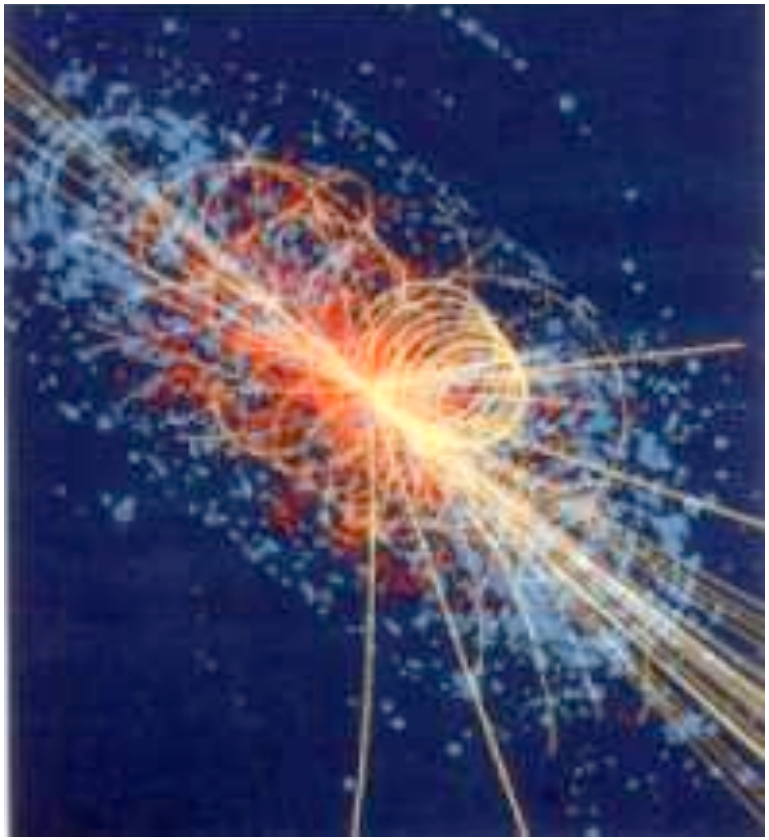
Higgs Physics at the LHC



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The Ohio State University Columbus, OH
September 10-15, 2006

Outline

- The Mystery of EWSB

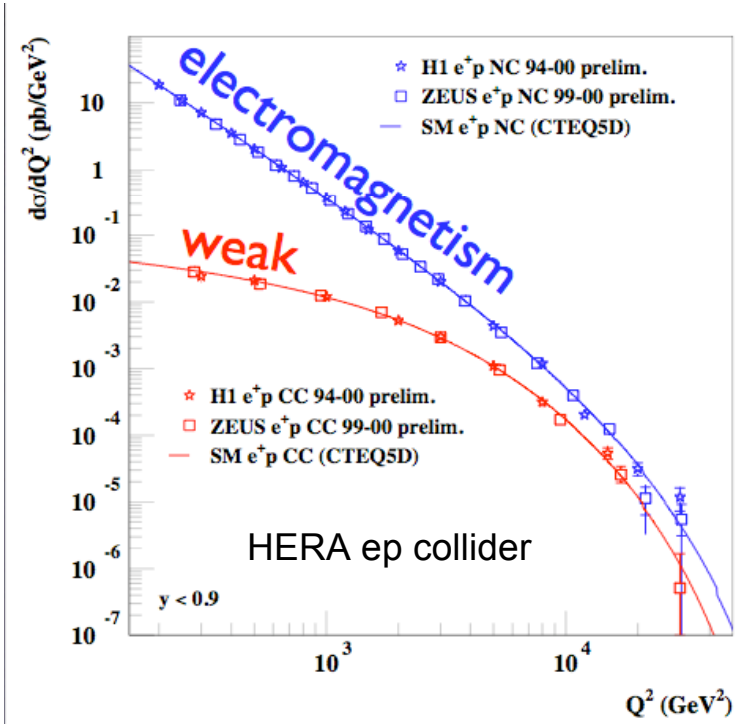
- Testing the Standard Model Higgs boson
  -- production channels, cross section measurements,
  mass measurements, determination of Higgs couplings

- The MSSM Higgs Bosons
  -- the impact of radiative corrections on the various SM-like Higgs search channels, on the A/H-->tau tau and $H^{\pm} \to \tau\nu$ channels
  -- tan beta measurements

- B and Higgs Physics at the Tevatron and LHC
  -- the impact of rare decays: $BR(B_s \to \mu^+\mu^-)$, $BR(b \to s\gamma)$ and $BR(B_u \to \tau\nu)$
  on direct Non_Standard Model Higgs searches

What is the origin of Mass of the Fundamental Particles ?
or
The mystery of Electroweak Symmetry Breakdown (EWSB)

- There is a Dark Field that fills all the Universe
  - -- it does not disturb gravity and electromagnetism but it renders the weak force short ranged
  - -- it slows down the fundamental particles from the speed of light



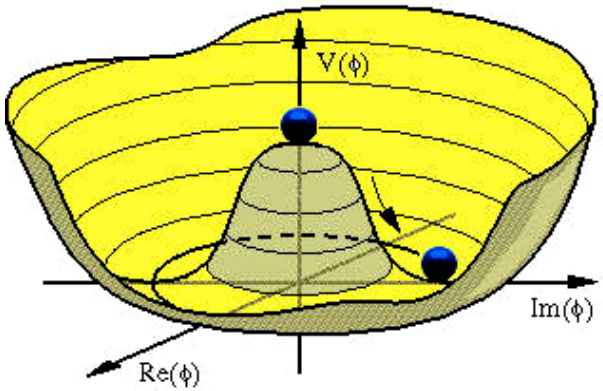
We know that the electromagnetic and weak forces are unified ==> electroweak theory

what breaks the symmetry
==> the Dark Field

We know EWSB occurs at the TeV scale
New phenomena associated to the Dark field should lie in the TeV range or below
within LHC/ILC reach

In the Standard Model: The Higgs Mechanism

a self interacting complex scalar doublet with no trivial quantum numbers under $SU(2)_L \times U(1)_Y$



The Higgs field acquires a non-zero value to minimize its energy:

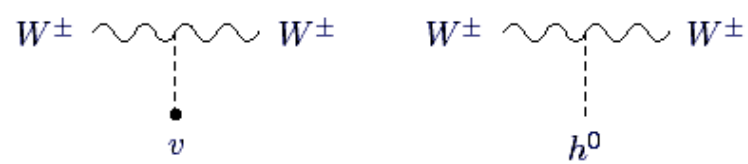
$$V(\phi) = -m^2\phi^2 + \frac{\lambda}{2}\phi^4$$

Higgs vacuum condensate $v \Longrightarrow$ scale of EWSB

- Spontaneous breakdown of the symmetry generates 3 massless Goldstone bosons which are absorbed to give mass to $V = W, Z$

  ⋆ interaction with gauge fields

  $m_V^2 = g_{\phi\ VV}\ v/2 \quad \longrightarrow v = 174$ GeV

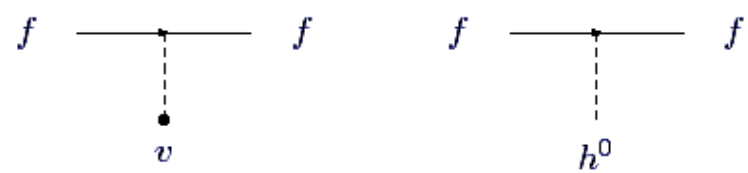


Higgs neutral under strong and electromagnetic interactions $\Longrightarrow$ $m_\gamma = 0$ $\quad m_g = 0$

exact symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y \quad \Longrightarrow \quad SU(3)_C \times U(1)_{em}$

⋆ mass to fermions via Yukawa interactions

$m_f = g_{\phi\ f\bar{f}}\ v$



- One state left in the spectrum: HIGGS Boson with mass $m_\phi^2 = 2\lambda v^2$

Discovering the Higgs will put the final piece of the Standard Model in place

It will prove that our simplest explanation for the origin of mass is indeed correct.

- First evidence of EWSB ==> masses of gauge bosons

Measuring the WWH and ZZ H couplings is essential to identify the Higgs as the agent of EWSB: without a v.e.v, no such trilinear coupling at tree level

==> we need to detect the Higgs in association with gauge bosons

- The other particle whose mass is related to the source of EWSB is the top quark

-- If there were other particles (Higgs) responsible for it, their v.e.v. will be small (not responsible for W,Z masses) and hence the couplings to the top would need to be too strong --

==> if the theory remains perturbative, the top mass will mainly come from a Higgs with SM-like couplings to W and Z

The first step is discovery:

Observe one Higgs boson or more.

Next Step:determine its basic properties :
mass, spin, total width, CP quantum numbers; couplings to boson and fermions, Higgs self couplings and reconstruct Higgs potential, observe rare decay modes

Use precision measurement of basic properties to learn about basic model of nature: Is this scalar a Higgs boson? Disentangle between SM , the MSSM, other non-minimal Higgs sector? Investigate CP viol., beyond the SM , via effects in the Higgs sector; Higgs mixings in ED

Both the LHC and the ILC will be crucial in establishing the nature of the EWSB mechanism

- <u>Direct Higgs search at LEP</u>

$$e^+e^- \xrightarrow{Z^*} H_{SM} Z \qquad m_{H_{SM}} > 114.6\text{GeV at } 95\% \text{ C.L.}$$

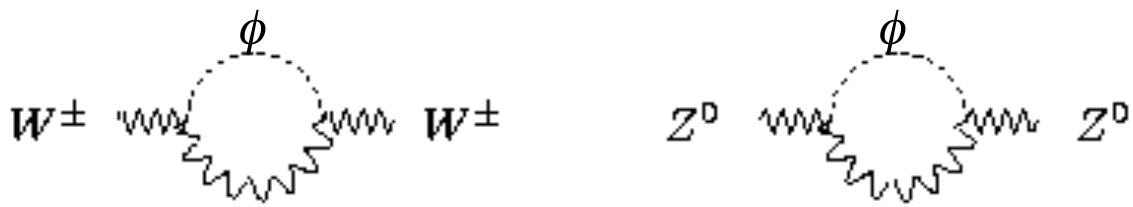
with $H_{SM} \to b\bar{b}, \tau^+\tau^-; Z \to q\bar{q}, l^+l^-, \nu\bar{\nu}$

final LEP result, 2003

- <u>Constraints on m_H from precision tests of the SM</u>

(accuracy at the per mille level) from CERN, Fermilab, SLAC

Although the Higgs boson has not been seen and its mass is unknown, it enters via loop corrections in electroweak observables: particle masses, decay rates, etc

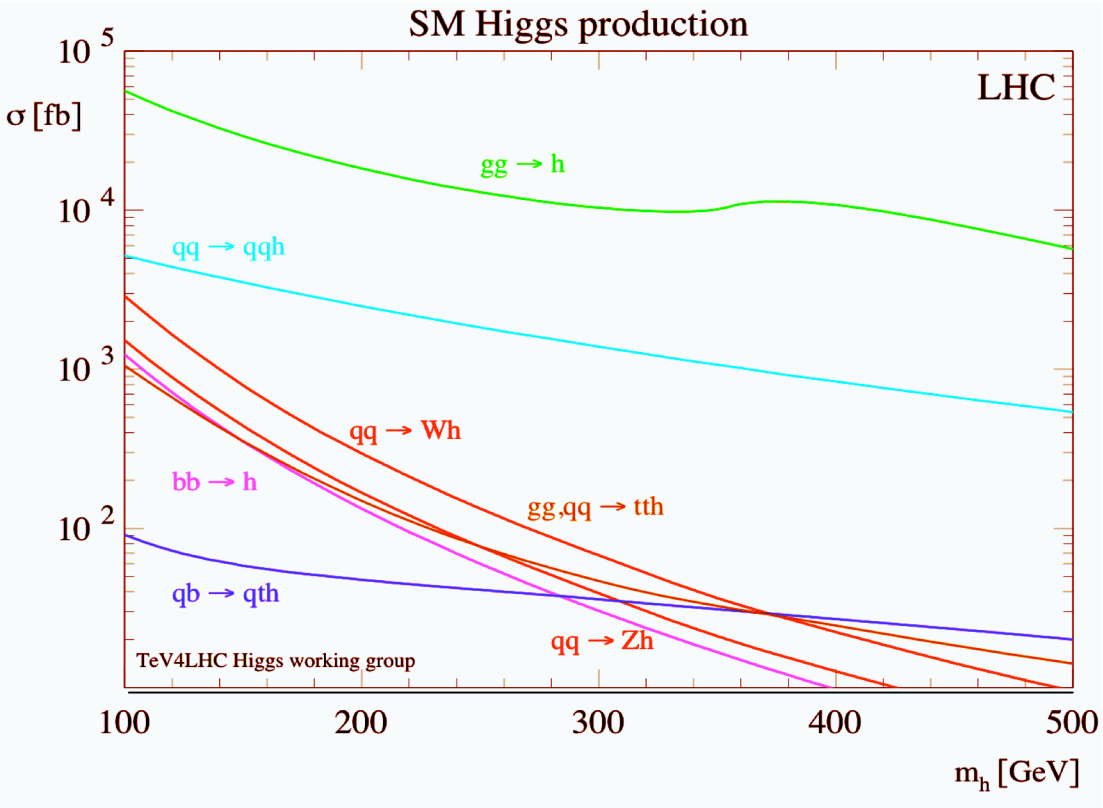


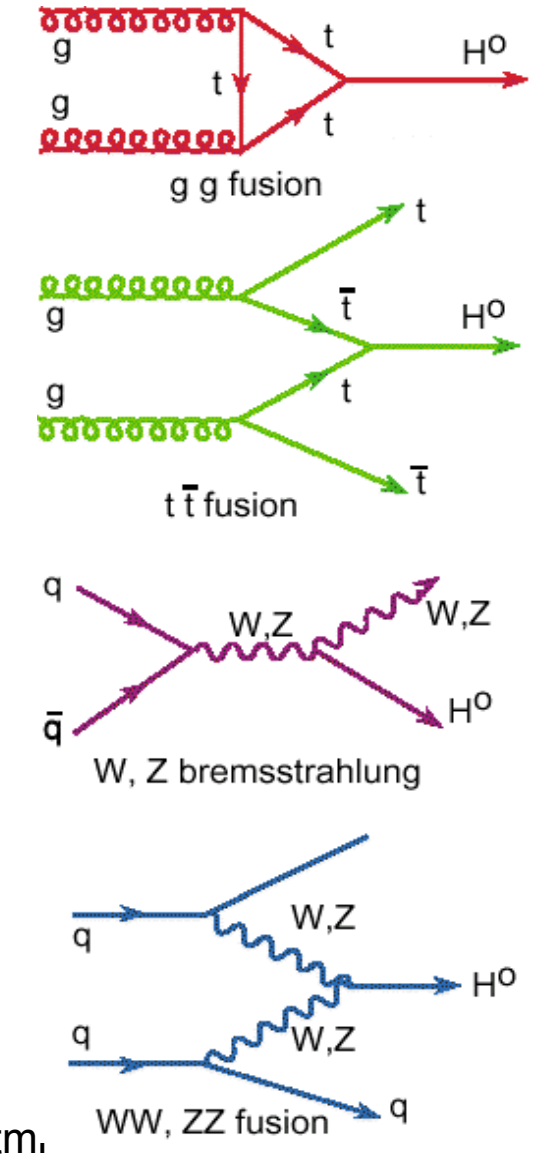
All electroweak parameters have at most logarithmic dependence on m_ϕ
However, preferred value of m_ϕ can be determined

