HiggsBounds: confronting arbitrary Higgs sectors with exclusion bounds from LEP & the Tevatron

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[see also arXiv:0811.4169 [hep-ph] and www.ippp.dur.ac.uk/HiggsBounds/]

outline :

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

- motivation

– Higgs search

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

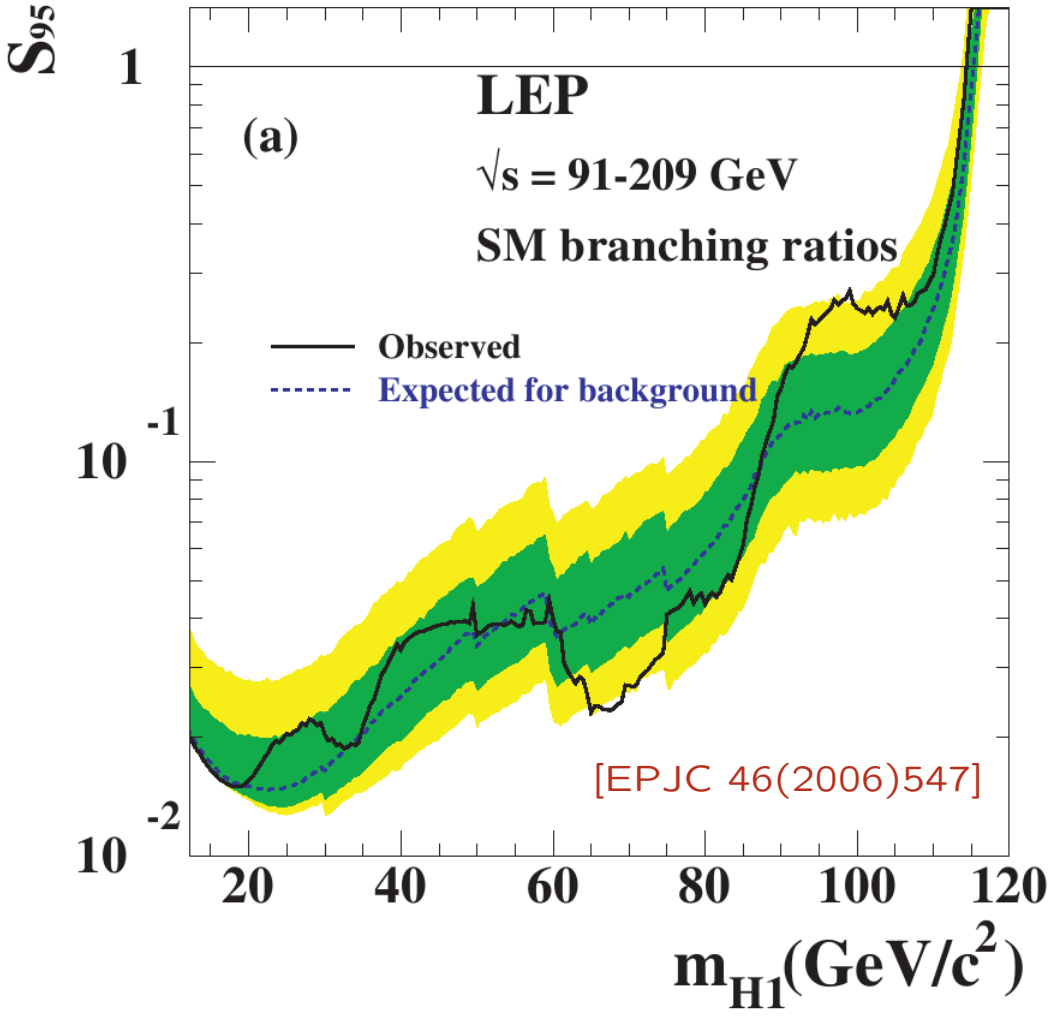
- So far: no Higgs signals.
  - LEP searched for them.
  - Tevatron is currently searching for them.

- 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. $e^+e^- \to h_i Z \to b\bar{b}Z$, $p\bar{p} \to h_i \to W^+W^-$,

  b) ... combinations of signal topologies
  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

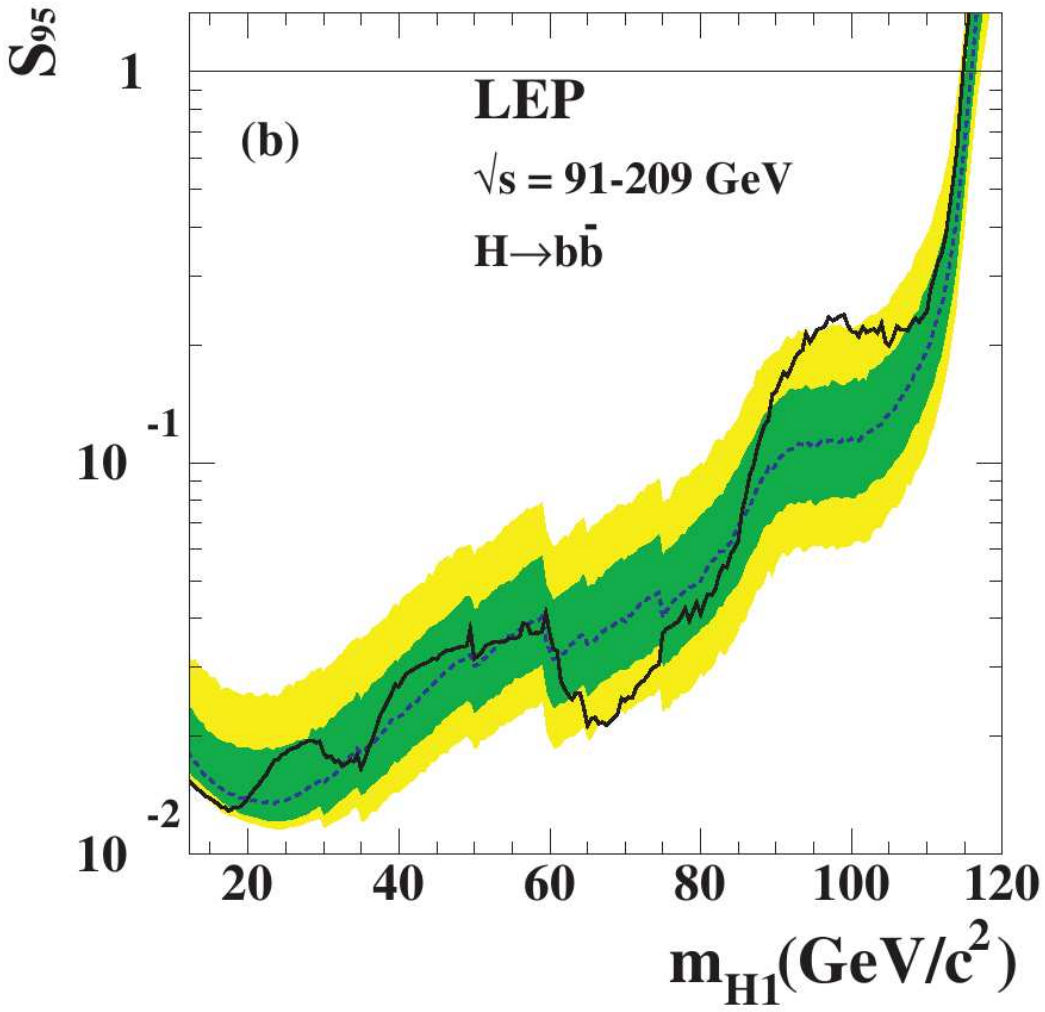
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{max}}(m_{H1})$$

