SUSY/Higgs lectures: overview

Sven Heinemeyer, IFCA (CSIC–UC)

Gausdal, 01/2007

1. Introduction to SUSY
2. The general MSSM and "simplified versions"
3. The Higgs Bosons in the MSSM
4. SUSY Higgs Phenomenology at the LHC

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SUSY/Higgs lectures (IV): SUSY Higgs Phenomenology at the LHC

Sven Heinemeyer, IFCA (CSIC–UC)

Gausdal, 01/2007

1. Discovering the Higgs
2. Past: Higgs search at LEP
3. Present: Higgs search at the Tevatron
4. Future: The Higgs at the LHC

1. Discovering the Higgs boson

What has to be done?

1. Find the new particle

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2. measure its mass ($\Rightarrow$ ok?)

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4. measure couplings to fermions

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5. measure self-couplings

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What has to be done?

1. Find the new particle
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4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

1. 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,

1. 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,

1. 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 (International Linear e^+e^- collider)

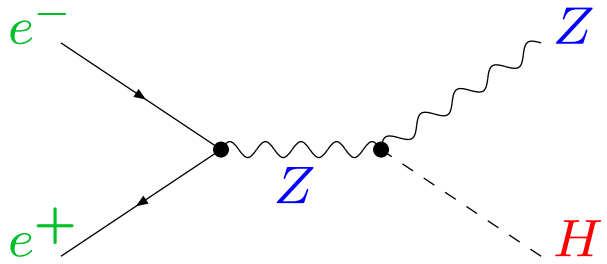
We need the LHC and the ILC to find the Higgs
and to establish the Higgs mechanism!

The LHC can do a crucial part ...

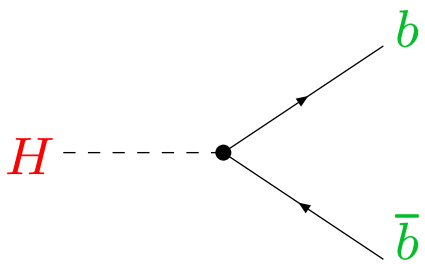
2. Past: Higgs search at LEP:

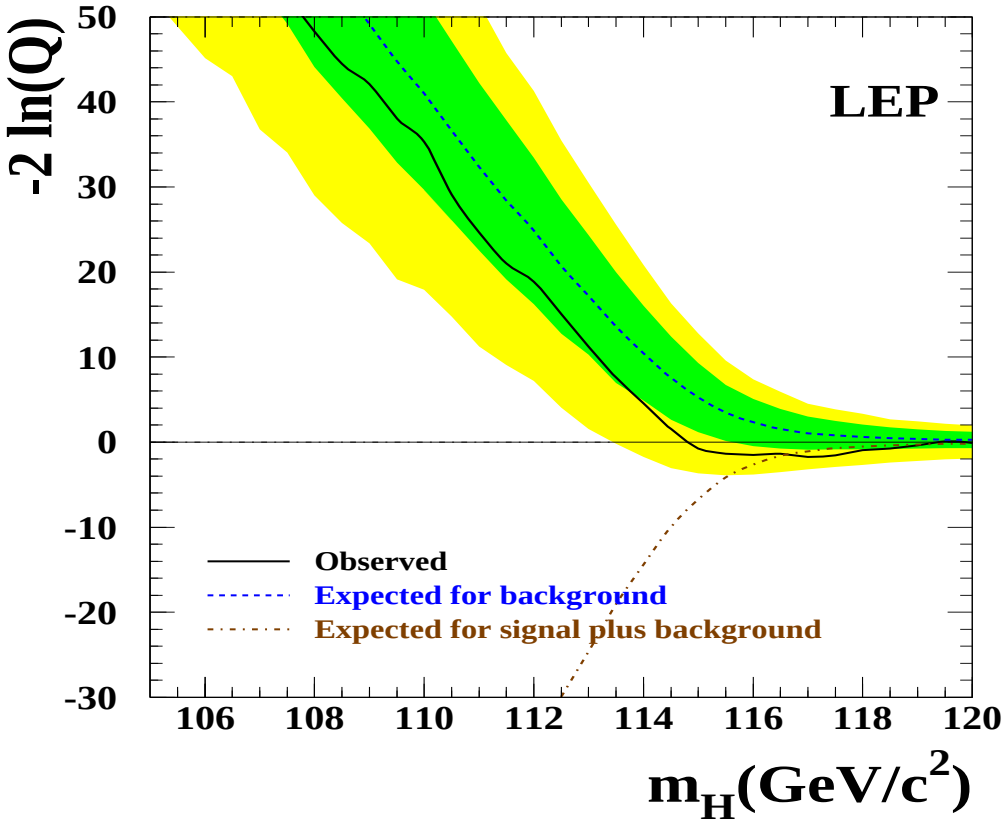
Search for the Standard Model Higgs at LEP: [*LEP Higgs WG '03*]

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



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





Exclusion limit, 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

→ investigate benchmark scenarios:

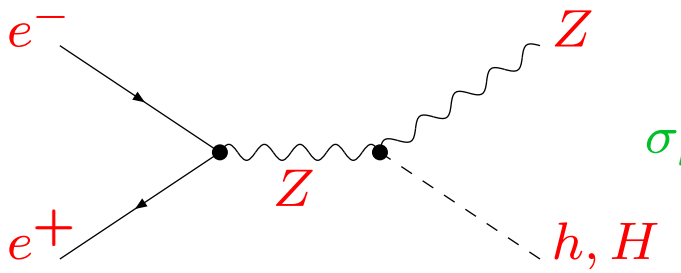
→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

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

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

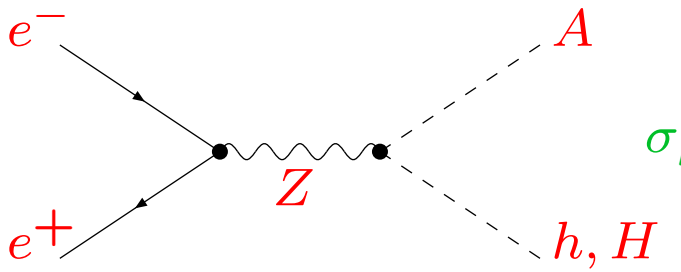
Search for neutral SUSY Higgs bosons:

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



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

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

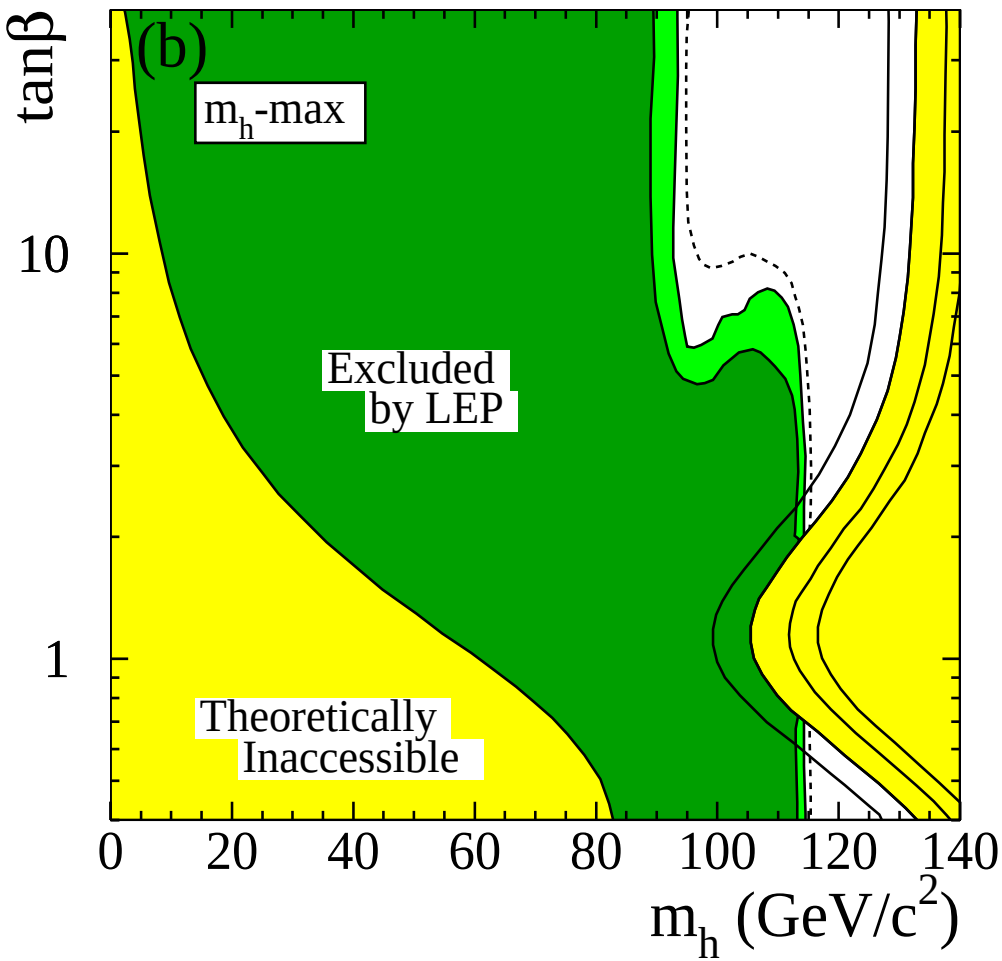


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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 $\sin^2(\beta - \alpha_{\text{eff}}) \ll 1$

"Excluded" $\tan\beta$ region:

$$0.7 < \tan\beta < 2.0$$

Note: this exclusion bound assumes

m_t, M_{SUSY} fixed, $m_t = 174.3$ GeV, $M_{\text{SUSY}} = 1$ TeV

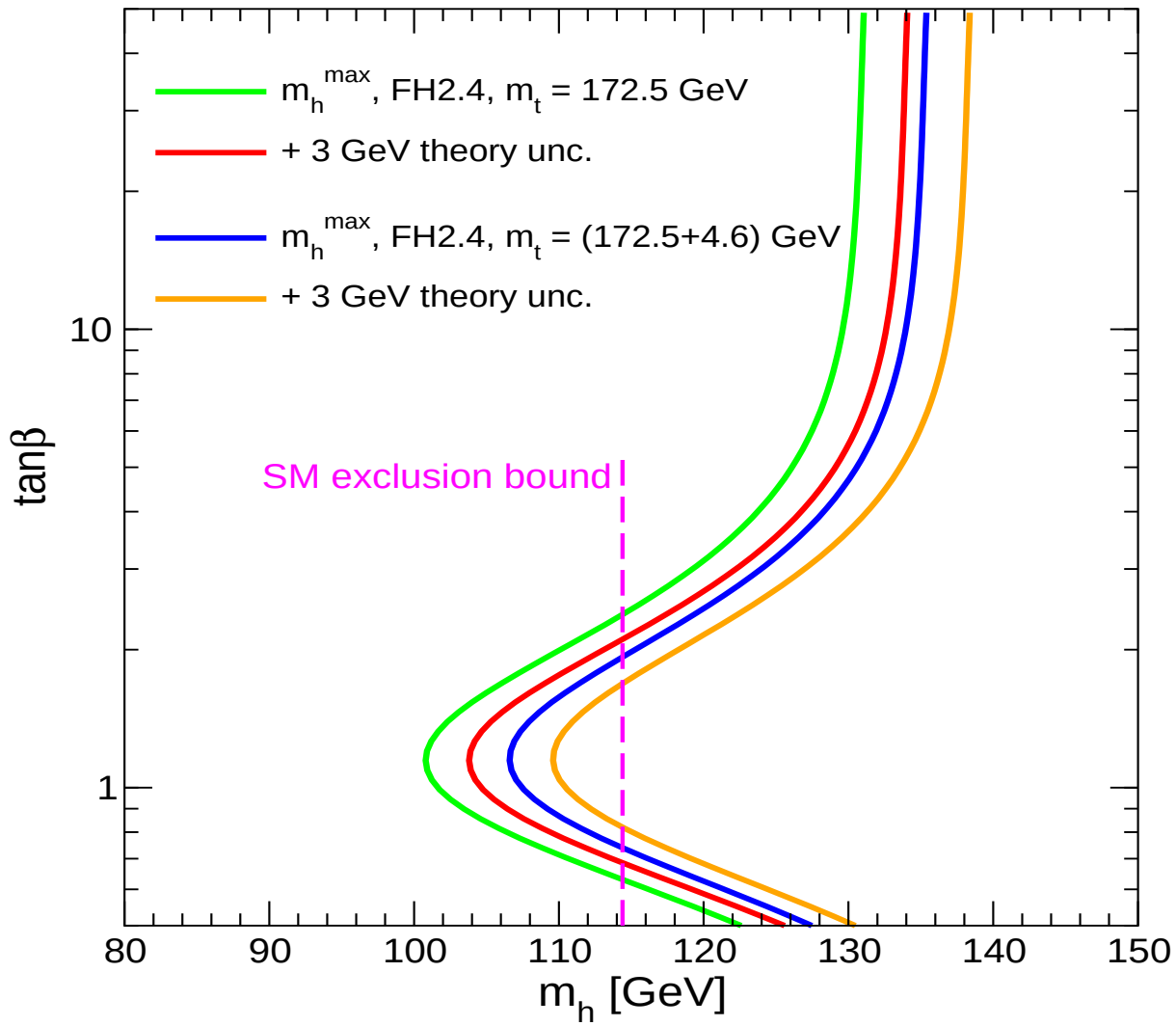
no theoretical uncertainties included

Note: new m_t value: $m_t = 171.4 \pm 2.1$ GeV [*Tevatron EWWG '06*]

parametric uncertainty: $\delta m_h^{\text{para}} \approx \delta m_t$

Effect of new corrections and $m_t \to m_t + 2\,\sigma_{m_t}$

[*S.H., W. Hollik, G. Weiglein '05*]



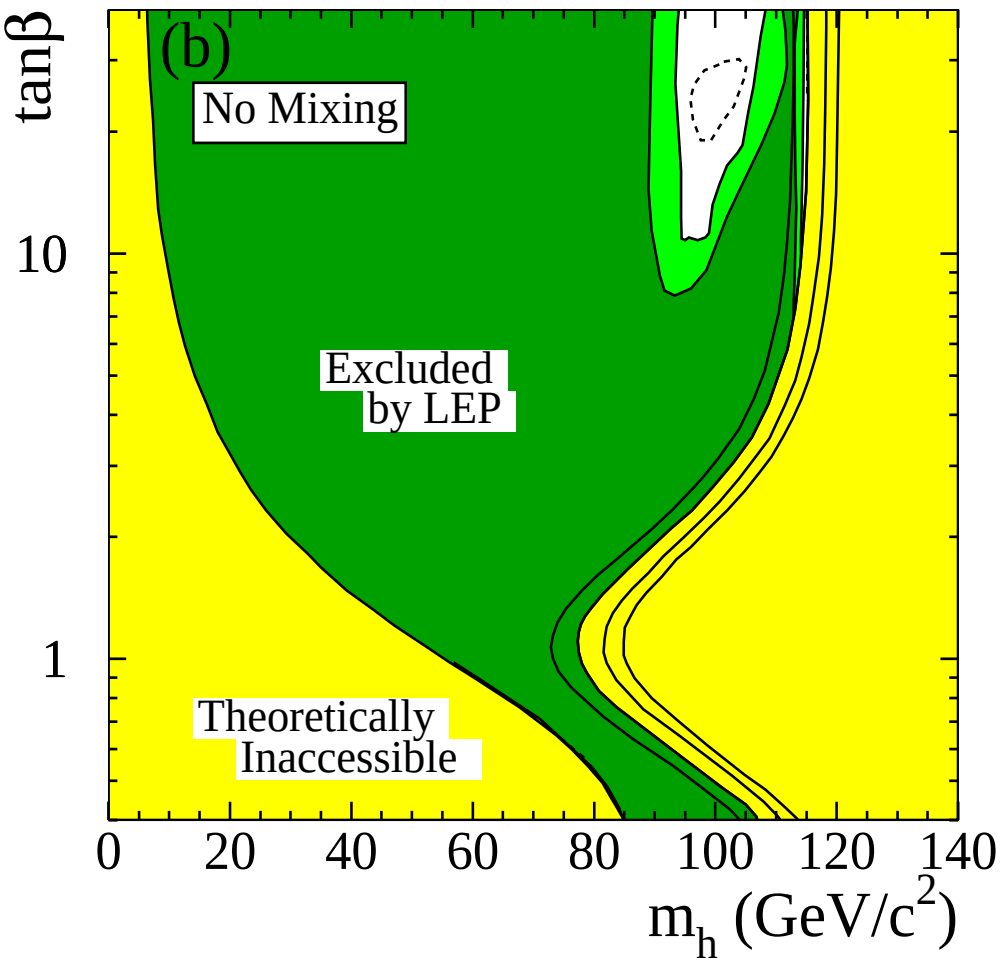
$\Rightarrow$ precise knowledge of m_t important!

