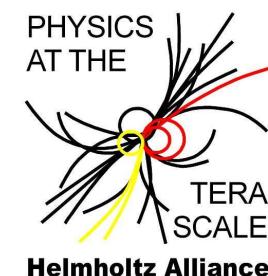


# Constraining Higgs Sectors using **HiggsBounds 3.6.1**

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## outline :

- HiggsBounds
  - overview of version 3.6.1 [beta]
  - some implementation details
  - status and outlook of the project
- Constraining Models
  - SM versus 4th generation model
  - SM+invisible model
  - Randall-Sundrum scalar sector
  - MSSM

- HiggsBounds

- overview of version 3.6.1 [beta]

- overview of version 3.6.1 [beta]

HiggsBounds : [Bechtle, OBr, Heinemeyer, Stefaniak, Weiglein, Williams '08-'11]

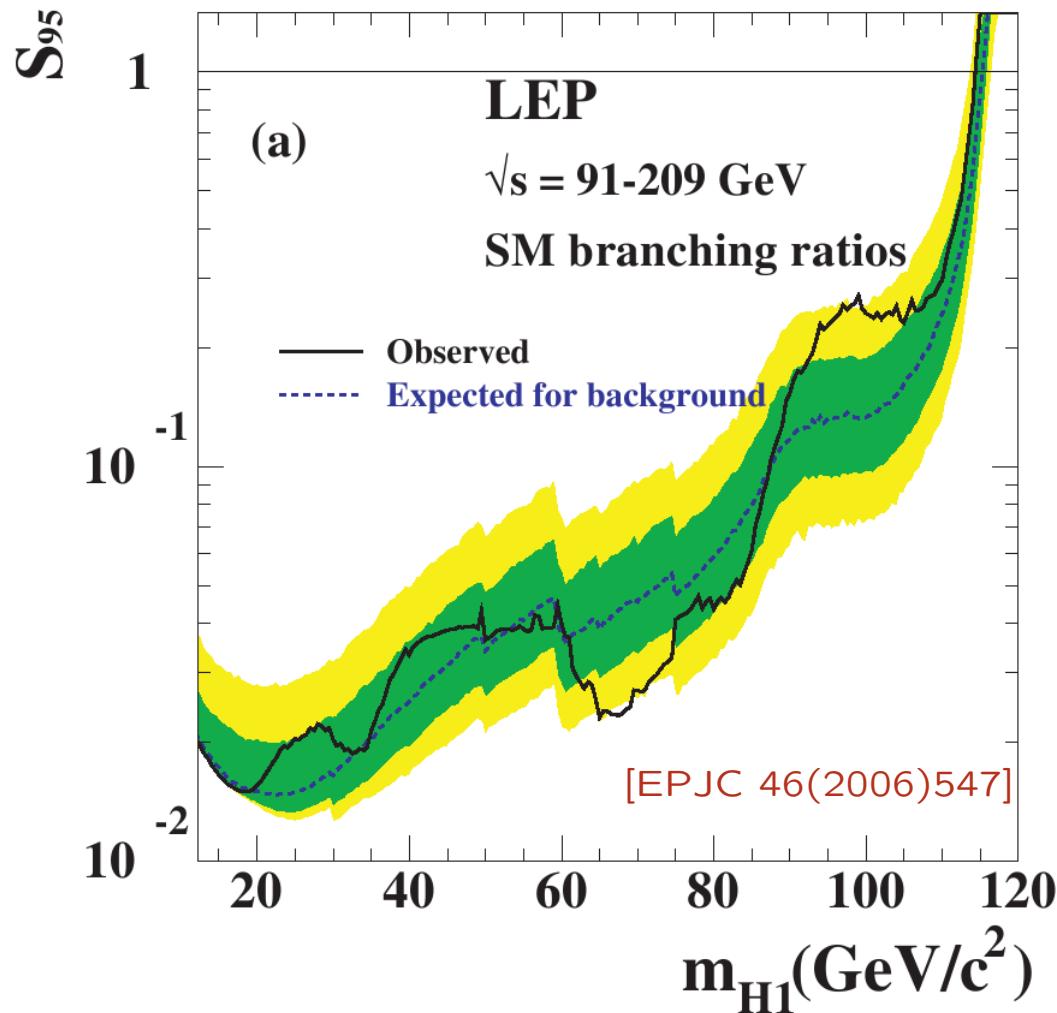
tests models with arbitrary Higgs sectors against exclusion bounds from direct searches.

- easy access to all relevant Higgs exclusion limits including information not available in the publications.  
(e.g. expected 95% CL cross section limits)
- applicable to models with arbitrary Higgs sectors (narrow widths assumed)  
HiggsBounds Input: the predictions of the model for:  
# of **neutral & charged** Higgs bosons  $h_i$  ,  $m_{h_i}$ ,  $\Gamma_{\text{tot}}(h_i)$ ,  $\text{BR}(h_i \rightarrow \dots)$ , production cross section ratios (wrt reference values)
- combination of results from LEP, Tevatron and LHC possible
- three ways to use HiggsBounds:
  - command line, □ subroutines (Fortran [77]/90), □ web interface:  
[projects.hepforge.org/higgsbounds](http://projects.hepforge.org/higgsbounds)

- some implementation details

## Higgs search results: example 1: LEP SM combined limit

exclusion = rejection of the Higgs hypothesis



$$S_{95}(m_{H1}) := \frac{\sigma_{\min}}{\sigma_{\text{SM}}}(m_{H1})$$

where  $\sigma_{\min}(m_{H1})$  is the Higgs signal cross section where data and Higgs hypothesis are compatible with only 5% probability.

A SM-like model with

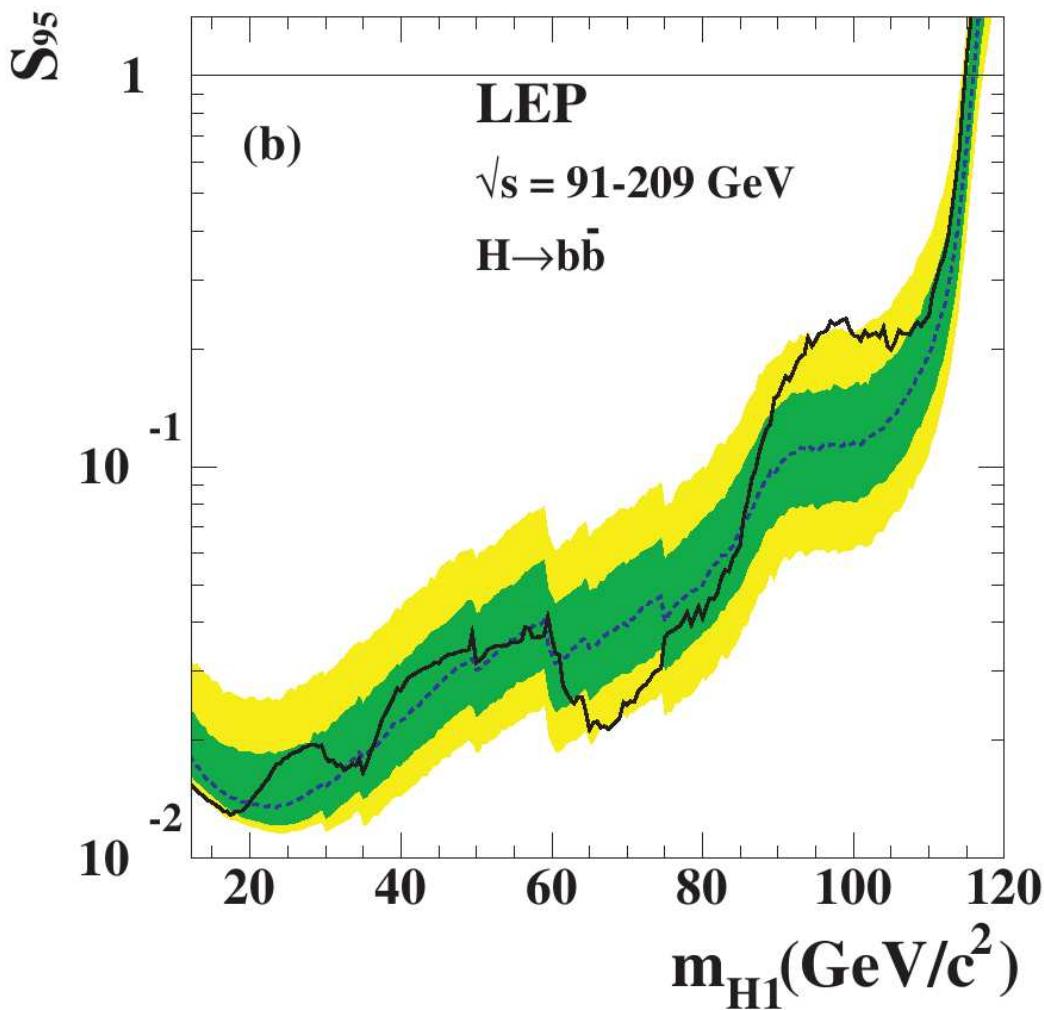
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\min}(m_{H1})$$

$$\text{or } \frac{\sigma_{\text{model}}(m_{H1})}{\sigma_{\min}(m_{H1})} > 1$$

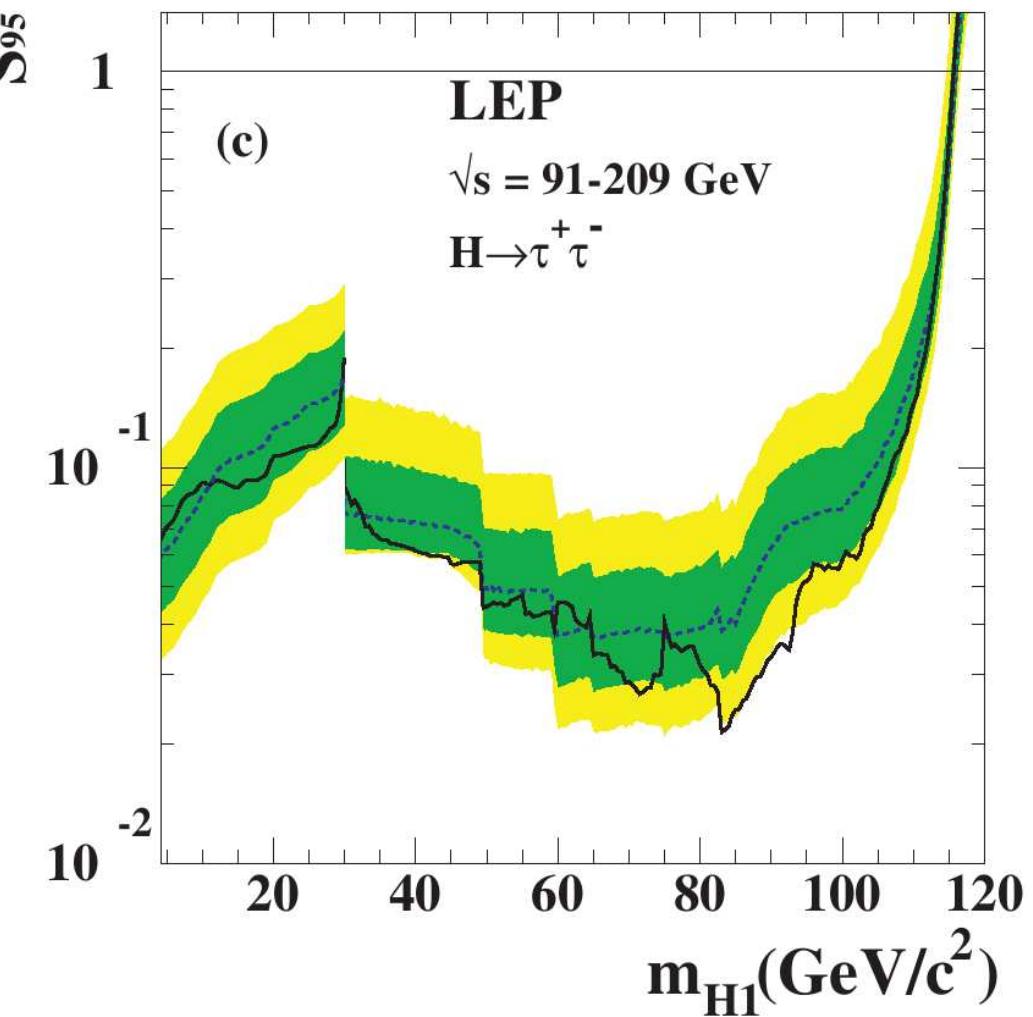
is said to be excluded at the 95% C.L.

example 2: LEP single topology limits, assuming  $HZ$  production and ...

a) ...  $\text{BR}(H \rightarrow b\bar{b})=1$

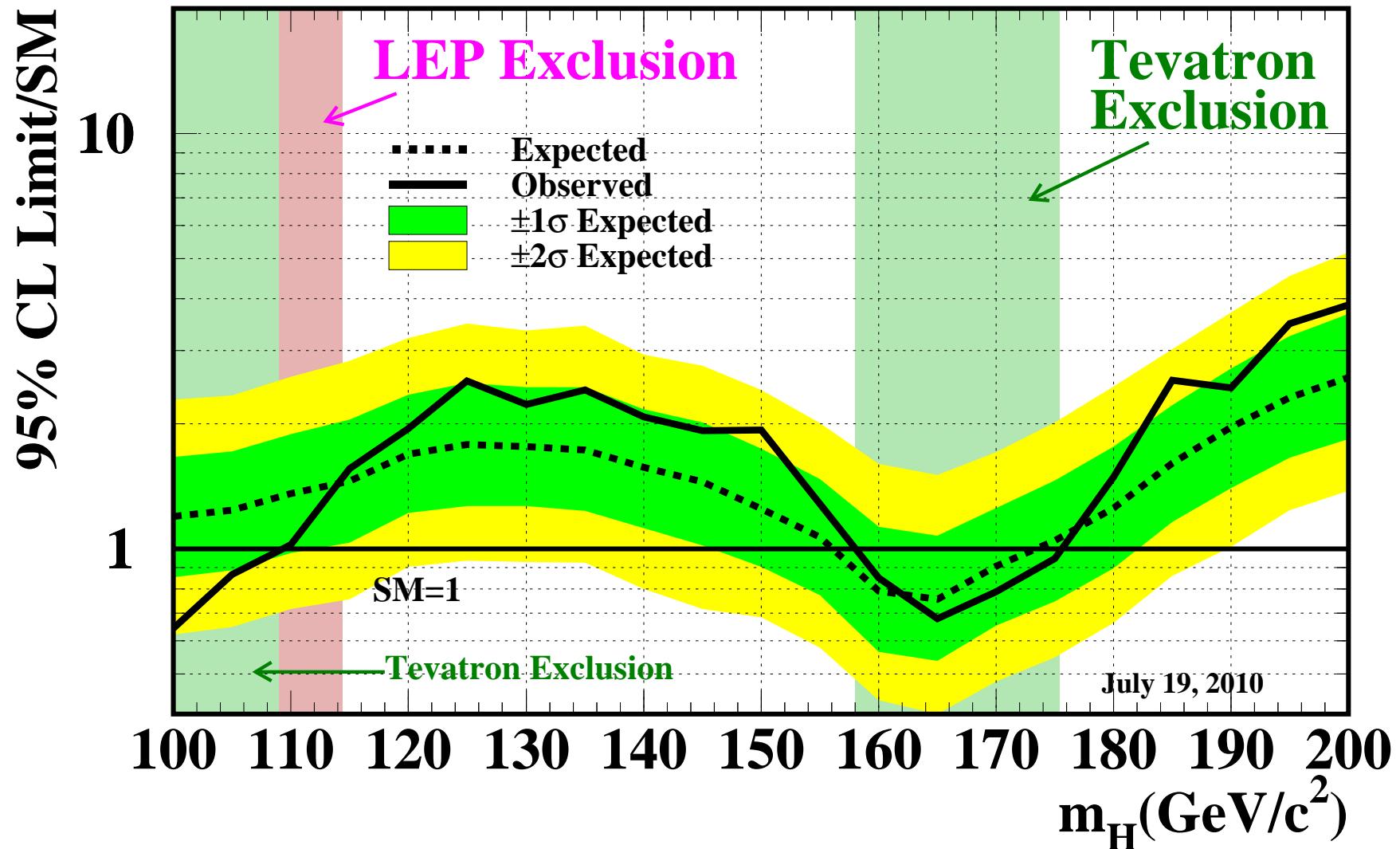


b) ...  $\text{BR}(H \rightarrow \tau^+\tau^-)=1$



example 3: Tevatron SM combined limit [CDF & DØ '10]

Tevatron Run II Preliminary,  $\langle L \rangle = 5.9 \text{ fb}^{-1}$



Considering many analyses for many Higgs bosons:

first a definition : **analysis application  $X$ :**

application of a certain analysis  $A_i$   
to a certain Higgs boson  $h_k$  (or a set)

that means:  $X$  corresponds to:

- \* a signal topology (or a set),
- \* the corresponding cross section prediction  $\bar{\sigma}_{\text{model}}(X)$ ,
- \* observed cross section limit  $\bar{\sigma}_{\text{observed}}(X)$  of analysis  $A$ ,
- \* expected cross section limit  $\bar{\sigma}_{\text{expected}}(X)$  of analysis  $A$ .

