Theoretical aspects of Higgs searches at hadron colliders

Abdelhak DJOUADI (LPT, U. Paris-Sud)

1. **The Higgs spectrum in the SM and in SUSY**
2. **The SM Higgs: decays, production and detection**
3. **The Higgs sector in the conventional MSSM**
4. **Some examples of very difficult scenarios**
5. **Conclusion**

1. The Higgs in the SM

To generate particle masses in an $\mathrm{SU(2)_L \times U(1)_Y}$ gauge invariant way:

Spontaneous Electroweak Symmetry Breaking or Higgs mechanism:

$\Rightarrow$ **introduce a doublet of complex scalar fields** $\mathbf{\Phi} = \binom{\phi^+}{\phi^0}$ **with** $\mathrm{Y}_{\mathbf{\Phi}} = 1$

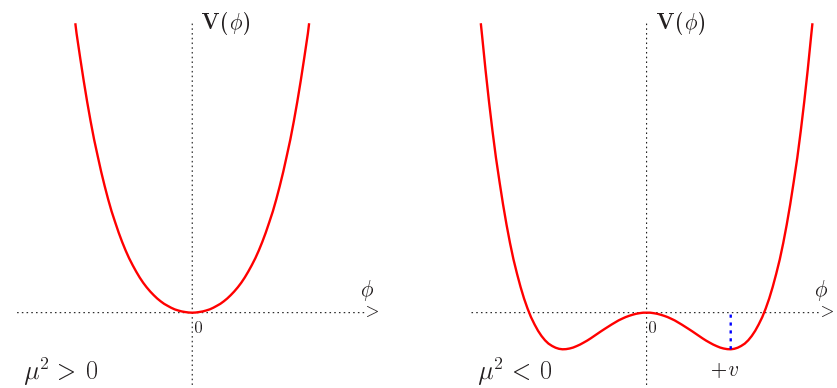
$$\mathcal{L}_{\mathbf{S}} = (\mathrm{D}^\mu \mathbf{\Phi})^\dagger (\mathrm{D}_\mu \mathbf{\Phi}) - \mu^2 \mathbf{\Phi}^\dagger \mathbf{\Phi} - \lambda (\mathbf{\Phi}^\dagger \mathbf{\Phi})^2$$

$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: Φ **develops a vev:**

$$\langle 0 | \mathbf{\Phi} | 0 \rangle = \binom{0}{\mathrm{v}/\sqrt{2}}$$

$$\mathrm{v} = \left(-\frac{\mu^2}{\lambda}\right)^{\frac{1}{2}} = 246 \ \mathrm{GeV}$$



$\Rightarrow$ **3 degrees of freedom for** $\mathrm{W^\pm_L, Z_L}$ **and thus** $\mathrm{M_{W^\pm}, M_Z; M_\gamma = 0}$

For fermion masses, use <u>same</u> doublet field Φ **and its <u>conjugate</u> field**

$$\mathcal{L}_{\mathrm{Yuk}} = -\mathbf{f_e}(\bar{\mathrm{e}}, \bar{\nu})_{\mathbf{L}} \mathbf{\Phi} \mathbf{e_R} - \mathbf{f_d}(\bar{\mathrm{u}}, \bar{\mathrm{d}})_{\mathbf{L}} \mathbf{\Phi} \mathbf{d_R} - \mathbf{f_u}(\bar{\mathrm{u}}, \bar{\mathrm{d}})_{\mathbf{L}} \tilde{\mathbf{\Phi}} \mathbf{u_R} + \cdots$$

The residual degree corresponds to the spin–zero Higgs particle, H.

1. The Higgs in the SM

- The Higgs boson: $J^{PC} = O^{++}$ quantum numbers
- Masses and self–couplings from $\mathcal{L}_S \propto \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$

$$M_H^2 = 2\lambda v^2 = -2\mu^2, \; g_{H^3} = 3i\, M_H^2/v \;, \; g_{H^4} = 3iM_H^2/v^2$$

- Higgs couplings derived the same way as the particle masses:

$$\mathcal{L}_{M_V} \sim M_V^2 (1 + H/v)^2 \;\; , \; \mathcal{L}_{m_f} \sim -m_f (1 + H/v)$$

$$\Rightarrow g_{Hff} = i m_f/v \;, \; g_{HVV} = -2iM_V^2/v \;, \; g_{HHVV} = -2iM_V^2/v^2$$

Since v is known, the only free parameter in SM is M_H or λ.

However, there are theoretical constraints:

– Very heavy Higgs: strong W/Z interactions

perturbative unitarity $\Rightarrow M_H \lesssim 700$ GeV

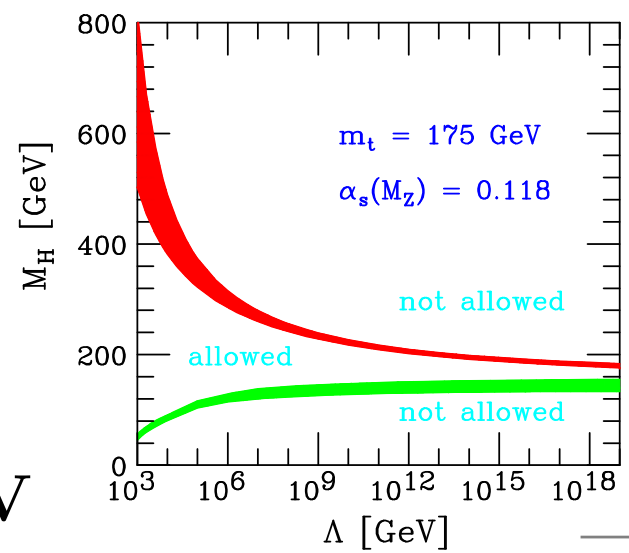
from lattice simulation $\Rightarrow M_H \lesssim 650$ GeV

– Triviality and stability bounds (Roman plot)

$\Lambda \sim 1$ TeV $\Rightarrow 70 \lesssim M_H \lesssim 700$ GeV

$\Lambda \sim 10^{16}$ GeV $\Rightarrow 130 \lesssim M_H \lesssim 180$ GeV

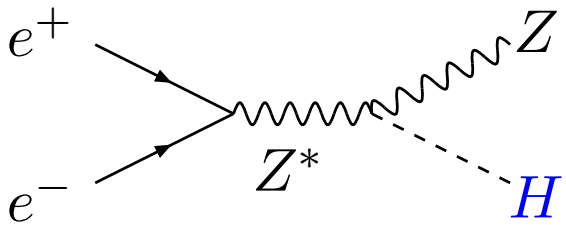
Hambye/Riesselmann



1. The Higgs in the SM: experimental constraints

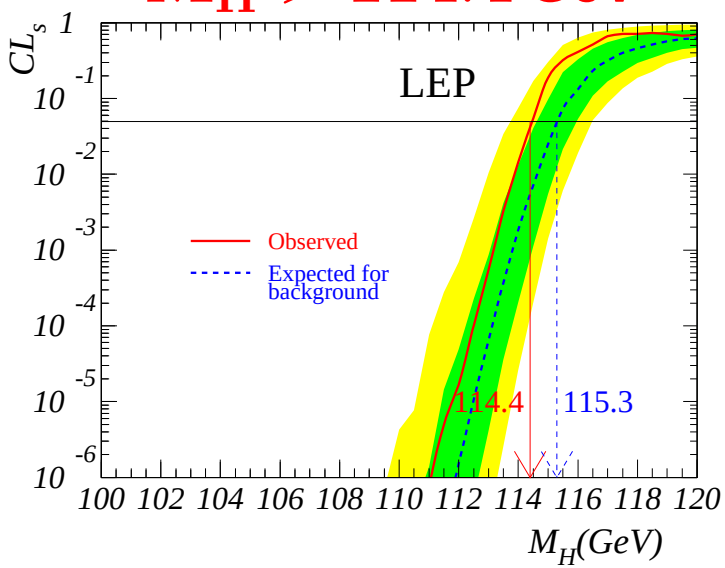
Direct searches at LEP:

H looked for in $e^+e^- \to ZH$



We have a limit at 95% CL:

$M_H > 114.4$ **GeV**

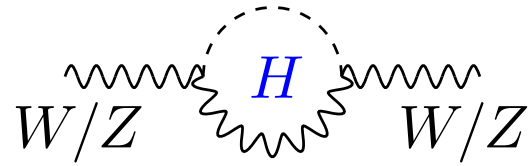


New results from the Tevatron:

rule out $M_H \approx 170$ GeV

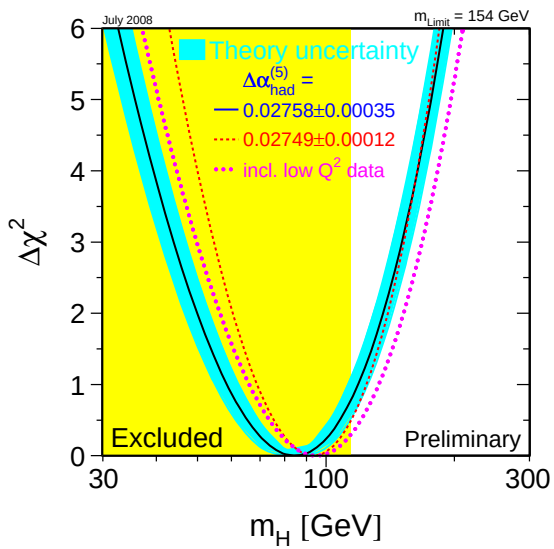
Indirect Higgs searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

one obtains $M_H = 84^{+34}_{-26}$ GeV, or



$M_H \lesssim 154$ **GeV at 95% CL**

Gfitter: $M_H = 116^{+18}_{-1.3}$ GeV $\lesssim 145$ GeV

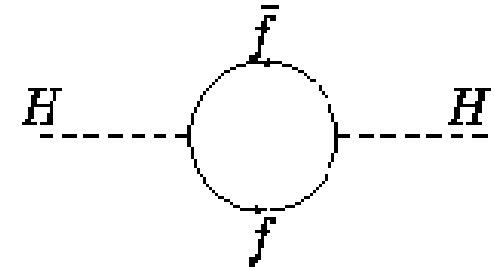
1. The Higgs sector in the MSSM

A major problem in the SM: the hierarchy/naturalness problem

- **Radiative corrections to M_H^2 in SM**

with a cut–off $\Lambda = M_{NP} = M_{GUT}$

$\Delta M_H^2 \propto$



$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 \log\frac{\Lambda}{m_f} - 2m_f^2] + \mathcal{O}(1/\Lambda^2)$$

M_H **prefers to be close to the high scale than to the EWSB scale.**

Technically solved in Supersymmetry by the contribution of SUSY particle

(needs $M_S \lesssim 1$ TeV otherwise the problem is back again).