$\Rightarrow$ Low $\tan\beta$ LEP exclusion region can vary strongly

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

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

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



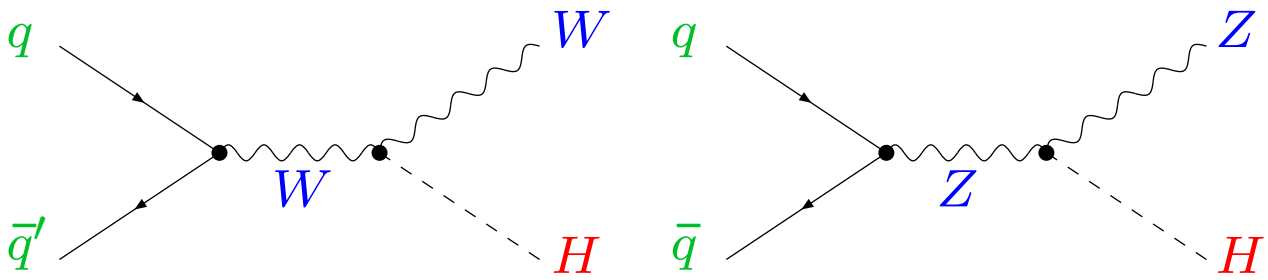
$m_h > 93.6$ GeV
(expected: 96.0 GeV), 95% C.L.

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

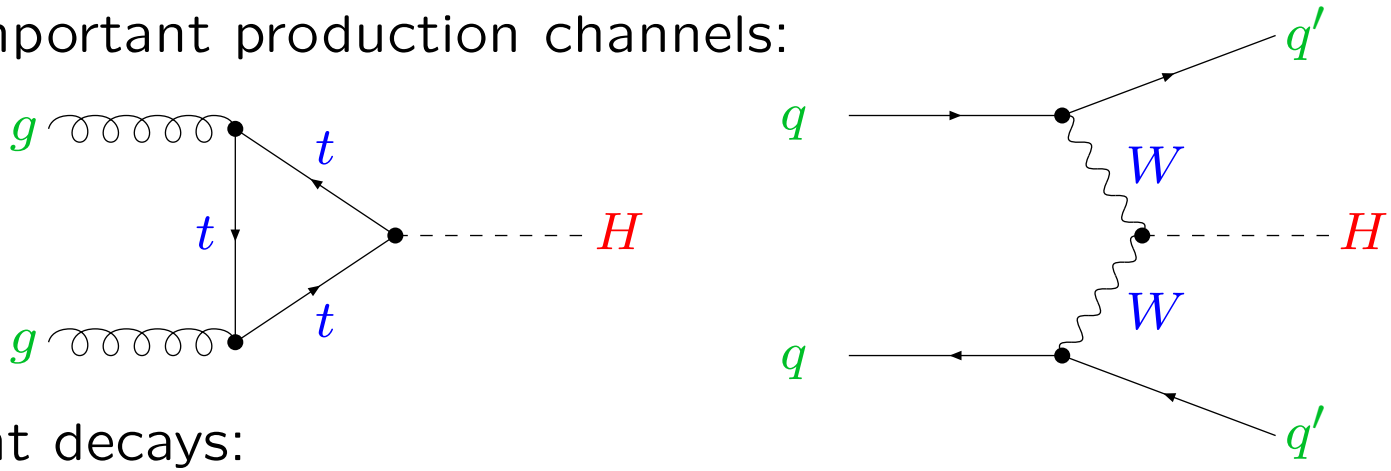
3. Present: Higgs search at the Tevatron

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

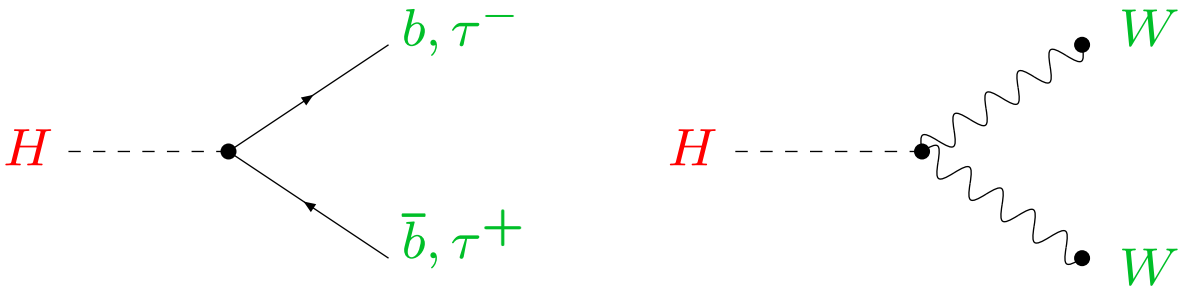
Production processes as at LEP:



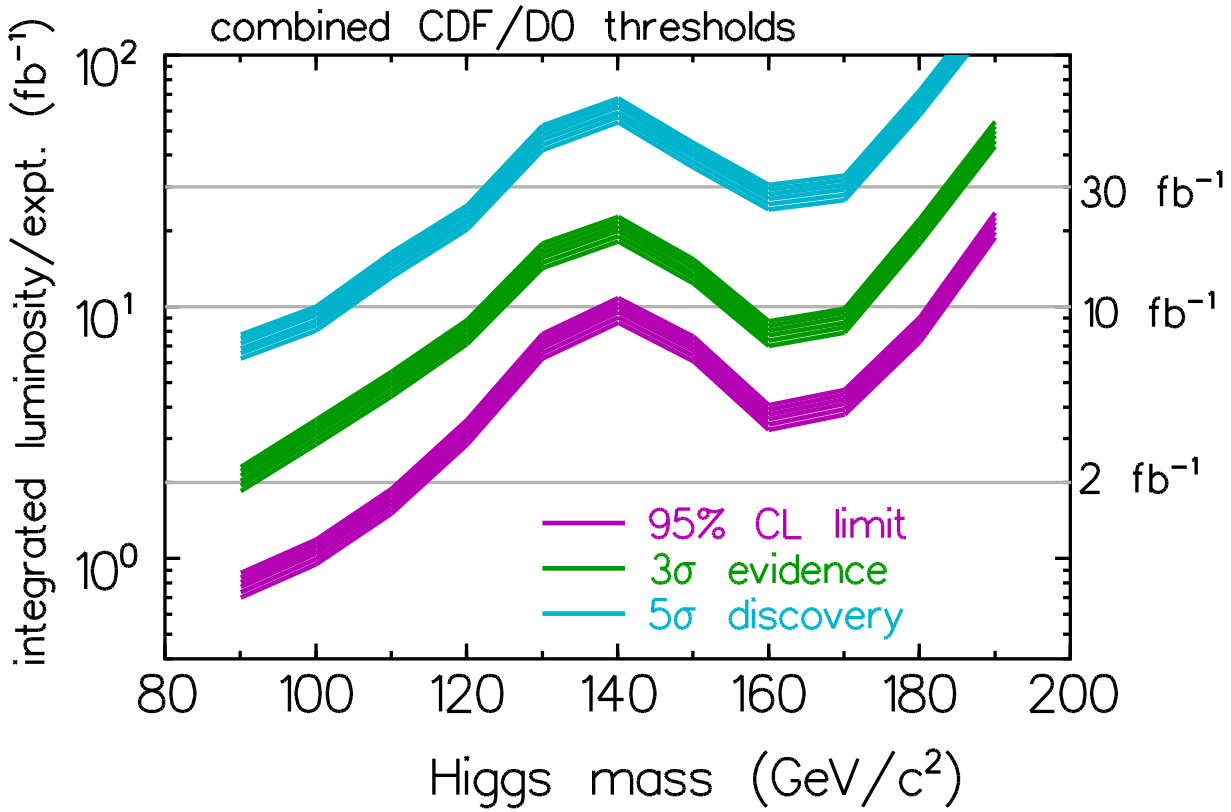
Other important production channels:



Dominant decays:



Expectations for Higgs discovery at the Tevatron:



Unfortunately: luminosity problems in the start of RunII
$\Rightarrow$ progress slower than anticipated

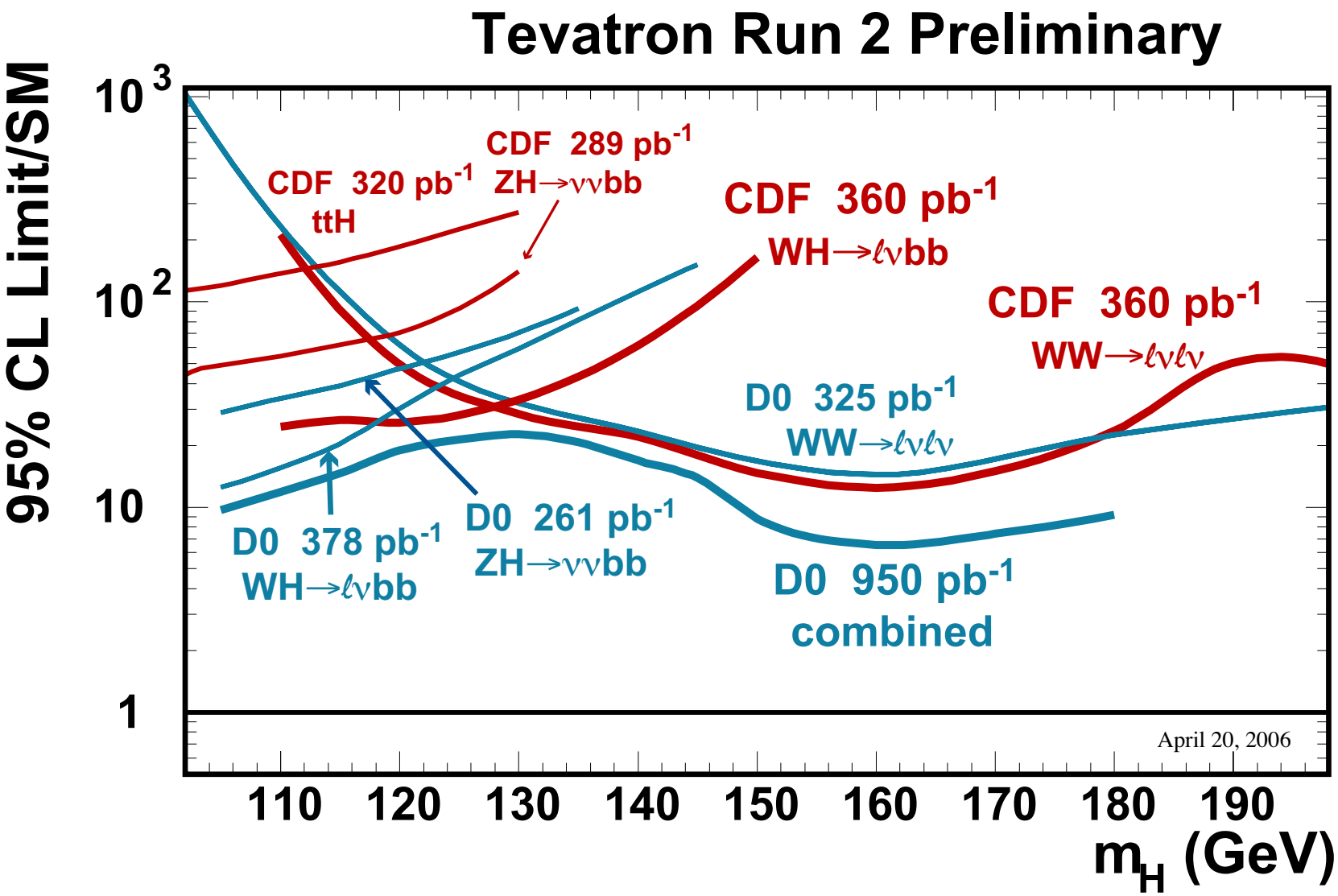
For SM Higgs boson with $M_H \sim 120$ GeV:

$\approx$ 2007/08: sensitivity for 95% C.L. exclusion

$\approx$ 2009: sensitivity for 3σ evidence
or exclude SM Higgs with $M_H \lesssim 130$ GeV

Results for various search channels for SM Higgs:

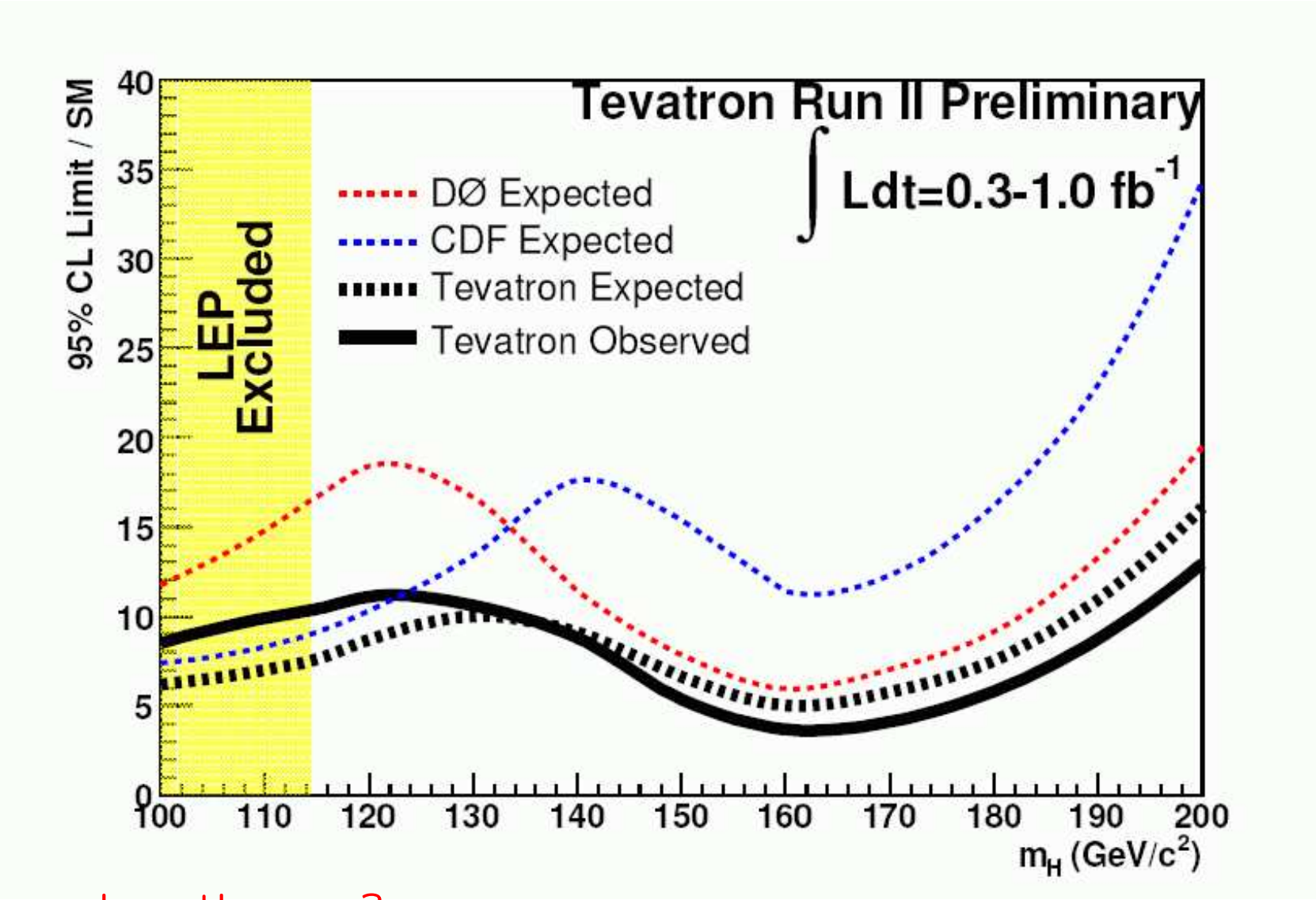
[*CDF, D0 '06*]



Can they close the gap?

Current status (latest results) of SM Higgs search:

[*CDF, D0 '06*]



Can they close the gap?

Tevatron MSSM Higgs searches (I): Search for a "SM-like" light Higgs:

Prediction in "simplified" versions of the MSSM:
($m_t^{\rm exp} = 171.4$ GeV, $\delta m_t^{\rm exp} = 2.1$ GeV, $M_{\rm SUSY} \lesssim$ few TeV)
[A. Dedes, S.H., S. Su, G. Weiglein '03] [S.H., W. Hollik, G. Weiglein '04,'05]

	max. m_h [GeV]	$\delta m_h/\delta m_t$	for $m_t^{\rm exp} + 2\delta m_t$
mSUGRA/CMSSM	124.8	0.65	127.5
mGMSB	119.1	0.70	122.0
mAMSB	120.8	0.58	123.2

Exclusion potential of the Tevatron: $M_H^{\rm SM} \lesssim 130$ GeV

mSUGRA/CMSSM, mGMSB, mAMSB: no suppression of hVV coupling
$\Rightarrow$ SM bound applies

$\Rightarrow$ Tevatron can exclude mSUGRA/CMSSM, mGMSB, mAMSB, ...

$\Rightarrow$ potentially huge impact on search strategies at LHC

Possible problem in SUSY:

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

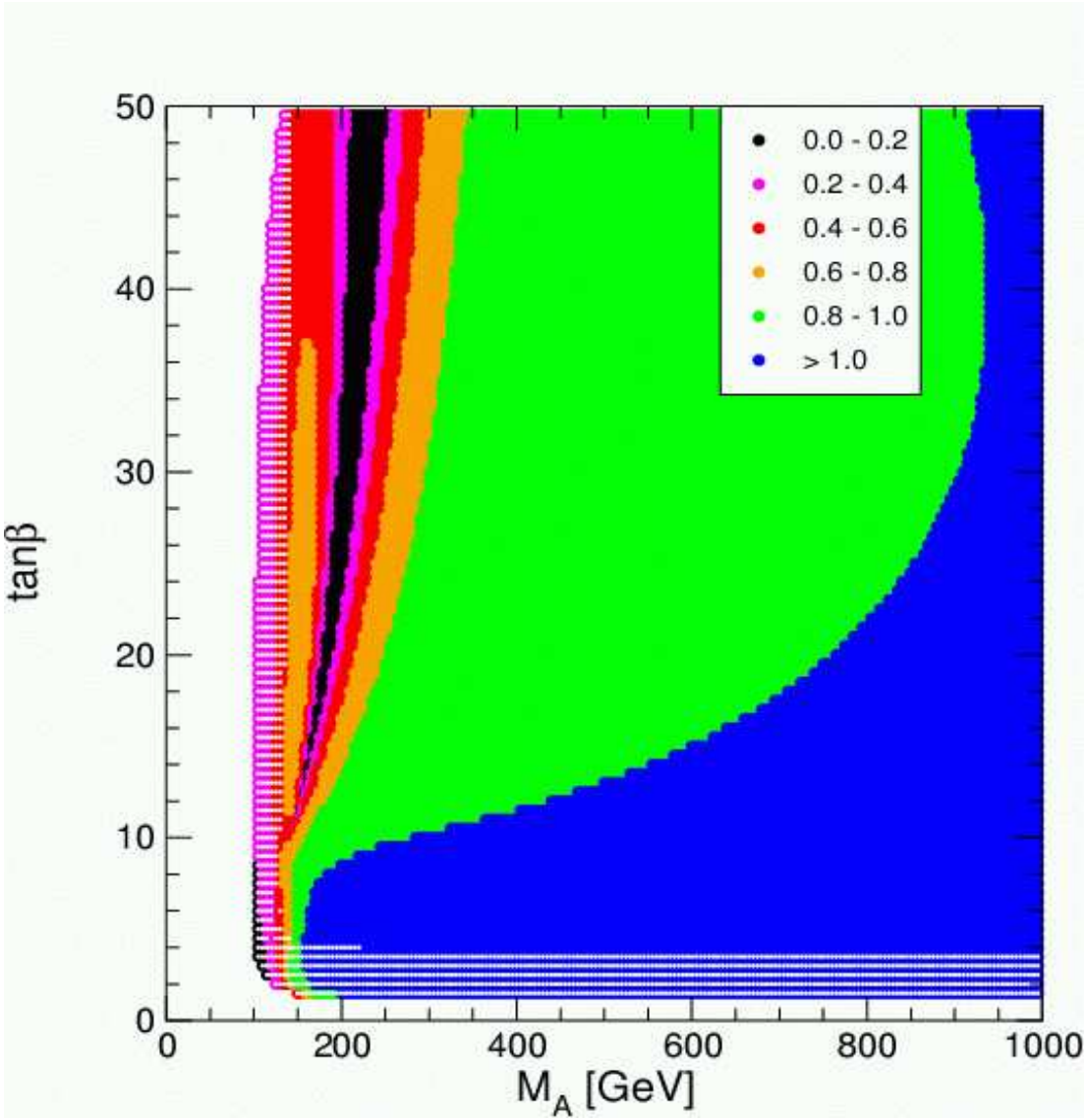
can be strongly suppressed

$\to$ "Small α_{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 (II): "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:

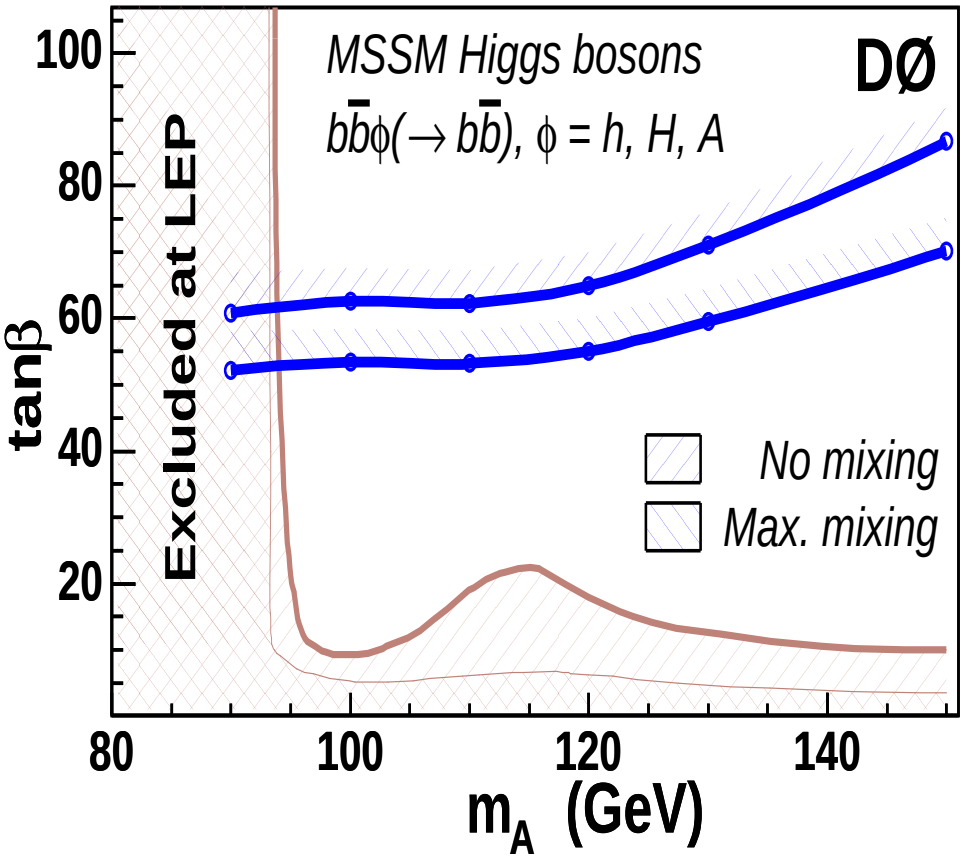
$$\sigma(b\bar{b}A) \times \mathrm{BR}(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\mathrm{SM}} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

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

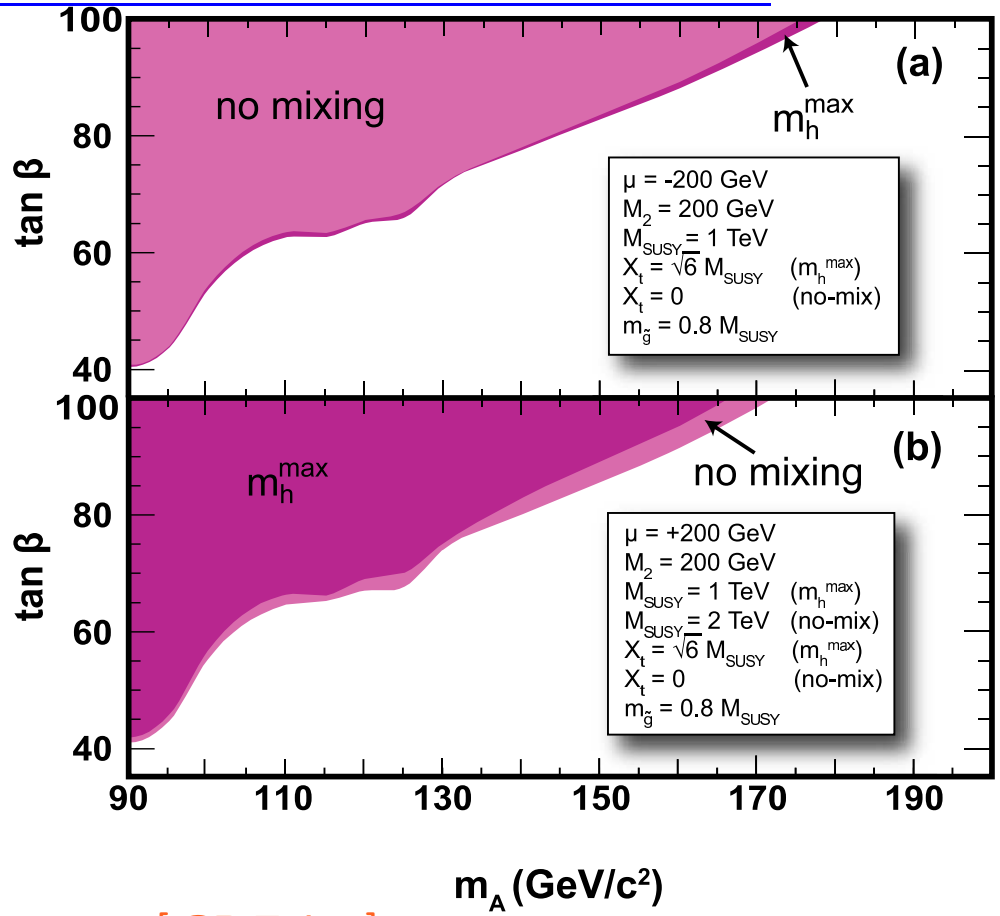
$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}}\,\mu\,\tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_t\,\mu\,\tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

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

Existing Tevatron data allows bounds on SUSY parameter space:



[D0 '05]



[CDF '05]

⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

$\tan\beta \approx 50$ excluded for $M_A \approx 100$ GeV

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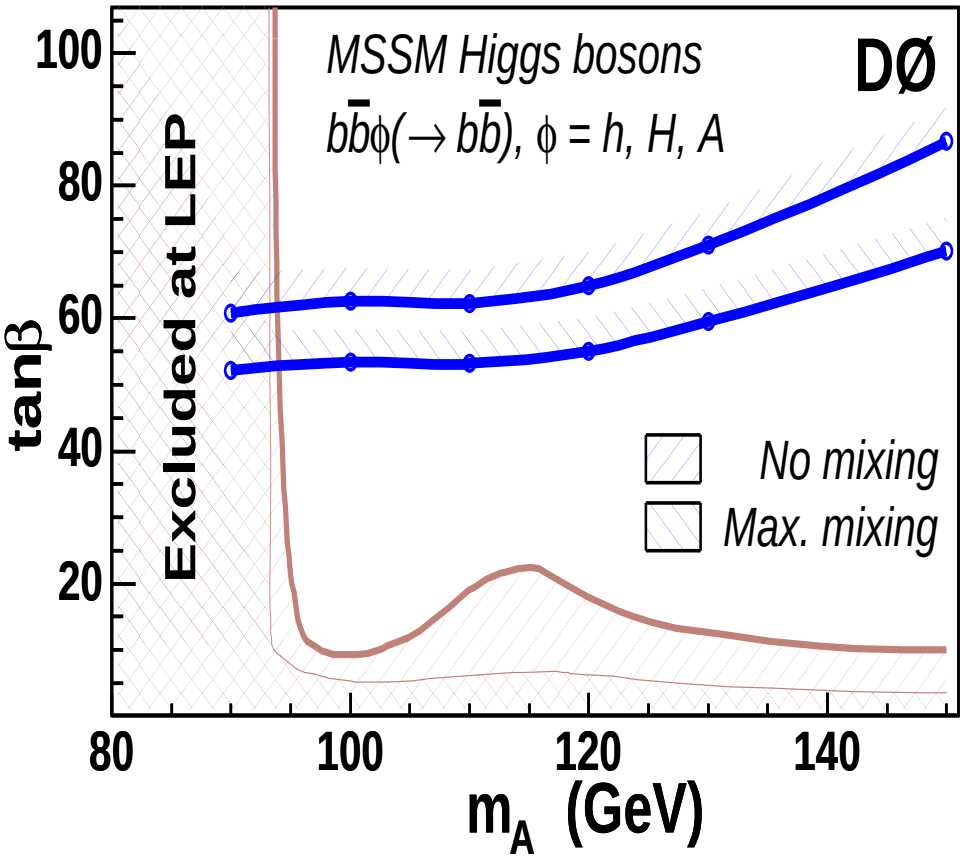
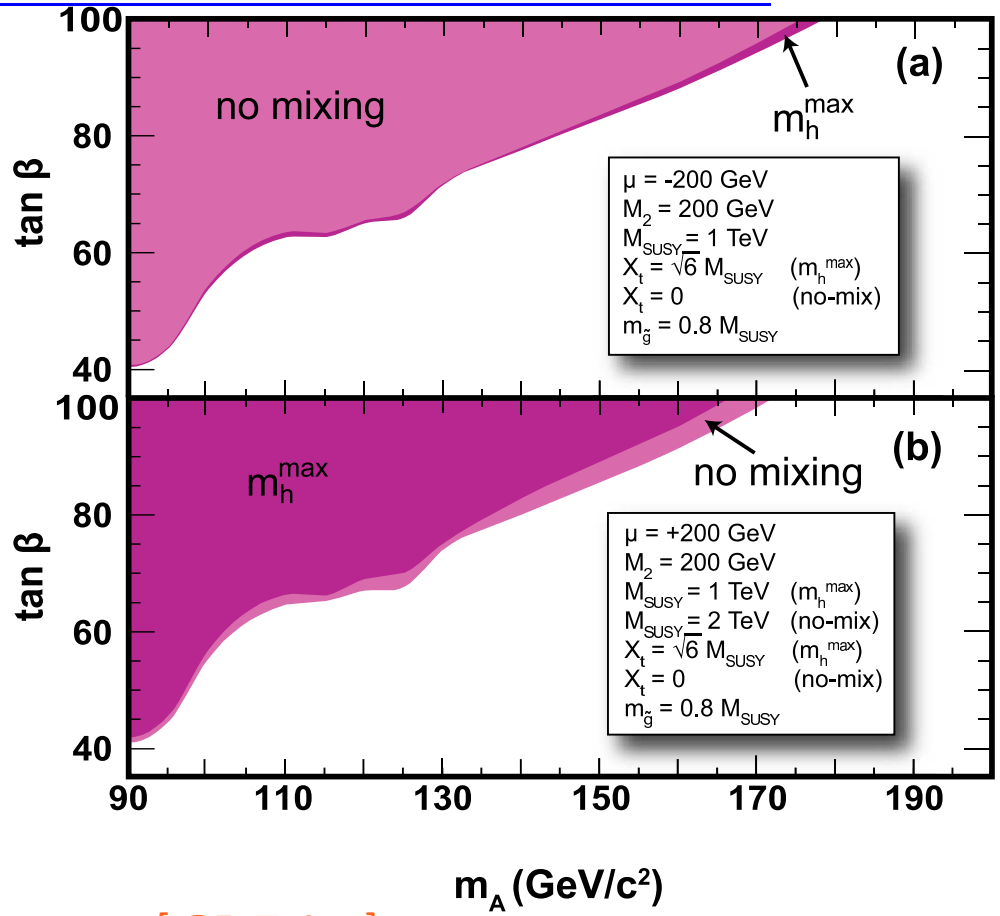


[D0 '05]



[CDF '05]

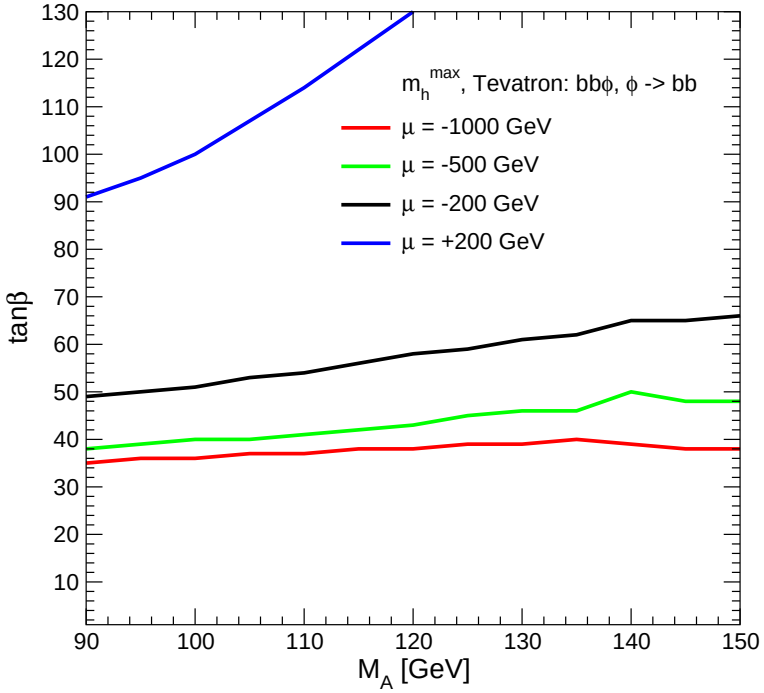
⇒ Bounds on the MSSM parameter space for low M_A, high $\tan\beta$:

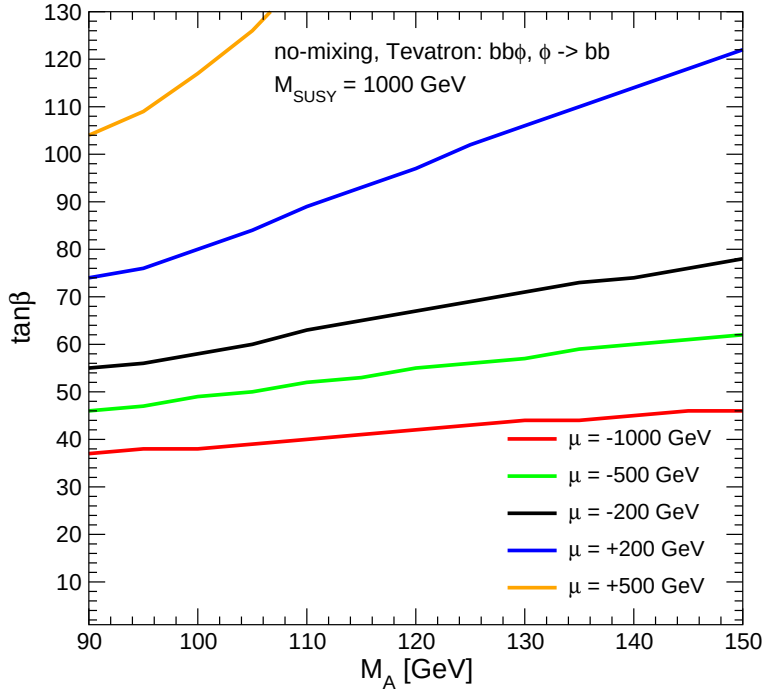
$\tan\beta \approx 50$ excluded for $M_A \approx 100$ GeV

in certain benchmark scenarios!

Dependence of Tevatron bounds from $b\bar{b}\phi, \phi \to b\bar{b}$ on μ:

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





⇒ strong variation with the sign and absolute value of μ

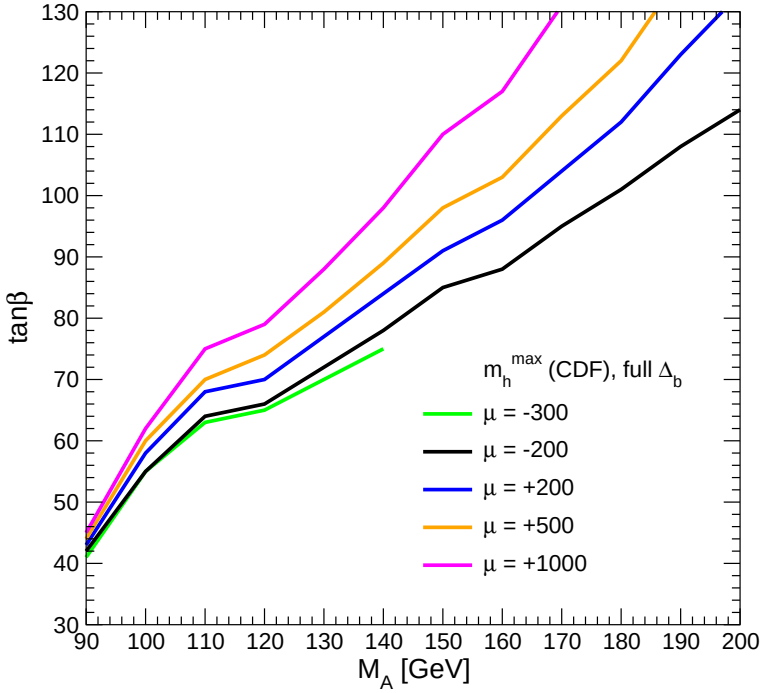
⇒ much stronger or weaker bounds possible

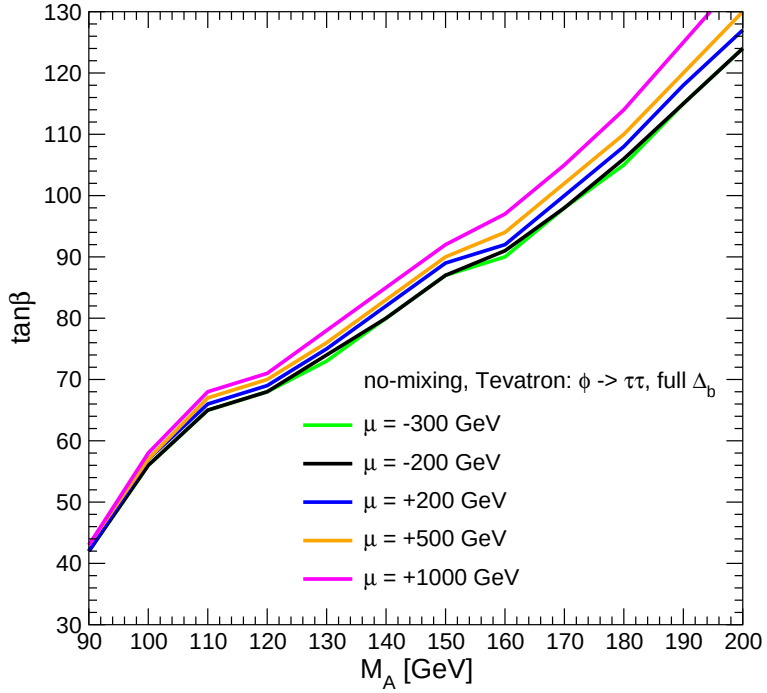
no bounds for $\mu \gtrsim 200$ GeV

(positive μ preferred by $(g-2)_\mu$)

Dependence of Tevatron bounds from $p\bar{p} \to \phi, \phi \to \tau^+\tau^-$ on μ:

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





⇒ less strong variation with the sign and absolute value of μ

(→ numerical compensations in production and decay)

⇒ still much stronger or weaker bounds possible

strong dependence on benchmark scenario

4. Future: The Higgs at the LHC

LHC: pp accelerator: start: fall 2007 $\rightarrow$ T

The (un)official (optimistic?) LHC timeline:

2007 (11/07): Pilot run, no acceleration in the LHC
first collisions at $\sqrt{s} = 2 \times 450$ GeV

2008: 0.1 fb^{-1} – $\mathcal{O}$(few) fb^{-1} (at best) $\Rightarrow$ probably no physics results yet

2009: $\mathcal{O}$(few) fb^{-1} $\Rightarrow$ first physics results?

2010 – 2012: 10 fb^{-1} per year $\Rightarrow$ physics results with "low" luminosity

2013 – ?: 100 fb^{-1} per year $\Rightarrow$ physics results with "high" luminosity

2015 + X (X > 0): upgrade to SLHC?

LHC: The Large Hadron Collider
The protons have not yet been accelerated to their full energy.
You need to supply more energy by raising the accelerator handle...
SPS Ring
LHC Ring
ALICE
CMS
ATLAS
LHCb
SPS now at 306.0 GeV (68)%...
Lift handle to accelerate the stream
PPEP
pp4ss
particle physics for scottish schools

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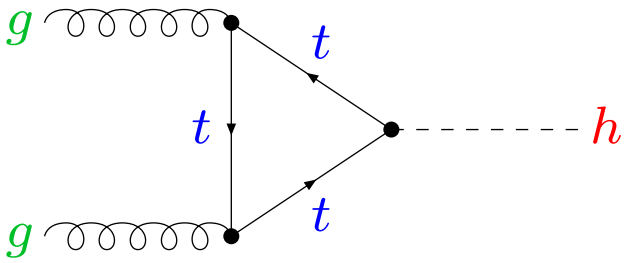
2015 + X (X > 0): upgrade to SLHC?

YOU live in an exciting time!!!

