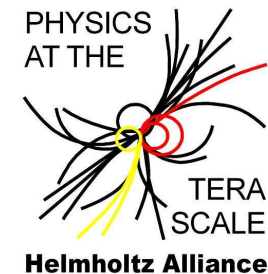


Constraining Higgs Sectors with LHC Searches using HiggsBounds 3.5.0

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outline :

- **HiggsBounds**
 - overview of version 3.5.0 [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 3.5.0 [beta]

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

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

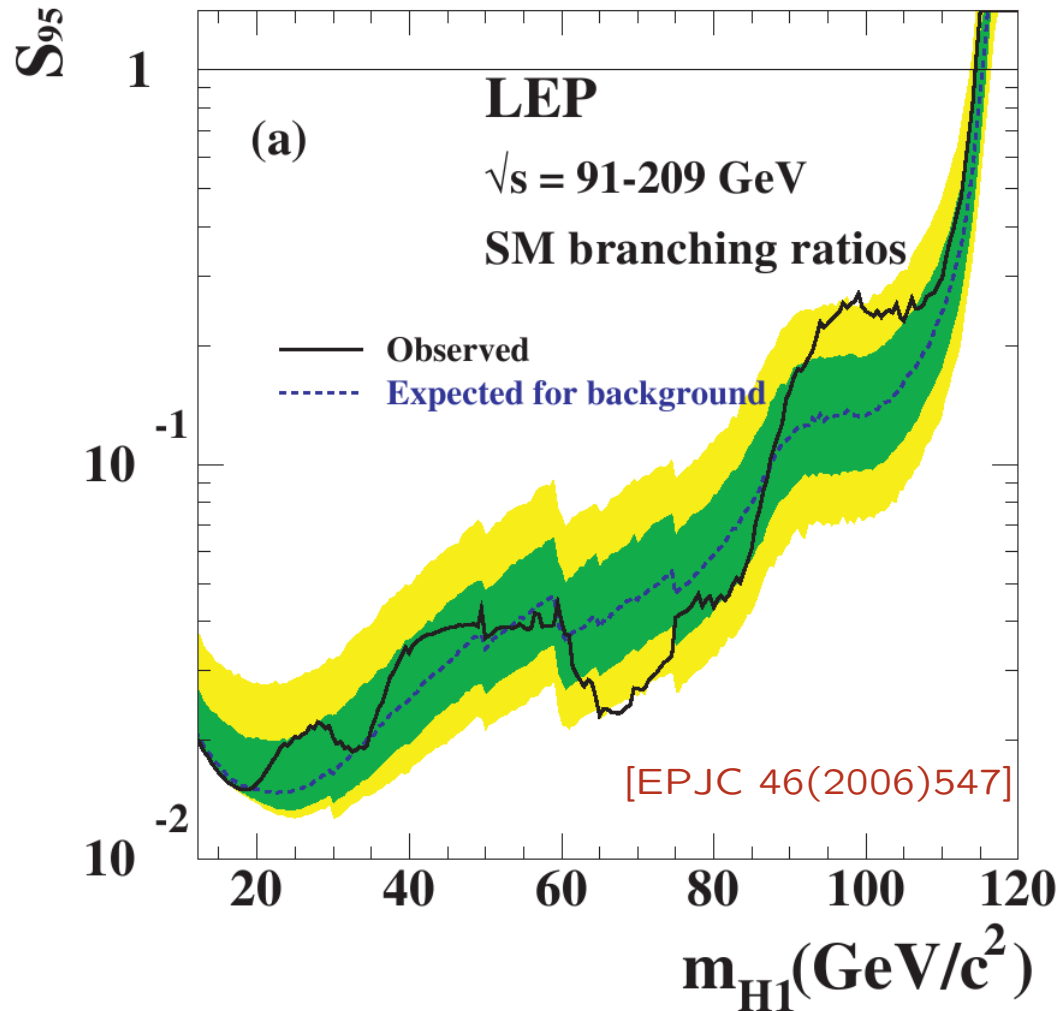
- easy access to all relevant Higgs exclusion limits including information not available in the publications. (e.g. expected 95% CL cross section limits)
- applicable to models with arbitrary Higgs sectors (narrow widths assumed)
HiggsBounds Input: the predictions of the model for:
of neutral & charged 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

– some implementation details

Higgs search results: example 1: LEP SM combined limit

exclusion = rejection of the Higgs hypothesis



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

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

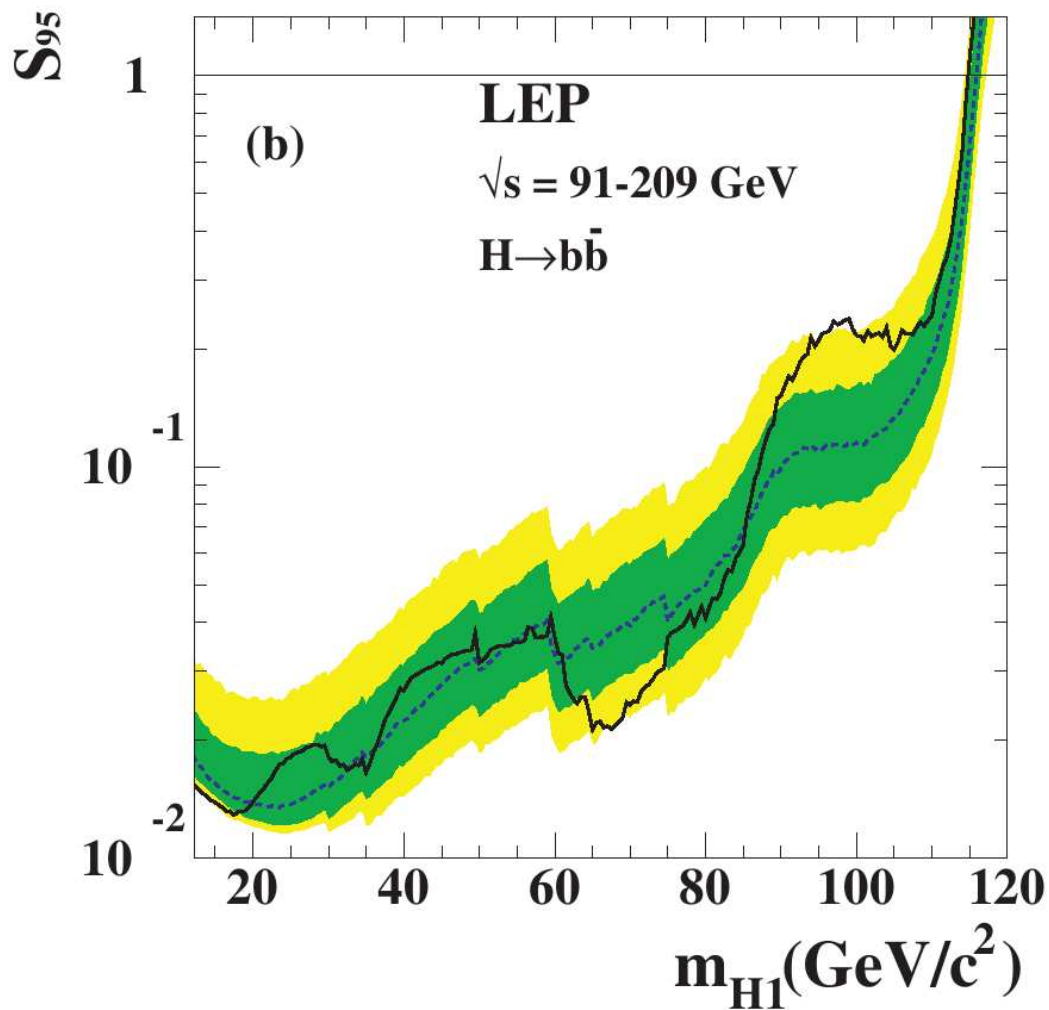
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\min}(m_{H1})$$

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

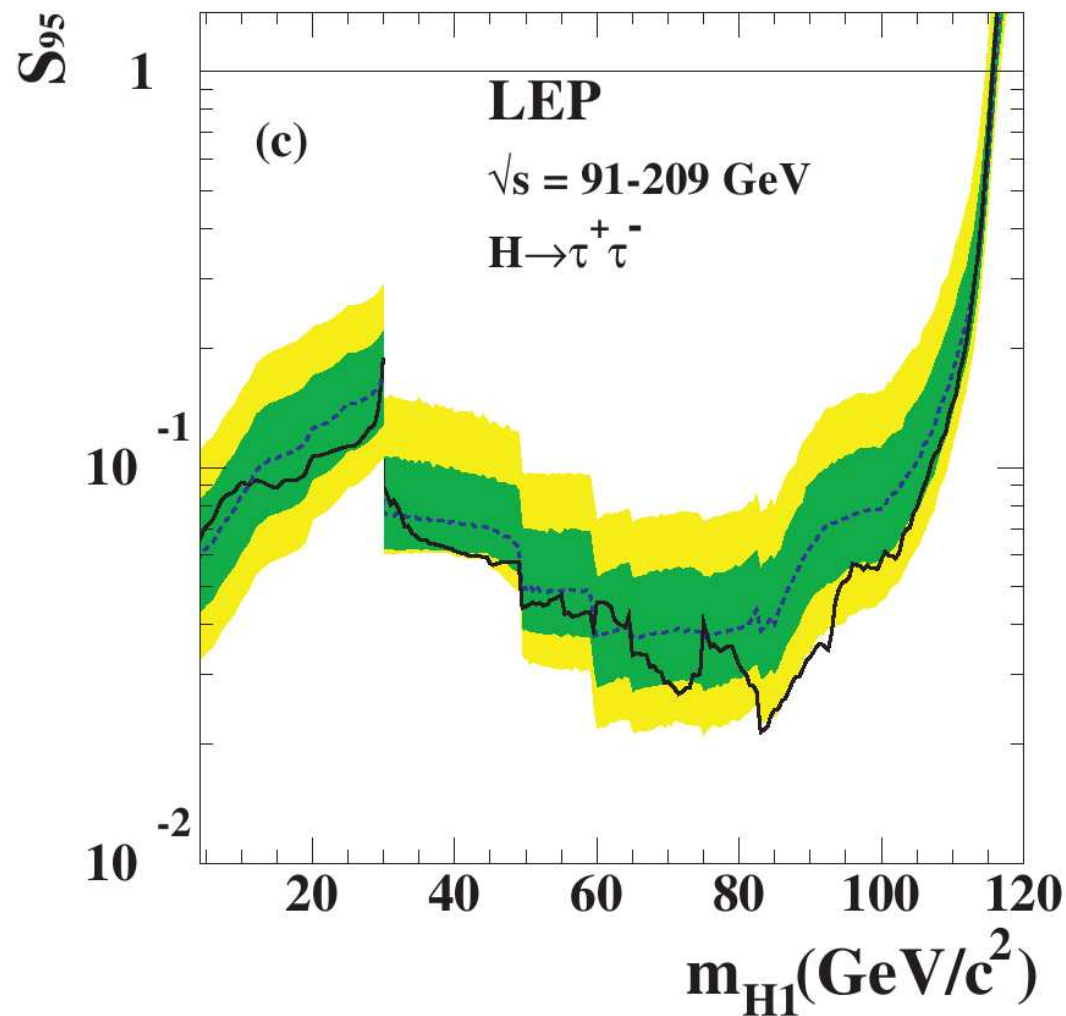
is said to be excluded at the 95% C.L.

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

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

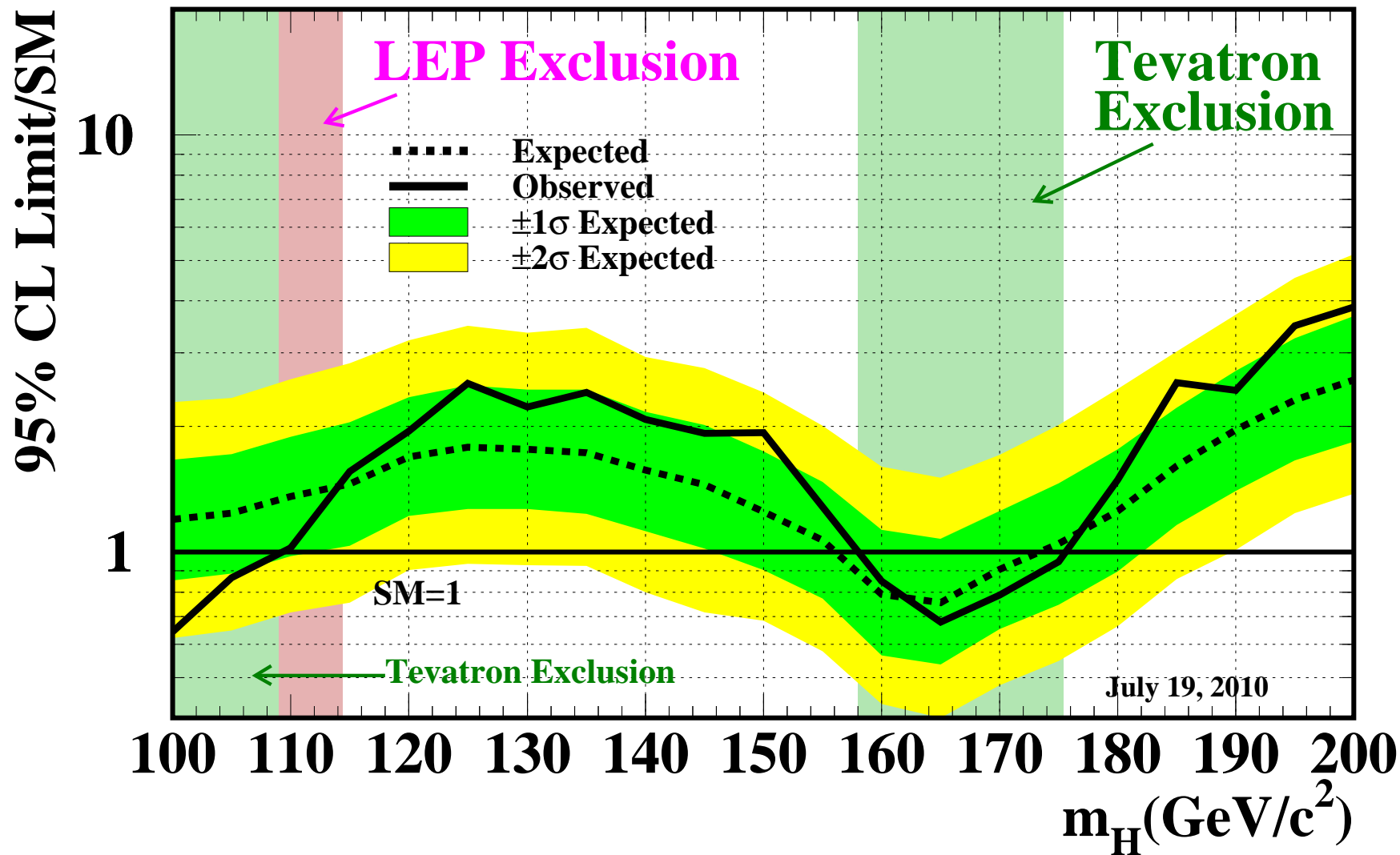


b) ... $\text{BR}(H \rightarrow \tau^+\tau^-)=1$



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

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



– some implementation details

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 $Q_{\text{model}}(X)$,
- ★ observed cross section limit $Q_{\text{observed}}(X)$ of analysis A ,
- ★ expected cross section limit $Q_{\text{expected}}(X)$ of analysis A .

