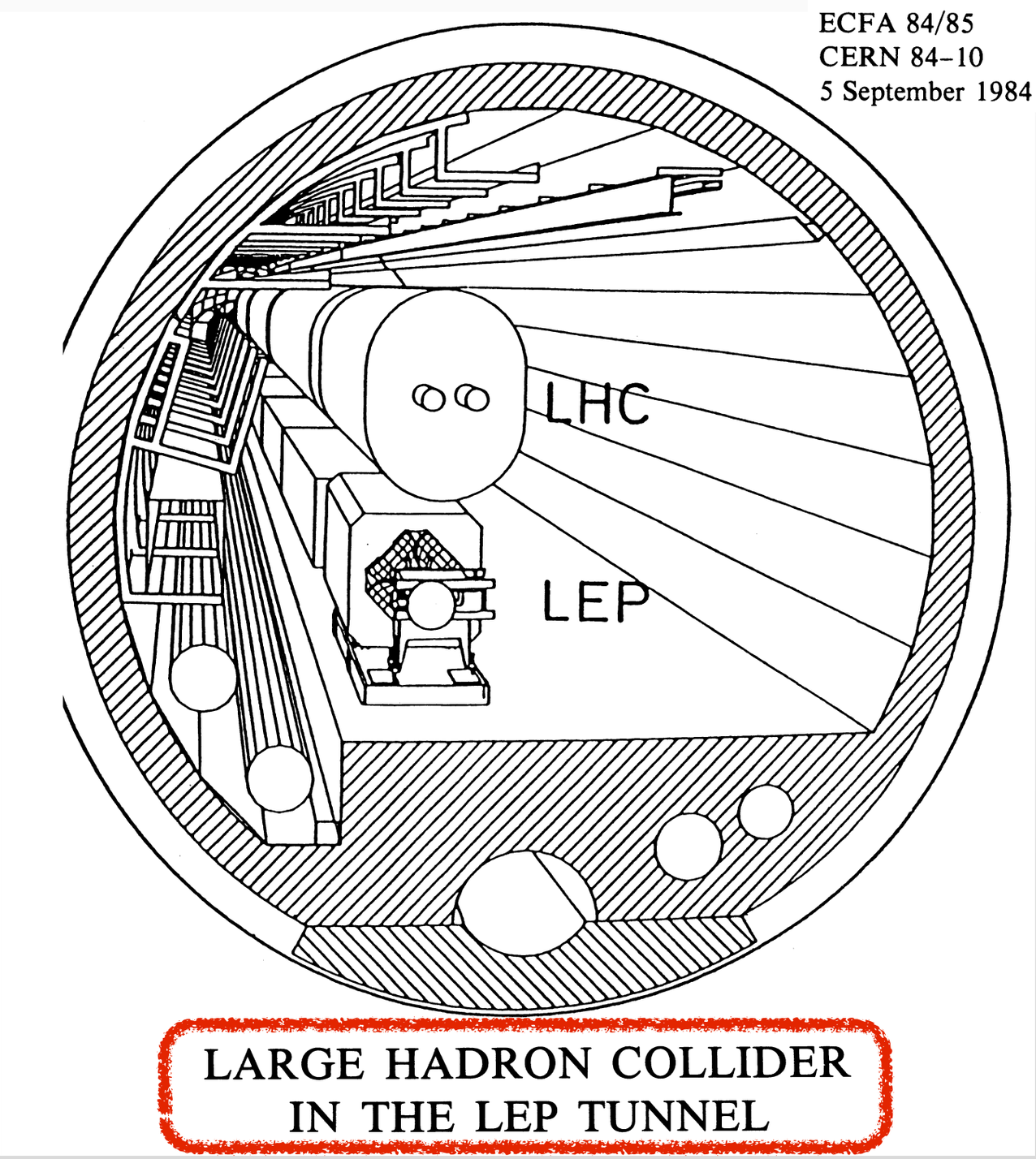
"New Data on Elusive Particle Shrouded in Secrecy"

What they are looking for is the beginning to the end of the longest and most expensive manhunt in the history of physics, one that has involved several generations of larger and larger particle accelerators ...

... Known as the Higgs boson, it is the cornerstone of modern physics, but confirmation of its existence has eluded scientists for 40 years.

Historical Prologue

- Lausanne-Geneva Workshop (21-27 March 1984)



first public discussion on the LHC project (28 years ago ...)

*Note :
LEP approved in 1981;
W discovery at CERN
ppbar collider in 1983

pp (ppbar) Collider with $\sqrt{S}$ ~ 10-20 TeV and L~ $10^{33(31)}$ $cm^{-2}s^{-1}$

probes interactions at $\sqrt{S'}$~ o(TeV)→ 10^{-17} cm

LHC Physics Case in '84 (ECFA 84/85, CERN 84-10)

- Exp's in 70's and early 80's beautifully confirmed the gauge theory picture of fundamental interact's based on

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

that solved problems arised in 30's to 60's related to :

what is the nature of the weak force?
what is the nature of the strong force?
what is the structure of hadrons?

- "not the end of the story but the opening of a new chapter"

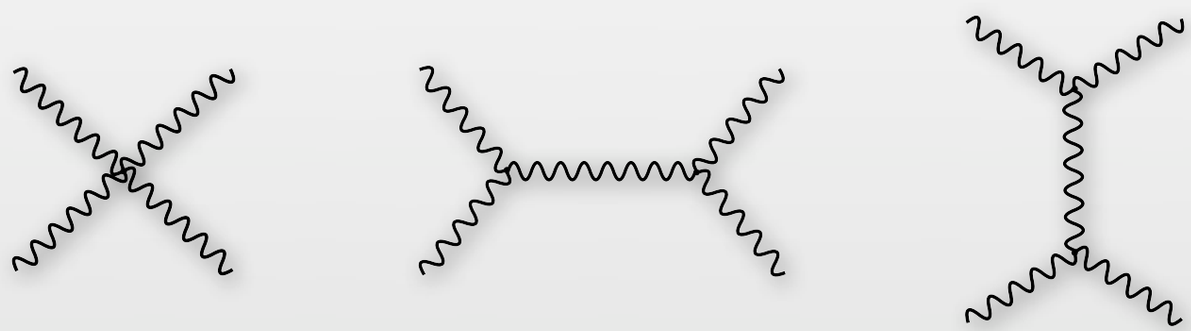
Llewellyn Smith

implies new phenomena at the TeV scale !

- the origin of mass
- the origin of flavour
- the origin of CP violation
- the connection between the electroweak, strong and gravitational forces.

Origin of mass: the Higgs mechanism ?

- in the SM all fundamental fields (EW gauge bosons + fermions) acquire mass through the Higgs mechanism
  - (symmetry-breaking) mass terms arising from scalar-field v.e.v.
  - keeps the theory renormalizable
- Higgs boson treats disease in the $W_L W_L$ scattering :



violates pert. unitarity at $\sqrt{S} \sim 1\text{-}2$ TeV !

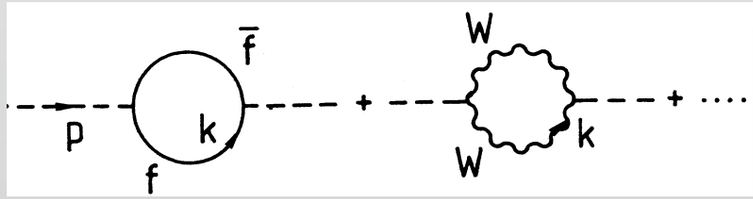
- NOTE !

  in case Higgs boson (with m_H<700 GeV) is not there, something else (beyond SM) must solve this problem !
  Hard to think LHC will not meet the challenge !

EWSB requires new phenomena at the TeV scale

- Higgs is a peculiar object : first fundamental scalar field (could be just an "effective description" of EWSB)
- problem with scalar fields :
  - $m_f \, \bar{\psi}\psi \xrightarrow{\text{chiral symmetry}} 0 \quad \Rightarrow \quad \delta m \sim m \, \ln \frac{\Lambda_{SM}}{m}$
  - $m_W^2 \, W_\mu W^\mu \xrightarrow{\text{gauge symmetry}} 0 \quad \Rightarrow \quad \delta m^2 \sim m^2 \, \ln \frac{\Lambda_{SM}}{m}$
  - $m_H^2 \, H^2$ no symmetry in the SM protects m_H

$$\Rightarrow \quad \delta m^2 \sim \Lambda_{SM}^2$$



extending SM up to large scales requires unnatural cancellations
→ fine-tuning (hierarchy) problem !

LHC : where we are today (pp collisions)

- in 2010, LHC delivered ~ 45 pb^{-1} at $\sqrt{S}$= 7 TeV
  (enough to improve bounds on direct signals from BSM models with respect to Tevatron limits)
- in 2011, LHC delivered ~ 5 fb^{-1} at $\sqrt{S}$= 7 TeV
- in 2012, LHC delivered up to now ~ 6.6 fb^{-1} at $\sqrt{S}$= 8 TeV

- ATLAS and CMS bounds on direct signals from BSM models:

(mass bounds from ~ 5 fb^{-1} at 7 TeV)

SUSY *(cMSSM, $m_q = m_g$)* > 1.4 TeV ;
Gauge bosons *(SSM)* > 2.2 TeV ;
Excited quarks > 3.3 TeV ;

- further ~ 10 fb^{-1} expected by end of 2012

hot days for Higgs physics at LHC !

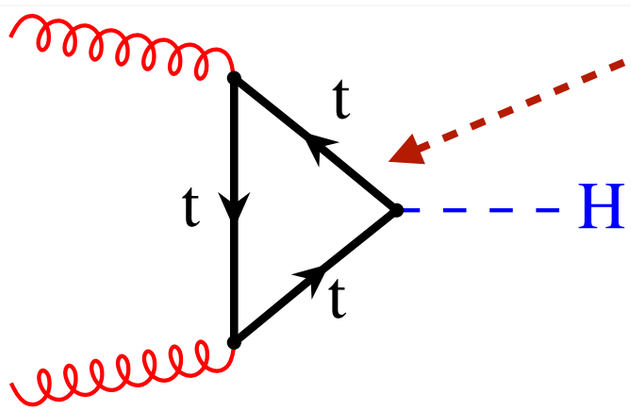
- we are about to <u>complete</u> the SM-Higgs **search**-phase, and find out whether :
  - there is a SM-Higgs-like signal !
    - ➜ start testing its properties
  - there is **not** a SM-Higgs-like signal !!!
    - ➜ what is there instead ?
    - ➜ it will take longer ...

- exp results presented here are according to Moriond 2012 (March 2012)
- CERN seminar at 9:00 CEST on 4 July to deliver the latest update in Higgs search

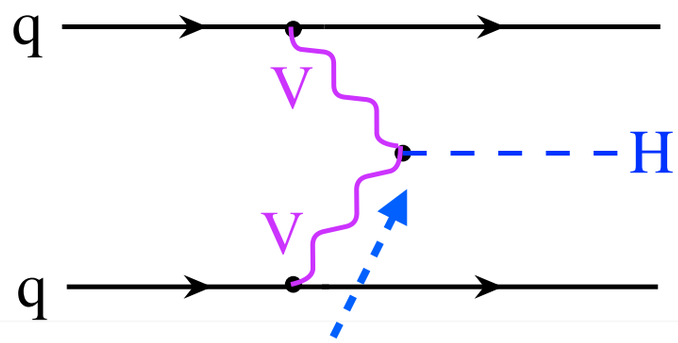
Higgs production (needs H coupled to heavy p.les !)

main channels

- **Gluon fusion**



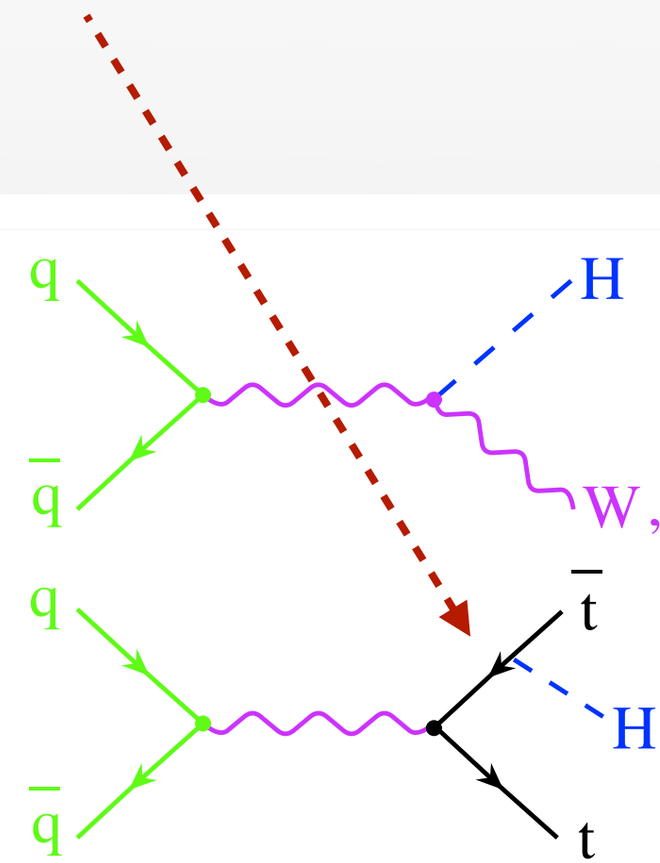
- **VBF**



test y_{Htt}

- **VH**

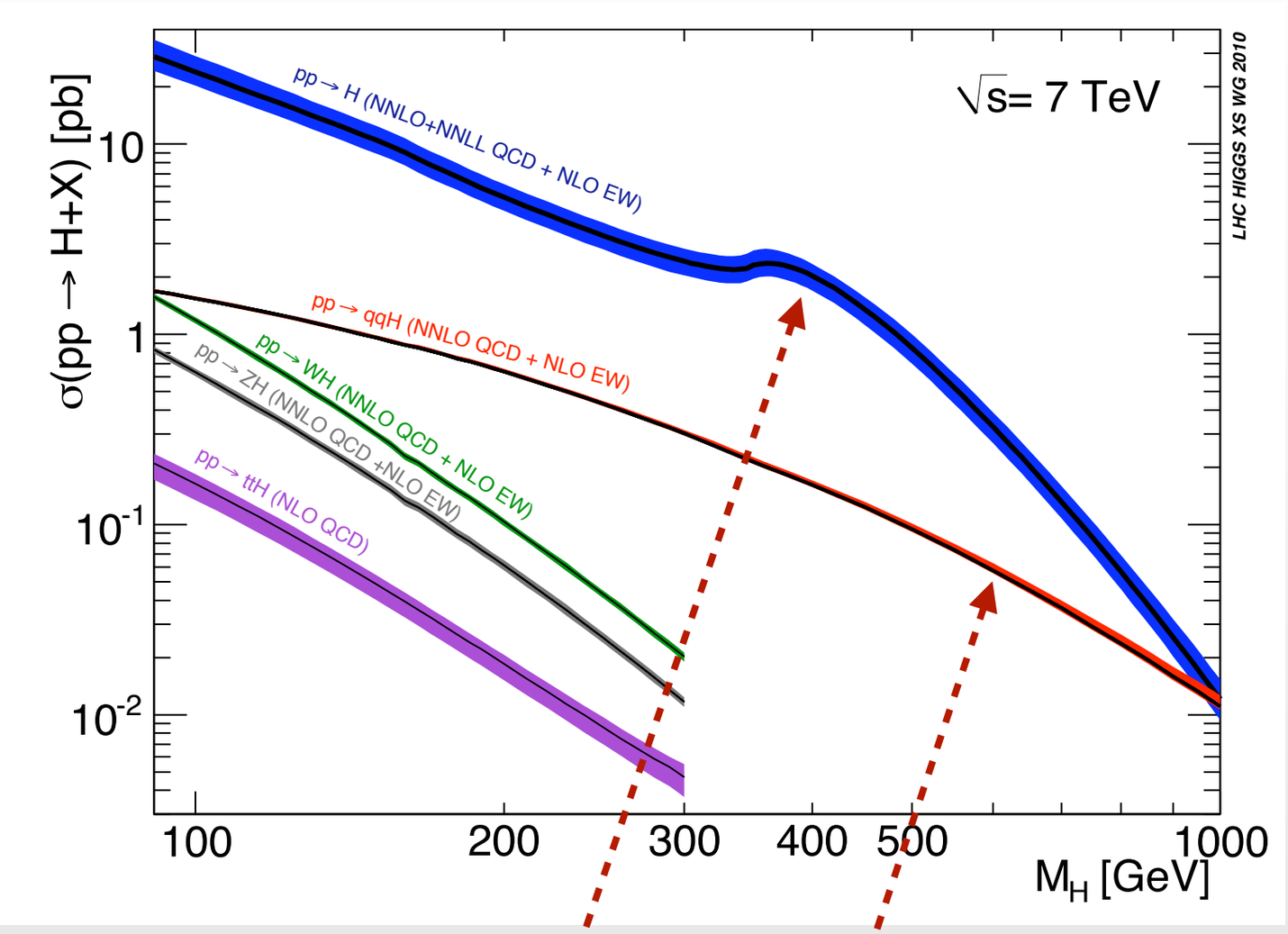
- **ttH**

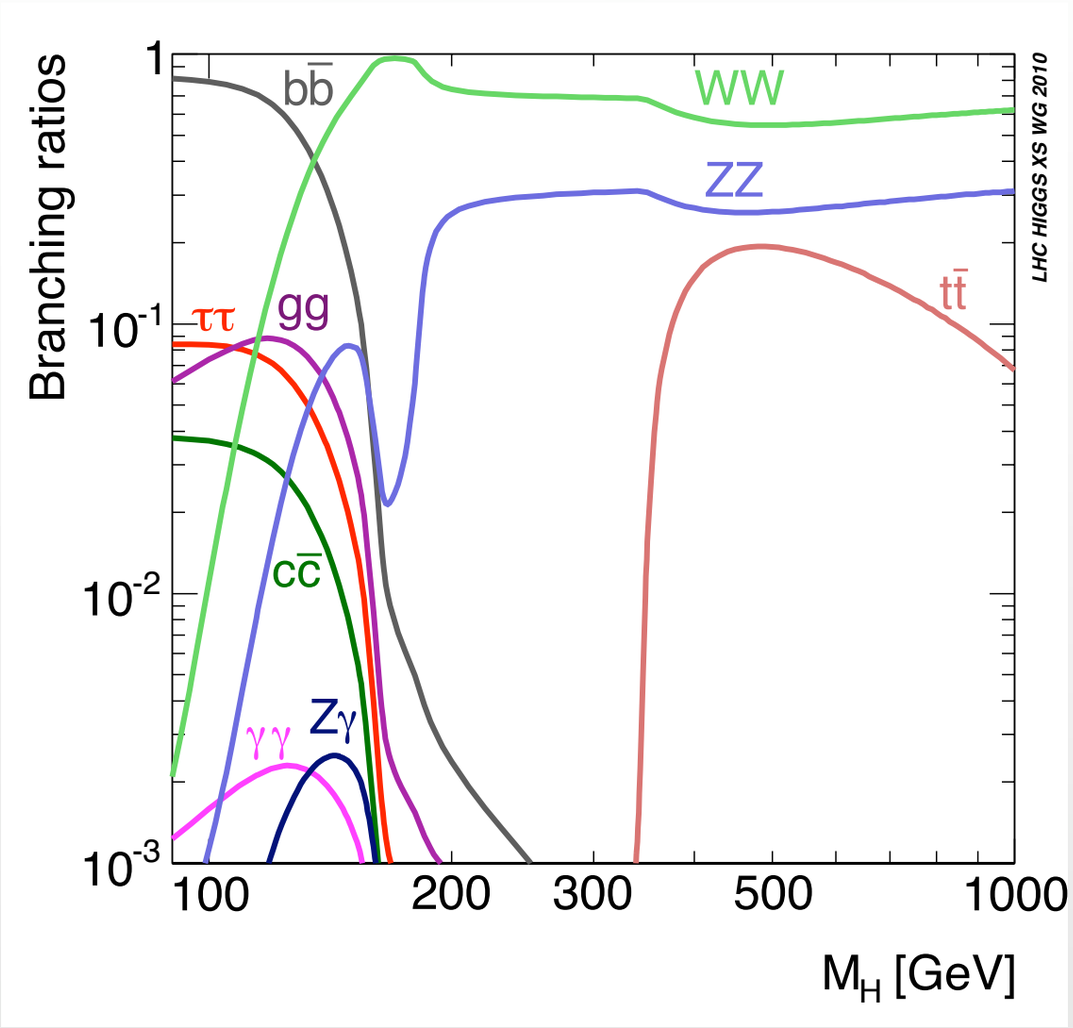


test y_{HVV}

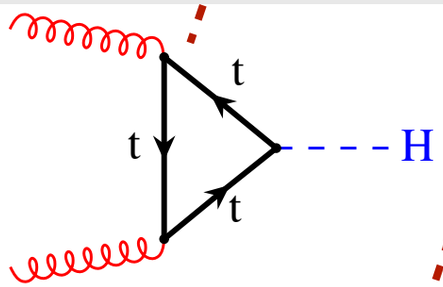
(high PT Higgs)

