Higgs and Electroweak Physics

Sven Heinemeyer, IFCA (Santander)

St. Andrews, 08/2009

1. The SM and the Higgs

2. The Higgs in Supersymmetry

3. Experimental facts and fiction (from a theorist's view)

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Higgs and Electroweak Physics (III):
Experimental facts and fiction

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1. Higgs boson searches at LEP
2. Higgs boson searches at the Tevatron
3. Higgs boson searches at the LHC
4. Higgs boson precision physics at the ILC

Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

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1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)

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4. measure couplings to fermions

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3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

Discovering the Higgs boson

What has to be done?

1. Find the new particle T
2. measure its mass ($\Rightarrow$ ok?) T
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

T = Tevatron,

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L
2. measure its mass ($\Rightarrow$ ok?)	T	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		
6. measure spin, ...		

T = Tevatron, L = LHC,

Discovering the Higgs boson

What has to be done?

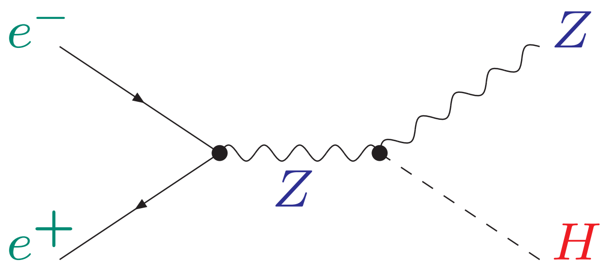
1. Find the new particle	T	L	I
2. measure its mass ($\Rightarrow$ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings			I
6. measure spin, . . .			I

T = Tevatron, L = LHC, I = ILC

We need the ILC to find the Higgs
and to establish the Higgs mechanism!
But the LHC can do a crucial part already!

1. Higgs search at LEP:

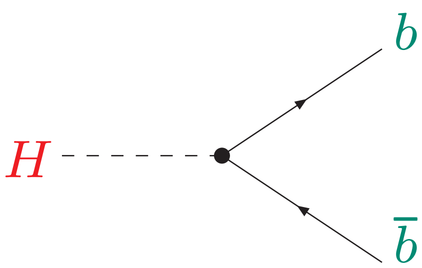
Dominant SM production process:
$e^+e^- \to ZH$:



$$\sigma(e^+e^- \to ZH) = \frac{G_\mu^2 M_Z^4}{96\,\pi\,s}\left[v_e^2 + a_e^2\right]\beta\,\frac{\beta^2 + 12M_Z^2/s}{(1 - M_Z^2/s)^2}$$

with $\beta^2 = (1 - (M_H + M_Z)^2/s)\,(1 - (M_H - M_Z)^2/s)$ (1)

Dominant decay process: $H \to b\bar{b}$

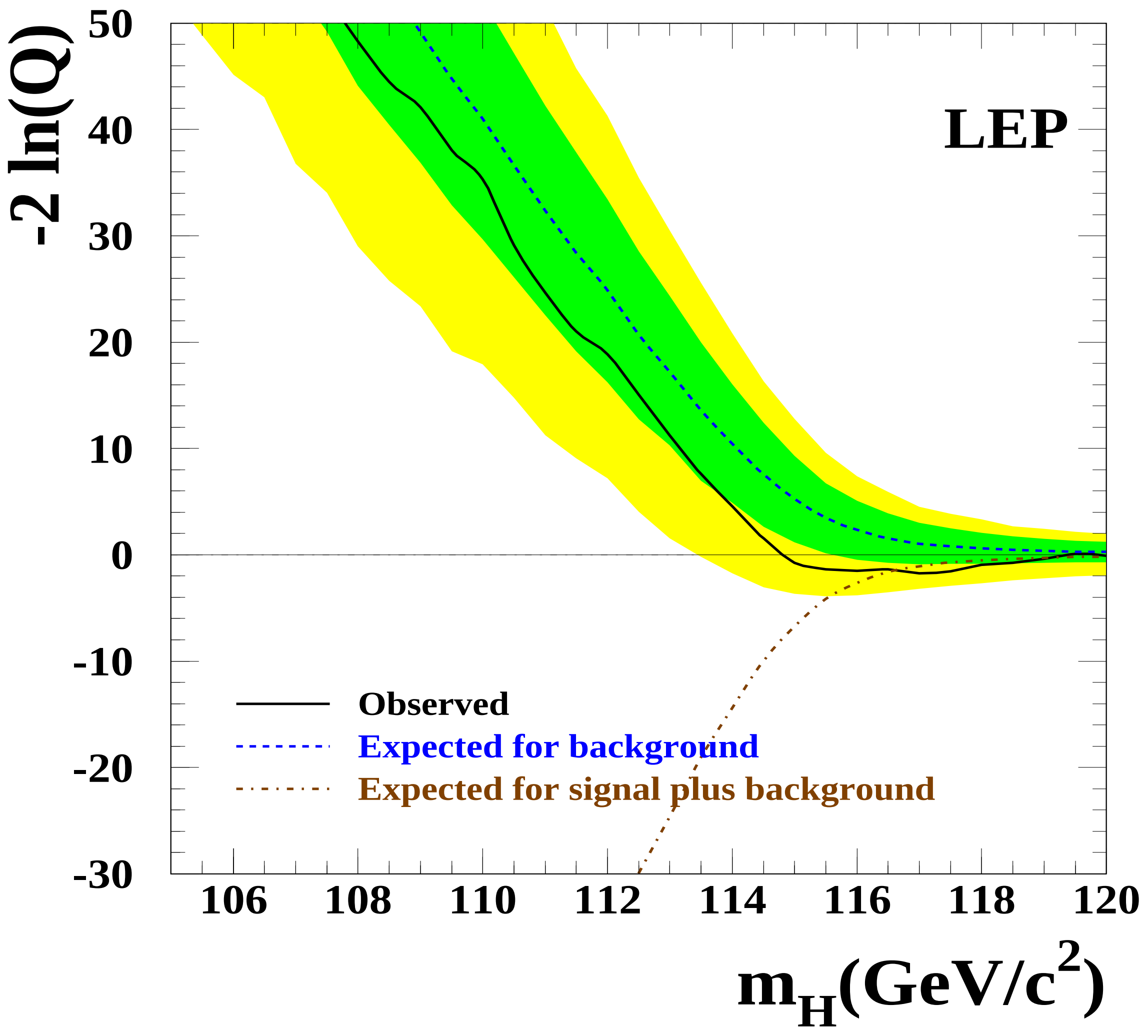


Exclusion limit
at the 95% C.L.:

$M_H > 114.4$ GeV

expected: 115.3 GeV

(LEP has seen exactly as many Higgs-like events as could be expected for $M_H \approx 116$ GeV, not more, not less)



Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

$\rightarrow$ investigate benchmark scenarios:

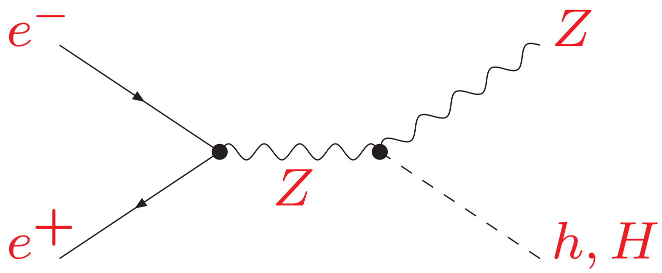
> $\rightarrow$ Vary only M_A and $\tan\beta$
> $\rightarrow$ Keep all other SUSY parameters fixed

1. m_h^{max} scenario:
   $\rightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)
2. no-mixing scenario
   $\rightarrow$ no mixing in the scalar top sector ($X_t = 0$)
3. small α_{eff} scenario
   $\rightarrow$ $hb\bar{b}$ coupling $\sim \sin\alpha_{\text{eff}}/\cos\beta$ can be zero: $\alpha_{\text{eff}} \rightarrow 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   $\rightarrow$ hgg coupling is small: main LHC production mode vanishes

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

Search for neutral SUSY Higgs bosons:

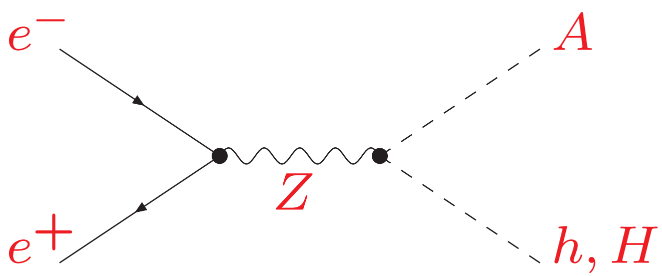
$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$e^+e^- \to Ah, AH$



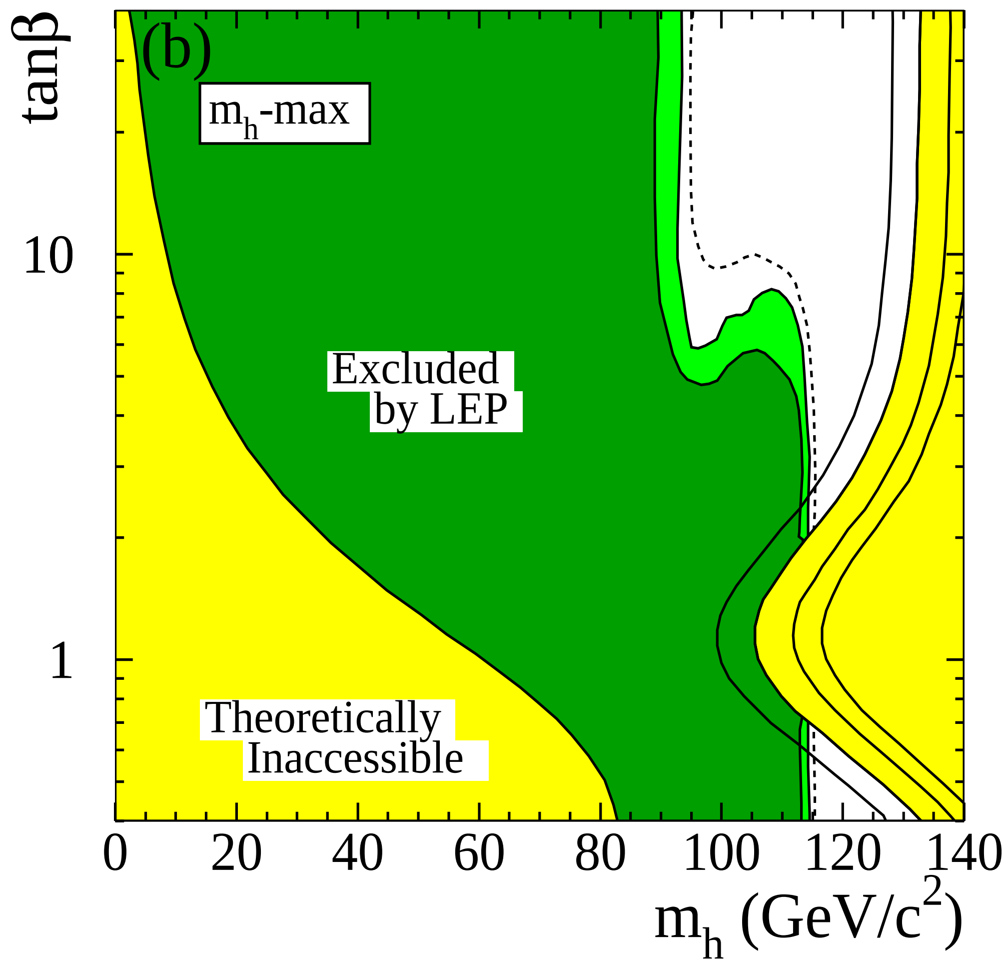
$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}})\sigma^{\text{SM}}_{hZ}$$

Constraints from the Higgs search at LEP [*LEP Higgs Working Group '06*]

Experimental search vs. upper m_h-bound (*FeynHiggs* 2.0)

m_h^{max}-scenario ($m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV):

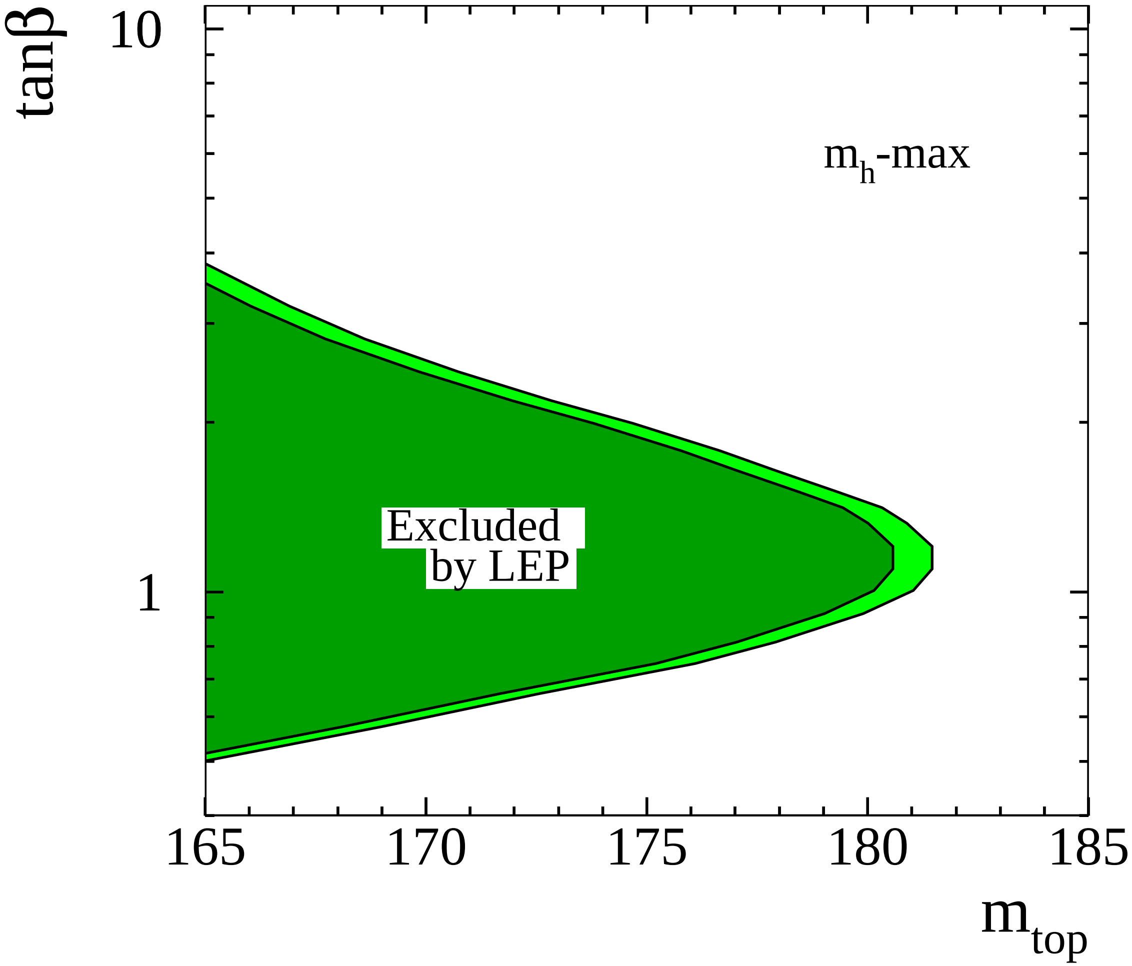


$m_h > 92.8$ GeV
(expected: 94.9 GeV), 95% C.L.

$M_A > 93.4$ GeV
(expected: 95.2 GeV)

Parameter region where experimental lower bound on M_h is significantly lower than SM bound, $M_H > 114.4$ GeV, corresponds to $\sin^2(\beta - \alpha_{\rm eff}) \ll 1$

"Excluded" $\tan\beta$ region:



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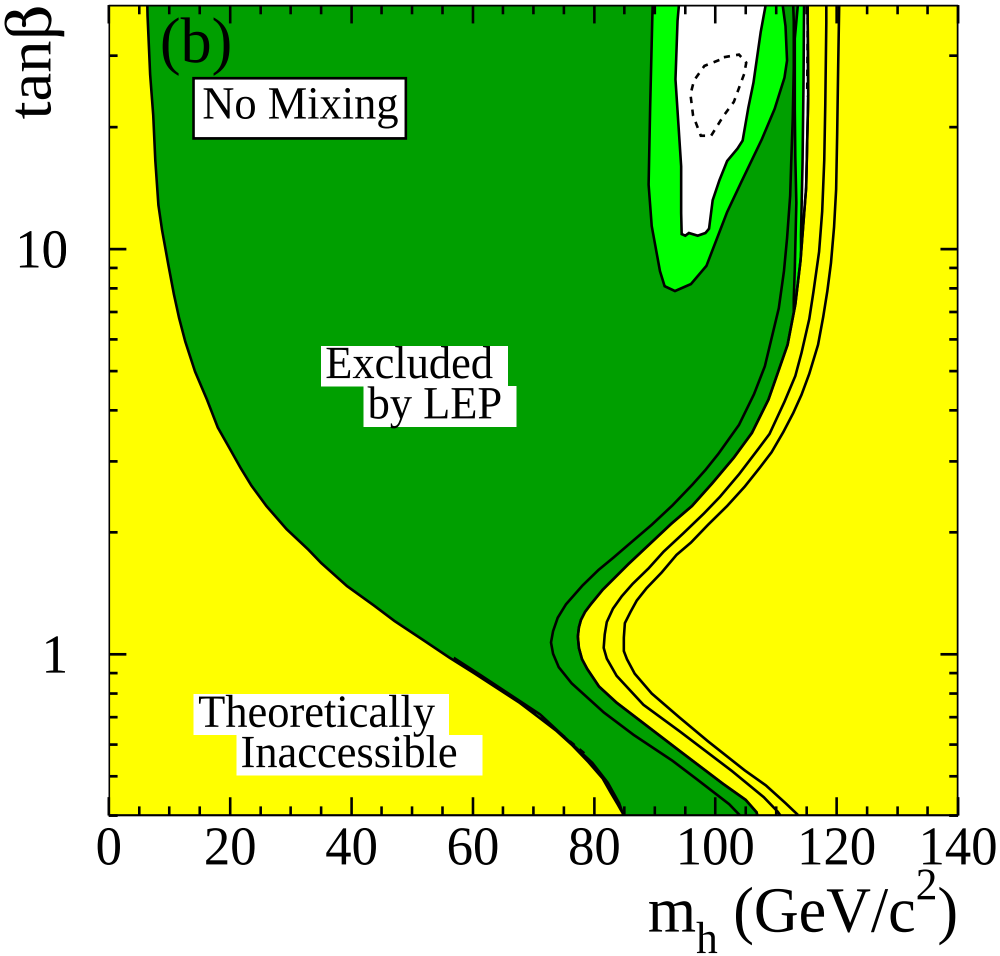
no-mixing scenario ($m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV):



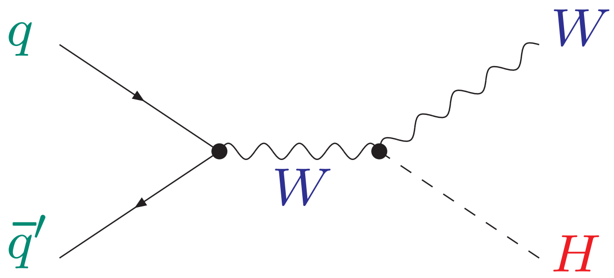
$m_h > 93.6$ GeV
(expected: 96.0 GeV), 95% C.L.