## Basic idea:

for an analysis application  $X$ :

- evaluate model prediction

$$\bar{\sigma}_{\text{model}}(X) = \frac{[\sigma \times \text{BR}]_{\text{model}}}{[\sigma \times \text{BR}]_{\text{ref}}} \quad (\text{reference: usually SM})$$

of the corresponding search topology for given Higgs masses + deviations from the reference.

- read off the corresponding observed 95% C.L. limit:  $\bar{\sigma}_{\text{observed}}(X)$ .
- If  $\bar{\sigma}_{\text{model}}(X) > \bar{\sigma}_{\text{observed}}(X)$  the model is excluded by this analysis application at 95% C.L.

→ Problem : how to combine analysis applications without losing the 95% C.L. ?

Answer: We can't do that.

Only a dedicated experimental analysis can do that.

However: we can always use the analysis application of highest statistical sensitivity.

How to preserve the 95% C.L. limit:

- Obtain for each  $X$  the experimental expected limit  $\bar{\sigma}_{\text{expected}}(X)$ .
- Determine the analysis application  $X_0$  with the highest sensitivity for the signal, i.e. of all  $X$ , find  $X_0$  where  $\frac{\bar{\sigma}_{\text{model}}(X)}{\bar{\sigma}_{\text{expected}}(X)}$  is maximal.
- If for this analysis application  $\bar{\sigma}_{\text{model}}(X_0) > \bar{\sigma}_{\text{observed}}(X_0)$ , the model is excluded at 95% C.L. by  $X_0$ .

- status and outlook of the project

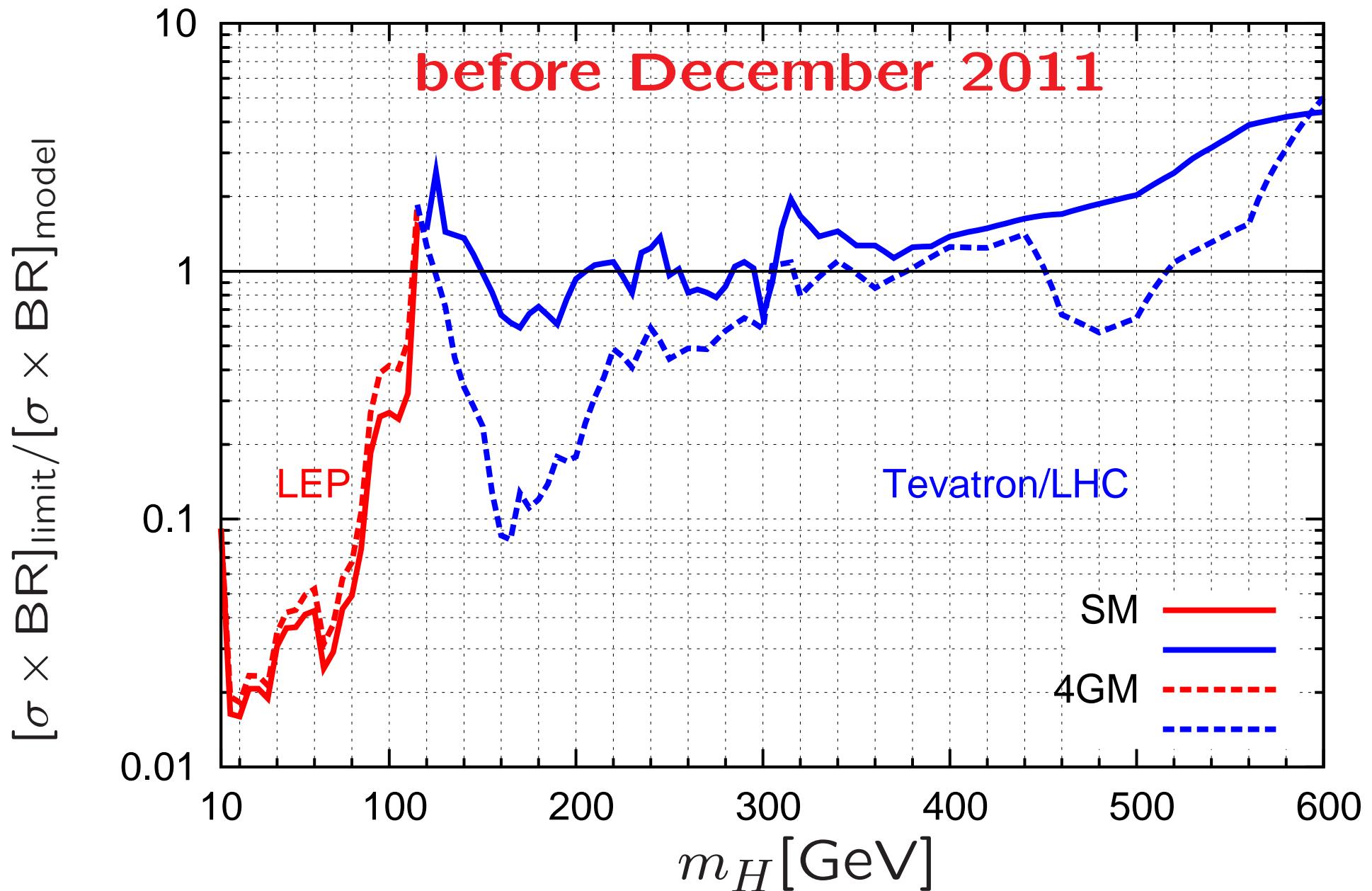
## ■ HiggsBounds: status and outlook

- The code is publicly available since Feb. 2009 (current version: 3.6.1 beta)  
→ [projects.hepforge.org/higgsbounds](http://projects.hepforge.org/higgsbounds)
  - Tevatron & LHC results up to December 2011 included
  - extended functionality ( $H^\pm$  searches, `onlyP` analyses selection, ...)
  - HiggsBounds 3.6.1 beta available to download
- Reception very good (> 100 users). Code used in/by:  
[FeynHiggs](#), [CPsuperH](#), [Fittino](#), [MasterCode](#), [2HDMC](#), [DarkSusy](#),  
[SuperIso](#), etc.
- Current work/plans:
  - finalising Fortran 77 version
  - going out of beta status
  - include new LHC/Tevatron results as they come out
  - ...

- Constraining Models

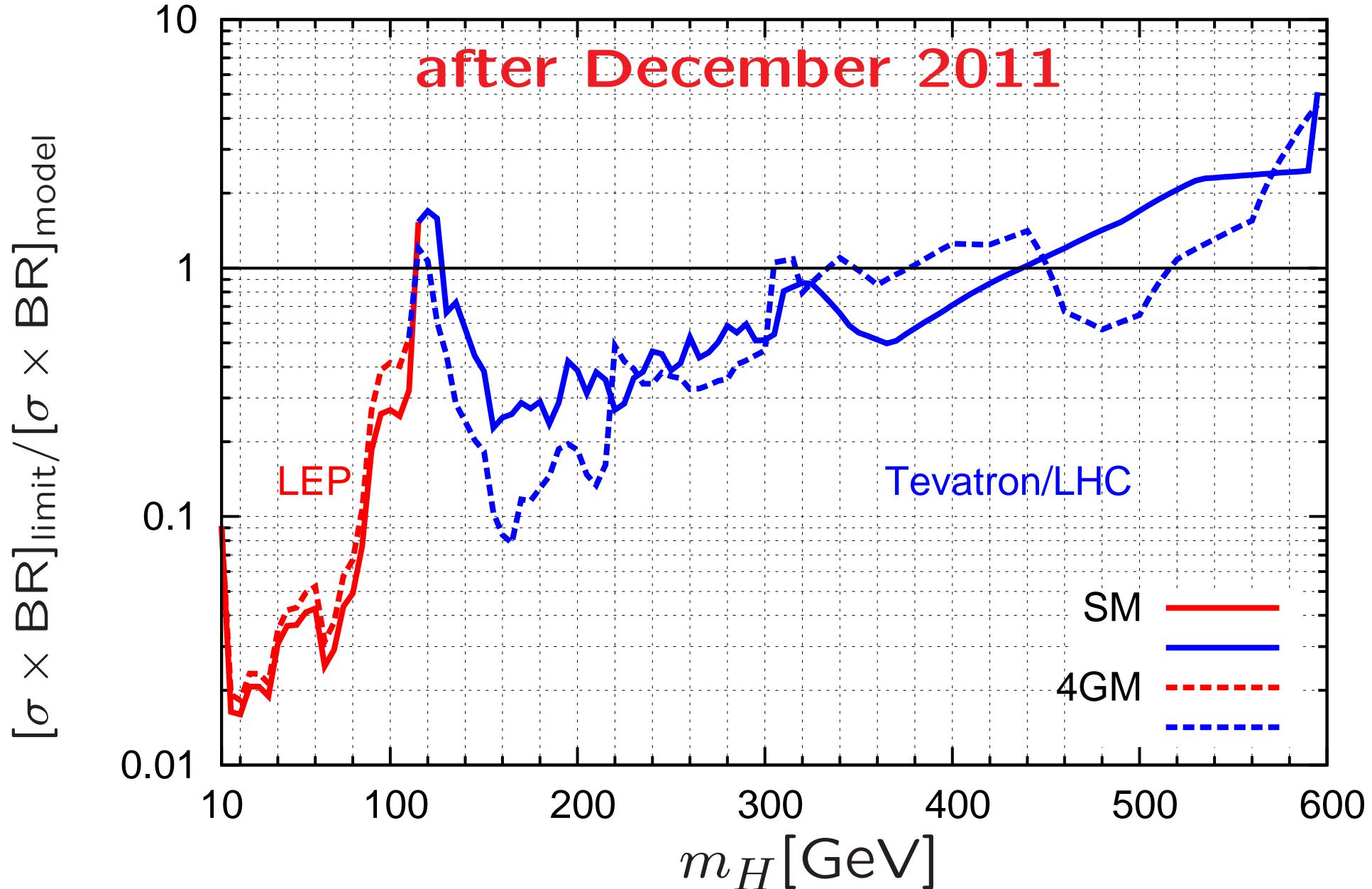
- SM versus 4th generation model

- SM versus 4th generation model [using  $\Gamma(H \rightarrow gg)_{\text{model}} = 9 \times \Gamma(H \rightarrow gg)_{\text{SM}}$ ]



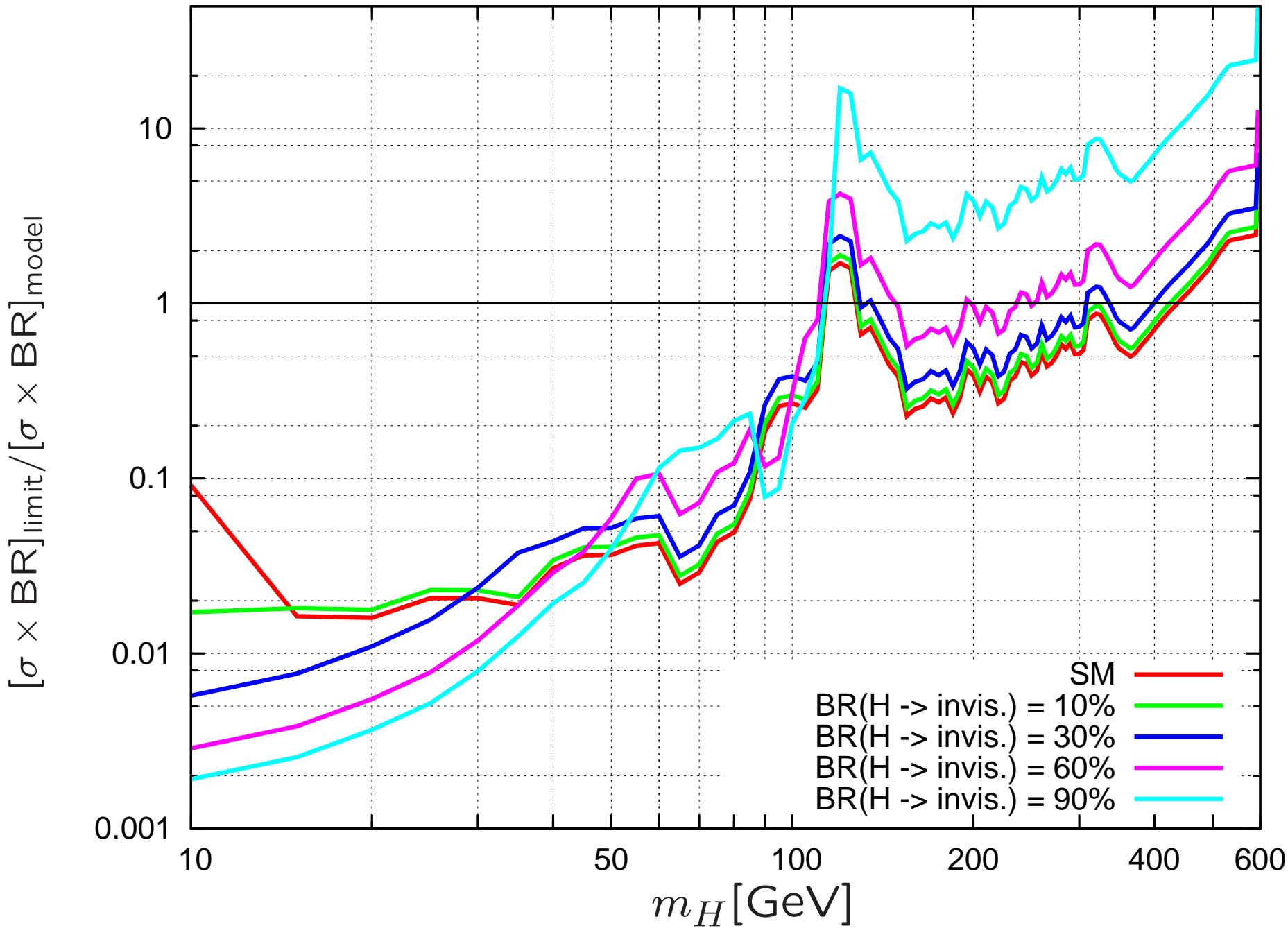
[ Constraining Models, SM vs. 4th generation model ]