$$m_\phi < 200 \text{ GeV at } 95\ \% \text{ C.L}$$

To avoid a light Higgs Boson, must have new phenomena below 1 TeV

SM Higgs production processes at hadron colliders



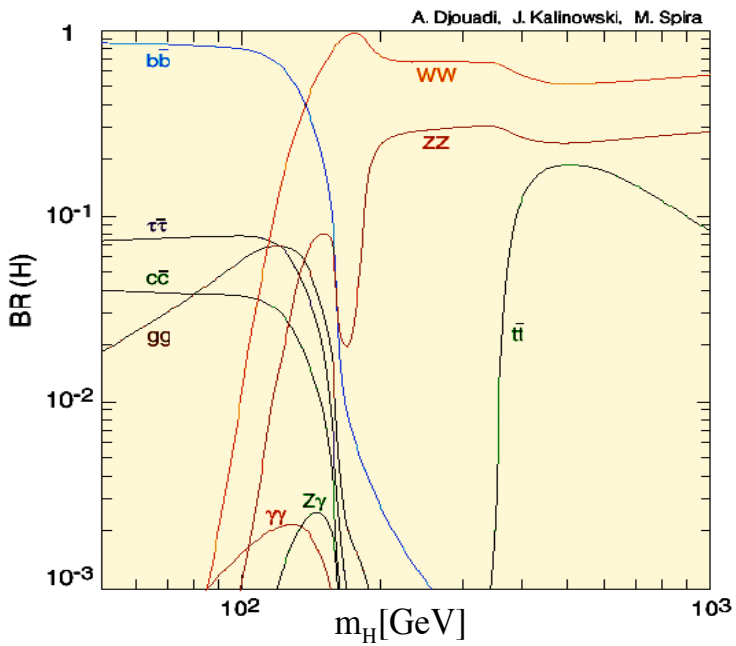


Crucial to compute production cross sections with high accuracy to obtain information from data about ratio of decay widths and eventually couplings and total witdh

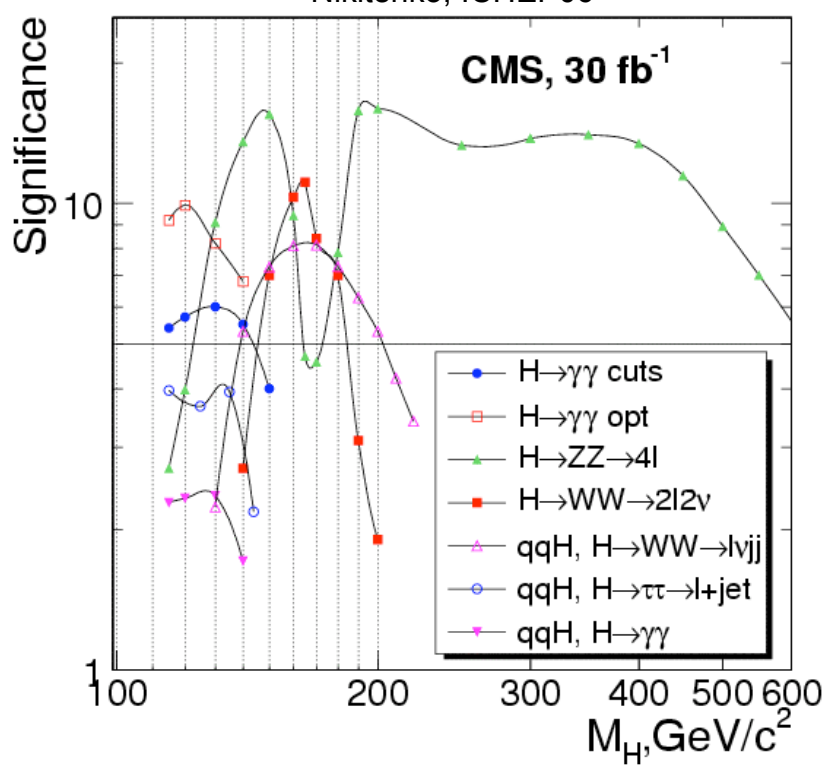
Much progress recently in computing
NLO and NNLO QCD corections

correctionshttp://maltoni.home.cern.ch/maltoni/TeV4LHC/SM.htm

Search Channels for the SM Higgs at the LHC



Nikitenko, ICHEP06



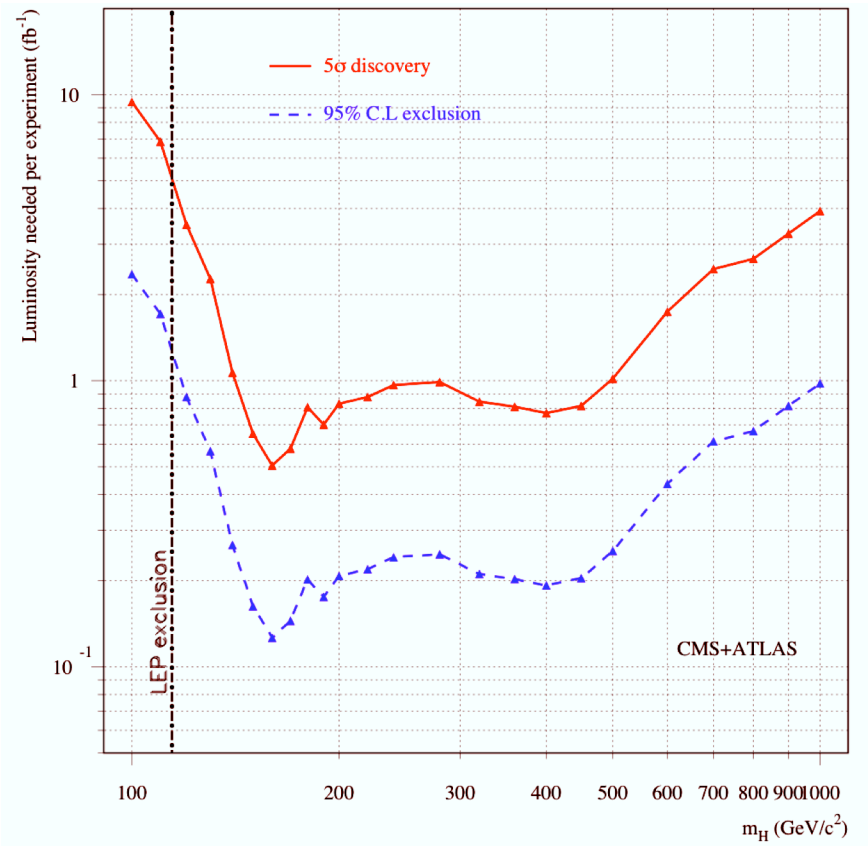
- **Low mass range** m_H < 200 GeV

Production DECAY	Inclusive	VBF	WH/ZH	ttH
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$			YES	YES
$H \rightarrow \tau\tau$		YES		
$H \rightarrow WW^*$	YES	YES	YES	
$H \rightarrow ZZ^*, Z \rightarrow l^+l^-$	YES			

- **Intermediate mass range**
  200 GeV < m_H< 700 GeV
  Inclusive H ==>WW/ZZ

- **Large mass range**: m_H> 700 GeV
  VBF with H ==>WW==>lν jj
  ZZ ==>ll νν

The LHC potential



Total sensitivity combining all channels plus two experiments

5 σ discovery possible over the entire SM Higgs mass range of interest with 5 fb-1

==> For m_H~120 GeV combination of many different channels necessary, hence, requires a good understanding of the detectors.

==> The Tevatron will explore such region

Higgs mass resolution: 0.1 to 1%, combining most channels for 300 fb-1 and both experiments, using H-->ZZ--> 4l or H-->gamma gamma

Total Width resolution: 5-8 % for m_H > 300 GeV, ATLAS 300 fb-1, H-->ZZ--> 4l

Measuring Higgs Couplings at LHC

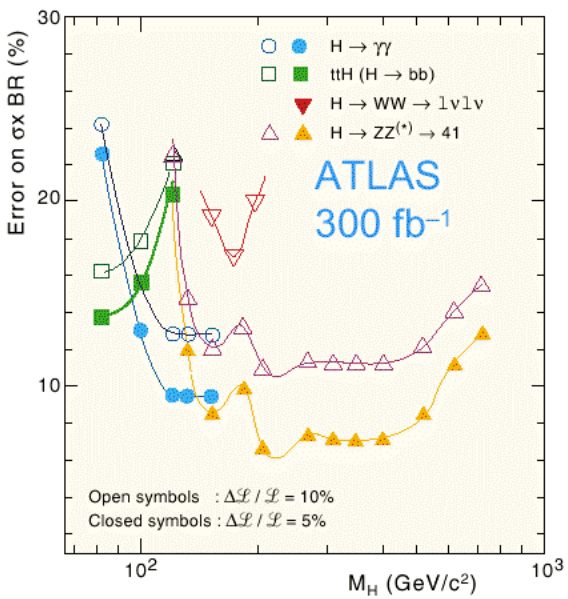
LHC rates for partonic processes are given by

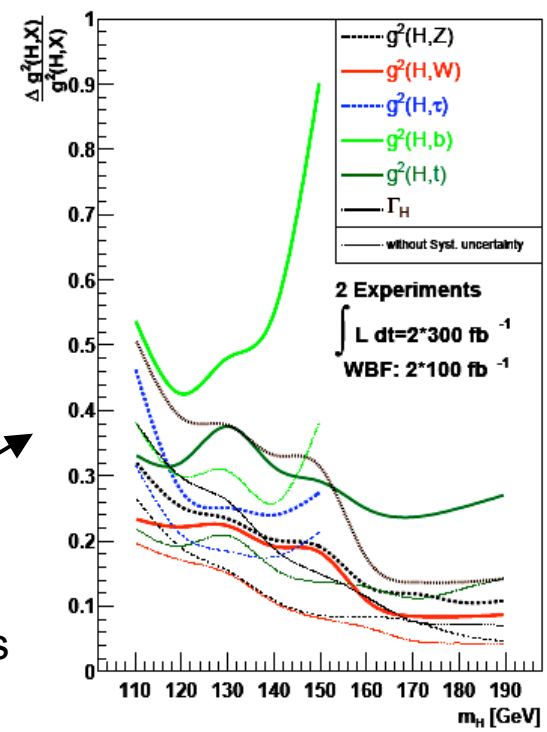
$$\sigma(pp \to H_{SM}) \times BR(H_{SM} \to YY) = \frac{\sigma^{SM}}{\Gamma_p^{SM}} \frac{\Gamma_p \Gamma_Y}{\Gamma}$$

Γ_p is the Higgs partial with involving the production couplings and BR $(H_{SM} \to YY) = \frac{\Gamma_Y (H_{SM} \to YY)}{\Gamma}$

•From precision on $\sigma \times BR$ ==> determine ratios of decay widths ==> with theoretical assumptions

ratios of couplings





Precision of 10-40% for Γ_Y
==> 5-20% in the couplings

- **Measuring HWW and HZZ couplings of order one (SM-like) will be evidence of a Higgs responsible for the EWSB**
  ==> WW fusion most relevant channel

The Higgs Sector in Minimal Supersymmetric Standard Model

- 2 Higgs SU(2) doublets ϕ_1 and ϕ_2 : after Higgs Mechanism

→ 2 CP-even h, H with mixing angle α
1 CP-odd A and a charged pair $H^{\pm}$

All Higgs masses and couplings given in terms of 2 parameters m_A and $\tan\beta = v_2/v_1$

$$\Rightarrow v^2 = v_1^2 + v_2^2 = 246\ \mathrm{GeV}$$

At tree level, one Higgs doublet couples only to down quarks and the other couples to up quarks only

$$-L = \overline{\psi}_L^i \left(\hat{h}_d^{ij+} \phi_1 d_R^j + \hat{h}_u^{ij+} \phi_2 u_R^j \right) + h.c.$$

Since the up and down sectors are diagonalized independently, the Higgs interactions remain flavor diagonal at tree level.