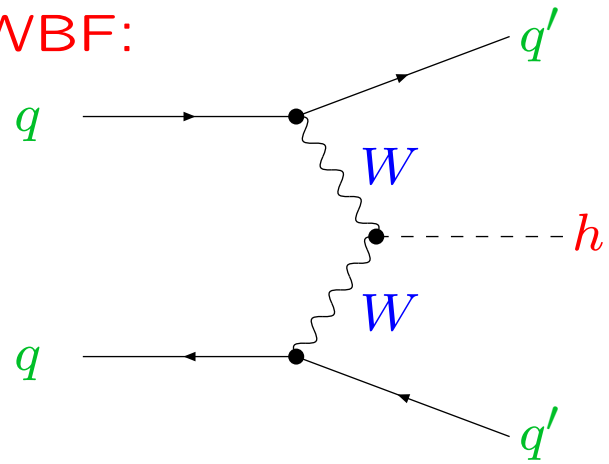
Examples for Higgs production and decay at the LHC:

Important production channel at the LHC:

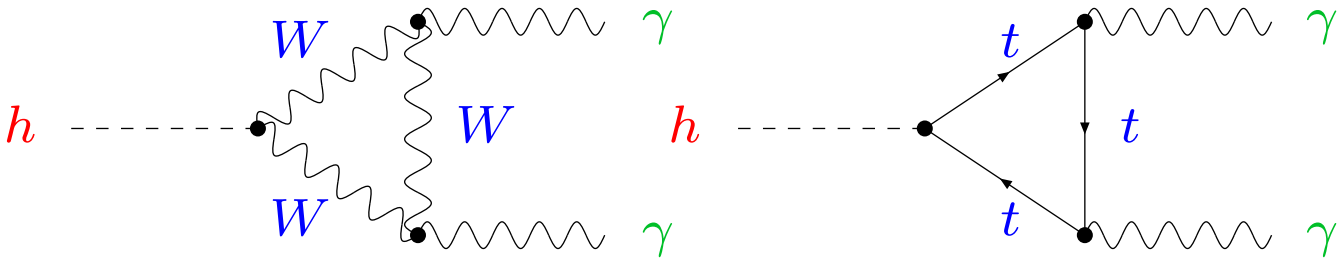
Gluon-Fusion:



WBF:

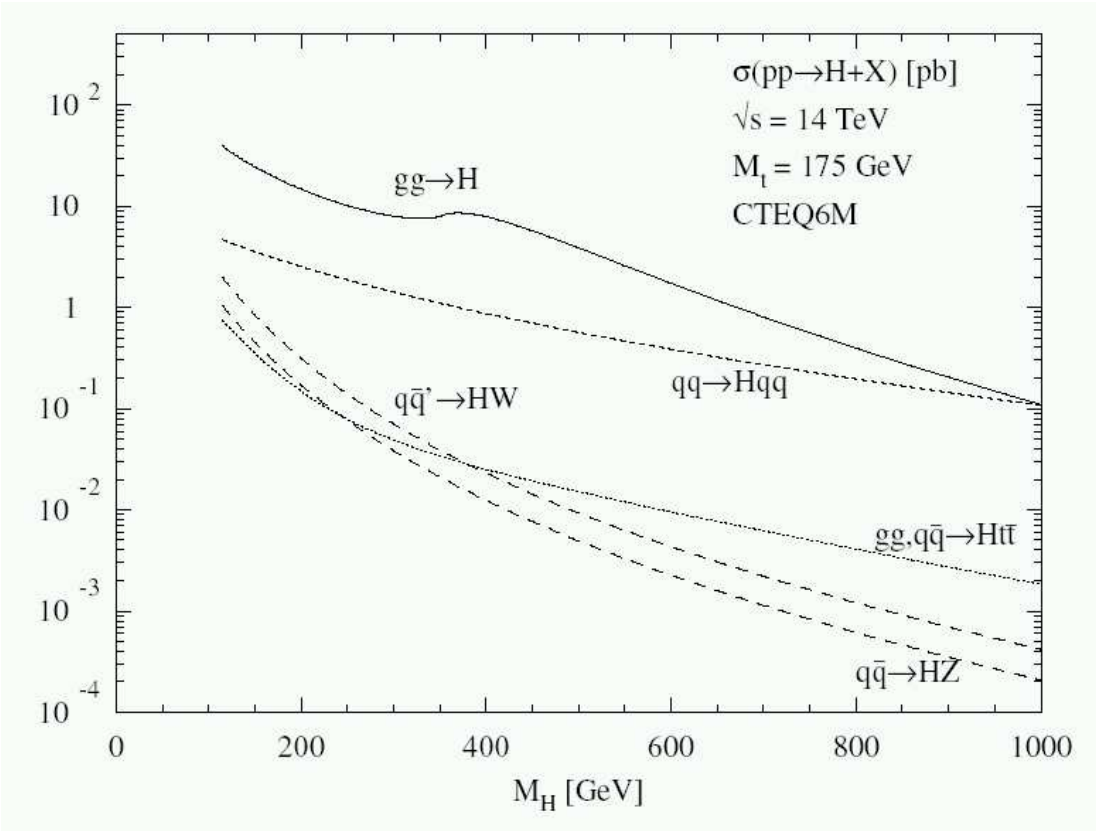


Important decay for Higgs mass measurement:



Step 1: Discovery of the new particle

SM Higgs production at the LHC:



gluon fusion: $gg \to H$

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

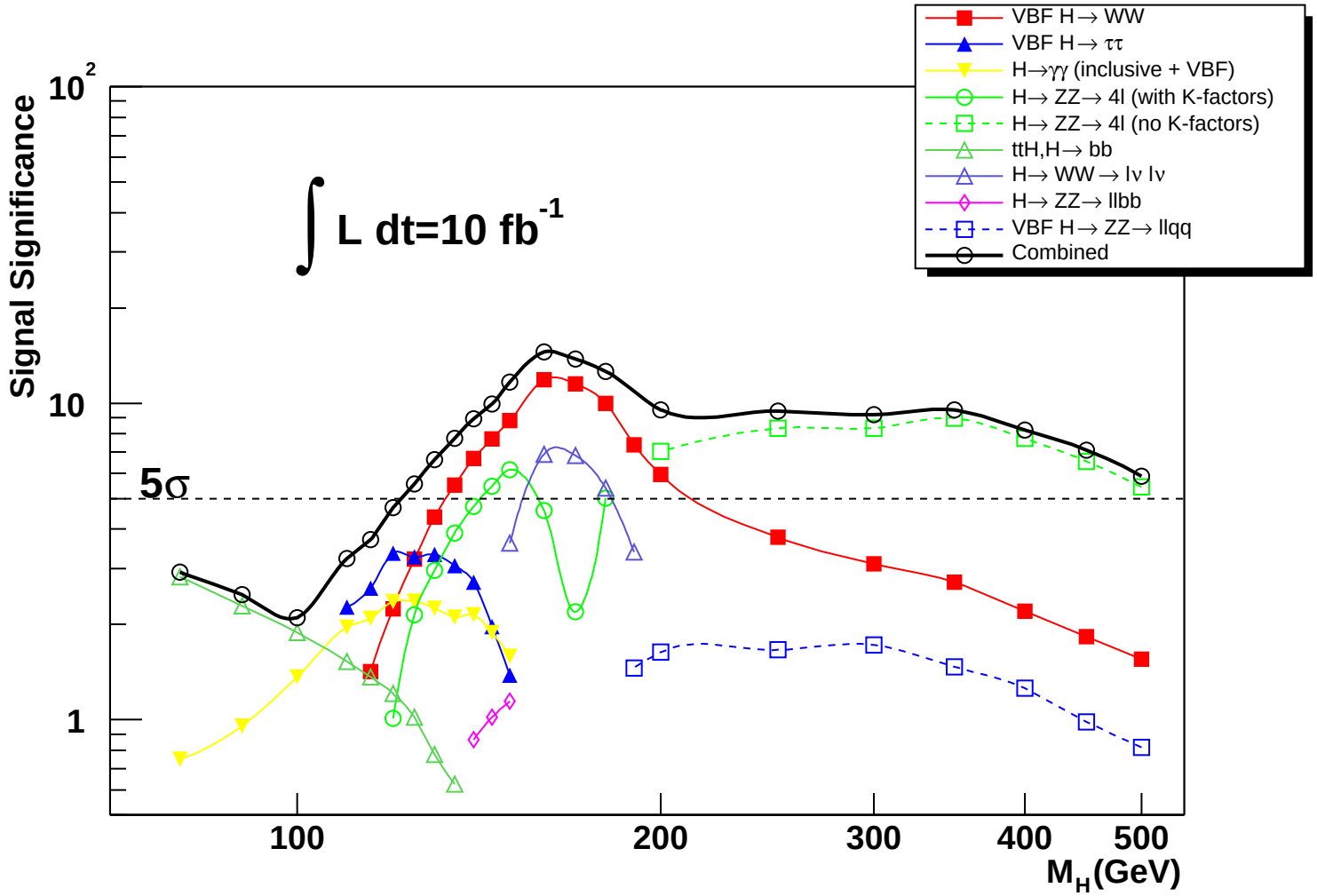
top quark associated production: $gg, q\bar{q} \to t\bar{t}H$

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

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

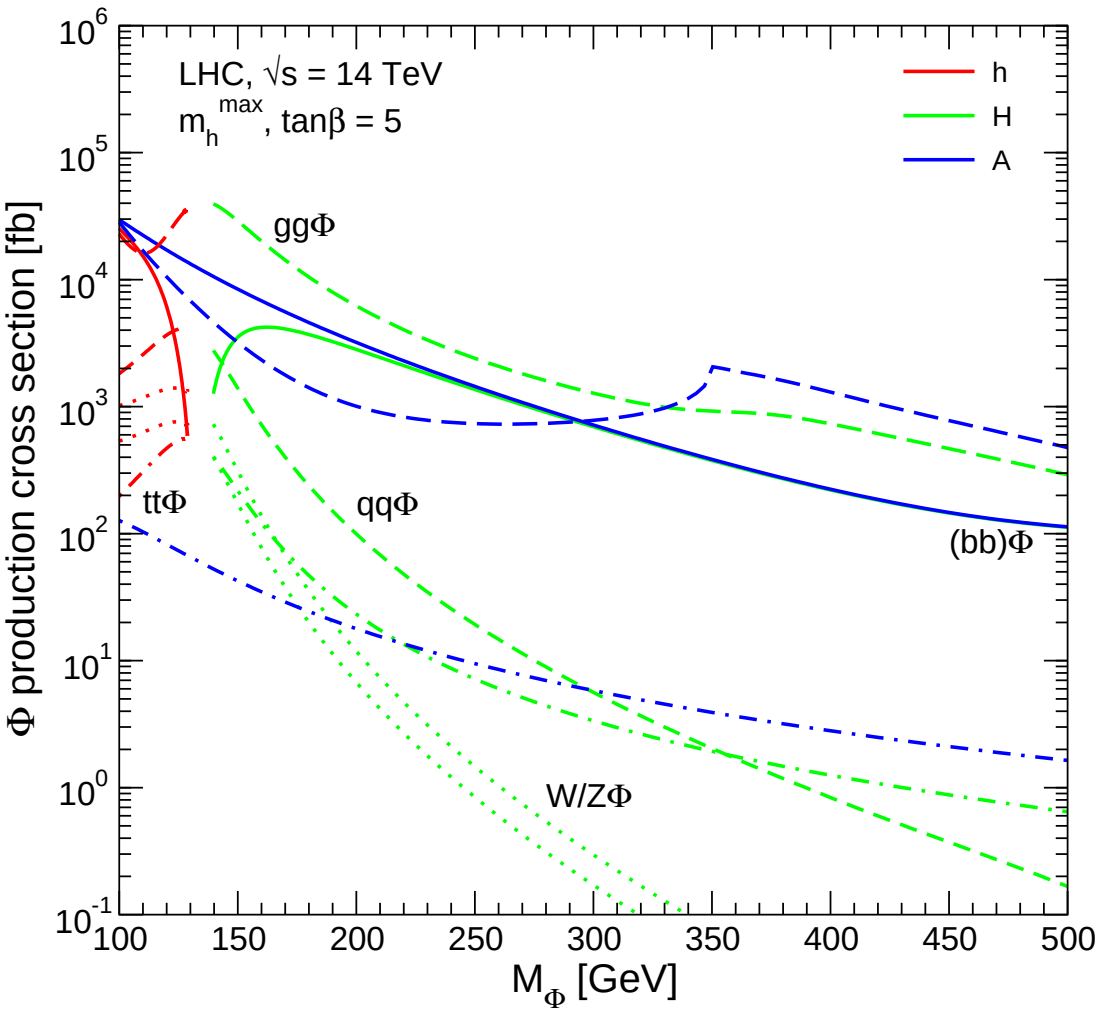
SM Higgs search at the LHC: ⇒ full parameter space accessible

[*ATLAS '05*]



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

[*T. Hahn, S.H., F. Maltoni, G. Weiglein, S. Willenbrock '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: $q\bar{q}' \to W\phi, Z\phi$

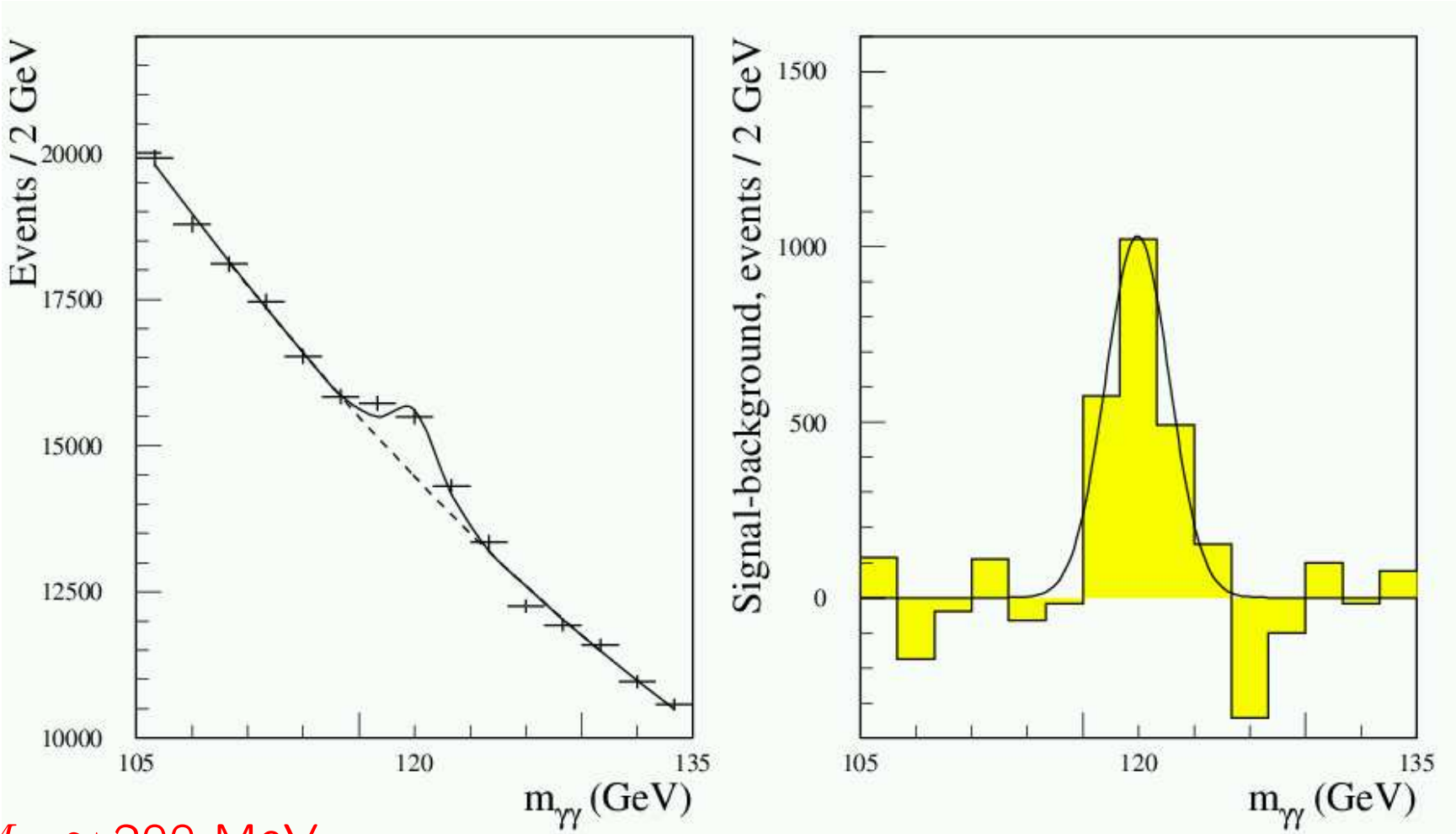
NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