In the MSSM: two Higgs doublets: $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ and $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$,

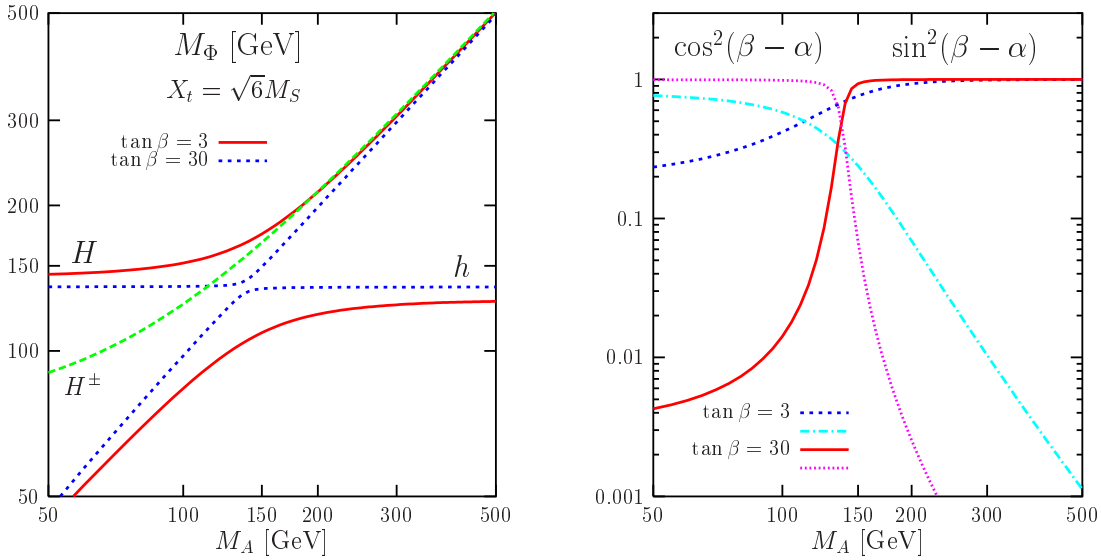
After EWSB (which can be made radiative: more elegant than in SM):

Three dof to make $W_L^\pm, Z_L \Rightarrow$ 5 physical states left out: $h, H, A, H^\pm$

Only two free parameters at tree–level: $\tan\beta, M_A$ but rad. cor. important

$$M_h \lesssim M_Z|\cos 2\beta| + RC \lesssim 130 \text{ GeV}\ , \quad M_H \approx M_A \approx M_{H^\pm} \approx M_{EWSB}$$

1. The Higgs sector in the MSSM



– **Couplings of h, H to VV are suppressed; no AVV couplings (CP).**

– **For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).**

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

In the decoupling limit: MSSM reduces to SM but with a light Higgs.

Constraints: $\mathbf{114 \lesssim M_H \lesssim 130\,GeV \text{ or } M_h, M_A \lesssim M_Z}$

1. The Higgs sector beyond the conventional MSSM

Giving up some assumptions: the example of the CP–violating MSSM

We can allow for some amount of CP–violation in eg. $\mathrm{M_i}$, μ and $\mathrm{A_f}$

Higgs sector: CP–conserving at tree level $\Rightarrow$ CP–violating at one–loop

(good to address the issue of baryogenesis at the electroweak scale....)

$\Rightarrow$ h, H,A are not CP definite states: $\mathrm{h_1}, \mathrm{h_2}, \mathrm{h_3}$ are CP mixtures

determination of Higgs spectrum slightly more complicated than usual

Additional Higgs representations: the example of the NMSSM

MSSM problem: μ is SUSY-preserving but $\mathcal{O}(\mathrm{M_Z})$; a priori no reason

Solution, μ related to the vev of additional singlet field, $\langle \mathrm{S} \rangle \propto \mu$

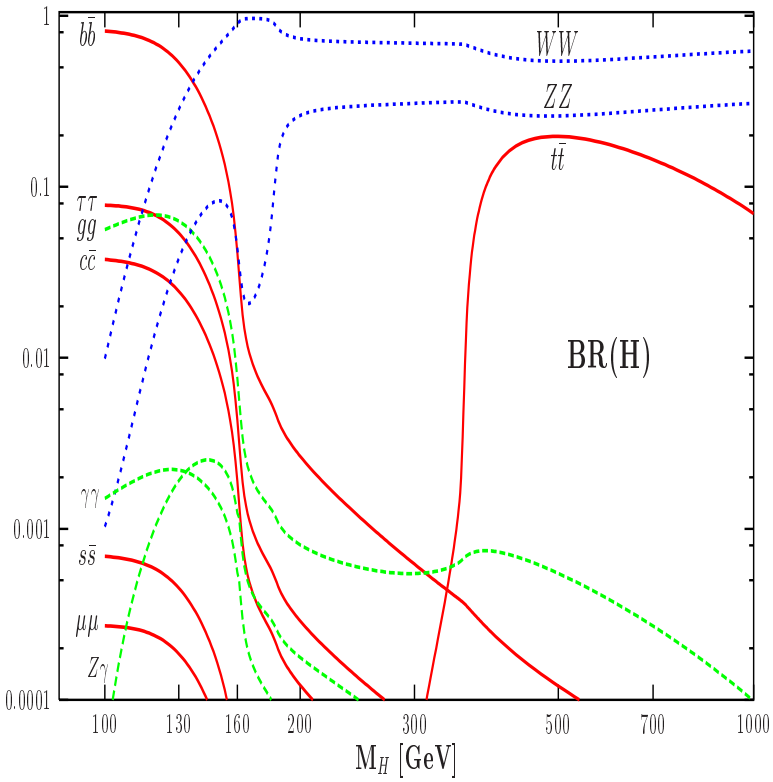
NMSSM: introduce a gauge singlet in Superpotential: $\lambda \hat{\mathrm{H}}_1 \hat{\mathrm{H}}_2 \hat{\mathrm{S}} + \frac{1}{3} \hat{\mathrm{S}}$

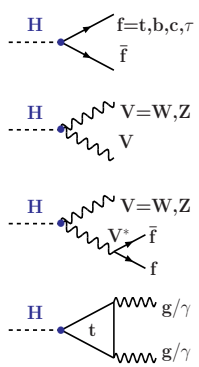
$\Rightarrow$ SUSY spectrum extended by χ_5^0 and two neutral Higgs particles $\mathrm{h_3}, \mathrm{a_2}$

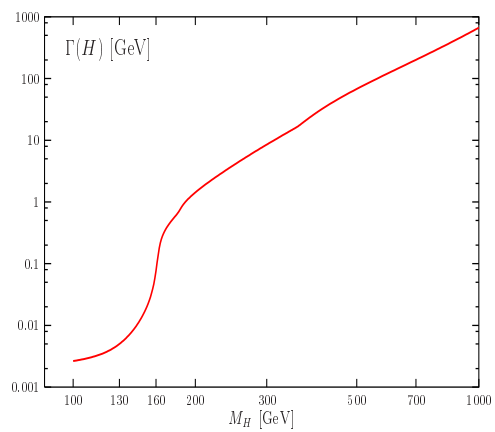
less fine-tuning, richer phenomenology, interesting constrained version, ..

Both lead to a possibly very light Higgs that has escaped detection!

