Higgs Physics
(in the SM and in the MSSM)

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- **The Higgs in the SM and beyond**
- **The standard Higgs at the LHC**
- **Implications of the discovery for the SM**

- **The MSSM Higgs sector**
- **Implications of the discovery for the MSSM**
- **What next?**

Back-up A: the Higgs mechanism in the SM and constraints

Back-up B: SM Higgs decays and production at the LHC

Back-up C: The Minimal Supersymmetric Standard Model

1. The Higgs in the SM and beyond

The Higgs solves the most crucial problem in particle physics:

how to generate particle masses in an SU(2)$\times$U(1) gauge invariant way?

in the Standard Model $\Rightarrow$ the Higgs–Englert–Brout mechanism

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

fields/interactions symmetric under SU(2)$\times$U(1) but vaccum not.

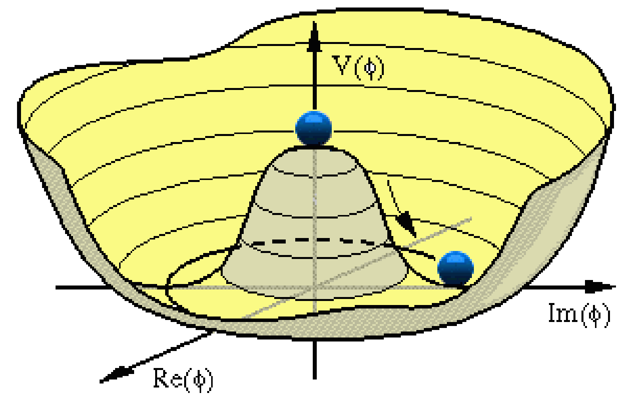
$$\mathcal{L}_{\rm S} = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^2$$

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

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

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

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



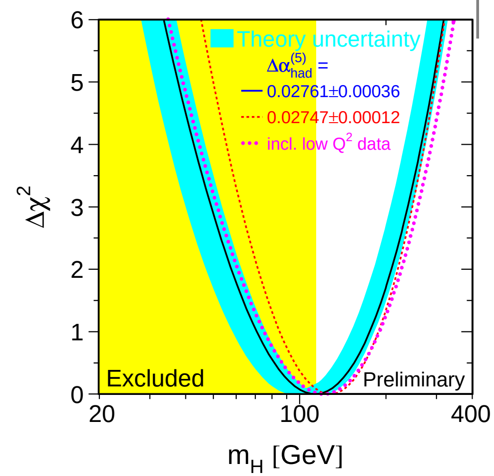
Residual d.o.f corresponds to spin–0 H particle.

- **The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers (CP–even).**
- **Mass: $M_H^2 = 2\lambda v^2$ only free parameter; should be $\lesssim \mathcal{O}(v)$**
- **Higgs couplings $\propto$ particle masses: $g_{Hff} = m_f/v, g_{HVV} = 2M_V^2/v$**
- **Higgs self–couplings from V : $g_{H^3} = 3M_H^2/v, \ldots$**

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

1. The Higgs in the SM and beyond

Pré–LHC constraints on the SM Higgs sectior and on the Higgs mass:



- **Experimental constraints:**

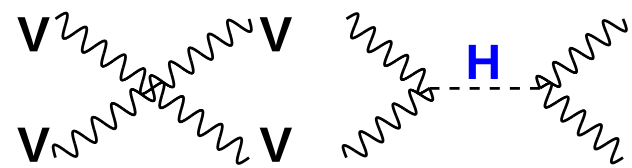
– indirect from global fit of EW precision data:

$\mathbf{M_H = 92^{+34}_{-26}}$ **GeV** $\Rightarrow \mathbf{M_H \lesssim 160}$ **GeV@95% CL**

– Direct searches at LEP and the Tevatron:

$\mathbf{M_H > 114}$ **GeV@95%CL and** $\mathbf{\neq 160-175}$ **GeV**

- **Constraints from unitarity at high energies:**

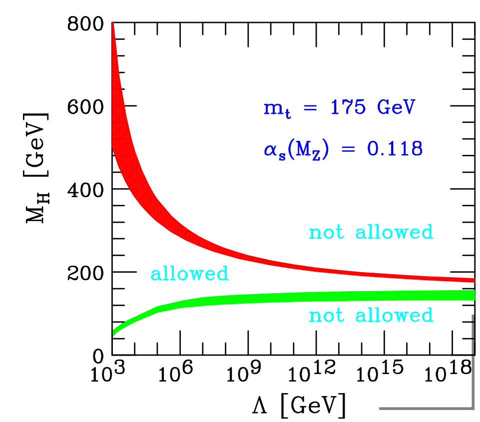


without Higgs: $\mathbf{|A_0(vv \to vv)| \propto E^2/v^2}$

including H with couplings as predicted:

$\mathbf{|A_0| \propto M_H^2/v^2} \Rightarrow$ **the theory is unitary but needs** $\mathbf{M_H \lesssim 700}$ **GeV...**

- **Constraints from triviality and stability@high scale:**



coupling $\mathbf{\lambda = 2M_H^2/v}$ **evolves with energy**

– $\mathbf{M_H}$ **too large: coupling non perturbative**

– $\mathbf{M_H}$ **too small: stability of the EW vaccum**

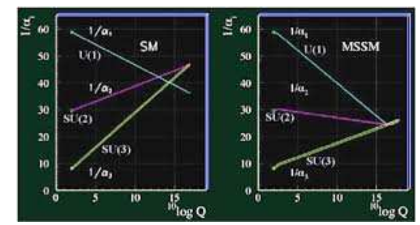
$\mathbf{\Lambda_C \approx 1\ TeV \Rightarrow 70 \lesssim M_H \lesssim 700\ GeV}$

$\mathbf{\Lambda_C \approx M_{Pl} \Rightarrow 130 \lesssim M_H \lesssim 180\ GeV}$

1. The Higgs in the SM and beyond

There are major theoretical and experimental problems in the SM:

- **does not incorporate masses for the neutrinos (there is no ν_R in SM);**
- **does not explain baryon asymmetry (baryogenesis?) in the universe;**
- **does not incorporate the fourth fundamental interaction, gravity;**
- **does not explain why $\mu^2 < 0$ and has too many (19!) free parameters.**



- **No real unification of the interactions:**

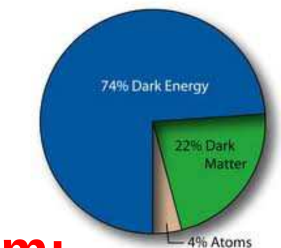
– $3 \neq$ gauge groups with $3 \neq$ couplings,

– no meeting of the couplings in SU(5).

- **No solution to the Dark Matter problem:**

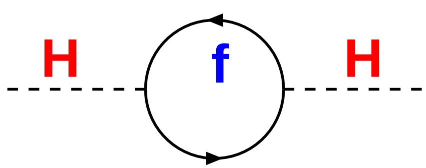
– 25% of the universe made by Dark Matter,

– no stable, neutral, weak, massive particle.



- **Above all: there is the hierarchy or naturalness problem:**

radiative corrections to M_H in SM with a cut–off $\Lambda = M_{NP} \approx M_P$

$\Delta M_H^2 \equiv$  $\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2!$

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

1. The Higgs in the SM and beyond

Three main avenues for solving the hierarchy or naturalness problems (stabilising the Higgs mass against high scales) have been proposed.

I. Compositeness/substructure:

there is yet another layer in structure!

All particles are not elementary ones.

Technicolor: as QCD but at TeV scale.

$\Rightarrow$ H bound state of two fermions

(no more spin–0 fundamental state).

$\Rightarrow$ H properties $\neq$ from of SM Higgs.

II. Extra space–time dimensions

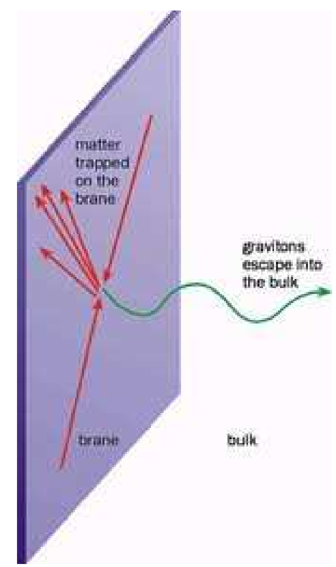
where at least s=2 gravitons propagate.

Gravity: effective scale $\mathrm{M_P^{eff}} \approx \Lambda \approx$ TeV

(and is now $\approx$ included in the game...).

EWSB mechanism needed in addition:

- same Higgs mechanism as in SM,
- but possibility of Higgsless mode!

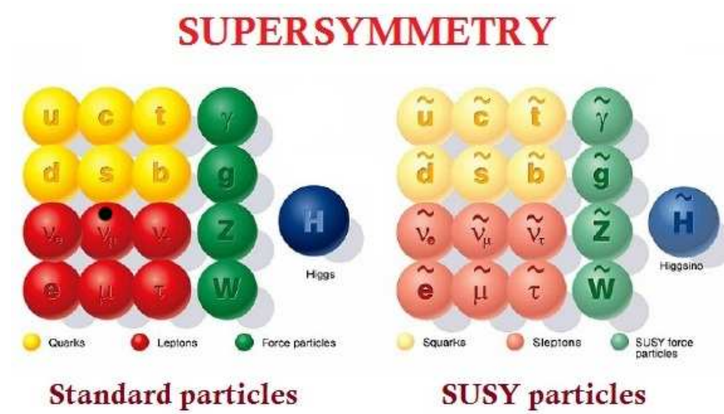


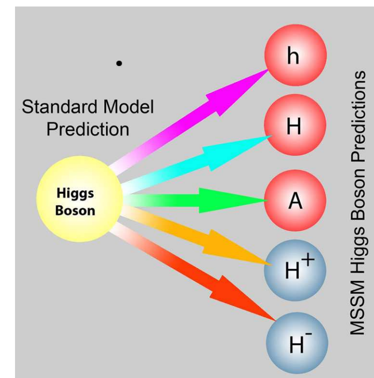
1. The Higgs in the SM and beyond

III. Supersymmetry: doubling the world.

- **SUSY = most attractive SM extension:**

– links s=$\frac{1}{2}$ fermions to s=1 bosons,
– links internal/space-time symmetries,
– if made local, provides link to gravity!
– naturally present in string theory (toe),
– natural $\mu^2 < 0$: radiative EWSB,
– fixes gauge coupling unification pb,
– has ideal candidate for Dark Matter...





- **Needs two scalar doublets for proper and consistent EWSB in the MSSM:**

$\Rightarrow$ extended Higgs sector: $\mathrm{h, H, A, H^+, H^-}$ with $\mathrm{h \oplus H \approx H_{SM}}$,
– SUSY $\Rightarrow$ only two basic inputs at tree-level: $\tan\beta = \mathrm{v_2/v_1}, \mathrm{M_A}$,
– SUSY $\Rightarrow$ hierarchical spectrum: $\mathrm{M_h \approx M_Z}$; $\mathrm{M_H \approx M_A \approx M_{H^\pm}}$.
(SUSY scale $\mathrm{M_S}$ pushes $\mathrm{M_h}$ to 130 GeV via radiative corrections).

- **Most often decoupling regime: $\mathrm{h \equiv H_{SM}}$, others decouple from W/Z.**

1. The Higgs in the SM and beyond

... and along the avenues, many possible streets, paths, corners ...

Just for EWSB, there are dozens of possibilities for the Higgs sector.

Which scenario is chosen by Nature? The LHC gave a first answer!

2. The standard Higgs at the LHC: decays

Since v is known, the only free parameter in the SM is $\mathrm{M_H}$ (or λ).

Once $\mathrm{M_H}$ known, all properties of the Higgs are fixed (modulo QCD).

First: Higgs decays in the SM

- **As $\mathrm{g_{HPP}} \propto \mathrm{m_P}$, H will decay into heaviest particle phase-space allowed:**
- $\mathrm{M_H} \lesssim 130\ \mathrm{GeV}$, $\mathrm{H \to b\bar{b}}$

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

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

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

– **below threshold decays possible**

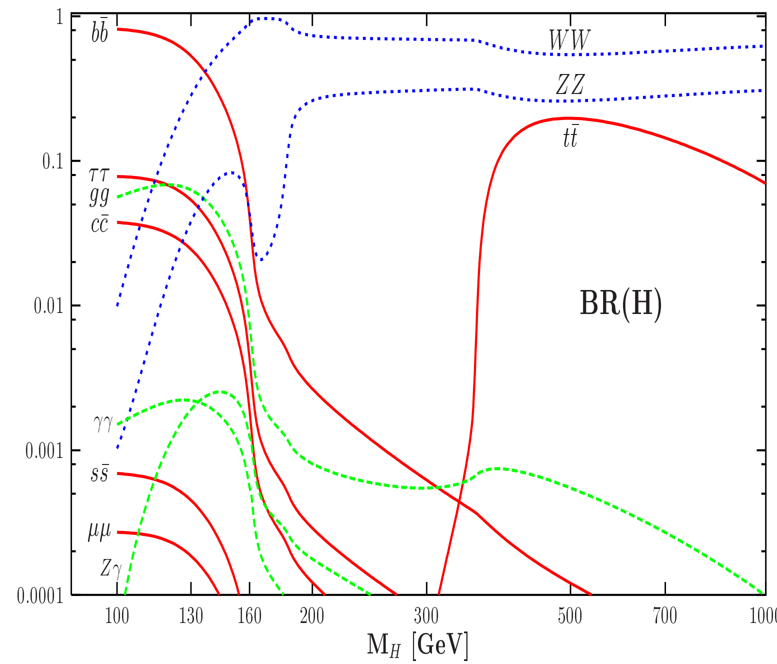
– **above threshold: B(WW)=$\frac{2}{3}$, B(ZZ)=$\frac{1}{3}$**

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

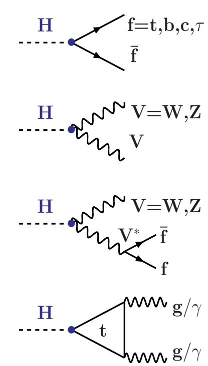
- **Total Higgs decay width:**

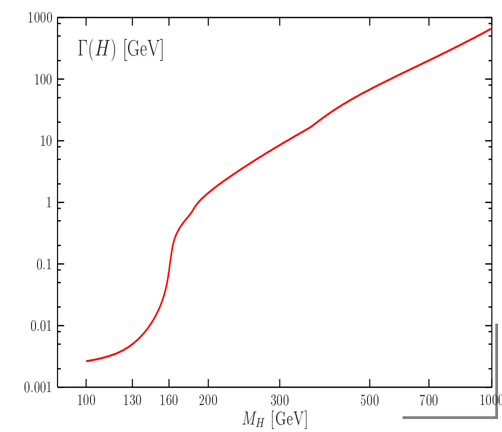
– **very small for a light Higgs**

– **comparable to mass for heavy Higgs**



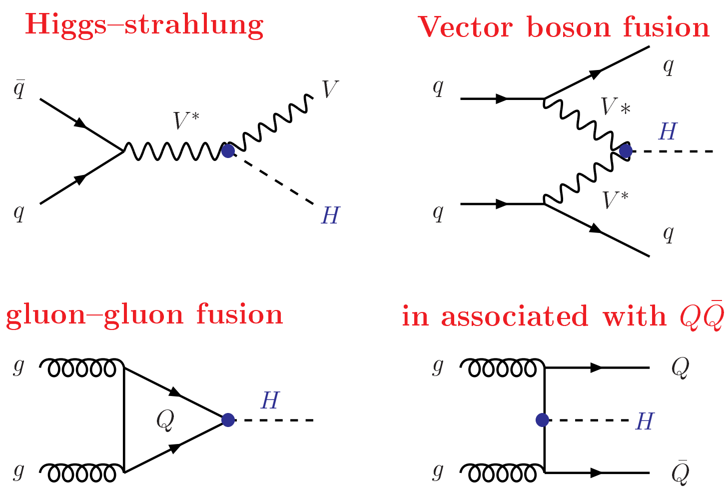
HDECAY$\Rightarrow$

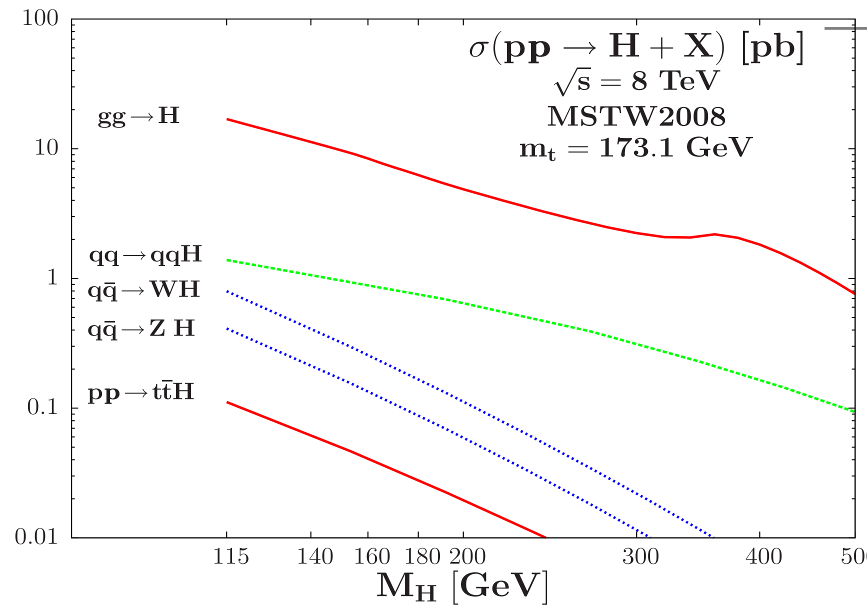




2. The standard Higgs at the LHC: production

Main Higgs production channels





Large production cross sections

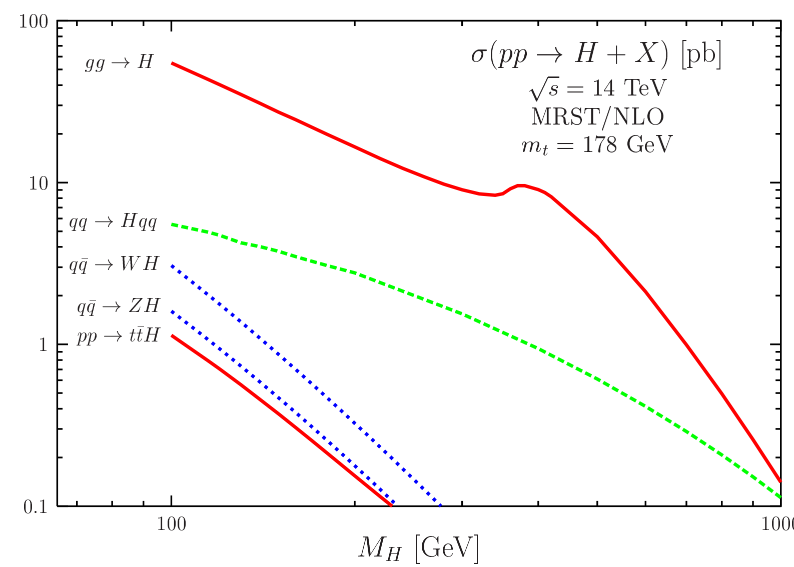
with gg$\to$ H by far dominant process

followed by VBF, VH and then by ttH

1 $\mathrm{fb}^{-1} \Rightarrow \mathcal{O}(10^4)$ events@lHC

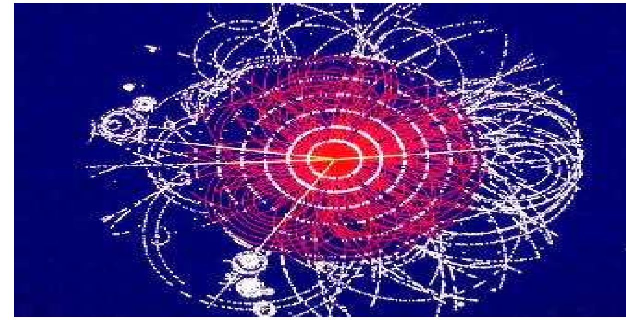
but eg BR(H$\to \gamma\gamma, \mathrm{ZZ} \to 4\ell) \approx 10^{-3}$

... a small # of events at the end...



2. The standard Higgs at the LHC: challenges

$\Rightarrow$ **an extremely 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 specific kinematic features of Higgs

- **Combine # decay/production channels**

(and eventually several experiments...)

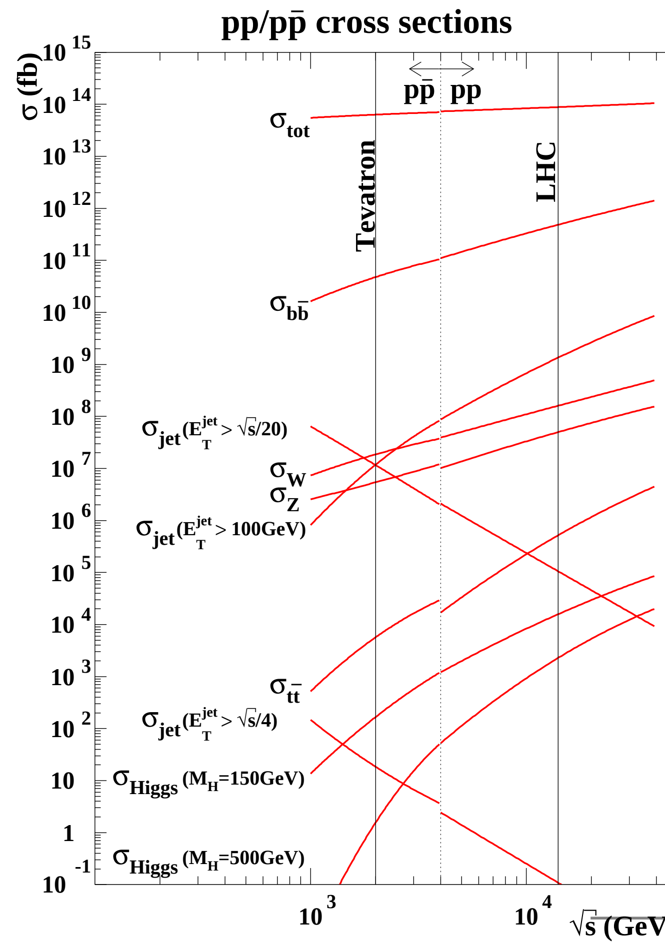
- **Have a precise knowledge of S and B rates**

(higher orders can be factor of 2! see later)

- **Gigantic experimental + theoretical efforts**

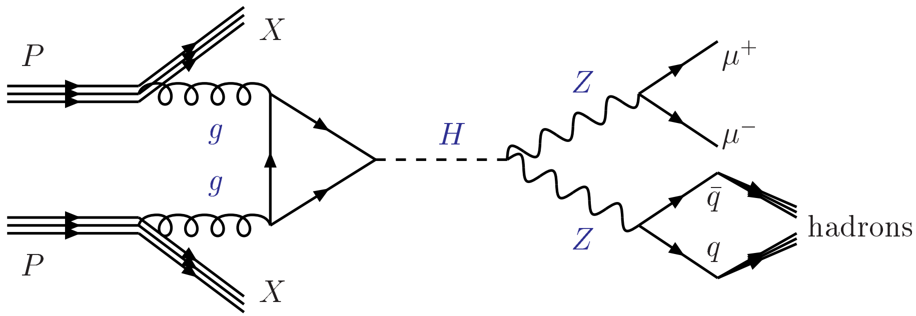
(more than 30 years of very hard work!)

For a flavor of how it is complicated from the theory side: a look at the $\mathrm{gg} \to \mathrm{H}$ case



2. The standard Higgs at the LHC: challenges

Best example of process at LHC to see how things work: $\mathrm{gg} \to \mathrm{H}$.



$$\mathrm{N_{ev}} = \mathcal{L} \times \mathrm{P(g/p)} \times \hat{\sigma}(\mathrm{gg \to H}) \times \mathrm{B(H \to ZZ)} \times \mathrm{B}(\mathrm{Z} \to \mu\mu) \times \mathrm{BR(Z \to qq)}$$

For a large number of events, all these numbers should be large!

Two ingredients: hard process (σ, B) and soft process (PDF, hadr).

Factorization theorem: the two can factorise in production at a scale $\mu_{\mathbf{F}}$.

The partonic cross section of the subprocess, $\mathrm{gg} \to \mathrm{H}$, given by:

$$\hat{\sigma}(\mathbf{gg} \to \mathbf{H}) = \int \frac{\mathbf{1}}{\mathbf{2\hat{s}}} \times \frac{\mathbf{1}}{\mathbf{2 \cdot 8}} \times \frac{\mathbf{1}}{\mathbf{2 \cdot 8}} |\mathcal{M}_{\mathbf{Hgg}}|^{\mathbf{2}} \frac{\mathrm{d}^{\mathbf{3}}\mathbf{p_H}}{(\mathbf{2}\pi)^{\mathbf{3}}\mathbf{2E_H}} (\mathbf{2}\pi^{\mathbf{4}}) \delta^{\mathbf{4}}(\mathbf{q} - \mathbf{p_H})$$

Flux factor, color/spin average, matrix element squared, phase space.

Convolute with gluon densities to obtain total hadronic cross section

$$\sigma = \int_{\mathbf{0}}^{\mathbf{1}} \mathrm{d}\mathbf{x_1} \int_{\mathbf{0}}^{\mathbf{1}} \mathrm{d}\mathbf{x_2} \frac{\pi^{\mathbf{2}}\mathbf{M_H}}{\mathbf{8\hat{s}}} \mathbf{\Gamma}(\mathbf{H} \to \mathbf{gg}) \mathbf{g}(\mathbf{x_1}) \mathbf{g}(\mathbf{x_2}) \delta(\hat{\mathbf{s}} - \mathbf{M_H^2})$$

2. The standard Higgs at the LHC: challenges

The calculation of $\sigma_{\rm born}$ is not enough in general at pp colliders:

need to include higher order radiative corrections which introduce terms of order $\alpha_{\rm s}^{\rm n} \log^{\rm m}({\rm Q}/{\rm M_H})$ where Q is either large or small...

- **Since α_s is large, these corrections are in general very important,**

$\Rightarrow$ **dependence on renormalisation/factorisations scales $\mu_{\rm R}/\mu_{\rm F}$.**

- **Choose a (natural scale) which absorbs/resums the large logs,**

$\Rightarrow$ **higher orders provide stability against $\mu_{\rm R}/\mu_{\rm F}$ scale variation.**

- **Since we truncate pert. series: only NLO/NNLO corrections available.**

$\Rightarrow$ **not known HO (hope small) corrections induce a theoretical error.**

$\Rightarrow$ **the scale variation is a (naive) measure of the HO: must be small.**

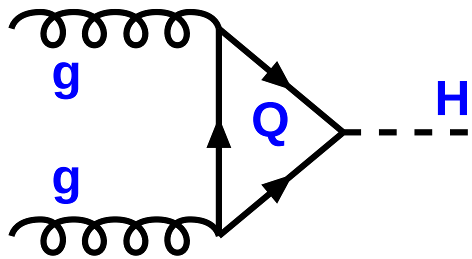
- **Also, precise knowledge of σ is not enough: need to calculate some kinematical distributions (e.g. $\rm p_T, \eta, \frac{d\sigma}{dM}$) to distinguish S from B.**
- **In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\rm s = N_S/\sqrt{N_B}$.**

$\Rightarrow$ **a lot of theoretical work is needed!**

But most complicated thing is to actually see the signal for S/B$\ll$1!

2. The standard Higgs at the LHC: gg fusion

Let us look at this main Higgs production channel at the LHC in detail.



$$\hat{\sigma}_{\rm LO}(gg \to H) = \frac{\pi^2}{8M_H}\Gamma_{\rm LO}(H \to gg)\delta(\hat{s} - M_H^2)$$

$$\sigma_0^H = \frac{G_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{4}\sum_q A_{1/2}^H(\tau_Q) \right|^2$$

Related to the Higgs decay width into gluons discussed previously.