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

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

Possible problem in SUSY:

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

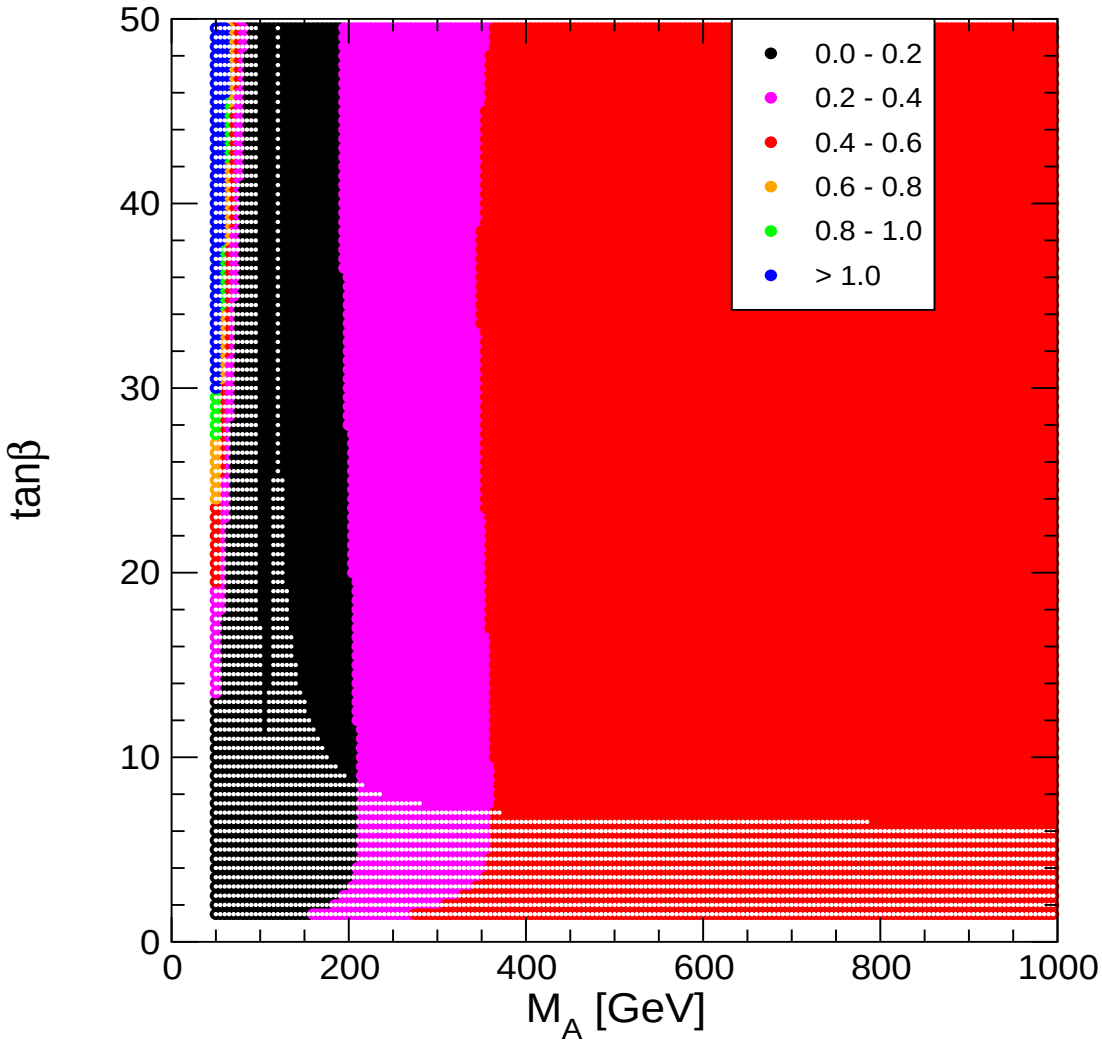
can be strongly suppressed

$\longrightarrow$ "gluophobic Higgs scenario"

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

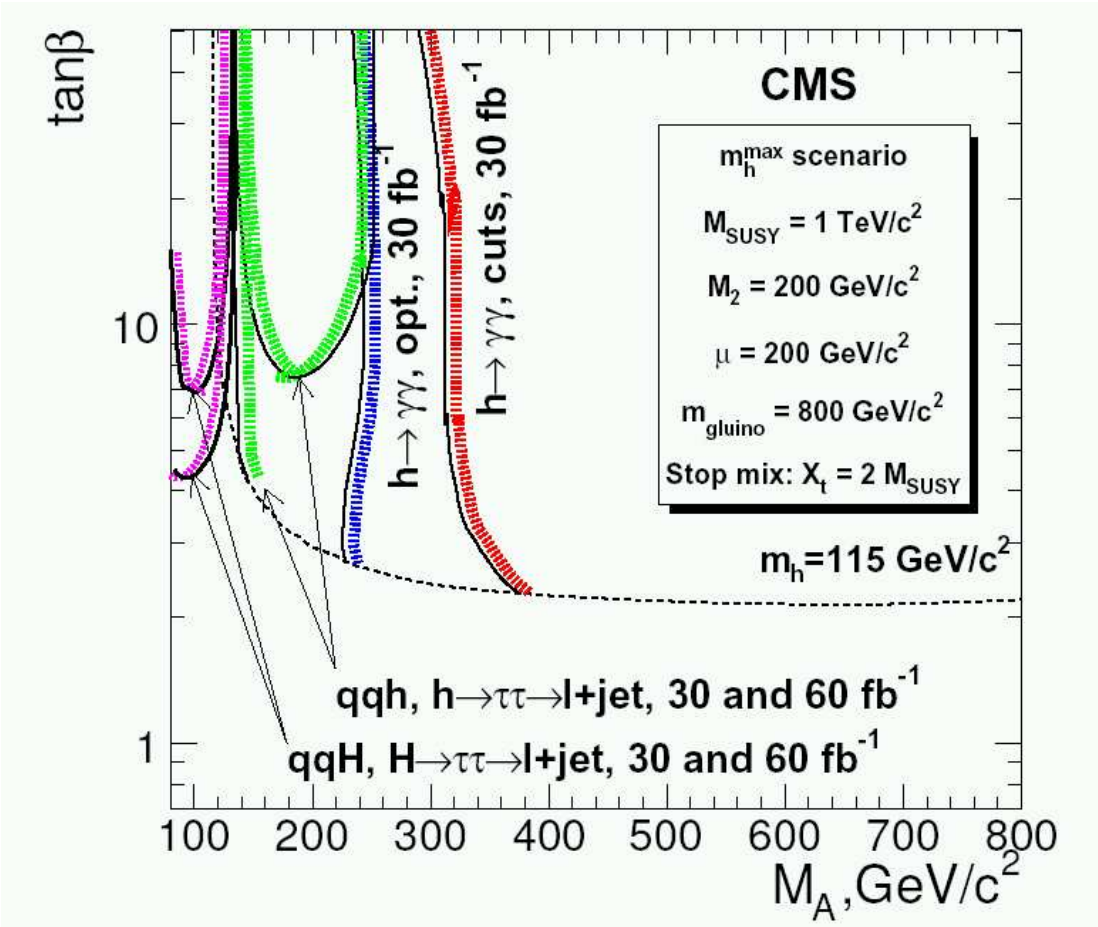
$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

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



And even in the "nice" $m_h^{\max}$ scenario there might be problems:

[*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

Step 3, 4: measurement of couplings to gauge bosons and fermions

Measurements for a SM Higgs (or SM-like MSSM Higgs) at the LHC:

Measurement of $\sigma \times$ BR: "narrow width" approximation:

$$\Rightarrow \sigma(H) \times \mathrm{BR}(H \to xx) \;=\; \sigma(H)^{\mathrm{SM}} \cdot \frac{\Gamma_{\mathrm{prod}}}{\Gamma_{\mathrm{prod}}^{\mathrm{SM}}} \times \frac{\Gamma_{\mathrm{partial}}}{\Gamma_{\mathrm{tot}}}$$

Observation of different channels

$\Rightarrow$ Information about combinations of $\Gamma_b, \Gamma_\tau, \Gamma_W, \Gamma_Z, \Gamma_g, \Gamma_\gamma, Y_t^2$

$\Rightarrow$ Additional theory assumptions necessary for absolute determination of partial widths

Only assumption:

$\rightarrow$ consider general multi Higgs-Doublet model
w/o additional Higgs-Singlets
($\Rightarrow$ includes e.g. MSSM)

$\Rightarrow$ Absolute Determination of Γ_{tot} and Higgs couplings in a global fit

$\Rightarrow$ (nearly) model independent analysis

Luminosity at the LHC:

- $2 * 30$ fb^{-1}: 30 fb^{-1} in each of the two experiments
- $(2*300+2*100)$ fb^{-1}: 300 fb^{-1} in each experiment, but only 100 fb^{-1} usable for gauge boson fusion

Estimate of errors:

1.) Statistical errors:

Assumption: SM rates for production and decay in all scenarios

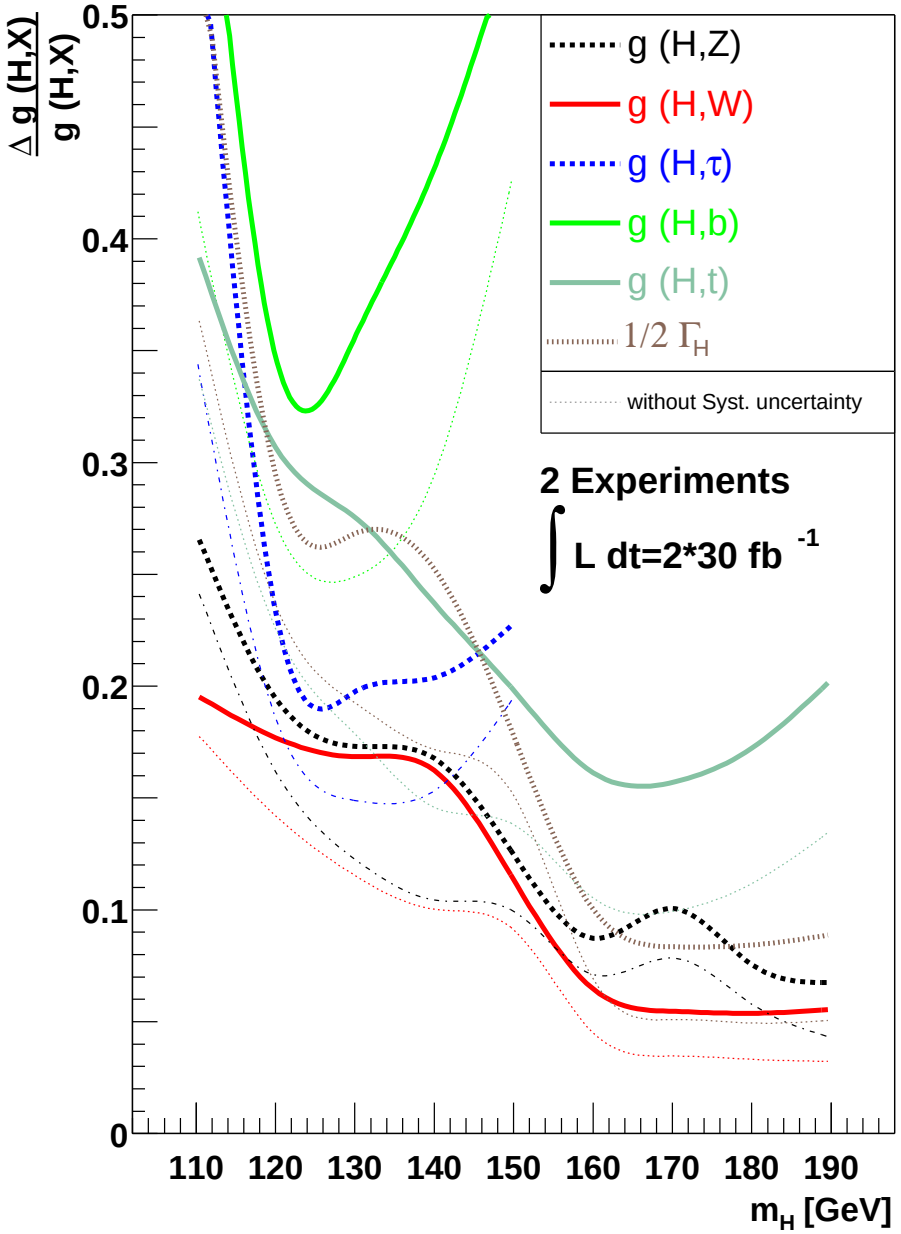
2.) Systematic errors:

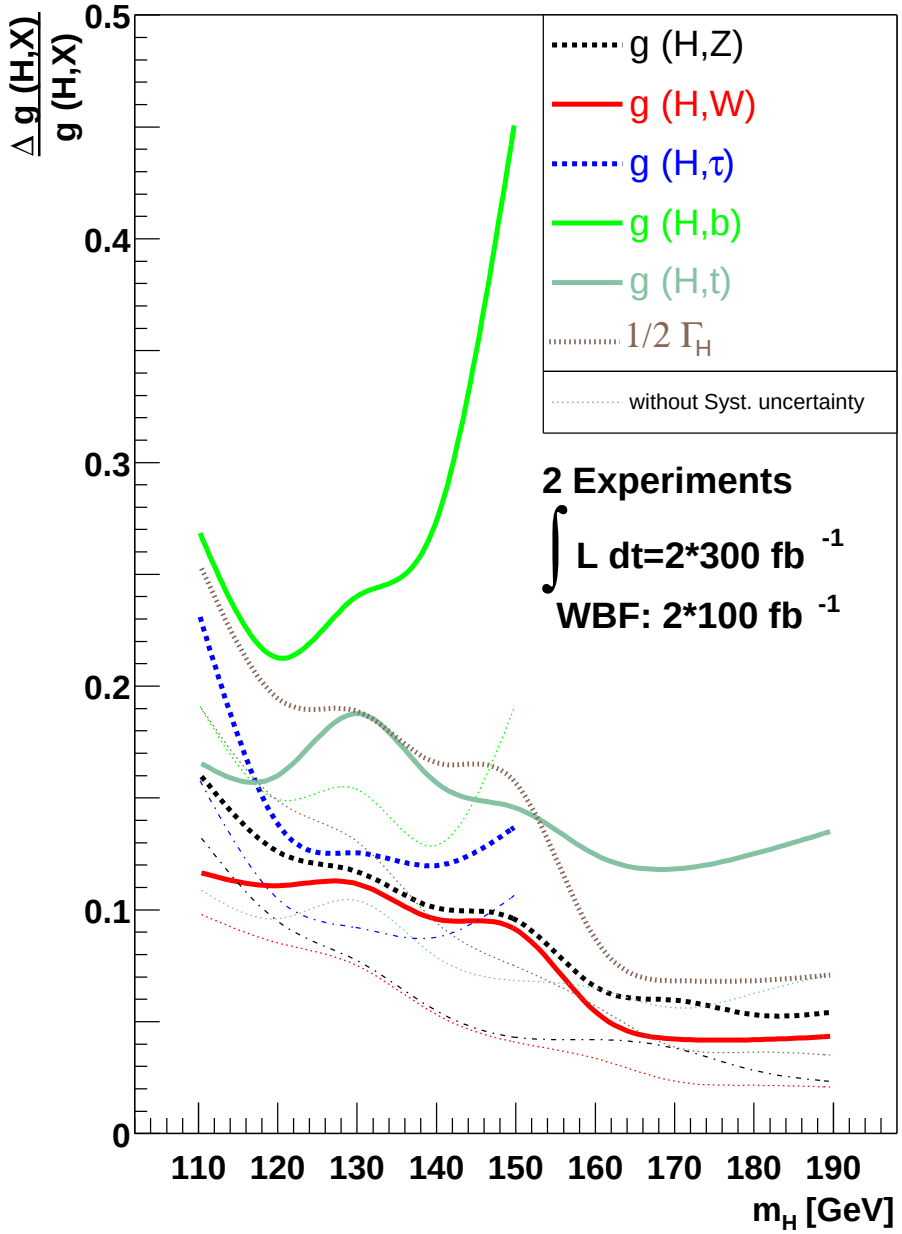
$\rightarrow$ attempt to include realisticly all possible errors