2. SM Higgs: decay modes







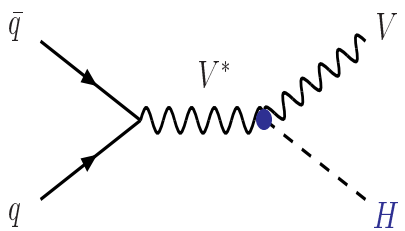
Higgs decays in the SM:

- **H decays into the heaviest particle available by phase space: $\mathbf{g \propto m}$.**
- $\mathbf{M_H \lesssim 130\ GeV, H \to b\bar{b}}$
  - $\mathbf{H \to cc, \tau^+\tau^-, gg = \mathcal{O}(few\ \%)}$
  - $\mathbf{H \to \gamma\gamma = \mathcal{O}(0.1\%)}$
- $\mathbf{M_H \gtrsim 130\ GeV, H \to WW, ZZ}$
  - **below threshold decays possible**
  - **above threshold: B(WW)=$\frac{2}{3}$, B(ZZ)=$\frac{1}{3}$**
  - **decays into $\mathbf{t\bar{t}}$ for heavy Higgs.**
- **Total Higgs decay width:**
  - **very small for a light Higgs**
  - **comparable to mass for heavy Higgs.**

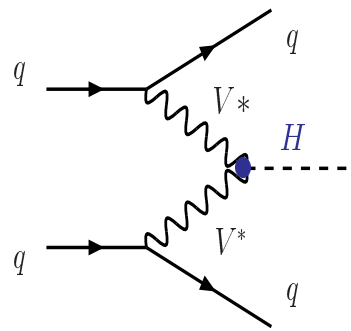
2. SM Higgs: production at the LHC

SM production mechanisms

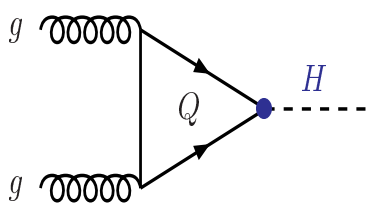
Higgs–strahlung



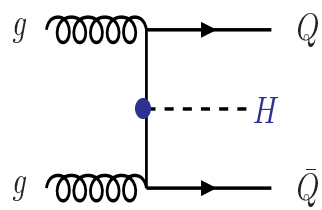
Vector boson fusion



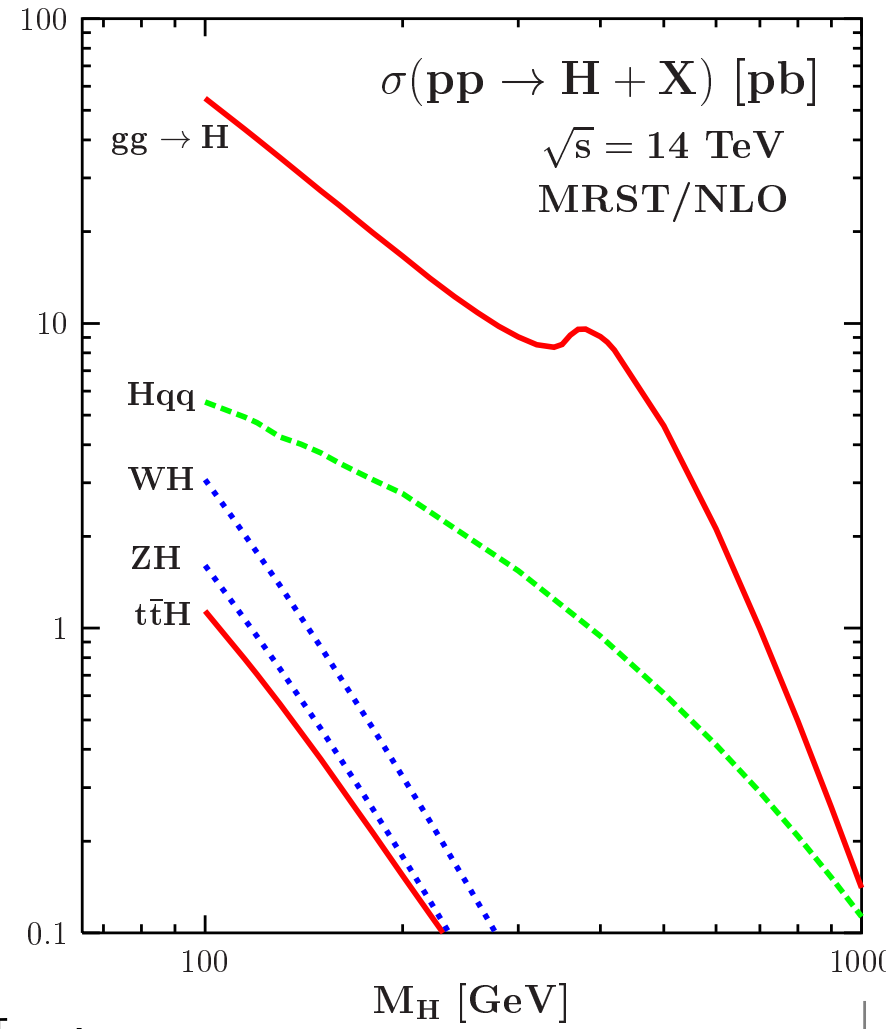
gluon–gluon fusion



in associated with $Q\bar{Q}$



Cross sections at the LHC



Bjorken, Georgi et al., Glashow et al.,

Cahn et al., Altarelli et al., Kunszt, ...

Also subleading processes, $gg \to HH$, etc...

2. SM Higgs: cross sections at higher orders

Summary of higher order calculations for production in the SM:

- **Very large corrections to the process $\mathrm{gg} \to \mathrm{H}$:**

+70% at NLO: **AD+Spira+Zerwas (exact case); Dawson ($\mathrm{m_t} \to \infty$);**

+30% at NNLO: Harlander et al; Melnikov et al; Ravindran et al; ($\mathrm{m_t} \to \infty$)

+5% with (soft-gluon) resumation: **Catani et al, Spira et al;**

10% for EW corrections: **AD+Gambino, Degrassi et al; Actis et al.**

- **Moderate corrections to the process $\mathrm{VV} \to \mathrm{H}$:**

+10% at NLO (QCD+EW): **Han+Valencia; Denner et al;**

- **Small corrections to $\mathrm{pp} \to \mathrm{t\bar{t}} + \mathrm{H}$**

+20% at NLO: **Spira et al; Zerwas et al; Dawson et al.**

- **Moderate corrections to $\mathrm{pp} \to \mathrm{VH}$**

+30% at NLO: Han et al; 5% at NNLO: Brein et al; also EW: Dittmaier et al.

also corrections to various distributions (MC): Catani ea; Zeppenfeld ea; .

H decays: QCD+EW under control in general/summarized in HDECAY.

2. SM Higgs: backgrounds

A very challenging task!

- **Huge cross sections for QCD processes.**
- **Small cross sections for EW Higgs signal.**

  S/B $\gtrsim 10^{10} \Rightarrow$ **a needle in a haystack!**
- **Need some strong selection criteria:**

Trigger: get rid of uninteresting events...

Select clean channels: $\mathrm{H} \to \gamma\gamma, \mathrm{VV} \to \ell$

Use different kinematic features for Higgs

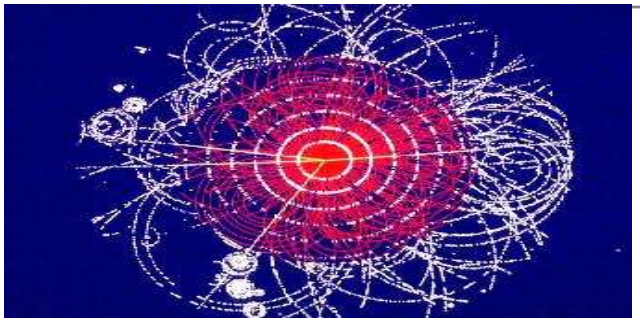
Combine different decay/production channels

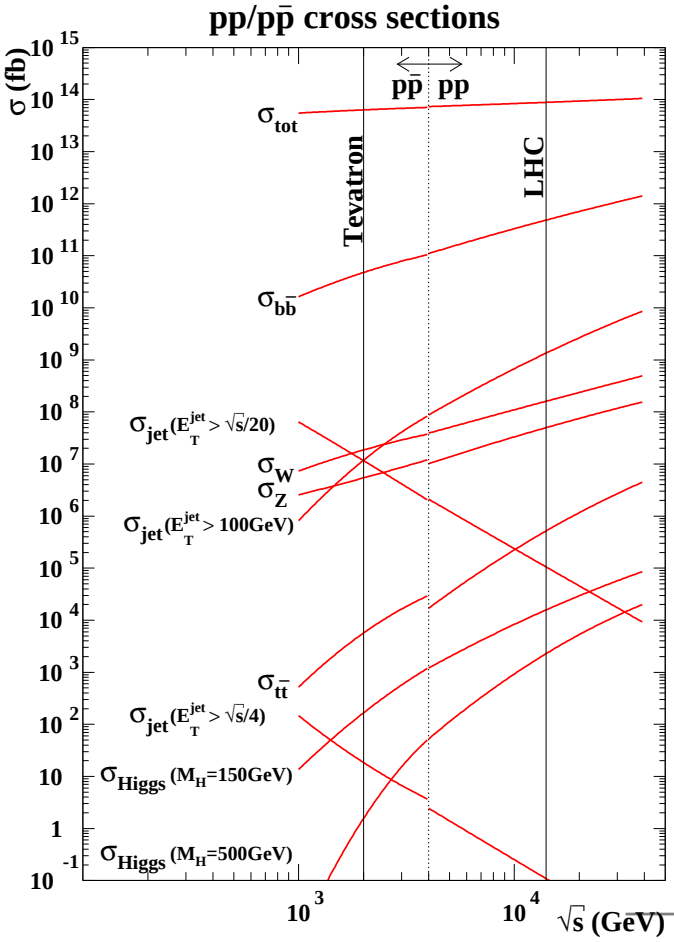
Have a precise knowledge of S and B rates.

(note: higher orders can be factor of 2!)

