The Physics of EWSB: The Higgs in the SM and beyond

Abdelhak Djouadi

(U. Paris-Sud / CERN TH)

1. The Higgs in the Standard Model: status

2. The Higgs at the Tevatron and the LHC

3. The Higgs beyond the SM

4. The Higgs in SUSY theories

5. Conclusion

1. The Higgs in the SM: EWSB

To generate particle masses in an SU(2)$\times$U(1) gauge invariant way:

introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ **with** $\langle 0|\Phi^0|0\rangle \neq 0$

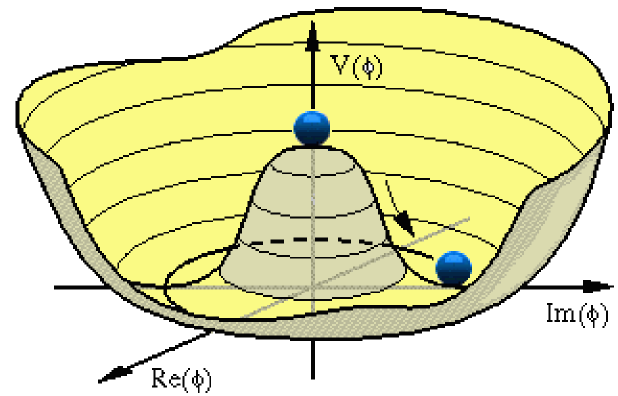
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2$$

$$v = (-\mu^2/\lambda)^{1/2} = 246 \text{ GeV}$$

$\Rightarrow$ **three d.o.f. for** $M_{W^\pm}$ **and** M_Z

For fermion masses, use <u>same</u> Φ**:**

$$\mathcal{L}_{Yuk} = -f_e(\bar{e}, \bar{\nu})_L \Phi e_R + \dots$$



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

- **The Higgs boson:** $J^{PC} = 0^{++}$ **quantum numbers.**
- **Masses and self–couplings from** V : $M_H^2 = 2\lambda v^2, g_{H^3} = 3\frac{M_H^2}{v}, \dots$
- **Higgs couplings** $\propto$ **particle masses:** $g_{Hff} = \frac{m_f}{v}, g_{HVV} = 2\frac{M_V^2}{v}$

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

1. The Higgs in the SM: constraints on M_H

Theory constraints from energy/M_H range up to which the SM is valid

- **Heavy Higgs: strong W/Z interactions**

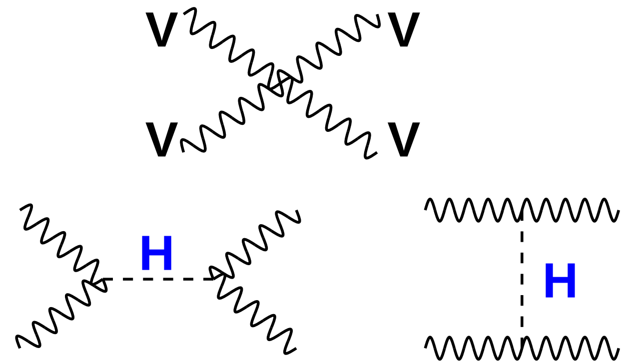
$$|A_0(VV \to VV)| \xrightarrow{s \gg M_H^2} \frac{M_H^2}{8\pi v^2} < \frac{1}{2}$$

$$\Rightarrow M_H \lesssim 710 \text{ GeV}$$

(OK with lattice: $M_H \lesssim 650$ GeV)

$$|A_0(VV \to VV)| \xrightarrow{s \ll M_H^2} \frac{s}{32\pi v^2} < \frac{1}{2}$$

$$\Rightarrow \sqrt{s} \lesssim 1.2 \text{ TeV}$$



- **Triviality and stability bounds:**

$$\lambda(Q^2) \approx \lambda(v^2) \left[1 - \frac{3}{4\pi^2}\lambda(v^2)\log\frac{Q^2}{v^2}\right]^{-1}$$

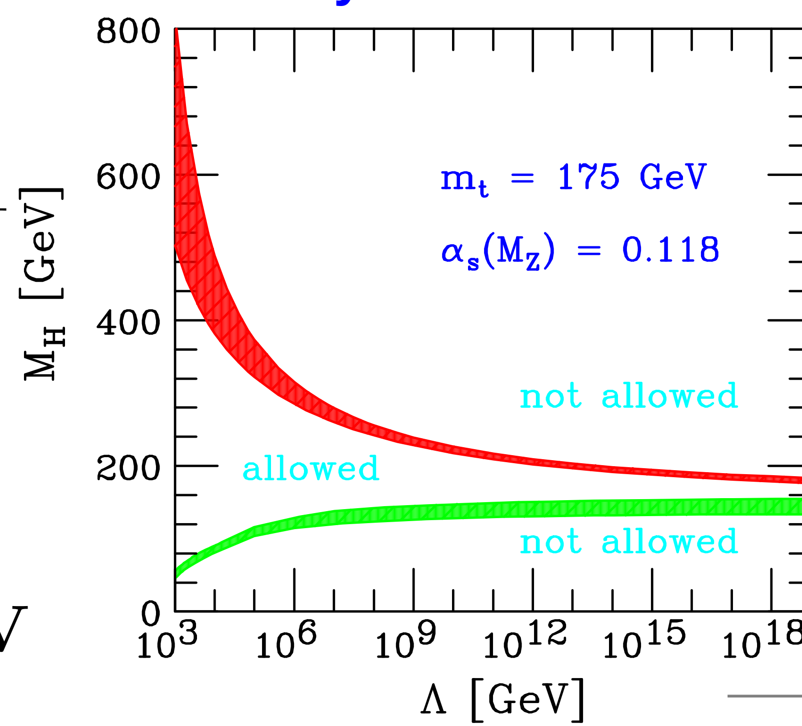
$\lambda \gg 1$ **coupling blows up (Landau pole)**

$\lambda \ll 1$ **potential unstable (no EWSB)**

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

$\Lambda \sim M_{GUT}$: $130 \lesssim M_H \lesssim 180$ GeV

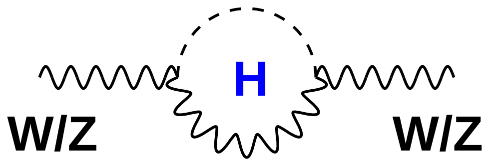
Hambye+Riesselman.



1. The Higgs in the SM: constraints on M_H

Indirect constraints from high–precision data

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

one obtains $M_H = 87^{+35}_{-26}$ GeV, or

$M_H \lesssim 157$ GeV at 95% CL

New Gfitter: $M_H \lesssim 153$ GeV@95%CL

?What top mass should be in the fit?

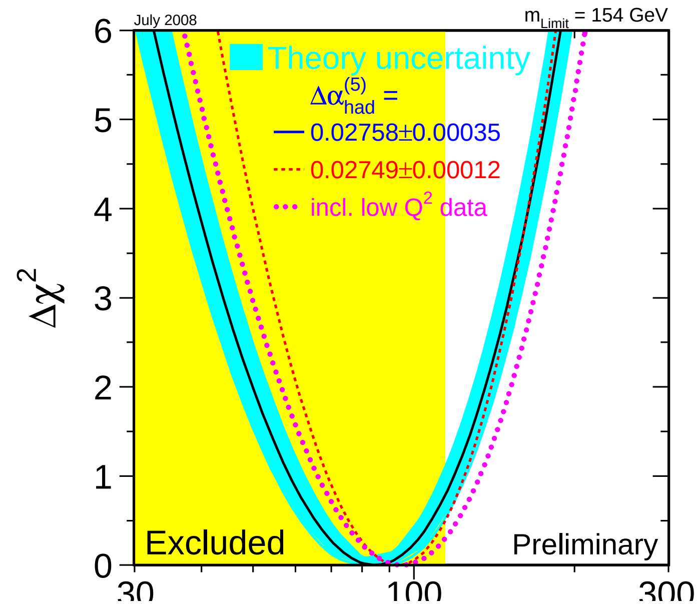
High precision data: on–shell mass

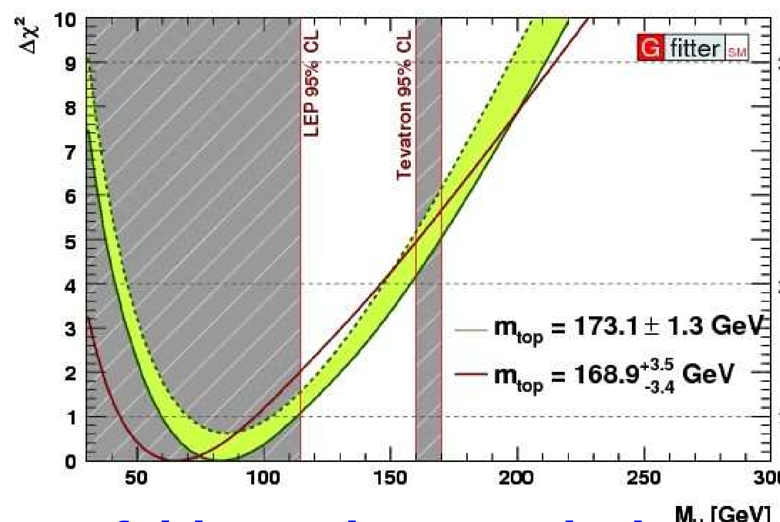
Tevatron: OS, $\overline{\rm MS}$ mass? 10 GeV diff.

$$m_t^{OS} = m_t^{\overline{\rm MS}}(\mu)\left(1 - \frac{\alpha_s}{\pi}\left[\frac{4}{3} + \log\frac{\mu^2}{m_t^2} + ..\right]\right)$$

$\overline{\rm MS}$ top mass from NNLO $\sigma(p\bar{p} \to t\bar{t})$

convert to $m_t^{\rm pole} \approx 169 \pm 3.5$ GeV





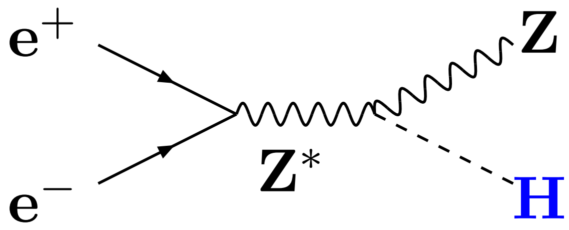
Langerfeld, Moch, Uwer (09).