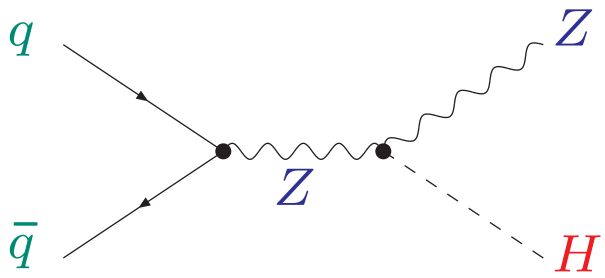
$M_A > 93.6$ GeV
(expected: 96.4 GeV)

2. Higgs search at the Tevatron

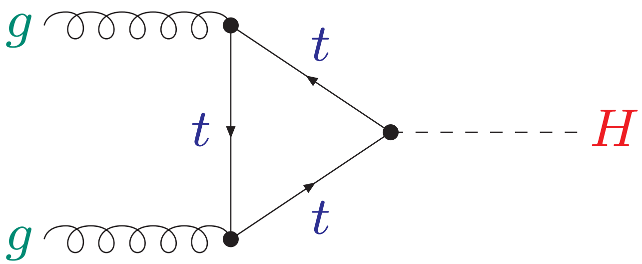
Tevatron: $p\bar{p}$ accelerator: → T

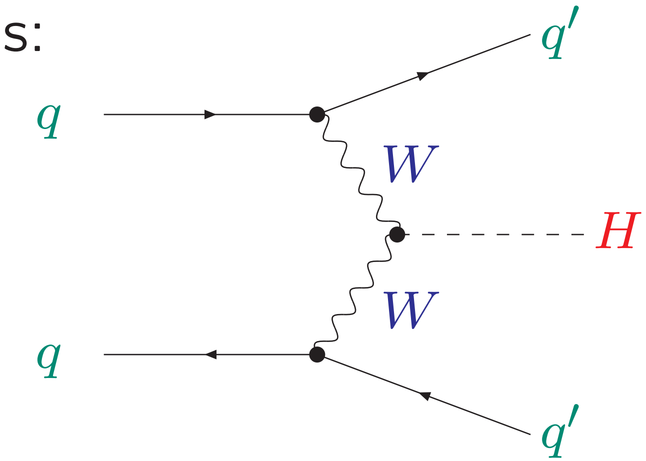
Production processes as at LEP:



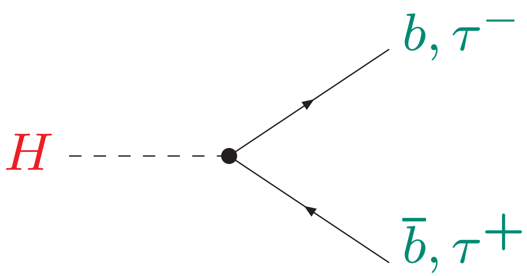


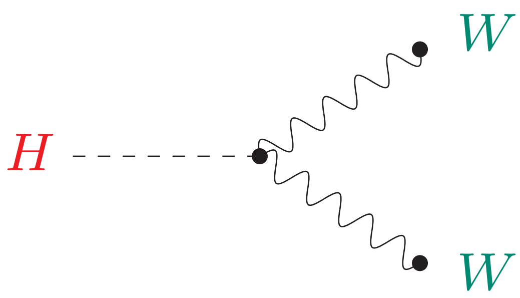
Other important production channels:





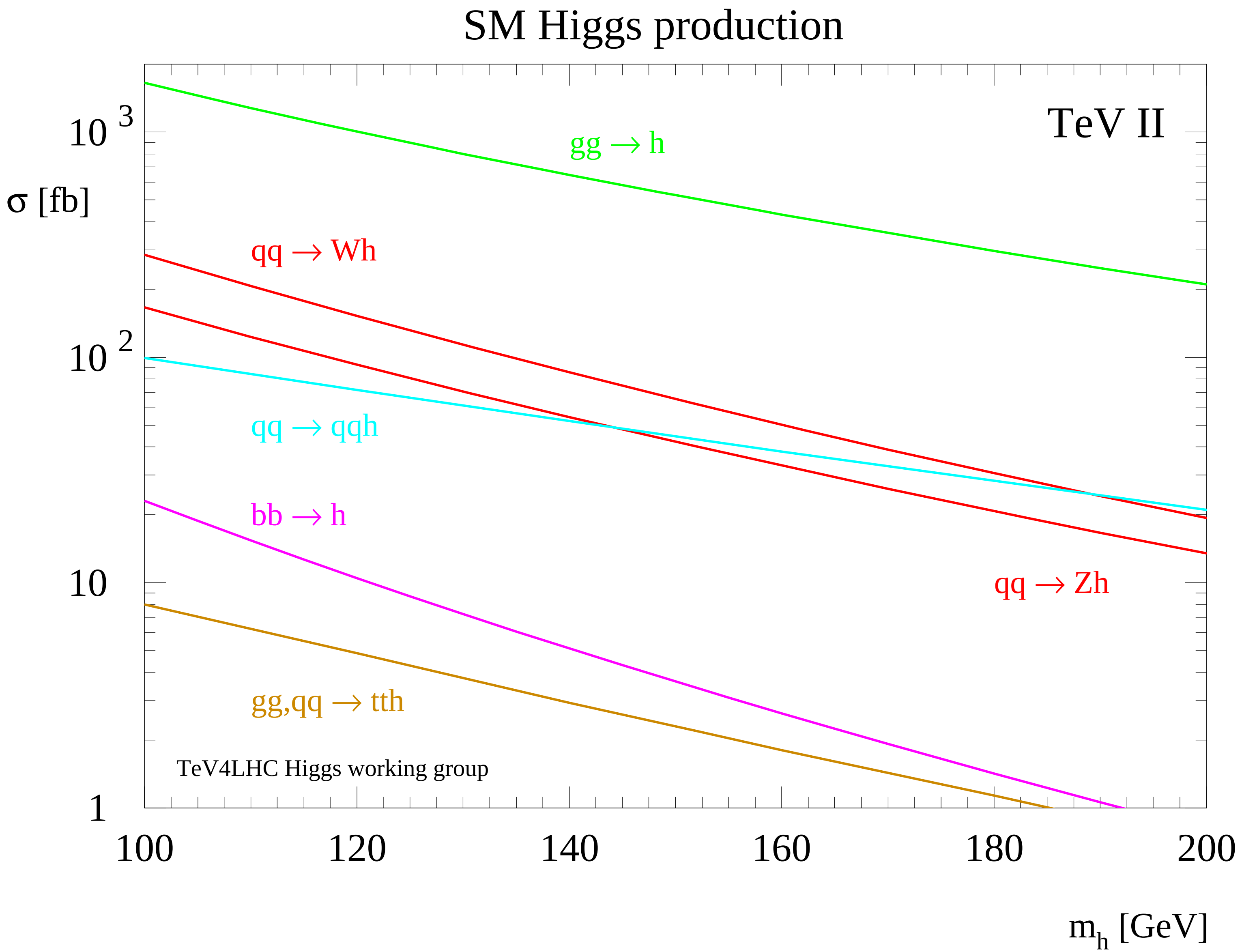
Dominant decays:



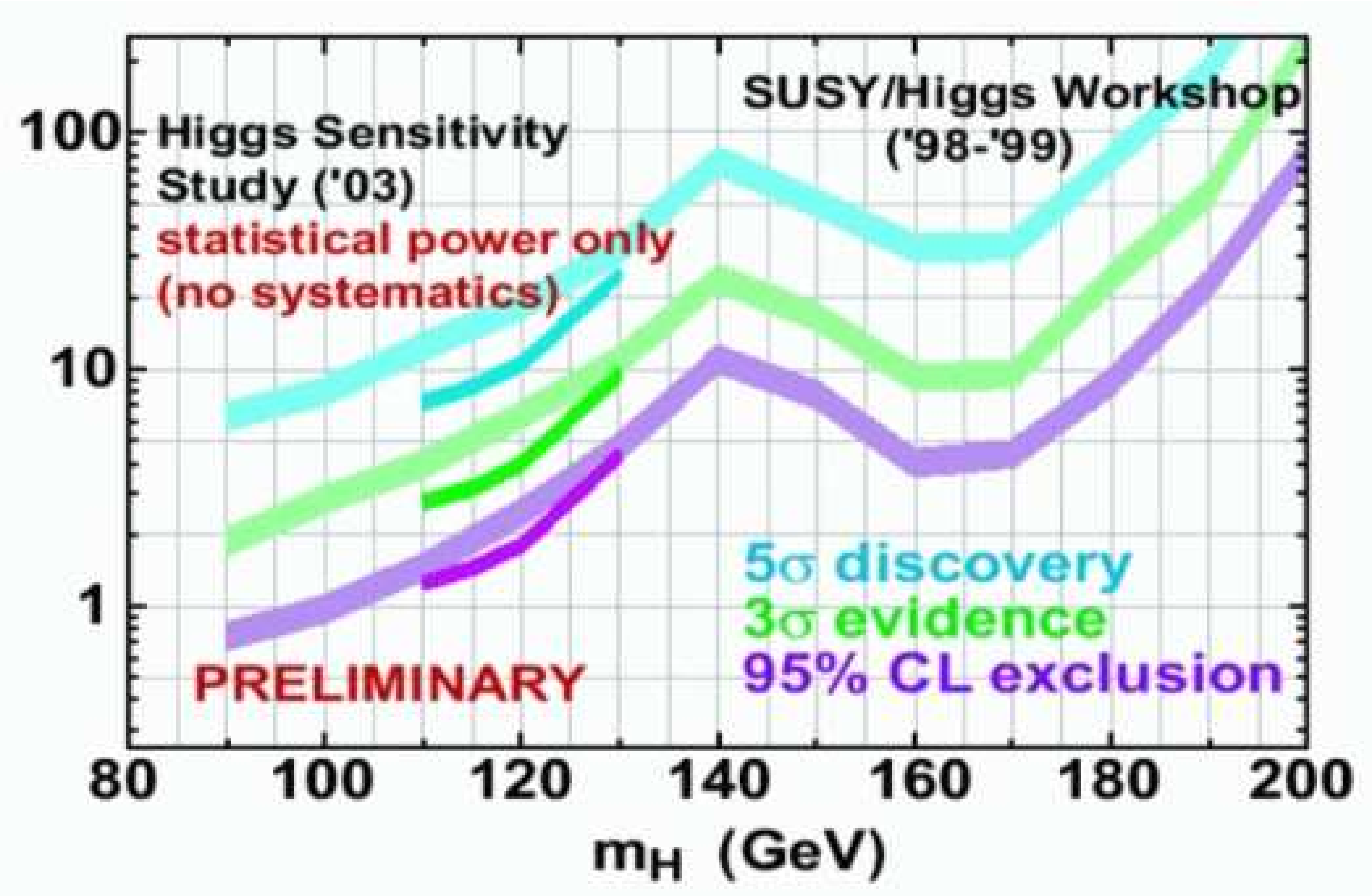


Overview of SM production cross sections:

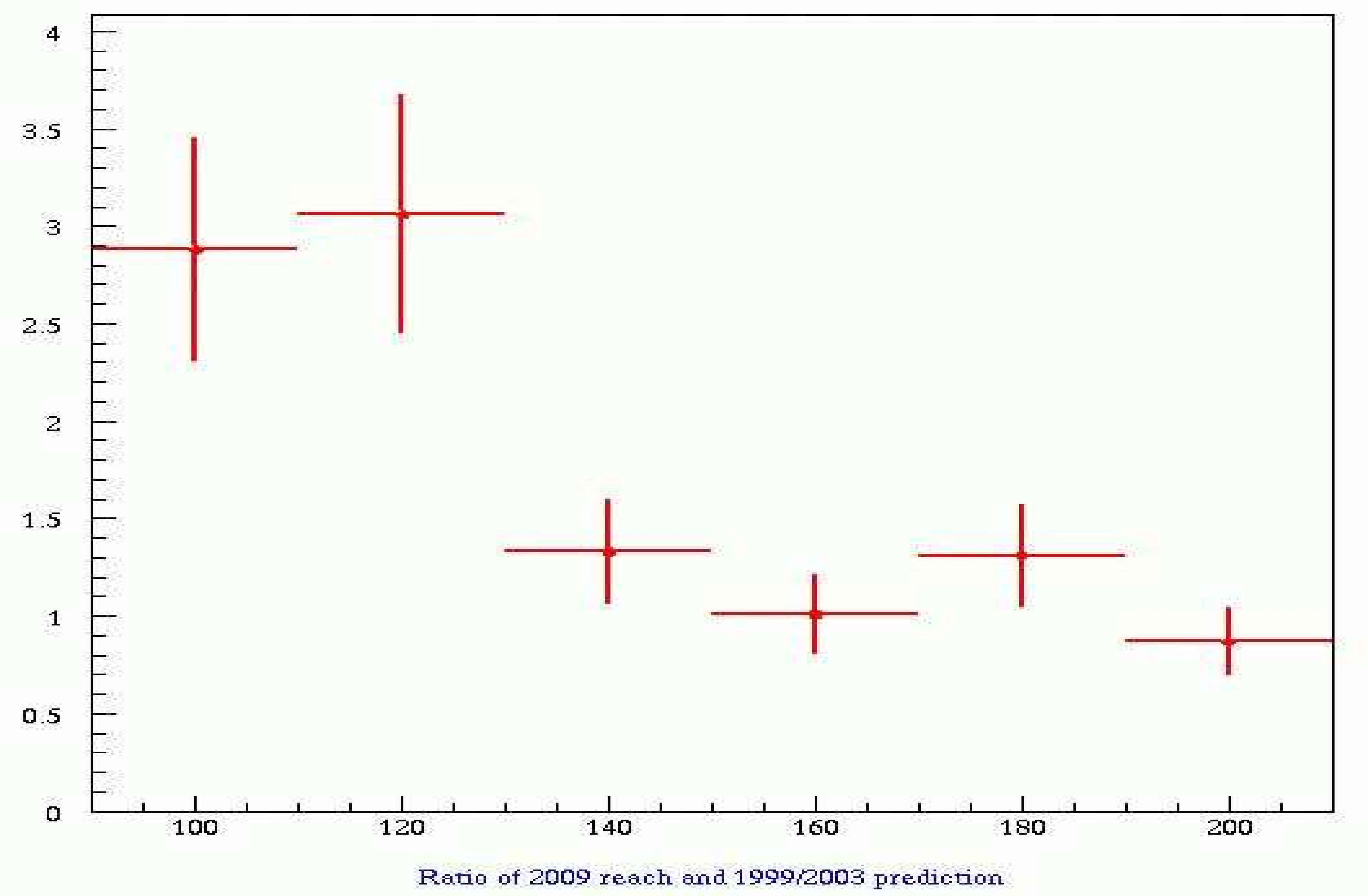
[F. Maltoni et al. '05]



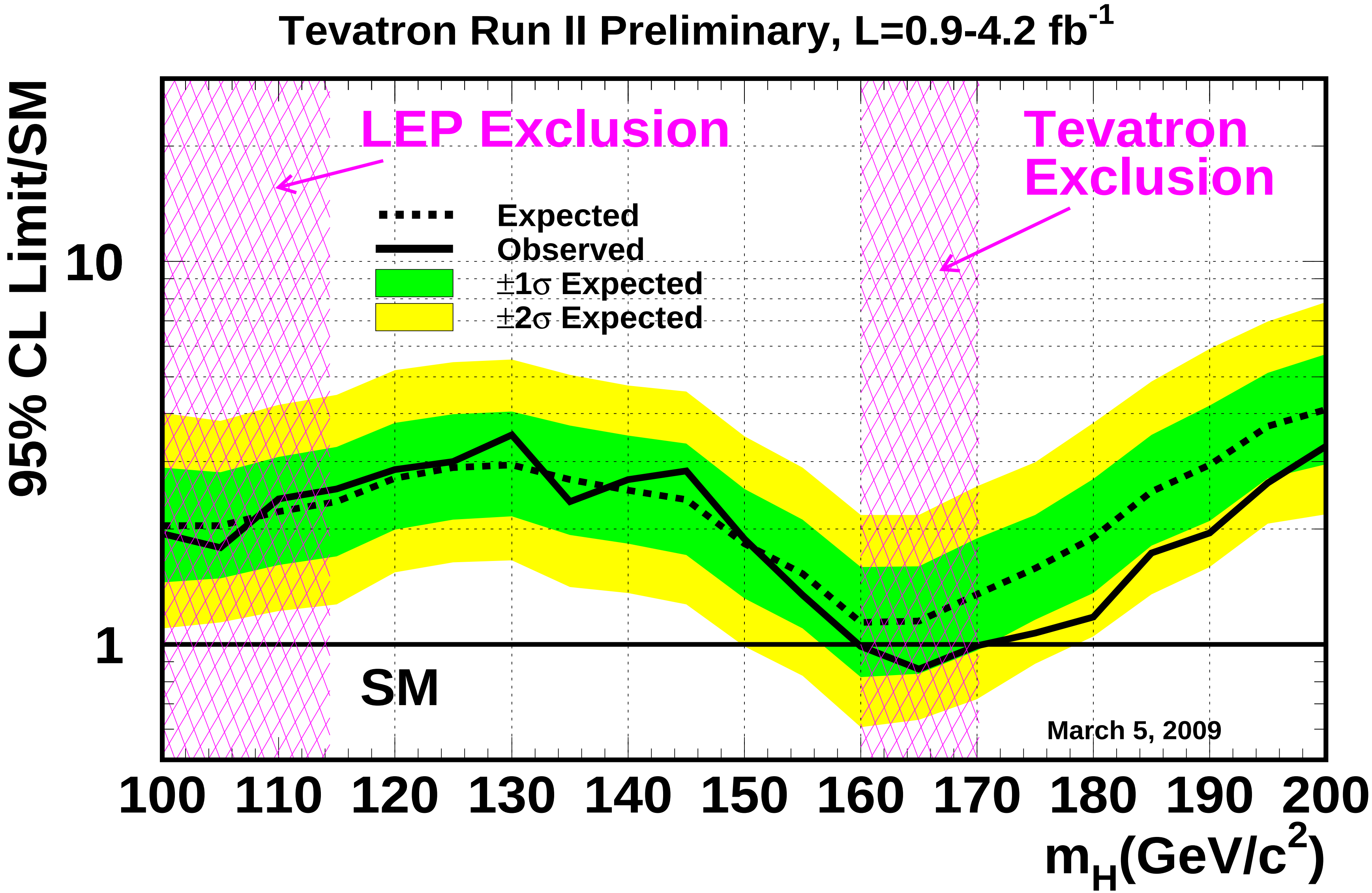
Expectations for Higgs discovery at the Tevatron:



Real performance compared with expectations: [*T. Dorigo '09*]



Current Status of SM Higgs searches at the Tevatron:



⇒ applies also to a SM-like light MSSM Higgs boson

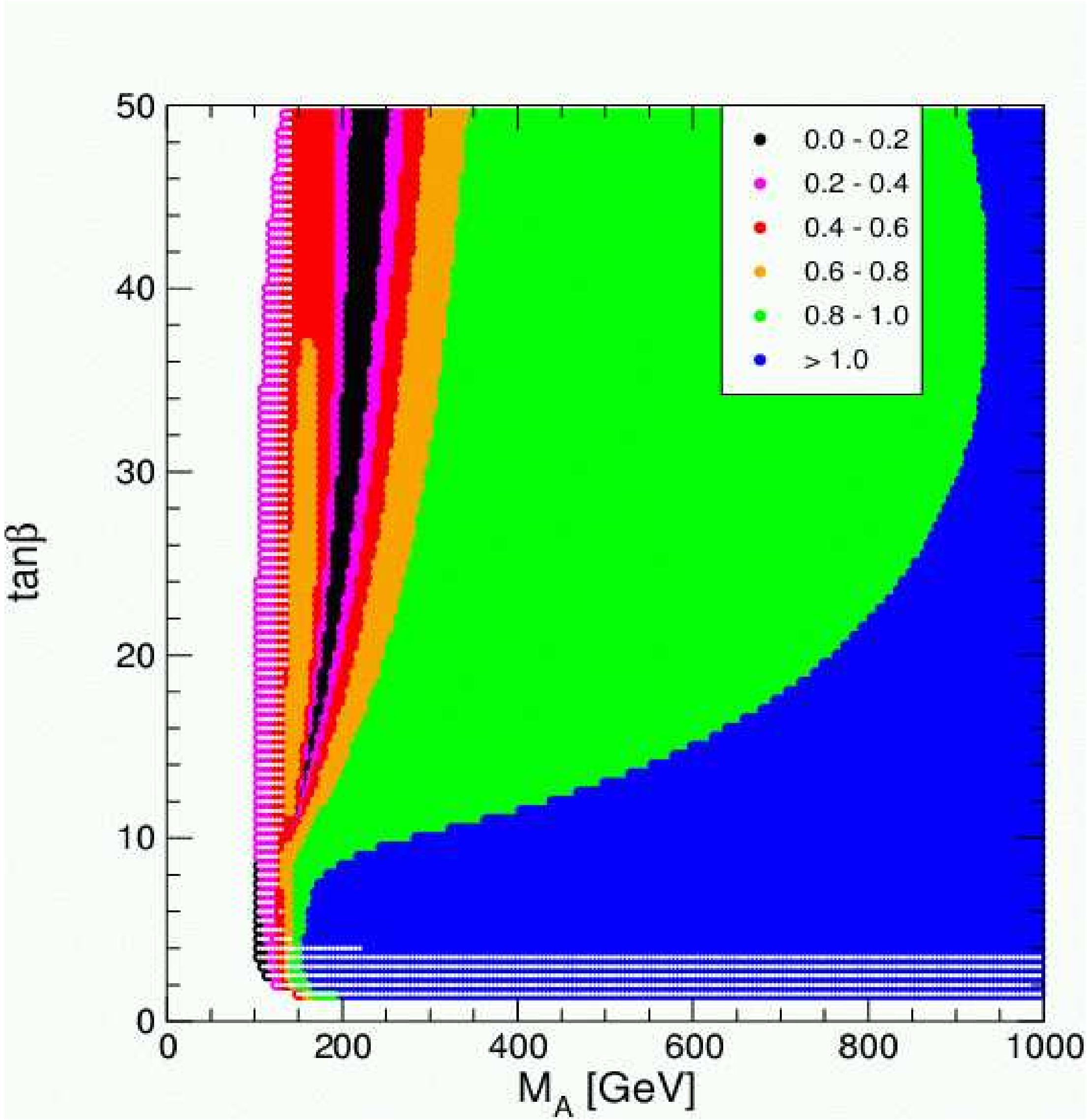
Possible problem in SUSY:

$$h \to b\bar{b}$$

can be strongly suppressed

$\to$ "Small $\alpha_{\rm eff}$ scenario"

[M. Carena, S.H., C. Wagner, G. Weiglein '02]



$\Rightarrow$ Strong suppression of $h \to b\bar{b}$ possible, up to $M_A \lesssim 350$ GeV

(not realized in mSUGRA/CMSSM, GMSB, AMSB, . . .)