Couplings to gauge bosons and fermions (SM normalized) →

$$\mathrm{hZZ,\ hWW,\ ZHA,\ WH^{\pm}H} \longrightarrow \sin(\beta-\alpha)$$
$$\mathrm{HZZ,\ HWW,\ ZhA,\ WH^{\pm}h} \longrightarrow \cos(\beta-\alpha)$$

$$(\mathrm{h,H,A})\ u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$$
$$(\mathrm{h,H,A})\ d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta$$

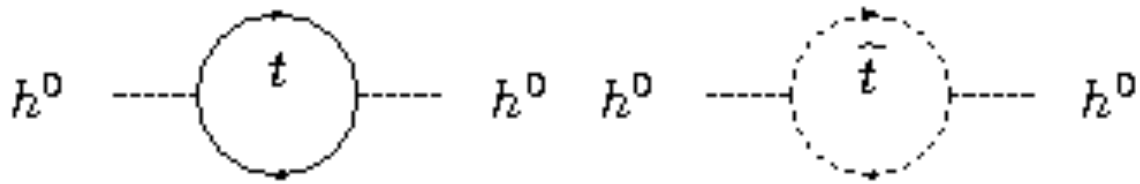
Decoupling limit $m_A >> m_Z$

==> lightest (SM-like) Higgs $m_h \leq m_Z$, others heavy and roughly degenerate

Radiative Corrections to Higgs Boson Masses

Important quantum corrections due to incomplete cancellation of particles and superparticles in the loops

Main effects: stops;
and sbottoms at large tan beta



$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2\, M_W^2} \left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12\, M_S^2} \right) \right] + \text{h.o.}$$

$$M_S^2 = \tfrac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) \text{ and } X_t = A_t - \mu/\tan\beta \longrightarrow \text{stop mixing}$$

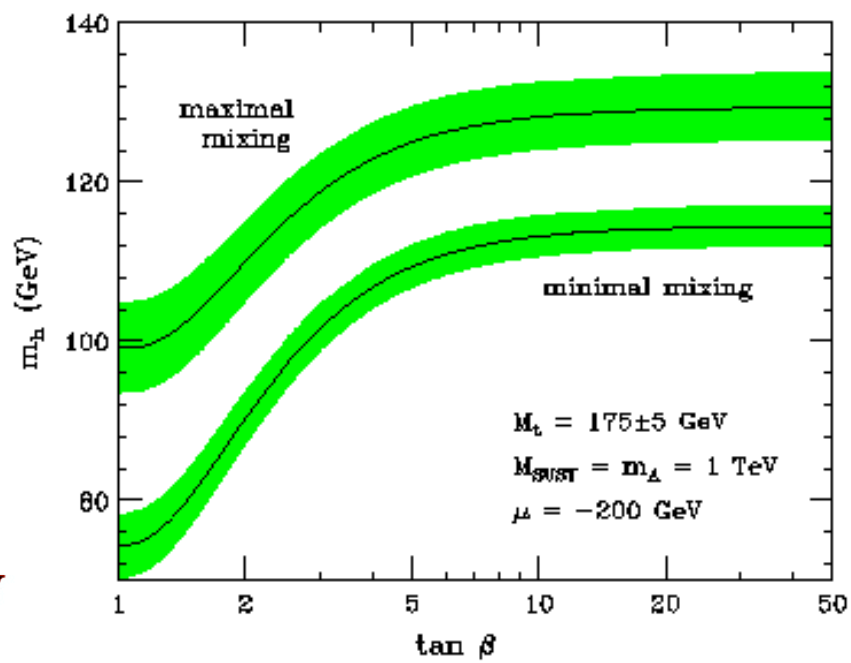
- m_t^4 **enhancement**
- **log sensitivity to stop masses** M_S
- **depend. on stop mass mixing** X_t

After 2 -loop corrections

$$m_h \leq 135\text{GeV}$$

stringent test of the MSSM

$$M_S = 1 \rightarrow 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2 - 5 \text{ GeV}$$
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$



Radiative Corrections to the Higgs Couplings

1 Through radiative corrections to the CP-even Higgs mass matrix δM_{ij}^2 , which defines the mixing angle α

$$\sin\alpha\cos\alpha = M_{12}^2 / \sqrt{\left(\mathrm{Tr}\, M^2\right)^2 - 4\det M^2}$$

The off diagonal elements are prop. to

$$M_{12}^2 \propto -\left(m_A^2 + m_Z^2\right)\cos\beta\sin\beta + \frac{m_t^4}{16\pi^2 \mathrm{v}^2}\frac{\mu X_t}{M_S^2}\left(\frac{X_t^2}{M_S^2} - 6\right)$$

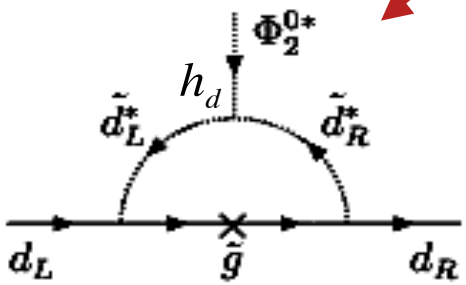
Important effects of rad. correc. on $\sin\alpha$ or $\cos\alpha$ depending on the sign of μX_t and the magnitude of X_t / M_S

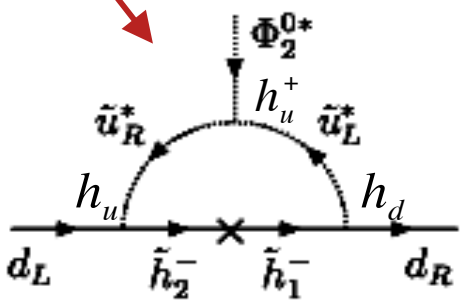
===> govern couplings of Higgs to fermions
===> via rad. correc. to $\cos(\beta-\alpha)$ and $\sin(\beta-\alpha)$ governs couplings to vector bosons

When off-diagonal elements vanish, possible for small m_A and large tan beta
===> either $\sin\alpha$ or $\cos\alpha$ vanish ===> strong
suppression of the SM-like Higgs boson coupling to bottom-quarks and tau-leptons

2) $\tan\beta$ enhanced loop corrections to neutral Higgs-fermion couplings

$$-L_{eff.} = \bar{d}_R^0 \hat{h}_d \left[\phi_1^{0^*} + \phi_2^{0^*} \left(\hat{\varepsilon}_0 + \hat{\varepsilon}_Y \hat{h}_u^+ \hat{h}_u \right) \right] d_L^o + \phi_2^0 \bar{u}_R^0 \hat{h}_u u_L^0 + h.c.$$





ε loop factors intimately connected to the structure of the squark mass matrices.

- **<u>In terms of the quark mass eigenstates</u>** Dedes , Pilaftsis

$h_u = M_u / v_2$

$$-L_{eff} = \frac{1}{v_2}\left(\tan\beta\, \Phi_1^{0^*} - \Phi_2^{0^*}\right) \bar{d}_R M_d \left[V_{CKM}^+ R^{-1} V_{CKM} \right] d_L + \frac{1}{v_2} \Phi_2^{0^*} \bar{d}_R M_d d_L + \Phi_2^0 \bar{u}_R M_u u_L + h.c.$$

and $R = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |h_u|^2$ ➔ R diagonal

Dependence on SUSY parameters →

$$\varepsilon_0^i \approx \frac{2\alpha_s}{3\pi} \frac{\mu^* M_{\tilde{g}}^*}{\max\left[m_{\tilde{d}_1^i}^2, m_{\tilde{d}_2^i}^2, M_{\tilde{g}}^2 \right]} \qquad \varepsilon_Y \approx \frac{\mu^* A_t^*}{16\pi^2 \max\left[m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2 \right]}$$

Looking at $V_{CKM} \cong I \Rightarrow$ <u>Flavor Conserving Higgs-fermion couplings</u>

$$-L_{eff} = \frac{1}{v_2}\left(\tan\beta\,\Phi_1^{0^*} - \Phi_2^{0^*}\right)\bar{b}_R M_b \frac{1}{R^{33}} b_L + \frac{1}{v_2}\Phi_2^{0^*}\bar{b}_R M_d b_L + h.c.$$

$$R^{33} = 1 + \left(\varepsilon_0^3 + \varepsilon_Y h_t^2\right)\tan\beta \equiv 1 + \Delta_b$$

In terms of h,H and A:

$$\phi_1^0 = -\sin\alpha\, h + \cos\alpha\, H + i\sin\beta\; A$$
$$\phi_2^0 = \cos\alpha\, h + \sin\alpha\, H - i\cos\beta\; A$$

Hence:

$$g_{hbb} \approx \frac{-m_b \sin\alpha}{(1+\Delta_b)\, v\cos\beta}\left(1 - \Delta_b/\tan\alpha\tan\beta\right)$$

$$g_{Hbb} \approx \frac{m_b \cos\alpha}{(1+\Delta_b)\, v\cos\beta}\left(1 - \Delta_b\tan\alpha/\tan\beta\right)$$

$$g_{Abb} \approx \frac{m_b \tan\beta}{(1+\Delta_b)v}$$

destroy basic relation

$$g_{h,H,Abb}/g_{h,H,A\,\tau\tau} \propto m_b/m_\tau$$

At large $\tan\beta \Rightarrow g_{Hbb} \approx g_{Abb}$

- <u>strong suppression</u> of coupling of h (H) to bottoms if
  $\tan\alpha \simeq \Delta_b/\tan\beta \longrightarrow g_{h\,b\bar{b}} \simeq 0$; $g_{h\,\tau\tau} \simeq -\frac{m_\tau}{v}\Delta_b$ (similar for H)

$\Longrightarrow$ main decay modes of SM-like MSSM Higgs: $b\bar{b} \sim 80\%$ $\tau^+\tau^- \sim 7-8\%$
drastically changed $\Longrightarrow$ other decay modes enhanced

How can different SUSY Benchmark Scenarios impact LHC Searches?

•The m_h^{max} scenario: $M_S = 1\ \mathrm{TeV}$; $X_t = 2.4\ M_S$; $m_{\tilde{g}} = 0.8\ M_S$; $M_2 = -\mu = 200\mathrm{GeV}$; $A_t = A_b$

-- Maximizes m_h and allows conservative tan beta bounds

-- $g_{hbb}, g_{h\tau\tau}$ enhanced due to $\sin\alpha_{eff}, / \cos\beta$ factor for low mA and Intermediate and large tan beta (analogous for H if small m_A)

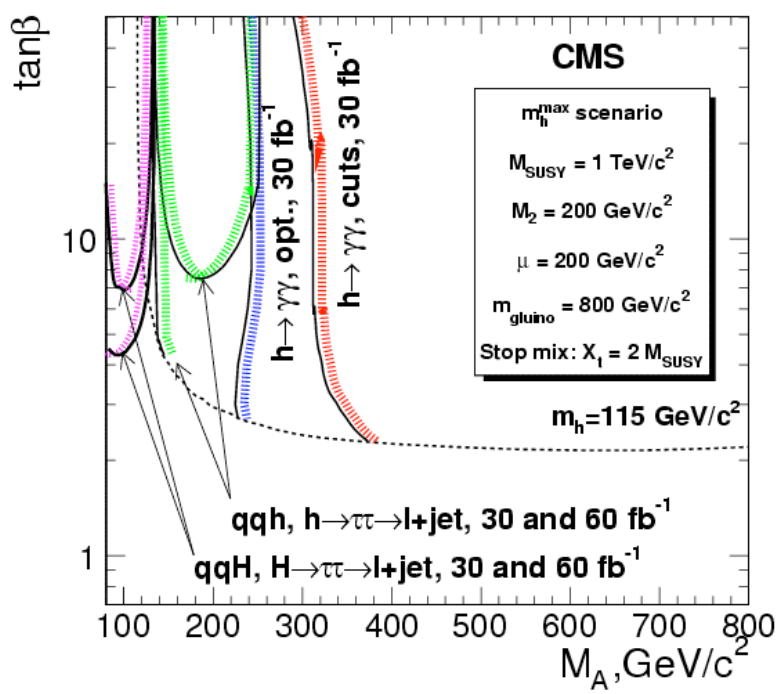
==> strong suppression of $h \rightarrow \gamma\gamma$

First, full simulation analysis of qqH, H->ττ->l+jet
Nikitenko, ICHEP 06

Optimized ==>NN with kinematics and γ isolation as input

•The No-Mixing scenario: X_t=0
==> similar behavior for Higgs couplings to tau leptons, bottom quarks and photons

Discovery reach for SM-like MSSM Higgs



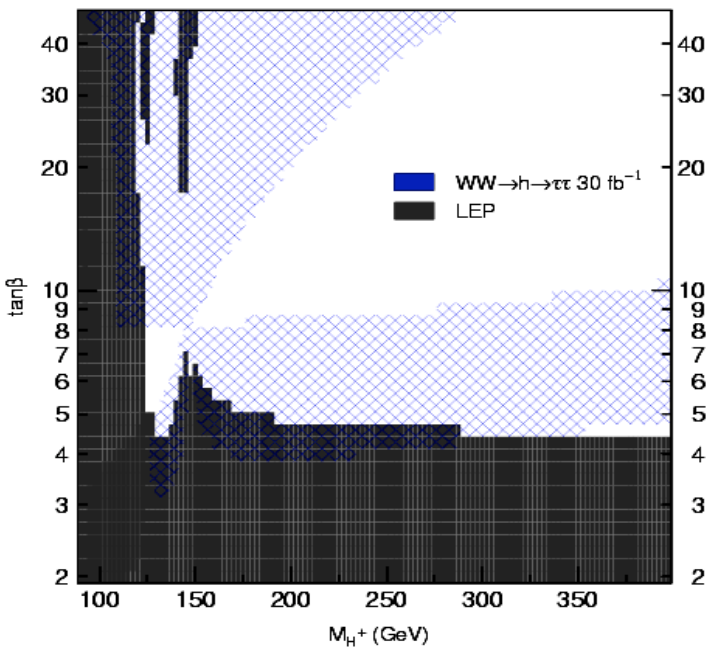
Prospects for SM–like Higgs searches at LHC: small $\sin\alpha_{eff.}$ scenario

