HiggsBounds :

confronting models with an arbitrary number of neutral Higgs bosons with LEP & Tevatron results

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[see also www.ippp.dur.ac.uk/HiggsBounds/]

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program demonstration by

Karina Williams

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outline :

- motivation
  - Higgs search
  - Why HiggsBounds?
- implementation
  - basic idea
  - LEP tables
  - Tevatron tables
- usage and applications
  - usage
  - applications

- motivation

– Higgs search

- The **search for Higgs bosons** is a major cornerstone in the endeavour to unravel the **nature of electroweak symmetry breaking**.

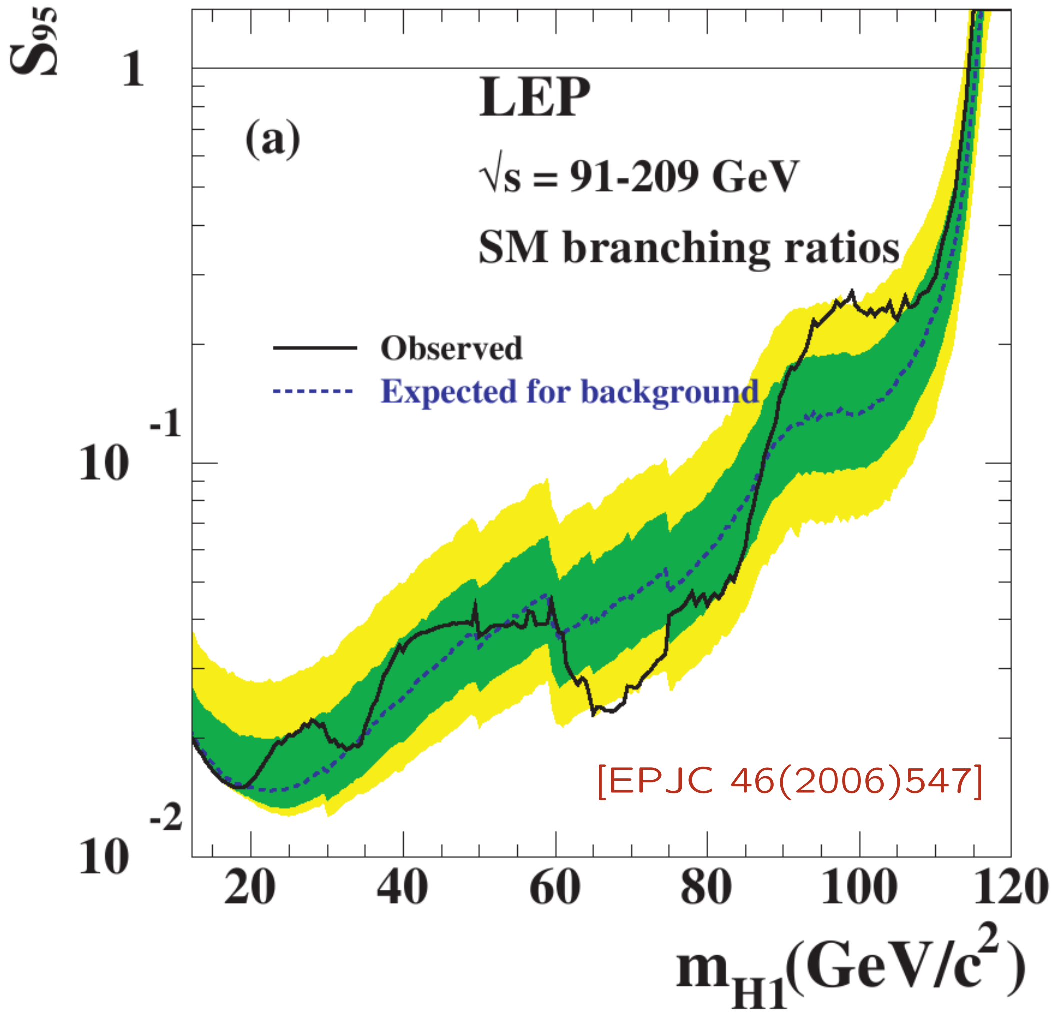
- So far no signals of Higgs bosons have been seen.
  - LEP searched for them.
  - Tevatron is currently searching for them.

- Tevatron and LEP turn(ed) the non-observation of Higgs signals into 95% C.L. limits on rates/cross sections of ...

  a) ... individual signal topologies (e.g. $h_i Z \to b\bar{b}Z$ or $h_i Z \to \tau^+\tau^- Z$)

  b) ... combinations of signal topologies according to the relative contribution to the total rate in specific models (e.g. SM, MSSM combined limits).

example 1: LEP SM combined limit



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

where $\sigma_{\text{max}}(m_{H1})$ is the maximal Higgs production cross section compatible with the background-only hypothesis at 95% C.L.

