Higgs Physics

as the origin of elementary particle masses

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- **The Standard Model of particle physics**
- **The Higgs mechanism**
- **The Higgs at the LHC**
- **Implications of a Higgs discovery**
- **Conclusion**

1. The Standard Model

The SM of the electromagnetic, weak and strong interactions:

- **is relativistic quantum field theory**
- **based on a local gauge symmetry:**

invariance under local symmetry group

- **more or less a carbon–copy of QED**

the QF theory of electromagnetism

QED: invariance under the local transformations of abelian group U(1)$_{\rm Q}$

– transformation of electron field: $\Psi(x) \to \Psi'(x) = e^{ie\alpha(x)}\Psi(x)$

– transformation of photon field: $A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$

The Lagrangian density is invariant under above field transformations:

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\, D_\mu\gamma^\mu\Psi \ \ - m_e\bar{\Psi}\Psi$$

field strength $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ **and cov. derivative** $D_\mu = \partial_\mu - ieA_\mu$

Very simple and successful quantum field theory:

– minimal		**predictive theory +**
– perturbative		**very precise measurements**
– renormalisable	$\Rightarrow$	**=**
– unitary		**most succesfull theory!**

1. The Standard Model: brief introduction

The Standard Model is based on the local gauge symmetry group

$$\mathrm{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- **The group $\mathrm{SU(3)_C}$ describes the strong force:**

– interaction between quarks which are SU(3) triplets: q, q , q

– mediated by 8 gluons, $\mathrm{G^a_\mu}$ corresponding to 8 generators of $\mathrm{SU(3)_C}$

– asymptotic freedom: interaction “weak” at high energy, $\alpha_\mathrm{s} = \frac{\mathrm{g_s^2}}{4\pi} \ll 1$

- **$\mathrm{SU(2)_L \times U(1)_Y}$ describes the electroweak interaction:**

– between the three families of quarks and leptons: $\mathrm{f_{L/R}} = \frac{1}{2}(1 \mp \gamma_5)\mathrm{f}$

$$\mathrm{I_f^{3L,3R}} = \pm\frac{1}{2}, 0 \quad \Rightarrow \mathrm{L} = \binom{\nu_\mathrm{e}}{\mathrm{e}^-}_\mathrm{L}, \ \mathrm{R} = \mathrm{e}^-_\mathrm{R}, \ \mathrm{Q} = \binom{\mathrm{u}}{\mathrm{d}}_\mathrm{L}, \ \mathrm{u_R}, \ \mathrm{d_R}$$

$$\mathrm{Y_f = 2Q_f - 2I_f^3}$$

Same holds for the two other generations: $\mu, \nu_\mu, \mathrm{c}, \mathrm{s}; \ \tau, \nu_\tau, \mathrm{t}, \mathrm{b}$.

There is no ν_R (and neutrinos are and stay exactly massless).

– mediated by the $\mathrm{W}^{1,2,3}_\mu$ (isospin) and B_μ (hypercharge) gauge bosons

$\mathcal{L}_\mathrm{SM}$: same structure as $\mathcal{L}_\mathrm{QED}$ but mathematically more involved ...

but gauge bosons, and fermions should be exactly massless....

1. The Standard Model: brief introduction

Indeed, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

$\frac{1}{2}\mathrm{M}_{\mathrm{V}}^2 \mathrm{V}^\mu \mathrm{V}_\mu$ **and/or** $\mathrm{m_f \bar{f} f}$ **terms: breaking of gauge symmetry.**

This statement can be visualized by taking the example of QED where

the photon is massless because of the local $\mathrm{U}(1)_{\mathrm{Q}}$ local symmetry:

$$\mathbf{\Psi}(\mathbf{x}) \to \mathbf{\Psi}'(\mathbf{x}) = \mathbf{e}^{\mathbf{ie}\alpha(\mathbf{x})}\mathbf{\Psi}(\mathbf{x})\ ,\ \mathbf{A}_\mu(\mathbf{x}) \to \mathbf{A}'_\mu(\mathbf{x}) = \mathbf{A}_\mu(\mathbf{x}) - \frac{\mathbf{1}}{\mathbf{e}}\partial_\mu\alpha(\mathbf{x}$$

- **For the photon (or B field for instance) mass we would have:**

$$\frac{\mathbf{1}}{\mathbf{2}}\mathbf{M}_{\mathbf{A}}^{\mathbf{2}}\mathbf{A}_\mu\mathbf{A}^\mu \to \frac{\mathbf{1}}{\mathbf{2}}\mathbf{M}_{\mathbf{A}}^{\mathbf{2}}(\mathbf{A}_\mu - \frac{\mathbf{1}}{\mathbf{e}}\partial_\mu\alpha)(\mathbf{A}^\mu - \frac{\mathbf{1}}{\mathbf{e}}\partial^\mu\alpha) \neq \frac{\mathbf{1}}{\mathbf{2}}\mathbf{M}_{\mathbf{A}}^{\mathbf{2}}\mathbf{A}_\mu\mathbf{A}^\mu$$

and thus, gauge invariance is violated with a photon mass.

- **For the fermion masses, we would have (e.g. for the electron):**

$$\mathbf{m_e \bar{e} e} = -\mathbf{m_e \bar{e}}\left(\frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1}-\gamma_\mathbf{5}) + \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1}+\gamma_\mathbf{5})\right)\mathbf{e} = -\mathbf{m_e}(\mathbf{\bar{e}_R e_L} + \mathbf{\bar{e}_L e_R})$$

manifestly non–invariant under SU(2) isospin symmetry transformations

We need a less “brutal” way to generate particle masses in the SM....