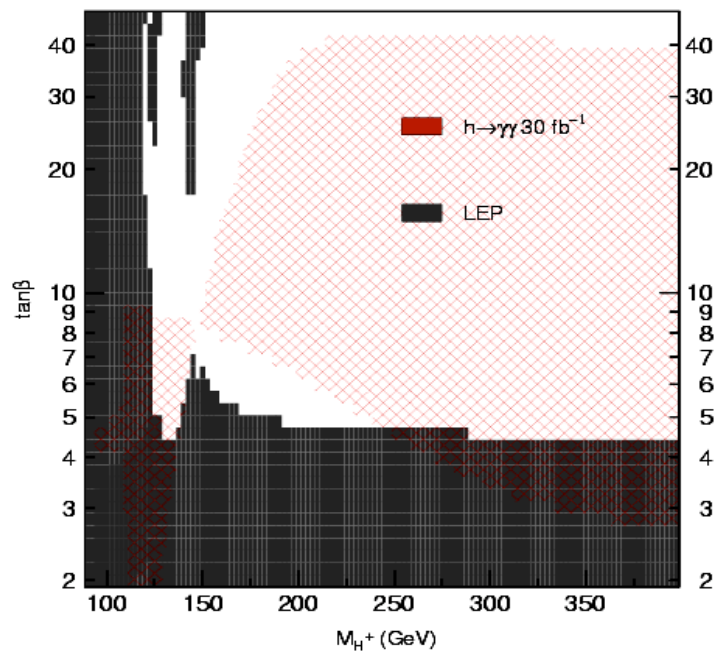
- The small $\sin\alpha_{eff.}$ (rad.correc. α) scenario:

$$M_S = 800\ \text{GeV}\ ;\quad X_t = -\ 1.2\ \text{TeV}\ ;\ \mu = 2.5\ M_s\ ;\ m_{\tilde{g}} = M_2 = 500\text{GeV};\ \ A_t = A_b$$

==> $g_{hbb},\ g_{h\tau\tau}$ importantly suppressed for large tan beta and small m_A, and in different ways due to Δ_b corrections

hence, $h \to \gamma\gamma$ channel enhanced with respect to SM





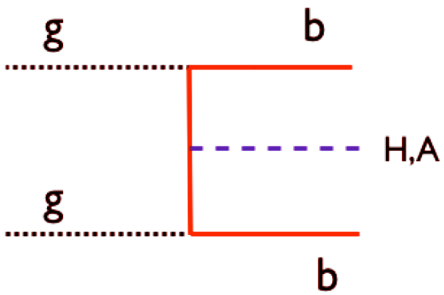
-- Complementarity in coverage

-- One can see a SM-like Higgs in the $\gamma\gamma$ channel and not in the $\tau^+\tau^-$channelr

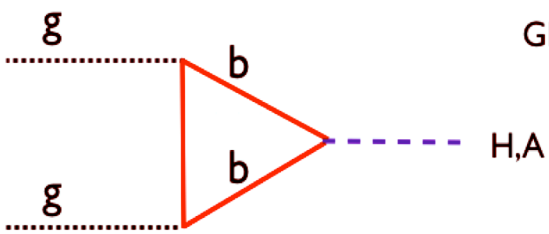
Non-Standard Higgs Production at the Tevatron and LHC

- Enhanced couplings to b quarks and tau-leptons
- Considering value of running bottom mass and 3 quark colors

$$BR(A \to b\bar{b}) \cong \frac{9}{9+(1+\Delta_b)^2} \qquad BR(A \to \tau^+\tau^-) \cong \frac{(1+\Delta_b)^2}{9+(1+\Delta_b)^2}$$



Associated Production



Gluon Fusion

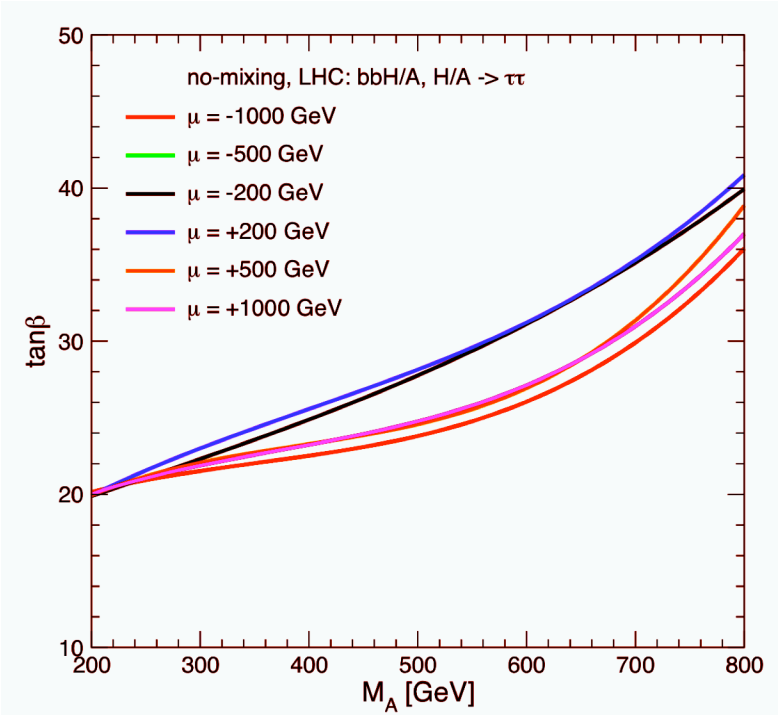
$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \cong \sigma(b\bar{b}A)_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

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

There is a strong dependence on the SUSY parameters in the bb search channel. This dependence is much weaker in the tau-tau channel

Searches for Non-Standard Neutral Higgs bosons at the LHC

$pp \to A/H\,X,\;\; A/H \to \tau^+\tau^-,$ rescaling CMS prospects for 30 fb^{-1} (similar for ATLAS)

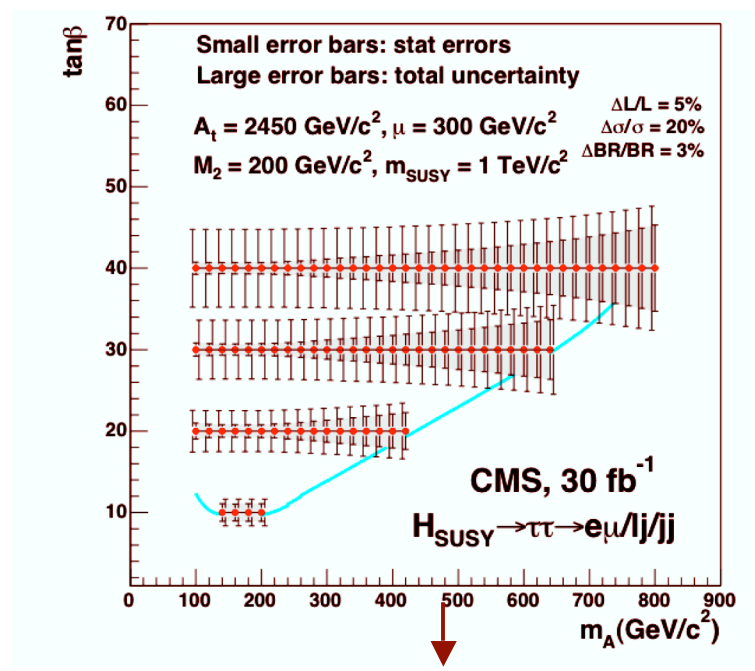


- Enhancement of Hbb and Abb couplings by factor $\tan\beta$ compared with SM Higgs.

  ==> large production cross section

  ==> decay dominated by $A/H \to \tau^+\tau^-$

  (with different decay modes of tau leptons)



Cancellation of Δ_b effects ==> projections stable under variations of SUSY space ==> $\boxed{\Delta\tan\beta \approx 8}$

main variation ==> $A/H \to \tilde{\chi}_i^0\tilde{\chi}_j^0,\;\; \tilde{\chi}_k^{\pm}\tilde{\chi}_l^{\mp}$

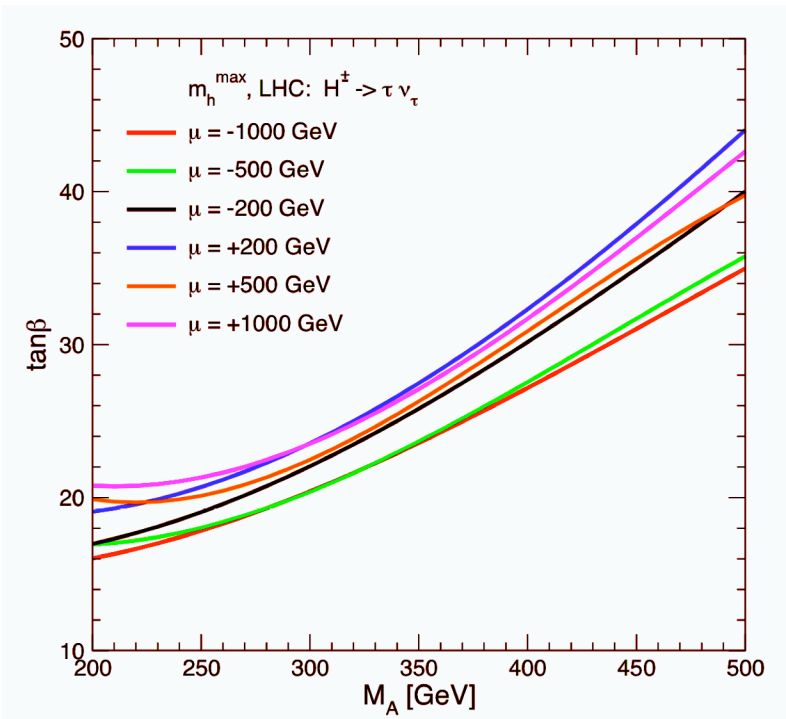
Robustness of results under variations of SUSY space ==>handle on tan beta

Charged Higgs searches at the LHC

- Similarly to the neutral Higgs case, there are tan beta enhanced loop corrections which depend on SUSY parameters

For $m_{H^\pm} > m_t + m_b$ expect $H^\pm \to tb$ decay, however

$$\sigma(gb \to H^\pm t) \times BR(H^\pm \to \tau\nu) \propto \frac{\tan\beta^2}{(1+\Delta_b)^2} \frac{(1+\Delta_b)^2}{(1+\Delta_b)^2 + 9\left(1 - m_t^2/m_{H^\pm}^2\right)^2}$$



Much more robust under radiative corrections

$$\Delta \tan\beta \leq 10$$

Including variation due to charged Higgs decay into SUSY particles for small mu

B and Higgs Physics at the Tevatron and the LHC

explore complementary regions of SUSY parameter space

Important Flavor Changing effects: 1) tree level ==> charged Higgs induced via
2) tan beta enhanced loop corrections both in the neutral and charged Higgs sectors
==> model dependent ==> assume Minimal Flavor Violation

A) **Bs mixing**: $\Delta M_S^{\mathrm{CDF.}} = 17.33^{+0.42}_{-0.21} \pm 0.07\, ps^{-1}$ and SM CKM fit $\Rightarrow -14.1 < \Delta M_{B_s}^{NP}[ps^{-1}] < 2.4$

Due to correlation between Bs mixing and $\mathrm{BR}(B_S \to \mu^+\mu^-)$ ==> if A/H at the reach of LHC then largest contribution to Δm_S due to new physics at most a few ps-1

B) $\mathrm{BR}(B_S \to \mu^+\mu^-)$ ==> SM rate of order 10^{-9} at the reach of LHC with about $10\mathrm{fb}^{-1}$, but important SUSY corrections can enhanced it by 2 orders of magnitude

$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto |\mu A_t|^2 \tan\beta^2 / m_A^4$$

C) $\mathrm{BR}(B_u \to \tau\nu)$: important constraint from recent measurement at Belle

$$\frac{\mathrm{BR}(B_u \to \tau\nu)^{SUSY}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = \left[1 - \left(\frac{m_B^2}{m_{H^\pm}^2}\right)\frac{\tan\beta^2}{(1+\Delta_b)}\right] \Leftrightarrow \frac{\mathrm{BR}(B_u \to \tau\nu)^{\exp}}{\mathrm{BR}(B_u \to \tau\nu)^{SM}} = 0.67^{+0.30}_{-0.27}$$

D) $B \to X_S\gamma$: good agreement with SM ==> $|\mathrm{BR}(B \to X_S\gamma)^{\exp} - \mathrm{BR}(B \to X_S\gamma)^{SM}| < 1.3 \times 10^{-4}$

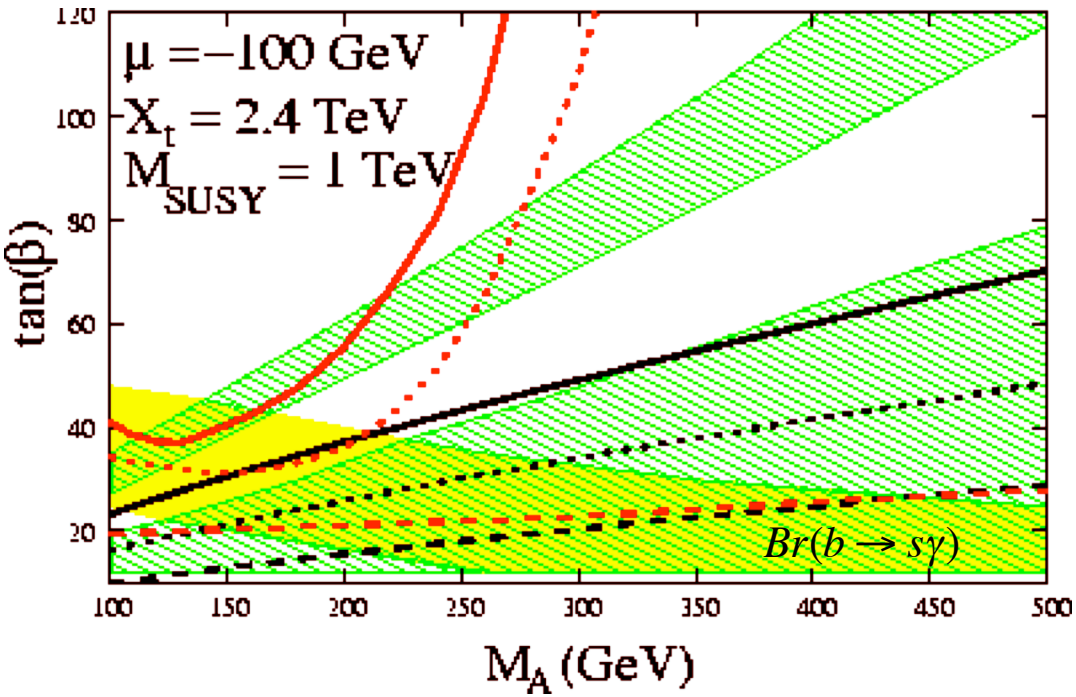
SUSY contributions from chargino-stop and charged Higgs-top loops need to partially cancel