A SM-like model with

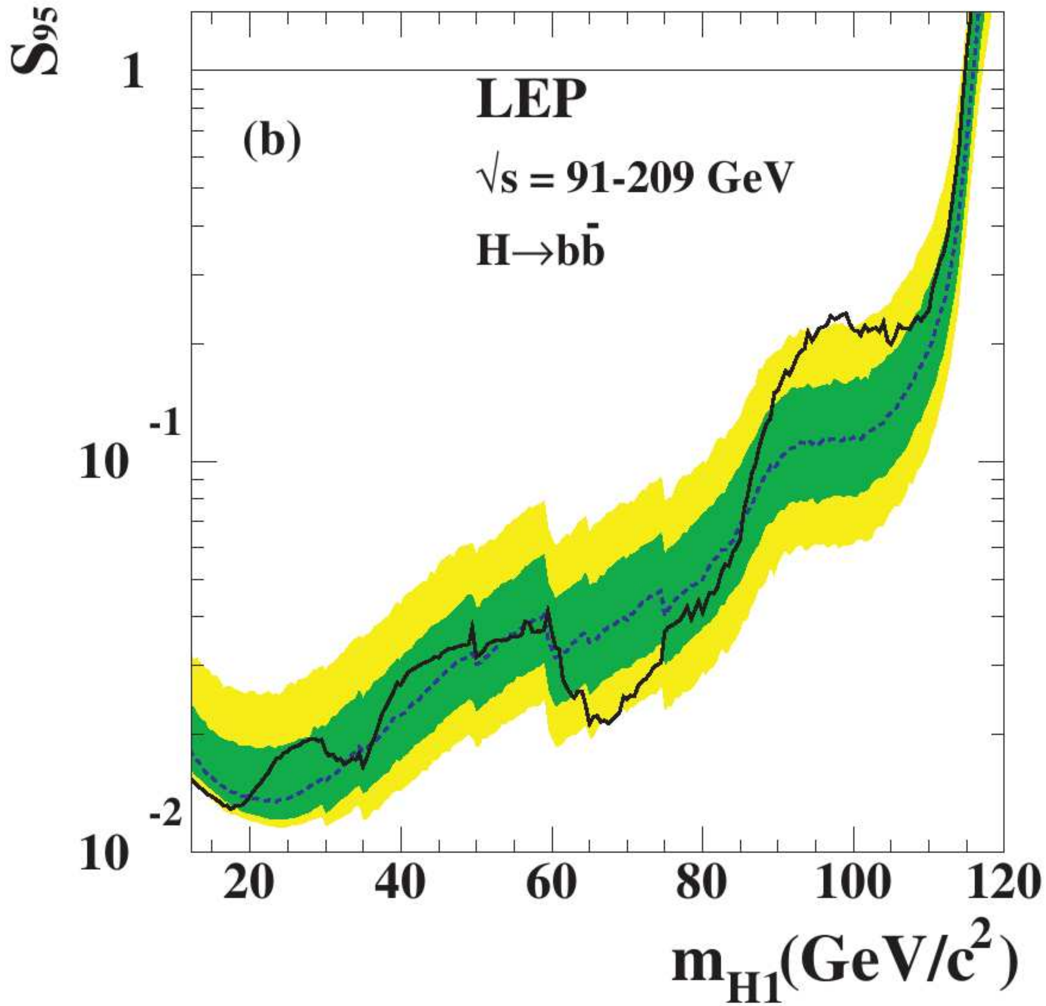
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{max}}(m_{H1})$$

or $\dfrac{\sigma_{\text{model}}(m_{H1})}{\sigma_{\text{max}}(m_{H1})} > 1$

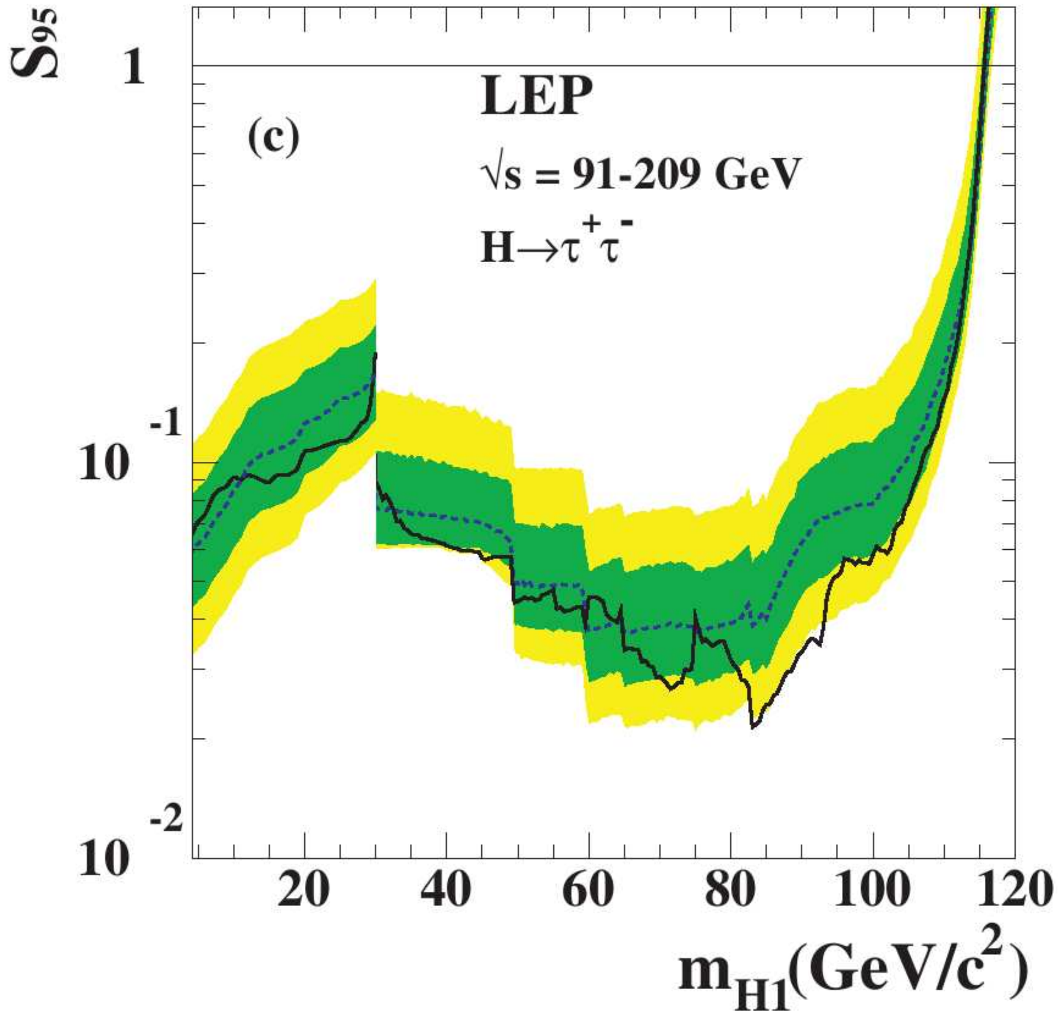
is said to be excluded at the 95% C.L.

