Higgs Physics: from LEP to a Linear Collider

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Outline

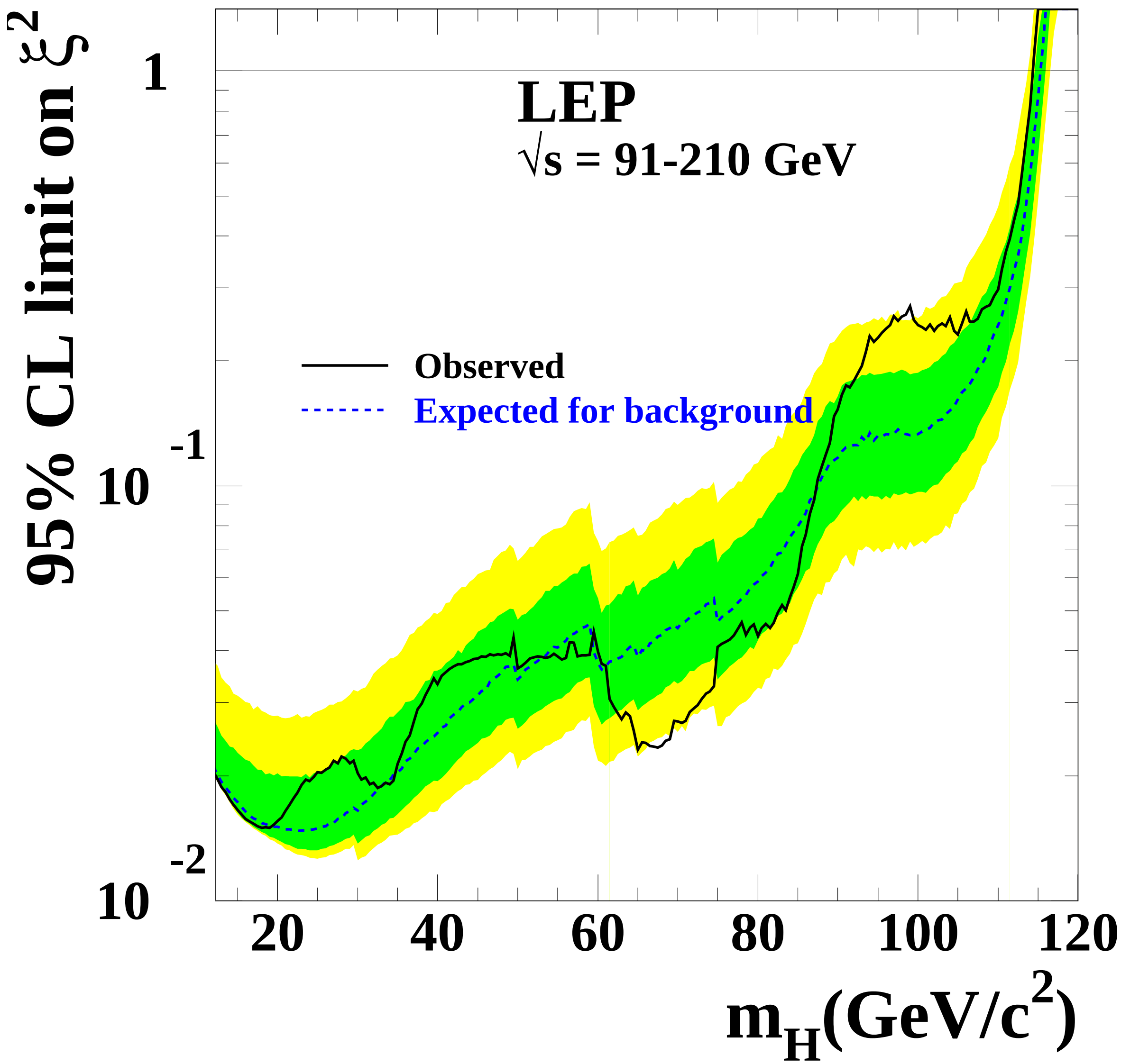
- HZZ Couplings
- Anomalous Couplings
- Minimal Supersymmetric Extension of the SM (MSSM):
  Dedicated Searches, Three-Higgs-Boson Hypothesis, Benchmark and General Scan Mass Limit
- CP-Violating Models
- Invisible Higgs Boson Decays
- Flavor-Independent Hadronic Decays
- Yukawa Process
- Singly and Doubly-Charged Higgs Bosons
- Fermiophobic, Uniform and Stealthy Higgs Scenarios
- LINEAR COLLIDER Potential
- Conclusions

Introduction

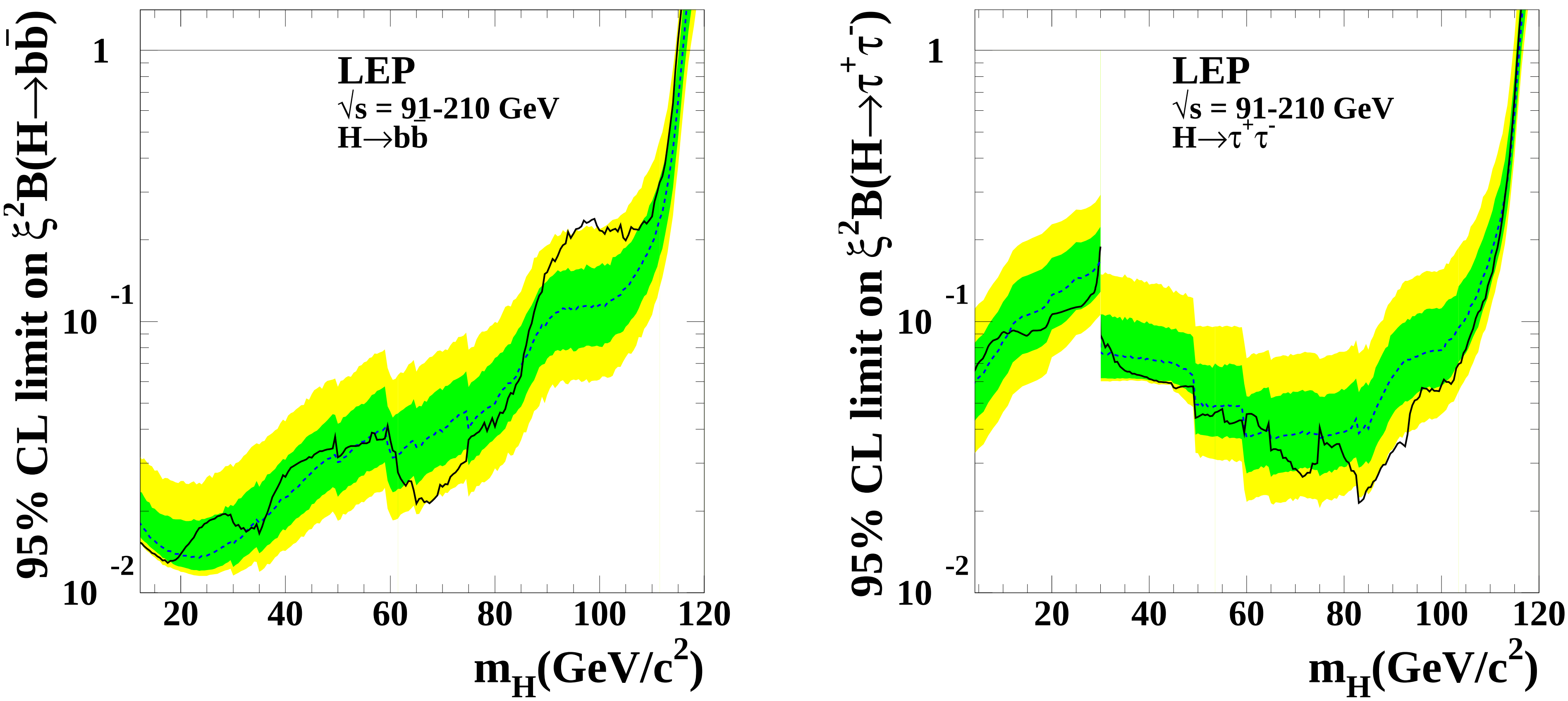
LEP experiments are finalizing their analyses for non-Standard-Model Higgs boson searches.

- Still very active and final results in sight: some results are *preliminary*.
- Accelerator: Very successful. Larger luminosity ($\mathcal{L} = 2461$ pb^{-1}) and higher energy (≤ 209 GeV) than anticipated.
- Data-taking ended November 3, 2000, although some data excess was observed.

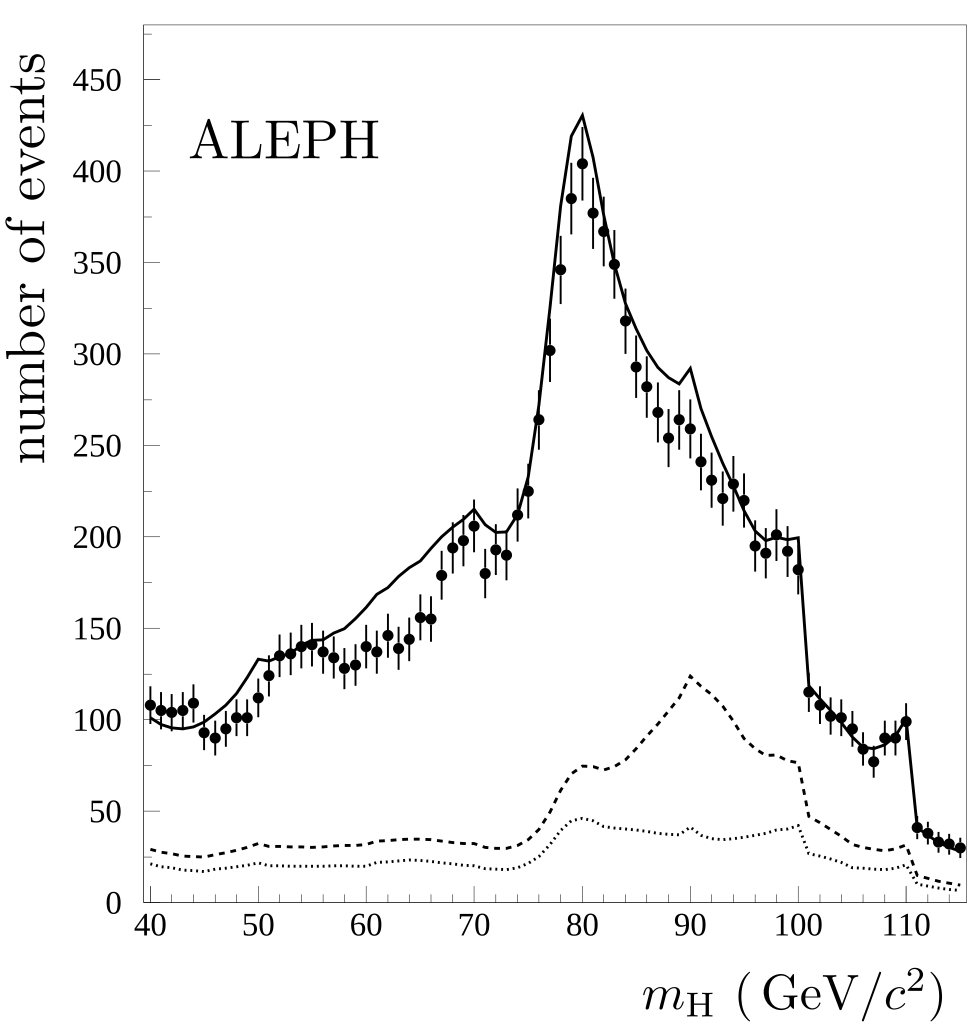
$\xi^2 = (g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}^{\mathrm{SM}})^2$ Coupling Limit: SM-like Decays

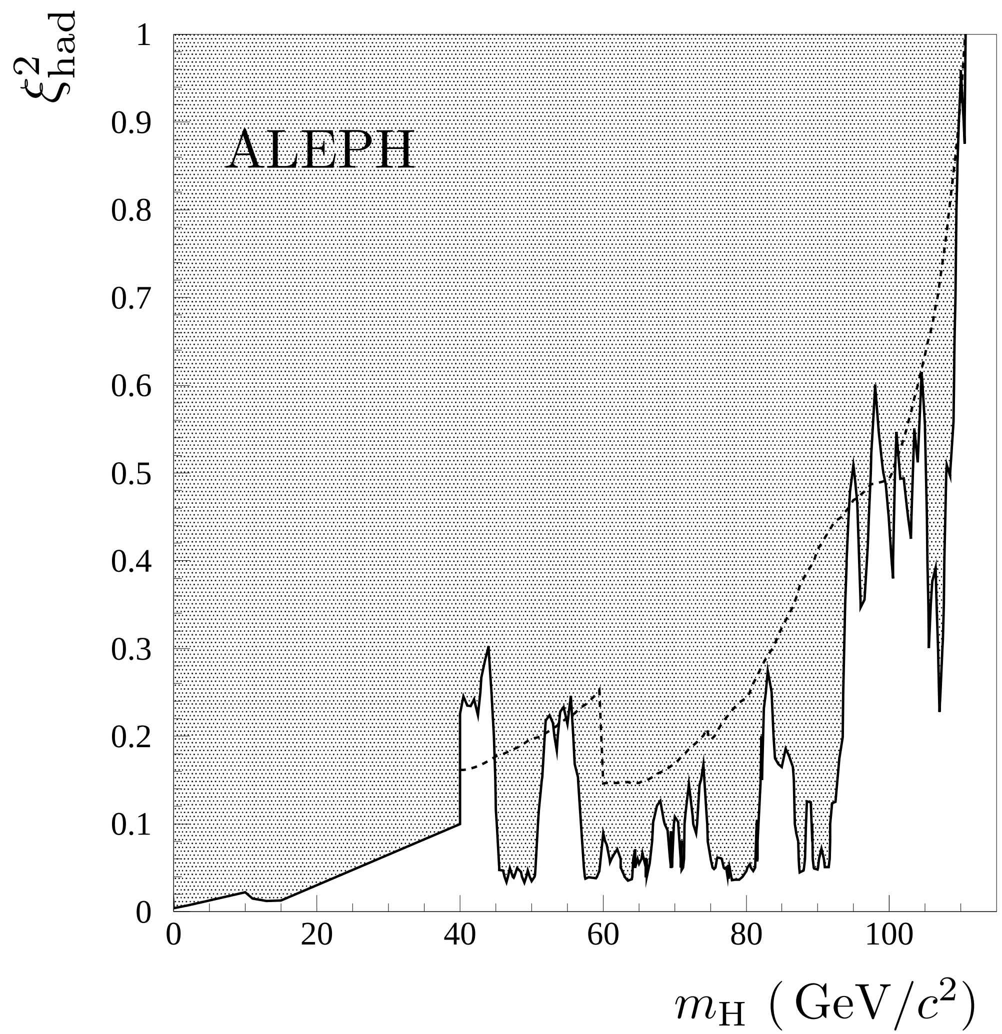


Coupling Limit: b-quark and τ-lepton Decay Mode



Coupling Limit: Hadronic Decay Mode

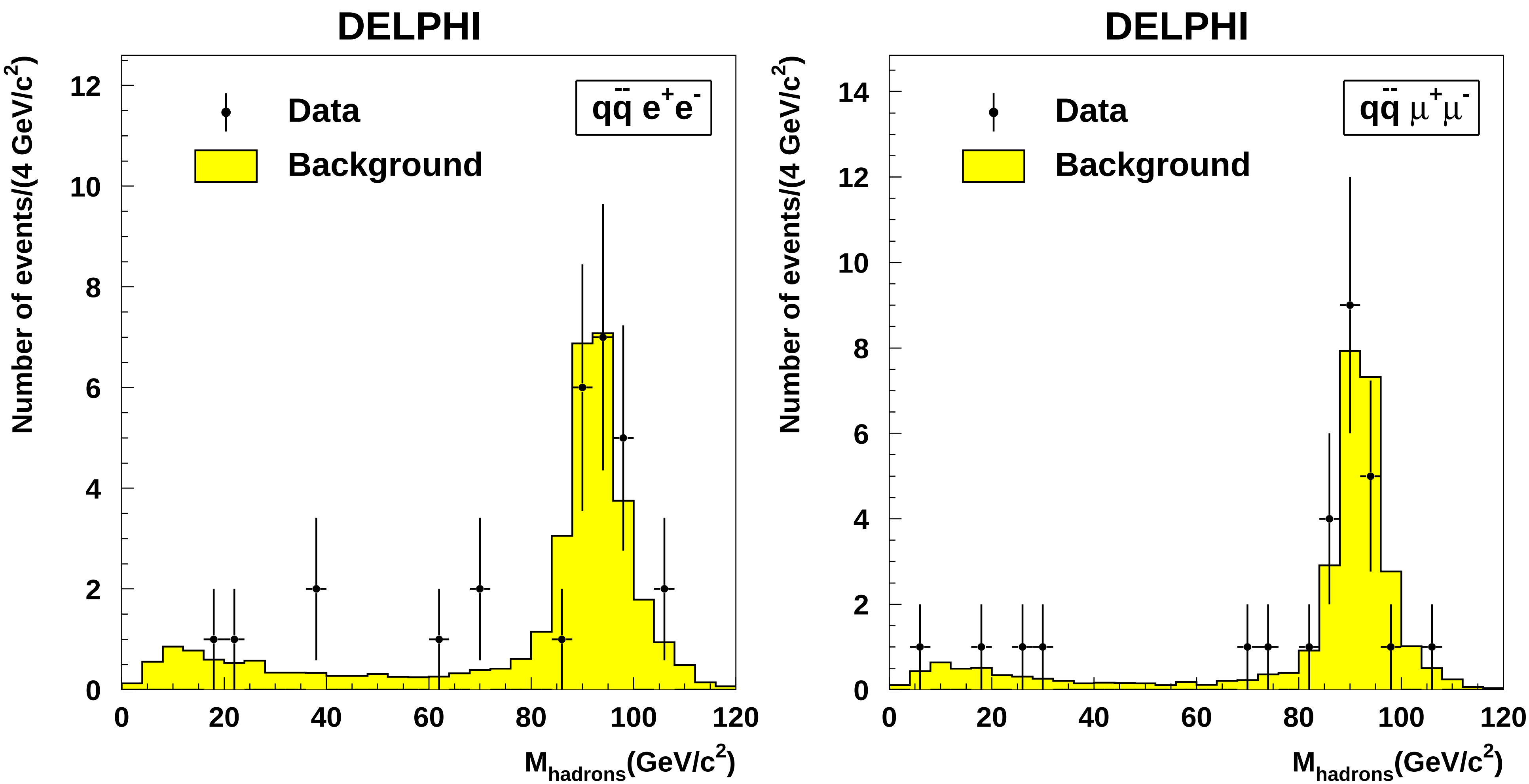




Flavor-Independent Hadronic hZ Searches

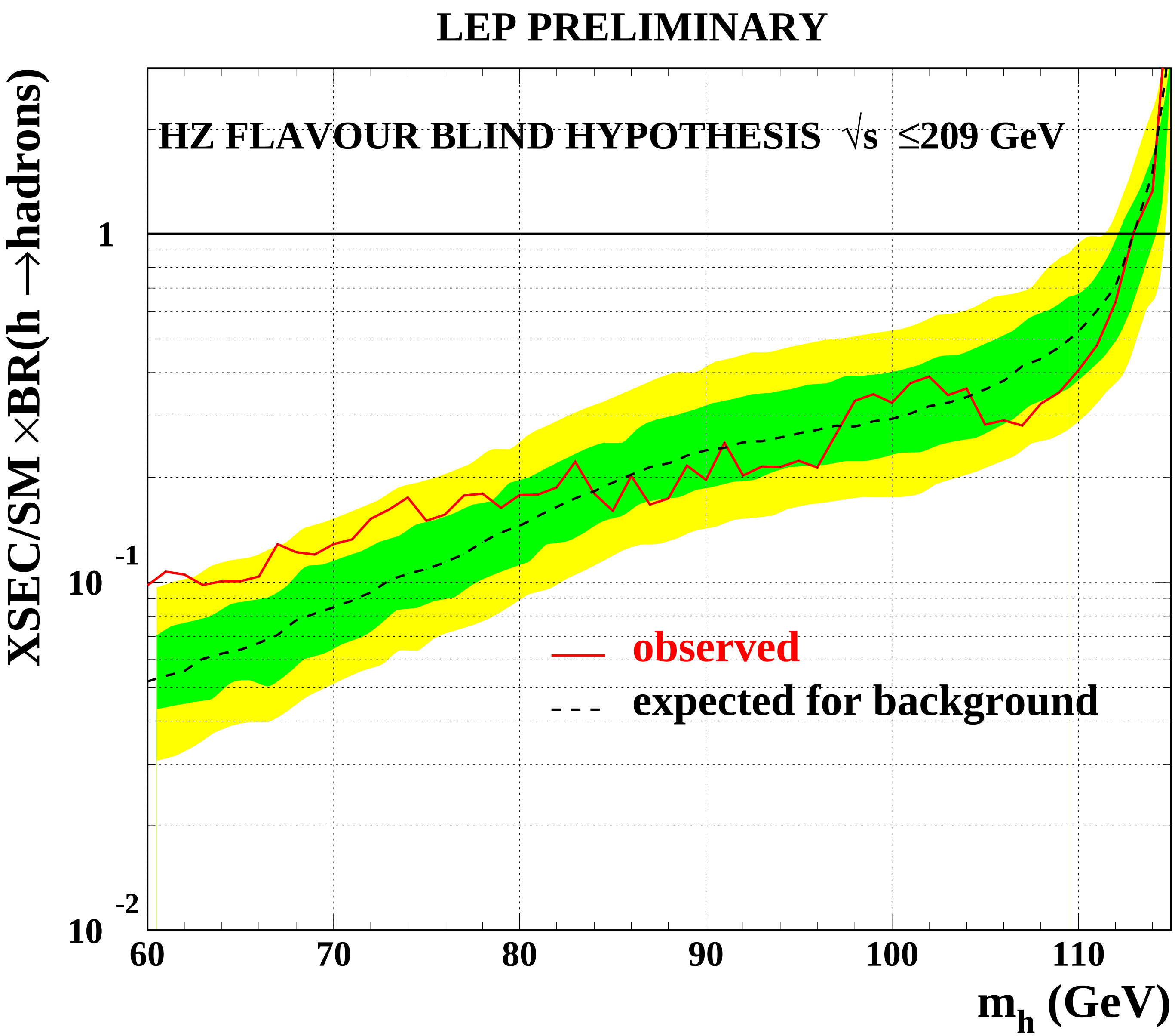
$hZ \rightarrow q\bar{q}l^+l^-$. $ZZ \rightarrow q\bar{q}l^+l^-$ background.

Efficiency $\approx$ 65% (e^+e^-) and 75% ($\mu^+\mu^-$)



Flavor-Independent Hadronic hZ Limits

No b-tagging requirement.