$\Rightarrow$ **The Brout–Engelert–Higgs (or Higgs for short) mechanism!**

2. The Higgs mechanism

In the SM, for the mechanism of spontaneous EW symmetry breaking,

⇒ introduce a doublet of complex scalar fields: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, $Y_\Phi = +1$

with a Lagrangian that is invariant under $SU(2)_L \times U(1)_Y$

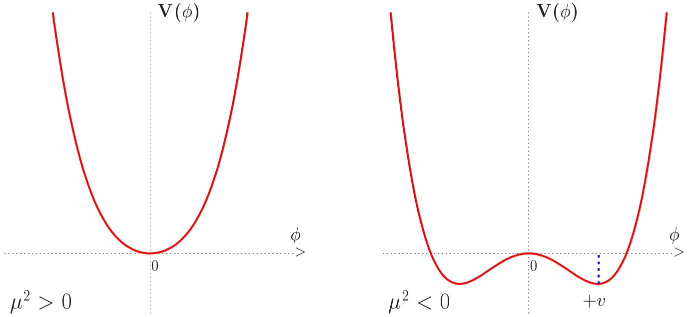
$$\mathcal{L}_S = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

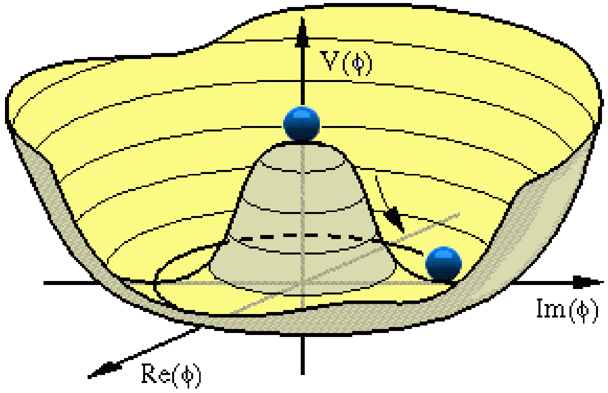
$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: Φ **develops a vev:**

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

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





To obtain the physical states,

write $\mathcal{L}_S$ **with the true vacuum...**

2. The Higgs mechanism: mass generation

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

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

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

⇒ The photon stays massless and thus $U(1)_{QED}$ is preserved.

- For fermion masses, use same doublet field Φ and its conjugate field

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

$$\Phi \to \frac{1}{\sqrt{2}} \binom{0}{H+v} \Rightarrow m_e = \frac{f_e\, v}{\sqrt{2}},\ m_u = \frac{f_u\, v}{\sqrt{2}},\ m_d = \frac{f_d\, v}{\sqrt{2}}$$

With same Φ, generated m_V, m_f while preserving (hidden) SU(2)xU(1)!

Residual dof corresponds to the spin–zero scalar Higgs boson, H.

- The Higgs boson mass is given by: $M_H^2 = 2\lambda v^2 = -2\mu^2$.
- The self–couplings are: $g_{H^3} = 3i\, M_H^2/v\,,\ g_{H^4} = 3i M_H^2/v^2$
- Higgs couplings to gauge bosons and fermions almost derived:

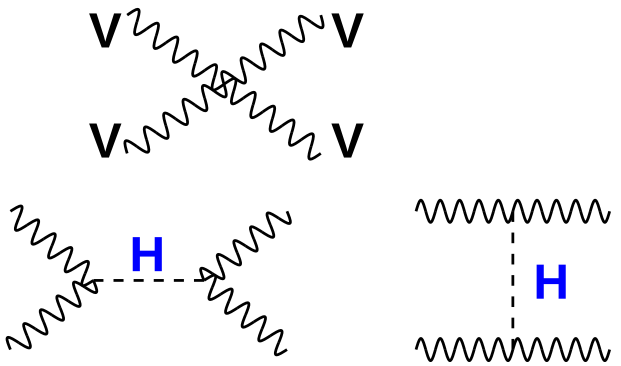
$$\mathcal{L}_{M_V} \sim M_V^2 (1 + H/v)^2\ ,\ \mathcal{L}_{m_f} \sim -m_f (1 + H/v)$$

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

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

2. The Higgs mechanism: constraints on M_H

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



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

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

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

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

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

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

- **Triviality and stability bounds:**

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

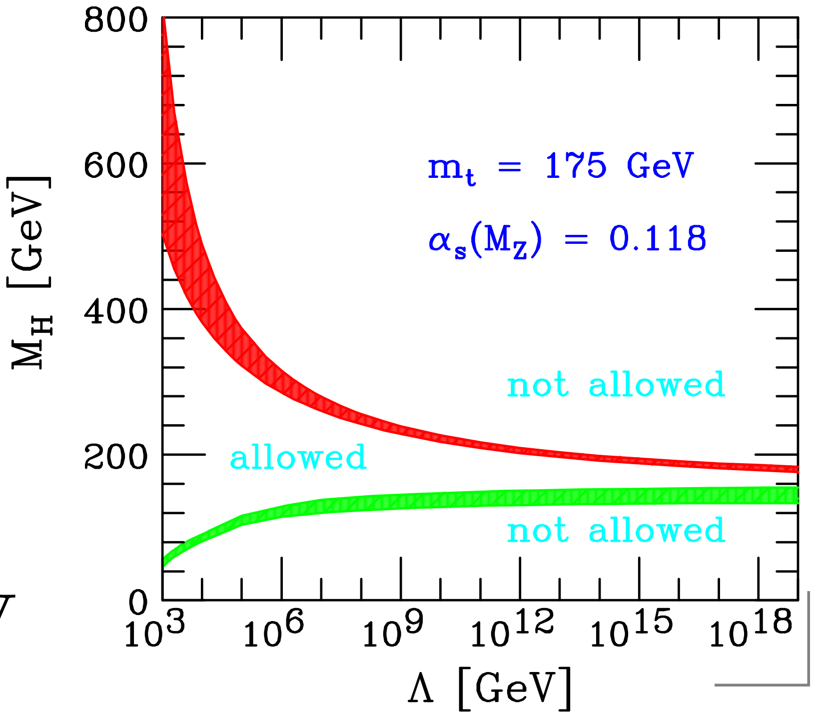
$\lambda \gg 1$ coupling blows up (Landau pole)

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

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

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

Hambye+Riesselman

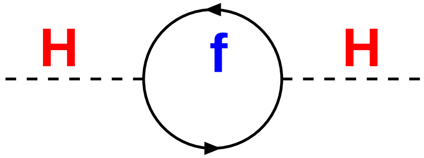


2. The Higgs mechanism: beyond the SM

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 $M_{H,H^\pm} \approx M_A \lesssim \mathrm{TeV}$

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)....