Tevatron MSSM Higgs searches: “Heavy” MSSM Higgs bosons

Search modes:

$$b\,\bar{b} \to \phi\, b\, \bar{b}\ , \quad \phi = h, H, A$$
$$p\,\bar{p} \to \phi \to \tau^+\,\tau^-\ , \quad \phi = h, H, A$$

Strong enhancement compared to the SM:

$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \;\simeq\; \sigma(b\bar{b}A)_{\mathrm{SM}}\, \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

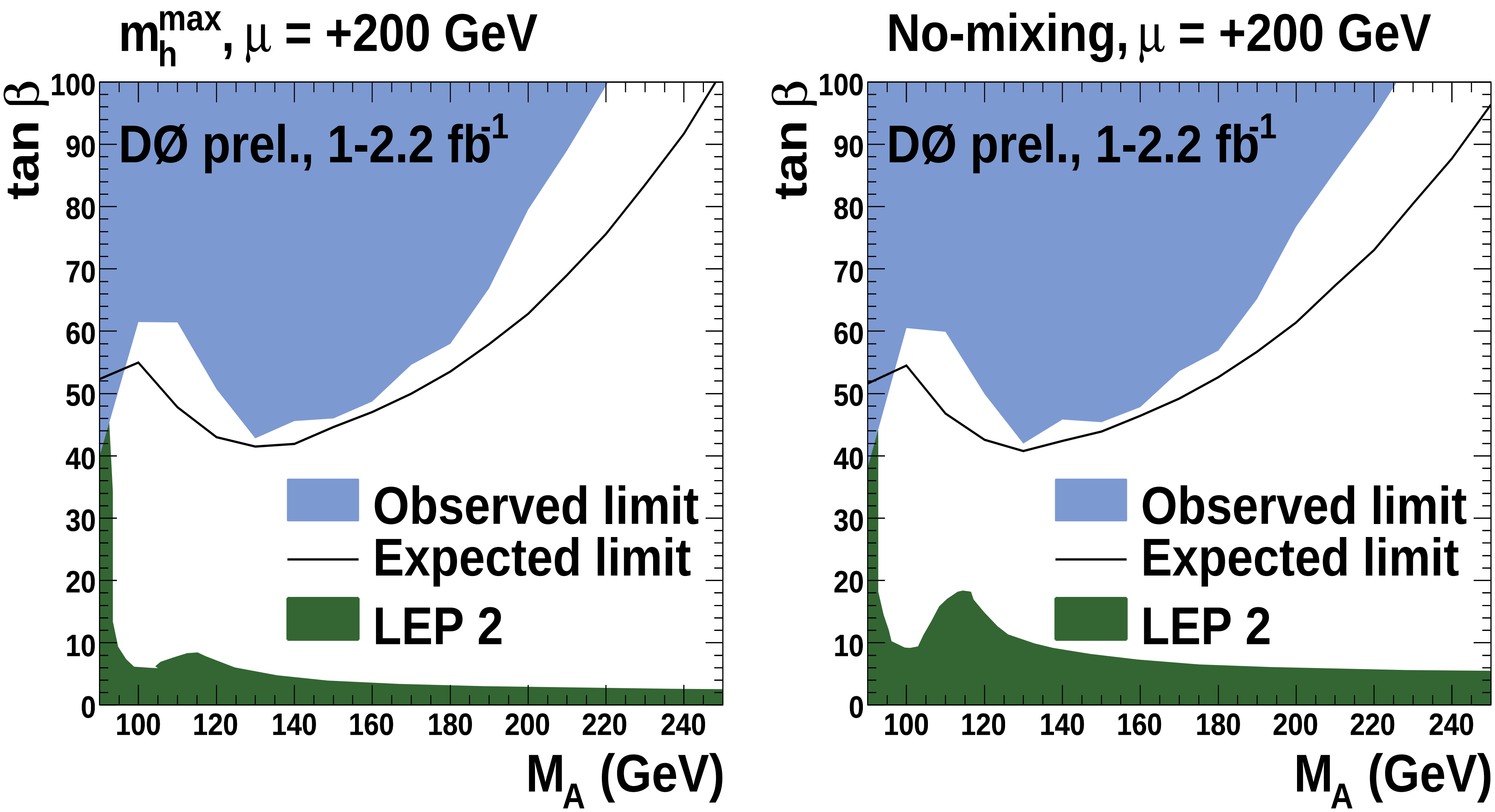
$$\sigma(gg, b\bar{b} \to A) \times \mathrm{BR}(A \to \tau^+\tau^-) \;\simeq\; \sigma(gg, b\bar{b} \to A)_{\mathrm{SM}}\, \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

$$\Delta_b \;=\; \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\,\mu\, \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \;+\; \frac{\alpha_t}{4\,\pi} A_t\,\mu\, \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

Either $H \approx A$ or $h \approx A$ $\Rightarrow$ another factor of 2

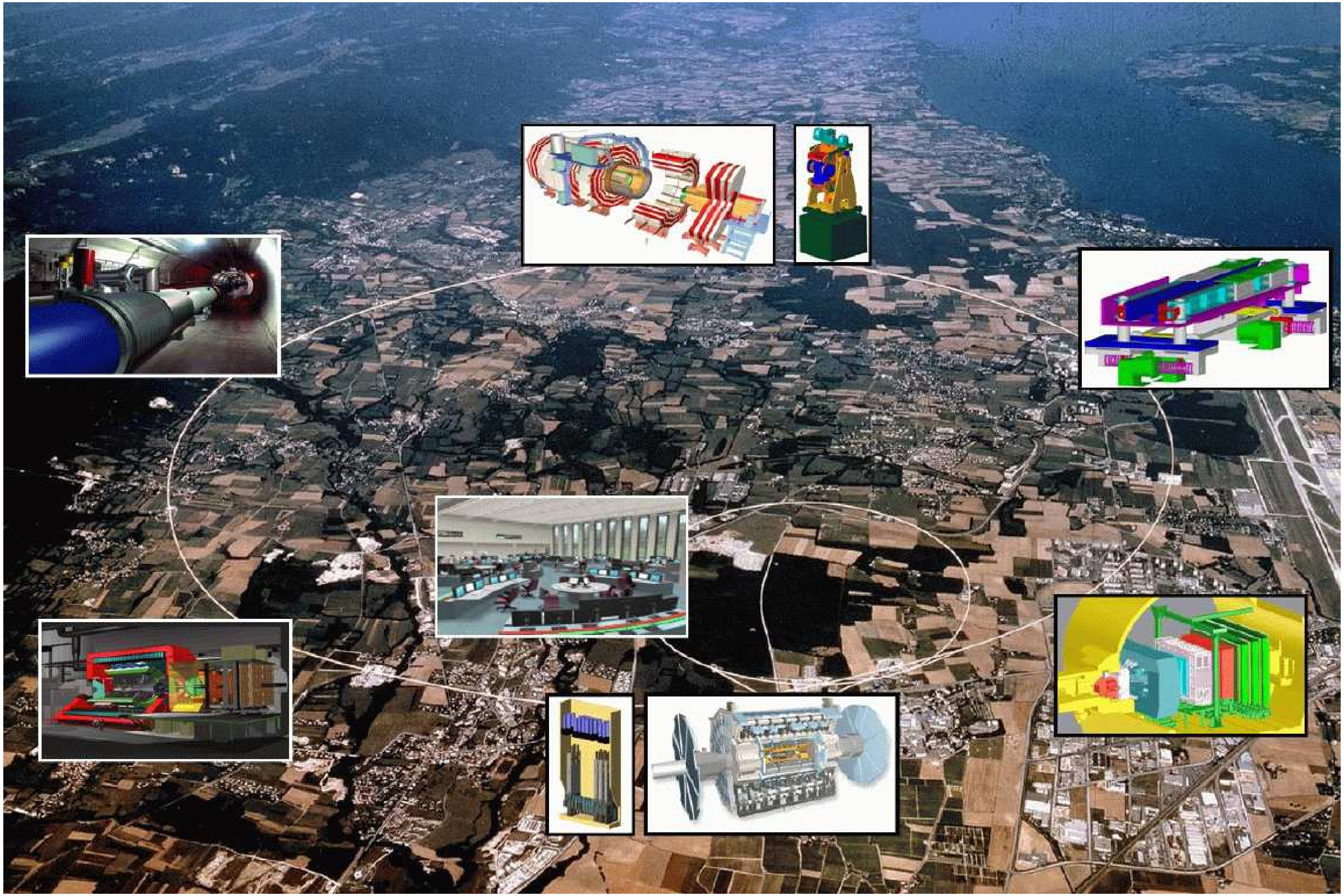
Example: $p\bar{p} \to h/H/A \to \tau^+\tau^-$ at D0 with 2 fb^{-1}

[*D0 '08*]



⇒ exclusion for light M_A and large $\tan\beta$

3. Higgs search at the LHC:



The (un)official (optimistic?) LHC time line:

2009: repairs, cool-down etc.,
first collisions by the end of the year?

2010: 0.1 fb^{-1} – 0.2 fb^{-1} (at $\sqrt{s} \leq 10$ TeV) $\Rightarrow$ first physics results?

2011: $\mathcal{O}$(few) fb^{-1} $\Rightarrow$ first physics results?

2012 – 2015: 10 fb^{-1} per year $\Rightarrow$ physics results with "low" luminosity

2016 – ?: 100 fb^{-1} per year $\Rightarrow$ physics results with "high" luminosity

2019 + X (X > 0): upgrade to SLHC?

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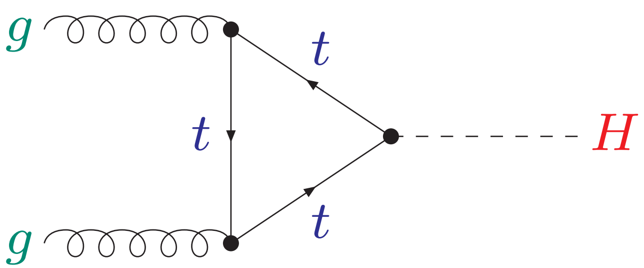
2016 – ?: 100 fb^{-1} per year $\Rightarrow$ physics results with "high" luminosity

2019 + X (X > 0): upgrade to SLHC?

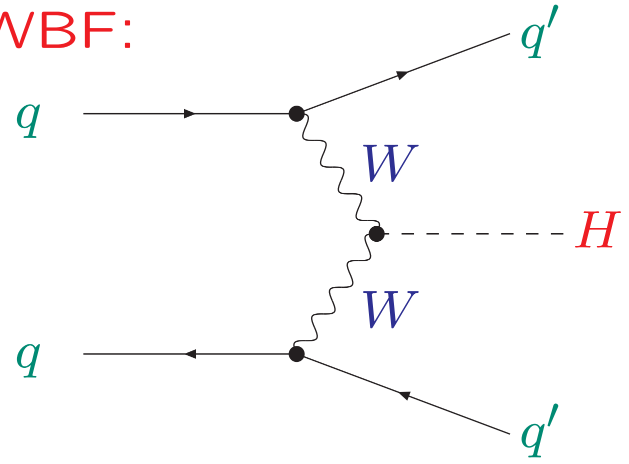
YOU live in an exciting time!!!

Important SM production channel at the LHC:

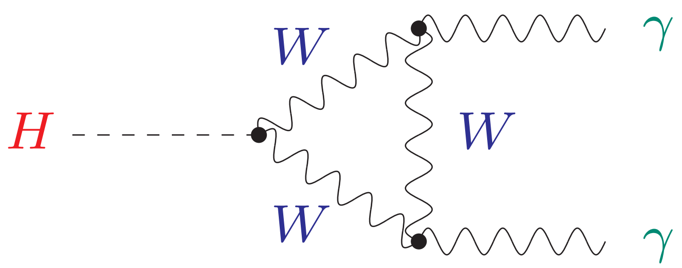
Gluon-Fusion:

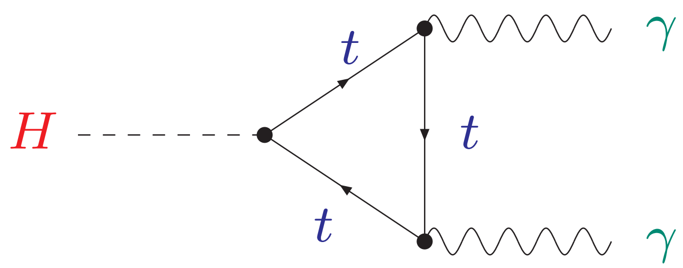


WBF:

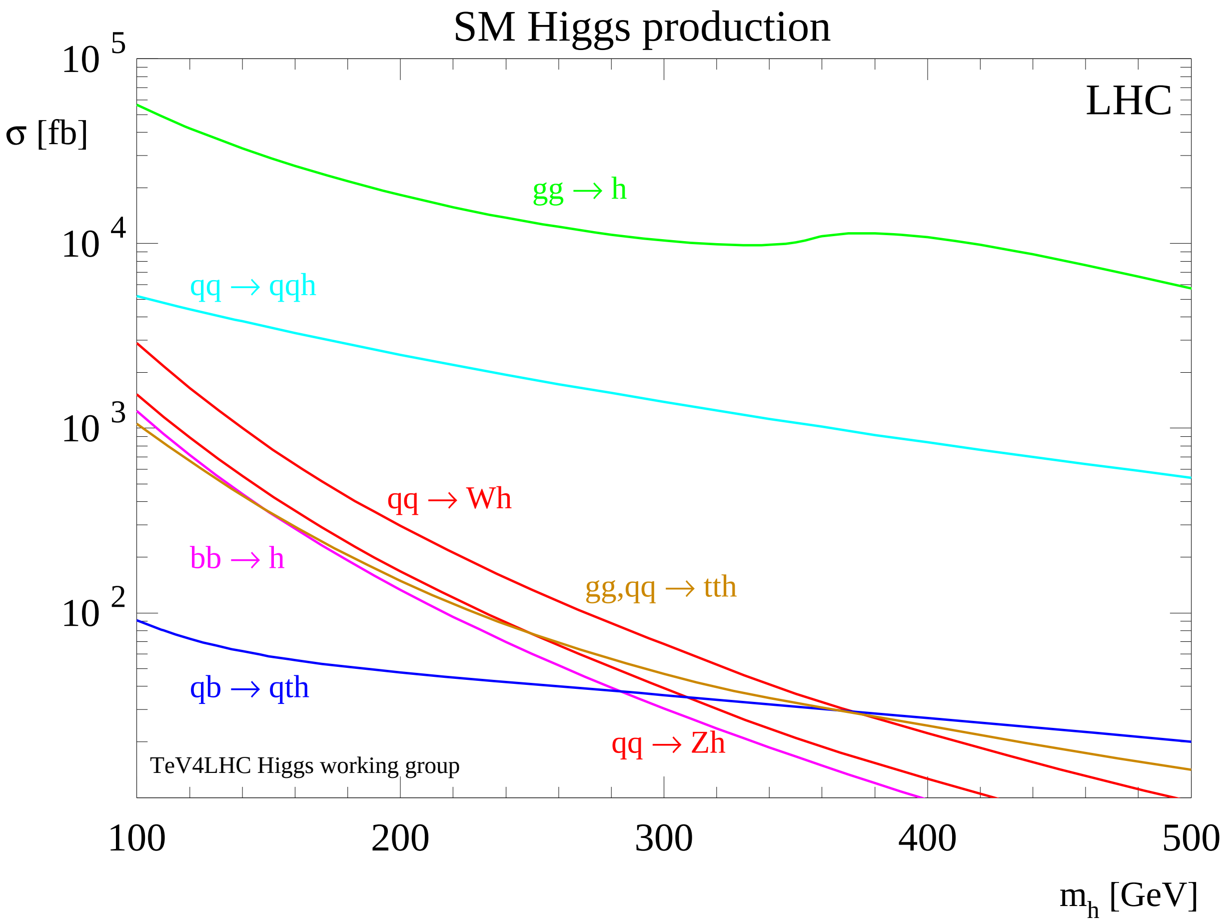


Important decay for Higgs mass measurement:





Overview of SM Higgs production at the LHC:



gluon fusion: $gg \to H$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

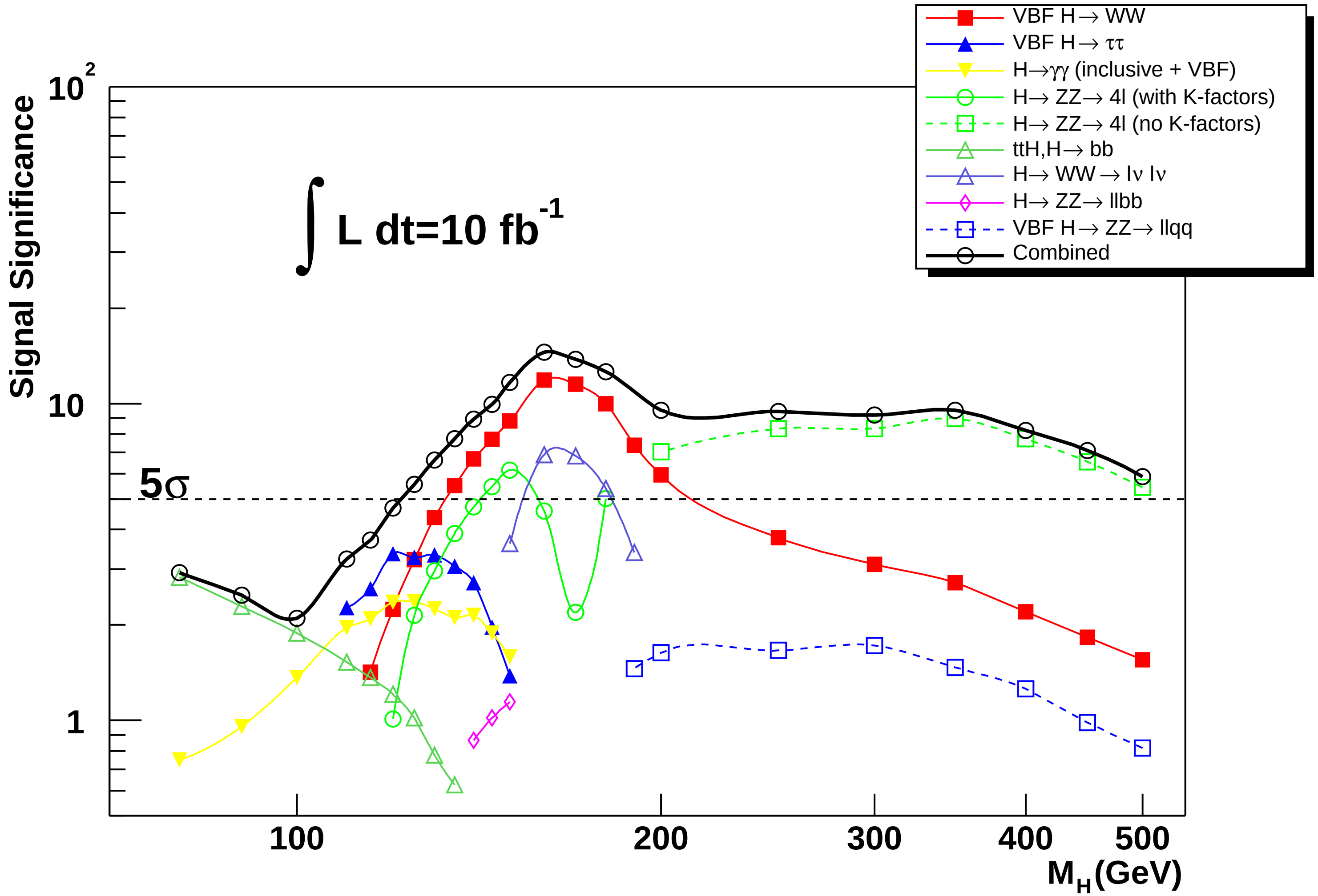
top quark associated production: $gg, q\bar{q} \to t\bar{t}H$

weak boson associated production: $q\bar{q}' \to WH, ZH$

SM Higgs search at the LHC: $\Rightarrow$ full parameter space accessible!?