- **In SM: only top quark loop relevant, b–loop contribution** $\lesssim 5\%$.
- **For** $m_Q \to \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3} =$ **constant and** $\hat{\sigma}$ **finite.**
- **Approximation** $m_Q \to \infty$ **valid for** $M_H \lesssim 2m_t = 350$ **GeV.**

Gluon luminosities large at high energy+strong QCD and Htt couplings

$gg \to H$ **is the leading production process at the LHC.**

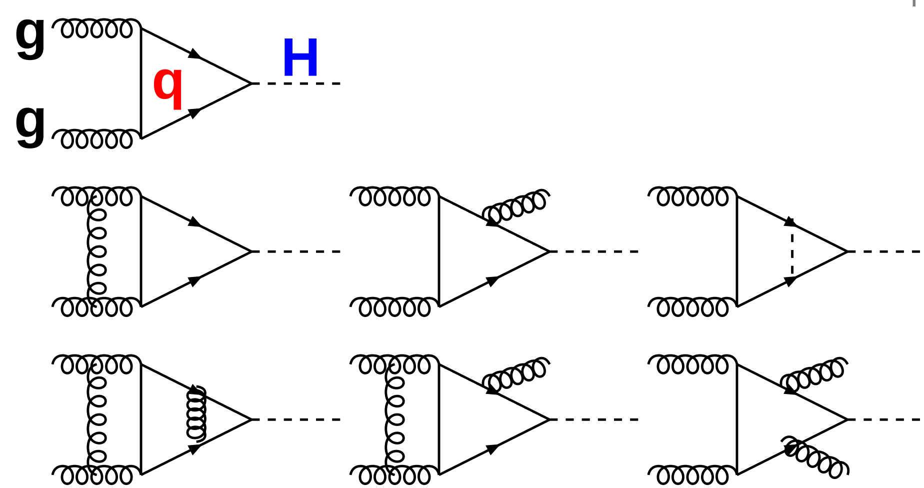
- **Very large QCD RC: the two– and three–loops have to be included.**
- **Also the Higgs** P_T **is zero at LO, must generated at NLO.**

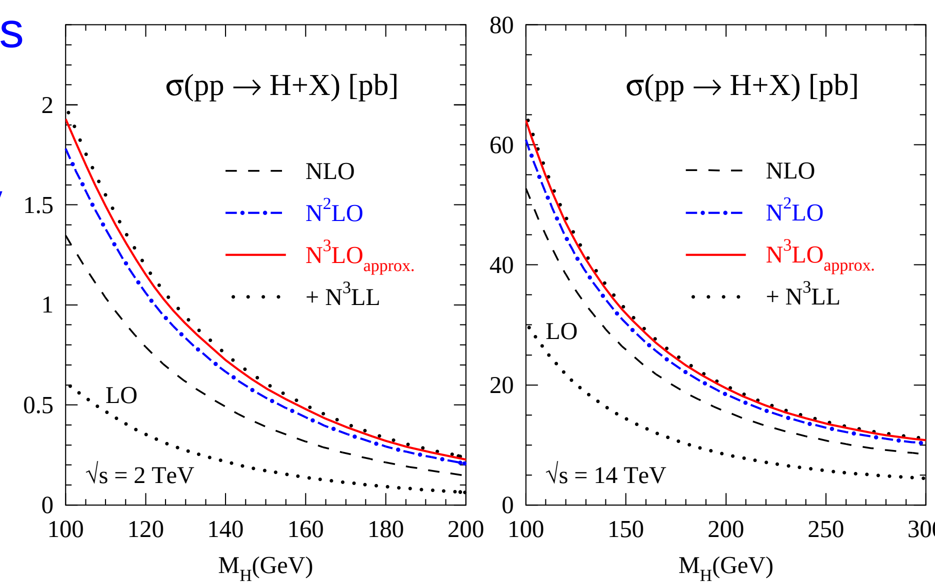
2. The standard Higgs at the LHC: gg fusion

LO[a]**: already at one loop**
QCD: exact NLO[b] **:** $\mathrm{K} \approx$ **(1.7)**
EFT NLO[c]**: good approx.**
EFT NNLO[d]**:** $\mathrm{K} \approx$ **(2)**
EFT NNLL[e]**:** $\approx +$ **(5%)**
EFT N3LO[f]**:** $\approx$ **3 %.**
EW: EFT NLO: [g]**:** $\approx \pm$ **very small**
exact NLO[h]**:** $\approx \pm$ **a few %**
QCD+EW[i]**: a few %**
Distributions: two programs[j]

[a] Georgi+Glashow+Machacek+Nanopoulos
[b] Spira+Graudenz+Zerwas+AD (exact)
[c] Spira+Zerwas+AD; Dawson (EFT)
[d] Harlander+Kilgore, Anastasiou+Melnikov
Ravindran+Smith+van Neerven
[e] Catani+de Florian+Grazzini+Nason
[f] Moch+Vogt; Anastasiou et al. (2015);
[g] Gambino+AD; Degrassi et al.
[h] Actis+Passarino+Sturm+Uccirati
[i] Anastasiou+Boughezal+Pietriello
[j] Anastasiou et al.; Grazzini

The $\sigma^{\rm theory}_{gg\to H}$ long story (1978–2015)





Moch+Vogt

2. The Higgs at the LHC: uncertainties

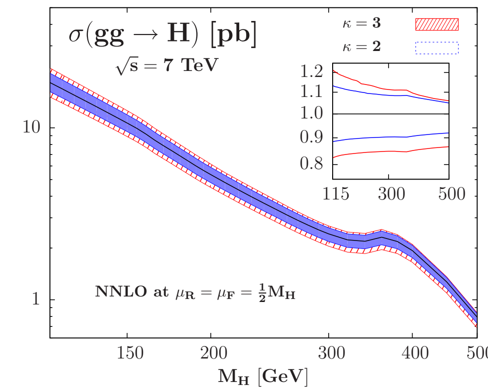
Despite of that, the $gg \to H$ cross section still affected by uncertainties

- **Higher-order or scale uncertainties:**

K-factors large $\Rightarrow$ HO could be important
HO estimated by varying scales of process

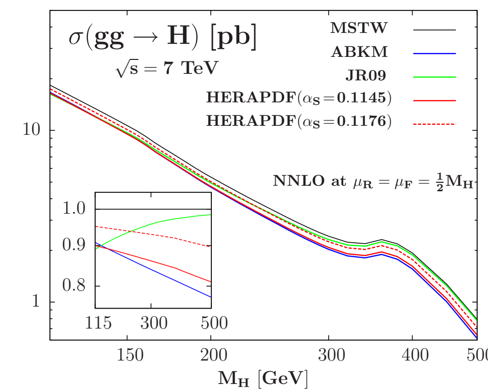
$$\mu_0/\kappa \le \mu_R, \mu_F \le \kappa\mu_0$$

at lHC: $\mu_0 = \frac{1}{2}M_H, \kappa = 2 \Rightarrow \Delta^{\rm NNLO}_{\rm scale} \approx 10\%$



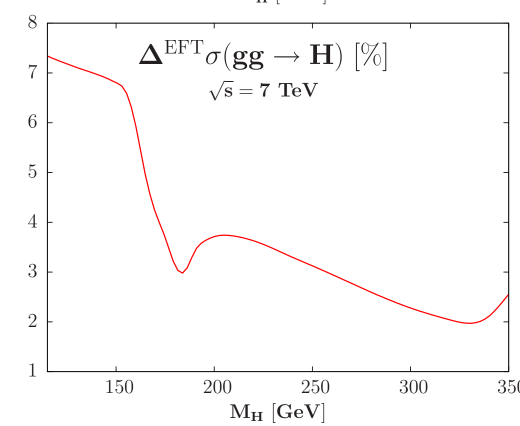
- **gluon PDF+associated α_s uncertainties:**

gluon PDF at high–x less constrained by data
α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$
$\Rightarrow$ large discrepancy between NNLO PDFs
PDF4LHC recommend: $\Delta_{\rm pdf} \approx 10\%$@lHC



- **Uncertainty from EFT approach at NNLO**

$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
but not above and not b ($\approx 10\%$), W/Z loops
Estimate from (exact) NLO: $\Delta_{\rm EFT} \approx 5\%$



- **Include ΔBR(H$\to$X) of at most few %**

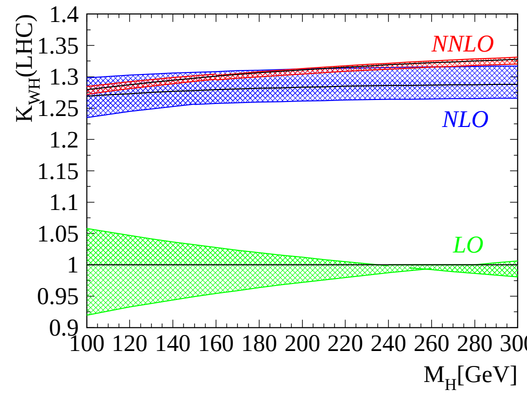
total $\Delta\sigma^{\rm NNLO}_{gg\to H\to X} \approx$ 15–20%@lHC

LHC-HxsWG; Baglio+AD $\Rightarrow$

2. The Higgs at the LHC: other channels

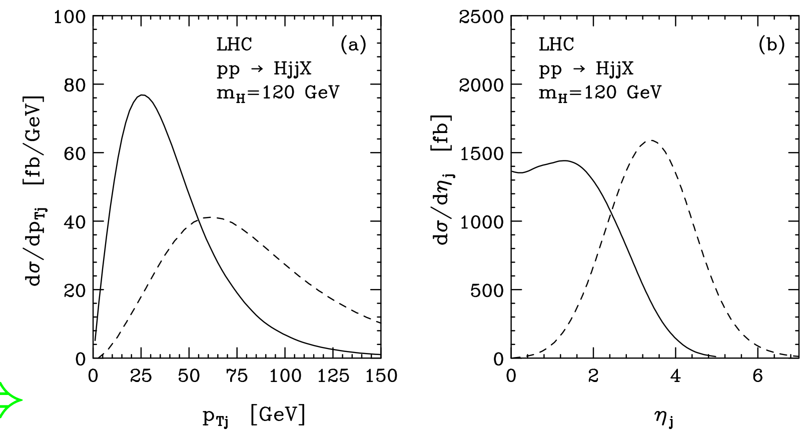
- **Higgs–strahlung: $q\bar{q} \to VH$**
- – Drell–Yan with $V^* \to VH$ decays
- – RC known at NNLO, rather moderate
- – $\ell\nu b\bar{b}$ main mode@Tevatron for light H
- – resurrected at LHC with boosted jets

Brein, AD, Harlander $\Rightarrow$



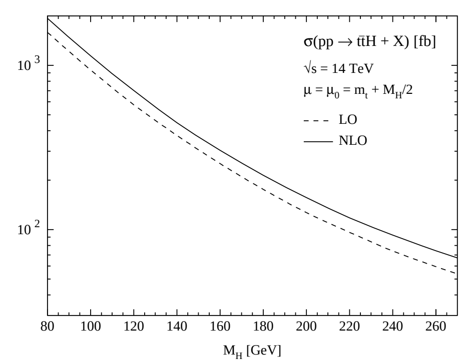
- **vector boson fusion: $qq \to Hqq$**
- – large cross section at high $\sqrt{s}$
- – p_T^{high} forward jets, central jeto veto, ..
- – TH clean (small RC) but ggH contam.
- – many H decay channels observable.

Zeppenfeld et al. $\Rightarrow$



- **Associated ttH production $pp \to t\bar{t}H$**
- – complicated process but probes g_{Htt}
- – small cross section but small RC too
- – too large bkg for H$\to$bb; boosted jets?

Beenakker et al. $\Rightarrow$



2. The Higgs at the LHC: expectations

Expectations for 2012 and beyond:

lHC: $\sqrt{s}=$7–8TeV and $\mathcal{L}\approx$ few fb^{-1}

5σ discovery for $\mathrm{M_H}\approx$130–200 GeV

95%CL sensitivity for $\mathrm{M_H}\lesssim$600 GeV

$\mathrm{gg\to H\to}\gamma\gamma$ **($\mathrm{M_H}\lesssim$ 130 GeV)**

$\mathrm{gg\to H\to WW\to}\ell\nu\ell\nu+0,1$ **jets**

$\mathrm{gg\to H\to ZZ\to}4\ell, 2\ell2\nu, 2\ell2\mathrm{b}$

$\mathrm{gg\to H\to}\tau\tau+0,1$ **jets**

$\mathrm{q\bar{q}\to VH\to Vb\bar{b}}$ **with** $\mathrm{V=Z\to}\ell\ell$

– at lHC with jet substructure

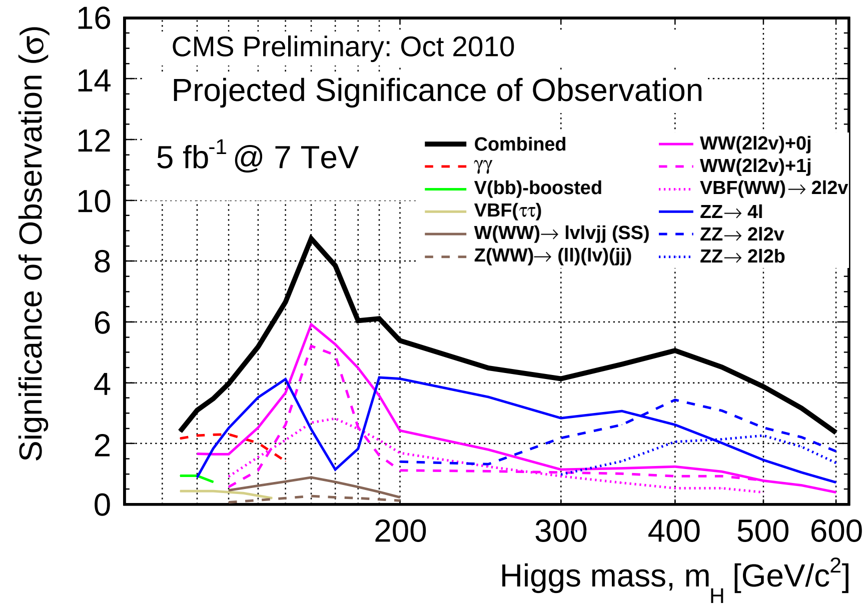
– also at Tevatron in $\mathrm{Wh\to}\ell\nu\mathrm{b\bar{b}}$

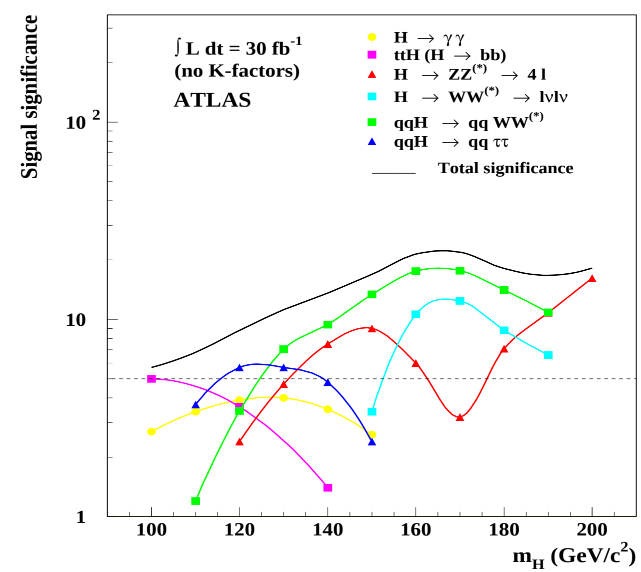
Full LHC: same as lHC plus some others

– VBF: $\mathrm{qqH\to}\tau\tau,\gamma\gamma,\mathrm{ZZ^*},\mathrm{WW^*}$

– VH$\to$Vbb with jet substructure tech.

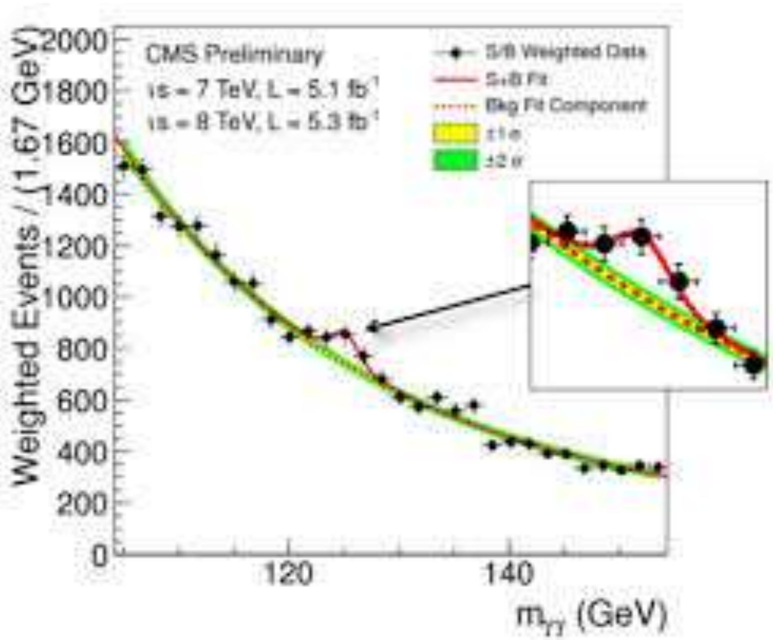
– ttH: H$\to\gamma\gamma$ bonus, H$\to\mathrm{b\bar{b}}$ hopeless?

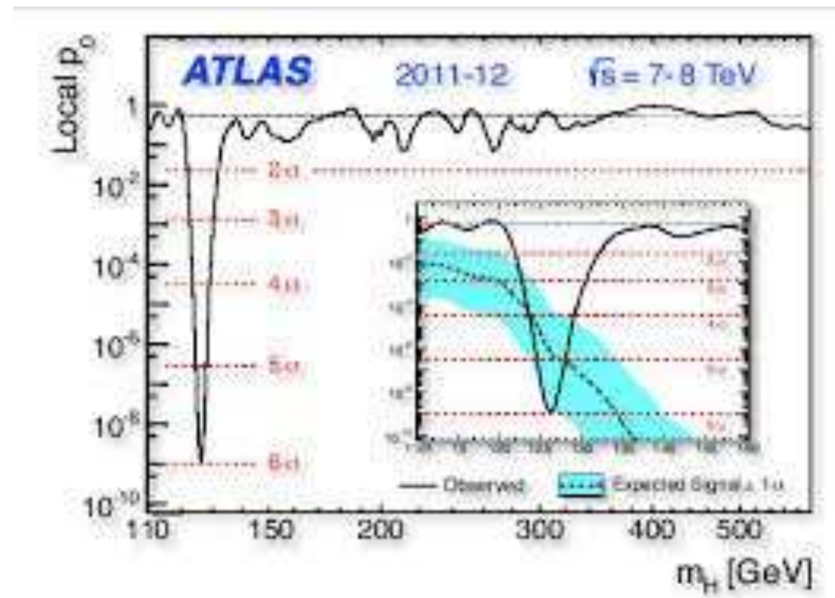




3. Implications of the discovery for the SM

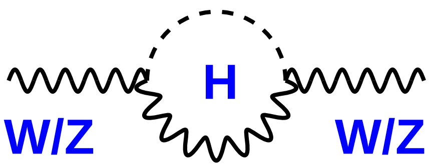
Discovery: a challenge met the 4th of July 2012: a Higgstorical day.





3. Implications of the discovery for the SM

And the observed new state looks
as the long sought SM Higgs boson:
a triumph for high-energy physics!
Indeed, constraints from EW data:
H contributes to the W/Z masses
through tiny quantum fluctuations:

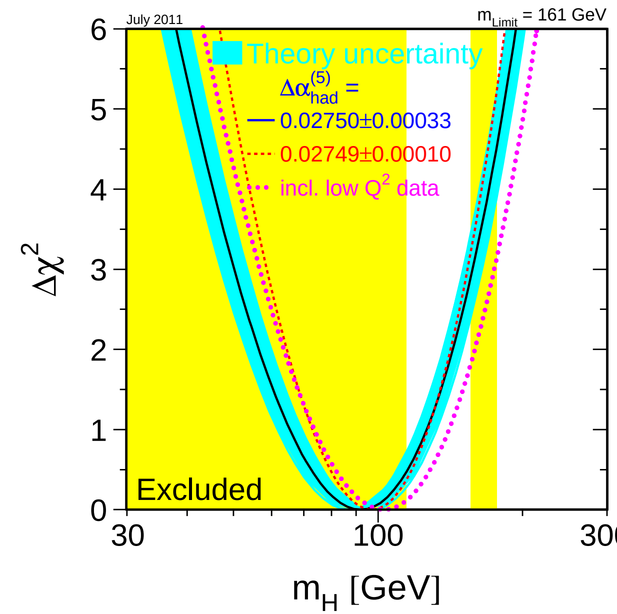


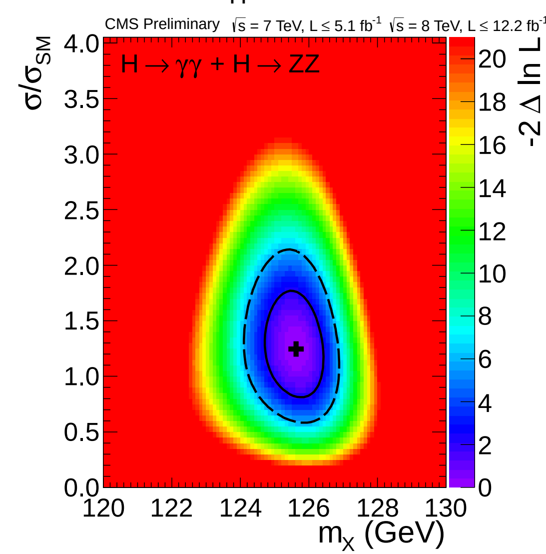
$$\propto \frac{\alpha}{\pi} \log \frac{\mathbf{M_H}}{\mathbf{M_W}} + \cdots$$

Fit the EW ($\lesssim$ 0.1%) precision data,
with all other SM parameters known,
one obtains $\mathbf{M_H = 92^{+34}_{-26}}$ GeV, or

$\mathbf{M_H \lesssim 160}$ GeV at 95% CL

versus "observed" $\mathbf{M_H = 125}$ GeV.
A very non–trivial check of the SM!





The SM is indeed a very successful theory, tested at the permille level...

3. Implications of the discovery for the SM

But lets check it is indeed a Higgs!

Spin: the state decays into $\gamma\gamma$

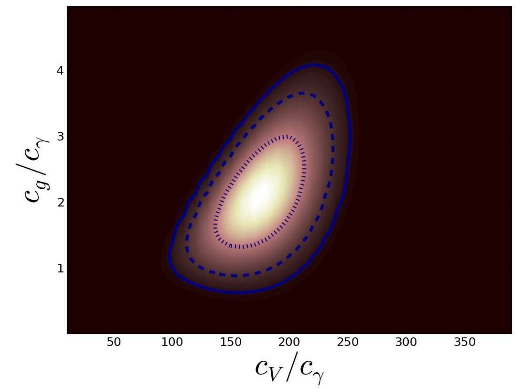
- **not spin–1: Landau–Yang**
- **could be spin–2 like graviton?** **Ellis et al.**

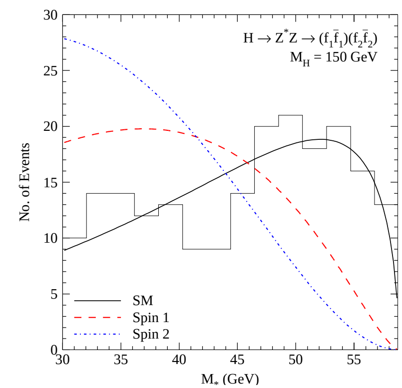
– miracle that couplings fit that of H,

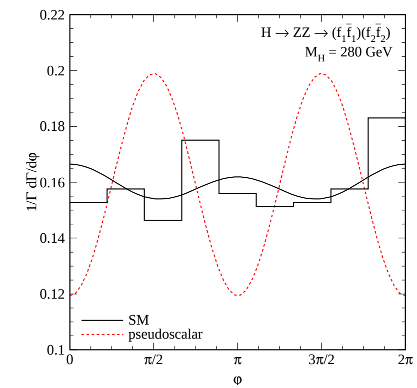
– "prima facie" evidence against it:

$$\text{e.g.: } \mathbf{c_g \neq c_\gamma, c_V \gg 35 c_\gamma}$$

many th. analyses (no suspense...)







CP no: even, odd, or mixture?

(more important; CPV in Higgs!)

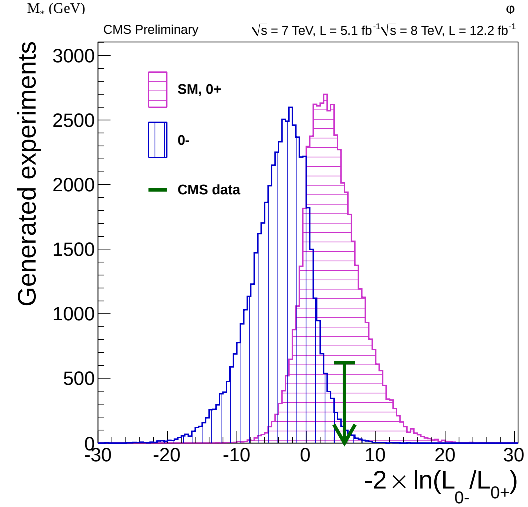
ATLAS and CMS CP analyses for

pure CP–even vs pure–CP–odd

$$\mathbf{HV_\mu V^\mu} \text{ versus } \mathbf{H\epsilon^{\mu\nu\rho\sigma} Z_{\mu\nu} Z_{\rho\sigma}}$$

$$\Rightarrow \frac{\mathbf{d\Gamma(H\to ZZ^*)}}{\mathbf{dM_*}} \text{ and } \frac{\mathbf{d\Gamma(H\to ZZ)}}{\mathbf{d\phi}}$$

MELA $\approx 3\sigma$ for CP-even..



3. Implications of the discovery for the SM

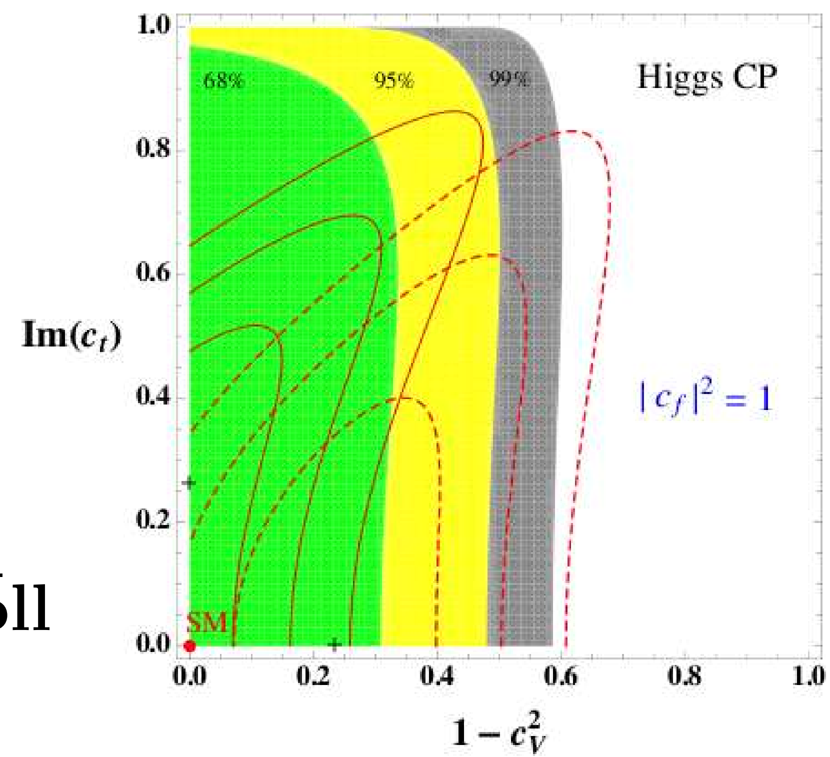
There are however some problems with this (too simple) picture:

– a pure CP odd Higgs does not couple to VV states at tree–level,
– coupling should be generated by loops or HOEF: should be small,
– H CP–even with small CP–odd admixture: high precision measurement,
– in $H \to VV$ only CP–even component projected out in most cases!

Indirect probe: through $\hat{\mu}_{VV}$
$g_{HVV} = c_V g_{\mu\nu}$ with $c_V \leq 1$
better probe: $\hat{\mu}_{ZZ} = 1.1 \pm 0.4!$

gives upper bound on CP mixture:
$\eta_{CP} \equiv 1 - c_V^2 \gtrsim 0.5 @ 68\% CL$

Direct probe: g_{Hff} more democratic
$\Rightarrow$ processes with fermion decays.
spin-corelations in $q\bar{q} \to HZ \to b\bar{b}ll$
or later in $q\bar{q}/gg \to Ht\bar{t} \to b\bar{b}t\bar{t}$.



Extremely challenging even at HL-LHC... Moreau...