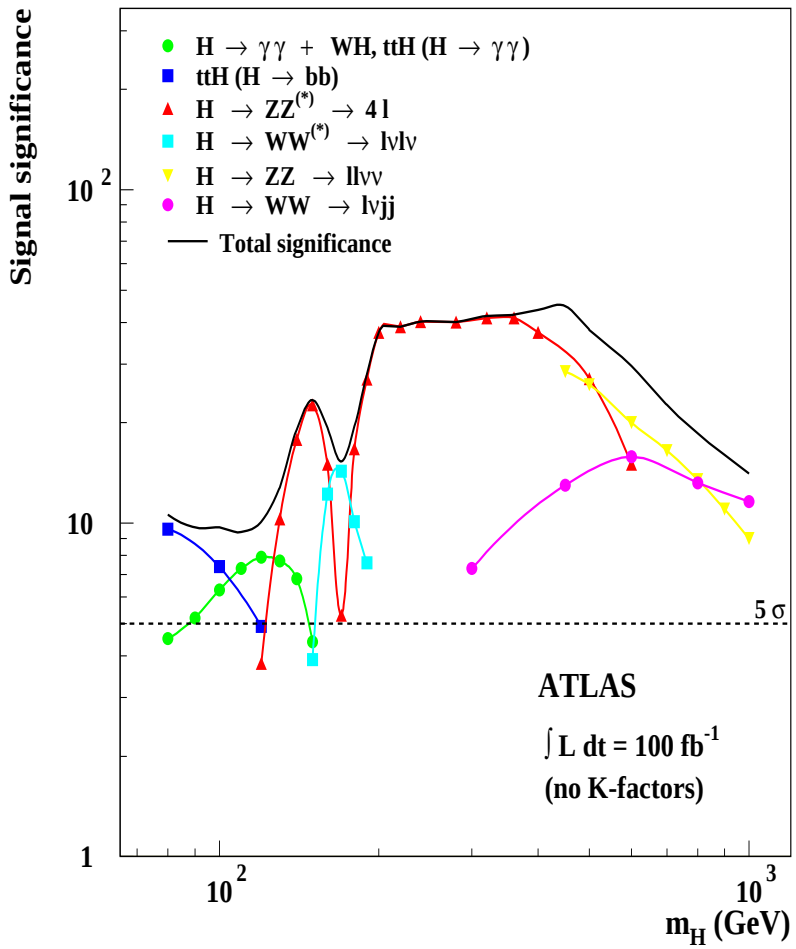
- **Gigantic experimental (+theoretical) efforts**

(more than 20 years of very hard work!)





2. SM Higgs: detection at the LHC



gluon–gluon fusion:

$\mathrm{gg} \to \tau\tau, \mathrm{b\bar{b}}, \mathrm{t\bar{t}}$ **hopeless**

$\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$ **(below** $\mathrm{M_H} \approx$ **150 GeV)**

$\mathrm{gg} \to \mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ **(130–500 GeV)**

$\mathrm{gg} \to \mathrm{H} \to \mathrm{WW} \to \ell\nu\ell\nu$ **(130–200 GeV)**

$\mathrm{H} \to \mathrm{ZZ}, \mathrm{WW} \to \mathrm{jj}+\ell$ **(above 500 GeV)**

Vector boson fusion:

S/B $\sim$ **1 after standard VBF cuts**

$\mathrm{pp} \to \mathrm{H} \to \tau\tau, \gamma\gamma, \mathrm{ZZ}^*, \mathrm{WW}^*$

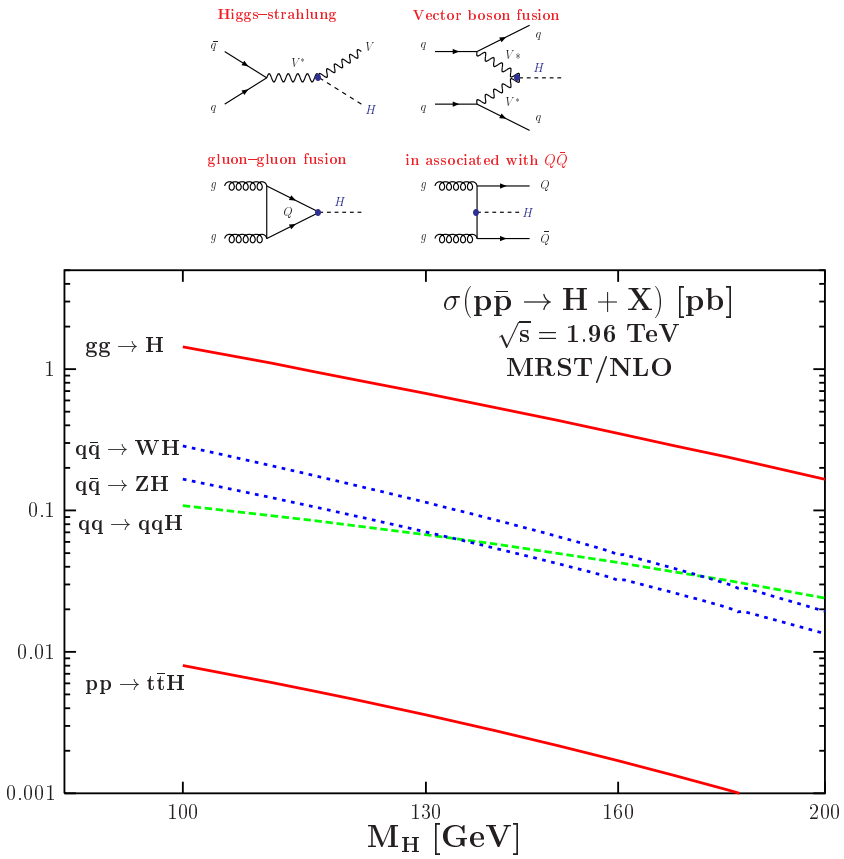
Association with top pairs:

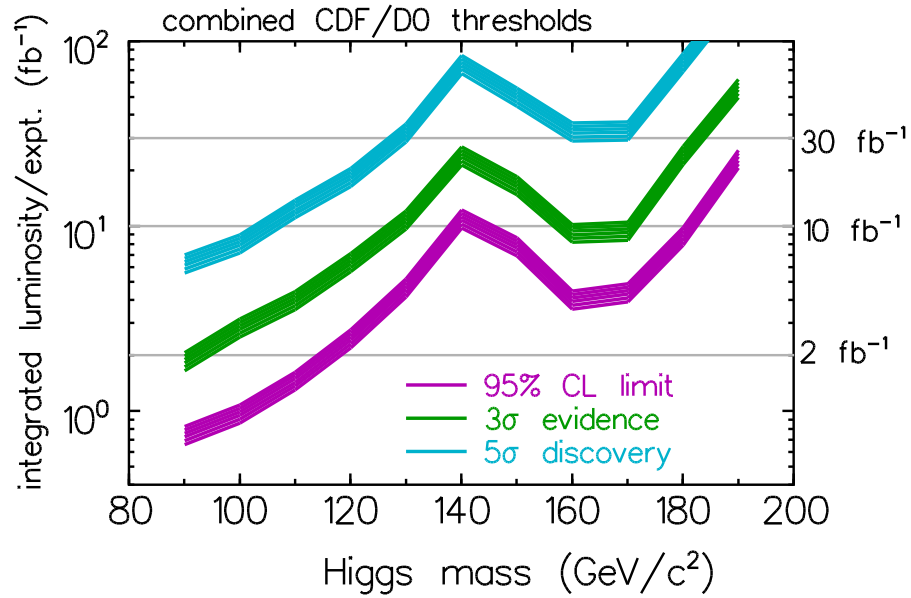
$\mathrm{H} \to \gamma\gamma$ **bonus,** $\mathrm{H} \to \mathrm{b\bar{b}}$ **hopeless?**

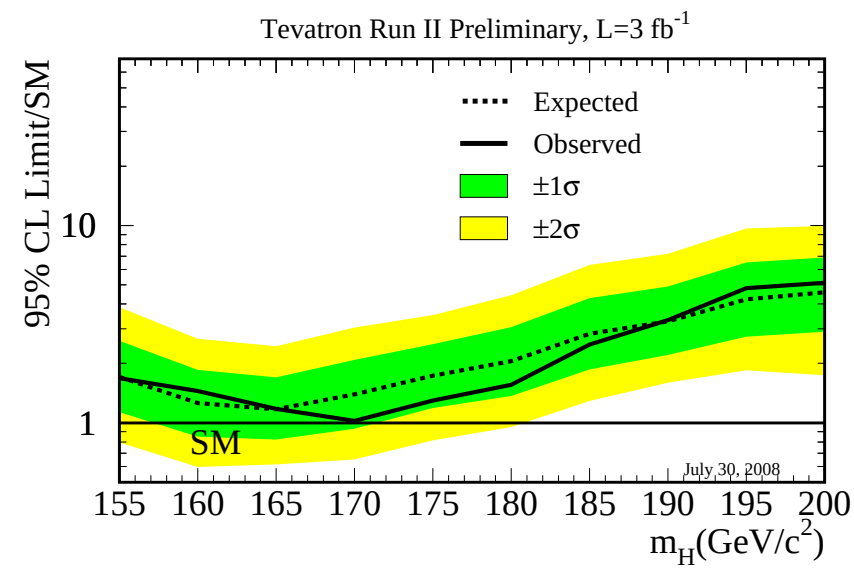
Association with W,Z:

marginal for discovery; measurements?