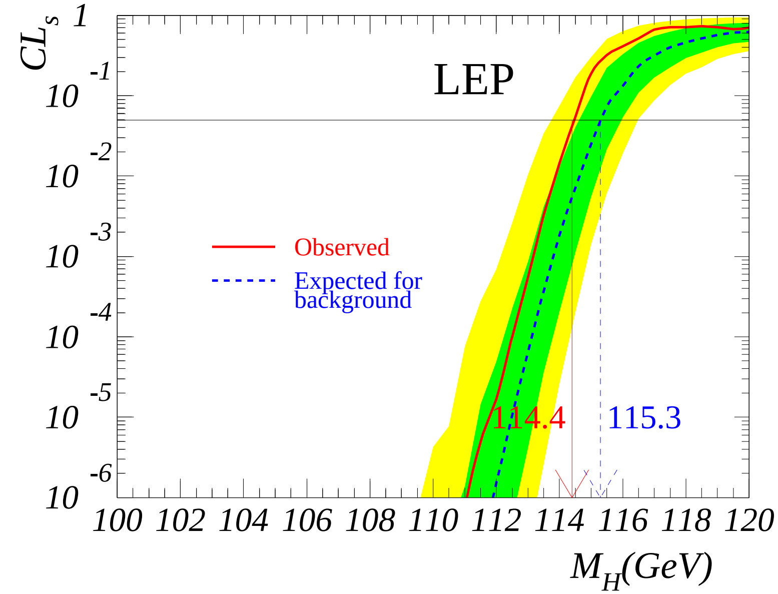
1. The Higgs in the SM: constraints on M_H

Constraints from Higgs non–observation at colliders (LEP/Tevatron).

- **Direct searches at LEP:**

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



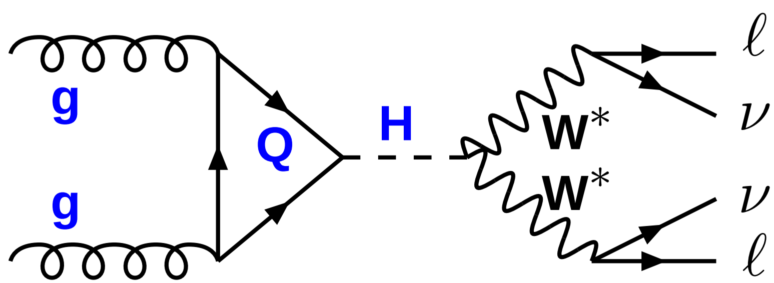


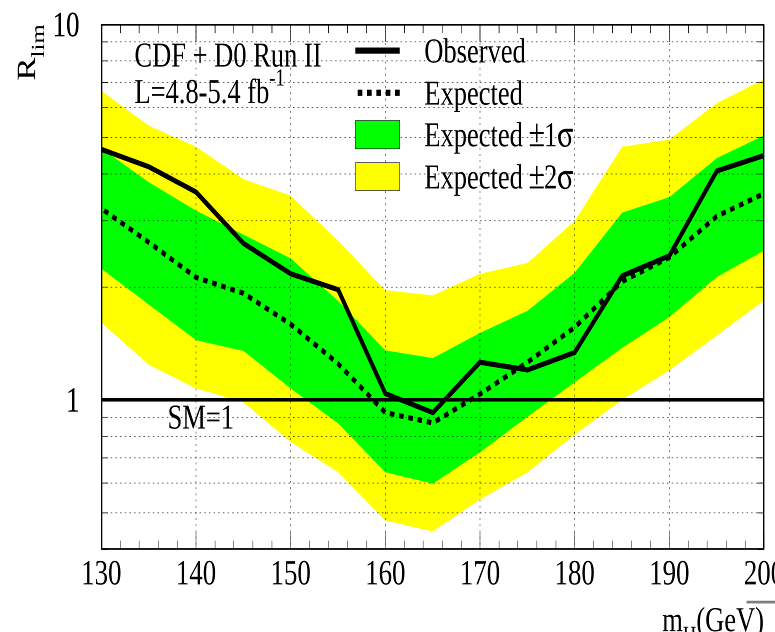
We have a limit at 95% CL:

$M_H > 114.4$ **GeV**

- **New results from the Tevatron:**

Mainly: $gg \to H \to WW \to \ell\ell\nu\nu$





exclude $M_H = 162 - 166$ **GeV**
(to be discussed in detail later).

1. The Higgs in the SM: decay modes

- **H decays into the heaviest particle available by phase space: $\mathrm{g} \propto \mathrm{m}$.**
- $\mathbf{M_H \lesssim 130\ GeV}$, $\mathrm{H \to b\bar{b}}$

– $\mathrm{H \to cc, \tau^+\tau^-, gg} = \mathcal{O}(\text{few}\ \%)$

– $\mathrm{H} \to \gamma\gamma = \mathcal{O}(0.1\%)$

- $\mathbf{M_H \gtrsim 130\ GeV}$, $\mathrm{H \to WW, ZZ}$

– below threshold decays possible

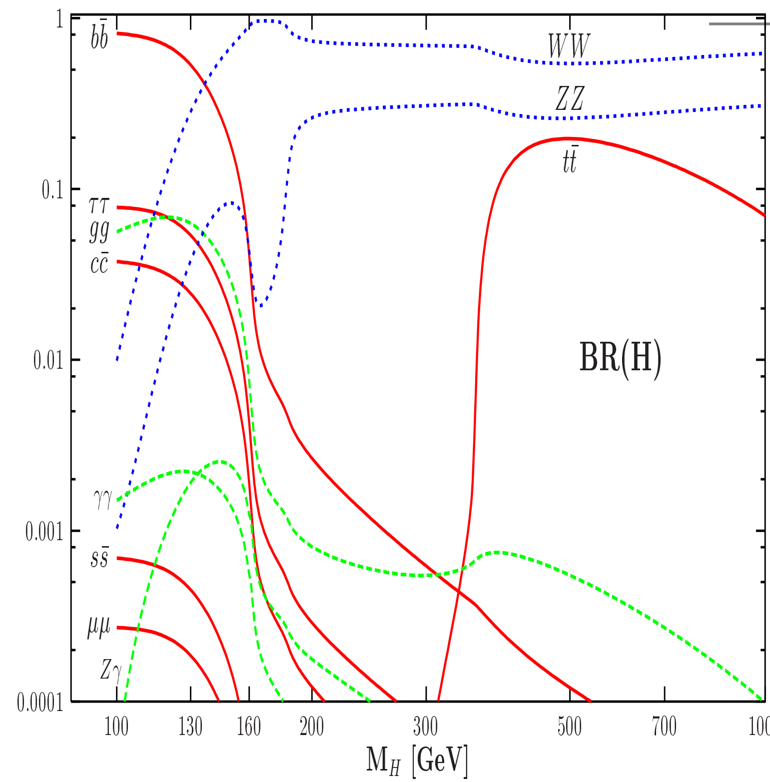
– above threshold: B(WW)=$\frac{2}{3}$, B(ZZ)=$\frac{1}{3}$

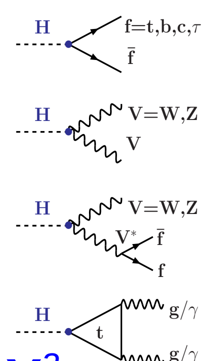
– decays into $\mathrm{t\bar{t}}$ for heavy Higgs.

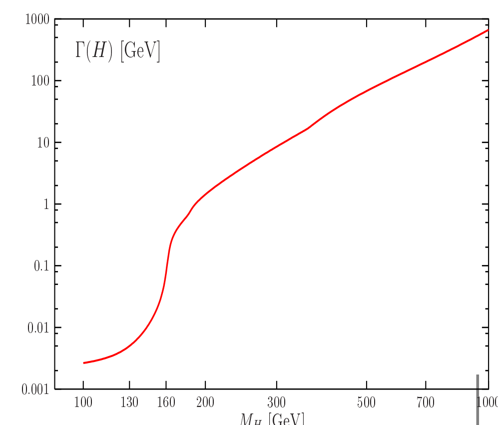
- **Total Higgs decay width:**

– very small for a light Higgs

– comparable to mass for heavy Higgs.







HDECAY[a]

[a] AD, Kalinowski, Spira (95–10). Includes all relevant higher order corretions.