SM Higgs search at the LHC: $\Rightarrow$ full parameter space accessible

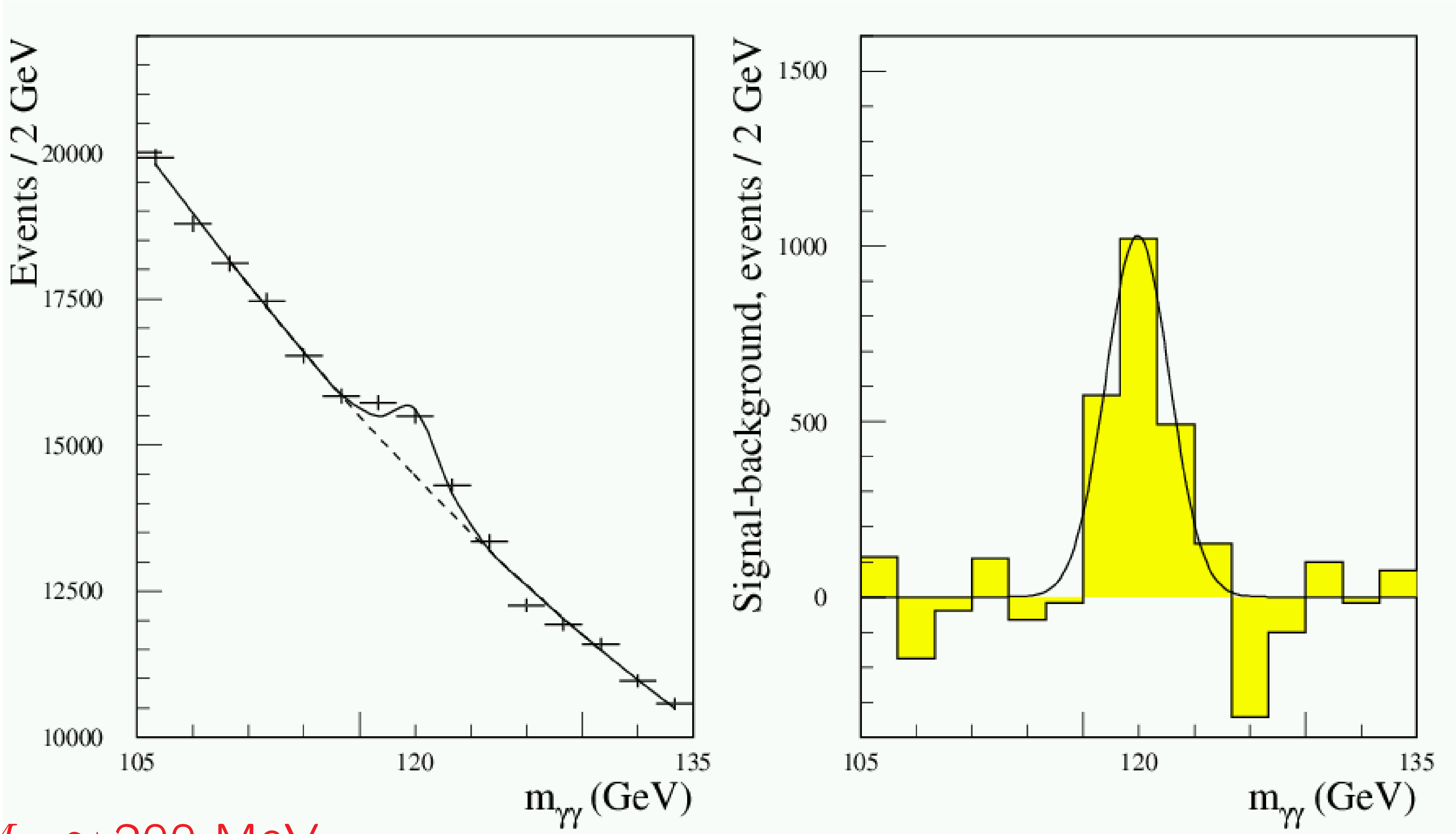
[*ATLAS '05*]



$\Rightarrow$ most problematic case also at the LHC: $M_H = 115 \ldots 120$ GeV

Step 2: Measurement of the mass

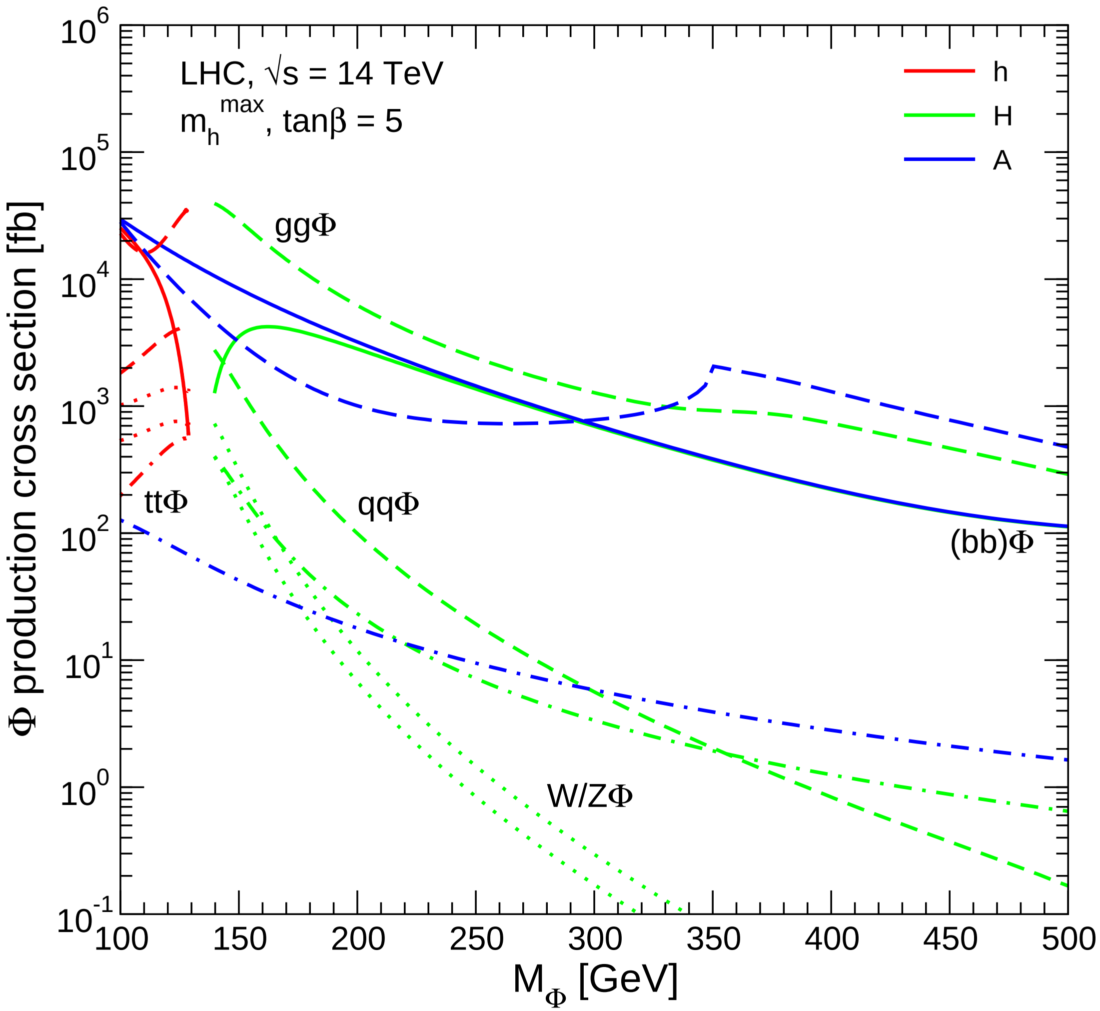
Best channel for mass measurement in the SM: $H \to \gamma\gamma$
[*ATLAS '99*]



$\Rightarrow \delta M_H \approx 200$ MeV

Situation is a bit more complicated for SUSY Higgses ($\phi = h, H, A$)

[*Tev4LHC Higgs working group report '06*]



gluon fusion: $gg \to \phi$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'\phi$

top quark associated production: $gg, q\bar{q} \to t\bar{t}\phi$

weak boson associated production: $q\bar{q}' \to W\phi, Z\phi$

NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

$\Rightarrow$ full parameter accessible   But there might be problems . . .

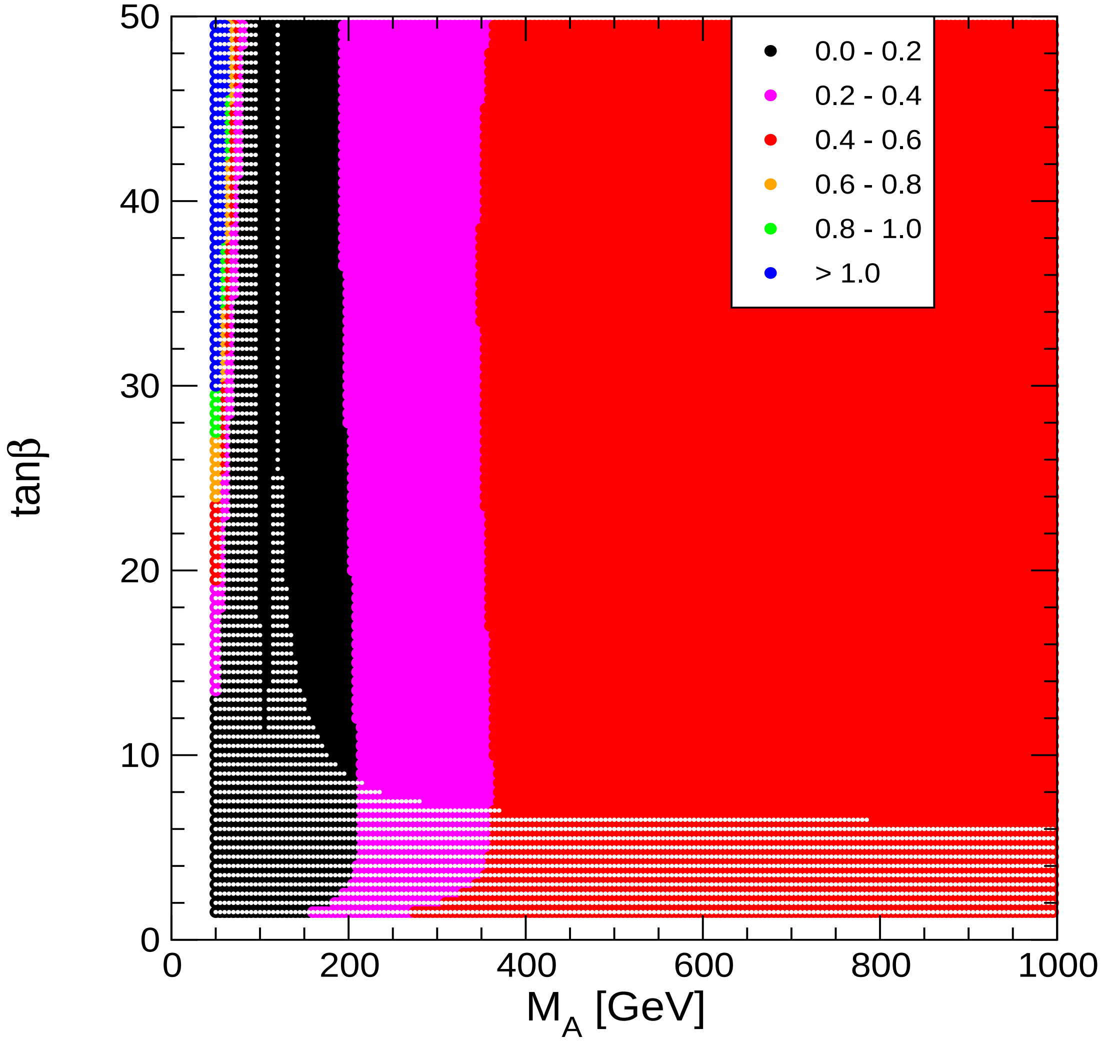
Possible problem in SUSY:

$$gg \to h \to \gamma\gamma$$

can be strongly suppressed

$\to$ "gluophobic Higgs scenario"

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

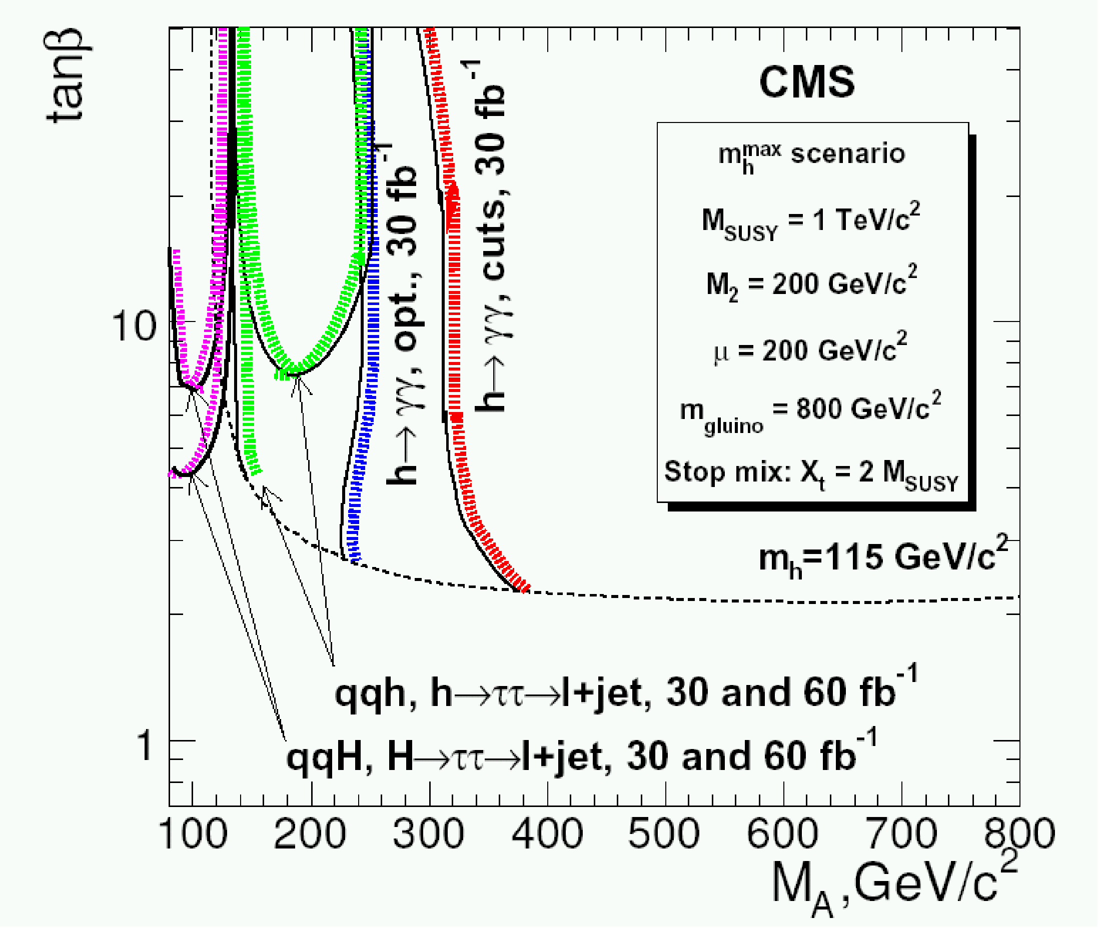


$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

(not realized in mSUGRA/CMSSM, GMSB, AMSB, . . .)

M_h measurement in the "nice" m_h^{max} scenario:

[*CMS '06*]



Measurement possible only for $M_A \gtrsim$ 250 GeV

$\Rightarrow \delta M_h \approx$ 200 MeV

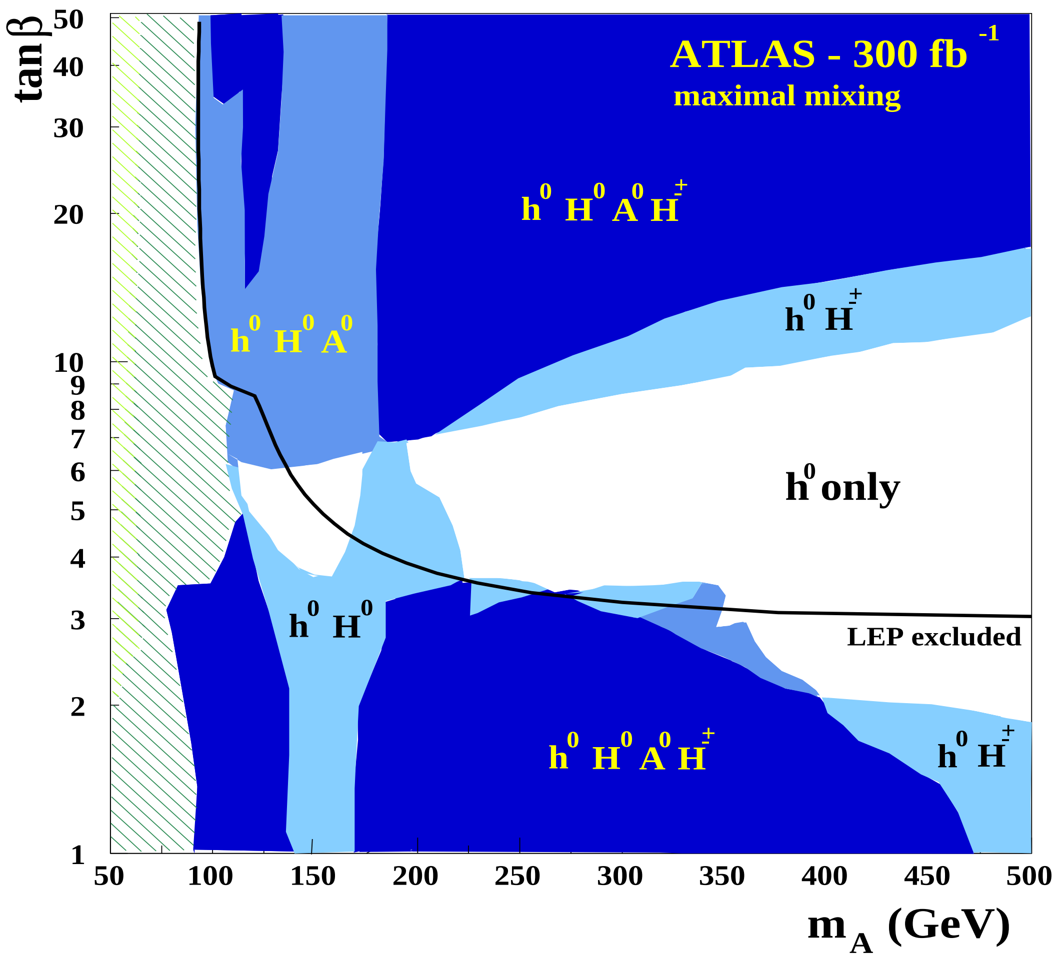
other channels:

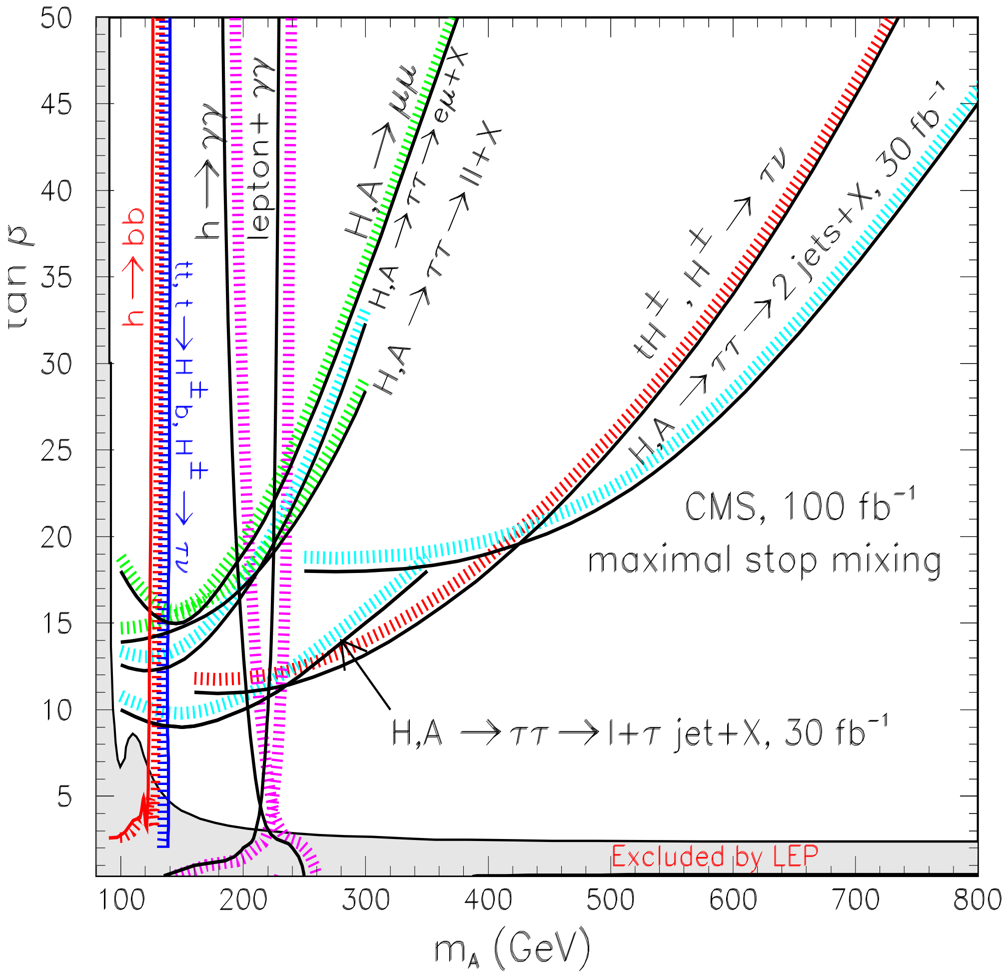
$h \to ZZ^* \to 4\mu$ ($M_h \gtrsim$ 130 GeV)

otherwise: $\delta M_h \gtrsim 1 - 2$ GeV

The heavy MSSM Higgs bosons

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\max}$ benchmark scenario): [*ATLAS '99*] [*CMS '03*]

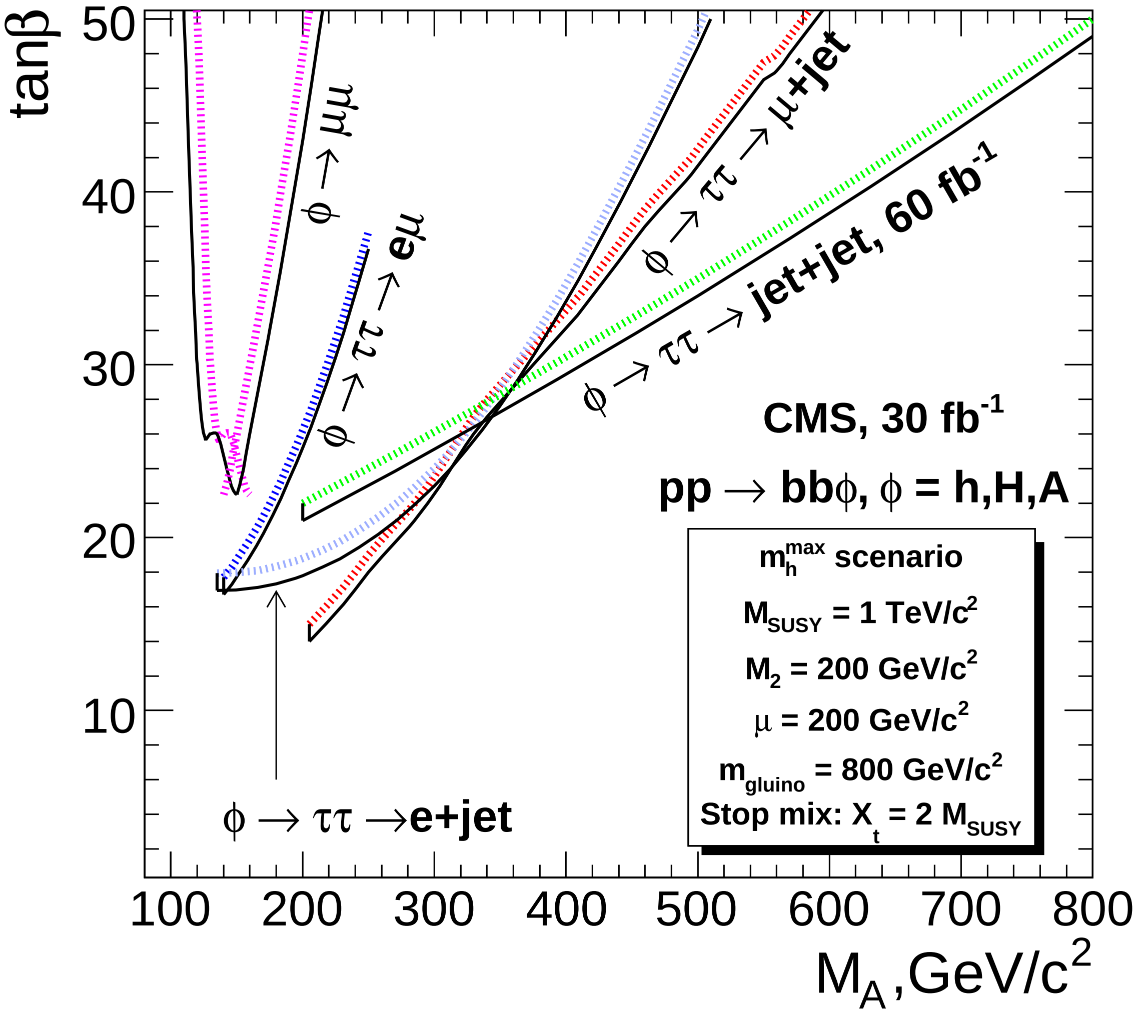




areas where only h is observable ⇒ "LHC wedge"

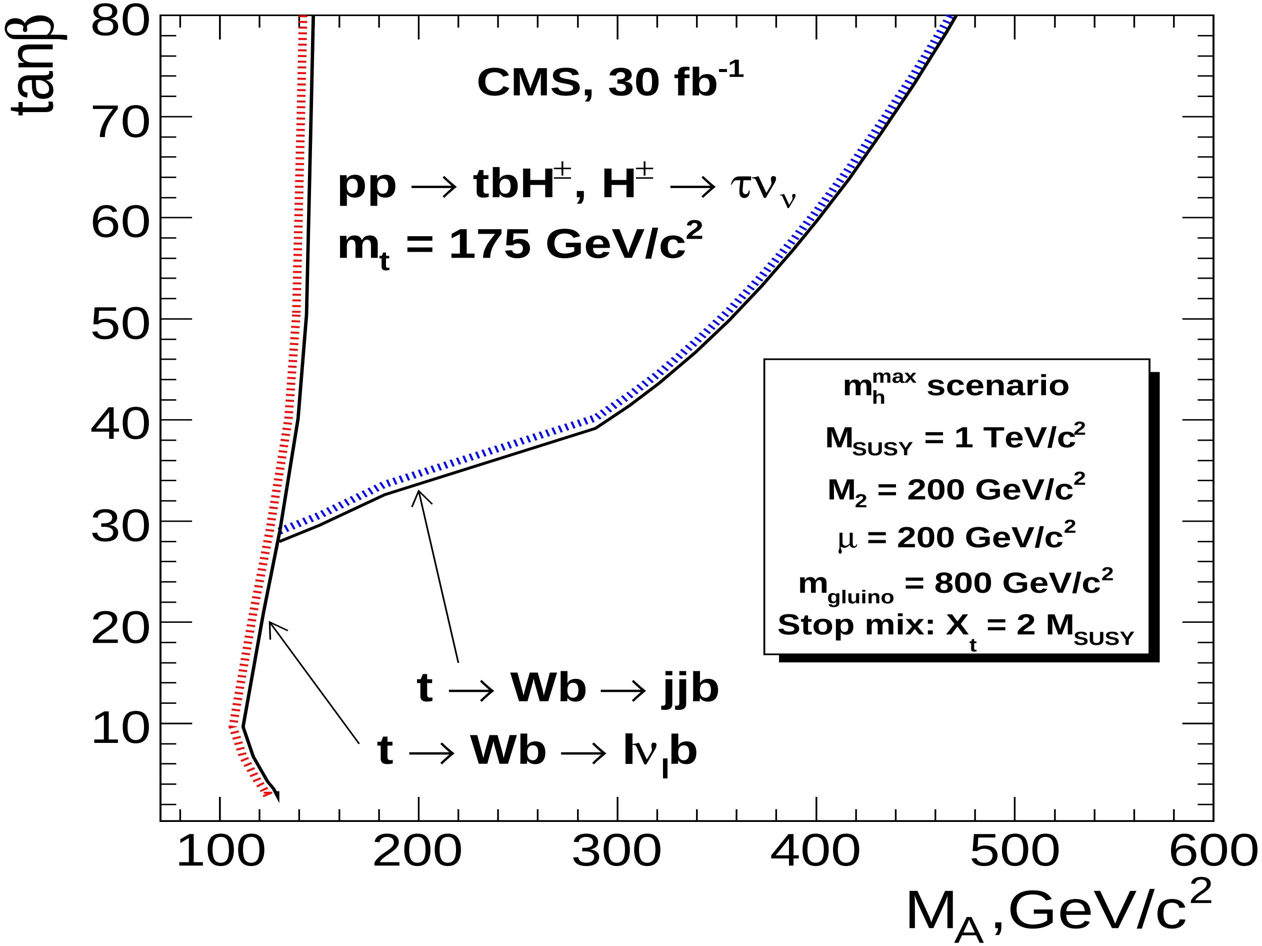
Latest results for neutral heavy Higgs bosons:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane $(\Phi = H, A)$
($m_h^{\rm max}$ benchmark scenario): [*CMS PTDR '06*]



Charged Higgs boson searches:

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane ($m_h^{\max}$ benchmark scenario): [*CMS PTDR '06*]



light charged Higgs:

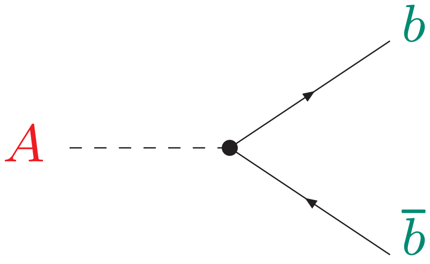
$$M_{H^\pm} < m_t$$

heavy charged Higgs:

$$M_{H^\pm} > m_t$$

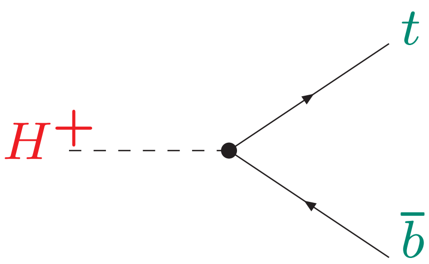
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1 + \Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



$$y_b \, \frac{\tan\beta}{1 + \Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\, \mu \, \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\,\pi} A_t\, \mu \, \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

Most powerful search modes for heavy MSSM Higgs bosons:

$$b\bar{b} \to H/A \to \tau^+\tau^- + X$$
$$gb \to tH^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$
$$pp \to t\bar{t} \to H^\pm + X, \;\; H^\pm \to \tau\nu_\tau$$

Enhancement factors compared to the SM case:

$$H/A \;:\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\mathrm{BR}(H \to \tau^+\tau^-) + \mathrm{BR}(A \to \tau^+\tau^-)}{\mathrm{BR}(H \to \tau^+\tau^-)_{\mathrm{SM}}}$$

$$H^\pm \;:\; \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \mathrm{BR}(H^\pm \to \tau\nu_\tau)$$

$\Rightarrow$ Δ_b effects so far neglected by ATLAS/CMS

also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

$\Rightarrow$ additional effects on $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

Suggestion for new benchmark scenarios:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]

→ investigate benchmark scenarios:

→ Vary only M_A and $\tan\beta$ (large!)
→ Keep all other SUSY parameters fixed

→ Vary in addition μ: $\mu = \pm 1000, \pm 500, \pm 200$ GeV
(if perturbativity allows)

1. m_h^{max} scenario:
   → obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\, M_{\text{SUSY}}$)

   A_t large ⇒ large $\mathcal{O}(\alpha_t)$ contribution to Δ_b

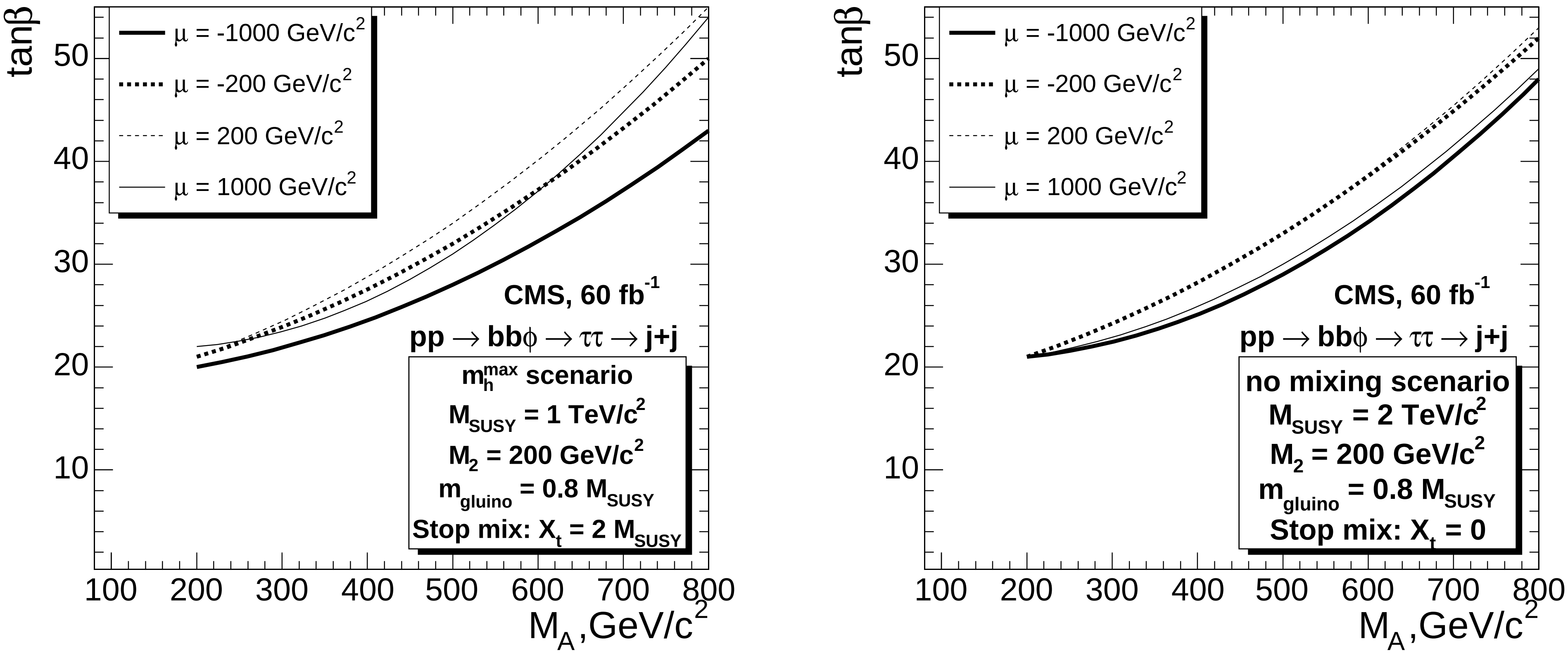
2. no-mixing scenario
   → no mixing in the scalar top sector ($X_t = 0$)

   A_t small ⇒ small $\mathcal{O}(\alpha_t)$ contribution to Δ_b

   ⇒ large difference to m_h^{max} scenario

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,$jets on μ:

[*S.H., A. Nikitenko, G. Weiglein et al. '06*]

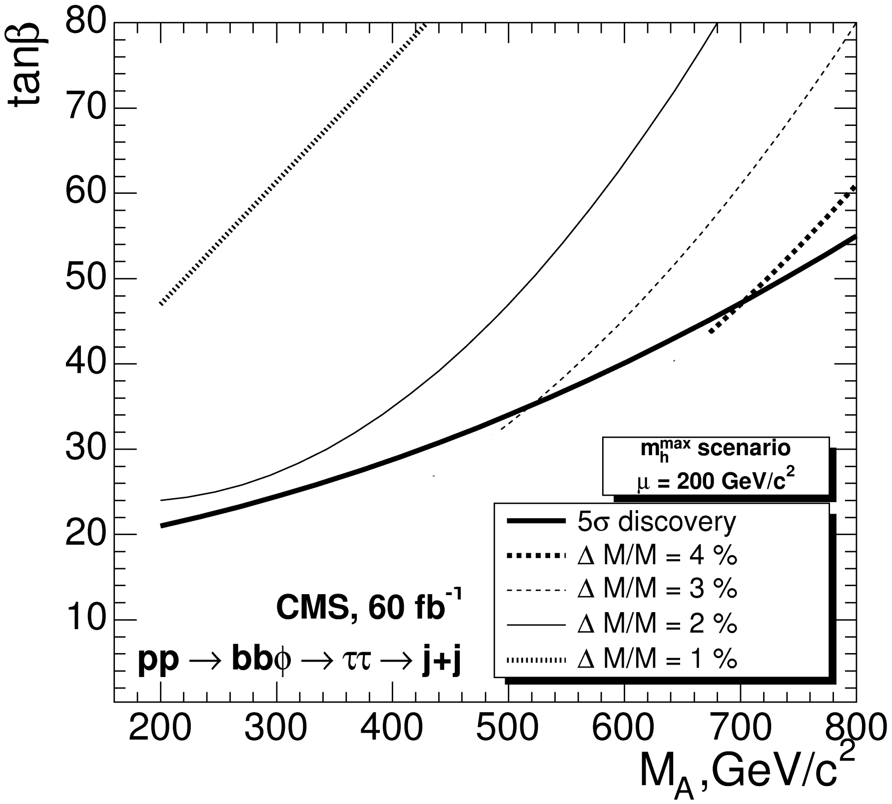


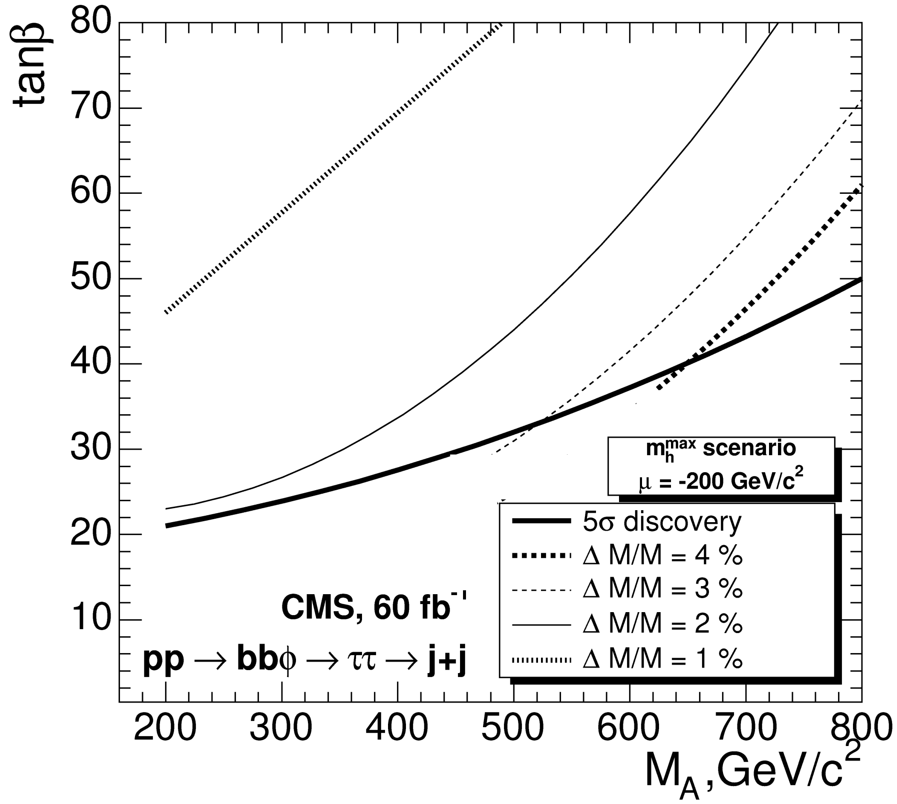
⇒ now based on full CMS simulation

⇒ non-negligible variation with the sign and absolute value of μ
(→ numerical compensations in production and decay)