Anomalous Couplings

$$g_{\mathrm{H}\gamma\gamma} = \frac{g}{2m_{\mathrm{W}}} \left(d\sin^2\theta_W + d_B\cos^2\theta_W\right) \quad (1)$$

$$g^{(1)}_{\mathrm{HZ}\gamma} = \frac{g}{m_{\mathrm{W}}} \left(\Delta g_1^{\mathrm{Z}}\sin 2\theta_W - \Delta\kappa_\gamma \tan\theta_W\right) \quad (2)$$

$$g^{(2)}_{\mathrm{HZ}\gamma} = \frac{g}{2m_{\mathrm{W}}} \sin 2\theta_W \ (d - d_B) \quad (3)$$

$$g^{(1)}_{\mathrm{HZZ}} = \frac{g}{m_{\mathrm{W}}} \left(\Delta g_1^{\mathrm{Z}}\cos 2\theta_W + \Delta\kappa_\gamma \tan^2\theta_W\right) \quad (4)$$

$$g^{(2)}_{\mathrm{HZZ}} = \frac{g}{2m_{\mathrm{W}}} \left(d\cos^2\theta_W + d_B\sin^2\theta_W\right) \quad (5)$$

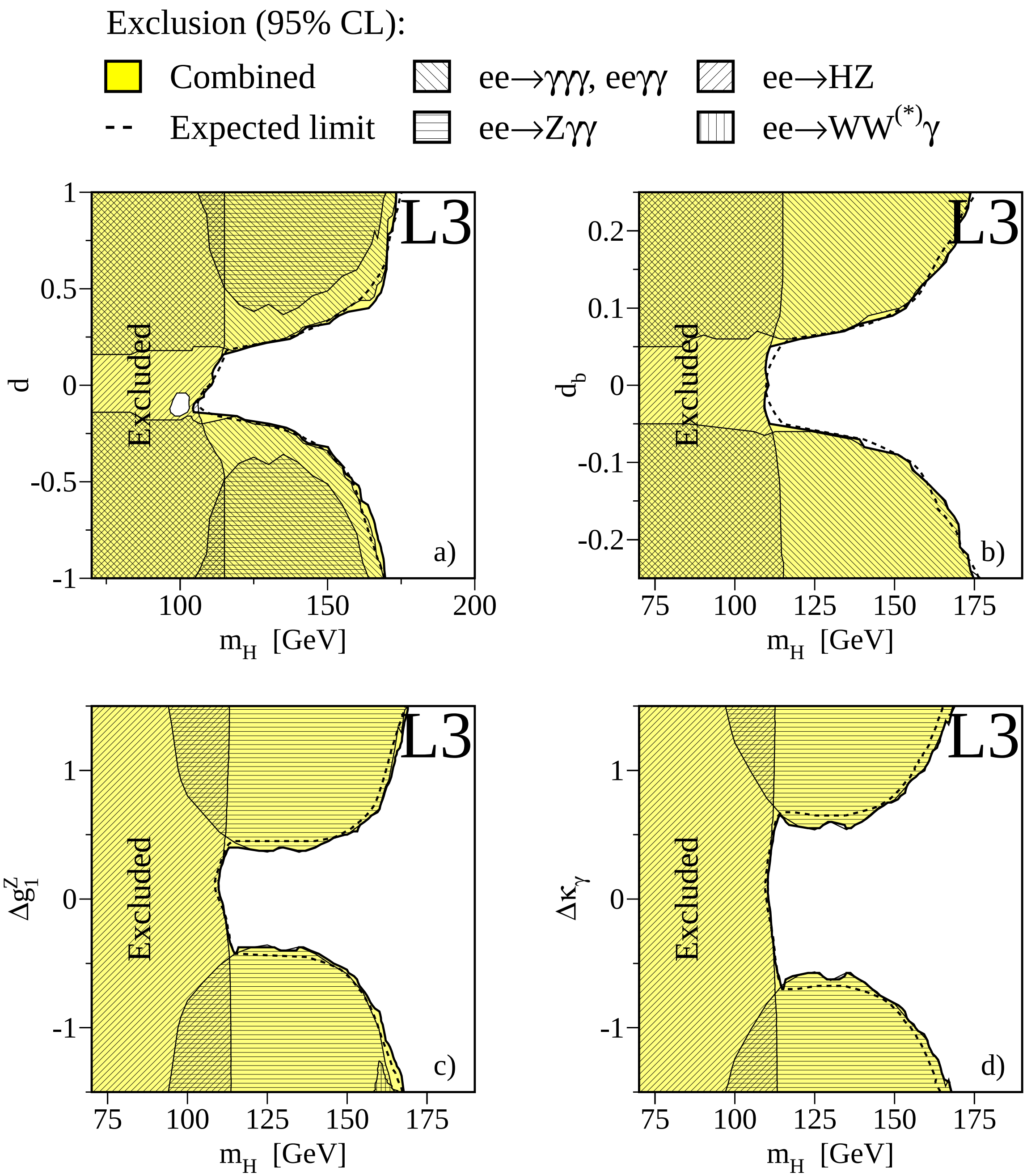
$$g^{(3)}_{\mathrm{HZZ}} = \frac{g\ m_{\mathrm{W}}}{2\ \cos^2\theta_W}\delta_{\mathrm{Z}}, \quad \xi^2 = (1+\delta_{\mathrm{Z}})^2 \quad (6)$$

$$g^{(1)}_{\mathrm{HWW}} = \frac{g\ m_{\mathrm{W}}}{m_{\mathrm{Z}}^2}\Delta g_1^{\mathrm{Z}} \quad (7)$$

$$g^{(2)}_{\mathrm{HWW}} = \frac{g}{m_{\mathrm{W}}}\frac{d}{\cos 2\theta_W} \quad (8)$$

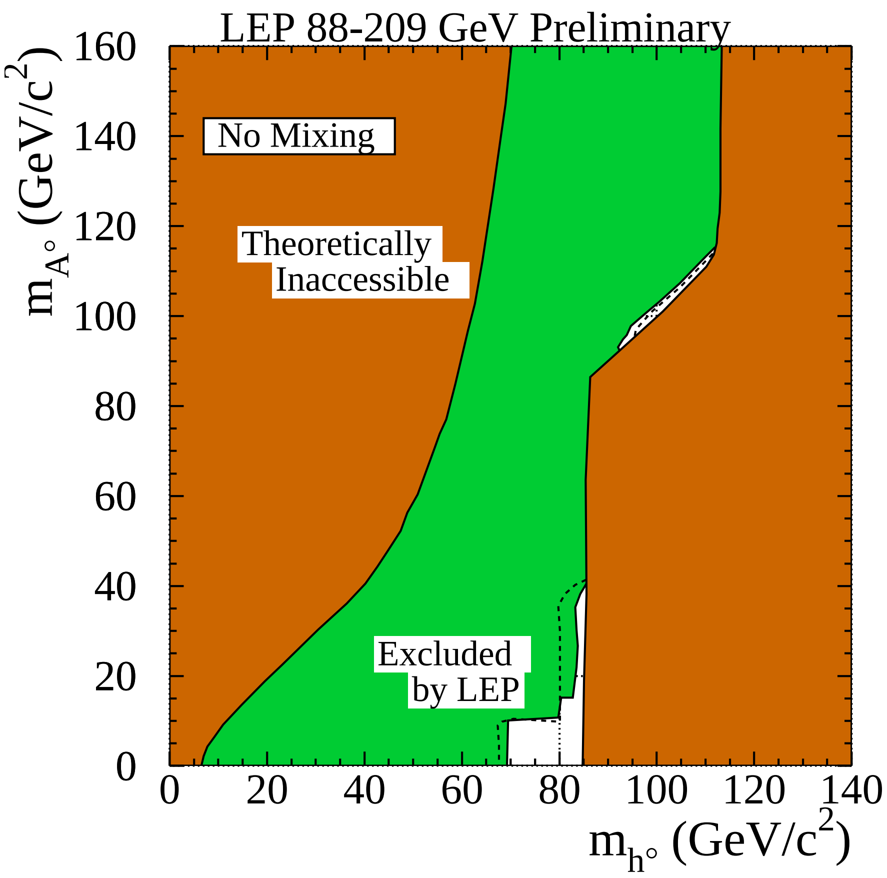
Parameters: d, d_B, Δg_1^{Z}, $\Delta\kappa_\gamma$

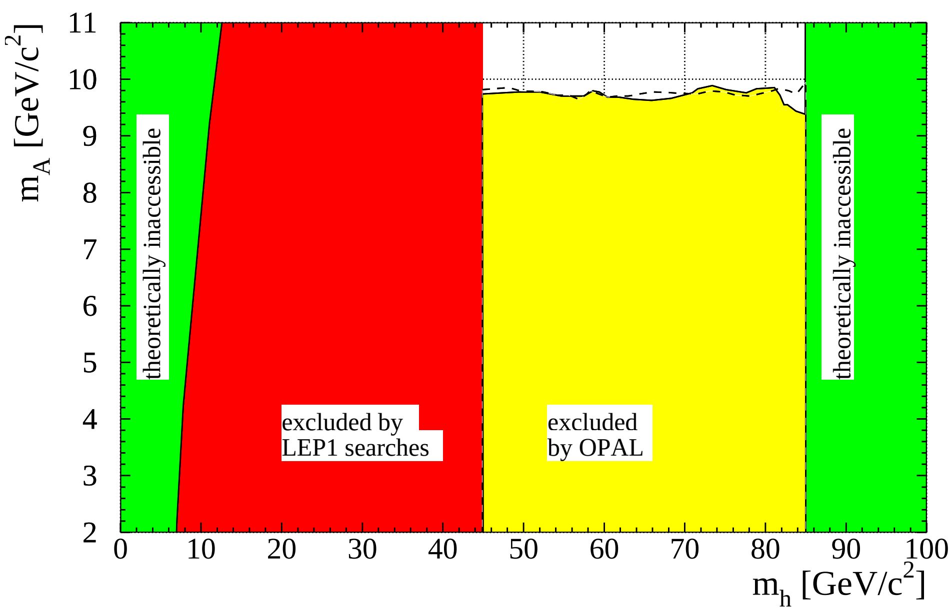
Anomalous Couplings: Parameter Limits



MSSM: Dedicated Low m_A Searches

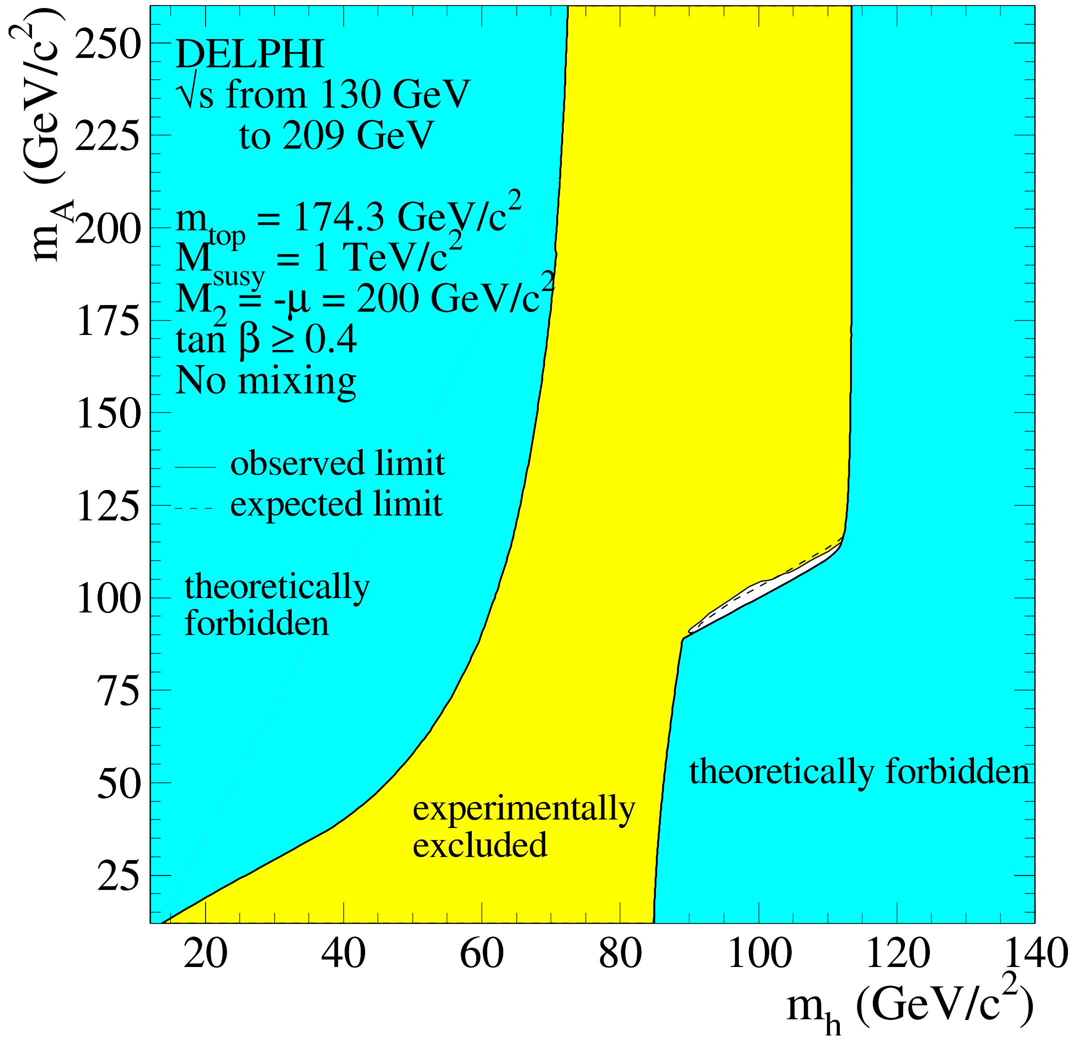
No mixing in scalar top sector (smallest scalar Higgs boson mass).





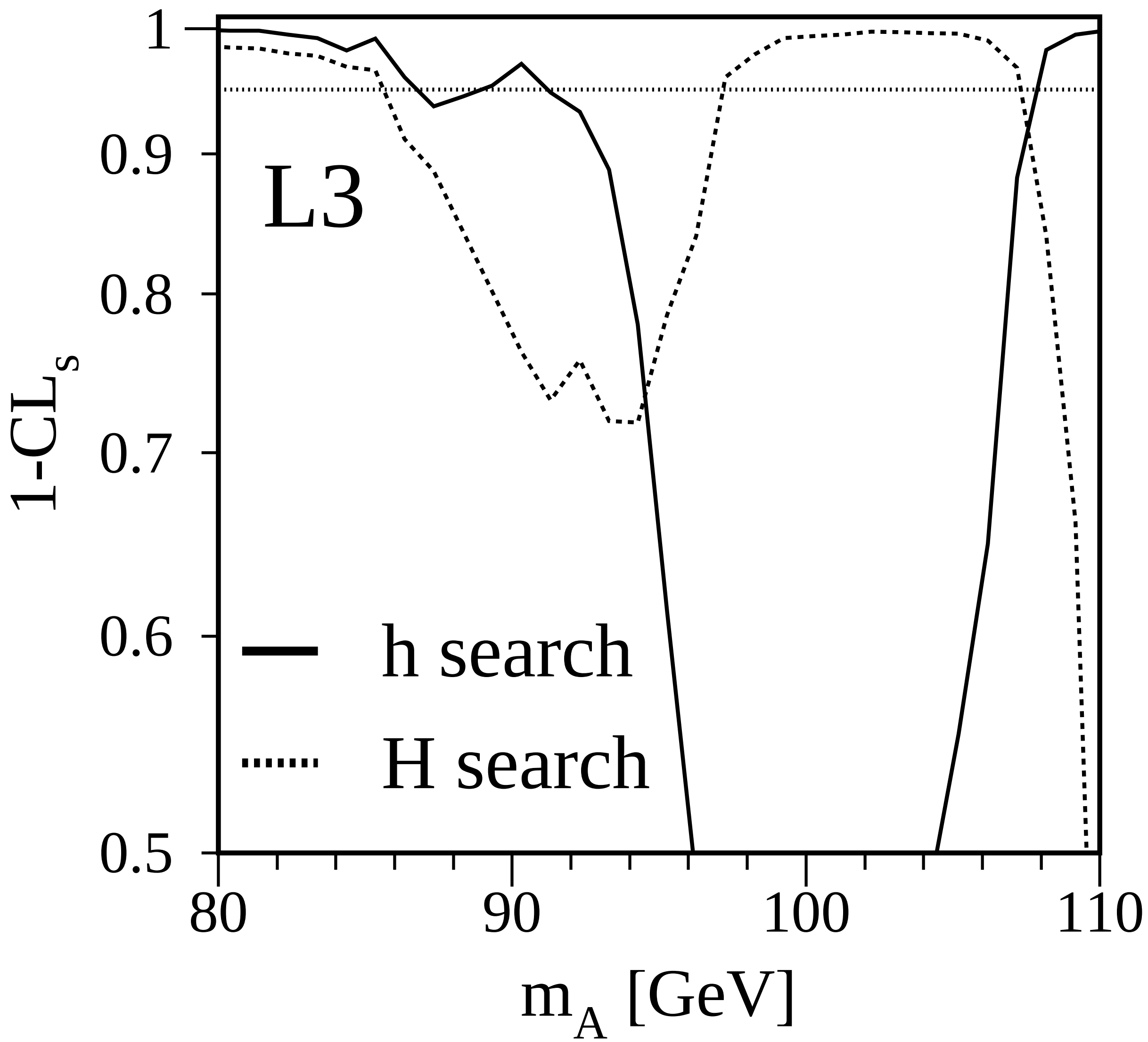
MSSM: Dedicated h → AA Searches

No mixing in scalar top sector.



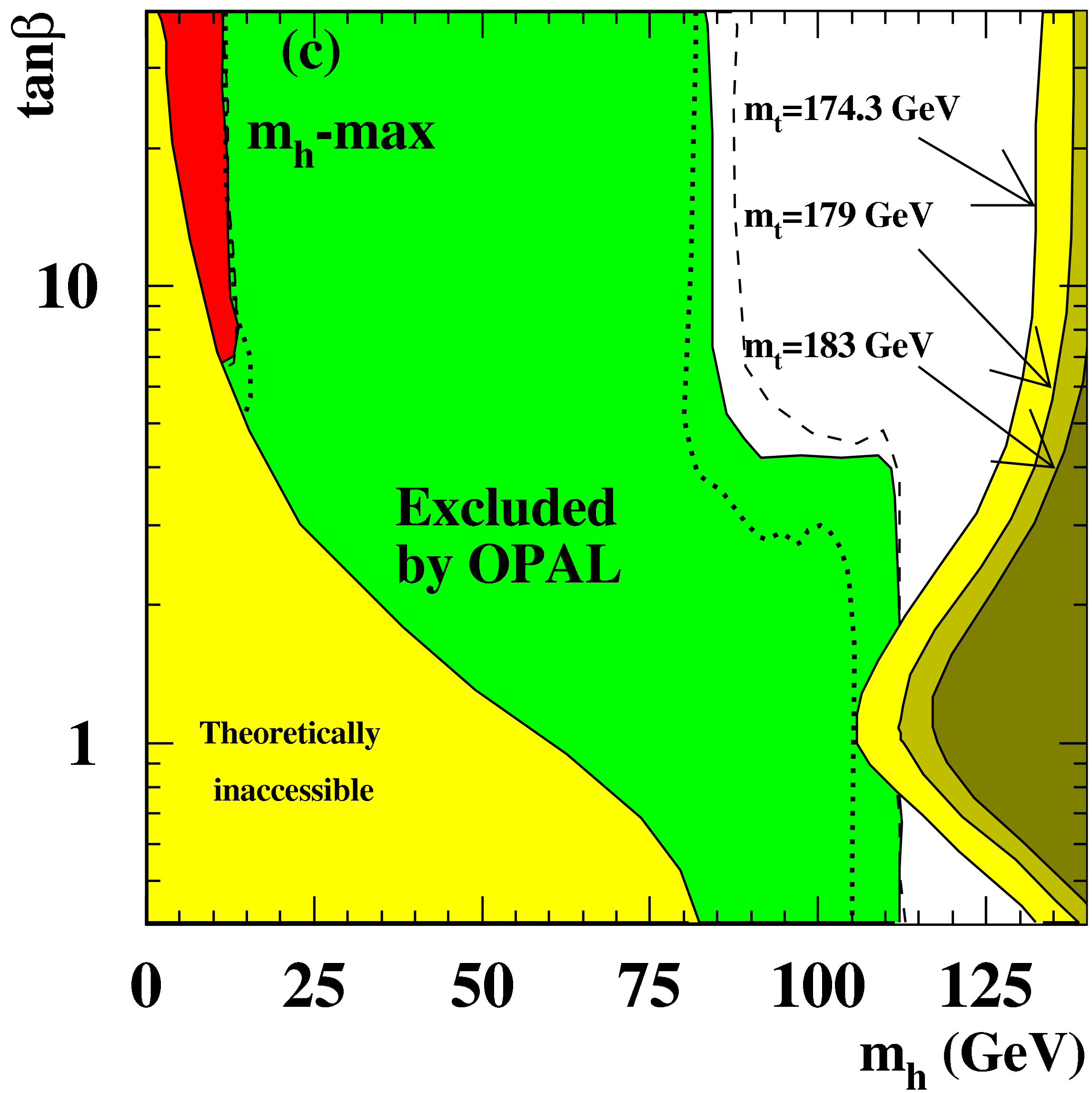
MSSM: Large $\tan\beta$ Scenario

hA is inaccessible and hZ is suppressed by $\sin(\beta-\alpha) \approx 0$, thus HZ production.



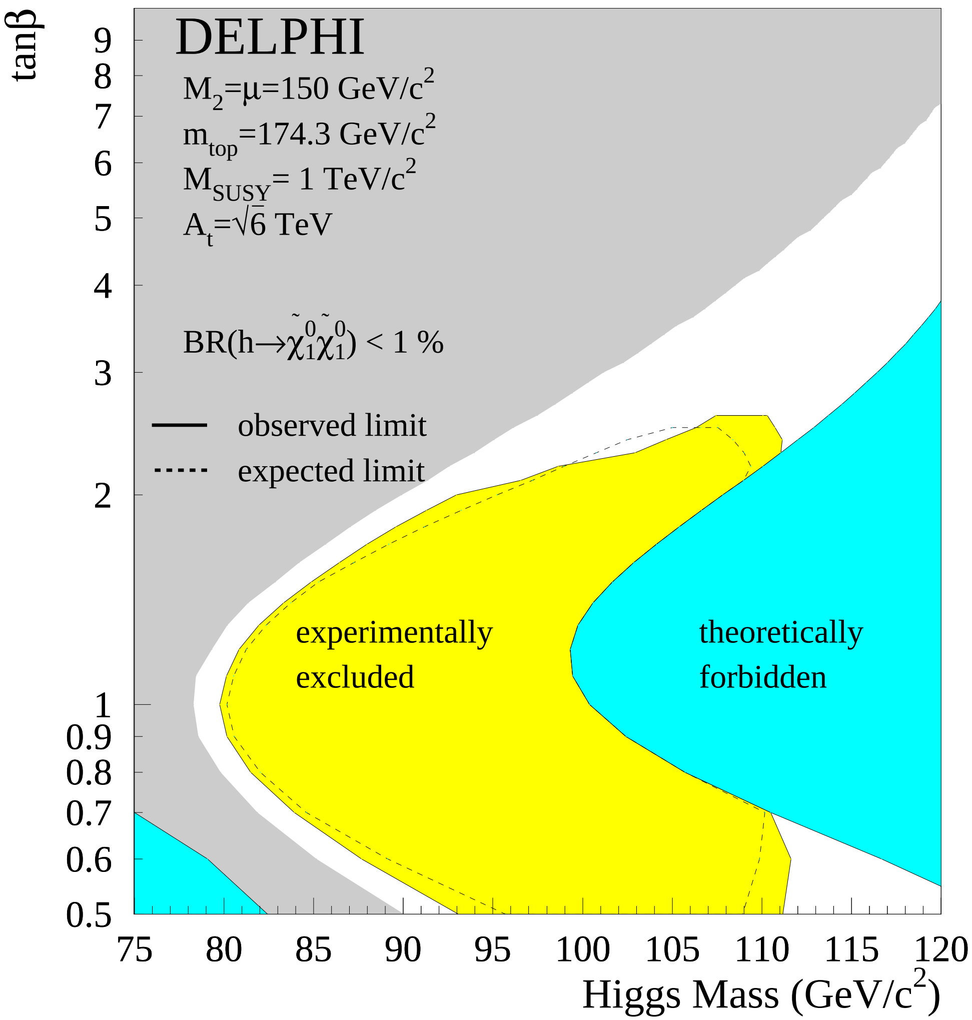
MSSM: Maximum m_h Scenario

New top quark mass: 178.0 ± 4.3 GeV: $\tan\beta$ limit strongly reduced.

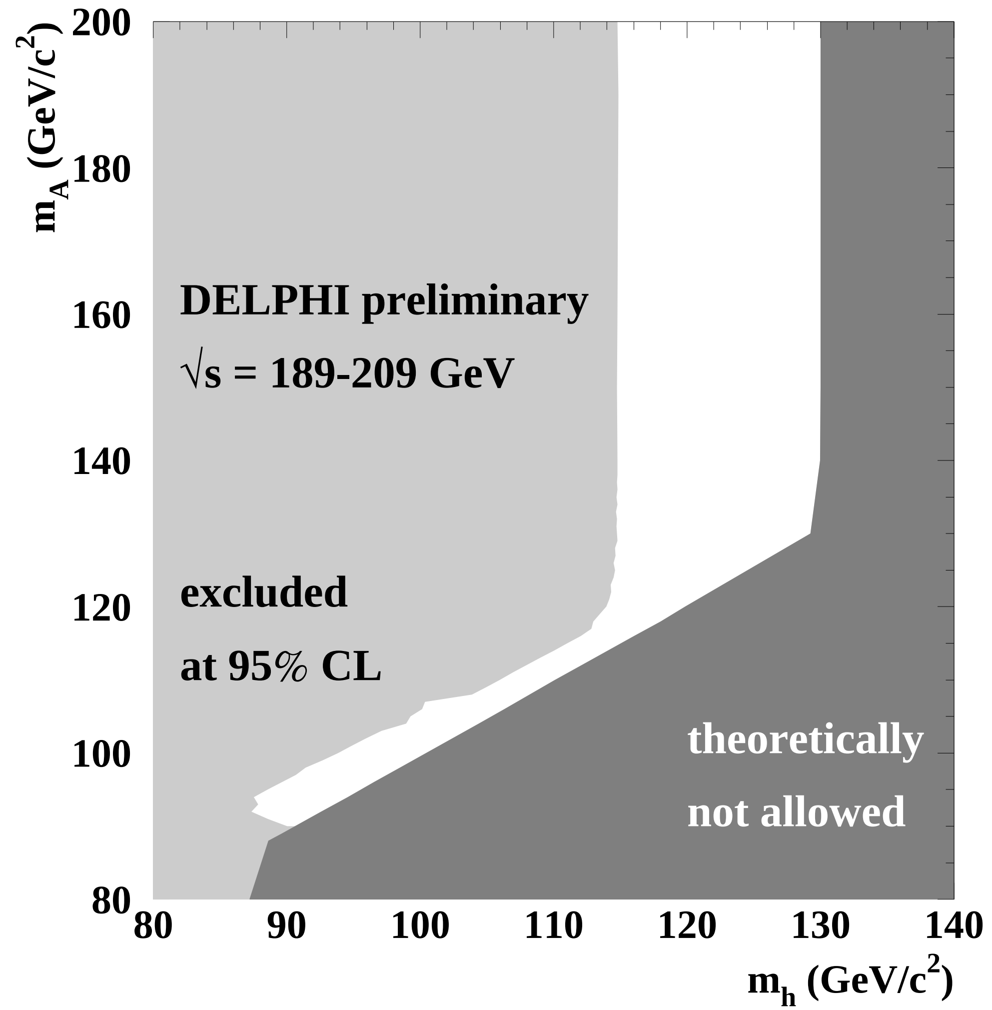


MSSM: Benchmark and Parameter Scan

Mass limits depend on invisible Higgs boson searches.