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

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



b) ... BR($H \to \tau^+\tau^-$)=1

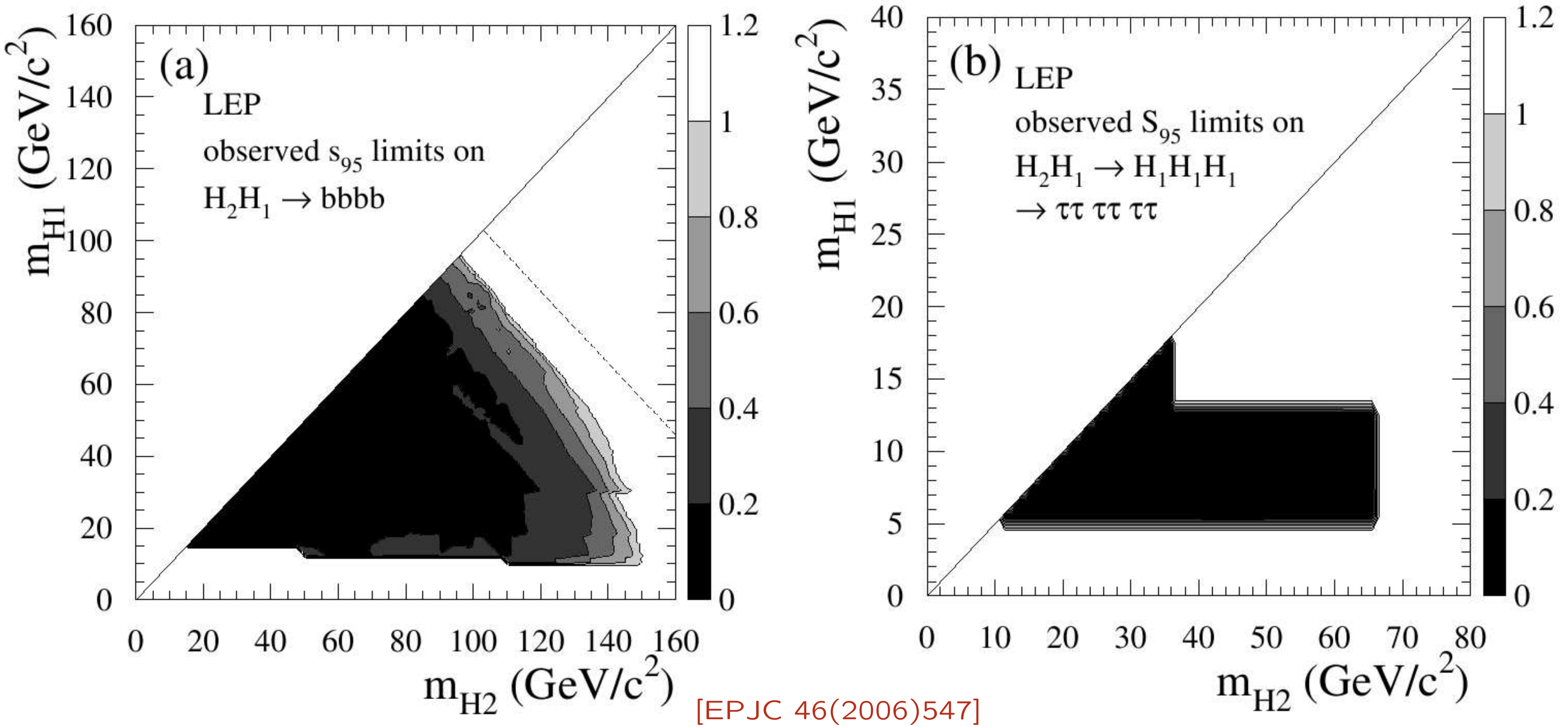


[EPJC 46(2006)547]

example 3: LEP single topology limits, assuming ...