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

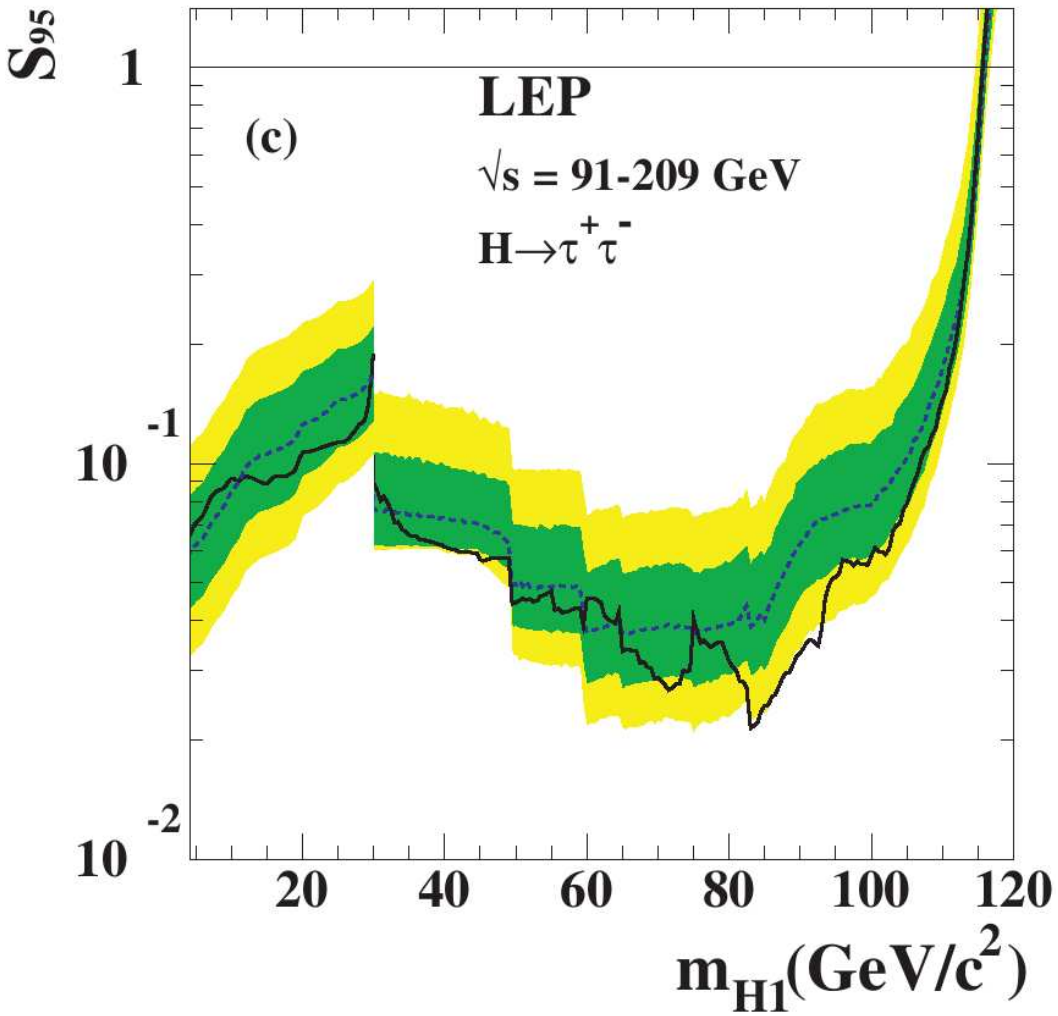
is said to be excluded at the 95% C.L.