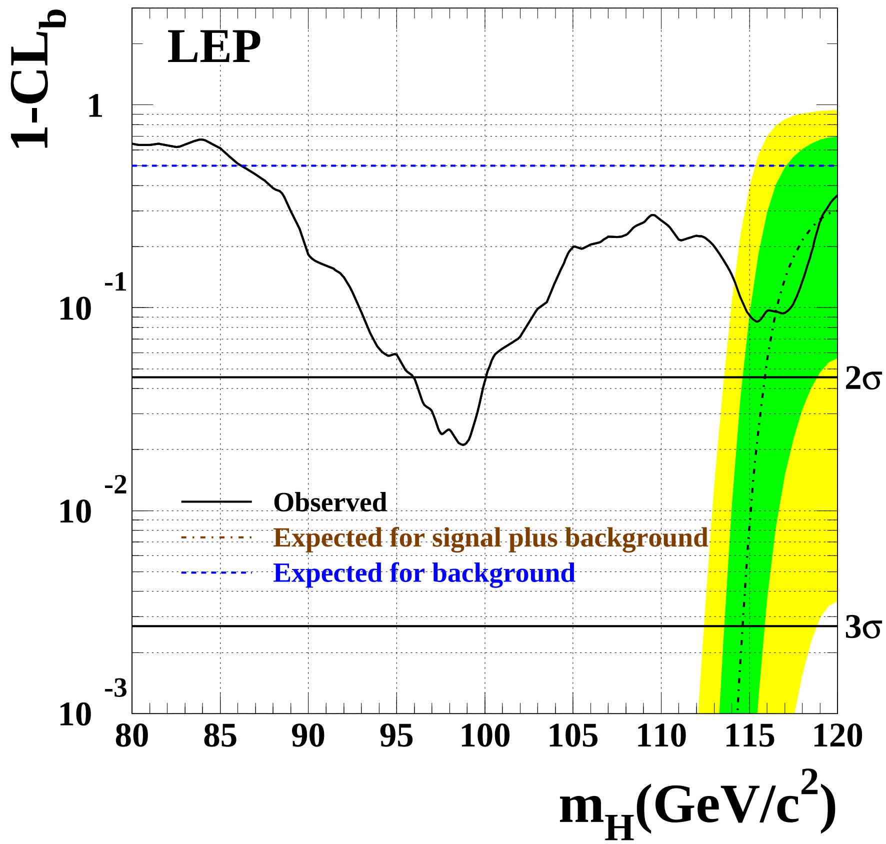


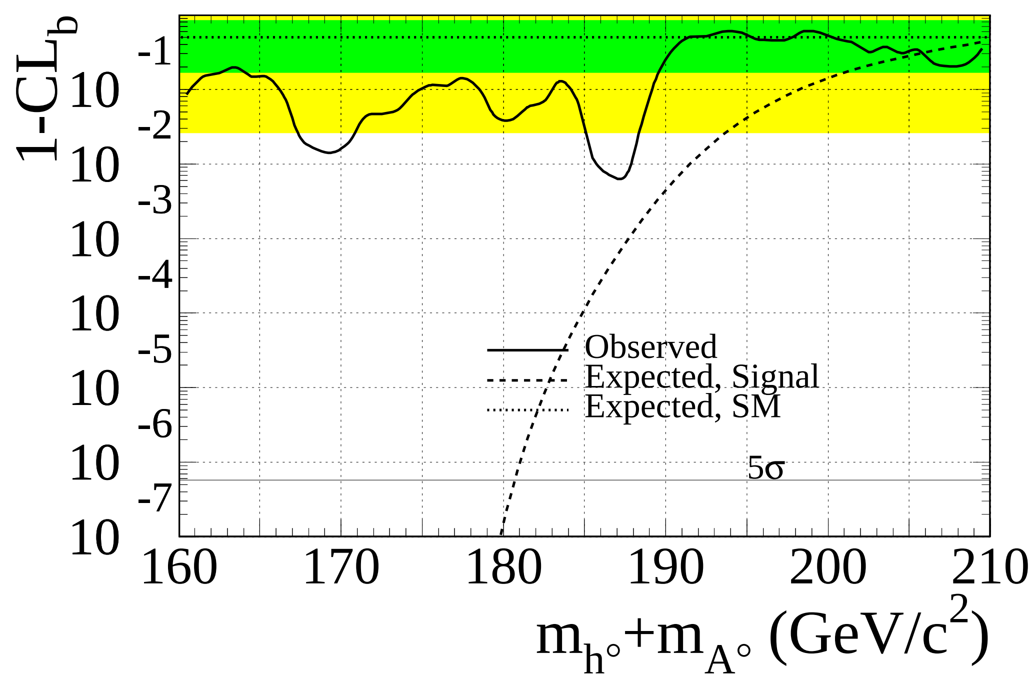
General parameter scan.



MSSM: 3 Higgs Boson Hypothesis

$m_\mathrm{h} \approx m_\mathrm{A} \approx 99$ GeV: hZ and hA production and HZ at 115 GeV.
General MSSM parameter scan gives this mass combination with reduced hZ cross section at 99 GeV compatible with data.



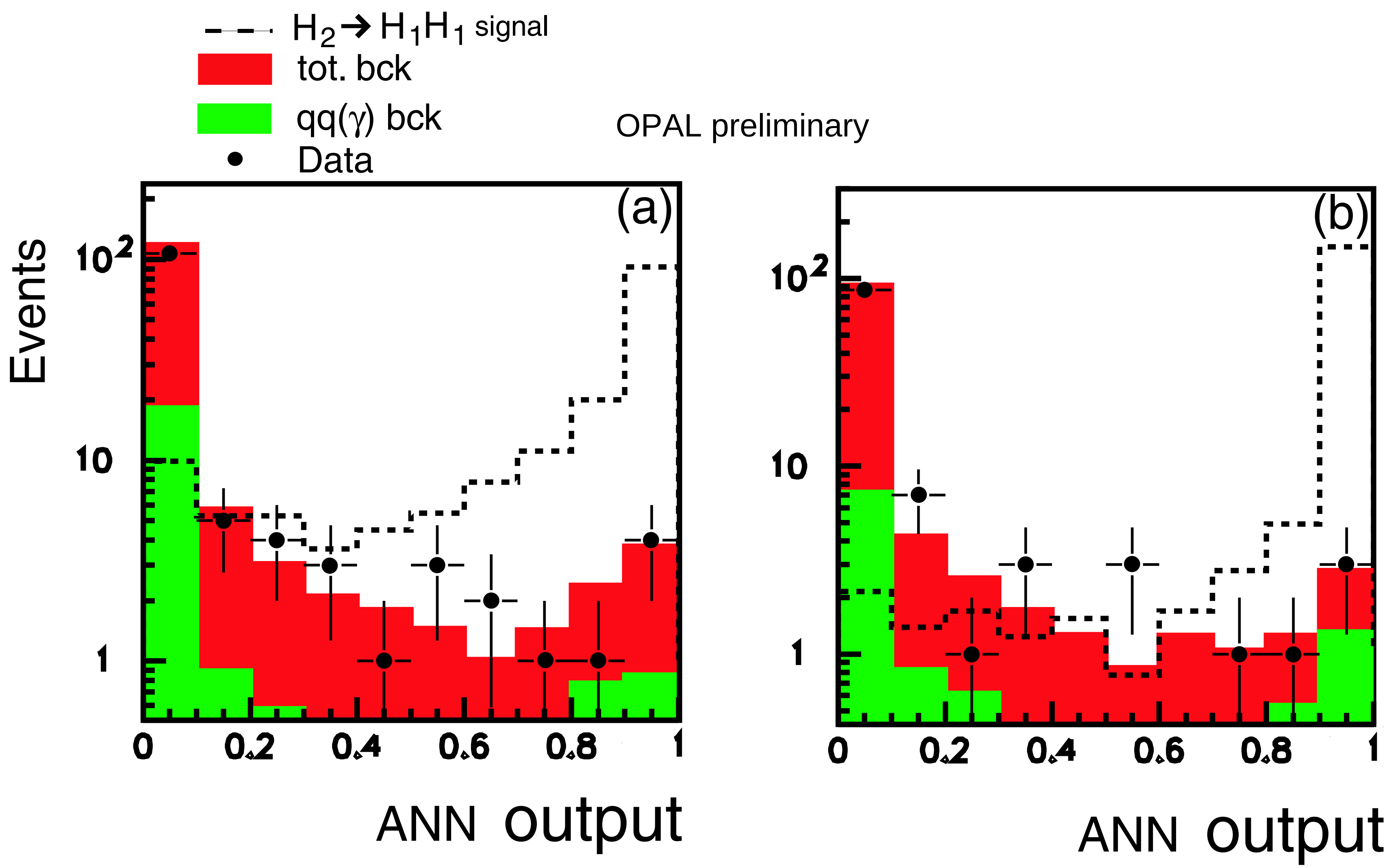


CP-Violating Models

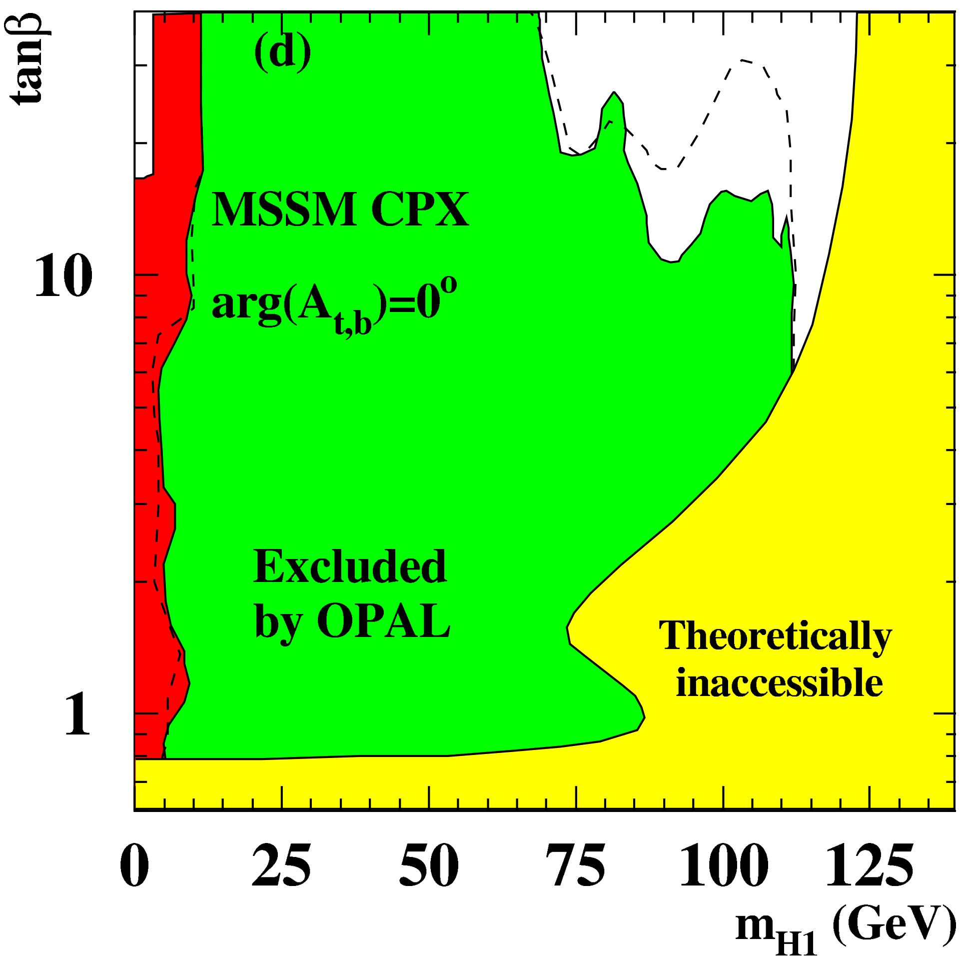
H_1, H_2, H_3 instead of h, H, A.

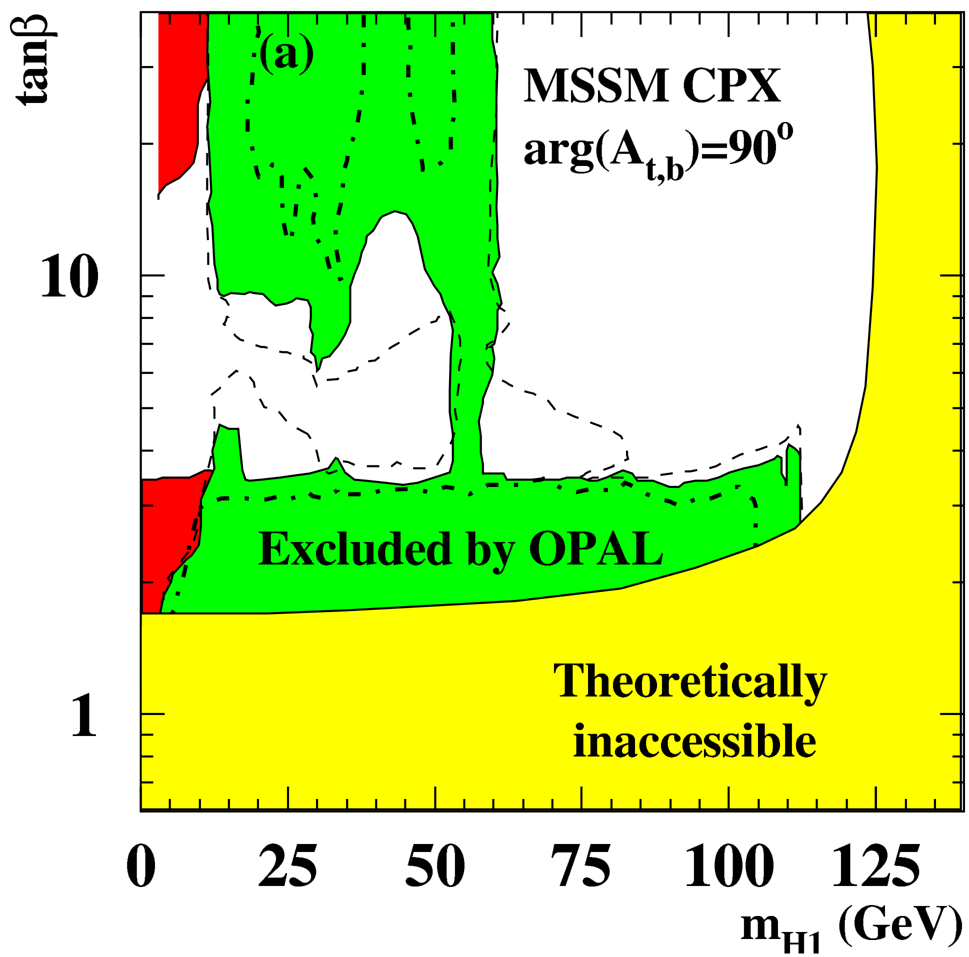
(a) $e^+e^- \rightarrow H_2Z \rightarrow b\bar{b}\nu\bar{\nu}$

(b) $e^+e^- \rightarrow H_2Z \rightarrow H_1H_1Z \rightarrow b\bar{b}b\bar{b}\nu\bar{\nu}$



No CP-Mixing to Full CP-Mixing: Reduced Limits





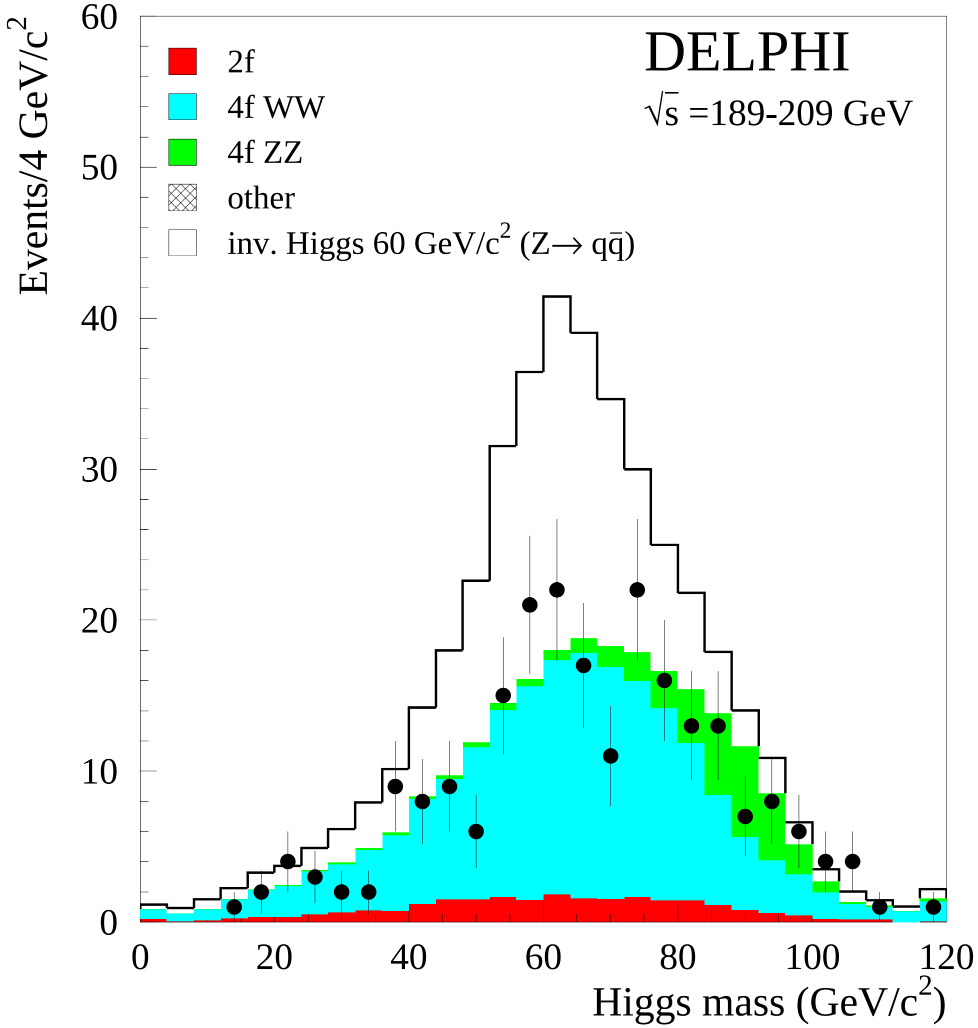
Invisible Higgs Boson Decays

$e^+e^- \rightarrow ZH$

$Z \rightarrow q\bar{q}, \mu^+\mu^-, e^+e^-$

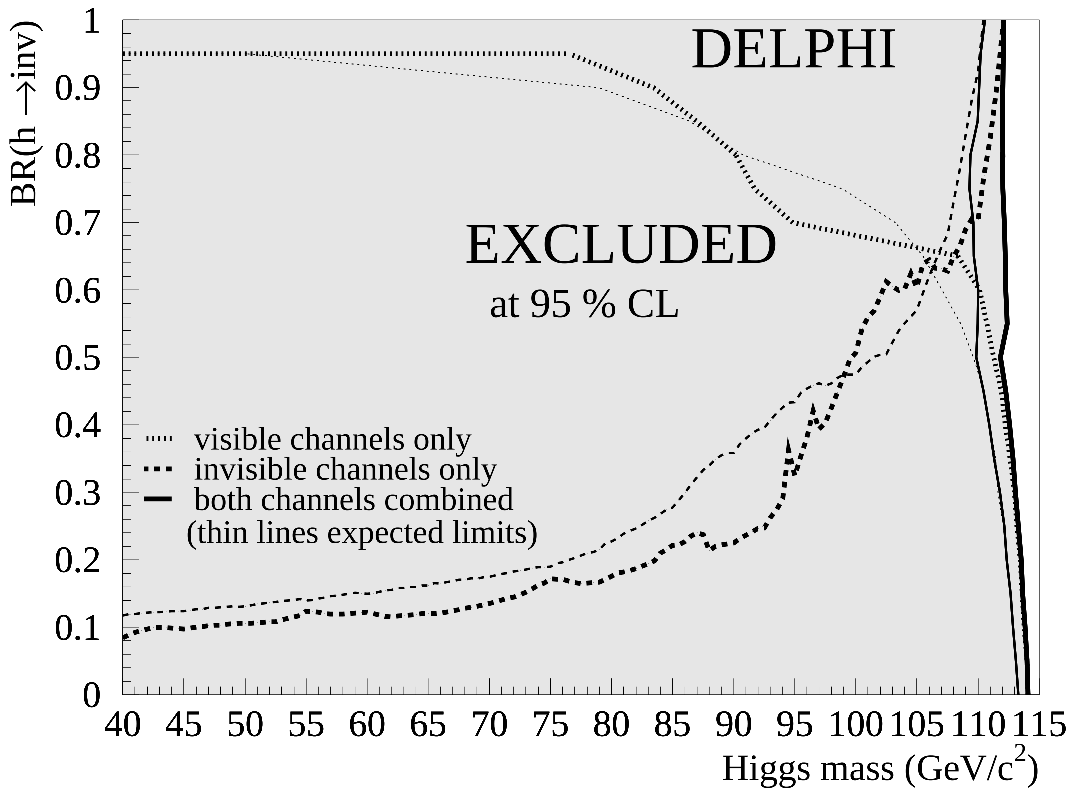
MSSM: $H \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$

Extra complex singlet: $H \rightarrow JJ$

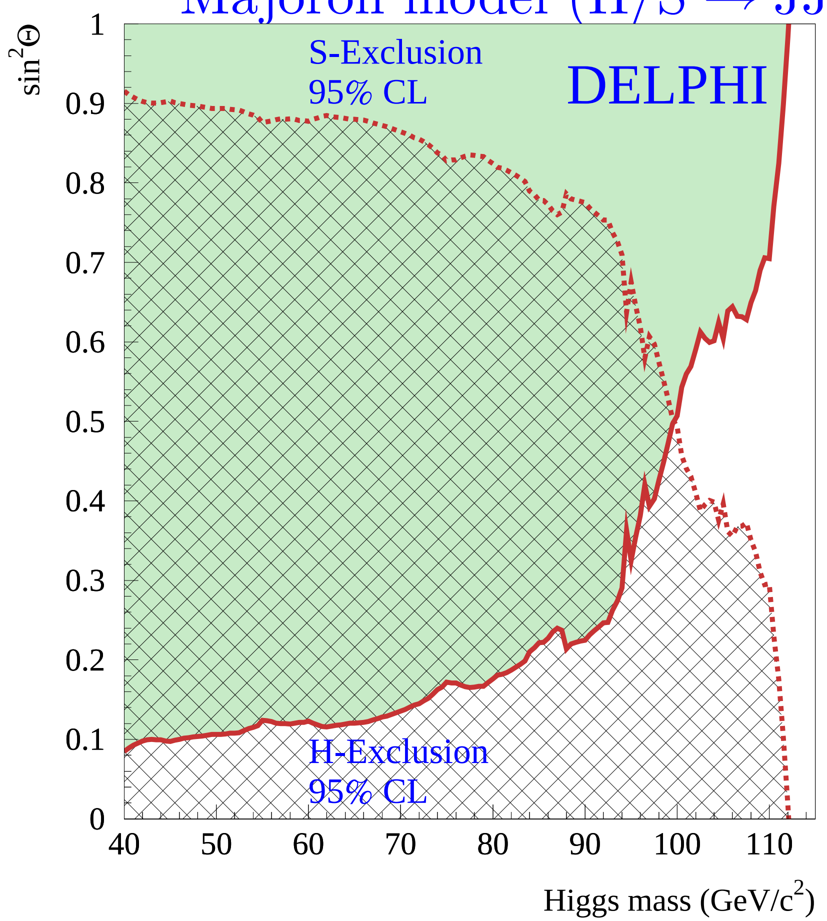


Invisible Higgs Boson Limits

SM and invisible searches combined.