a) ... H_2H_1 production and $\text{BR}(H_i \to b\bar{b}) = 1$

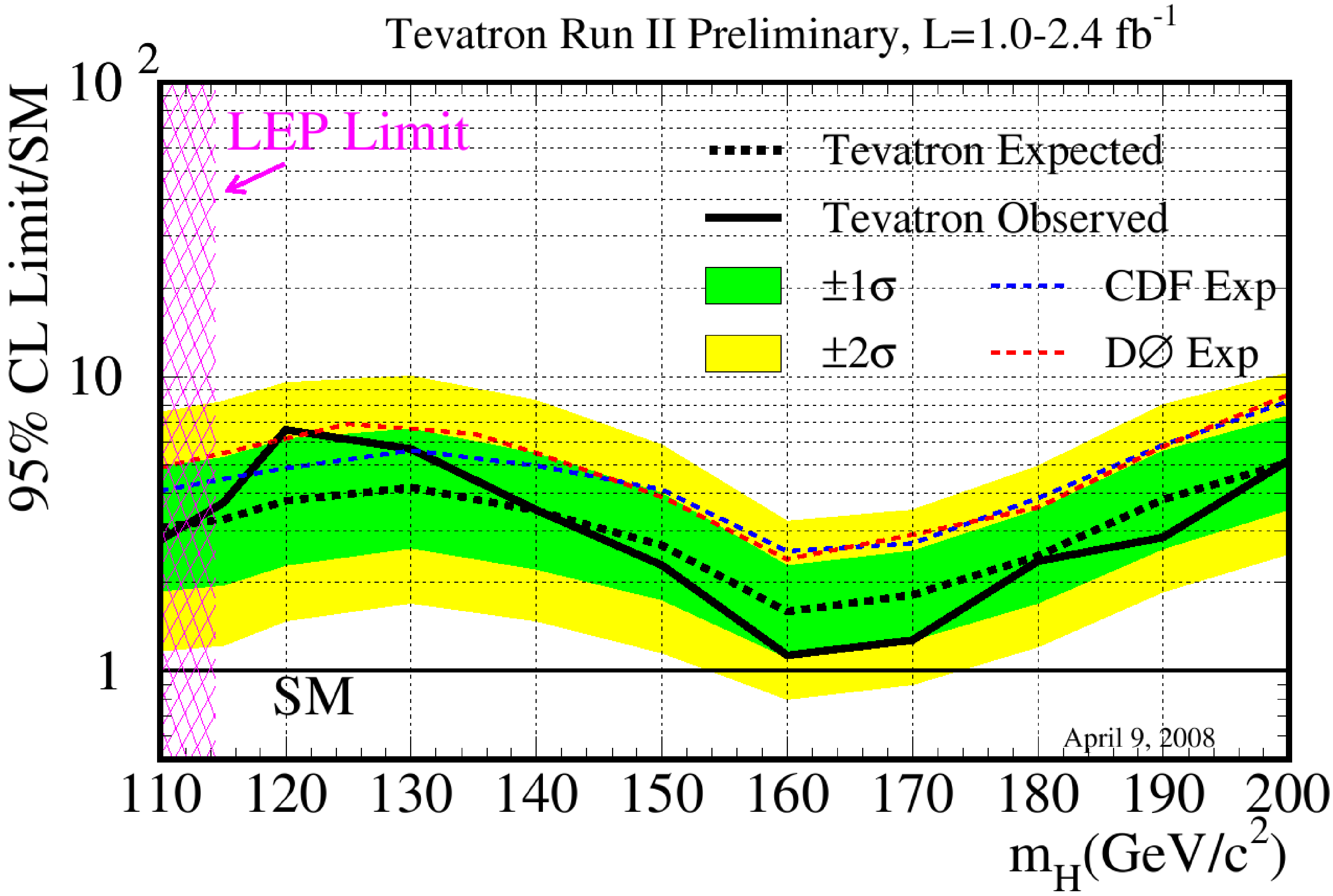
b) ... H_2H_1 production and $\text{BR}(H_i \to \tau^+\tau^-) = \text{BR}(H_2 \to H_1H_1) = 1$