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

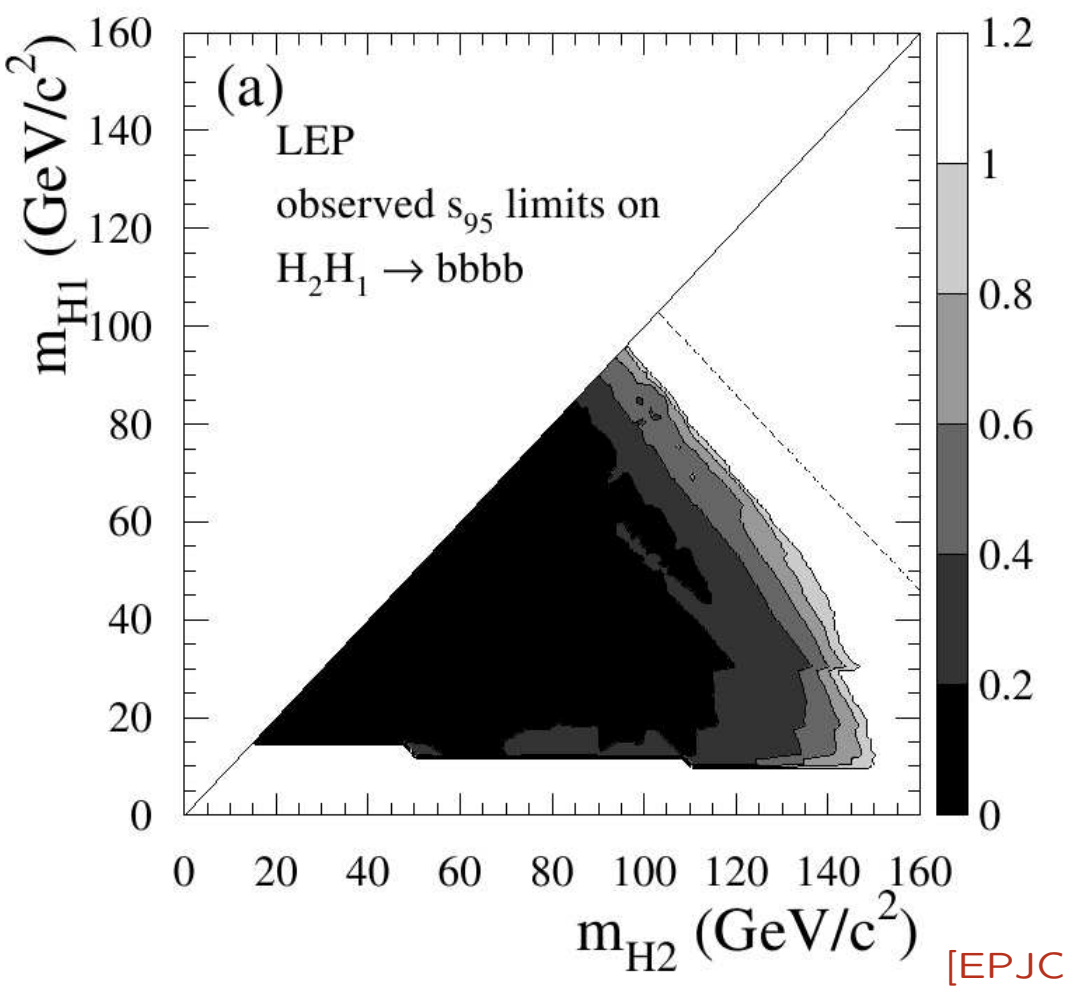


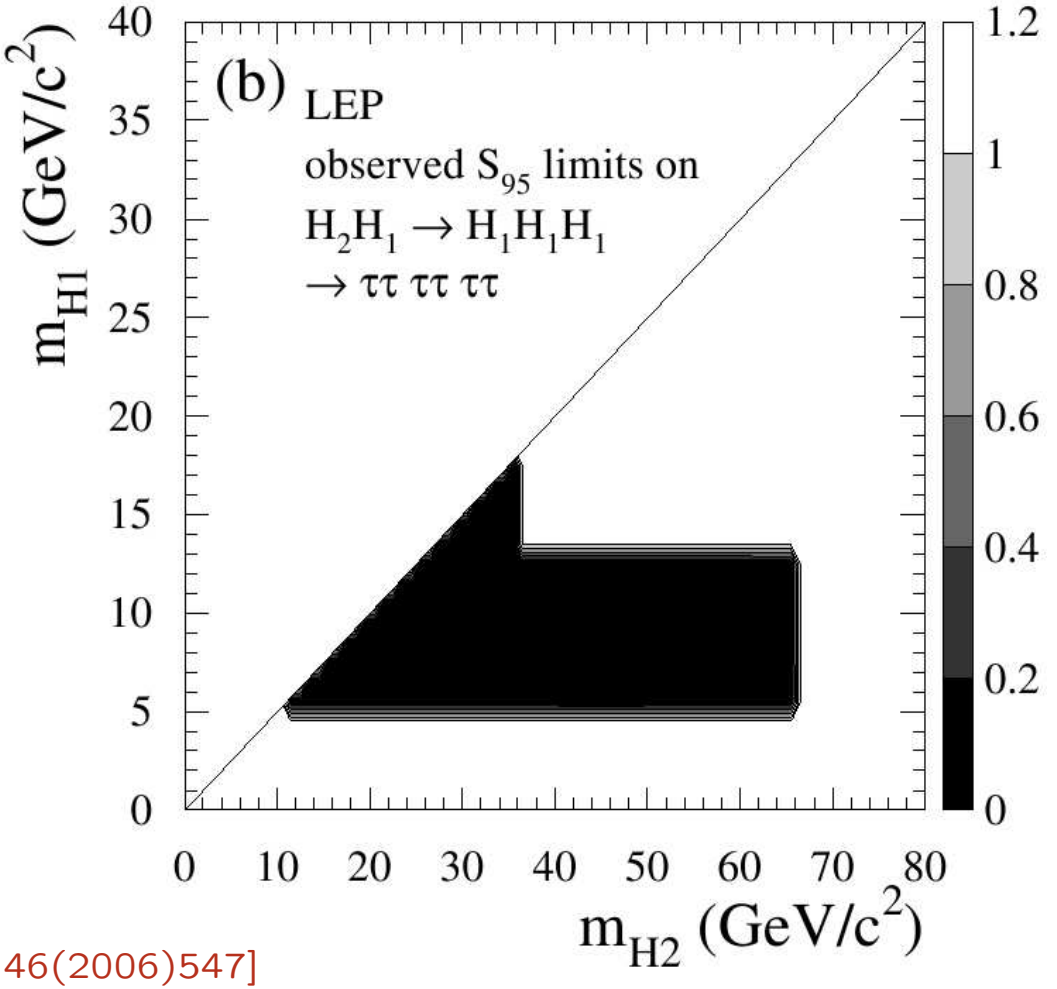
[EPJC 46(2006)547]