2. SM Higgs: production at the Tevatron







Relevant two main processes:

$$pp \to WH/ZH \to \ell\nu b\bar{b}/\nu\bar{\nu}b\bar{b}$$

$$gg \to H \to W^*W \to \ell\nu\ell\nu$$

3. MSSM Higgses: decay modes

Higgs decays in the MSSM:

General features:

- h: **same as** $\mathrm{H_{SM}}$ **in general**

(in particular in decoupling limit)

$\mathrm{h} \to \mathrm{b\bar{b}}$ **and** $\tau^+\tau^-$ **same or enhanced**

- A: **only** $\mathrm{b\bar{b}}, \tau^+\tau^-$ **and** $\mathrm{t\bar{t}}$ **decays**

(no VV decays, hZ **suppressed).**

- H: **same as** A **in general**

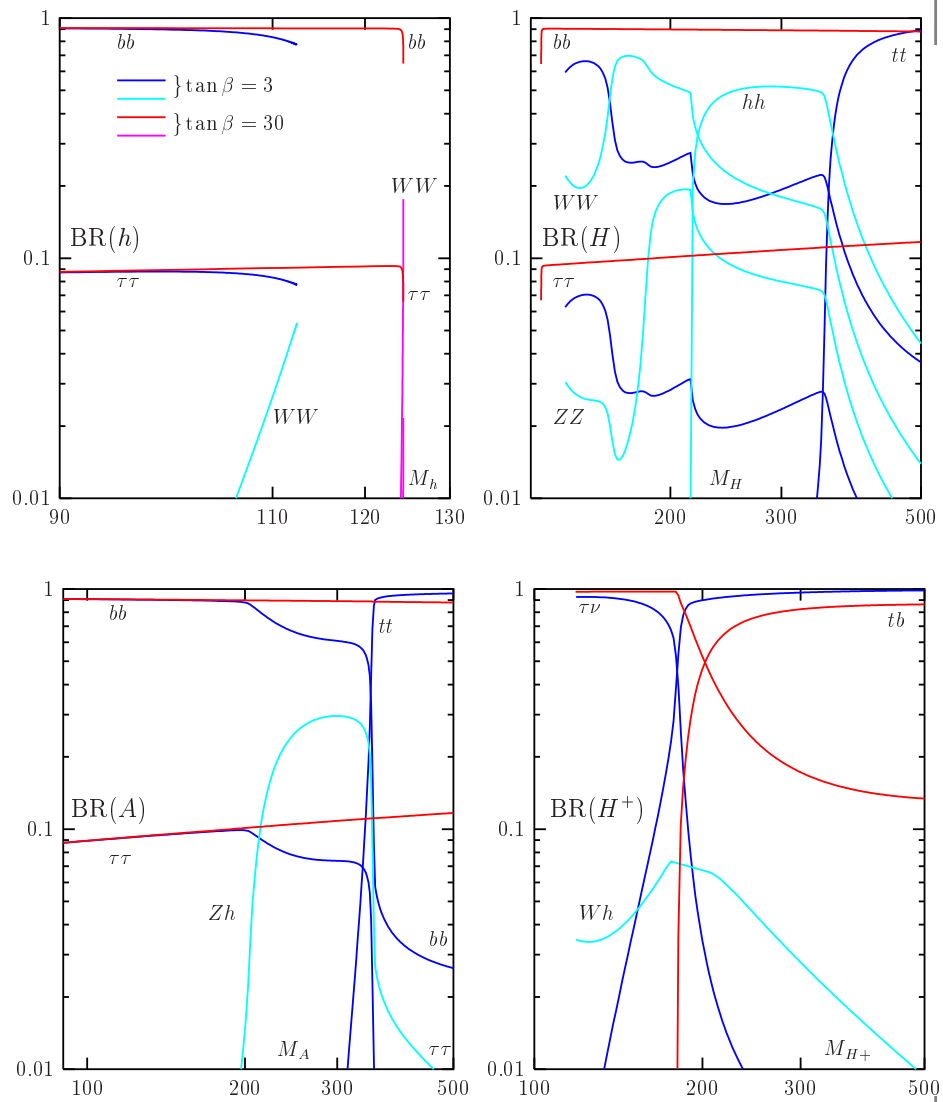
$(\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ **decays suppressed).**

- $\mathrm{H}^\pm$: $\tau\nu$ **and** tb **decays**

(depending if $\mathrm{M_{H^\pm}} <$ **or** $>$ $\mathrm{m_t}$**).**

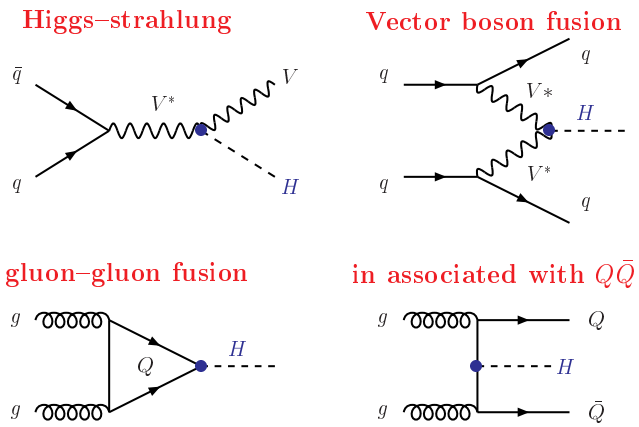
Possible new effects from SUSY

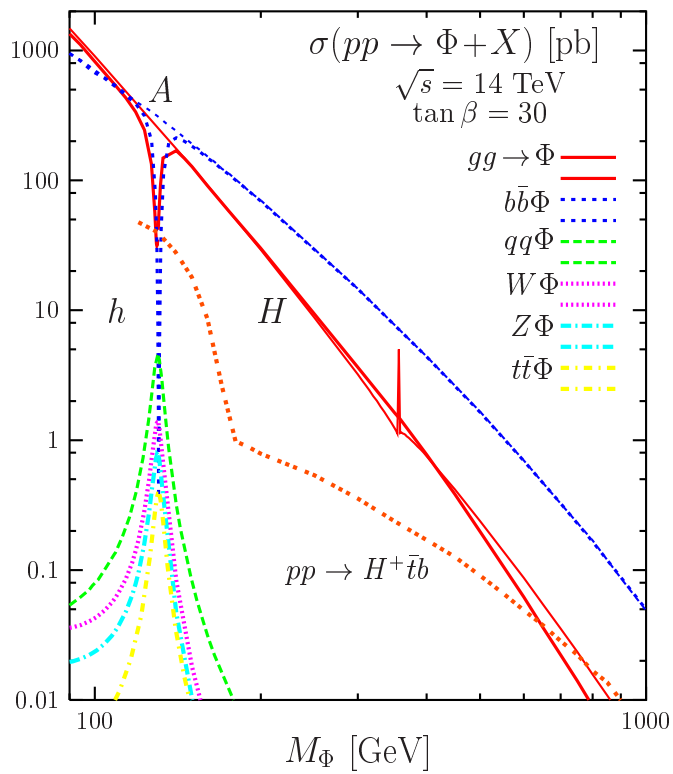
Note: total decay widths small....



3. MSSM Higgses: production cross sections

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**

– **in ΦV, $qq\Phi$ h/H complementary**

– $\sigma(h) + \sigma(H) = \sigma(H_{SM})$

– **additional mechanism: qq $\to$ A+h/H**

- **For $gg \to \Phi$ and $pp \to tt\Phi$**

– **include the contr. of b–quarks**

– **dominant contr. at high tanβ!**

- **For pseudoscalar A boson:**

– **CP: no ΦA and qqA processes**

– $gg \to A$ **and** $pp \to bbA$ **dominant.**

- **For charged Higgs boson:**

– $M_H \lesssim m_t$: $pp \to t\bar{t}$ **with** $t \to H^+ b$

– $M_H \gtrsim m_t$: **continuum** $pp \to t\bar{b}H^+$

3. MSSM Higgses: cross sections in higher orders

Summary of higher order calculations in MSSM (for SM see earlier)

For h/H: same processes as for SM Higgs (esp. for $\mathrm{M_A} \gg \mathrm{M_Z}$) but:

- Include b–loop contributions to $\mathrm{gg} \to \mathrm{h/H}$ and new $\mathrm{gg} \to \mathrm{A}$

K–factors only at NLO ($\sim$ 1.5–2) AD+Graudenz+Spira+Zerwas

- Include b–final states in $\mathrm{pp} \to \mathrm{b\bar{b}} + \mathrm{h/H}$ (dominant at high $\tan\beta$)

large K–factors at NLO (50%) Spira ea; Zerwas ea; Dawson ea

- Additional SUSY–QCD corrections in $\mathrm{pp} \to \mathrm{V} + \mathrm{h/H}$;$\mathrm{qq} + \mathrm{h/H}$:

rather small at NLO (a few %) for heavy $\tilde{\mathrm{q}}/\tilde{\mathrm{g}}$ AD+Spira