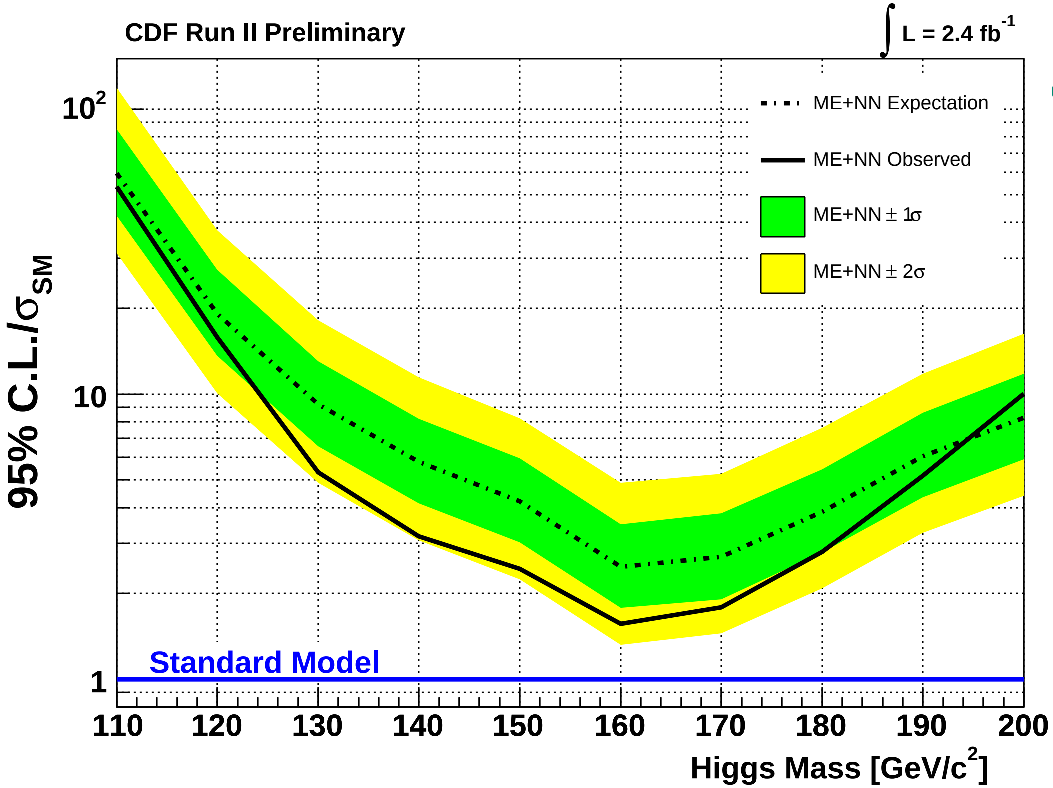


[EPJC 46(2006)547]

here: $S_{95}(m_{H1}, m_{H2}) := \frac{\sigma_{\text{max}}}{\sigma_{\text{ref}}}(m_{H1}, m_{H2})$ with a reference $\sigma_{\text{ref}}(m_{H1}, m_{H2})$

example 4: Tevatron SM combined limit





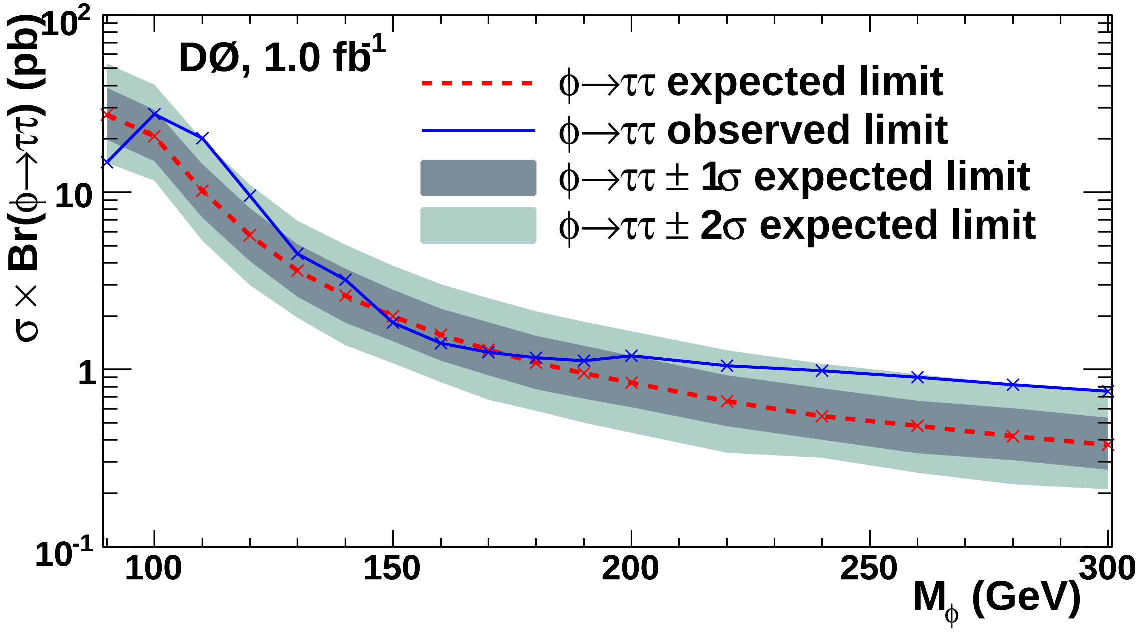
example 5: Tevatron single topology limits

a) $p\bar{p} \to H \to WW^\star$ using 1.9 fb^{-1}
[CDF note 8958]

cross section ratio limit

b) $p\bar{p} \to H \to \tau^+\tau^-$ using 1 fb^{-1}
[DØ hep-ex/0805.2491]

absolute cross section limit



– Why HiggsBounds?

- Many limits on individual topologies (from LEP/Tevatron) and combined results available, more to be expected from the Tevatron and the LHC (hopefully not for too long).

- In general, models with Higgs sectors beyond the SM are not SM-like, i.e. individual Higgs signal topologies contribute in different proportions than in the SM.

- To test a parameter scenario of such models against LEP and Tevatron results, one needs to check the model predictions for all cross sections of individual search topologies against the corresponding published experimental limits.

HiggsBounds:

Decide for model scenarios with an arbitrary number of neutral Higgs bosons, with given deviations from the SM Higgs production cross sections and decay branching ratios, whether it is excluded at the 95% C.L. by LEP or Tevatron.

- Easy access to all relevant Higgs exclusion limits

- Simple, model-independent input
  (even the # of Higgs bosons can be chosen)

- Possibility to combine LEP and Tevatron results

- Interfaces to specific models allow to have exclusion plots with LEP/Tevatron data for the parameter scenario of one's own choice.

- implementation

• implementation

– basic idea

- Evaluate model prediction Q_{model} for cross section times BR (normalised to a reference value or not) of all search channels X for given Higgs masses and deviations from the SM and compare to experimental limit.