Higgs production and decay: at low m_H many channels contributing

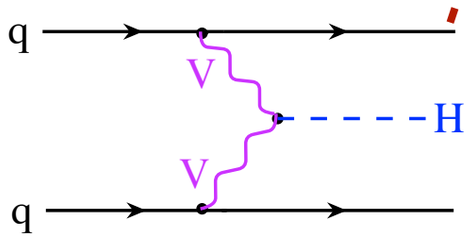




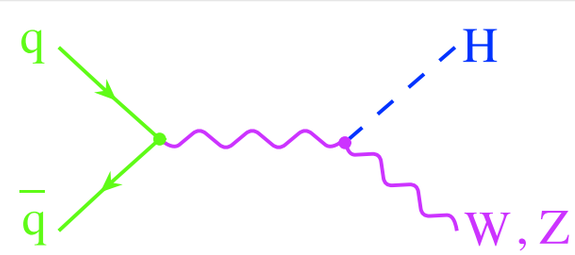
- Gluon fusion



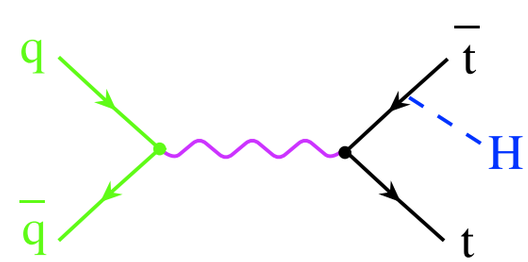
- VBF



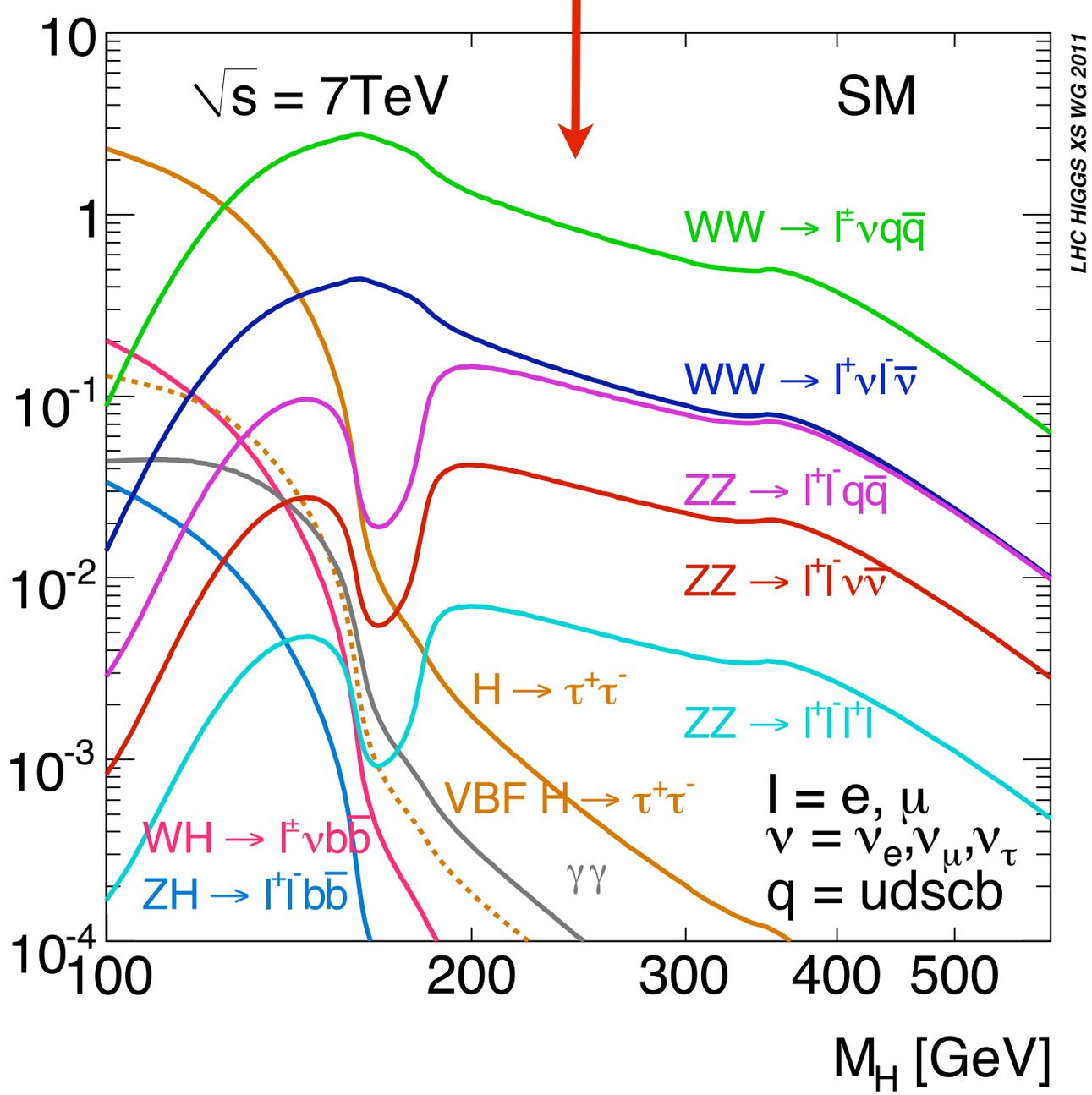
- VH



- ttH



σ x BR [pb] (rate / signature)



Events produced in 1 fb^{-1}

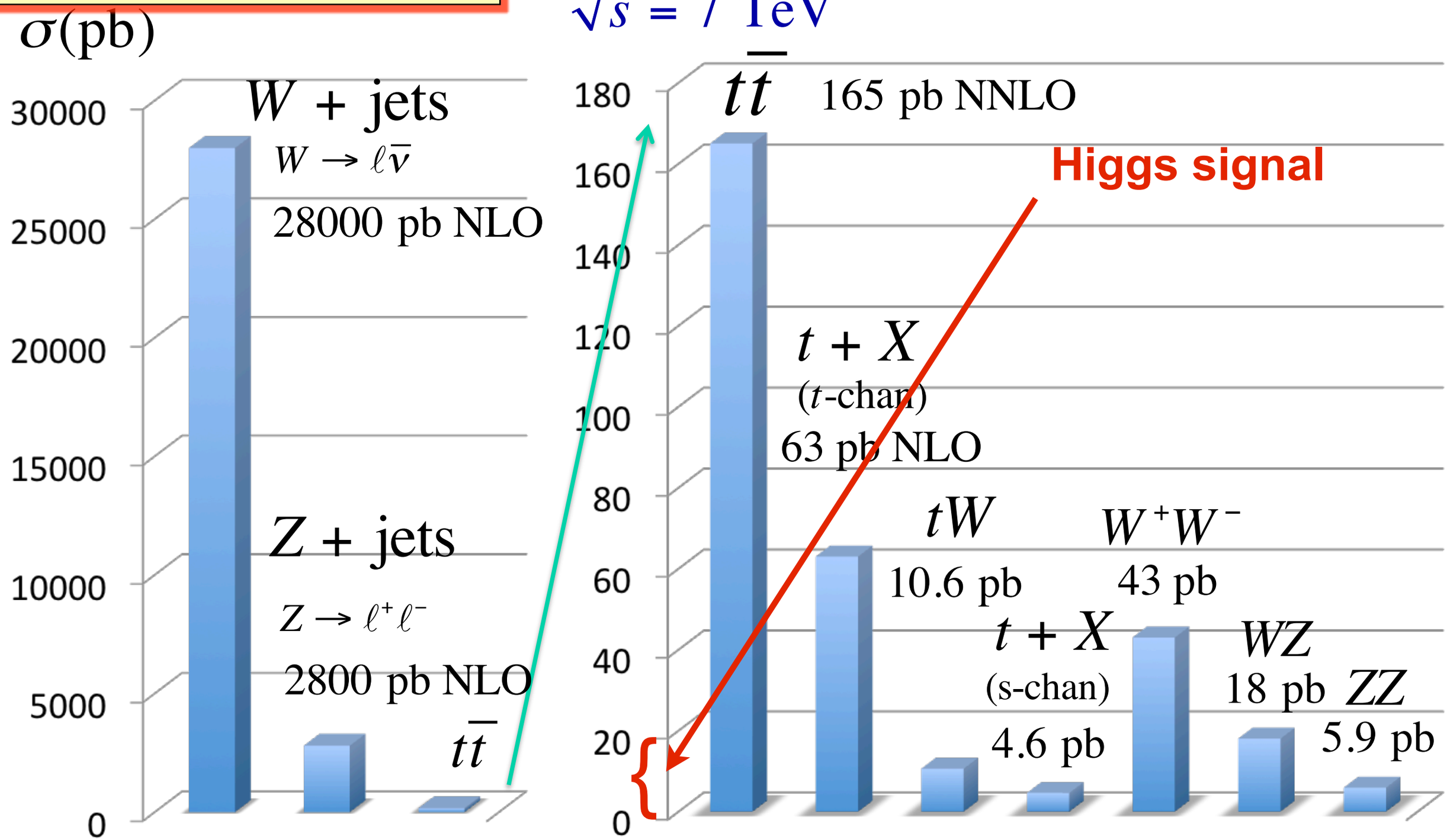
m_H, GeV	WW→2l2ν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

Process	Dominant Backgrounds
H→γγ	γγ, γ-jet
H→ττ	Z→ττ, top, EW, QCD
H→bb	Vbb, V+jets, top
H→WW→lνlν	**WW**, V+jets, top
H→WW→lνqq	**WW**, V+jets, top
H→ZZ→llll	**ZZ**, top, Zbb
H→ZZ→llνν	**ZZ**/WZ/WW, top, Z+jets
H→ZZ→llqq	**ZZ**/WZ/WW, top, Z+jets

Cross Sections for Key SM Background Processes

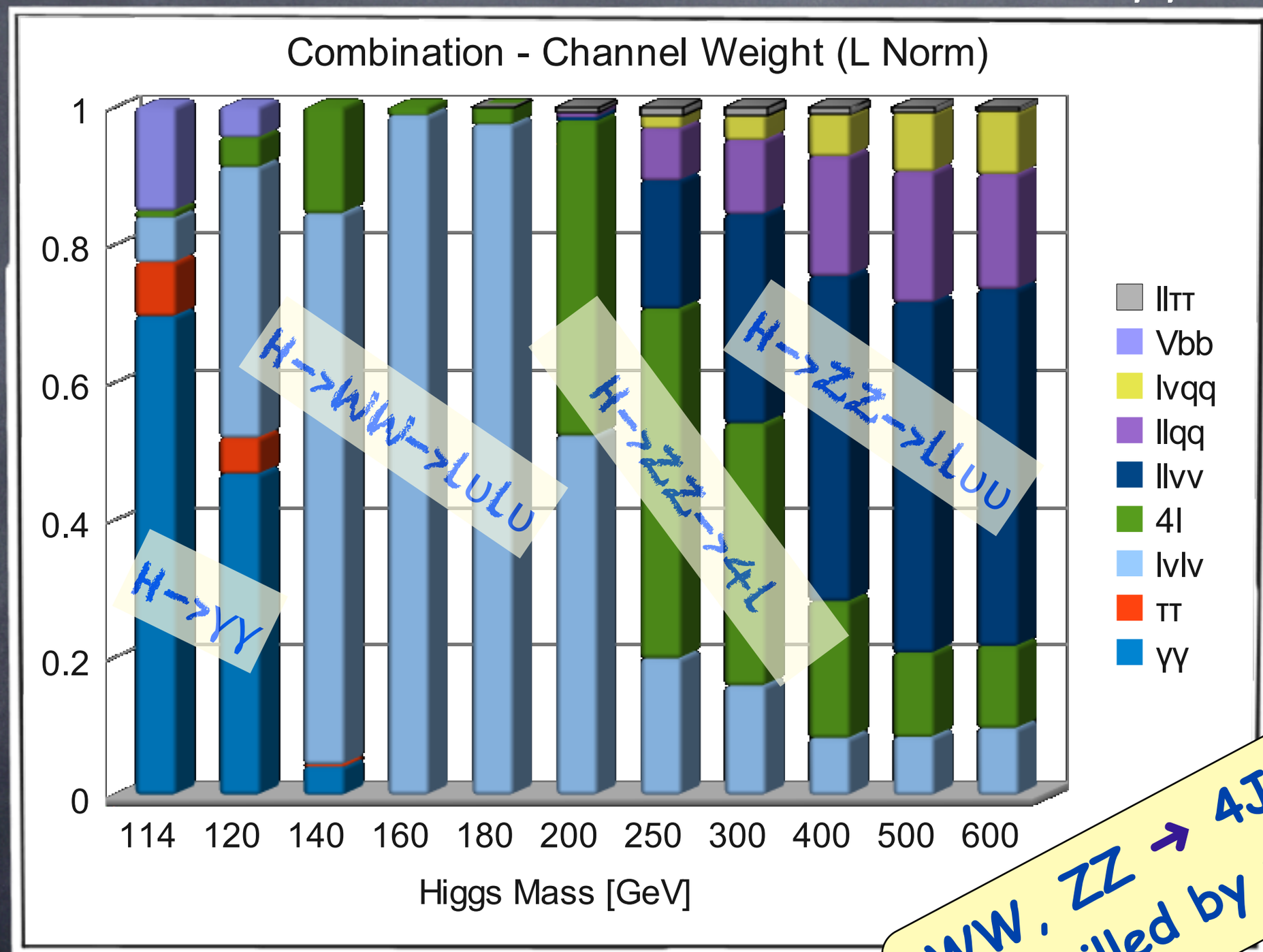
this is why H searches are so difficult !

(V.Sharma, LP11)



ATLAS+CMS Channels Weight

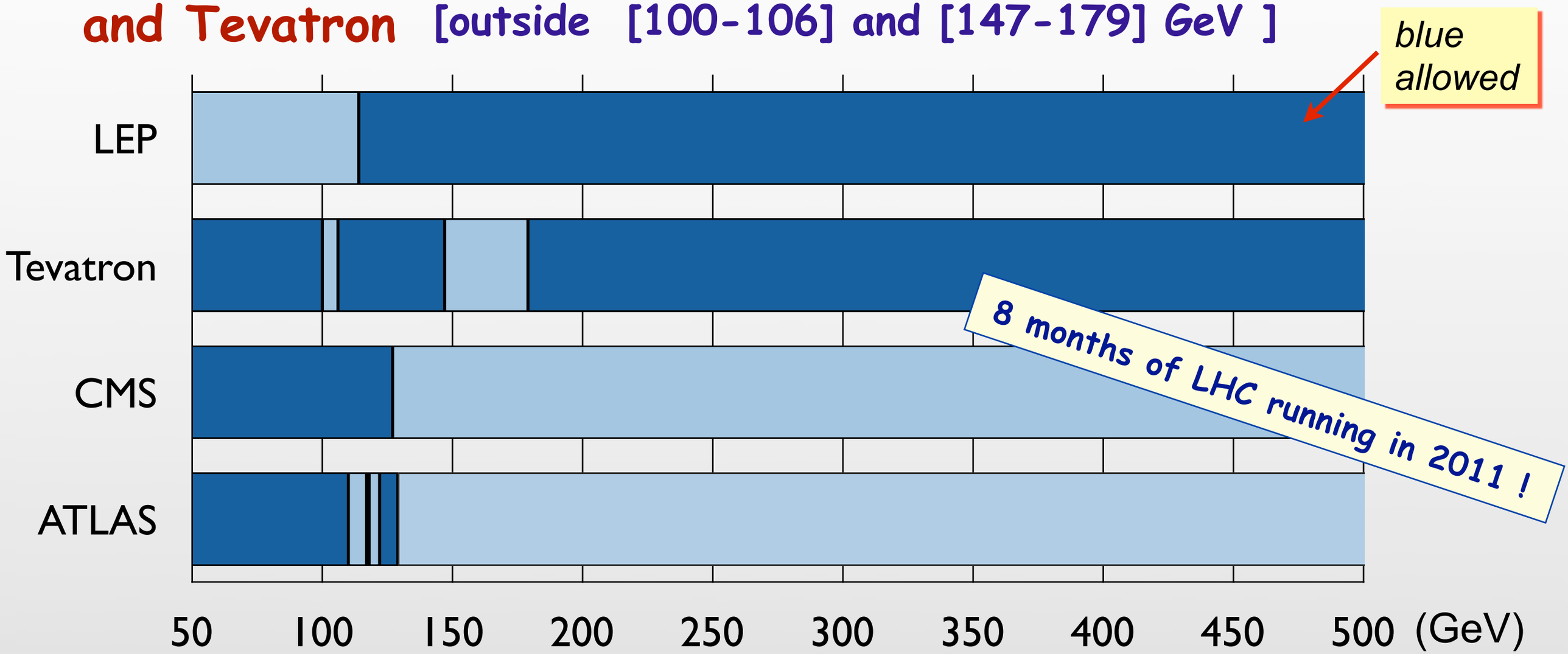
- Distinct mass regions γγ, lνlν, 4l, llνν+llqq



WW , ZZ → 4J channels killed by trigger

present exclusion bounds on SM Higgs

- well-deep into the yet-unexplored regime by LEP (>114 GeV) and Tevatron [outside [100-106] and [147-179] GeV]



[127,5-600] 95%CL

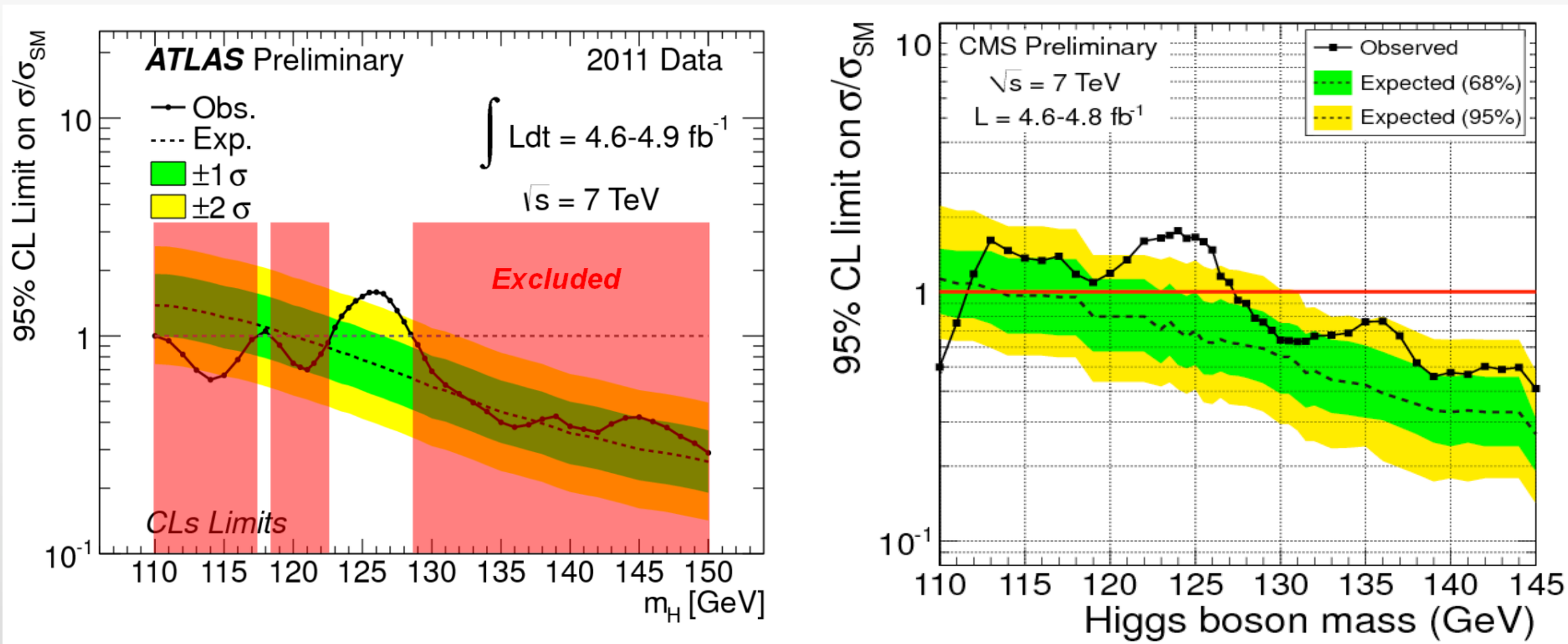
CMS-PAS-HIG-12-008

[110-117,5], [118,5-122,5] & [129-539] GeV 95%CL

ATLAS-CONF-2012-019

low-m_H region in Atlas and CMS

~ 2 sigma excess in $H \rightarrow \gamma\gamma$ in 2011 data
at m_H ~ 126 and 124 GeV, respectively



Integrated luminosity needed for Discovery of Higgs

Year	fb-1	signal (in σ)	Beam Energy	
2011	5	2.5	3.5	
2012	15	5	3.5	Needed
2012	11.5	5	4.0	Needed
2012	13.3	5	4.0	addditional 15% for pile up and margin

bonus at $m_H \sim 125$ GeV

- many production channels :

$$\sigma(pp \to h) = (15.3 \pm 2.6)\,\mathrm{pb}, \qquad \sigma(pp \to jjh) = 1.2\,\mathrm{pb},$$
$$\sigma(pp \to Wh) = 0.57\,\mathrm{pb}, \qquad \sigma(pp \to Zh) = 0.32\,\mathrm{pb},$$

and decay channels :

$$\mathrm{BR}(h \to b\bar{b}) = 58\%, \qquad \mathrm{BR}(h \to WW^*) = 21.6\%, \qquad \mathrm{BR}(h \to \tau^+\tau^-) = 6.4\%,$$
$$\mathrm{BR}(h \to ZZ^*) = 2.7\%, \qquad \mathrm{BR}(h \to gg) = 8.5\%, \qquad \mathrm{BR}(h \to \gamma\gamma) = 0.22\%,$$
$$\mathrm{BR}(h \to c\bar{c}) = 2.7\%$$

contributing at a detectable level !

$$B\sigma(p\bar{p} \to h \to X_{\mathrm{SM}}) \equiv \sigma(p\bar{p} \to h)\frac{\Gamma(h \to X_{\mathrm{SM}})}{\Gamma_{\mathrm{total}}}$$

- event rates depend on 3 quantities !

