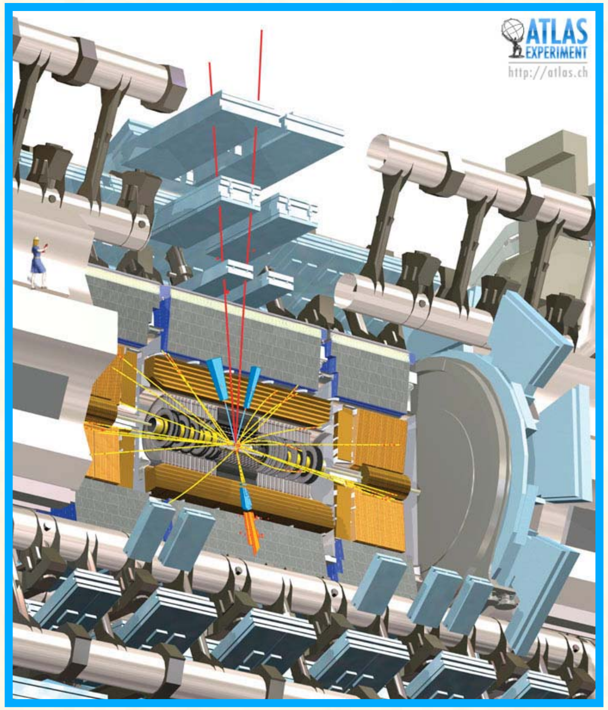
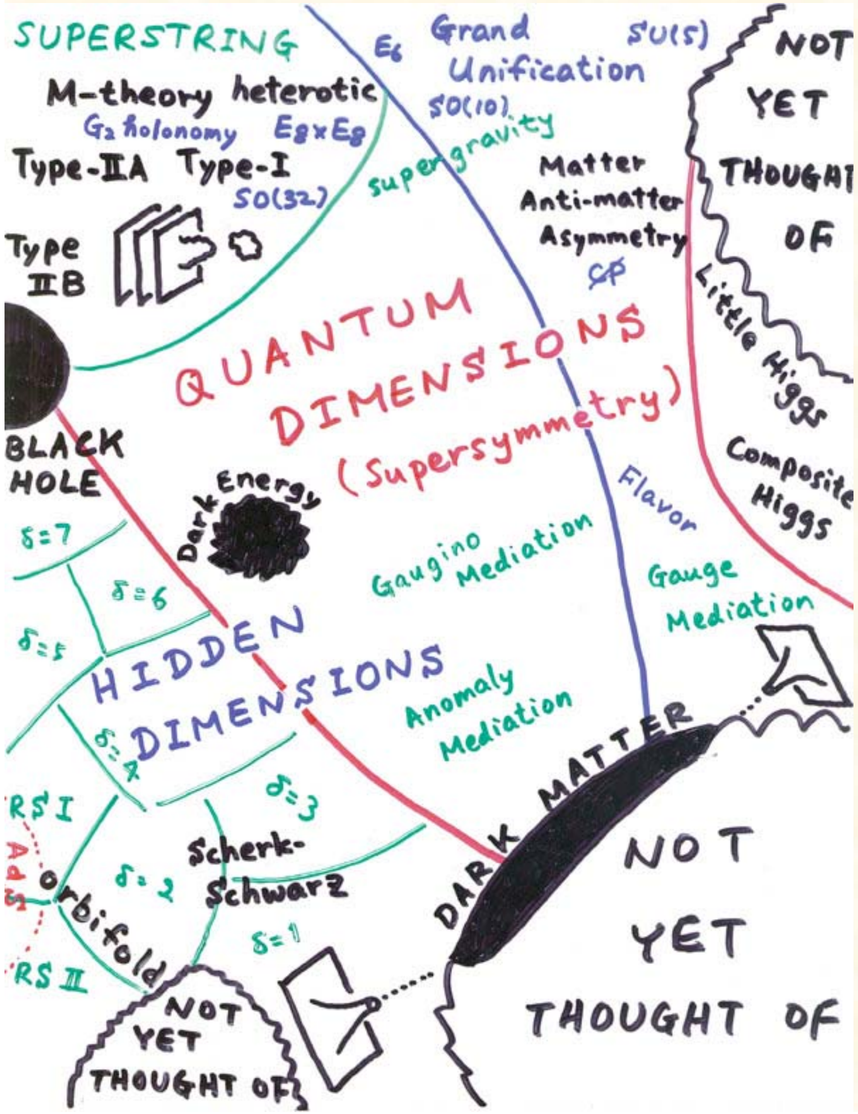
Higgs boson searches at hadron colliders

Part 4



- Higgs Bosons in the MSSM
- Invisibly decaying Higgs bosons
- Composite Higgs boson
- WW scattering

Non-Standard-Model Higgs Scenarios



We really don‘t know what is going on at the TeV scale....

... be prepared for other scenarios

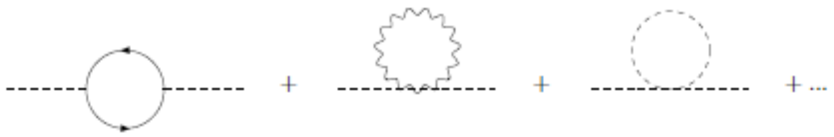
Hitoshi Murayama, Physics at the LHC, Hamburg, June 2010

Why alternative scenarios?

A. Pomarol, IFAE Barcelona

- „There must be more than a single Higgs.
  Although the Standard Model is *consistent*, it is *not natural.*“

- In quantum field theories it is difficult to protect scalar masses from large radiative corrections



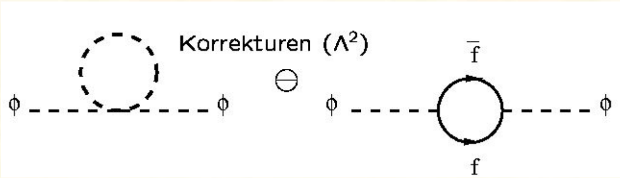
$$\delta m_H^2 = -\frac{\lambda_F^2}{8\pi^2}[\Lambda^2 - m_F^2 \ln \frac{\Lambda^2}{m_F^2}] + ...$$

Extreme “finetuning” needed, if theory valid up to a high scale Λ

Possible solutions

(i) An additional symmetry

- Supersymmetry



$$\Delta m_H = f(m_B^2 - m_f^2)$$

- The Higgs is not elementary: Composite Higgs

(ii) Lower the UV scale

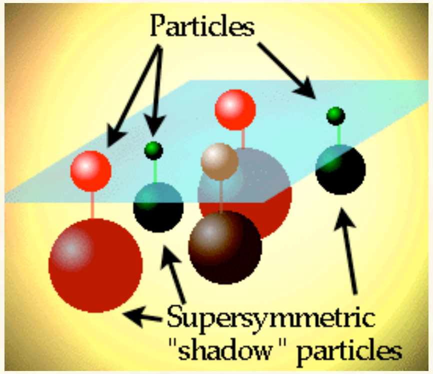
- Large extra dimensions

(iii) Remove the Higgs

- Technicolor models

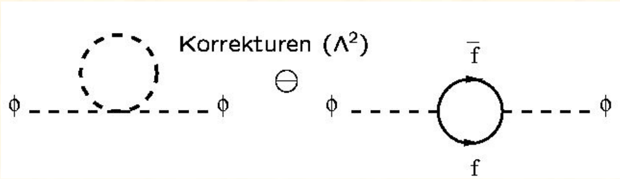
The Higgs Sector

in the MSSM



Why do we like SUSY so much?

1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

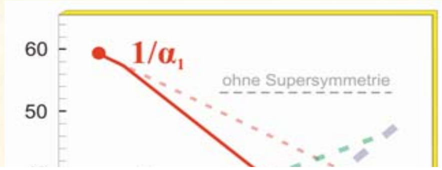


$$\Delta m_H = f(m_B^2 - m_f^2)$$

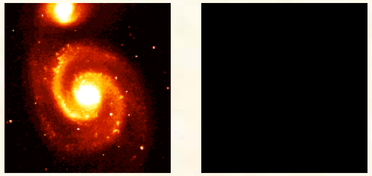
→ $m_{SUSY} \sim 1$ TeV

(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible

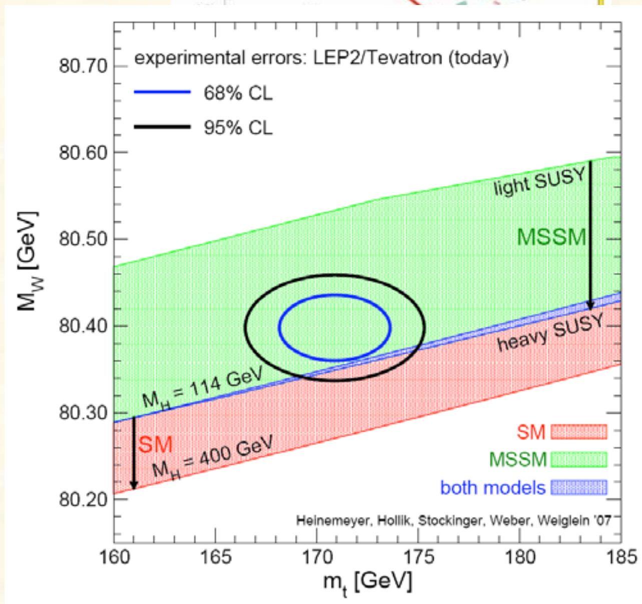


3. SUSY provides a candidate for dark matter



The lightest SUSY particle (LSP)

4. A SUSY extension is a small perturbation, consistent with the electroweak precision data



The Higgs Sector in the MSSM

Two Higgs doublets: 5 Higgs particles **H, h, A** **H^+, H^-**

determined by two parameters: m_A, $\tan\beta$

fixed mass relations at tree level:
(Higgs self coupling in MSSM fixed by gauge couplings)

$$m^2_{H,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_Z m^2_A \cos^2 2\beta}\right)$$

$$m^2_h \leq m^2_Z \cos^2 2\beta \leq m^2_Z$$

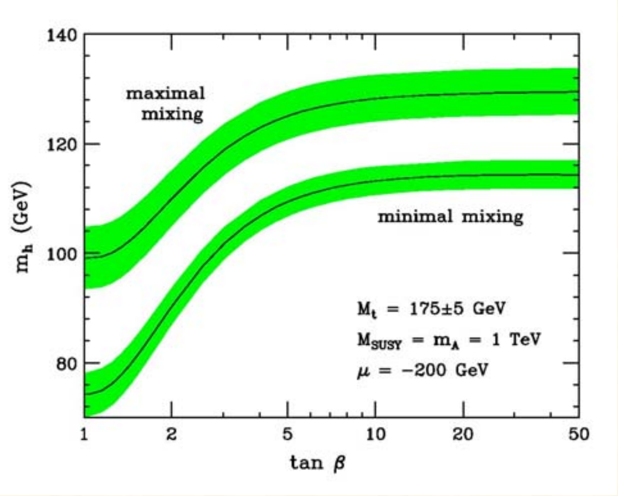
Important radiative corrections !! (tree level relations are significantly modified)
→ upper mass bound depends on top mass and mixing in the stop sector

$$m^2_h \leq m^2_Z + \frac{3g^2 m^4_t}{8\pi^2 m^2_W}\left[\ln\left(\frac{M^2_S}{m^2_t}\right) + x^2_t\left(1 - \frac{x^2_t}{12}\right)\right]$$

where: $M^2_S = \frac{1}{2}\left(M^2_{\tilde{t}_1} + M^2_{\tilde{t}_2}\right)$ and $x_t = (A_t - \mu \cot\beta) / M_S$

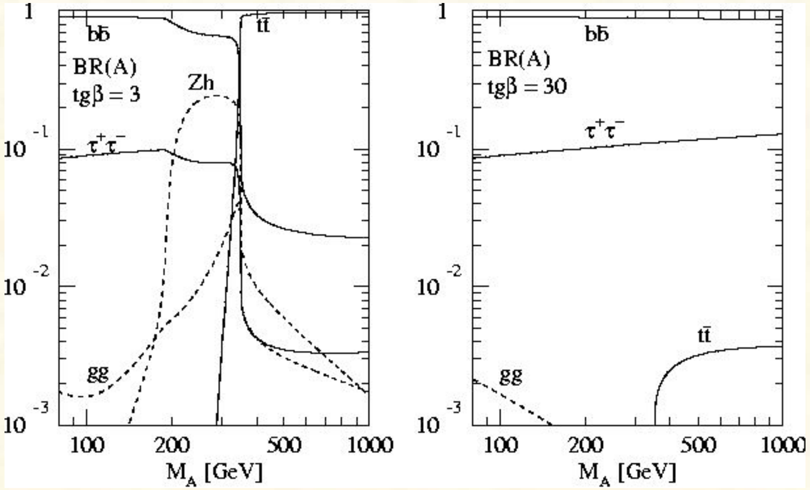
→ $m_h < 115$ GeV for no mixing
→ $m_h < 135$ GeV for maximal mixing