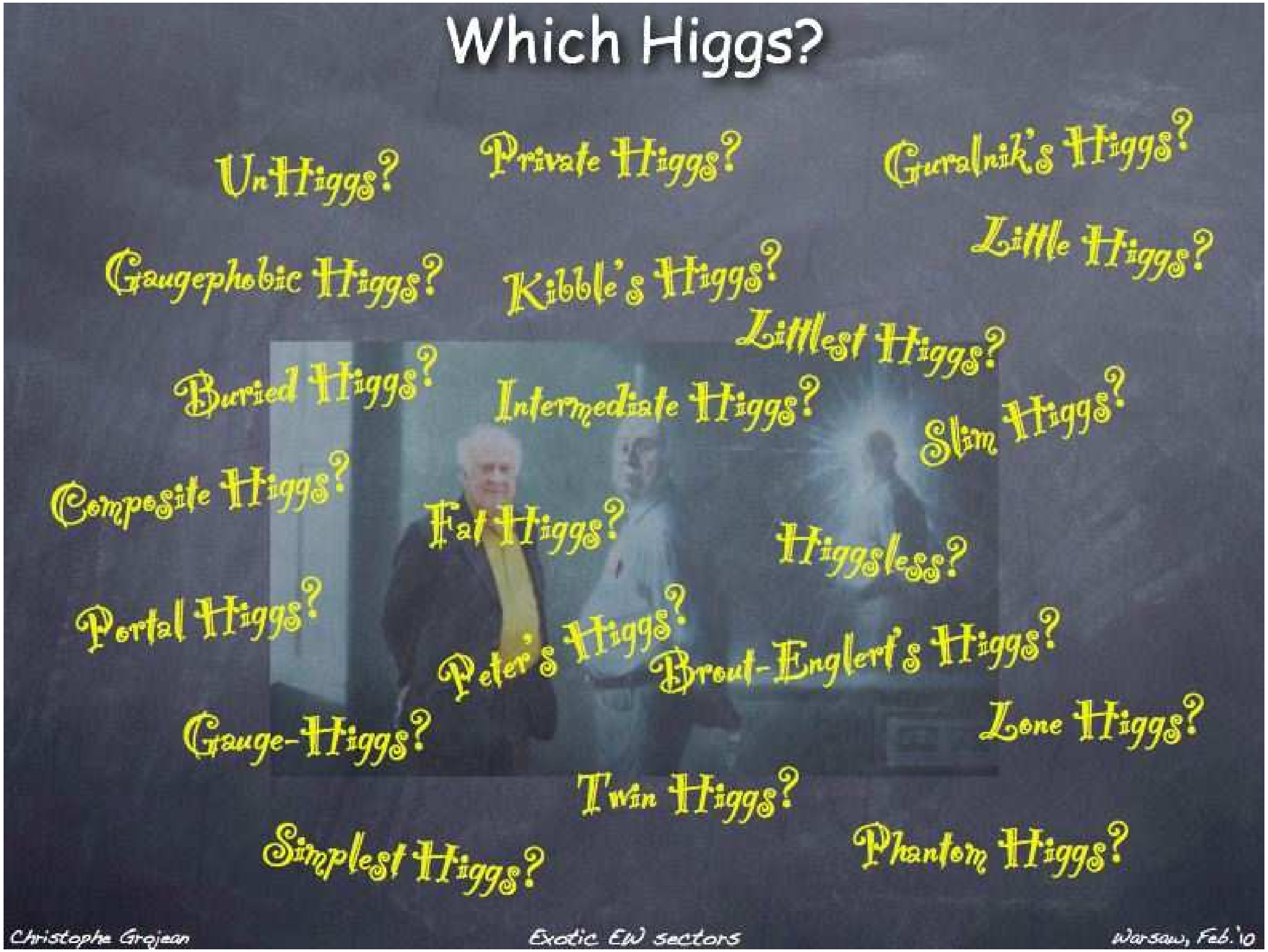
Strong interactions/compositness: the Higgs is not an elementary scalar.

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

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

2. The Higgs mechanism: beyond the SM

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



Which Higgs?

UnHiggs?
Private Higgs?
Guralnik's Higgs?
Little Higgs?
Gaugephobic Higgs?
Kibble's Higgs?
Littlest Higgs?
Buried Higgs?
Intermediate Higgs?
Slim Higgs?
Composite Higgs?
Fat Higgs?
Higgsless?
Portal Higgs?
Peter's Higgs?
Brout-Englert's Higgs?
Gauge-Higgs?
Lone Higgs?
Twin Higgs?
Simplest Higgs?
Phantom Higgs?

Christophe Grojean Exotic EW sectors Warsaw, Feb.'10

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

3. The Higgs at hadron colliders: 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 $\mathrm{g_{HPP} \propto m_P}$, H will decay into heaviest particle phase-space allowed:

- $\mathrm{M_H \lesssim 130\ GeV}$, $\mathrm{H \to b\bar{b}}$

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

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

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

– below threshold decays possible

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

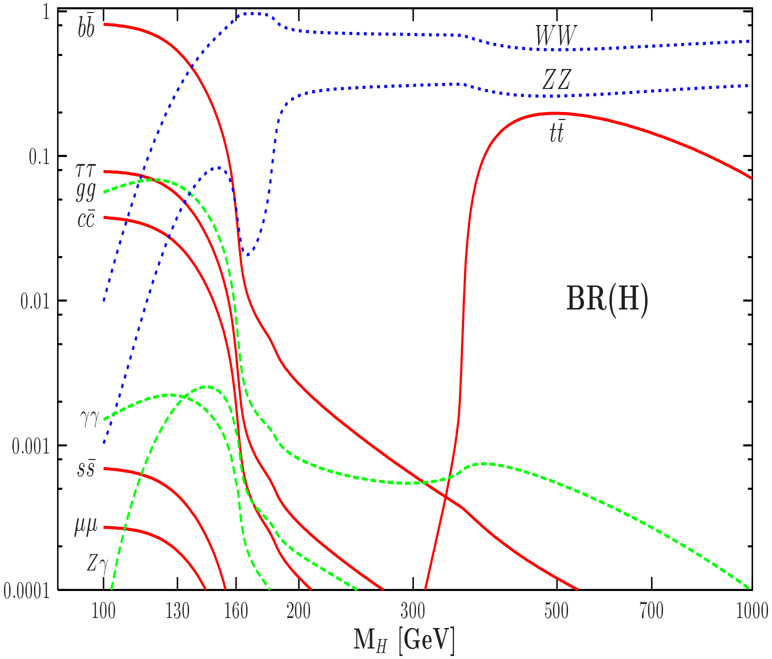
– decays into $\mathrm{t\bar{t}}$ for heavy Higgs