(to keep in mind for a model independent analysis)

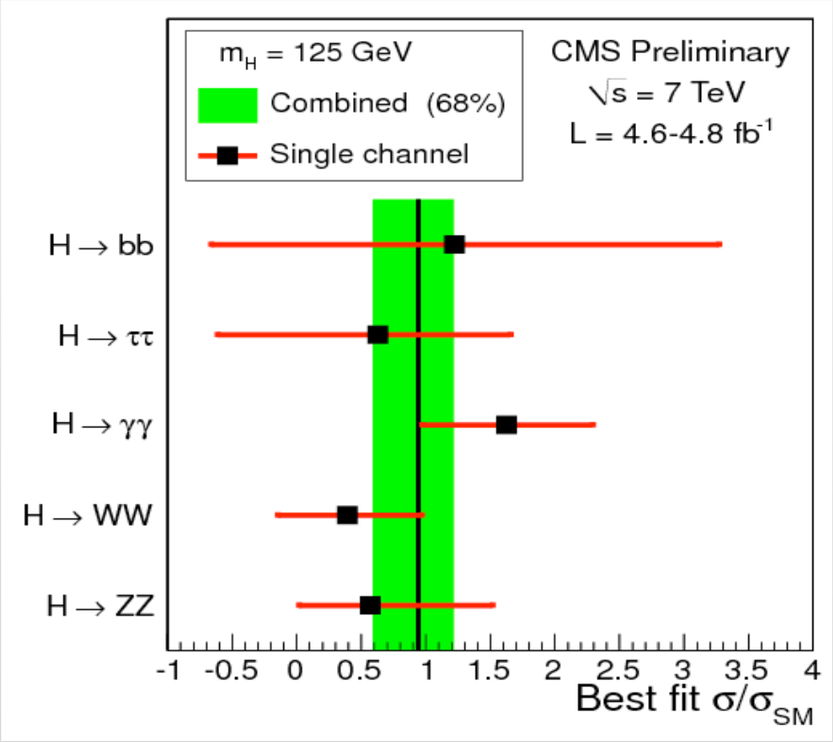
- a common rescaling of all couplings can be accomodated by an extra invisible (=non-detected) contribution to Γ_{total}

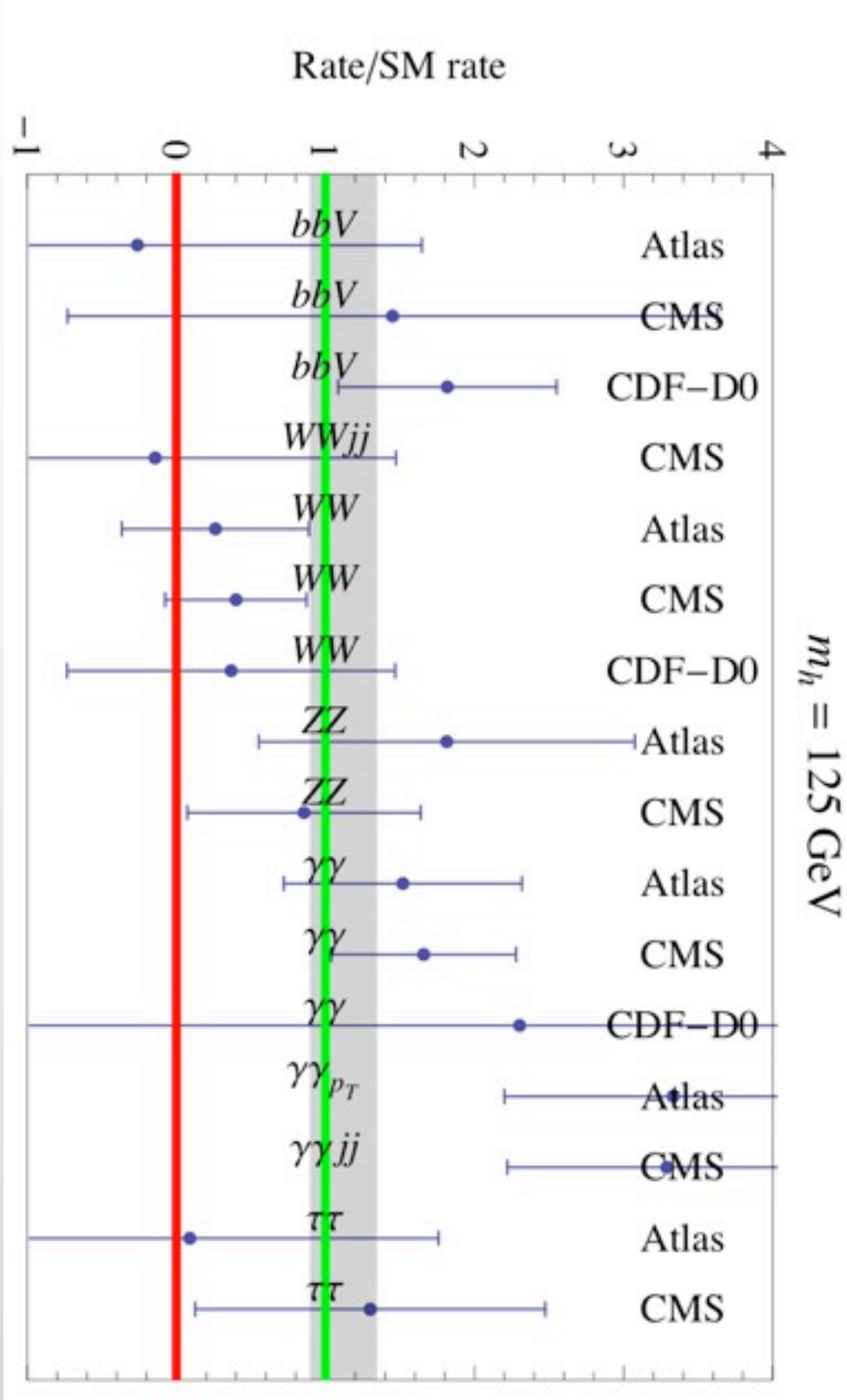
H coupling measurements

- bounds and couplings are determined by measurements of

$$\kappa_{p,d} = (\sigma_p \times \mathrm{BR}_d)/(\sigma_p \times \mathrm{BR}_d)^{\mathrm{SM}}$$

- coupling absolute-value determination is model dependent !
- presently-inconclusive exercise ...





Giardino et al, arXiv:1203.4254

Big hierarchy in observed fermion mass spectrum

(m_f's , or Y_{Hff}'s)

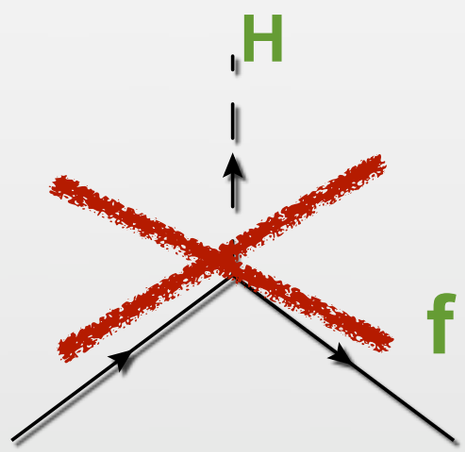
WHY is that ?

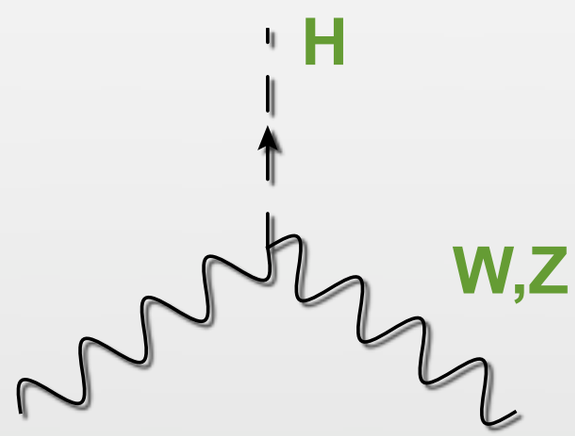
... no explanation for m_f's hierarchy in the SM !

hierarchy in m_f's ?

a non-standard scenario :

a Fermio-Phobic (FP) Higgs





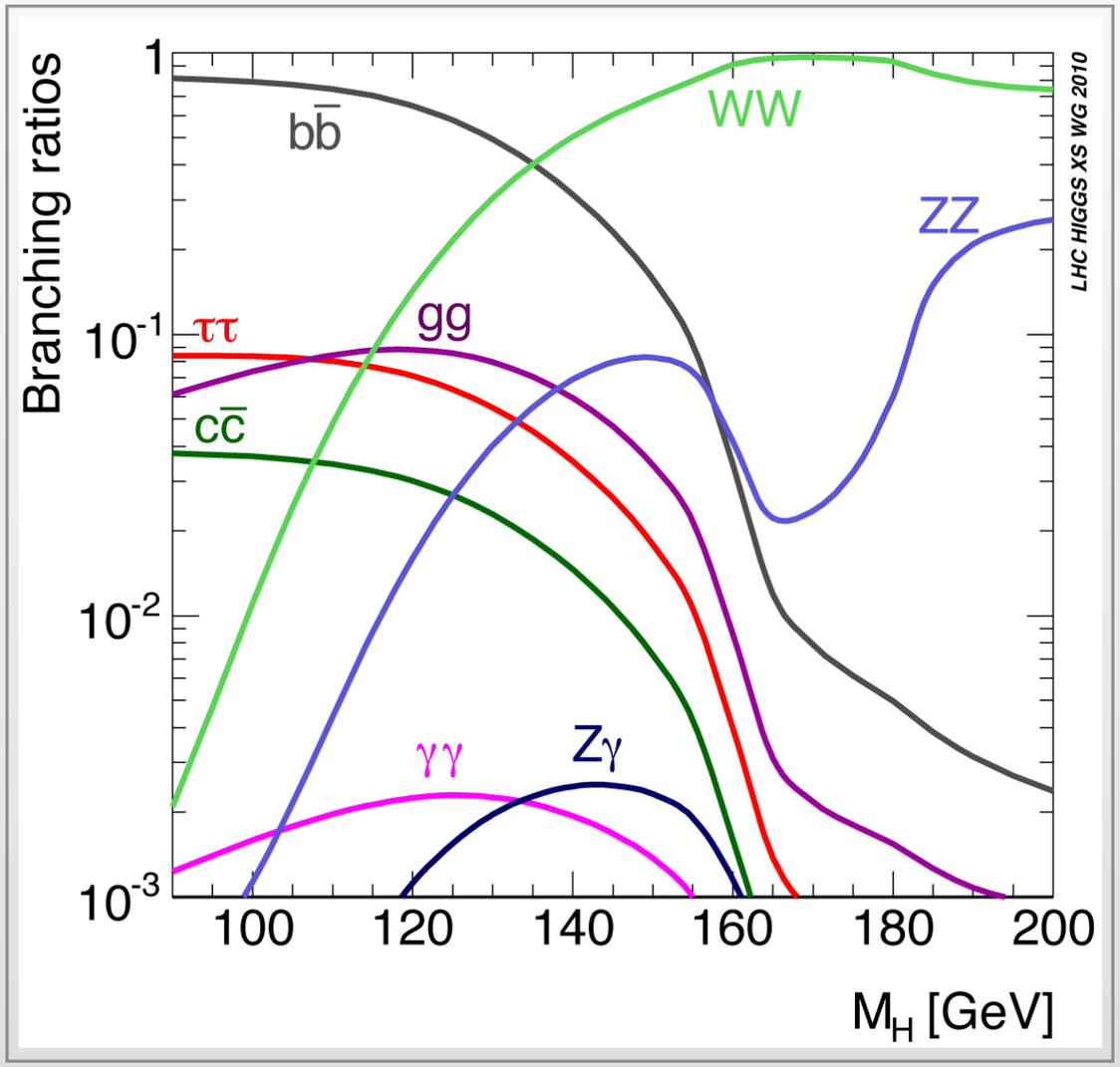
- no Yukawas at tree-level !
- the Higgs mechanism gives rise to EWSB and $M_{W,Z}$, as in the SM, but is not responsible for ChSB and m_f's

Higgs decays : FP vs SM

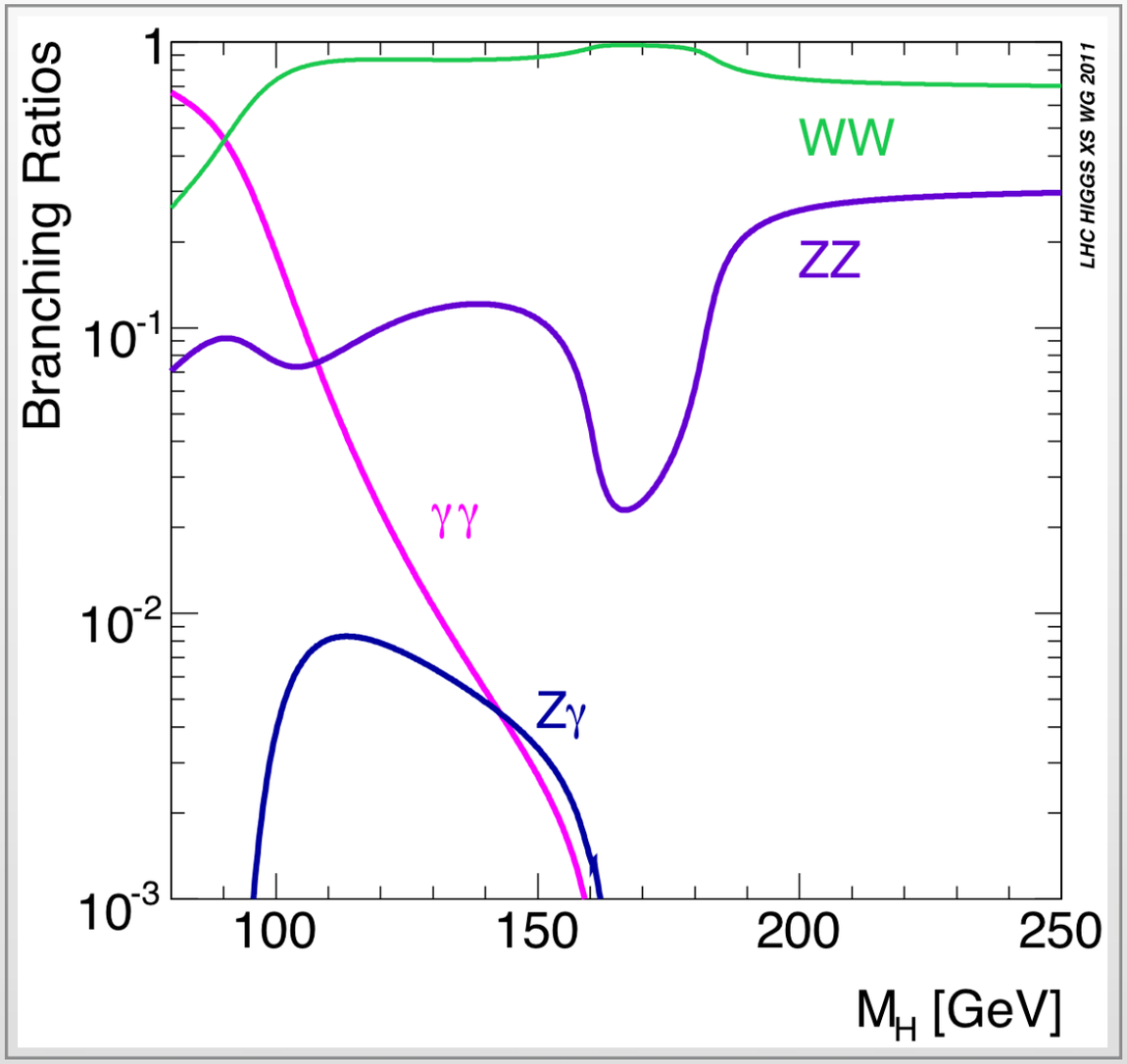
[through W loops (no-top loops)]

$H \rightarrow WW, ZZ, \gamma\gamma, Z\gamma$ enhanced at low m_H !

SM Higgs



FP Higgs



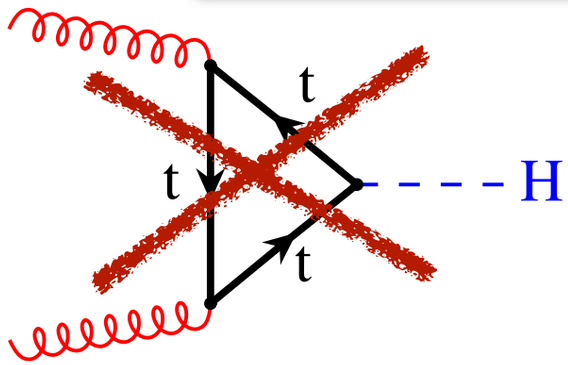
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Fermiophobic

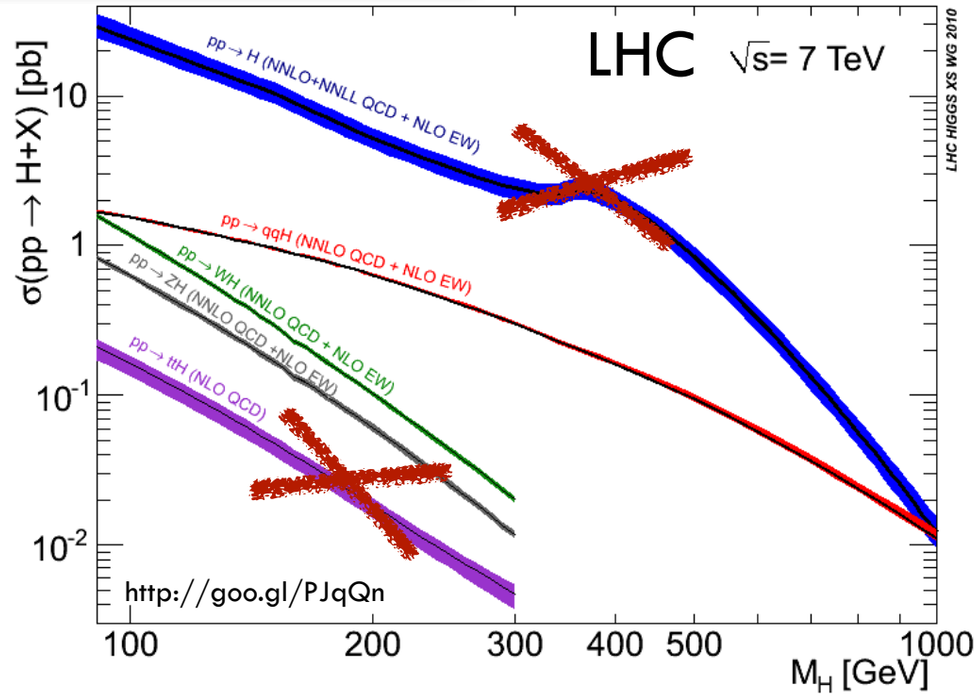
for m_H ~[100,110,120,125] GeV : $BR(\gamma\gamma)_{FP}$ ~[110,30,10, 6.7] x$BR(\gamma\gamma)_{SM}$

Higgs cross sections : FP vs SM

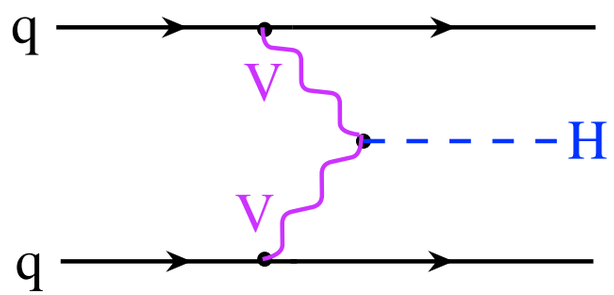
dominant gg → H channel lost !

