HiggsBounds 2.0.0

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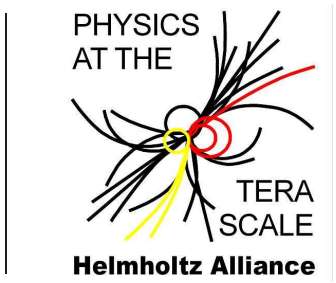


in collaboration with

K. Williams, P. Bechtle, S. Heinemeyer, G. Weiglein

[see arXiv:0811.4169 [hep-ph] and try it out at www.ippp.dur.ac.uk/HiggsBounds/]

outline :

- motivation
  - Higgs search
  - What is HiggsBounds ?
- implementation
  - basic idea
  - implemented analyses
- usage and applications
  - applications

- motivation

– Higgs search

Higgs search results:

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

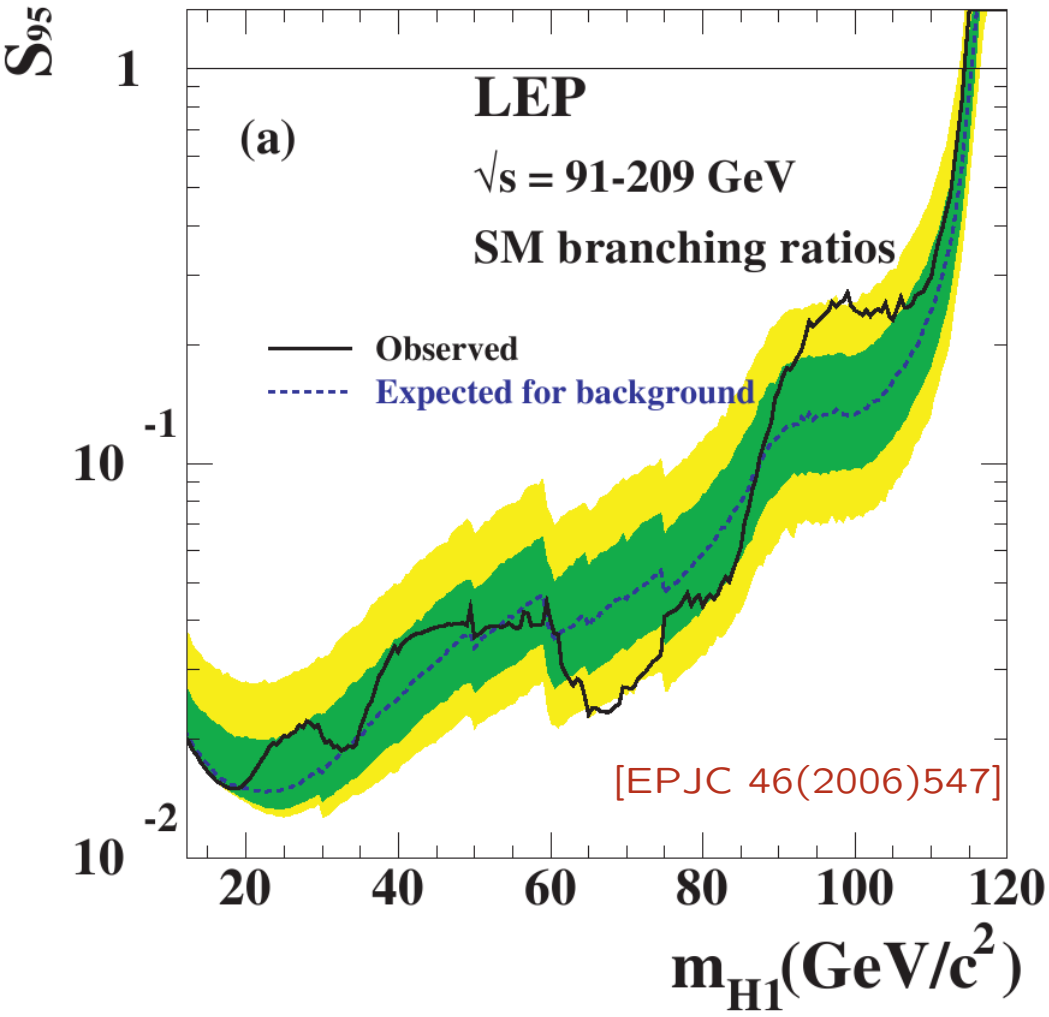
- Tevatron and LEP turn(ed) the non-observation of Higgs signals into 95% C.L. limits on rates/cross sections of ...

  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.