Precision of $\delta M/M$ from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,$jets:

[*S.H., A. Nikitenko, G. Weiglein et al. '06*]



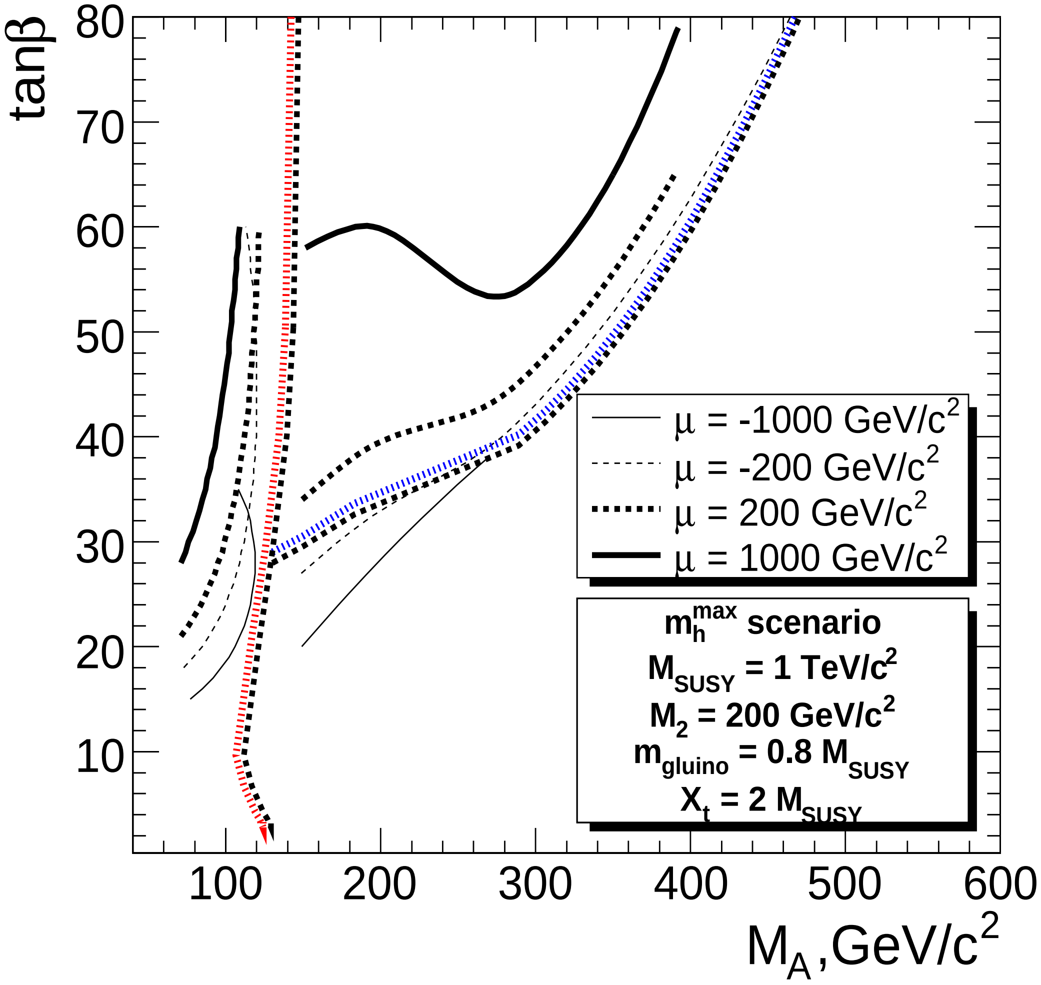


$\Rightarrow$ now based on full CMS simulation

$\Rightarrow$ high precision measurement of heavy Higgs boson masses possible

Charged Higgs: comparison with CMS PTDR (m_h^{max} scenario):

[*M. Hashemi, S.H., R. Kinnunen, A. Nikitenko, G. Weiglein '07*]



→ note: M_A–$\tan\beta$ plane

light charged Higgs:

always worse than PTDR

better $M_{H^\pm}$ calculation!

inclusion of Δ_b effects

heavy charged Higgs:

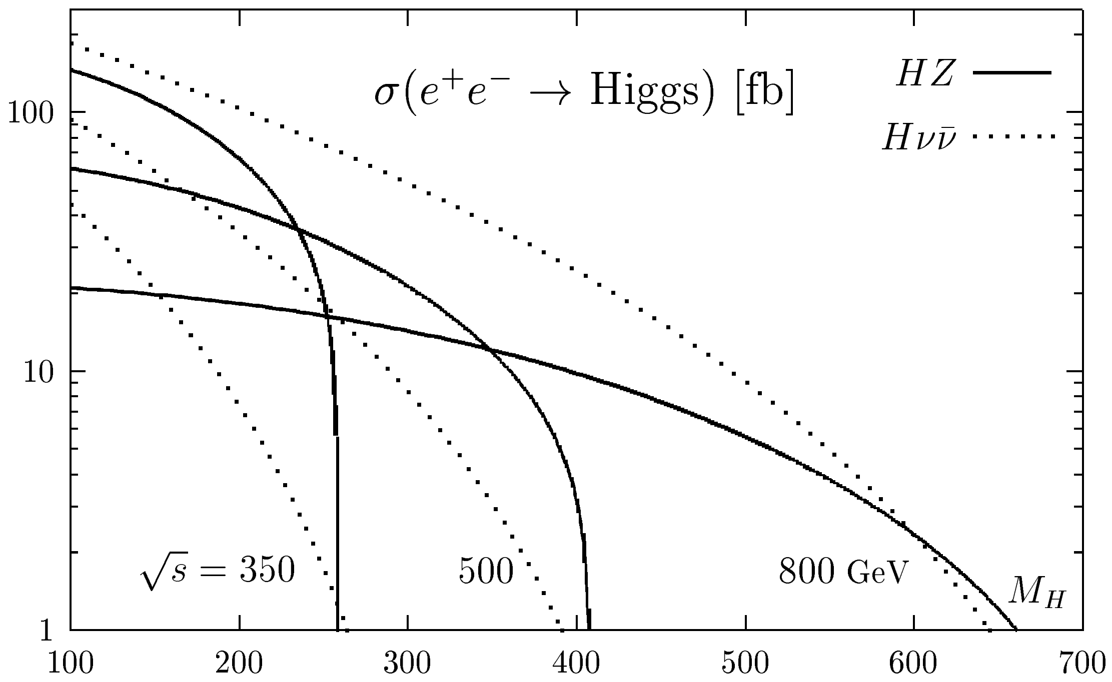
PTDR in "the middle"

new results partially

substantially worse

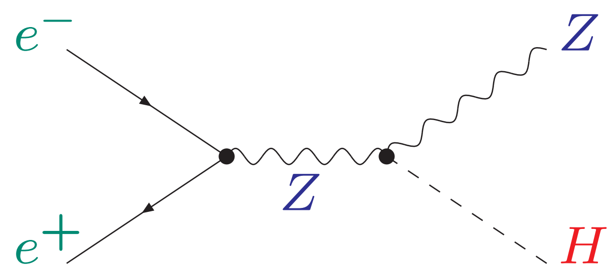
4. Higgs precision physics at the ILC

Higgs production at the ILC:



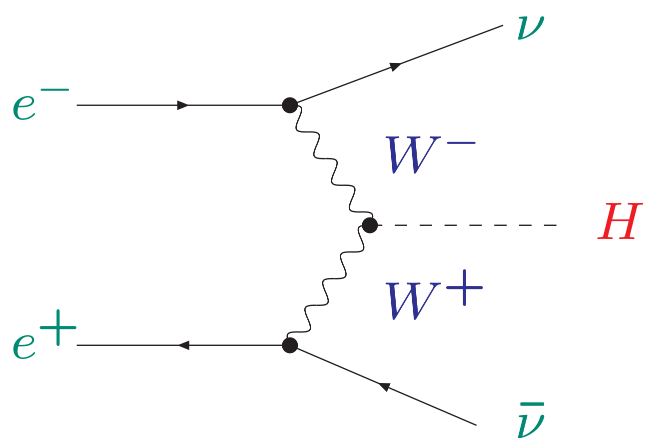
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e+e- \to \nu\bar{\nu}H$



$\Rightarrow$ Measurement of masses, couplings, . . . in per cent/per mille

Some ILC specifics:

recoil method: $e^+e^- \to ZH,\ Z \to e^+e^-,\ \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

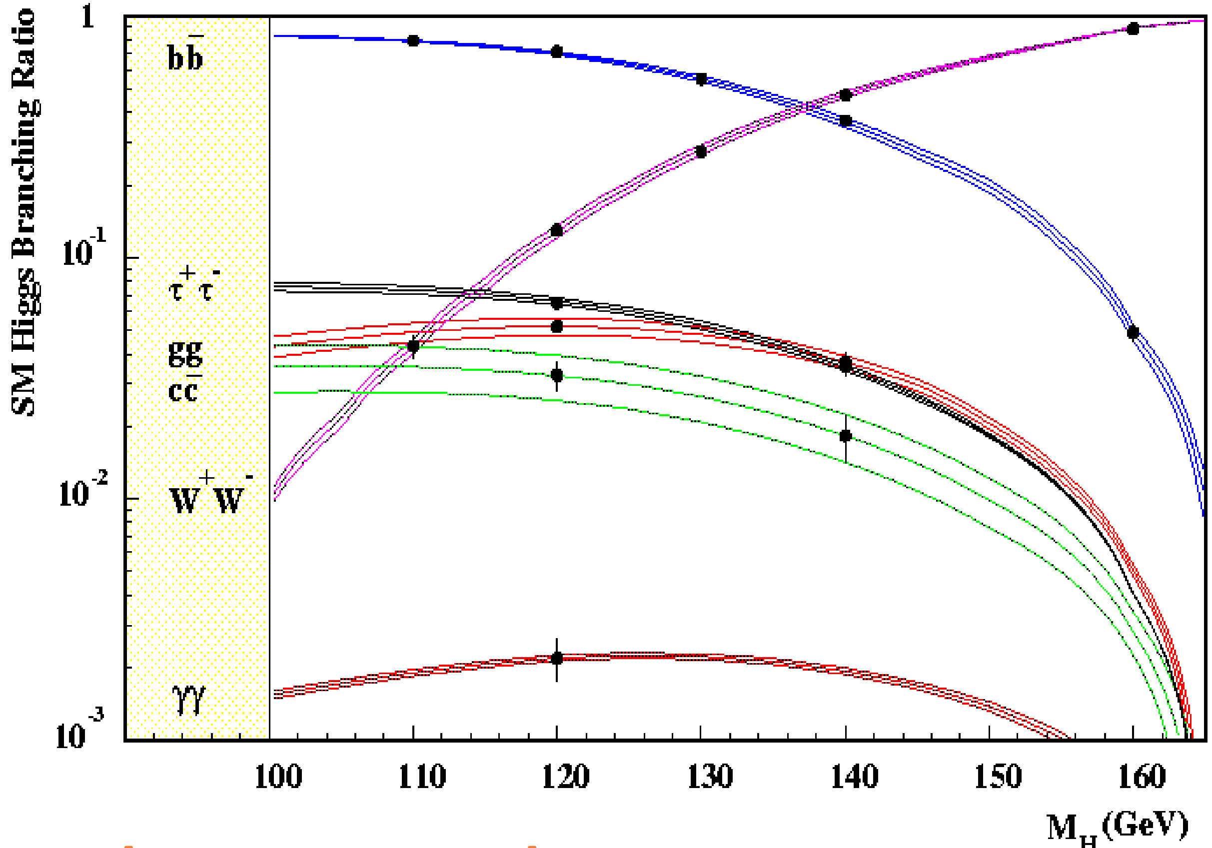
Some ILC results (500 fb^{-1}@$\sqrt{s} = 350$ GeV):

$\delta M_H \approx 50$ MeV
$\delta g_{ZZH} \approx 2.5\%$, $\delta g_{WWH} \approx 2 - 5\%$
$\delta g_{Hb\bar{b}} \approx 1 - 2\%$ (for $M_H \lesssim 150$ GeV)

Higgs physics at the ILC:

SM Higgs @ ILC:
Precise measurement of:

1. Higgs boson mass,
   $\delta M_H \approx 50$ MeV
2. Higgs boson width
   (direct/indirect)
3. Higgs boson couplings,
   $\mathcal{O}$ (few%) $\Rightarrow$
4. Higgs boson quantum
   numbers: spin, . . .



[*TESLA TDR '01*]

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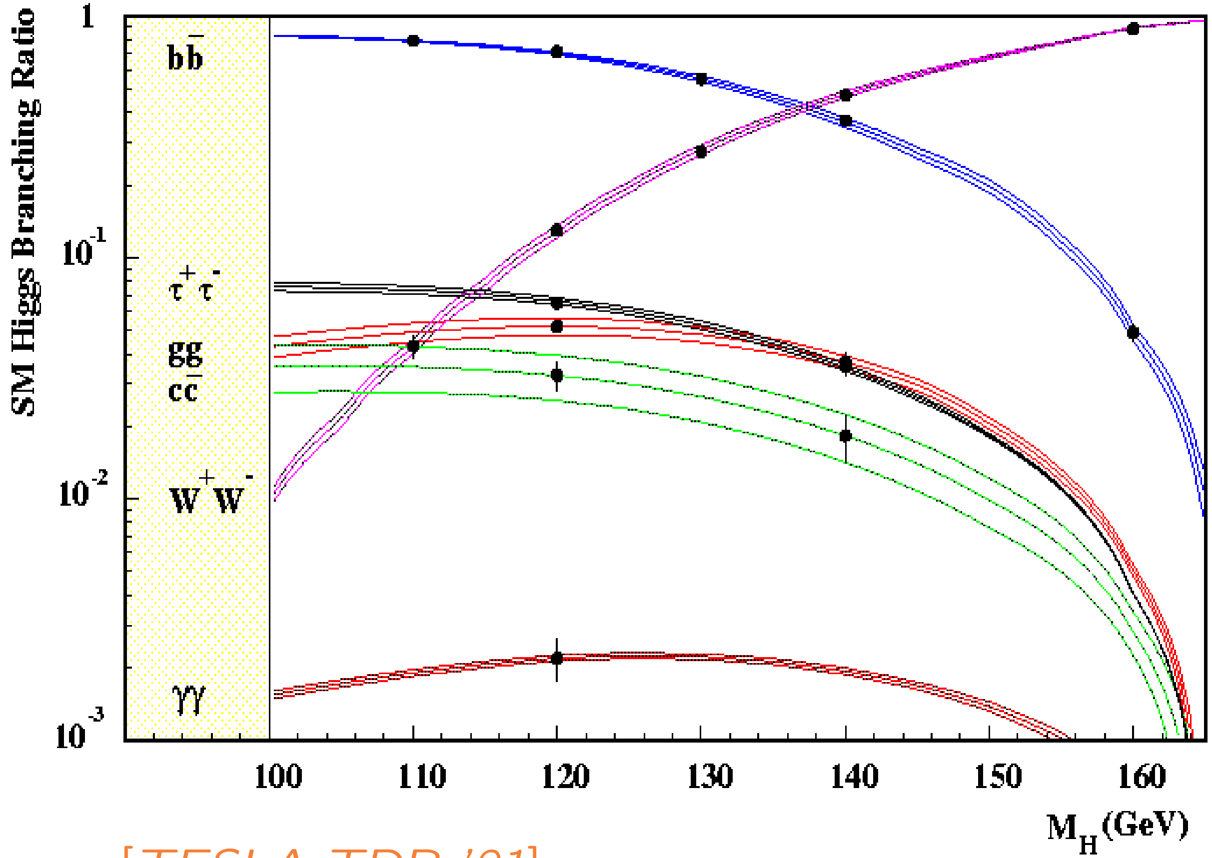

[*TESLA TDR '01*]

But do we need the ILC precision?