For A: rates including K–factors approx the same as above for h/H

For $\mathrm{H}^\pm$: main process is $\mathrm{pp} \to \mathrm{tt}^{(*)} \to \mathrm{tbH}^\pm$ in general

relevant corrections known exactly at NLO Plehn; Zhou; Kidonakis

h,H,A,$\mathrm{H}^\pm$ decays: well under control including SUSY+NL0 corrections

summarized in the program HDECAY AD+Kalinowski+Spira

3. MSSM Higgses: detection at the LHC

The lighter Higgs boson:

same as in the SM for $\mathrm{M_h} \lesssim 140$ **GeV**

(in particular in the decoupling regime)

$$\mathrm{gg} \to \mathrm{h} \to \gamma\gamma, \mathrm{WW}^*$$

$$\mathrm{pp} \to \mathrm{hqq} \to \mathrm{qq}\gamma\gamma, \mathrm{qq}\tau\tau, \mathrm{qqWW}^*$$

The heavier neutral Higgses:

same production/decays for H/A in general

$$\mathrm{pp} \to \mathrm{b\bar{b}} + \mathrm{H/A} \to \mathrm{b\bar{b}} + \tau\tau/\mu\mu$$

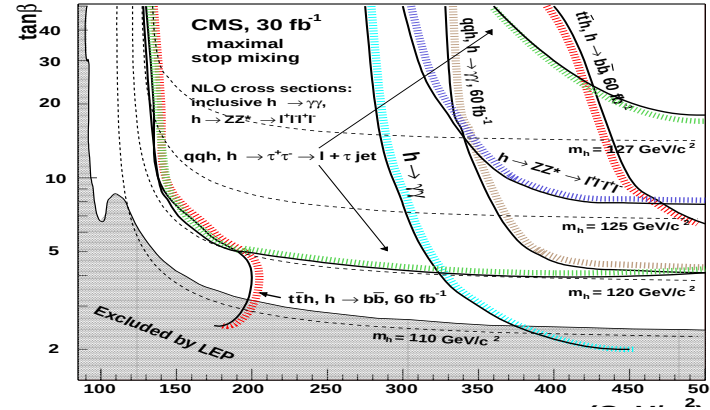
(as in SM for H in anti-decoupling regime).

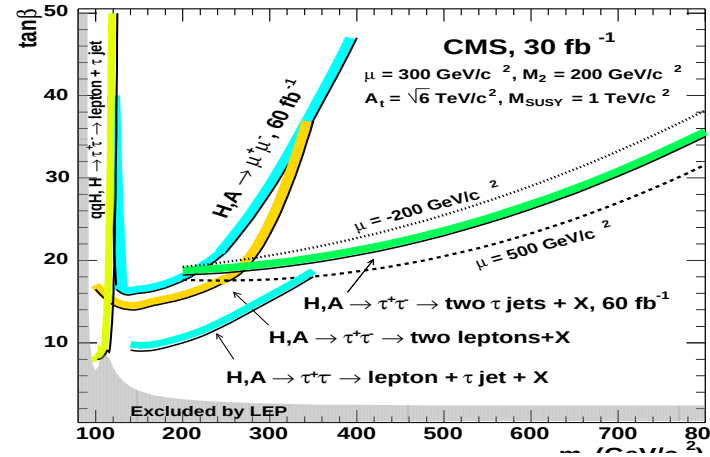
The charged Higgs:

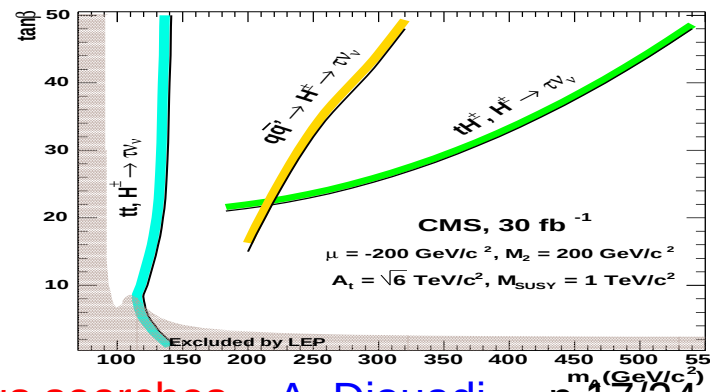
$$\mathrm{t} \to \mathrm{bH^-} \to \mathrm{b}\tau\nu \text{ for } \mathrm{M_H} \lesssim \mathrm{m_t}$$

$$\mathrm{gb} \to \mathrm{tH^+} \to \mathrm{t}\tau\nu \text{ for } \mathrm{M_H} \gtrsim \mathrm{m_t}$$

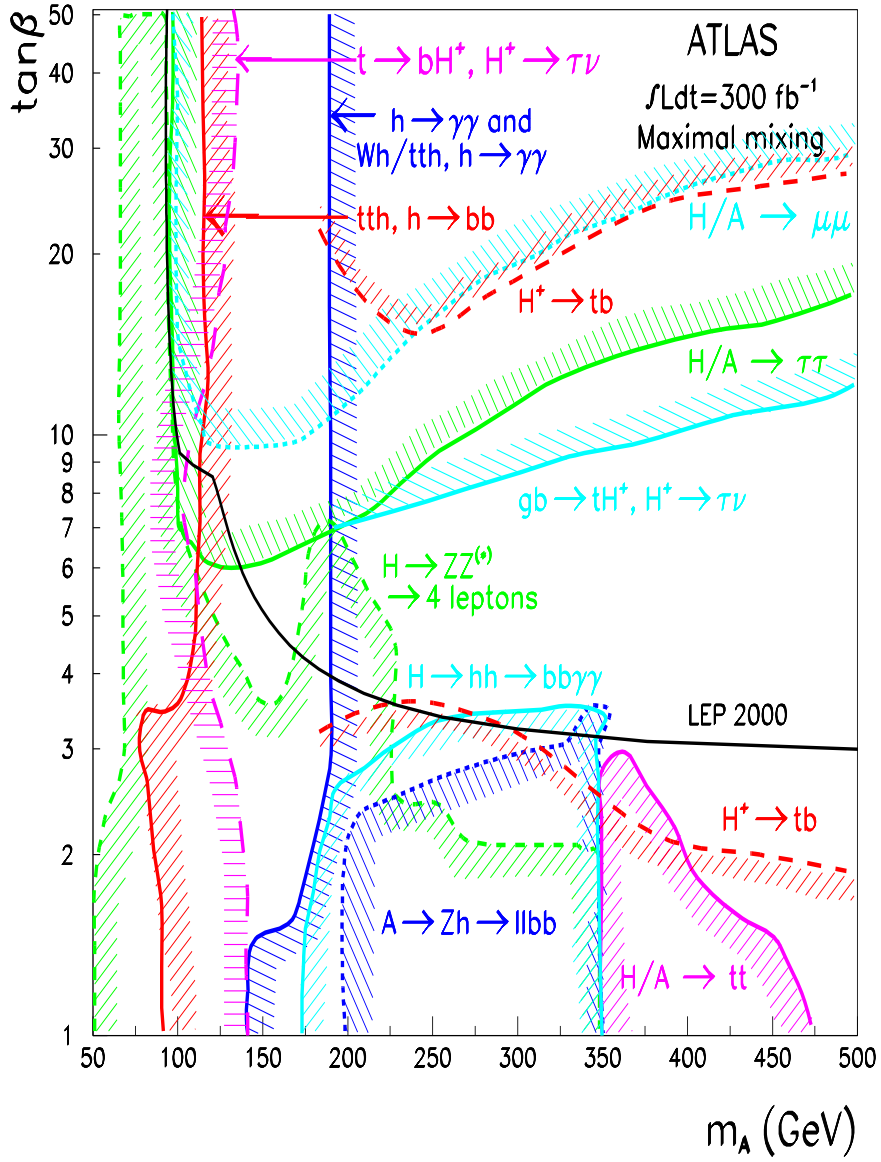
reach depends on $\mathrm{M_A}$ **and tan**β