– some implementation details

for an analysis application X :

- evaluate model prediction

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

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

- read off the corresponding observed 95% C.L. limit: $Q_{\text{observed}}(X)$.
- If $\frac{Q_{\text{model}}(X)}{Q_{\text{observed}}(X)} > 1$ 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 $Q_{\text{expected}}(X)$.
- Determine the analysis application X_0 with the highest sensitivity for the signal, i.e. of all X , find X_0 where $\frac{Q_{\text{model}}(X)}{Q_{\text{expected}}(X)}$ is maximal.
- If for this analysis application $\frac{Q_{\text{model}}(X_0)}{Q_{\text{observed}}(X_0)} > 1$, the model is excluded at 95% C.L. by X_0 .

– status and outlook of the project

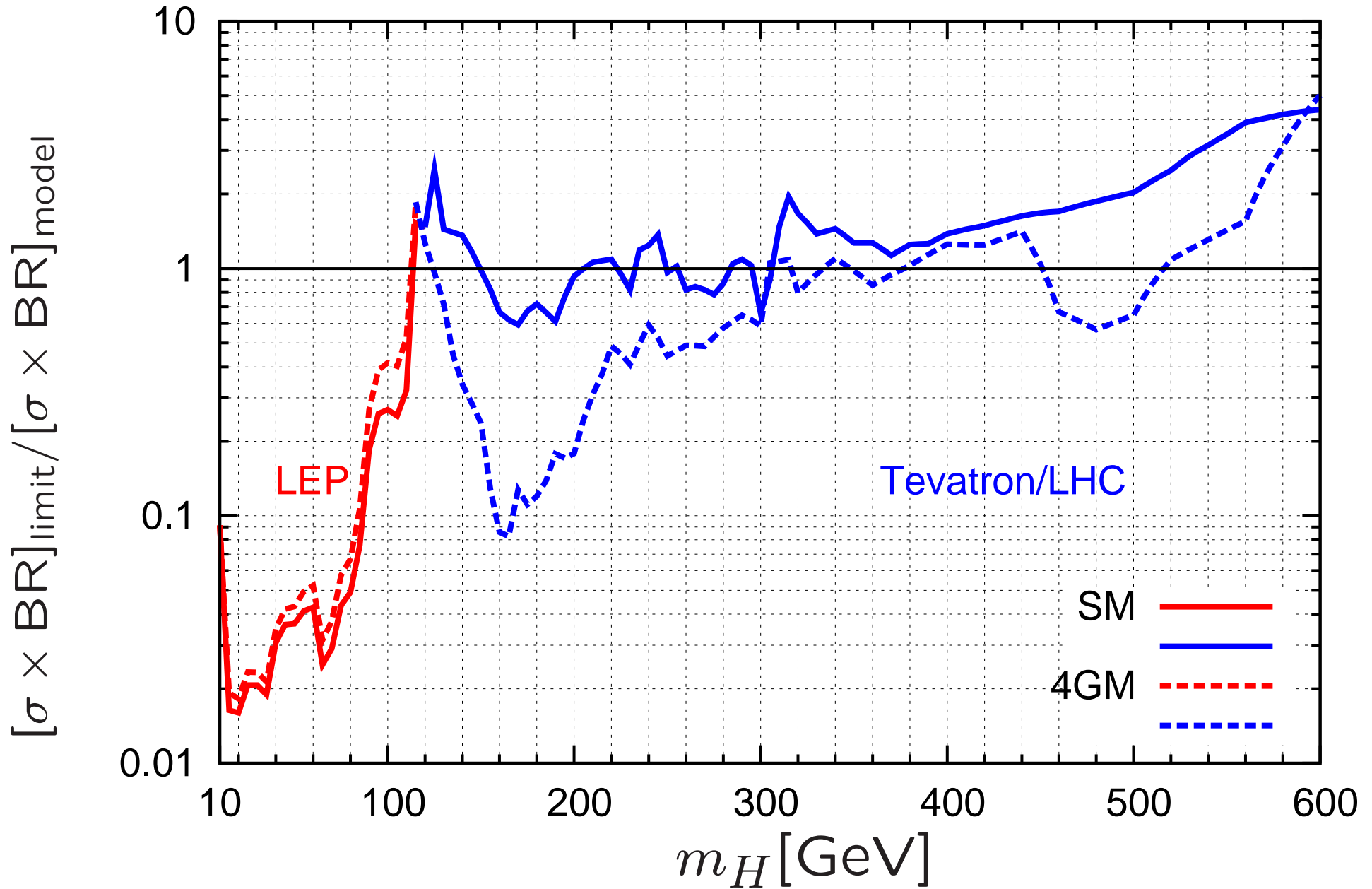
■ HiggsBounds: status and outlook

- The code is publicly available since Feb. 2009 (current version: 3.5.0 beta)
 - projects.hepforge.org/higgsbounds
 - Tevatron & LHC results up to Lepton-Photon 2011 included
 - extended functionality (H^\pm searches, `onlyP` analyses selection, ...)
 - HiggsBounds 3.5.0 beta available to download
 - includes: SLHA input option, χ^2 fitting for LEP channels,
optional addition: [SusyBounds](#) (Chargino, Neutralino bounds)
- Reception very good (> 100 users). Code used in/by:
[FeynHiggs](#), [CPsuperH](#), [Fittino](#), [MasterCode](#), [2HDMC](#), [DarkSusy](#),
[SuperIso](#), etc.
- Current work/plans:
 - new LHC results from last week
 - searches for fermiophobic models
 - doubly charged Higgs searches, LEP searches for $m_H < 10$ GeV
 - inclusion of width-dependent limits

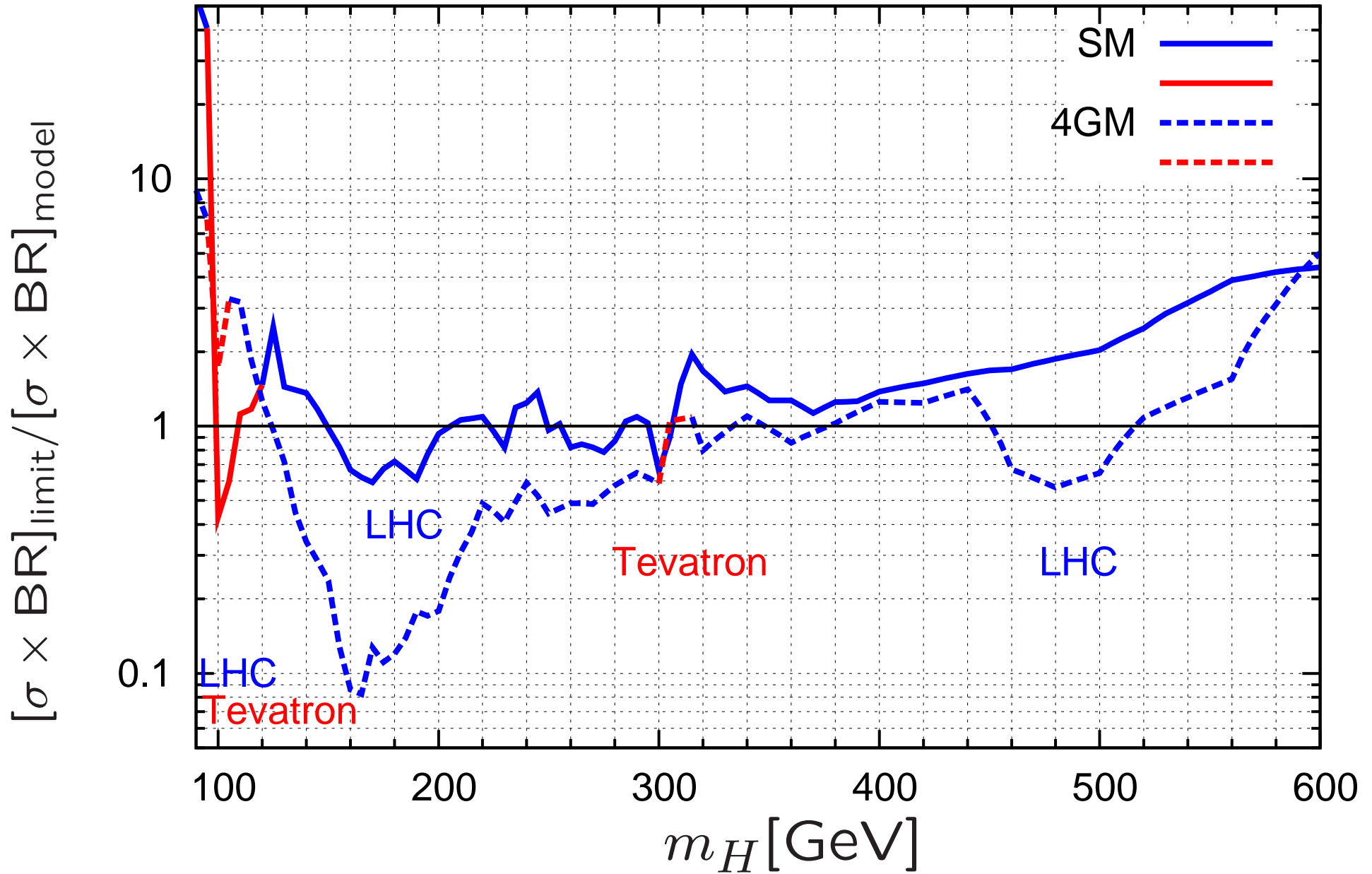
- Constraining Models

– SM versus 4th generation model

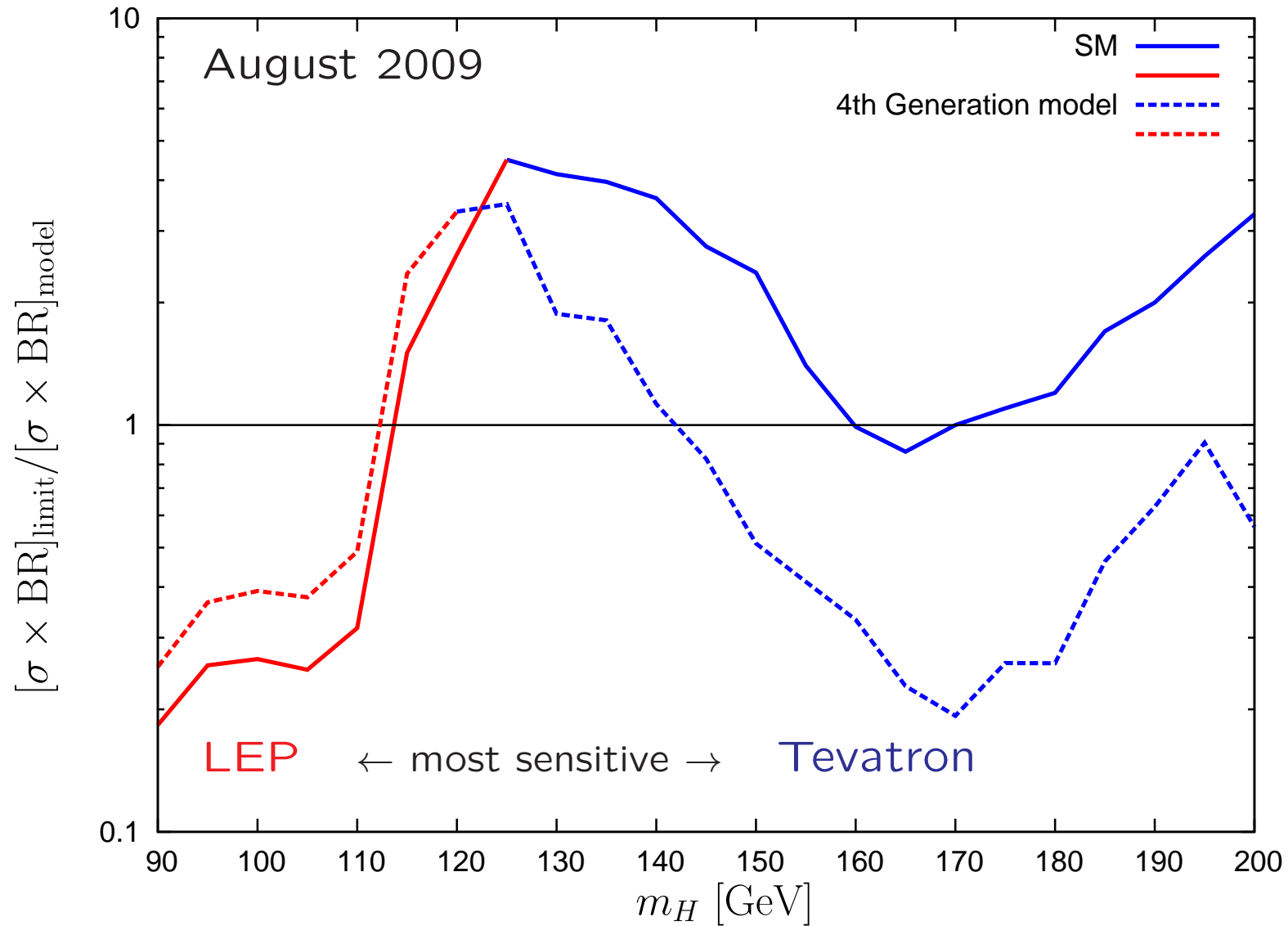
– SM versus 4th generation model [using $\Gamma(H \rightarrow gg)_{\text{model}} = 9 \times \Gamma(H \rightarrow gg)_{\text{SM}}$]