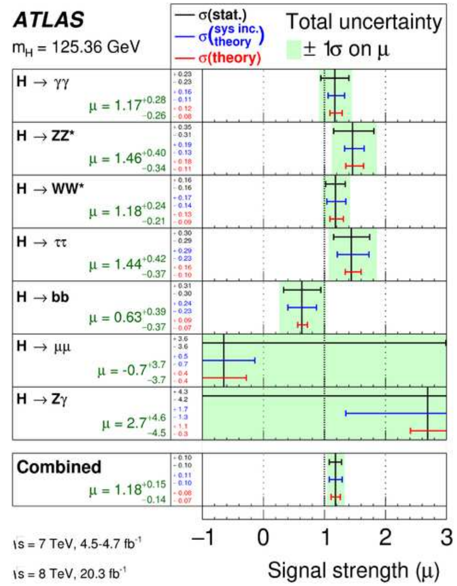
3. Implications of the discovery for the SM

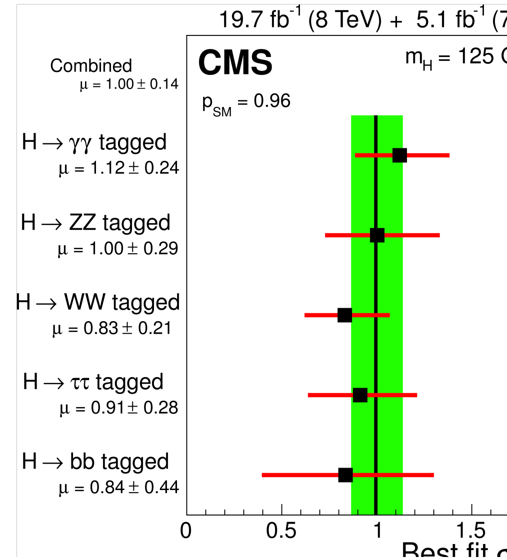
$\sigma\times$BRs compatible with those expected in the SM

Fit of all LHC Higgs data $\Rightarrow$ agreement at 15–30% level

$\mu_{\rm tot}^{\rm ATLAS} = 1.18 \pm 0.15$

$\mu_{\rm tot}^{\rm CMS} = 1.00 \pm 0.14$





Precise at the 10% level and no deviation from the SM expectation!

run 1 legacy: $\mu_{\rm tot}^{\rm ATLAS+CMS} = 1.09^{+0.07+0.04+0.07}_{-0.07-0.04-0.06} \approx 1.1 \pm 0.1$

Higgs couplings to elementary particles as predicted by BEH mechanism:

- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs,**
- **couplings proportional to masses as expected for the Higgs boson.**

So, it is not only a “new particle” or ”new state” etc..., it is a Higgs boson!

But is it THE SM Higgs boson or A Higgs boson from some extension?

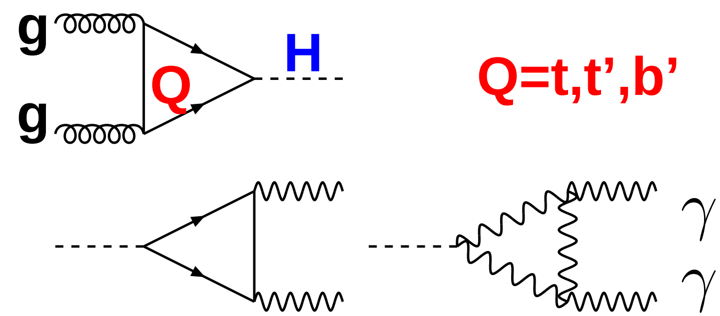
For the moment, it looks SM–like... and the SM is really in good shape...

3. Implications of the discovery for the SM

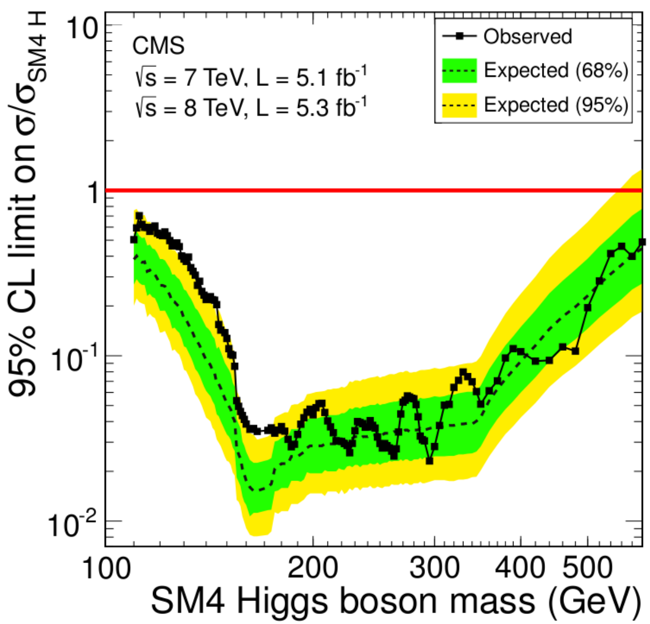
Particle spectrum looks complete: no room for 4th fermion generation!

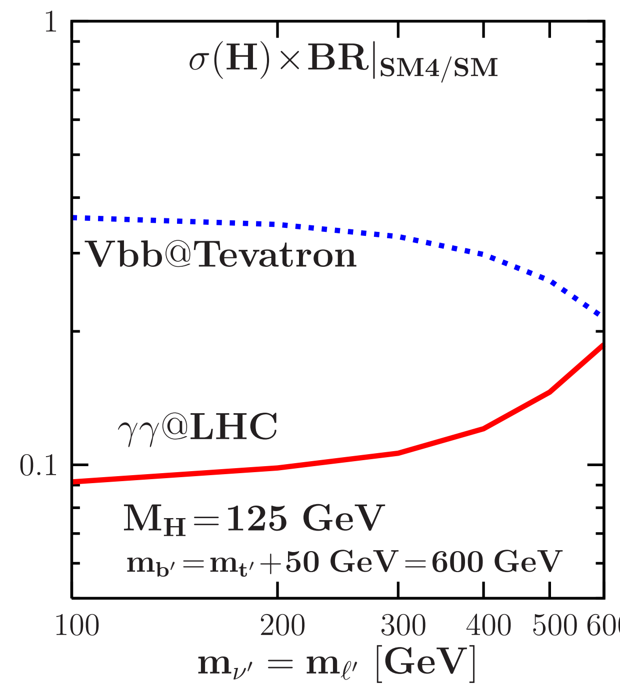
Indeed, an extra doublet of quarks and leptons (with heavy ν') would:

- **increase $\sigma(\mathrm{gg} \to \mathrm{H})$ by factor ≈ 9**
- **H$\to$gg suppresses BR(bb,VV) by $\approx$2**
- **strongly suppresses $\mathrm{BR}(\mathrm{H} \to \gamma\gamma)$**



NLO $\mathcal{O}(\mathrm{G_F m^2_{F'}})$ effects very important:





(Direct seach also constraining..) **Lenz....**

3. Implications of the discovery for the SM

- **For theory to preserve unitarity:**

we need Higgs with $M_H \lesssim 700$ GeV...

We have a Higgs and it is light: OK!

- **Extrapolable up to highest scales.**

$\lambda = 2M_H^2/v$ **evolves with energy**

– too high: non perturbativity

– too low: stability of the EW vacuum

$$\frac{\lambda(Q^2)}{\lambda(v^2)} \approx 1 + 3\,\frac{2M_W^4 + M_Z^4 - 4m_t^4}{16\pi^2 v^4} \log\frac{Q^2}{v^2}$$

$$\lambda \geq @M_{Pl} \Rightarrow M_H \gtrsim 129\,\mathrm{GeV}!$$

at 2loops for $m_t^{pole} = 173$ GeV.....

$\Rightarrow$ **Degrassi et al., Bezrukov et al.**

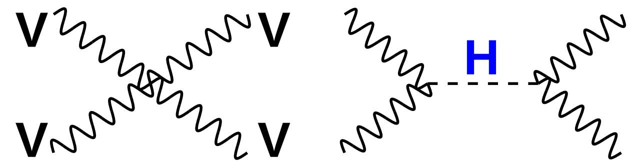
but what is measured m_t at TEV/LHC

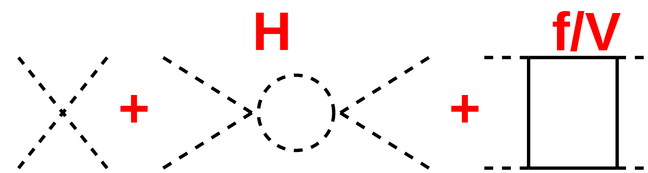
$m_t^{pole}?m_t^{MC}?$ **not clear; much better:**

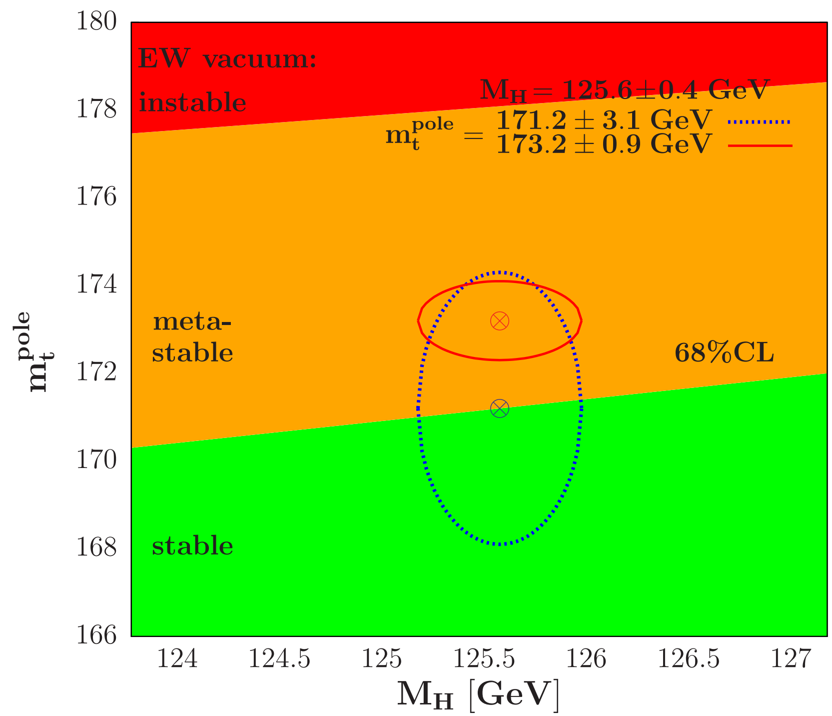
$m_t = 171 \pm 3$**GeV from** $\sigma(pp \to t\bar{t})$

issue needs further studies/checks...

Alekhin....







3. Implications of the discovery for the SM

Let us now ummarise the situation after this first run of the LHC:

A. We have observed a 125 GeV Higgs particle and it seems to be SM–like.

B. We do not observe any new particle beyond this Higgs boson.

Maybe we have the theory of everything, the Standard Model?

- has all good theory features: renormalisable, unitary, perturbative, ...
- extrapolable to the hightest scale (EW vacuum (meta)stable to $\mathrm{M_P}$).
- Very successful in describing present data (with all pbs disappearing..).

It requires some extensions though to address some of the SM problems..

- dark matter: maybe Peccei-Quinn axion (needed for QCD CP problem)?
- small neutrino masses, baryon asymmetry in the universe and the gauge unification problem: fixed in SO(10) with $\mathrm{M_I} \approx 10^{11}$ GeV?

(see for instance Altarelli and Meloni, arXiv:1305.1001)

But remains the "mother of all problems": hierarchy pb calls for BSM. But

- spin–zero Higgs $\equiv$ bound-state $\Rightarrow$ Technicolor: in "mortuary"?
- cut–off at TeV scale $\Rightarrow$ extra space-time dimensions: in "hospital"?
- new protecting symmetry $\Rightarrow$ Supersymmetry: in "trouble"?

Beyond the SM: the MSSM

Next time, I will discuss the case of beyond the SM
I will take the example of Supersymmetry and stick to the MSSM.

Higgs Physics

Abdelhak DJOUADI
(LPT CNRS & U. Paris-Sud)

- **The Higgs in the SM and beyond**
- **The standard Higgs at the LHC**
- **Implications of the discovery for the SM**

- **The MSSM Higgs sector**
- **Implications of the discovery for the MSSM**
- **What next?**

Back-up A: the Higgs mechanism in the SM and constraints
Back-up B: SM Higgs decays and production at the LHC
Back-up C: The Minimal Supersymmetric Standard Model

4. The Higgs sector of the MSSM

In the MSSM we need two Higgs doublets $H_1 = \binom{H_1^0}{H_1^-}$ and $H_2 = \binom{H_2^+}{H_2^0}$,
to generate up/down-type fermion masses while having chiral anomalies.
after EWSB, three dof for $W_L^\pm, Z_L \Rightarrow$ 5 physical states: $h, H, A, H^\pm$.
Only two free parameters at tree-level to describe the system $\tan\beta, M_A$:

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

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$\tan 2\alpha = \frac{-(M_A^2+M_Z^2)\sin 2\beta}{(M_Z^2-M_A^2)\cos 2\beta} = \tan 2\beta \, \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2} \quad \left(-\frac{\pi}{2} \le \alpha \le 0\right)$$

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

- 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 decoupling limit: MSSM Higgs sector reduces to SM with a light h.

4. The Higgs sector of the MSSM

Life is more complicated and radiative corrections have to be included.

The CP-even Higgses described by 2×2 matrix including corrections:

$$\mathbf{M_S^2} = \mathbf{M_Z^2} \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + \mathbf{M_A^2} \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta\mathcal{M}_{11}^2 & \Delta\mathcal{M}_{12}^2 \\ \Delta\mathcal{M}_{12}^2 & \Delta\mathcal{M}_{22}^2 \end{pmatrix}$$

and the two Higgs masses and the mixing angle α are given by:

$$\mathbf{M_{h/H}^2} = \tfrac{1}{2}\left(\mathbf{M_A^2} + \mathbf{M_Z^2} + \mathbf{C_+} \mp \sqrt{\mathbf{M_A^4} + \mathbf{M_Z^4} - 2\mathbf{M_A^2}\mathbf{M_Z^2}\mathbf{c}_{4\beta} + \mathbf{C}}\right)$$

$$\alpha = \frac{2\boldsymbol{\Delta}\mathcal{M}_{\mathbf{12}}^2 - (\mathbf{M_A^2} + \mathbf{M_Z^2})\mathbf{s}_\beta}{\mathbf{C_-} + (\mathbf{M_Z^2} - \mathbf{M_A^2})\mathbf{c}_{2\beta} + \sqrt{\mathbf{M_A^4} + \mathbf{M_Z^4} - 2\mathbf{M_A^2}\mathbf{M_Z^2}\mathbf{c}_{4\beta} + \mathbf{C}}}$$

with

$$\mathbf{C}_\pm = \boldsymbol{\Delta}\mathcal{M}_{\mathbf{11}}^2 \pm \boldsymbol{\Delta}\mathcal{M}_{\mathbf{22}}^2$$

$$\mathbf{C} = 4\boldsymbol{\Delta}\mathcal{M}_{\mathbf{12}}^4 + \mathbf{C}_-^2 - 2(\mathbf{M_A^2} - \mathbf{M_Z^2})\mathbf{C}_-\mathbf{c}_{2\beta} - 4(\mathbf{M_A^2} + \mathbf{M_Z^2})\boldsymbol{\Delta}\mathcal{M}_{\mathbf{12}}^2\mathbf{s}_{2\beta}$$

The dominant corrections come from stop/top sector with a leading term:

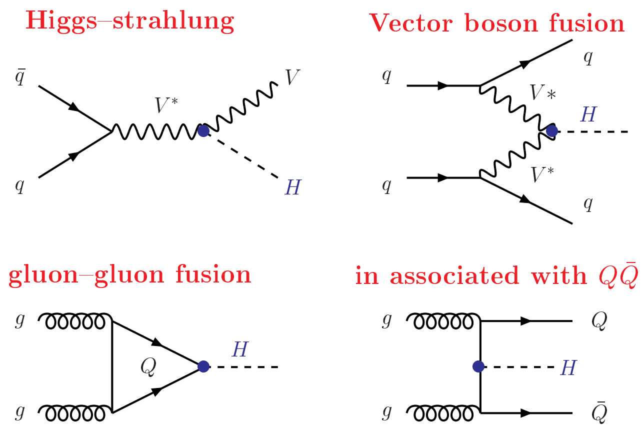
$$\boldsymbol{\Delta}\mathcal{M}_{\mathbf{11/12}}^2 \sim \mathbf{0}\,,\ \boldsymbol{\Delta}\mathcal{M}_{\mathbf{22}}^2 \sim \epsilon = \frac{\mathbf{3\,\bar{m}_t^4}}{\mathbf{2}\pi^{\mathbf{2}}\mathbf{v^2}\sin^{\mathbf{2}}\beta}\left[\log\frac{\mathbf{M_S^2}}{\mathbf{\bar{m}_t^2}} + \frac{\mathbf{X_t^2}}{\mathbf{M_S^2}}\left(\mathbf{1} - \frac{\mathbf{X_t^2}}{\mathbf{12\,M_S^2}}\right)\right]$$

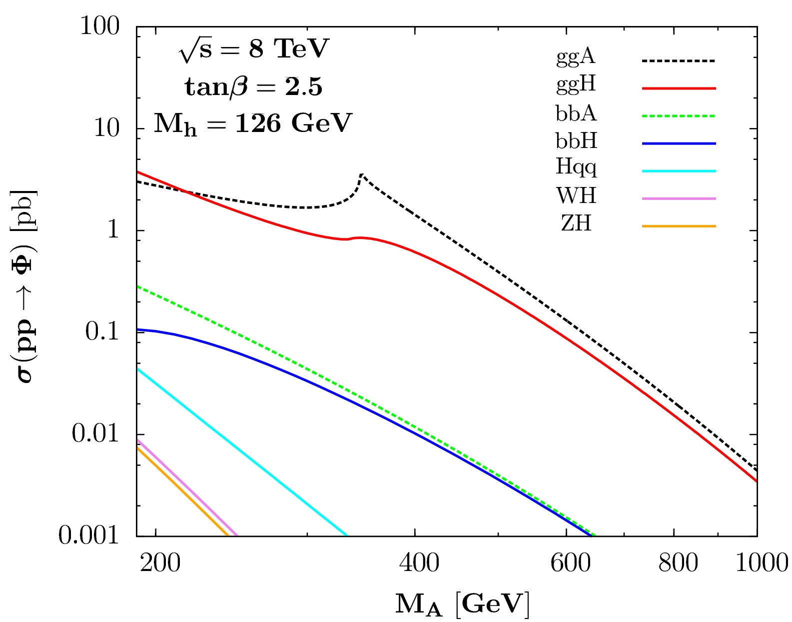
still a simple picture but with a few additional parameters $\mathrm{M_S}, \mathrm{X_t}$...

4. The Higgs sector of the MSSM

MSSM Higgs production: besides the SM–like h, the heavier H/A and $H^{\pm}$ s

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**
  – **in ΦV, $qq\Phi$ h/H complementary**
  – **additional mechanism: qq $\to$ A+h/H**
- **For $gg \to \Phi$ and $pp \to QQ\Phi$**
  – **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 $pp \to t\bar{b}H^-$**

At high tanβ values:
– **h as in SM with $M_h = 115 - 130$GeV**
– **dominant channel: $gg, b\bar{b} \to \Phi \to \tau\tau$**

4. The Higgs sector of the MSSM

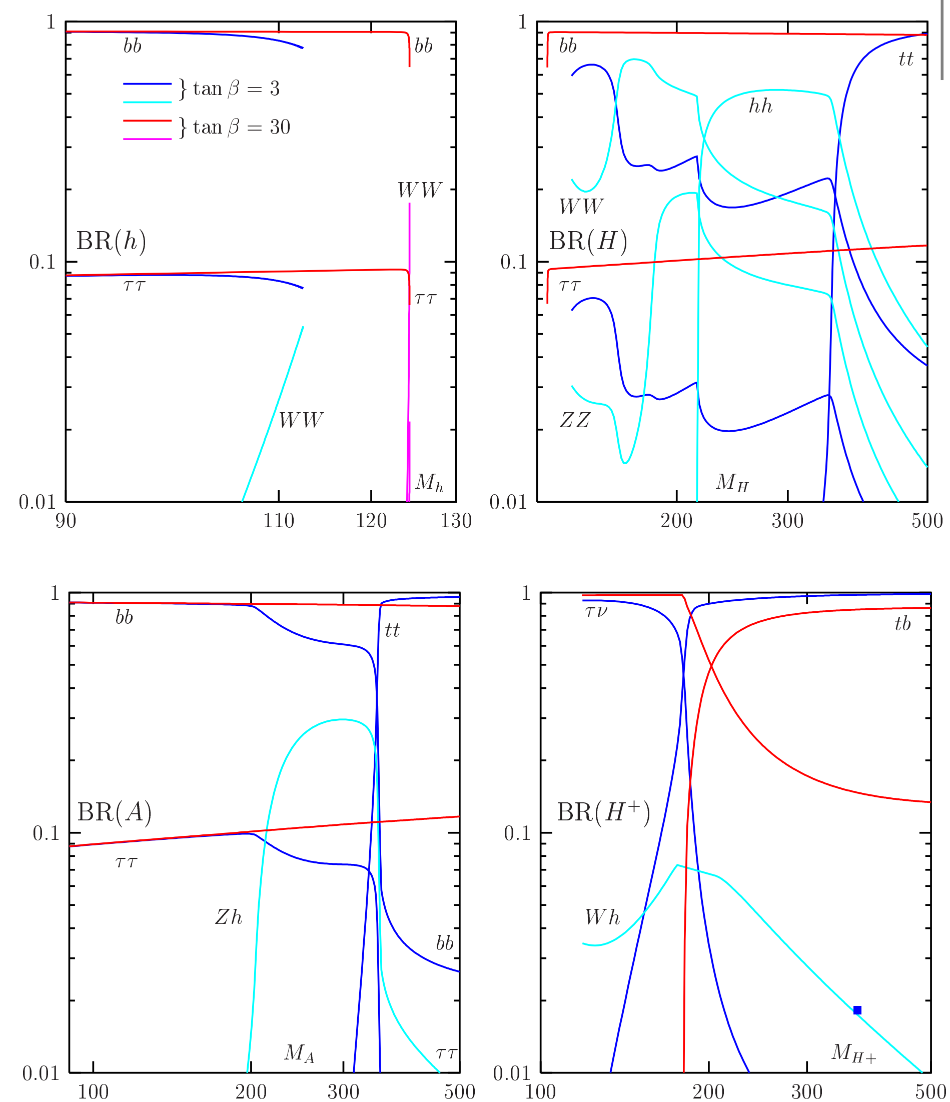
MSSM Higgs detection modes:

General features for h/H/A/H$^{\pm}$

- **h: same as $\mathrm{H_{SM}}$ in general (especially in decoupling limit).**
- **A: only $\mathrm{b\bar{b}}, \tau^+\tau^-$, $\mathrm{t\bar{t}}$ decays (no VV decays, hZ suppressed).**
- **H: same as A in general as $\mathbf{WW}, \mathbf{ZZ}, \mathbf{hh}$ modes suppressed.**
- **$\mathrm{H}^{\pm}$: $\tau\nu$ and tb decays (depending if $\mathrm{M_{H^\pm}} < $ or $>$ $\mathrm{m_t}$).**

– loop decays strongly suppressed

– possible new effects from SUSY!?



For tan$\beta \gg$1, only decays into b/τ:

BR: $\Phi \to \mathrm{b\bar{b}} \approx 90\%$, $\Phi \to \tau\tau \approx 10\%$

For tan$\beta \approx$1, other good channels:

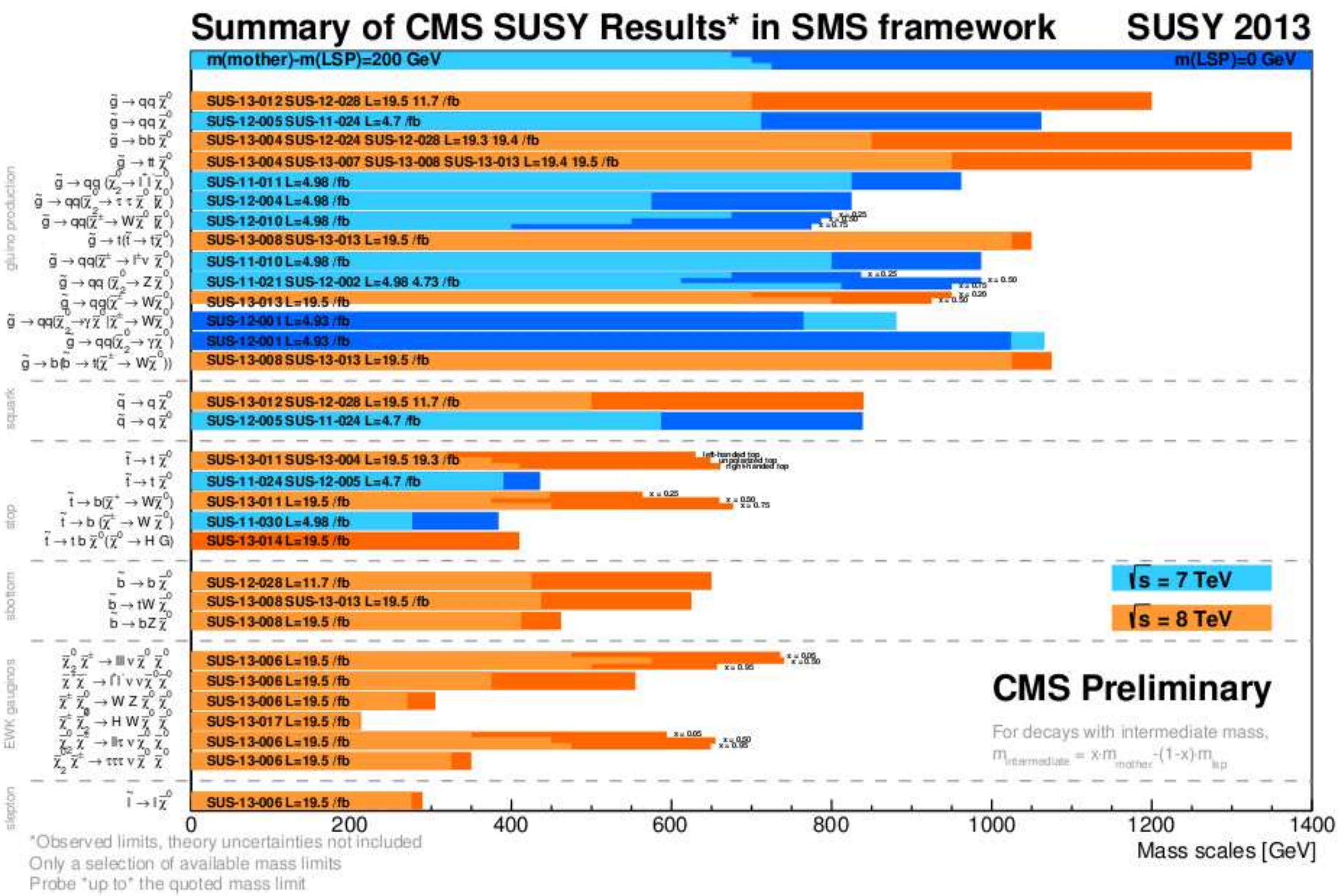
$$\mathbf{H/A \to tt, H \to WW, ZZ}$$
$$\mathbf{A \to hZ, H \to hh}$$

4. The Higgs sector of the MSSM

Of course, also searches for superparticles but no signal was found

$\Rightarrow$ **searches exclude squarks and gluinos with masses well beyond 1 TeV.**

$\Rightarrow$ **searches exclude weakly interacting superparticles up to few 100 GeV.**



5. Implications of LHC Higgs results on the MSSM

The mass value 126 GeV is rather large for the MSSM h boson,

$\Rightarrow$ one needs from the very beginning to almost maximize it...

Maximizing M_h is maximizing the radiative corrections; at 1-loop:

$$M_h \overset{M_A \gg M_Z}{\to} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

- **decoupling regime with $M_A \sim \mathcal{O}$(TeV);**
- **large values of tan$\beta \gtrsim 10$ to maximize tree-level value;**
- **maximal mixing scenario: $X_t = A_t - \mu \cot\beta = \sqrt{6} M_S$;**
- **heavy stops, i.e. large $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.**

We choose at maximum $M_S \lesssim 3$ TeV, not to have too much fine-tuning....

- **Do the complete job: two-loop corrections and full SUSY spectrum.**
- **Use RGE code (Suspect) with RC in $\overline{\rm DR}$/compare with FeynHiggs (OS).**

Perform a full scan of phenomenological MSSM with 22 free parameters:

- **determine regions of parameter space where $123 \leq M_h \leq 129$ GeV**

(3 GeV uncertainty includes both “experimental” and “theoretical” error);

- **require h to be SM–like: $\sigma(h) \times BR(h) \approx H_{SM}$ ($H = H_{SM)}$ later).**

Many anlayses! Here, the one from Arbey et al. 1112.3028+1207.1348.