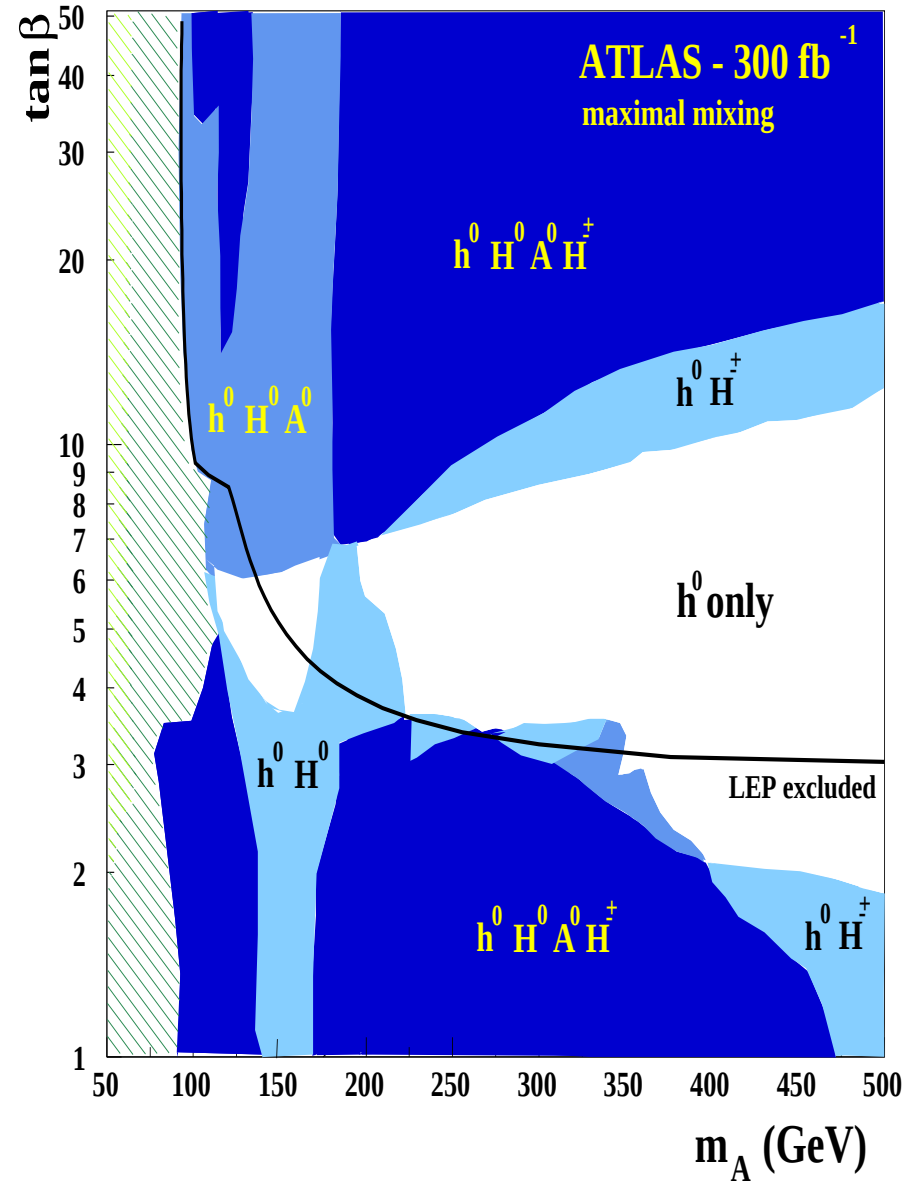






3. MSSM Higgses: detection at the LHC





4. Difficult scenarios: in the MSSM

However: life can be much more complicated even in this MSSM

- **There is the "bad luck" scenario in which only h is observed:**

– **looks SM–like at the 10% level (and $\mathrm{M_{SUSY}} \gtrsim 3$ TeV...): SM**

- **There are scenarii where searches are different from standard case:**

– **The intense coupling regime: h,H,A almost mass degenerate....**

- **SUSY particles might play an important role in production/decay:**

– **light $\tilde{\mathrm{t}}$ loops might make $\sigma(\mathrm{gg} \to \mathrm{h} \to \gamma\gamma)$ smaller than in SM.**

– **Higgses can be produced with sparticles ($\mathrm{pp} \to \tilde{\mathrm{t}}\tilde{\mathrm{t}}^*\mathrm{h}$,..).**

– **Cascade decays of SUSY particles into Higgs bosons....**

- **SUSY decays, if allowed, might alter the search strategies:**

– **$\mathrm{h} \to \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$ are still possible in non universal models...**

– **Decays of $\mathrm{A}, \mathrm{H}, \mathrm{H}^\pm$ into $\chi_\mathrm{i}^\pm, \chi_\mathrm{i}^0$ are possible but can be useful...**

Life can be even more complicated in extensions of the MSSM

4. Difficult scenarios: the CP–violating MSSM

h, H,A are not CP definite states and h_1, h_2, h_3 are CP–mixed states

The relation for the Higgs masses and couplings different from MSSM.

There is the possibility of a light Higgs which has escaped detection.

An example is the CPX scenario **(Carena et al; Ellis et al; ....)**

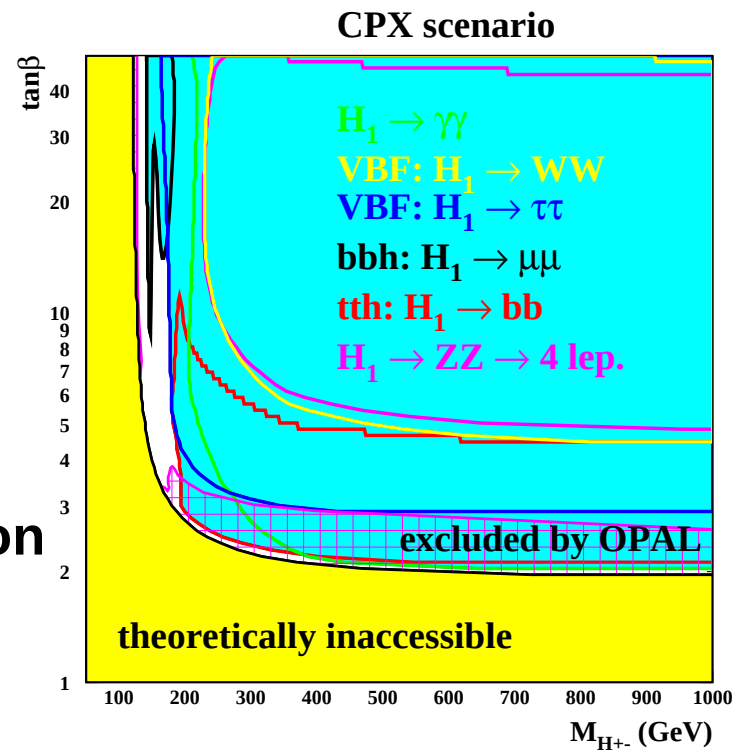
- **h_1 light but weak cplgs to W,Z**
- **$h_2 \to h_1 h_1$ decays allowed**
- **h_3 couplings to VV reduced...**

All neutral Higgses escape detection:

only (SM-like) h_2 has large cross section

$h_2 \to h_1 h_1 \to 4b, 4\tau$ unobservable.

Still, one has $t \to H^+ b \to b + hW^*$



Schumacher/ATLAS

4. Difficult scenarios: the NMSSM

In the NMSSM with $h_{1,2,3}, a_{1,2}, h^{\pm}$ one can have Higgs to Higgs decays:

then the possibility of missing all Higgs bosons is not yet ruled out!
(Ellwanger, Hugonie, Gunion, Moretti; King..., Nevzorov..., Barger...)

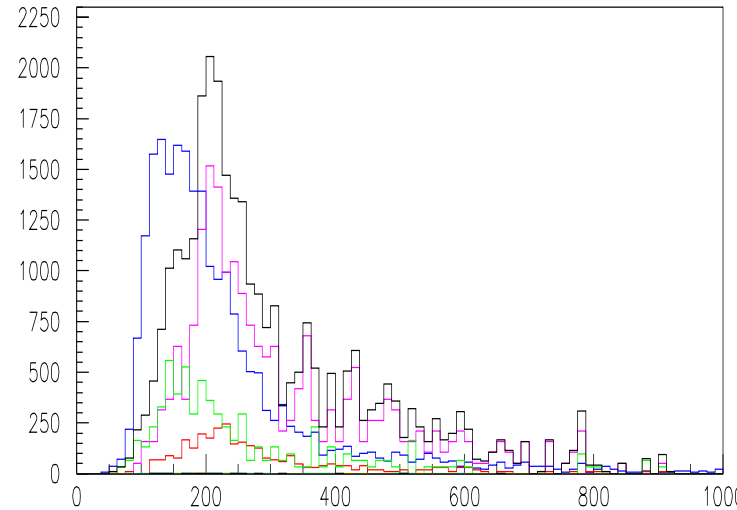
Higgs $\rightarrow$ Higgs+Higgs $\rightarrow 4b, 2b2\tau$

searches very difficult at the LHC:

$$pp \rightarrow qq \rightarrow\rightarrow W^*W^*qq \rightarrow h_1qq$$

$$\text{——} \; h_1 \rightarrow a_1a_1 \rightarrow b\bar{b}\tau\tau \times 500$$

(Ellwanger..., Baffioni+D.Zerwas)



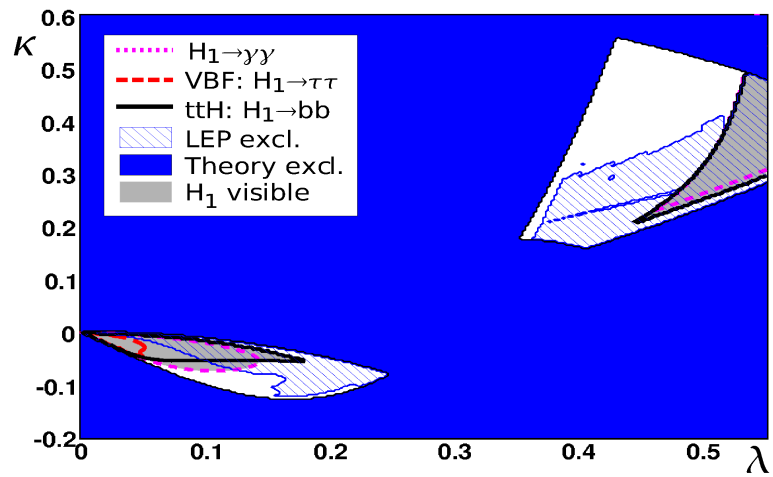
Higgs $\rightarrow$ Higgs+Higgs $\rightarrow 4\tau \rightarrow 4\ell X$

also difficult but detection possible

using VBF + all h_1 decay channels

(same for all Higgses can be done)

(Nikitenko .., Schumacher+Rottlander)



4. Difficult scenarios: invisible Higgs?

There are many scenarios in which a Higgs boson would decay invisibly

- **In MSSM, Higgs $\to \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$, etc.. as already discussed.**
- **In MSSM with $\not{R}_p$: Higgs $\to$ JJ could be dominant.** Valle ea
- **The SM when minimally extended to contain a singlet scalar field (which decouples from f/V), $H \to SS$ can be dominant** Bij, Wells ea,..
- **In large extra dimensions H mixing with graviscalars.** Gunion ea

... or very different couplings to fermions and bosons...