i.e., no mixing scenario: in LEP reach
max. mixing: easier to address at the LHC

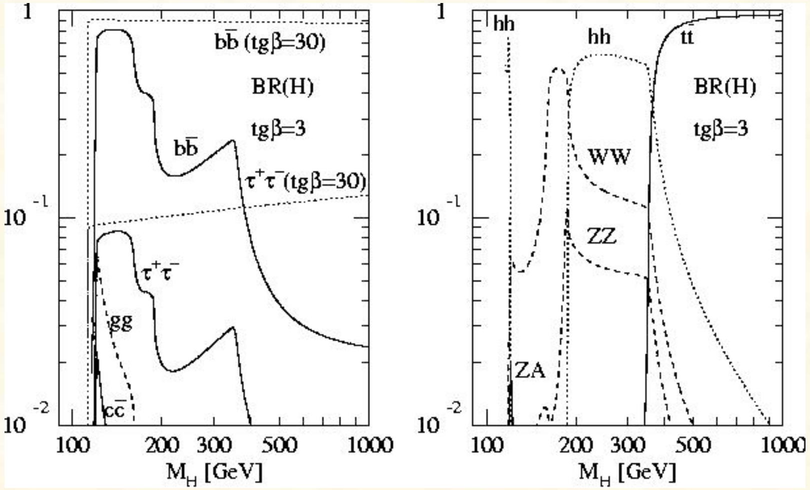


Branching ratios of MSSM Higgs bosons

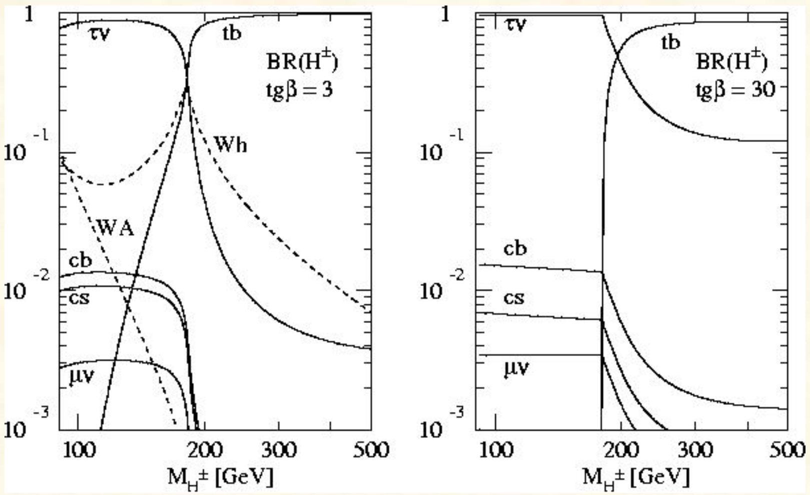
A



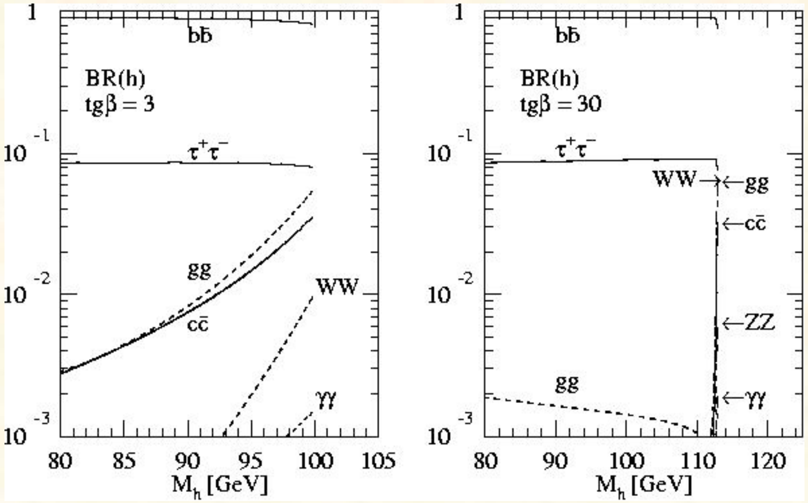
H



H±



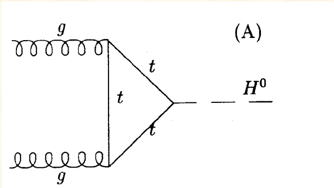
h



Production of MSSM Higgs bosons

At large tan β: enhanced couplings of Higgs bosons H and A to down-type fermions

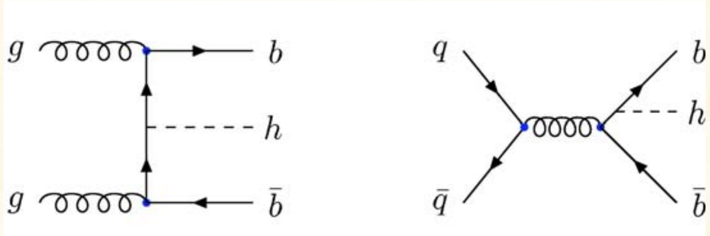
→ important production processes:



gg → bb H/A
qq → bb H/A

gg → H/A

(**b**, t quarks and **SUSY-particles** in loop)



Cross section calculation:*

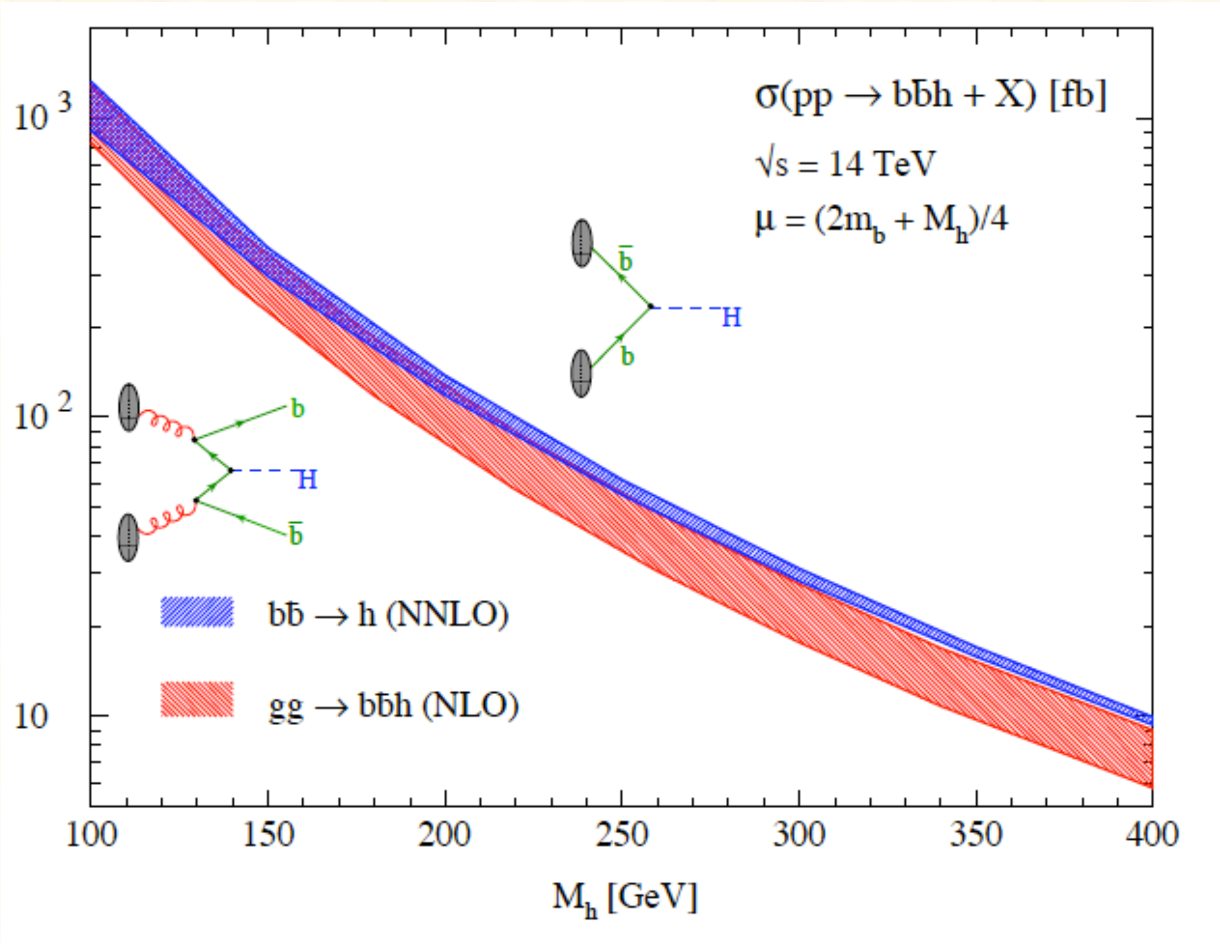
- associated bbH production becomes dominant process
- NLO calculations are available

  two approaches –long discussions among theorists-
  - four flavour scheme (bb from gluon splitting)   K ~ 1.3 – 1.5 (Tevatron – LHC)
  - five flavour scheme (use b-quark parton distributions, bb →h, gb → bh)
- Finally: reasonable agreement (within respective scale uncertainties) between the NLO four-** and the NNLO five-flavour*** calculation is found for the inclusive (no b-tags) cross section.

*) For a review, see: J. Campbell et al. Proc. Les Houches 2003, hep-ph/0405302.
**) S. Dittmaier, M. Krämer and M. Spira, Phys. Rev. D70 (2004) 074010; S. Dawson et al., Phys. Rev. D69 (2004) 0740027.
***) D. Dicus,T.Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D59 (1999) 094016; R. Harlander and W.B. Kilgore Phys. Rev. D68 (2003) 013001.

Production of MSSM Higgs bosons

Agreement between the four and five flavour scheme calculations:



MSSM benchmark scenarios

Masses and couplings of the Higgs bosons depend –in addition to tanβ and m_A- on the SUSY parameters through radiative corrections

Most relevant parameters: A_t = trilinear coupling in the stop sector ($X_t = A_t - \mu \cot \beta$)
μ = Higgs mass parameter
M_2 = gaugino mass term (M_1 from gauge unification)
m_g = gluino mass
m_{SUSY} = common scalar mass

m_h-max: SUSY parameters chosen such that max mass value for h achieved;
No mixing: vanishing mixing in the stop sector, $X_t = 0$;
Gluophobic: coupling to gluons strongly suppressed, large stop mixing, cancellation between top-quark and stop loop contributions;
Small α: effective mixing angle between CP-even Higgs bosons is small, reduced BR into bb and $\tau\tau$ for large tanβ and intermediate values of m_A.

M. Carena, S. Heinemeyer, C.E.Wagner, G. Weiglein, Eur.Phys. J. C26 (2003) 601.

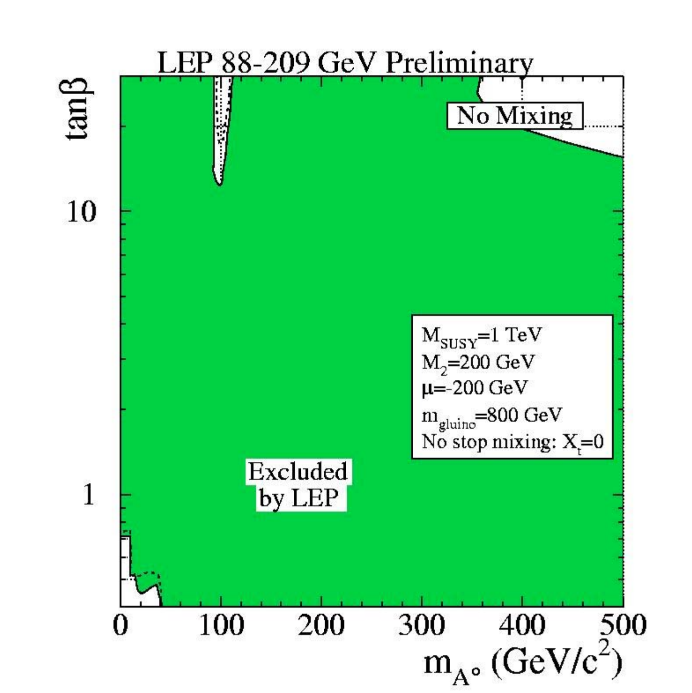
	m_{SUSY} (GeV/c^2)	μ (GeV/c^2)	M_2 (GeV/c^2)	X_t (GeV/c^2)	m_g (GeV/c^2)
m_h-max	1000	200	200	2000	800
No mixing	1000	200	200	0	800
Gluophobic	350	300	300	−750	500
Small α	800	2000	500	−1100	500

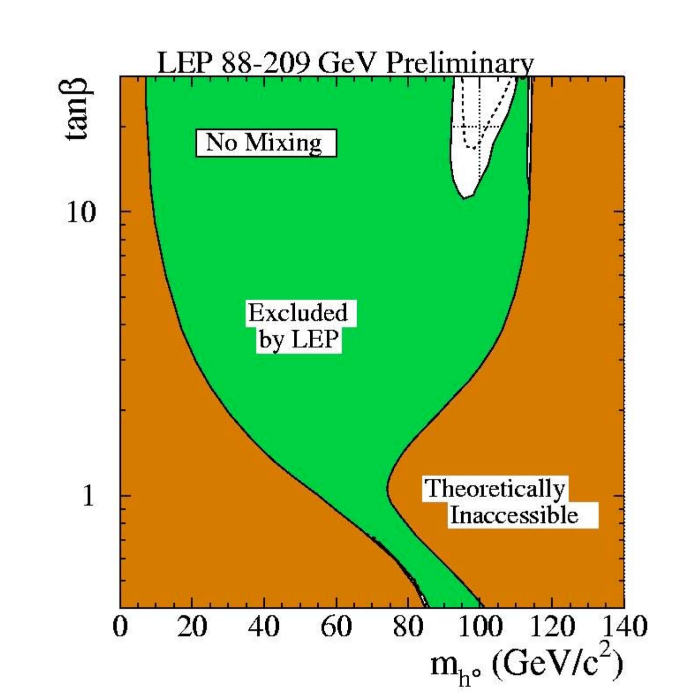
LEP results for the no-mixing scenario:

Search for $e^+e^- \rightarrow h\,A \rightarrow bb\,bb$ and $e^+e^- \rightarrow h\,Z$

$\rightarrow bb\,\tau\tau$

No significant excess found $\rightarrow$
set limits in MSSM Higgs boson parameter space (M_A-tan β)