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

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

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

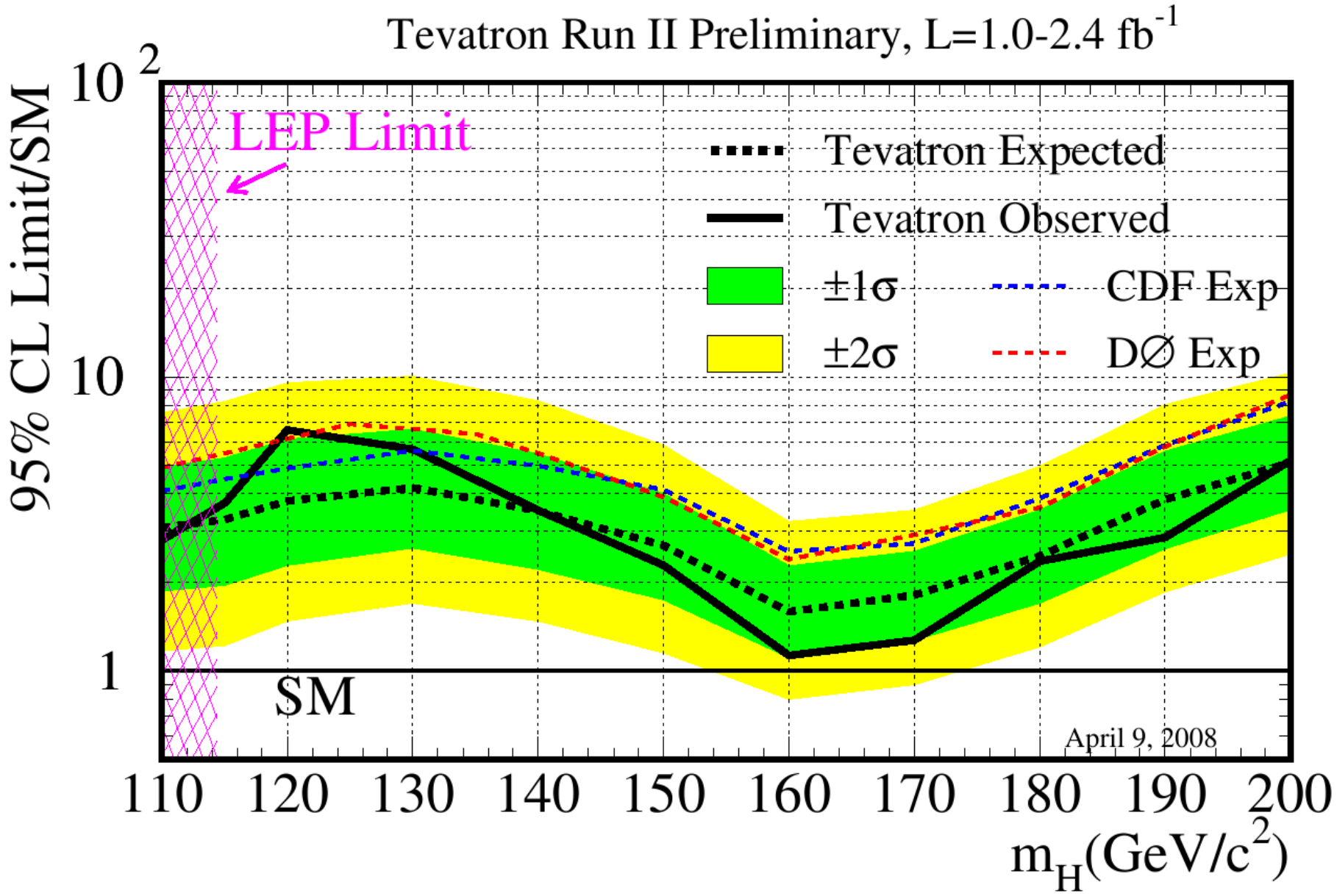




[EPJC 46(2006)547]