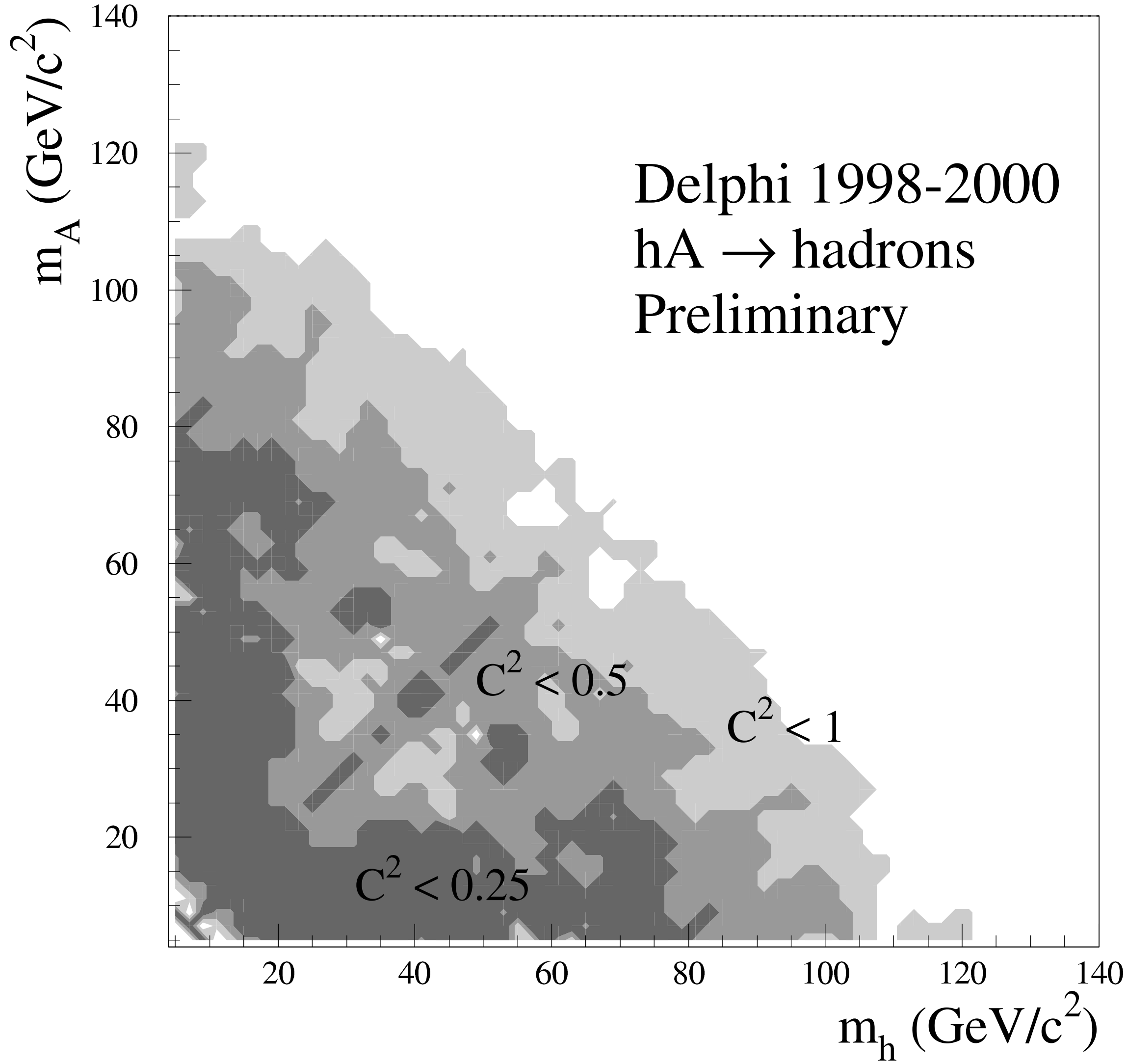


Majoron model (H/S → JJ)

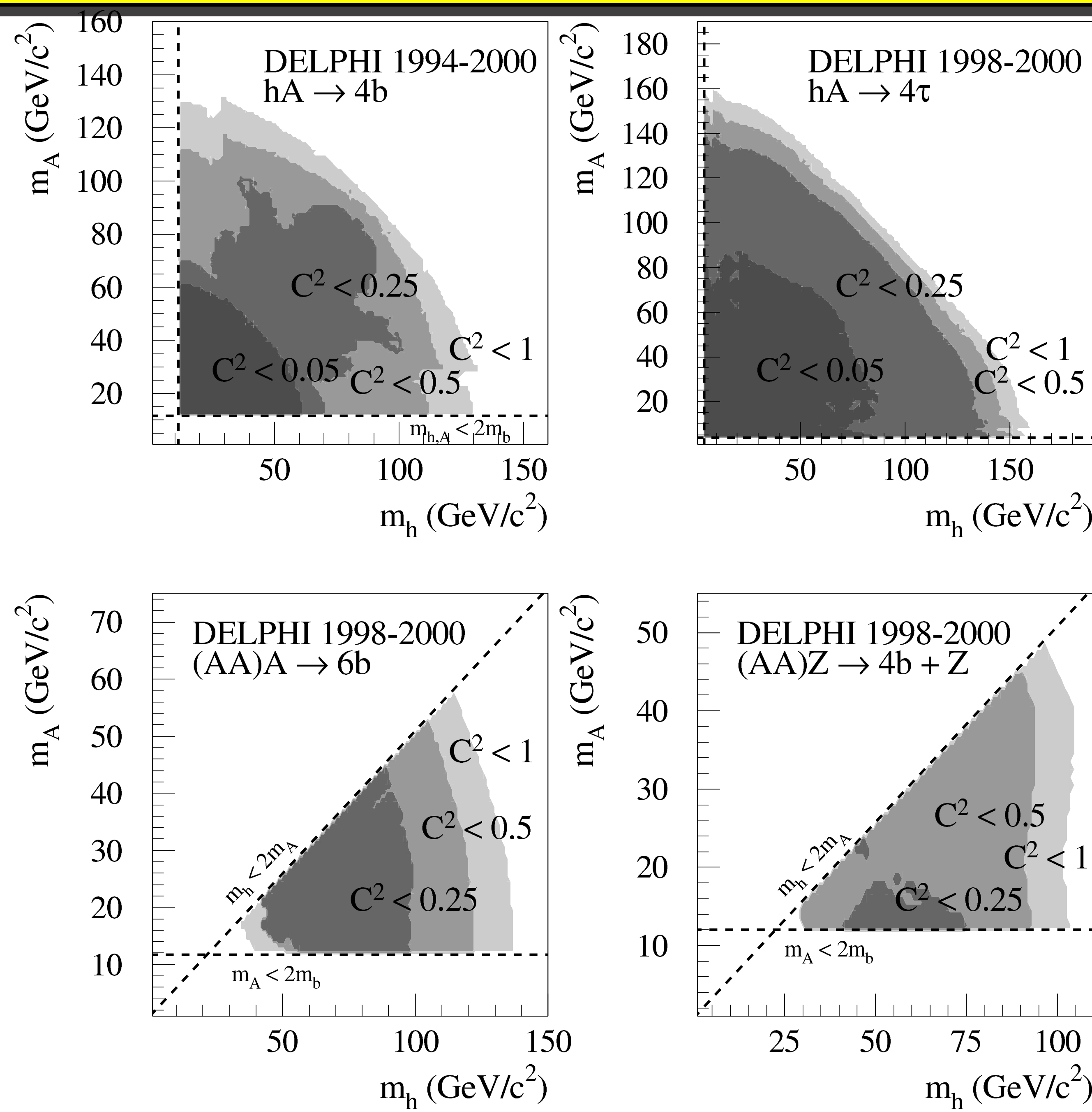


Flavor-Independent Hadronic hA Limits

No b-tagging requirement.



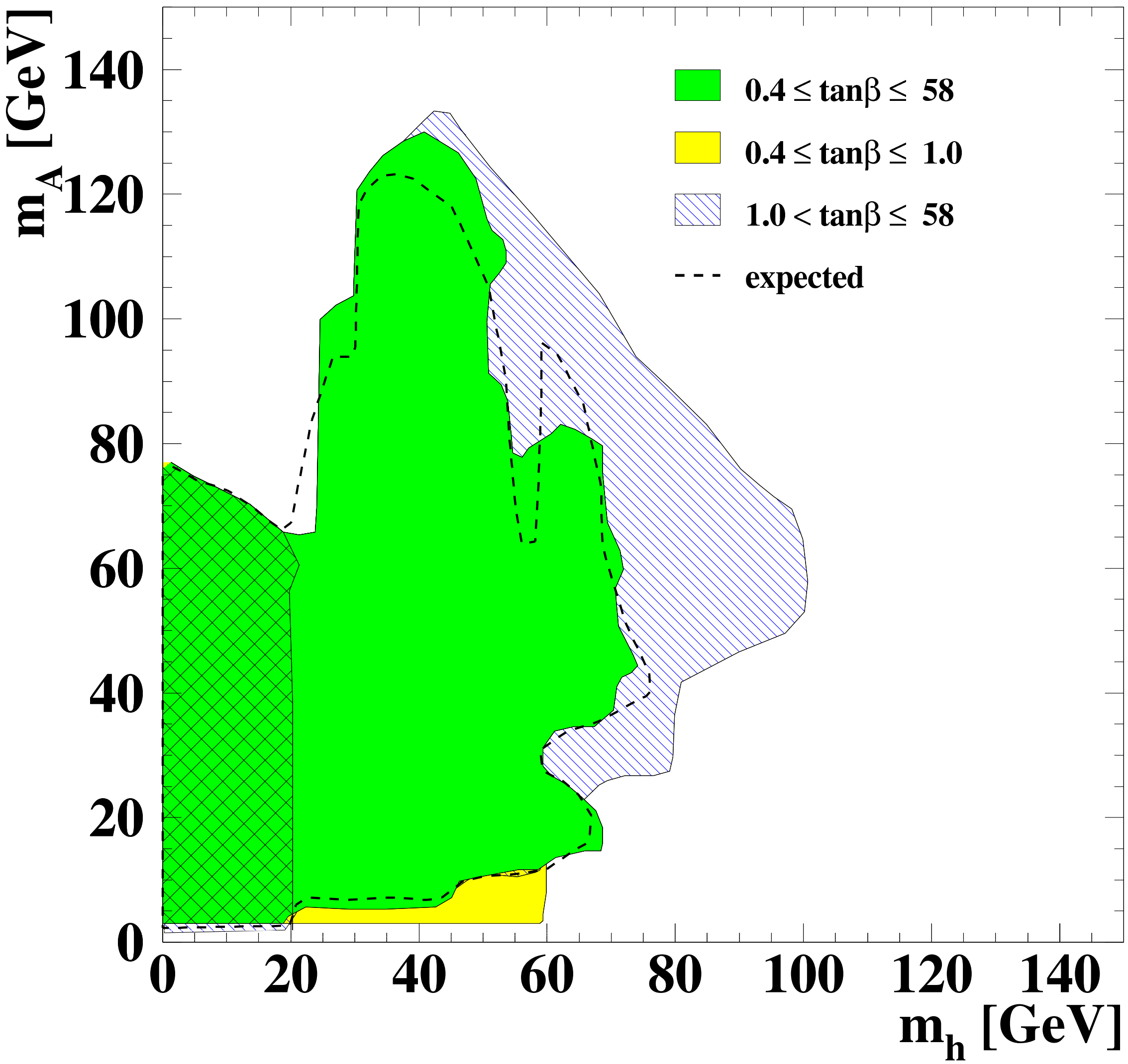
General 2-Higgs Doublet Model: hA Limits



General 2-Higgs Doublet Model: Parameter Scan

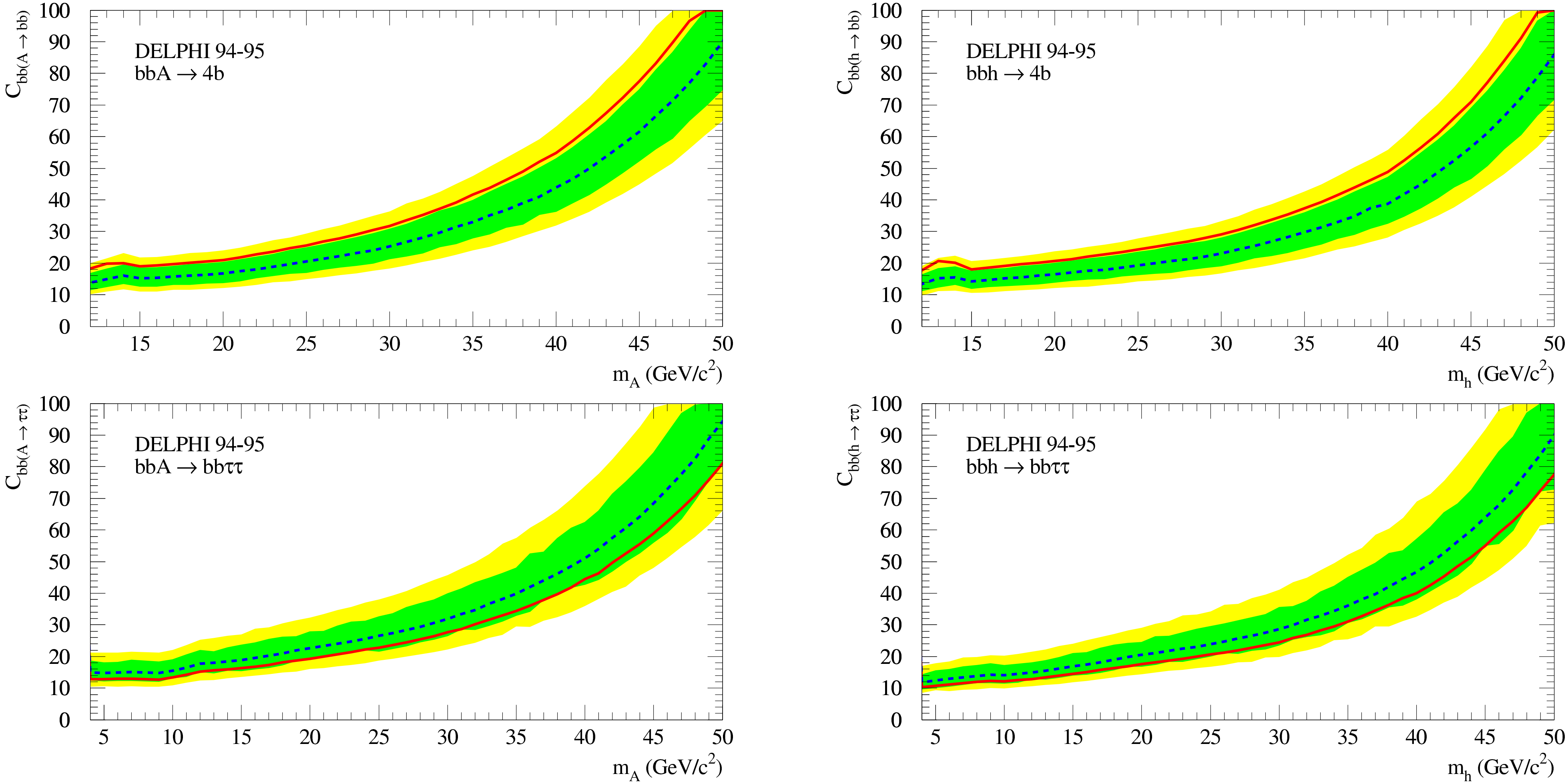
Combination of b-tagging and flavor-independent searches.

OPAL PRELIMINARY



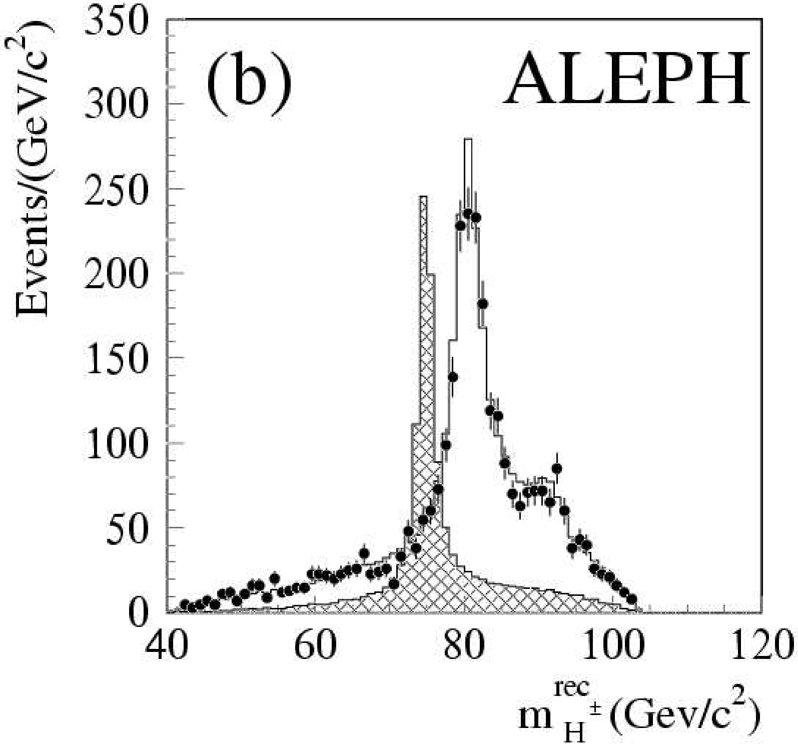
General 2-Higgs Doublet Model: Yukawa $b\bar{b}h$, $b\bar{b}A$

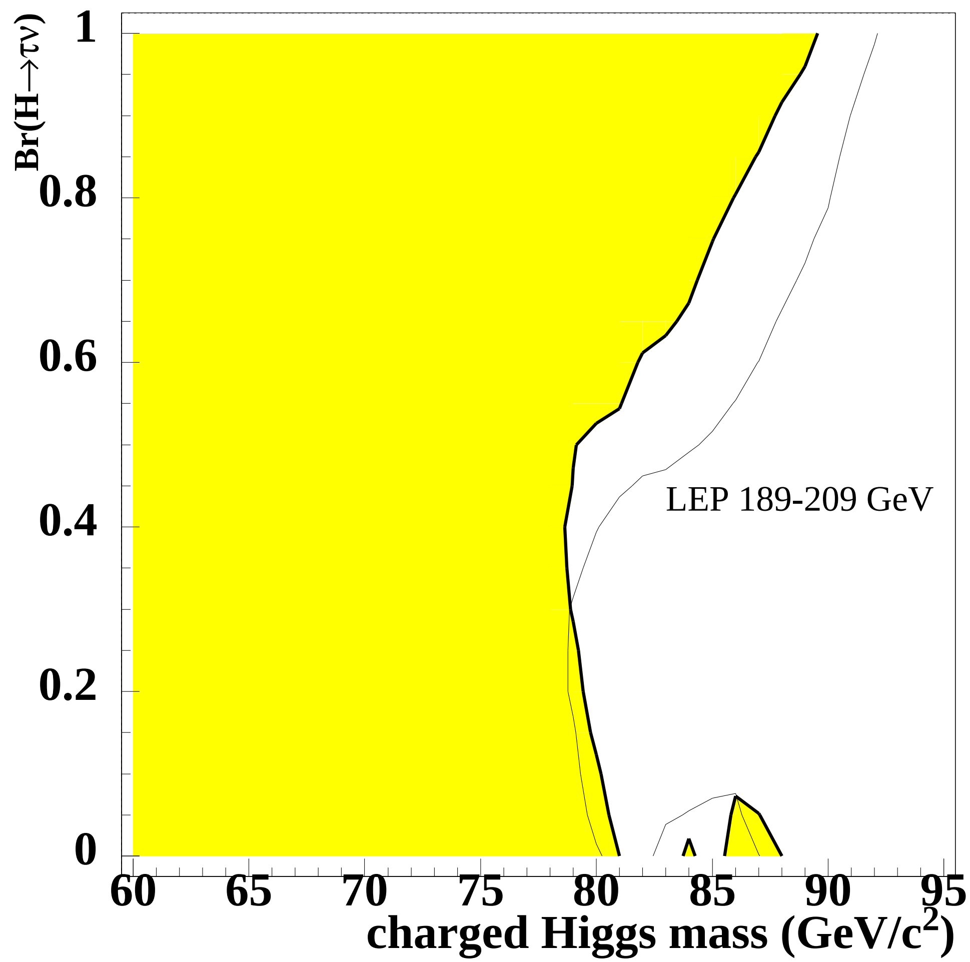
Enhancement (C): $\tan\beta$ for bbA, $\sin\alpha/\cos\beta$ for bbh.



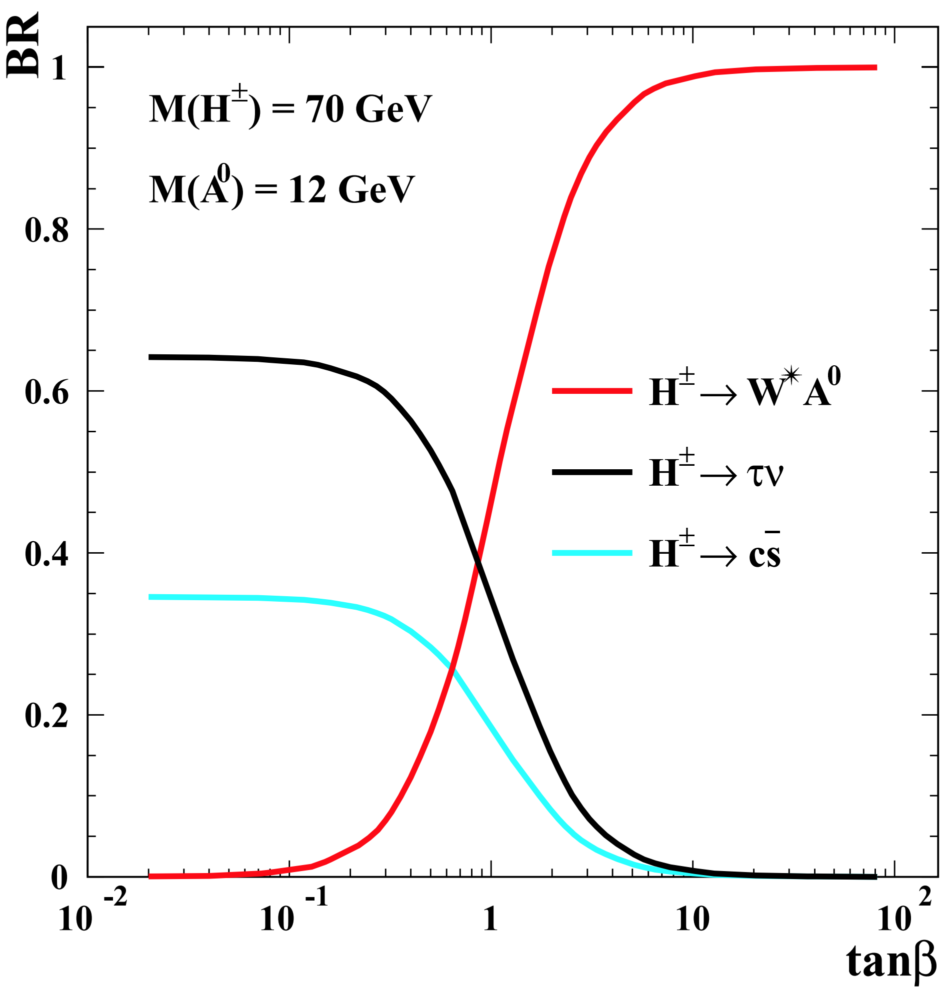
General 2-Higgs Doublet Model: $H^{\pm}$

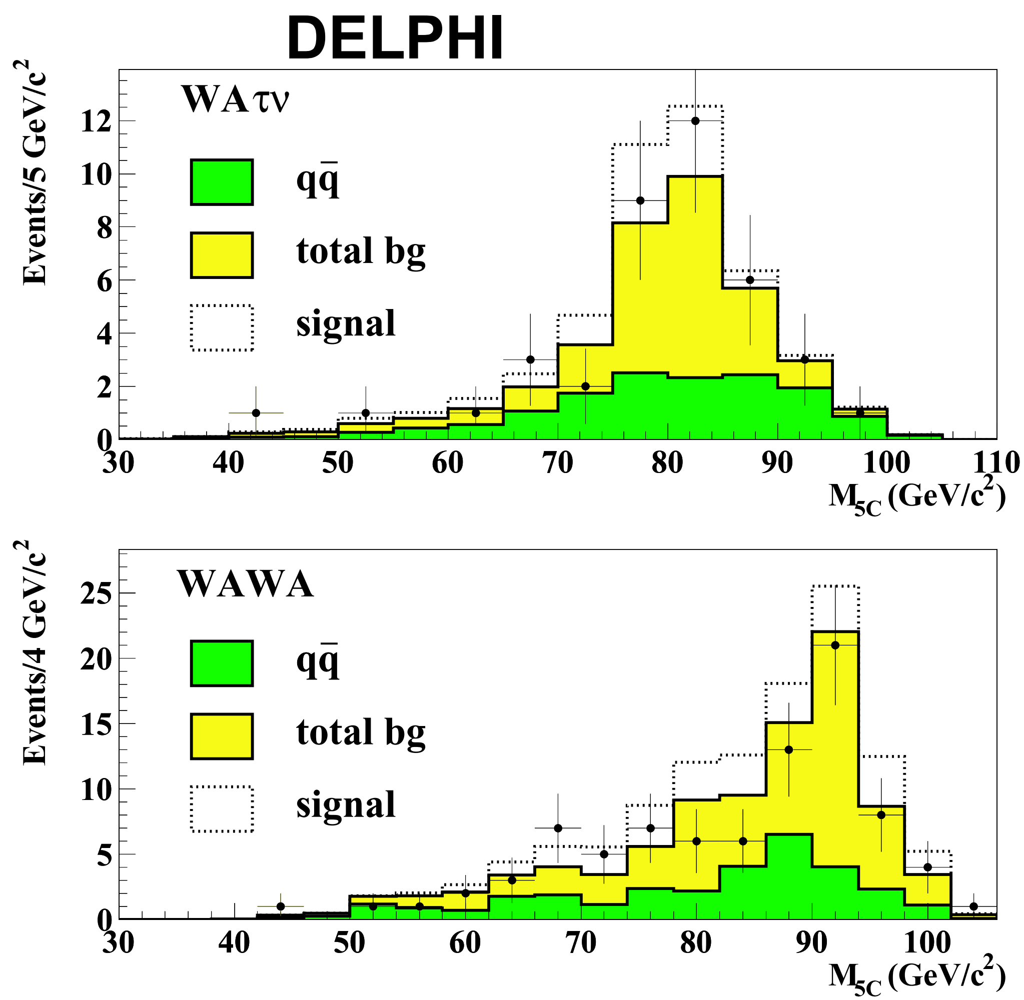
$e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}\bar{c}s,\ cs\tau\nu,\ \tau^+\nu\tau^-\bar{\nu}$