2. The Higgs at Tevatron and LHC

H discovery: 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

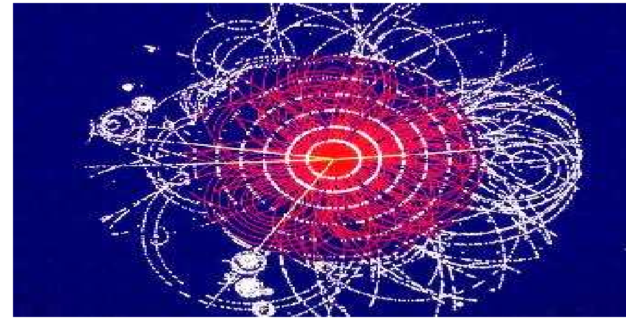
Combine different decay/production channels

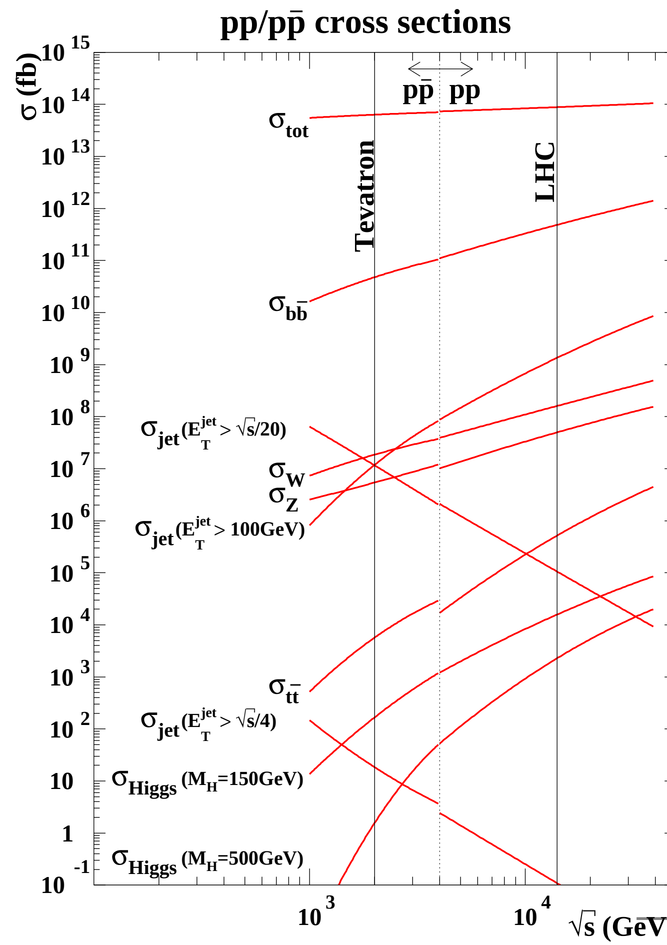
Have a precise knowledge of S and B rates.

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

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

(more than 20 years of very hard work!)





2. Higgs at Tevatron: production

• $M_H \gtrsim 150$ GeV : $gg \to H$
(with $H \to W^*W^* \to \ell\ell\nu\nu$)

LO[a] already at one loop

exact NLO[b] : $K \approx 2$ (1.7)

EFT NLO[c]: good approx.

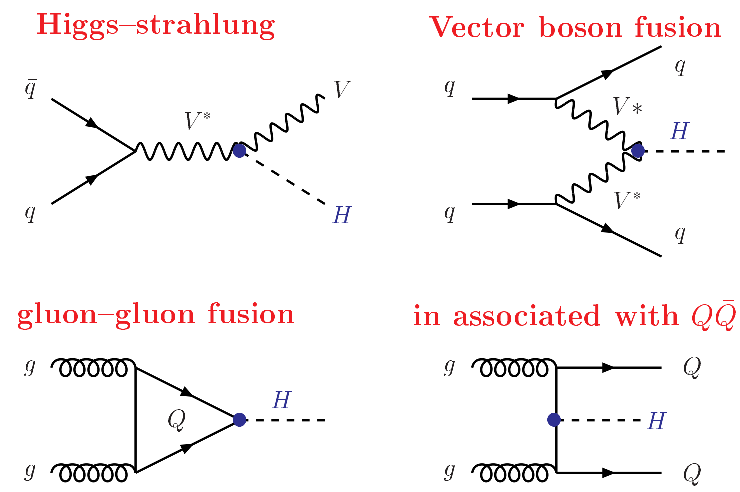
QCD: EFT NNLO[d]: $K \approx 3$ (2)

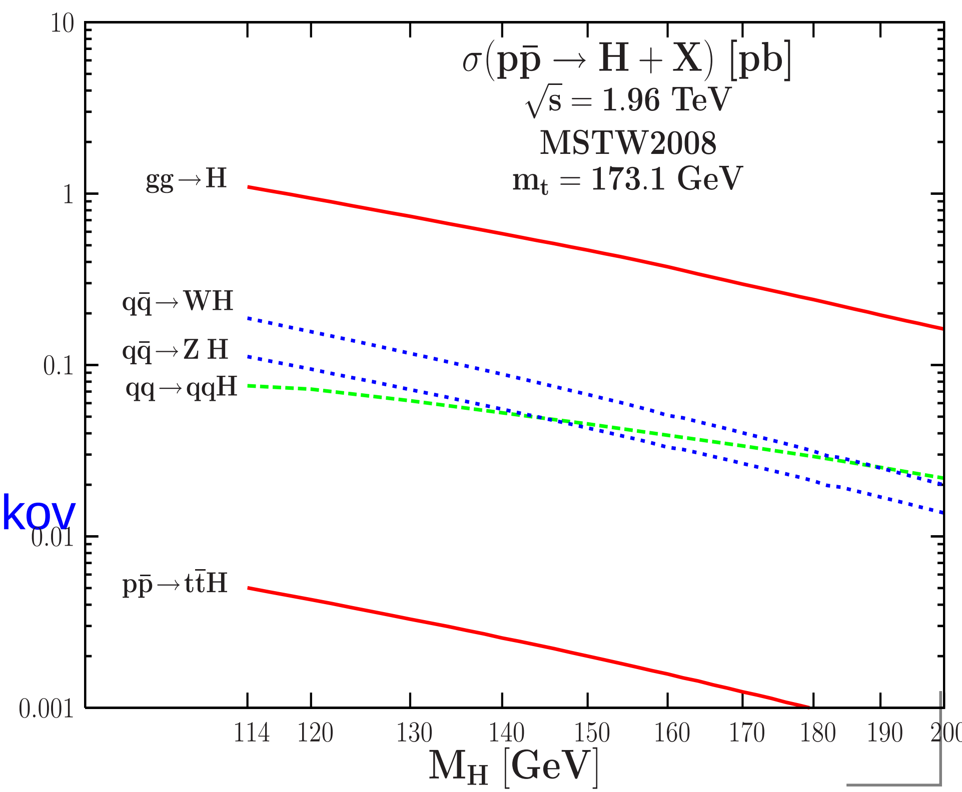
EFT NNLL[e]: $\approx +10\%$ (5%)

EFT NLO EW[f]: $\approx \pm$ very small

exact NLO EW[g]: $\approx \pm$ a few %

EFT NNLO QCD+EW[h]: a few %





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[a] Georgi et al., Ellis et al, Wilczek
[b] Spira+AD+Graudenz+Zerwas (exact)
[c] AD, Spira, Zerwas; Dawson (EFT)
[d] Harlander+Kilgore, Anastasiou+Melnikov
Ravindran+Smith+van Neerven
[e] Catani+de Florian+Grazzini+Nason
[f] AD,Gambino; Degrassi et al.
[g] Actis+Passarino+Sturm+Uccirati
[h] Anastasiou+Boughezal+Pietriello

2. Higgs at the Tevatron: production

- $\mathbf{M_H \lesssim 150\ GeV}$: $\mathbf{q\bar{q} \to HV}$

$\mathbf{q\bar{q} \to HW \to b\bar{b}\ell\nu}$

$\mathbf{q\bar{q} \to HZ \to b\bar{b}\ell\ell, b\bar{b}\nu\bar{\nu}}$

$\mathbf{q\bar{q} \to HW \to \ell\ell\ell\nu\nu\nu}$

LO[a]: $\equiv \sigma(\mathrm{V}^*) \times \mathrm{BR}(\mathrm{V}^* \to \mathrm{VH})$

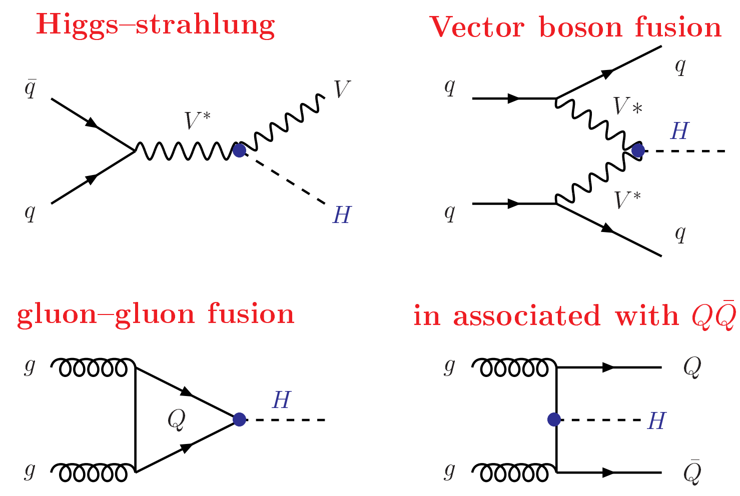
exact NLO QCD[b] : $\mathrm{K} \approx$**1.4**