– SM versus 4th generation model [using  $\Gamma(H \rightarrow gg)_{\text{model}} = 9 \times \Gamma(H \rightarrow gg)_{\text{SM}}$ ]

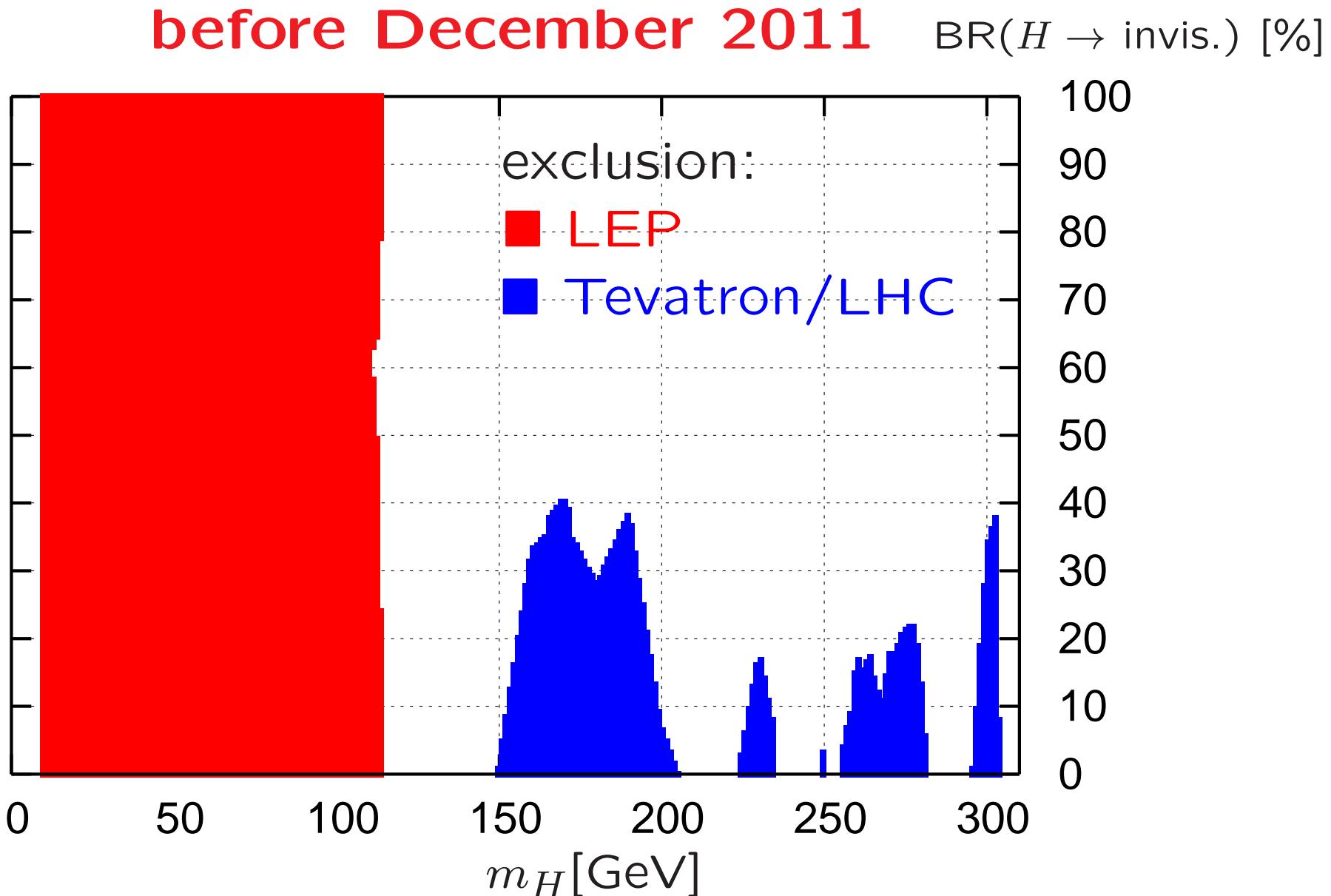


- SM+invisible model

- SM+invisible model: SM + one extra decay mode  $H \rightarrow \text{invisible}$

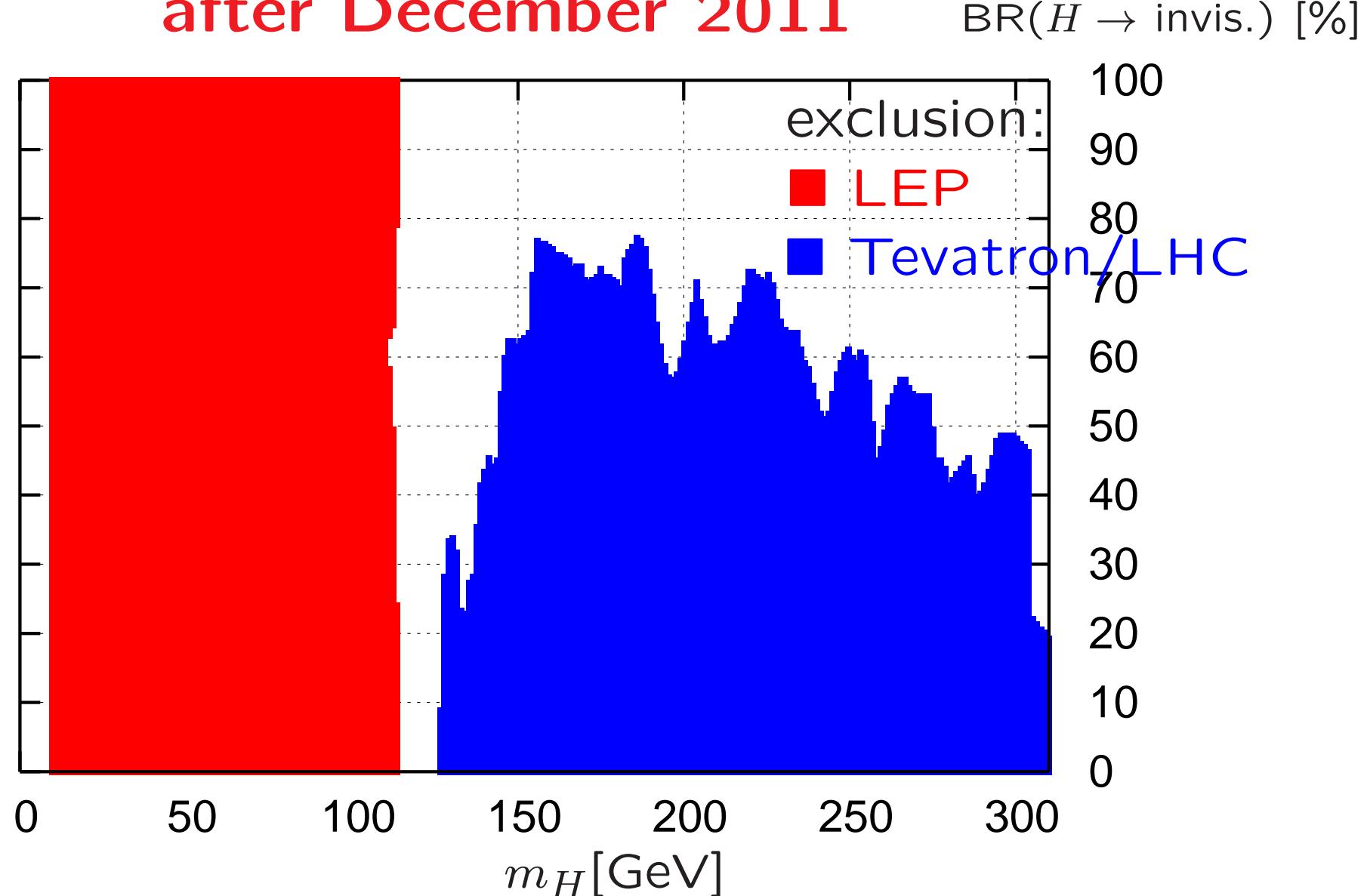


- SM+invisible model: SM + one extra decay mode  $H \rightarrow$  invisible

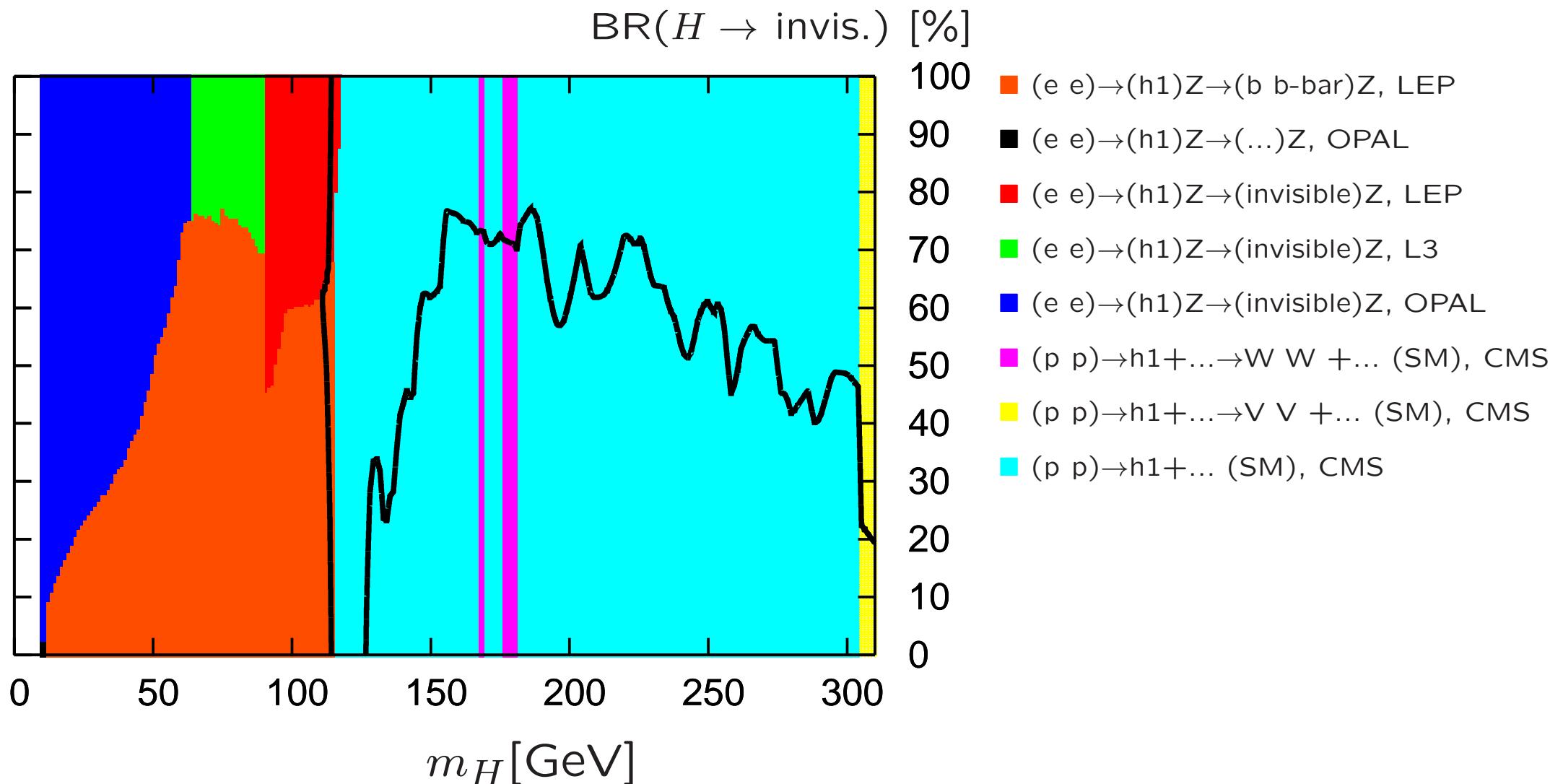


- SM+invisible model: SM + one extra decay mode  $H \rightarrow \text{invisible}$

after December 2011



- SM+invisible model: SM + one extra decay mode  $H \rightarrow \text{invisible}$



- Randall-Sundrum scalar sector  
December 2011 results not included (sorry)

## – Randall-Sundrum scalar sector

## ■ Randall Sundrum model basics:

[Randall, Sundrum '99]

- space has  $D = 3 + 1$  dimensions, metric:

$$ds^2 = e^{-2kr_c\phi} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2, \quad \phi \in [0, \pi].$$

Spacetime is a slice of 5d anti-de-Sitter space:

two boundaries:  $\phi = \pi$  : IR brane (our 3-space)

$\phi = 0$  : UV brane

- $k, r_c^{-1}$  are  $\mathcal{O}(M_{\text{Pl}})$  with  $kr_c \approx 12$ .

This “little hierarchy” can be generated & stabilized [Goldberger, Wise '00]  
 $\Rightarrow$  fluctuations of  $r_c$ : scalar d.o.f  $\varphi$ , gets a VEV  $\Lambda_\phi$

- resolution of the hierarchy problem: Why is the EW scale  $\ll M_{\text{Pl}}$  ?: mass parameters in the fundamental 5d model  $m_0$  appear in our visible space as:

$$m = m_0 e^{-kr_c\pi} \approx m_0 10^{-16}.$$

- propagating in extra dimension:

originally: only gravity,

nowadays: gauge bosons, fermions [EW & flavour observables!]

But: Higgs needs to be localized on/near IR brane [hierarchy problem!]

## ■ Randall Sundrum scalar sector:

- There is one graviscalar in 5d: the **radion**  $\varphi$   
(typically the lightest new particle to appear)
- Higgs – radion mixing via the interaction

$$\mathcal{L} = -\xi \sqrt{-g_{\text{ind}}} R(g_{\text{ind}}) \Phi^\dagger \Phi$$

with  $g_{\text{ind}}(\varphi(x), \dots)$ : induced 4d metric on IR brane,  $R$ : Ricci scalar.

