Higgs Physics

as the origin of elementary particle masses

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- **EWSB and Higgs particles**
- **Higgs decays**
- **The Higgs at the LHC**
- **Implications of a Higgs discovery**
- **Conclusion**

1. EWSB and Higgs particles

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

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

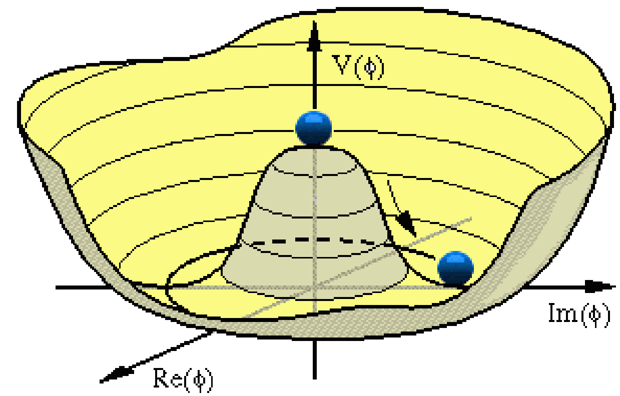
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$

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

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

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

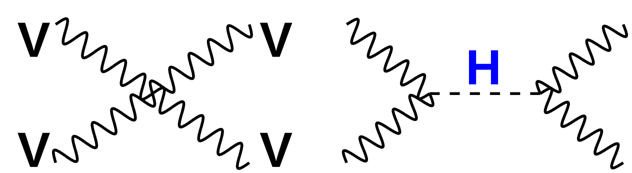
$\mathcal{L}_{\rm Yuk} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R + \ldots$



Residual dof corresponds to spin–0 H particle.

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

The Higgs unitarizes the theory:



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

including H with couplings as predicted:

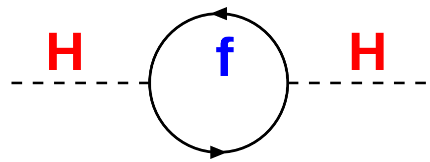
$|A_0| \propto M_H^2/v^2 \Rightarrow$ **the theory is unitary but needs** $M_H \lesssim 700$ **GeV...**

1. EWSB and Higgs particles

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

Radiative corrections to M_H^2 in SM with a cut–off $\Lambda = M_{NP} \sim M_{Pl}$

$\Delta M_H^2 \equiv$



$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$

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

Three main avenues for solving the hierarchy problem:

Supersymmetry: a set of new/light SUSY particles cancel the divergence.

– MSSM $\equiv$ two Higgs doublet model $\Rightarrow$ 5 physical states $h, H, A, H^\pm$

– very predictive: only two free parameters at tree–level ($\tan\beta, M_A$)

– upper bound on light Higgs $M_h \lesssim 130$ GeV and $M_{H,H^\pm} \approx M_A \lesssim$ TeV

Extra dimensions: there is a cut–off at TeV scale where gravity sets in.

– in most cases: SM–like Higgs sector but properties possibly affected

– but in some cases, there might be no Higgs at all (Higgsless models)....

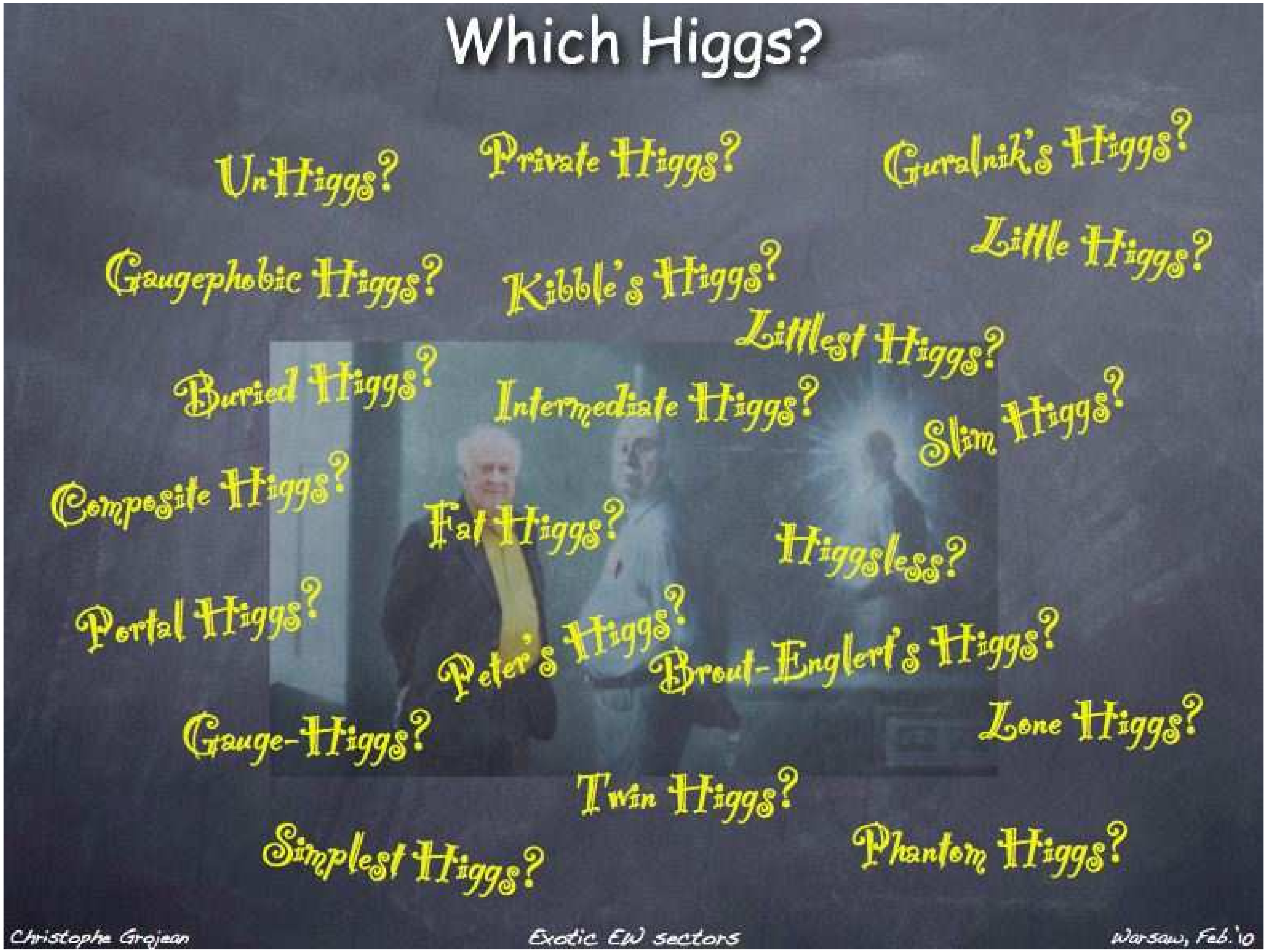
Strong interactions/compositness: the Higgs is not an elementary scalar.

– H is a bound state of fermions like for the pions in QCD...

– H emerges as a Nambu–Goldstone of a strongly interacting sector..

1. EWSB and Higgs particles

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



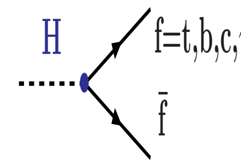
Which scenario chosen by Nature? The LHC will/should tell!

2. Higgs decays

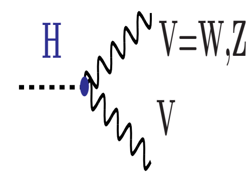
Higgs couplings proportional to particle masses: once $\mathrm{M_H}$ is fixed,

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

$$\mathrm{H \to f\bar{f}}:\ \Gamma = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H m_f^2 \beta_f^3$$

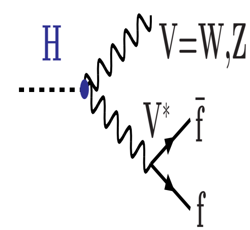


- **only $\mathrm{b\bar{b}}, \mathrm{c\bar{c}}, \tau^+\tau^-, \mu^+\mu^-$ and eventually $\mathrm{t\bar{t}}$**
- **QCD RC very large $\Rightarrow \mathrm{m_b^{\overline{MS}}(M_H^2) \sim 3\,GeV}$.**
- **also direct QCD (3-loops) and EW (1-loop).**



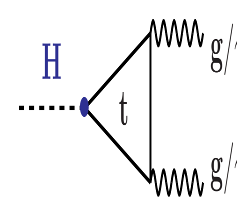
$$\mathrm{H \to VV}:\ \Gamma = \frac{G_\mu M_H^3}{16\sqrt{2}\pi} \delta_V \beta_V \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right)$$

- **above $2\mathrm{M_Z}$ th. dominant: BR(WW)=$\frac{2}{3}$, BR(ZZ)=$\frac{1}{3}$**
- **$\mathrm{M_H} \gg \mathrm{M_V}$: very large $\Gamma_{\mathrm{VV}} \propto \mathrm{M_H^3}$ $(\Gamma_{\mathrm{tt}} \propto \mathrm{M_H})$**
- **below th. decays possible/important $(\mathrm{m_b} \ll \mathrm{M_V})$!**



$\mathrm{H \to gg/\gamma\gamma, Z\gamma}$: **loop induced $\propto \mathcal{O}(\alpha_s^2/\alpha^2)$**

- **heavy particles do not decouple! mainly t(W) loops**
- **$\mathrm{H \to gg}$: large (#2) RC; reverse of $\mathrm{gg \to H}$!**
- **$\mathrm{H \to \gamma\gamma}$: much smaller ($\propto \alpha^2/\alpha_s^2$) but clean!**