$\Rightarrow$ "log likelihood" function,
based on statistical and systematic errors

Relative precision for partial and total Higgs widths: two scenarios

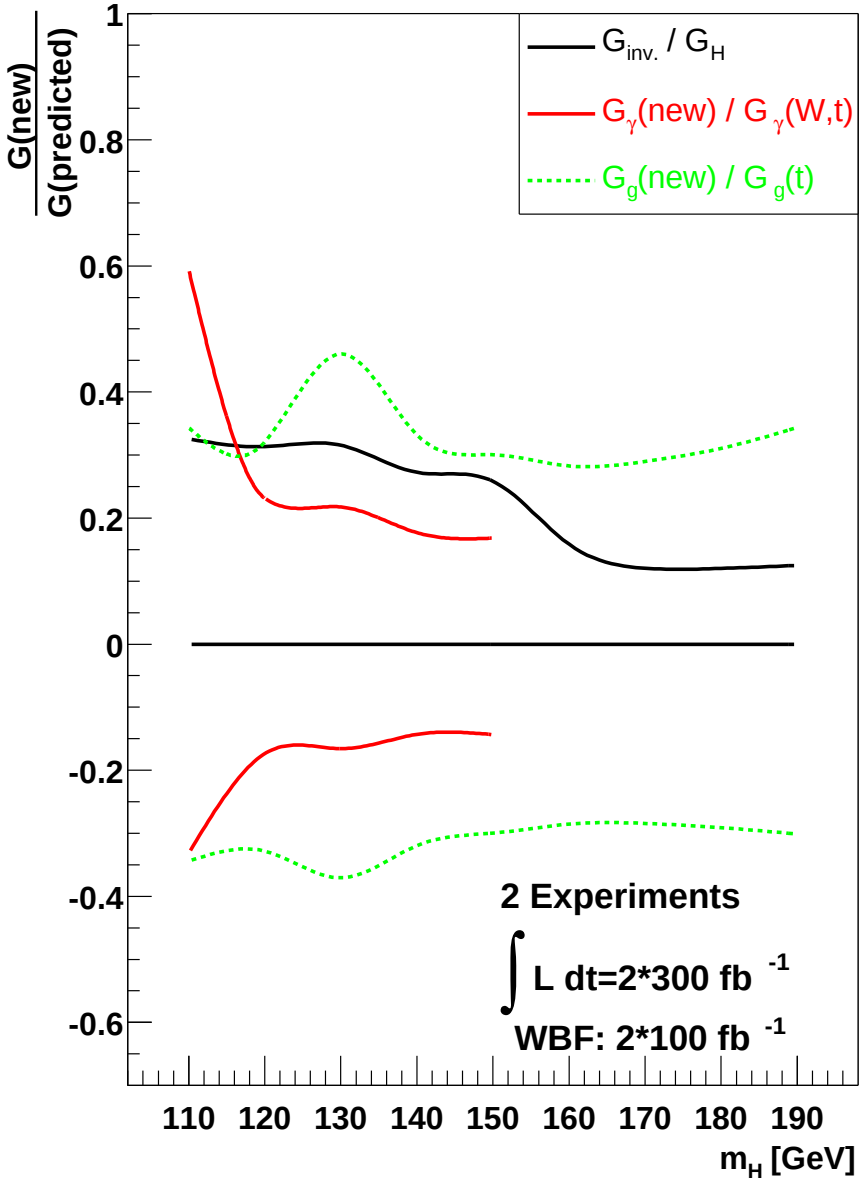
[*M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04*]





Constraints on extra partial widths:

[*M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04*]



measurement of SM rates

$\Rightarrow$ constraints on widths:

$(2 * 300 + 2 * 100)$ fb^{-1} scenario:

$$\Delta\Gamma_\gamma \leq 0.2 \times \Gamma_\gamma^{\rm SM}$$

$$\Delta\Gamma_g \leq 0.4 \times \Gamma_g^{\rm SM}$$

$$\Delta\Gamma_{\rm inv} \leq 0.2 \times \Gamma_{\rm tot}^{\rm SM}$$

$\Rightarrow$ restrictions on new physics!

Results:

Absolute determination of Higgs couplings is possible!

Scenario with low luminosity: $2 * 30$ fb^{-1} :

for a light Higgs: results significantly worse in comparison with higher luminosity

Scenario with higher luminosity: $(2 * 300 + 2 * 100)$ fb^{-1} :

– typical precision of 15-25% for $m_H \lesssim 150$ GeV

– 5% accuracy for HVV couplings above WW threshold

Systematic errors contribute about 50% to the total error, especially at high luminosity

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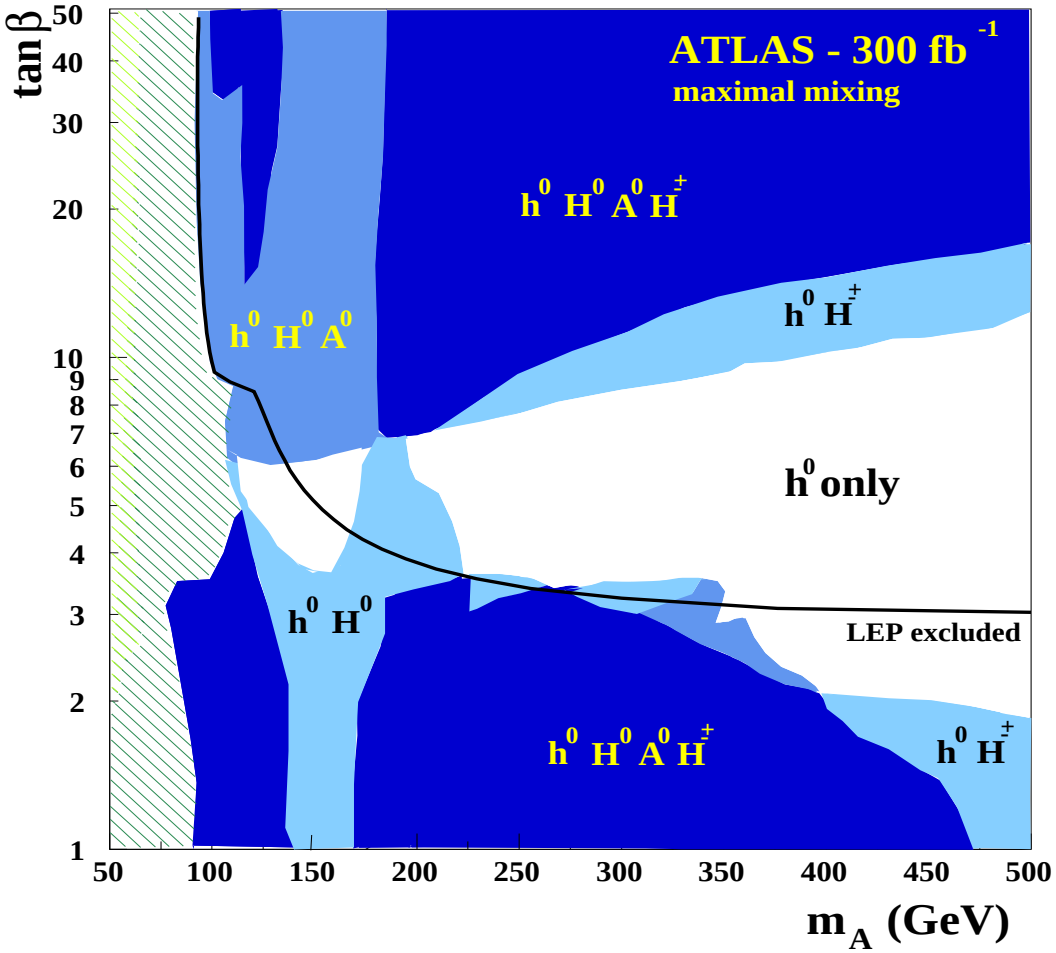
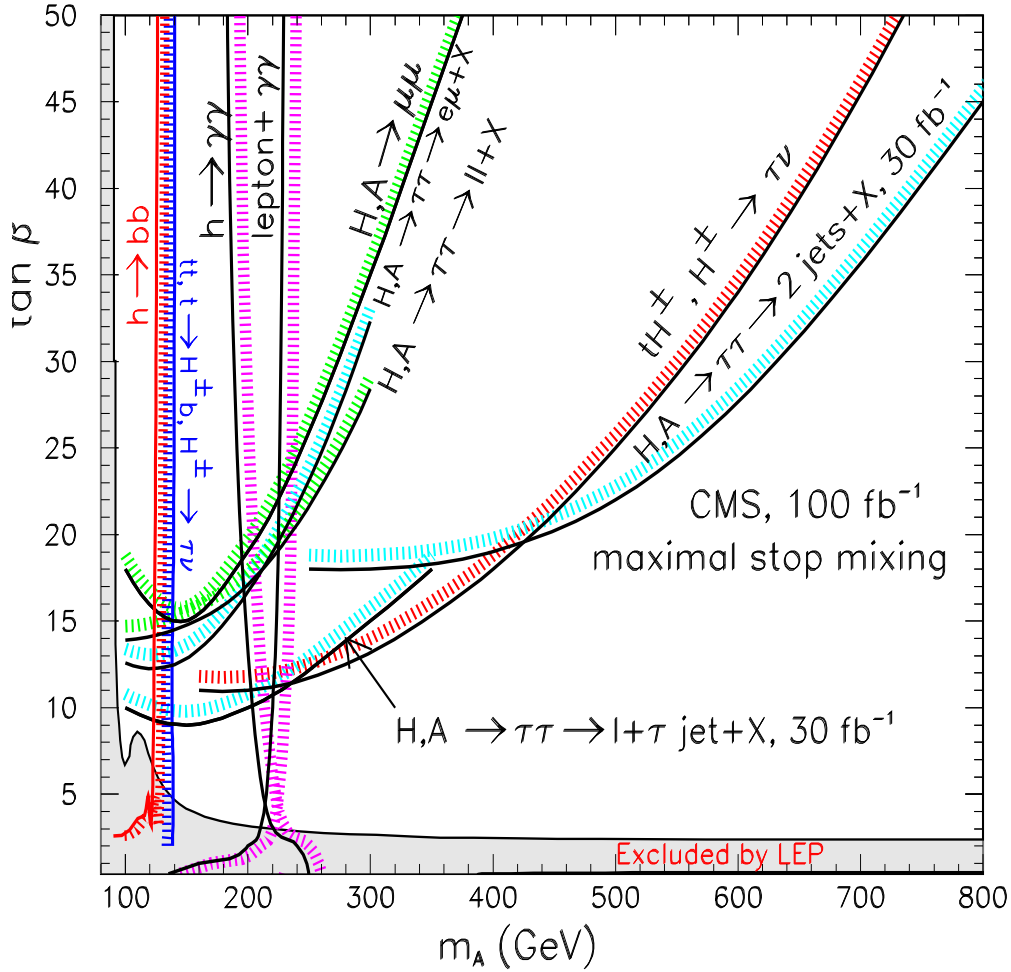
What happens with non-SM rates?

$\Rightarrow$ not analyzed yet . . .

"Heavy" MSSM Higgs searches:

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





areas where only h is observable $\Rightarrow$ "LHC wedge"

Most powerful search modes for heavy MSSM Higgs bosons:

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

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

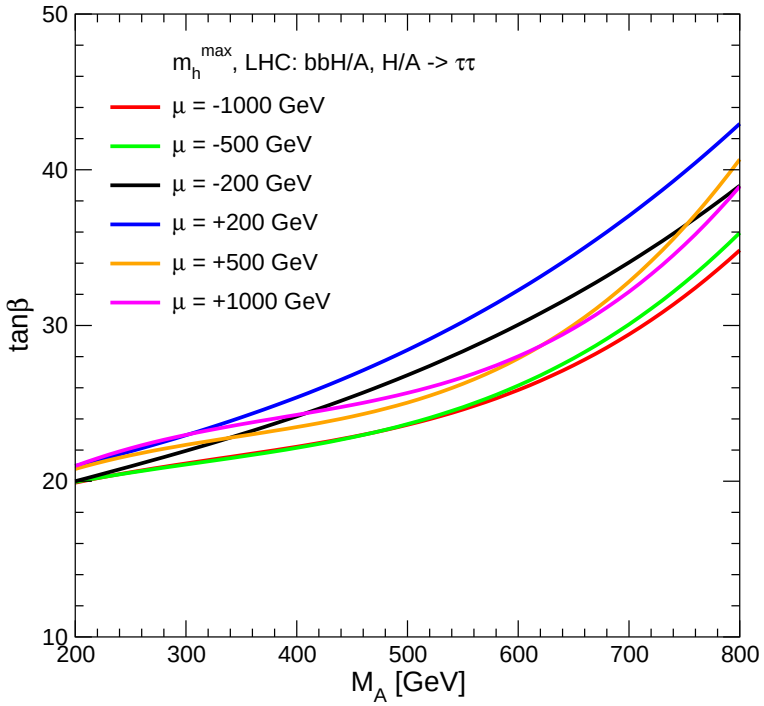
also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