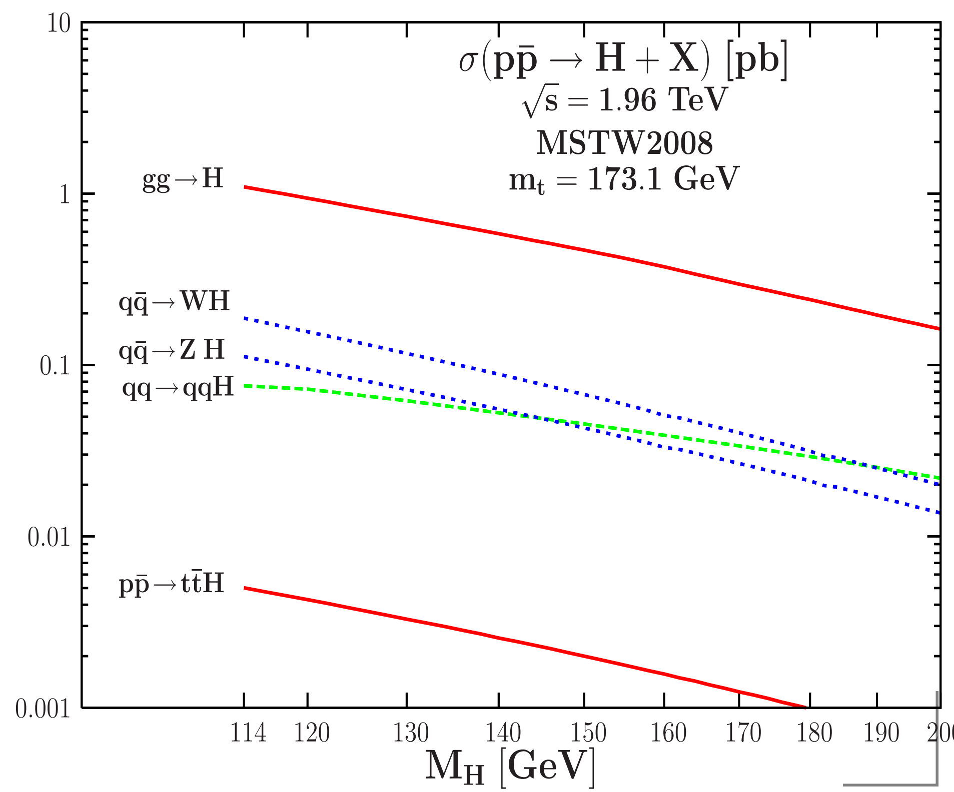
exact NNLO QCD[c]: $\mathrm{K} \approx$**1.5**

exact NLO EW[d] :$\approx -$**5%**

In practice combine ggH+HZ/HW

- $\mathbf{p\bar{p} \to Hqq}$: **bkg. too high.**
- $\mathbf{p\bar{p} \to Ht\bar{t}}$: **rates too low.**





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[a] Glashow, Nanopoulos, Yildiz
[b] Altarelli et al; Han, Willenbrock
[c] Hamberg+van Neerven+Matsuura; Brein+AD+Harlander
[d] Ciccolini+Dittmaier+Krämer

2. Higgs at the Tevatron: $gg \to H$

- **K factors very large:**

good: Tevatron sensitive to H_{SM}!
bad: perturbation theory in danger
uggly: HO corrections important...

- **Analysis of theory errors on σ:**

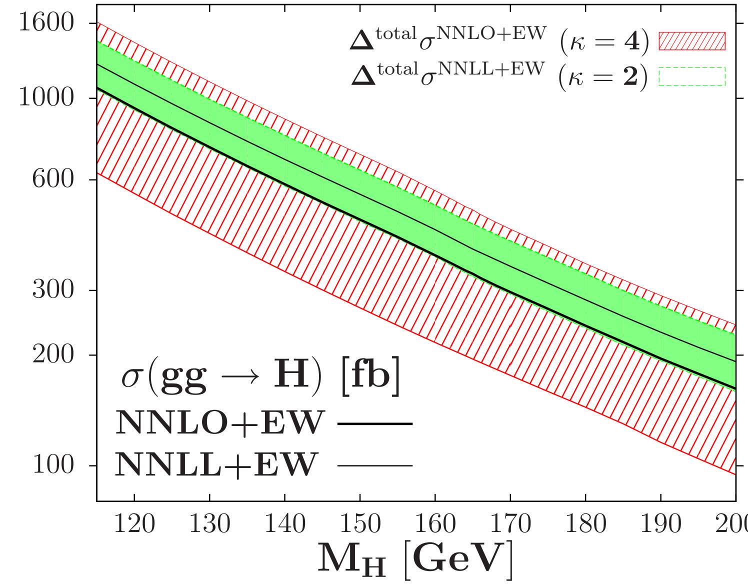
– from scale: $\frac{M_H}{3} \leq \mu_{F/R} \leq 3M_H$
very important (HO large) $\approx$ 20%
– PDFs: small within given param.
but # param. large spread $\approx$20%
– Difference due to $\Delta^{exp+th}\alpha_s$:
$\alpha_s(M_Z^2)$=0.1171$\pm$0.0034$\pm$0.003
– Use of EFT for σ^{NNLO}: $\approx$5%

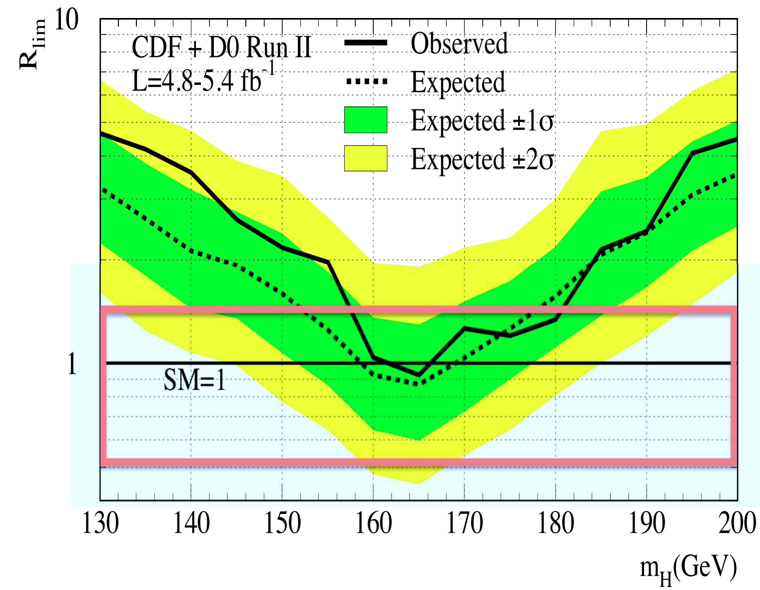
- **Combine all theory errors:**

– PDFs on σ^{max}_{min} + EFT $\approx$40%
– CDF/D0 assign only 10% error

- **Same for HV: $\approx$10% error**

Baglio+AD (2010)





CDF/D0 exclusion range M_H=162–166 GeV needs to be reconsidered.

2. Higgs at the LHC: the case of the ℓHC

ℓ**HC:** $\sqrt{s}=7$ TeV, $\int\mathcal{L}=1\ \mathrm{fb}^{-1}$

Same production as at Tevatron:

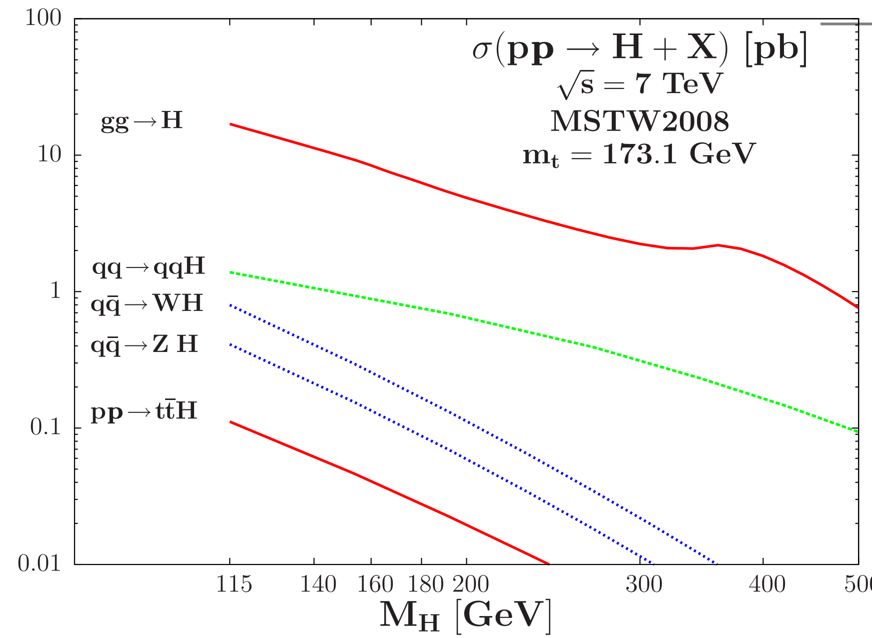
– rates $\approx$ 10 times higher

– much larger backgrounds

– much lower luminosity: $1\ \mathrm{fb}^{-1}$

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

($\approx$ 200 of Higgs signal events)



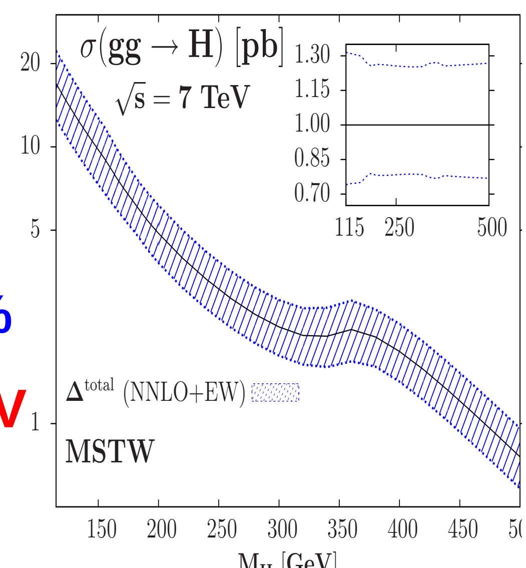
Compared to the Tevatron case:

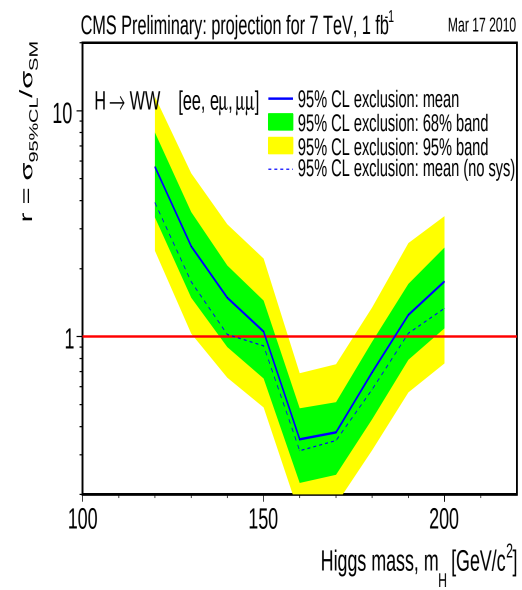
Baglio+AD

- **Smaller HO: $K_{NNLO}=2,5$**
- **Scale: κ=2 enough $\Rightarrow$ 15%**
- **PDF errors smaller, $\approx$10%**
- **Again 5% error from EFT**

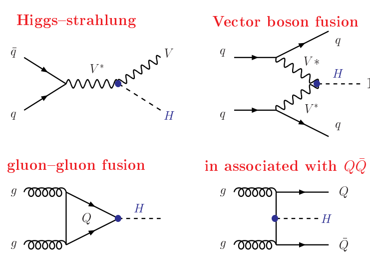
Combined uncertainty $\approx \pm$30%

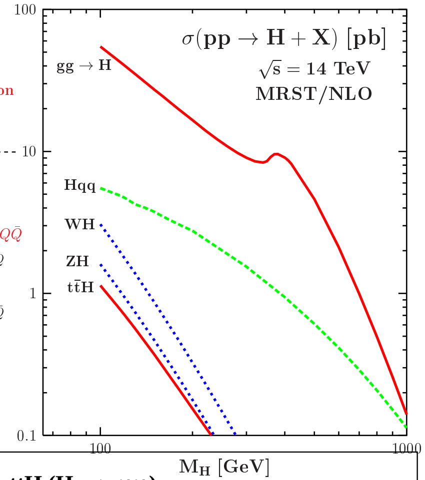
excludes $M_H \approx 150-190$ GeV

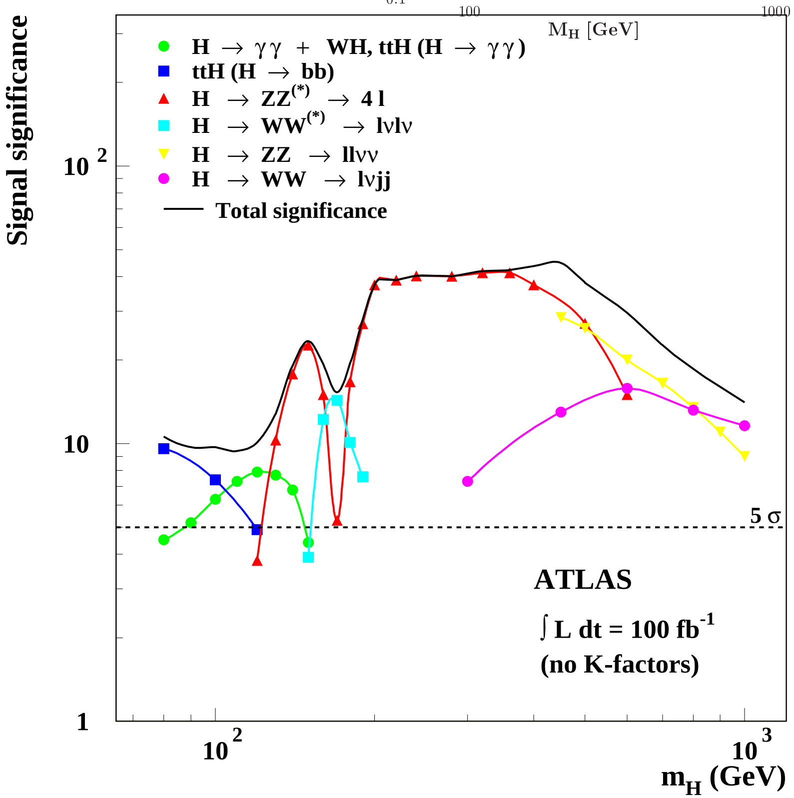




2. SM Higgs at the (full) LHC







LHC: $\sqrt{s}=7+7=14$ TeV $\Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \sim 5$ TeV
$\mathcal{L} \sim 10\ {\rm fb}^{-1}$ first years and $100\ {\rm fb}^{-1}$ later

gluon–gluon fusion:

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

$gg \to H \to \gamma\gamma$ (below $M_H \approx$ 150 GeV)

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

$gg \to H \to WW \to \ell\nu\ell\nu$ (130–200 GeV

$H \to ZZ, WW \to jj + \ell$ (above 500 GeV

Vector boson fusion:

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

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

Association with top pairs:

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

Association with W,Z:

jet substructure; measurements?

Only question: when?

3. Beyond the SM

The SM has many attractive theoretical/experimental features:

- **Based on gauge principle, unitary, perturbative, renormalisable** $\cdots$
- **Once** M_H **fixed: everything is predictible with great accuracy.**
- **And has passed all experimental tests up to now.**

But the model has too many shortcomings:

- **Too many free parameters (19!) in the model, put by hand...**
- **No satisfactory explanation for** $\mu^2 < 0$ **(put ad hoc).**
- **Does not include the fourth fundamental force, gravity, ..**
- **Does not say anything about the masses of the neutrinos.**
- **No real unification of the three gauge interactions.**
- **Does not explain the baryon asymmetry in the universe.**
- **There is no stable, weak, massive particle for dark matter.**

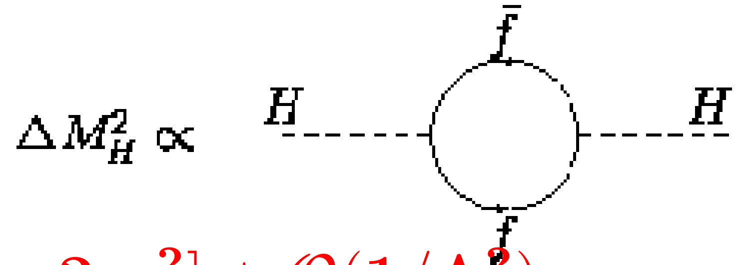
And above all that, there is the hierarchy or naturalness problem.

3. BSM: the hierarchy problem

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

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

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



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

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

This is the hierarchy problem...

But we want a light Higgs ($M_H \lesssim 1$ TeV) for unitarity etc... reasons.
We need thus to make: $M_H^2|^{\rm Physical} = M_H^2|^0 + \Delta M_H^2$+ countreterm
And adjust this counterterm with a precision of 10^{-30} (30 digits)

This fine-tunning would be very unnatural...

Adding the gauge boson and Higgs loops does not help:

$$\Rightarrow \Delta M_H^2 \propto [3(M_W^2 + M_Z^2 + M_H^2)/4 - \sum m_f^2](\Lambda^2/M_W^2)$$

Unless, $M_H \sim 200$ is very finely adjusted (with some problems).

However: does not work at two–loop level or at higher orders....

3. BSM: the hierarchy problem

- **“Easiest” solution: no fundamental scalar particle in the game.**

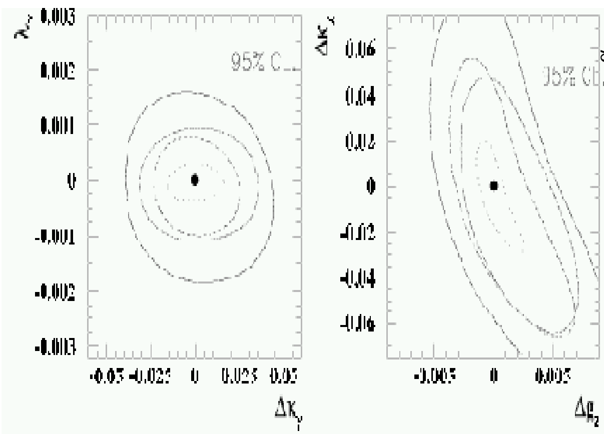
– Technicolor theories: QCD–like theories with f_π at the TeV scale.

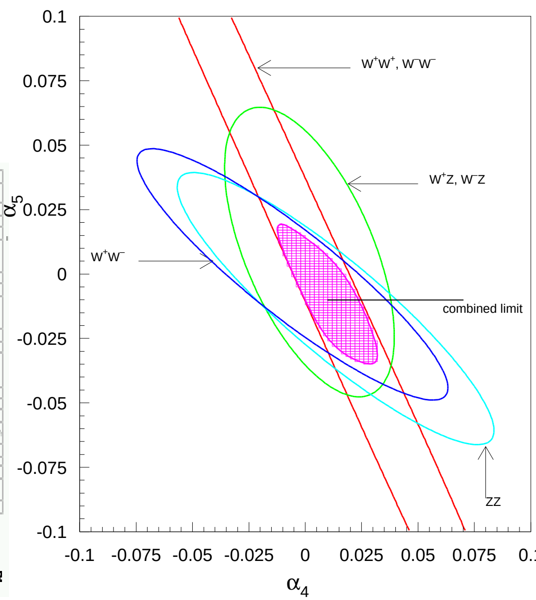
– Extra dimension models: EWSB via choice of boundary conditions.