- **Radion mixing in warped extra dimension models: suppressed f/V couplings and Higgs decays to radions** Hewett+ Rizzo, Gunion ea
- **Presence of new quarks which alter production** Moreau ea
- **Composite light Higgs boson** Grojean ea

... Many possible surprises/difficult scenarios.....

5. Conclusions

The LHC will tell!

But: probably in 2-3 years we will find the Higgs (and maybe nothing else) after celebrating, should we declare Particle Physics closed and go home? No. We need to check that it is indeed responsible of spontaneous EWSB.

Measure its fundamental properties in the most precise way:

- **its mass and total decay width and check $\mathbf{J^{PC} = 0^{++}}$,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction),**
- **its self–couplings to reconstruct the potential $\mathbf{V_H}$ that makes EWSB.**
- **If SUSY is there, plenty of other very important things to do...**

A very ambitious and challenging program!

which is even more difficult to achieve than the Higgs discovery itself...

For this, LHC is not sufficient and a more precise machine is needed!

5. Measurements at the LHC

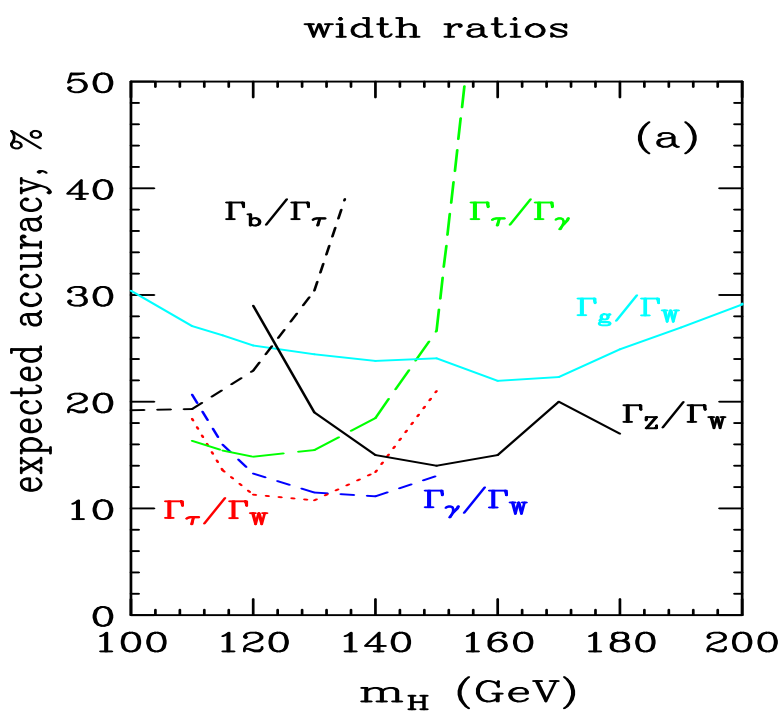
Lightest Higgs: as in SM

Higgs mass $\mathrm{h} \to \gamma\gamma, \mathrm{ZZ}^*$

Higgs couplings from $\sigma\times$ **BR**

Higgs spin+CP numbers: hard

Higgs self-couplings hopeless...



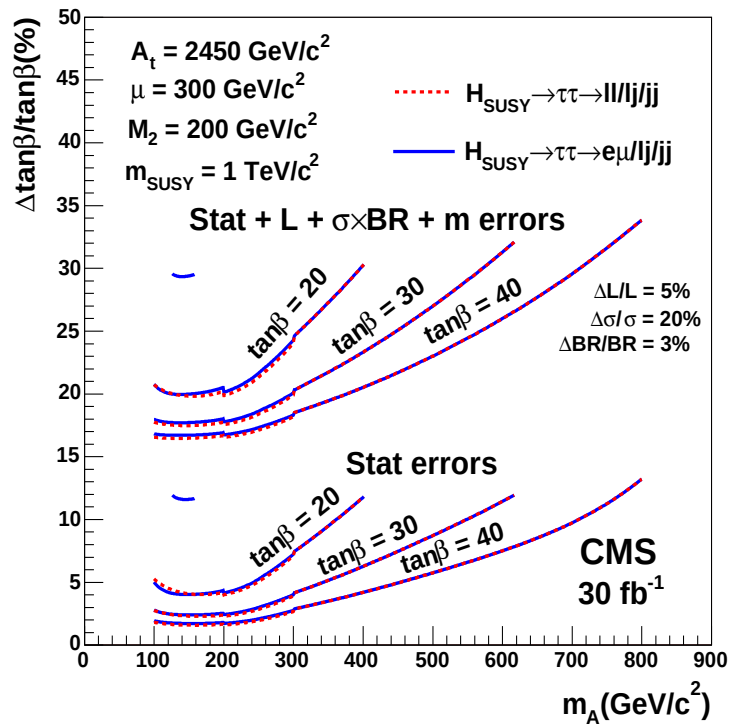
M. Dührssen et al.

The heavy Higgsses

Masses from $\mathrm{H/A} \to \mu^+\mu^-$

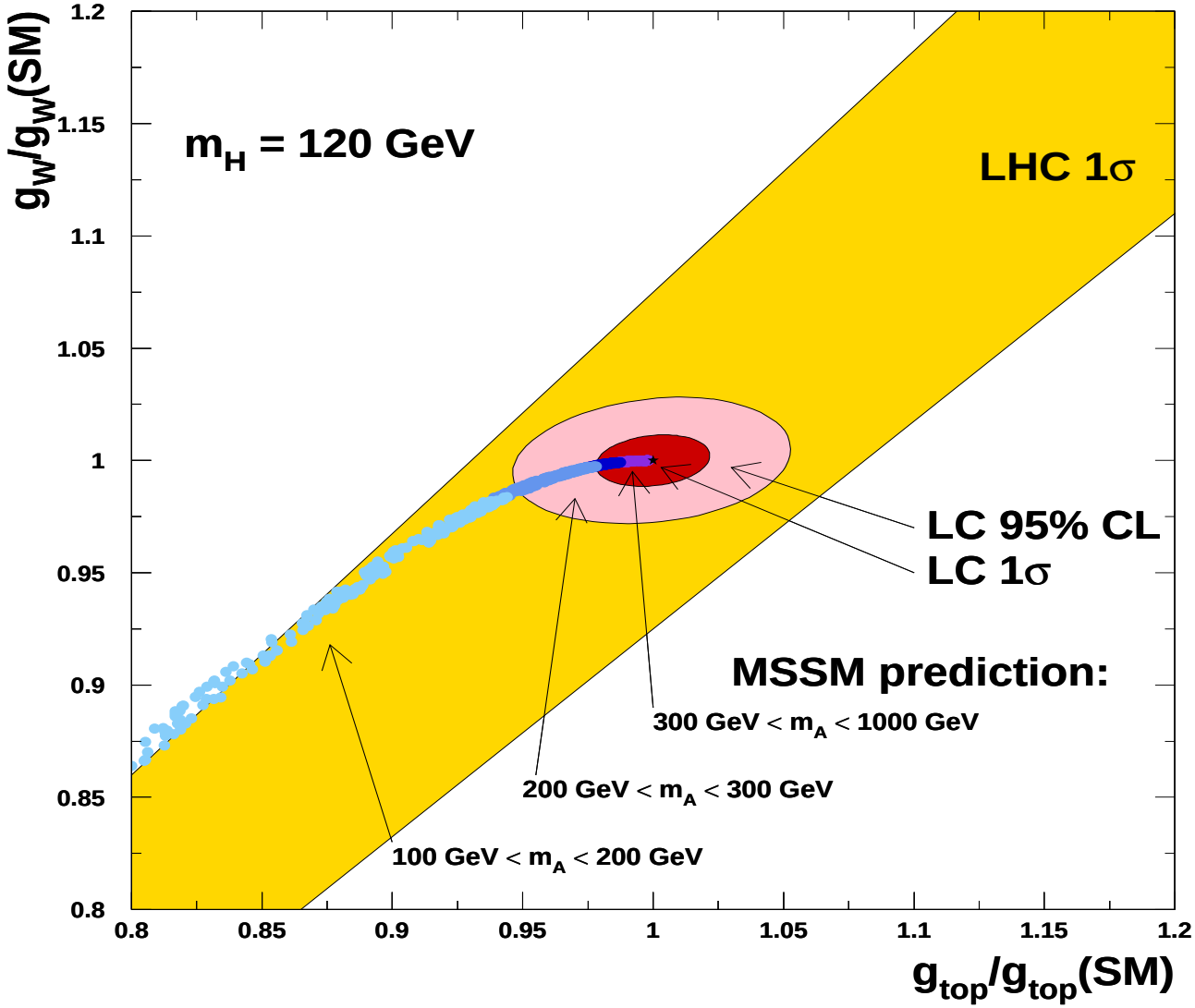
$\tan\beta$ **in** $\mathrm{pp} \to \mathrm{H/A} + \mathrm{b\bar{b}}$

H/A separation difficult



S. Nikitenko et al.

5. Why do we need the ILC?



Desch et al..