- **Gluon fusion**

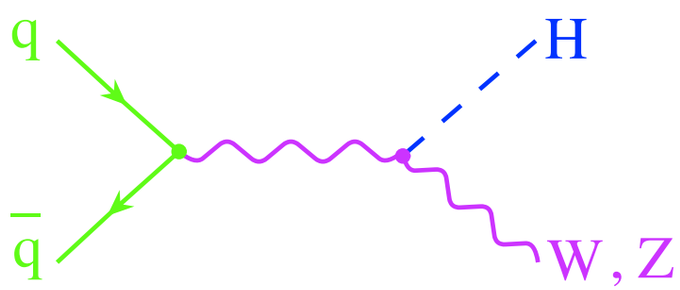




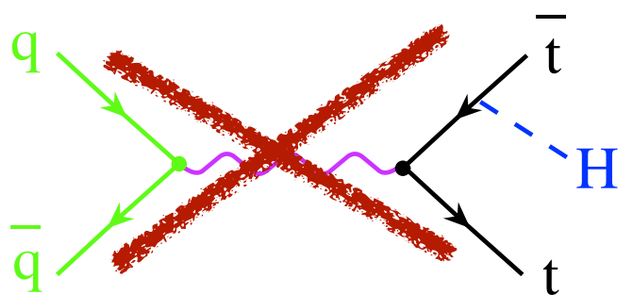
- **VBF**

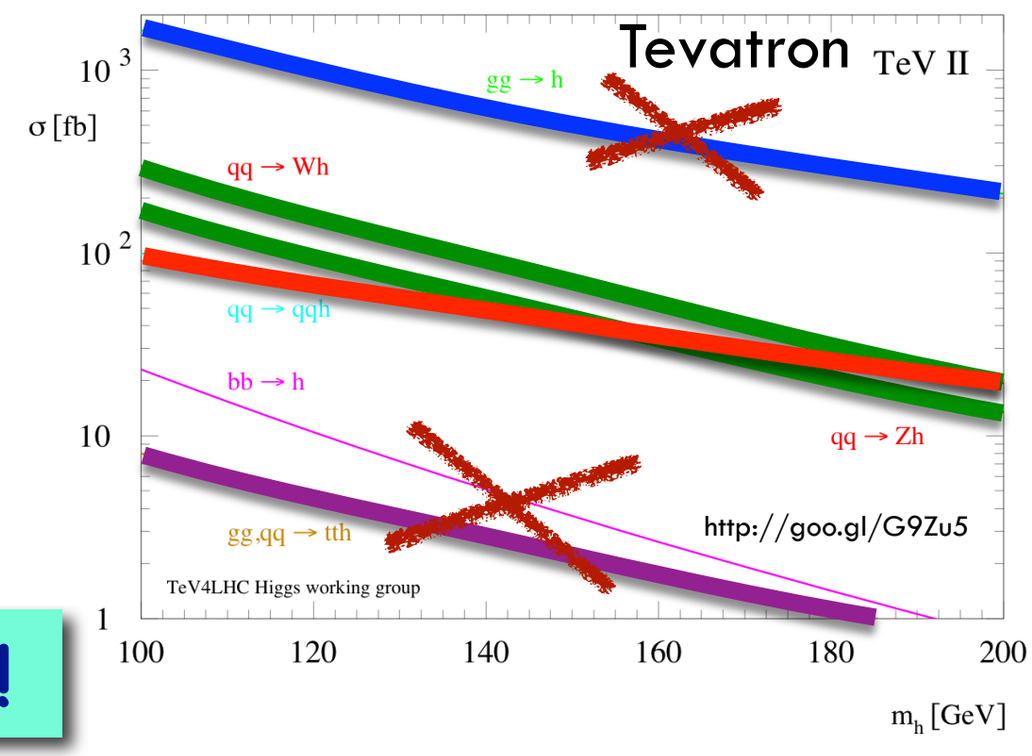


- **VH**



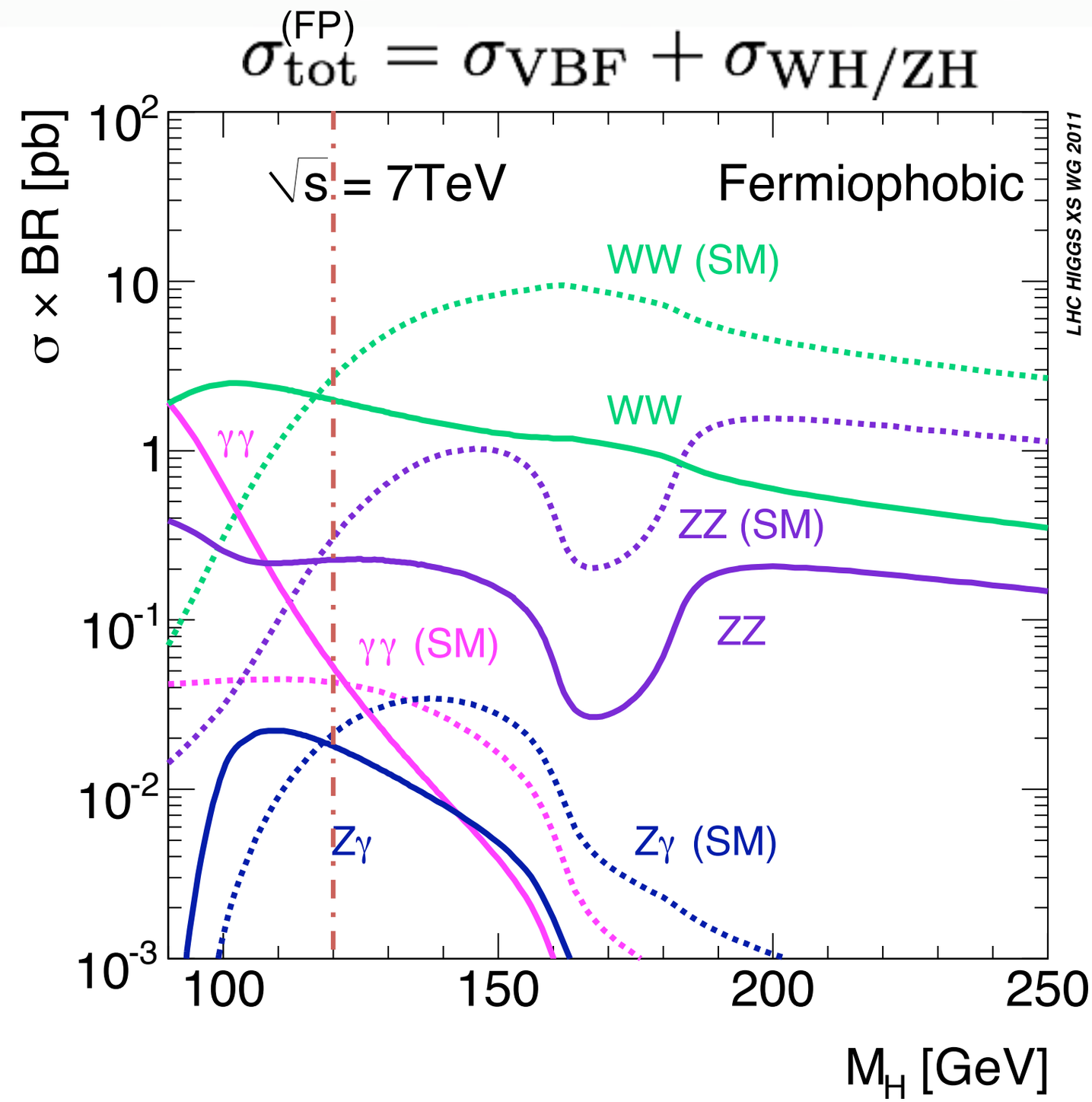
- **ttH**





harder $P_T(H)$ spectrum → better S/B !

σ x BR: FP(mostly VBF) vs SM(mostly gg)



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

- for M_H ~ 120 GeV, comparable SM and FP rates in WW, ZZ, γγ, γZ
  (larger BR_{FP} compensates for lower x-sections !)
- for M_H < 120 GeV, excess over SM in all decay channels WW, ZZ, γγ, γZ

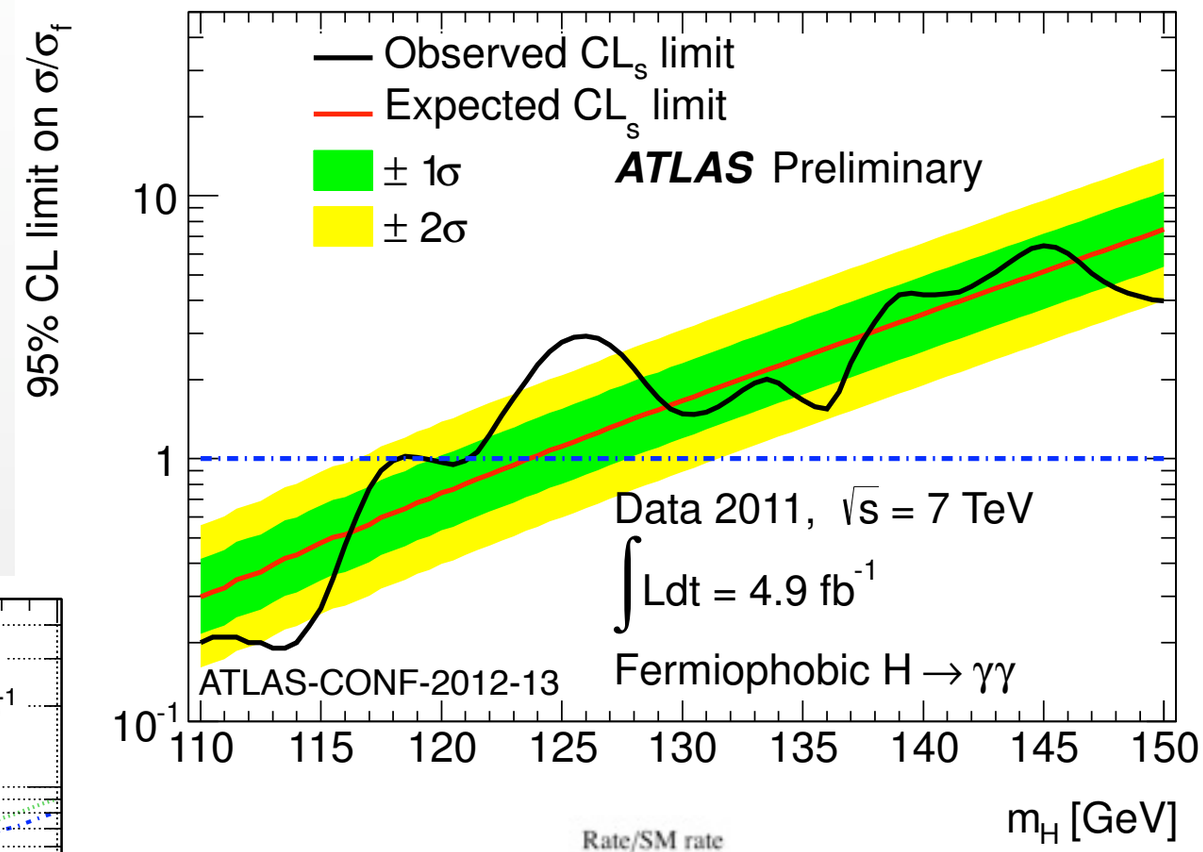
exp lower bounds on FP m_H (95% CL)

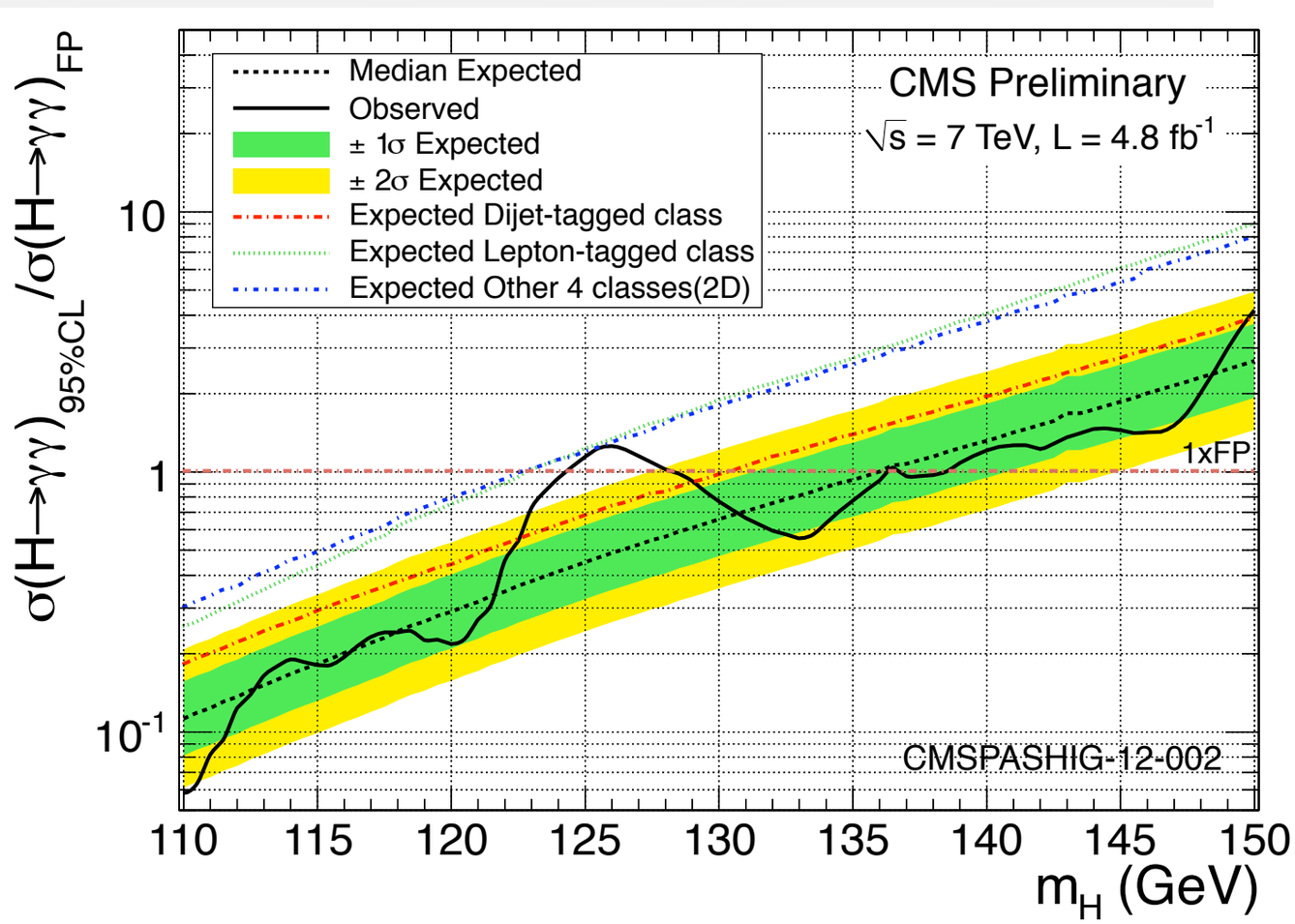
- quite a number of exp studies on <u>tree-level</u> FP scenario
  - LEP → 109.7 GeV (comb. $\gamma\gamma$ data on 4 exps, hep-ex/0212038)
    (108.3 GeV, comb. $\gamma\gamma$ +WW* in L3)
  - CDF → (100-114) GeV 7.0 fb^{-1}
  - D0 → (100-112.9) GeV 8.2 fb^{-1}
  - CMS → (110-124), (128,136) GeV 4.8 fb^{-1}, 7 TeV
  - Atlas→(110.0-118.0)(119.5-121.0) GeV,4.9 fb^{-1} 7TeV

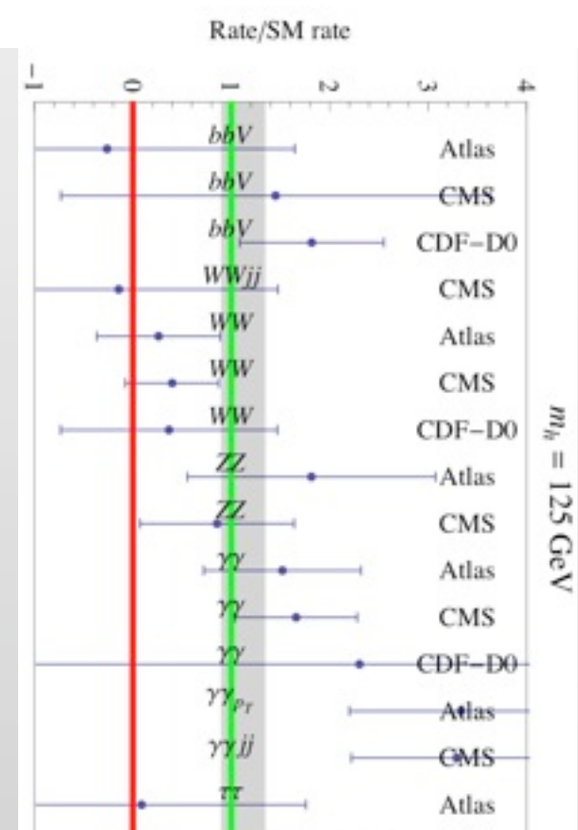
hint of a FP Higgs at ~ 125 GeV

- VBF kinematics (dominant) easier to distinguish from bckgr

➜ dedicated fermiophobic Higgs analysis enhancing efficiencies on high-p_T $\gamma\gamma$ events







how radiative corr's affect FP H scenario

- switching off Yukawa couplings in the SM
  (and keeping non-vanishing m_f's)
  gives a non-renormalizable theory

  → UV divergences do not cancel !!!

how radiative corr's affect FP H scenario

- two possible ways to proceed :

  - construct a renormalizable FP extension of the SM (further d.o.f., e.g. 2HDM), and study a particular model

  - here we consider a more general approach : treat the SM with all $Y_f=0$ and m_f's $\neq 0$ as an <u>Effective Field Theory</u> (EFT)

  ➜ get a unifying description of a wide class of possibilities, where one keeps the Higgs mechanism to generate M_W and M_Z , but m_f's have different origin !

based on

E. Gabrielli, BM,

arXiv:1005.2498 (PRD), arXiv:1102.3361(PRD), arXiv:1112.5993

E. Gabrielli, BM, and M.Raidal,

arXiv:1202.1796

E. Gabrielli, K.Kannike, BM, A.Racioppi and M.Raidal,
arXiv:1204.0080

theoretical framework

- in the SM, ChSB (m_f) and EWSB ($M_{W,Z}$) generated by Higgs mechanism at the same scale ~ $v = \langle H \rangle$

$$\mathcal{L} \;=\; Y_f H \,\bar{\Psi}_f \Psi_f \quad \Rightarrow \quad m_f = Y_f \, v$$

- assume instead ChSB and EWSB have different origin
- switch off Y_f's in the Lagrangian
- m_f's generated by some new (unknown) mechanism set at a high-energy scale Λ (>> EW scale)
- Higgs gives dominant contribution to M_W and M_Z (contributions to EWSB arising from ChSB assumed small)
- only SM degrees of freedom propagating at energies below Λ
- a light Higgs