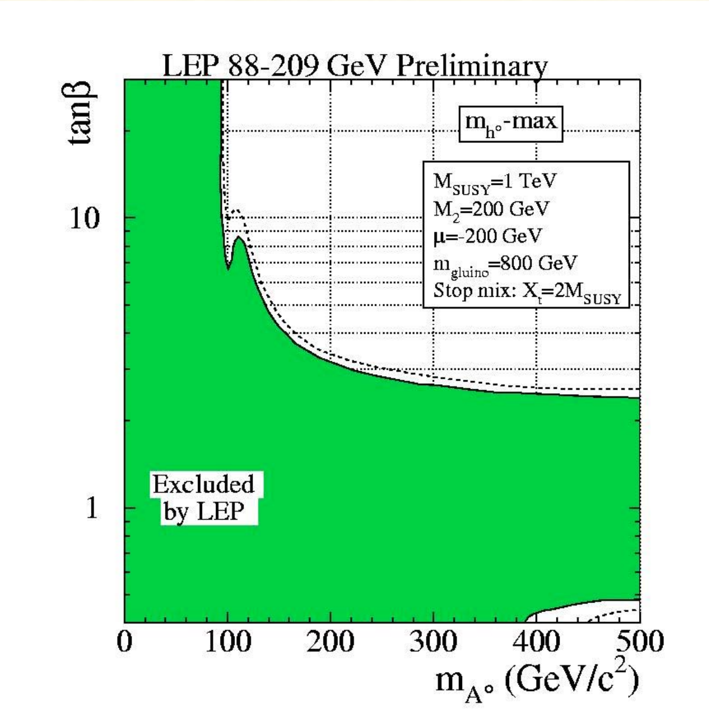


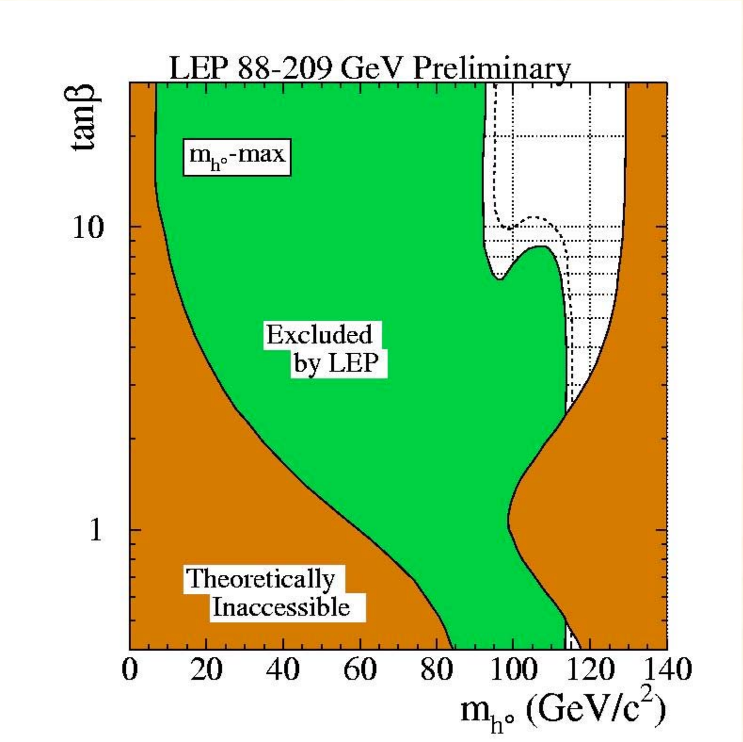
$M_h > 91.5$ GeV/c^2

$m_A > 92.2$ GeV/c^2

Excluded tan β range: $0.7 < \tan\beta < 10.5$

Results for the m_h-max scenario:





$M_h > 91.0$ GeV/c^2

$m_A > 91.9$ GeV/c^2

Excluded tan β range: $0.5 < \tan\beta < 2.4$ (m_t =175 GeV/c^2)

< 1.9 (m_t = 179 GeV/c^2)

MSSM Higgs Boson Searches at the LHC

Important channels in the MSSM Higgs boson search:

1. The Standard Model decay channels
   - $h \rightarrow \gamma\gamma$
   - qq h, $h \rightarrow \tau\tau$

   evaluation of performance is based on SM results

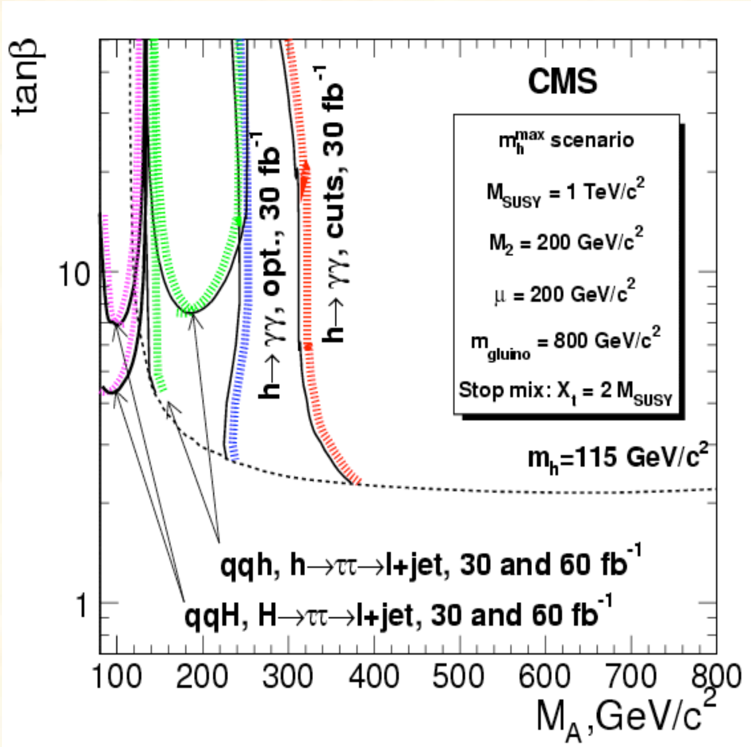
2. Modes strongly enhanced at large tan β:
   - **H/A $\rightarrow \tau^+ \tau^-$** $\quad$ **$H^+ \rightarrow \tau \nu$**
   - **H/A $\rightarrow \mu^+ \mu^-$**

3. Other interesting channels:
   - H/A $\rightarrow$ Zh $\rightarrow \ell\ell\, \gamma\gamma$

     $\rightarrow \ell\ell$ bb
   - H $\rightarrow$ hh

Search for the light CP-even Higgs boson h

- Standard search channels can be used
- Vector boson fusion channels contribute significantly

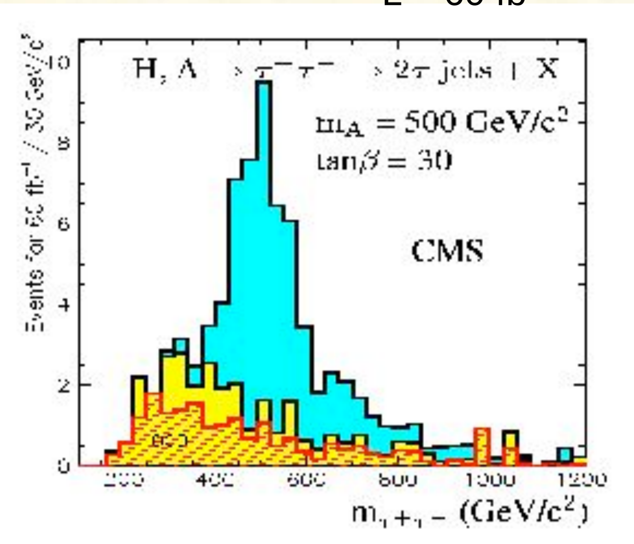


- Uncovered region at small m_A → look for heavier Higgs bosons
- Large integrated luminosities are needed

Search for the heavy Higgs bosons H and A

at large tan β: **bb H/A → bb $\tau\tau$** plays a key role
in addition: bb H/A → $\mu\mu$,
bb H/A → bb bb very difficult at the LHC
(trigger, backgrounds,....)

L = 60 fb^{-1}



- Selection requires excellent b and τ identification
- detailed studies → both leptonic and hadronic tau decays can be used

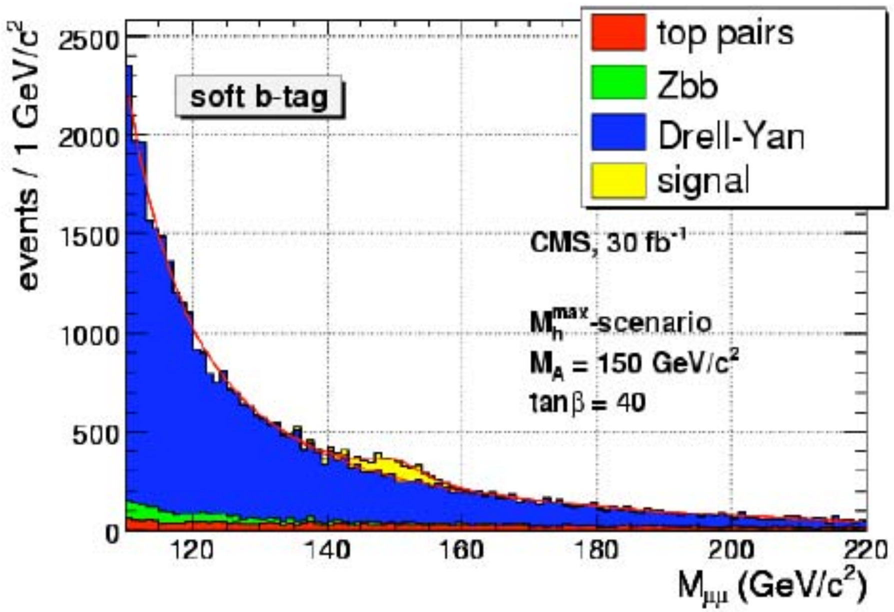
$m_{H/A}$ < 400 GeV/c^2 (ℓ -τ_{had}) dominates
> 400 GeV/c^2 (τ_{had}-τ_{had}) contributes significantly

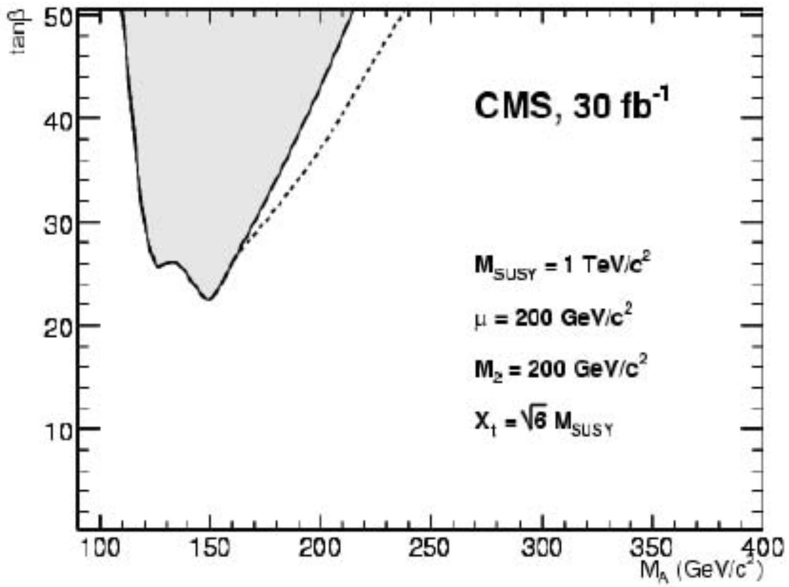
- H/A mass can be reconstructed, collinear approx.
- Dominant backgrounds: W+jet, tt production

at small tan β: add. modes: search for H/A → h decays
allows for simultaneous observation for two Higgs bosons
examples: H → hh, A → Zh

A/H → μμ

For MSSM Higgs bosons also the μμ decay mode can be used (large tanβ)





5σ discovery contours for 30 and 100 fb^{-1}

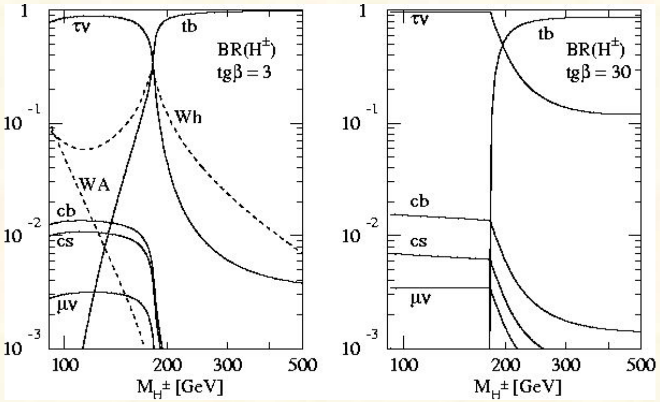
Search for the Charged Higgs Boson

Detection of a charged Higgs boson $\rightarrow$ ***Physics Beyond the Standard Model***

Production: depends strongly on $m_{H\pm}$

(i) via top decays: $t \rightarrow H^{\pm} b$
(iii) $gg \rightarrow H^{\pm} tb$ or $gb \rightarrow H^{\pm} t$
(v) $gg, qq \rightarrow H^{\pm} W$
(iv) $qq \rightarrow H^{+} H^{-}$

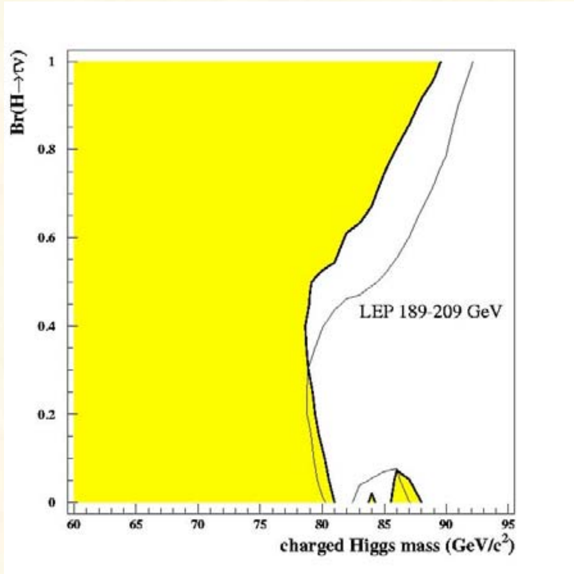
Decays: depend strongly on $m_{H\pm}$



$\tau\nu$ decay mode significant at large tan β

LEP results on m_{H+}:

search for $H^{+} \rightarrow cs$ and $\tau\nu$

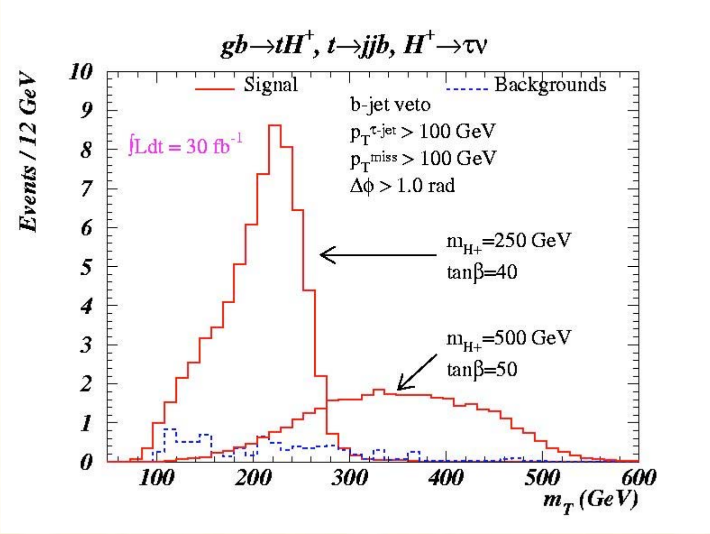


M_{H}^{+} > 78.6 GeV/c² (95% CL)