→ Radion  $\varphi$  and physical Higgs  $h$  mix to form two mass eigenstates

- $\varphi$  coupling to massive fermions and gauge bosons  $\propto$  mass, but
  - \*  $\varphi b\bar{b}$  coupling **suppressed** wrt SM Higgs
  - \*  $\varphi gg$  coupling **enhanced** wrt SM Higgs
  - \*  $\varphi \gamma\gamma$  coupling **suppressed** wrt SM Higgs

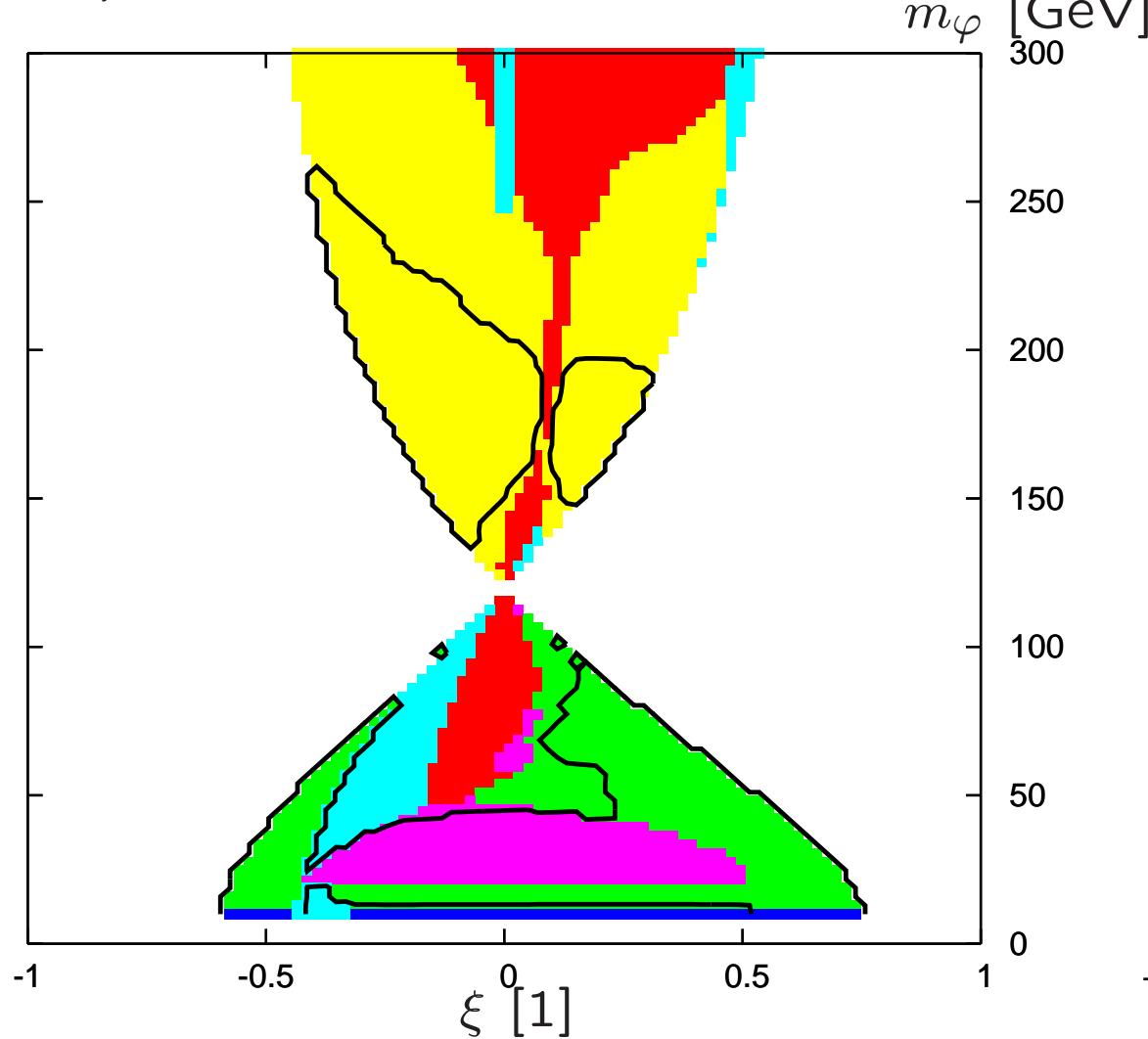
→ two scalars in the spectrum with modified couplings  
compared to the SM Higgs boson

Exclusion range and sensitivity map:  $\xi - m_\varphi$  plane w/o LHC data (12/2010)

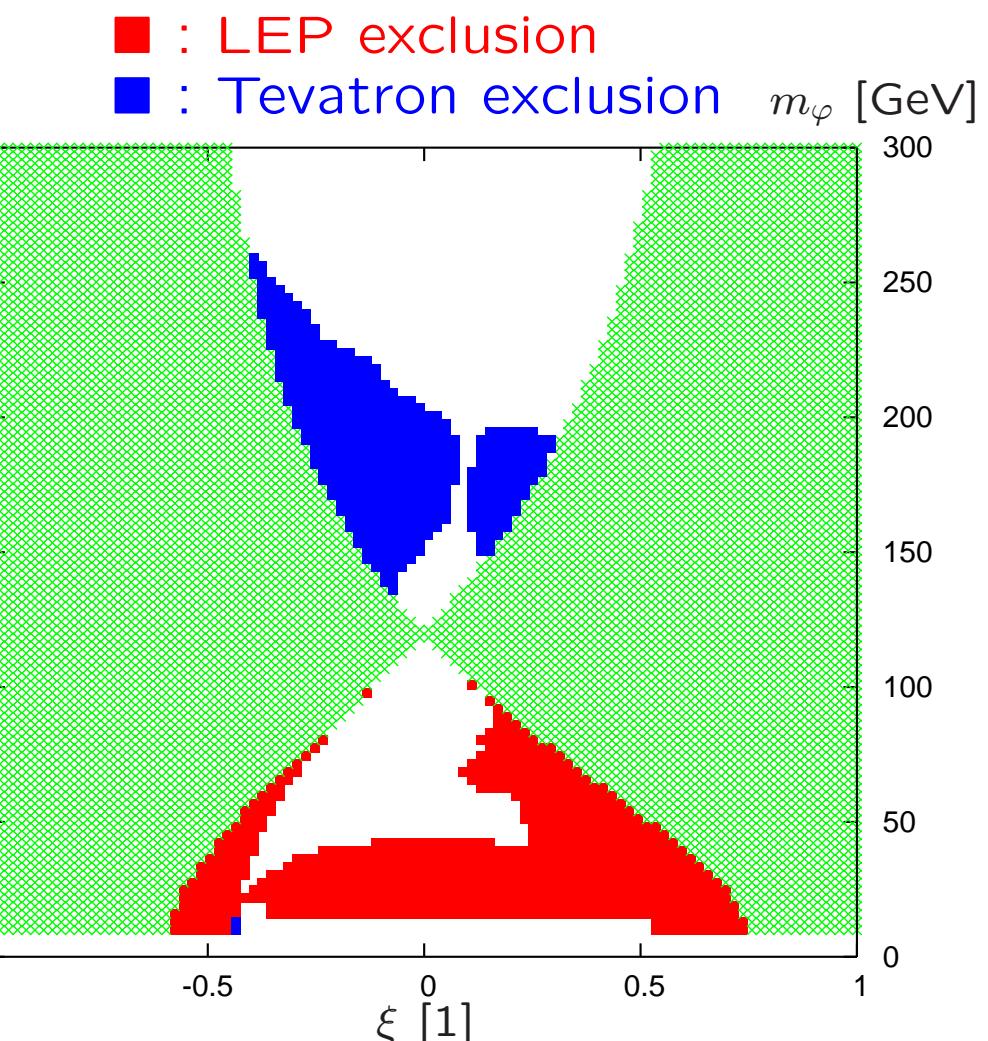
ee  $\rightarrow$  h Z, h  $\rightarrow$  bb  
 ee  $\rightarrow$  phi Z, phi  $\rightarrow$  bb  
 ee  $\rightarrow$  phi Z, phi  $\rightarrow$  anything  
 ee  $\rightarrow$  phi Z, phi  $\rightarrow$  hadrons  
 pp  $\rightarrow$  single h, h  $\rightarrow$  WW  
 pp  $\rightarrow$  single phi, phi  $\rightarrow$  WW

parameter:  
 $\Lambda_\varphi = 1 \text{ TeV}$   
 $m_h = 120 \text{ GeV}$

a) highest sensitivity



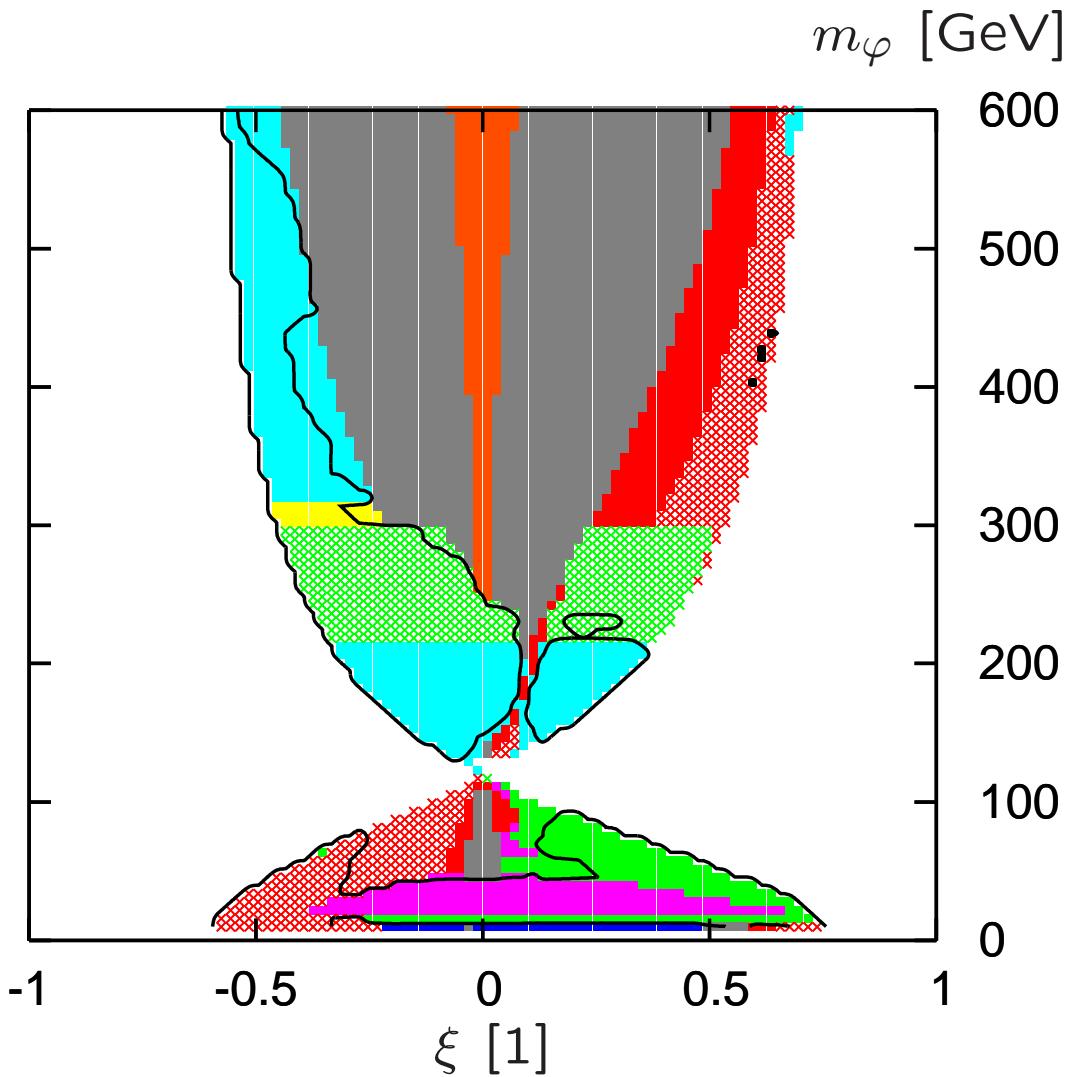
b) exclusion



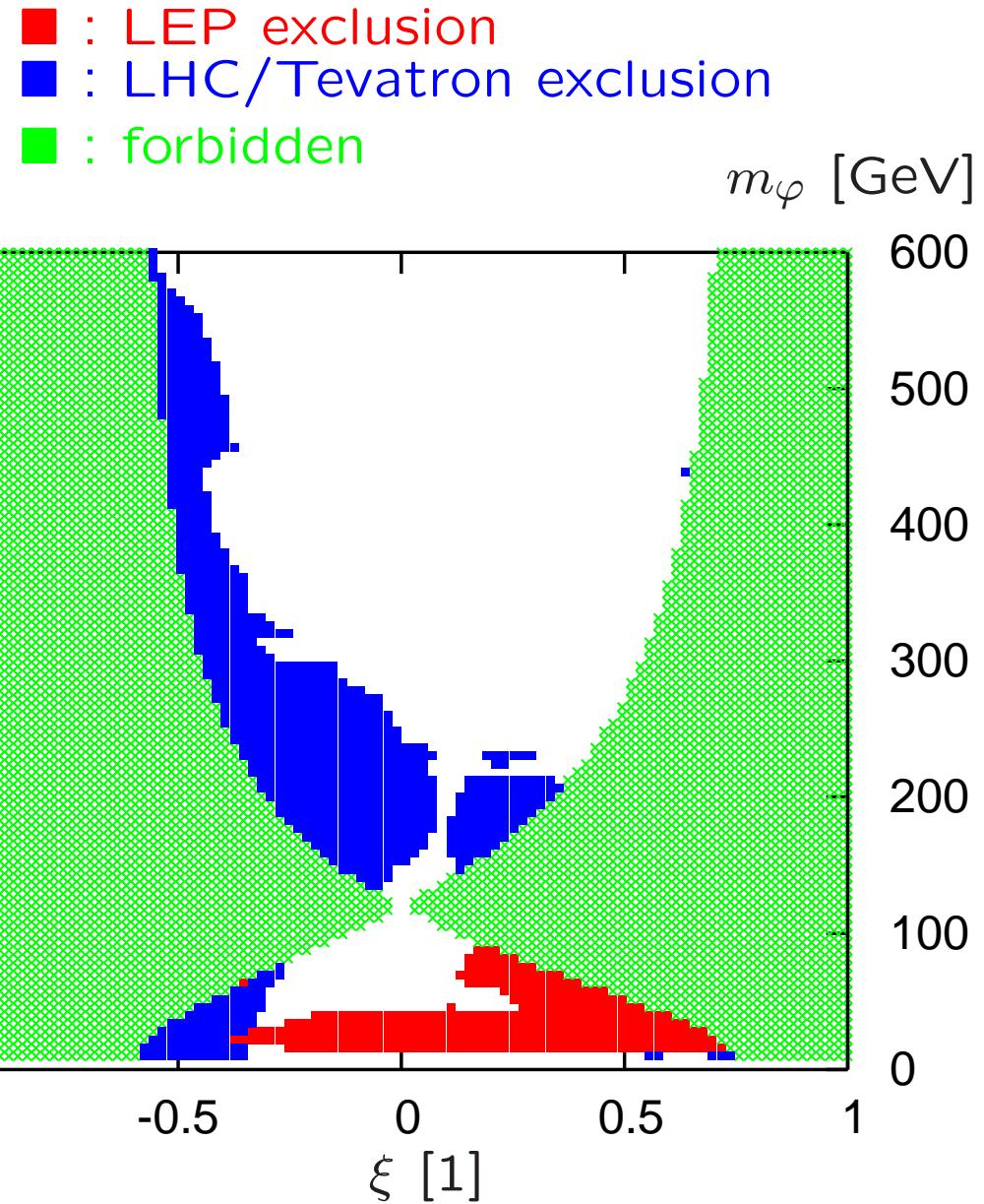
# Exclusion range and sensitivity map: $\xi - m_\varphi$ plane with LHC data