Higgs search results: example 1: LEP SM combined limit

exclusion = rejection of the Higgs hypothesis



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

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

A SM-like model with

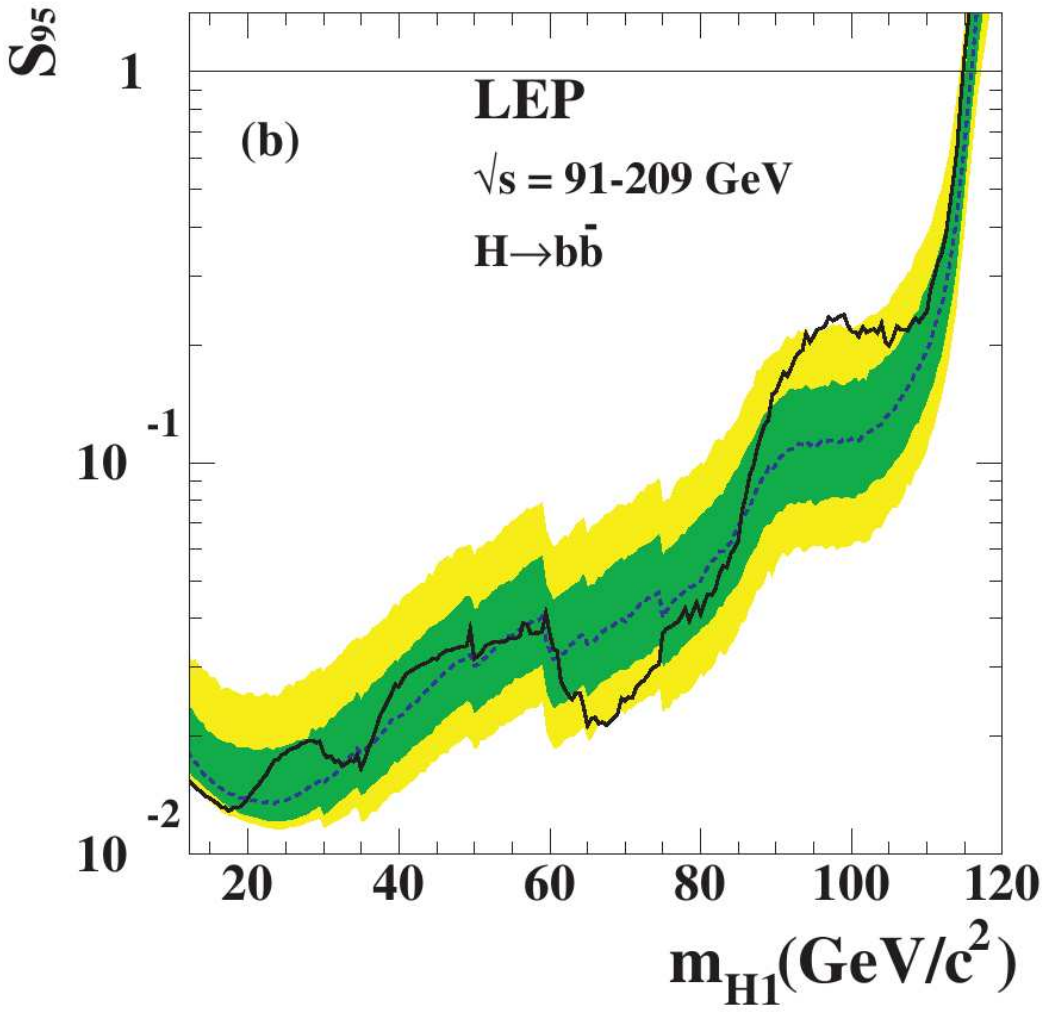
$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{min}}(m_{H1})$$

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

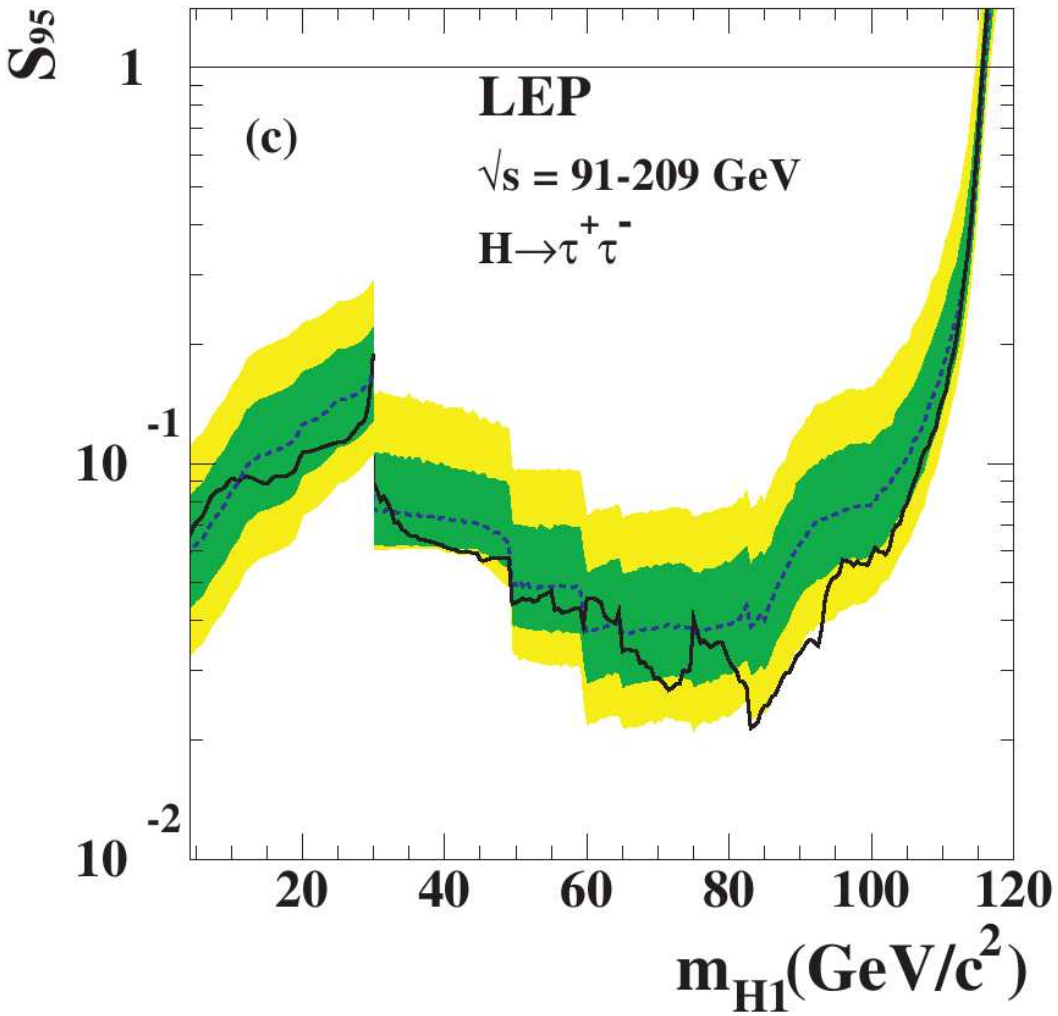
is said to be excluded at the 95% C.L.