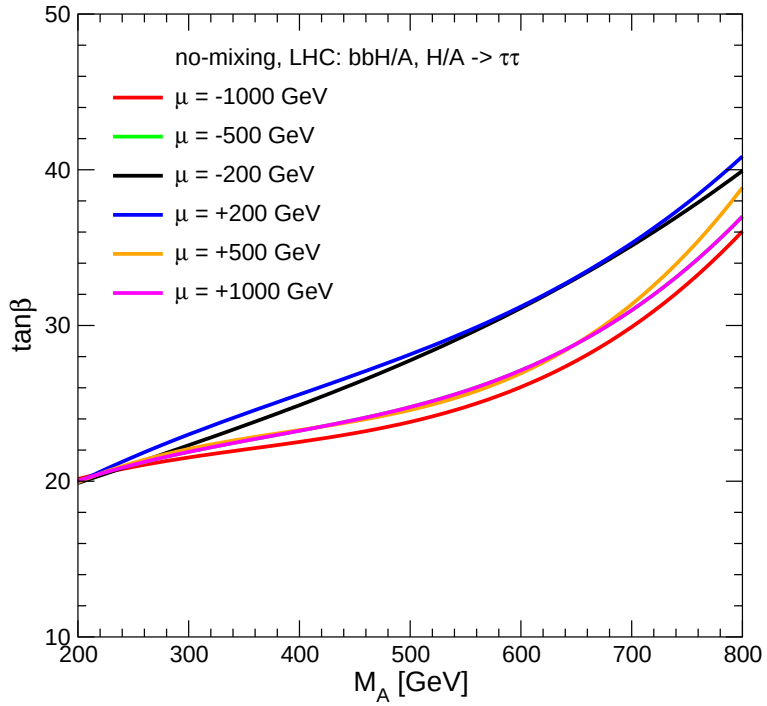
also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

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

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

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





⇒ non-negligible variation with the sign and absolute value of μ

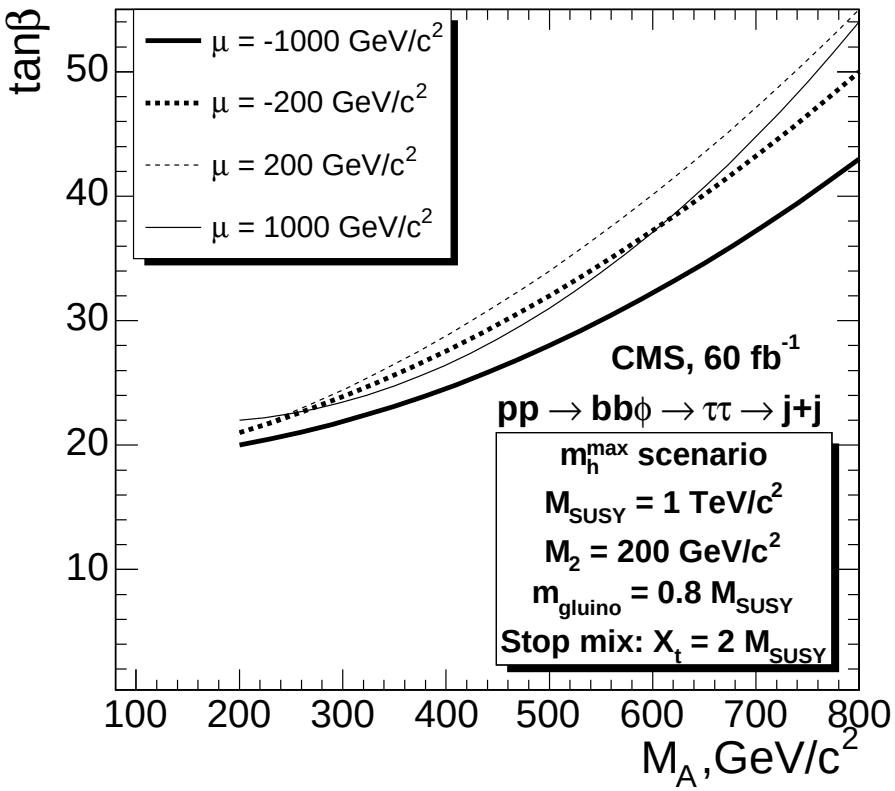
(→ numerical compensations in production and decay)

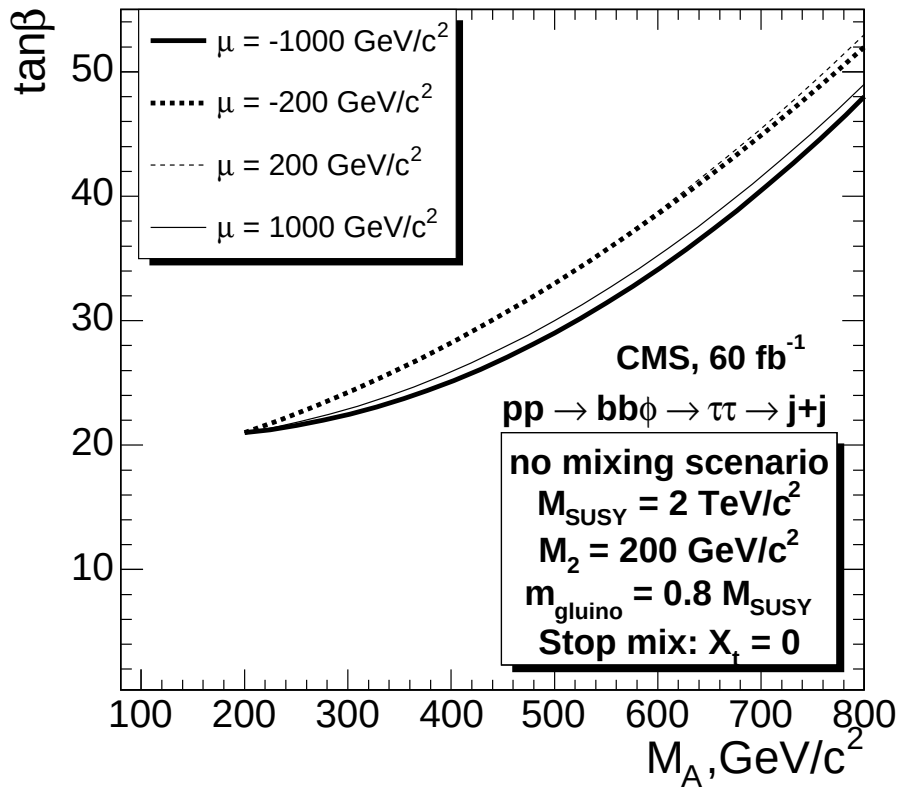
⇒ much stronger or weaker bounds possible

than in older analysis

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

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





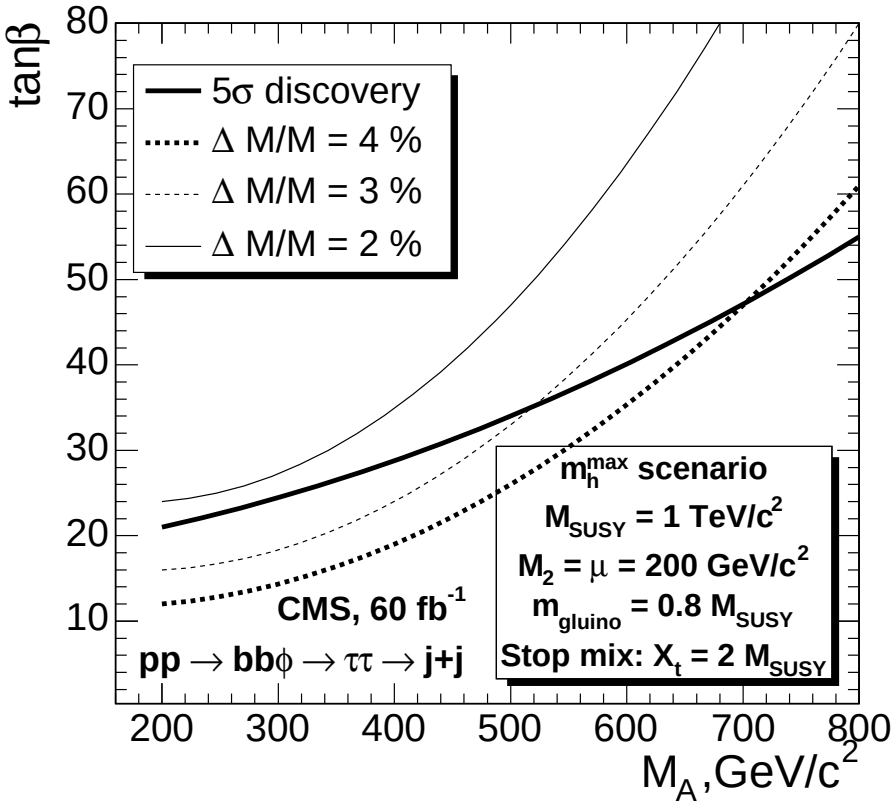
⇒ now based on full CMS simulation

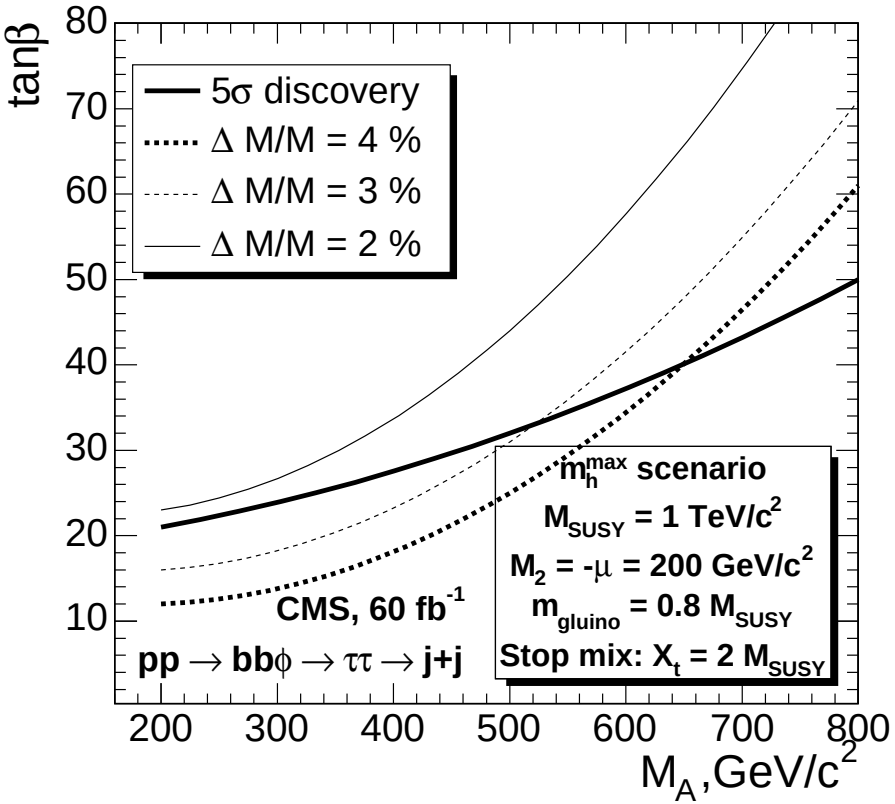
⇒ non-negligible variation with the sign and absolute value of μ

(→ 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*]



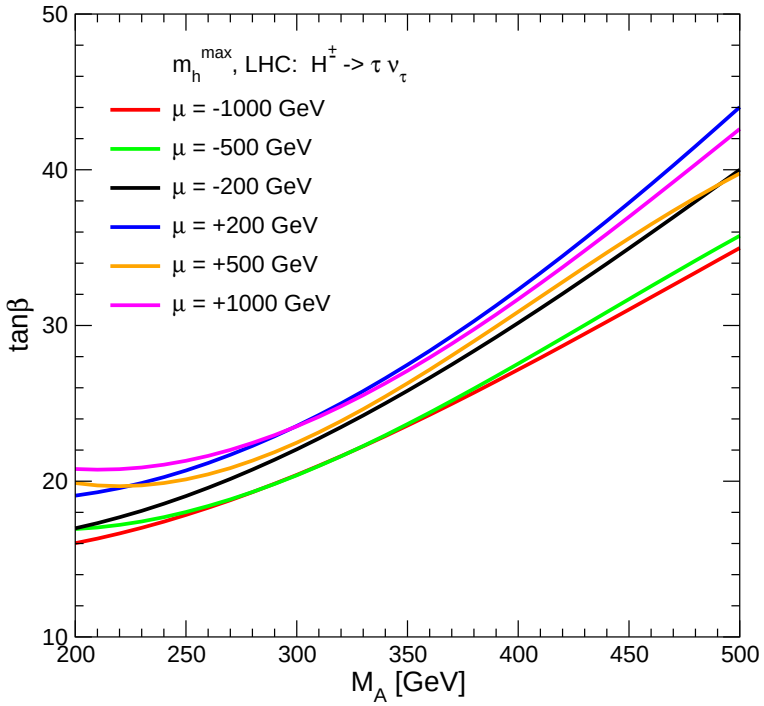


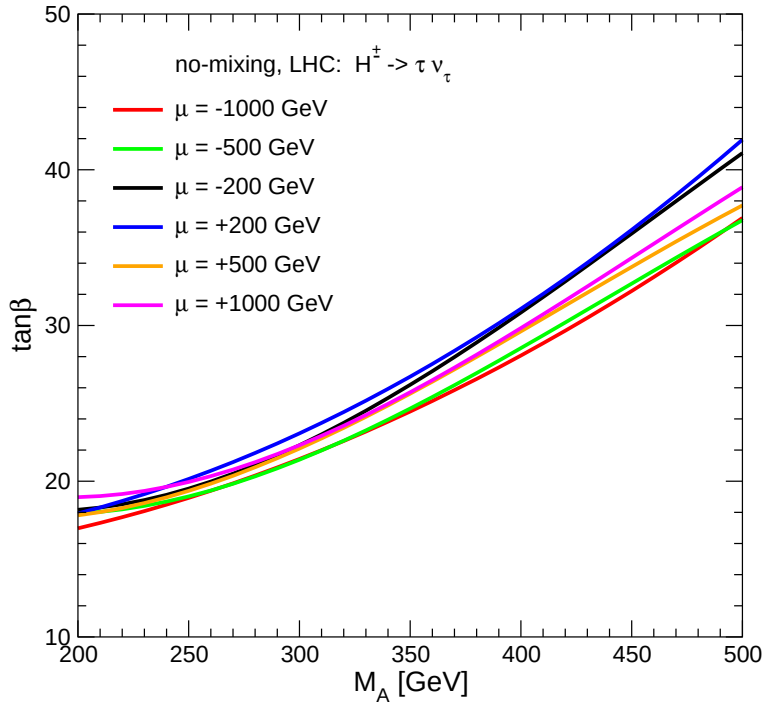
⇒ now based on full CMS simulation

⇒ high precision measurement of heavy Higgs boson masses possible

Dependence of the LHC wedge from $pp \to tH^\pm, H^\pm \to \tau\nu_\tau$ on μ:

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





$\Rightarrow$ non-negligible variation with the sign and absolute value of μ

($\to$ numerical compensations in production and decay)

$\Rightarrow$ much stronger or weaker bounds possible

than in older analysis

Outlook

- 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 low-energy SUSY and the Higgs

$\Rightarrow$ 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