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

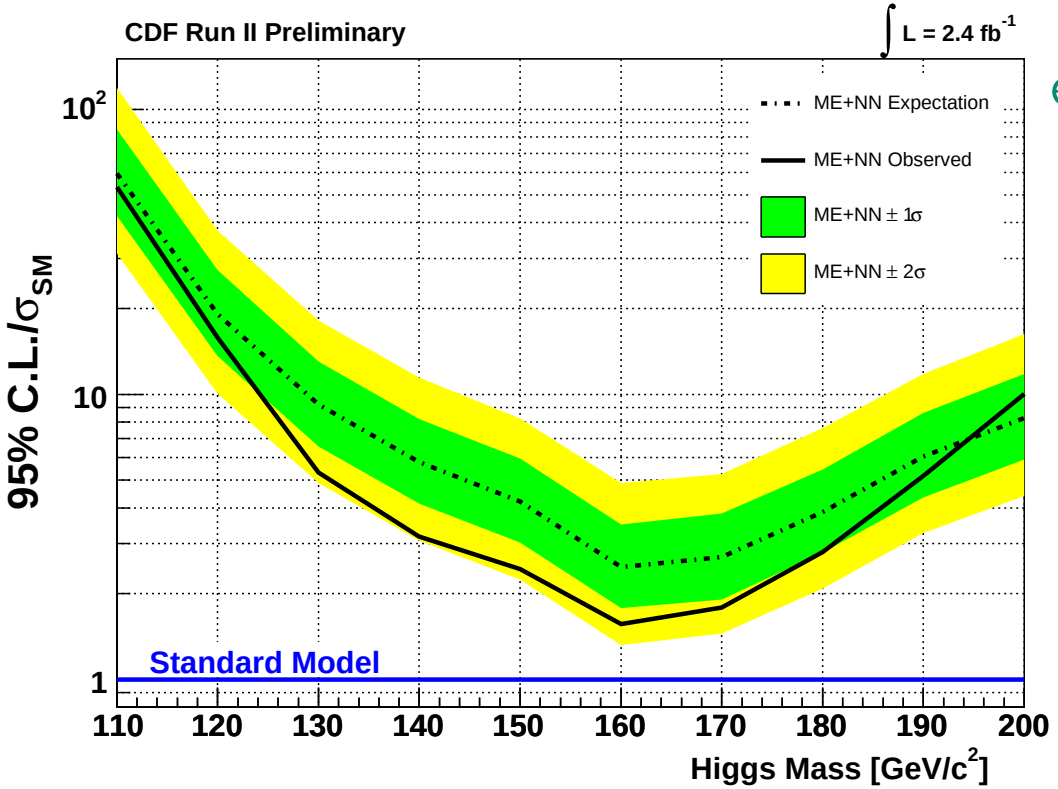
example 4: Tevatron SM combined limit



example 5: Tevatron single topology limits

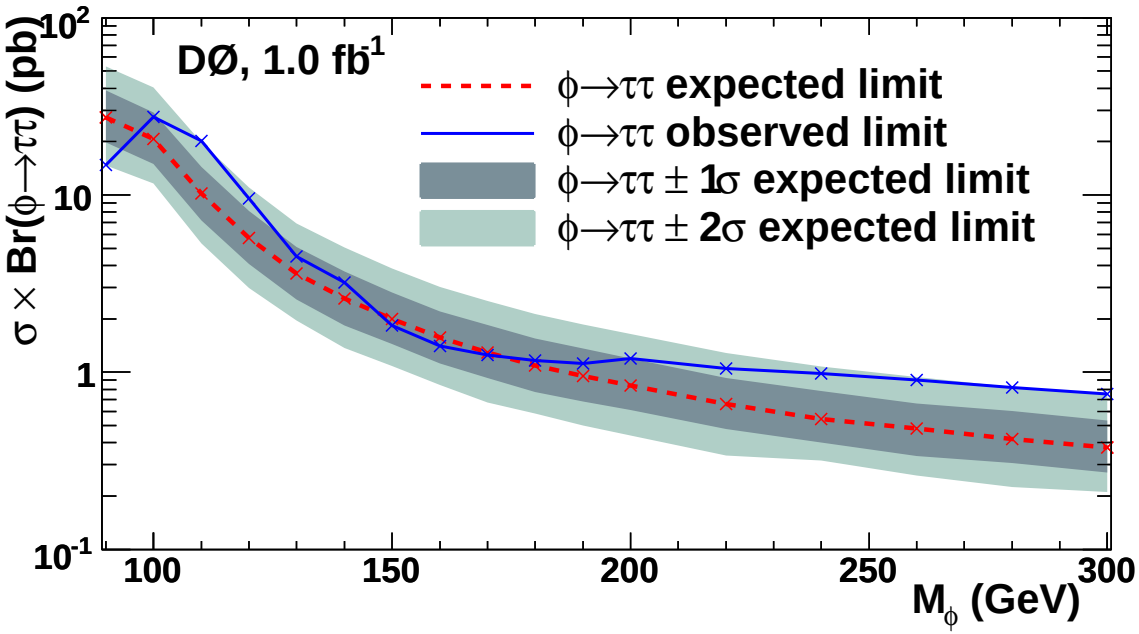
a) $p\bar{p} \to H \to WW^{\star}$ using 1.9 fb^{-1}
[CDF note 8958]

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, BSM models contribute to individual Higgs signal topologies in different proportions than in the SM.
  → SM combined analyses cannot be used

- To test such models against LEP and Tevatron results:
  check model predictions for cross sections
  of individual search topologies
  against the experimental limits.

HiggsBounds:

Test theoretical predictions of models with arbitrary Higgs sectors against exclusion bounds obtained from Higgs searches at LEP and the Tevatron.

- Easy access to all relevant Higgs exclusion limits

- Applicable to models with arbitrary Higgs sectors

  HiggsBounds Input: the predictions of the model for:
  # of Higgs bosons h_i , m_{h_i}, $\Gamma_{\rm tot}(h_i)$, BR($h_i \to \ldots$),
  production cross section ratios (wrt reference values)

- Possibility to combine results from LEP and Tevatron

- 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), we evaluate

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

- 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. ?

Answer: We can't do that.

Only a dedicated experimental analysis can do that.

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

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

- Determine for each search channel X the experimental expected limit $Q_{\text{expected}}(X)$.
- Determine the channel X_0 with the highest sensitivity for the signal, i.e. of all channels X find the channel X_0 where $\frac{Q_{\text{model}}(X)}{Q_{\text{expected}}(X)}$ 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 analyses

We include expected 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.

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.

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

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

– Tevatron analyses

At the moment, the following analyses of Higgs production signatures by CDF and DØ have been included in HiggsBounds:

search topology X (analysis)	reference
$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (CDF with 1.0 fb^{-1})	CDF'08*
$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (CDF with 2.4 fb^{-1})	CDF note 9475
$p\bar{p} \to ZH \to l^+l^-b\bar{b}$ (DØ with 2.3 fb^{-1})	D0 note 5570
$p\bar{p} \to WH \to l\nu b\bar{b}$ (DØ with 1.7 fb^{-1})	D0 note 5472
$p\bar{p} \to WH \to l\nu b\bar{b}$ (CDF with 2.7 fb^{-1})	CDF note 9463
$p\bar{p} \to WH \to W^+W^-W^\pm$ (DØ with 1.0 fb^{-1})	D0 note 5485
$p\bar{p} \to WH \to W^+W^-W^\pm$ (CDF with 1.9 fb^{-1})	CDF note 7307
$p\bar{p} \to H \to W^+W^- \to l^+l'^-$ (DØ with 3.0 fb^{-1})	D0 note 5757
$p\bar{p} \to H \to W^+W^- \to l^+l'^-$ (CDF with 3.0 fb^{-1})	CDF'08*
$p\bar{p} \to H \to \gamma\gamma$ (DØ with 1.1 fb^{-1})	D0'08*
$p\bar{p} \to H \to \gamma\gamma$ (DØ with 2.68 fb^{-1})	D0 note 5737
$p\bar{p} \to H \to \tau^+\tau^-$ (DØ with 1.0 fb^{-1})	D0'08*
$p\bar{p} \to H \to \tau^+\tau^-$ (CDF with 1.8 fb^{-1})	CDF note 9071
$p\bar{p} \to bH, H \to b\bar{b}$ (CDF with 1.9 fb^{-1})	CDF note 9284
$p\bar{p} \to bH, H \to b\bar{b}$ (DØ with 1.0 fb^{-1})	D0'08*
$p\bar{p} \to bH, H \to b\bar{b}$ (DØ with 2.6 fb^{-1})	D0 note 5726

Evaluation of model predictions Q_{model}: similar to LEP case.

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

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

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.

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

with

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

- usage and applications

– usage

Command-line version:

Command:

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

with

<analyses to use>	:	LandT (LEP and Tevatron)
	:	onlyT (only Tevatron)
	:	onlyL (only LEP)
	:	singH (only analyses involving one Higgs)
<input mode>	:	part (partonic CS ratios)
	:	hadr (hadronic CS ratios)
	:	effC (effective couplings)
<number of Higgses>	:	1 to 9 (extendable)
<fileprefix>	:	prefix for input files (optional, can also be a subdirectory)

The command-line version works on a set of input files.
Which set depends on the selected analyses and input mode.