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

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

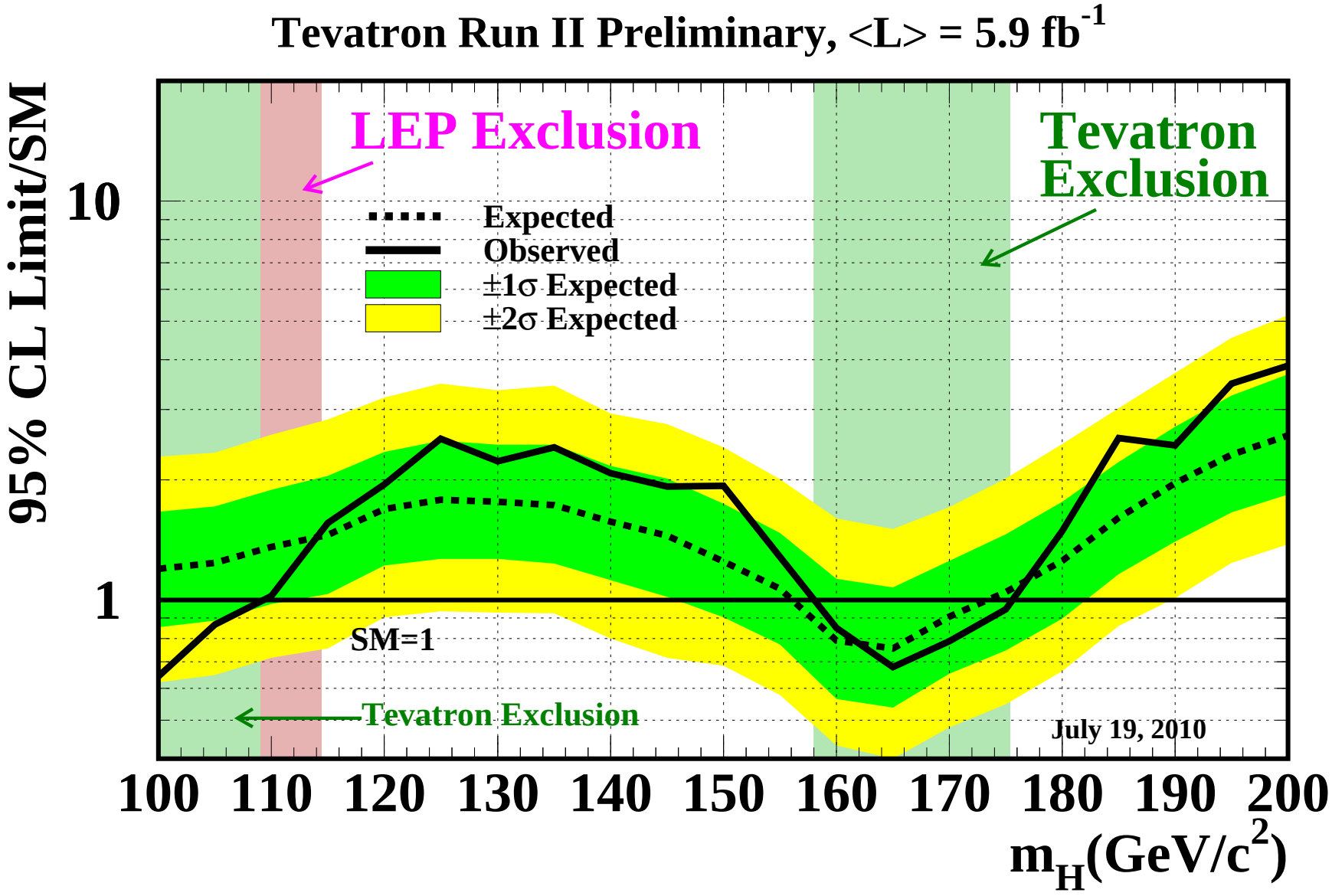


b) ... BR($H \to \tau^+\tau^-$)=1



[EPJC 46(2006)547]

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



– What is HiggsBounds ? [Bechtle, OBr, Heinemeyer, Weiglein, Williams '08]

HiggsBounds : tests models with arbitrary Higgs sectors against exclusion bounds from LEP/Tevatron Higgs searches.

- easy access to all relevant Higgs exclusion limits
  including information not available in the publications.
  (e.g. expected 95% CL cross section limits for some LEP combinations)

- 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}, $\Gamma_{\rm tot}(h_i)$, BR($h_i \to \ldots$),
  production cross section ratios (wrt reference values)

- combination of results from LEP and Tevatron possible

- three ways to use HiggsBounds:
  ☐ command line, ☐ subroutines (Fortran 77/90), ☐ web interface:

  www.ippp.dur.ac.uk/HiggsBounds

- implementation

– basic idea

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.

– basic idea

for an analysis application X:

- evaluate model prediction

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

  of the correponding 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.

implemented analyses :

⋆ neutral Higgs, LEP [HiggsBounds 2.0.0]

$e^+e^- \to h_k Z, h_k \to bb$ or $h_k \to \tau\tau$ [LEP, EPJC46(2006)547)]

$e^+e^- \to h_k Z, h_k \to$ anything [OPAL, EPJC 27(2003)311]

$e^+e^- \to h_k Z, h_k \to$ invisible [hep-ex/0107032], DELPHI [hep-ex/0401022]
L3 [hep-ex/0501033], OPAL [hep-ex/0707.0373]

$e^+e^- \to h_k Z, h_k \to \gamma\gamma$ [LEP, LHWG note 2002-02]

$e^+e^- \to h_k Z, h_k \to$ hadrons [LEP combined limit]

$e^+e^- \to b\bar{b}h_k \to b\bar{b}b\bar{b}$, h_k CP even or odd, DELPHI [hep-ex/0410017]

$e^+e^- \to b\bar{b}h_k \to b\bar{b}\tau\tau$, h_k CP even or odd, DELPHI [hep-ex/0410017], OPAL [hep-ex/0111010]

$e^+e^- \to \tau\tau h_k \to \tau\tau\tau\tau$, h_k CP even or odd, DELPHI [hep-ex/0410017]

$e^+e^- \to h_k Z, h_k \to h_i h_i, h_i \to bb$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k Z, h_k \to h_i h_i, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k, h_i \to bb$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k \to h_i h_i, h_i \to bb$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k \to h_i h_i, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k Z, h_k \to h_i h_i, h_i \to bb, \tau\tau$ [LEP, EPJC 46(2006)547]