Search for the charged Higgs bosons $H^\pm$ at large mass

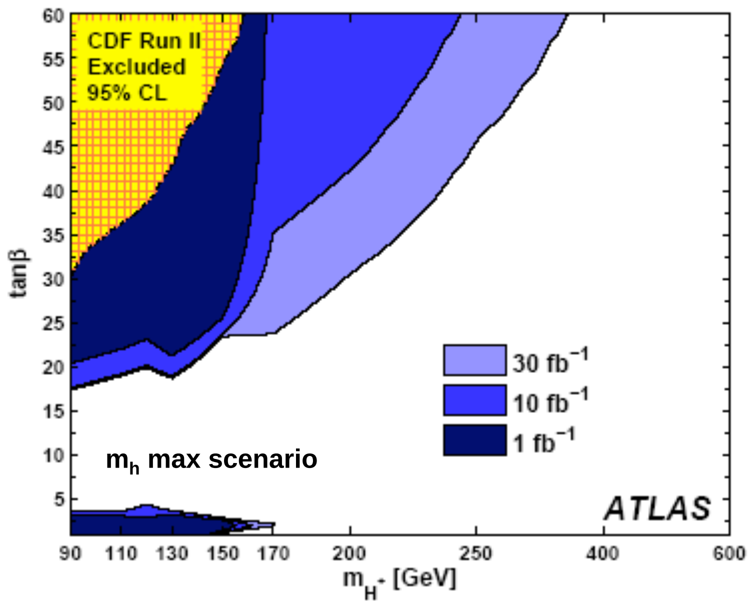
- $H^\pm \to tb$ decays:
  - promising channel: (i) $gb \to H^\pm t \to tb\, t \to \ell\nu bb\, qqb$
    require three b-tags + top-reconstruction → large background suppression
  - more difficult: (ii) $gg \to H^\pm tb \to tb\, tb \to \ell\nu bb\, qqbb$
    require four b-tags + top-reconstruction (larger comb. background in rec. of $H^\pm$)

- **$H^\pm \to \tau\nu$ decays:**
  - promising channel: (i) $gb \to H^\pm t \to \tau\nu\, t \to h\nu\nu\, qqb$
    exploit hadronic decays of the τ and t quark
    → transverse mass distribution (τ_{had} + E_T^{miss})
    can be used to reconstruct the $H^\pm$ mass
  - additional channel:
    (ii) $gg \to H^\pm tb \to \tau\nu\, tb \to h\nu\nu\, qqbb$
    require two b-tags

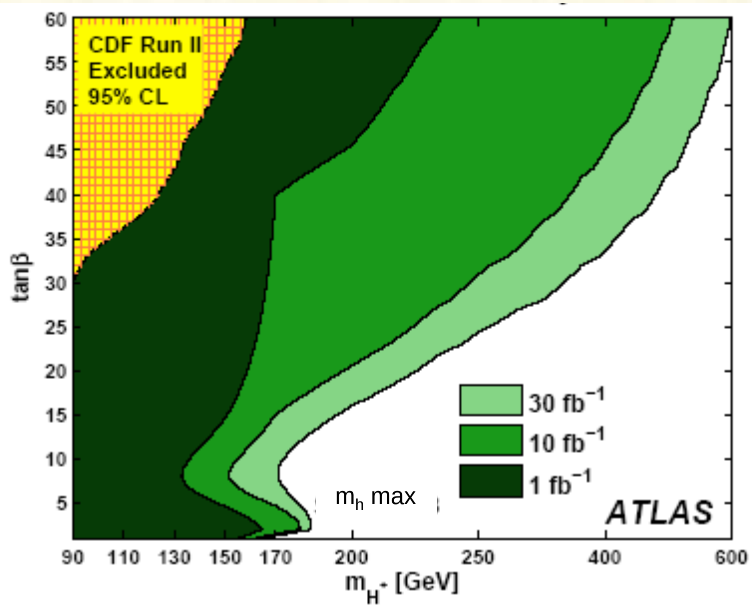


- Other decay modes ($H^\pm \to Wh, WH$)
  marginal - hopeless in MSSM

Some examples of updated MSSM studies



5σ discovery contours for 1 to 30 fb-1



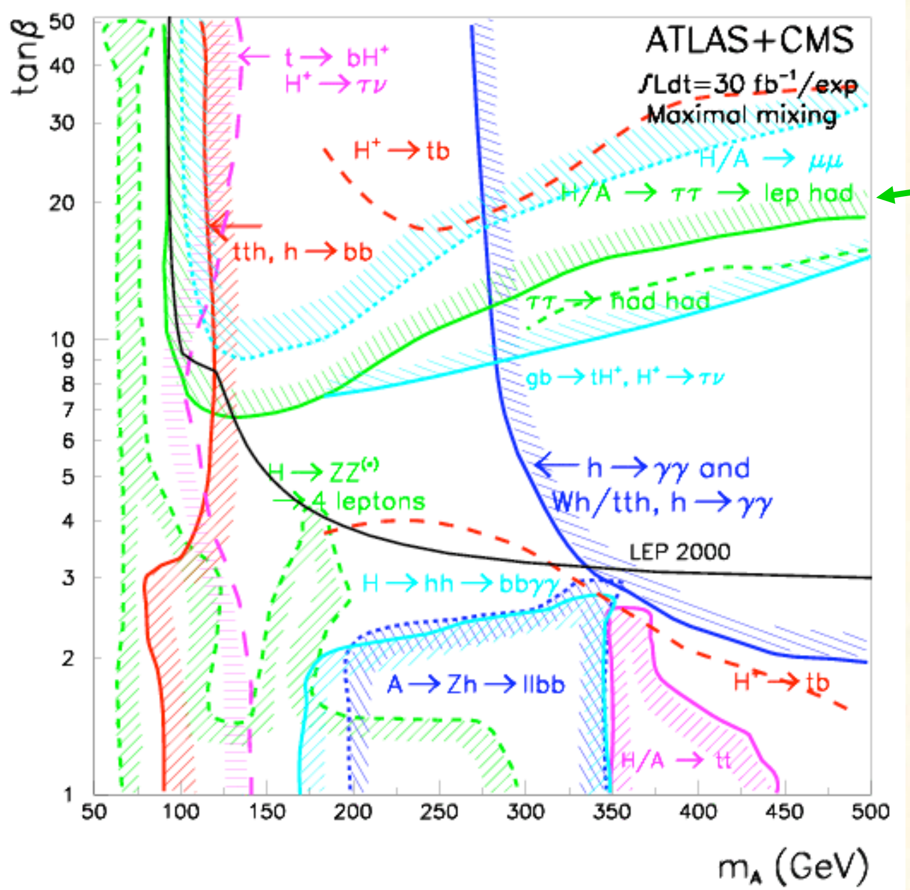
95% CL exclusions for 1 to 30 fb-1

ATLAS: Charged Higgs boson searches

$H^+ \rightarrow \tau\nu$ and tb decay modes

MSSM Higgs bosons h, H, A, H ±

m_h < 135 GeV
$m_A \approx m_H \approx m_{H\pm}$ at large m_A

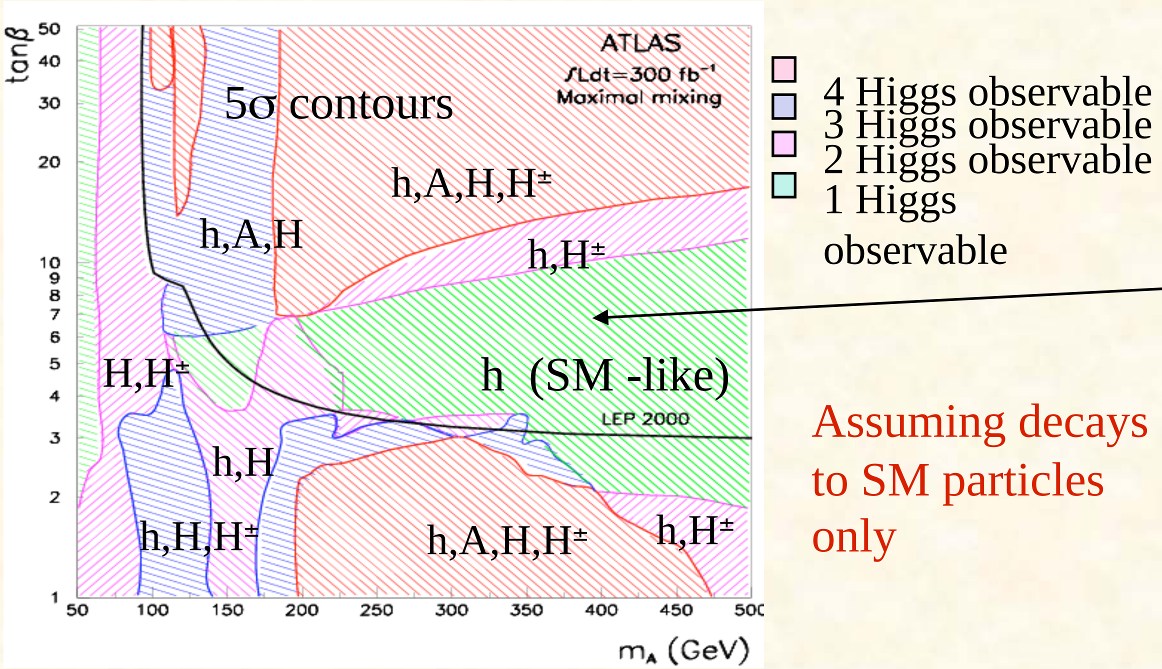


A, H cross-section ~ $\tan^2\beta$ (tree level)

- best sensitivity from A/H → ττ, and H^+→ tb and τν

-A/H → μμ experimentally easier

LHC discovery potential for MSSM Higgs bosons



Here only SM-like h observable if SUSY particles neglected.

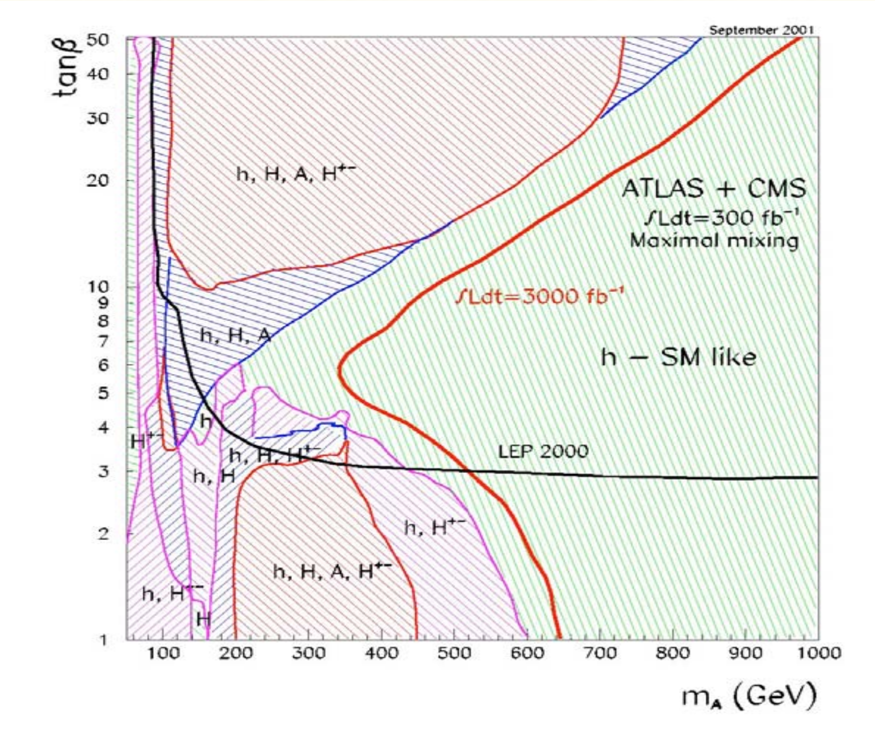
Assuming decays to SM particles only

- Region at large m_A and moderate tan β only covered by h; difficult to detect other Higgs bosons

Possible coverage: * via SUSY decays (model dependent, see below)
* luminosity (only moderate improvement)

MSSM discovery potential for Super-LHC

ATLAS + CMS, 2 x 3000 fb^{-1}



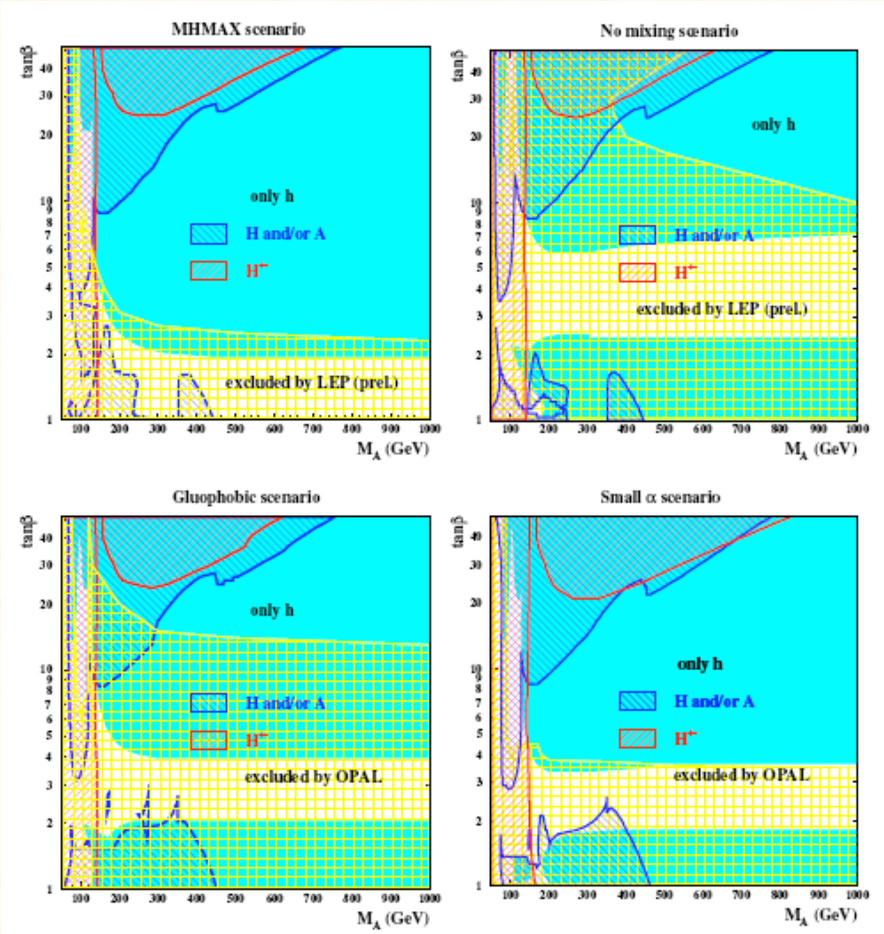
- Situation can be improved, in particular for m_A < ~400 GeV
- But: (s)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum ....