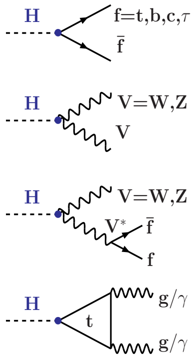
- Total Higgs decay width:

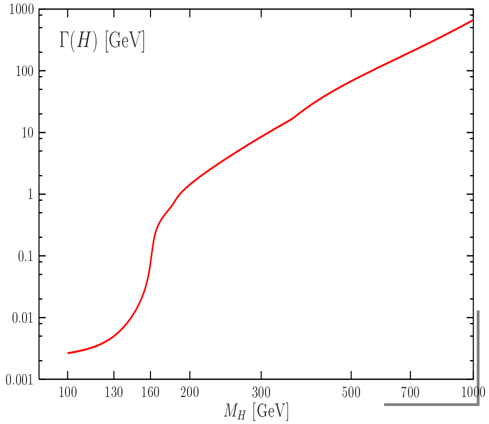
– very small for a light Higgs

– comparable to mass for heavy Higgs

HDECAY: Kalinowski, Spira, AD ⇒



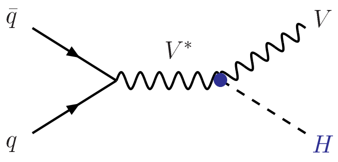




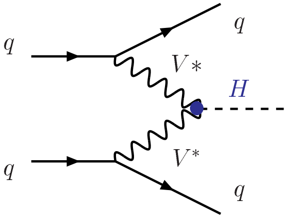
3. The Higgs at hadron colliders: production

Main Higgs production channels

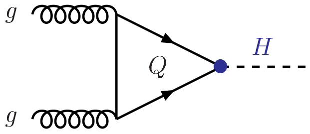
Higgs–strahlung



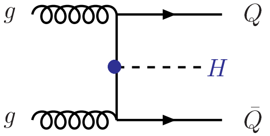
Vector boson fusion

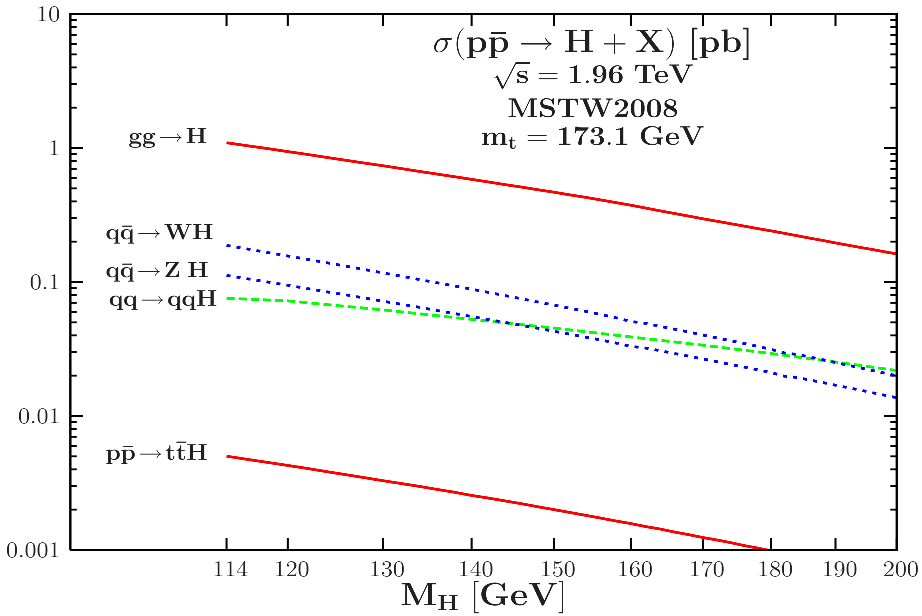


gluon–gluon fusion



in associated with $Q\bar{Q}$





Large production cross sections

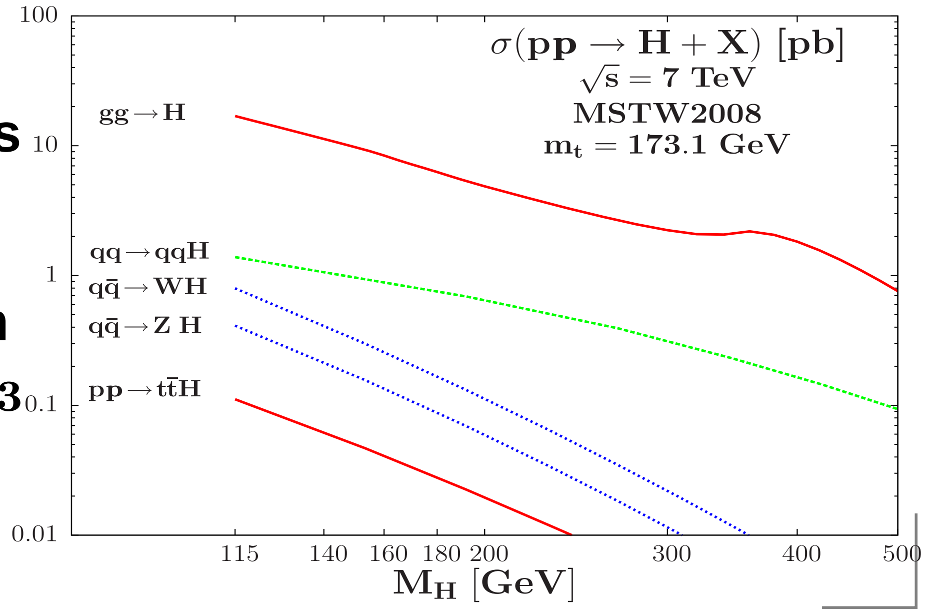
with gg$\to$ H by far dominant process

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

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

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

... 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...)