- Depending on the way the exclusion result (table) for a particular search channel (topology) has been published (relative or absolute limit, BR assumed to be 1), we evaluate

$$Q_{\text{model}} = \frac{[\sigma \times \text{BR}]_{\text{model}}}{[\sigma \times \text{BR}]_{\text{ref}}} \quad \text{or} \quad \frac{[\sigma \times \text{BR}]_{\text{model}}}{\sigma_{\text{ref}}} \quad \text{or} \quad [\sigma \times \text{BR}]_{\text{model}}.$$

- From the experimental results we read off the value $Q_{\text{observed}}(X)$ corresponding to the observed 95% C.L. limit.

- If $\frac{Q_{\text{model}}(X)}{Q_{\text{observed}}(X)} > 1$ the model is excluded by this channel at 95% C.L.

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

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

- Determine for each search channel X the experimental predicted limit $Q_{\text{predicted}}(X)$.

- Determine the channel X_0 with the highest sensitivity for the signal, i.e. of all channels X find the channel X_0 where $\frac{Q_{\text{model}}(X)}{Q_{\text{predicted}}(X)}$ is maximal.

- If for this channel $\frac{Q_{\text{model}}(X_0)}{Q_{\text{observed}}(X_0)} > 1$ the model is excluded at 95% C.L. by the corresponding experimental analysis for the search channel X_0

– LEP tables

We include predicted and observed S_{95} values for the following search channels [EPJC 46(2006)547]

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$,
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$,
3. $e^+e^- \to (h_k \to h_ih_i)Z \to (b\bar{b}b\bar{b})Z$,
4. $e^+e^- \to (h_k \to h_ih_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$,
5. $e^+e^- \to (h_kh_i) \to (b\bar{b}b\bar{b})$,
6. $e^+e^- \to (h_kh_i) \to (\tau^+\tau^-\tau^+\tau^-)$,
7. $e^+e^- \to (h_k \to h_ih_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$,
8. $e^+e^- \to (h_k \to h_ih_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$,
9. $e^+e^- \to (h_k \to h_ih_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$,
10. $e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$,
11. $e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$,

Inclusion of additional channels, e.g. with $h_k \to$ invisible, is work in progress.

[implementation, LEP tables]

With the input

$$\sigma_{\text{model}}(X)/\sigma_{\text{ref}}(X)\,, \qquad \text{BR}_{\text{model}}(h_i \to b\bar{b})\,, \qquad \text{BR}_{\text{model}}(h_i \to \tau^+\tau^-)\,,$$
$$\text{BR}_{\text{model}}(h_k \to h_i h_i)\,.$$

we can evaluate the corresponding model predictions S_{model} to compare with S_{95} as e.g.

$$S_{\text{model}}\left[(h_1)Z \to (b\bar{b})Z\right] = \frac{\sigma_{\text{model}}(h_1 Z)}{\sigma_{\text{ref}}(h_1 Z)}\text{BR}_{\text{model}}(h_1 \to b\bar{b})\,,$$

$$S_{\text{model}}\left[(h_2 \to h_1 h_1)Z \to (b\bar{b}b\bar{b})Z\right] =$$
$$\frac{\sigma_{\text{model}}(h_2 Z)}{\sigma_{\text{ref}}(h_2 Z)}\text{BR}_{\text{model}}(h_2 \to h_1 h_1)\text{BR}_{\text{model}}(h_1 \to b\bar{b})^2$$

– Tevatron tables

At the moment, signatures of the following combinations of Higgs production process P and final states F have been searched for by CDF and DØ:

$$p\bar{p} \to W^\pm H \to \begin{cases} l\nu b\bar{b} \\ W^\pm W^+ W^- \\ \gamma\gamma \end{cases}$$

$$p\bar{p} \to ZH \to \begin{cases} \nu\bar{\nu} b\bar{b} \\ l^+ l^- b\bar{b} \\ \gamma\gamma \end{cases}$$

$$p\bar{p} \to H \to \begin{cases} W^+ W^- \to l^\pm \nu l^\mp \nu \\ \tau^+ \tau^- \\ \gamma\gamma \end{cases}$$

$$p\bar{p} \to Hb \to 3\ b\text{-jets}$$

$$p\bar{p} \to H \text{ via VBF}, H \to \gamma\gamma$$

We have included 25 tables for predicted and observed S_{95} values.

[implementation, Tevatron tables]

The evaluation of the corresponding model predictions Q_{model} is similar as in the LEP case.

However, for the cross section input of each search channel X, ratios of hadronic cross sections are needed in principle:

$$R(X, m_H) = \frac{\sigma_{\text{model}}(X, m_H)}{\sigma_{\text{SM}}(X, m_H)} = \left(\frac{\sigma_{\text{model}}(P)}{\sigma_{\text{SM}}(P)}\right)\left(\frac{\text{BR}_{\text{model}}(H \to F)}{\text{BR}_{\text{SM}}(H \to F)}\right)$$

This input option is supported. However, it can be rather inconvenient for the user.