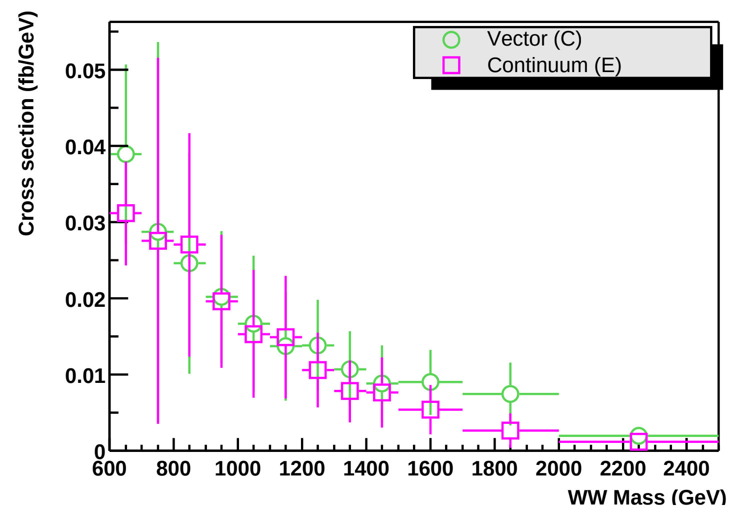
If no Higgs to unitarise the theory: strongly interacting W/Z bosons

Deviations in V^3 and V^4 cplgs: Resonances at the TeV scale

$$\mathrm{pp} \to \mathrm{V}, \mathrm{VV}, \mathrm{VVV}$$
$$\mathrm{pp} \to \mathrm{V^*V^*} \to \mathrm{VV}$$





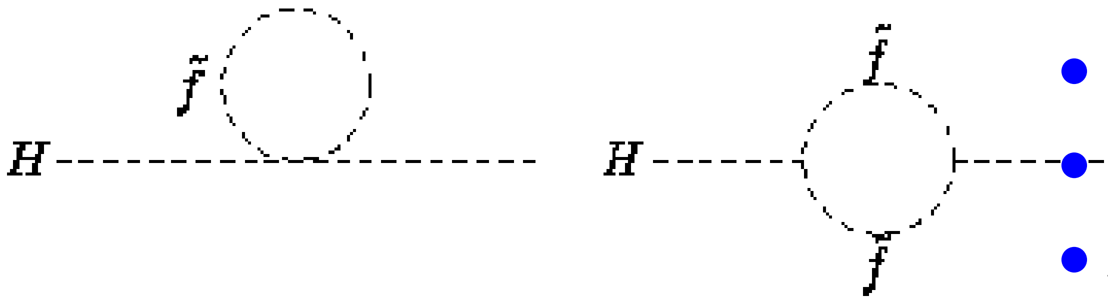


- **Higgs as a composite object: a $\mathrm{t\bar{t}}$ condensate...**
- **Bring $\Lambda_{\rm NP}$ down to 1 TeV: extra dimensions, etc...**
- **A protecting symmetry: the SUSY path.**

3. BSM: the SUSY path

Imagine now that you have additional scalar particles:

Add the contributions of scalar fermion partner loops to ΔM_H^2



- $\lambda_f^2 = -\lambda_S$.
- $N_S = N_f$ **(nb: 2 scalars).**
- $m_1 = m_2 = m_S$.
- **Add f+S contributions.**

$$\Delta M_H^2|^{\rm tot} = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right]$$

The quadratic divergences have disappeared in the sum!! (same job for W/Z/H). Logarithmic divergence still there, but contribution small.

No divergences at all if in addition $m_S = m_f$ (exact SUSY)!

$\Rightarrow$ Symmetry fermions–scalars $\rightarrow$ no divergence in Λ^2

“Supersymmetry” no divergences at all: M_H is protected!

Note that if $M_S \gg 1$ TeV the fine tunning problem is back!!!

3. BSM: the SUSY path

SUSY: symmetry relating fermions s=$\frac{1}{2}$ and bosons s=0,1

$$\mathcal{Q}|\mathrm{fermion}>=|\mathrm{boson}>\ ,\ \ \mathcal{Q}|\mathrm{boson}>=|\mathrm{fermion}>$$

is the most attractive extension of SM also for other reasons

- **Links internal and space–time symmetries: larger for S matrix..**
- **If SUSY is gauged $\Rightarrow \mathrm{s}=\frac{3}{2},2 \Rightarrow$ link with 4th force, gravity...**
- **Naturally present in Superstrings (theory of everything?).**

In the MSSM with minimal group/particles/interactions+soft–SUSY breakin

- **The spectrum of superparticles fixes unification of couplings and $\not{P}$.**
- **Possibility of unifying the fermion Yukawa couplings at $\mathrm{M_{GUT}}$.**
- **SUSY SO(10): extra space for a Majorana neutrino, see–saw $\rightarrow m_\nu$.**
- **Heavy neutrinos trigger baryogenesis via leptogenesis.**
- **The LSP can have the right relic density and solve the DM problem.**
- **Radiative breaking of the EW symmetry: $\mu^2>0$ at $\mathrm{M_{GUT}}, <0$ at $\mathrm{M_{EW}}$**

$\cdots$ **and all this at once** $\cdots$ **But we need $\mathrm{M_{SUSY}} \sim \mathcal{O}$(TeV)!**

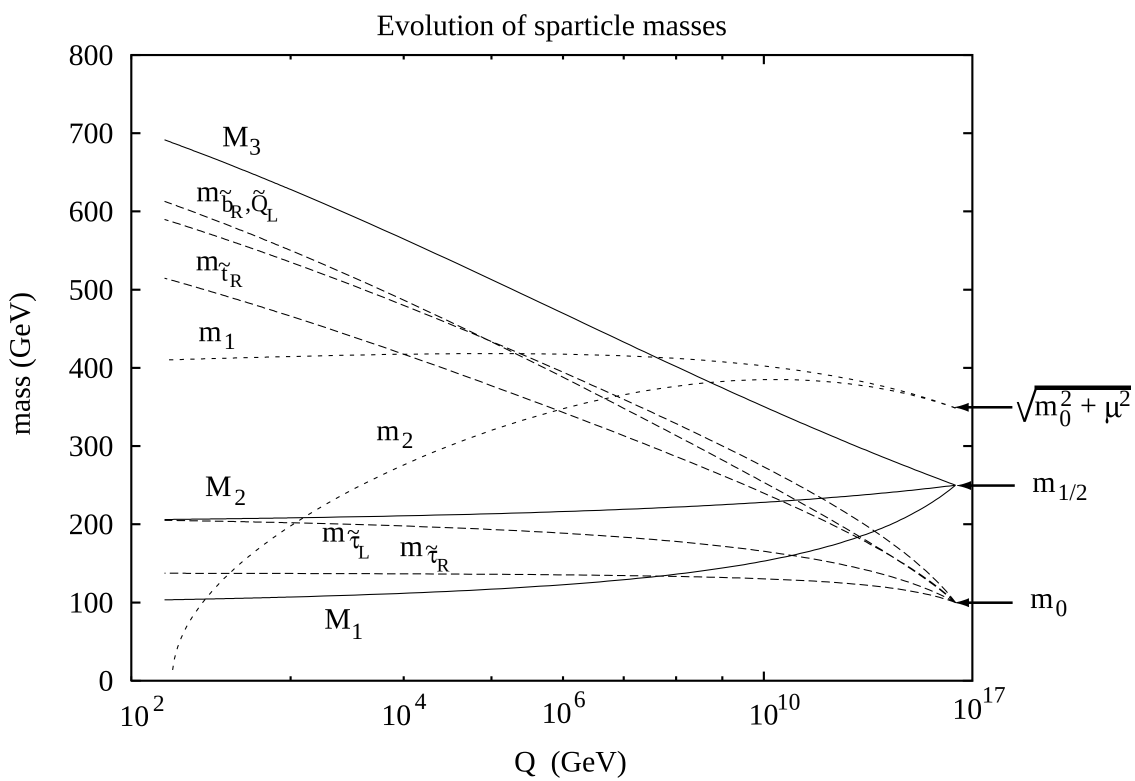
otherwise, back to the hierarchy, dark matter and unification problems $\cdots$

3. BSM: the SUSY path

Only 4.5 param: $\tan\beta\ ,\ \mathbf{m_{1/2}}\ ,\ \mathbf{m_0}\ ,\ \mathbf{A_0}\ ,\ \ \mathrm{sign}(\mu)$

All soft breaking parameters at M_S are obtained through RGEs.

With $\mathrm{M_{GUT}} \sim \mathbf{2 \cdot 10^{16}}$ GeV and $\mathrm{M_{SUSY}} \sim \sqrt{\mathbf{m_{\tilde{t}_L} m_{\tilde{t}_R}}}$:



Radiative EWSB occurs since $\mathrm{M^2_{H_2}} < \mathbf{0}$ at scale $\mathrm{M_Z}$ $(\mathbf{t}/\tilde{\mathbf{t}}\ \mathbf{loops})$

$\Rightarrow$ EWSB more natural in MSSM ($\mu^2 < 0$ from RGEs) than in SM!

4. The Higgs sector in the MSSM

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

- to cancel the chiral anomalies introduced by the new $\tilde{h}$ field,
- give separately masses to d and u fermions in SUSY invariant way.