EFT approach connects Λ and m_H scales

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

$$Y_f(\Lambda) = 0$$

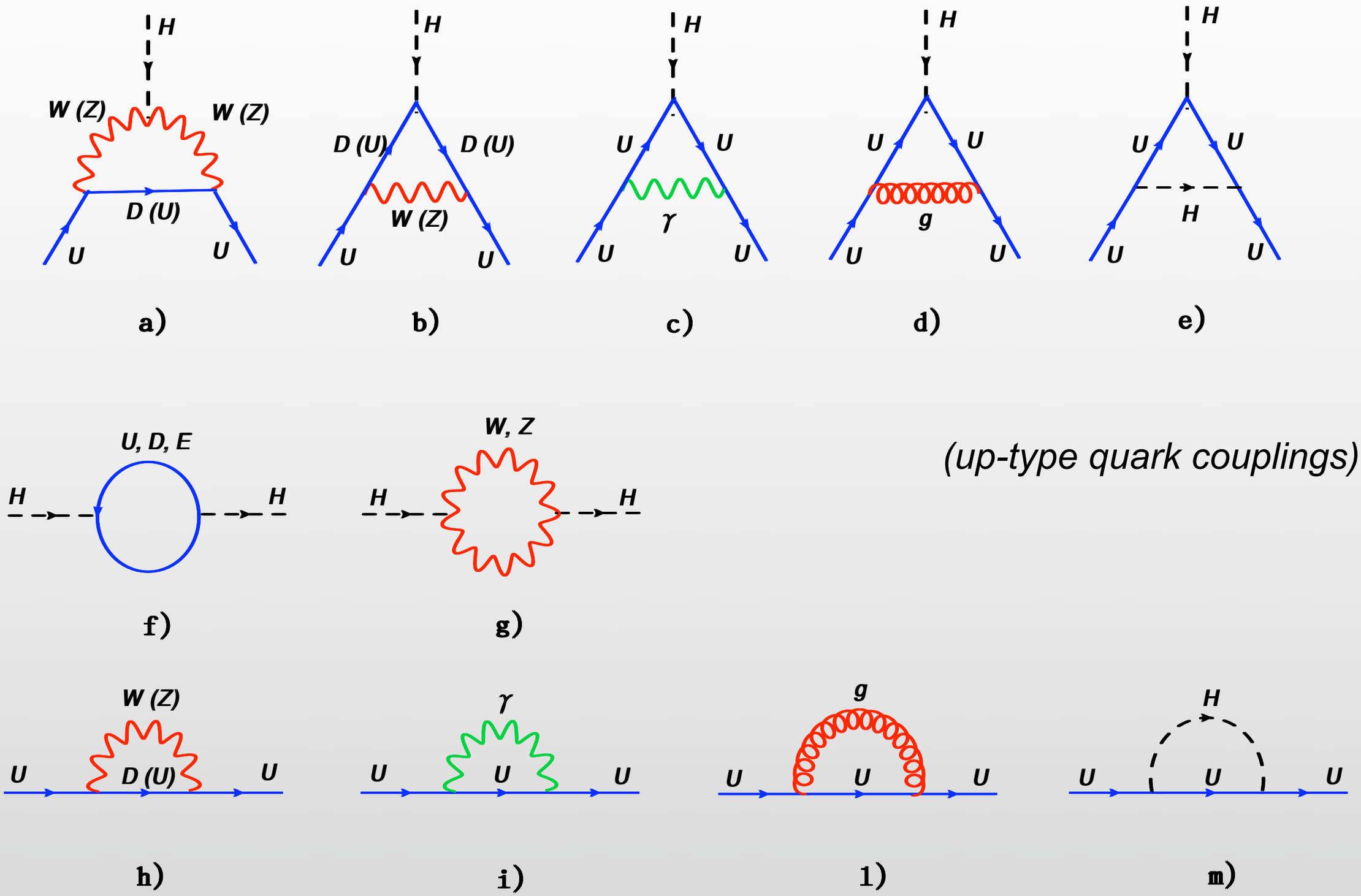
- due to ChSB, Y_f's are <u>not protected</u> under radiative corrections → radiatively generated (m_f control param.)
- large (universal) logs $g_i^{2n} \log^n (\Lambda/m_H)$ can be summed up by Renormalization Group Equation (RGE) technique

$$Y_f(\Lambda) = 0 \quad \xrightarrow{RGE} \quad Y_f(m_H)$$

(high energy) (low energy)

- note ! SM RGE's (where Y_f's and m_f's are related) not suitable here → new RGE's derived by keeping Y_f's and m_f's as independent parameters !

diagrams contributing to Y_f's beta function



(up-type quark couplings)

1-loop RGE's for Y_f's (flavor diagonal)

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

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

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

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

W_L polarization

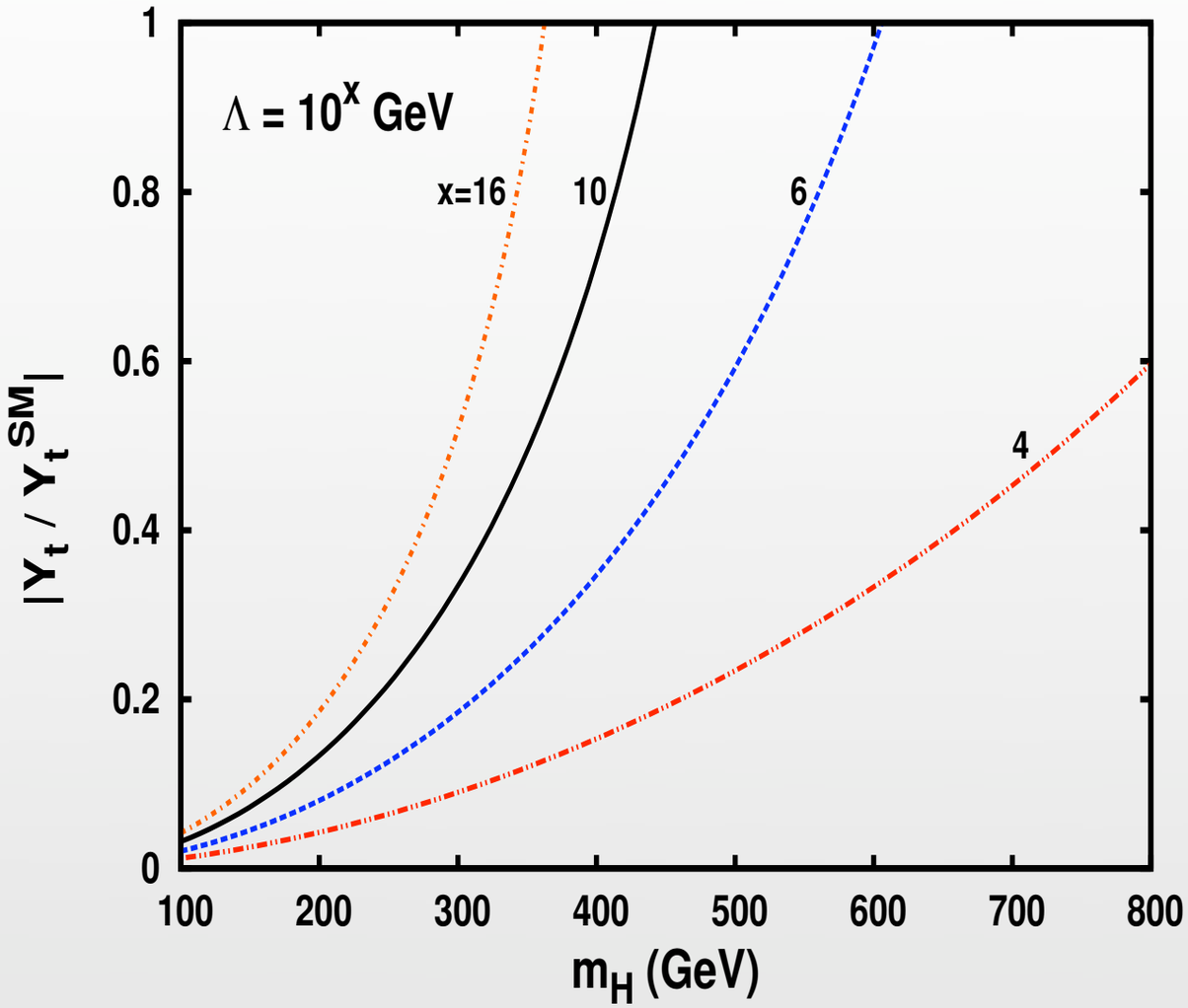
$$\mathbf{Y_f^{SM}} \equiv \frac{g_2}{\sqrt{2}M_W}\mathrm{diag}[m_{\mathrm{f}_1}, m_{\mathrm{f}_2}, m_{\mathrm{f}_3}]$$

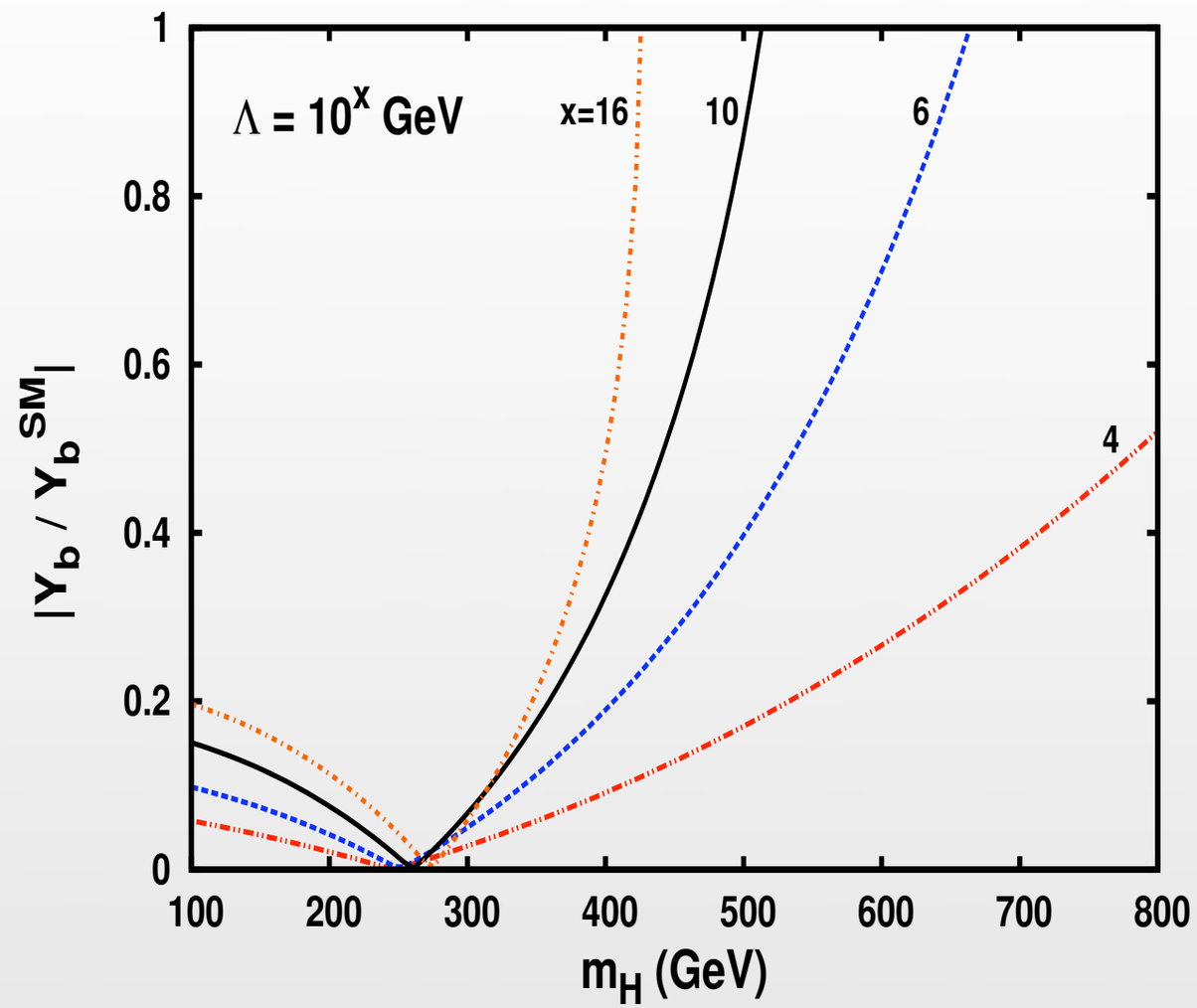
ChSB terms

$$\mathbf{Y} \equiv N_c\mathbf{Y_U}\mathbf{Y_U} + N_c\mathbf{Y_D}\mathbf{Y_D} + \mathbf{Y_E}\mathbf{Y_E}$$

SM RGE's recovered for → $\mathbf{Y_f^{SM}} \to \mathbf{Y_f}$

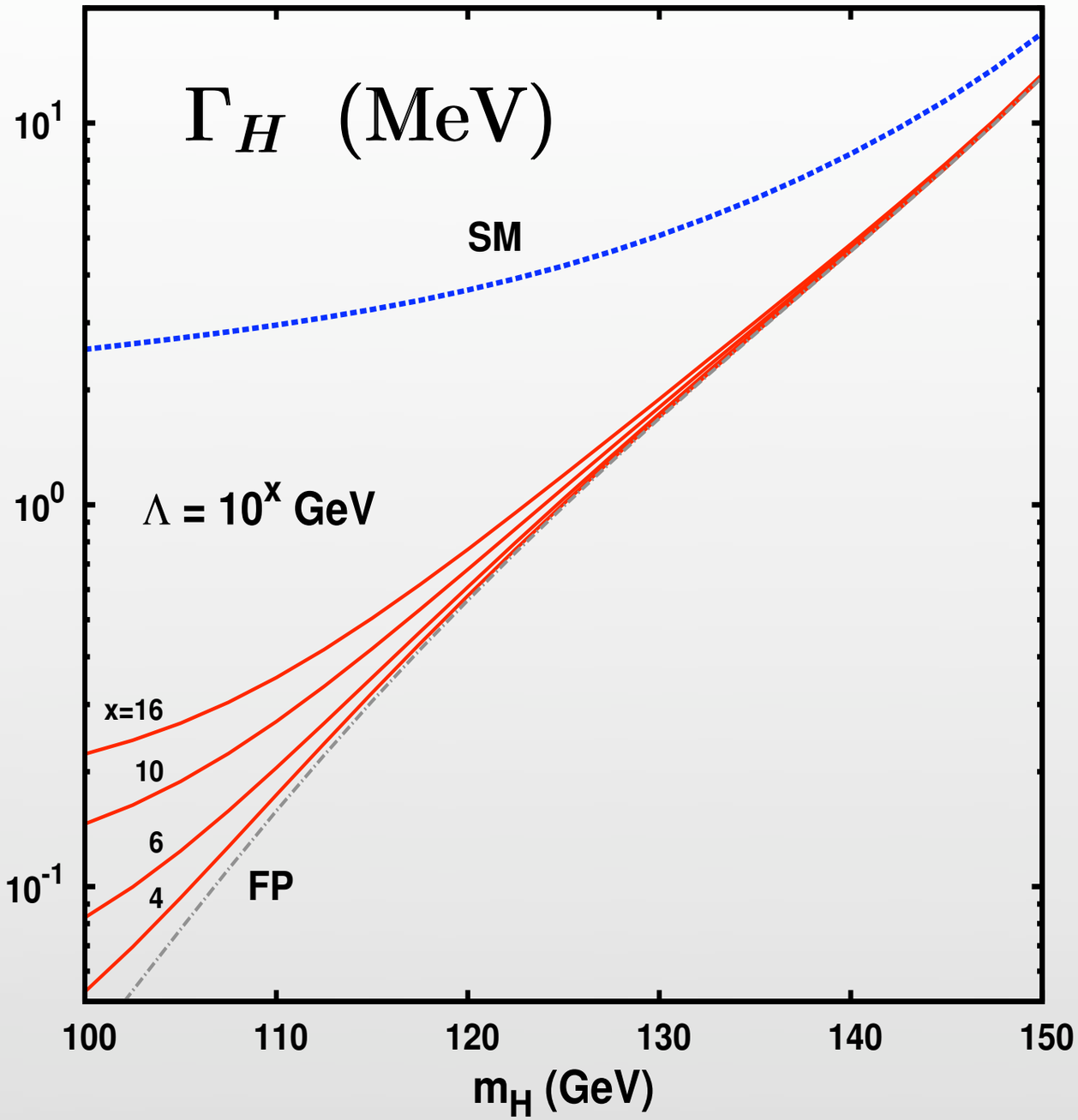
Results for $Y_t(m_H)/Y_t^{SM}$ and $Y_b(m_H)/Y_b^{SM}$

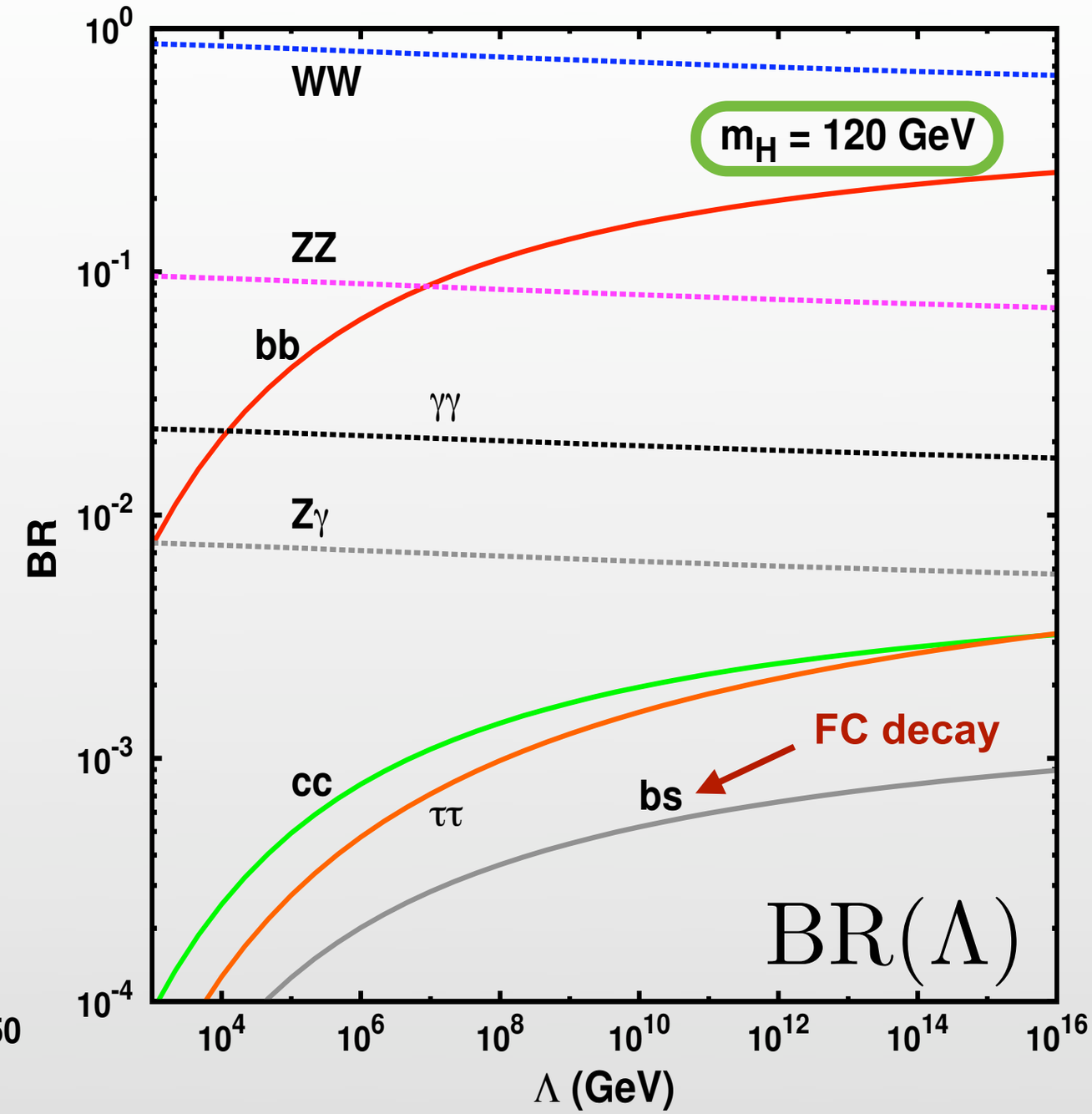




- Λ varied between 10^4 and 10^{16} GeV
- because of terms $\xi_H \equiv \frac{g_2 m_H}{2M_W}$, Y_f grows at large m_H
- for m_H < <H> ~ 246 GeV, all Y_f's perturbative !