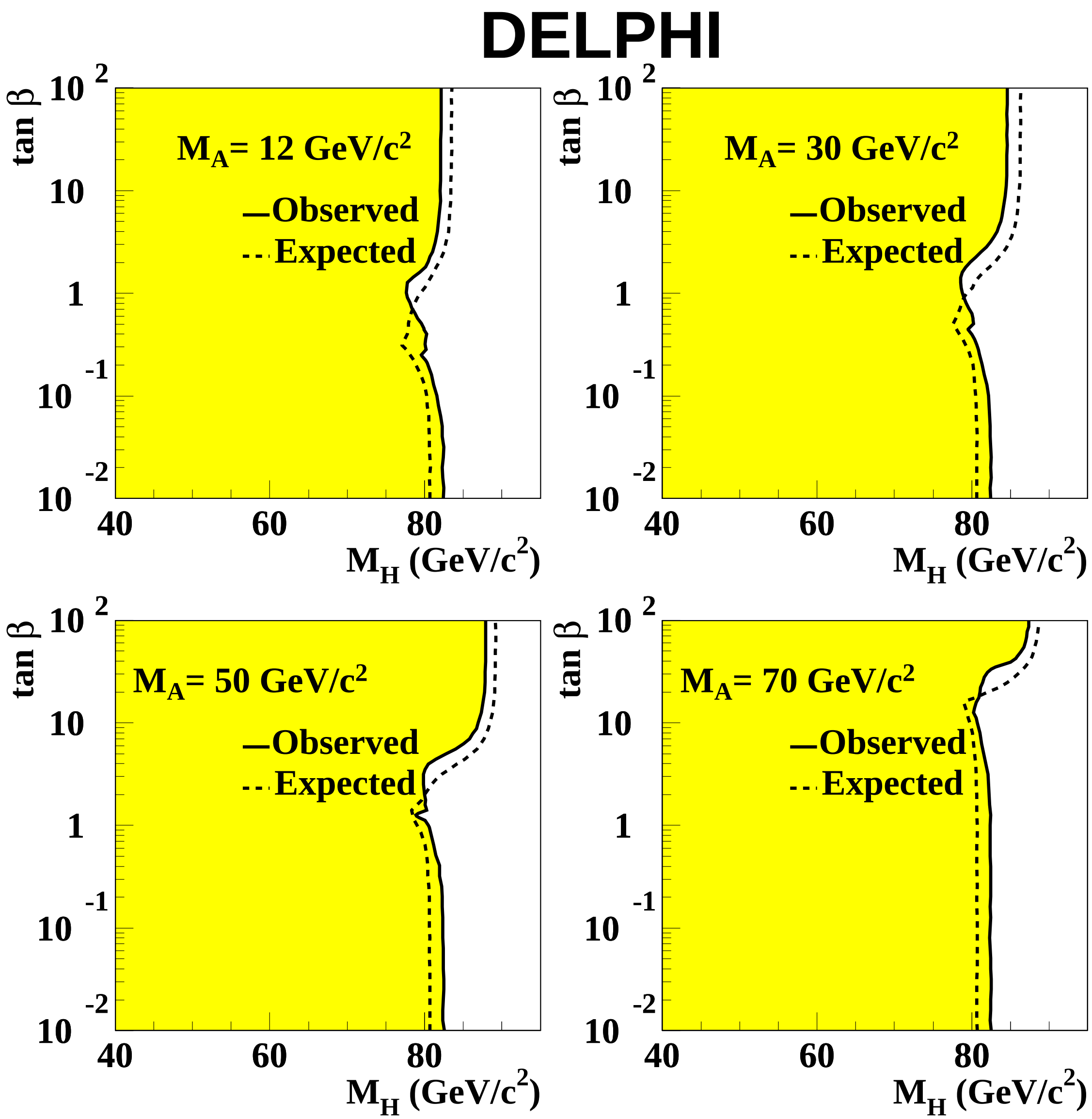


General 2-Higgs Doublet Model: $H^{\pm} \rightarrow W^{\pm}A$



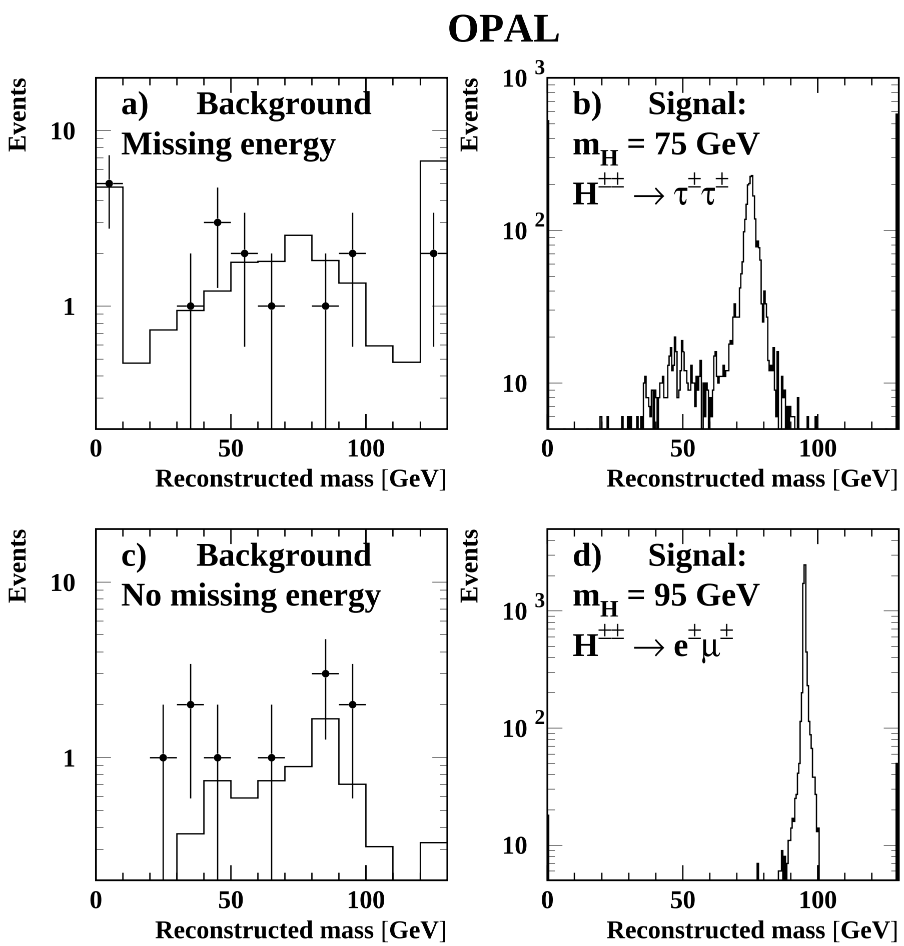


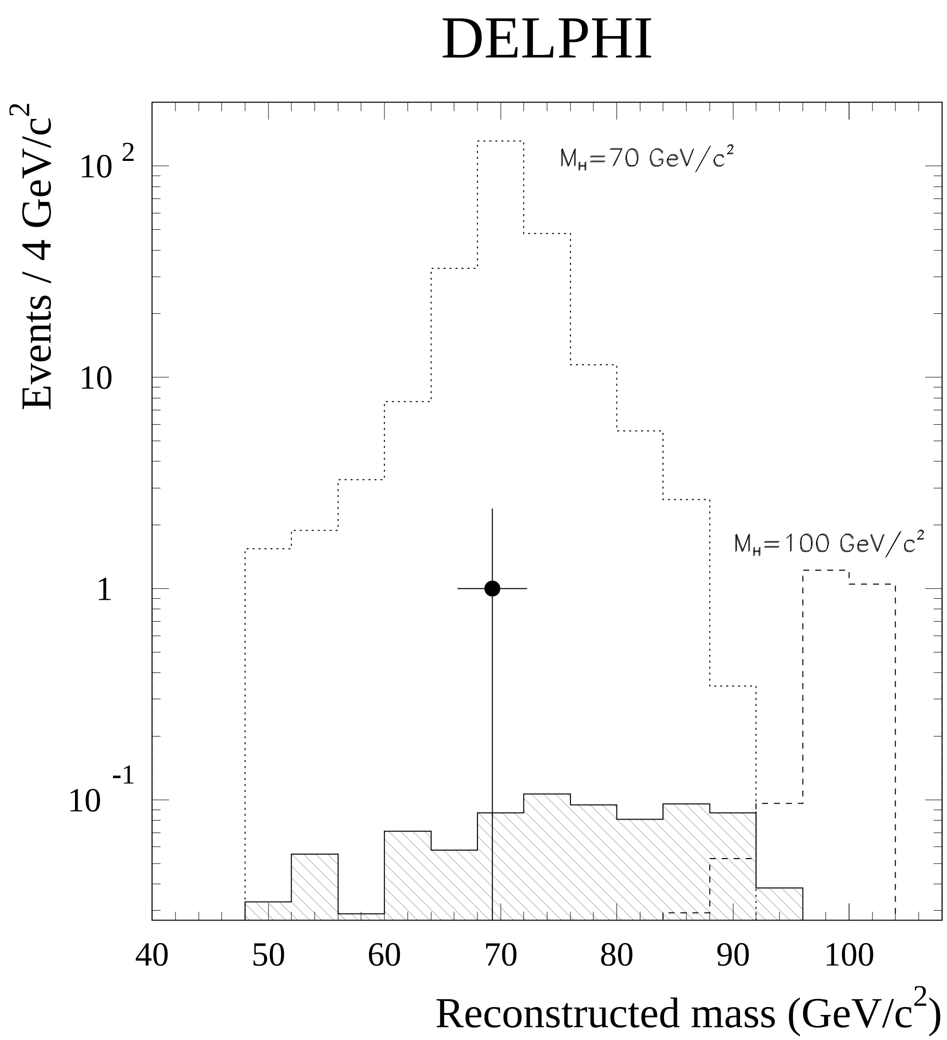
General 2-Higgs Doublet Model: $H^{\pm} \rightarrow W^{\pm}A$ Limits



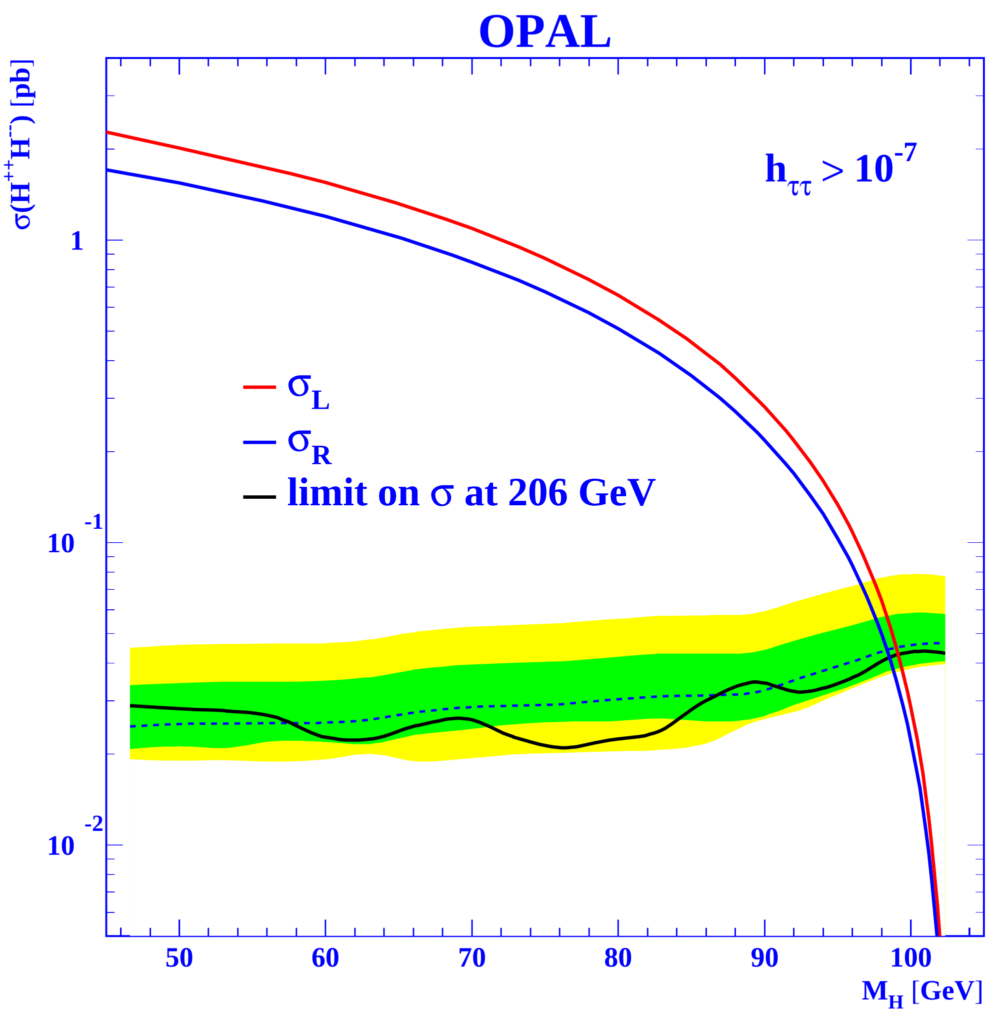
Doubly Charged Higgs Bosons: H^{++}

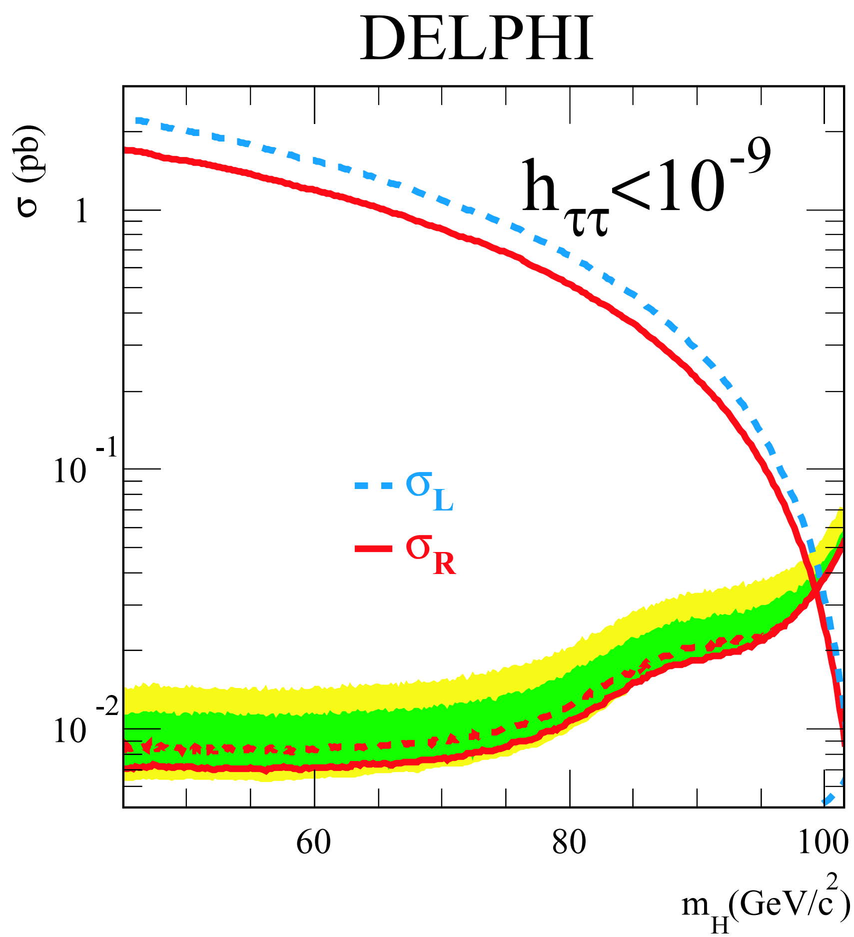
$e^+e^- \to H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$: Decay at interaction point ($h_{\tau\tau} \geq 10^{-7}$), secondary vertex signature, or stable massive particle.





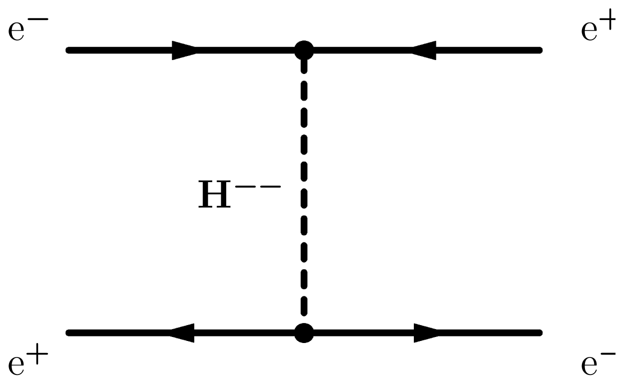
Doubly Charged Higgs Bosons: Mass Limits

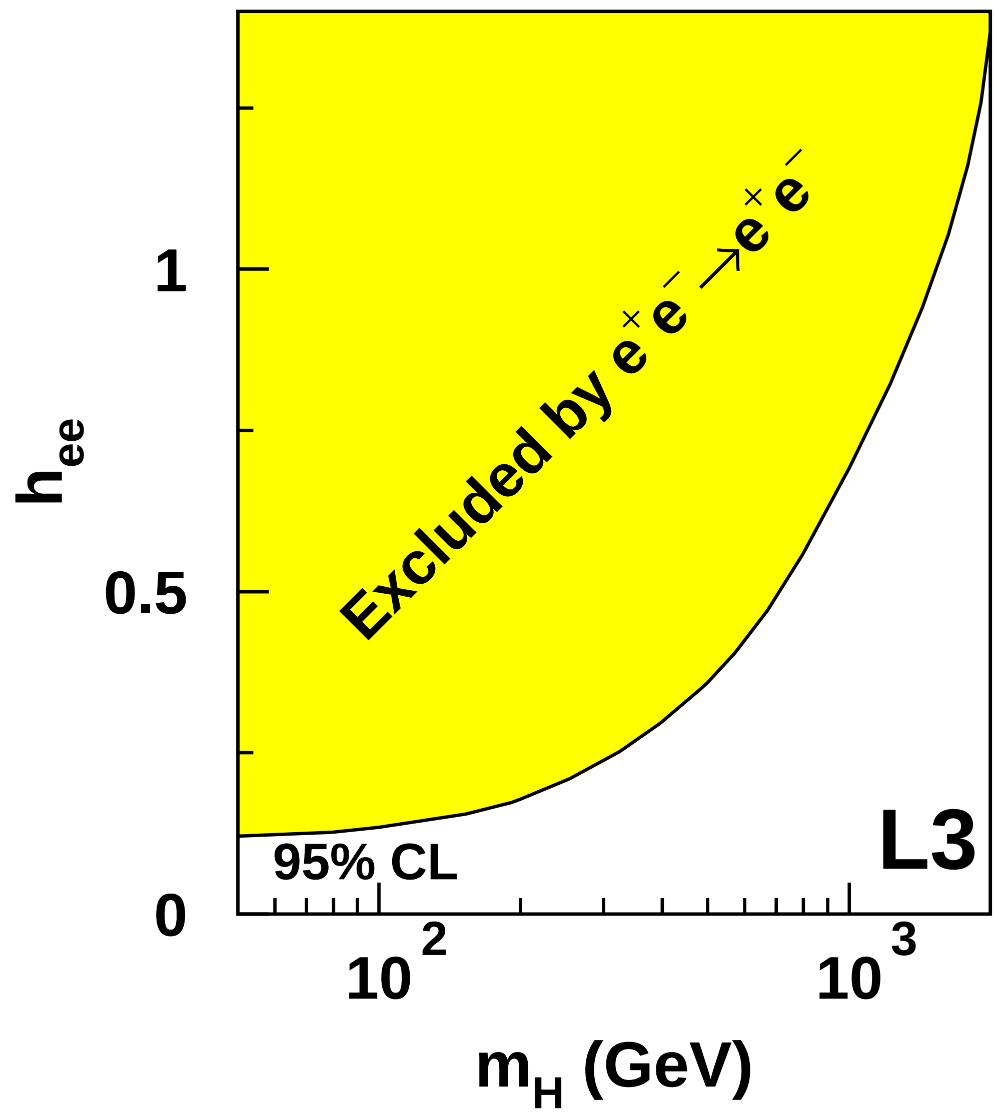




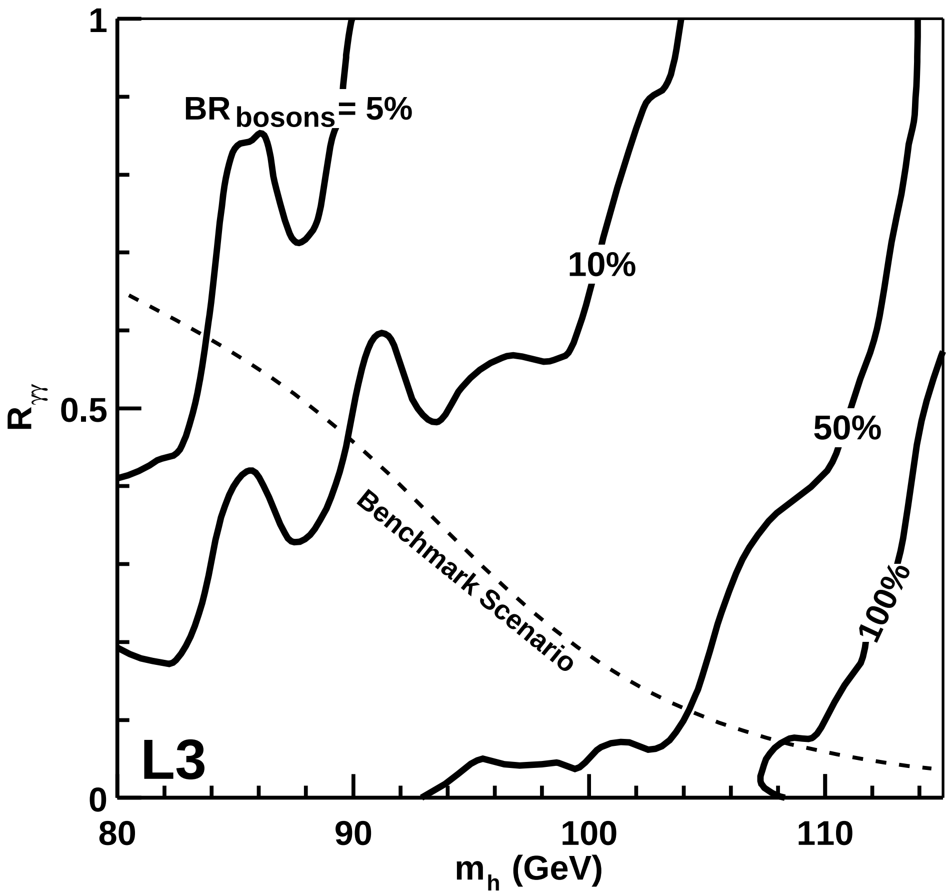
Doubly Charged Higgs Bosons: Mass Limits

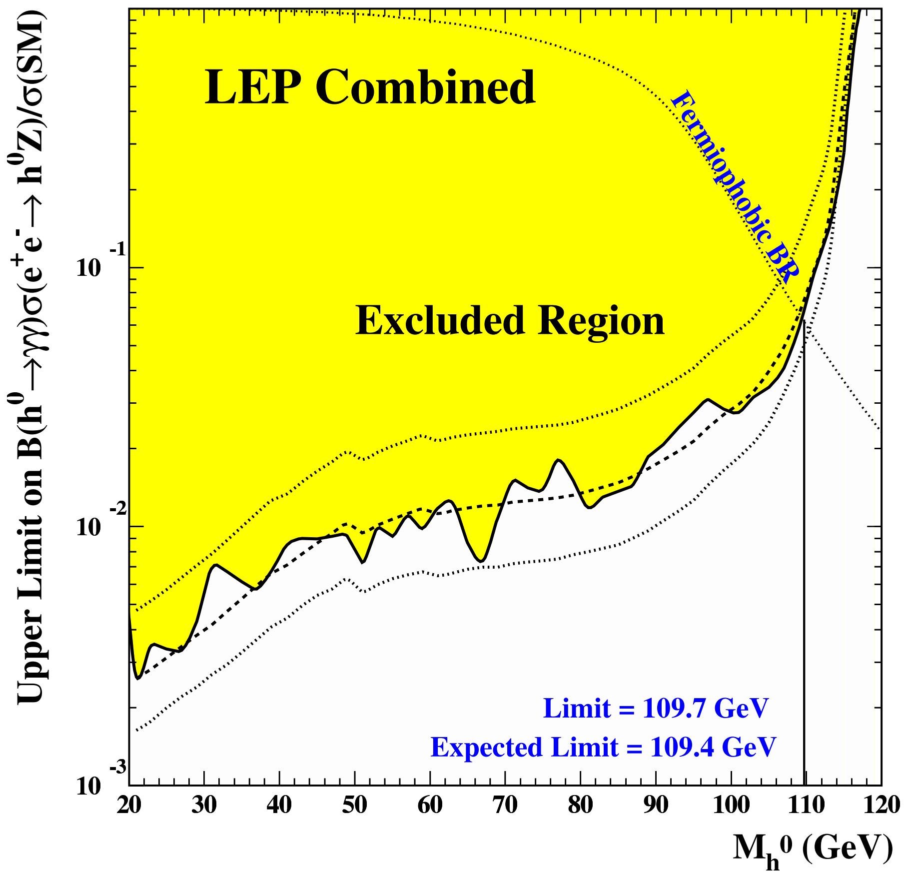
Cross section and forward-backward asymmetry of $e^+e^- \to e^+e^-$ limit H^{++}.