5. Implications of LHC Higgs results on the MSSM

Main results:

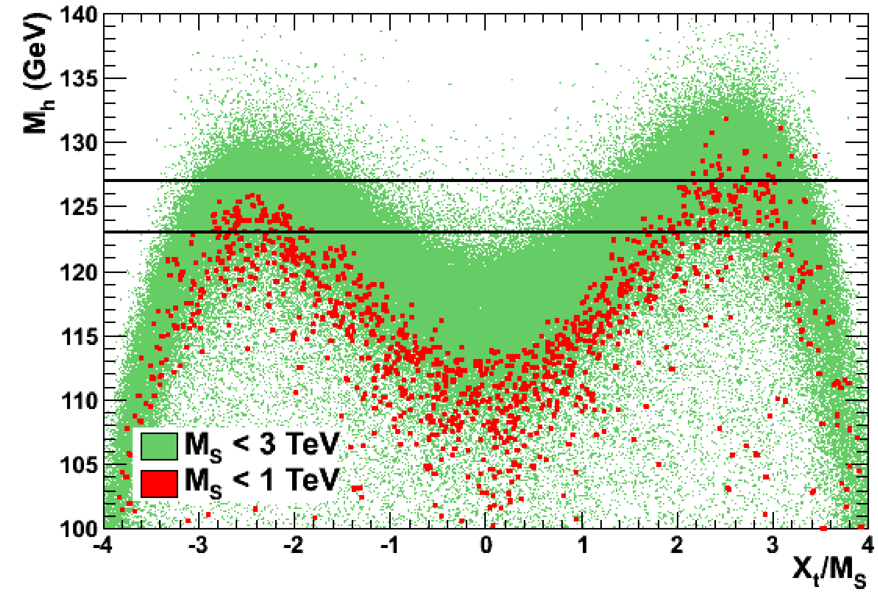
- Large $\mathrm{M_S}$ values needed:

– $\mathrm{M_S} \approx 1$ TeV: only maximal mixing,

– $\mathrm{M_S} \approx 3$ TeV: only typical mixing.

- Large tanβ values are favored,

but tan$\beta \approx 3$ possible if $\mathrm{M_S} \approx 3$TeV.



How light sparticles can be with the constraint $\mathrm{M_h} = 126$ GeV?

- 1s/2s gen. $\tilde{\mathrm{q}}$ should be heavy...

But not main player here: the stops:

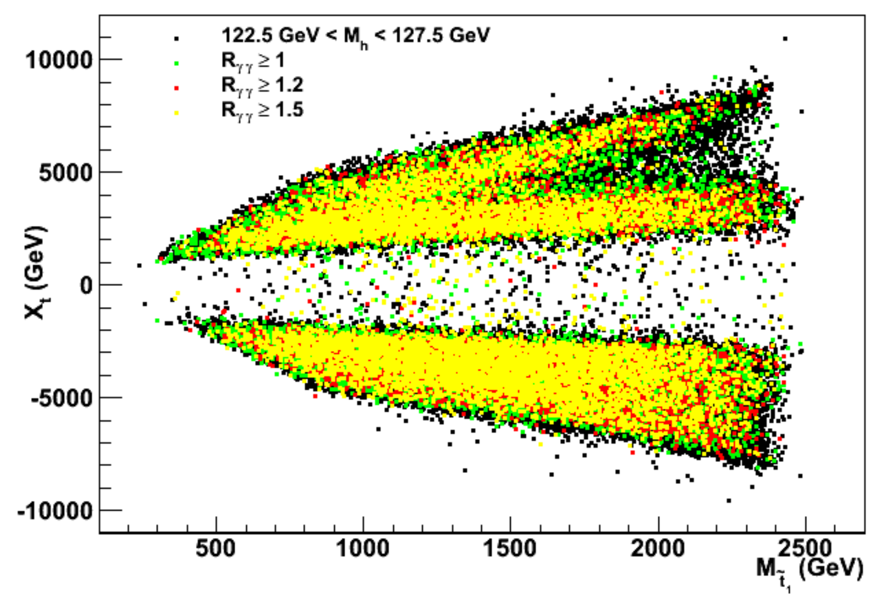
$\Rightarrow \mathrm{m}_{\tilde{\mathrm{t}}_1} \lesssim 500$ GeV still possible

(and compatible with direct limits).

- $\mathrm{M_1}, \mathrm{M_2}$ and μ unconstrained,
- non-univ. $\mathrm{m}_{\tilde{\mathrm{f}}}$: decouple $\tilde{\ell}$ from $\tilde{\mathrm{q}}$.

EW sparticles can be still very light

but watch out the new LHC limits..



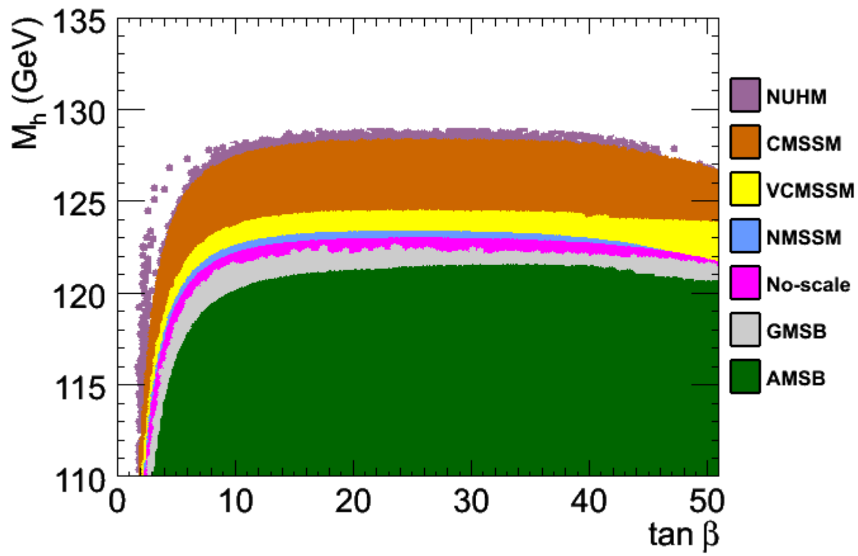
5. Implications of LHC Higgs results on the MSSM

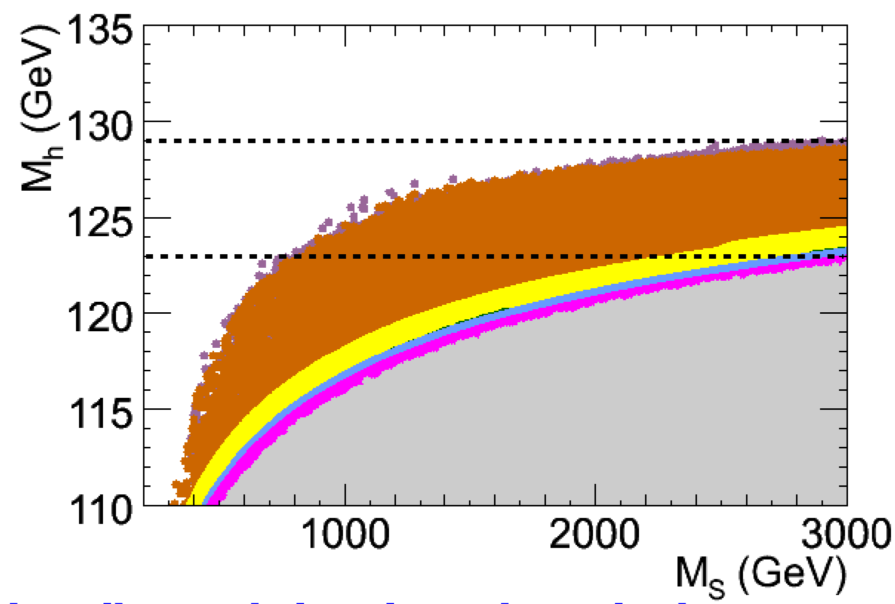
Constrained MSSMs are interesting from model building point of view:

– concrete schemes: SSB occurs in hidden sector $\xrightarrow{\text{gravity,..}}$ MSSM fields,
– provide solutions to many problems in general MSSM: CP, flavor, CCB,..
– parameters obey boundary conditions $\Rightarrow$ small number of basic inputs.

- **mSUGRA**: $\tan\beta\ ,\ m_{1/2}\ ,\ m_0\ ,\ A_0\ ,\ \text{sign}(\mu)$
- **GMSB:** $\tan\beta\ ,\ \text{sign}(\mu)\ ,\ M_{\rm mes}\ ,\ \Lambda_{\rm SSB}\ ,\ N_{\rm mess\ fields}$
- **AMSB:**, $m_0\ ,\ m_{3/2}\ ,\ \tan\beta\ ,\ \text{sign}(\mu)$

full scans of the model parameters with $123\ \text{GeV} \leq M_h \leq 129\ \text{GeV}$.





very strong constraints and some (minimal) models already ruled out...

5. Implications of LHC Higgs results on the MSSM

As the scale $\mathrm{M_S}$ seems to be large, consider two extreme possibilities.

• **Split SUSY: allow fine–tuning:**
scalars (including $\mathrm{H_2}$) at high scale
gauginos–higgsinos at weak scale
(unification+DM solutions still OK).
$\mathrm{M_h} \propto \log(\mathrm{M_S}/\mathrm{m_t}) \Rightarrow$ larger.

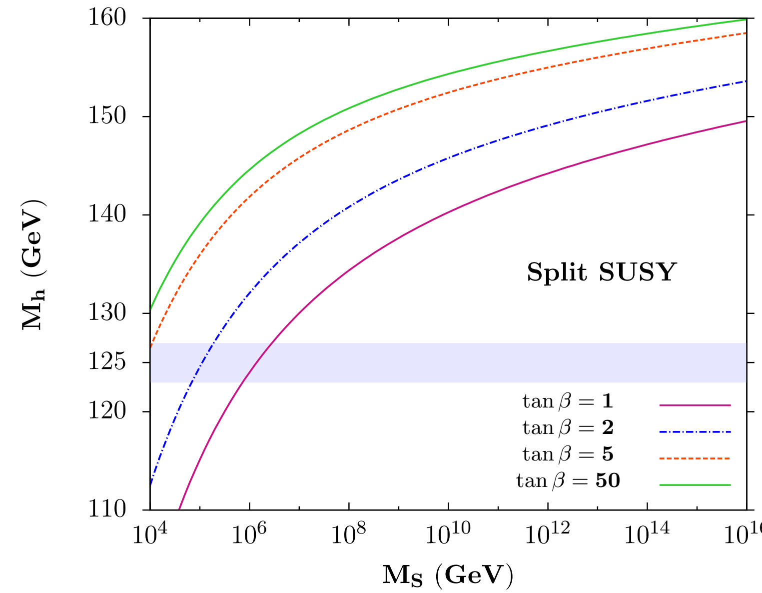
• **SUSY broken at the GUT scale:**
give up fine-tuning and everything else
still, $\lambda \propto \mathrm{M_H^2}$ related to gauge cplgs

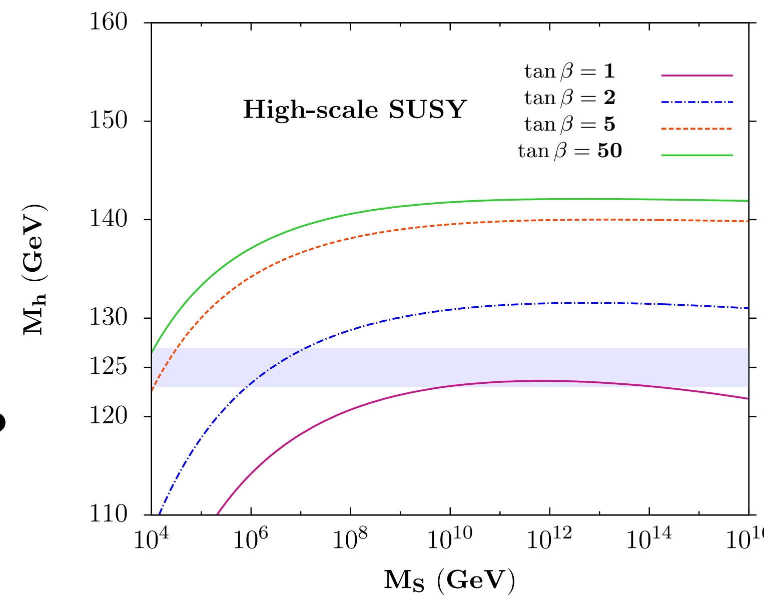
$$\lambda(\tilde{\mathrm{m}}) = \frac{\mathrm{g_1^2}(\tilde{\mathrm{m}}) + \mathrm{g_2^2}(\tilde{\mathrm{m}})}{8}(1 + \delta_{\tilde{\mathrm{m}}})$$

... leading to $\mathrm{M_H} =$120–140 GeV ...

In both cases small $\tan\beta$ are needed.
note 1: $\tan\beta \approx 1$ still possible,
note 2: $\mathrm{M_S}$ large but not $\mathrm{M_A}$ possible!?

Consider general MSSM with $\tan\beta \approx 1$!





5. Implications of LHC Higgs results on the MSSM

In principle, once the angles β and α known, all h couplings are fixed:

MSSM: $\mathbf{c_V^0 = \sin(\beta-\alpha)\,,\; c_t^0 = \cos\alpha/\sin\beta\,,\; c_b^0 = -\sin\alpha/\cos\beta}$

if only radiative corrections to masses $M_{h/H}$ and α taken into account.

However also direct/vertex corrections have to be included! $\Rightarrow$ Figure.

The two important SUSY (QCD) corrections affect the t,b couplings:

$\mathbf{c_b \approx c_b^0 \times [1 - \frac{\Delta_b}{1+\Delta_b} \times (1 + \cot\alpha\cot\beta)]}$ with $\tan\alpha \overset{M_A \gg M_Z}{\longrightarrow} \frac{-1}{\tan\beta}$

$$\mathbf{c_t \approx c_t^0 \times [1 + \frac{m_t^2}{4 m_{\tilde t_1}^2\, m_{\tilde t_2}^2}(m_{\tilde t_1}^2 + m_{\tilde t_2}^2 - (A_t - \mu\cot\alpha)(A_t + \mu\tan\alpha))]}$$

- c_τ, c_c and c_t from $pp \to Ht\bar t$ do not involve same vertex corrections.
- $gg \to h$ process has $\tilde t, \tilde b$ loops and $h \to \gamma\gamma$ has also $\tilde\tau$ and $\chi_i^\pm$ loops.

In general case, we need (at least) 7 couplings $c_g, c_\gamma, c_t, c_b, c_c, c_\tau, c_V$.
(not to mention the invisible Higgs decay width that enters all BRs...)

8 parameters fit difficult; simpler to make reasonable approximations:

- low sensitivity on $h \to c\bar c$, $h \to \tau\tau$ and $pp \to ttH$ at the LHC....
- in $h \to \gamma\gamma$ additional $\tilde b, \tilde\tau, \chi_1^\pm$ contributions smaller than those of $\tilde t$.

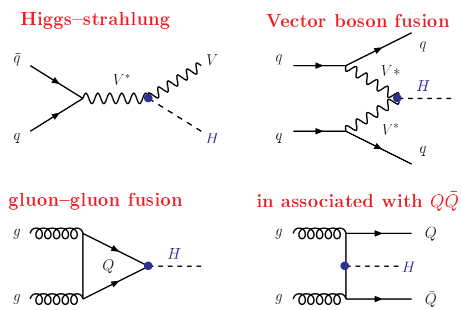
$\Rightarrow$ assume $c_c = c_t, c_\tau = c_b$ and $c_t(ttH) = c_t(ggF), c_\gamma \approx c_g \approx c_t$:

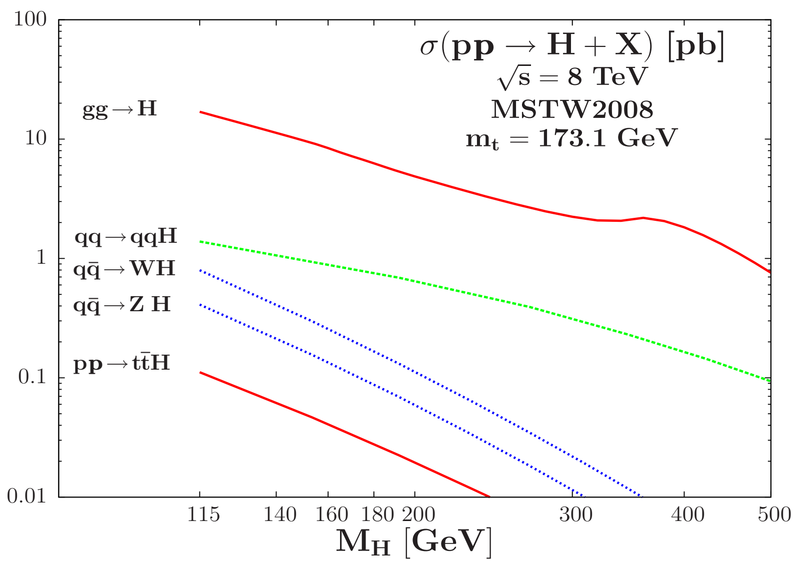
reduce the problem to a fit of three couplings: c_V, c_b, c_t.

5. Implications of LHC Higgs results on the MSSM

Adapt the SM Higgs rates to that of h close to the decoupling limit...

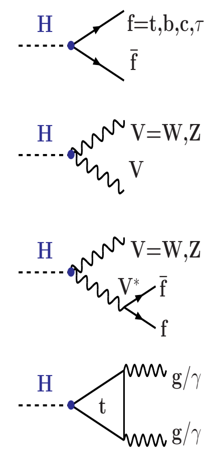
Main Higgs production channels:

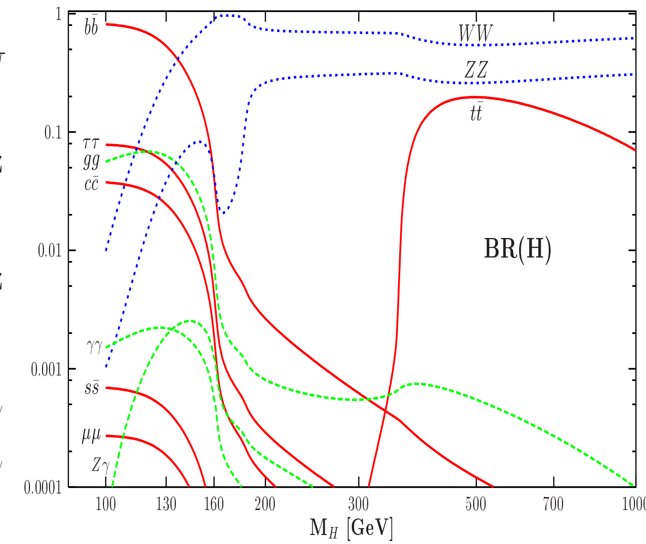




gg$\to$ h by far dominant process proceeds via heavy quark loops!

Higg decays branching ratios:





– $\mathbf{h \to b\bar{b} \approx 60\%}$: **dominant**

– $\mathbf{h \to cc, \tau\tau, gg = \mathcal{O}(\text{few } \%)}$

– $\mathbf{h \to \gamma\gamma, ZZ^* \to 4\ell^{\pm} \propto 10^{-3}}$

main points besides $\alpha, \beta \Rightarrow$

change in $h \to b\bar{b}$ drastic,

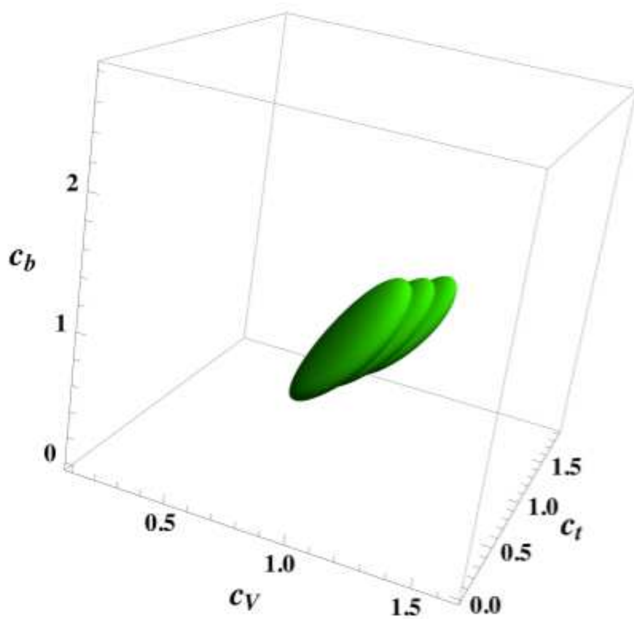
more loops in $h \to gg, \gamma\gamma$...

5. Implications of LHC Higgs results on the MSSM

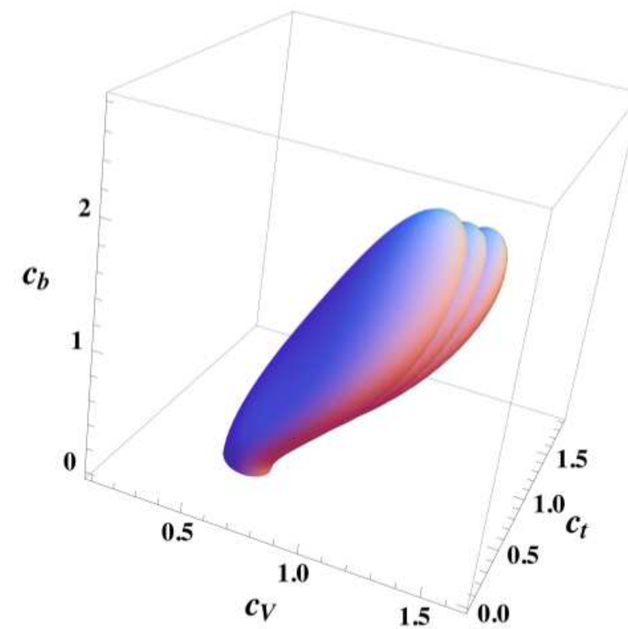
$\Rightarrow$ **general MSSM at LHC is described by M_h and c_V, c_t, c_b.**

3-dimensional fit in $[c_t, c_b, c_V]$ space: AD, Maiani,Polosa,Quevillon,Riquer

- **ATLAS+CMS 2013 data for signal strengths in all channels;**
- **consider the ($\approx$ 15–20%) theory uncertainty as a bias not nuisance;**
- **use ratios of signal strengths where theory uncertainty cancels out.**



general 1σ 3–dimension fit



general 3σ 3–dimension fit

Best-fit value: $c_t = 0.894,\ c_b = 1.007, c_V = 1.02$ with χ^2 =64.80 (71).

5. Implications of LHC Higgs results on the MSSM

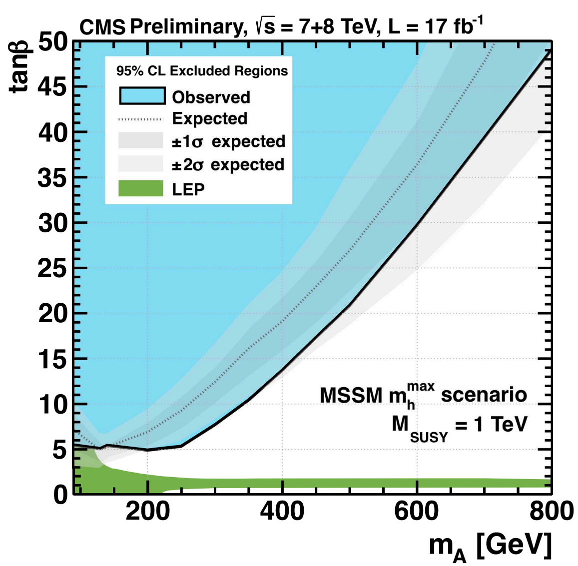
Most efficient channels for the production of the heavier MSSM Higgses.

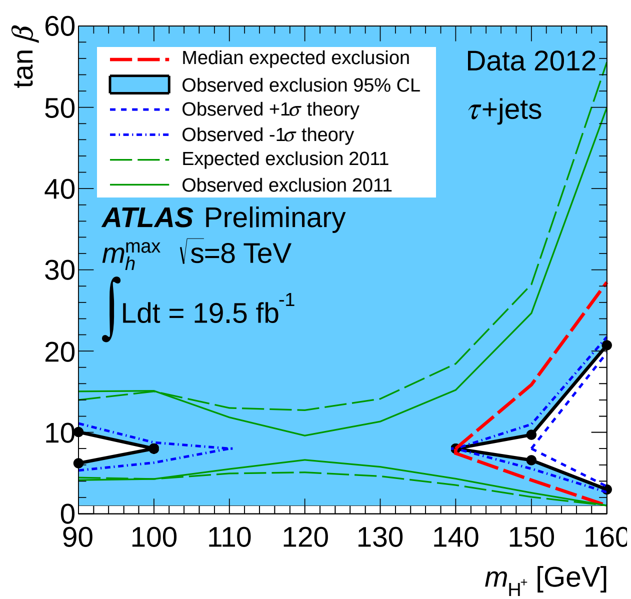
- **Searches for the $\mathrm{pp} \to \mathrm{A/H/(h)} \to \tau\tau$ resonant process:**

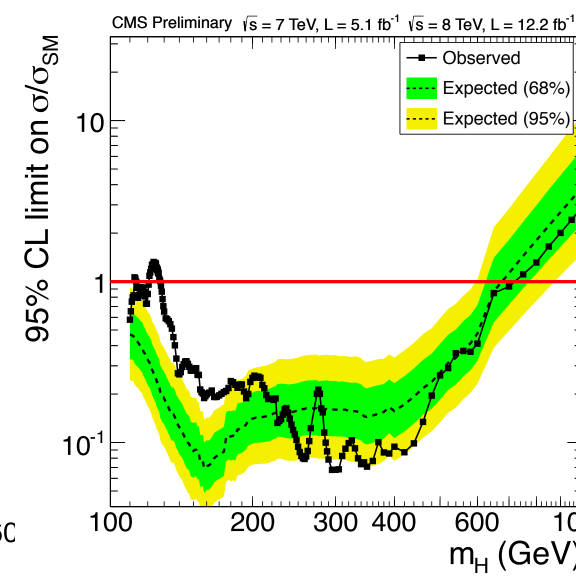
  $\Rightarrow$ **rules out high $\tan\beta$ for low $\mathrm{M_A}$ values.**
- **Searches for charged Higgs in $\mathrm{t} \to \mathrm{bH^+} \to \mathrm{b}\tau\nu$ decays:**

  $\Rightarrow$ **rules out almost any $\tan\beta$ value for $\mathrm{M_{H^\pm}} \lesssim 160$ GeV.**
- **Non observation of heavier Higgs bosons in H$\to$ZZ,WW modes:**

  $\Rightarrow$ **no analysis yet!? The width is different from SM-case.**
- **Also searches for $\mathrm{A} \to \mathrm{hZ}$ and $\mathrm{H} \to \mathrm{hh}$ but not in the MSSM....**
- **Searches for heavy tt resonances but not in the MSSM ($\mathrm{KK}, \mathrm{Z'}$)...**







5. Implications of LHC Higgs results on the MSSM

Model independent – effective – approach

Habemus MSSM (hMSSSM):

AD, Maiani,Polosa,Quevillon,Riquer

- **We turn** $M_h \approx M_Z |\cos 2\beta| +$**RC to**
  RC= 125 GeV - $f(M_A, \tan\beta)$

ie. we "trade" RC with the measured M_h

MSSM with only 2 inputs at HO: $M_A, \tan\beta$

$$M_H^2 = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}\right)$$

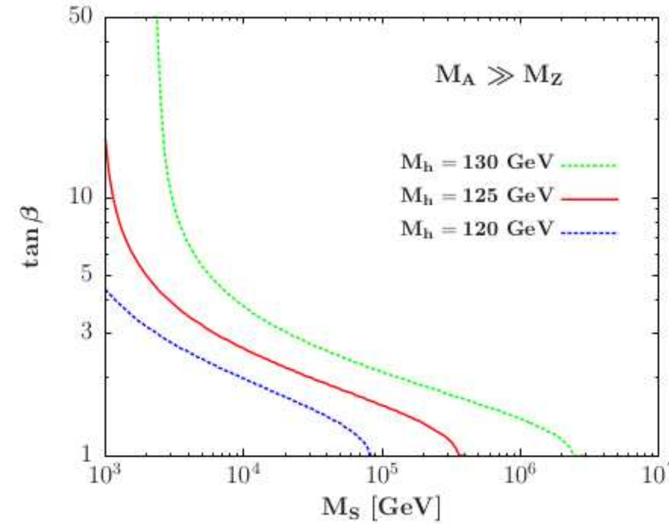
$$M_{H^\pm} \simeq \sqrt{M_A^2 + M_W^2}$$

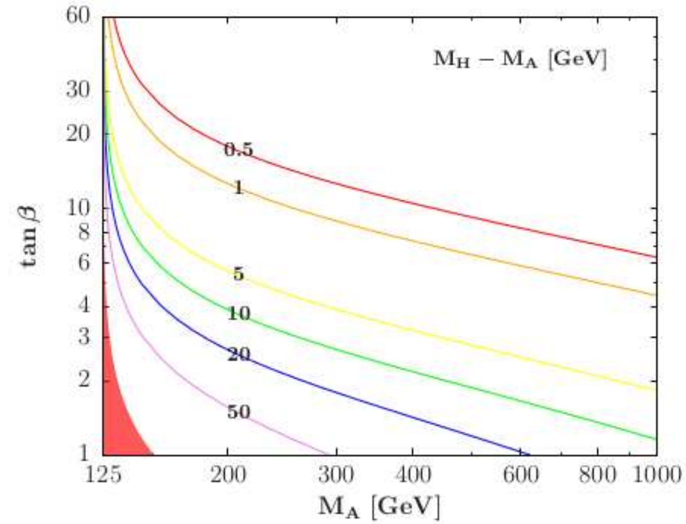
Clearly works when leading RC only:

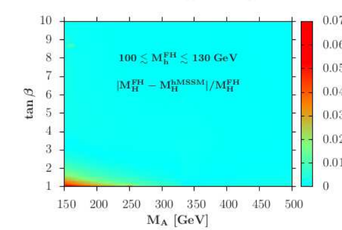
$$\Delta\mathcal{M}_{22}^2 = \frac{M_h^2(M_A^2+M_Z^2-M_h^2) - M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

But we checked that it is also good

in general, ie for $\Delta\mathcal{M}_{11,12}^2 \neq 0$.