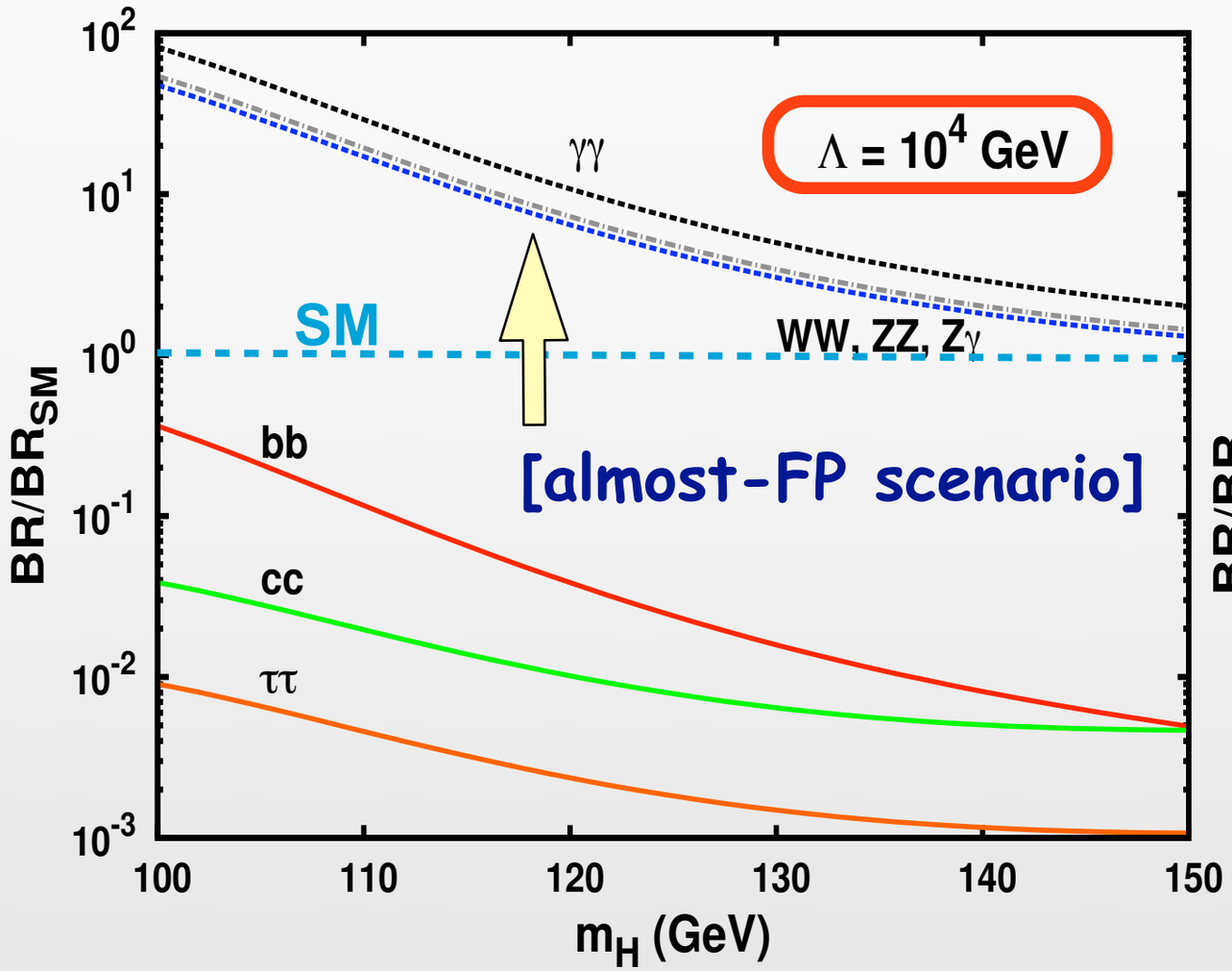
Results for Γ_H and BR's vs Λ

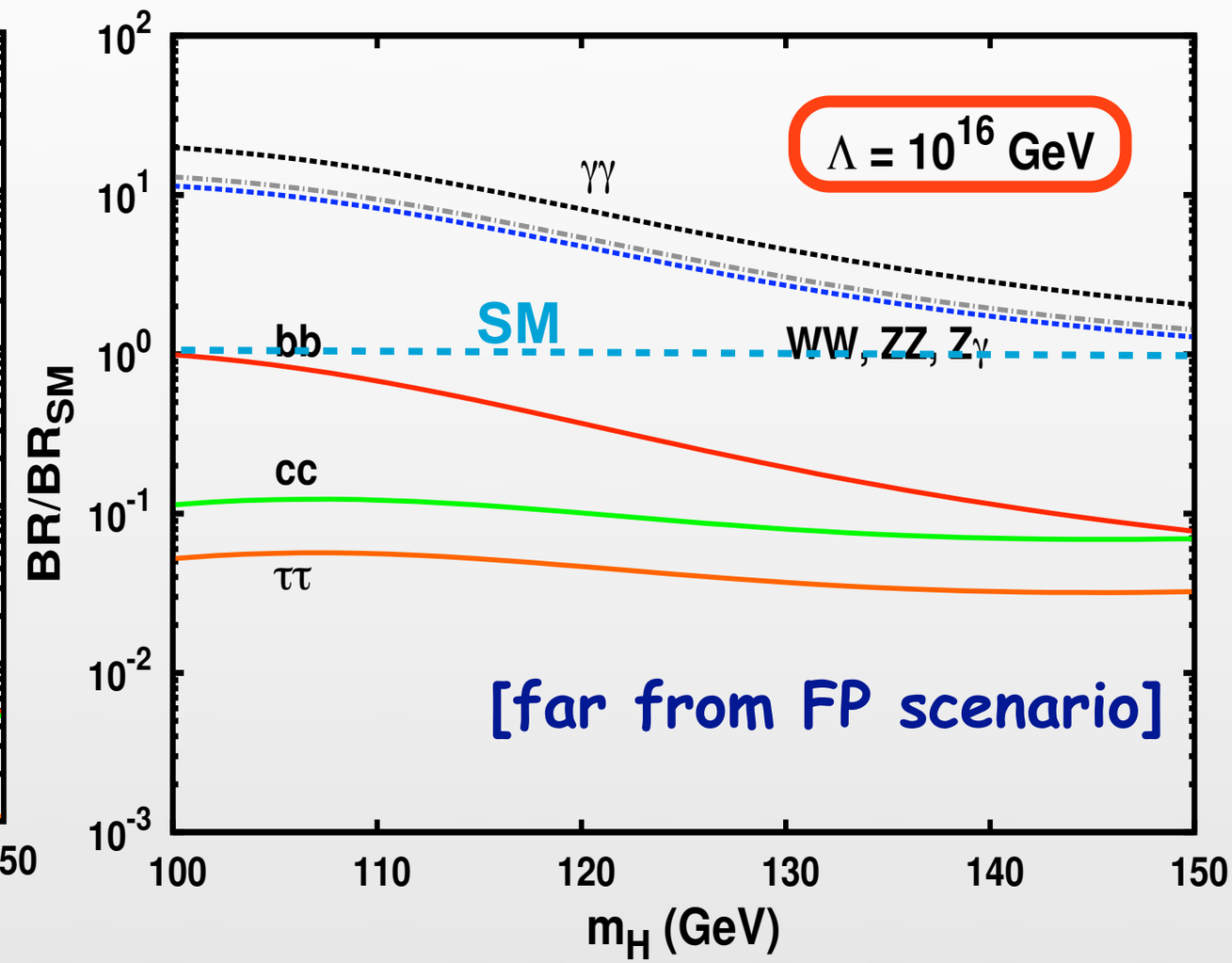




- small Higgs total width enhances radiative BR's !
- large effects at large Λ: BR(bb) approaches SM values !

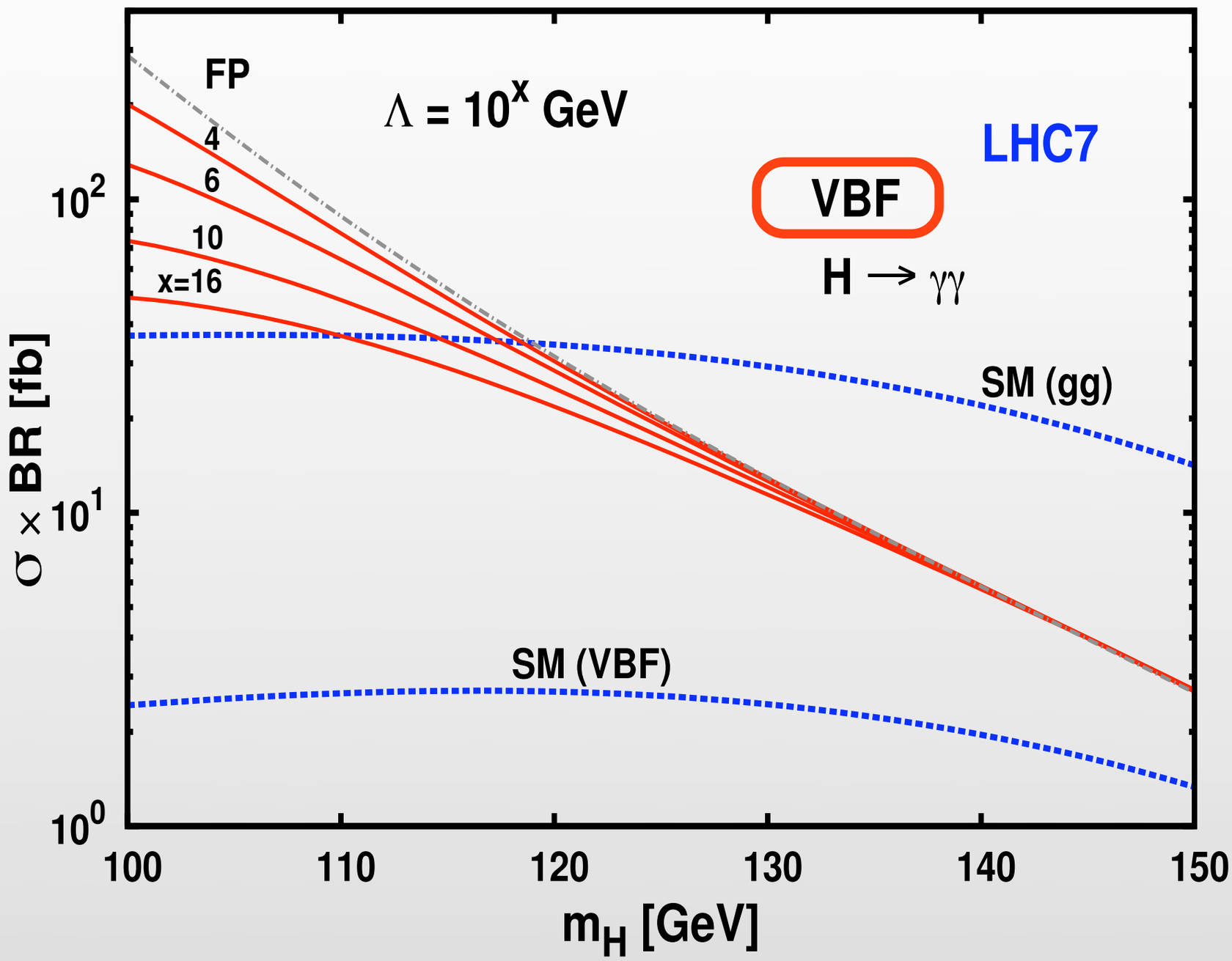
BR / BR(SM) : $\Lambda \sim (10^4 \rightarrow 10^{16})$ GeV





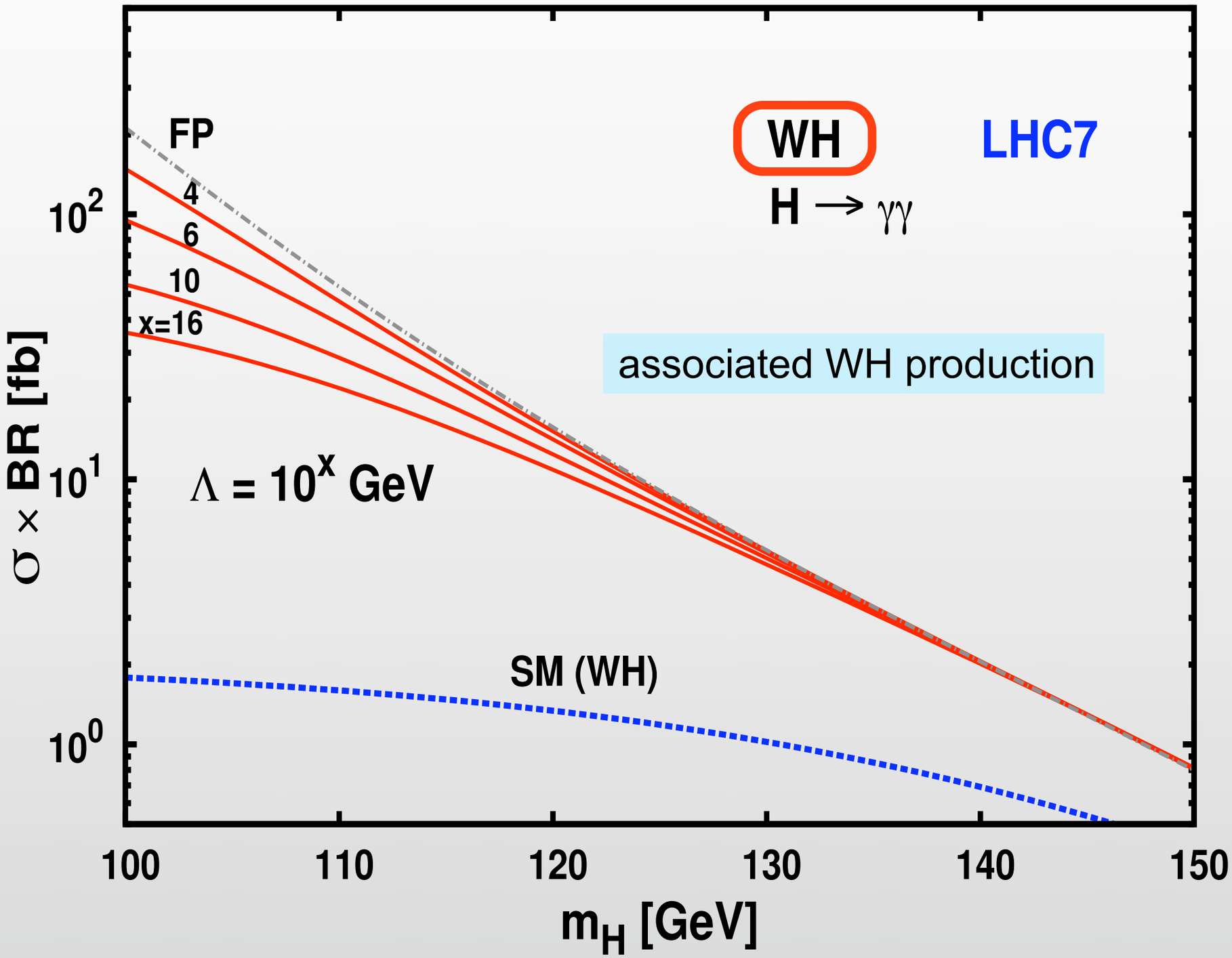
- Effective Y_f's increase at lower m_H and larger Λ
- $BR(bb) \sim BR_{SM}$ for $m_H \sim 100$ GeV and $\Lambda \sim 10^{16}$ GeV

LHC (VBF) : H → γγ



- nice sensitivity to Λ for m_H lower than ~125 GeV !

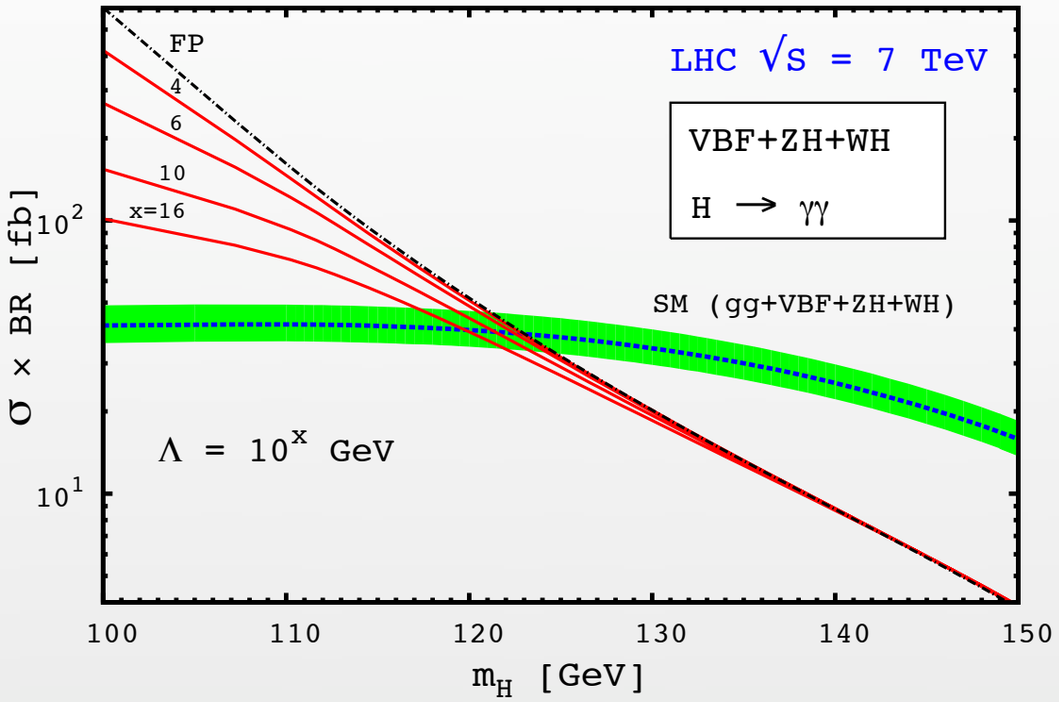
LHC (WH) : H → γγ

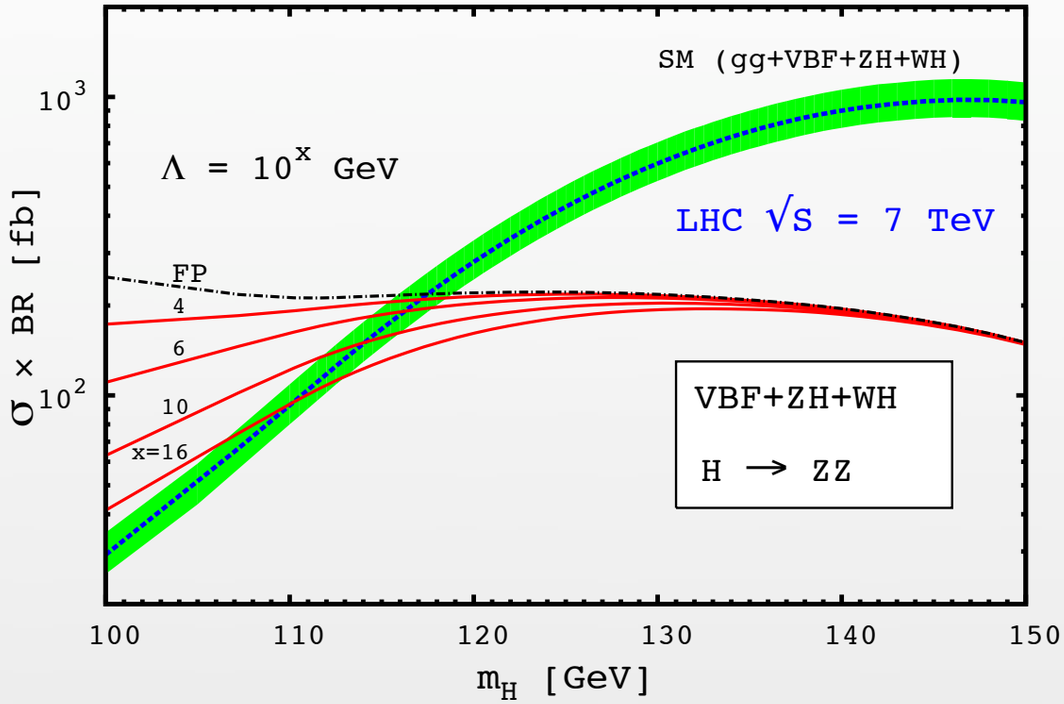


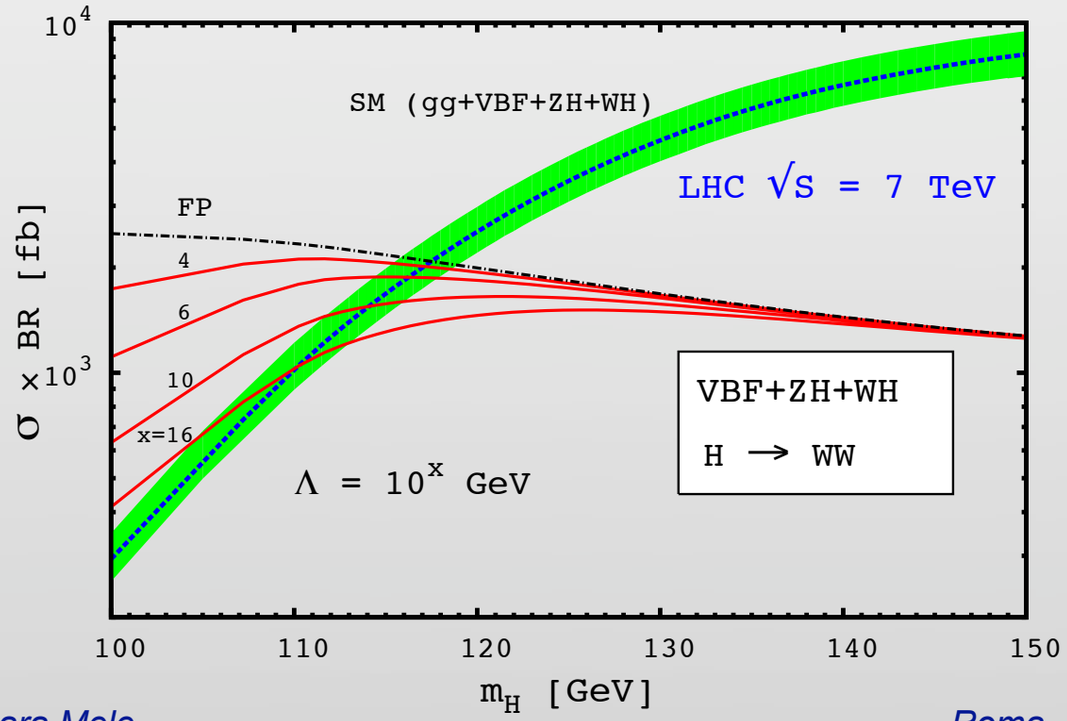
- promising role of exclusive associated production !