.... although the observation of sparticles will clearly indicate that additional Higgs bosons should exist.

Updated MSSM scan for different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,   30 fb^{-1},   5σ discovery



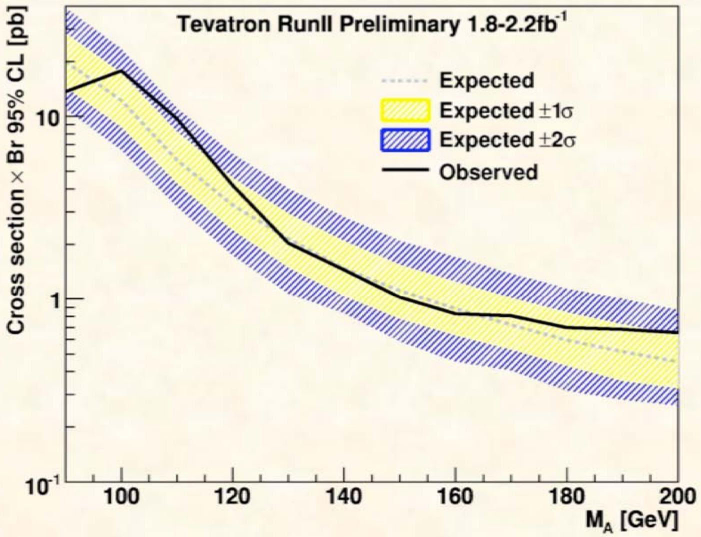
MHMAX scenario (M_{SUSY} = 1 TeV/c^2)
maximal theoretically allowed region for m_h

Nomixing scenario (M_{SUSY} = 2 TeV/c^2)
(1TeV almost excl. by LEP)
small m_h → difficult for LHC

Gluophobic scenario (M_{SUSY} = 350 GeV/c^2)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for g g → H, H→ γγ and Z→4 ℓ

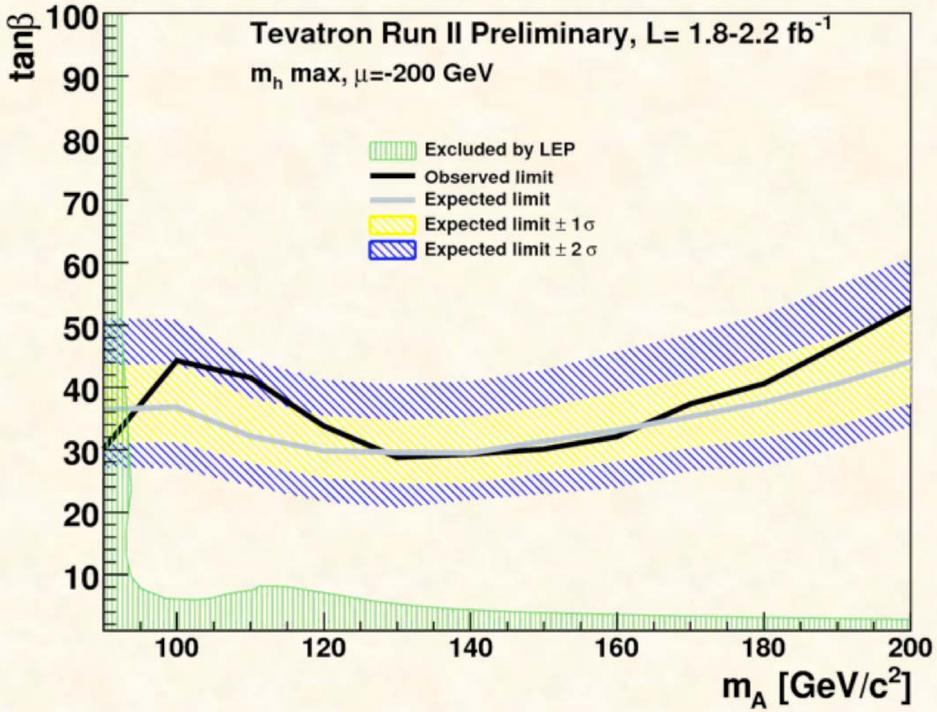
Small α scenario (M_{SUSY} = 800 GeV/c^2)
coupling to b (and **t**) suppressed
(cancellation of sbottom, gluino loops) for large tan β and M_A 100 to 500 GeV/c^2

Tevatron exclusions on MSSM Higgs bosons

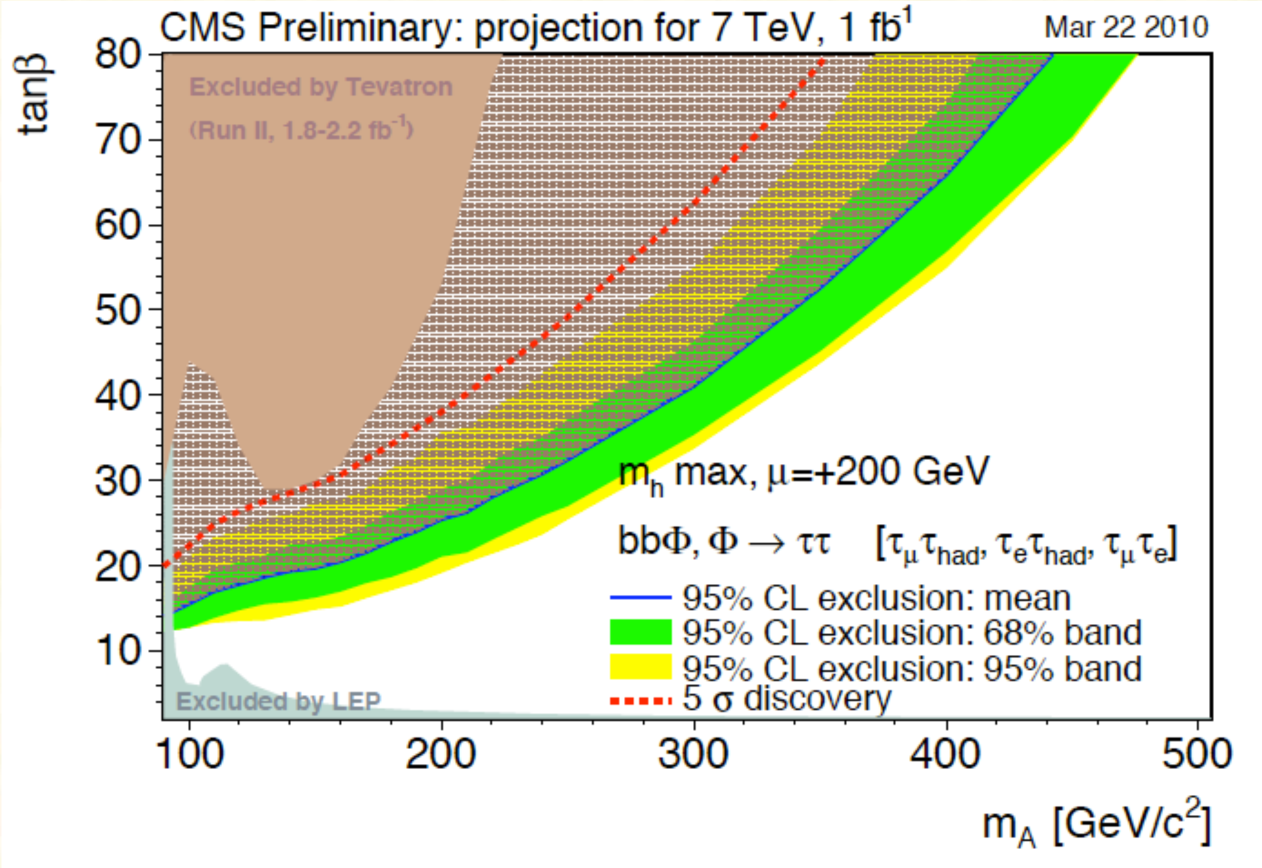


Excluded cross section (95% C.L. limits)

Combination of the CDF and D0 results on $bb\Phi$, $\Phi \rightarrow \tau\tau$



Expectations at the LHC for $\sqrt{s}$ = 7 TeV and 1 fb^{-1}



- Seems competitive at low mass
- Higher masses ….for later

A light SUSY Higgs or

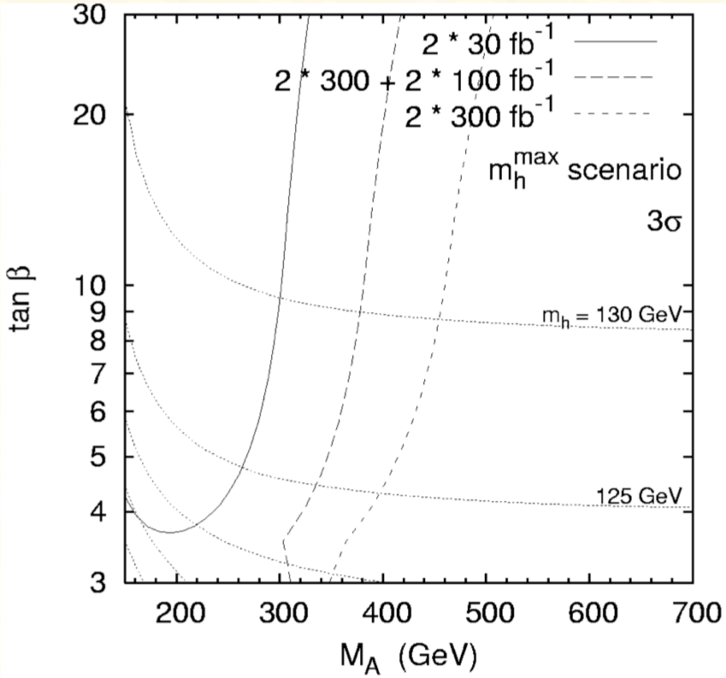
a light Standard Model Higgs?

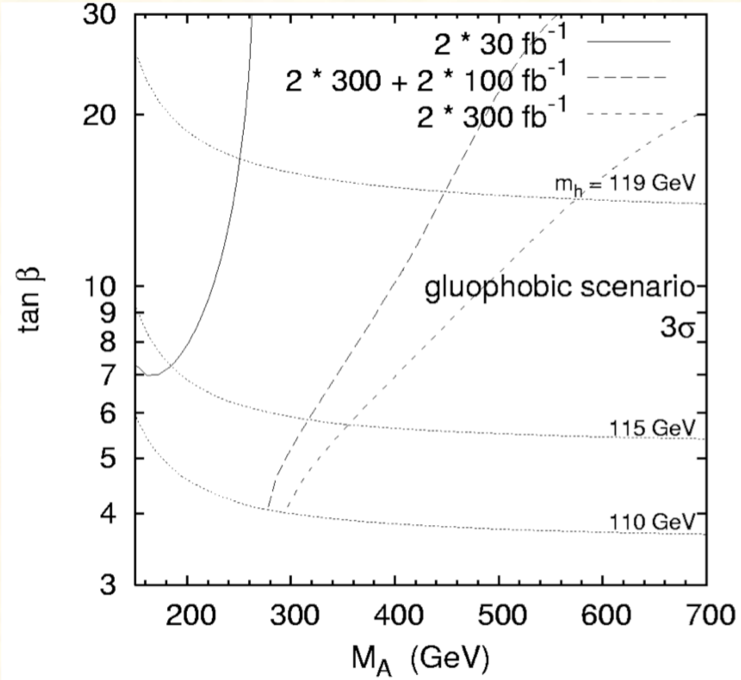
Discrimination between a SM or MSSM Higgs

In some regions of MSSM parameter space only one light Higgs boson is visible

⇒ Try to exclude MSSM using a χ^2 analysis of coupling fits

M. Dührssen et al., Phys. Rev. D70 (2004) 113009.





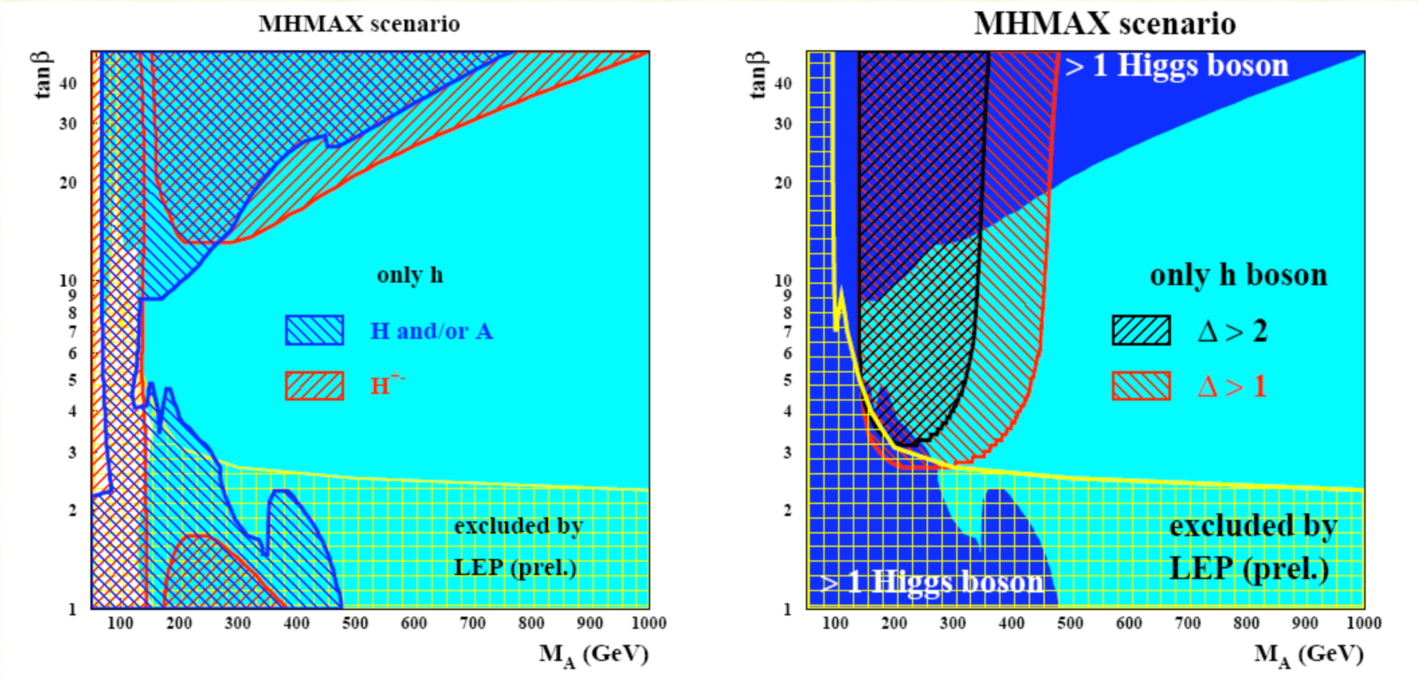
Discrimination between a SM or MSSM Higgs (cont.)