$e^+e^- \to h_k h_i, h_k \to bb, h_i \to \tau\tau$ [LEP, EPJC 46(2006)547]

[implementation, analyses]

⋆ neutral Higgs, Tevatron, single topology [HiggsBounds 2.0.0]

$p\bar{p} \to Zh_k \to llb\bar{b}$, CDF with 5.7 fb^{-1} [CDF note 10235] and with 2.7 fb^{-1} [hep-ex/0908.3534]

$p\bar{p} \to Zh_k \to llb\bar{b}$, D0 with 6.2 fb^{-1} [D0 note 6089]

$p\bar{p} \to Wh_k \to l\nu b\bar{b}$, D0 with 5.3 fb^{-1} [D0 note 6092] and with 1.1 fb^{-1} [hep-ex/0808.1970],
CDF with 5.6 fb^{-1} [CDF note 10217] and with 2.7 fb^{-1} [hep-ex/0906.5613]

$p\bar{p} \to bh_k \to 3b$ jets, CDF with 2.5 fb^{-1} [CDF note 10105],
D0 with 2.6 fb^{-1} [D0 note 5726] and with 1 fb^{-1}[hep-ex/0805.3556]

$p\bar{p} \to$ single $h_k \to WW$,
CDF with 3.0 fb^{-1} [hep-ex/0809.3930], CDF & D0 with 4.8/5.4 fb^{-1} [hep-ex/1005.3216]

$p\bar{p} \to h_k \to \tau\tau$ absolute limits,
D0 with 1 fb^{-1} [hep-ex/0805.2491] and with 2.2 fb^{-1} [D0 note 5740],
CDF with 1.8 fb^{-1} [hep-ex/0906.1014],
CDF & D0 with up to 2.2 fb^{-1} [hep-ex/1003.3363]

$p\bar{p} \to Wh_k \to 3W$, D0 with 3.6 fb^{-1} [D0 note 5873], CDF with 2.7 fb^{-1} [CDF note 7307v3]

$p\bar{p} \to bh_k \to b\tau\tau$,
D0 with 2.7 fb^{-1} [hep-ex/0912.0968, D0 note 5985] and with 4.3 fb^{-1} [D0 note 6083]

$p\bar{p} \to t\bar{t}h_k \to t\bar{t}b\bar{b}$, D0 with 2.1 fb^{-1} [D0 note 5739]

$p\bar{p} \to h_k \to Z\gamma$, D0 with 1.0 fb^{-1} absolute limits [hep-ex/0806.0611]

[implementation, analyses]

⋆ neutral Higgs, Tevatron, combined topologies I [HiggsBounds 2.0.0]

$p\bar{p} \to V h_k \to b\bar{b}$+miss. $E_T(V = W, Z)$ SM combined,

CDF with 5.7 fb^{-1} [CDF note 10212] and with 2.1 fb^{-1} [hep-ex/0911.3935],

D0 with 6.4 fb^{-1} [D0 note 6087] and with 5.2 fb^{-1} [hep-ex/0912.5285]

$p\bar{p} \to h_k + X \to WW + X$ SM combined,

CDF with 5.3 fb^{-1} [CDF note 10102] and with 4.8 fb^{-1} [hep-ex/1001.4468],

D0 with 4.2 fb^{-1} [D0 note 5871] and with 6.7 fb^{-1} [D0 note 6082],

D0 with 5.4 fb^{-1} [hep-ex/1001.4481], CDF & D0 with 4.8-5.4 fb^{-1} [hep-ex/1001.4162]

$p\bar{p} \to h_k \to WW \to ll$, D0 with 3.0 fb^{-1} SM combined [D0 note 5757]

$p\bar{p} \to h_k + X$, CDF & D0 SM combined with 2-4.8 fb $^{-1}$ [hep-ex/0712.2383]

$p\bar{p} \to h_k + X \to \tau\tau$ SM combined,

CDF with 2.0 fb^{-1} [CDF note 9248],

D0 with 4.9 fb^{-1} [D0 note 5845] and with 1.0 fb^{-1} [hep-ex/0903.4800]

$p\bar{p} \to h_k + X$ SM combined, CDF & D0 with 1-2.4 fb^{-1} [hep-ex/0804.3423]

CDF & D0 with 3 fb^{-1} [hep-ex/0808.0534], D0 with 0.44 fb^{-1} [hep-ex/0712.0598]

CDF with 2.0-4.8 fb^{-1} [CDF note 9999], D0 with 2.1-5.4 fb^{-1} [D0 note 6008],

CDF & D0 with 2.1-5.4 fb^{-1} [hep-ex/0911.3930],

CDF & D0 SM with up to 6.7 fb^{-1} [hep-ex/1007.4587]

⋆ neutral Higgs, Tevatron, combined topologies II [HiggsBounds 2.0.0]

$p\bar{p} \to h_k + X \to bb + X$, CDF with 4 fb^{-1} SM combined [CDF note 10010]

$p\bar{p} \to Vh_k \to VVV \to$ same sign di-lepton(e,mu) (V=W,Z),

D0 with 6.4 fb^{-1} SM combined [D0 note 6091]

$p\bar{p} \to h_k \to \gamma\gamma$ SM combined,

D0 with 4.2 fb^{-1} [D0 note 5858] and with 2.7 fb^{-1} [hep-ex/0901.1887],

CDF with 5.4 fb^{-1} [CDF note 10065]

⋆ charged Higgs, LEP [HiggsBounds 2.0.0]

$e^+e^- \to H^+H^- \to$ 4 jets [LEP, hep-ex/0107031],

$e^+e^- \to H^+H^- \to$ 4 jets [DELPHI, hep-ex/0404012],

$e^+e^- \to H^+H^- \to \tau\nu\tau\nu$ [DELPHI, hep-ex/0404012].