Large to moderate values of X_t ==> SM like Higgs heavier than 120 GeV

$BR(B_S \to \mu^+\mu^-) \propto |\mu A_t|^2 \Rightarrow$ Experimental bound ==> small μ

Small $\mu < 0$ ==> $\cong$ constant H^+ and enhanced negative $\chi^+ - \tilde{t}$ contributions to $BR(b \to s\gamma)$

M. C. et al. hep-ph/0603106 and in preparation



Red Lines: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
with 1,4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC

black lines: $BR(B_s \to \mu^-\mu^+)$ reach:

Tevatron: 1×10^{-7} (present);

2×10^{-8} ($8fb^{-1}$)

LHC: 5.5×10^{-9} ($10\ fb^{-1}$)

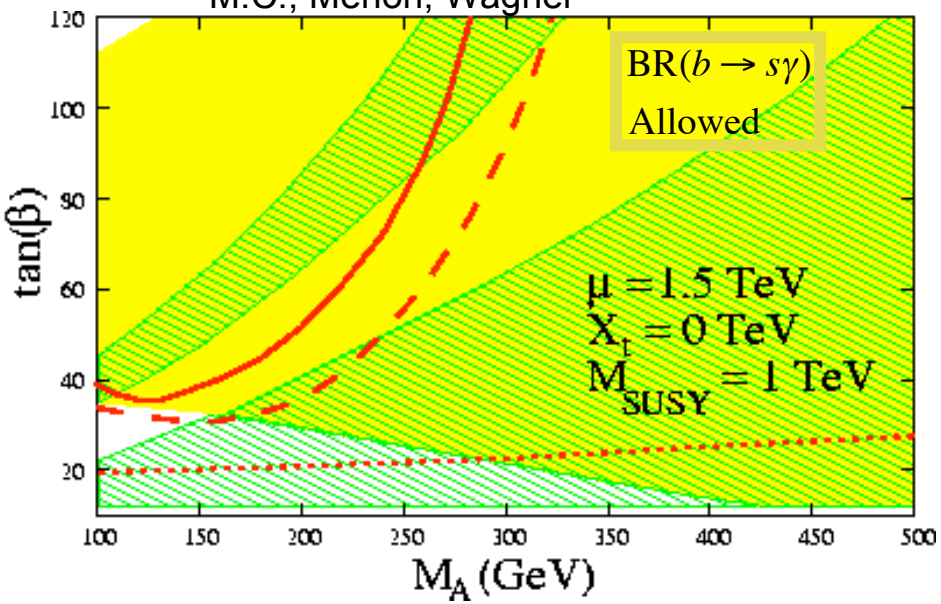
Hatched Area: $BR(B_u \to \tau\nu)$ Allowed

Yellow: $BR(b \to s\gamma)$Allowed

- Sizeable LR stop mixing <==> small/moderate mu
  ==> **B searches more powerful than Non-SM like Higgs searches**
- **SM-like Higgs: full coverage with 30fb^{-1} but needs both** $h \to \tau\tau$ and $h \to \gamma\gamma$

- **Small X_t, sizeable μ ==> No mixing scenario**
  - Interesting region since light SM-like Higgs lighter than 125 GeV
  - **No constraints from** $\mathrm{BR}(B_s \to \mu^+\mu^-)$
  - Mild constraints from $\mathrm{BR}(\mathrm{b} \to \mathrm{s}\gamma)$ if large $\mu\, \mathrm{M}_{\tilde{g}} > 0$
  - Important constraint from recent measurement of $\mathrm{BR}(B_u \to \tau\nu)$

M.C., Menon, Wagner



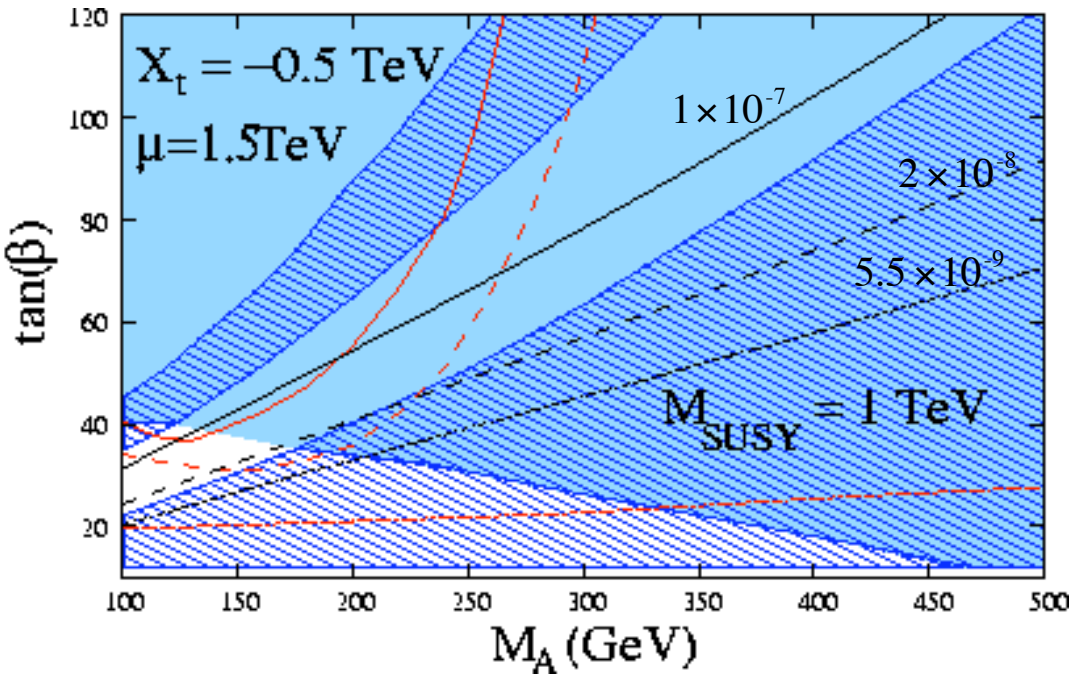
Red Lines: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
with 1,4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC

Green : Allowed by $\mathrm{BR}(B_u \to \tau\nu)$

-- small stop mixing (Xt≈0) and large Higgsino mass parameter mu
==> good for the Tevatron ==> has sensitivity to discover all 3 MSSM neutral Higgs bosons
-- SM-like Higgs at the LHC: needs di-tau and di-photon channels to discover (30 fb-1)

Tevatron and LHC searches at small/moderate X_t and large mu

- H/A Higgs reach is marginal at the Tevatron, unless $\mathrm{BR}(B_S \to \mu^+\mu^-)$ observed as well
- A relatively large region of SUSY parameter space can be probed at the LHC even for relatively "low" luminosities



Red Lines: $p\bar{p}, pp \to H/A \to \tau^+\tau^-$
with 1,4 fb^{-1} at the Tevatron
with 30 fb^{-1} at the LHC

black lines: $BR(B_s \to \mu^-\mu^+)$ reach:

Tevatron: 1×10^{-7} (present);

2×10^{-8} (8fb^{-1})

Hatched Area: $\mathrm{BR}(B_u \to \tau\nu)$ Allowed

Yellow: $BR(b \to s\gamma)$Allowed

-- increasing the stop mixing for sizeable mu

==> Tevatron A/H searches become marginal, excellent region for LHC

-- for SM-like Higgs similar situation as the small $\sin\alpha_{eff}$ scenario

Conclusions

- SM Higgs observable in multiple channels at the LHC

- Information on Higgs couplings with 5--20% accuracy with 300 fb^{-1} of data

- SUSY SM-like Higgs ==> strong variation in the discovery reach depending on SUSY parameter space via radiative corrections

- Other MSSM Higgs bosons ==> Need sizeable $\tan\beta$ enhancement for discovery

$A/H \rightarrow \tau^+\tau^-$ and $H^\pm \rightarrow \tau\nu \rightarrow$ robust results under variation of SUSY space

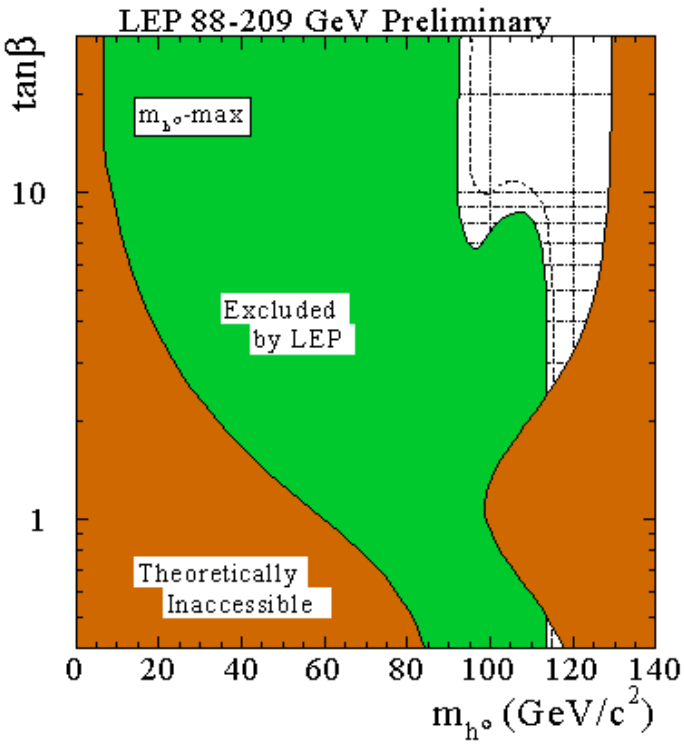
↓

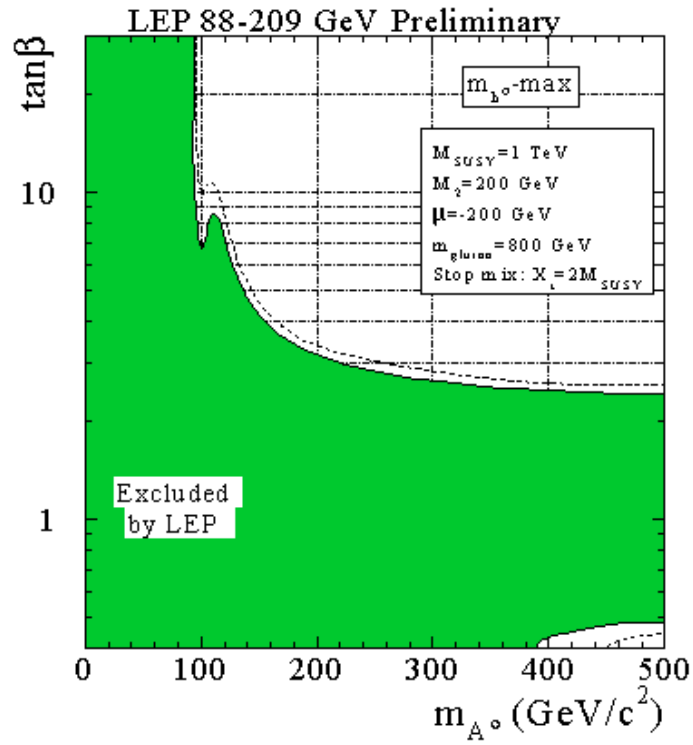
moderate sensitivity to tan beta

- The Non-Standard MSSM Higgs searches at the LHC can be strongly constrained by B physics measurements depending on the SUSY parameter space.

$$e^+e^- \xrightarrow{Z^*} hZ, HZ, Ah, AH$$

main decay mode $h \to b\bar{b}$





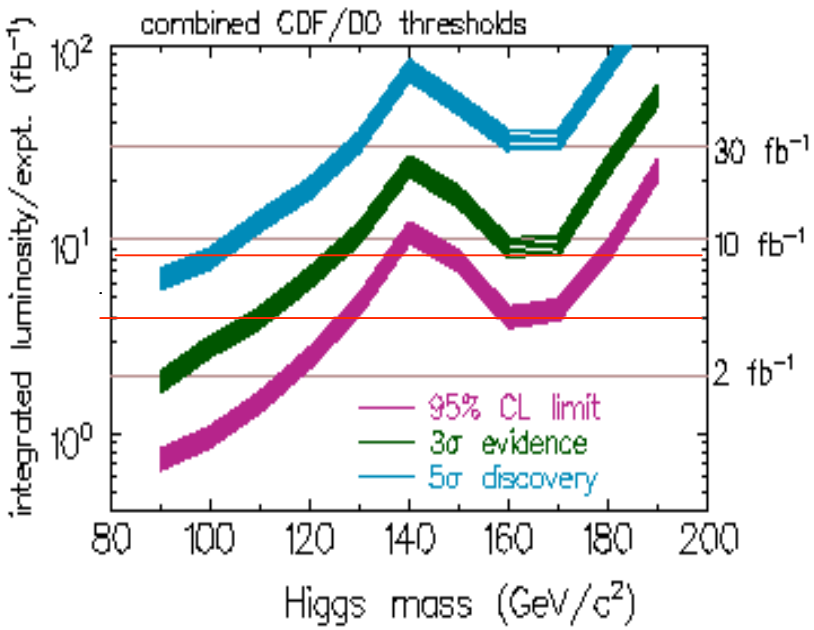
$$m_h > 91.0GeV; m_A > 91.9GeV$$

$$m_{H^\pm} > 78.6GeV$$

$$m_h > 114.6GeV$$

•**Tevatron can search for a Higgs in parts of the mass range preferred by precision data**