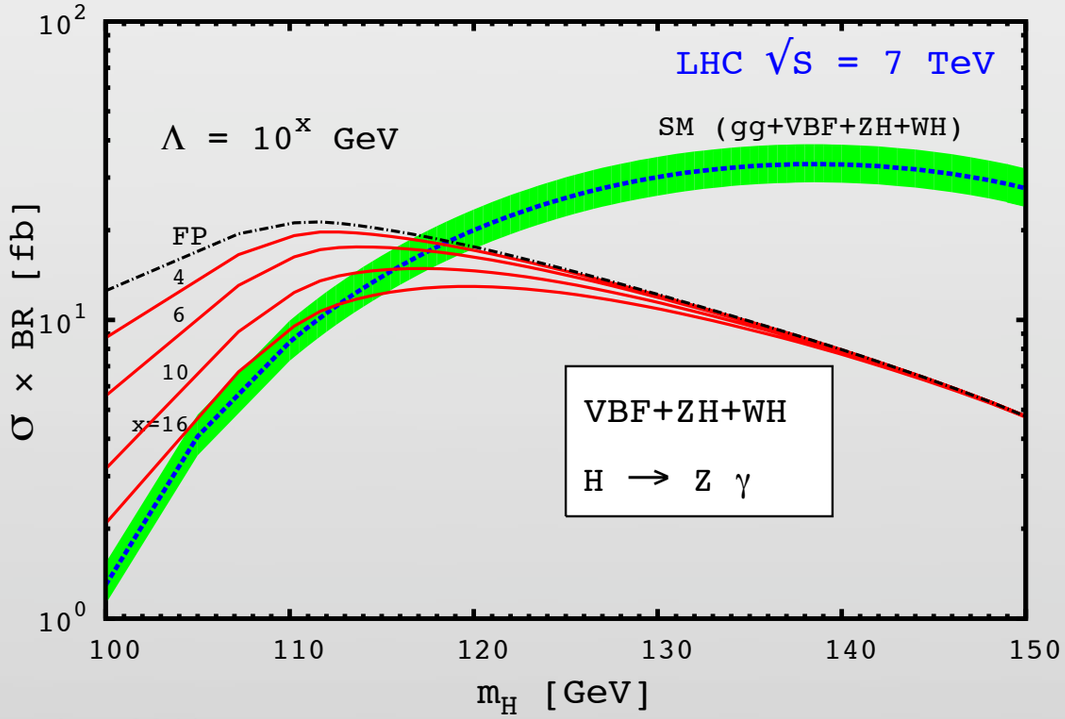
FP vs SM : inclusive rates

- m_H matching point with SM values depends on Λ



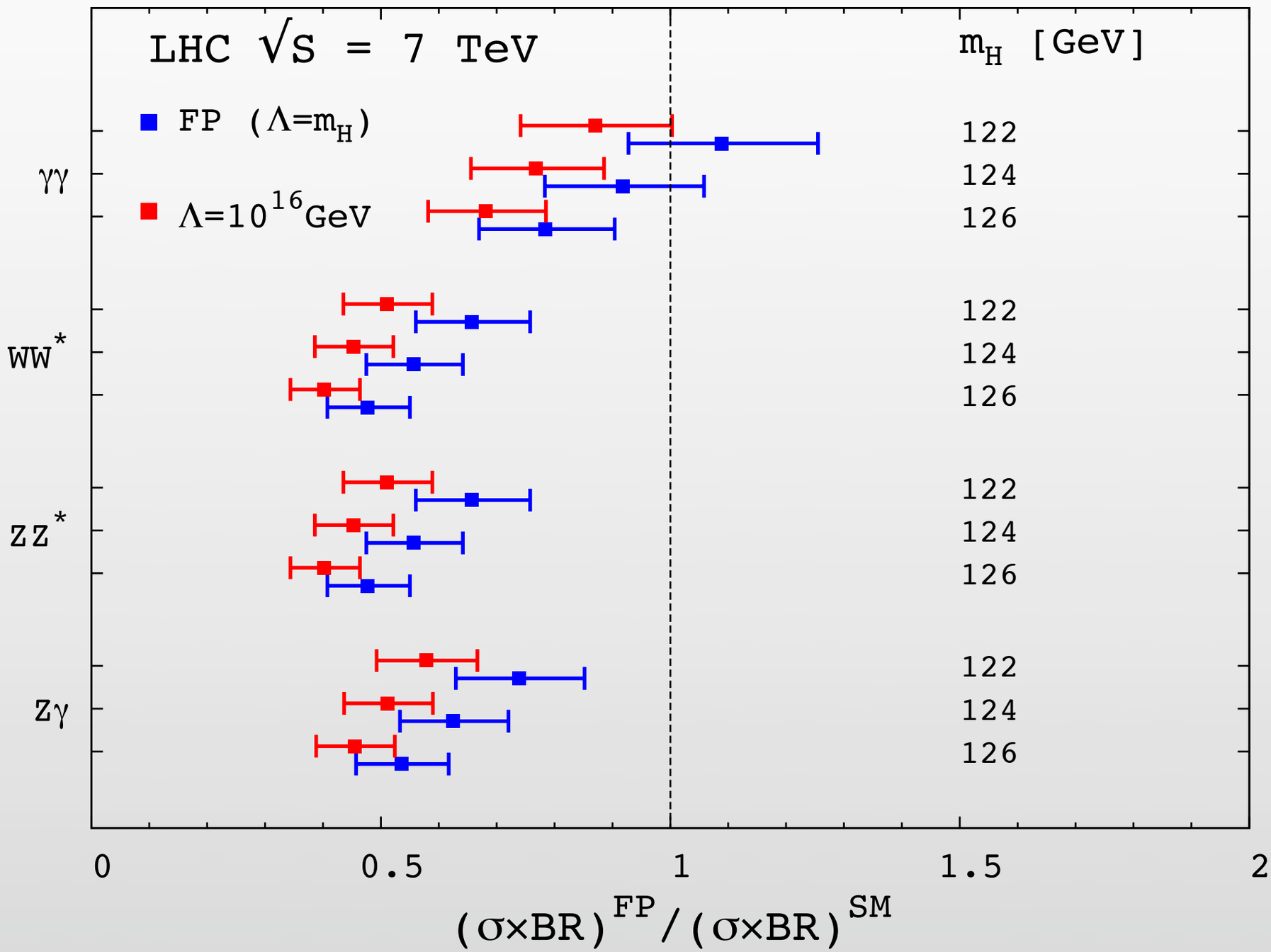




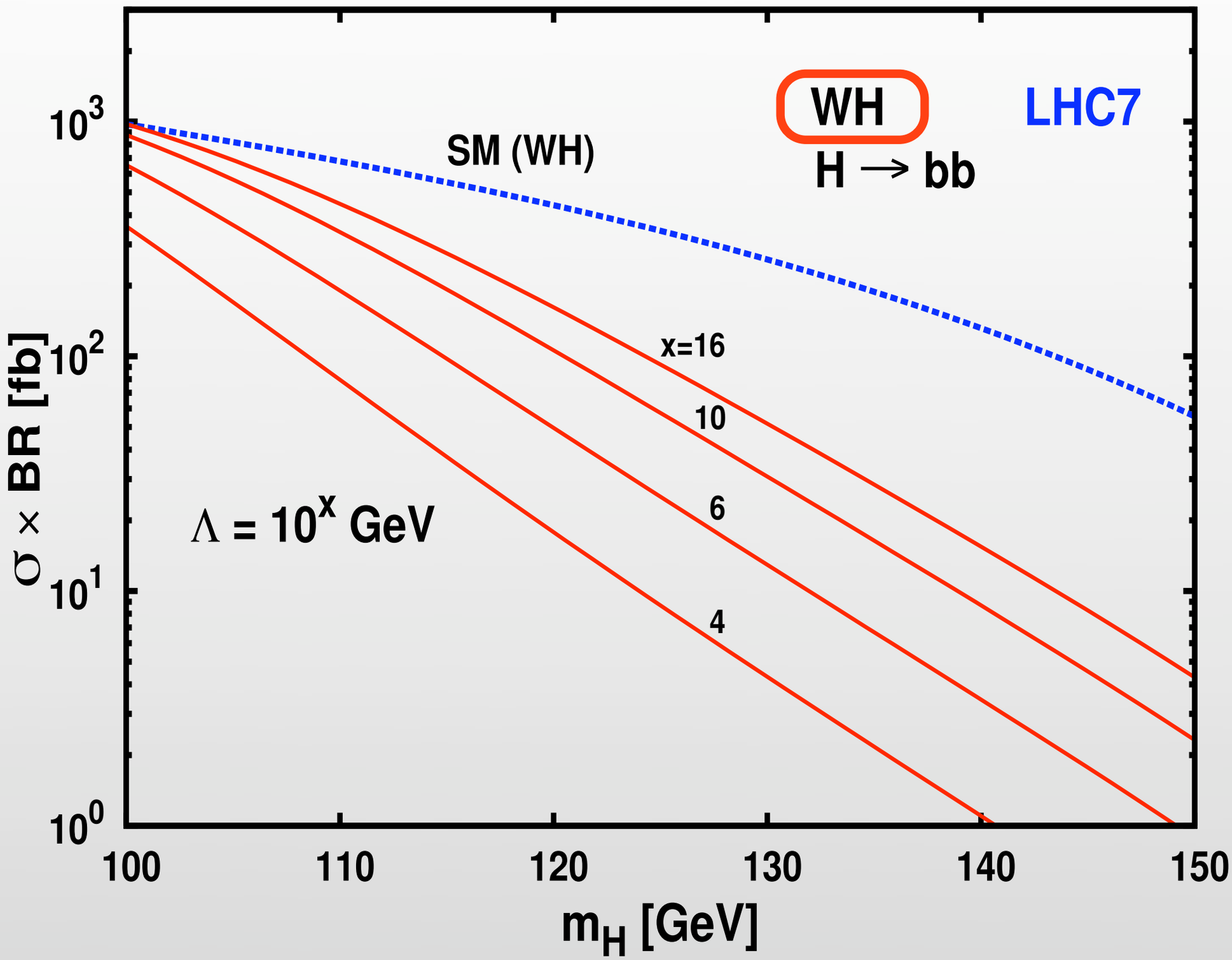


FP/SM Rate Ratio around 125 GeV

- Blue = Tree Level FP ; Red = max radiative effect

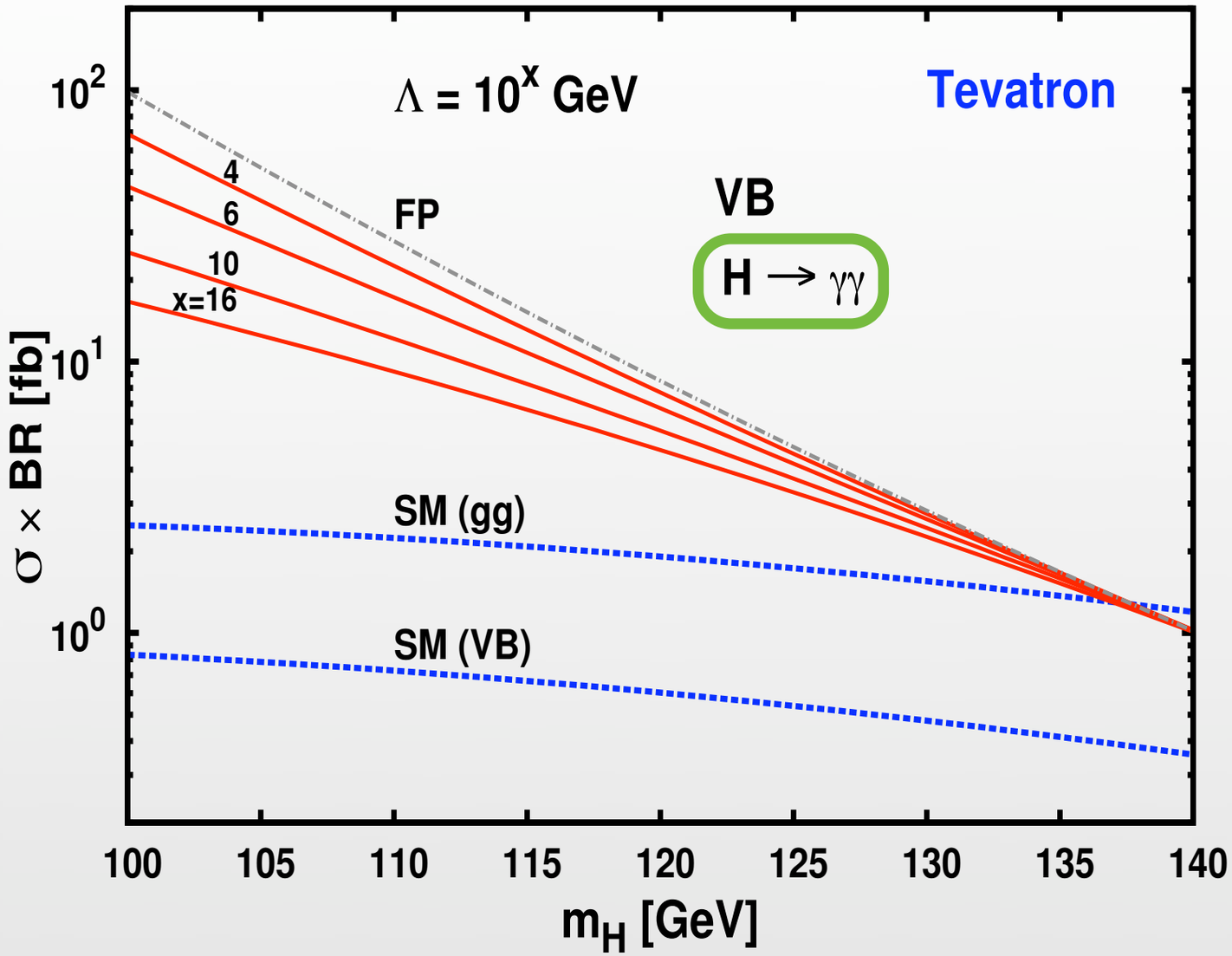


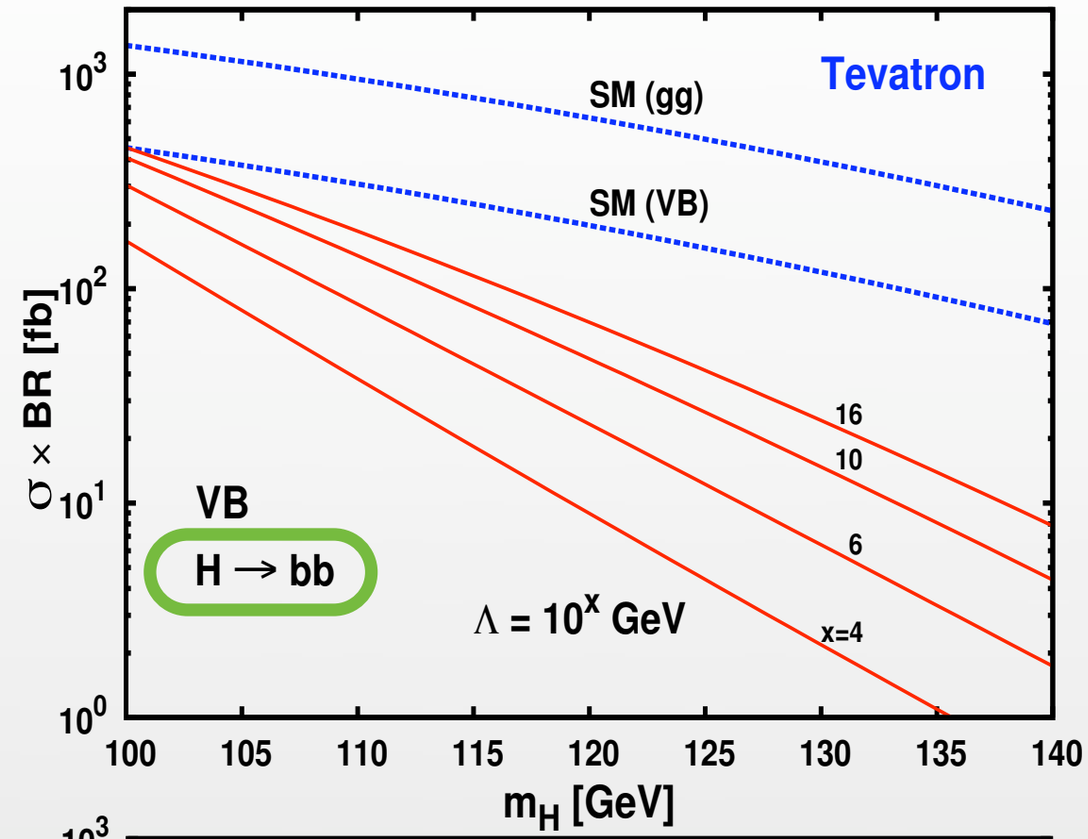
LHC (WH) : H → bb

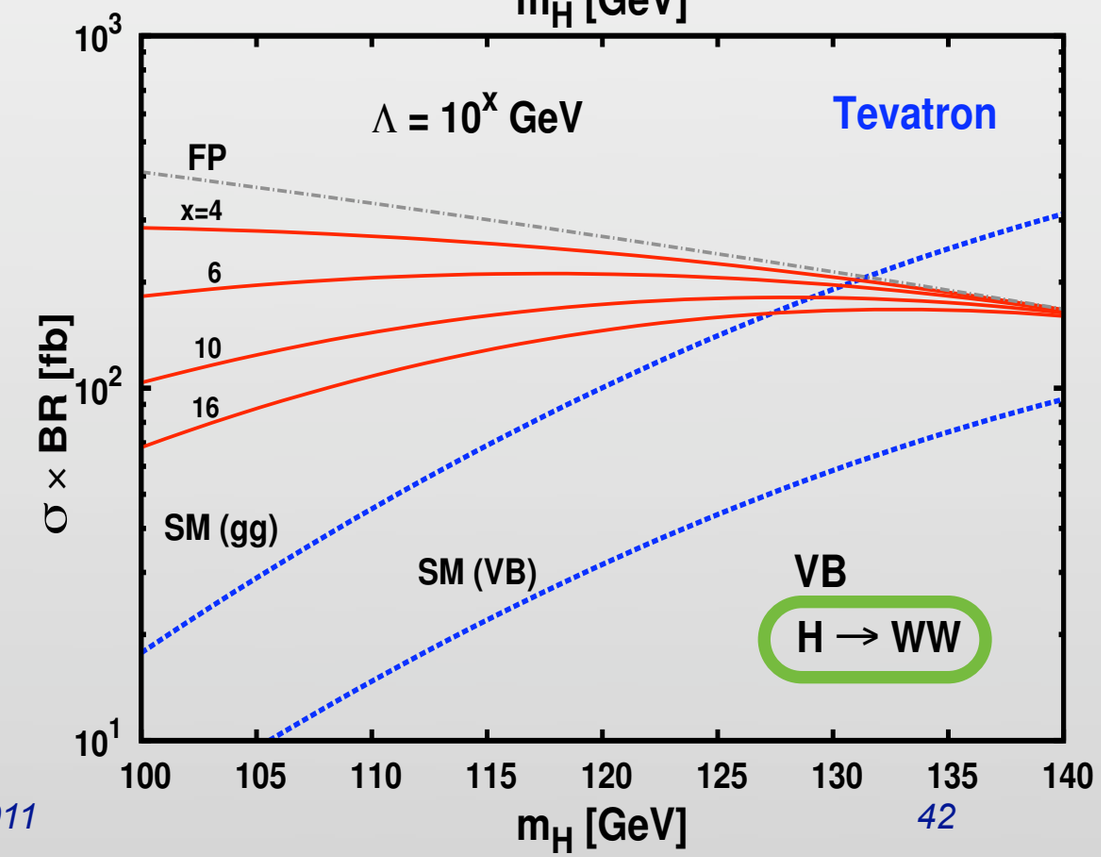


- how far can one push boosted Higgs techniques ?