– SM versus 4th generation model only hadron collider searches

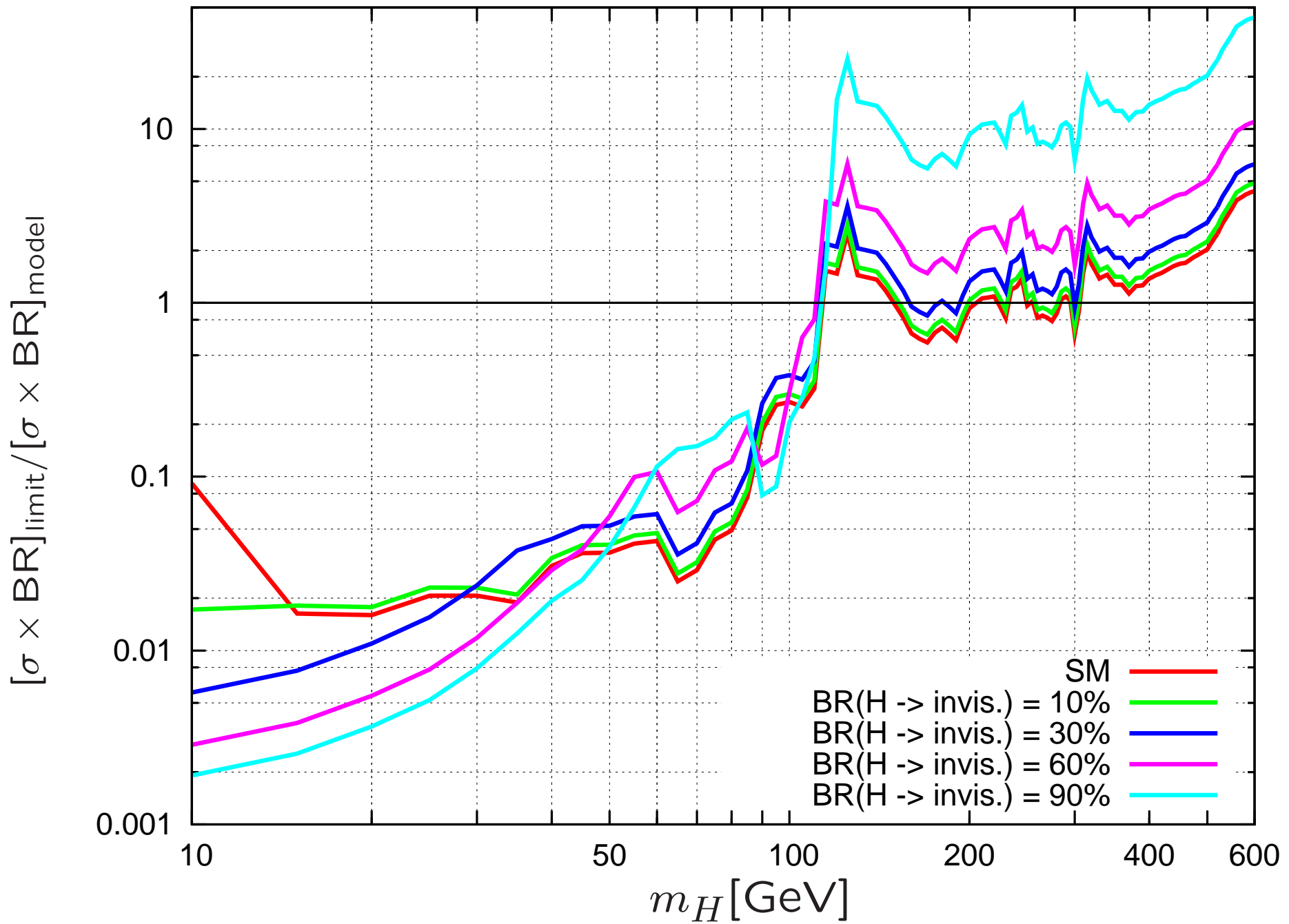


for comparison: status in August 2009 (without LHC results)

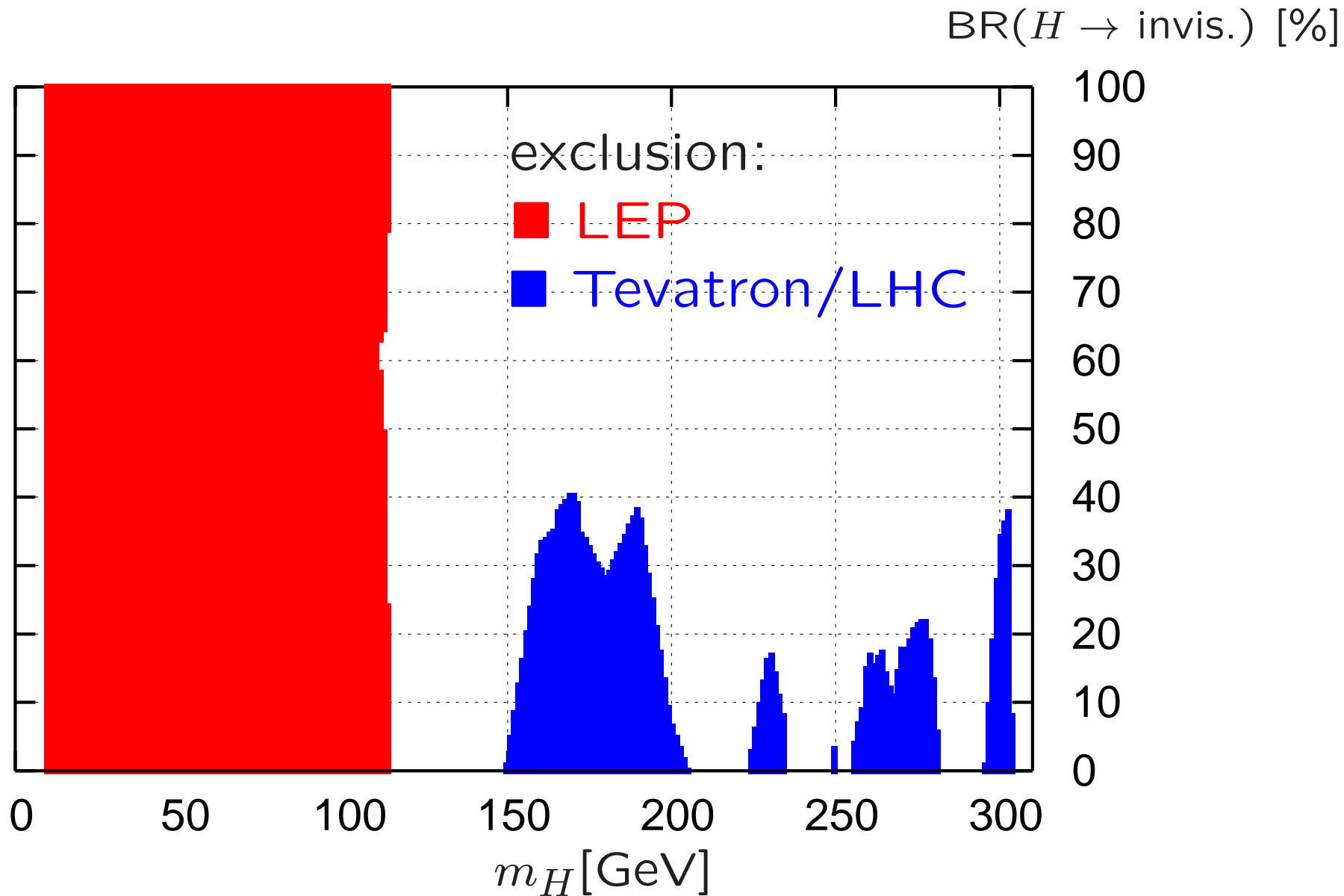


– SM+invisible model

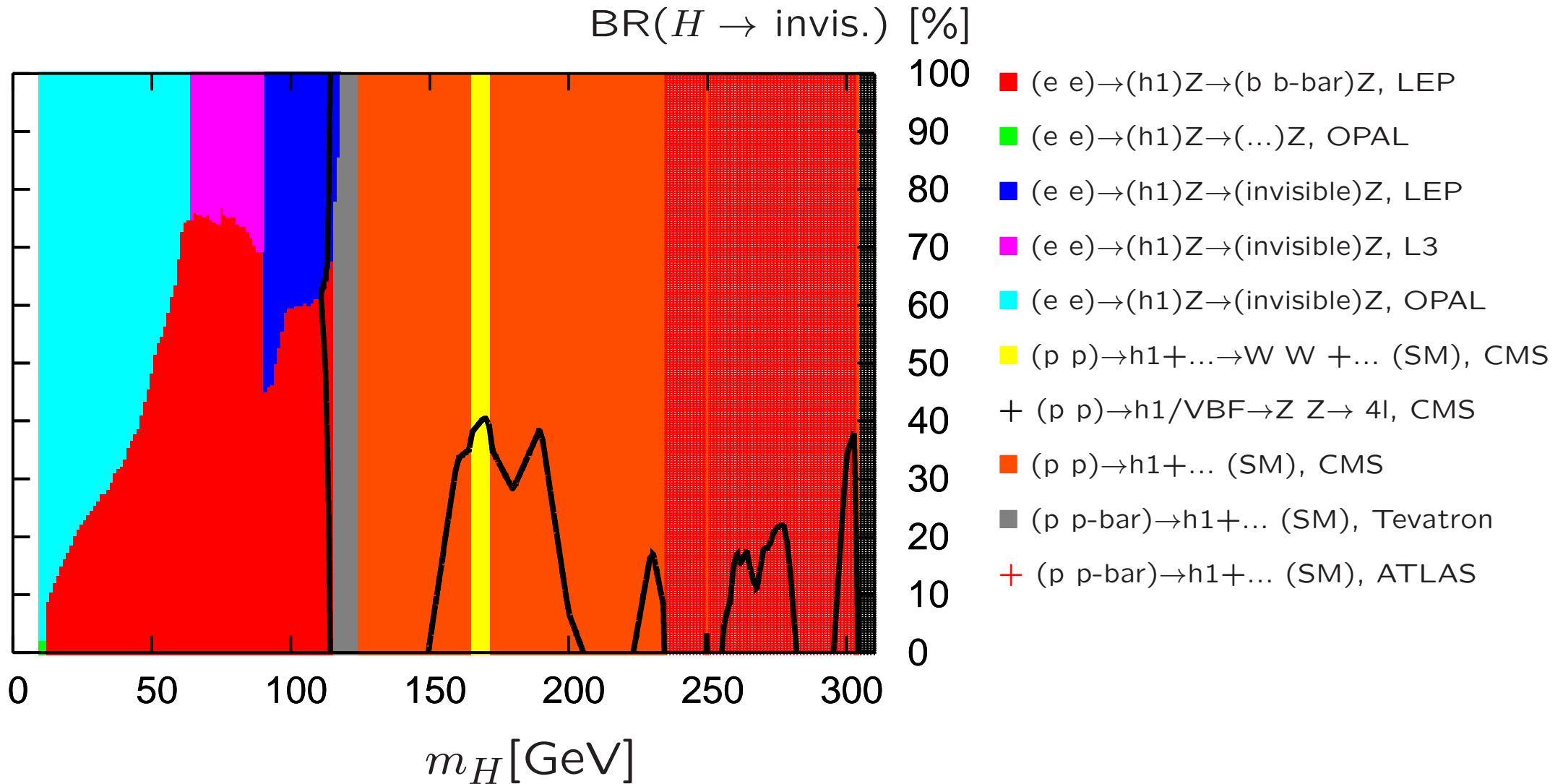
– SM+invisible model: SM + one extra decay mode $H \rightarrow$ invisible



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– Randall-Sundrum scalar sector

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■ 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]

- 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** φ
(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_{ind} : induced 4d metric on IR brane, R : Ricci scalar.