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

Only two free parameters at the tree level: $\tan\beta, M_A$; others are:

$$M^2_{h,H} = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$M^2_{H^\pm} = M_A^2 + M_W^2 \quad ; \quad \tan 2\alpha = \tan 2\beta \, \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}$$

We have important constraint on the MSSM Higgs boson masses:

$$M_h \leq \min(M_A, M_Z)\cdot|\cos 2\beta| \leq M_Z, \; M_{H^\pm} > M_W, M_H > M_A \ldots$$

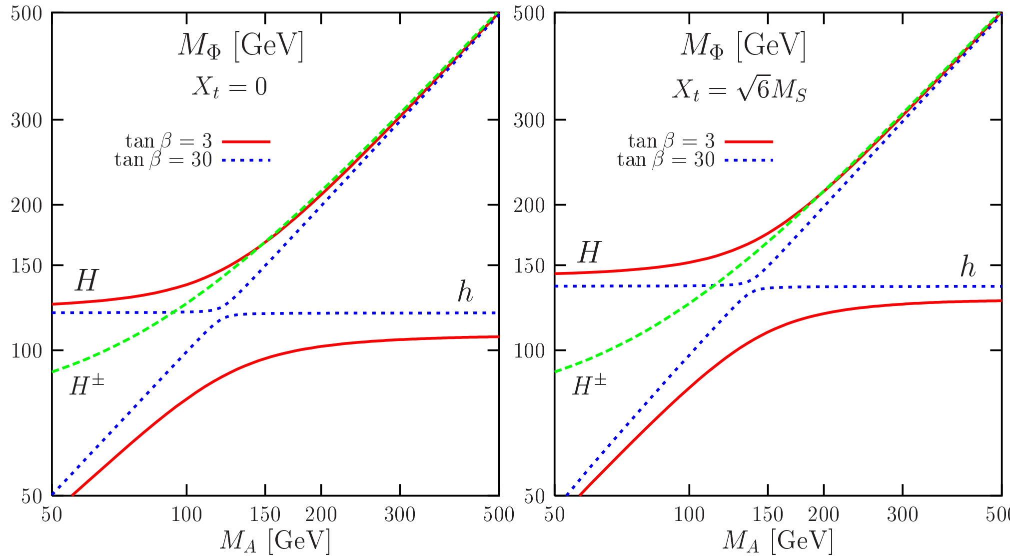
Radiative corrections important in MSSM Higgs sector; dominant one:

$$\Delta M_h^2 = \frac{3g^2}{2\pi^2}\frac{m_t^4}{M_W^2}\log\frac{m_{\tilde{t}}^2}{m_t^2} \text{ large: } \xrightarrow{M_h^{max} \to M_Z + 40\,\text{GeV}} \gtrsim 115\,\text{GeV}$$

$M_A \gg M_Z$: decoupling regime, all Higgses heavy except for h.

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

4. 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: $114 \lesssim \mathrm{M_H} \lesssim 130\,\mathrm{GeV}$ or $\mathrm{M_h}, \mathrm{M_A} \lesssim \mathrm{M_Z}$

4. 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**

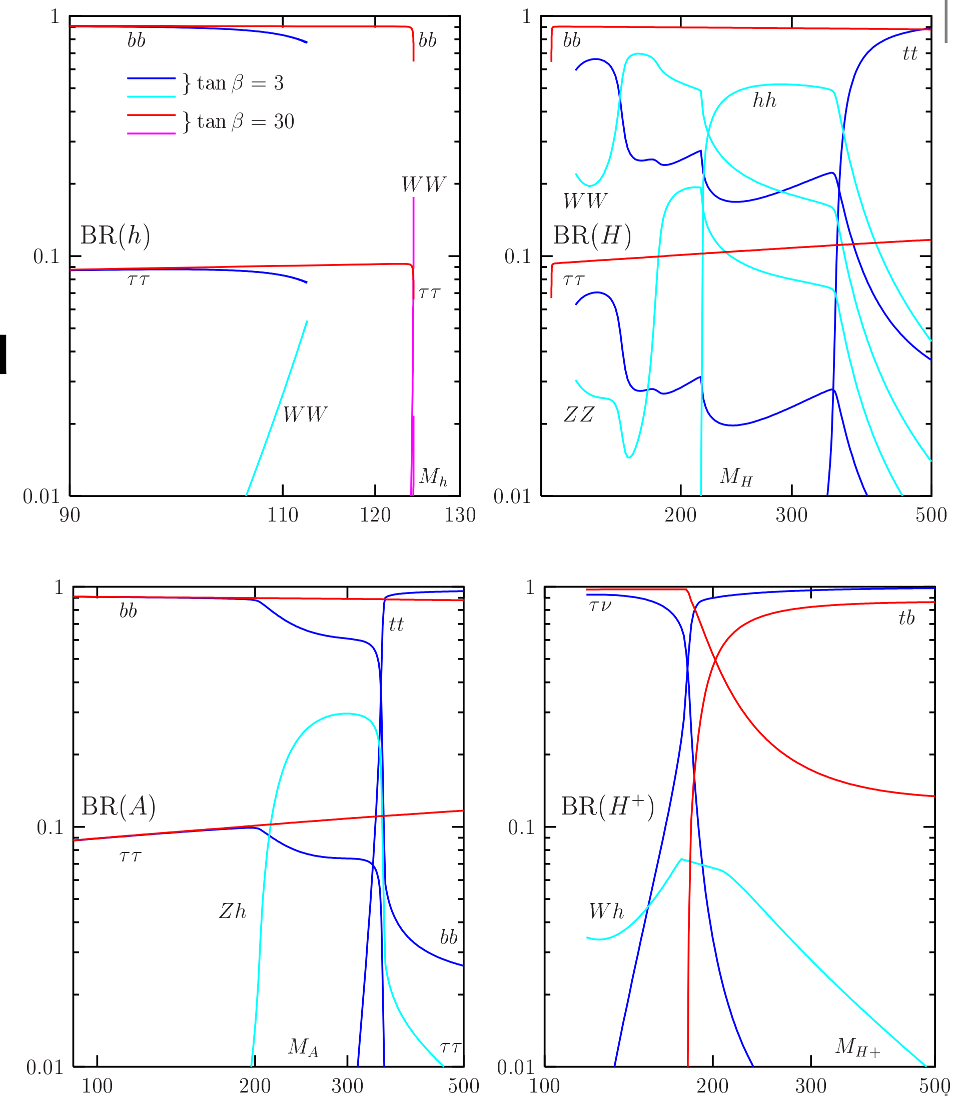
$(\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ decays suppressed).

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

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

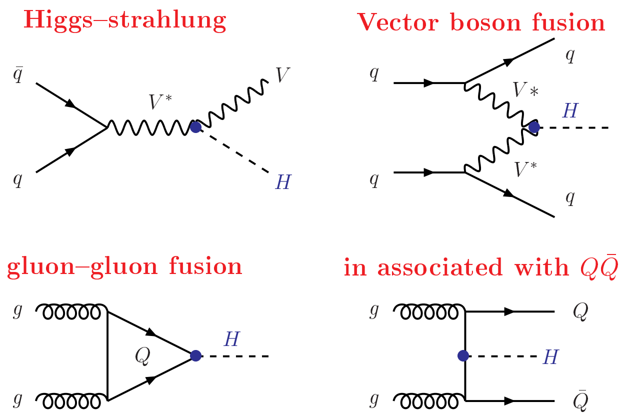
Possible new effects from SUSY

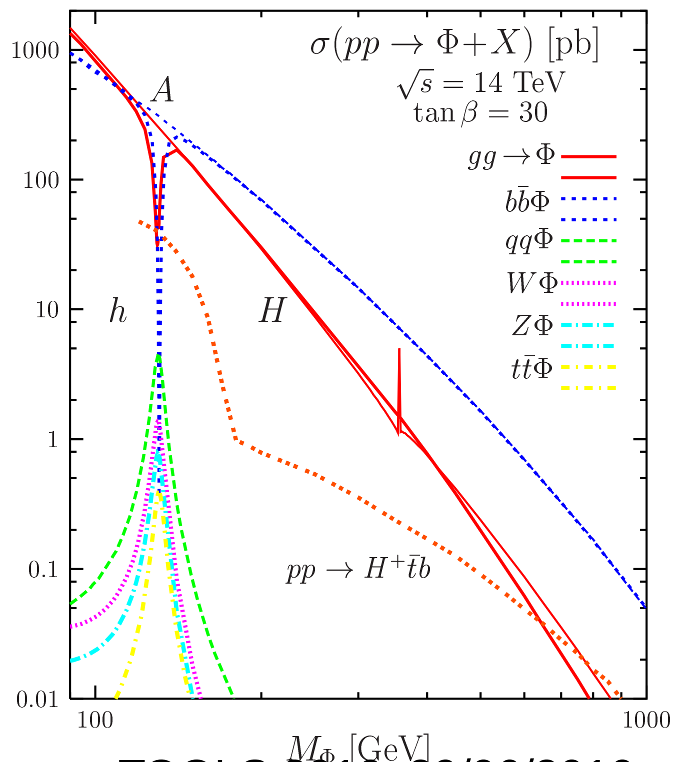
Note: total decay widths small....