⋆ charged Higgs, Tevatron [HiggsBounds 2.0.0]

$p\bar{p} \to tt, t \to H + b$(& c.c.), $H^+ \to cs$, D0 with 1.0 fb^{-1} [hep-ex/0908.1811],

CDF with 2.2 fb^{-1} [hep-ex/0907.1269]

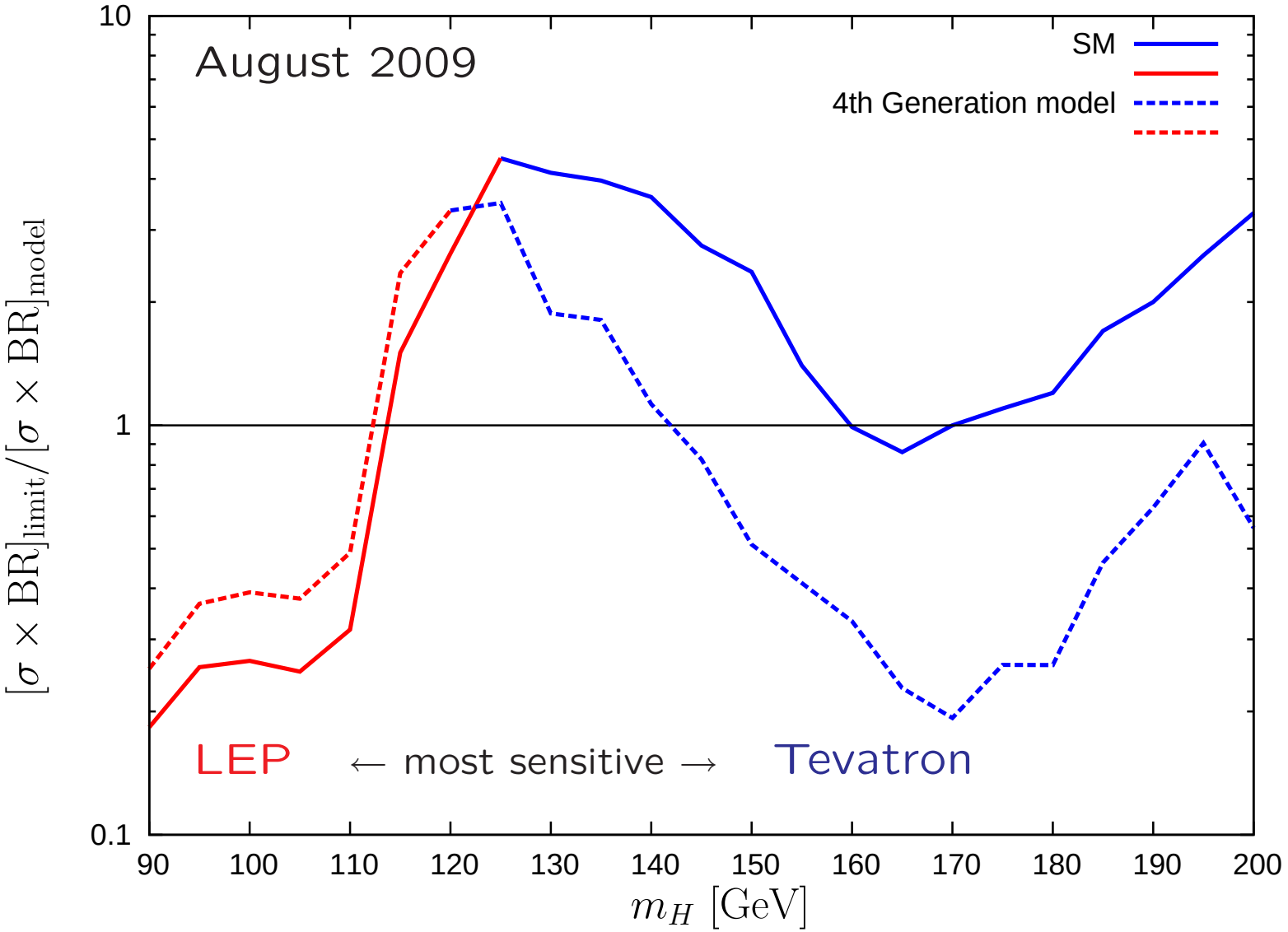
$p\bar{p} \to tt, t \to H + b$(& c.c.), $H^+ \to \tau\nu$, D0 with 1.0 fb^{-1} published [hep-ex/0908.1811]

implemented in total: 82 analyses (29 LEP, 53 Tevatron)

- usage and applications

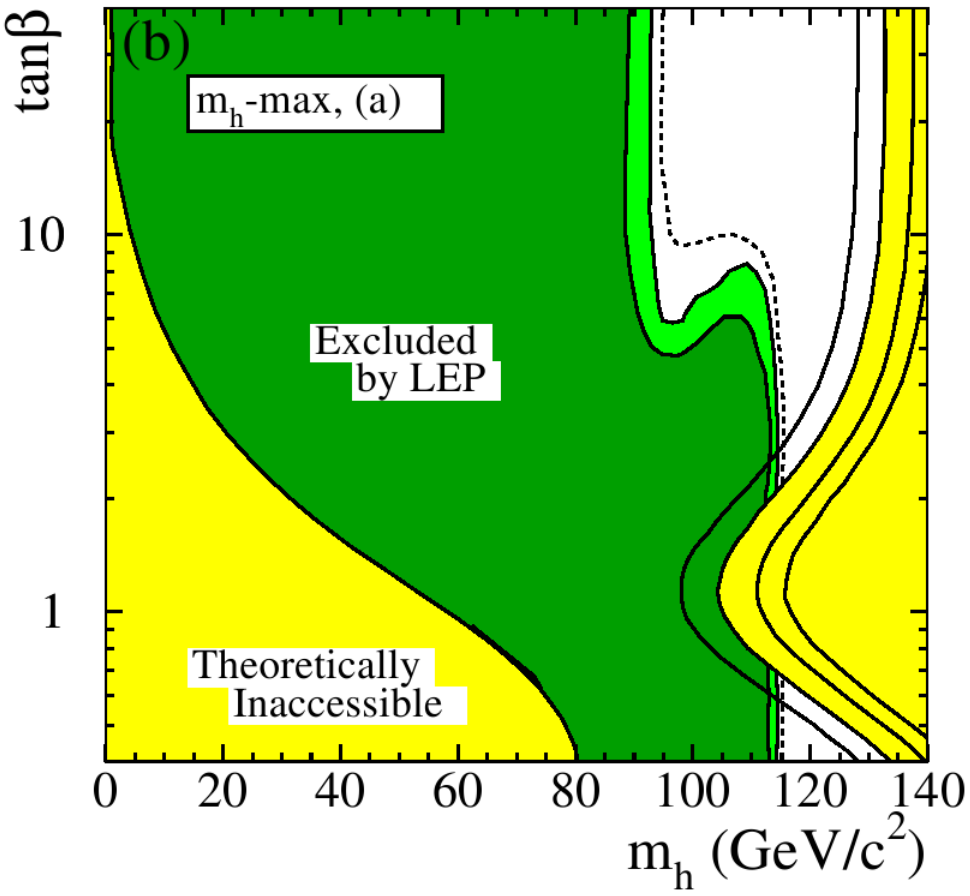
application 1: SM versus Fourth Generation Model exclusion