→ Radion φ and physical Higgs h mix to form two mass eigenstates

- φ coupling to massive fermions and gauge bosons \propto mass, but

- ★ $\varphi b\bar{b}$ coupling **suppressed** wrt SM Higgs

- ★ φgg coupling **enhanced** wrt SM Higgs

- ★ $\varphi \gamma\gamma$ coupling **suppressed** wrt SM Higgs

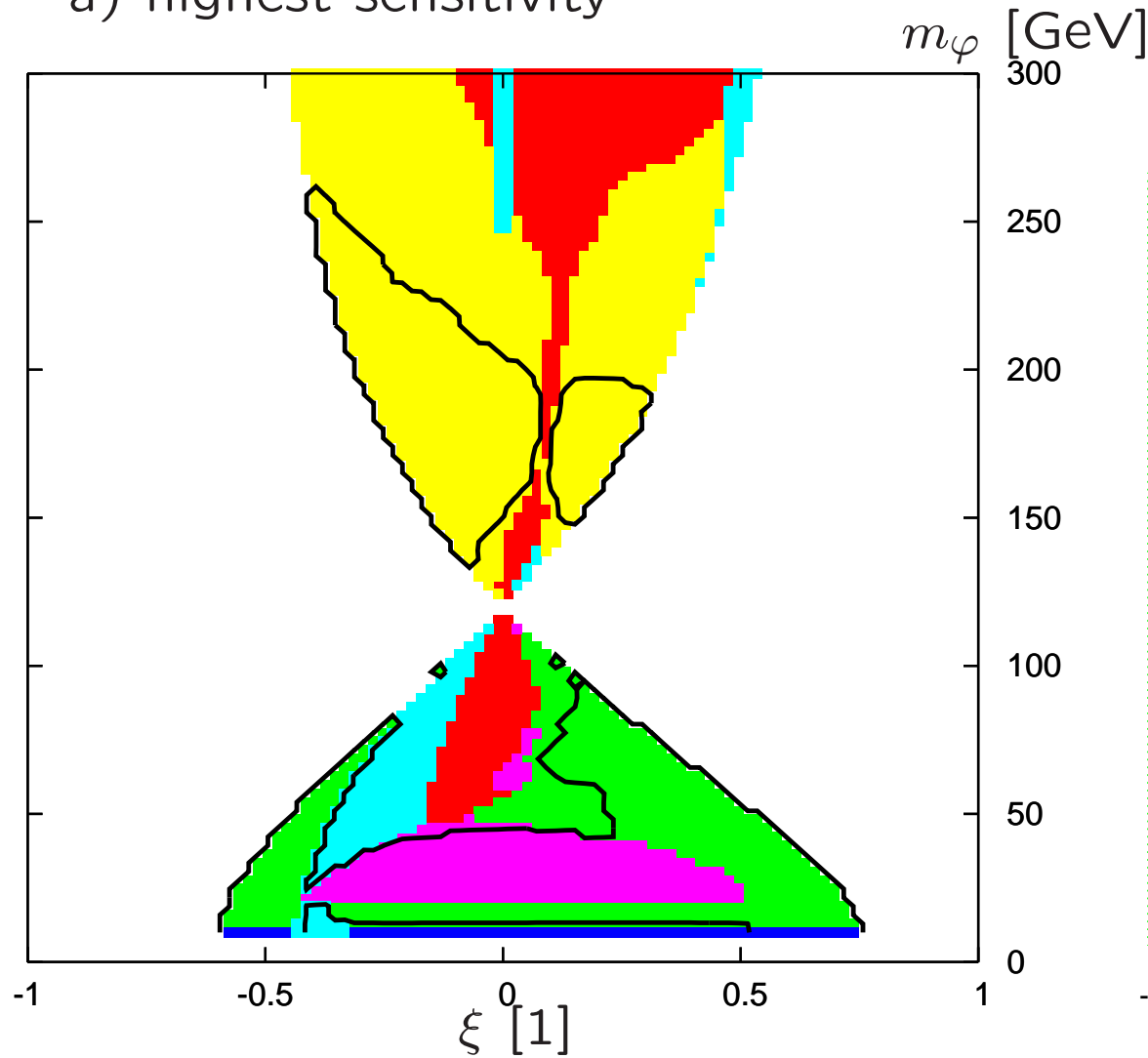
→ two scalars in the spectrum with modified couplings compared to the SM Higgs boson

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

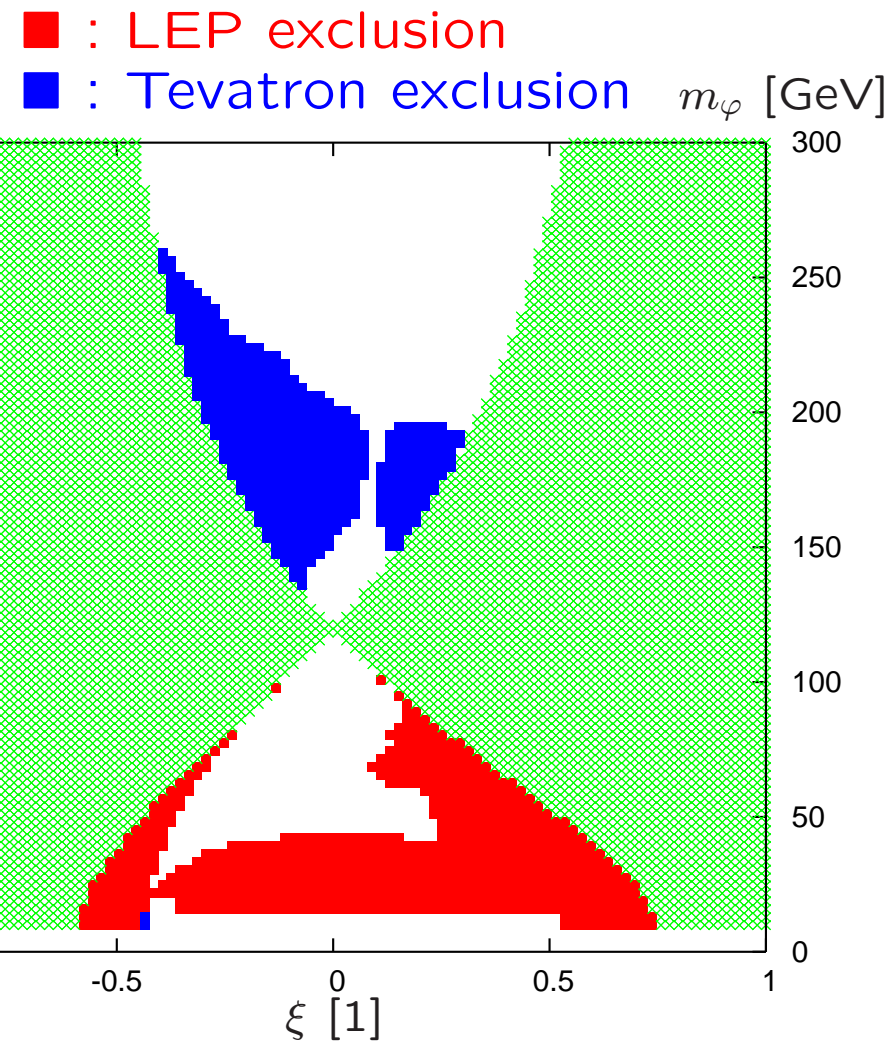
$ee \rightarrow h Z, h \rightarrow bb$
 $ee \rightarrow \phi Z, \phi \rightarrow bb$
 $ee \rightarrow \phi Z, \phi \rightarrow \text{anything}$
 $ee \rightarrow \phi Z, \phi \rightarrow \text{hadrons}$
 $pp \rightarrow \text{single } h, h \rightarrow WW$
 $pp \rightarrow \text{single } \phi, \phi \rightarrow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

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

a) highest sensitivity



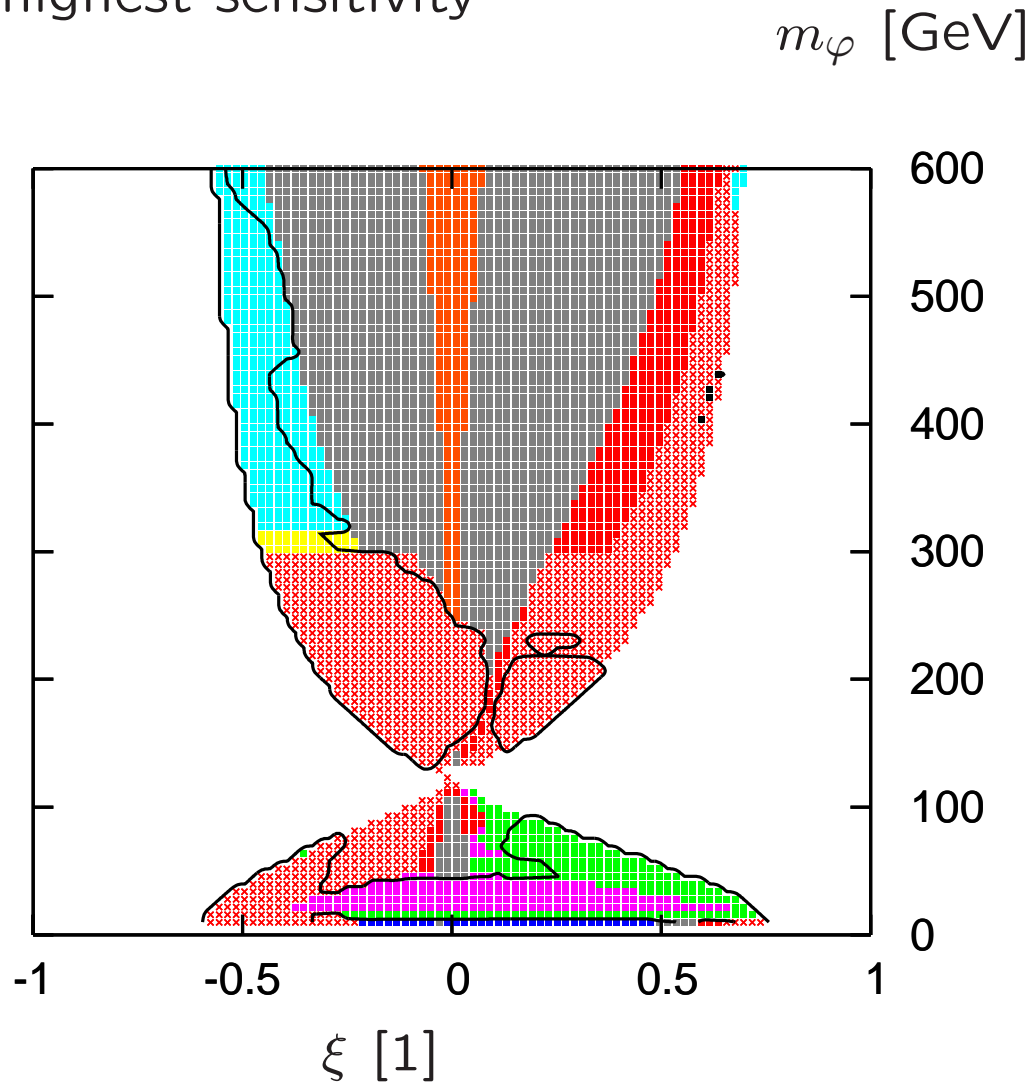
b) exclusion



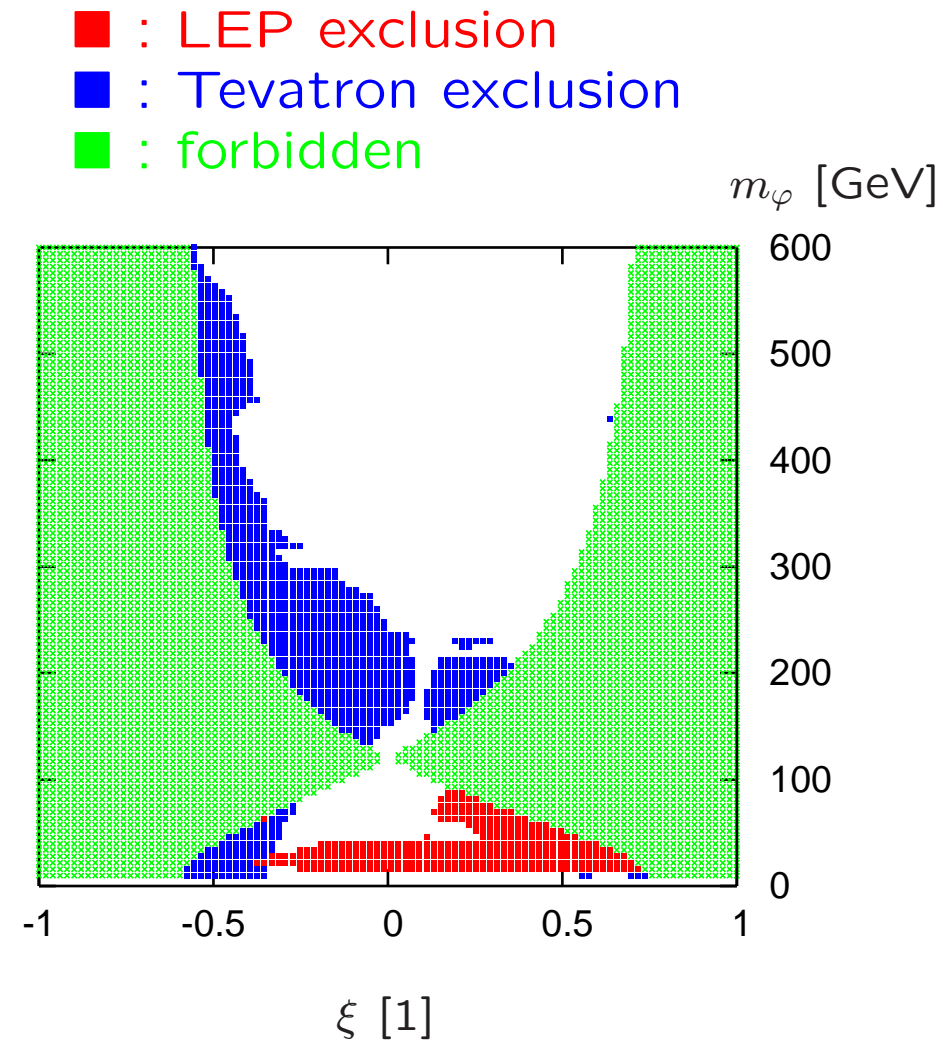
Exclusion range and sensitivity map: $\xi - m_\varphi$ plane with LHC data