4. 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**
- $\sigma(\mathrm{h}) + \sigma(\mathrm{H}) = \sigma(\mathrm{H_{SM}})$
- **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 $pp \to t\bar{b}H^-$**

4. MSSM Higgses: detection at the LHC

The lighter Higgs boson:

same as in the SM for $M_h \lesssim 140$ GeV

(in particular in the decoupling regime)

$gg \to h \to \gamma\gamma, WW^*$

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

The heavier neutral Higgses:

same production/decays for H/A in general

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

reach depends on M_A and tanβ

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

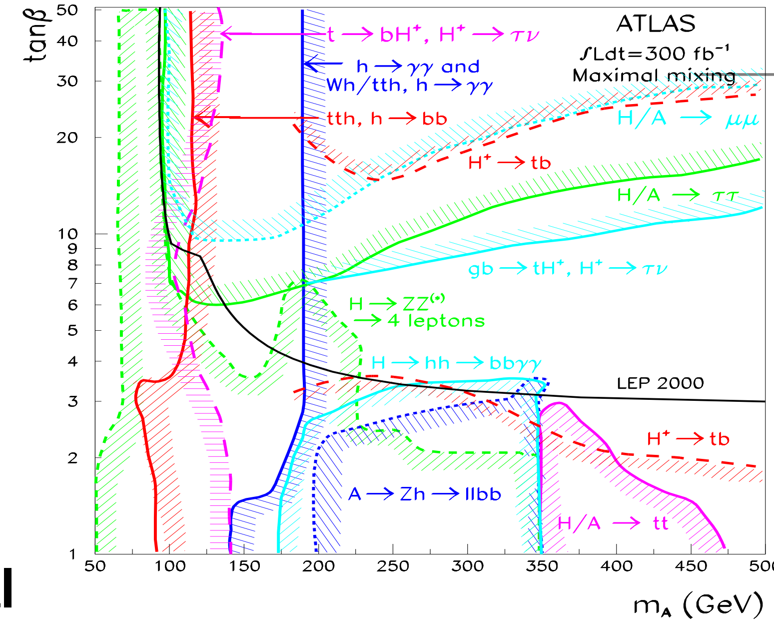
The charged Higgs:

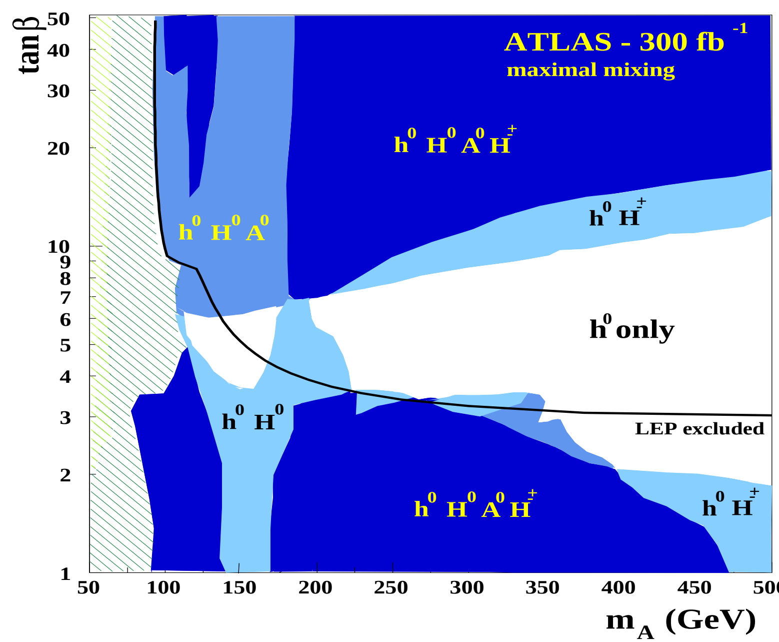
$t \to bH^- \to b\tau\nu$ for $M_H \lesssim m_t$

$gb \to tH^+ \to t\tau\nu$ for $M_H \gtrsim m_t$

reach depends on M_A and tanβ

but at least one Higgs to be found!





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 $M_{SUSY} \gtrsim 3$ 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 $\tilde{t}$ loops might make $\sigma(gg \to h \to \gamma\gamma)$ smaller than in SM.

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

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

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

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

– Decays of $A, H, H^\pm$ into $\chi_i^\pm, \chi_i^0$ are possible but can be useful...

Life can be even more complicated in extensions of the MSSM

4. The Higgs sector beyond the MSSM

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

We can allow for some amount of CP–violation in eg. M_i, μ and 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: h_1, h_2, 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 $\mathcal{O}(M_Z)$; a priori no reason

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

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

Nilles et al, Frere et al, Ellis et al, Drees, Ellwanger et al, King et al, ...

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

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

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

Many Other possibilities also exist (e.g.: E6SSM, King+Moretti+...)!

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; ....)**

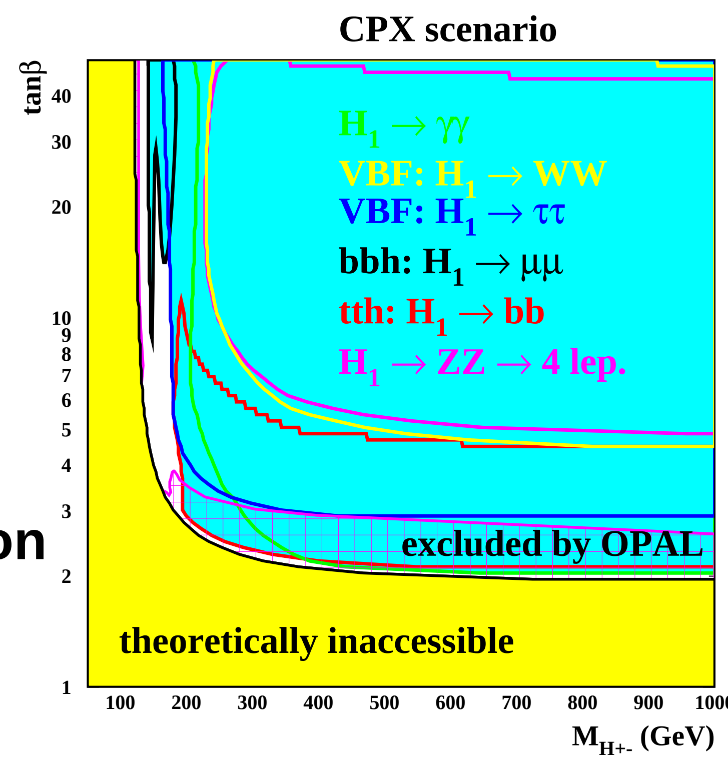
- **h_1 light but weak cplgs to W,Z**
- **$h_2 \to h_1 h_1$ decays allowed**
- **h_3 couplings to VV reduced...**

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 $\mathbf{h_{1,2,3}, a_{1,2}, h^\pm}$ 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...)

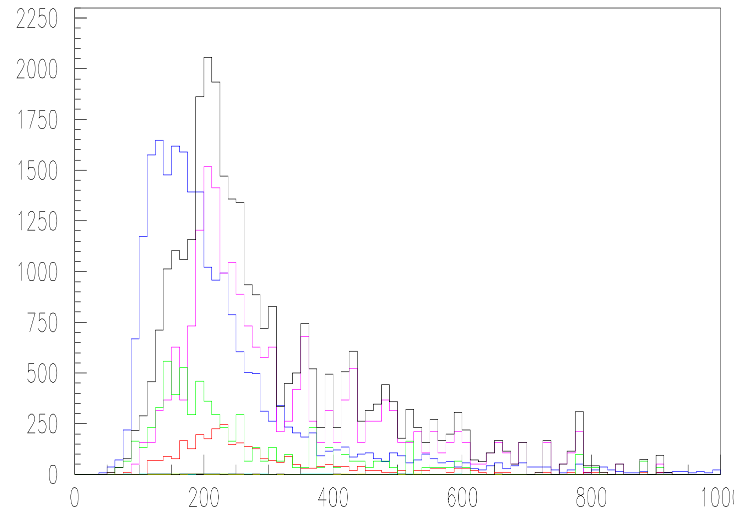
Higgs $\to$ Higgs+Higgs $\to \mathbf{4b, 2b2\tau}$

searches very difficult at the LHC:

$$\mathbf{pp \to qq \to\to W^*W^*qq \to h_1qq}$$

$$\text{——– } \mathbf{h_1 \to a_1a_1 \to b\bar{b}\tau\tau \times 500}$$

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



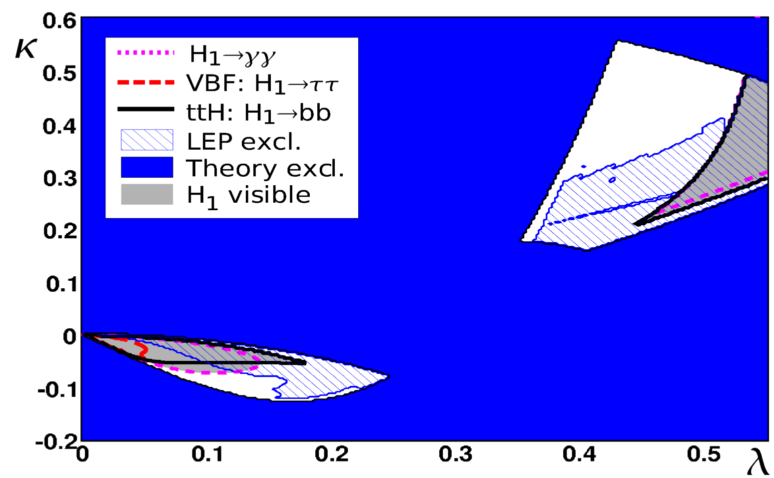
Higgs $\to$ Higgs+Higgs $\to \mathbf{4\tau \to 4\ell X}$

also difficult but detection possible

using VBF + all $\mathbf{h_1}$ 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 $\rightarrow \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$, etc.. as already discussed.
- In MSSM with $R\!\!\!/_p$: Higgs $\rightarrow$ JJ could be dominant. Valle ea
- The SM when minimally extended to contain a singlet scalar field (which decouples from f/V), $H \rightarrow SS$ 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 a few years we will find the Higgs (and maybe nothing els

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 $\mathrm{J^{PC} = 0^{++}}$,**
- **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 $\mathrm{V_H}$ 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...

There is still some way to go.....