2. Higgs decays: branching ratios

Branching ratios: $\mathrm{BR}(\mathrm{H} \to \mathbf{X}) \equiv \frac{\Gamma(\mathbf{H}\to\mathbf{X})}{\Gamma(\mathbf{H}\to\mathbf{all})}$

- **'Low mass range', $\mathrm{M_H} \lesssim 130$ GeV:**

– $\mathrm{H} \to \mathrm{b\bar{b}}$ **dominant, BR = 60–90%**

– $\mathrm{H} \to \tau^+\tau^-, \mathrm{c\bar{c}}, \mathrm{gg}$ **BR= a few %**

– $\mathrm{H} \to \gamma\gamma, \gamma\mathrm{Z}$, **BR = a few permille.**

- **'High mass range', $\mathrm{M_H} \gtrsim 130$ GeV:**

– $\mathrm{H} \to \mathbf{WW^*}, \mathbf{ZZ^*}$ **up to** $\gtrsim 2\mathrm{M_W}$

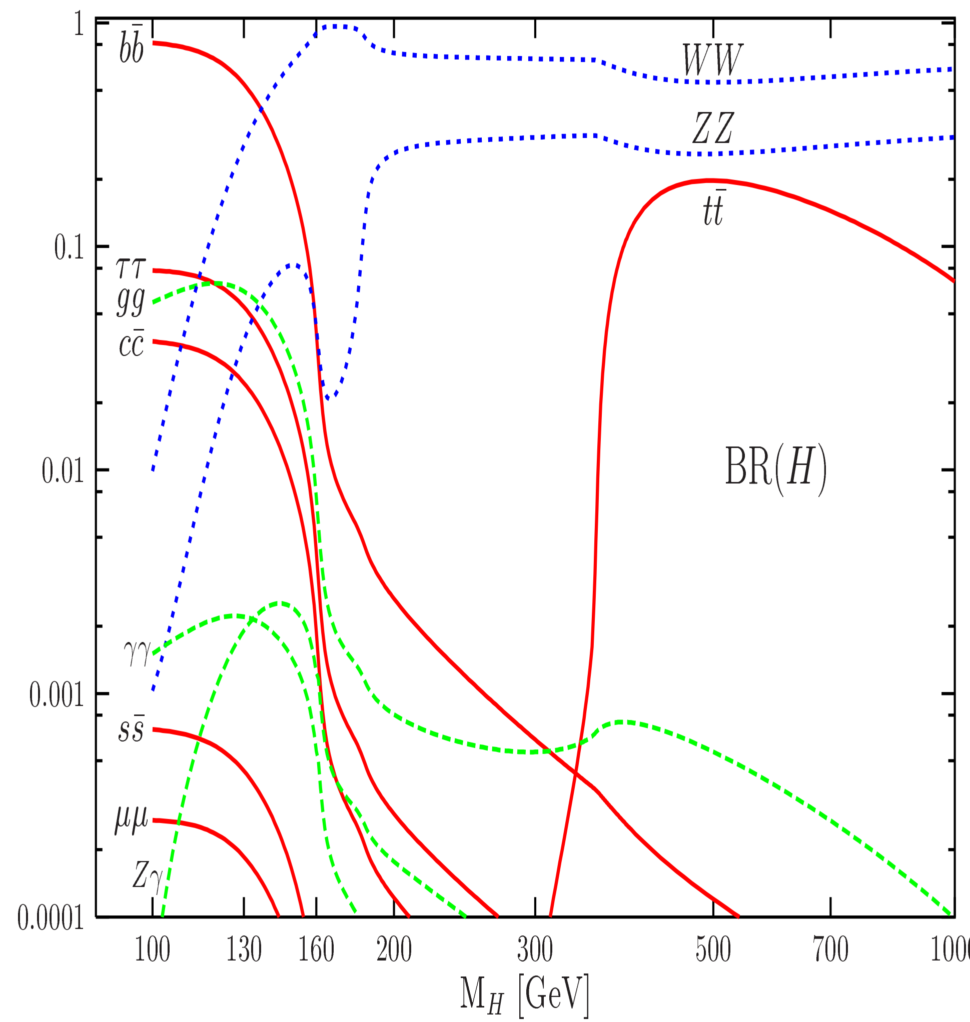
– $\mathrm{H} \to \mathbf{WW}, \mathbf{ZZ}$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

– $\mathrm{H} \to \mathrm{t\bar{t}}$ **for high** $\mathrm{M_H}$**; BR** $\lesssim 20\%$.

- **Total Higgs decay width:**

– $\mathcal{O}$**(MeV) for** $\mathrm{M_H} \sim 100$ **GeV (small)**

– $\mathcal{O}$**(TeV) for** $\mathrm{M_H} \sim 1$ **TeV (obese).**



HDECAY: AD, Kalinowski, Spira (95–10). Includes all relevant higher orders.

2. Higgs decays: total width

Total decay width: $\Gamma_H \equiv \sum_X \Gamma(H \to X)$

- **'Low mass range', $M_H \lesssim 130$ GeV:**

– $H \to b\bar{b}$ **dominant, BR = 60–90%**

– $H \to \tau^+\tau^-, c\bar{c}, gg$ **BR= a few %**

– $H \to \gamma\gamma, \gamma Z$, **BR = a few permille.**

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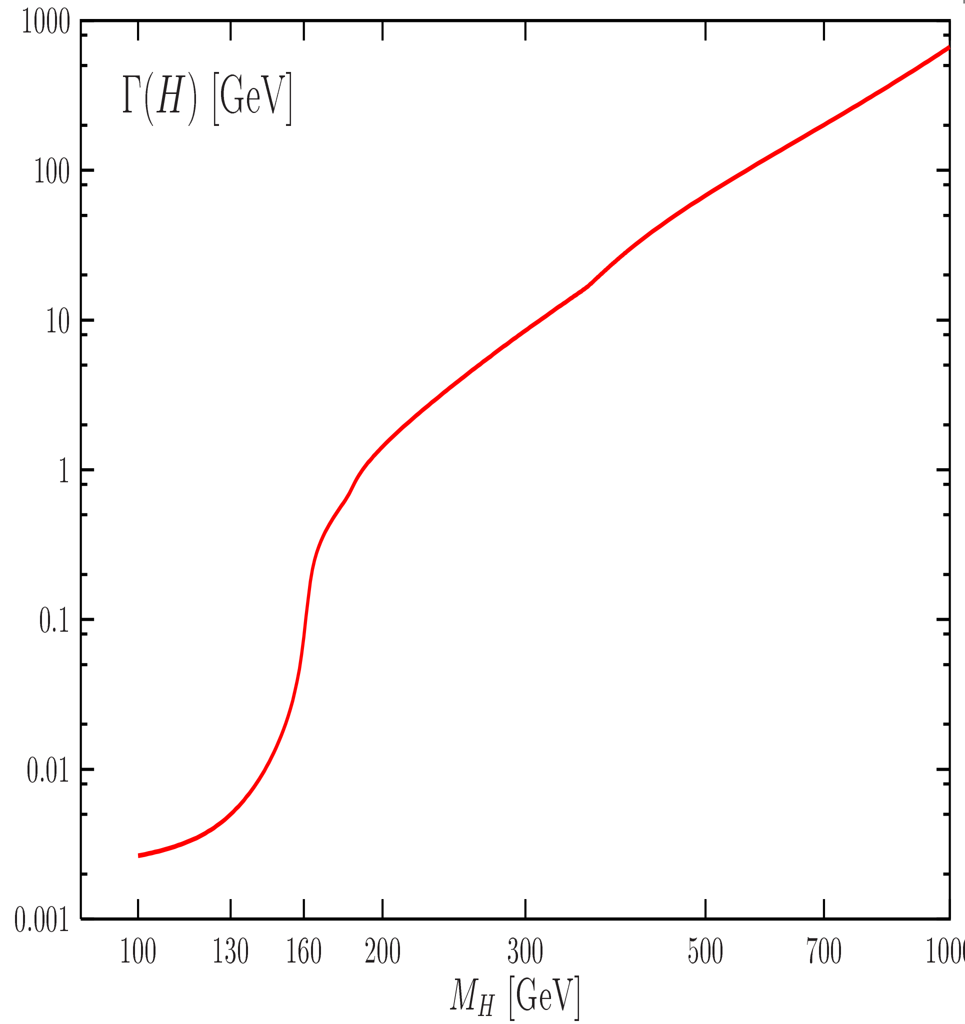


HDECAY: AD, Kalinowski, Spira (95–10). Includes all relevant higher orders.

2. Higgs decays: theory uncertainties

However: there is QCD at work: theory uncertainties!