Tevatron (VB=WH+ZH+VBF)

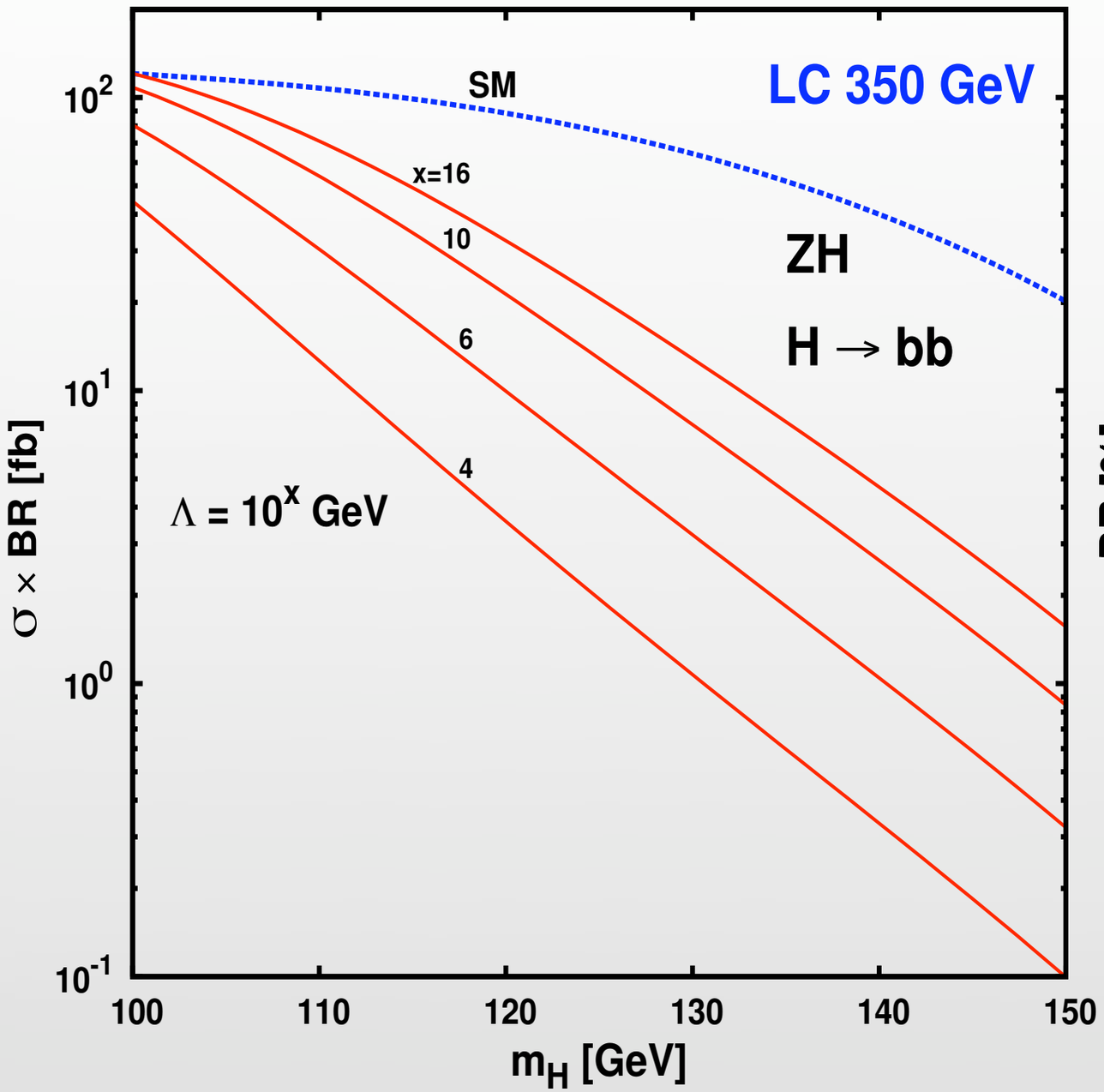


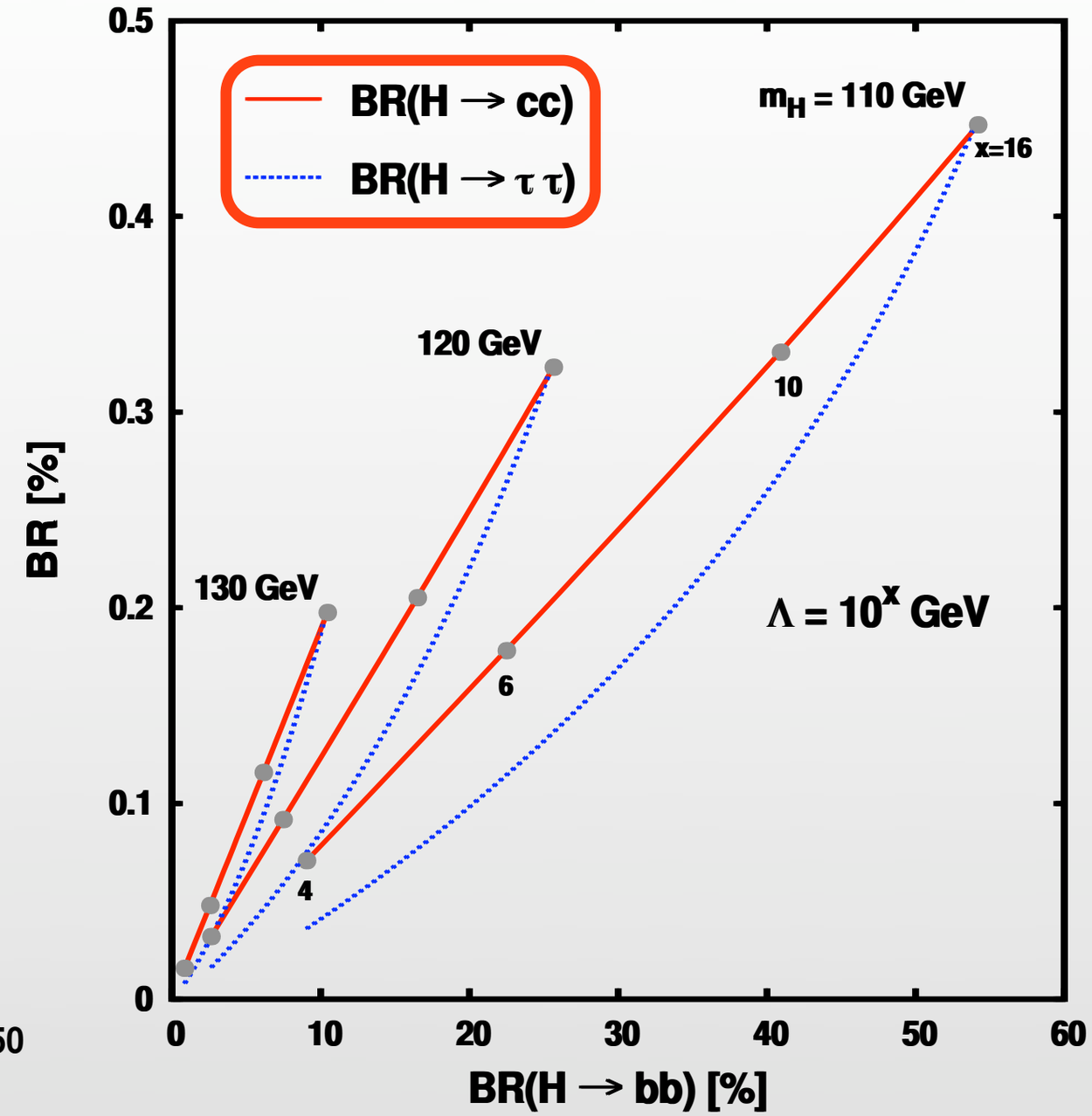




- Tevatron can constrain the model !

Linear Collider case





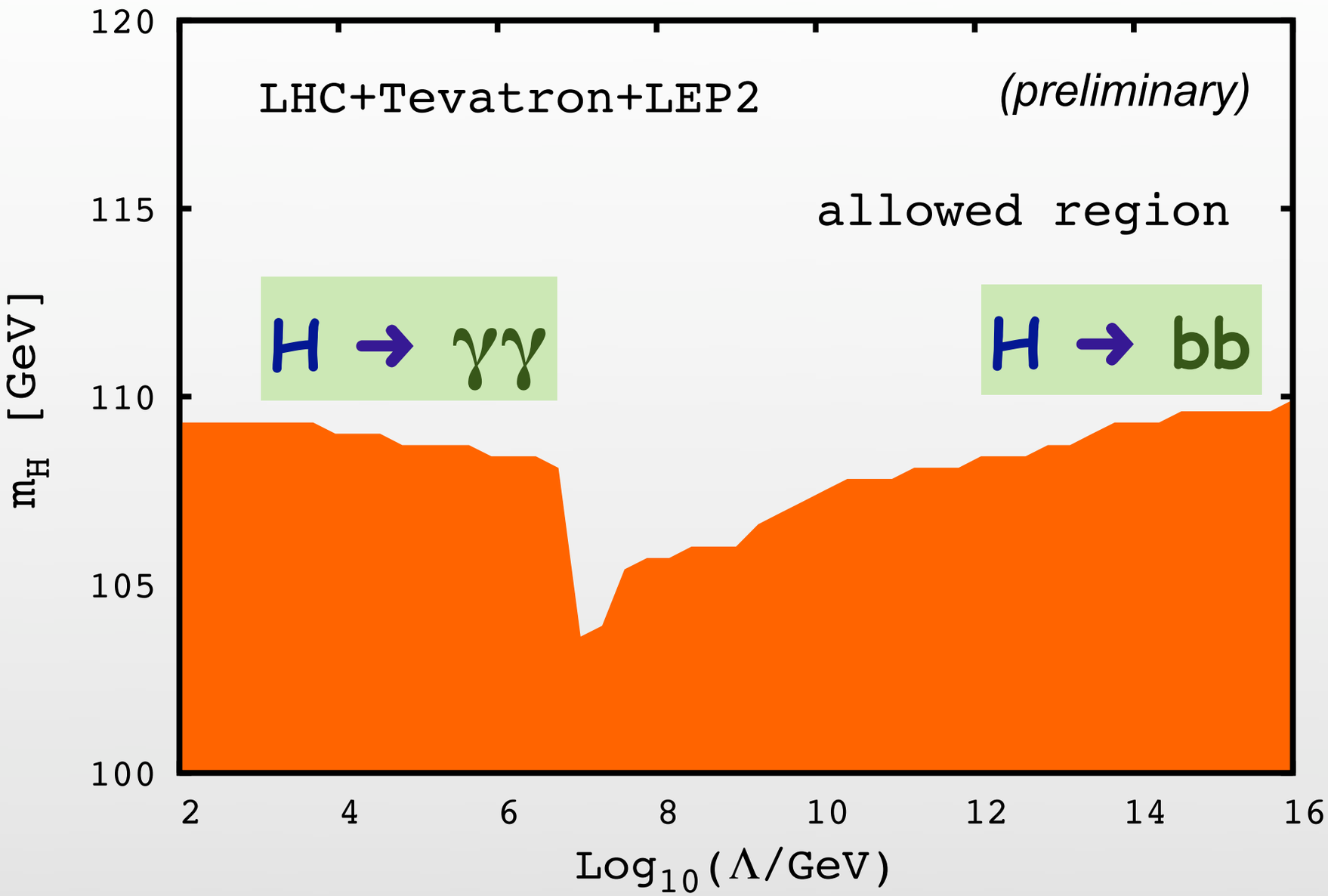
- testing BR's correlations crucial to prove Effective Y_f's scenario !

exp lower bounds on improved FP m_H

- bounds in "Effective Y_f" scenario need dedicated studies !

- in general weaker than in tree level FP Higgs, and depending on Λ

exp bounds : m_H^{min} vs Λ

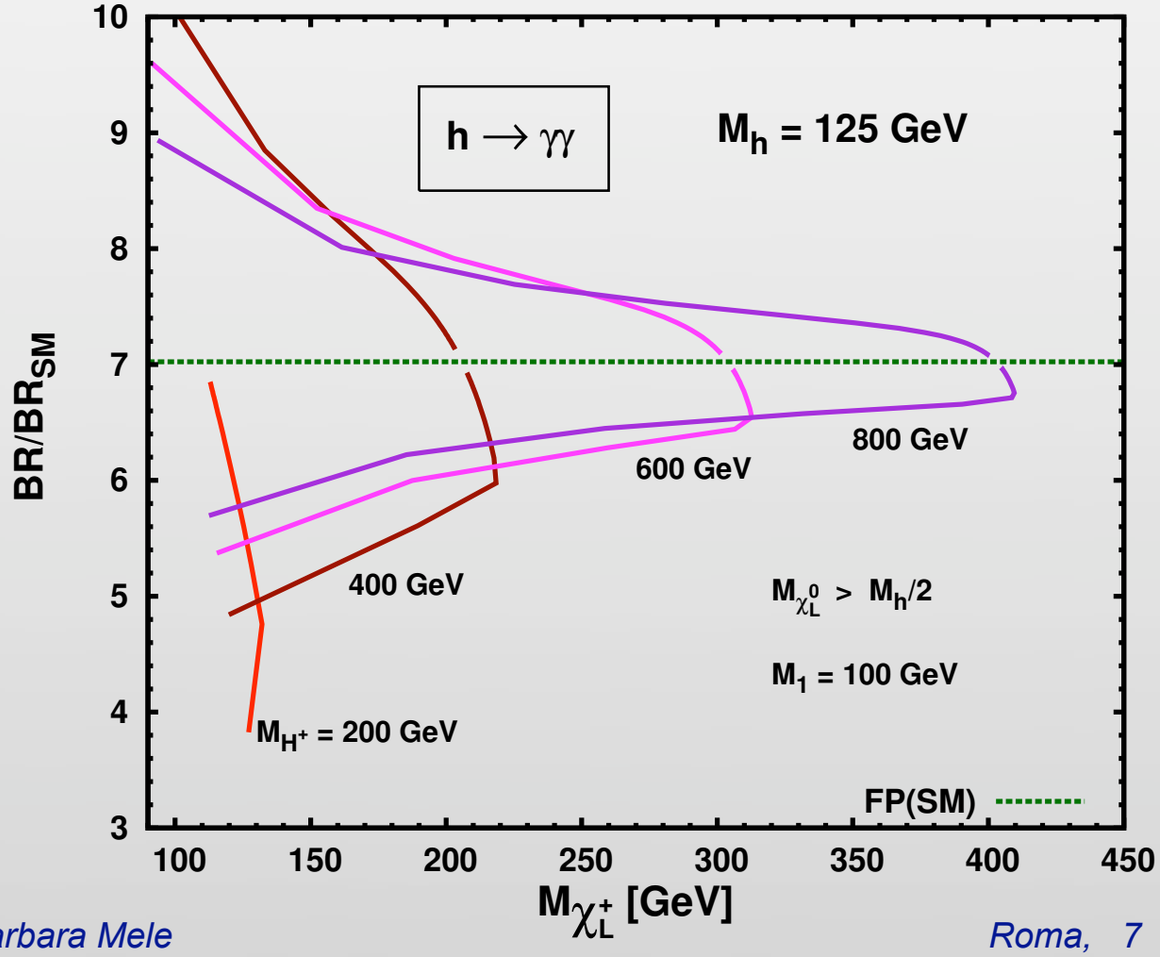


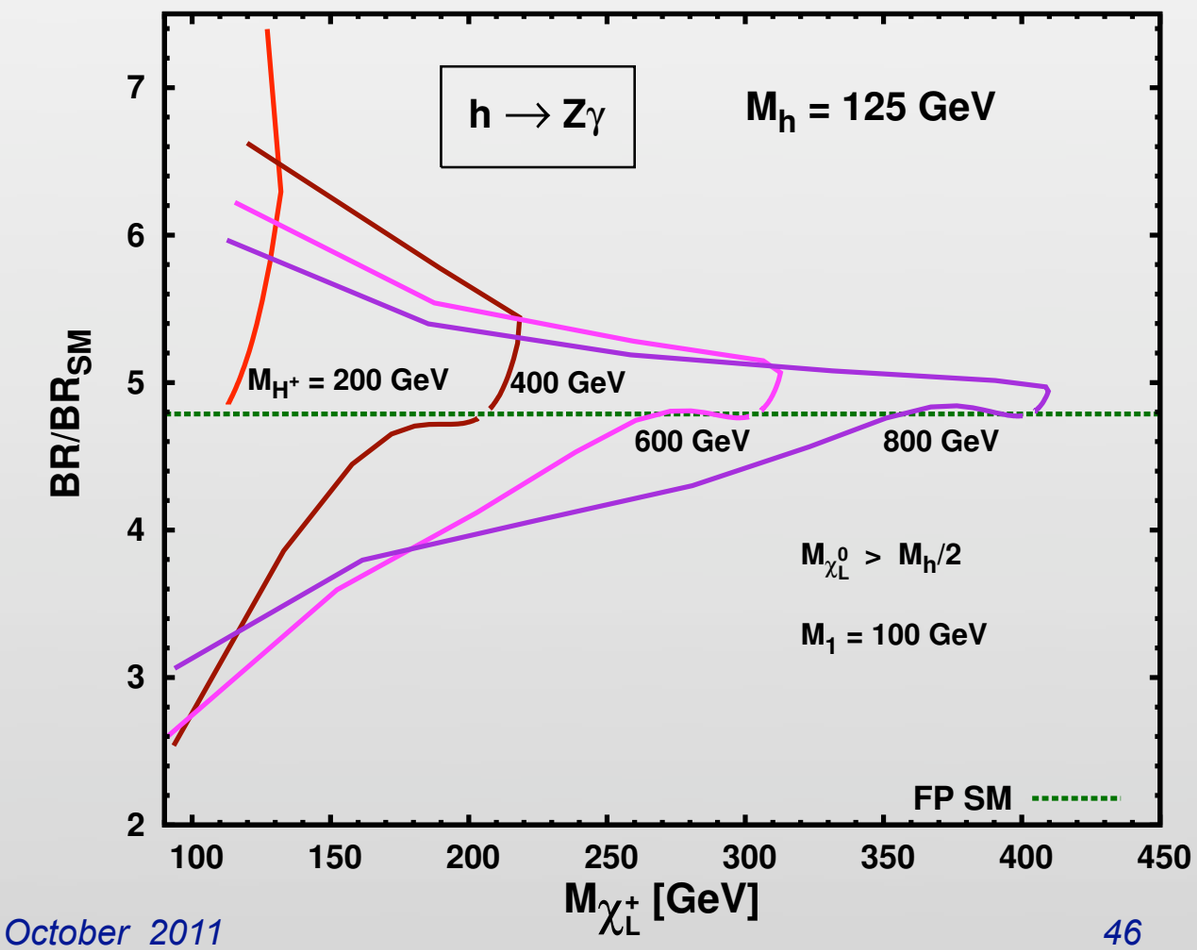
based on Higgsbounds-3.4.0beta (end 2011, to be updated)

- interplay between the $H \to \gamma\gamma$ and $H \to bb$ channels
  → non-trivial dependence of m_H^{min} on Λ !

SuSy model with FP Higgs ?

- in MSSM with Y_f=0, radiative corr.s not big enough to generate m_H ~ 125 GeV from a tree-level value <M_Z
- need nMSSM (with Z_3 discrete symmetry Yf=0 in SuperV)
- SUSY fine-tuning relaxed by factor $N_c y_t^4/g^4 \sim 25$
- sparticle masses solve naturalness for m~2-3 TeV





Summary on Fermiophobic Higgs

- Fermiophobic Higgs scenario is unstable !
  ChSB regenerates Yukawa couplings !

- if the scale connected to the origin of m_f's is large, Higgs BR's into heavy fermions can be moderately lower than the SM ones !

- PHENO: intermediate scenario between pure FB Higgs and SM Higgs; production mechanism is cleaner than SM (higher-pT Higgs) since gg production is almost missing

- setting exp limits on this scenario needs dedicated analysis !

Outlook

- the LHC is by now mature for an early Higgs discovery (waiting for the 4th-July CERN seminar...)
- the confirmation of the hint at 125 GeV in $\gamma\gamma$ would wide open the stage of particle-properties determination
- present plan : after 2012, running LHC from end 2014 up to 2021 collecting a few 100 fb^{-1} at 14 TeV
- whatever we will find (about Higgs/Higgses or beyond that), and however appealing for the media we will make it, the outcome is going to deeply affect our comprehension of fundamental interactions in the many-TeV regime !

LHC 10 year plan

	J	F	M	A	M	J	J	A	S	O	N	D
2011		1	2	3	4	5	6	7	8	9	IONS	
2012			1	2	3	4	5	6	7	8	IONS	
2013	LS1 - SPLICE CONSOLIDATION											
2014									RECOM	RECOM	1	2
2015	1	2	3	4	5	6	7	8	9	10	IONS	
2016		1	2	3					8	9	IONS	
2017		1	2	3	4	5	6	7	8	9	IONS	
2018	LS2											
2019		1	2	3	4	5	6	7	8	9	IONS	
2020		1	2	3					8	9	IONS	
2021		1	2	3	4	5	6	7	8	9	IONS	
2022	HL-LHC upgrade											

LS1

PHYSICS AT 6.5/7 TeV

LS2

"ULTIMATE" PHYSICS

LS3

HL-LHC

Technical stop or shutdown
Proton physics
Ion Physics
Recommissioning

NB: not yet approved