parameter:  $\Lambda_\varphi = 1 \text{ TeV}$ ,  $m_h = 120 \text{ GeV}$

a) highest sensitivity



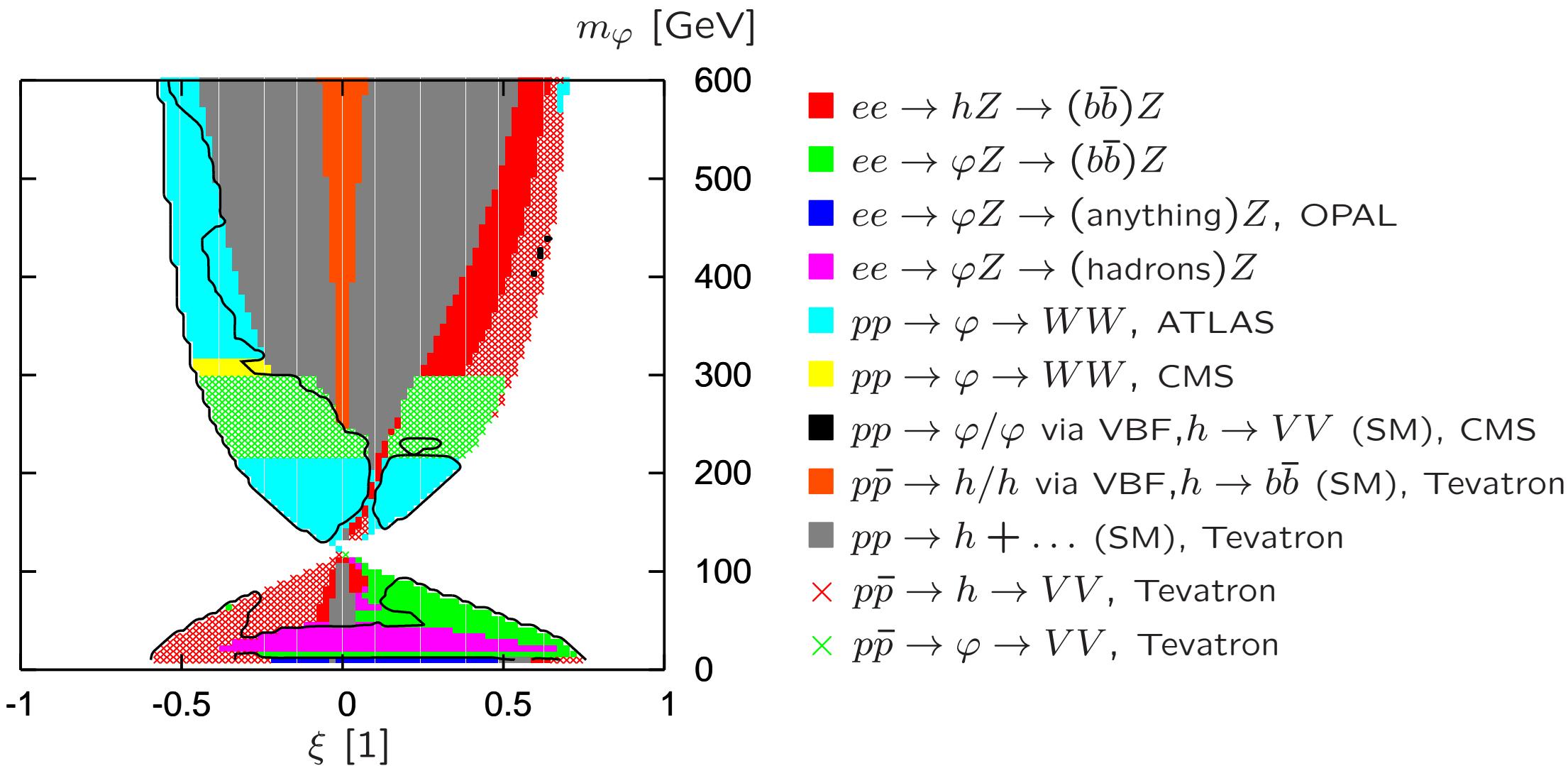
b) exclusion



# Exclusion range and sensitivity map: $\xi - m_\varphi$ plane with LHC data

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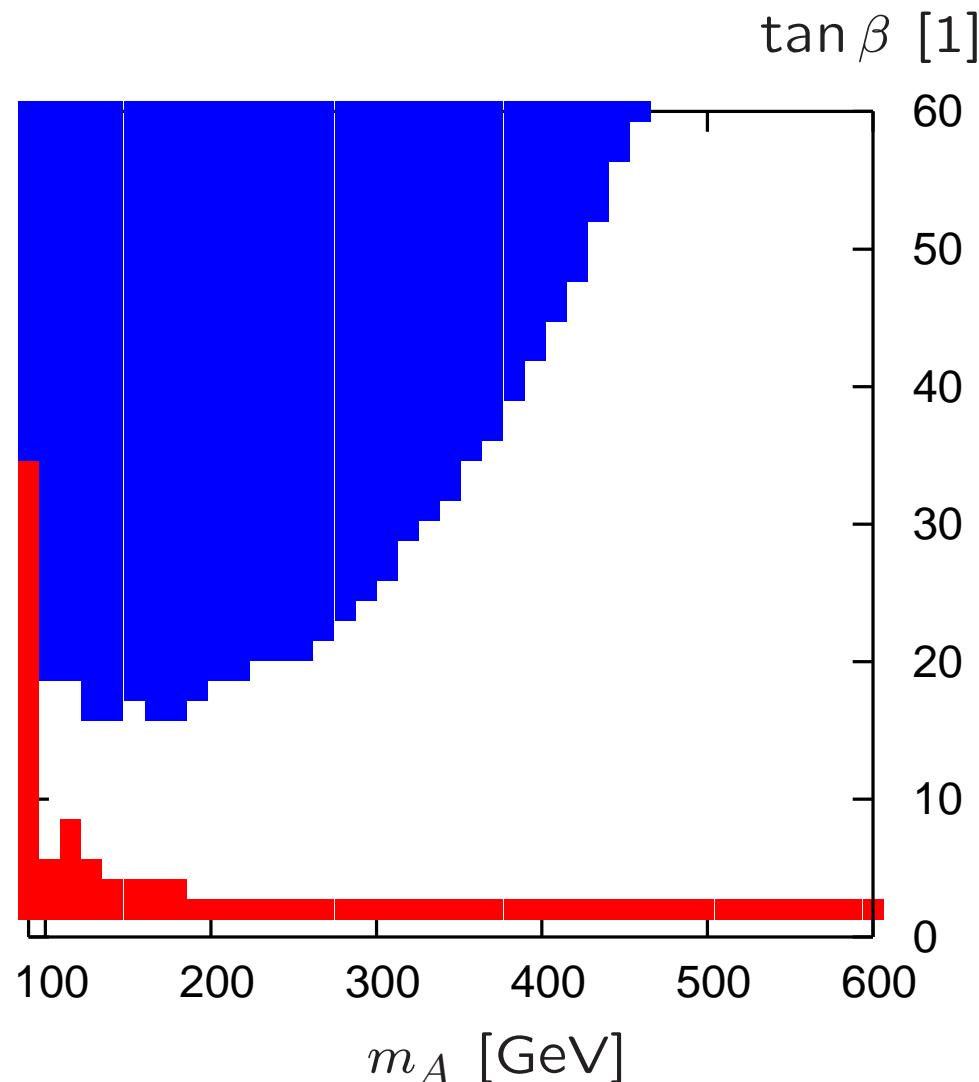


## – MSSM

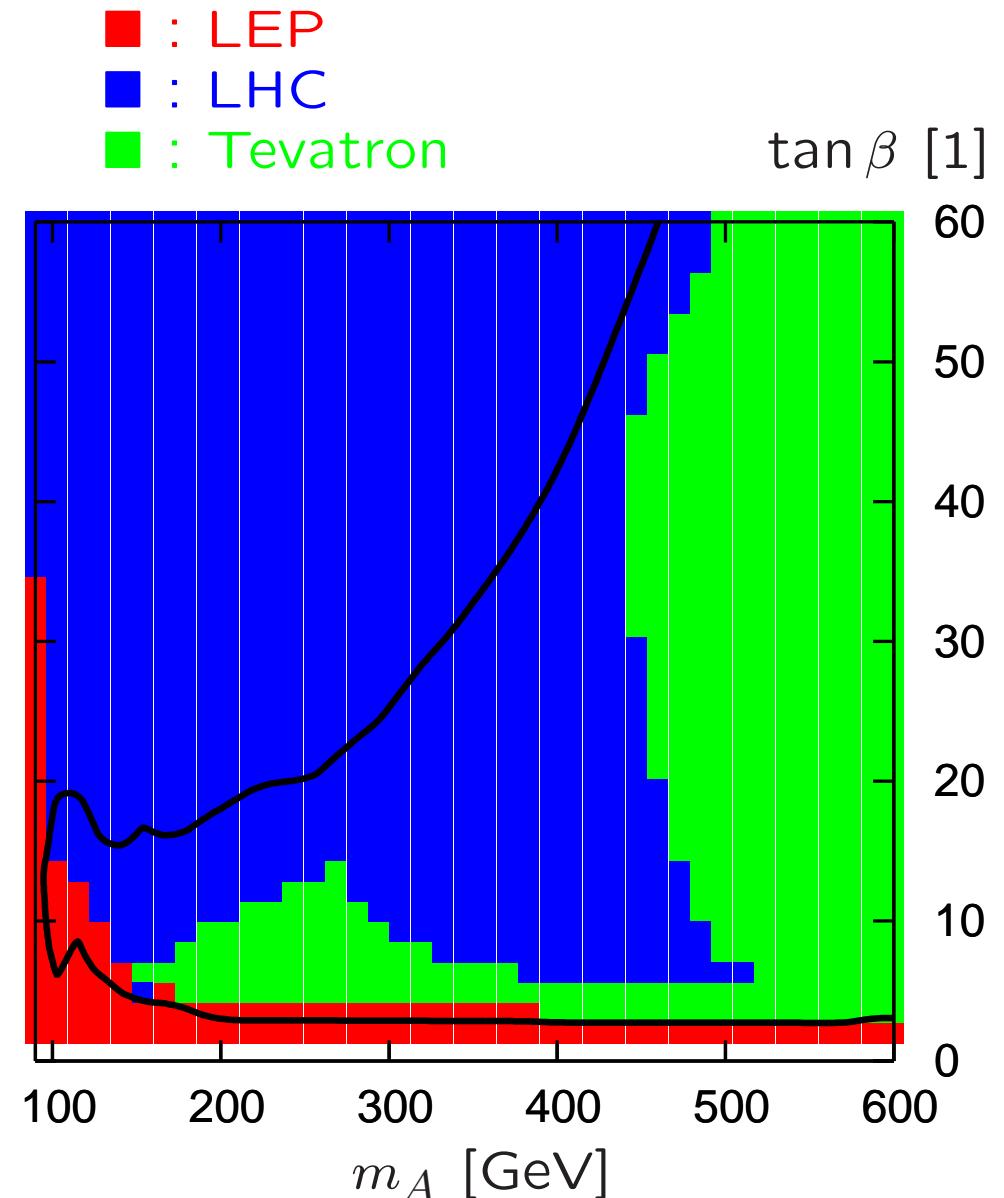
December 2011 results not included (sorry)