Similar analysis based on direct comparison of ratios of rates in different final states, using VBF production

M. Schumacher et al., hep-ph/0410112

Consider variables $R := BR(h \to \tau\tau) / BR(h \to WW)$

$\Delta := (R_{MSSM} - R_{SM}) / \sigma_{exp}$



30 fb^{-1}

(only stat. errors considered so far, m_H assumed to be known with high precision)

Can SUSY particles be used to detect
Higgs bosons ??

or

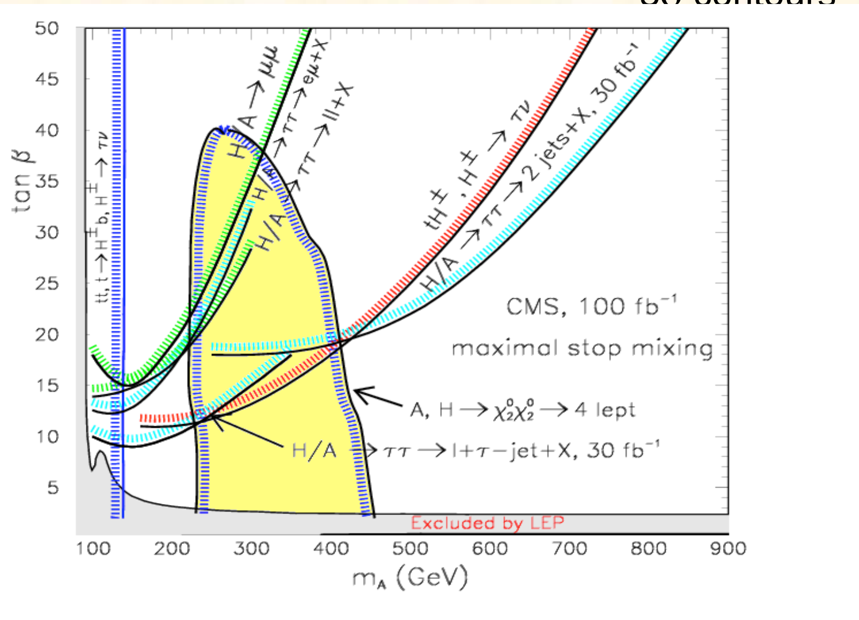
the interplay between the
Higgs sector and SUSY particles

so far: SUSY particles have been assumed to be
too heavy to play a role in Higgs boson decay phenomenology

CMS study: MSSM scenario

$H/A \rightarrow \chi^0_2\chi^0_2 \rightarrow \ell\ell\chi^0_1\ \ell\ell\chi^0_1$

5σ contours



special choice in MSSM (no scan)

M_1 = 60 GeV

M_2 = 110 GeV

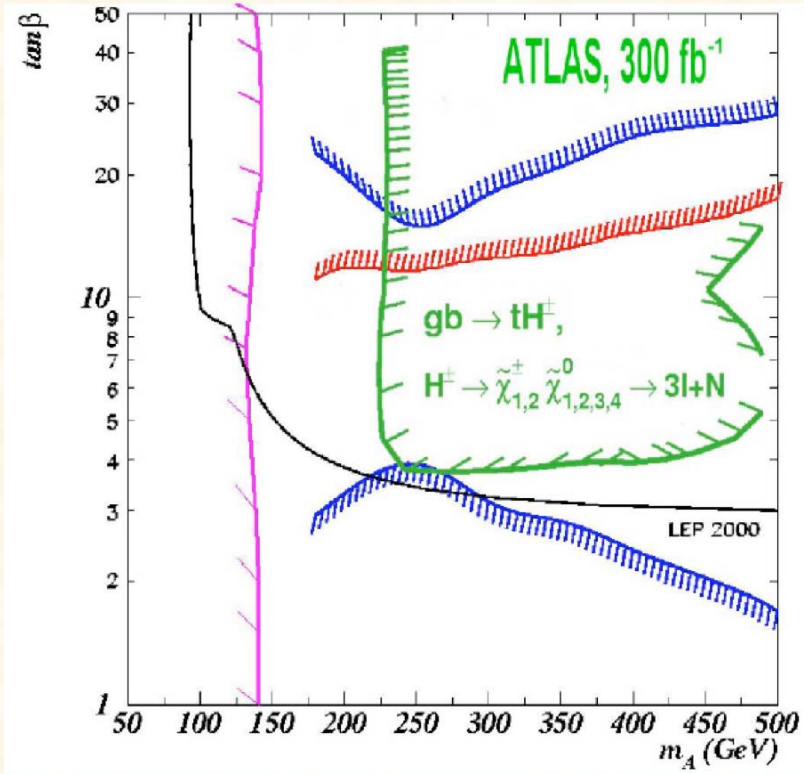
μ = -500 GeV

Exclusions depend on MSSM parameters
(slepton masses, μ)

Search for $H^{\pm}$ decays into SUSY particles

gb→tH+, $H^{\pm} \rightarrow \chi_{2,3}^0 \chi_{1,2}^{\pm} \rightarrow 3\ell + E_T^{miss}$

special choice in MSSM (no scan)
M_2 = 210 GeV
μ = 135 GeV
m(s-ℓ_R) = 110 GeV
m(s-τ_R) = 210 GeV
m_g = 800 GeV
m_{SUSY} = 1000 GeV



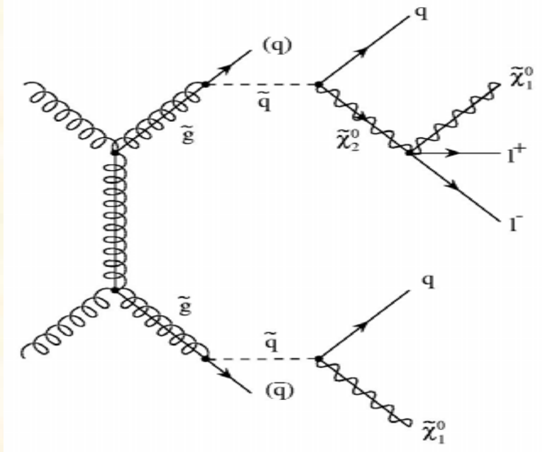
complementary discovery potential

Excursion: Search for Supersymmetry

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy

- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



$\Rightarrow$ combination of Jets, Leptons, E_T^{miss}

$\Rightarrow$ **Heavy Higgs bosons might appear in cascades decays,**

e.g. cascade decays of squarks and gluinos via heavy charginos and neutralinos

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \to \chi_2^{\pm}, \chi_3^0, \chi_4^0 + X$$
$$\to \chi_1^{\pm}, \chi_2^0, \chi_1^0 + h, H, A, H^{\pm} + X$$

$$pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g} \to \chi_1^{\pm}, \chi_2^0 + X$$
$$\to \chi_1^0 + h, H, A, H^{\pm} + X$$

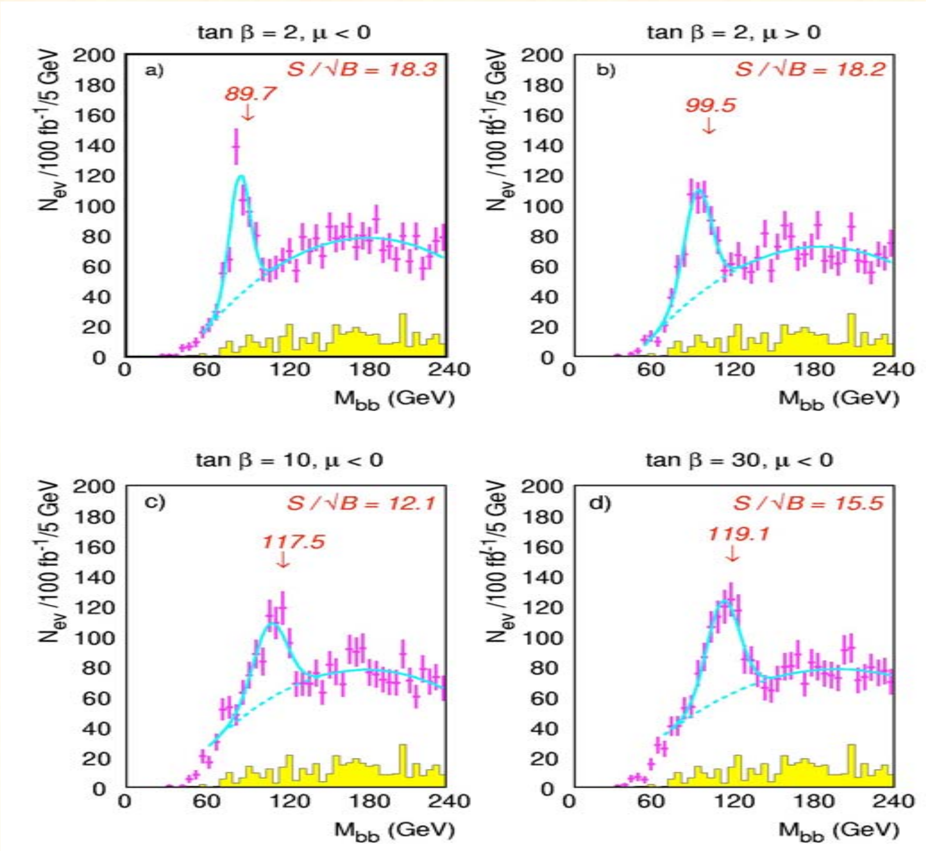
Search for Higgs decays in standard channels: bb, ττ, τν

Search for h →bb in SUSY cascade decays

Applying a cut on E_T^{miss} ⇒ suppresses the Standard Model background (QCD-jets), dominant background from SUSY production

h → bb:

CMS study, mSUGRA



important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases

Could be a Higgs discovery mode !

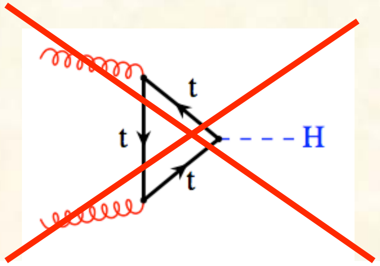
Can invisibly decaying Higgs bosons be detected ?

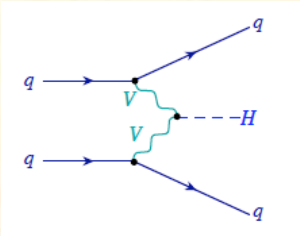
<u>Motivation</u>:

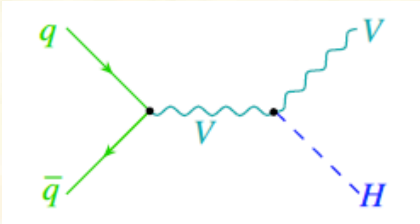
- Invisibly decaying Higgs bosons appear in several extensions of the Standard Model

  e.g. Higgs bosons can decay into weakly interacting neutralinos, gravitinos, scalar particles, ...

- To detect invisibly decaying Higgs bosons, the associated production modes must be used; most promising are VBF and ZH associated production

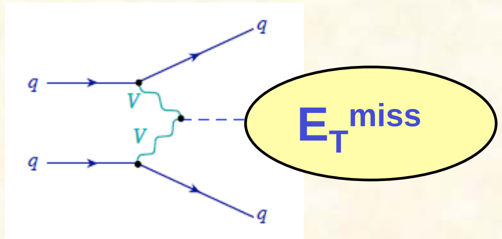






Invisible Higgs decays ?