- **Input quark masses in $\mathbf{H \to b\bar{b}, c\bar{c}}$**

$$\mathbf{M_Q^{pole} \to \overline{m}_Q(\mu = M_H)}$$

– $\mathbf{\overline{m}_b(M_b) = 4.19^{+.0.036}_{-0.012}}$ **GeV**

– $\mathbf{\overline{m}_c(M_c) = 1.27^{+.0.014}_{-0.018}}$ **GeV**

- **Theory+experimental error on α_s :**

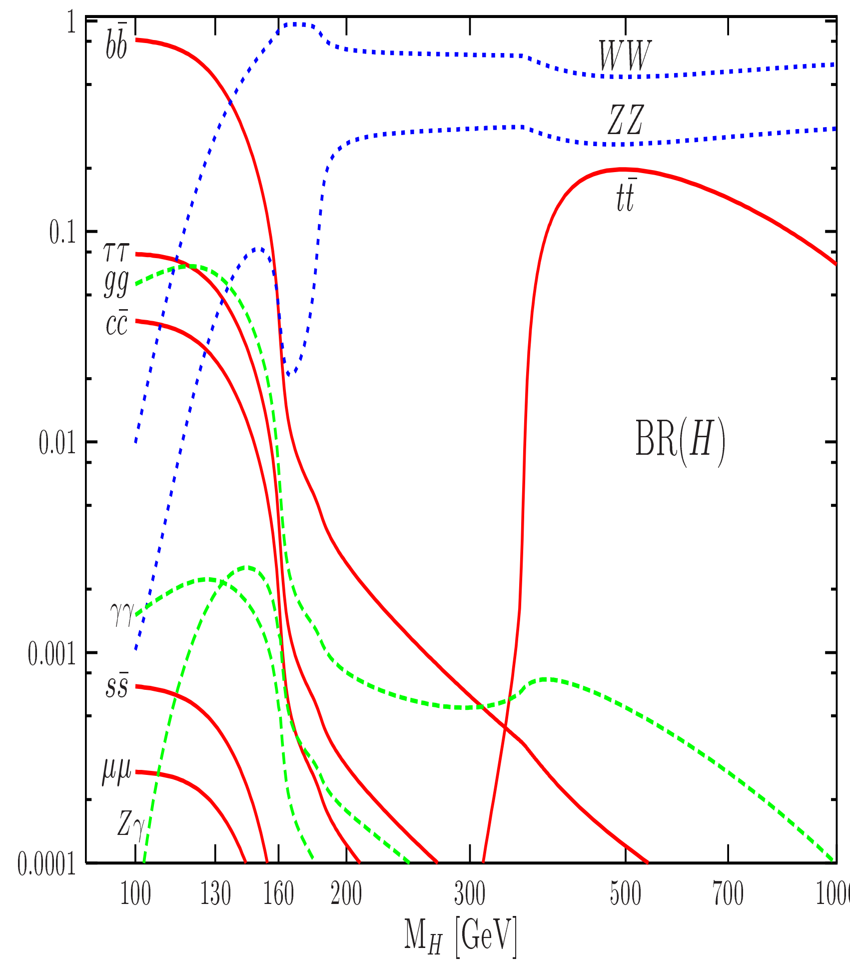
$\alpha_s(\mathbf{M_Z^2}) = \mathbf{0.1171 \pm 0.0028}$ **@NNLO**

- **Scale error: measure of higher orders**

$$\mathbf{\tfrac{1}{2}M_H \le \mu \le 2M_H}$$

- **Scale and α_s errors in $\mathbf{H \to gg}$**

$\mathbf{\Gamma(H \to gg) \propto \alpha_s^2 + large\ \mathcal{O}(\alpha_s^3)}$



- **No uncertainty on H$\to \tau\tau$,WW,ZZ**

(QCD effects appear at high orders).

2. Higgs decays: theory uncertainties

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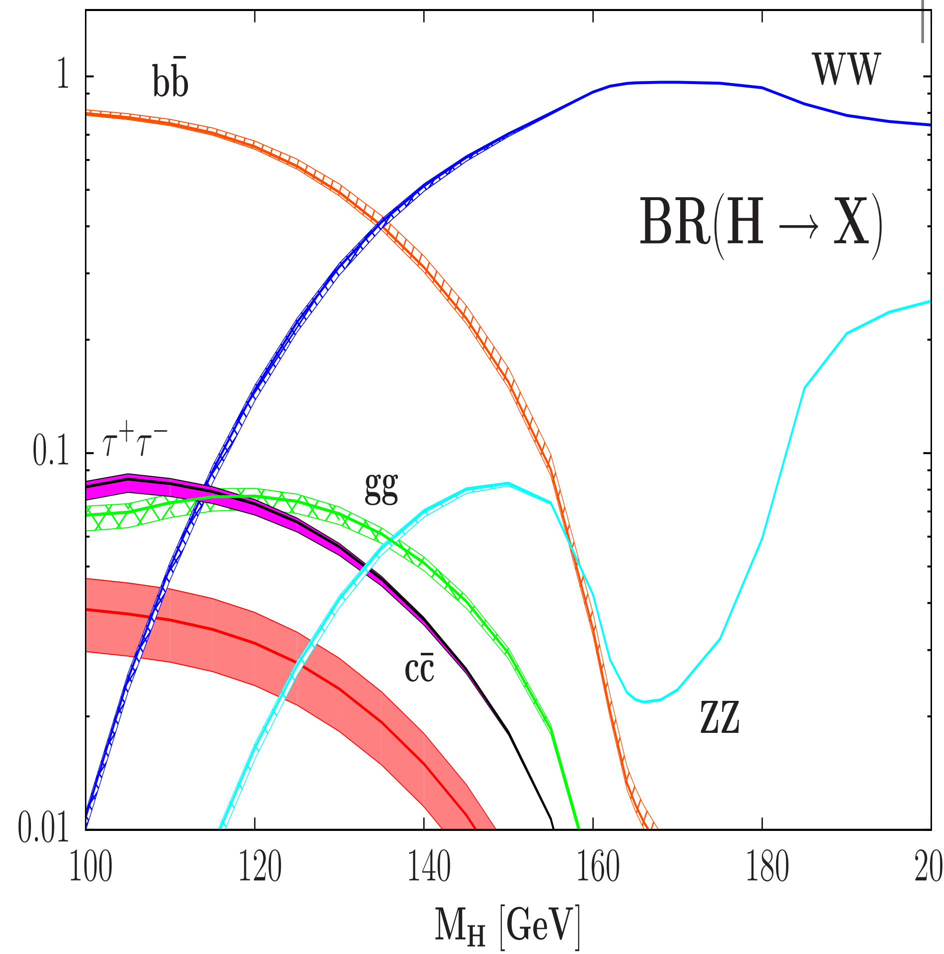


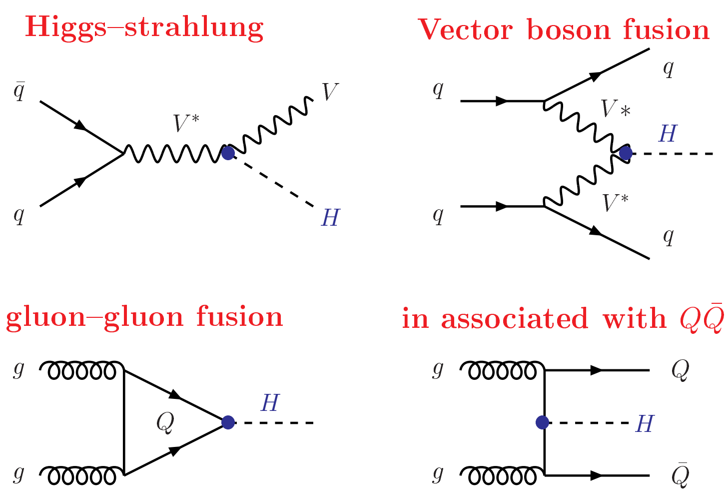
Baglio,AD

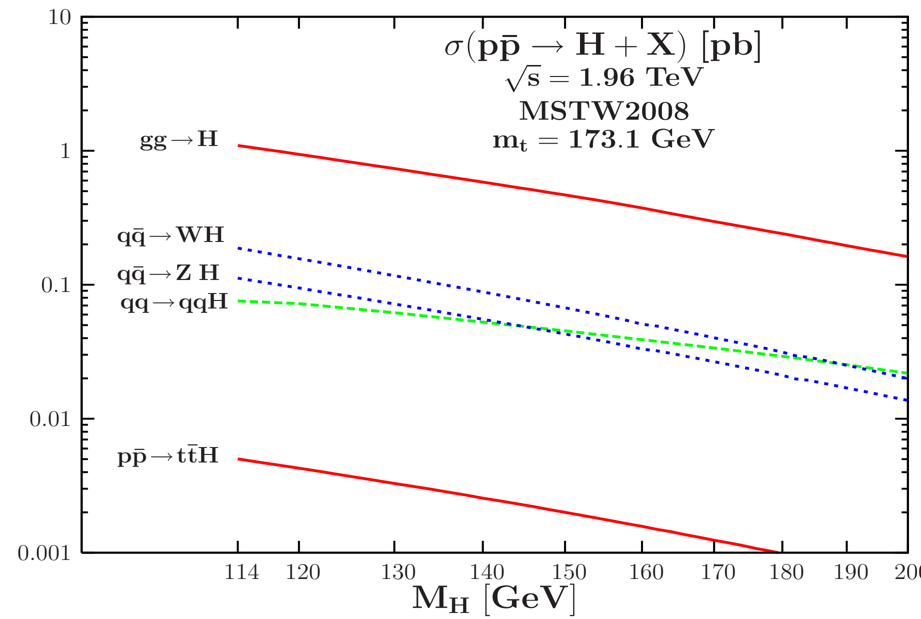
Include all items $\Rightarrow$ non–negligible uncertainties...