# Exclusion range and sensitivity map: $\tan\beta - m_A$ plane : $m_h^{\max}+$ scenario

a) exclusion

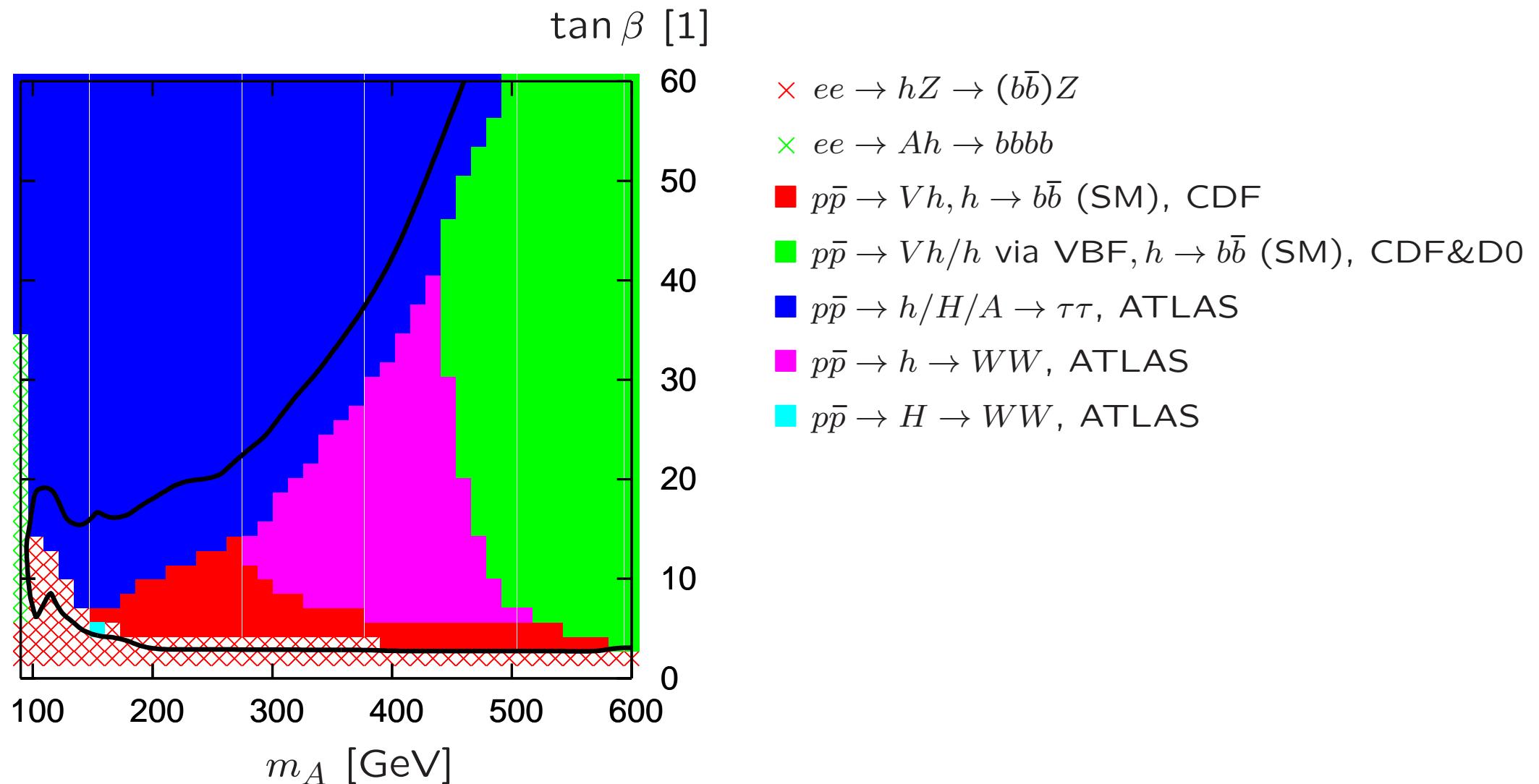


b) highest sensitivity experiment



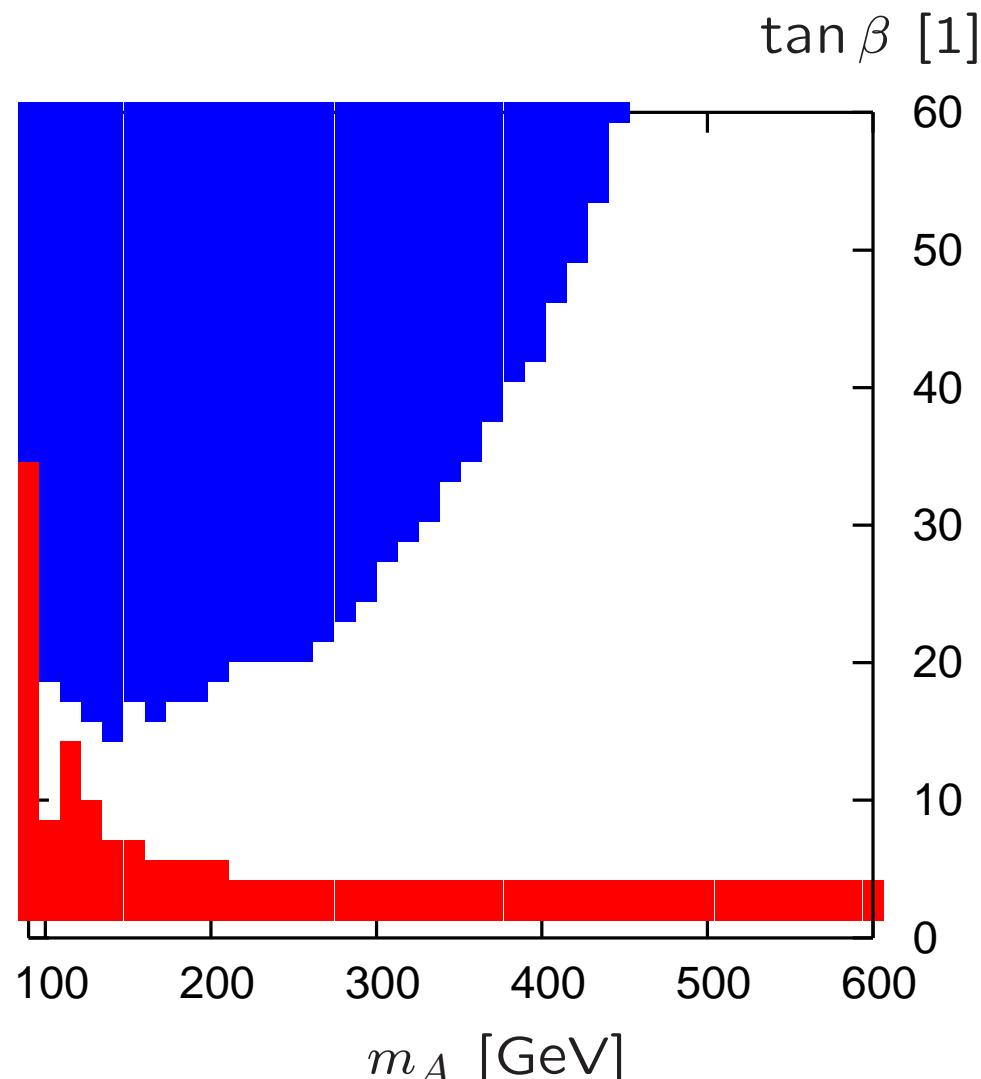
# Exclusion range and sensitivity map: $\tan\beta - m_A$ plane : $m_h^{\max}+$ scenario

c) highest sensitivity analysis



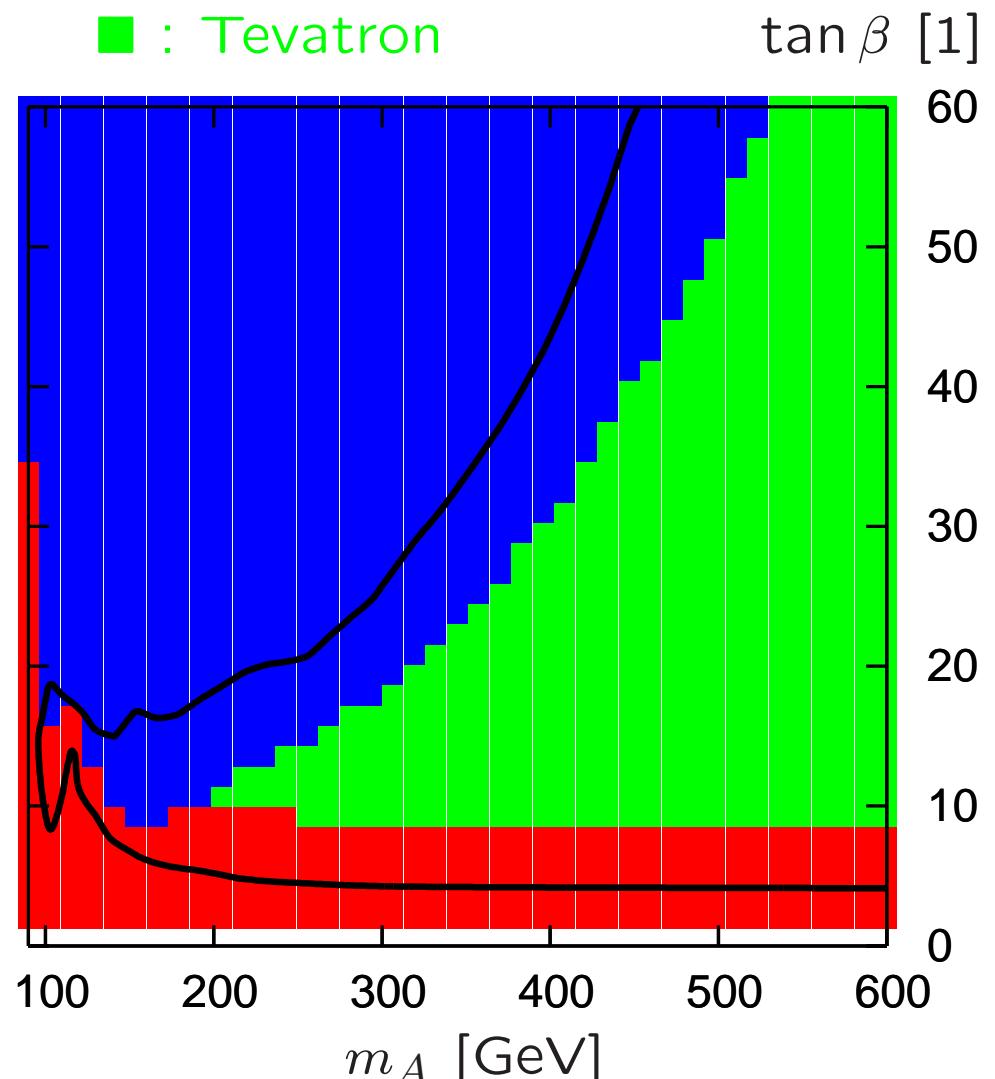
Exclusion range and sensitivity map:  $\tan \beta - m_A$  plane :  $m_h^{\max} + (400)$  scenario  
 $[M_{\text{SUSY}} = 400 \text{ GeV}]$

a) exclusion



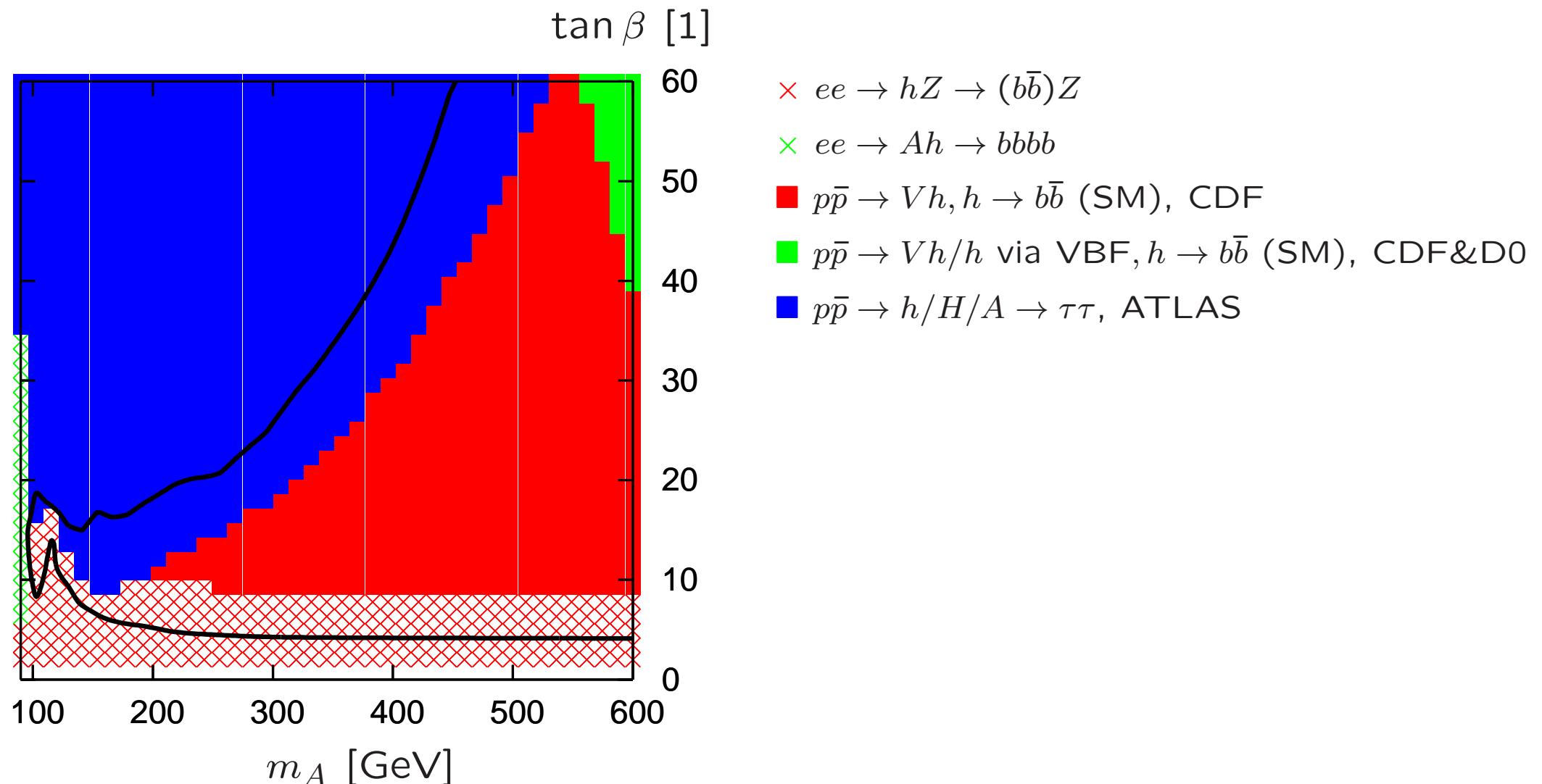
b) highest sensitivity experiment

- : LEP
- : LHC
- : Tevatron



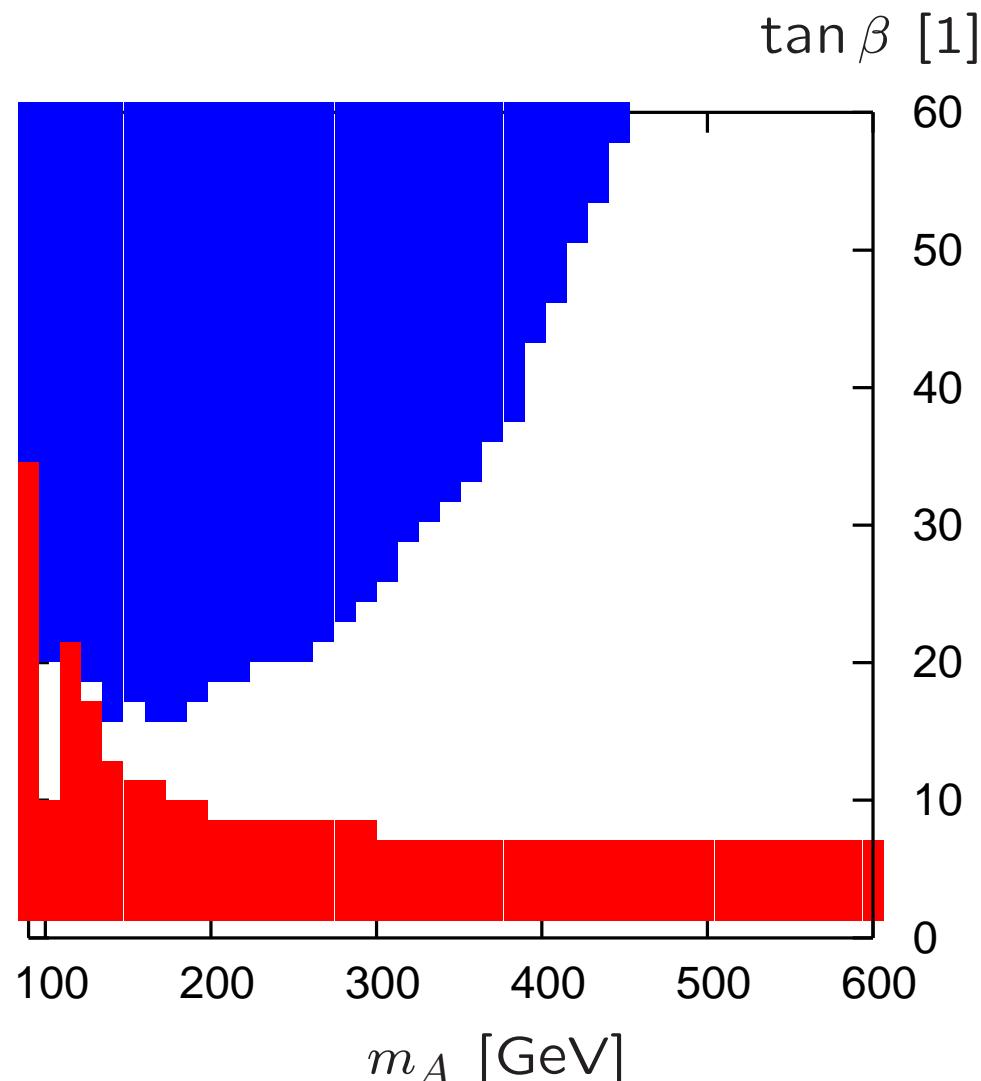
Exclusion range and sensitivity map:  $\tan\beta - m_A$  plane :  $m_h^{\max} + (400)$  scenario  
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c) highest sensitivity analysis