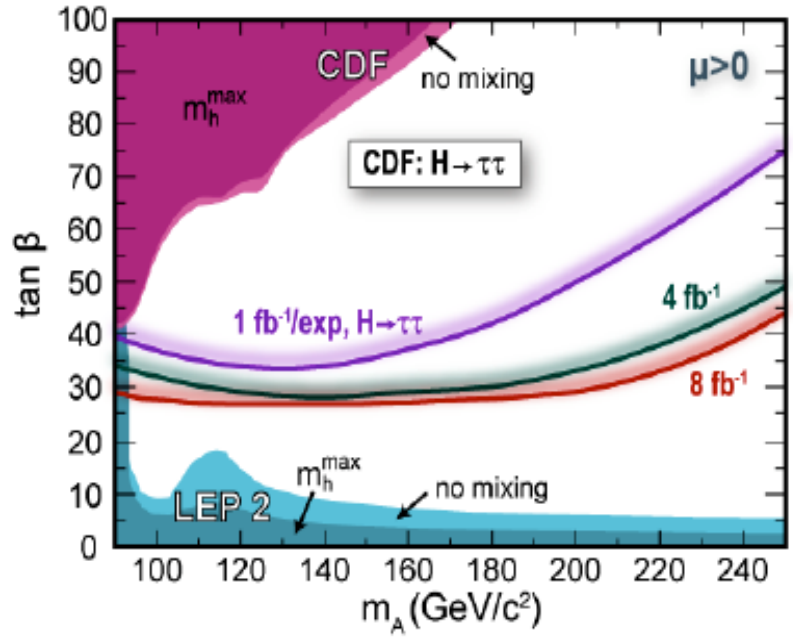
$$p\bar{p} \to V\,H \to Vb\bar{b} \quad \text{with } V = W, Z$$



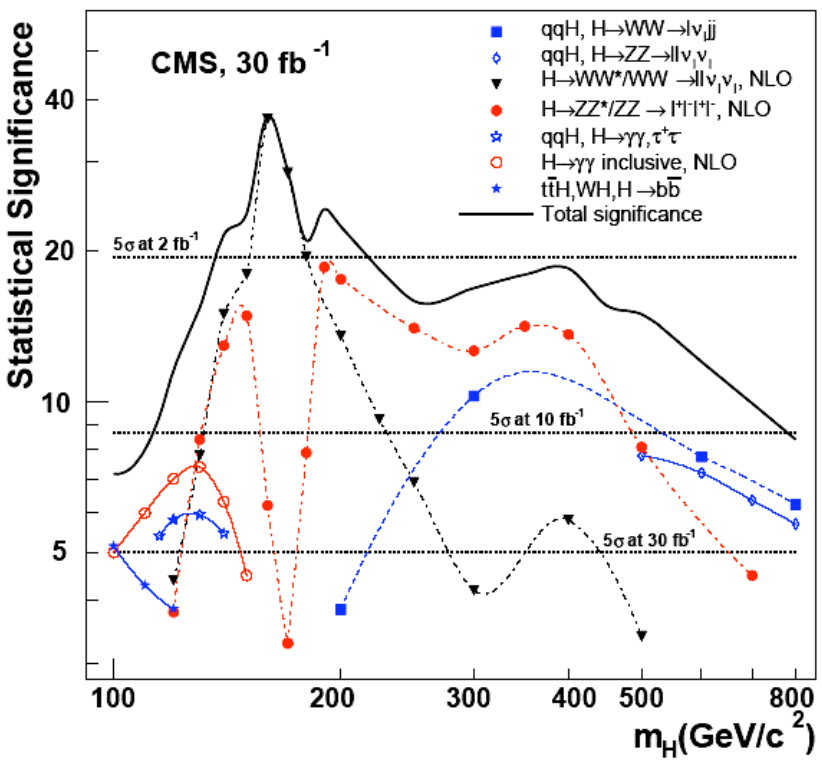
Quite challenging! Evidence of a signal will mean that the Higgs has strong (SM-like) couplings to W and Z

Heavy neutral MSSM Higgs searches

- **$pp \to Ab+X \to bbb+X$**
- **$pp \to A+X \to \tau\tau+X$**

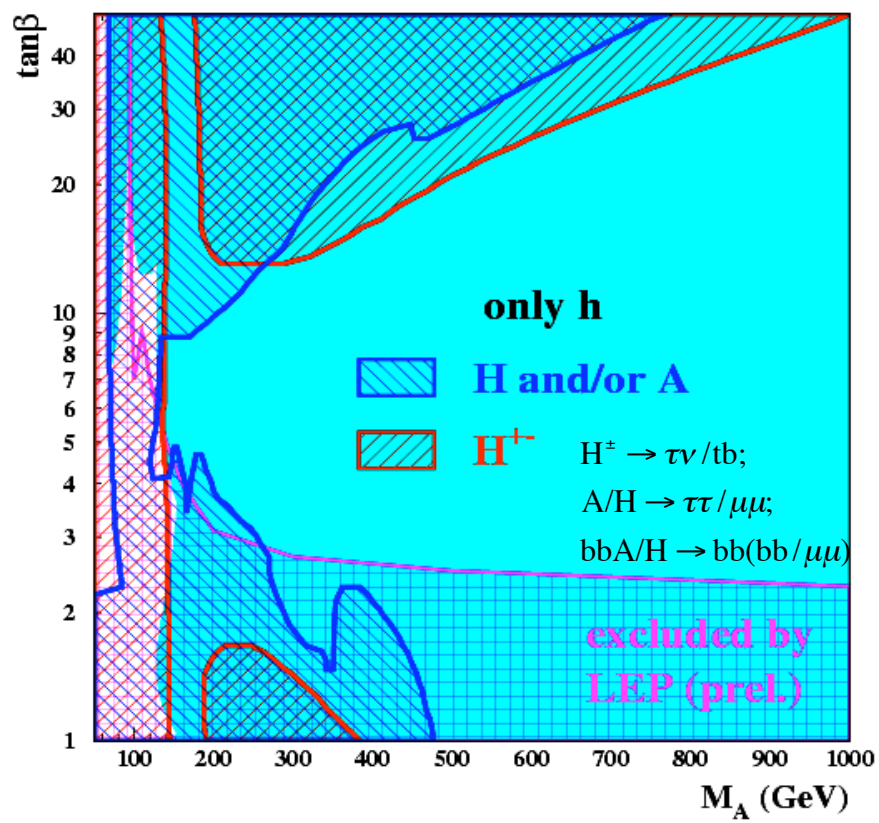


- LHC can search for a Higgs via many channels, already in the first few years



- Many SUSY Higgs production and decay processes accessible with full LHC potential

ATLAS and CMS with 300fb^{-1}



Still regions where only a SM-like Higgs is visible

The Origin of Mass of the Fundamental Particles

or The Quest for ElectroWeak Symmetry Breaking (EWSB):

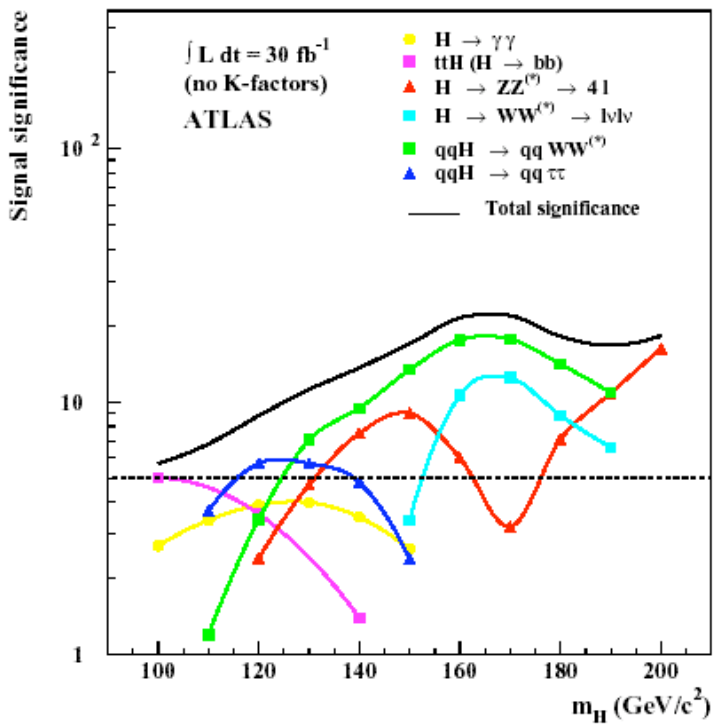
is the search for the dynamics that generates the Goldstone bosons that are the source of mass for the W and Z.

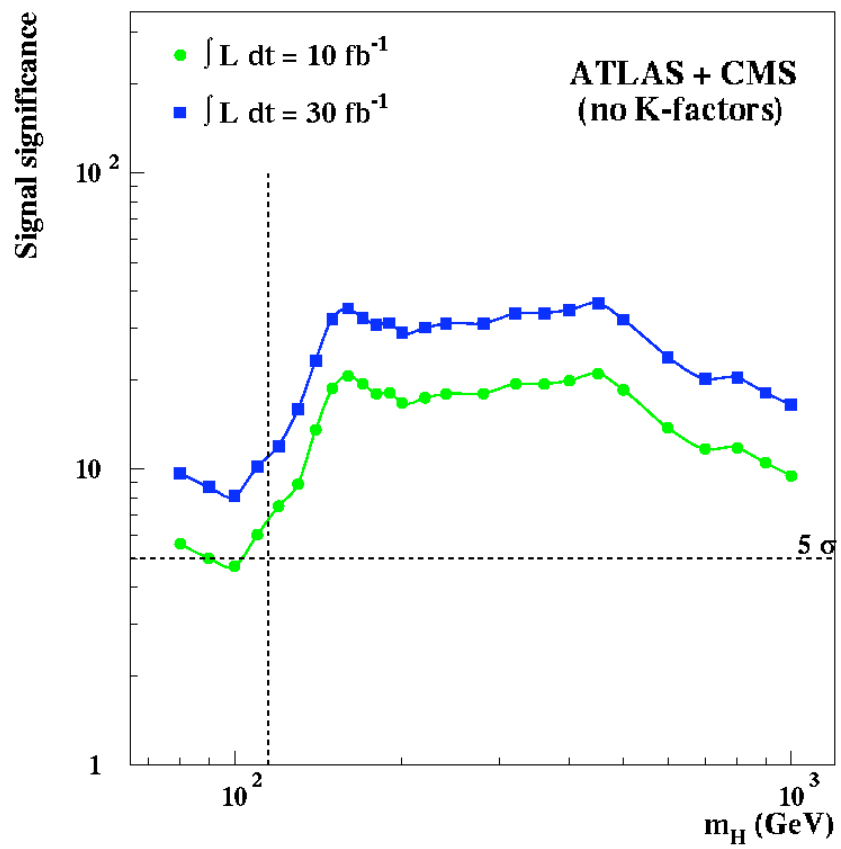
- **We know EWSB occurs at the TeV scale**

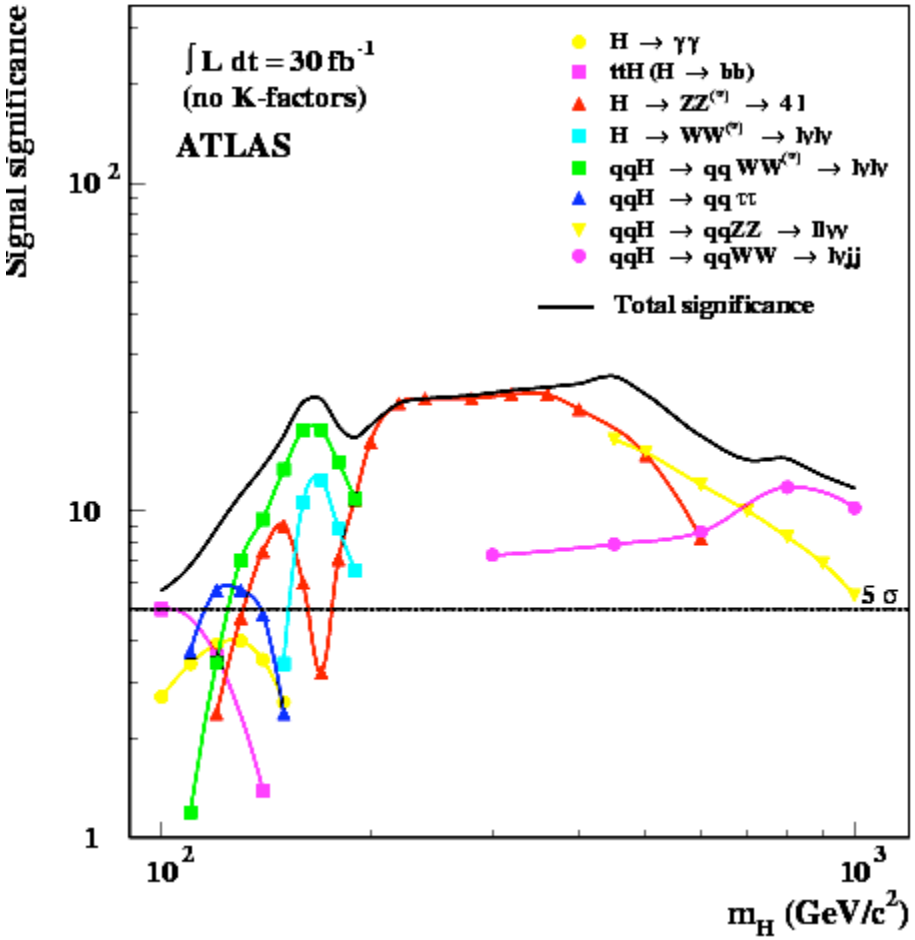
$\Longrightarrow$ New Phenomena should lie in the TeV range or below, within LHC/LC reach