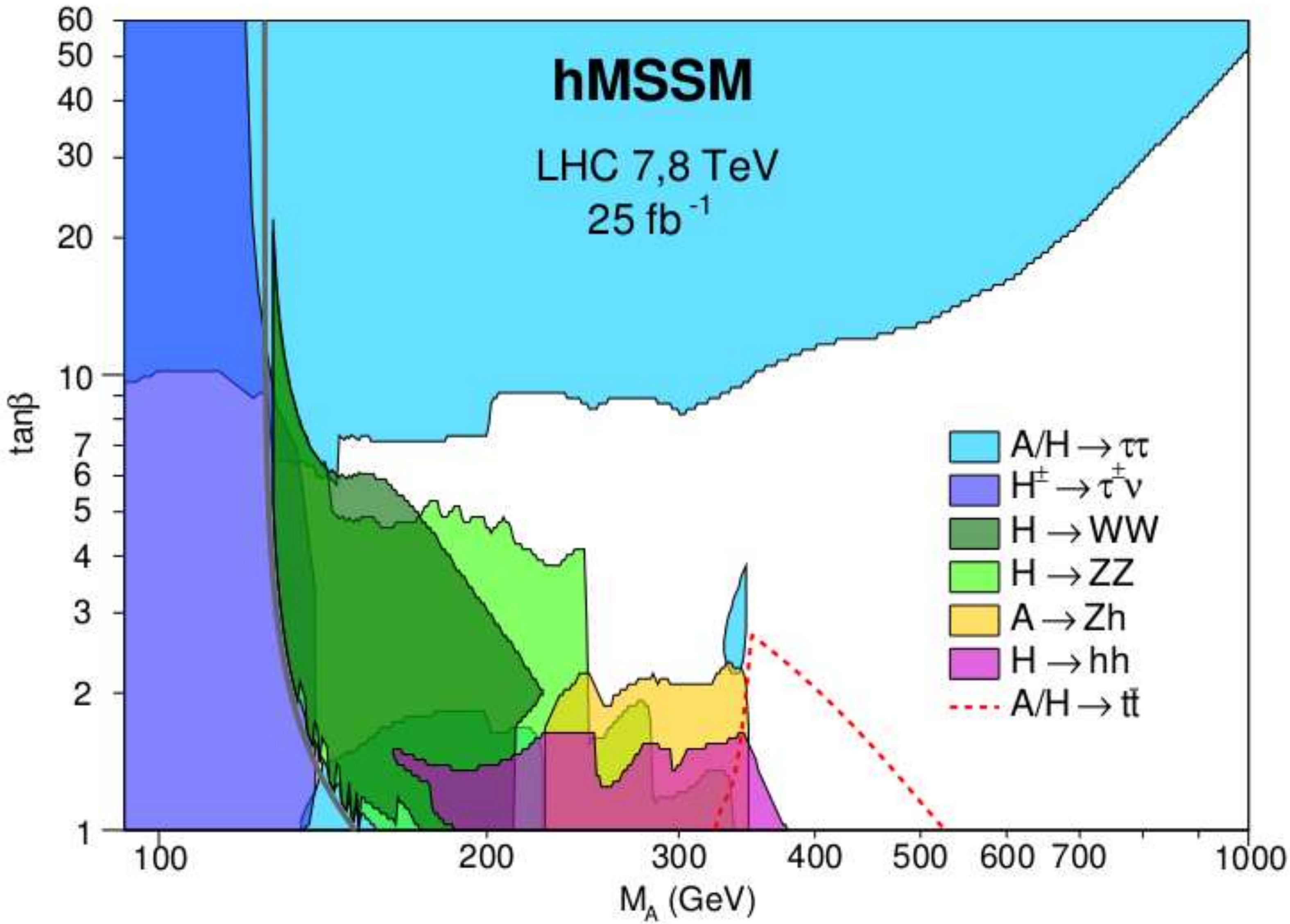




5. Implications of LHC Higgs results on the MSSM

LHC run 1 legacy on the MSSM $[\mathrm{M_A}, \tan\beta]$ plane in the hMSSM:

AD, Maiani,Polosa,Quevillon,Riquer (2015)



5. Implications of LHC Higgs results on the MSSM

Let us come back to the indirect constraints from the Higgs couplings:

If one assumes that sparticles are heavy and direct corrections are small

we are then back to the hMSSM with two free parameters

3D fit in $[c_t, c_b, c_V]$ space $\Rightarrow$ 2D fit on $\tan\beta, M_A$ parameters.

$c_t = 0.894$

$c_b = 1.007$

$c_V = 1.02$

$\Rightarrow$

$\tan\beta \approx 1$

$M_A \approx 560$ **GeV**

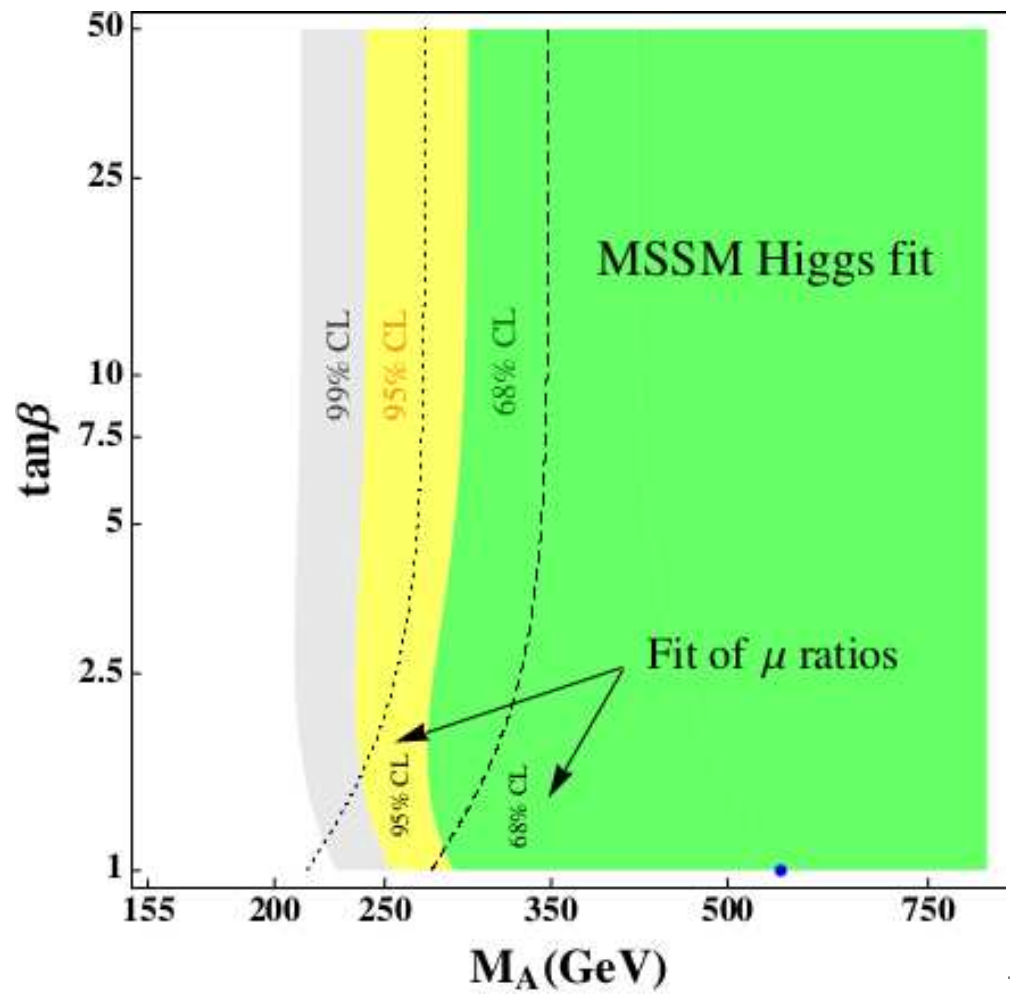
$\Rightarrow$

$M_H \approx 580$ **GeV**

$M_{H^\pm} \approx 560$ **GeV**

Maiani ....

close to be tested!



6. What next?

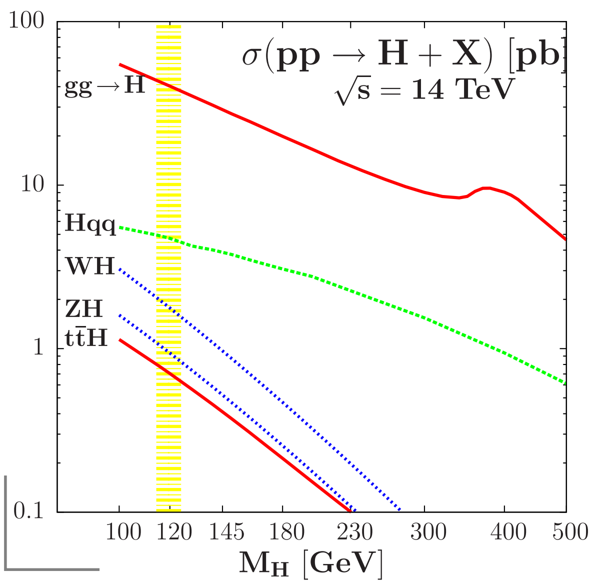
So what should we be doing the next 10–30 years in Particle Physics?

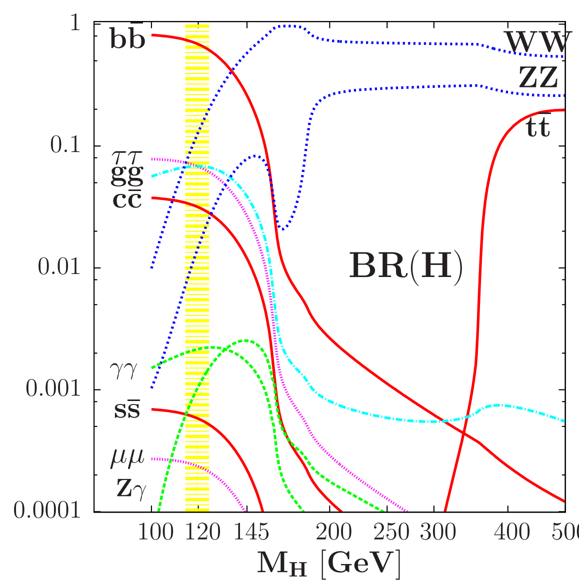
1) Need to check that H is indeed responsible of sEWSB (and SM-like?)

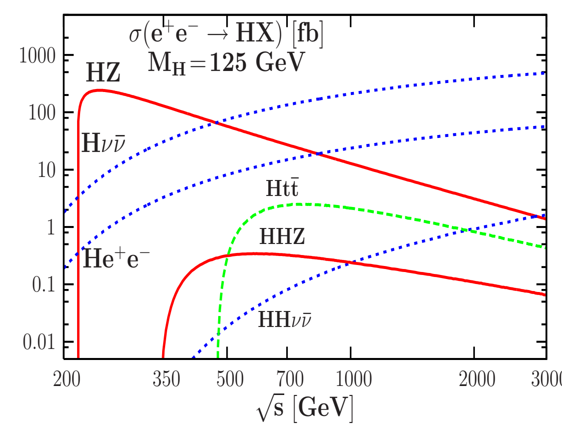
$\Rightarrow$ measure its fundamental properties in the most precise way:

- **its mass and total decay width (invisible width due to dark matter?),**
- **its spin–parity quantum numbers (CP violation for baryogenesis?),**
- **its couplings to fermions and gauge bosons and check if they are only proportional to particle masses (no new physics contributions?),**
- **its self-couplings to reconstruct the potential V_S that makes EWSB.**

Possible for $M_H \approx$ 125 GeV as all production/decay channels useful!







6. What next?

- Look at various H production/decay channels and measure $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$
- But large errors mainly due to:

– experimental: stats, system., lumi...

– theory: PDFs, HO/scale, jetology...

total error about 15–20% in $\mathrm{gg} \to \mathrm{H}$

Hjj contaminates VBF (now 30%)..

$\Rightarrow$ ratios of σxBR: many errors out!

Deal with width ratios $\Gamma_{\mathrm{X}}/\Gamma_{\mathrm{Y}}$

– TH on σ and some EX errors

– parametric errors in BRs

– TH ambiguities from $\Gamma_{\mathrm{H}}^{\mathrm{tot}}$

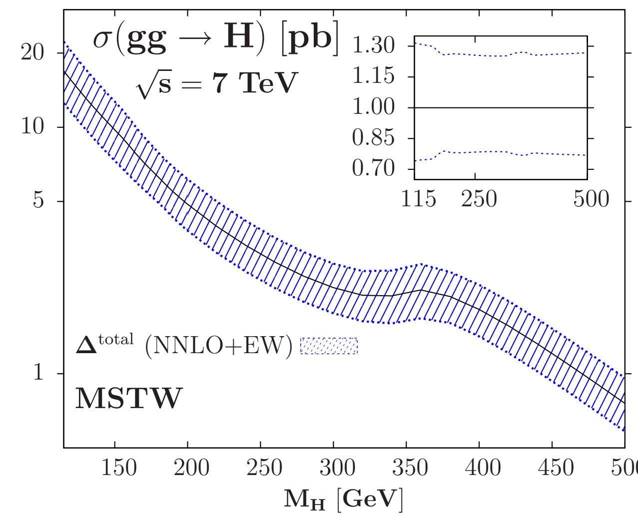
- Achievable accuracy:

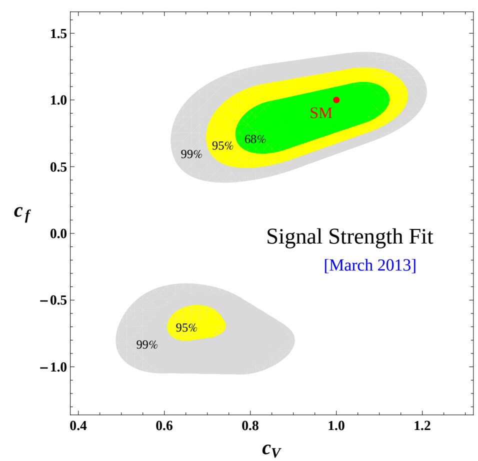
– now: 20–30% on $\mu_{\frac{\gamma\gamma}{\mathrm{VV}}}, \mu_{\frac{\tau\tau}{\mathrm{VV}}}$

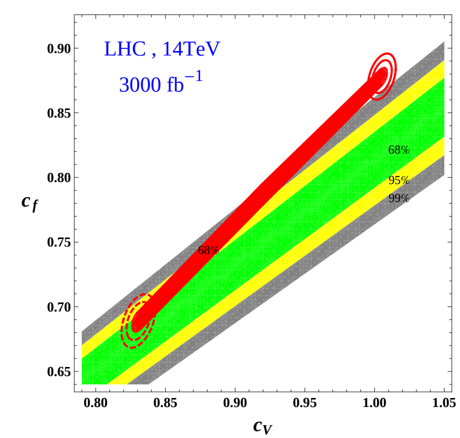
– future: few % at HL–LHC!

Sufficient to probe BSM physics?

Baglio...







Moreau...

6. What next?

- **Total width**: $\Gamma_H = 4$ MeV, too small to be resolved experimentally.
– very loose bound from interference gg$\to$ZZ (a factor 10 at most..).
– no way to access it indirectly (via production rates) in a precise way.
- **Invisible decay width:** more easily accessible at the LHC

Direct measurement:

$q\bar{q} \to HZ$ and $qq \to Hqq$; $H \to \mathrm{inv}$

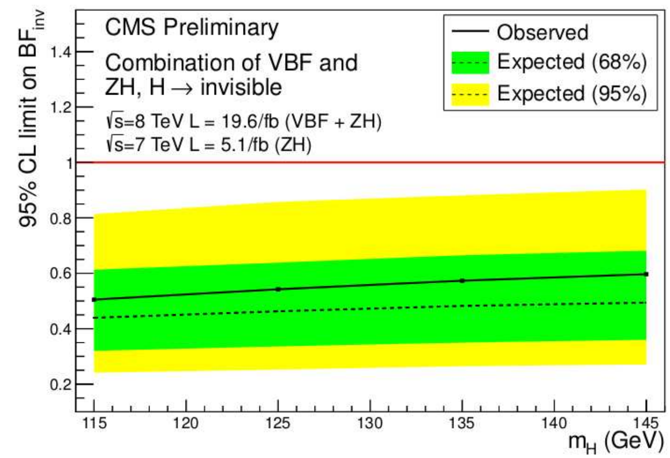
Combined HZ+VBF search from CMS

$\mathrm{BR_{inv}} \lesssim$ 50%@95%CL for SM Higgs

More promising in the future: monojets

$gg \to H + j \to j + \not{E}_T$

Falkowski...



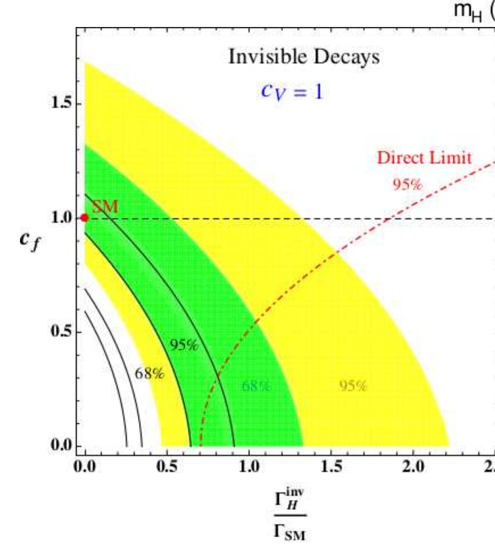
Indirect measurement:

again assume SM–like Higgs couplings

constrain width from signal strengths

$\mathrm{BR_{inv}} \lesssim 50\%$@95%CL for $c_f = c_V = 1$

Moreau...



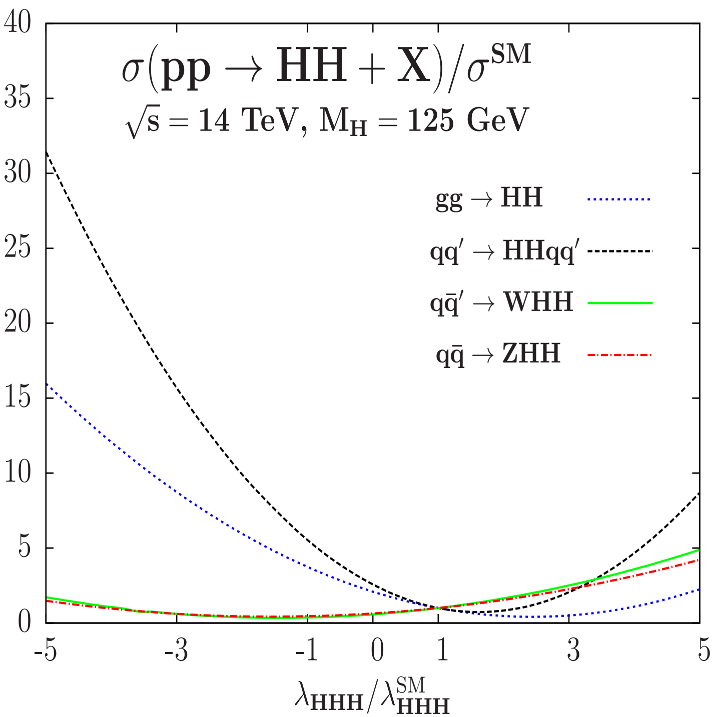
Improvement in future: 10% @ HL–LHC?

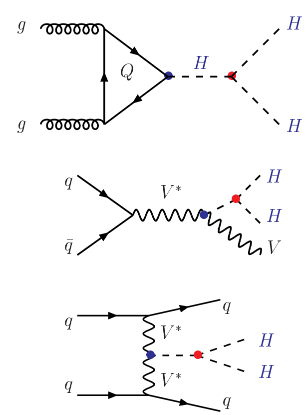
6. What next?

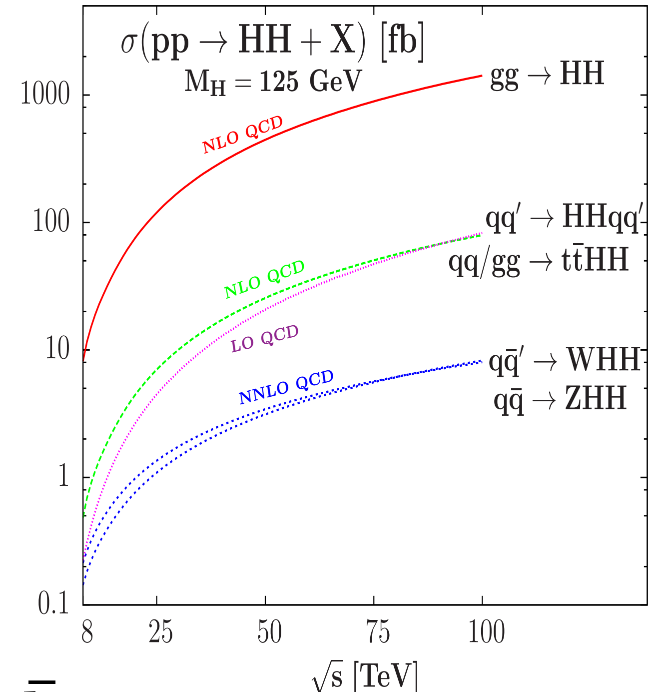
Another challenge: measure Higgs self-couplings and access to V_H.

- g_{H^3} from $pp \to HH + X \Rightarrow$
- g_{H^4} from pp→3H+X, hopeless.

Various processes for HH prod:
only $gg \to HHX$ relevant...





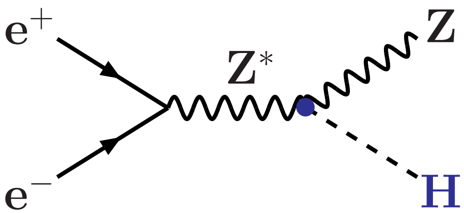


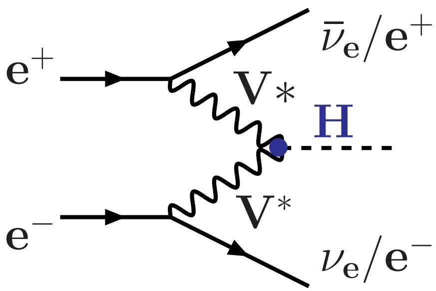
Baglio et al., arXiv:1212.5581

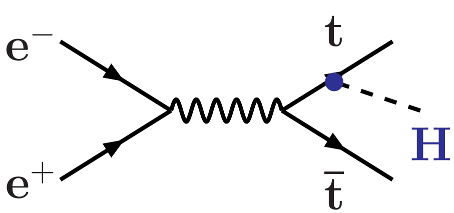
- $H \to b\bar{b}$ **decay alone not clean**
- $H \to \gamma\gamma$ **decay very rare,**
- $H \to \tau\tau$ **would be possible?**
- $H \to WW$ **not useful?**

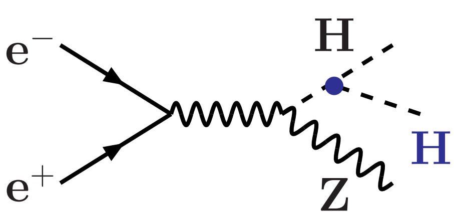
– $bb\tau\tau$, $bb\gamma\gamma$ **viable?**
– **but needs very large luminosity.**

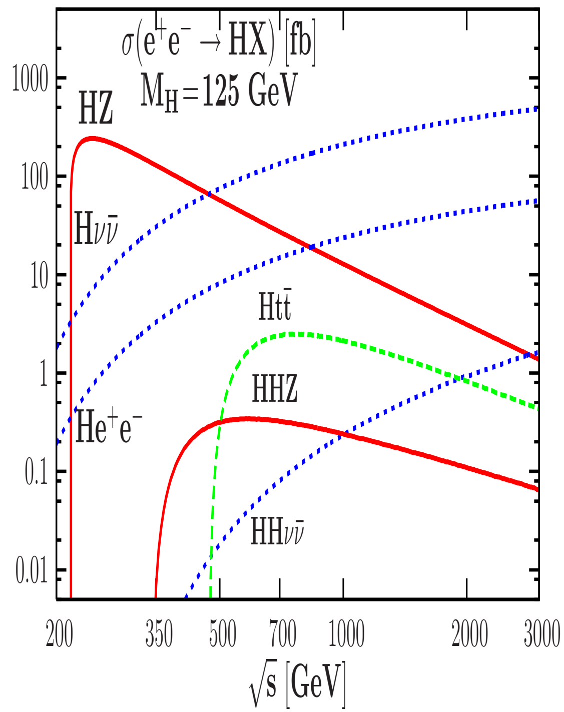
6. What next?











Very precise measurements mostly at $\sqrt{s} \lesssim$ 500 GeV and mainly in $e^+e^- \to ZH$ (with $\sigma \propto 1/s$) and ZHH, ttH

g_{HWW}	± 0.012
g_{HZZ}	± 0.012
g_{Hbb}	± 0.022
g_{Hcc}	± 0.037
$g_{H\tau\tau}$	± 0.033
g_{Htt}	± 0.030
λ_{HHH}	± 0.22
M_H	± 0.0004
Γ_H	± 0.061
CP	± 0.038

$\Rightarrow$ **difficult to be beaten by anything else for $\approx$ 125 GeV Higgs**

$\Rightarrow$ **welcome to the e^+e^- precision machine!**

6. What next?

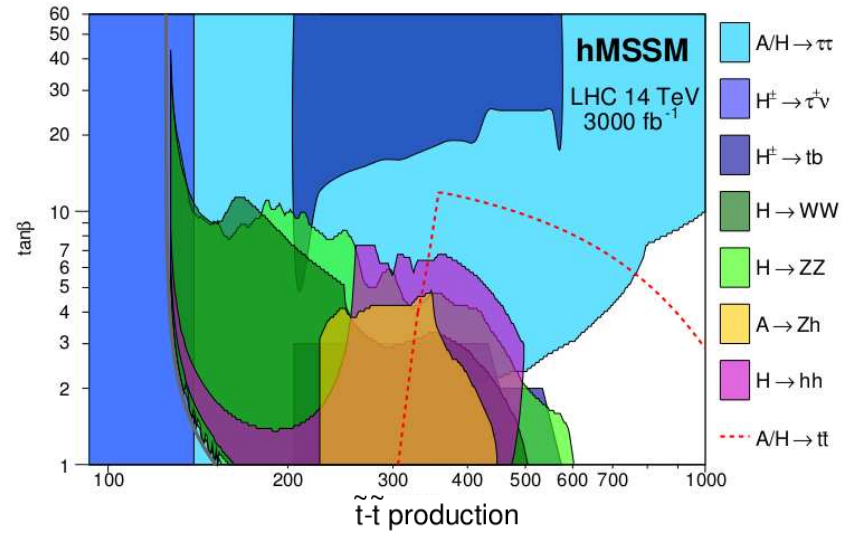
2) Fully probe the TeV scale that is relevant for the hierarchy problem
$\Rightarrow$ continue to search for heavier Higgses and new (super)particles.