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

a) highest sensitivity



b) exclusion

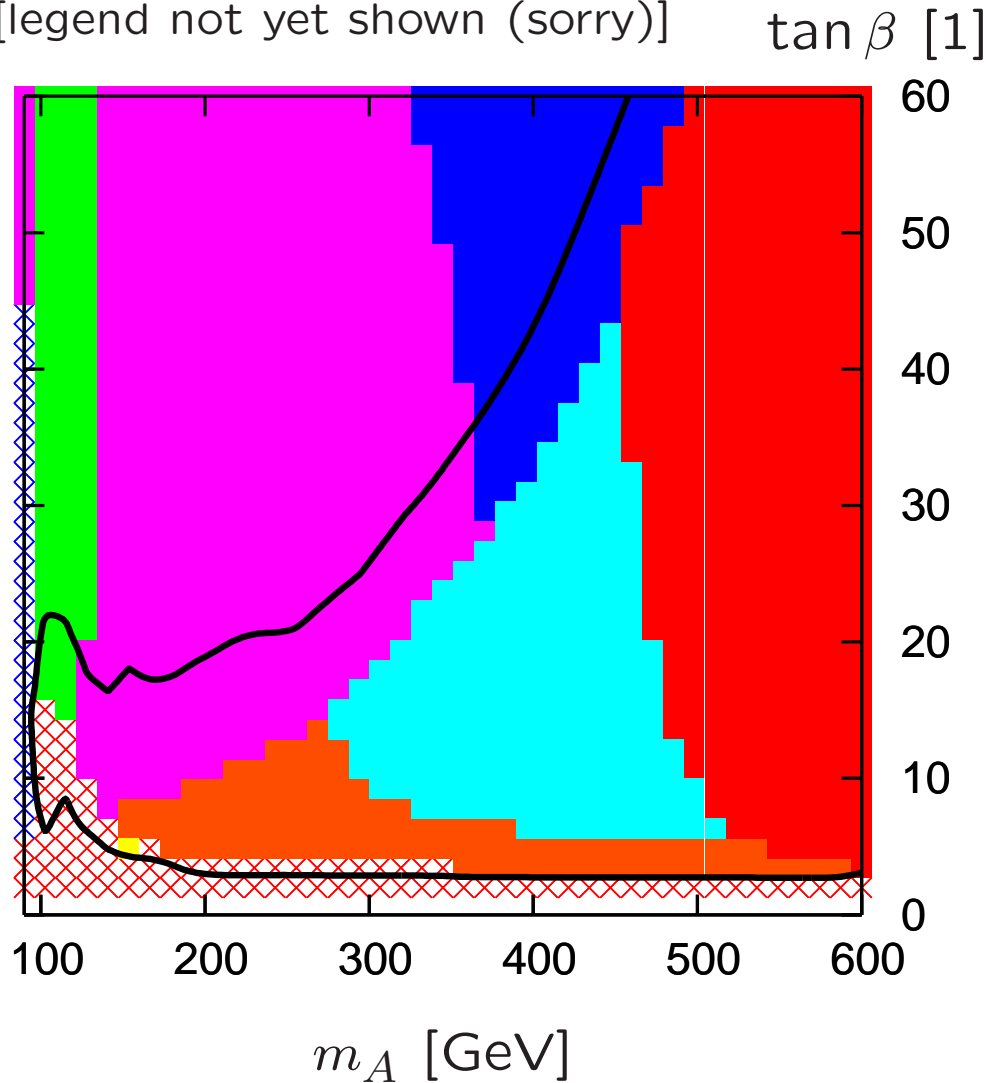


– MSSM

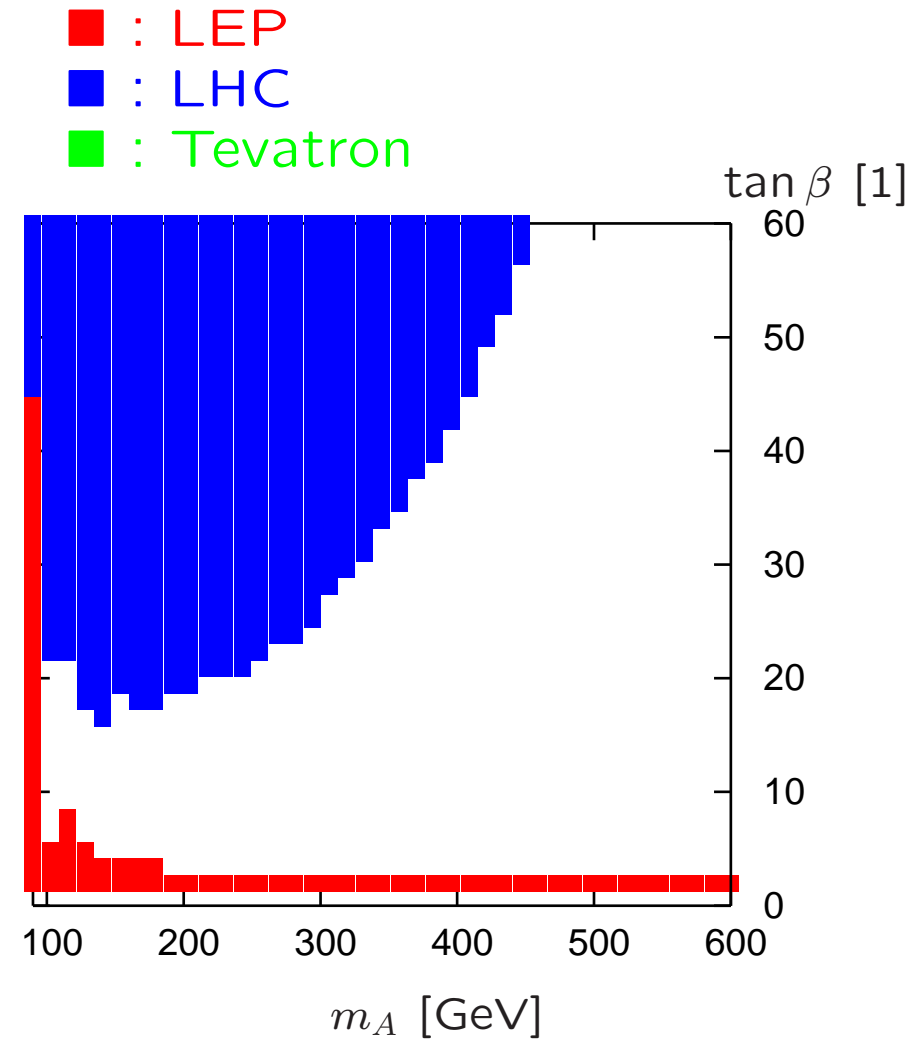
Exclusion range and sensitivity map: $\tan\beta - m_A$ plane

mhmax+ scenario

a) highest sensitivity analysis
[legend not yet shown (sorry)]



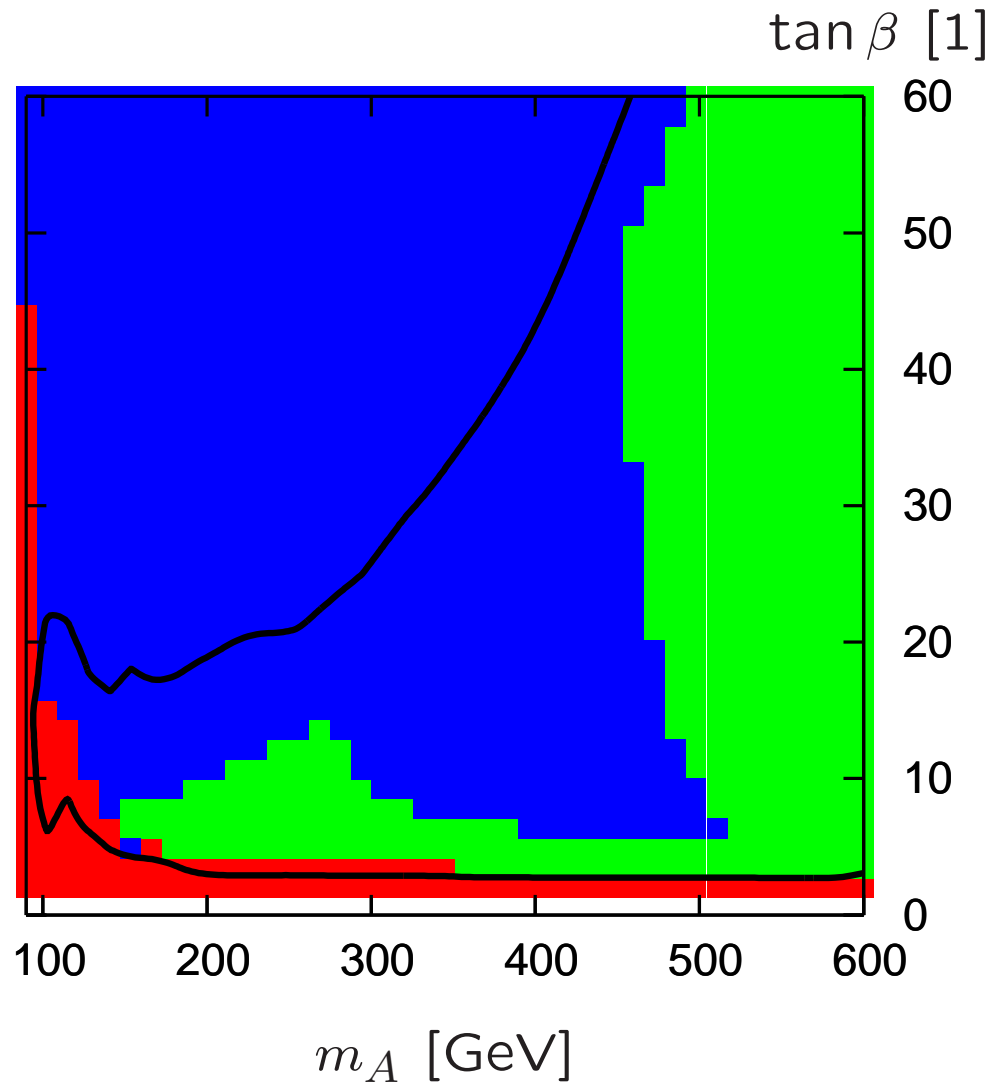
b) exclusion



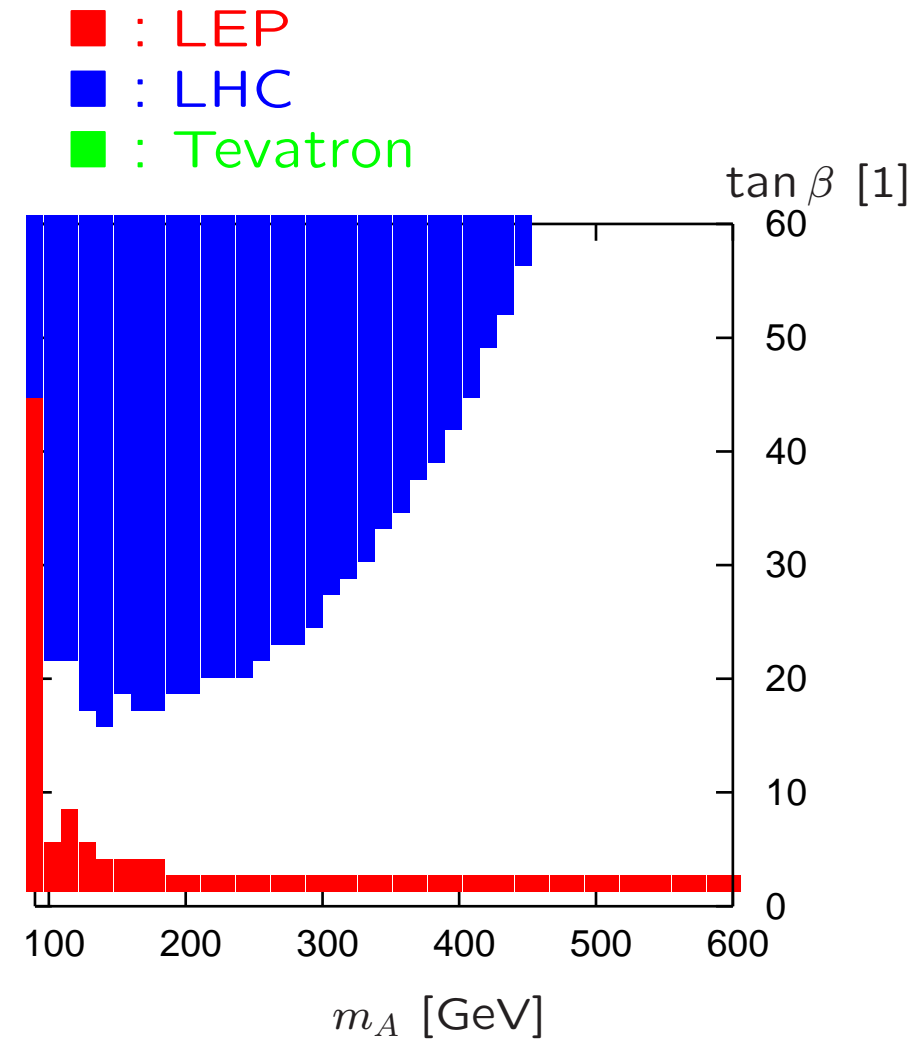
Exclusion range and sensitivity map: $\tan\beta - m_A$ plane