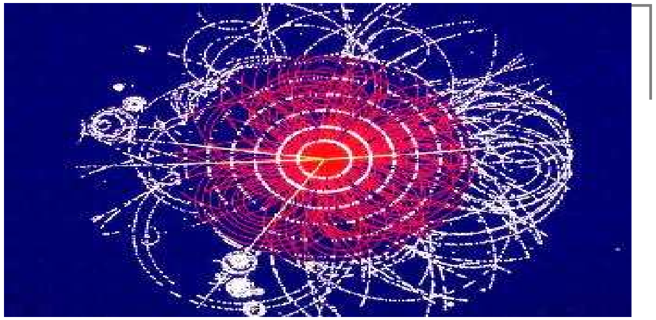
- Have a precise knowledge of S and B rates

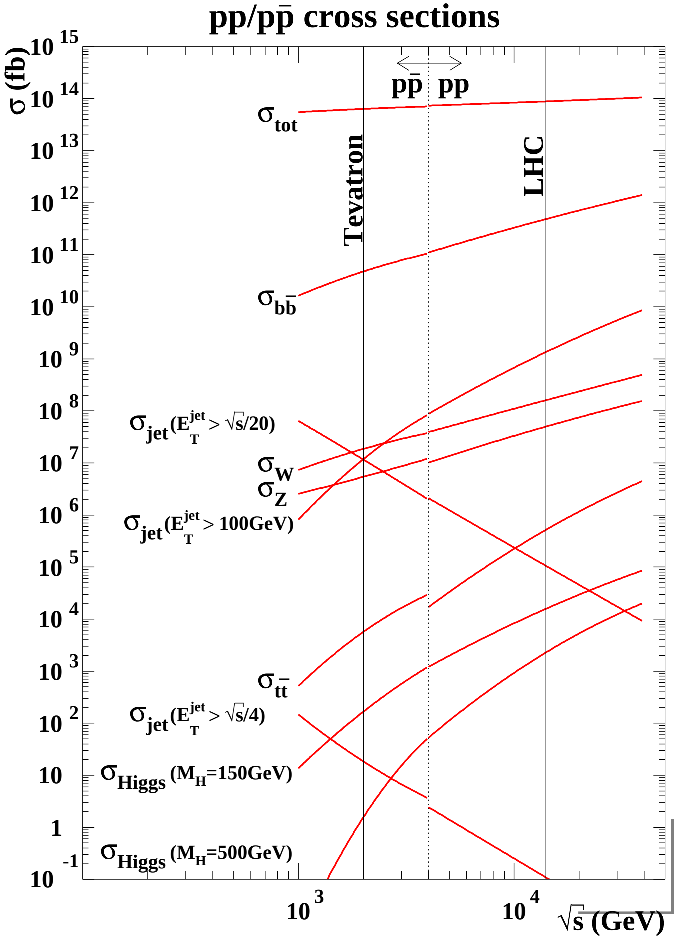
(higher orders can be factor of 2! see later)

- 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] : $K \approx$ 2 (1.7)

EFT NLO[c]: good approx.

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

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

EFT other HO[f]: a few %.

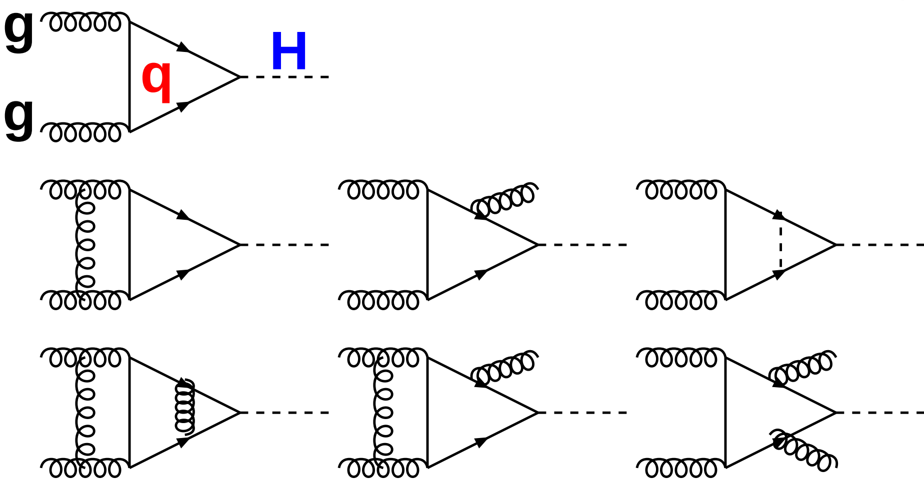
EW: EFT NLO: [g]: $\approx \pm$ very small

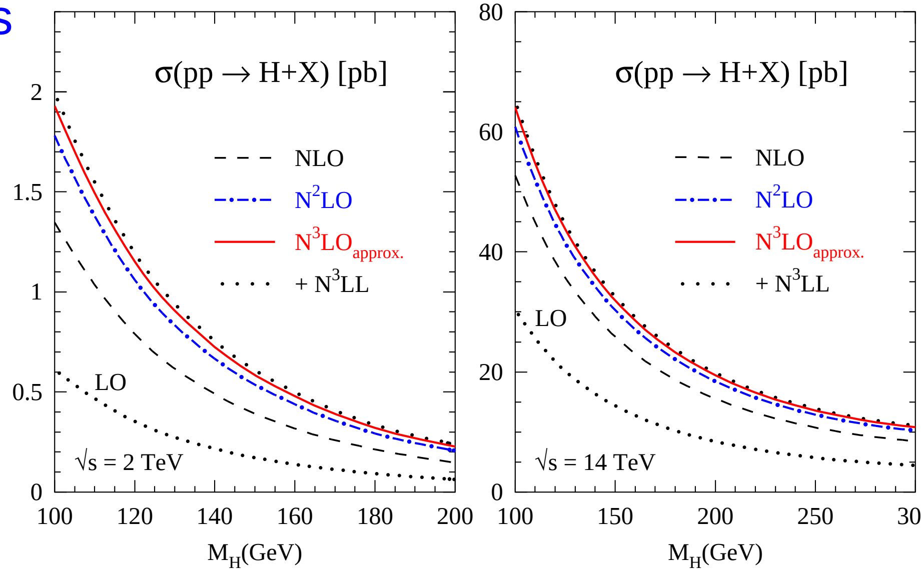
exact NLO[h]: $\approx \pm$ a few %

QCD+EW[i]: a few %

Distributions: two programs[j]

The $\sigma^{\rm theory}_{gg\to H}$ long story (70s–now) ...