esp. for M_h ≈120–150 GeV: ≈ 5–10% for $H \to b\bar{b}$ and $H \to WW^*$

3. The Higgs at hadron colliders: production

Main Higgs production channels





Large production cross sections

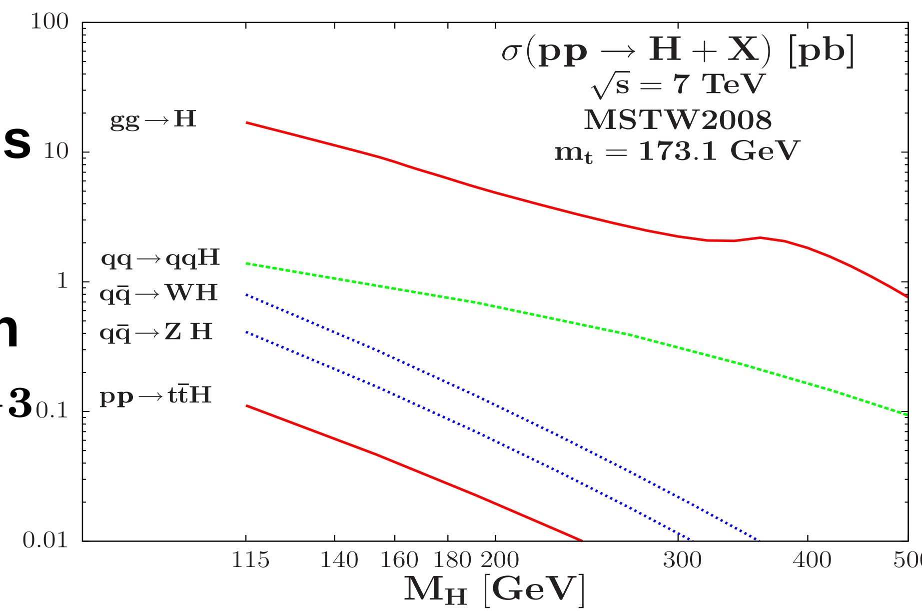
with gg$\longrightarrow$ H by far dominant process

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

$\Rightarrow \mathcal{O}(10^3)$ events @Tevatron

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

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



3. The Higgs at hadron colliders: 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...)

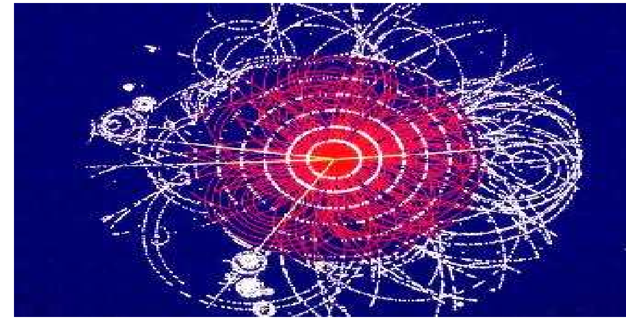
- **Have a precise knowledge of S and B rates**

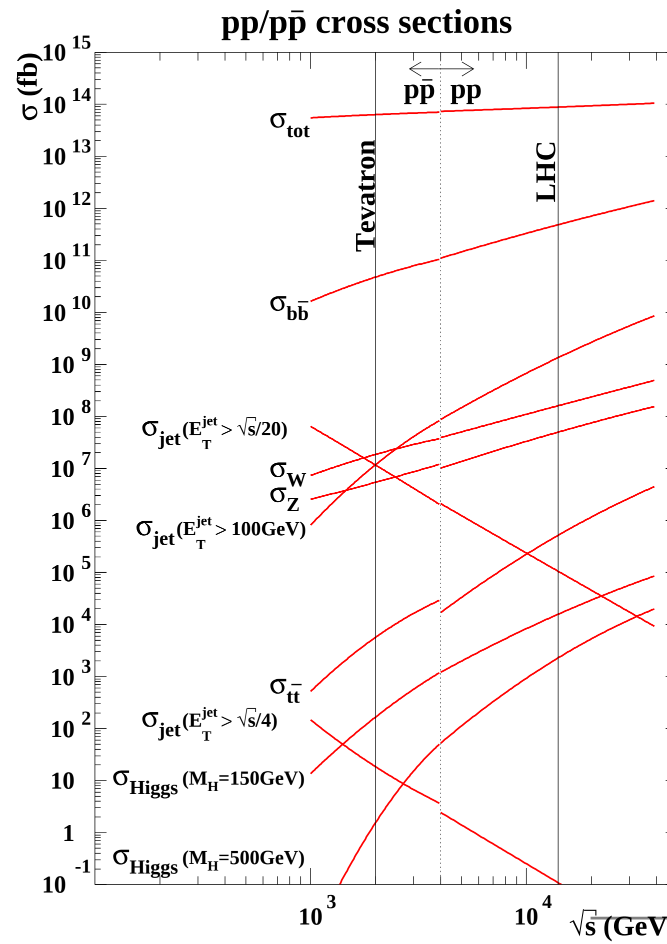
(higher orders can be factor of 2! see later)

- **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**



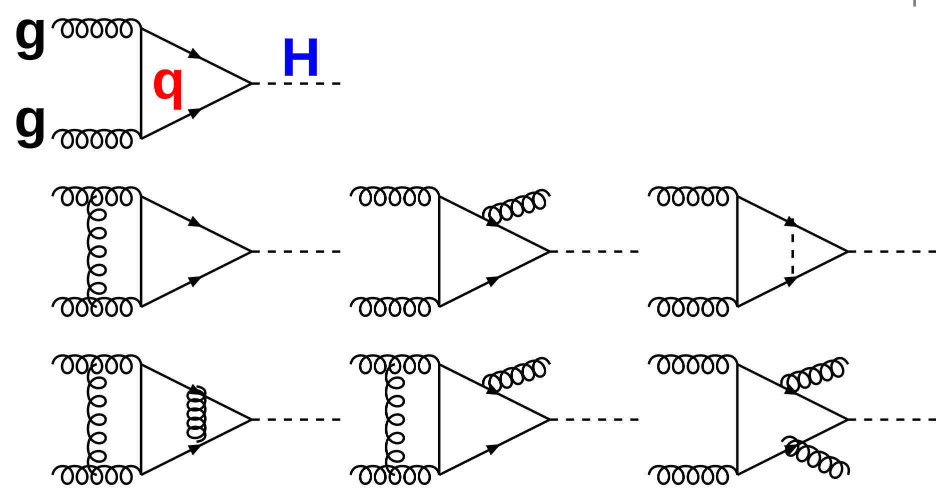


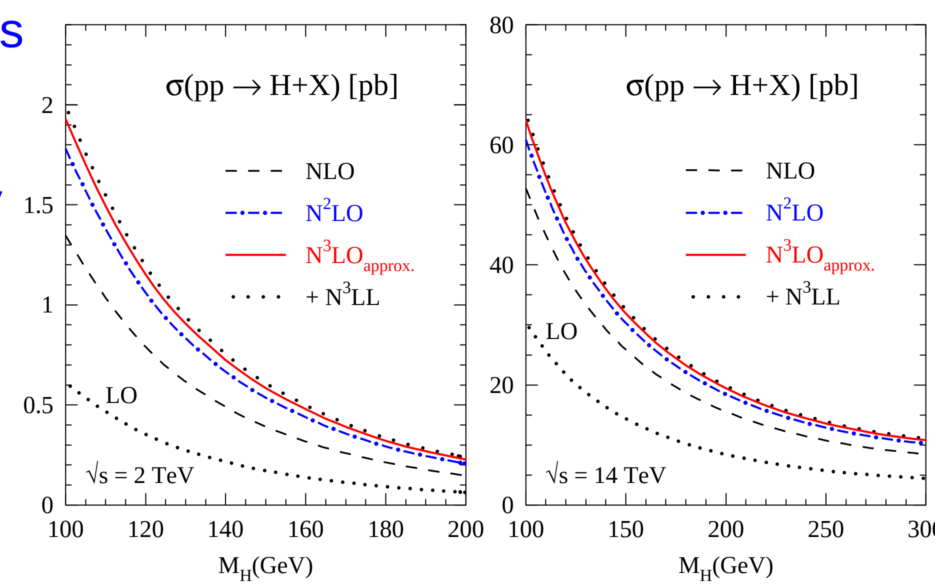
3. The Higgs at hadron colliders: gg fusion

LO[a]**: already at one loop**
QCD: exact NLO[b] **: $\mathrm{K}\approx$2 (1.7)**
EFT NLO[c]**: good approx.**
EFT NNLO[d]**: $\mathrm{K}\approx$3 (2)**
EFT NNLL[e]**: $\approx +$10% (5%)**
EFT other HO[f]**: a few %.**
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; Ahrens et al.
[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 (70s–now) ...