mhmax+ scenario

a') highest sensitivity experiment



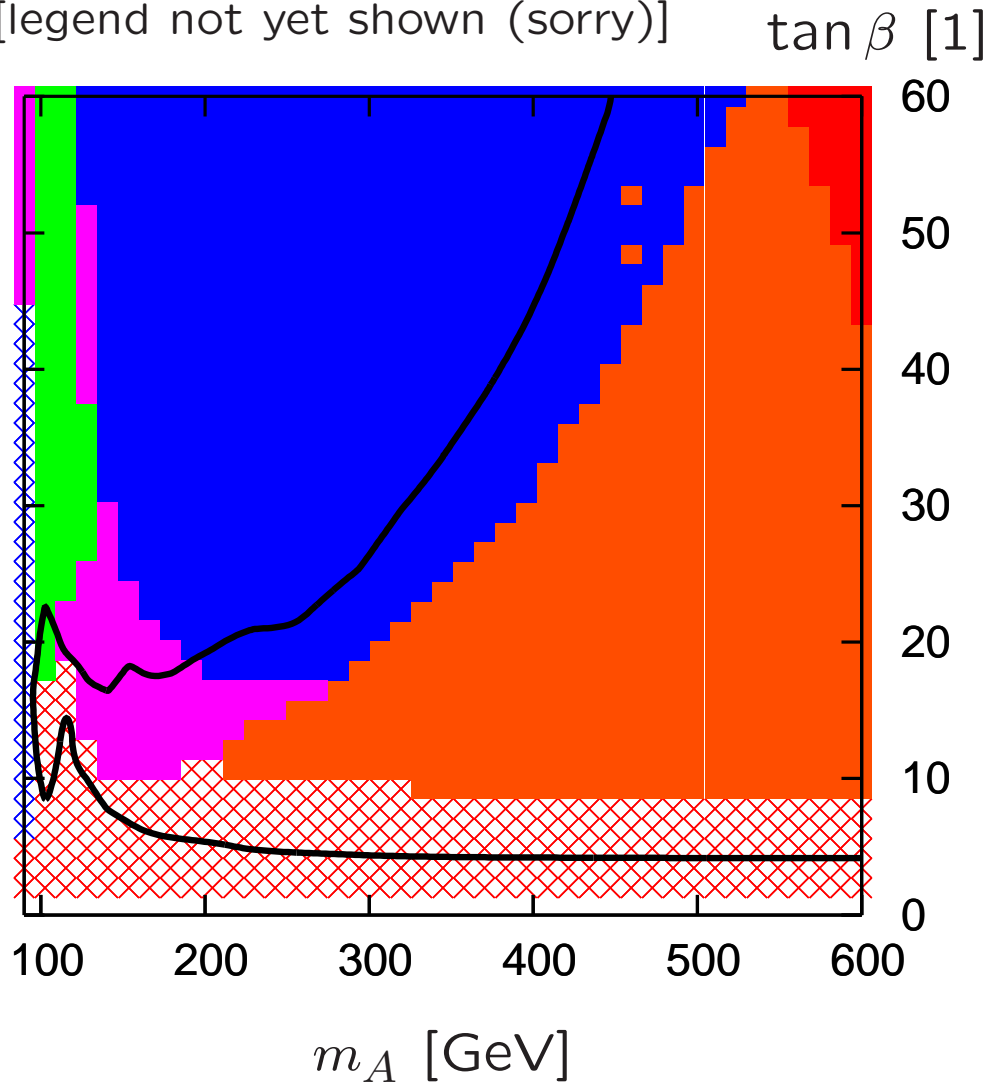
b) exclusion



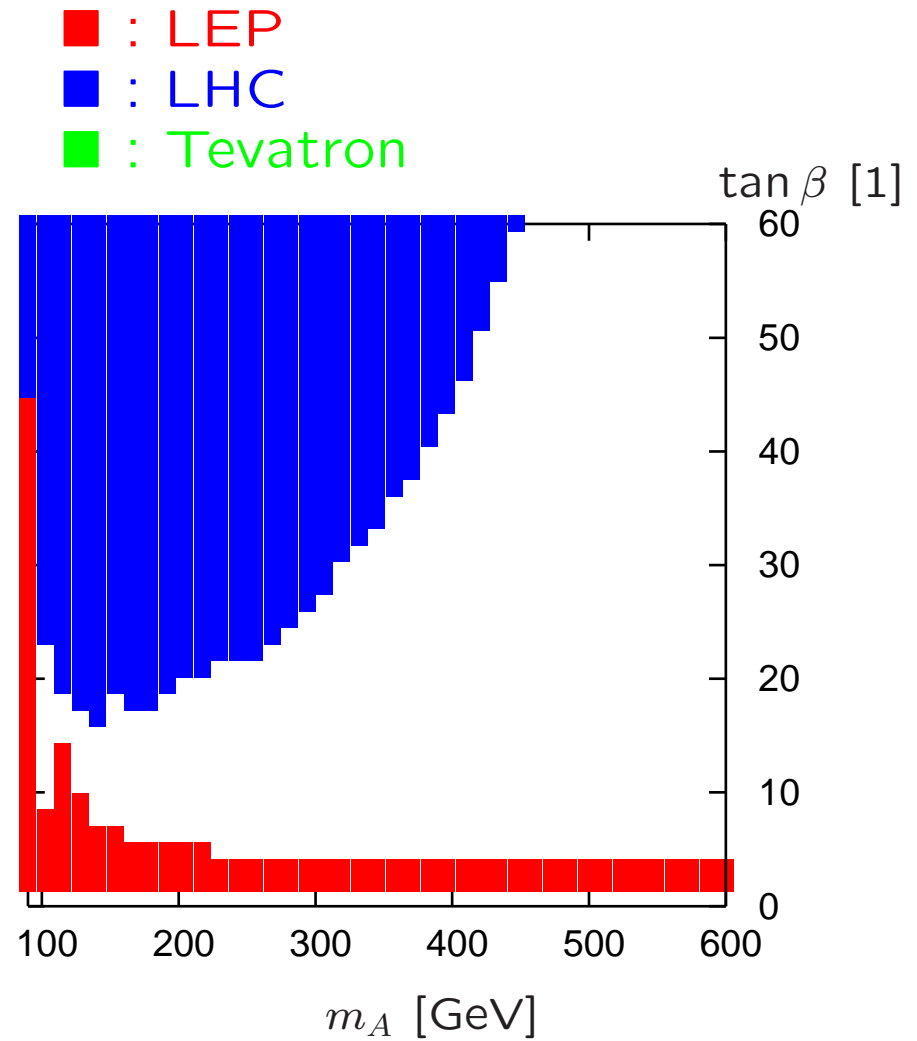
Exclusion range and sensitivity map: $\tan \beta - m_A$ plane

mhmax+(400) scenario
 $[M_{\text{SUSY}} = 400 \text{ GeV}]$

a) highest sensitivity analysis
 [legend not yet shown (sorry)]



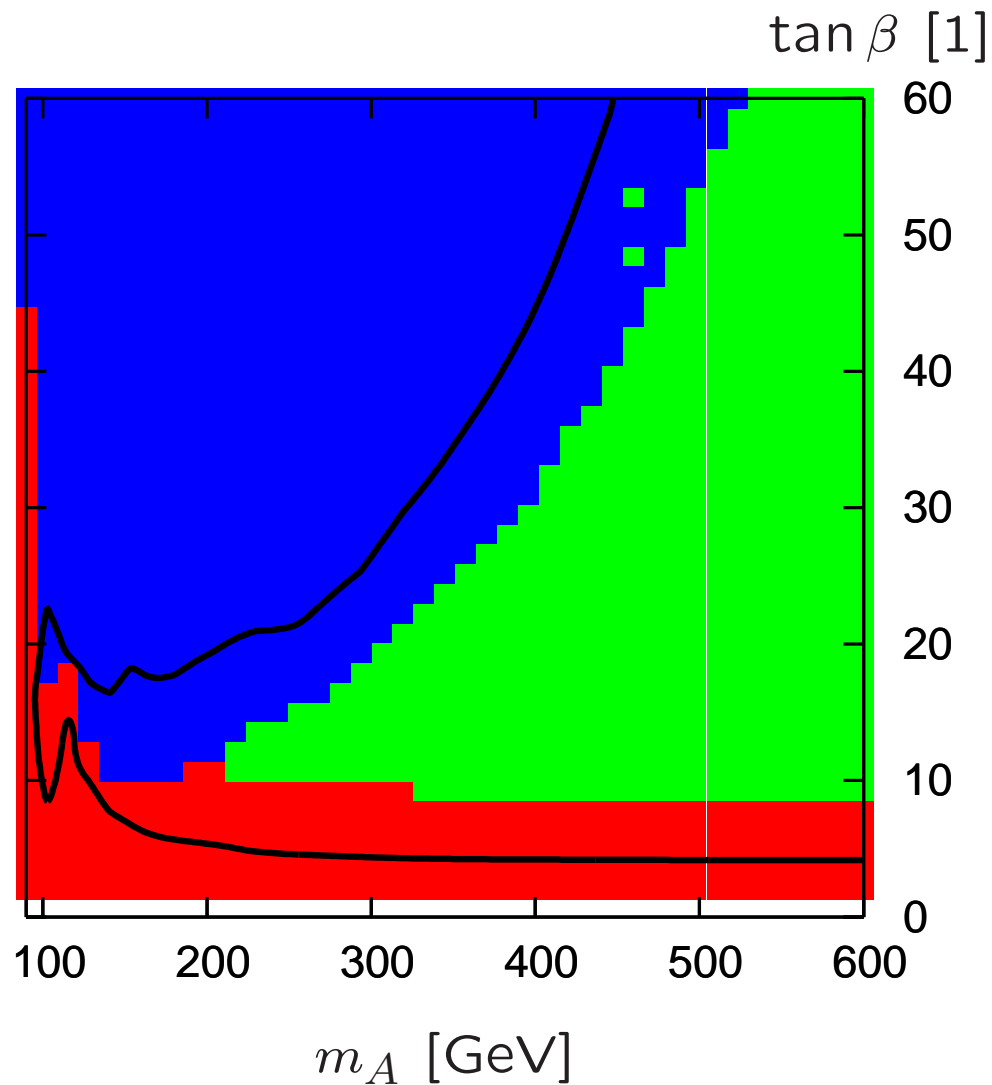
b) exclusion



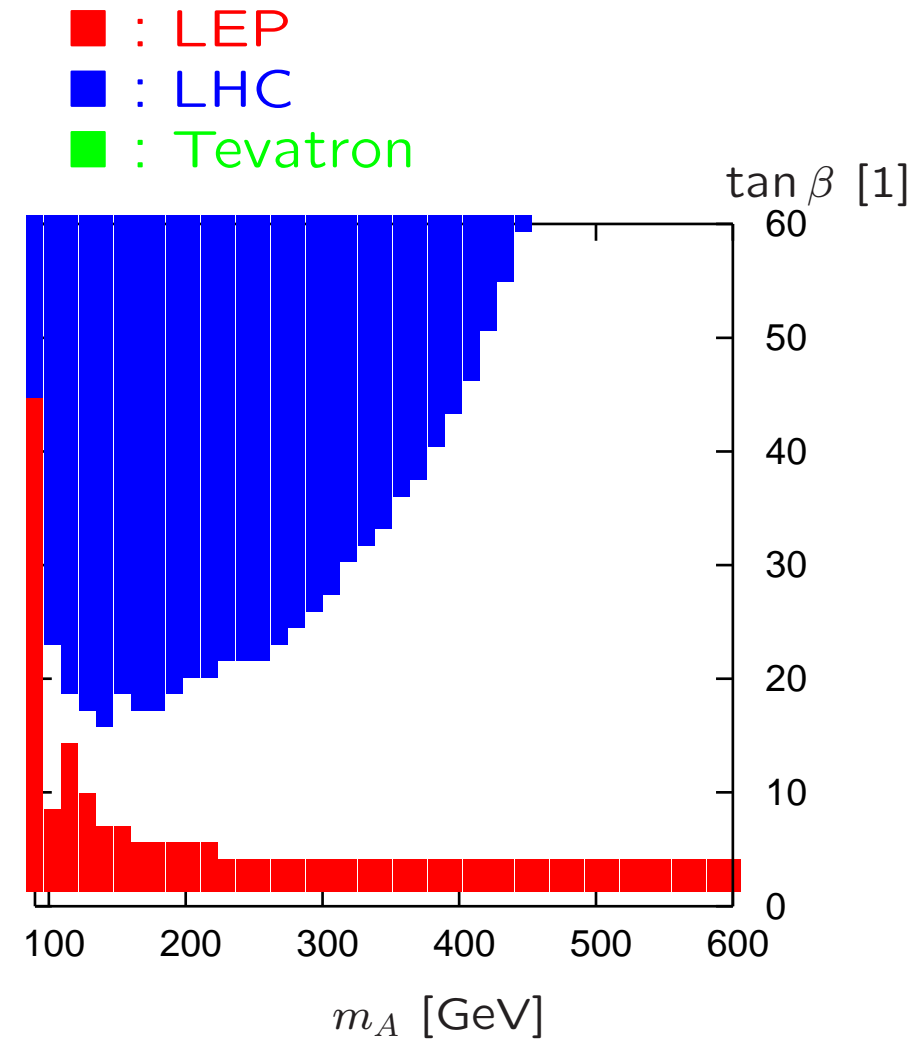
Exclusion range and sensitivity map: $\tan\beta - m_A$ plane