- **Search for heavier SUSY Higgses:**

– $\mathrm{pp} \to \mathrm{H/A} \to \tau\tau, \mathrm{t\bar{t}}$
– $\mathrm{pp} \to \mathrm{H} \to \mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$
– $\mathrm{pp} \to \mathrm{A} \to \mathrm{hZ}$
– $\mathrm{pp} \to \mathrm{H^-t} \to \mathrm{Wb}\tau\nu$

$\Rightarrow$ **extend reach as much as possible.**

AD, Maiani,Polosa,Quevillon (2013) $\Rightarrow$



- **Search for supersymmetric particles:**

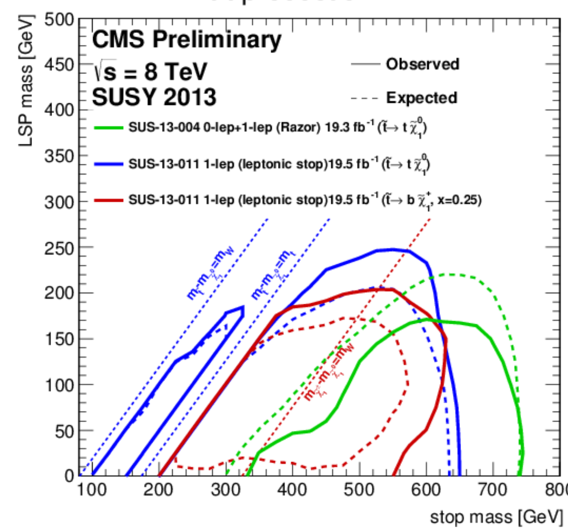
(not only strong but also electroweak)

– squarks and gluinos up to a few TeV,

– chargino/neutralino/sleptons to 1 TeV,

– LSP/DM neutralino upto few 100 GeV.

example of CMS reach in $\tilde{t}/\chi_1^0$ space $\Rightarrow$



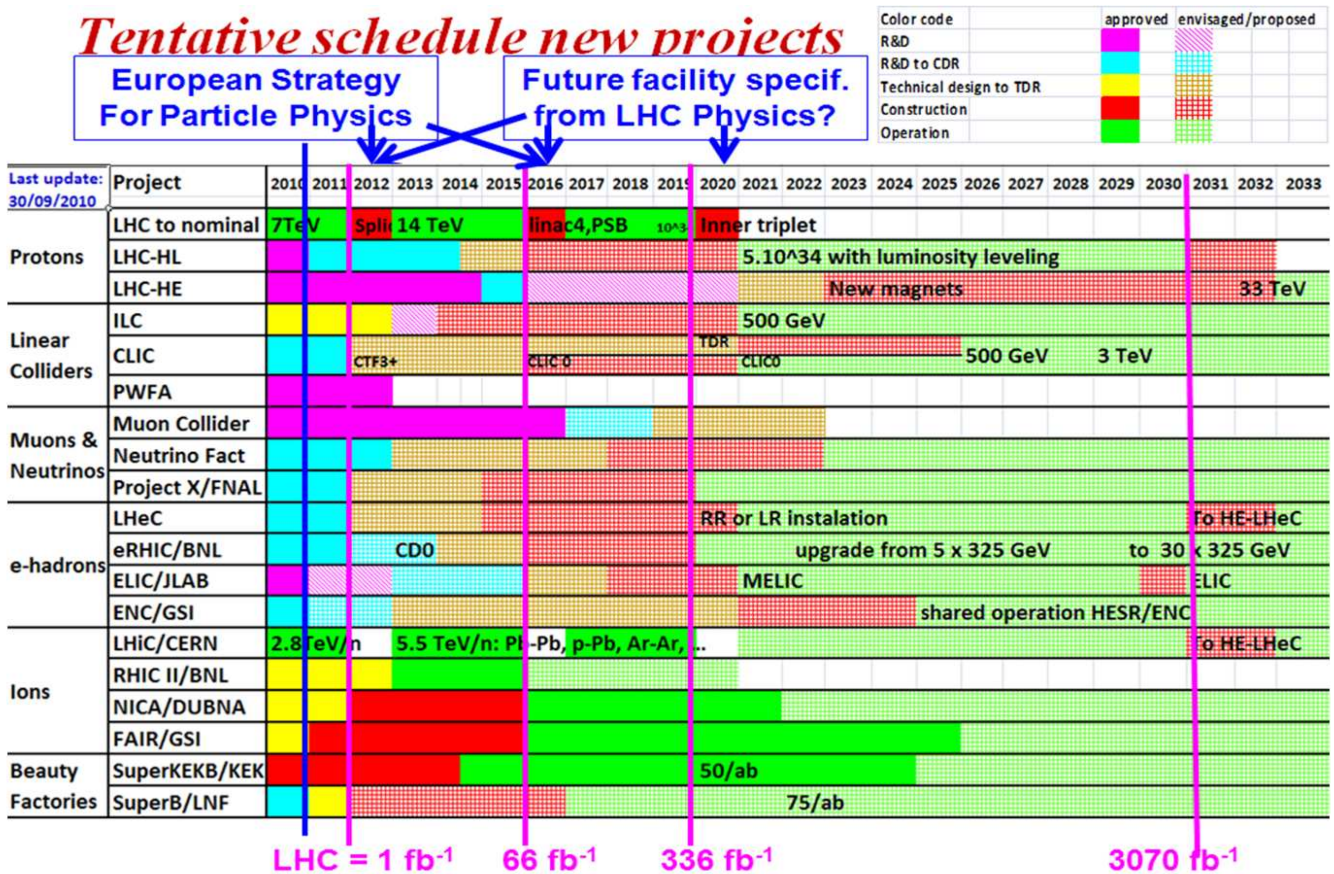
3) Search for any new particle: new $\mathrm{f}, \mathrm{Z'}, \mathrm{V_{KK}}$, etc... at TeV scale!

6. What next?

Hence, we need to continue search for New Physics and falsify the SM:

- **indirectly via high precision Higgs measurements (HL-LHC, ILC, ...),**
- **directly via heavy particle searches at high-energy (HE-LHC, CLIC),**

and we should plan/prepare/construct the new facilities already now!



See Patrick Janot Lectures!

6. What next?

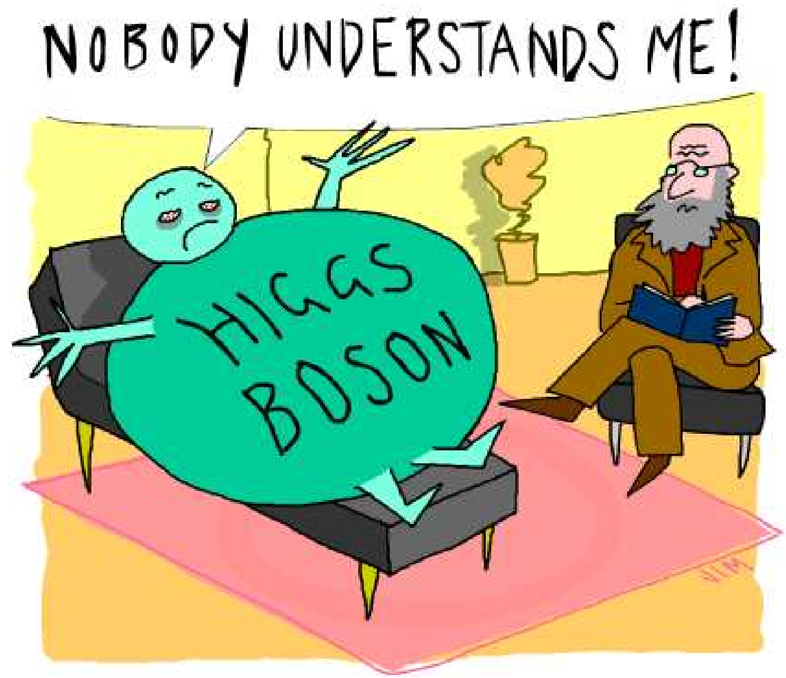
The end of the story is not yet told!

“Now, this is not the end.
It is not even the beginning to the end.
But it is perhaps the end of the beginning.”

Sir Winston Churchill, November 1942
(after the battle of El-Alamein, Egypt...).

We hope that <u>at the end</u> we finally understand the EWSB mechanism.
But there is a long way until then,
and there might be many surprises.

We should keep going!



A: The Higgs mechanism in the SM and constraints

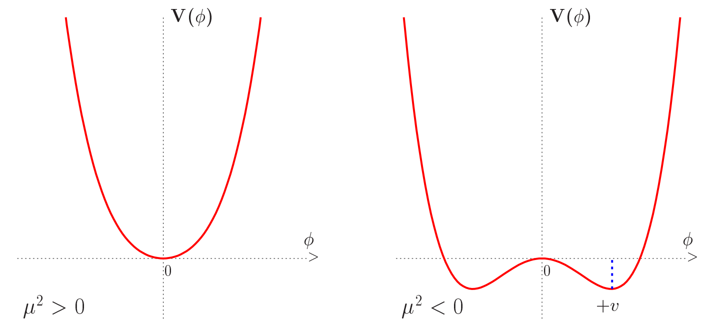
Brout-Englert-Higgs: spontaneous electroweak symmetry breaking $\Rightarrow$
introduce a new doublet of complex scalar fields: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, $Y_\Phi = +1$
with a Lagrangian density that is invariant under $SU(2)_L \times U(1)_Y$

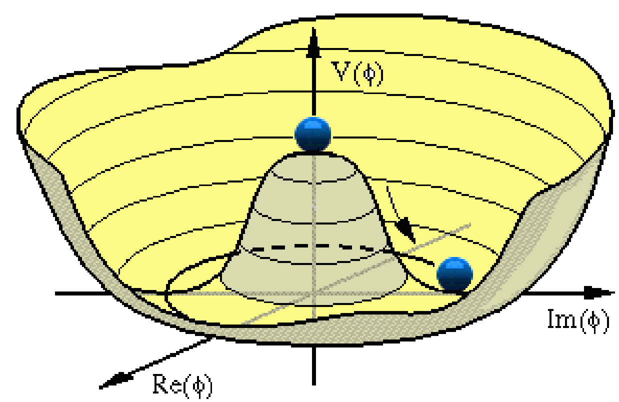
$$\mathcal{L}_S = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$\mu^2 > 0$: **4 scalar particles..**
$\mu^2 < 0$: Φ **develops a vev:**

$$\langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

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





– symmetric minimum: unstable
– true vacuum: degenerate

$\Rightarrow$ to obtain the physical states,
write $\mathcal{L}_S$ with the true vacuum
(diagonalised fields/interactions).

A: The Higgs mechanism in the SM and constraints

- **Write Φ in terms of four fields $\theta_{1,2,3}(x)$ and H(x) at 1st order:**

$$\Phi(x) = e^{i\theta_a(x)\tau^a(x)/v} \frac{1}{\sqrt{2}}\binom{0}{v+H(x)} \simeq \frac{1}{\sqrt{2}}\binom{\theta_2+i\theta_1}{v+H-i\theta_3}$$

- **Make a gauge transformation on Φ to go to the unitary gauge:**

$$\Phi(x) \to e^{-i\theta_a(x)\tau^a(x)}\,\Phi(x) = \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$$

- **Then fully develop the term $|D_\mu\Phi)|^2$ of the Lagrangian $\mathcal{L}_S$:**

$$|D_\mu\Phi)|^2 = \left|\left(\partial_\mu - ig_1\frac{\tau_a}{2}W_\mu^a - i\frac{g_2}{2}B_\mu\right)\Phi\right|^2$$

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{i}{2}(g_2W_\mu^3+g_1B_\mu) & -\frac{ig_2}{2}(W_\mu^1-iW_\mu^2) \\ -\frac{ig_2}{2}(W_\mu^1+iW_\mu^2) & \partial_\mu+\frac{i}{2}(g_2W_\mu^3-g_1B_\mu)\end{pmatrix}\binom{0}{v+H}\right|^2$$

$$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8}g_2^2(v+H)^2|W_\mu^1+iW_\mu^2|^2 + \frac{1}{8}(v+H)^2|g_2W_\mu^3-g_1B_\mu|^2$$

- **Define the new fields $W_\mu^\pm$ and Z_μ [A_μ is the orthogonal of Z_μ]:**

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)\,,\; Z_\mu = \frac{g_2W_\mu^3-g_1B_\mu}{\sqrt{g_2^2+g_1^2}}\,,\; A_\mu = \frac{g_2W_\mu^3+g_1B_\mu}{\sqrt{g_2^2+g_1^2}}$$

$$\text{with}\;\; \sin^2\theta_W \equiv g_2/\sqrt{g_2^2+g_1^2} = e/g_2$$

A: The Higgs mechanism in the SM and constraints

- And pick up the terms which are bilinear in the fields $\mathbf{W^\pm, Z, A}$:

$$\mathbf{M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu}$$

$\Rightarrow$ 3 degrees of freedom for $\mathbf{W_L^+, W_L^-, Z_L}$ and thus $\mathbf{M_{W^\pm}, M_Z}$:

$$\mathbf{M_W = \frac{1}{2} v g_2 \;,\; M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2} \;,\; M_A = 0 \;,}$$

with the value of the vev given by: $\mathbf{v = 1/(\sqrt{2} G_F)^{1/2} \sim 246\ GeV}$.

$\Rightarrow$ the photon stays massless and $\mathbf{U(1)_{QED}}$ is preserved as it should.

- For fermion masses, use <u>same</u> doublet field Φ and its <u>conjugate</u> field $\tilde{\Phi} = i\tau_2 \Phi^*$ and introduce $\mathcal{L}_{\rm Yuk}$ which is invariant under SU(2)xU(1):

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

$$\mathbf{= -\frac{1}{\sqrt{2}} f_e (\bar{\nu}_e, \bar{e}_L) \binom{0}{v+H} e_R \cdots = -\frac{1}{\sqrt{2}} (v + H) \bar{e}_L e_R \cdots}$$

$$\Rightarrow \mathbf{m_e = \frac{f_e\, v}{\sqrt{2}} \;,\; m_u = \frac{f_u\, v}{\sqrt{2}} \;,\; m_d = \frac{f_d\, v}{\sqrt{2}}}$$

With same Φ, we have generated gauge boson and fermion masses, while preserving SU(2)xU(1) gauge symmetry (which is now hidden)!

What about the residual degree of freedom?

A: The Higgs mechanism in the SM and constraints

It will correspond to the physical spin–zero scalar Higgs particle, H.

The kinetic part of H field, $\frac{1}{2}(\partial_\mu H)^2$, comes from $|D_\mu \Phi)|^2$ term.

Mass and self-interaction part from $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$:

$$V = \frac{\mu^2}{2}(0, v + H)\binom{0}{v+H} + \frac{\lambda}{2}|(0, v + H)\binom{0}{v+H}|^2$$

Doing the exercise you find that the Lagrangian containing H is,

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V = \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

The Higgs boson mass is given by: $M_H^2 = 2\lambda v^2 = -2\mu^2$.

The Higgs triple and quartic self–interaction vertices are:

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

What about the Higgs boson couplings to gauge bosons and fermions?

They were almost derived previously, when we calculated the masses:

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

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

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

A: The Higgs mechanism in the SM and constraints

Propagators of the gauge and Goldstone bosons in a general ξ gauge:

$\longrightarrow \mathbf{q}$ $\quad \frac{-i}{q^2-M_V^2+i\epsilon}\left[g_{\mu\nu} + (\xi-1)\frac{q_\mu q_\nu}{q^2-\xi M_V^2}\right]$

$\omega^{\pm}, \omega^0 :$ $\quad \longrightarrow$ **q** - - - - - - - - - - $\quad \frac{-i}{q^2-\xi M_V^2+i\epsilon}$

$\xi = \infty$: **Landau gauge**

$\xi = 1$: **'t Hooft-Feynman**

● **In unitary gauge, Goldstones do not propagate and gauge bosons have usual propagators of massive spin–1 particles (old IVB theory).**

● **Massive boson polarisations:** $\epsilon_\pm = \frac{1}{\sqrt{2}}(0,1,\pm \mathrm{i},0)$, $\epsilon_\mathrm{L} = \frac{1}{\mathrm{m}}(\mathrm{p_Z},0,0,\mathrm{E})$: **longitudinal polarisation dominates largely,** $\epsilon_\mathrm{L} \propto \mathrm{E}$, **at high energies..**

● **At very high energies,** $\sqrt{\mathrm{s}} \gg \mathrm{M_V}$, **a good approximation is** $\mathrm{M_V} \sim 0$. **The** $\mathrm{V_L}$ **components of V can be replaced by the Goldstones,** $\mathrm{V_L} \to \mathrm{w}$.

● **In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones; in VV scattering eg:**

$$\mathrm{A}(\mathrm{V_L^1}\cdots\mathrm{V_L^n} \to \mathrm{V_L^1}\cdots\mathrm{V_L^{n'}}) = (\mathrm{i})^\mathrm{n}(-\mathrm{i})^{\mathrm{n}'}\mathrm{A}(\mathrm{w^1}\cdots\mathrm{w^n} \to \mathrm{w^1}\cdots\mathrm{w^{n'}})$$

Thus, we can simply replace Vs by ws in the scalar potential and use ws:

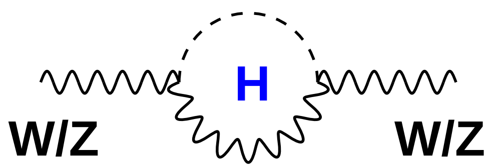
$$\mathrm{V} = \frac{\mathrm{M_H^2}}{2\mathrm{v}}(\mathrm{H^2} + \mathrm{w_0^2} + 2\mathrm{w^+w^-})\mathrm{H} + \frac{\mathrm{M_H^2}}{8\mathrm{v^2}}(\mathrm{H^2} + \mathrm{w_0^2} + 2\mathrm{w^+w^-})^2$$

A: The Higgs mechanism in the SM and constraints

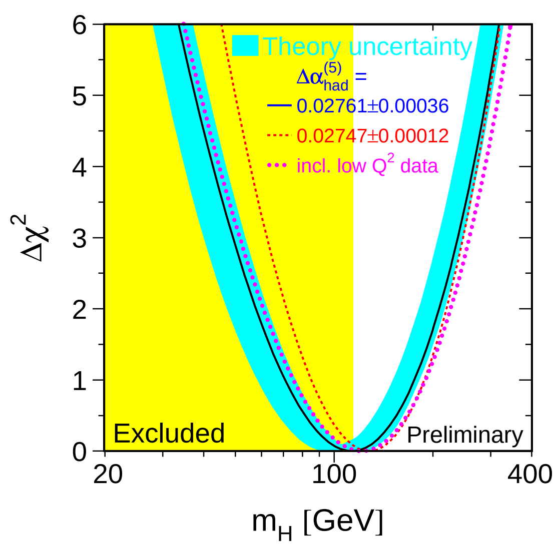
Constraints on $\mathrm{M_H}$ from pre–LHC experiments: LEP, Tevatron...

Indirect Higgs boson searches:

H contributes to RC to W/Z masses:



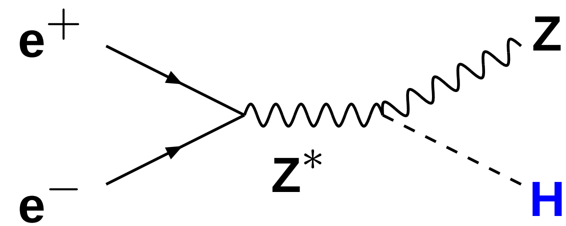
Fit the EW precision measurements:
we obtain $\mathrm{M_H} = 92^{+34}_{-26}$ GeV, or



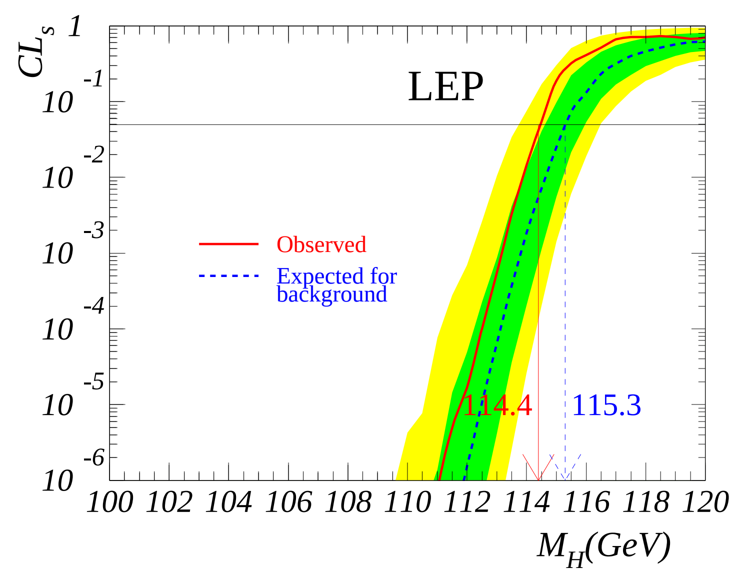
$\mathrm{M_H} \lesssim 160$ **GeV at 95% CL**

Direct searches at colliders:

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



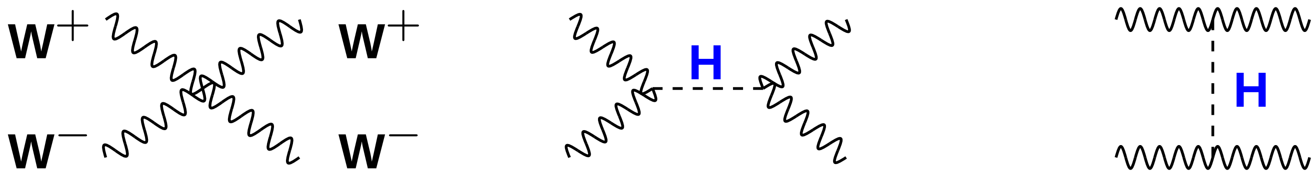
$\mathrm{M_H} > 114.4$ **GeV** $@95\%$**CL**



Tevatron $\mathrm{M_H} \neq 160-175$ GeV

A: The Higgs mechanism in the SM and constraints

Scattering of massive gauge bosons $V_L V_L \to V_L V_L$ at high-energy



Because w interactions increase with energy (q^μ terms in V propagator),

$s \gg M_W^2 \Rightarrow \sigma(w^+w^- \to w^+w^-) \propto s$: $\Rightarrow$ **unitarity violation possible!**

Decomposition into partial waves and choose J=0 for $s \gg M_W^2$:

$$a_0 = -\frac{M_H^2}{8\pi v^2}\left[1 + \frac{M_H^2}{s-M_H^2} + \frac{M_H^2}{s}\log\left(1+\frac{s}{M_H^2}\right)\right]$$

For unitarity to be fullfiled, we need the condition $|\mathrm{Re}(a_0)| < 1/2$.

- **At high energies, $s \gg M_H^2, M_W^2$, we have: $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$**

$$\text{unitarity} \Rightarrow M_H \lesssim 870\ \text{GeV} \ \ (M_H \lesssim 710\ \text{GeV})$$

- **For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$**

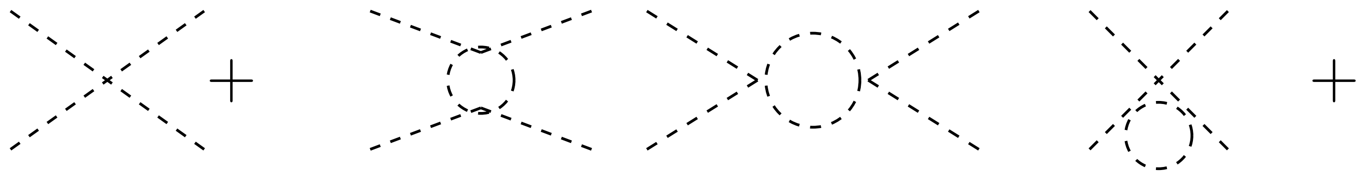
$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV} \ \ (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

Otherwise (strong?) New Physics should appear to restore unitarity.

A: The Higgs mechanism in the SM and constraints

The quartic coupling of the Higgs boson λ ($\propto \mathrm{M_H^2}$) increases with energy.

If the Higgs is very heavy: the H contributions to λ are by far dominant.



The RGE evolution of λ with $\mathrm{Q^2}$ and its solution are given by:

$$\frac{\mathrm{d}\lambda(\mathbf{Q^2})}{\mathrm{d}\mathbf{Q^2}} = \frac{\mathbf{3}}{4\pi^2}\lambda^2(\mathbf{Q^2}) \Rightarrow \lambda(\mathbf{Q^2}) = \lambda(\mathbf{v^2})\left[\mathbf{1} - \frac{\mathbf{3}}{4\pi^2}\lambda(\mathbf{v^2})\log\frac{\mathbf{Q^2}}{\mathbf{v^2}}\right]^{-1}$$

- **If $\mathrm{Q^2} \ll \mathrm{v^2},\ \lambda(\mathrm{Q^2}) \to 0_+$: the theory is trivial (no interaction).**
- **If $\mathrm{Q^2} \gg \mathrm{v^2},\ \lambda(\mathrm{Q^2}) \to \infty$: Landau pole at $\mathrm{Q} = \mathrm{v}\exp\left(\frac{4\pi^2 \mathrm{v^2}}{\mathrm{M_H^2}}\right)$.**

The SM is valid only at scales before coupling λ becomes infinite:

If $\Lambda_\mathrm{C} = \mathrm{M_H},\ \lambda \lesssim 4\pi \Rightarrow \mathrm{M_H} \lesssim 650$ GeV

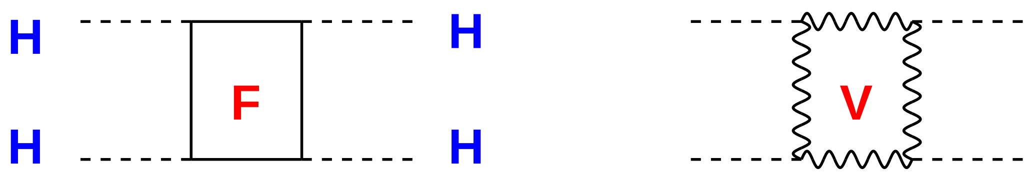
(comparable to results obtained with simulations on the lattice!)

If $\Lambda_\mathrm{C} = \mathrm{M_P},\ \lambda \lesssim 4\pi \Rightarrow \mathrm{M_H} \lesssim 180$ GeV

(SM extrapolated up to ultimate scales, the GUT/Planck scales!).

A: The Higgs mechanism in the SM and constraints

The top quark and gauge bosons also contribute to the evolution of λ:
the contributions dominate over that of the H itself at low M_H values.



The RGE evolution of the coupling at one–loop order is given by:

$$\lambda(Q^2) = \lambda(v^2) + \frac{1}{16\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

If λ is small (i.e. H is light), top loops might lead to $\lambda(0) < \lambda(v)$:

v is not the minimum of the potentiel and EW vacuum is unstable

$\Rightarrow$ impose that the coupling λ stays always positive:

$$\lambda(Q^2) > 0 \Rightarrow M_H^2 > \frac{v^2}{8\pi^2}\left[-12\frac{m_t^4}{v^4} + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]\log\frac{Q^2}{v^2}$$

Very strong constraint: $Q = \Lambda_C \sim 1\ \mathrm{TeV} \ \Rightarrow M_H \gtrsim 70$ **GeV**

(a good reason why we have not observed the Higgs before LEP2...)