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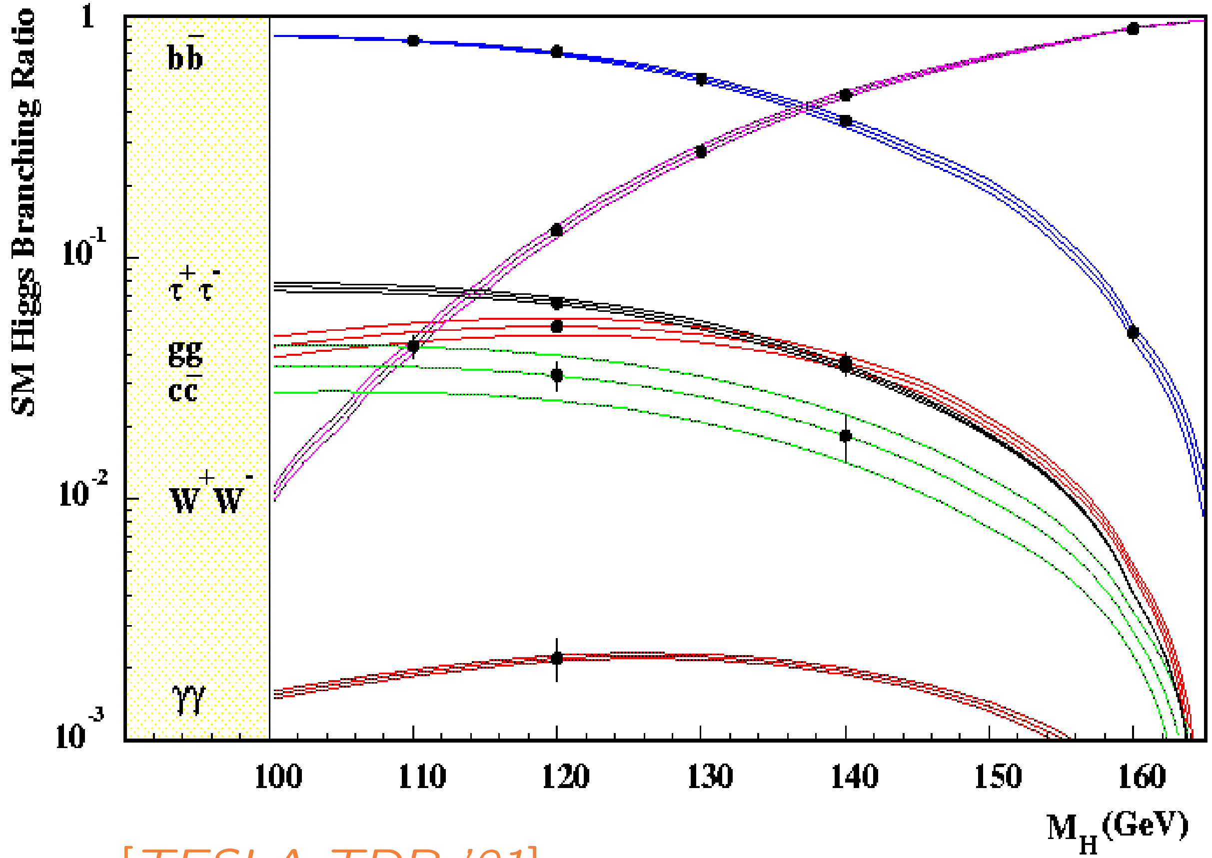
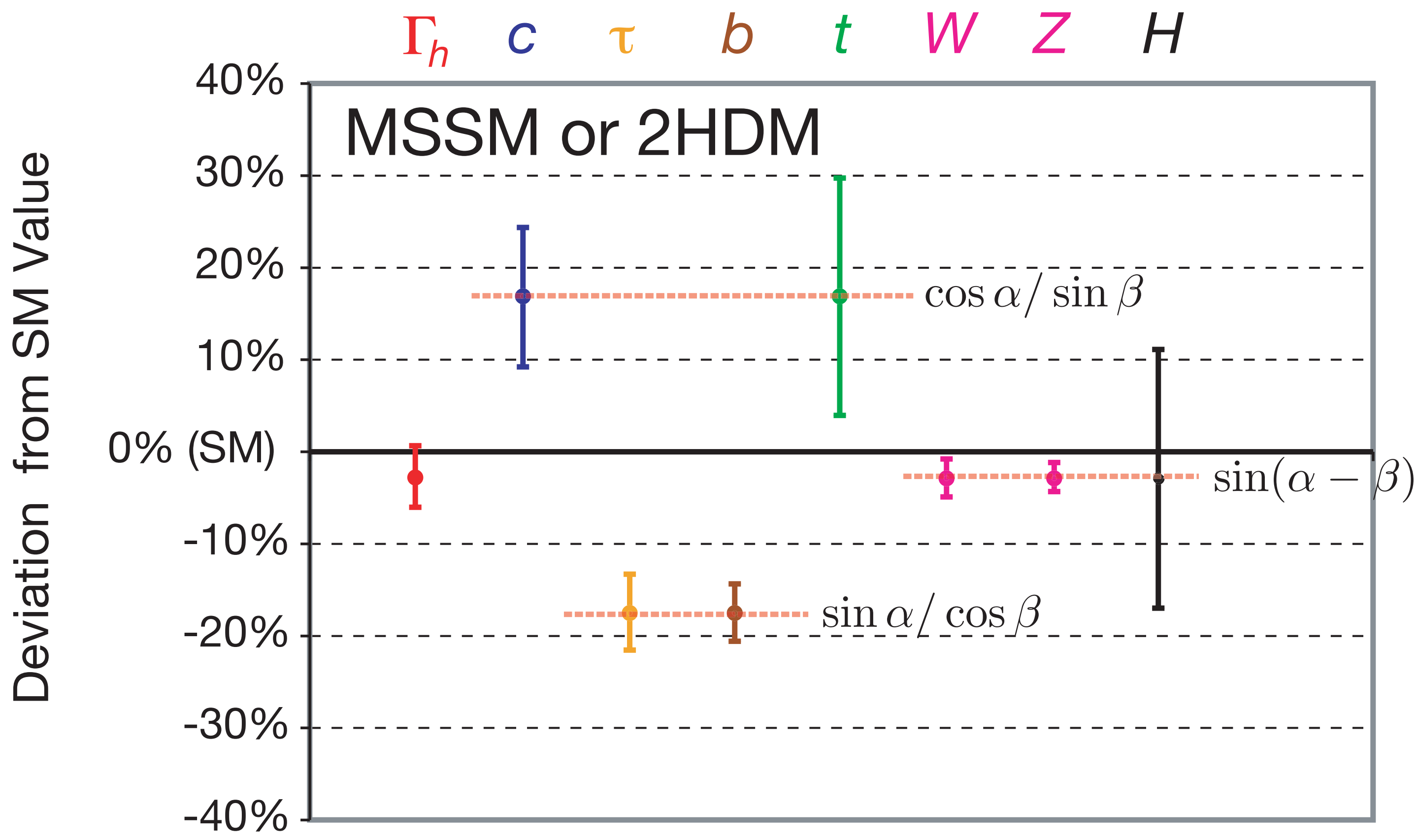


[*TESLA TDR '01*]

But do we need the ILC precision?
YES! To discriminate between the SM and extensions

Example I: Higgs couplings in the MSSM:

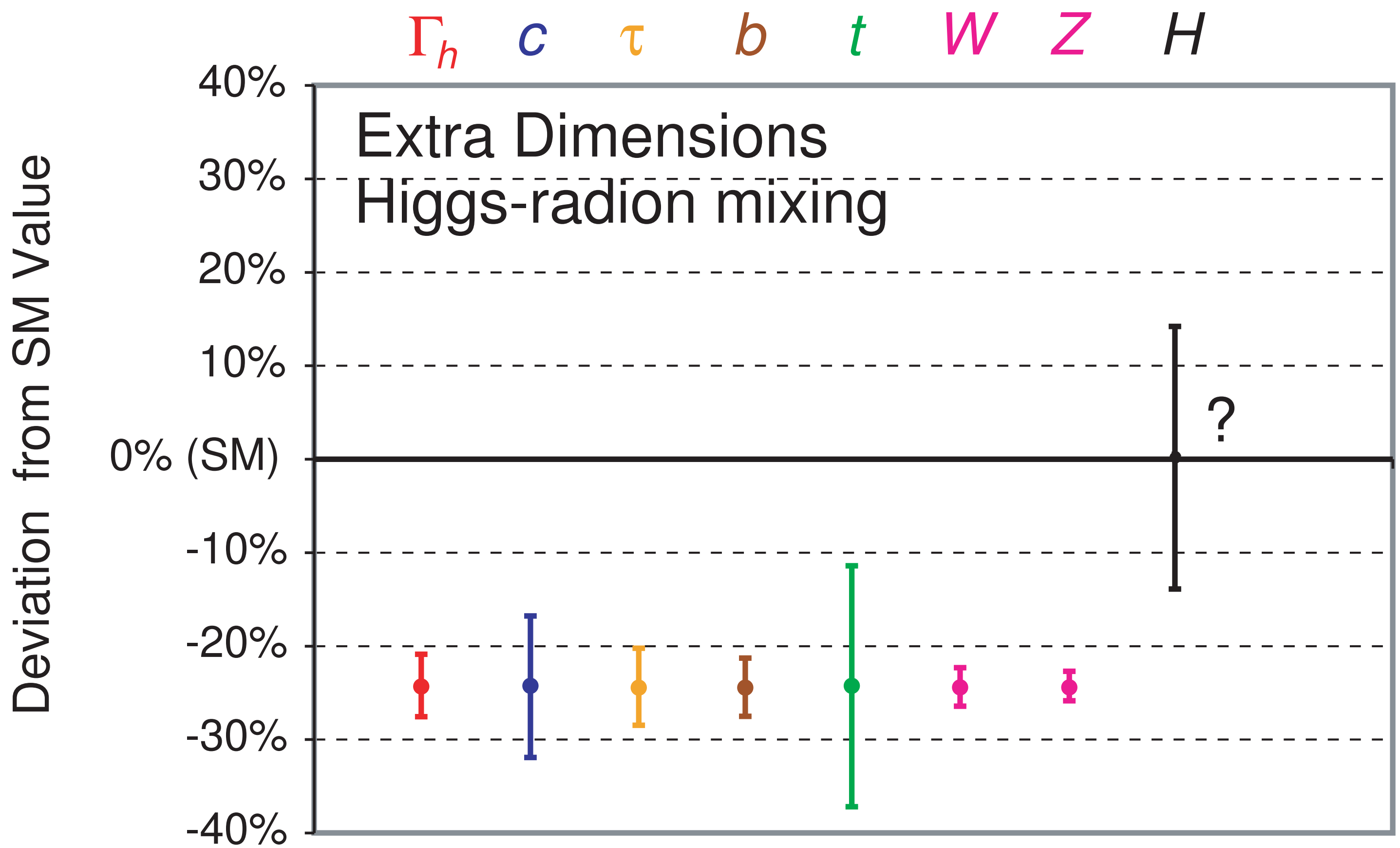
"Normal" MSSM scenario:



$\Rightarrow$ measurable deviations over large parts of the parameter space

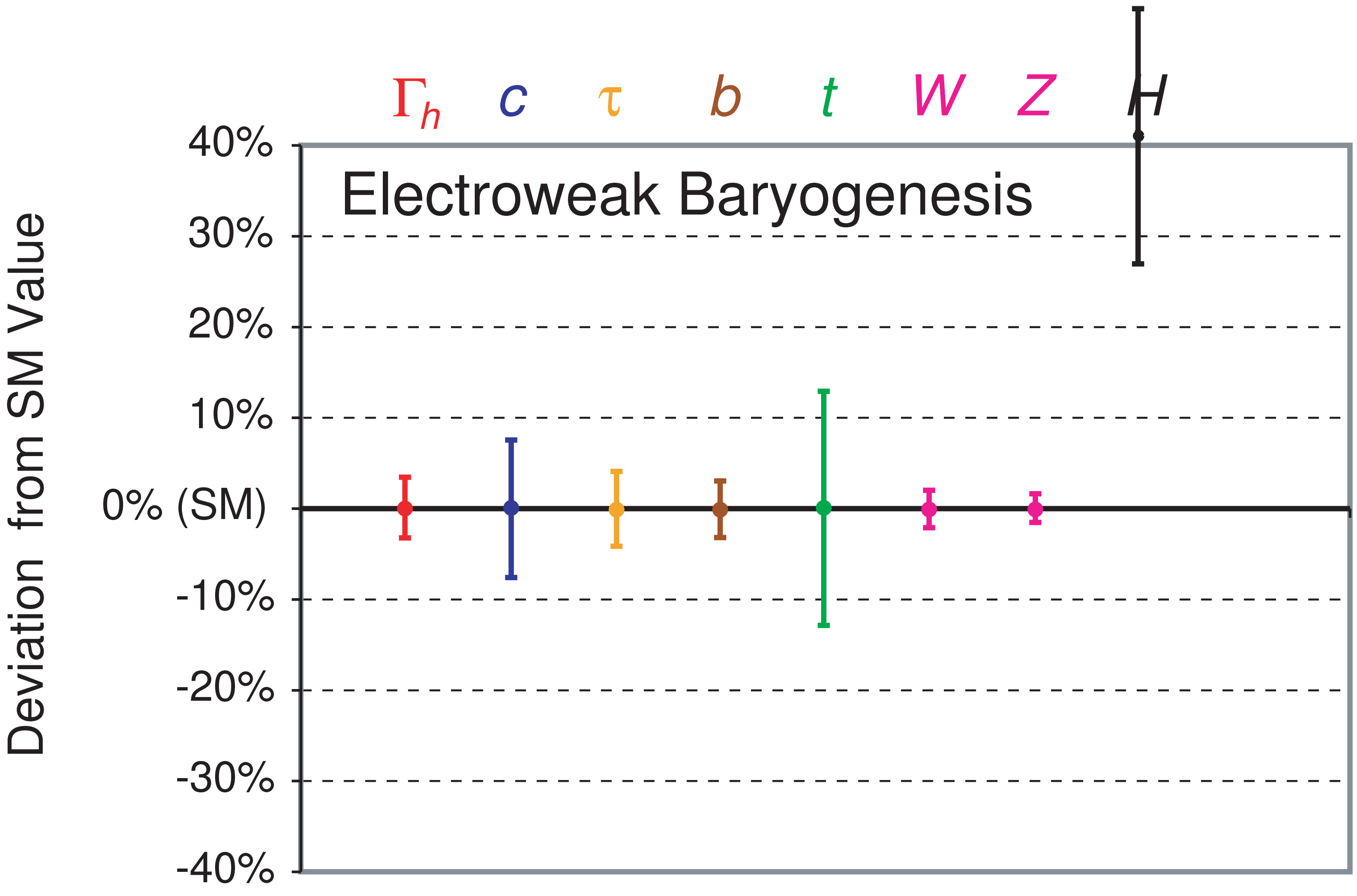
Example II: Higgs couplings in model with extra dimensions:

Effects of Kaluza Klein towers:



$\Rightarrow$ measurable deviations over large parts of the parameter space

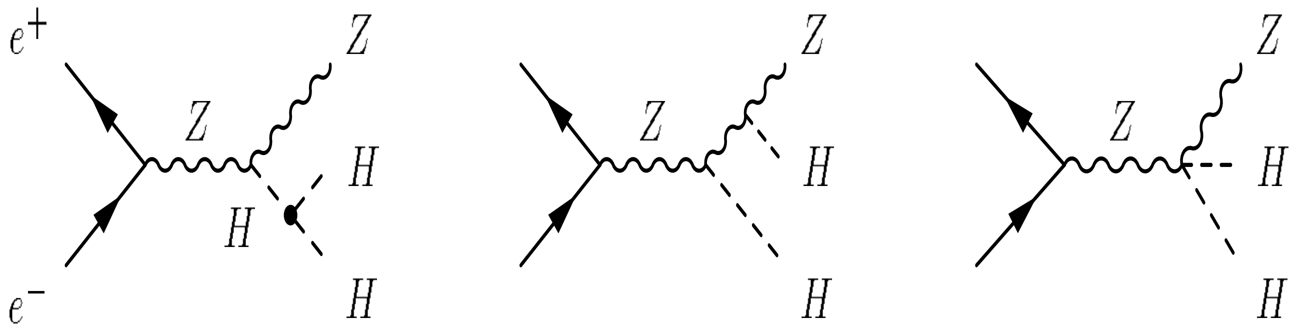
Example III: Higgs couplings in a baryogenis motivated SM extension:



⇒ Only Higgs self coupling deviates, measurement possible!

Step 5: measurement of the Higgs boson self-coupling

⇒ only possible at the ILC



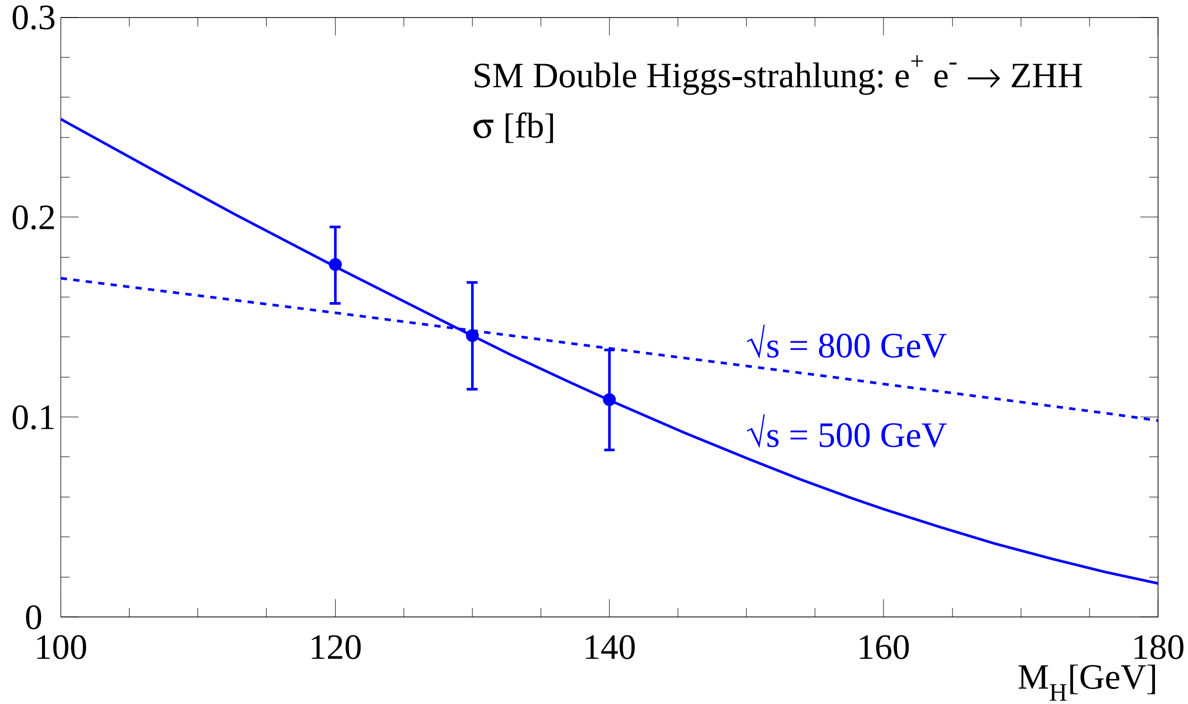
Parton-level study:

[*Djouadi, Kilian, Mühlleitner, Zerwas '99*]

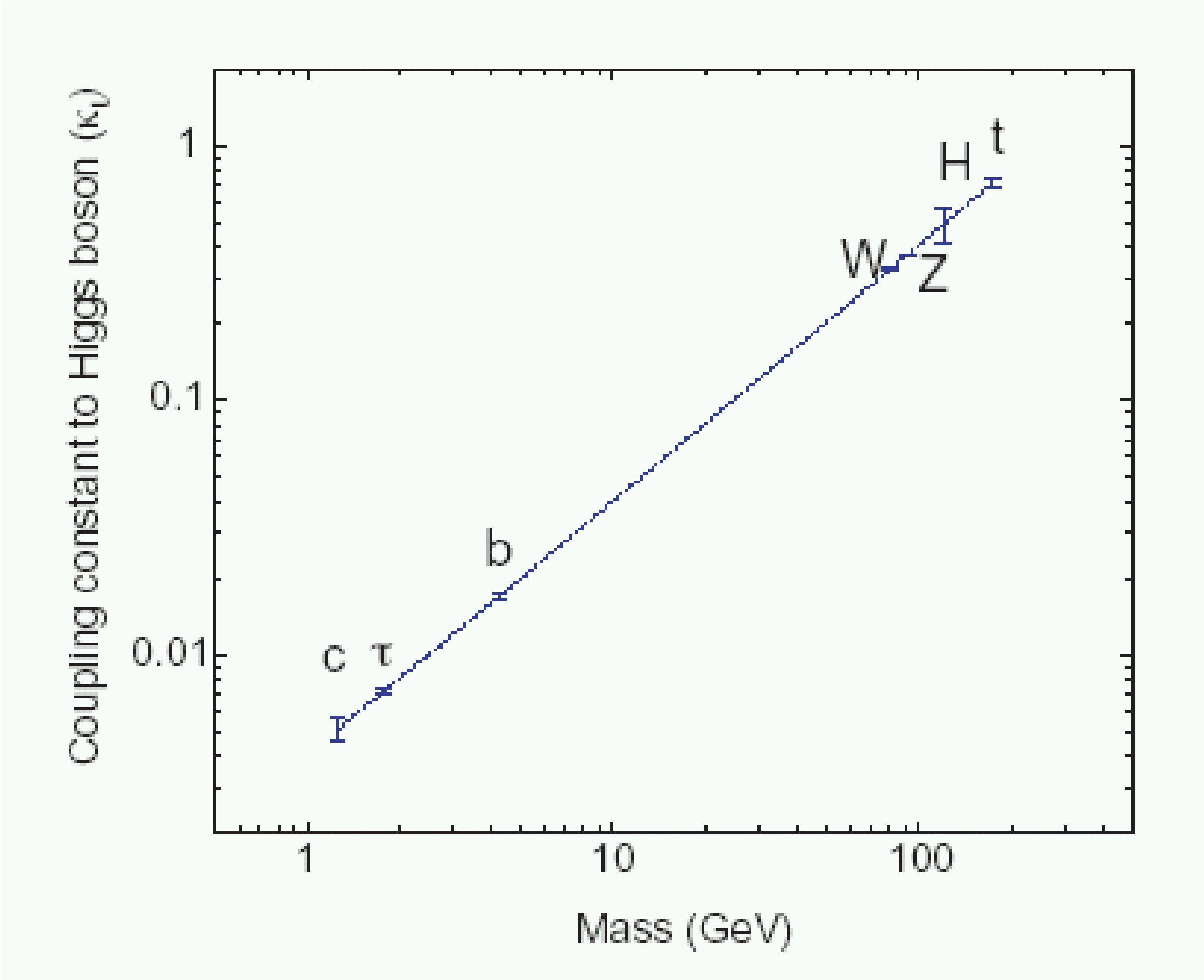
1 ab^{-1} ⇒ 20–30% measurement of $\lambda = \lambda_{HHH}$

However:

$\lambda = \lambda_{HHHH}$ out of reach for all foreseeable colliders

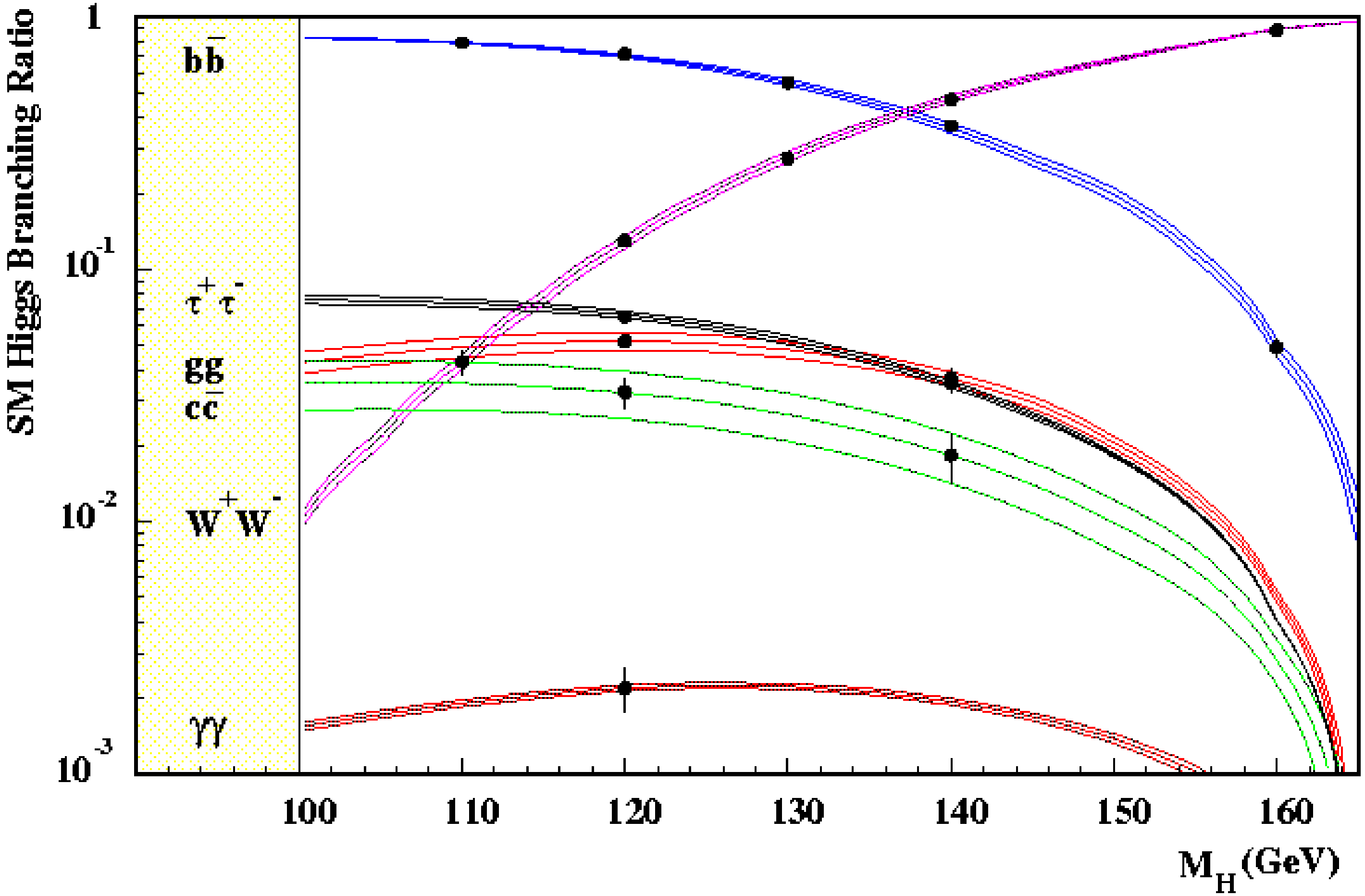


⇒ only Lepton Colliders can "verify" the Higgs mechanism



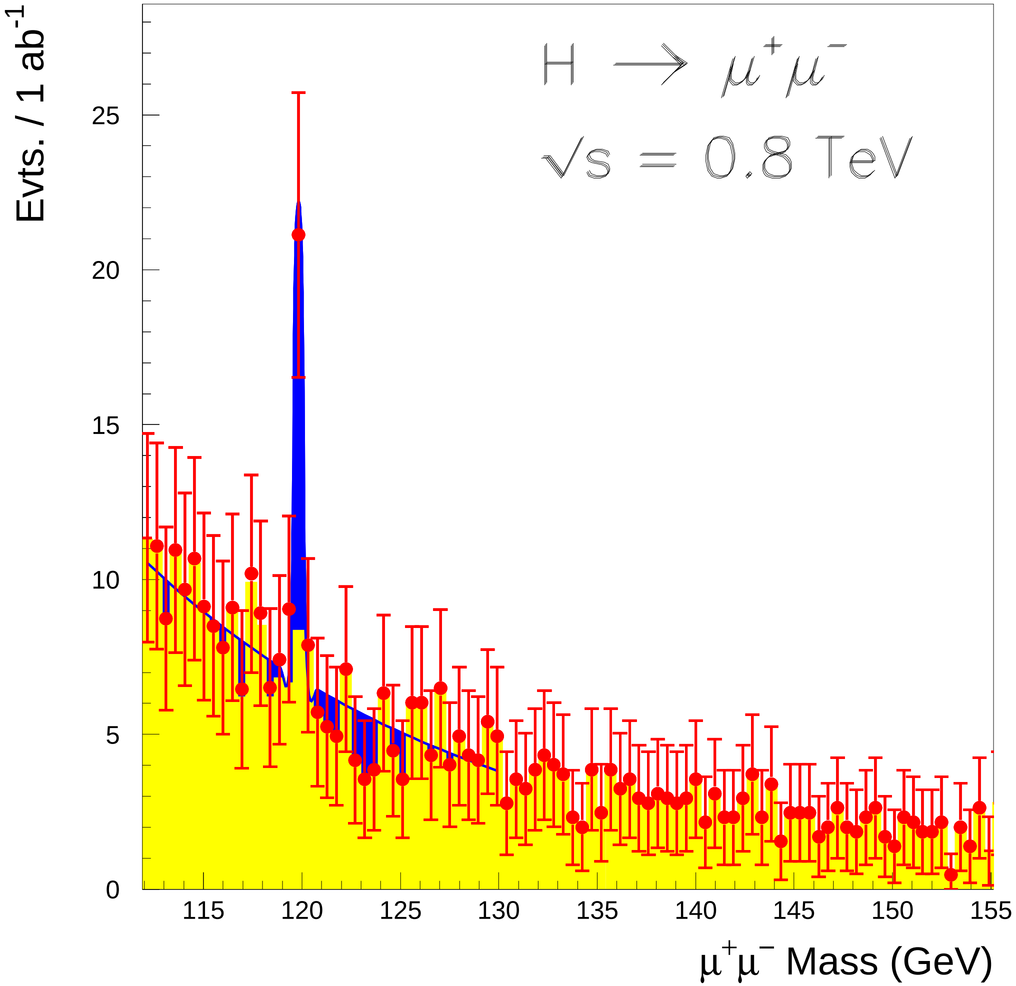
. . . including couplings to the second family!

⇒ coupling to the c quark:



. . . including couplings to the second family!

⇒ coupling to the muon:



$(M_H = 120$ GeV, $\sqrt{s} = 800$ GeV, $\mathcal{L}_{\text{int}} = 1$ ab$^{-1})$

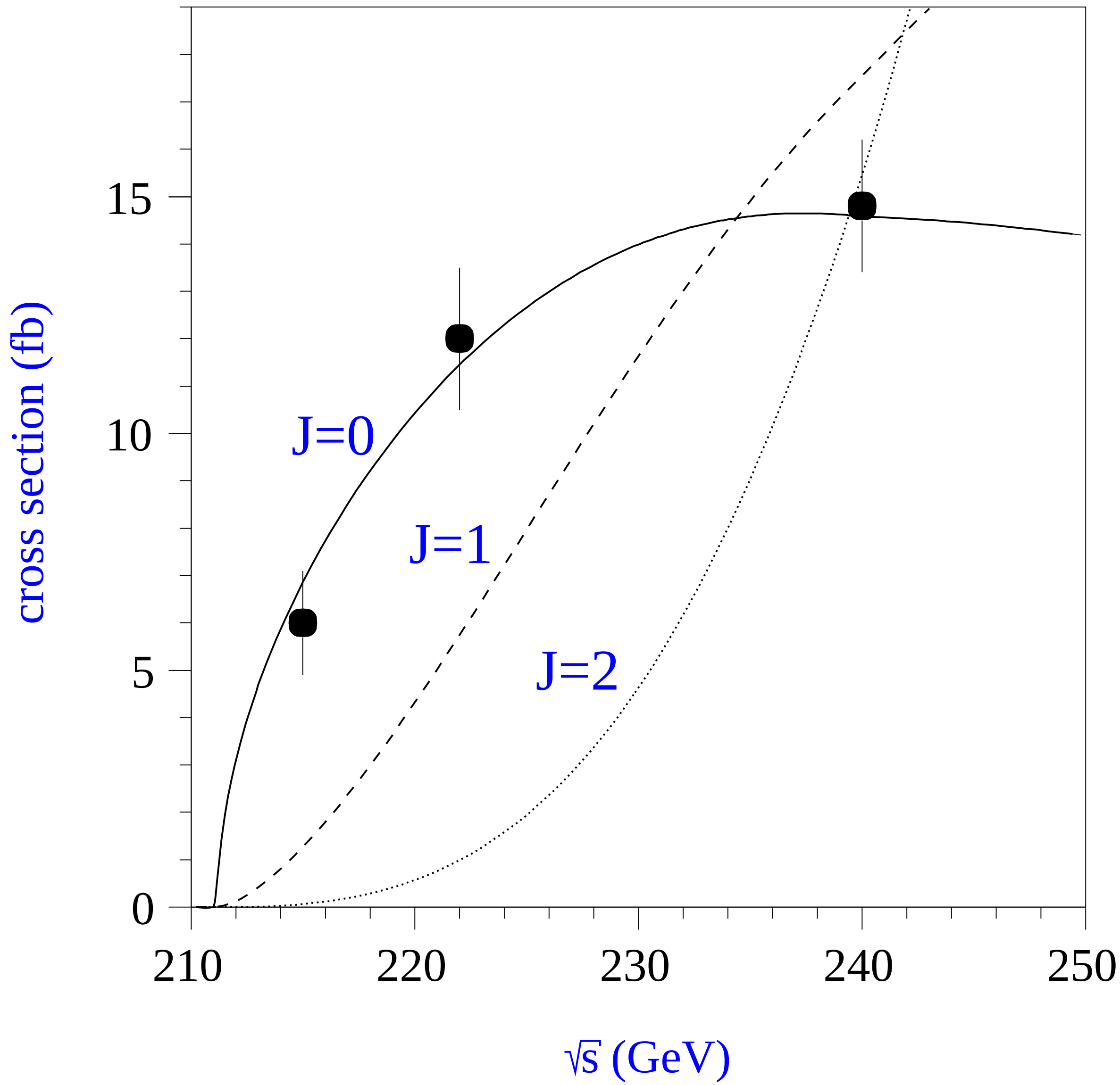
Step 6: measurement of the Higgs boson spin

$\Rightarrow$ easy at the ILC

Threshold scan for
$\sigma(e^+e^- \to ZX)$:

$X = H \Rightarrow \sigma \sim \beta$
(β from kinematics)

20 fb^{-1}
$\Rightarrow$ identification easy



Indirect determination of unknown Higgs sector parameters

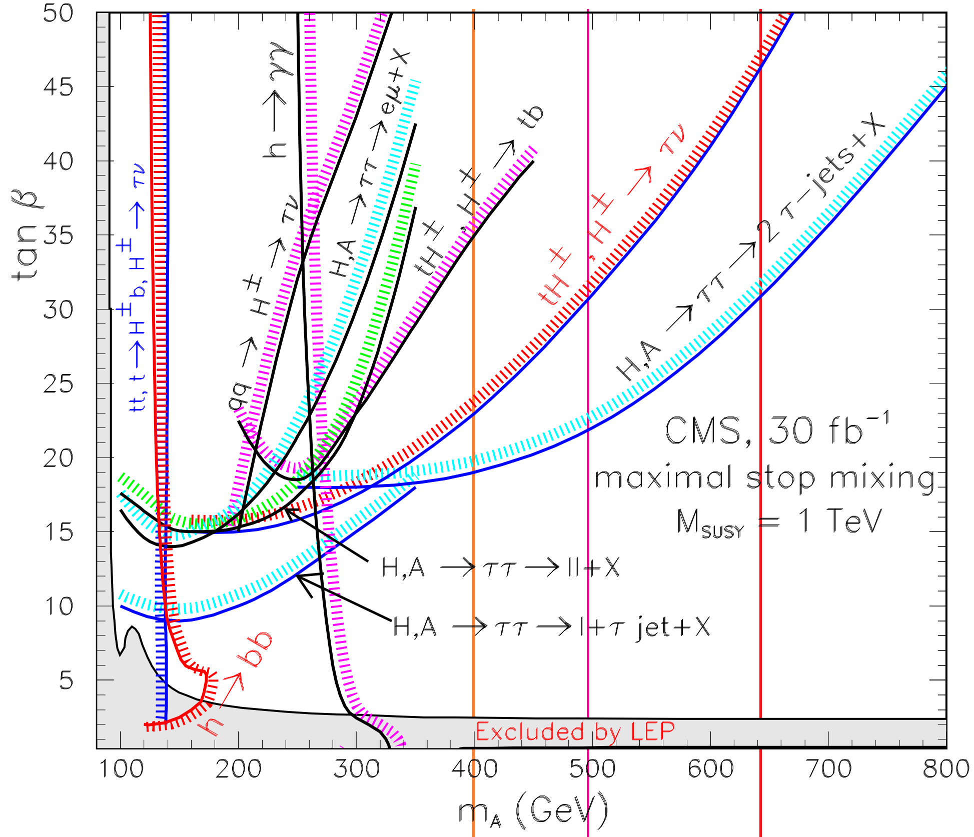
LHC/ILC reach for MSSM Higgs bosons:

LHC:

h : all $M_A - \tan\beta$ plane

H, A : unreachable parts

CMS, 30 fb^{-1}, $m_h^{\rm max}$ scenario: $\Rightarrow$



ILC: $\sqrt{s} = 800$ GeV

$\sqrt{s} = 1000$ GeV

ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2$

$\to \sqrt{s} = 800$ GeV

$\to \sqrt{s} = 1000$ GeV

$\gamma\gamma$:

kinematic limit: $M_A \lesssim 0.8\sqrt{s}$

$\gamma\gamma$: $\sqrt{s} = 800$ GeV

Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

⇒ indirect determination of M_A in LHC wedge

Existing LHC analyses neglect:

– MSSM intrinsic uncertainties
– parametric SM uncertainties
– anticipated parametric MSSM uncertainties

⇒ existing analyses unrealistic

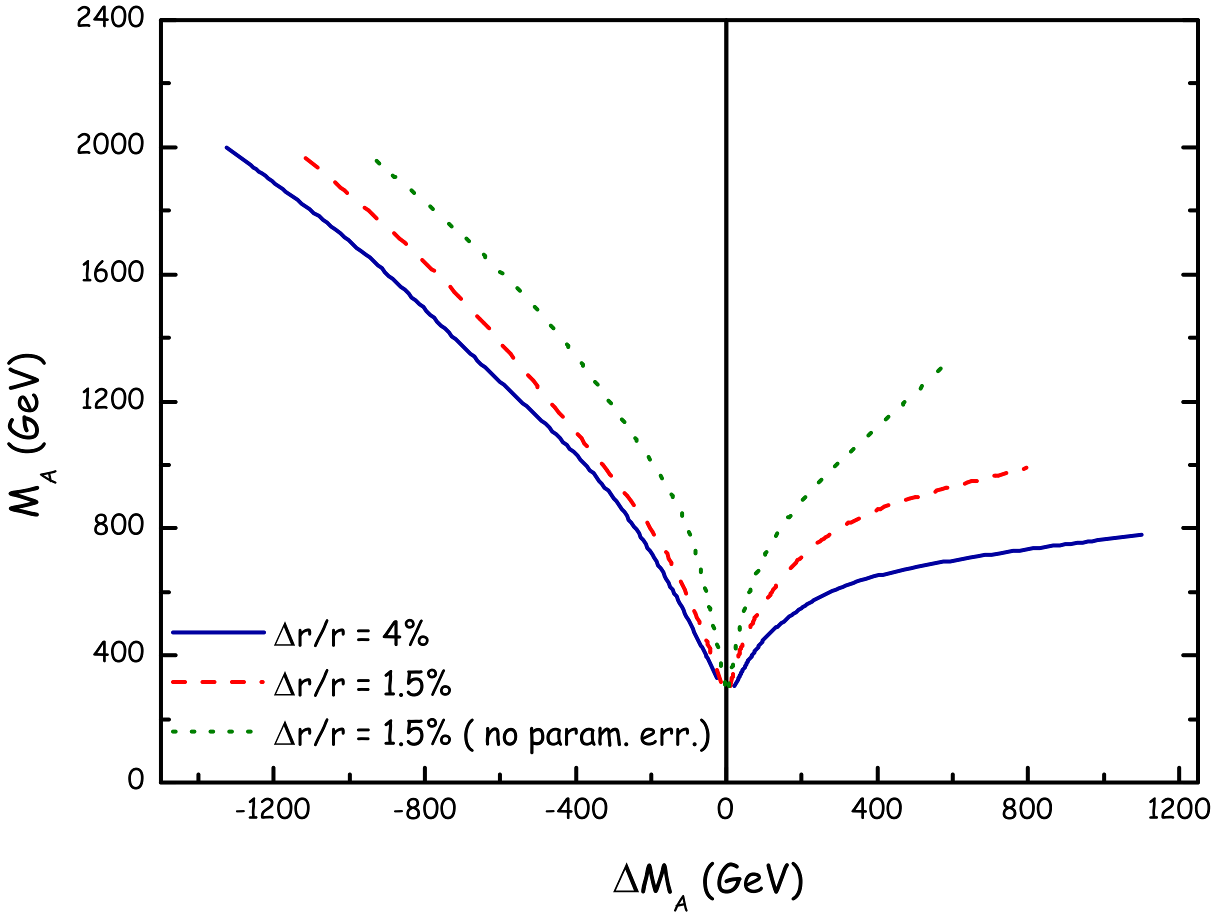
One analysis includes all uncertainties: [K. Desch et al. '04]

⇒ needs ILC uncertainty of

$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

+ input for masses, mixing angles from LHC ⊕ ILC

 [K. Desch et al. '04]



$\Delta r/r = 4\%$: upper limit on M_A up to $M_A \lesssim 800$ GeV

$\Delta r/r = 1.5\%$: $\Delta M_A/M_A = 20(30)\%$ for $M_A = 600(800)$ GeV

inclusion of parametric errors crucial for reliable bounds

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

A: Of course!

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC?

A: Of course! Or better: even more!

The ILC provides:

– precise Higgs coupling measurements

– precision observable measurements with the GigaZ option

⇒ Only the ILC can find deviations from the SM predictions via the various precision measurements

⇒ Only the ILC can point towards extensions of the SM

Outlook

- The quest for electroweak symmetry breaking continues!
- Low-energy Supersymmetry continues to be our best bet for physics beyond the Standard Model
- Data rules:

  We need experimental information from Tevatron, LHC, ILC,
  ν experiments, dark matter searches, low-energy experiments, ...
  to verify / falsify our ideas about electroweak symmetry breaking,
  the Higgs, extensions of the SM, ...
- The experiments in the next years will bring a decisive test of our ideas about the Higgs and electroweak symmetry breaking

$\Rightarrow$ Very exciting prospects for the coming years

Expect the unexpected!

Interested in Theory Predictions?

Interested in

- theory predictions for the Tevatron?
- theory predictions for the LHC?
- theory predictions for the ILC?
- phenomenology analyses in Higgs/SUSY?

⇒ You can do your PhD at IFCA (Santander, Spain)

contact: Sven.Heinemeyer @ cern.ch

Santander, Spain: (15 minutes by foot from the institute :-)

contact: Sven.Heinemeyer @ cern.ch