Moch+Vogt

[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

3. The Higgs at hadron colliders: 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: $\mu_0 = \frac{1}{2} M_H, \kappa = 2 \Rightarrow \Delta_{\rm scale} \approx 10\%$

- **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

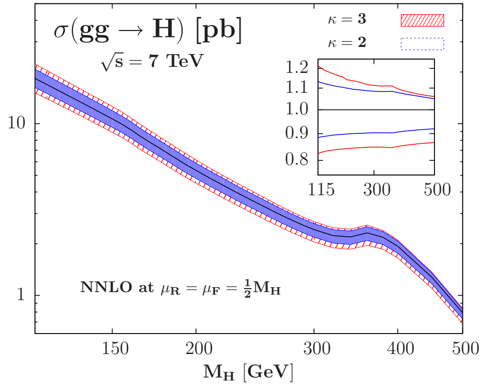
- **Uncertainty from EFT approach at NNLO**

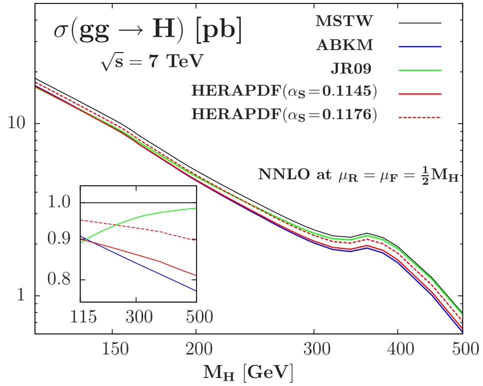
$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
but not above and not b ($\approx 10\%$), W/Z loops
Estimate from (exact) NLO: $\Delta_{\rm EFT} \approx 5\%$

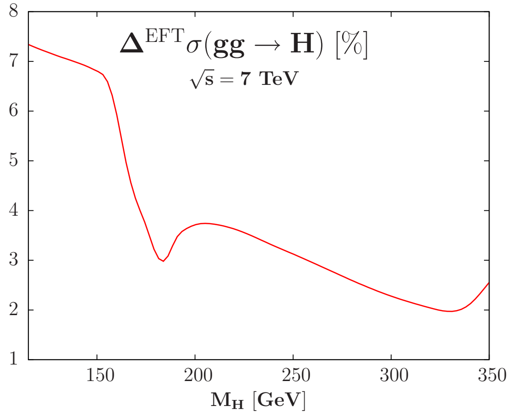
- **Include ΔBR(H$\longrightarrow$X) of at most few %**

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

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^{-}

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

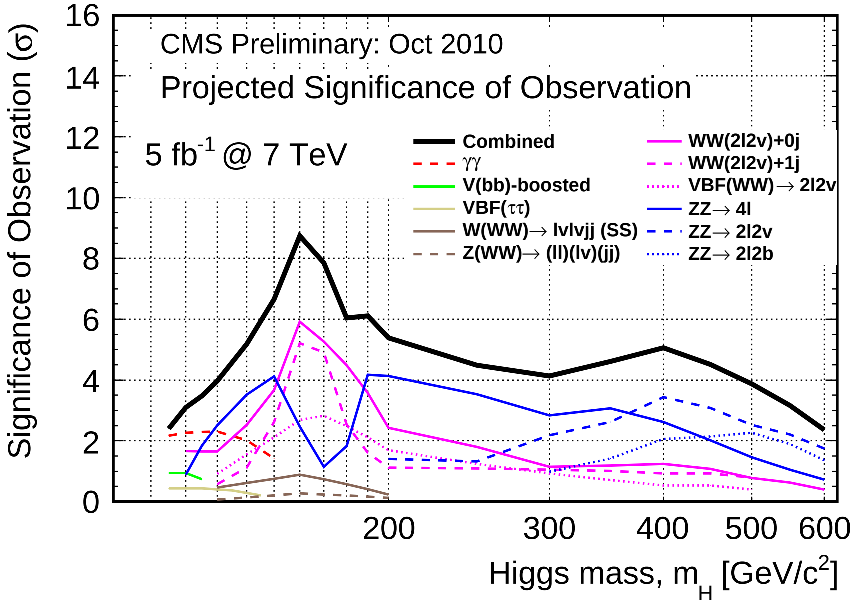
95%CL sensitivity for $M_H\lesssim$600 GeV

$gg\to H\to\gamma\gamma$ **($M_H\lesssim$ 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.

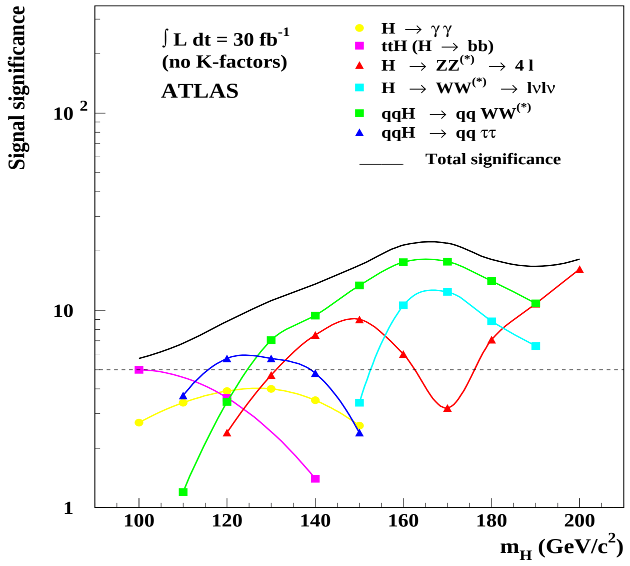
Still $HV\to b\bar{b}\ell X @ M_H\lesssim$130 GeV!