using $\Gamma(H \to gg)_{\text{model}} = 9 \times \Gamma(H \to gg)_{\text{SM}}$



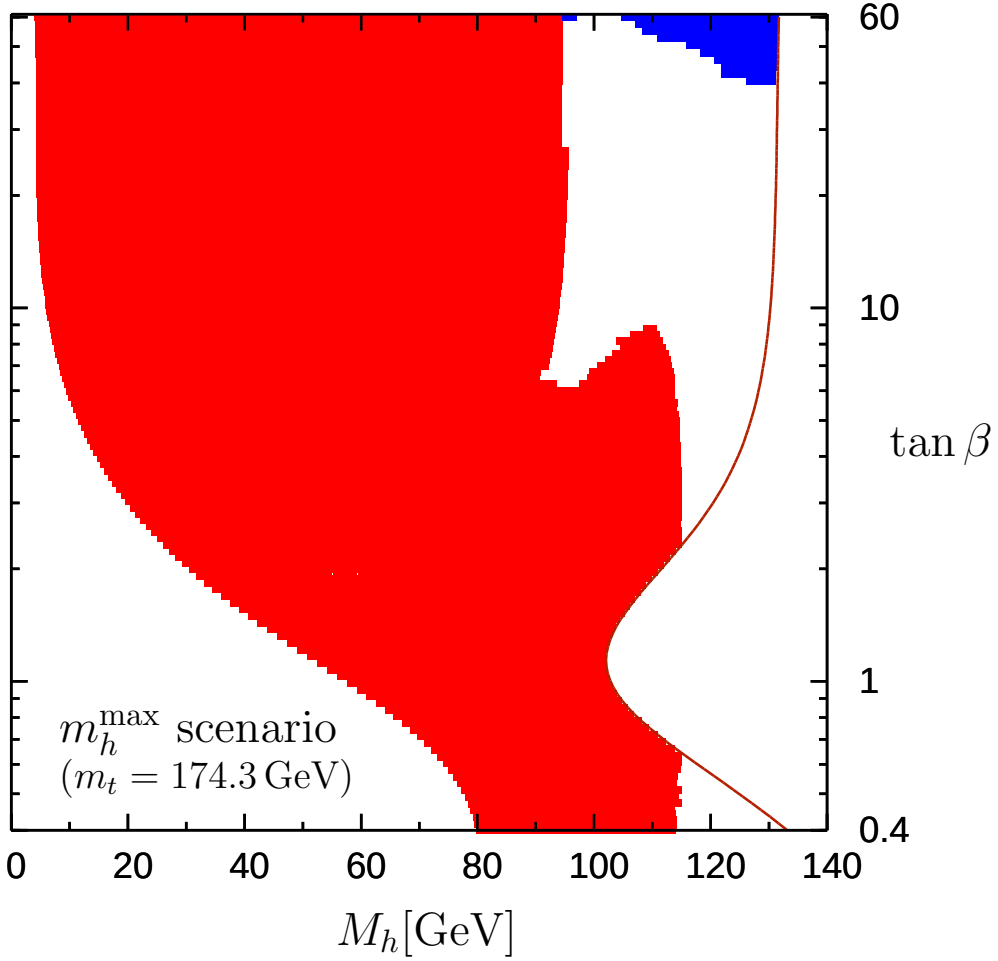
application 2: MSSM benchmark scenarios, exclusion update

a) [EPJC 46(2006)547]



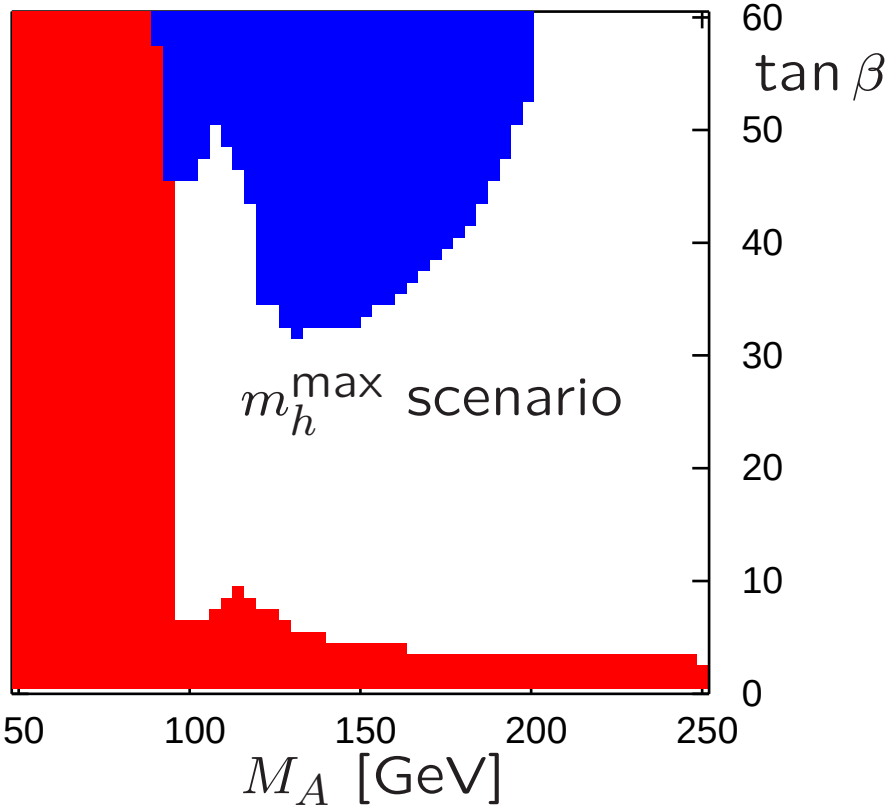
b) `HiggsBounds`

with: new m_t, impoved m_h prediction,
Tevatron data included (■)