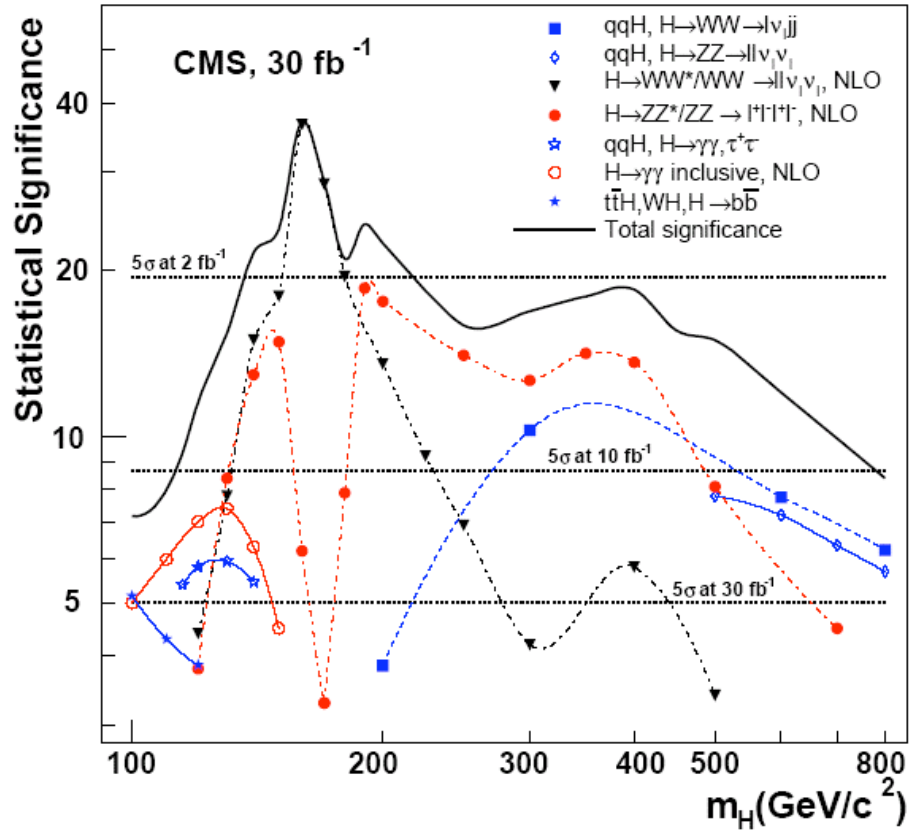
In the Standard Model

Introduce a self-interacting complex scalar doublet $\Longrightarrow$ Higgs with non-trivial quantum numbers under $SU(2)_L \times U(1)_Y$.


Signal significance
∫L dt = 30 fb-1
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ(*) → 4l
H → WW(*) → lνlν
qqH → qq WW(*)
qqH → qq ττ
Total significance
10 2
10
1
100
120
140
160
180
200
mH (GeV/c2)


Signal significance
∫L dt = 10 fb-1
∫L dt = 30 fb-1
ATLAS + CMS
(no K-factors)
10 2
10
1
5 σ
10 2
10 3
mH (GeV)



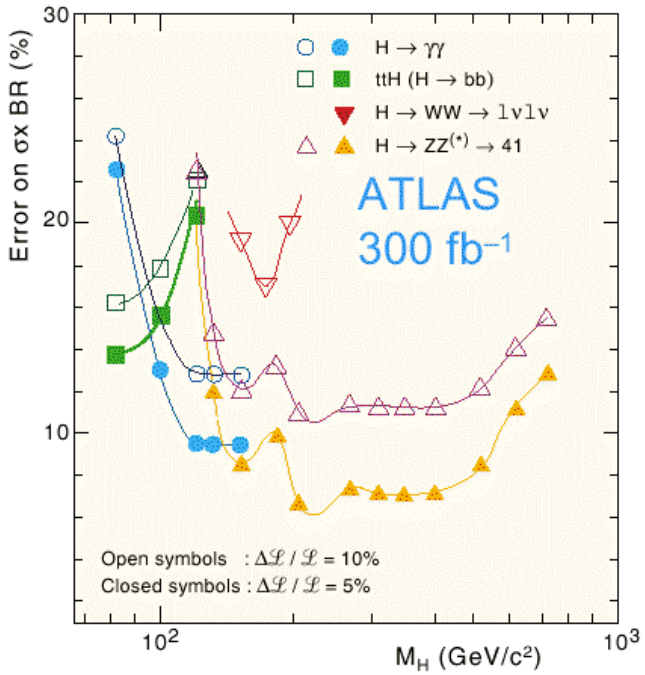


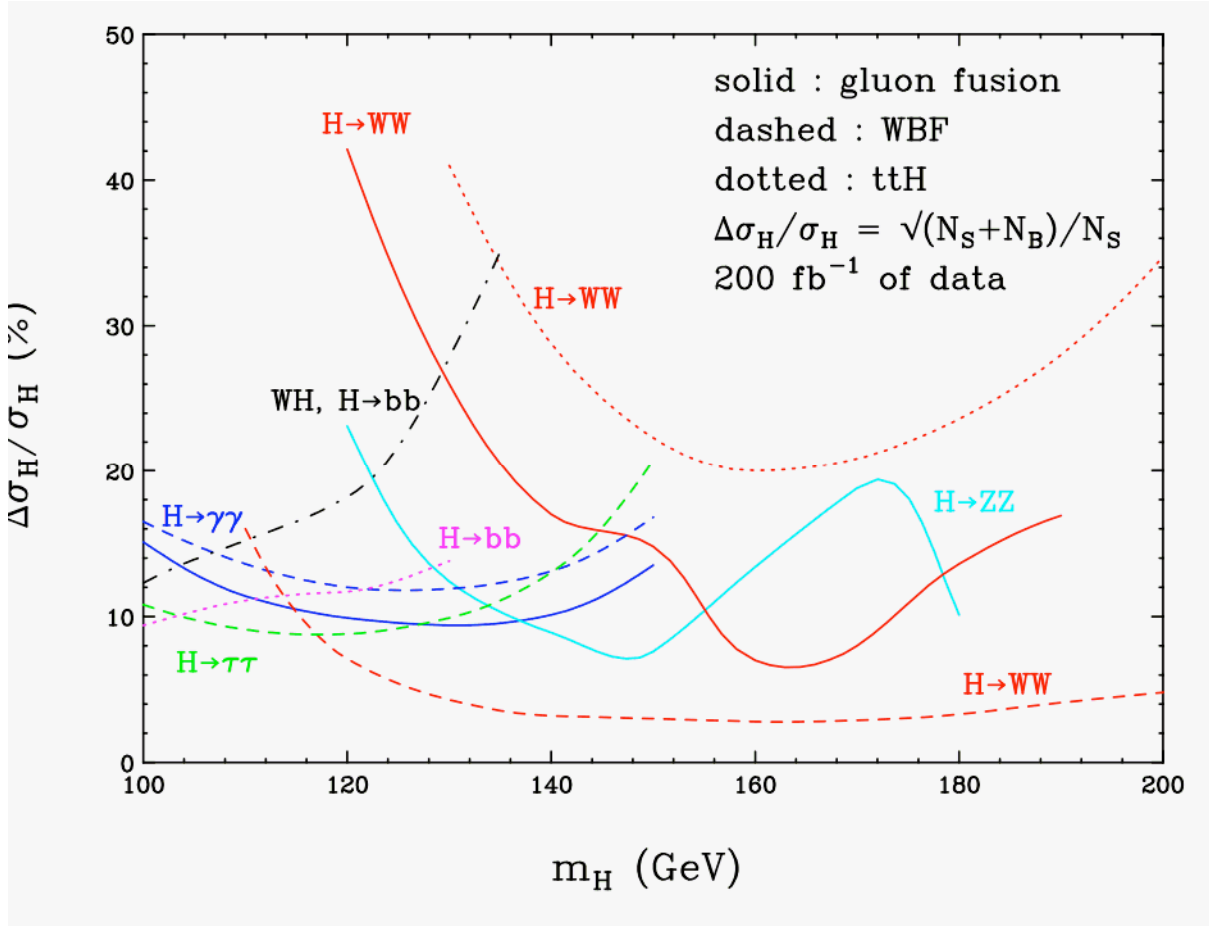
$$gg \to H_{SM} \to \gamma\gamma, \quad gg \to H_{SM} \to VV^{(*)} \quad with \quad V = W, Z$$

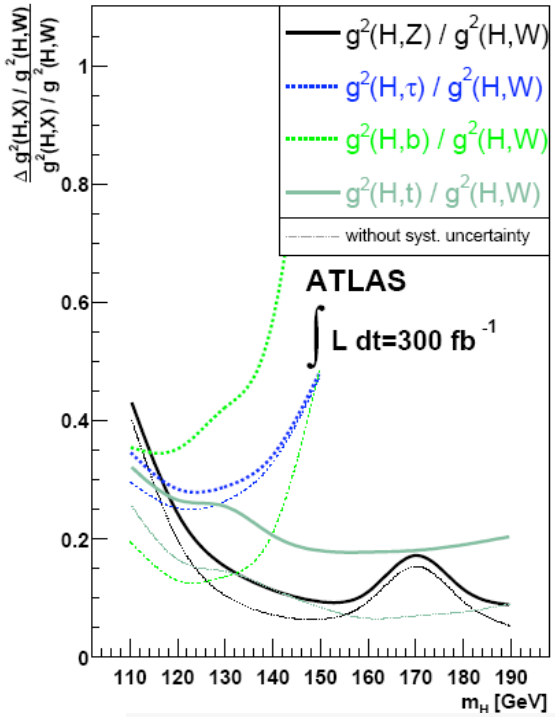
$$qq \to V^{(*)}V^{(*)} \to qqH_{SM}, \quad H_{SM} \to \gamma\gamma, \tau^+\tau^-, V\ V^{(*)}$$

$$q\bar{q}^{(')} \to V^{(*)} \to VH_{SM}, \quad H_{SM} \to b\bar{b}, WW^{(*)}$$

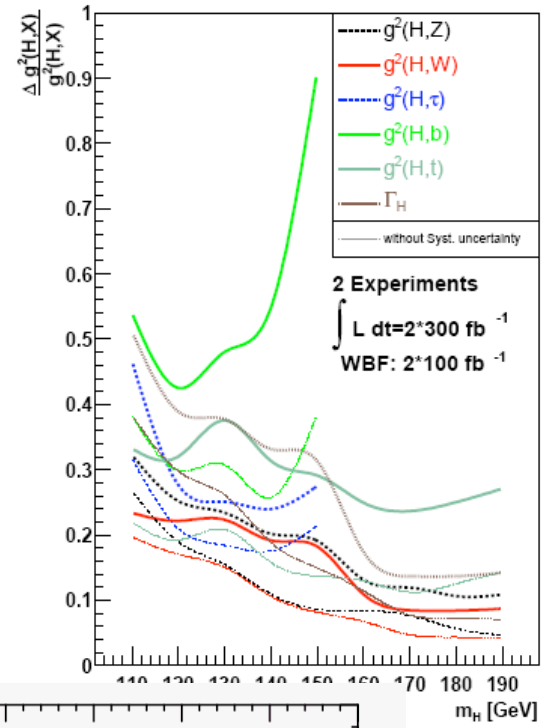
$$gg, q\bar{q} \to t\bar{t}H_{SM}, \quad H_{SM} \to b\bar{b}, \gamma\gamma, WW^{(*)}$$

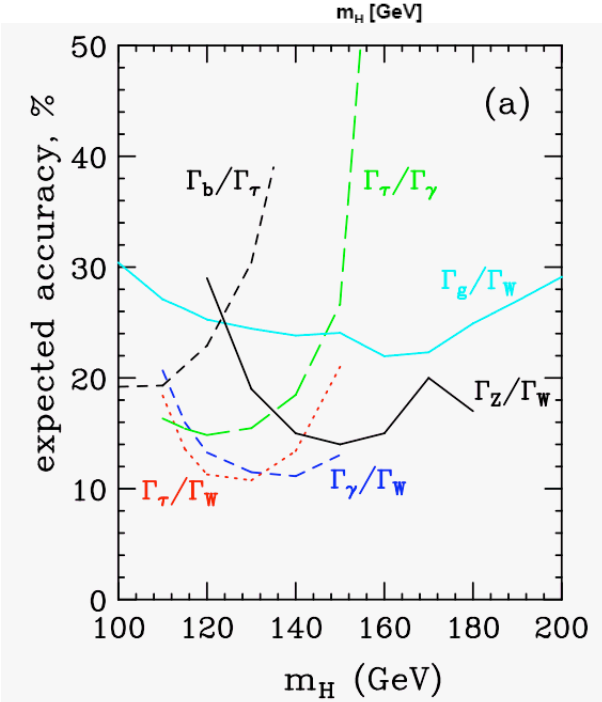

Error on σx BR (%)
30
20
10
H → γγ
ttH (H → bb)
H → WW → lνlν
H → ZZ(*) → 4l
ATLAS
300 fb-1
Open symbols : ΔL / L = 10%
Closed symbols : ΔL / L = 5%
10^2
10^3
M_H (GeV/c²)