Possible searches: tt H → ℓνb qqb + E_T^{miss}
W/Z H → ℓν (ℓℓ) + E_T^{miss}
qq H → qq + E_T^{miss}

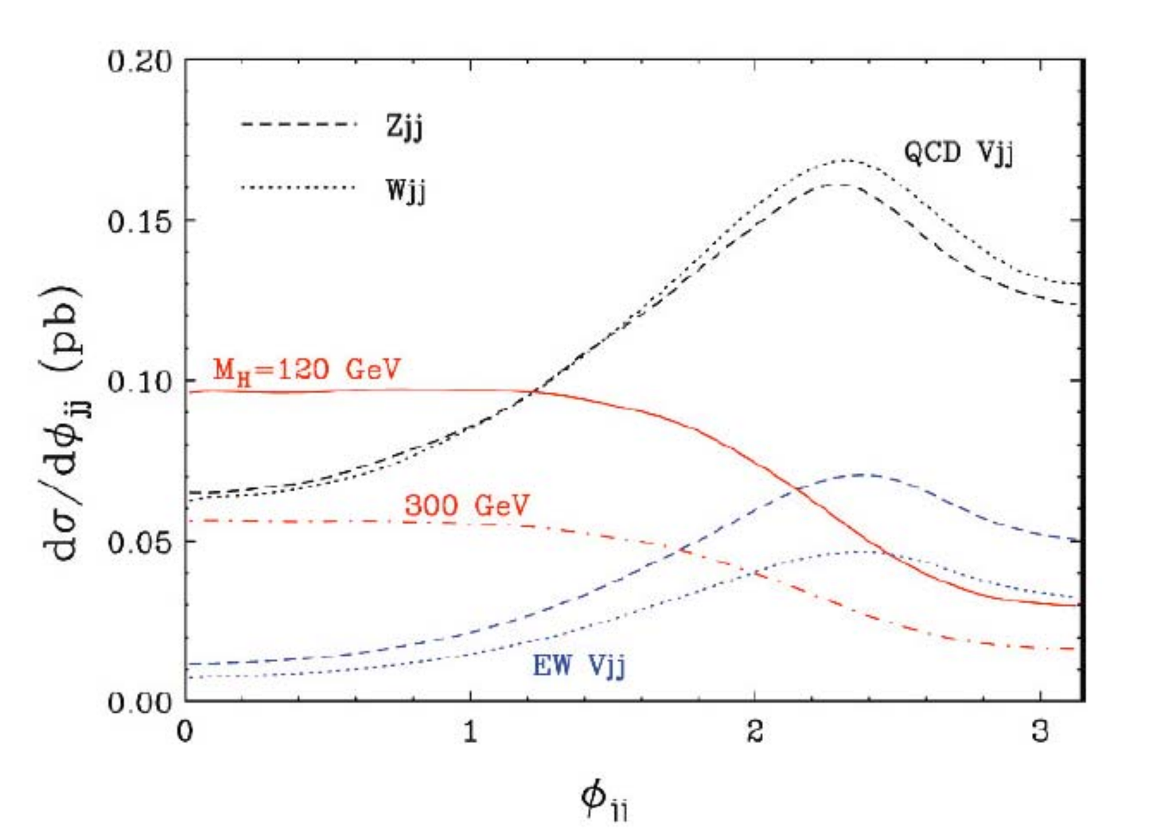


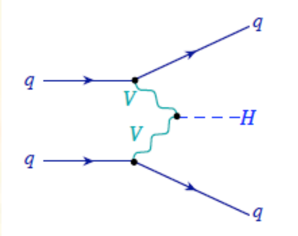
ATLAS study:
Search for invisibly decaying Higgs boson in the VBF mode and in the associated ZH production

Event selection: 2 tag jets, (P_T, $\Delta\eta$, M_{jj}>1200 GeV)
P_T^{miss} > 100 GeV
Lepton and Jet veto (no jets with P_T> 20 GeV)

Main backgrounds: W jj production (W → ℓν)
Z jj production (Z → νν)
QCD jet production, fake E_T^{miss}

Discriminating variable: $\Delta \phi_{jj}$ (separation between tag jets)
expect differences due to Higgs coupling structure:



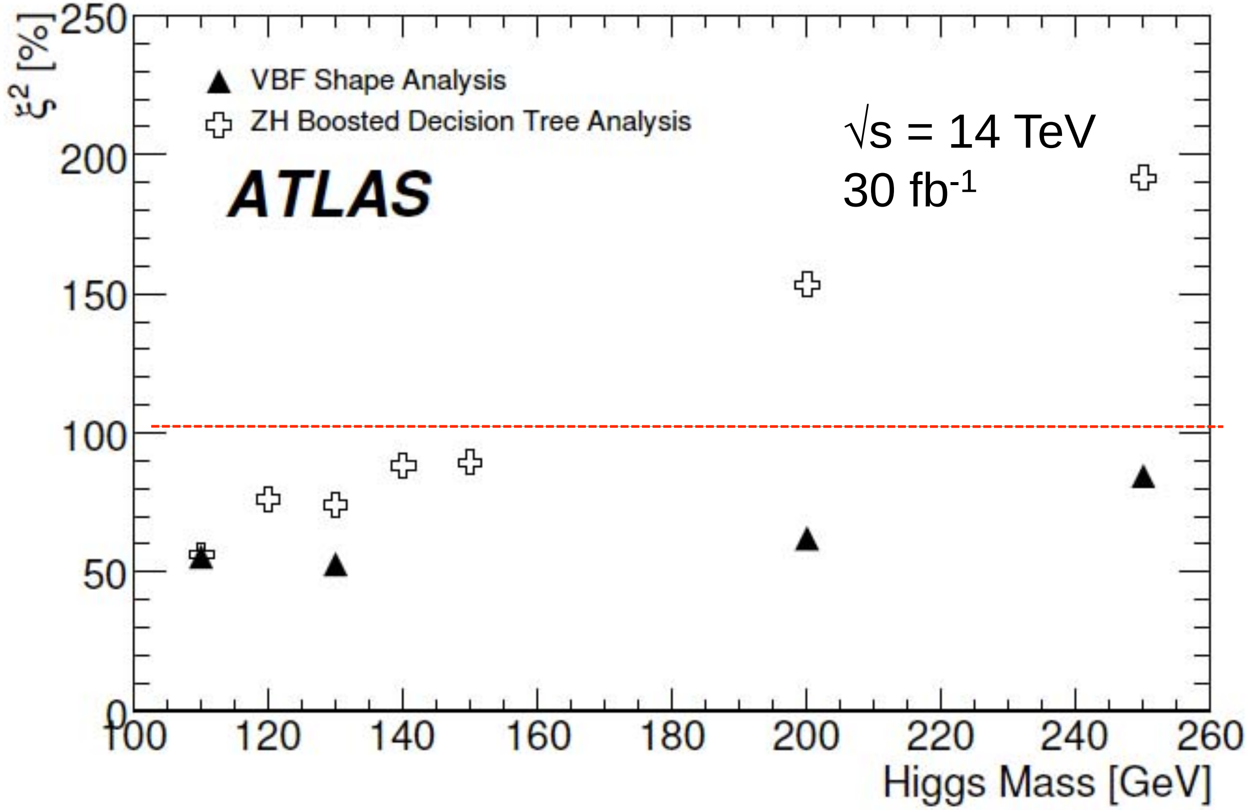


D. Zeppenfeld et al.

Sensitivity:

$$\xi^2 = Br(H \to Inv.) \frac{\sigma_{qq \to qqH}}{\sigma_{qq \to qqH}\big|_{SM}}$$

95% C.L. limits (incl. systematic uncertainties)



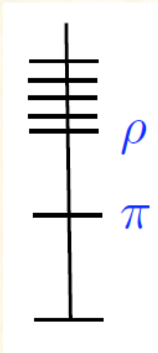
- Sensitivity to large invisible branching ratios (SM production) in VBF channel
- Proof that the nature of the invisibly decaying object is a Higgs boson is difficult

Composite Higgs Bosons ?

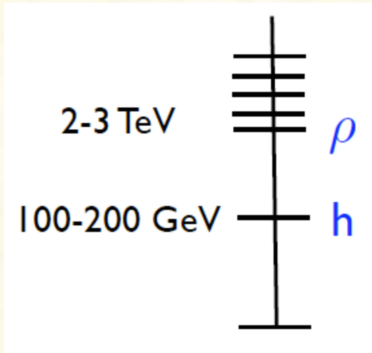
Composite Higgs models

- Composite Higgs models are inspired by QCD where one observes that the (pseudo)scalar mesons are the lightest states

  - pseudo-Nambu-Goldstone bosons, mass protected by global symmetries in QCD



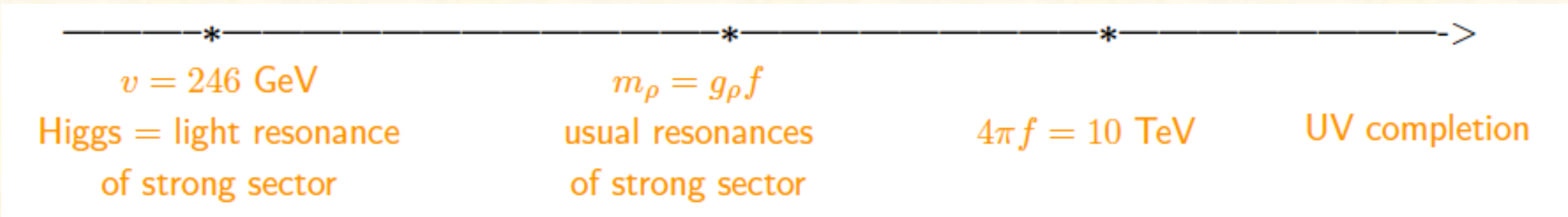
QCD



QCD like sector

  - in analogy, a light Higgs can be obtained as a Goldstone boson of a globally broken symmetry at a scale f

- Energy / mass scales:



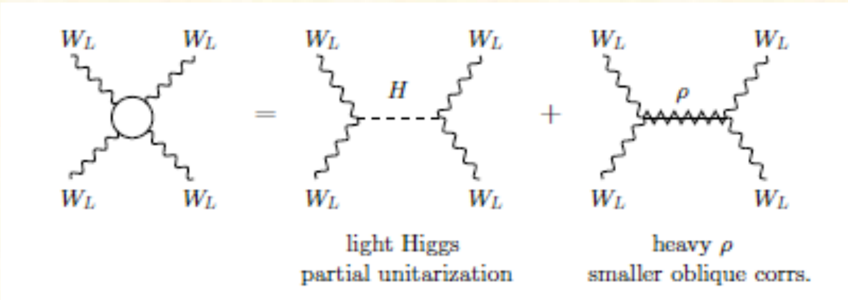
Composite Higgs models (cont.)*

- Couplings of composite Higgs are altered, deviate from Standard Model couplings

HWW: $a\frac{2M_W^2}{v}$ HHWW: $b\frac{2M_W^2}{v^2}$

Standard Model: a = b = 1

Composite models: - deviations from 1,
- non perfect cancellation of unitarity problems by light Higgs
- heavier ρ-like states needed



*)
- Giudice, Grojean, Pomarol, Ratazzi
- Contino et al.
- Espinosa, Grojean, Mühlleitner
- ....

Composite Higgs models (cont.)

- Continuous interpolation between the Standard Model and Technicolour:

$$\xi = \left(\frac{v}{f}\right)^2 = \left(\frac{weak\ scale}{strong\ coupling\ scale}\right)^2$$

$\xi = 0$: Standard Model

$\xi = 1$: Technicolour

Higgs decouples, vector resonances like in TC

- Modified couplings in composite models
  e.g. Minimal Composite Higgs Models (MCHM):

MCHM4:

$$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$$

$$g_{Hff} = g_{Hff}^{SM}\sqrt{1-\xi}$$

universal shift of couplings, no change in branching ratios

MCHM5:

$$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$$

$$g_{Hff} = g_{Hff}^{SM}\frac{1-2\xi}{\sqrt{1-\xi}}$$

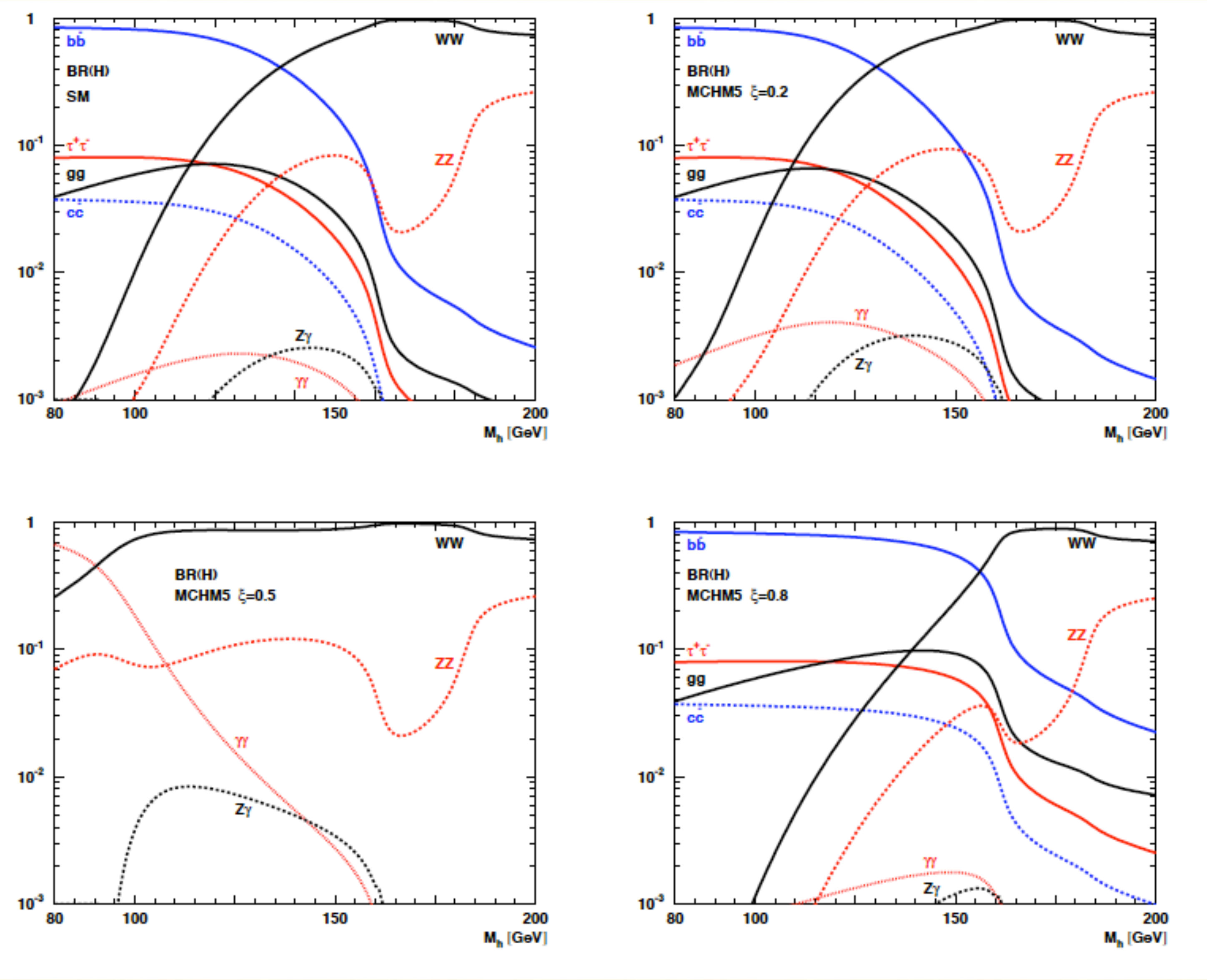
change in BR, depend on ξ, vanishes for $\xi=0.5$

...and: lower production rates !!