application 2: MSSM benchmark scenarios, exclusion update (August 2009)

a) LEP and Tevatron exclusion



■ : LEP exclusion

■ : Tevatron exclusion

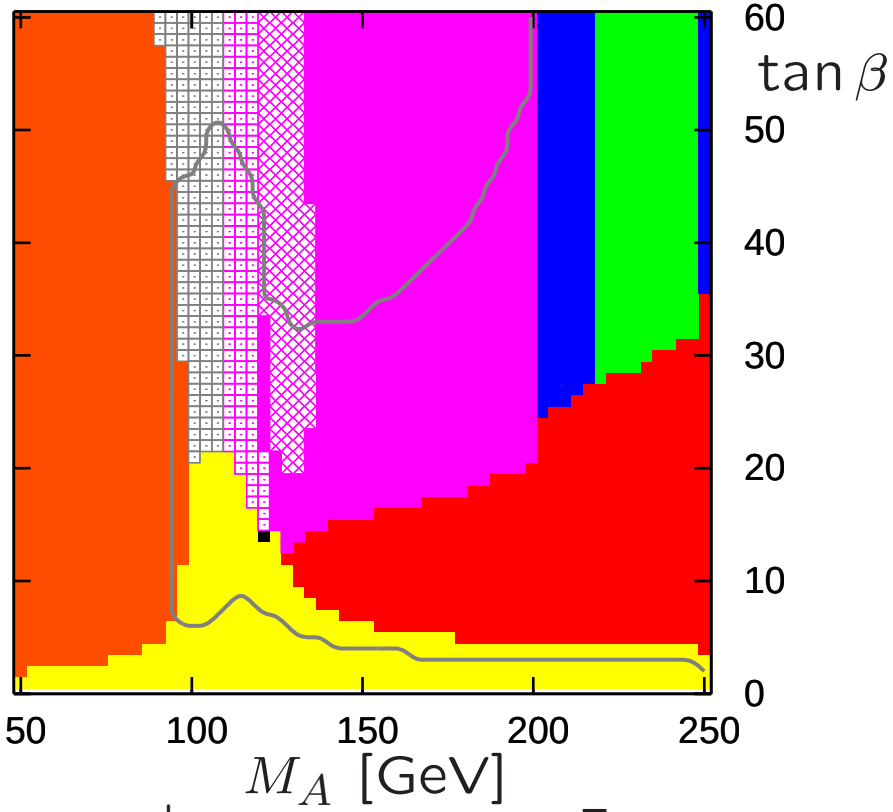
⊡ : $p\bar{p} \to b\,h/A \to b\tau^+\tau^-$ [D0 note 5985]

⊡: $p\bar{p} \to h/A \to \tau^+\tau^-$ [CDF & D0 '09]

■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF & D0 '09]

×: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ [CDF & D0 '09]

b) highest sensitivity



■ : $e^+e^- \to hZ, h \to b\bar{b}$ [LEP EPJC 46 ...]

■ : $e^+e^- \to hA \to b\bar{b}b\bar{b}$ [LEP EPJC 46 ...]

■: $p\bar{p} \to hW \to b\bar{b}l\nu$ [CDF '09]

■: $p\bar{p} \to HW \to b\bar{b}l\nu$ [CDF '09]

■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [CDF '09]

■: $p\bar{p} \to H/A \to \tau^+\tau^-$ [D0 note 5740]

application 3: Randall-Sundrum model, excluded parameter space

– There is one graviscalar in 5d: the radion φ

– 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, R: Ricci scalar.

$\rightarrow$ 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

⋆ $\varphi\, gg$ coupling enhanced wrt SM Higgs

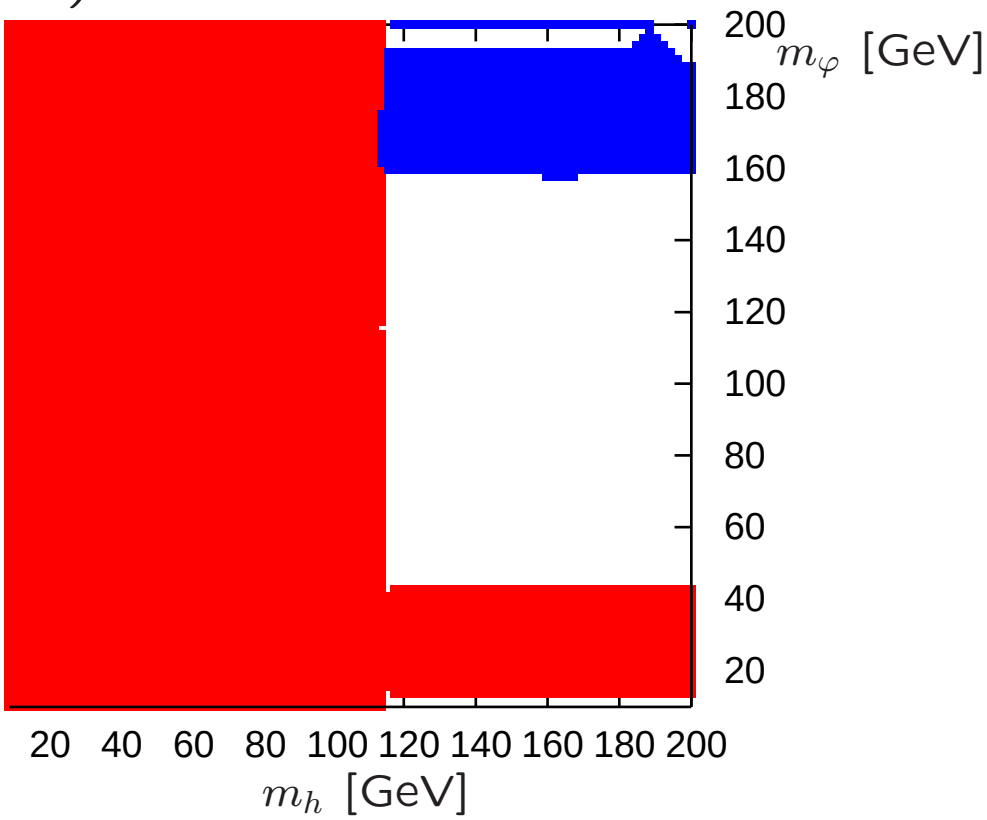
⋆ $\varphi\, \gamma\gamma$ coupling suppressed wrt SM Higgs