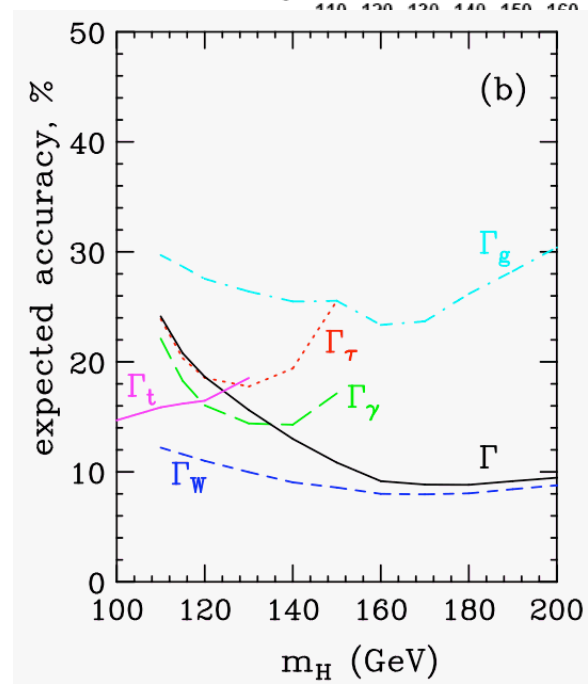

solid : gluon fusion
dashed : WBF
dotted : ttH
Δσ_H/σ_H = √(N_S+N_B)/N_S
200 fb^-1 of data
H→WW
H→WW
WH, H→bb
H→γγ
H→bb
H→ZZ
H→ττ
H→WW
Δσ_H/σ_H (%)
m_H (GeV)
0
10
20
30
40
50
100
120
140
160
180
200



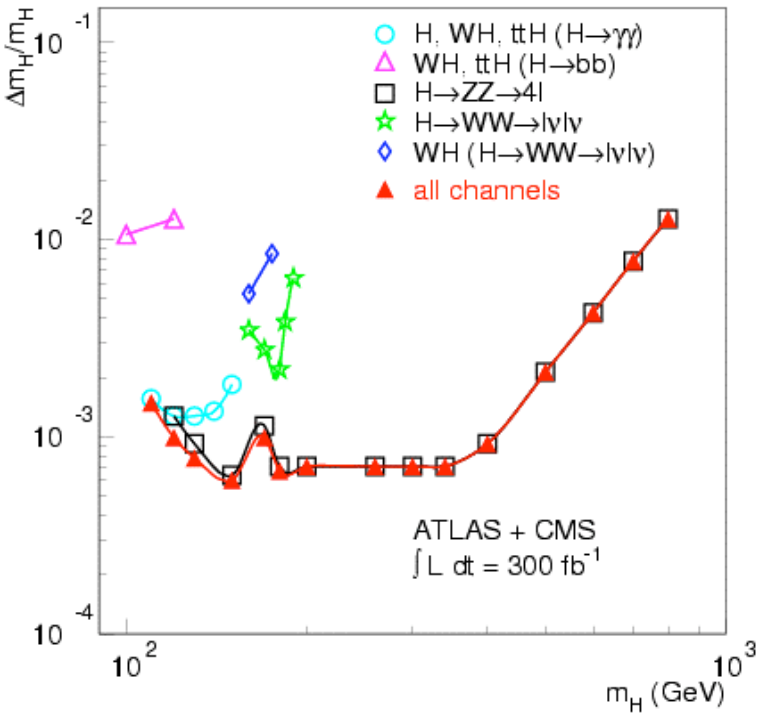
Absolute normalization of the HWW coupling from VBF with H-->WW

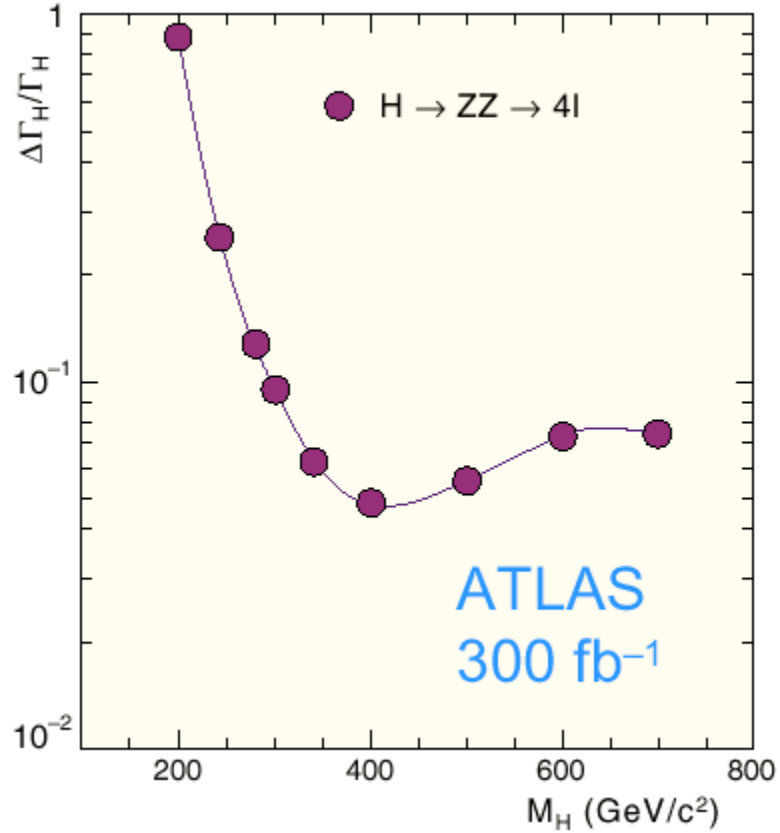






Mass and Width Resolution





MSSM Higgs	Δm/m (%) 300 fb^{-1}
h, A, H → γγ	0.1–0.4
H → 4 ℓ	0.1–0.4
H/A → μμ	0.1-1.5
h → bb	1–2
H → hh → bb γγ	1-2
A → Zh → bb ℓℓ	1–2
H/A → ττ	1-10

Analysis of indirect widths for mass range below 200 GeV:

10-20% precision

What can we learn from Bs-mixing?

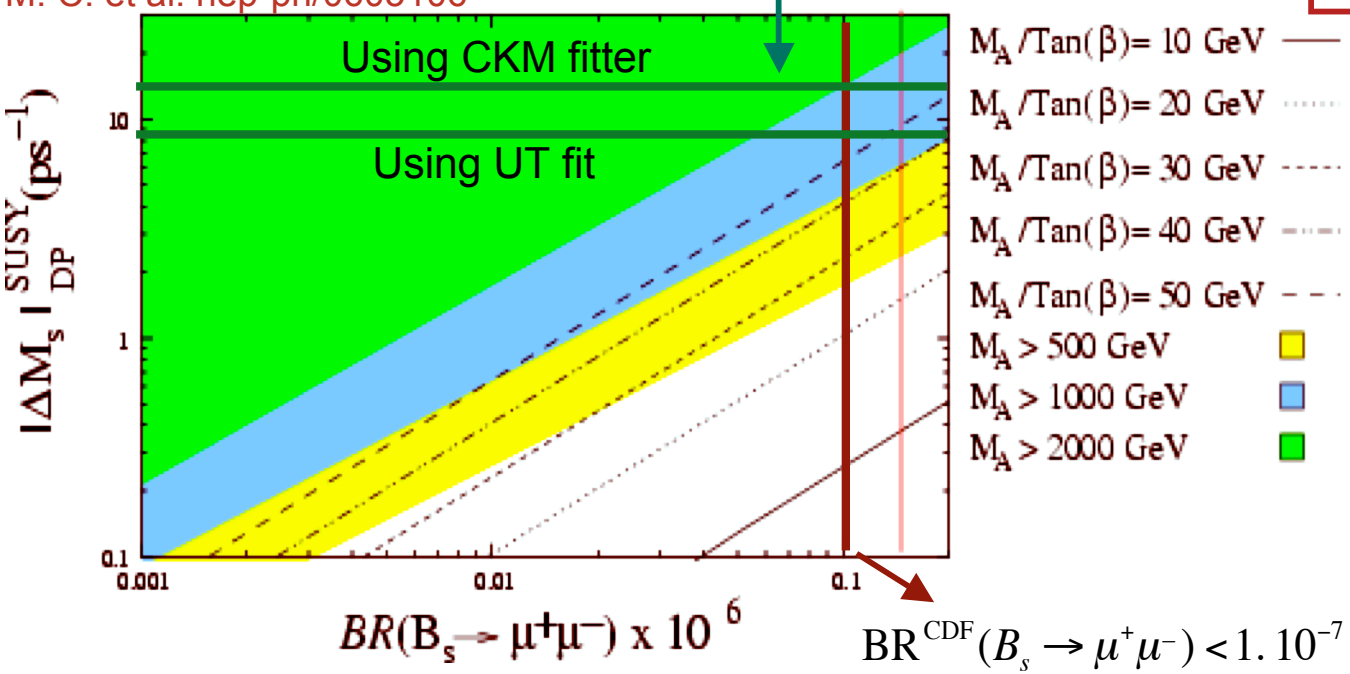
How strong is the bound on $\mathrm{BR}(B_s \to \mu^+\mu-)$?

Upper bound on NP from CDF ==> $\Delta M_S = 17.33^{+0.42}_{-0.21} \pm 0.07\, ps^{-1}$

$\Delta M_S^{CKM} = 21.7^{+5.9(+9.7)}_{-4.2(-6.8)}\, ps^{-1}$

$\Delta M_S^{UT} = 21.5 \pm 2.6\, ps^{-1}$

M. C. et al. hep-ph/0603106



$\mathrm{BR}^{CDF}(B_s \to \mu^+\mu^-) < 1.\, 10^{-7}$

A/H at the reach of the Tevatron or the LHC

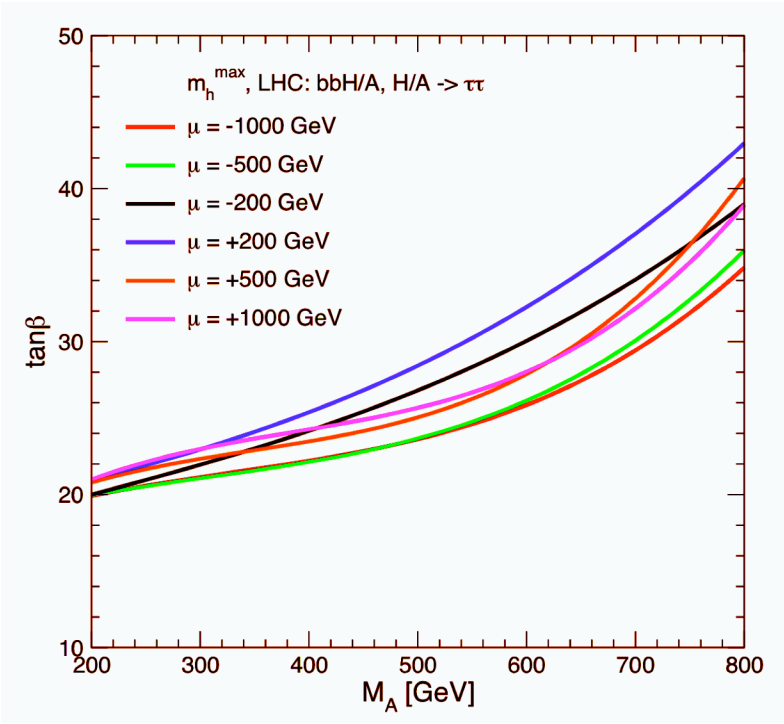
strong constraints on $|\Delta M_S|^{SUSY}_{DP}$

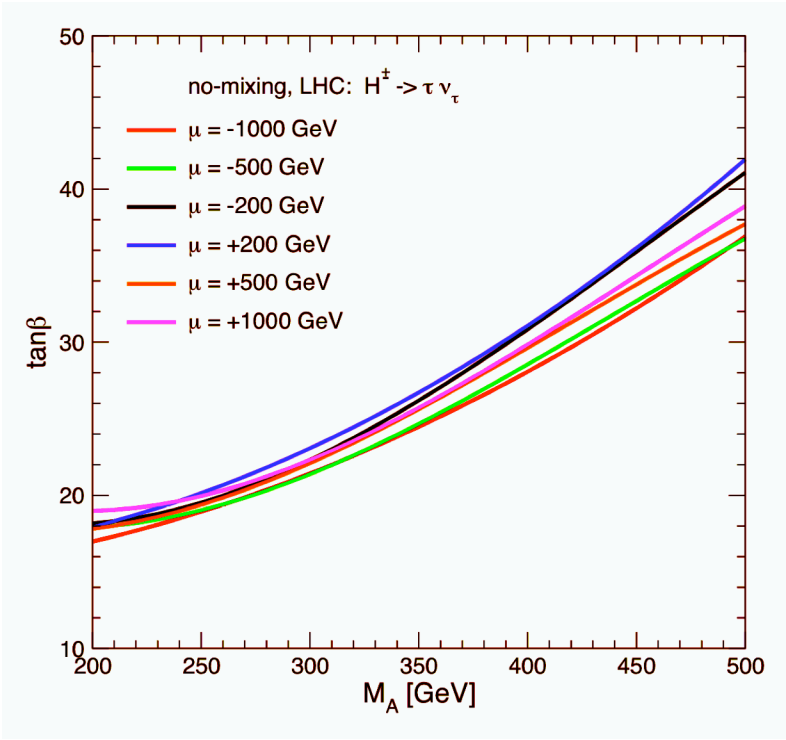
large ε factors implies heavy squark mass and trilinear terms

For natural values of m_A< 1000 GeV ==> largest contributions at most a few ps-1

$|\Delta M_{B_S}|^{SUSY}_{DP} \approx 3\, ps^{-1}$ $\Rightarrow$ improve the agreement with experiment

$\Rightarrow$ imply that $\mathrm{BR}(B_S \to \mu^+\mu^-)$ should be at the Tevatron reach


m_h^{max}, LHC: bbH/A, H/A -> ττ
μ = -1000 GeV
μ = -500 GeV
μ = -200 GeV
μ = +200 GeV
μ = +500 GeV
μ = +1000 GeV
tanβ
M_A [GeV]
50
40
30
20
10
200
300
400
500
600
700
800


no-mixing, LHC: $H^{\pm}$ -> τ ν_τ
μ = -1000 GeV
μ = -500 GeV
μ = -200 GeV
μ = +200 GeV
μ = +500 GeV
μ = +1000 GeV
tanβ
M_A [GeV]
50
40
30
20
10
200
250
300
350
400
450
500