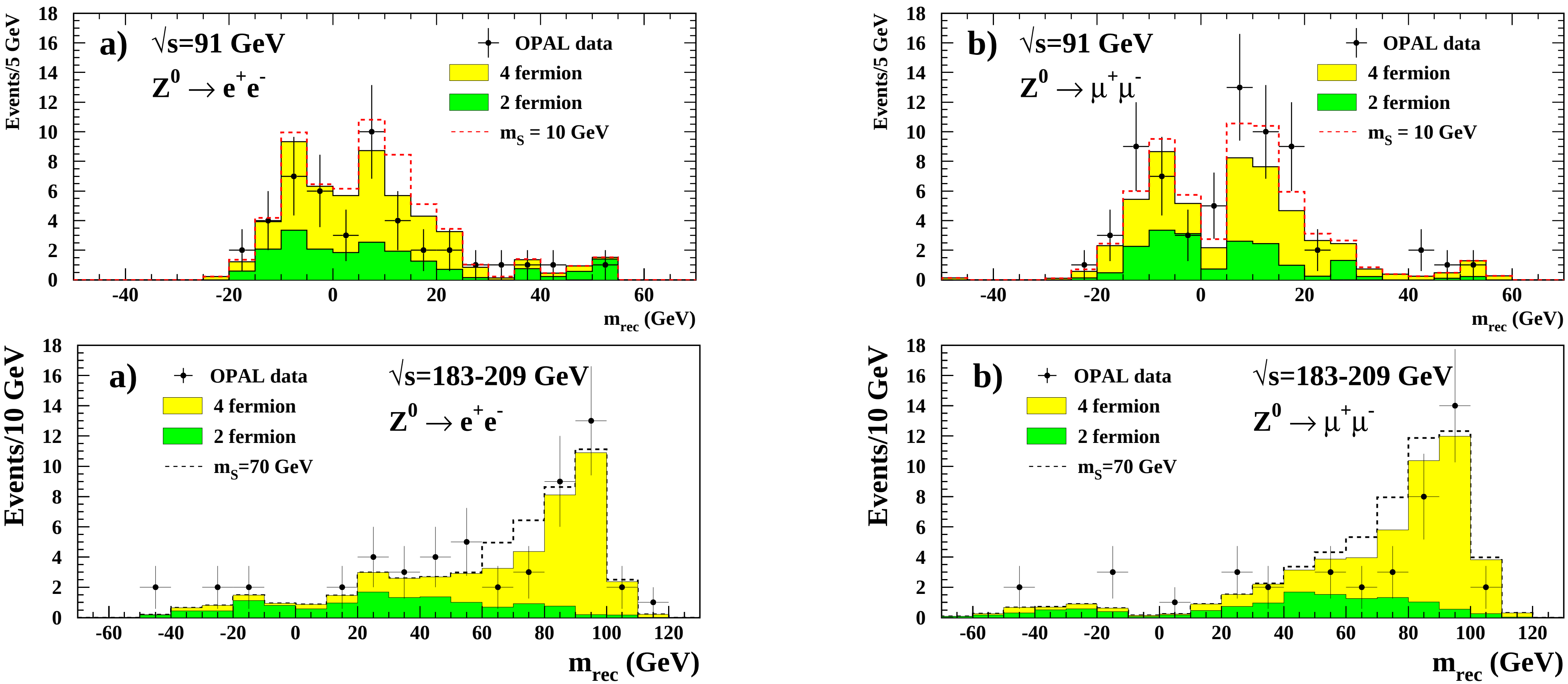
Fermiophobic Higgs Boson Decays: $h \to$ WW, ZZ, $\gamma\gamma$





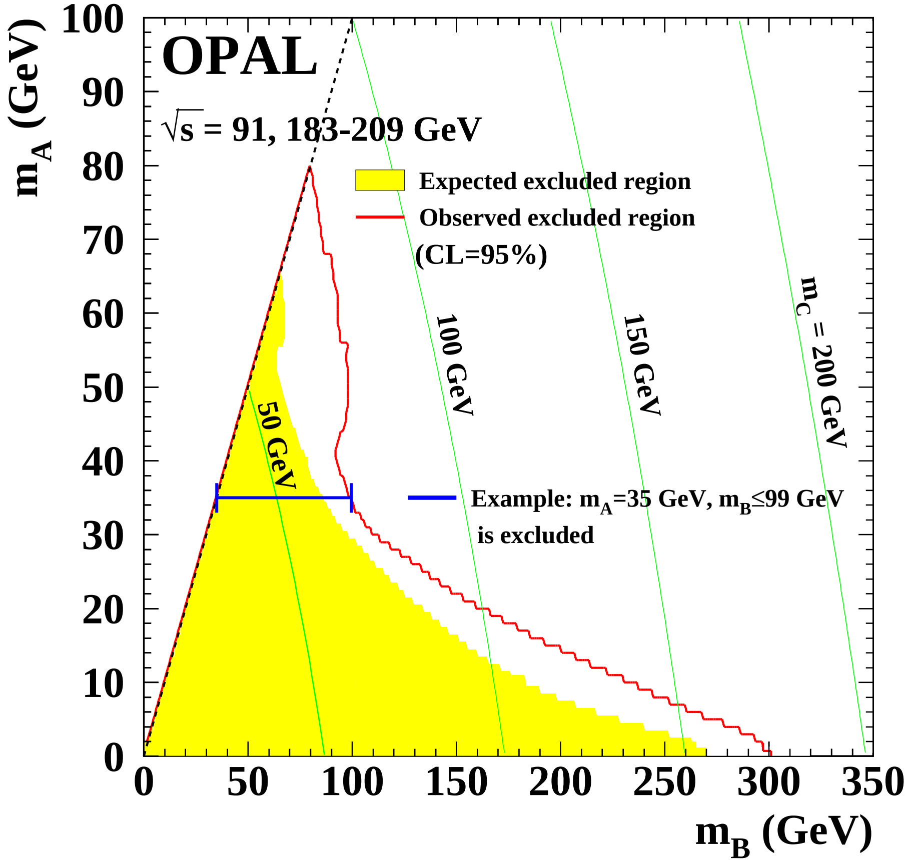
Uniform and Stealthy Higgs: Recoiling Mass

$e^+e^- \rightarrow S^0Z$. Independent of decay mode of S^0.



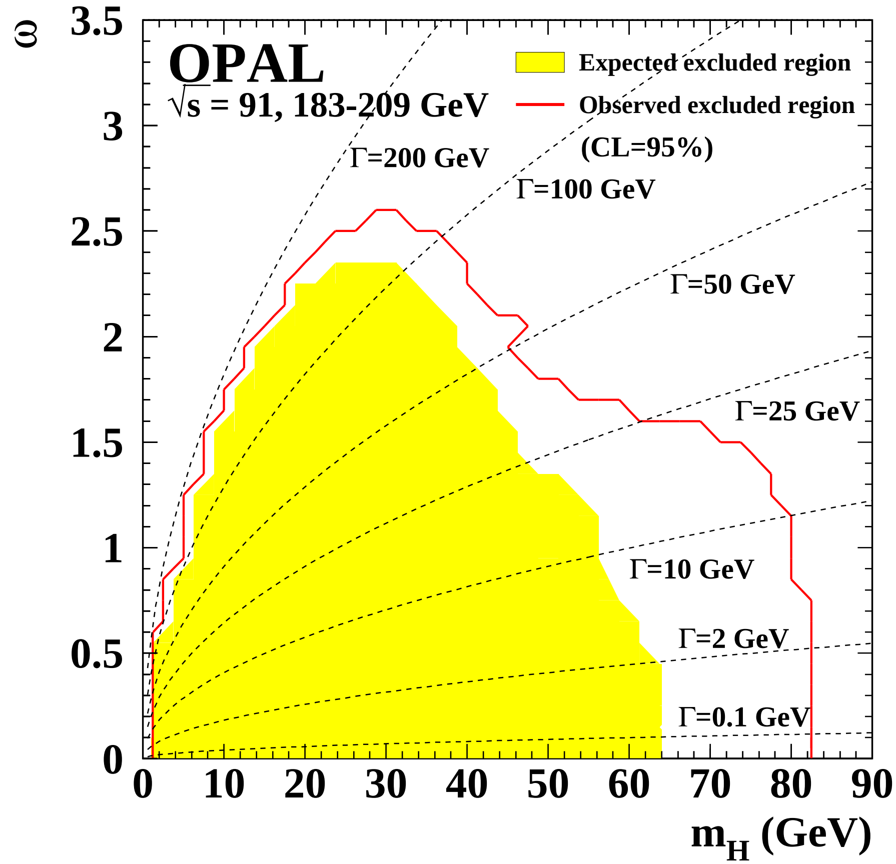
Uniform and Stealthy Higgs Scenarios: Limits

Uniform Higgs boson states in the mass range m_{A} to m_{B}. Espinosa, Gunion



Stealthy Higgs with large decay widths due to extra singlets ($N \gg 1$)

$\Gamma_{\mathrm{H}} = \Gamma_{\mathrm{SM}} + \frac{\omega^2 v^2}{32\pi m_{\mathrm{H}}}$ Binoth, van der Bij



LEP Summary-I

- LEP: Immense progress over 14 years.
- Small data excess at 99 and 116 GeV. Various stringent limits.
- Excellent collaboration: theory and LEP experimental groups.
- Much knowledge gained in preparation for new searches.

Search	Experiment	Limit (95% CL)
HZZ Coupling	LEP	$\xi^2 = 1 : m_{\rm H}^{\rm SM} > 114.4$ GeV
Reduced rate and SM decay		$\xi^2 > 0.05 : m_{\rm H} > 85$ GeV
Reduced rate and $\rm b\bar{b}$ decay		$\xi^2 > 0.04 : m_{\rm H} > 80$ GeV
Reduced rate and $\tau^+\tau^-$ decay		$\xi^2 > 0.2 : m_{\rm H} > 113$ GeV
Reduced rate and hadronic decay		$\xi^2 = 1 : m_{\rm H} > 112.9$ GeV
		$\xi^2 > 0.3 : m_{\rm H} > 97$ GeV
Anomalous couplings	L3	$d,\ d_B,\ \Delta g_1^{\rm Z},\ \Delta\kappa_\gamma$ exclusions
MSSM (no scalar top mixing)	LEP	almost entirely excluded
New top mass result		strongly reduced $\tan\beta$ limits
HZ production for large $\tan\beta$	L3	$97 < m_{\rm A} < 108$ GeV excluded

LEP Summary-II

General MSSM scan	DELPHI	$m_{\rm h} > 87$ GeV, $m_{\rm A} > 90$ GeV
CP-violating	OPAL	strongly reduced limits
Visible/invisible decays	DELPHI	$m_{\rm H} > 111.8$ GeV
Majoron model		max. mix.: $m_{\rm H,S} > 112.1$ GeV
Fl.-ind. had. decay($\sigma_{\rm max}$)	DELPHI	$\rm hA \rightarrow q\bar{q}q\bar{q}$: $m_{\rm h} + m_{\rm A} > 110$ GeV
2DHM	DELPHI	$\rm b\bar{b}b\bar{b}$: $m_{\rm h} + m_{\rm A} > 150$ GeV
(for $\sigma_{\rm max}$)		$\tau^+\tau^-\tau^+\tau^-$: $m_{\rm h} + m_{\rm A} > 160$ GeV
		$\rm (AA)A \rightarrow 6b$: $m_{\rm h} + m_{\rm A} > 150$ GeV
		$\rm (AA)Z \rightarrow 4b\ Z$: $m_{\rm h} > 90$ GeV
General 2DHM scan	OPAL	$\tan\beta > 1$: $m_{\rm h} \approx m_{\rm A} > 85$ GeV
Yukawa process	DELPHI	$C > 40$: $m_{\rm h,A} > 40$ GeV
Singly-charged Higgs	LEP	$m_{\rm H^\pm} > 78.6$ GeV
$\rm W^\pm A$ decay mode	DELPHI	$m_{\rm H^\pm} > 76.7$ GeV
Doubly-charged Higgs	DELPHI/OPAL	$h_{\tau\tau}$: $m_{\rm H^{++}} > 99$ GeV
$\rm e^+e^- \rightarrow e^+e^-$	L3	$h_{\rm ee} > 0.5$: $m_{\rm H^{++}} > 700$ GeV

Future Linear Collider Potential

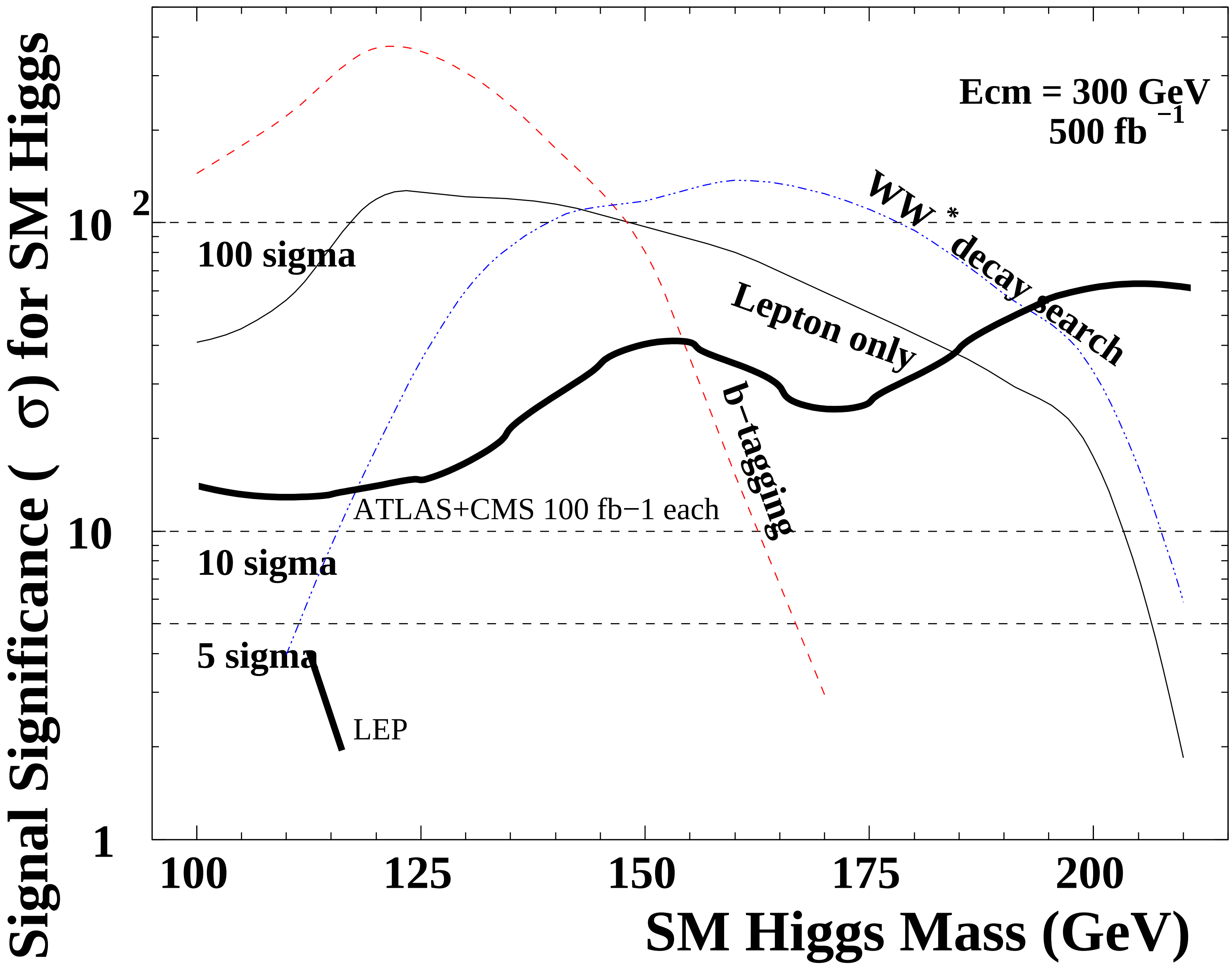
- Standard Model Physics
  - Higgs boson production mechanism
  - Direct branching ratio measurements
  - Characterization of the Higgs boson potential
  - Higgs boson strahlung from top quarks
- The General Two-Doublet Higgs Model
  - Charged Higgs bosons
  - Determination of the ratio of the VEV $\tan\beta$
- MSSM and beyond
  - Invisible Higgs boson decays
  - Higgs boson parity
  - Distinction of Higgs boson models

Natural Continuation of Successful e^+e^- Programme

- High luminosity linear e^+e^- collider of at least $\sqrt{s} = 500$ GeV: large potential to study Higgs bosons and understand electroweak symmetry-breaking and mass generation.
- LEP: immense progress for Higgs boson searches, almost background free LEP-1, sensitivity beyond expectations LEP-2.
- 12 years of Linear Collider Higgs studies: from discovery to precision measurements.
- Close to decoupling limit (MSSM→SM), LC precision studies are essential. (Haber, LCWS Paris 2004)
- Intense-coupling regime: More complex, $m_A \approx m_h$ and large $\tan\beta$. Large Higgs boson widths. In some cases significantly different branching fractions cf. SM. (Boos, Djouadi, Mühlleitner, Vologdin, LCWS Paris 2004)
- Recent milestones: Snowmass 2001, Korea LCWS 2002, Paris LCWS 2004.

SM Higgs Significance

$e^+e^- \rightarrow Z \rightarrow HZ$ Yamashita et.al., hep-ph/0109166 (LEP Higgs Working Group, July 2002 F.Gianotti et.al, LHCC, July 2000)



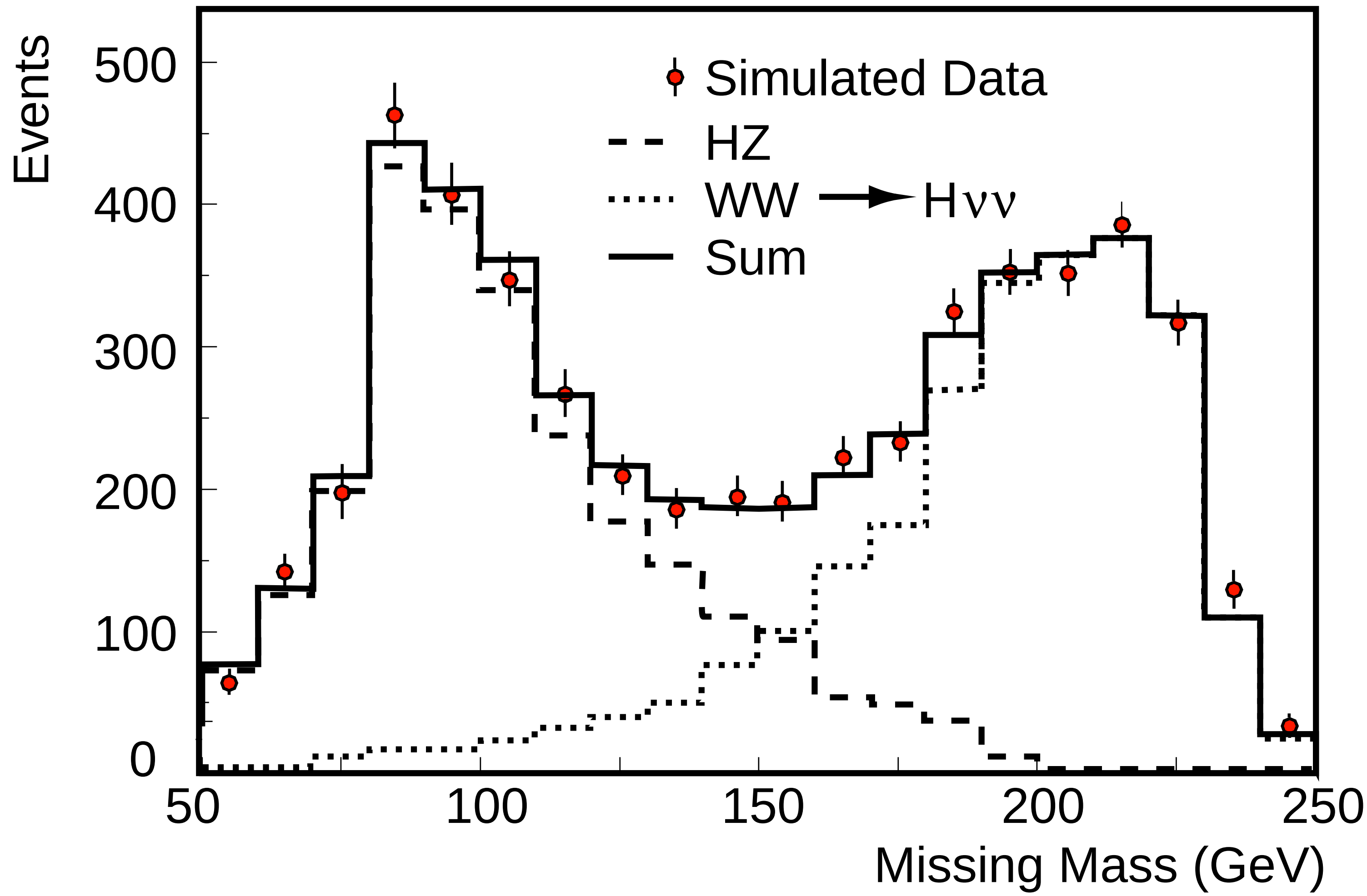
Very high sensitivity at a LC, and extended mass reach at the LHC.

Higgs Boson Strahlung/Fusion

$e^+e^- \rightarrow ZH \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b}$

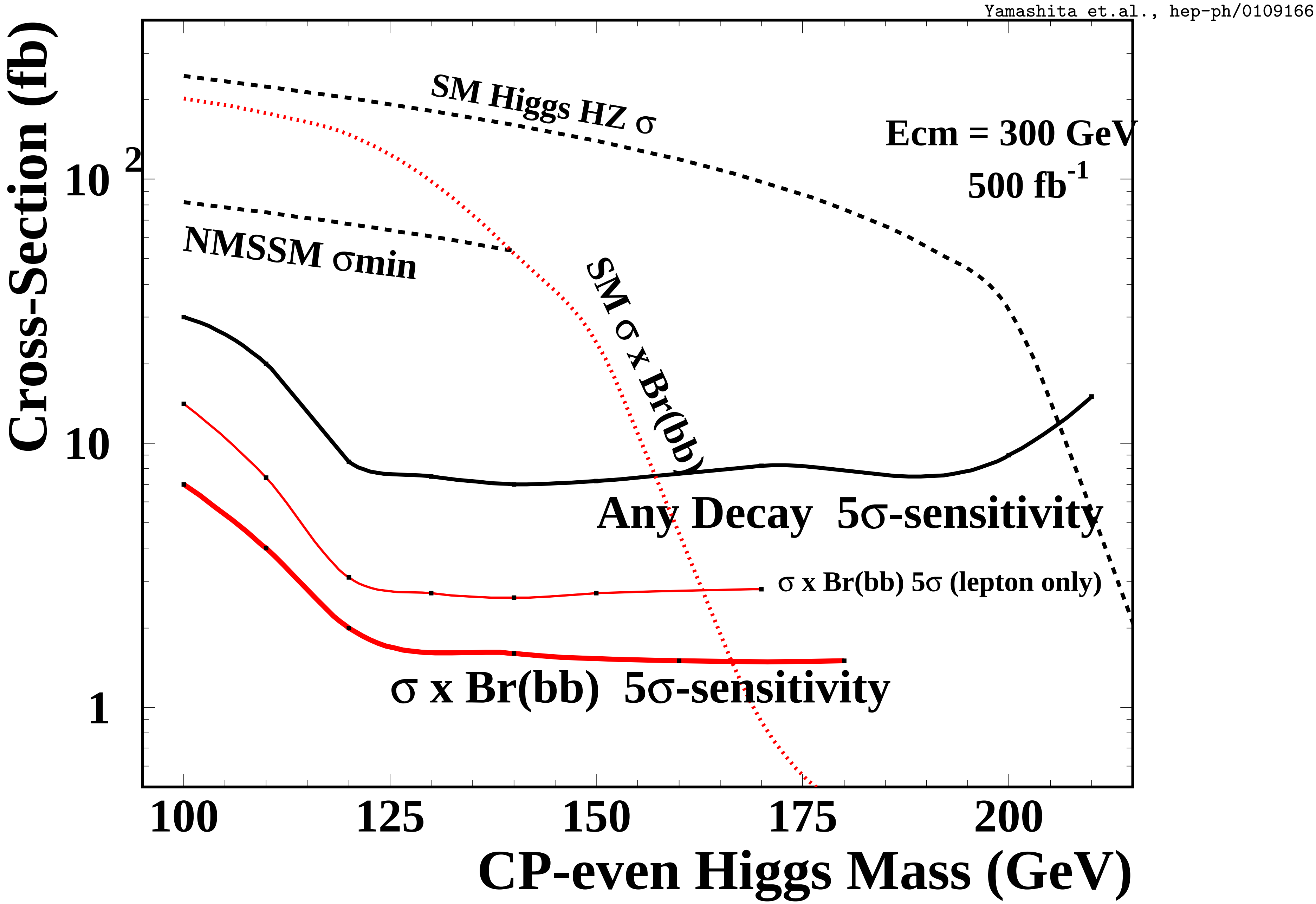
$e^+e^- \rightarrow W^+W^-\nu\bar{\nu} \rightarrow \nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b}$

Van Kooten, LCWS, Baltimore, March 2001



Detailed determination of Higgs boson production mechanism.

General Cross Section Sensitivity



SM Decay Branching Ratios

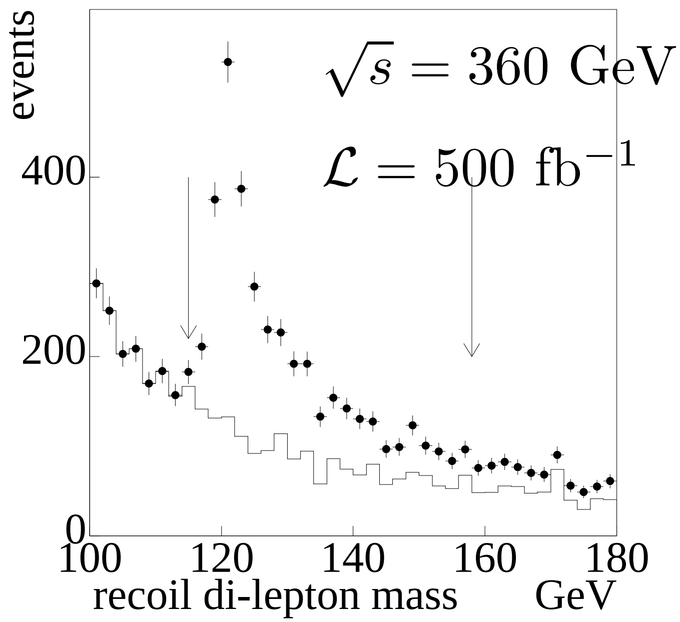
$e^+e^- \to HZ \to H\nu\nu$ direct $BR(H \to X)$ determination: Barklow, LCWS Paris 2004

m_H (GeV)	120	140	160	200
$\Delta BR/BR_{b\bar{b}}(\%)$	1.6	1.8	2.0	9.0

$e^+e^- \to HZ \to H\ell^+\ell^-$ direct $BR(H \to X)$ determination: Brient, LC-PHSM-2002-003

Selection of a HZ sample $Z \to \ell^+\ell^-$, where $m_H = m^{recoil}_{\ell^+\ell^-}$.