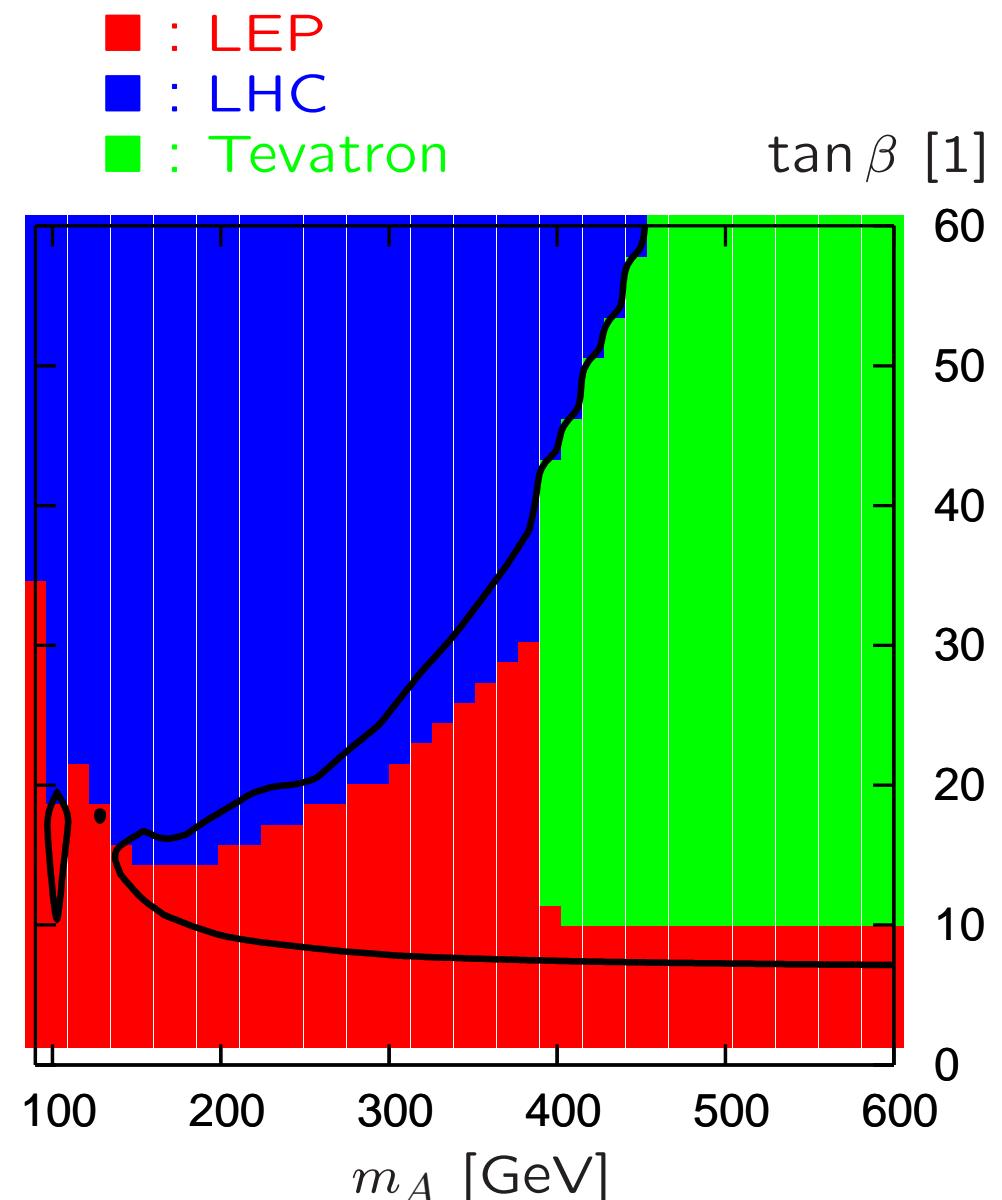


Exclusion range and sensitivity map:  $\tan \beta - m_A$  plane : nomix+ scenario

a) exclusion

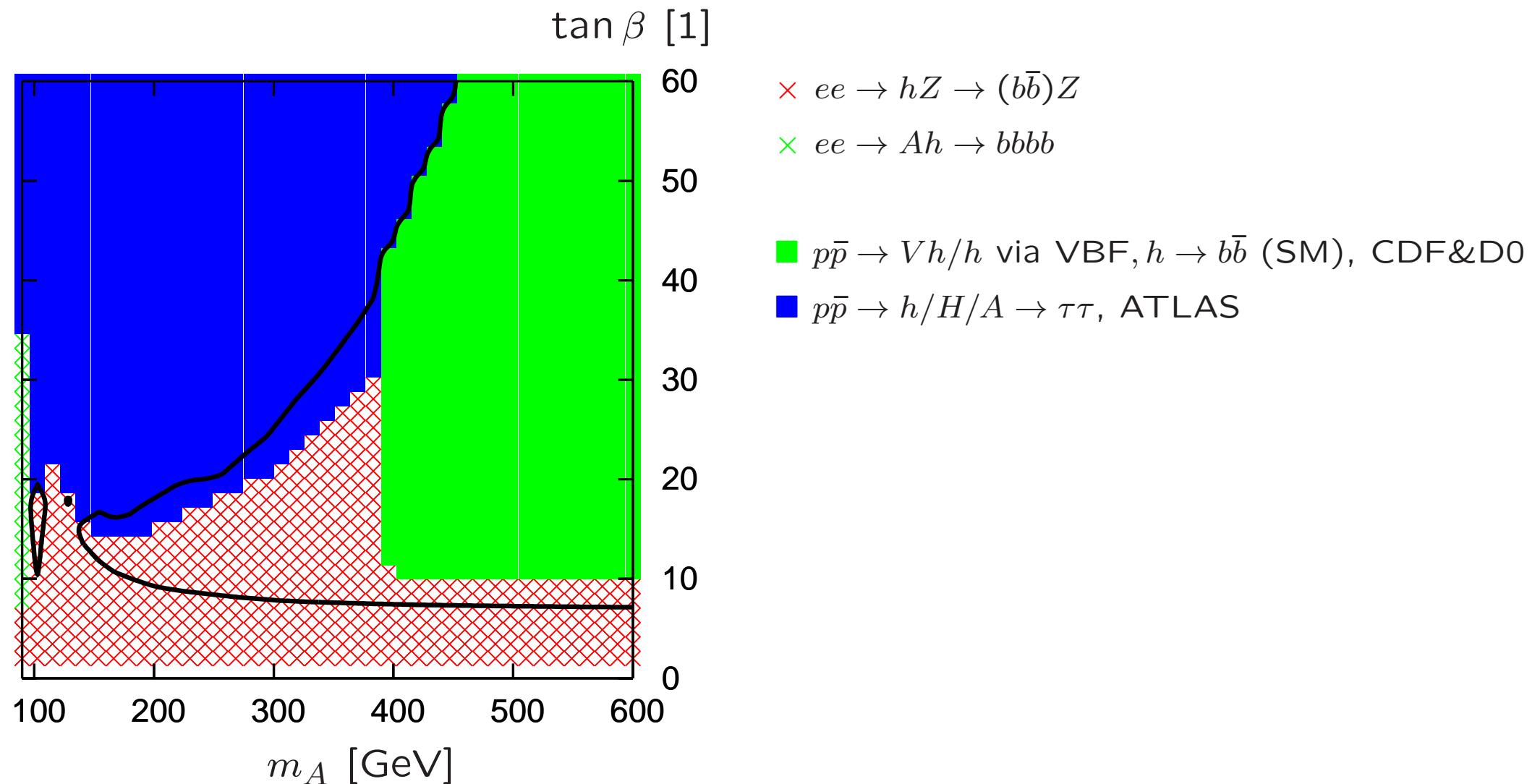


b) highest sensitivity experiment



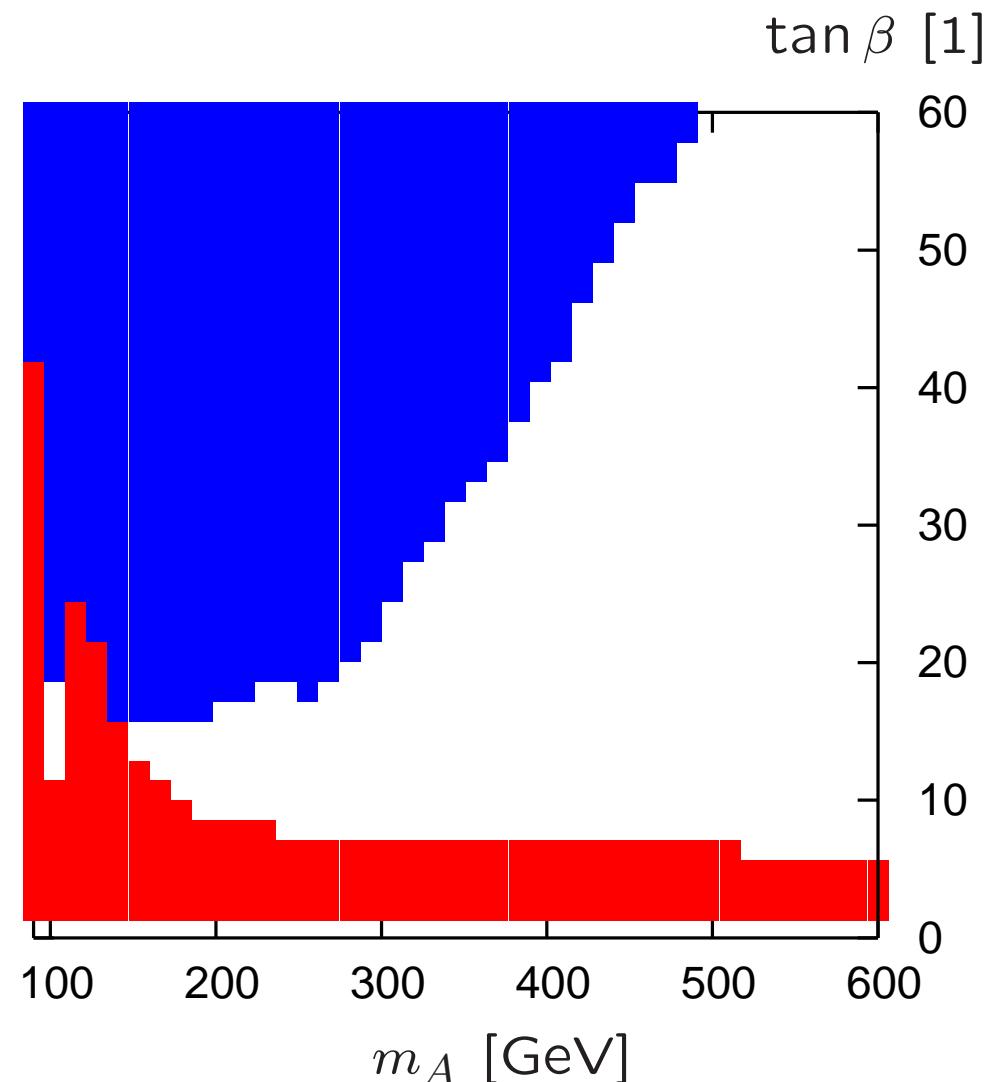
Exclusion range and sensitivity map:  $\tan\beta - m_A$  plane : nomix+ scenario

c) highest sensitivity analysis

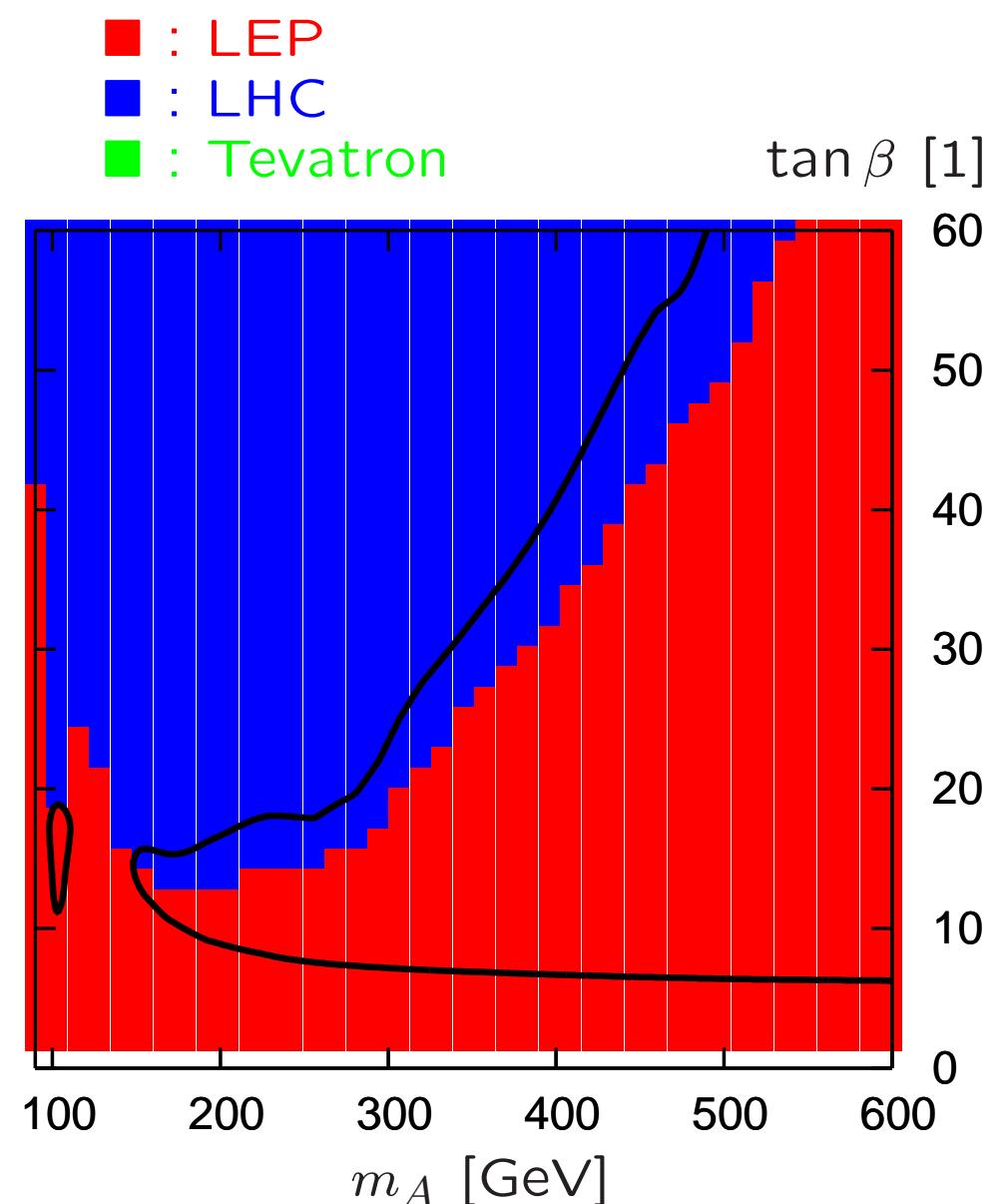


Exclusion range and sensitivity map:  $\tan \beta - m_A$  plane : gluophobic scenario