mhmax+(400) scenario
 $[M_{\text{SUSY}} = 400 \text{ GeV}]$

a') highest sensitivity experiment



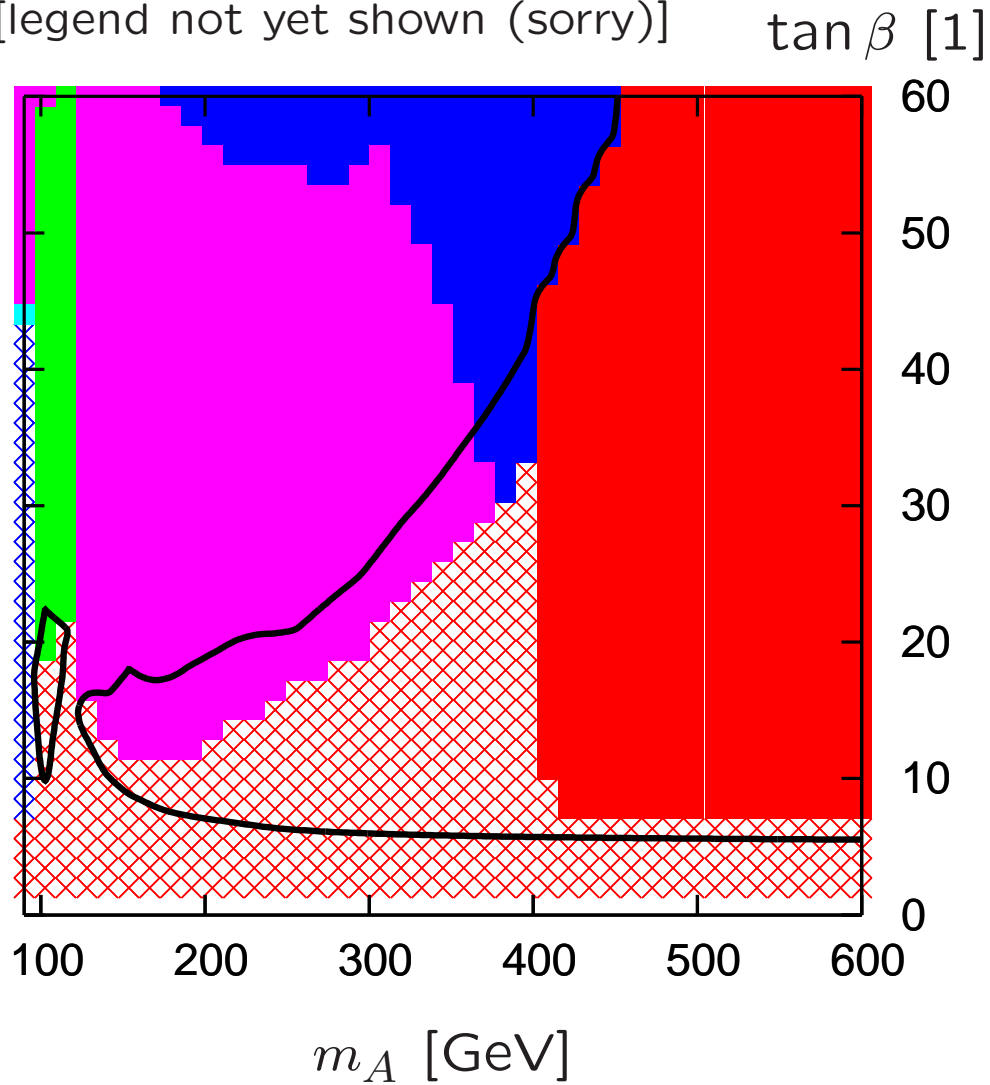
b) exclusion



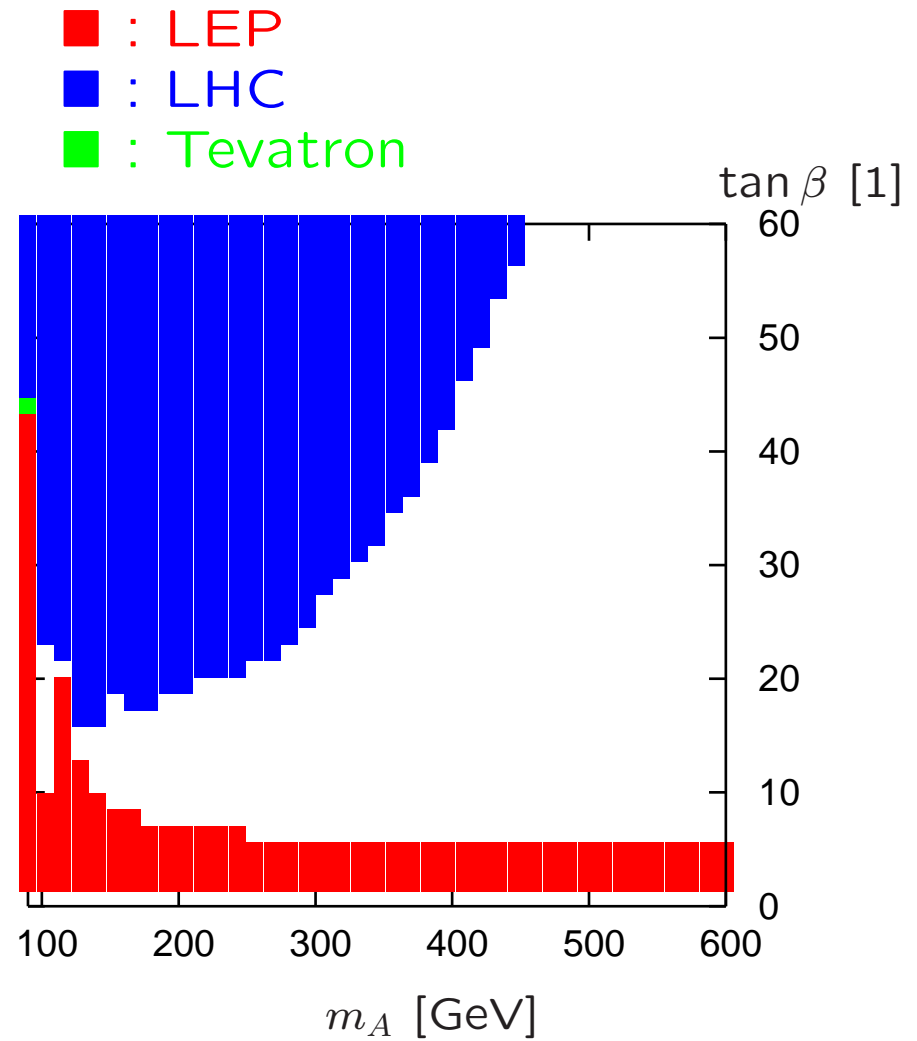
Exclusion range and sensitivity map: $\tan \beta - m_A$ plane

nomix+ scenario

a) highest sensitivity analysis
[legend not yet shown (sorry)]



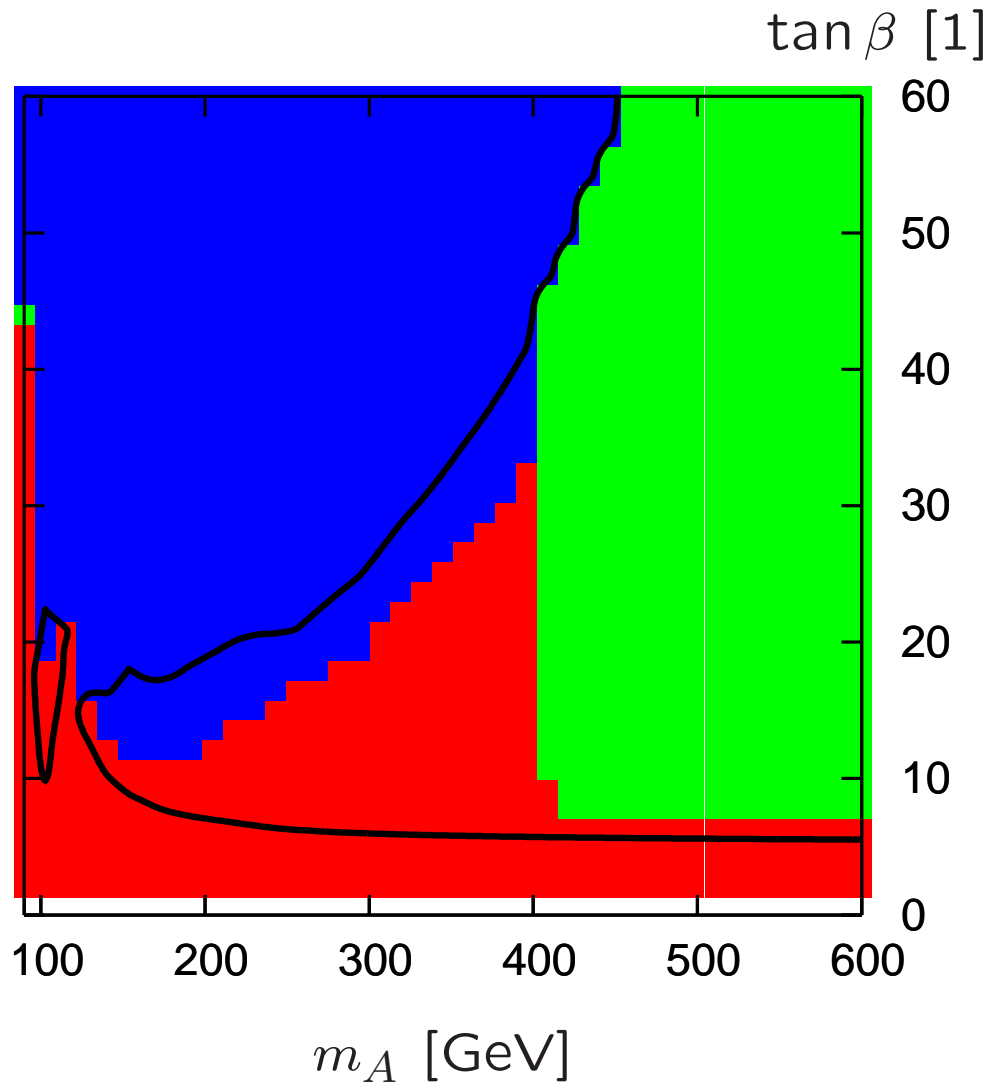
b) exclusion



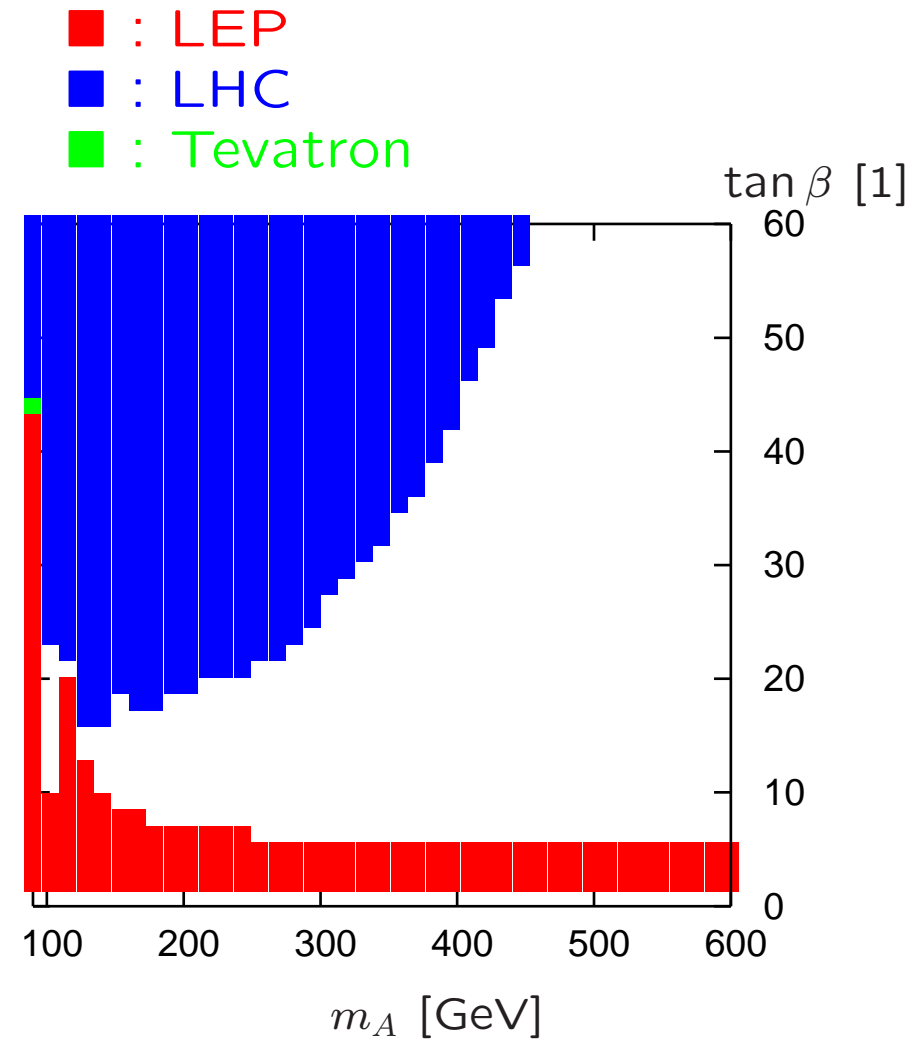
Exclusion range and sensitivity map: $\tan \beta - m_A$ plane