WWW version:

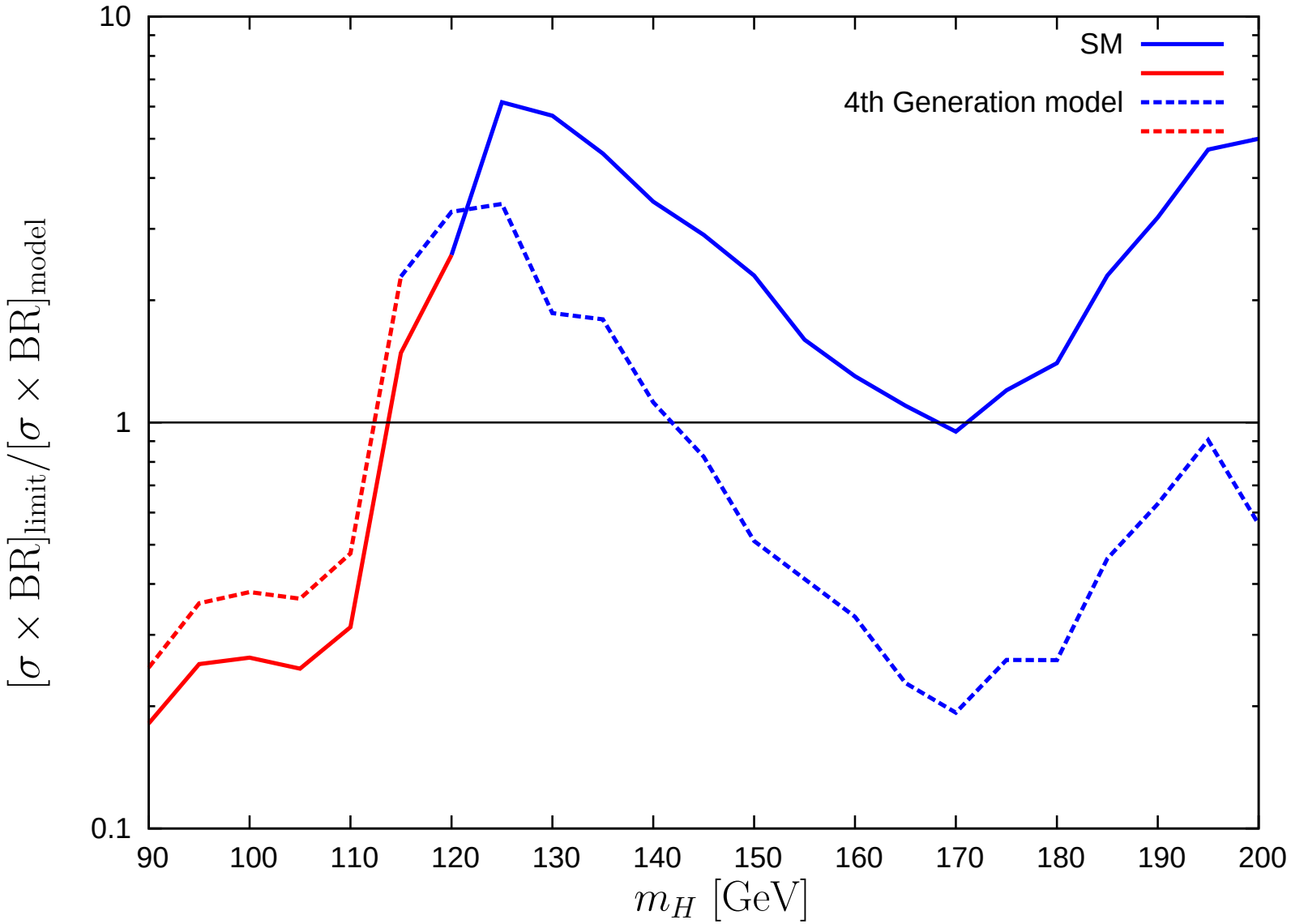
options similar to command-line version, pointwise input only

(see www.ippp.dur.ac.uk/HiggsBounds/)

Fortran subroutine version: e.g. for effective couplings input

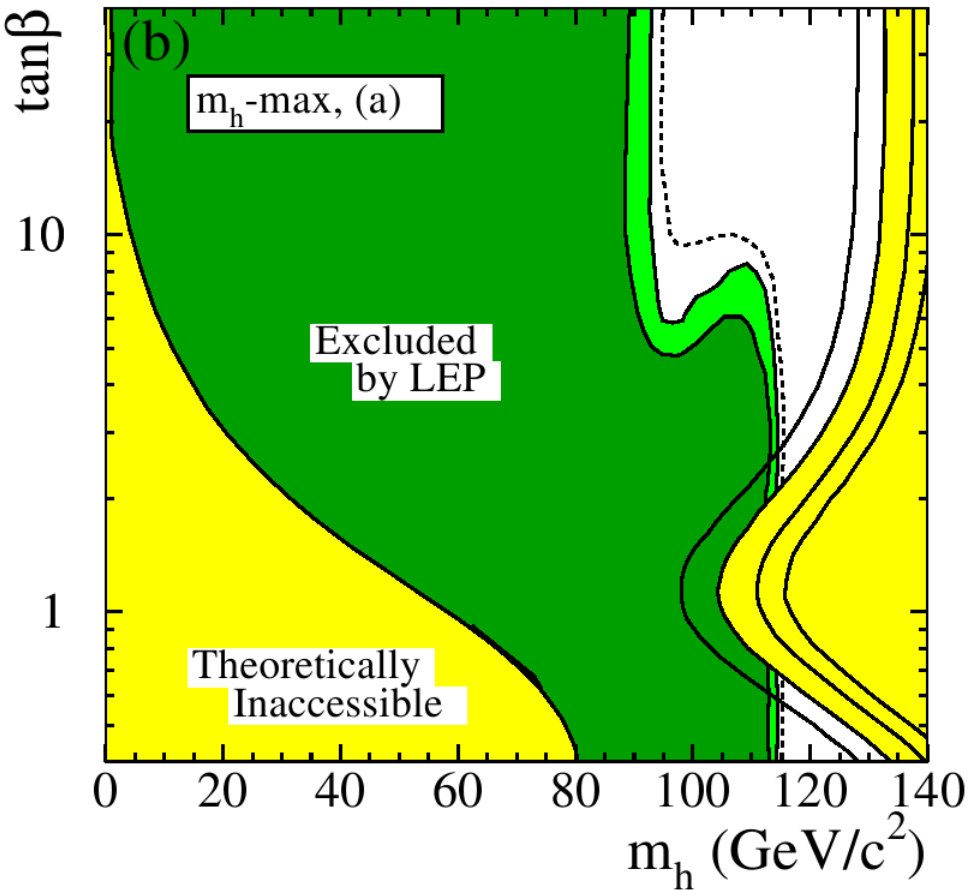
```
      call run_HiggsBounds_effC(nH,<analyses to use>,
     &     Mh,GammaTotal,
     &     g2hjbb,g2hjtautau,g2hjWW,g2hjZZ,
     &     g2hjgaga,g2hjgg,g2hjhiZ,
     &     BR_hjhihi,
     &     HBresult,chan,
     &     obsratio, ncombined )
```