a) exclusion

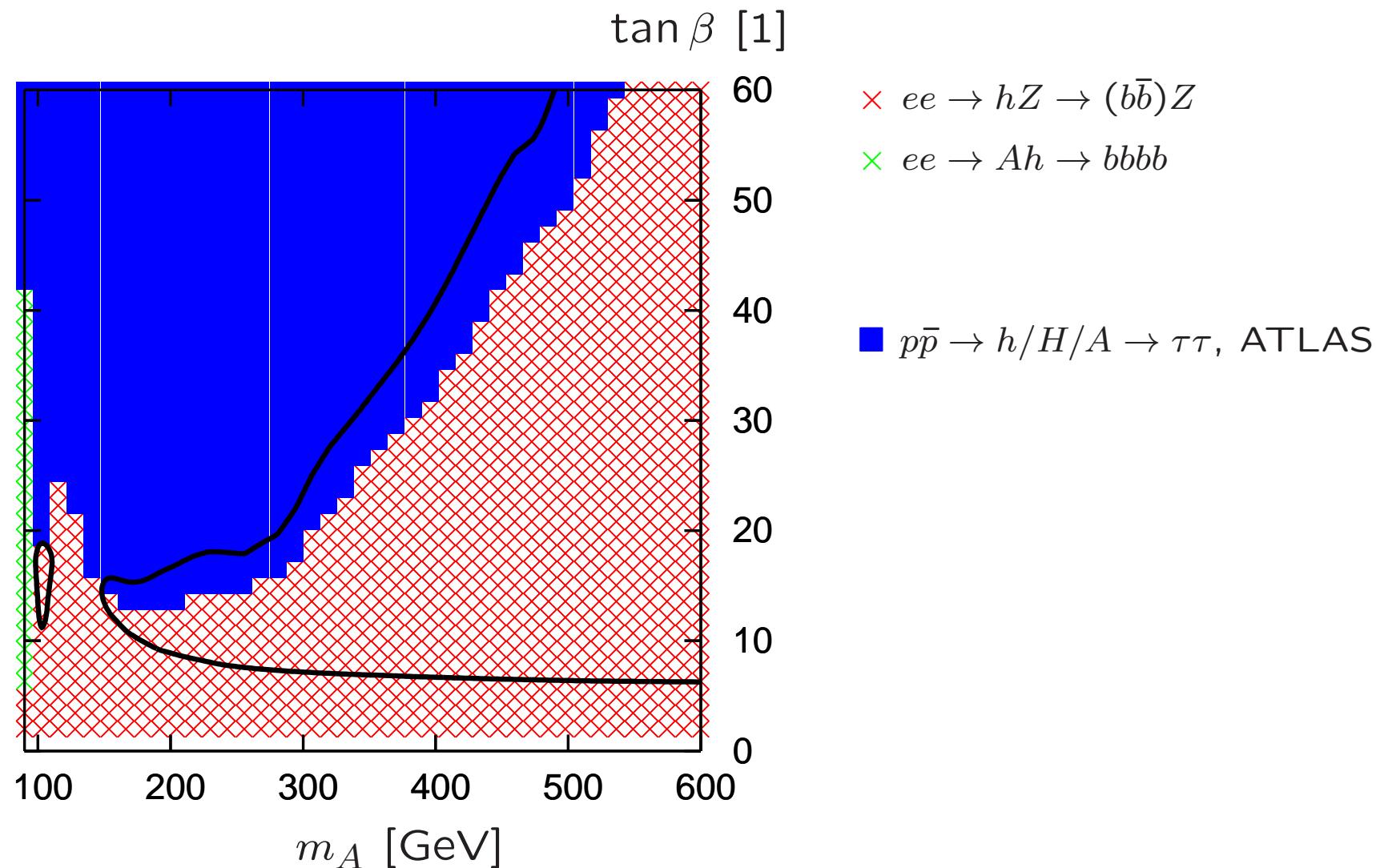


b) highest sensitivity experiment



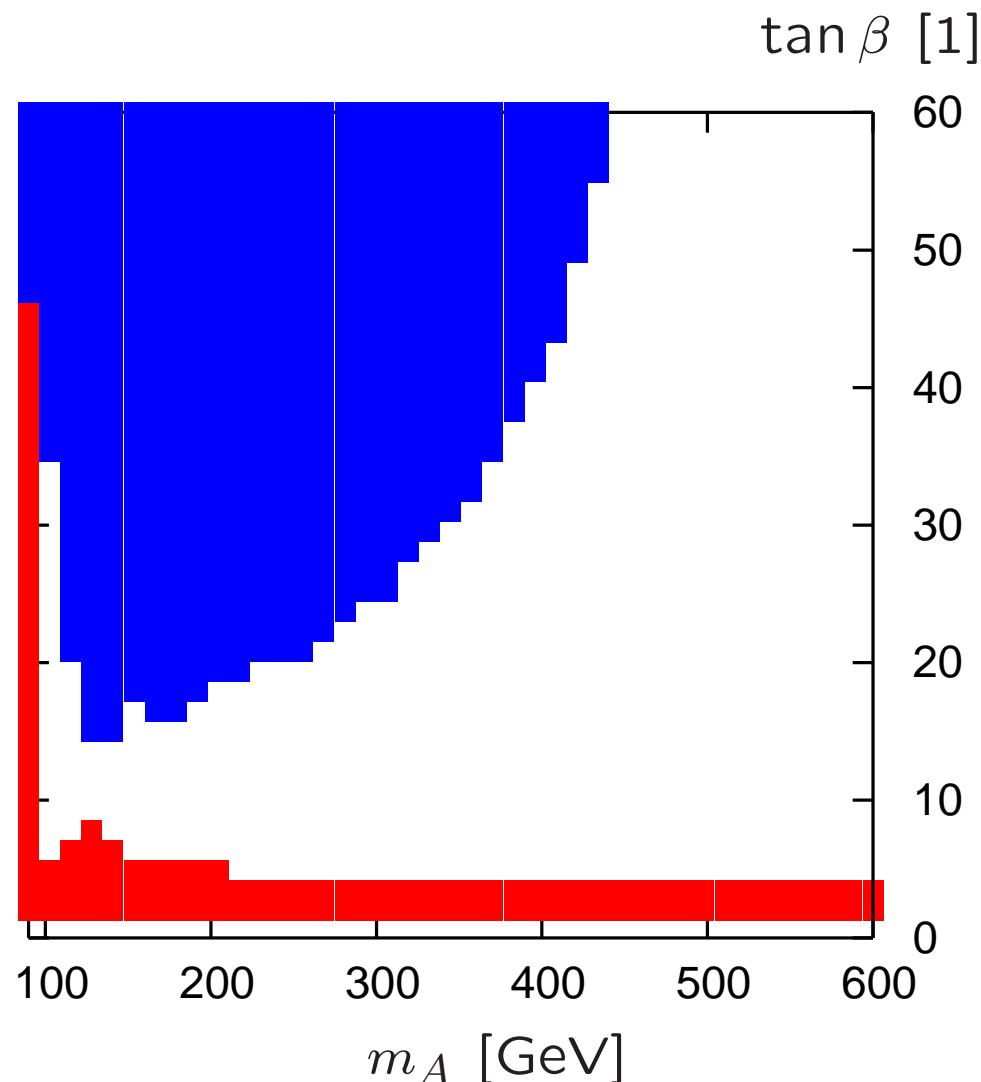
Exclusion range and sensitivity map:  $\tan \beta - m_A$  plane : gluophobic scenario

c) highest sensitivity analysis

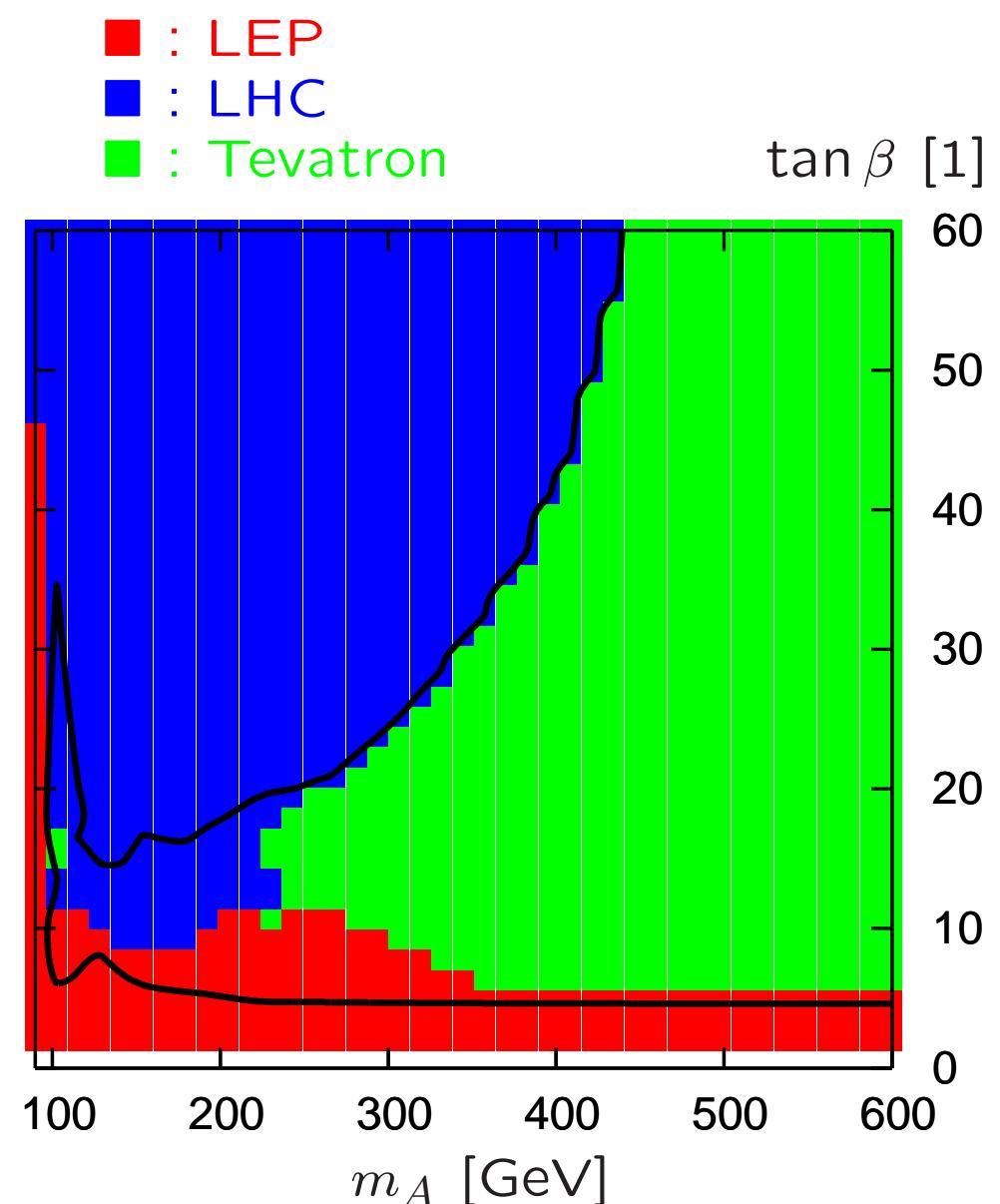


Exclusion range and sensitivity map:  $\tan \beta - m_A$  plane : small  $\alpha_{\text{eff}}$  scenario

a) exclusion

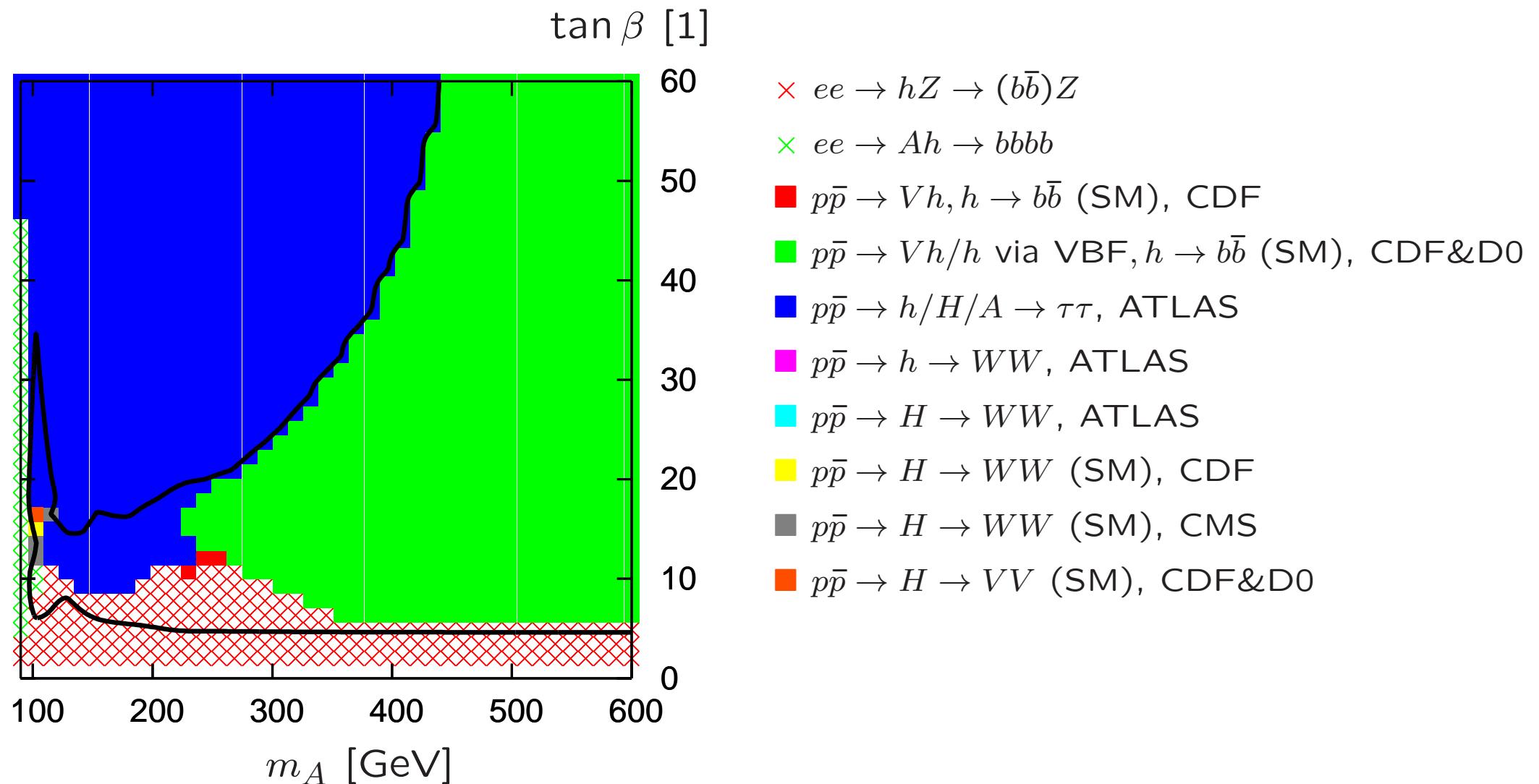


b) highest sensitivity experiment



Exclusion range and sensitivity map:  $\tan\beta - m_A$  plane : small  $\alpha_{\text{eff}}$  scenario

c) highest sensitivity analysis



## summary

- HiggsBounds: powerful tool for constraining Higgs sectors of new physics models systematically.
- Tevatron has only few places left where it keeps the highest sensitivity in Higgs search. LHC takes over!
- ... that's also true for the MSSM benchmark scenarios
- Current LHC (& Tevatron) results rule out large parts of the Randall-Sundrum model's parameter space in addition to the LEP constraints.