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:

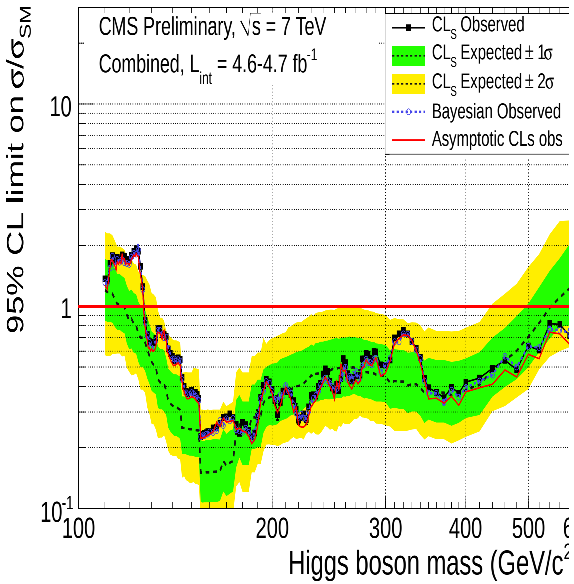
– SM Higgs excluded everywhere except for M_H=123.5-127.5 GeV

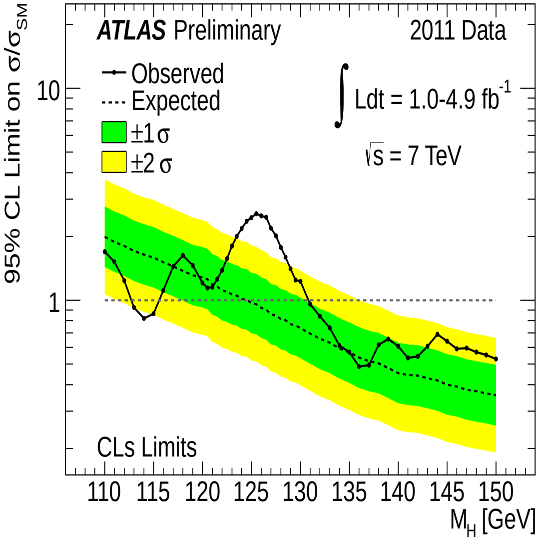
– a $\approx 3\sigma$ signal at M_H $\approx$125 GeV

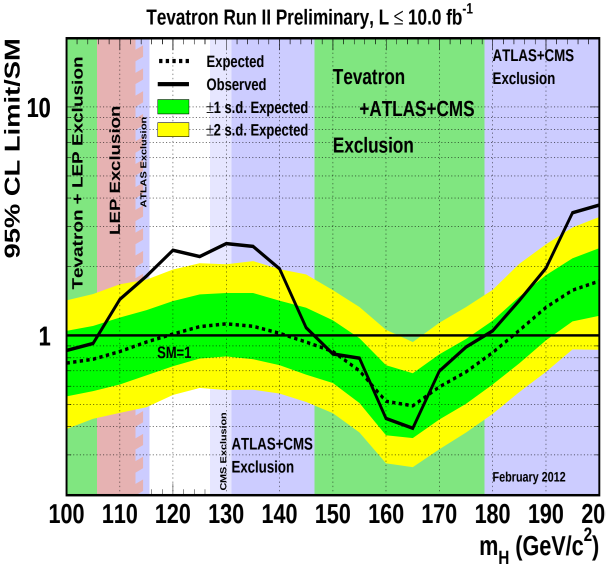
→ thanks to LHC, ATLAS, CMS!

(let us hope it will not go away....)

Also a 2.2σ “hint” from Tevatron!







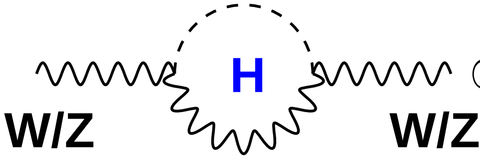
4. Implications of Higgs discovery: SM

The SM: a rather predictive theory:

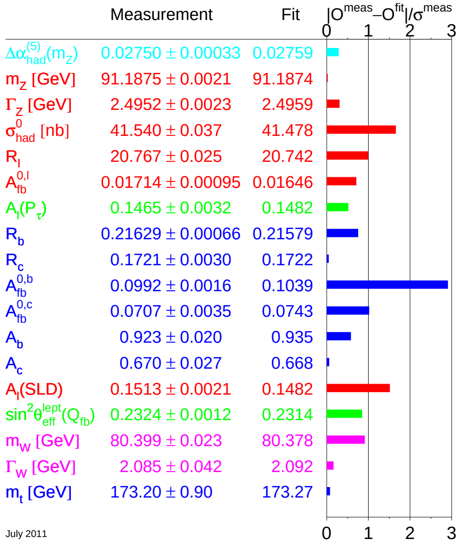
A triumph for high-energy physics!

Indirect constraints from EW data[a]

H contributes to RC to W/Z masses:



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



	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.742	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1482	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.378	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.20 ± 0.90	173.27	

Fit the EW precision measurements,

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

$M_H \lesssim 161$ GeV at 95% CL

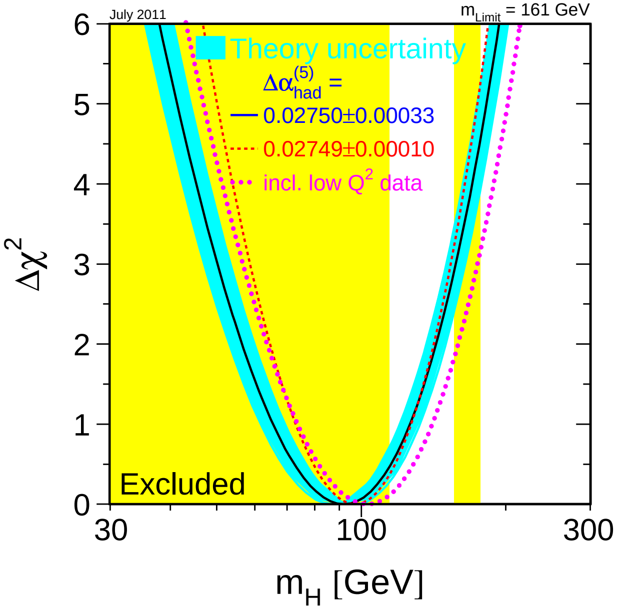
compared with "observed" $M_H = 125$ GeV

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_{FB}^b (LEP), A_{FB}^t (TeV) and $g-2$ but not severe...