application 1: SM versus Fourth Generation Model exclusion



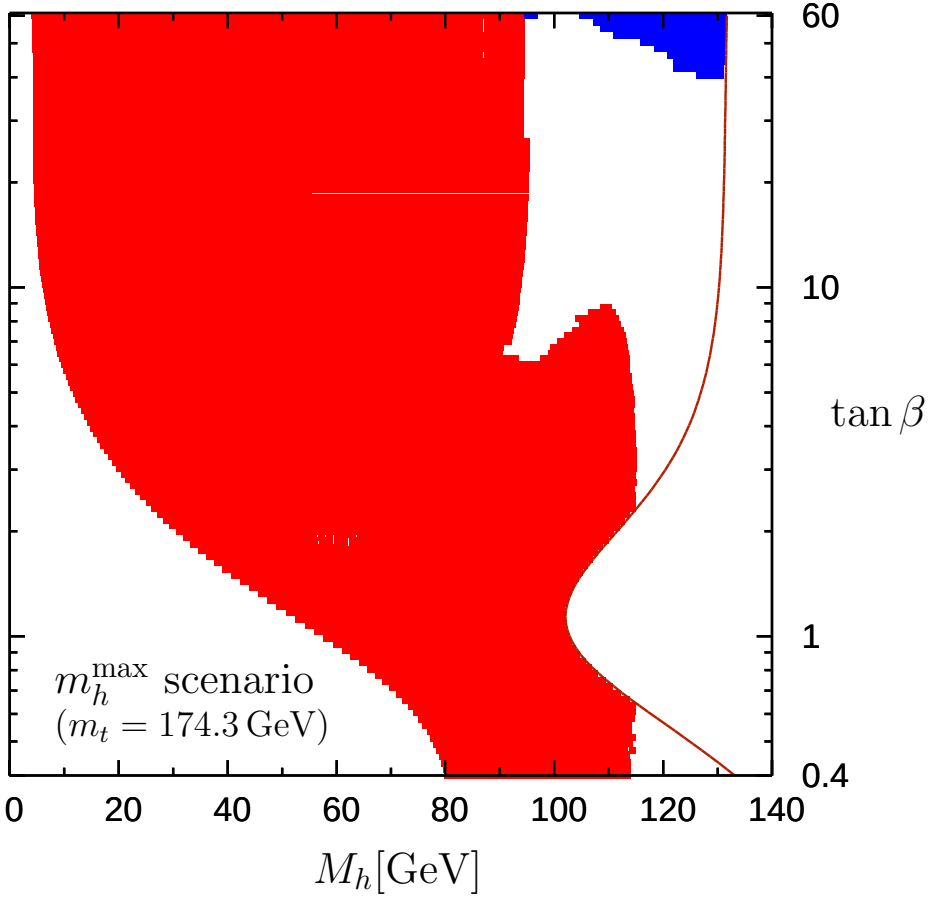
application 2: MSSM benchmark scenarios, exclusion update

a) [EPJC 46(2006)547]