Moch+Vogt

3. The Higgs at hadron colliders: uncertainties

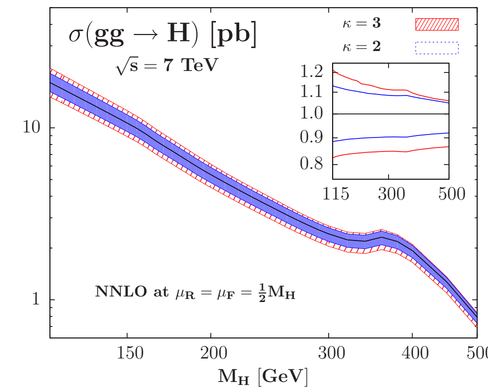
Despite of that, the $\mathrm{gg}\to\mathrm{H}$ cross section still affected by uncertainties

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

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

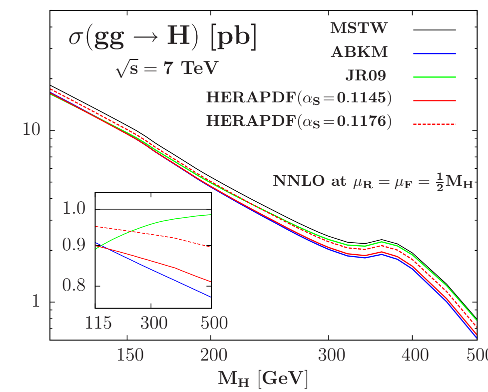
$$\mu_0/\kappa \leq \mu_{\rm R}, \mu_{\rm F} \leq \kappa\mu_0$$

at lHC: $\mu_0 = \frac{1}{2}\mathrm{M_H}, \kappa = 2 \Rightarrow \Delta_{\rm scale} \approx 10\%$



- **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



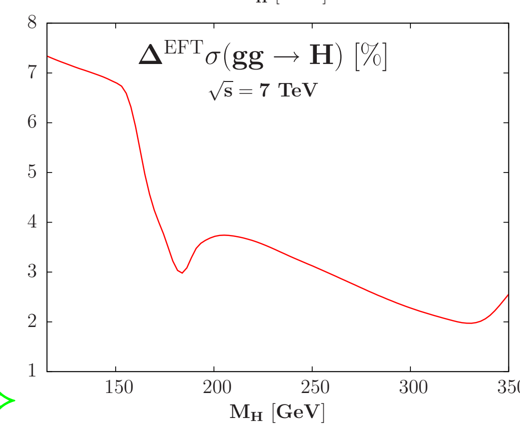
- **Uncertainty from EFT approach at NNLO**

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

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

total $\Delta\sigma^{\rm NNLO}_{\rm gg\to H\to X} \approx$ 20–25%@lHC

QCD at work again! LHC-HxsWG; Baglio+AD $\Rightarrow$



3. The Higgs at hadron colliders: expectations

Expectations for 2011 and beyond:

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

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

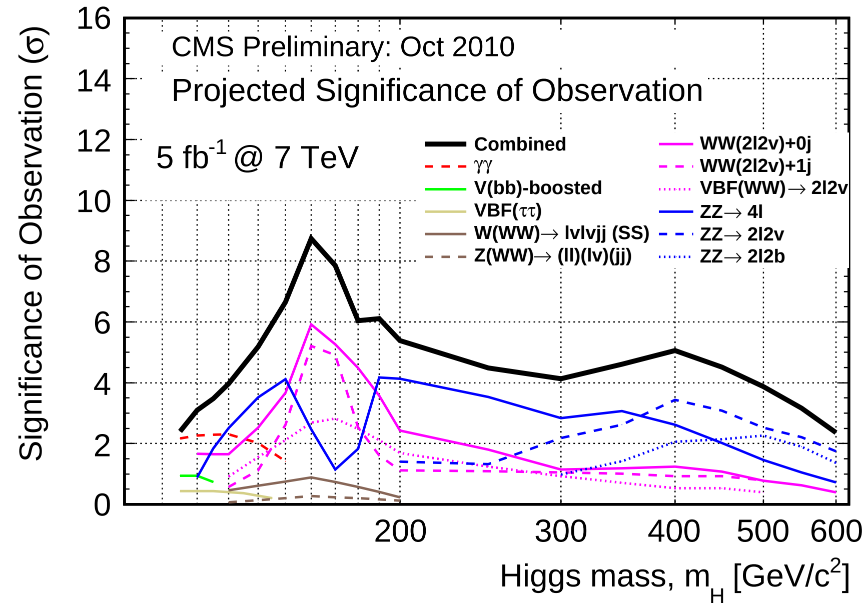
95%CL sensitivity for $M_H \lesssim$600 GeV

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

$gg \to H \to WW \to \ell\nu\ell\nu + 0,1$ jets

$gg \to H \to ZZ \to 4\ell, 2\ell 2\nu, 2\ell 2b$

Help from VBF/VH; $gg \to H \to \tau\tau$?



Tevatron: some data still to be analyzed

now surpassed by lHC in all channels.

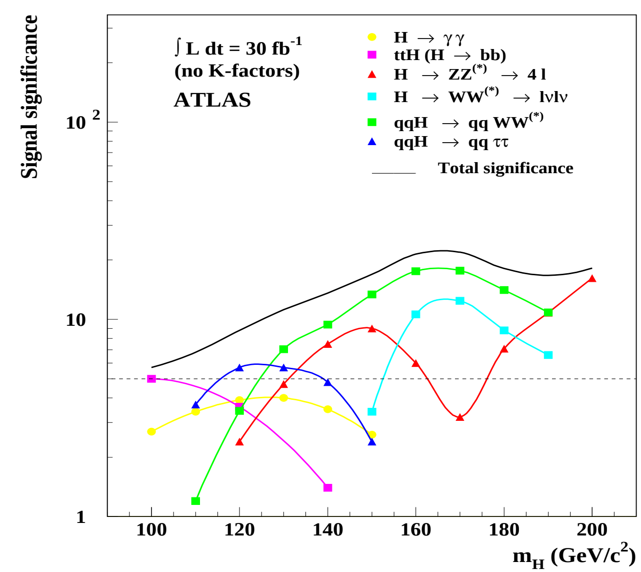
Still $HV \to b\bar{b}\ell X @ M_H \lesssim$130 GeV!

Full LHC: same as lHC plus some others

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

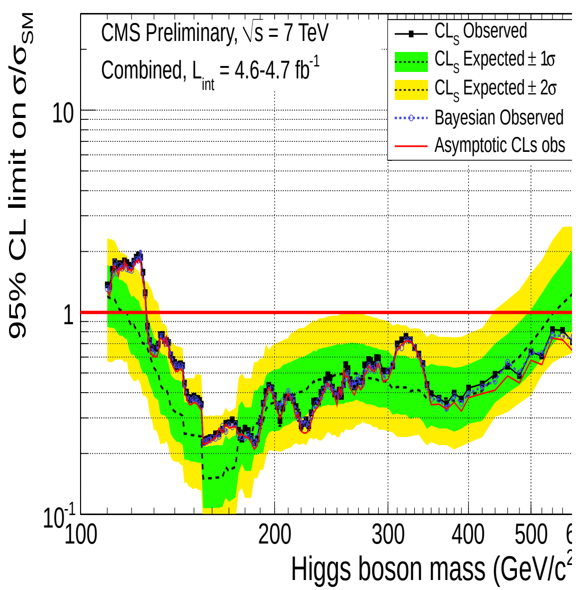
– VH$\to$Vbb with jet substructure tech.

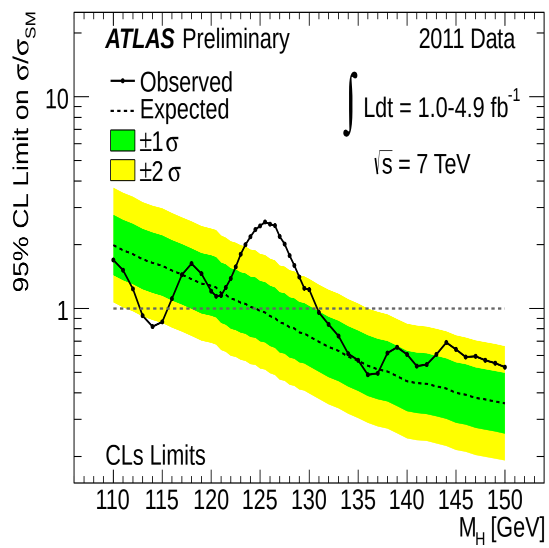
– ttH: H$\to\gamma\gamma$ bonus, H$\to b\bar{b}$ hopeless?

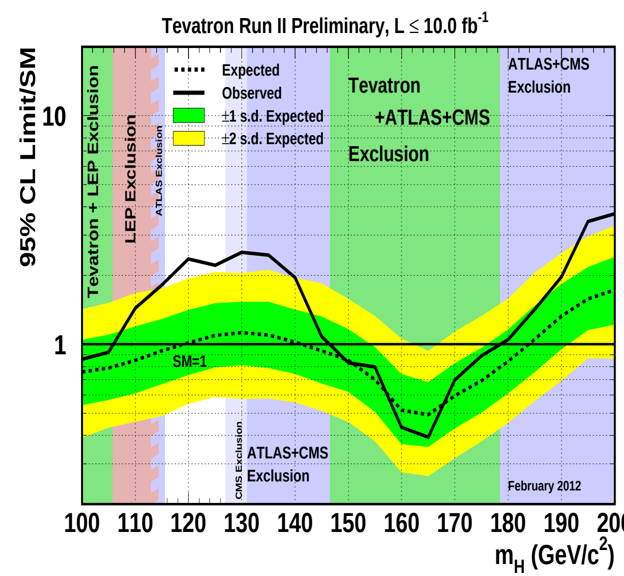


4. Implications of Higgs discovery

We desperately wanted a Higgs for last Christmas and we got:
– SM Higgs excluded everywhere except for $\mathrm{M_H}$=123.5-127.5 GeV
– a $\approx 3\sigma$ signal at $\mathrm{M_H}$ $\approx$125 GeV
$\rightarrow$ thanks to LHC, ATLAS, CMS!
(let us hope it will not go away....)
Also a 2.2σ "hint" from Tevatron!