If SM up to high scales: $Q = M_P \sim 10^{18}\ \mathrm{GeV} \ \Rightarrow M_H \gtrsim 130$ **GeV**

A: The Higgs mechanism in the SM and constraints

Combine the two constraints and include all possible effects:

– dominant corrections at two loops,

– theoretical and experimental errors

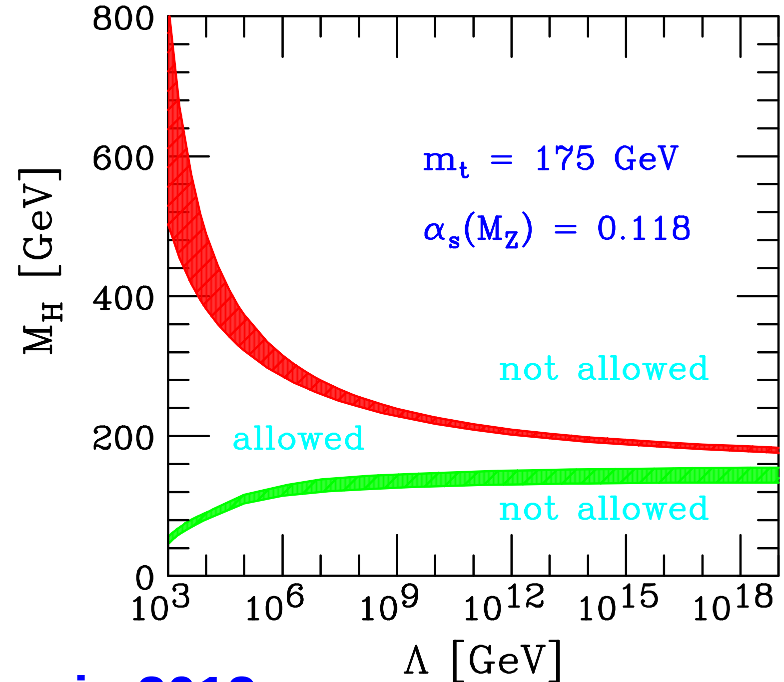
– all possible refinements $\cdots$

$\Lambda_C \approx 1\ \mathrm{TeV} \Rightarrow 70 \lesssim M_H \lesssim 700\ \mathrm{GeV}$

$\Lambda_C \approx M_{Pl} \Rightarrow 130 \lesssim M_H \lesssim 180\ \mathrm{GeV}$

Cabibbo, Maiani, Parisi, Petronzio

Hambye, Riesselmann



More up-to date (full two-loop) calculations in 2012:

Degrassi et al. and Berzukov et al.

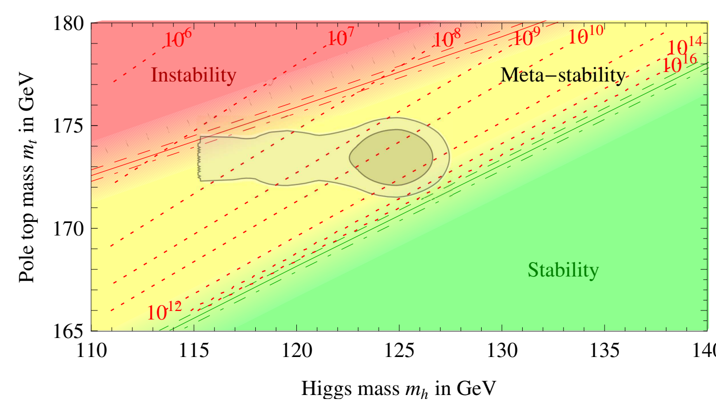
At two–loop for $m_t^{\rm pole}$=173.1 GeV:

fully stable vacuum $M_H \gtrsim 129$ GeV,

but vacuum metastable below that!

metastability of vacuum is still OK:

unstable but long lived $\tau_{\rm tunel} \gtrsim \tau_{\rm univ}$!

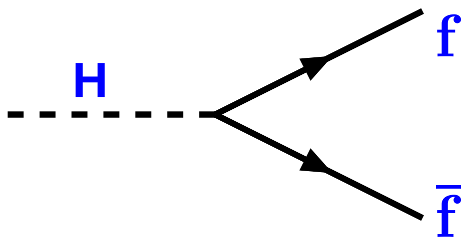


B. Higgs decays and production at the LHC

Higgs couplings proportional to particle masses: once M_H is fixed:

- **the profile of the Higgs boson is determined and its decays fixed,**
- **the Higgs has tendancy to decay into heaviest available particle.**

Higgs decays into fermions:



$$\Gamma_{\rm Born}(H \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f^3$$

$$\beta_f = \sqrt{1 - 4m_f^2/M_H^2} : \ f \text{ velocity}$$

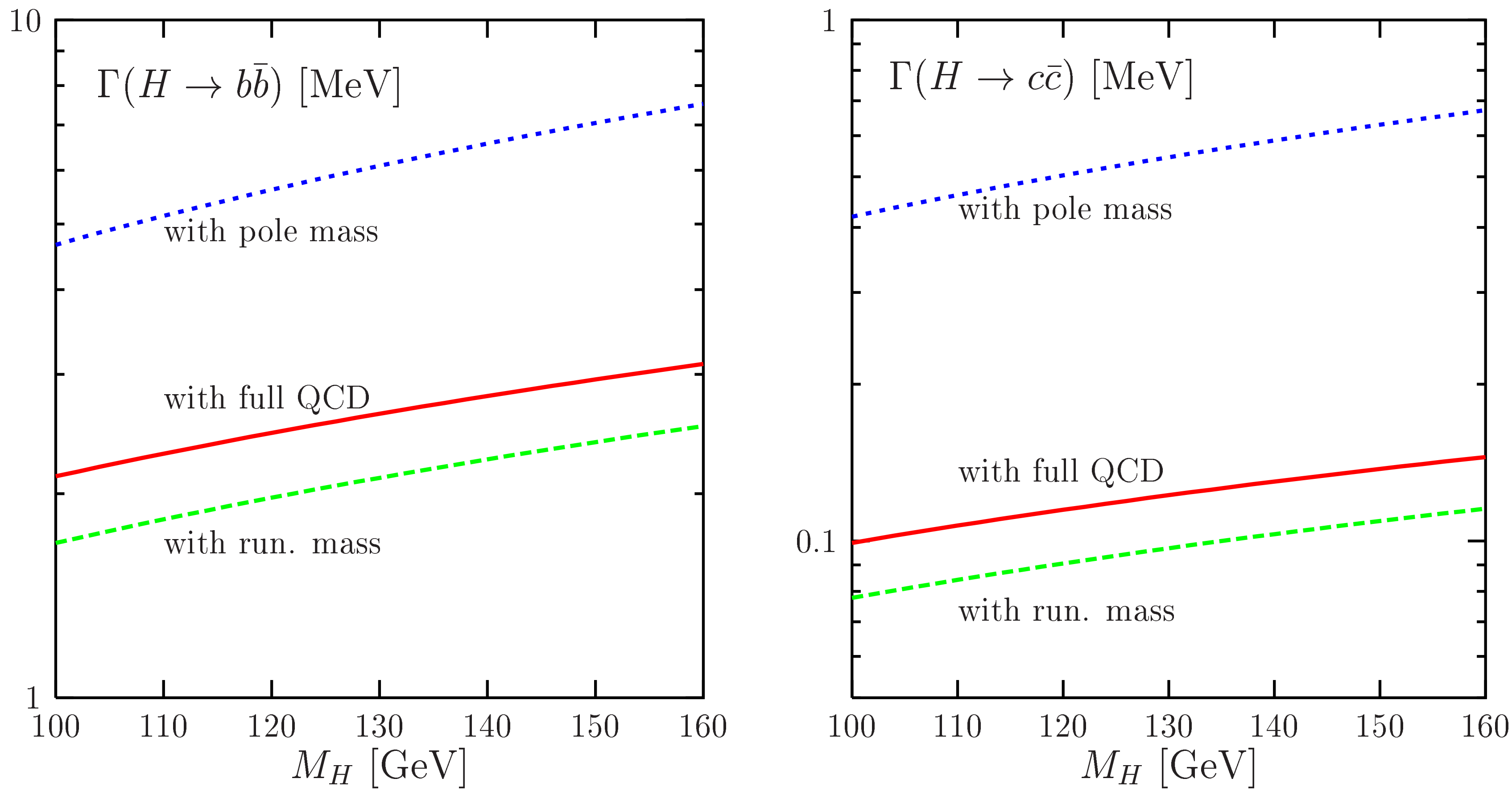
$$N_c = \text{color number}$$

- **Only $b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ for $M_H \lesssim 350$ GeV, also $H \to t\bar{t}$ beyond.**
- **$\Gamma \propto \beta^3$: H is CP–even scalar particle ($\propto \beta$ for pseudoscalar Higgs).**
- **Decay width grows as M_H: moderate growth with the mass....**
- **QCD RC: $\Gamma \propto \Gamma_0[1 - \frac{\alpha_s}{\pi} \log \frac{M_H^2}{m_q^2}] \Rightarrow$ very large: absorbed/summed**

using running masses at scale M_H : $m_b(M_H^2) \sim \frac{2}{3} m_b^{\rm pole} \sim 3\,{\rm GeV}$.

- **Include also direct QCD corrections (3 loops) and EW (one-loop).**

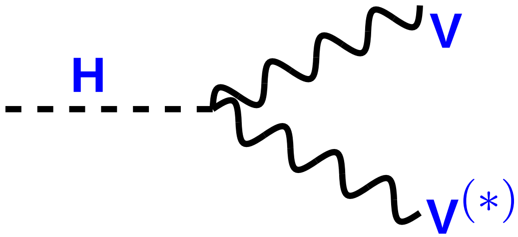
B. Higgs decays and production at the LHC



Partial widths for the decays $\mathrm{H} \to \mathrm{b\bar{b}}$ and $\mathrm{H} \to \mathrm{c\bar{c}}$ as a function of $\mathrm{M_H}$:

Q	$\mathrm{m_Q}$	$\mathrm{\overline{m}_Q(m_Q)}$	$\mathrm{\overline{m}_Q(100\ GeV)}$
c	1.64 GeV	1.23 GeV	0.63 GeV
b	4.88 GeV	4.25 GeV	2.95 GeV

B. Higgs decays and production at the LHC



$$\Gamma(\mathrm{H} \to \mathrm{VV}) = \frac{\mathrm{G}_\mu \mathrm{M}_\mathrm{H}^3}{16\sqrt{2}\pi} \delta_\mathrm{V} \beta_\mathrm{V} (1 - 4\mathrm{x} + 12\mathrm{x}^2)$$

$$\mathrm{x} = \mathrm{M}_\mathrm{V}^2/\mathrm{M}_\mathrm{H}^2,\ \beta_\mathrm{V} = \sqrt{1-4\mathrm{x}}$$

$$\delta_\mathrm{W} = 2,\ \delta_\mathrm{Z} = 1$$

- **For a very heavy Higgs boson:**

$$\Gamma(\mathrm{H} \to \mathrm{WW}) = 2 \times \Gamma(\mathrm{H} \to \mathrm{ZZ}) \Rightarrow \mathrm{BR}(\mathrm{WW}) \sim \frac{2}{3}, \mathrm{BR}(\mathrm{ZZ}) \sim \frac{1}{3}$$

$\Gamma(\mathrm{H} \to \mathrm{WW} + \mathrm{ZZ}) \propto \frac{1}{2} \frac{\mathrm{M}_\mathrm{H}^3}{(1\ \mathrm{TeV})^3}$ **because of contributions of $\mathrm{V_L}$:**

heavy Higgs is obese: width very large, comparable to $\mathrm{M_H}$ at 1 TeV.

EW radiative corrections from scalars large because $\propto \lambda = \frac{\mathrm{M}_\mathrm{H}^2}{2\mathrm{v}^2}$.

- **For a light Higgs boson:**

$\mathrm{M_H} < 2\mathrm{M_V}$: **possibility of off–shell V decays, $\mathrm{H} \to \mathrm{VV}^* \to \mathrm{Vf\bar{f}}$.**

Virtuality and addition EW cplg compensated by large $\mathrm{g_{HVV}}$ vs $\mathrm{g_{Hbb}}$.

In fact: for $\mathrm{M_H} \gtrsim$ 130 GeV, $\mathrm{H} \to \mathrm{WW}^*$ dominates over $\mathrm{H} \to \mathrm{b\bar{b}}$.

B. Higgs decays and production at the LHC

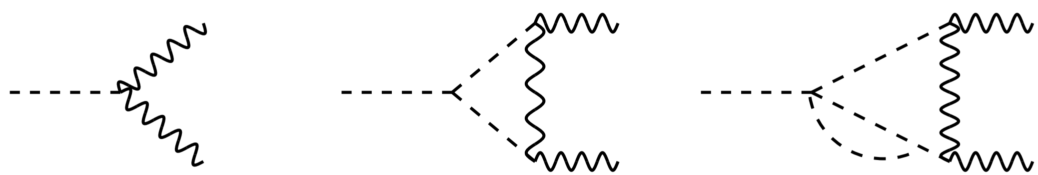
Electroweak radiative corrections to $\mathbf{H \to VV}$:

Using the low–energy/equivalence theorem for $\mathbf{M_H \gg M_V}$, Born easy..

$$\mathbf{\Gamma(H \to ZZ) \sim \Gamma(H \to w_0 w_0) = \left(\frac{1}{2M_H}\right)\left(\frac{2!M_H^2}{2v}\right)^2 \frac{1}{2}\left(\frac{1}{8\pi}\right) \to \frac{M_H^3}{32\pi v^2}}$$

$\mathbf{H \to WW}$: **remove statistical factor:** $\mathbf{\Gamma(H \to W^+W^-) \simeq 2\Gamma(H \to ZZ)}$.

Include now the one– and two–loop EW corrections from H/W/Z only:



$$\mathbf{\Gamma_{H \to VV} \simeq \Gamma_{Born}\left[1 + 3\hat{\lambda} + 62\hat{\lambda}^2 + \mathcal{O}(\hat{\lambda}^3)\right] \;\; ; \quad \hat{\lambda} = \lambda/(16\pi^2)}$$

$\mathbf{M_H \sim \mathcal{O}(10\ TeV) \Rightarrow}$ **one–loop term = Born term.**

$\mathbf{M_H \sim \mathcal{O}(1\ \ TeV) \Rightarrow}$ **one–loop term = two–loop term**

$\Rightarrow$ **for perturbation theory to hold, one should have $\mathbf{M_H \lesssim 1}$ TeV.**

Approx. same result from the calculation of the fermionic Higgs decays:

$$\mathbf{\Gamma_{H \to ff} \simeq \Gamma_{Born}\left[1 + 2\hat{\lambda} - 32\hat{\lambda}^2 + \mathcal{O}(\hat{\lambda}^3)\right]}$$

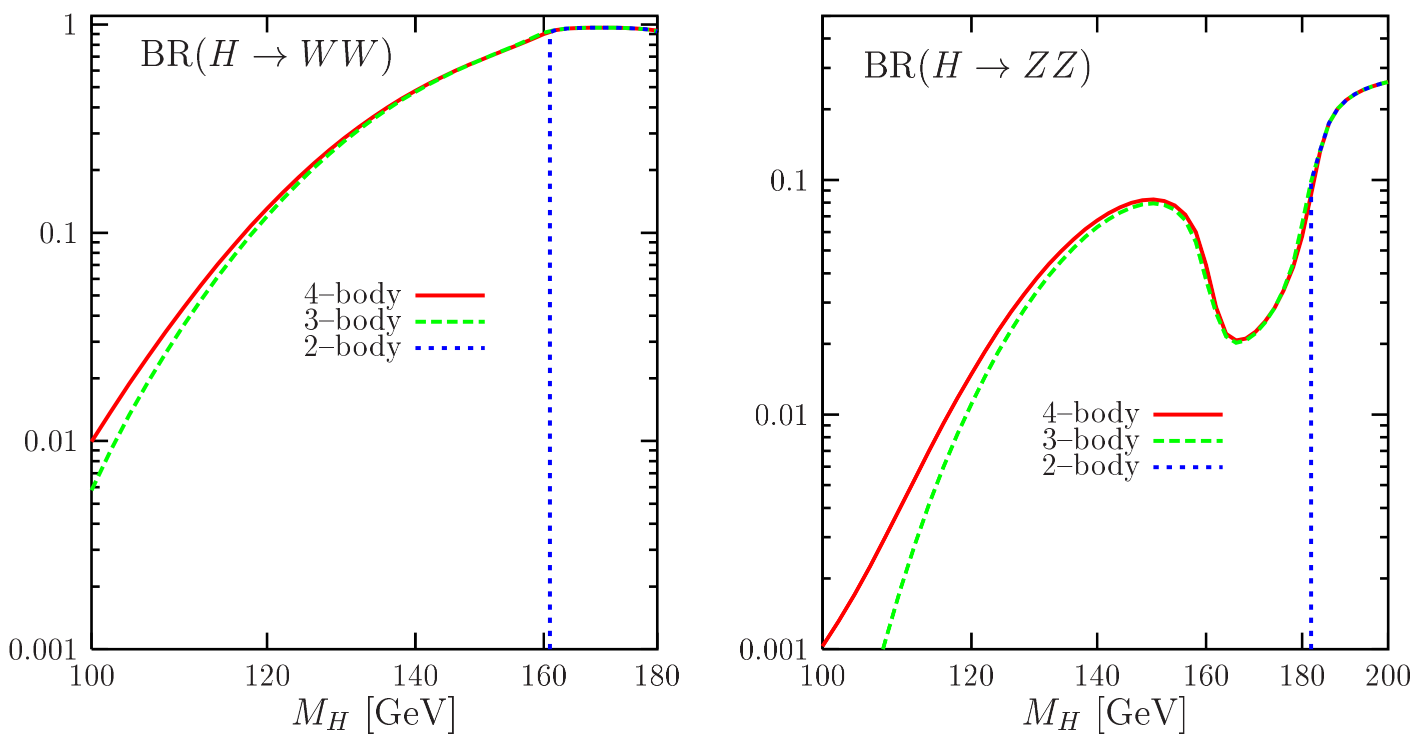
B. Higgs decays and production at the LHC

more convenient, 2+3+4 body decay calculation of $\mathbf{H \to V^* V^*}$:

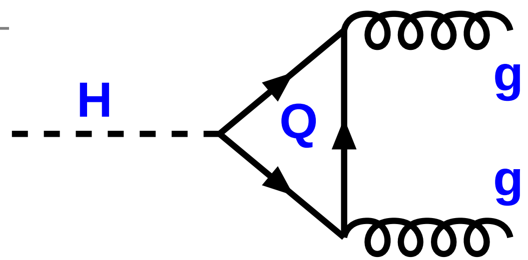
$$\Gamma(H \to V^* V^*) = \frac{1}{\pi^2} \int_0^{M_H^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \int_0^{(M_H - q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0$$

$$\lambda(x, y; z) = (1 - x/z - y/z)^2 - 4xy/z^2 \text{ with } \delta_{W/Z} = 2/1$$

$$\Gamma_0 = \frac{G_\mu M_H^3}{16\sqrt{2}\pi} \delta_V \sqrt{\lambda(q_1^2, q_2^2; M_H^2)} \left[\lambda(q_1^2, q_2^2; M_H^2) + \frac{12 q_1^2 q_2^2}{M_H^4} \right]$$



B. Higgs decays and production at the LHC



$$\Gamma(H \to gg) = \frac{G_\mu \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_Q A_{1/2}^H(\tau_Q) \right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1) f(\tau)]\,\tau^{-2}$$

$$f(\tau) = \arcsin^2 \sqrt{\tau} \text{ for } \tau = M_H^2/4m_Q^2 \leq 1$$

- Gluons massless and Higgs has no color: must be a loop decay.
- For $m_Q \to \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3} =$ constant and Γ is finite!

Width counts the number of strong inter. particles coupling to Higgs!

- In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.
- Loop decay but QCD and top couplings: comparable to cc, $\tau\tau$.
- Approximation $m_Q \to \infty / \tau_Q = 1$ valid for $M_H \lesssim 2m_t = 350$ GeV.

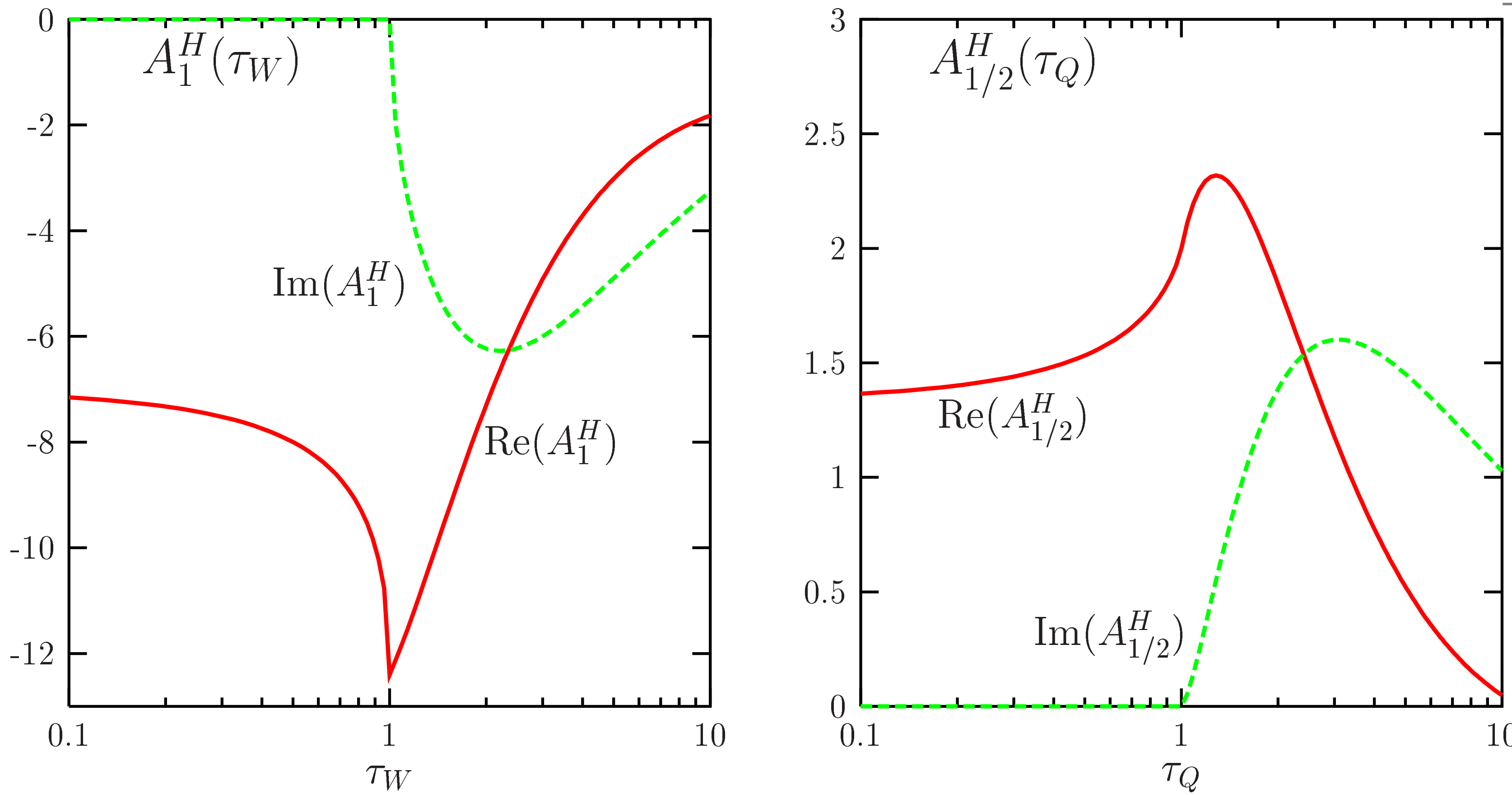
Good approximation in decay: include only t–loop with $m_Q \to \infty$.

- But very large QCD RC: two– and three–loops have to be included:

$$\Gamma = \Gamma_0 [1 + 18 \tfrac{\alpha_s}{\pi} + 156 \tfrac{\alpha_s^2}{\pi^2}] \sim \Gamma_0 [1 + 0.7 + 0.3] \sim 2\Gamma_0$$

- Reverse process $gg \to H$ very important for Higgs production in pp!

B. Higgs decays and production at the LHC



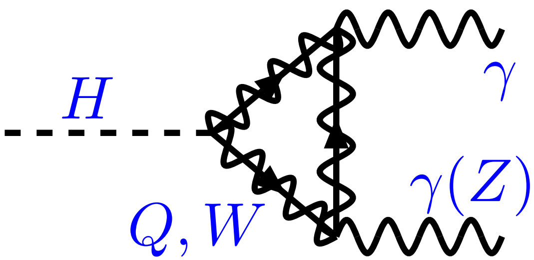
W and fermion amplitudes in $\mathrm{H} \to \gamma\gamma$ as function of $\tau_i = \mathrm{M_H^2}/4\mathrm{M_i^2}$.

Trick for an easy calculation: low energy theorem for $\mathrm{M_H} \ll \mathrm{Mi}$:

– top loop: works very well for $\mathrm{M_H} \lesssim 2\mathrm{m_t} \approx 350$ GeV;

– W loop: works approximately for $\mathrm{M_H} \lesssim 2\mathrm{M_W} \approx 160$ GeV.

B. Higgs decays and production at the LHC



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c e_f^2 A_{\frac{1}{2}}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2}$$

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\,\tau^{-2}$$

- **Photon massless and Higgs has no charge: must be a loop decay.**
- **In SM: only W–loop and top-loop are relevant (b–loop too small).**
- **For $m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3}$ and $A_1 = -7$: W loop dominating!**

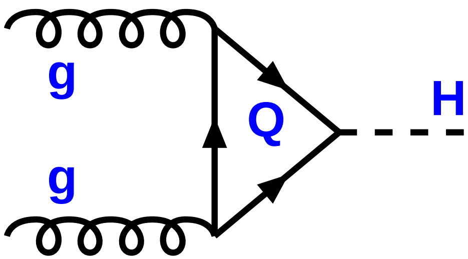
(approximation $\tau_W \to 0$ valid only for $M_H \lesssim 2M_W$: relevant here!).

$\gamma\gamma$ width counts the number of charged particles coupling to Higgs!

- **Loop decay but EW couplings: very small compared to $H \to gg$.**
- **Rather small QCD (and EW) corrections: only of order $\frac{\alpha_s}{\pi} \sim 5\%$.**
- **Reverse process $\gamma\gamma \to H$ important for H production in $\gamma\gamma$.**
- **Same discussions hold qualitatively for loop decay $H \to Z\gamma$.**

B. Higgs decays and production at the LHC

Let us look at this main Higgs production channel at the LHC in detail.



$$\hat{\sigma}_{\rm LO}(\mathbf{gg \to H}) = \frac{\pi^2}{8M_H}\Gamma_{\rm LO}(\mathbf{H \to gg})\delta(\hat{s} - M_H^2)$$

$$\sigma_0^H = \frac{G_\mu \alpha_s^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q A_{1/2}^H(\tau_Q) \right|^2$$

Related to the Higgs decay width into gluons discussed previously.

- **In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.**
- **For $m_Q \to \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3}$ = constant and $\hat{\sigma}$ finite.**
- **Approximation $m_Q \to \infty$ valid for $M_H \lesssim 2m_t = 350$ GeV.**

Gluon luminosities large at high energy+strong QCD and Htt couplings

$gg \to H$ is the leading production process at the LHC.

- **Very large QCD RC: the two– and three–loops have to be included.**
- **Also the Higgs P_T is zero at LO, must generated at NLO.**

B. Higgs decays and production at the LHC

- At NLO: corrections known exactly, i.e. for finite $m_{t,b}$ and M_H:

– quark mass effects are important for $M_H \gtrsim 2m_t$ and b–loop.

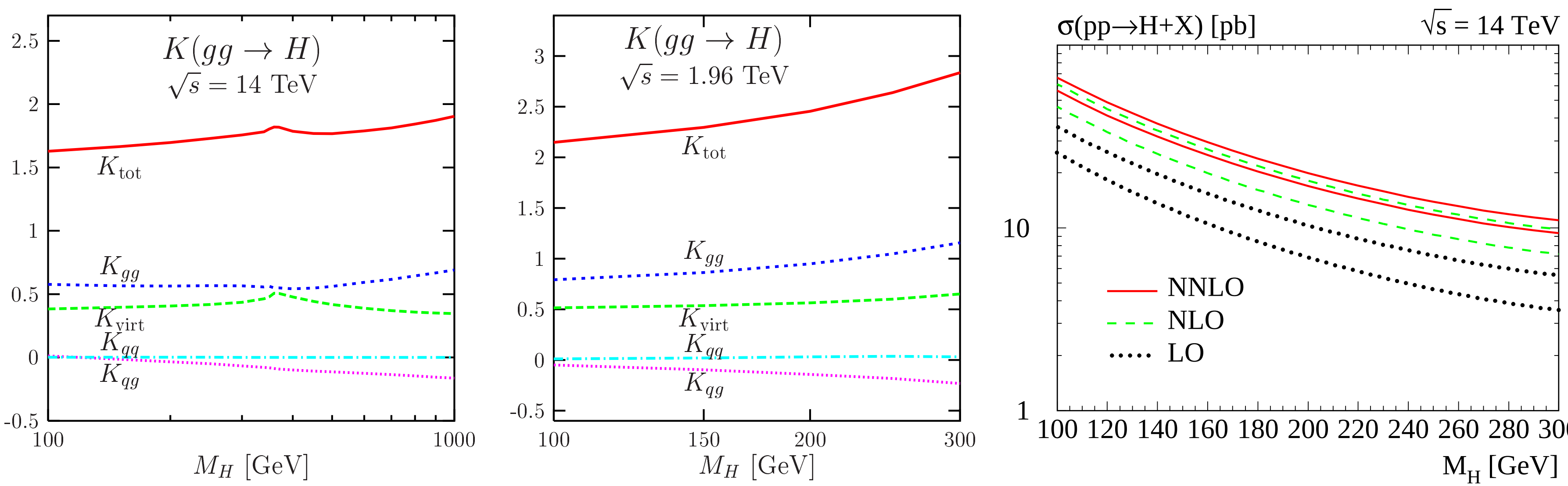
– $m_t \to \infty$ is still a good approximation for masses below 300 GeV.