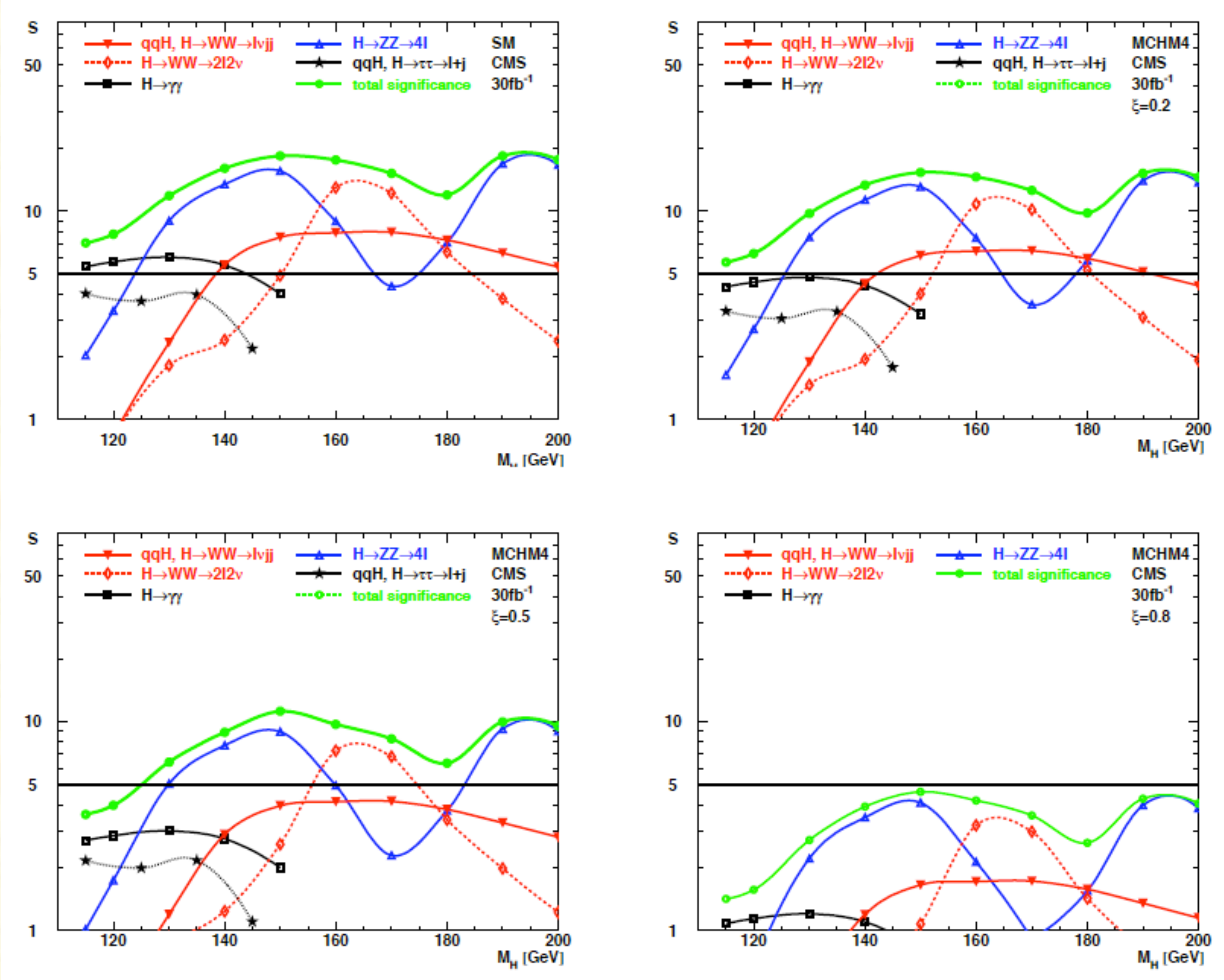
Branching ratios in MCHM5 model

M. Mühlleitner, Physics at the LHC, Hamburg June 2010

Espinosa, Grojean, Mühlleitner



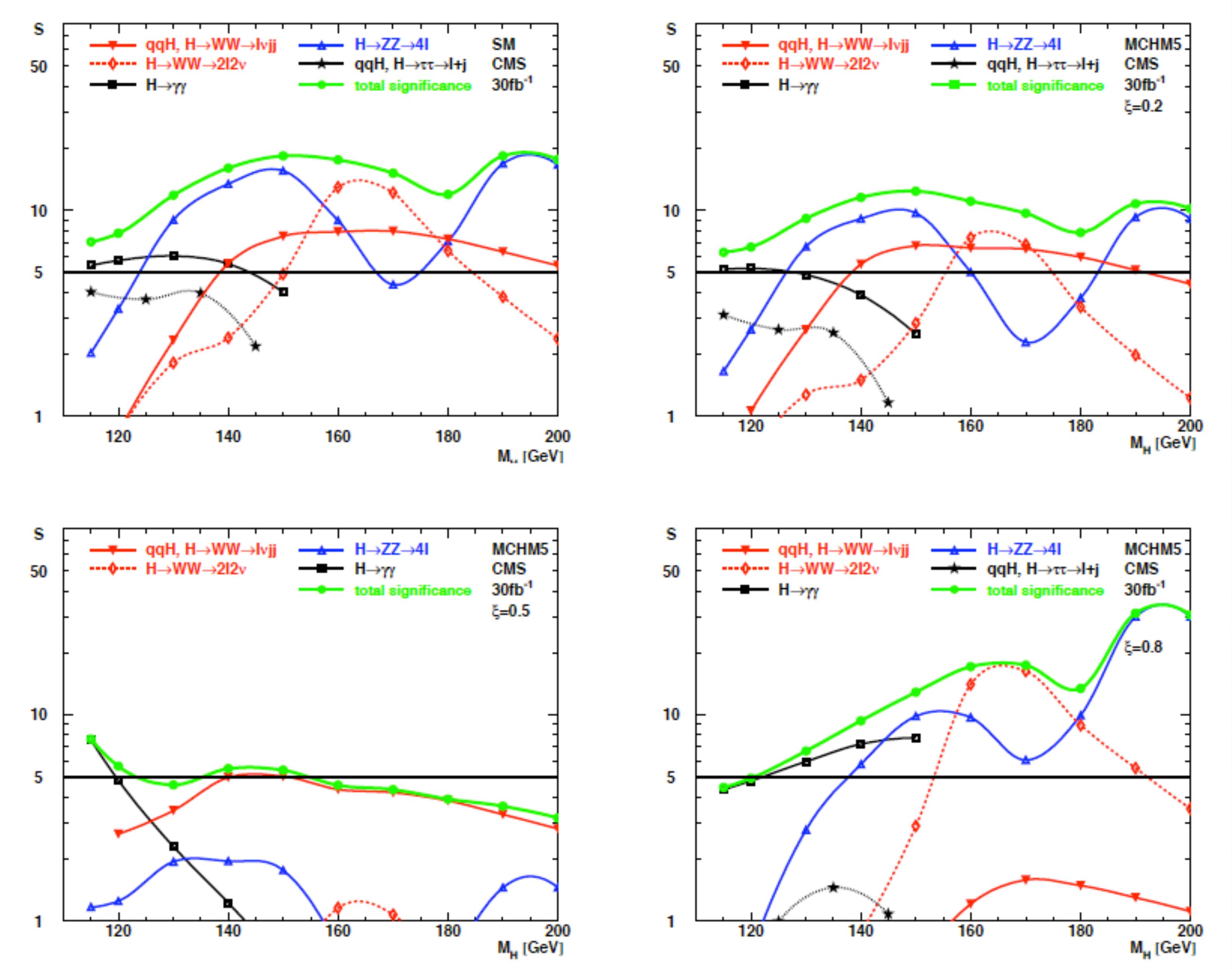
LHC sensitivity to such models: MCHM4



M. Mühlleitner, Physics at the LHC, Hamburg June 2010

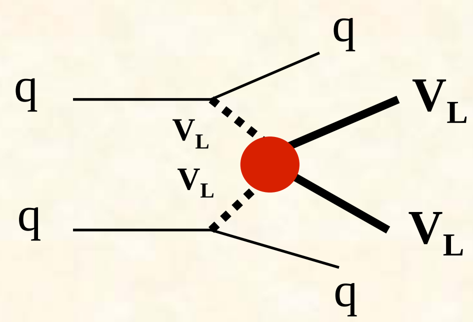
Espinosa, Grojean, Mühlleitner

LHC sensitivity to such models: MCHM5



Espinosa, Grojean, Mühlleitner

What if the LHC does not find the Higgs Boson ?



- Study of longitudinal gauge boson scattering is the key
  High luminosities, i.e. sLHC, required to make quantitative measurements (strong physics case)

- If no Higgs, expect strong $V_L V_L$ scattering (resonant or non-resonant) at ~ 1TeV

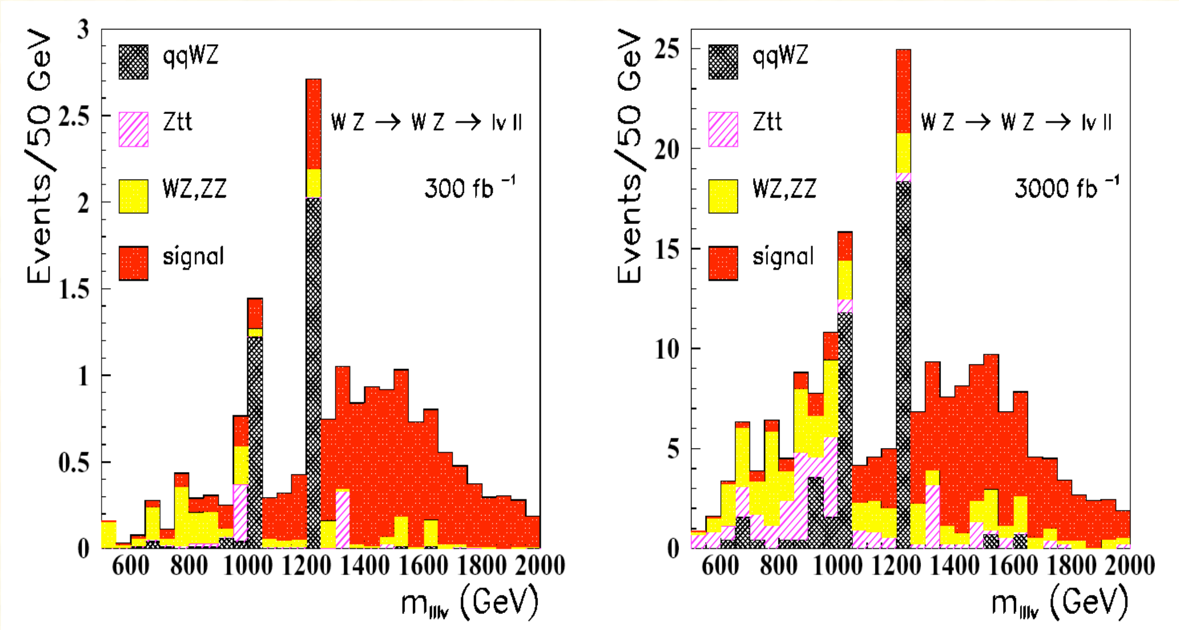
- Also the question of a composite Higgs boson will profit from these measurements

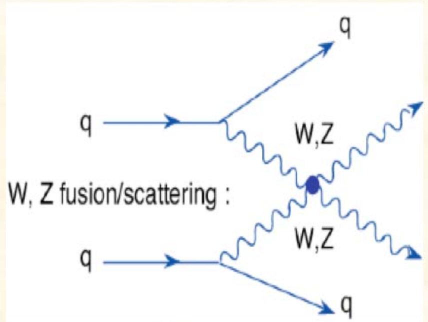
WZ resonances in Vector Boson Scattering

Example: Vector resonance (ρ-like) in $W_L Z_L$ scattering
from Chiral Lagrangian model

m = 1.5 TeV ⇒ 300 fb^{-1} (LHC) vs. 3000 fb^{-1} (sLHC)

Lepton cuts: $p_T^1 > 150$ GeV, $p_T^2 > 100$ GeV, $p_T^3 > 50$ GeV; $E_T^{miss} > 75$ GeV





These studies require both forward jet tagging and central jet vetoing!
Expect degradation of sLHC performance

At LHC: S = 6.6 events,
B = 2.2 events

At sLHC: S/√B ~ 10

Conclusions

- Should a SM Higgs boson exist, it cannot escape detection at the LHC
- MSSM parameter space can be covered for several benchmark scenarios (incl. LHC-phobic scenarios)
- Tevatron might have a 3-σ evidence window;
  Information on bb decays important complementary information to LHC
- On the longer term, LHC can perform first, important measurements of Higgs boson parameters, which are needed to probe the underlying theory

"Exiting times ahead of us"

Acknowledgements:

I am grateful to:

K. Assamagan, R. Bernhard, S. Dittmaier, A. Djouadi, C. Grojean,
R. Harlander, C. Mariotti, M. Mühlleitner, H. Murayama, A. Pomarol,
M. Schumacher, M. Spira, R. Thorne, G. Watts, G. Weiglein, C. Weiser,
D. Zeppenfeld

for useful discussions on the various Higgs topic….and for their "indirect" contributions to these lectures via their excellent talks at conferences and workshops, from which I profited a lot.