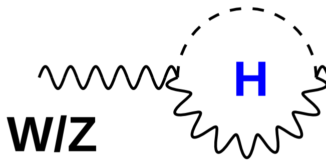
4. Implications of Higgs discovery: SM

The SM: a rather predictive theory:

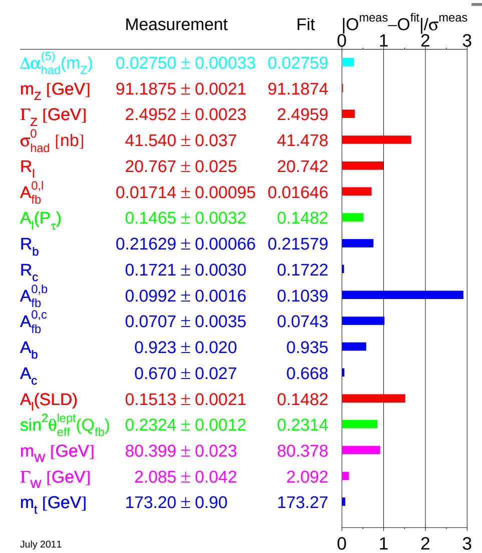
A triumph for high-energy physics!

Indirect constraints from EW data[a]

H contributes to RC to W/Z masses:



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



Fit the EW precision measurements,

one obtains $M_H = 92^{+34}_{-26}$ GeV, or

$M_H \lesssim 161$ GeV at 95% CL

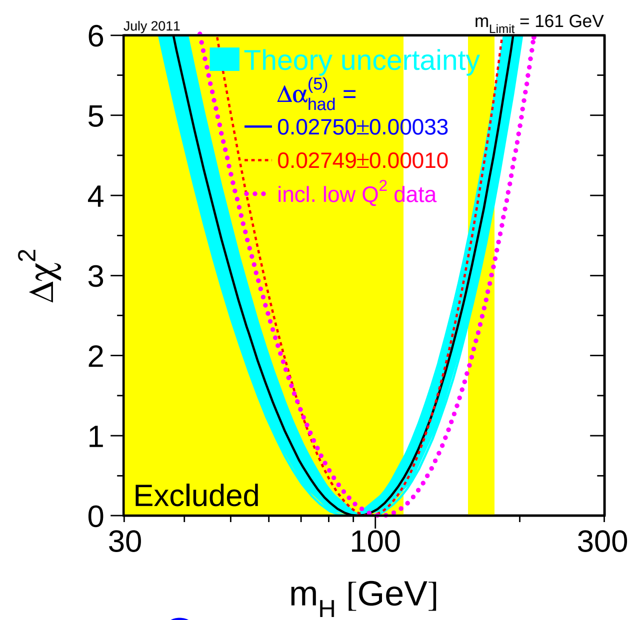
compared with "observed" $M_H = 125$ GeV

A very non–trivial check of SM consistency!

In 1995: top discovery with $m_t \approx 175$ GeV

while best-fit in the SM is for same value:

it was considered as a great achievement....



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[a] Still some problems with A^b_{FB} (LEP), A^t_{FB} (TeV) and $g-2$ but not severe...

4. Implications of Higgs discovery: SM

If excess due to Higgs: spectrum complete

no room for a 4th fermionic generation!

extra fermion doublet (with heavy ν') will:

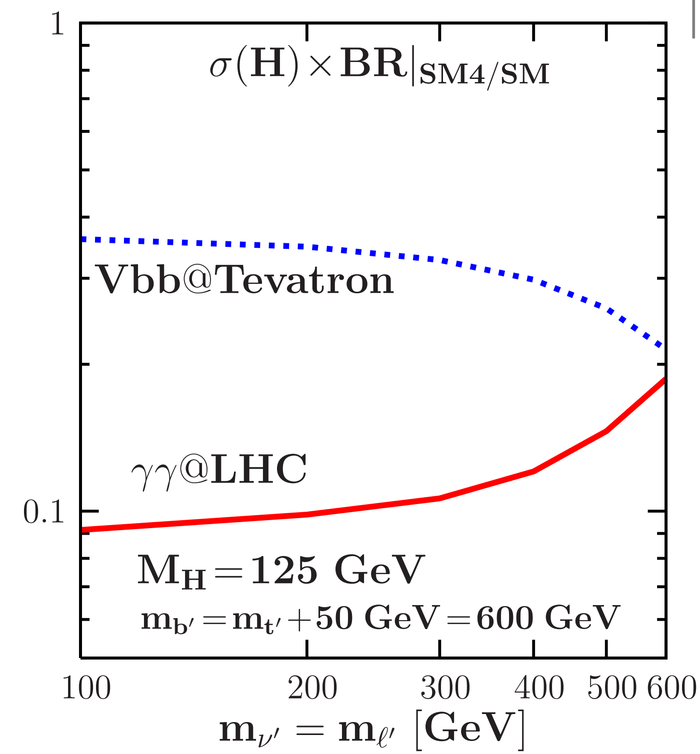
– increase $\sigma(gg \to H)$ by factor ≈ 9

– H$\longrightarrow$gg suppresses BR(bb,VV) by $\approx$2

– strongly suppresses $\mathrm{BR}(H \to \gamma\gamma)$

If indeed a 125GeV H: SM4 ruled out...

AD+Lenz (2012) $\Rightarrow$



$M_H = 125$ GeV, SM valid up to M_{GUT}

No problem with triviality: $M_H \lesssim 180$ GeV

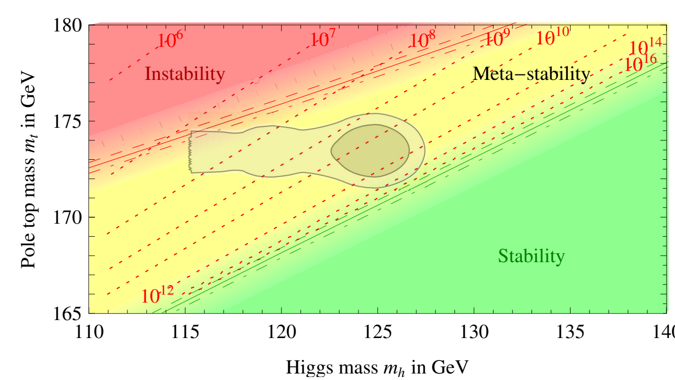
SM valid only if v$\equiv$EW-min, ie $\lambda(Q^2) > 0$

$\Lambda_C \sim M_P \Rightarrow M_H \gtrsim 130\,\mathrm{GeV}$

refinements+uncertainties+metastability $\Rightarrow$

A 125 GeV Higgs is still OK!

Espinosa et al. 2011



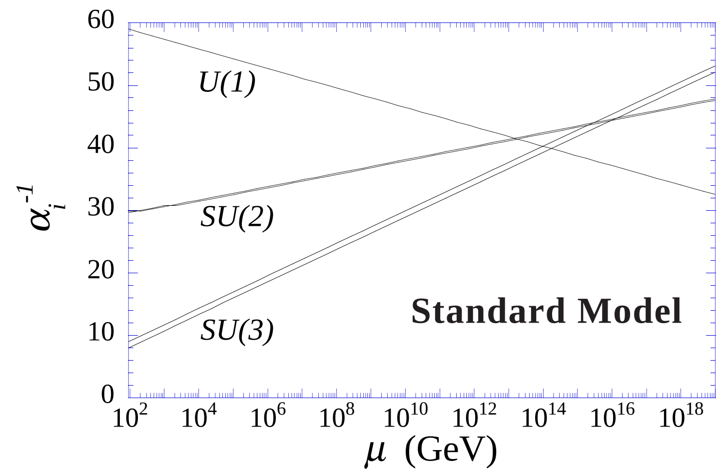
4. Implications of Higgs discovery: SM respectable theory?

With the Higgs, the SM is a perturbative, renormalisable, unitary theory.
Can be extrapolated up to very high energy (even ultimate) scales.

However there are theoretical problems:

- **extremely fine–tuned.... so what?**
- **no coupling unification; thresholds?**
- **not a theory of flavor; too bad...**

$\Rightarrow$ **Maybe nature is not perfect?**



To be extended to cope with experiment:

- **needs framework for neutrino masses**

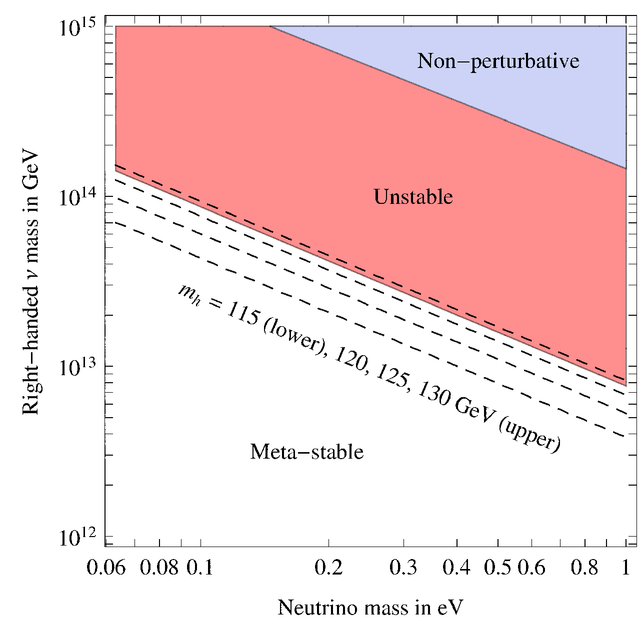
$\Rightarrow$ **simply add ν_R's at very high scale**
will enter stability limit and help BAU?

Espinosa et al, 2011

- **no thermal dark matter candidate**

$\Rightarrow$ **axion would make it? try harder...**

Maybe minimal SM extension is the TO(a)E?
(esp. no hint of new physics@LHC yet...)