nomix+ scenario

a') highest sensitivity experiment



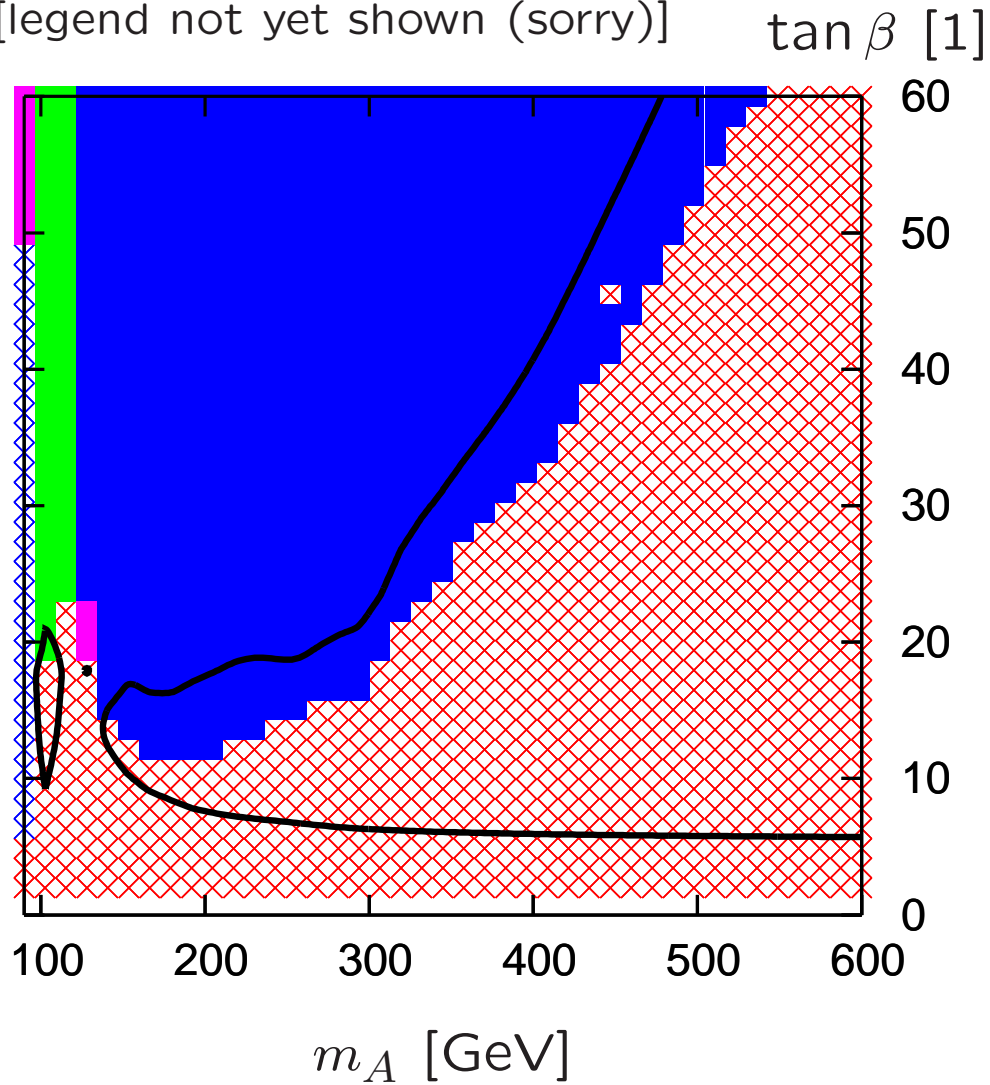
b) exclusion



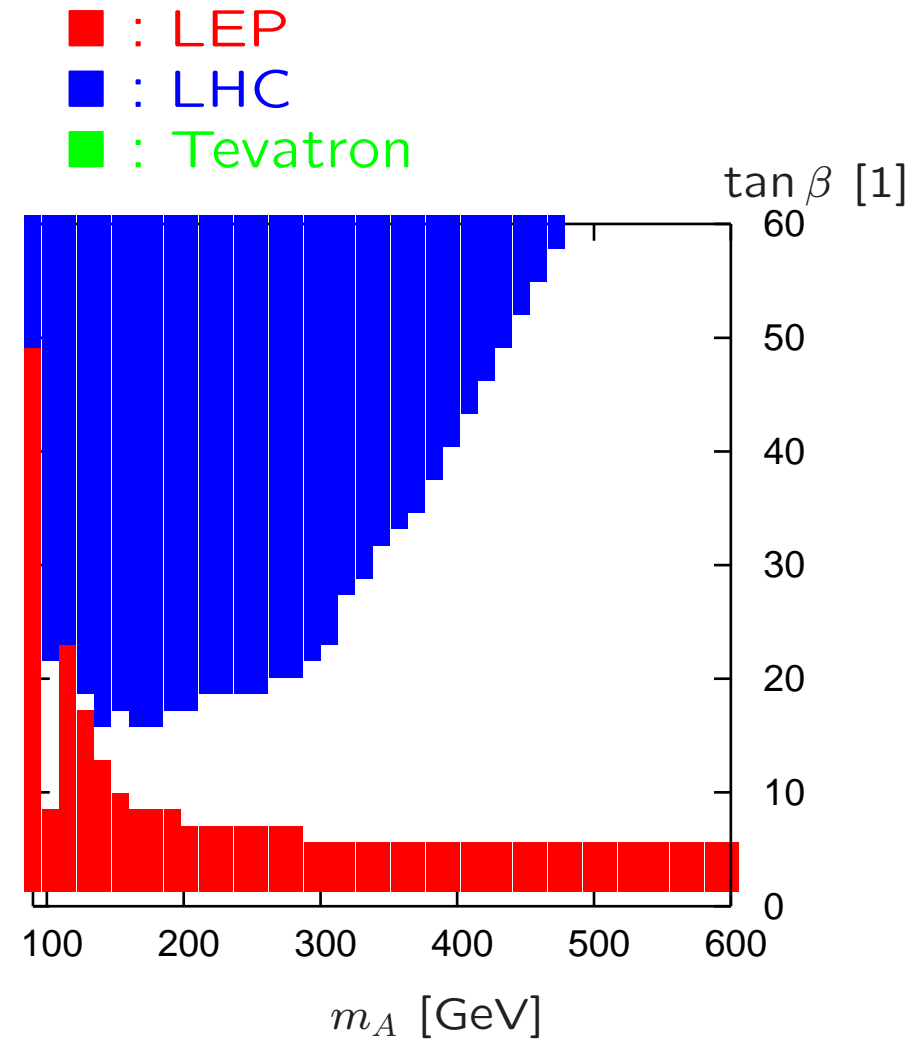
Exclusion range and sensitivity map: $\tan \beta - m_A$ plane

gluophobic scenario

a) highest sensitivity analysis
[legend not yet shown (sorry)]



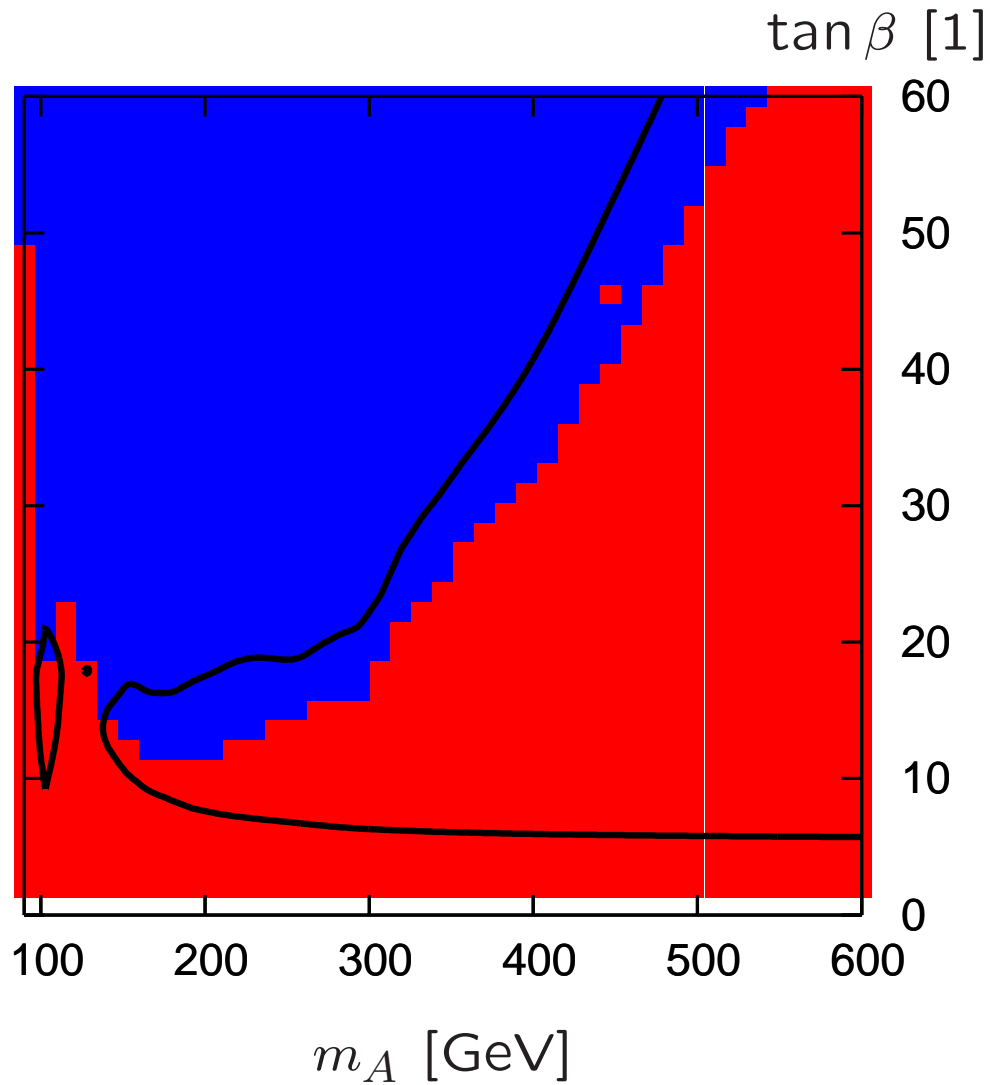
b) exclusion



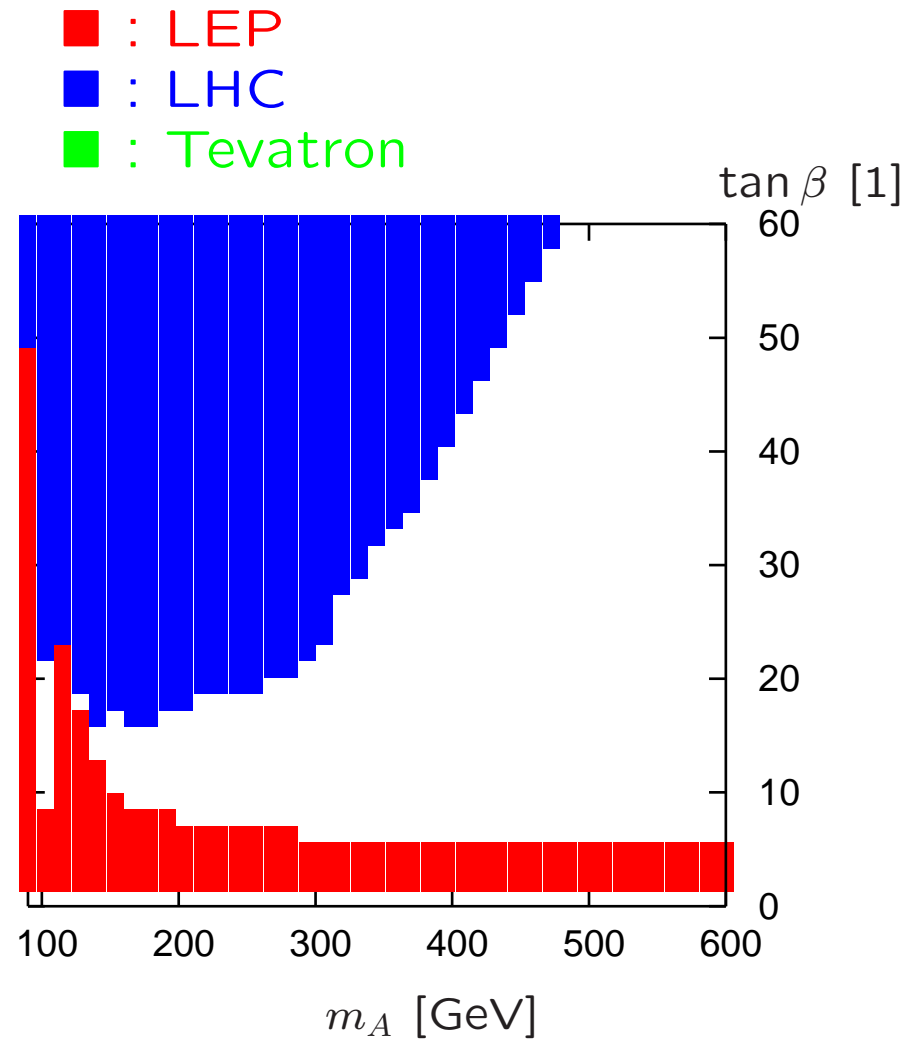
Exclusion range and sensitivity map: $\tan \beta - m_A$ plane

gluophobic scenario

a') highest sensitivity experiment



b) exclusion



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 additional parts of the Randall-Sundrum model's parameter space (compared to LEP results).