– corrections are large, increase cross section by a factor 2 at LHC.

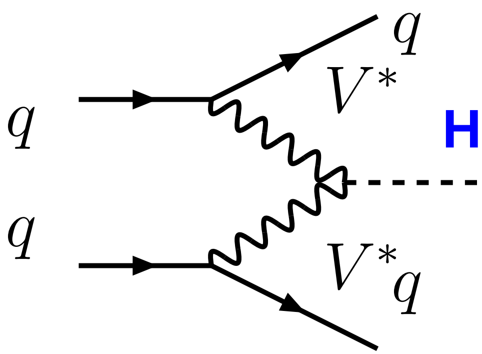
- Corrections have been calculated in $m_t \to \infty$ limit beyond NLO.

– moderate increase at NNLO by 30% and stabilisation with scales...
– soft–gluon resummation performed up to NNLL: $\approx$ 5–10% effects.
– recently, also N3LO RC calculated! Very small and small scale variation.

Note 1: NLO corrections to P_T, η distributions are also known.
Note 2: NLO EW corrections are also available, they are rather small.



B. Higgs decays and production at the LHC



$$\hat{\sigma}_{\rm LO} = \frac{\mathbf{16\pi^2}}{\mathbf{M_H^3}}\Gamma(\mathbf{H \to V_L V_L})\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}} \sim \frac{\alpha}{\mathbf{4\pi^3}}(\mathbf{v_q^2} + \mathbf{a_q^2})^{\mathbf{2}} \log\left(\frac{\hat{\mathrm{s}}}{\mathbf{M_H^2}}\right)$$

Three–body final state: analytical expression rather complicated...

Simple form in LVBA: σ related to $\Gamma(\mathrm{H} \to \mathbf{VV})$ and $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}|_{\mathbf{V_L V_L/qq}}$.

Not too bad approximation at $\sqrt{\hat{\mathrm{s}}} \gg \mathrm{M_H}$: a factor 2 of accurate.

Large cross section: in particular for small $\mathrm{M_H}$ and large c.m. energy:

$\Rightarrow$ most important process at the LHC after $\mathrm{gg} \to \mathrm{H}$.

NLO QCD radiative corrections small: order 10% (also for distributions).

In fact: at LO in/out quarks are in color singlets and at NLO: no gluons are exchanged between first/second incoming (outgoing) quarks:

QCD corrections only consist of known corrections to the PDFs!

– NNLO corrections recently calculated in this scheme: very small.

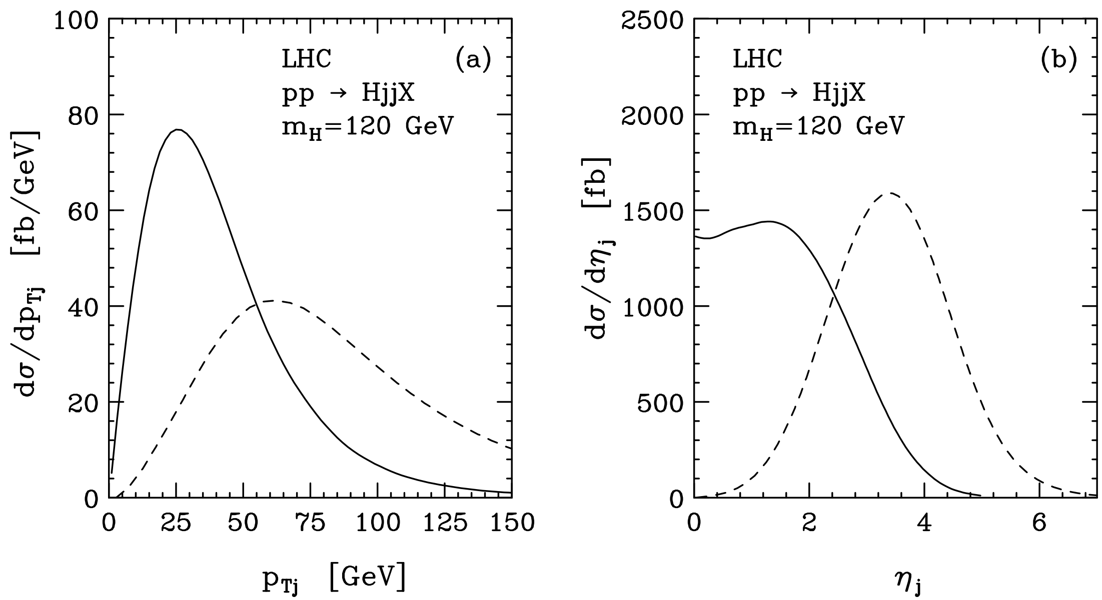
– EW corrections are also small, of order of a few %.

B. Higgs decays and production at the LHC

Kinematics of the process: very specific for scalar particle production....

- **Forward jet tagging: the two final jets are very forward peaked.**
- **They have large energies of $\mathcal{O}$(1 TeV) and sizeable $\mathrm{P_T}$ of $\mathcal{O}(\mathrm{M_V})$.**
- **Central jet vetoing: Higgs decay products are central and isotropic.**
- **Small hadronic activity in the central region no QCD (trigger uppon).**

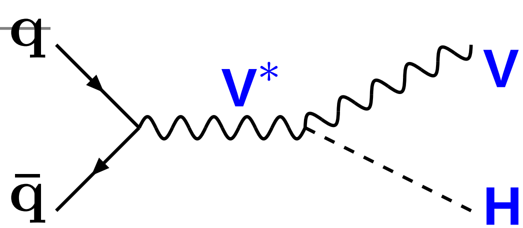
$\Rightarrow$ allows to suppress backgrounds to the level of H signal: $\mathrm{S/B} \sim 1$.



—– lowest/central jet **– – highest/central jet**

However, the various VBF cuts make the signal theoretically less clean:
– dependence on many cuts and variables, impact of HO less clear,
– contamination from the $\mathrm{gg \to H + jj}$ process not so small...

B. Higgs decays and production at the LHC



$$\hat{\sigma}_{\rm LO} = \frac{G_\mu^2 M_V^4}{288\pi \hat{s}} \times (\hat{v}_q^2 + \hat{a}_q^2)\lambda^{1/2}\frac{\lambda + 12M_V^2/\hat{s}}{(1-M_V^2/\hat{s})^2}$$

Similar to $e^+e^- \to HZ$ for Higgs@LEP2.

$\hat{\sigma} \propto \hat{s}^{-1}$ sizable only for $M_H \lesssim 200$ GeV.

At both LHC/Tevatron: $\sigma(W^\pm H) \approx \sigma(ZH)$.

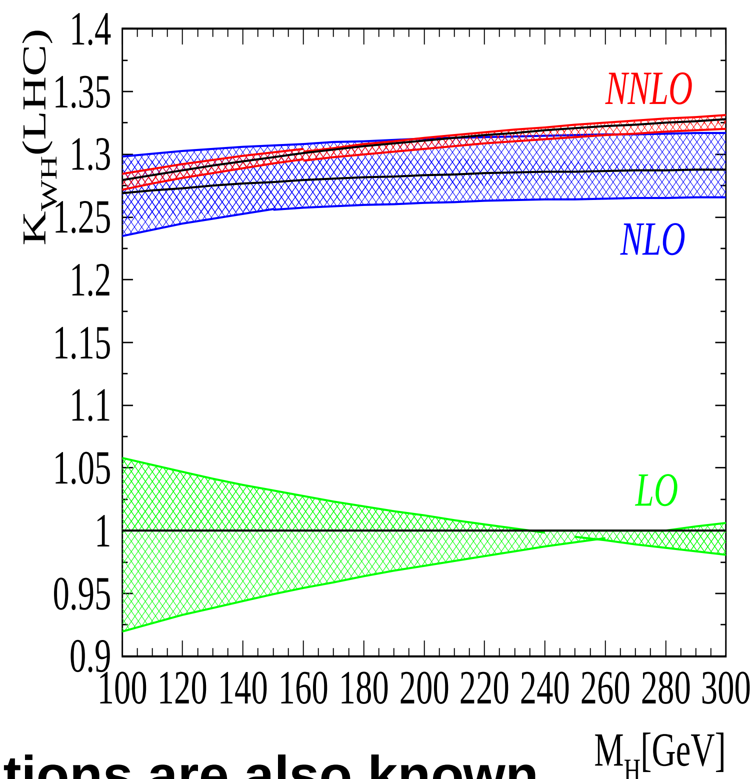
In fact, simply Drell–Yan production of virtual boson with $q^2 \neq M_V^2$:

$$\hat{\sigma}(q\bar{q} \to HV) = \hat{\sigma}(q\bar{q} \to V^*) \times \frac{d\Gamma}{dq^2}(V^* \to HV).$$

RC $\Rightarrow$ those of known DY process (2-loop: $gg \to HZ$ in addition).

QCD RC in HV known up to NNLO (borrowed from Drell-Yan: K$\approx$ 1.4)

EW RC known at $\mathcal{O}(\alpha)$: very small.



- **Radiative corrections to various distributions are also known.**
- **Process fully implemented in various MC programs used by experiment**

B. Higgs decays and production at the LHC

Up-to-now, it plays a marginal role at the LHC (not a discover channel..).
Interesting topologies: $\mathrm{WH} \to \gamma\gamma\ell, \mathrm{b\bar{b}}\ell, 3\ell$ **and** $\mathrm{ZH} \to \ell\ell\mathrm{b\bar{b}}, \nu\nu\mathrm{b\bar{b}}$.
At high Higgs $\mathrm{P_T}$**: one can use jet substructure (**$\mathrm{H} \to \mathrm{b\bar{b}} \neq \mathrm{g}^* \to \mathrm{q\bar{q}})$.
Analyses by ATLAS+CMS: 5σ **disc. possible at 14 TeV with** $\mathcal{L} \gtrsim 100$ **fb.**
But clean channel esp. when normalized to $\mathrm{pp} \to \mathrm{Z}$**: precision process!**

However: WH channel is the most important at Tevatron:

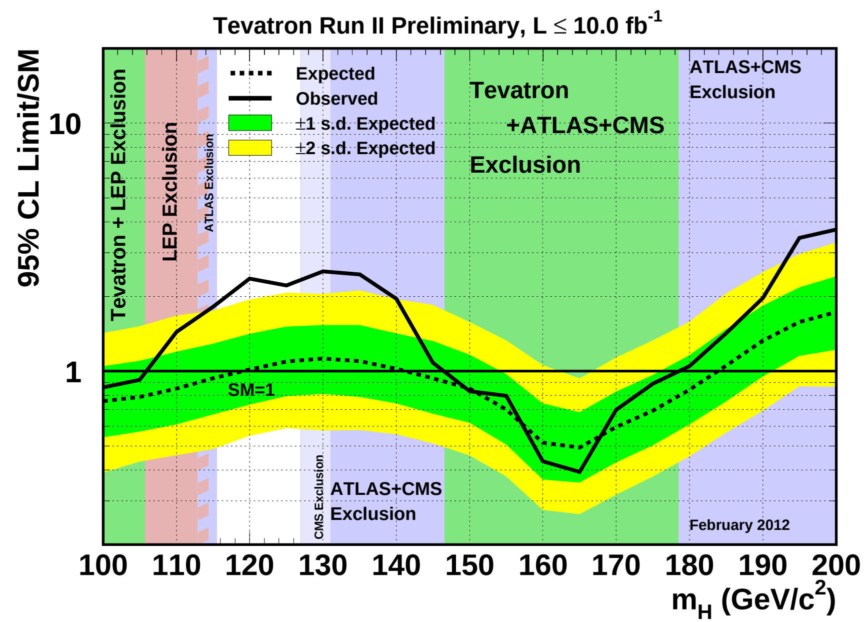
$\mathrm{M_H} \lesssim 130$ **GeV:** $\mathrm{H} \to \mathrm{b\bar{b}}$

$\Rightarrow \ell\nu\mathrm{b\bar{b}},\ \nu\bar{\nu}\mathrm{b\bar{b}},\ \ell^+\ell^-\mathrm{b\bar{b}}$

(help for $\mathrm{HZ} \to \mathrm{b\bar{b}}\ell\ell, \mathrm{b\bar{b}}\nu\nu)$

$\mathrm{M_H} \gtrsim 130$ **GeV:** $\mathrm{H} \to \mathrm{WW}^*$

$\Rightarrow\ \ell^\pm\ell^\pm\mathrm{jj},\ 3\ell^\pm$



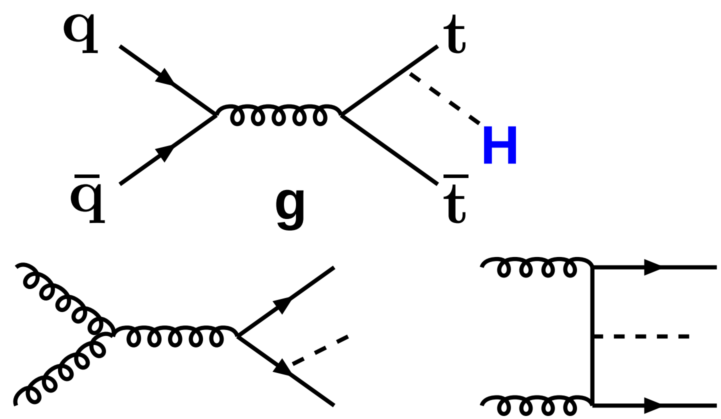
Sensitivity in the low H mass range: excludes low $\mathrm{M_H} \lesssim 110$ **GeV values**

$\approx$3σ excess for $\mathrm{M_H} =$115–135 GeV at the end of the Tevatronn run!

B. Higgs decays and production at the LHC

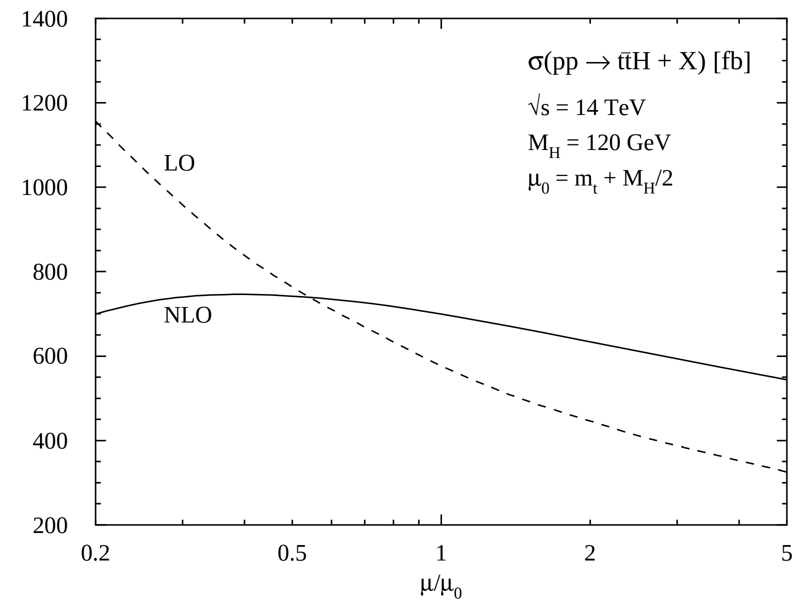
Most complicated process for Higgs production at hadron colliders:

– qq and gg initial states channels
– three-body massive final states.
– at least 8 particles in final states..
– small Higgs production rates
– very large ttjj+ttbb backgrounds.



NLO QCD corrections calculated:
small K–factors $(\approx$ 1–1.2)
strong reduction of scale variation!

Small corrections to kinematical distributions (e.g: $\mathrm{p_T^{top}}, \mathrm{P_T^H}$), etc...
Small uncertainties from HO, PDFs.



Processes with heavy quarks in BSM:
– Single top+Higgs: $\mathrm{pp \to tH + X}$.
– Production with bs: $\mathrm{pp \to bbH}$.

- **Important for Htt Yukawa coupling!**
- **Interesting final states: $\mathrm{pp \to Htt \to \gamma\gamma + X}, \nu\nu\ell^\pm\ell^\mp, \mathrm{b\bar{b}}\ell^\pm$.**
- **Possibility for a 5 signal at $\mathrm{M_H \lesssim 140}$ GeV at high luminosities.**

C. The Minimal Supersymmetric Standard Model

The MSSM is the most economical low energy SUSY extension of the SM.

It is based on the following simplifying assumptions:

- **Minimal gauge group, the SM one $\mathbf{SU(3)_C \times SU(2)_L \times U(1)}$:**

The SM spin–1 $\mathrm{B, W_i, g_i}$ gauge bosons
and their spin–$\frac{1}{2}$ gaugino partners $\mathrm{\tilde{b}, \tilde{w}, \tilde{g}}$ $\Big\} \Rightarrow$ **put in vector superfields.**

- **Minimal particle content: 3 fermion generations + two Higgs doublets**

(no chiral anomalies, $\sum_{\mathrm{f}} \mathrm{Q_f} \equiv 0$, and no conjugate H^* for mass terms):

fermions and their spin–0 $\mathrm{\tilde{f}_{L/R}}$ partners
Higgsses and their spin–$\frac{1}{2}$ $\mathrm{\tilde{h}_{1/2}}$ partners $\Big\} \Rightarrow$ **chiral supermultiplets.**

– current eigenstates $\mathrm{\tilde{f}_{L/R}}$ mix to make the two mass eigenstates $\mathrm{\tilde{f}_{1/2}}$,

– charged/neutral winos+higgsinos $\Rightarrow$ charginos $\chi^{\pm}_{1,2}$/neutralinos $\chi^0_{1,2,3,4}$

- **Discrete and multiplicative symmetry called R–parity is conserved:**

$$\mathrm{R_p} = (-1)^{2s+3B+L} \Rightarrow \begin{cases} = +1 \text{ for all ordinary SM particles,} \\ = -1 \text{ for all the SUSY particles.} \end{cases}$$

Important consequences: $\begin{cases} \text{– sparticles always produced in pairs,} \\ \text{– decay into odd number of sparticles,} \\ \text{– lightest one (LSP) is absolutely stable.} \end{cases}$

C. The Minimal Supersymmetric Standard Model

• **We need a superpotential to implement the Yukawa interactions**

most general one compatible with SUSY, gauge invariance, R_p, etc..:

$$W = \sum_{i,j} Y^u_{ij}\, \hat{u}^i_R \hat{H}_2.\hat{Q}^j + Y^d_{ij}\, \hat{d}^i_R \hat{H}_1.\hat{Q}^j + Y^l_{ij}\, \hat{l}^i_R \hat{H}_1.\hat{L}^j + \mu \hat{H}_1.\hat{H}_2$$

– $Y^{u,d,l}_{ij}$ **Yukawa couplings among generations (generalisation of SM),**

– μ **supersymmetric Higgs–higgsino parameter: only additional one!**

At this stage everything is supersymmetric and uniquely specified!

But need to break SUSY $\Rightarrow$ soft-breaking not to have Λ^2 terms in M_H:

introduce a collection of soft–SUSY breaking terms of dims. 2 and 3:

$$\mathcal{L}_{\rm gaugino} = \frac{1}{2}\left[M_1 \tilde{b}\tilde{b} + M_2 \Sigma_{a=1}^3 \tilde{w}^a \tilde{w}_a + M_3 \Sigma_{a=1}^8 \tilde{g}^a \tilde{g}_a + \text{h.c.} \right]$$

$$\mathcal{L}_{\rm sf.} = \Sigma_i m^2_{\tilde{Q},i} \tilde{Q}^\dagger_i \tilde{Q}_i + m^2_{\tilde{L},i} \tilde{L}^\dagger_i \tilde{L}_i + m^2_{\tilde{u},i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d},i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{l},i} |\tilde{l}_{R_i}|^2$$

$$\mathcal{L}_{\rm Higgs} = m_2^2 H_2^\dagger H_2 + m_1^2 H_1^\dagger H_1 + B\mu (H_2.H_1 + \text{h.c.})$$

$$\mathcal{L}_{\rm tr} = \Sigma_{i,j} \left[A^u_{ij} Y^u_{ij} \tilde{u}_{R_i} H_2.\tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}_{R_i} H_1.\tilde{Q}_j + A^l_{ij} Y^l_{ij} \tilde{l}_{R_i} H_1.\tilde{L}_j + \text{h.c.} \right]$$

Then life becomes complicated and problematic with this potential!

$\Rightarrow$ **too many free parameters (+105!) and thus not very predictive;**

$\Rightarrow$ **leads generically to problematic pheno (FCNC, CPV, CCB, $\not{M}_Z$).**

C. The Minimal Supersymmetric Standard Model

A more phenomenologically viable MSSM is defined by assuming:

- **all soft SUSY–breaking parameters are real (no new CP violation);**
- **masses and trilinear couplings for sfermions diagonal (no FCNC);**
- **1st/2d sfermion generation universality (no problem with Kaons..).**

Define phenomenological MSSM (pMSSM) with 22 free parameters:

$\tan\beta$: **the ratio of the vevs of the two–Higgs doublet fields;**
$\mathbf{m^2_{H_u}, m^2_{H_d}}$: **the two soft-SUSY breaking Higgs mass parameters;**
$\mathbf{M_1, M_2, M_3}$: **the bino, wino and gluino mass parameters;**
$\mathbf{m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}}$: **1st/2d generation sfermion mass parameters;**
$\mathbf{m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}}$: **third generation sfermion mass parameters;**
$\mathbf{A_t, A_b, A_\tau}$: **the third generation trilinear couplings;**
$\mathbf{A_u, A_d, A_e}$: **the first/second generation trilinear couplings.**

In fact, a much simpler situation in the pMSSM compared to general case:

- **You can trade $\mathbf{m^2_{H_u}, m^2_{H_d}}$ with more "physical" μ and $\mathbf{M_A}$ parameters.**
- **$\mathbf{A_u, A_d, A_e}$ in general not relevant for phenomenology (come with $\mathbf{m_f}$).**
- **If focus on given sector (Higgs, $\chi, \tilde{\mathbf{f}}$) only few parameters to deal with...**

$\Rightarrow$ **phenomenologically more viable model and more predictive!**

C. The Minimal Supersymmetric Standard Model

All MSSM problems solved with universal boundary conditions at high scale:

$\mathrm{SU\!\!\!/ SY}$ **in hidden sector communicating with visible through gravity only!**

$\Rightarrow$ **universal soft** $\mathrm{SU\!\!\!/ SY}$ **terms emerge if interactions are "flavor–blind".**

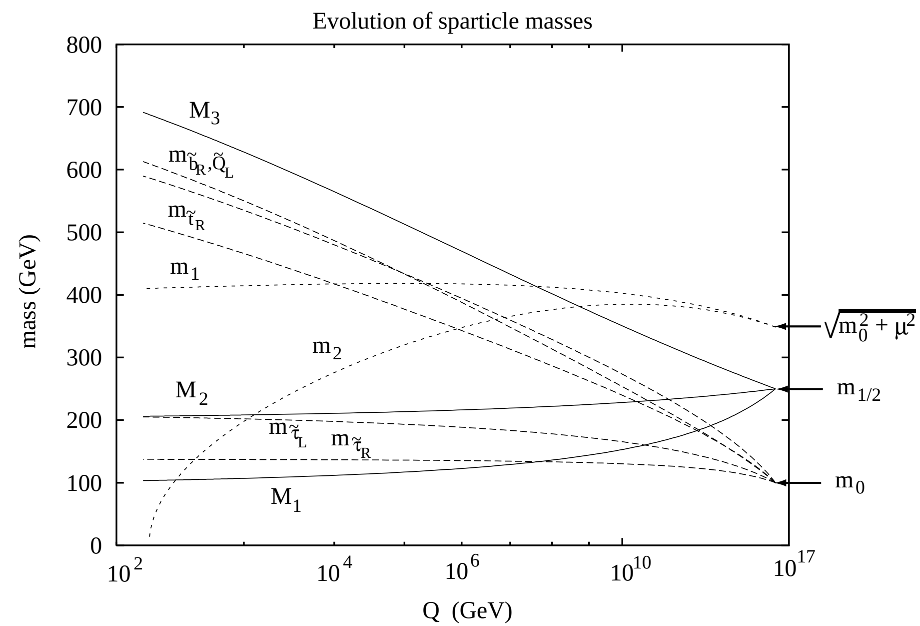
Besides $\mathbf{g_{1,2,3}}$ **unification which fix the GUT scale** $\mathrm{M_{GUT}} \sim \mathbf{2 \cdot 10^{16}}$ **GeV:**

unification of gaugino, scalar masses and trilinear cplgs at $\mathrm{Q = M_{GUT}}$**.**

- $\mathbf{M_1 = M_2 = M_3 \equiv m_{1/2}}$
- $\mathbf{M_{\tilde{Q}_i} = M_{\tilde{L}_i} = M_{H_i} \equiv m_0}$
- $\mathbf{A^u_{ij} = A^d_{ij} = A^l_{ij} \equiv A_0\, \delta_{ij}}$
- **B and** μ^2 **from correct EWSB (and minimisation of** $\mathbf{V_{Higgs}}$**):**

$$\mu^2 = \frac{1}{2}\Big[\mathbf{t_{2\beta}}\Big(\mathbf{m^2_{H_u}}\, \mathbf{t}_\beta - \frac{\mathbf{m^2_{H_d}}}{\mathbf{t}_\beta}\Big) - \mathbf{M^2_Z}\Big]$$

$$\mathbf{B}\mu = \frac{1}{2}\mathbf{s_{2\beta}}\big[\mathbf{m^2_{H_u}} + \mathbf{m^2_{H_d}} + 2\mu^2\big]$$



mSUGRA: only 4 free parameters+sign: $\tan\beta, \mathbf{m_{1/2}}, \mathbf{m_0}, \mathbf{A_0}, \mathbf{sign}(\mu)$

$\Rightarrow$ **all soft parameters at scale** $\mathrm{M_{SUSY}} = \sqrt{\mathbf{m_{\tilde{t}_L} m_{\tilde{t}_R}}}$ **obtained through RGEs**

$\Rightarrow$ **radiative EWSB as** $\mathrm{M^2_{H_2}} < 0$ **at scale** $\mathrm{M_Z}$ **from** $\mathrm{t}/\tilde{\mathrm{t}}$ **loops: more natural!**

C. The Minimal Supersymmetric Standard Model

Scalar EWSB potential V_H in terms of $\overline{m}^2_{1,2} = |\mu|^2 + m^2_{H_{1,2}}$, $\overline{m}^2_3 = B\mu$

$$V_H = \overline{m}_1^2 |H_1^0|^2 + \overline{m}_2^2 |H_2^0|^2 + \overline{m}_3^2 (H_1^0 H_2^0 + \mathrm{hc}) + \frac{M_Z^2}{4v^2} (|H_1^0|^2 - |H_2^0|^2)^2$$

- **Quartic couplings given by $g_i \Rightarrow$ 3 free parameters $\overline{m}^2_{1,2,3}$ instead of 6!**
- **$\bar{m}_{1,2}$ real and $\bar{m}_{1,2}$ complex but phase rotated $\Rightarrow V_H$ conserves CP!**
- **If $B\mu = 0$, $\bar{m}^2_{1,2} \geq 0$; $V_H = 0$ only if $\langle H_1^0 \rangle = \langle H_2^0 \rangle = 0$: SSB $\Rightarrow \overline{m}_{1,2,3} \neq 0$**

$\Rightarrow$ connection of electroweak symmetry breaking and SUSY breaking!

Physical Higgs masses and mixing angle α from minimisation of V_H:

$$M_A^2 = -\bar{m}_3^2 (\tan\beta + \cot\beta) = -2\bar{m}_3^2 / \sin 2\beta$$

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

$$M^2_{H^\pm} = M_A^2 + M_W^2$$

$$\tan 2\alpha = \frac{-(M_A^2 + M_Z^2) \sin 2\beta}{(M_Z^2 - M_A^2) \cos 2\beta} = \tan 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \quad \left(-\frac{\pi}{2} \leq \alpha \leq 0\right)$$

Gives important constraints on the MSSM h boson masses (tree-level):

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

The relations are broken by large radiative corrections in the HIggs sector.