Therefore, we also allow for the input of ratios of partonic cross sections and calculate the ratios of hadronic cross sections from it.

$$\left(\frac{\sigma_{\text{model}}(P)}{\sigma_{\text{SM}}(P)}\right) \approx \sum_{\{n,m\}} R^{H+y}_{nm}(\hat{s}_{\text{thr.}}, m_H) \frac{\sigma_{\text{SM}}(p\bar{p} \to nm \to H + y, m_H)}{\sigma_{\text{SM}}(p\bar{p} \to H + y, m_H)},$$

with

$$R^{H+y}_{nm}(\hat{s}, m_H) := \frac{\hat{\sigma}^{\text{model}}_{nm \to H+y}(\hat{s}, m_H)}{\hat{\sigma}^{\text{SM}}_{nm \to H+y}(\hat{s}, m_H)}.$$

- usage and applications

– usage

Fortran 90 and 77 version:

Command:

```
HiggsBounds <tables to use> <input mode> <number of Higgses> [<fileprefix>]
```

with

<tables to use>	:	LandT (LEP and Tevatron)
	:	onlyT (only Tevatron)
	:	onlyL (only LEP)
	:	singH (only single Higgs tables)
<input mode>	:	full (partonic CS ratios)
	:	fullhad (hadronic CS ratios)
	:	effC (effective couplings)
	:	SLHA (SLHA format input)
<number of Higgses>	:	1 to 10
<fileprefix>	:	prefix for input files (optional, can also be a subdirectory)

WWW version:

options similar, pointwise input only (see www.ippp.dur.ac.uk/HiggsBounds/)

Input files for Fortran versions:

Input mode: `effC`	LandT	onlyT	onlyL	singH
`MH_GammaTot.dat`	X	X	X	X
`BR_2H.dat`	X	X	X	
`effC.dat`	X	X	X	X

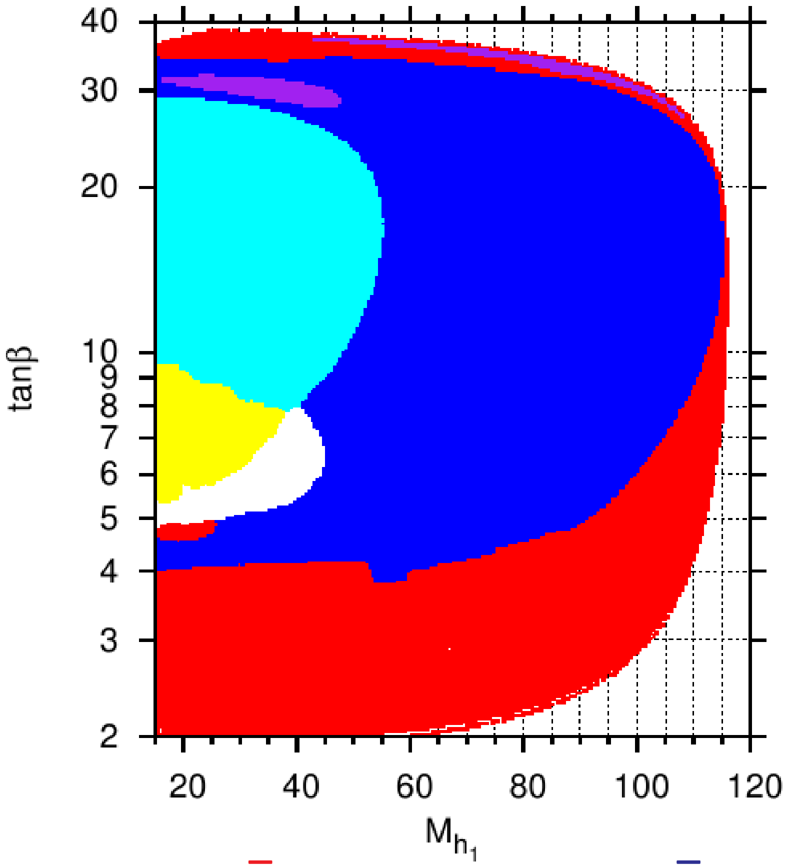
Input mode: `fullhad`	LandT	onlyT	onlyL	singH
`MH_GammaTot.dat`	X	X	X	X
`BR_1H.dat`	X	X	X	X
`BR_2H.dat`	X	X	X	
`LEP_HZ_CS_ratios.dat`	X		X	X
`LEP_2H_CS_ratios.dat`	X		X	
`TEV_1H_hadCS_ratios.dat`	X	X		X

Input mode: full	LandT	onlyT	onlyL	singH
MH_GammaTot.dat	X	X	X	X
BR_1H.dat	X	X	X	X
BR_2H.dat	X	X	X	
LEP_HZ_CS_ratios.dat	X		X	X
LEP_2H_CS_ratios.dat	X		X	
TEV_H_0jet_partCS_ratios.dat	X	X		X
TEV_H_1jet_partCS_ratios.dat	X	X		X
TEV_H_2jet_partCS_ratios.dat	X	X		X
TEV_HW_partCS_ratios.dat	X	X		X
TEV_HZ_partCS_ratios.dat	X	X		X