Selection in this sample of individual Higgs decay modes.



Decays mode	SM branching ratio(%)	$\Delta BR/BR(\%)$
bb	68	1.5
$\tau\tau$	6.9	4.1
cc	3.1	5.8*
gluons	7.0	3.6
$\gamma\gamma$	0.22	21
WW*	13	2.7

* 12.1% with new c-tagging simulation. Kuhl, LCWS Paris 2004

Complementarity with LHC, higher precision and all decay modes. Test: $g_{Hff} \propto m_f$

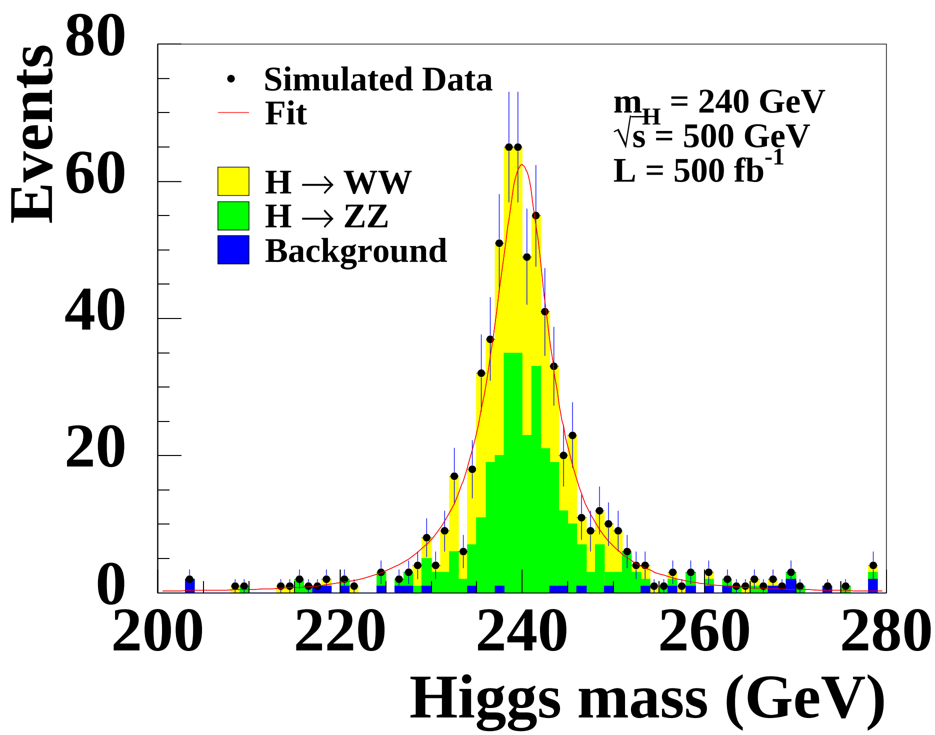
SM Higgs Mass and Decay Width

4C and 5C fits: $m_{\mathrm{H}} = 120 \pm 0.04$ GeV. Need $\delta E/E_{\mathrm{beam}} < 10^{-4}$. Raspereza, LCWS Paris 2004

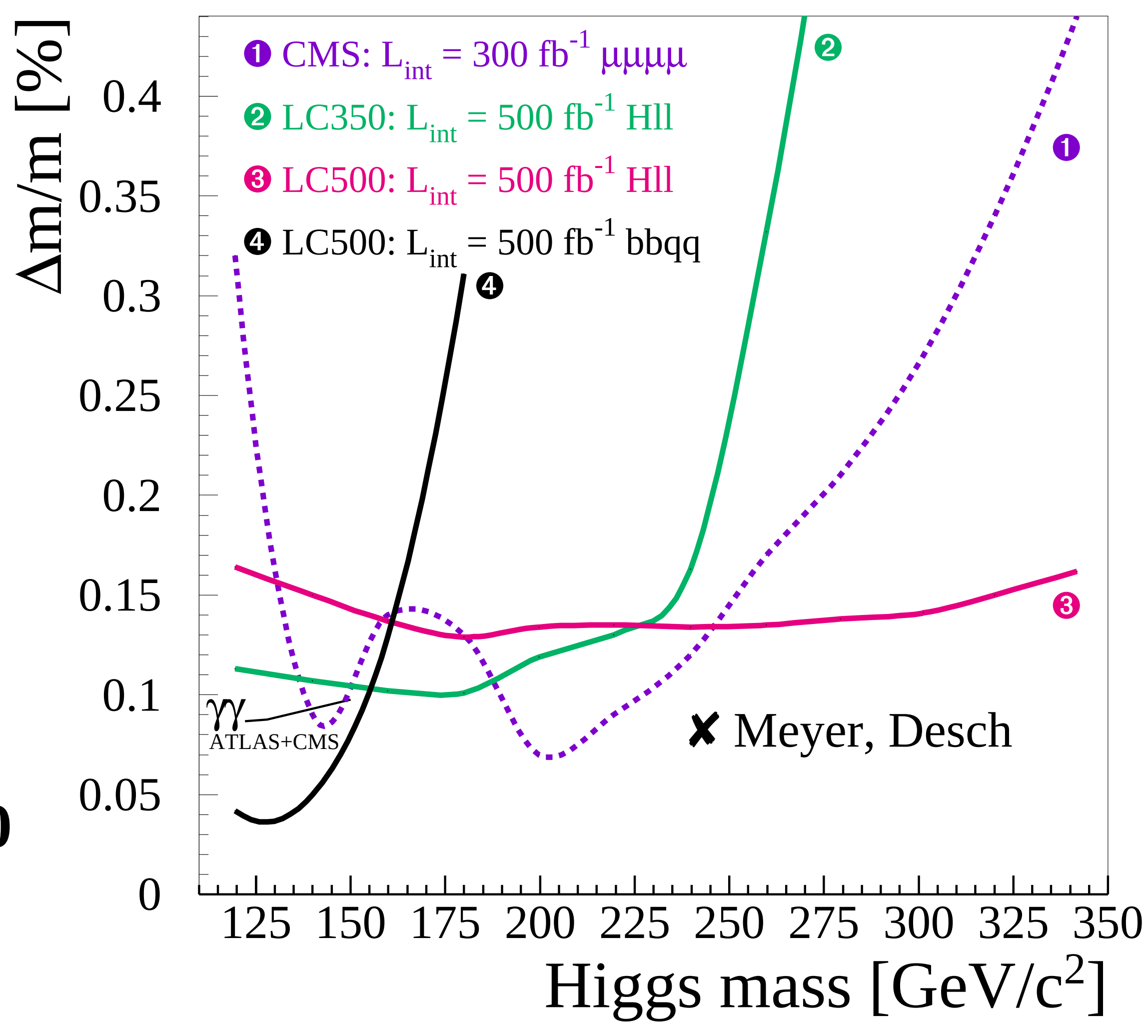
$e^+e^- \rightarrow \mathrm{HZ} \rightarrow \mathrm{WWZ}$

$e^+e^- \rightarrow \mathrm{HZ} \rightarrow \mathrm{ZZZ}$

Meyer, Desch, LCWS St.Malo, March 2002



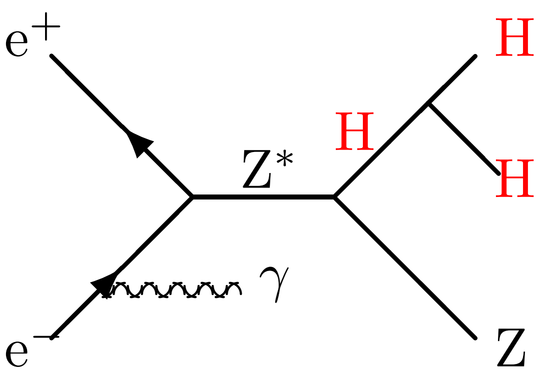
Drollinger, Sopczak, EPJdirect **C-N1** (2001) 1



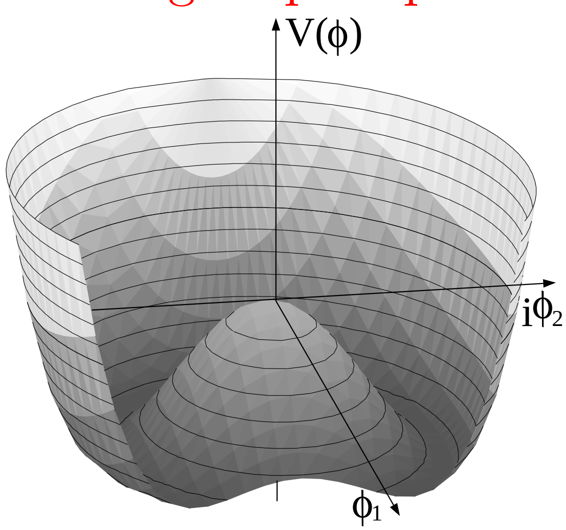
$\Delta m_{\mathrm{H}}/m_{\mathrm{H}} = 0.08\%$, $\Delta\Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}} = 11\%$

SM Higgs Boson Potential

$e^+e^- \to HZ \to HHZ$:



Probing shape of potential

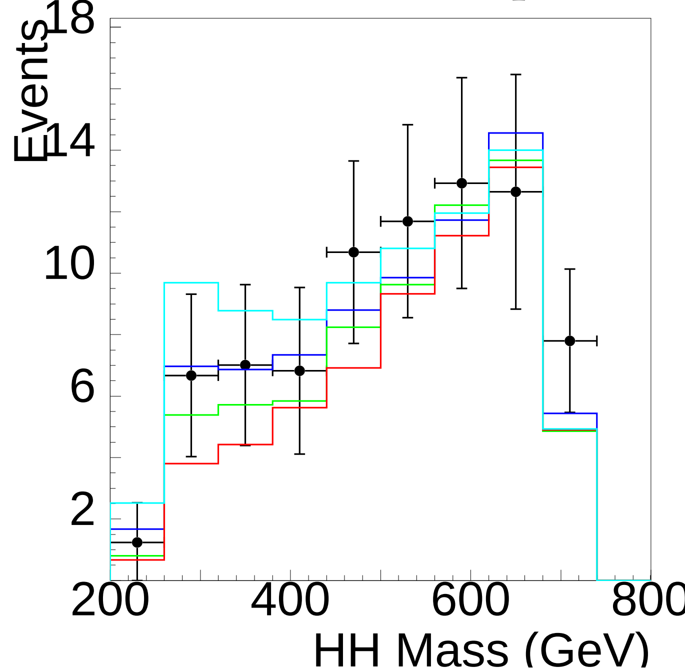


$g_{\mathrm{HHH}} = 3m_H^2/2v.$

Battaglia, Boos, Yao, hep-ph/0111276

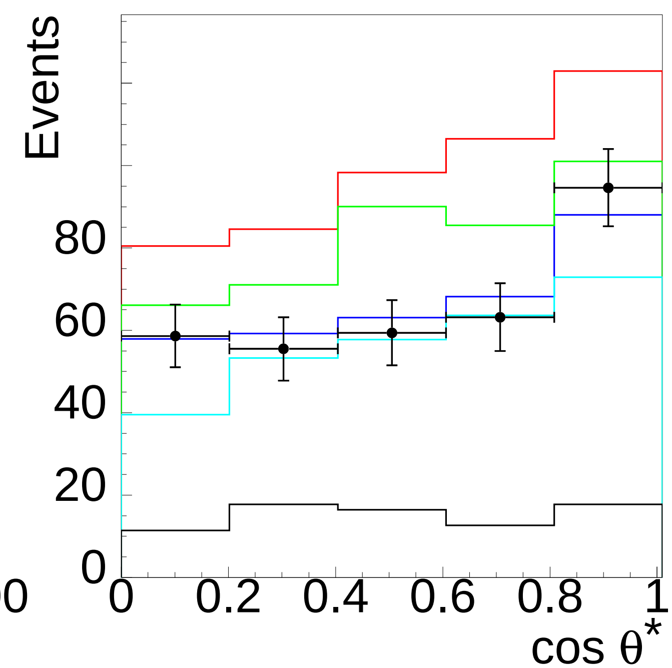
$\sqrt{s}$=800 GeV $\mathcal{L}$=1000 fb^{-1}

invariant mass of HH pair



$\sqrt{s}$=3 TeV $\mathcal{L}$=5000 fb^{-1}

angle between H and HH



Lines $g_{\mathrm{HHH}}/g^{\mathrm{SM}}_{\mathrm{HHH}} = 1.25,\ 1.00,\ 0.75,\ 0.50$

Sensitivity $\Delta g/g = 29\%$

Sensitivity $\Delta g/g = 7\%$

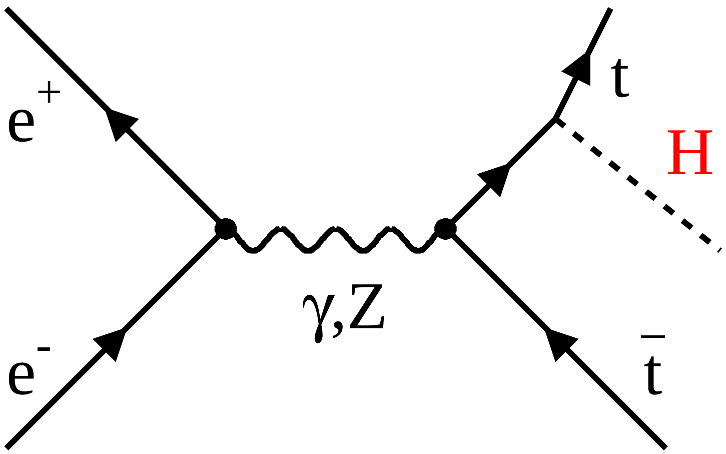
SM Higgsstrahlung ttH

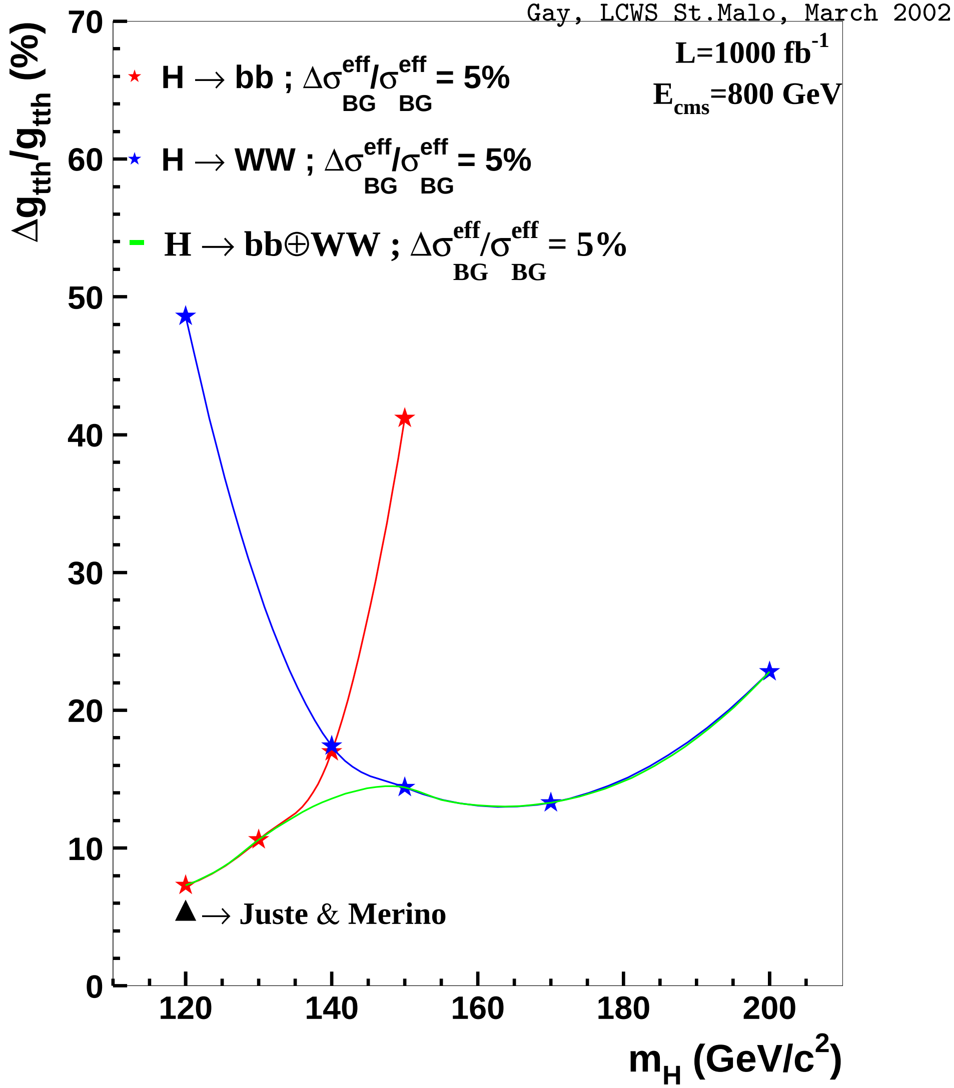
$e^+e^- \rightarrow t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

$e^+e^- \rightarrow t\bar{t}H \rightarrow t\bar{t}W^+W^-$

Challenge:

5% precision on the background.





$\Delta g_{\mathrm{ttH}}/g_{\mathrm{ttH}} = 5$ to 20%

Similar sensitivity achieved in a new analysis. Yamashita, LCWS Paris 2004

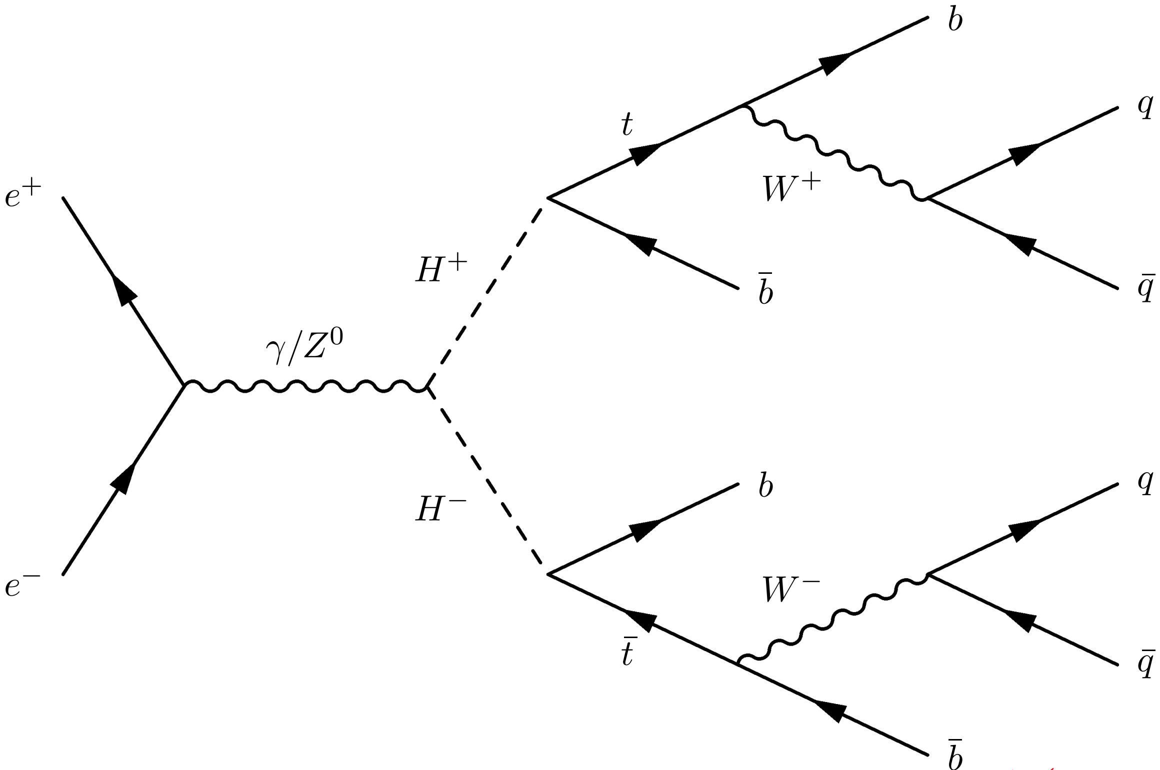
6-fermion background: small effect. H → ZZ under study. Gay, Besson, Winter, LCWS Paris 2004

2DHM Charged Higgs Bosons

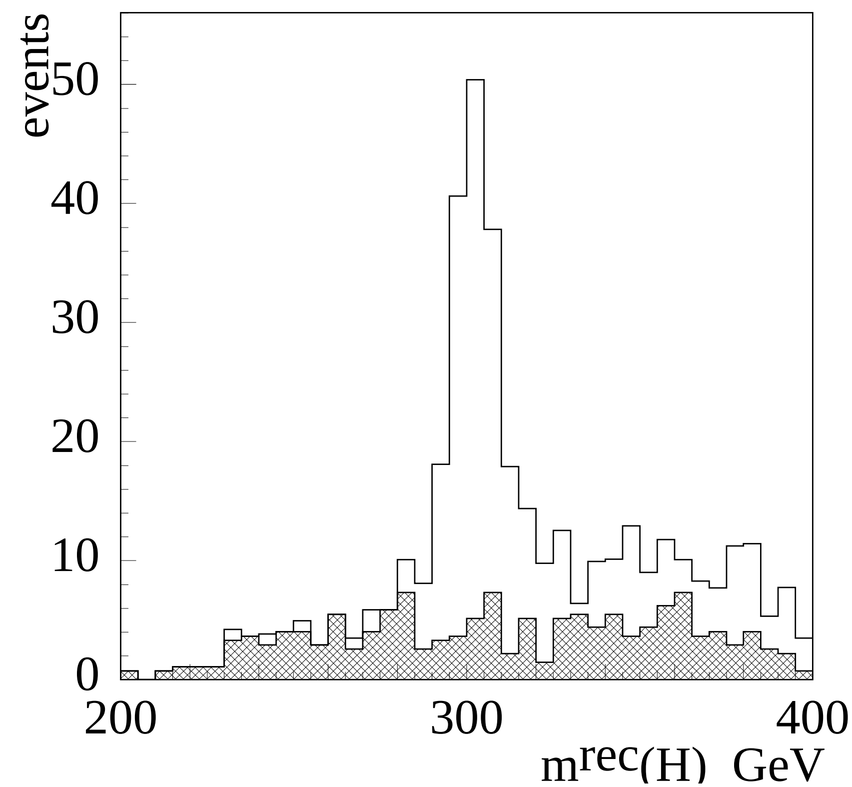
$e^+e^- \to Z \to H^+H^- \to t\bar{b}\bar{t}b$

Battaglia, Ferrari, Kiiskinen, hep-ph/0112015

Detailed reconstruction of the entire decay chain.