4. Implications of Higgs discovery: MSSM

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

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

After EWSB (which can be made radiative: more elegant than in SM):
three dof to make $W_L^\pm, Z_L \Rightarrow$ 5 physical states left out: $h, H, A, H^\pm$
Only two free parameters at the tree level: $\tan\beta, M_A$; others are:

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

We have important constraint on the MSSM Higgs boson masses:

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

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

$$M_h \sim M_Z|\cos 2\beta| \le M_Z!\,,\ M_H \sim M_{H^\pm} \sim M_A\,,\ \alpha \sim \frac{\pi}{2} - \beta$$

$\Rightarrow$ Inclusion of radiative corrections to M_h important and necessary.

4. Implications of Higgs discovery: pMSSM

The mass value 125 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:

$$M_h \overset{M_A \gg M_Z}{\longrightarrow} M_Z|\cos 2\beta| + \frac{3\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{2M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

- **decoupling regime with $M_A \sim \mathcal{O}$(TeV);**
- **large values of tan$\beta \gtrsim 10$ to maximize tree-level value;**
- **maximal mixing scenario: $X_t = \sqrt{6} M_S$;**
- **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 as in real life:

- **small contributions of entire SUSY spectrum: $\Phi, \chi_i^\pm, \chi_i^0, \tilde{q}_i, \tilde{l}_i, \tilde{g}$...**
- **complete radiative corrections up to two–loops**

We use the RGE codes Suspect Kneur+Moultaka+AD **and Softsusy** Allanach
which implement the known radiative corrections in the $\overline{\rm DR}$ scheme.

4. Implications of Higgs discovery: pMSSM

To evaluate M_h, perform a full scan of the MSSM parameter space;
too complicated in the general MSSM as there are 105 free parameters
$\Rightarrow$ work in the phenomenological MSSM or pMSSM:
– no CP or flavor-violation: no new phase and diagonal $\tilde{m}, A$ matrices,
– universal first and second generation sfermions to cope with flavor.
Only 22 free parameters: $\tan\beta, M_A, \mu, M_{1,2,3}, m_{\tilde{f}_L}, m_{\tilde{f}_R}, A_f$
and only a few of them will play and important role in the Higgs sector..

Perform a full and fine scan of the pMSSM parameter space:

$$1 \le \tan\beta \le 60\,,\ 50\ \text{GeV} \le M_A \le 3\ \text{TeV},\ -9\ \text{TeV} \le A_f \le 9\ \text{TeV},$$

$$50\ \text{GeV} \le m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \le 3\ \text{TeV}, 50\ \text{GeV} \le M_1, M_2, |\mu| \le 1.5\ \text{TeV}$$

- determine the regions of parameter space where $123 \le M_h \le 127$ GeV
(2 GeV uncertainty includes both "experimental" and "theoretical" error)
- require h to be SM–like: $\sigma(h) \times BR(h \to VV) \gtrsim 0.9 H_{SM}$
(we will also consider the possibility that H is the H_{SM}, see later).

4. Implications of Higgs discovery: pMSSM

Main results:

- **Large M_S values needed:**

– $M_S \approx 1$ TeV: only maximal mixing

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

- **Large tanβ values favored**

but tan$\beta \approx 3$ possible if $M_S \approx 3$TeV

- **What about other benchmarks?**

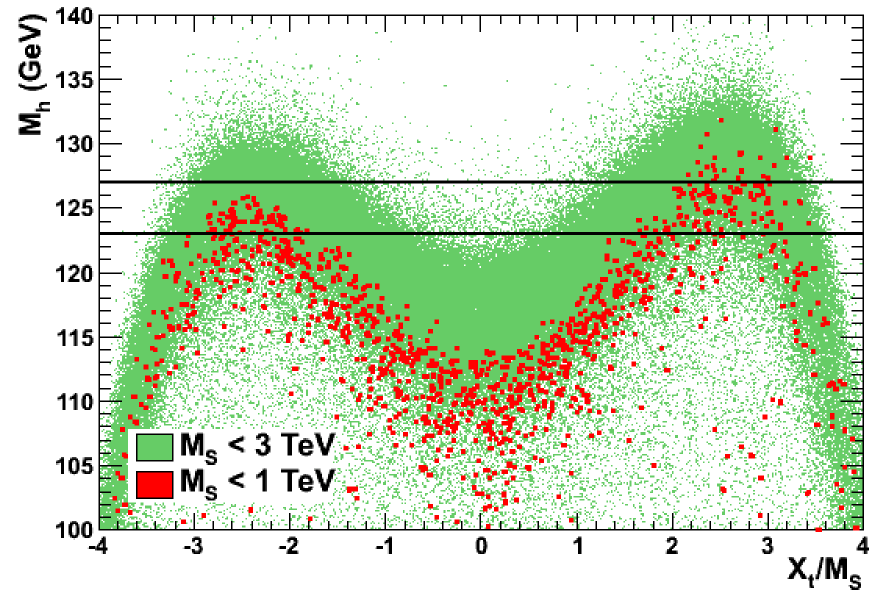
Carena+Heinemeyer+Wagner+Weiglein

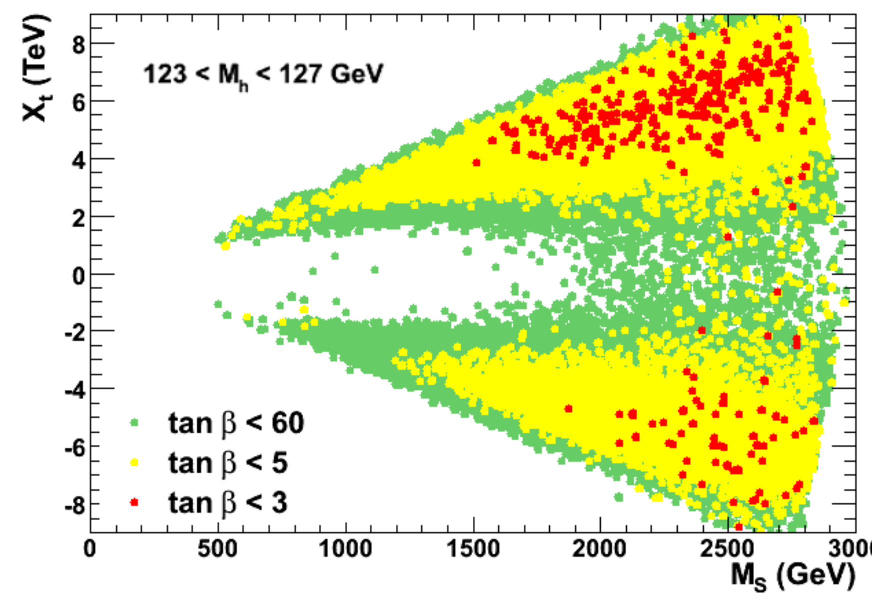
– small $\alpha_{\rm eff}$ scenario with $g_{hbb} \approx 0$: ruled out by LHC/Tevatron data.

– gluophobic h with $g_{hgg} \ll g_{H_{SM}gg}$ ruled out by $4\ell^+, \gamma\gamma$ signals at LHC (difficult to achieve as $\tilde{t}_1$ heavy..).

– no SUSY regime with light sparticles: BR($h \to \chi_1^0\chi_1^0$) should be small...

– max and no-mix need to be updated!





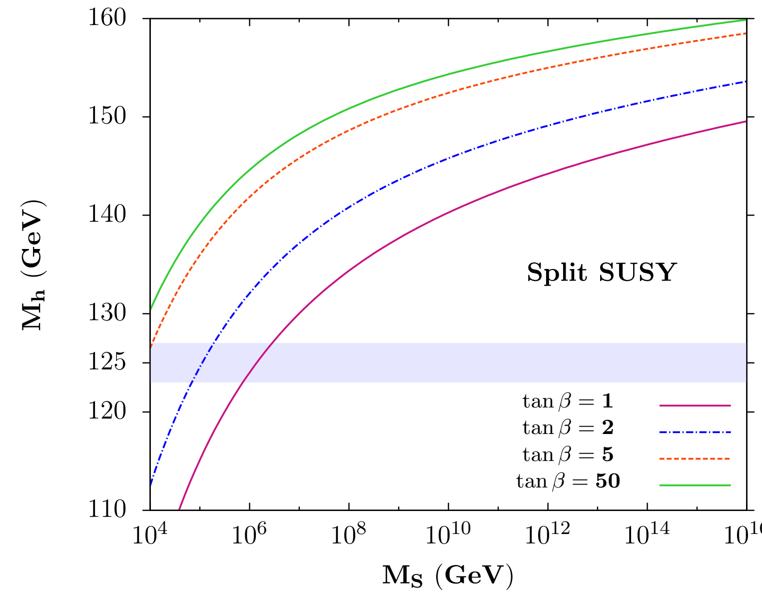
4. Implications of Higgs discovery: high scale SUSY

The scale M_S seems to be large. There are two extreme possibilities

- **Split SUSY: allow fine–tuning**

scalars (including H_2) at high scale
gauginos–higgsinos at weak scale
(unification+DM solutions still OK)
$M_h \propto \log(M_S/m_t) \rightarrow$ **large**

Arkani-Hamed+Dimopoulos
Giudice, Romanino



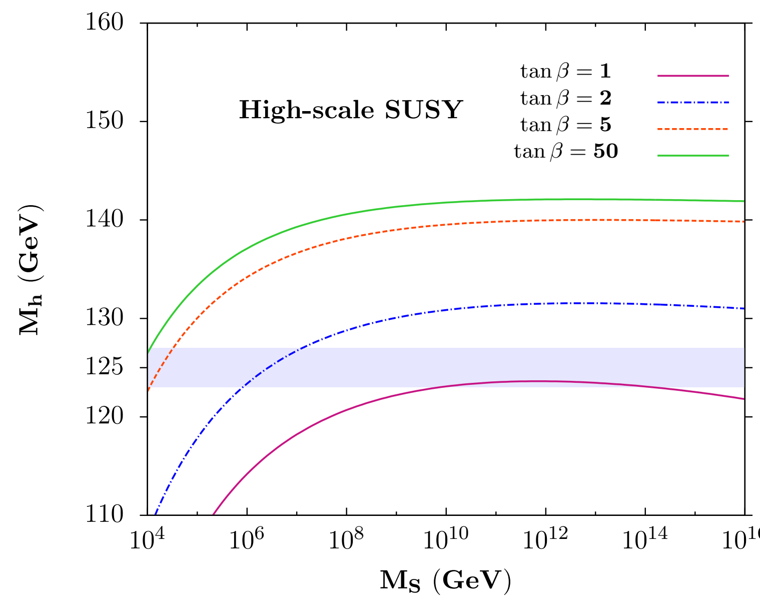
- **SUSY broken at the GUT scale...**

give up fine-tuning and everything else
still, $\lambda \propto M_H^2$ related to gauge cplgs

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

... leading to $M_H =$120–140 GeV ...