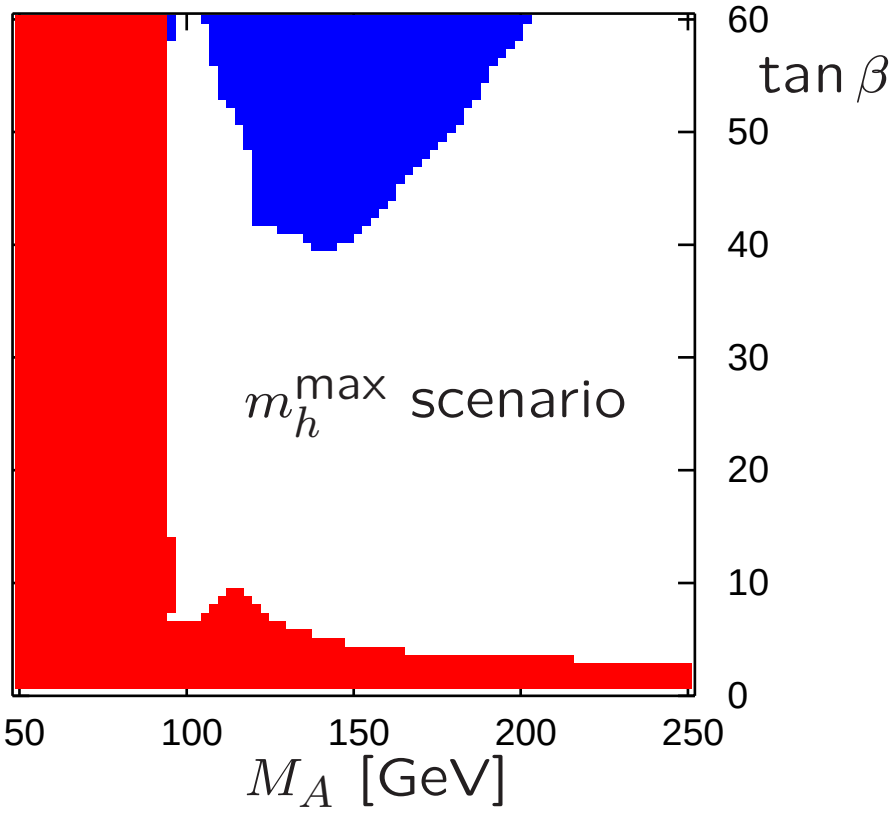
b) HiggsBounds

with: new m_t,
impoved m_h prediction,
Tevatron data included



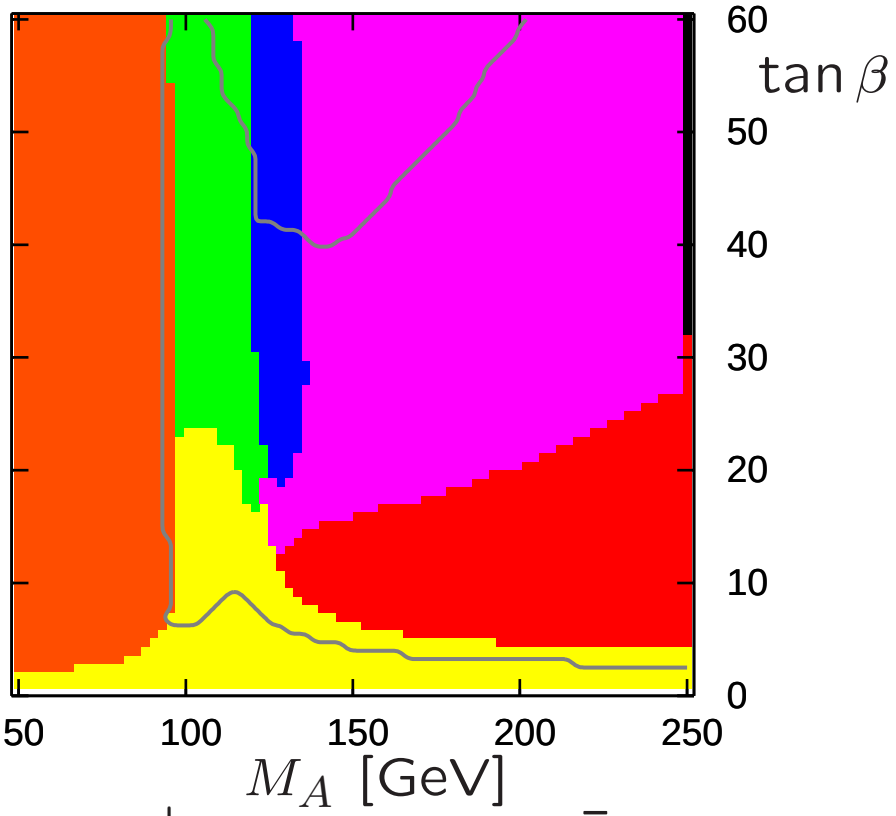
application 2: MSSM benchmark scenarios, exclusion update

a) LEP and Tevatron exclusion



■ : LEP exclusion
■ : Tevatron exclusion

b) highest sensitivity



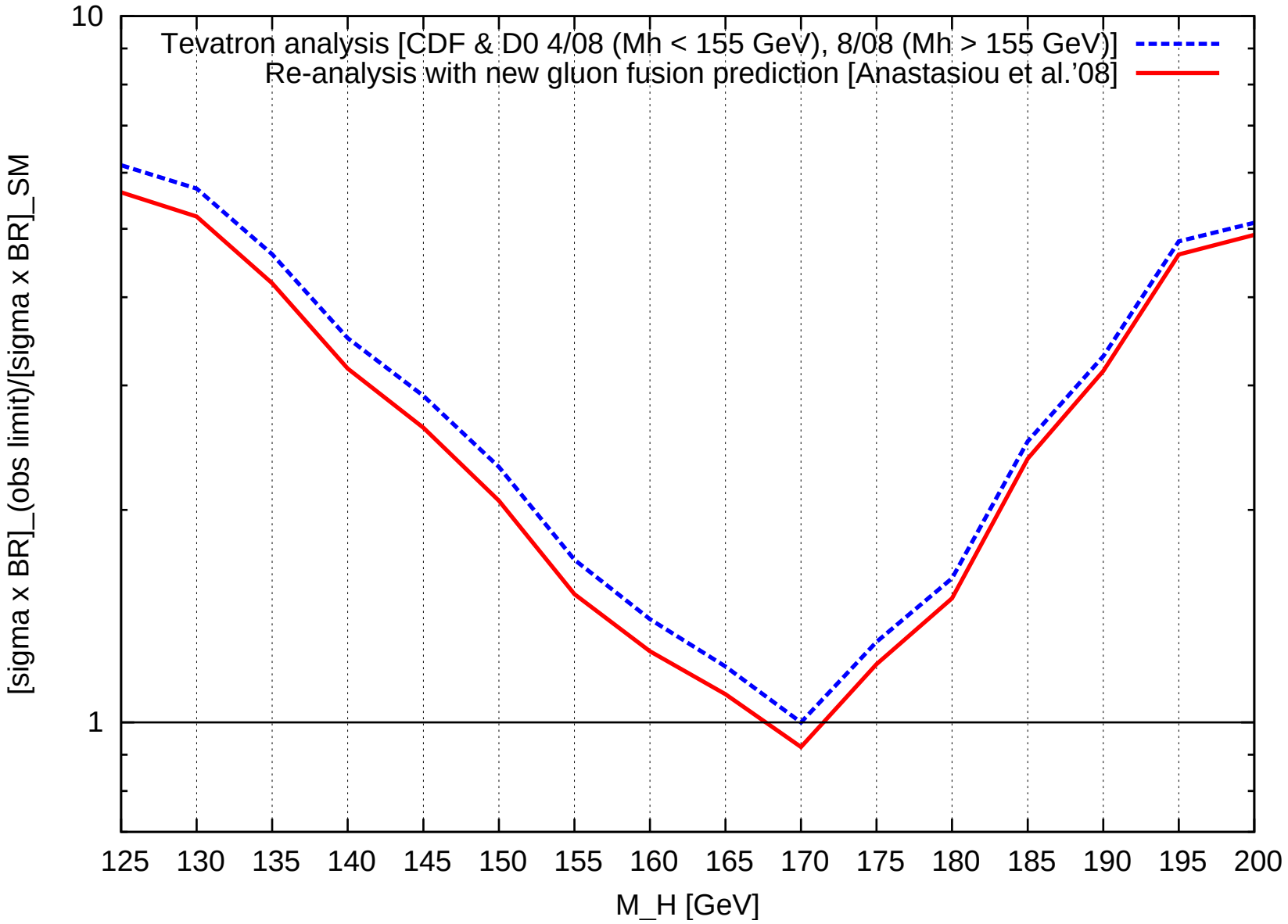
■ : $e^+e^- \to hZ, h \to b\bar{b}$
■ : $e^+e^- \to hA \to b\bar{b}b\bar{b}$
■ : $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF note 9071]
■ : $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF note 9071]
■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF note 9071]
■ : $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF note 9463]
■ : $p\bar{p} \to H/A \to \tau^+\tau^-$ [DØ'08]

application 3: re-evaluation of SM exclusion with improved prediction

This Monday: New SM result for $\sigma(p\bar{p} \to gg \to H)$,
"Mixed QCD-Electroweak corrections to Higgs boson production in gluon fusion"
by Anastasiou, Boughezal, Petriello [arXiv:0811.3458 [hep-ph]]:

"Our results motivate a reconsideration of the Tevatron exclusion limits."

application 3: re-evaluation of SM exclusion with improved prediction



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.