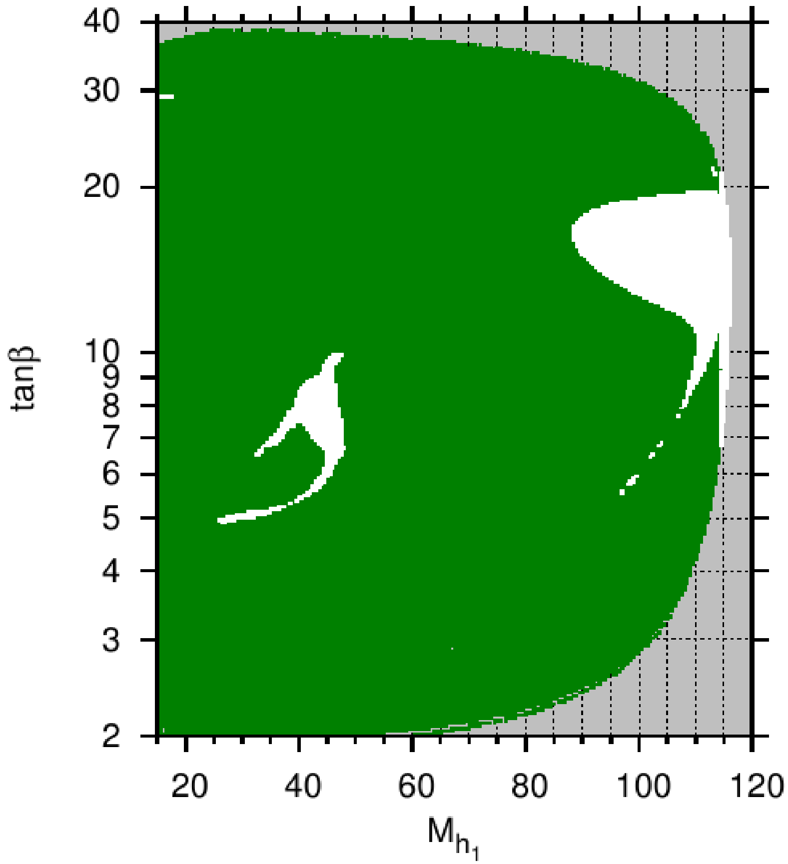
Input mode: SLHA : work in progress

– applications   example: LEP exclusion of the MSSM in the CPX scenario

channel with highest sensitivity



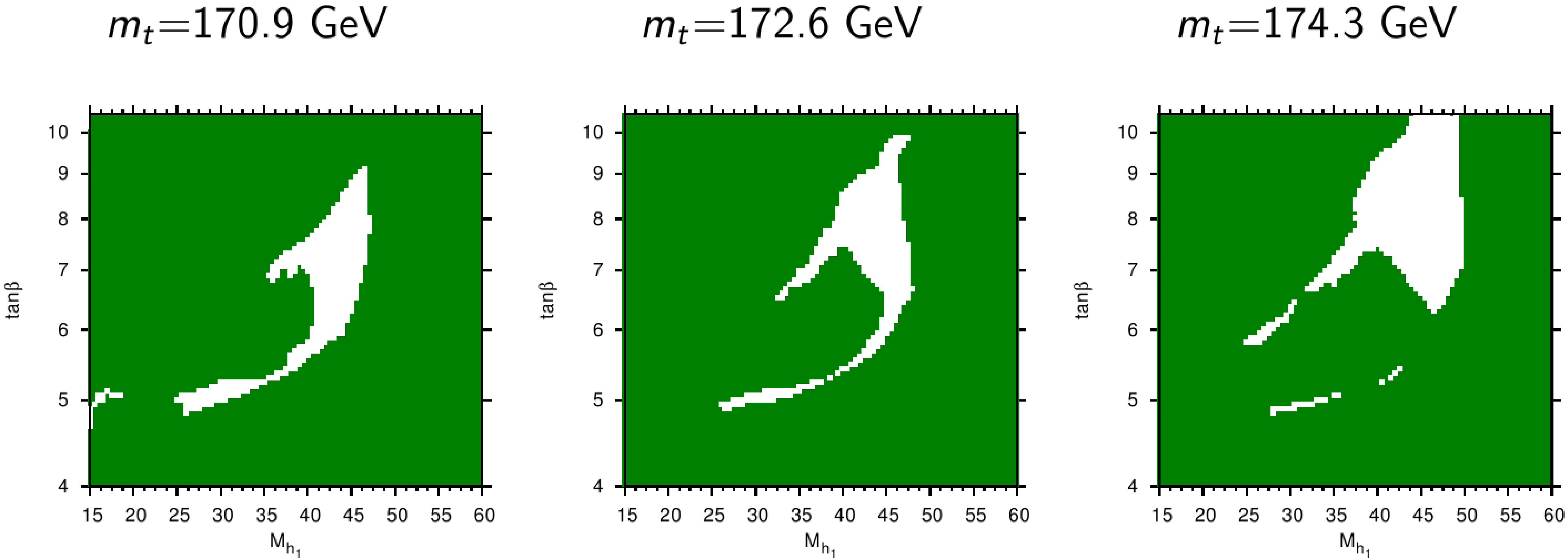
excluded region



- • $h_1 Z \to b\bar{b}Z$ • $h_2 Z \to b\bar{b}Z$
- ○ $h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- • $h_2 h_1 \to b\bar{b}b\bar{b}$ • $h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$
- • other channels

example: LEP exclusion of the MSSM in the CPX scenario

top mass dependence of the “CPX hole”



More examples in Karina's demonstration

summary

- The Higgs search at Tevatron and LEP turn(ed) out many limits on cross sections of individual and combined signal topologies.

- Those limits are published as figures and tables in many individual papers which don't allow for making use of all of them in a convenient way.

- HiggsBounds offers easy access to a wealth of published limits in form of a FORTRAN program and a web page (`www.ippp.dur.ac.uk/HiggsBounds/`).

- HiggsBounds is a model-independent tool which offers a flexible range of input formats for the necessary model predictions (including the number of neutral Higgs bosons).

The code will be publicly released soon. Please send an e-mail to `oliver.brein@durham.ac.uk` or `k.e.williams@durham.ac.uk` to get notified.