Hall+Nomura, Giudice+Strumia
Bernal+Slavich+AD



In both cases small $\tan\beta$ needed...

4. Implications of Higgs discovery: cMSSM

Constrained MSSMs are interesting from model building point of view:

– provide concrete schemes for supersymmetry breaking

– solve some problems of unconstrained MSSM: flavor, CPV, universality, .

– reduce number of input parameters and are thus more predictive

Prototype model: the minimal supergravity model (mSUGRA).

– Underlying assumption: SUSY–breaking occurs in a hidden sector communicating with visible sector through gravitational interactions,

– parameters obey a set of boundary conditions at $M_{GUT} \approx 10^{16}$ GeV

– universal soft terms emerge if the interactions are "flavor–blind"

$\Rightarrow$ only 4.5 inputs: $\tan\beta\,,\ m_{1/2}\,,\ m_0\,,\ A_0\,,\ \text{sign}(\mu)$

In GMSB, SSB transmitted to MSSM fields via SM gauge interactions.

Minimal inputs: $\tan\beta\,,\ \text{sign}(\mu)\,,\ M_{\text{mes}}\,,\ \Lambda_{\text{SSB}}\,,\ N_{\text{mess fields}}$

In AMSB, SSB in hidden sector transmitted via (super-Weyl) anomalies.

Minimal inputs: $m_0\,,\ m_{3/2}\,,\ \tan\beta\,,\ \text{sign}(\mu)$

Using Suspect+Softsusy, perform scans of the models parameter space and confront them with LHC constraint $123\ \text{GeV} \leq M_h \leq 127\ \text{GeV}$

4. Implications of Higgs discovery: cMSSM

The following ranges are considered for the model input parameters besides $1 \leq \tan\beta \leq 60$ and sign(μ)$=\pm 1$ that are common to all:

mSUGRA: 50GeV $\leq m_0 \leq$2TeV, 50GeV $\leq m_{1/2} \leq$3TeV, $|A_0| \leq 9$TeV;

mGMSB: 10TeV$\leq \Lambda \leq$1000 TeV, 1 $\leq M_{mes}/\Lambda \leq 10^{11}$, N_{mess} =1;

mAMSB: 1 TeV$\leq m_{\frac{3}{2}} \leq$ 100TeV,50 GeV $\leq m_0 \leq$ 2 TeV.

In mSUGRA we further consider the following (over–constrained) cases:

- **no–scale: $m_0 = A_0 = 0$**
- **cNMSSM: $m_0 = 0, A_0 = -\frac{1}{4}m_{1/2}$**
- **vcMSSM: $m_0 = A_0$**

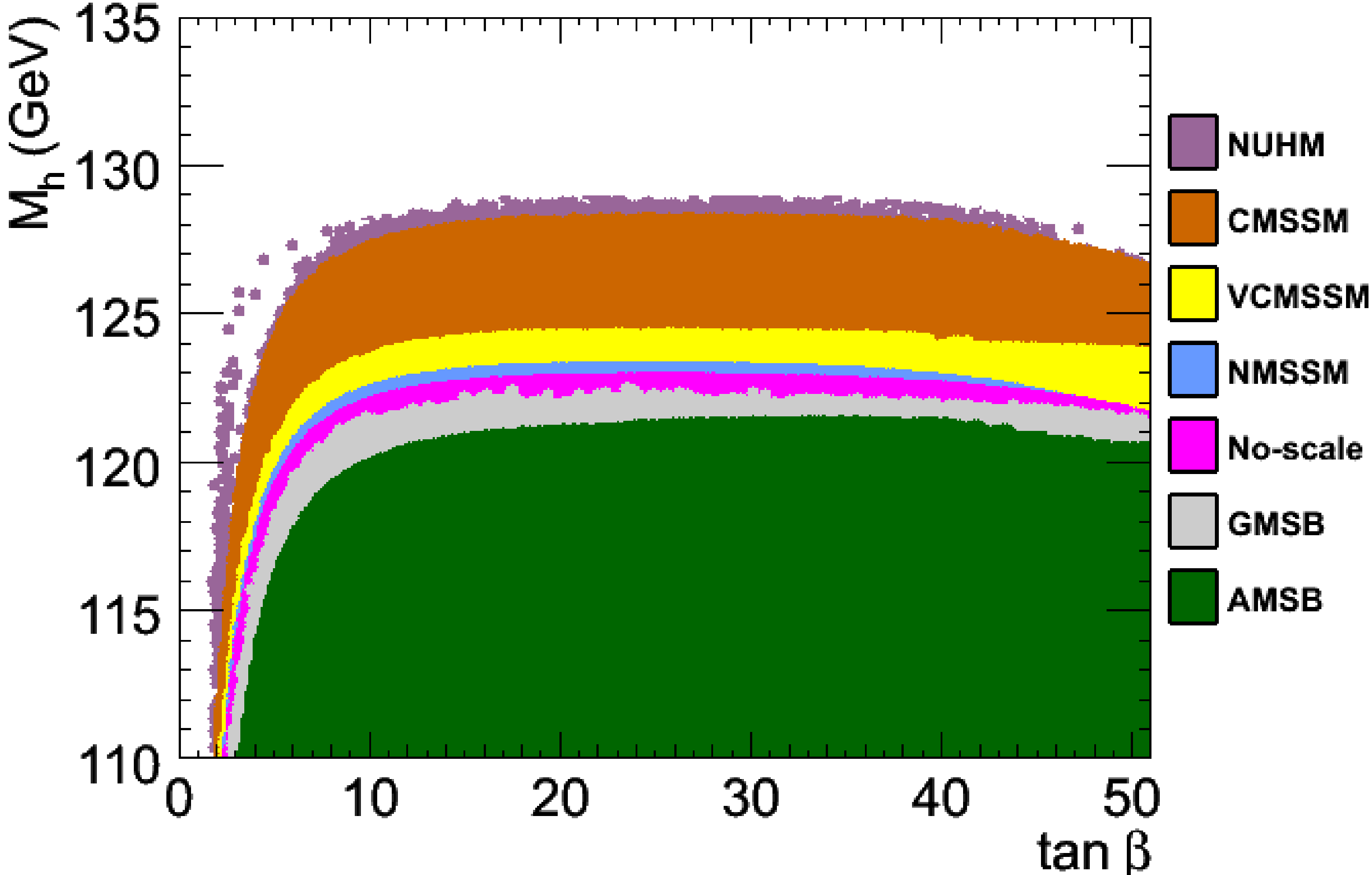
as well as as the less constrained non–universal Higgs mass model:

- **NUHM: $m_{1/2}, m_0, A_0$ and m_{H_u}, m_{H_d}**

In mSUGRA case and its variants, we impose in addition bounds from:
– correct relic density of DM neutralino as measured by WMAP,
– constraints from flavor physics: $b \to s\gamma, B_s \to \mu\mu$,
– constraints from heavy MSSM Higgs production at the LHC.

Less freedom for $A_t \Rightarrow M_h$ is much more constraining!

4. Implications of Higgs discovery: cMSSM



model	amsb	gmsb	sugra	noscale	cnmssm	vcmssm	nuhm
M_h^{max}	120	121	128	123	123	126	128

5. Conclusions

There is a hint of a 125 GeV Higgs but many questions remain:

– is the 125 GeV Higgs really there? any wrong cable connection?

– if yes, is it really SM–like? What about the $\gamma\gamma, 4\ell^{\pm}, b\bar{b}$ rates?

– if indeed OK, a triumph for the Standard Model: Standarissimo!

A 125 GeV Higgs provides information on BSM and SUSY in particular:

- **$M_H = 119$ GeV would have been a boring value: everybody OK..**
- **$M_H = 145$ GeV would be a devastating value: mass extinction..**
- **$M_H \approx 125$ GeV is Darwinian: (natural) selection among models..**

SUSY spectrum heavy; except maybe for weakly interacting sparticles and also stops $\Rightarrow$ more focus on them in SUSY searches!

Some answers in July or December. More complete picture later!

My personal feeling or bet: maybe the rather optimistic scenario?

– a $(5 \oplus 5\sigma?...)$ Higgs in 2012, Higgstoric year!

– a stop and a chargino in 2015: my favorite/best–guess SUSY signal:

$$pp \to \tilde{t}_1 \tilde{t}_1 \to b\chi_1^+ \bar{b}\chi_1^- \to b\bar{b}e\mu + \not{E}_T$$

– following years, search for $gg \to \tilde{t}_1 \tilde{t}_1 h$ and measurement of A_t...