$\sqrt{s} = 800$ GeV and $\mathcal{L} = 1000$ fb^{-1}

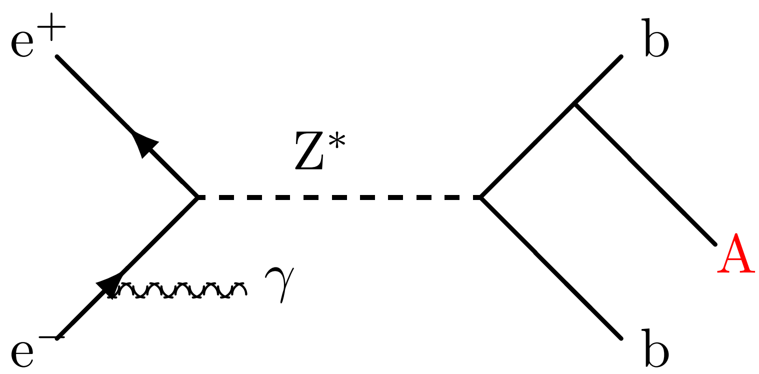


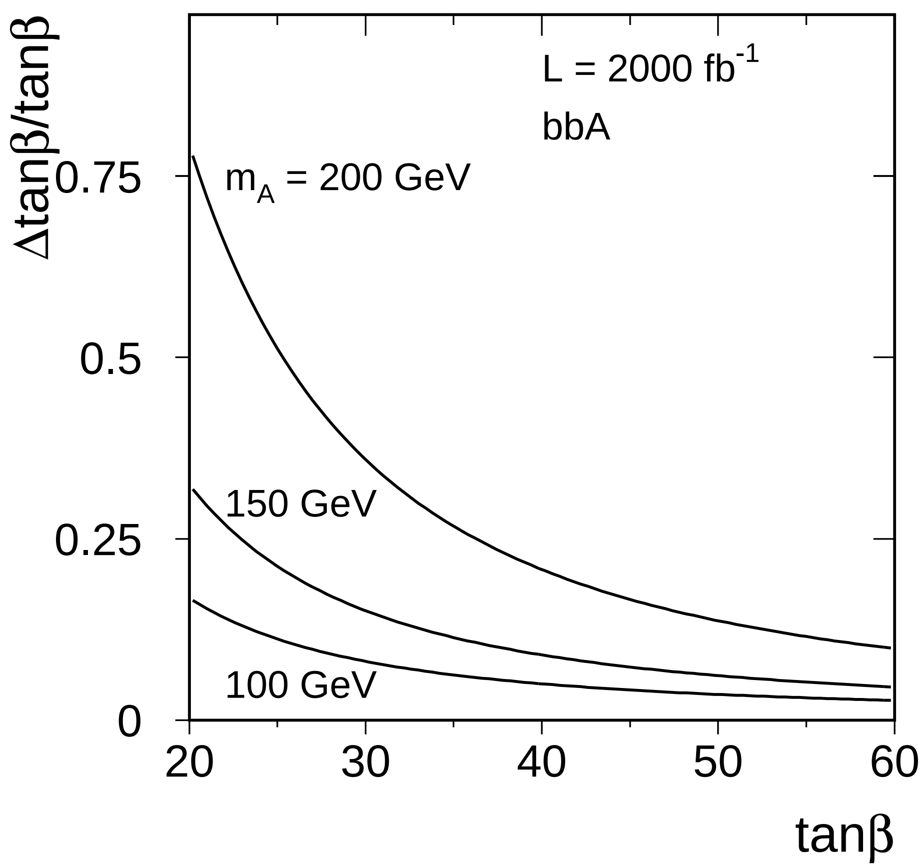
$\Delta(\sigma BR(H^+ \to t\bar{b}))/\sigma BR(H^+ \to t\bar{b}) = 8.8\%$

2DHM Higgsstrahlung bbA

Gunion, Han, Jiang, Sopczak, PLB 2003

$e^+e^- \to b\bar{b} \to b\bar{b}A \to b\bar{b}b\bar{b}$





Measure $\tan\beta \equiv \mathrm{VEV}_1/\mathrm{VEV}_2$

1) bbA rate $\propto g^2_{\mathrm{bbA}} \propto \tan^2\beta$

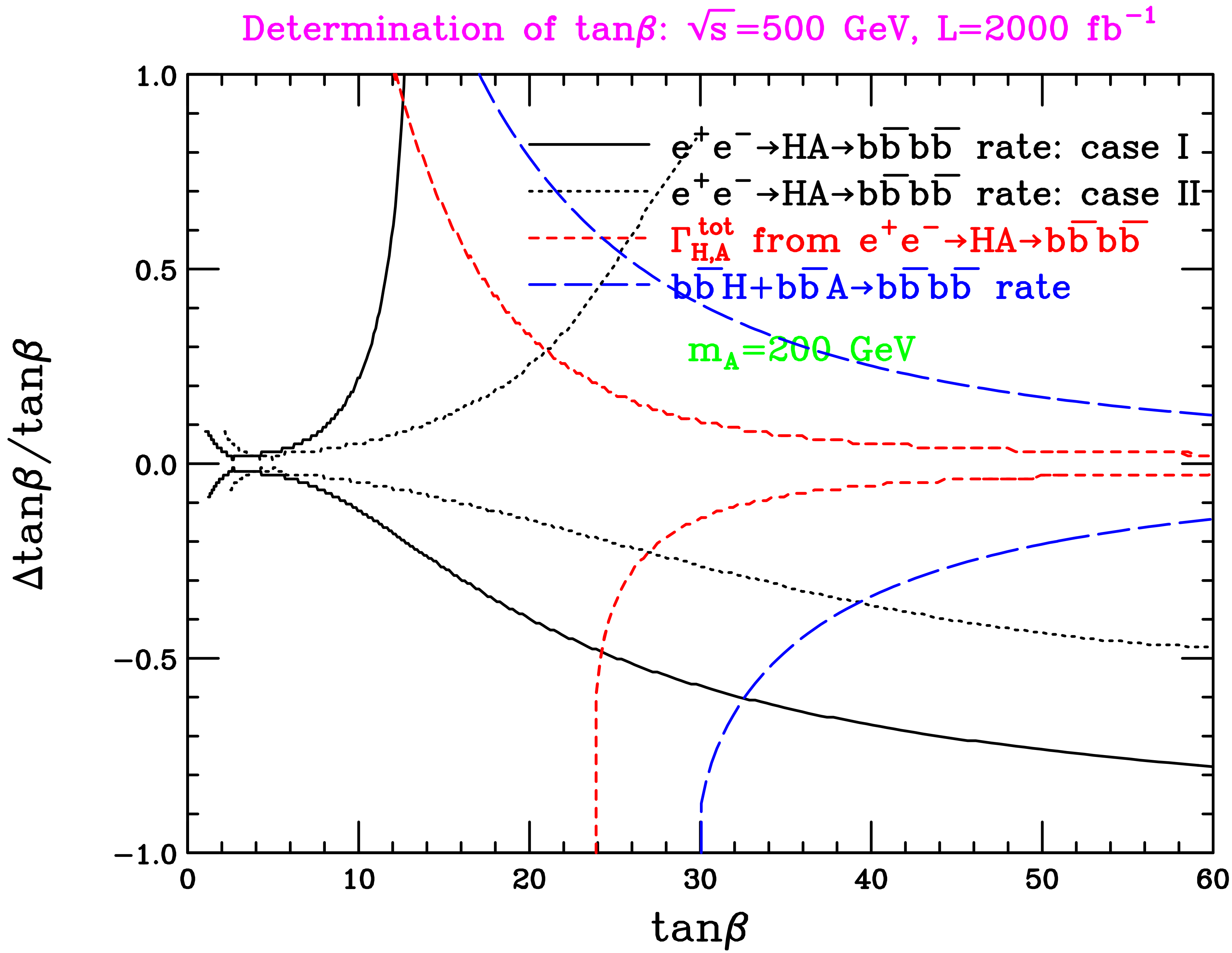
Further methods:

2) $e^+e^- \to \mathrm{HA} \to b\bar{b}b\bar{b}$ rate

3) H,A decay width

4) H^+ decay width

MSSM Higgsstrahlung bbH

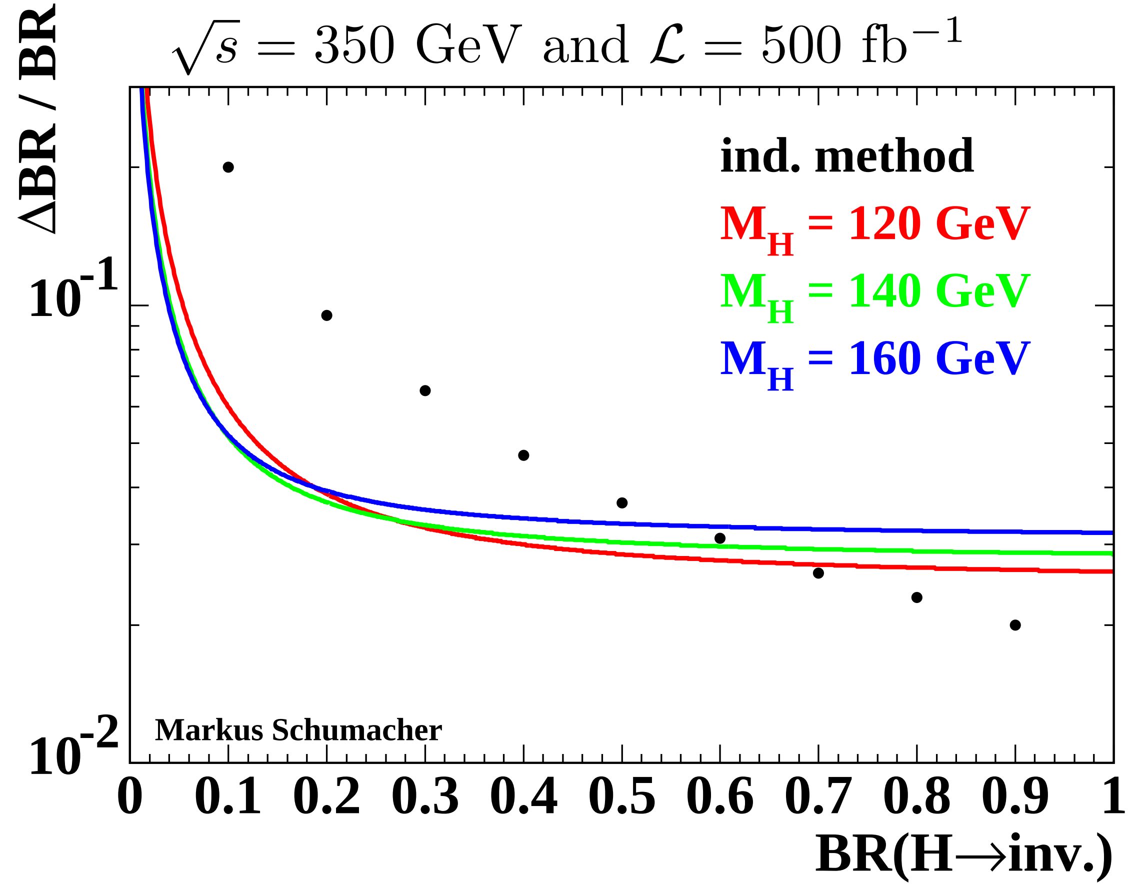


MSSM Invisible Higgs Boson Decays

$e^+e^- \rightarrow ZH \rightarrow Z\tilde{\chi}^0\tilde{\chi}^0$: $m_H = m_Z^{recoil}$ Schumacher, LCWS, Cracow, Sep. 2001

LEP: All Z decay modes, here first $Z \rightarrow q\bar{q}$.

Higher sensitivity cf. indirect method (1− sum of visible H decay modes).



$\Delta BR/BR < 4\%$ for $BR(\mathrm{H} \rightarrow \mathrm{inv.}) > 20\%$ and SM production rate.

Higgs Boson Parity

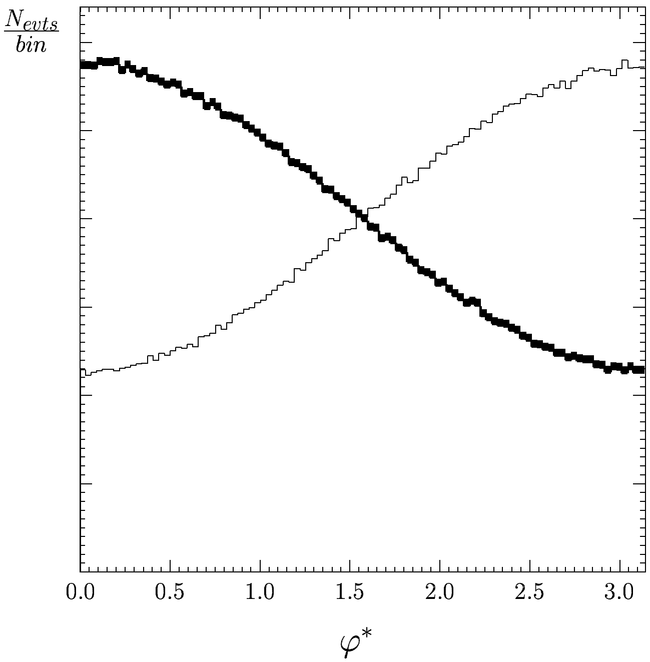
H: CP-even

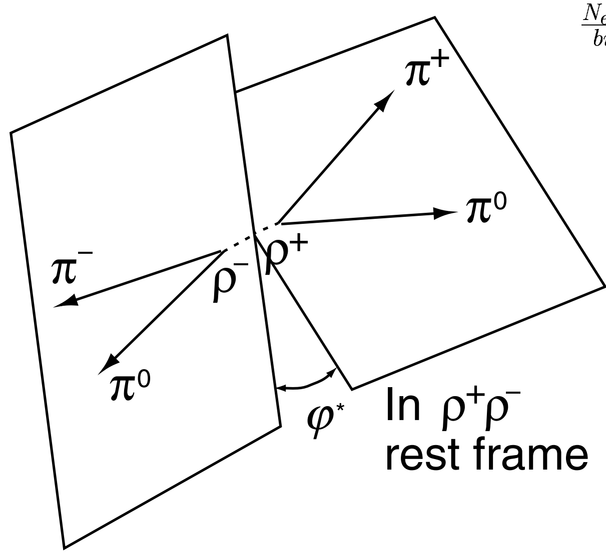
A: CP-odd

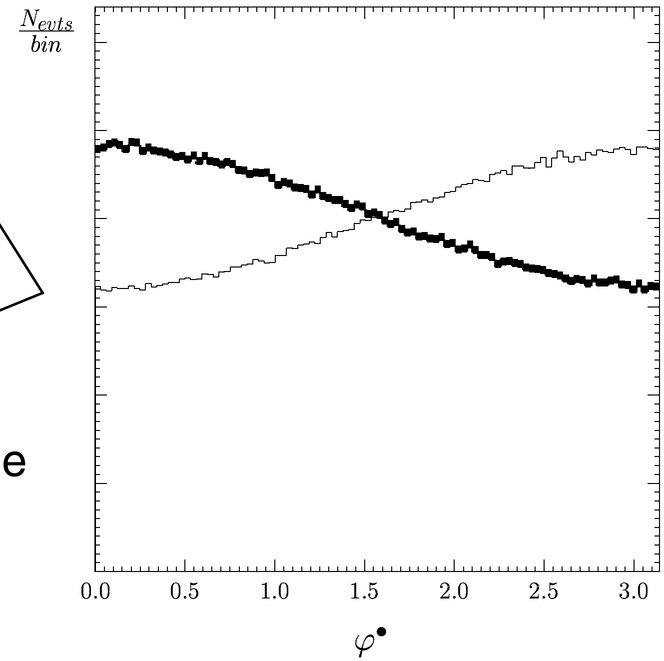
$$H/A \rightarrow \tau^+\tau^- \rightarrow \rho^+\bar{\nu}_\tau\rho^-\nu_\tau \rightarrow \pi^+\pi^0\bar{\nu}_\tau\pi^-\pi^0\nu_\tau$$

Bower, Pierzchal, Wąs, Worek, hep-ph/0204292

$\rho^+\rho^-$ acoplanarity angle before and after detector simulation





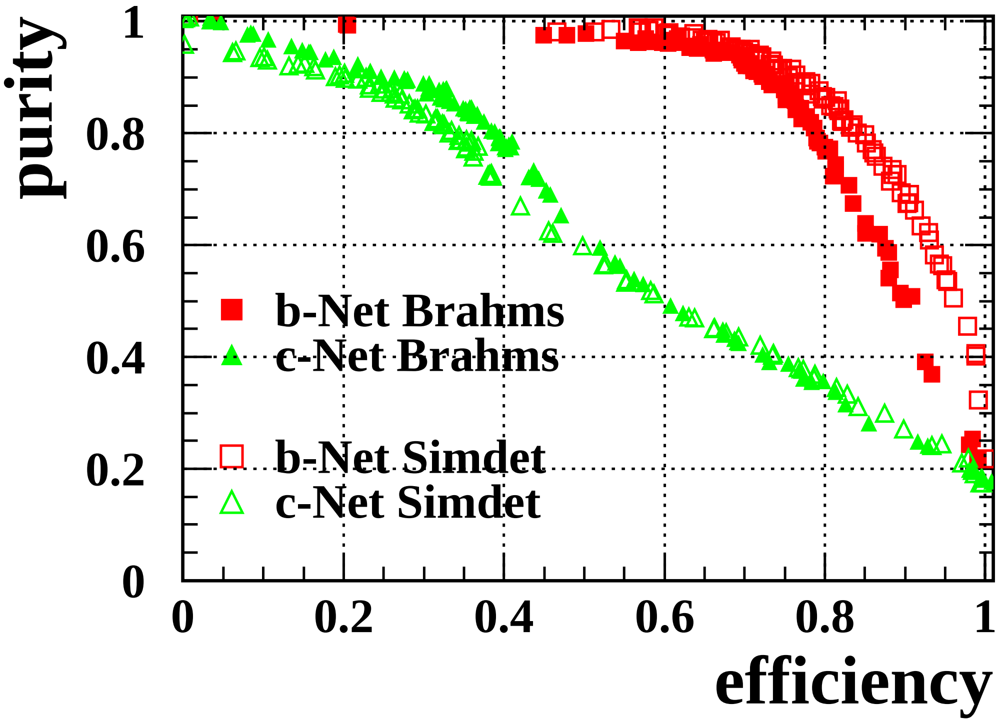


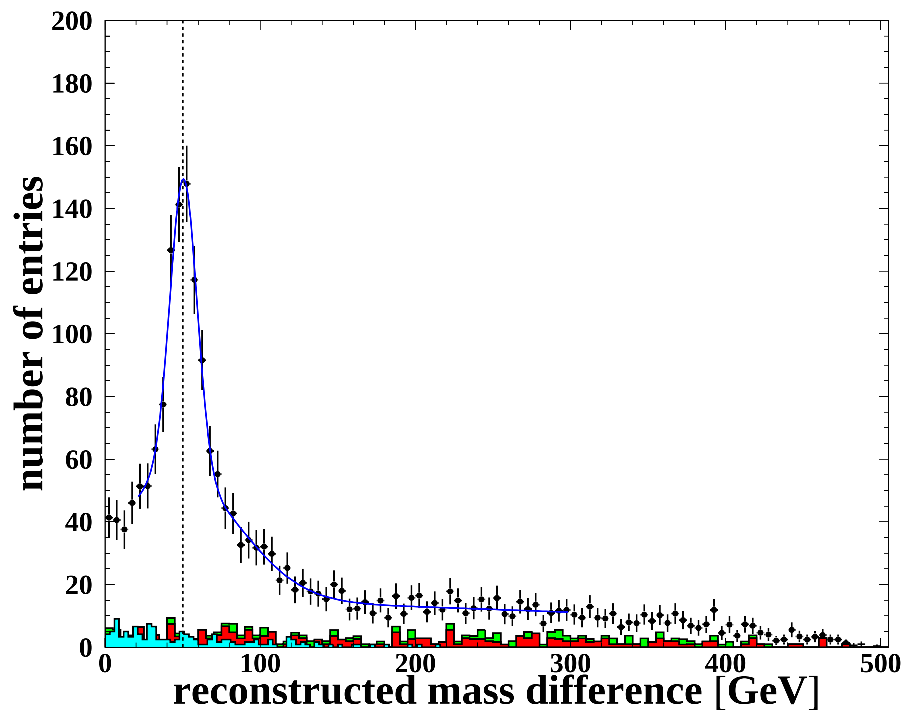
Difference between scalar (thick line) and pseusoscalar (thin line) Higgs bosons can be determined.

MSSM Higgs Boson Masses

- h: $\Delta m_{\mathrm{exp}} \approx 0.05$ GeV difficult to match in theoretical prediction
  $\Delta m_{\mathrm{th}} \approx 3$ GeV and $\Delta m_{\mathrm{th}}^{\mathrm{future}} \approx 0.5$ GeV Heinemeyer, LCWS Paris 2004

b-tagging and HA $\rightarrow \mathrm{b\bar{b}b\bar{b}}$ at $\sqrt{s} = 800$ GeV. Desch, Klimkovish, Kuhl, Raspereza, LC-PHSM-2004-006



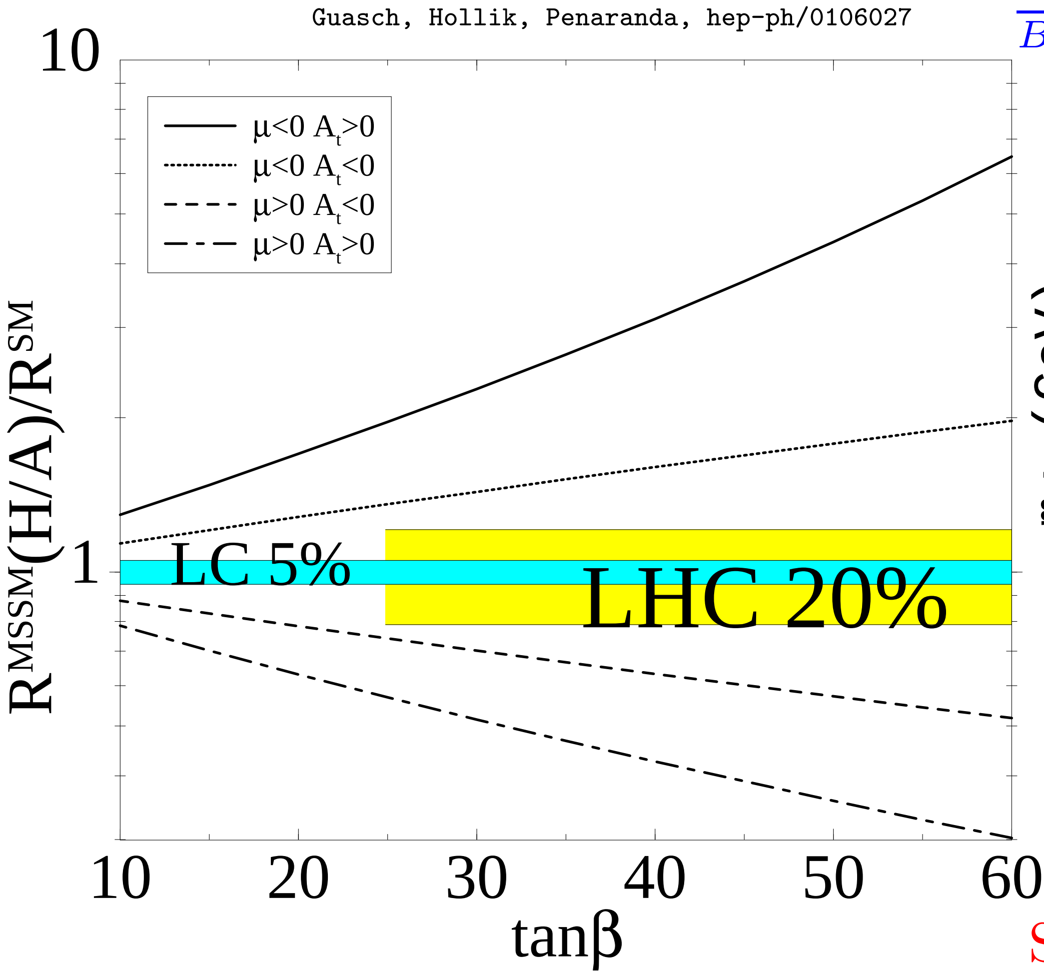


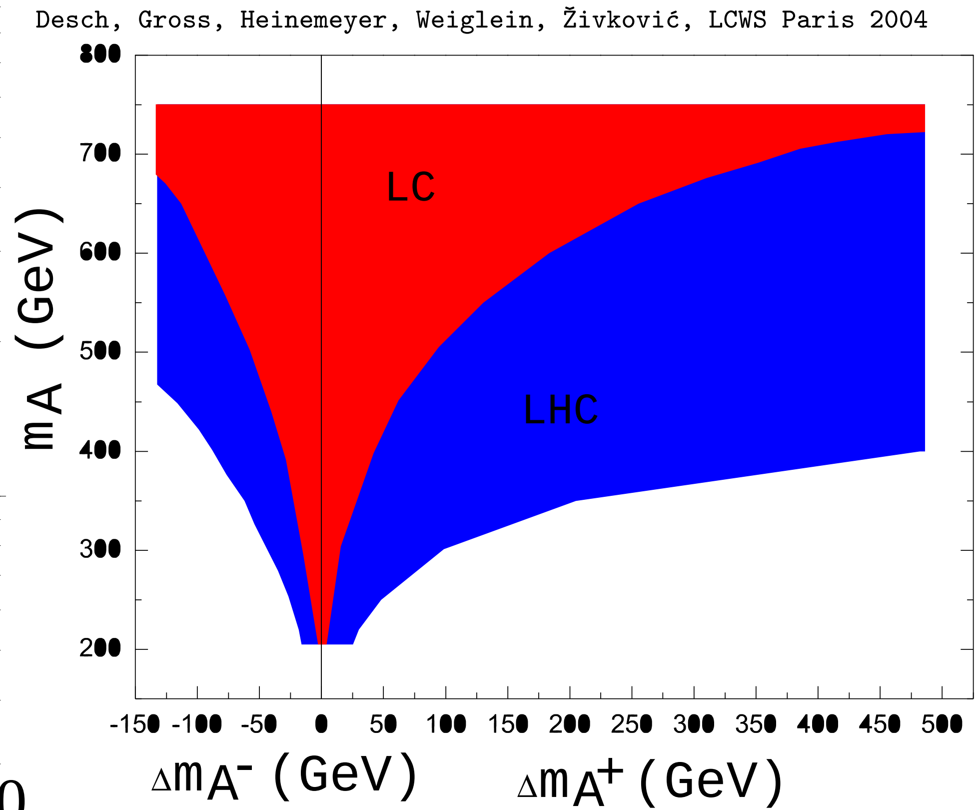
(300,250) $\Delta m_{\mathrm{H}} \approx \Delta m_{\mathrm{A}} \approx 0.45$ GeV.

Distinction of Models

$R = BR(\mathrm{H} \to \mathrm{b\bar{b}})/BR(\mathrm{H} \to \tau^+\tau^-)$

$$\frac{BR(\mathrm{H}\to\mathrm{b\bar{b}})/BR^{\mathrm{SM}}_{\mathrm{b\bar{b}}}}{BR(\mathrm{H}\to\mathrm{W^+W^-})/BR^{\mathrm{SM}}_{\mathrm{W^+W^-}}} < 3.5\% < 20\%$$





Stronger A mass prediction at a LC.

Predict $\Delta m_A/m_A \approx 20\%$ for m_A = 600 GeV.

MSSM predicts large effects in all scenarios:

LHC large $\tan\beta$, LC all $\tan\beta$

Conclusions

- After a first discovery at the Tevatron or the LHC and initial precision measurements, already in the first phase of a LC, all Higgs boson decay modes will be measured with very high precision.
- Models like the SM, the general 2DHM, the MSSM or the NMSSM will be distinguished for a wide range of parameters.
- The underlying mechanism of symmetry breaking and mass generation will be tested.
- The model parameters will be measured and the Higgs boson might be known as precisely as is the Z boson today.
- Like for the top quark (LEP mass prediction, Tevatron observation), important consistencies of the model can be probed with combined LC and LHC physics.
- After 12 years of preparational studies the LC has a solid case and the HEP community is prepared to answer fundamental questions over the next decades.