$\rightarrow$ two scalars in the spectrum with modified couplings compared to the SM Higgs boson

application 3: Randall-Sundrum model, excluded parameter space

parameter: $\Lambda_\varphi = 1$ TeV, $\xi = 0$, mass eigenvalues: m_h, m_φ

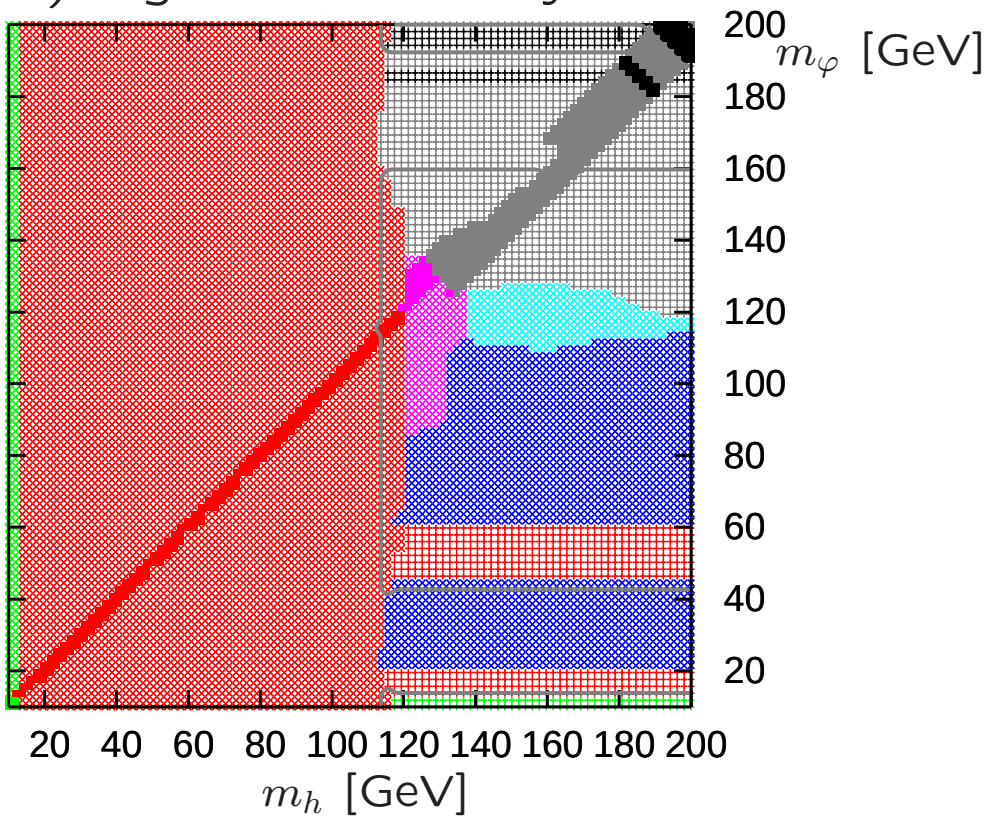
a) LEP and Tevatron exclusion



■ : LEP exclusion

■ : Tevatron exclusion

b) highest sensitivity



×/+/■ ($\phi = h/\varphi$/both): $e^+e^- \to \phi Z, \phi \to b\bar{b}$ [EPJC 46 ...]

×/+/■: $e^+e^- \to \phi Z, \phi \to$ anything [OPAL '03]

×: $e^+e^- \to \phi Z, \phi \to$ 2 jets [LEP Higgs WG]

×/■: $p\bar{p} \to \phi W \to b\bar{b}l\nu$ [CDF note 9596]

×: $p\bar{p} \to \phi W \to 3W$ [D0 note 5873]

+/■: $p\bar{p} \to \phi \to WW \to l\nu l\nu$ [D0 note 5757]

+/■: $p\bar{p} \to \phi \to WW \to l\nu l\nu$ [CDF '08]

– status and outlook

- The code is publicly available (current verison: 2.0.0 released July 2010)
  - all accessible results presented at ICHEP'10 included
  - extended functionality ($H^\pm$ searches, `onlyP` analyses selection, ...)
  - new manual available

    → www.ippp.dur.ac.uk/HiggsBounds/

- Reception very good. Code used in or by:

  FeynHiggs, CPsuperH, Fittino, MasterCode,
  2HDMC, DarkSusy, SuperIso, etc.
  S. Kraml et al., M. Carena et al., W. Bernreuther et al., etc.

- Current work/plans:
  - providing CL_{s+b} for given m_H and $\sigma \times$ BR (→ useful for model fitting)
  - inclusion of width-dependent limits
  - ...

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 3 ways: command line, subroutines, web interface.

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

The code is publicly available (current verison: 2.0.0).

Please visit the web page `www.ippp.dur.ac.uk/HiggsBounds/` for downloading the package or using the web interface.