4. Implications of Higgs discovery: SM

If excess due to Higgs: spectrum complete

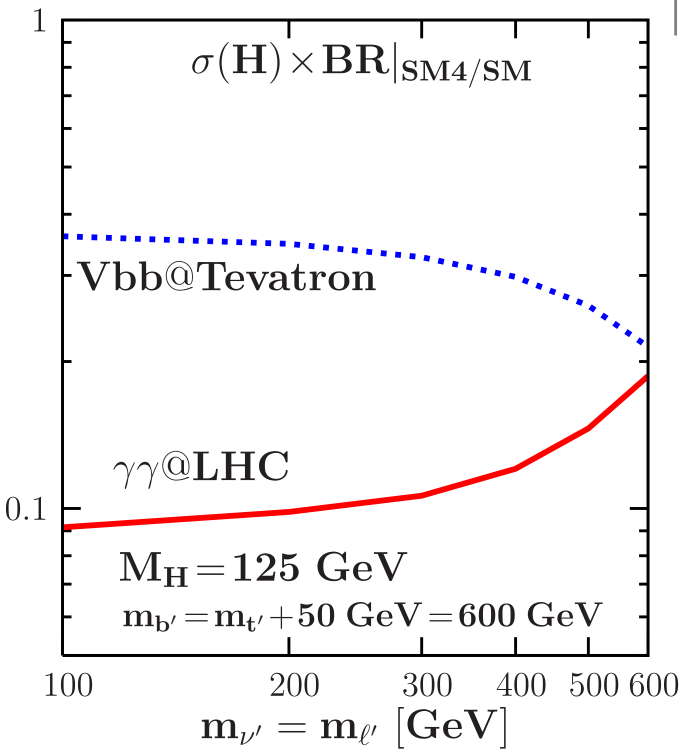
no room for a 4th fermionic generation!

extra fermion doublet (with heavy ν') will:

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

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

AD+Lenz (2012) $\Rightarrow$



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

No problem with triviality: $\mathrm{M_H} \lesssim 180$ GeV

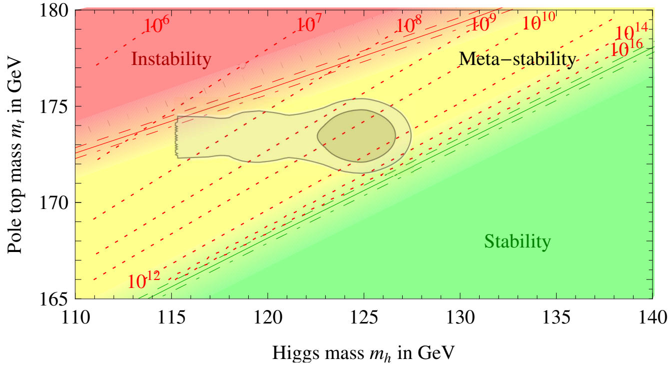
SM valid only if v$\equiv$EW-min, ie $\lambda(\mathrm{Q^2}) > 0$

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

refinements+uncertainties+metastability $\Rightarrow$

A 125 GeV Higgs is still OK!

Espinosa et al. 2011



4. Implications of Higgs discovery: SM respectable theory?

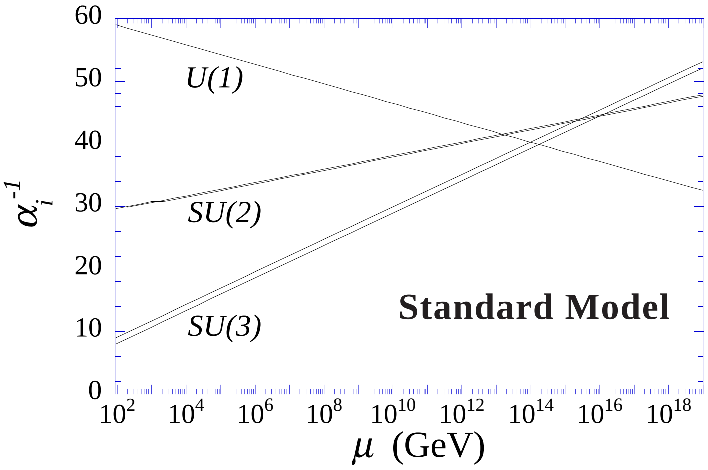
With the Higgs, the SM is a perturbative, renormalisable, unitary theory.

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?**



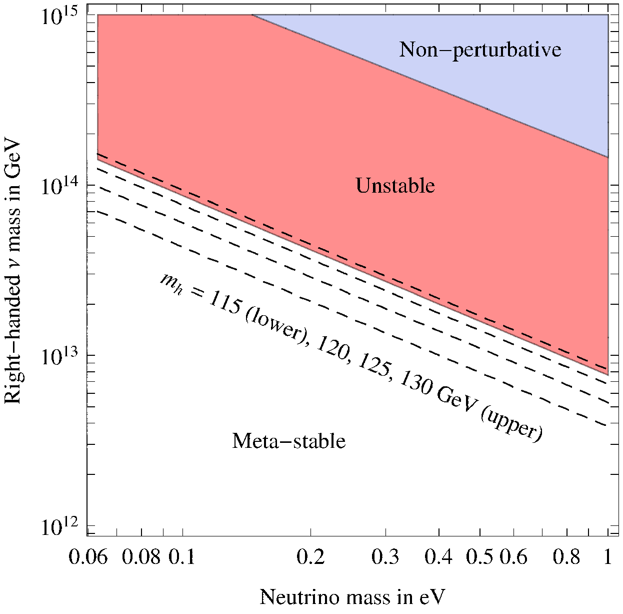
To be extended to cope with experiment:

- **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:

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

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

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

$\Rightarrow$ 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:

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

- **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:

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

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

- **determine the regions of parameter space where $123 \leq M_h \leq 127$ Ge**

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

- **require h to be SM–like: $\sigma(h)\times \mathrm{BR}(h\to VV) \gtrsim 0.9 H_{SM}$**

(we will also consider the possibility that H is the H_{SM}, see later).

4. Implications of Higgs discovery: pMSSM

Main results:

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

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

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

- **Large tanβ values favored**

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

- **What about other benchmarks?**

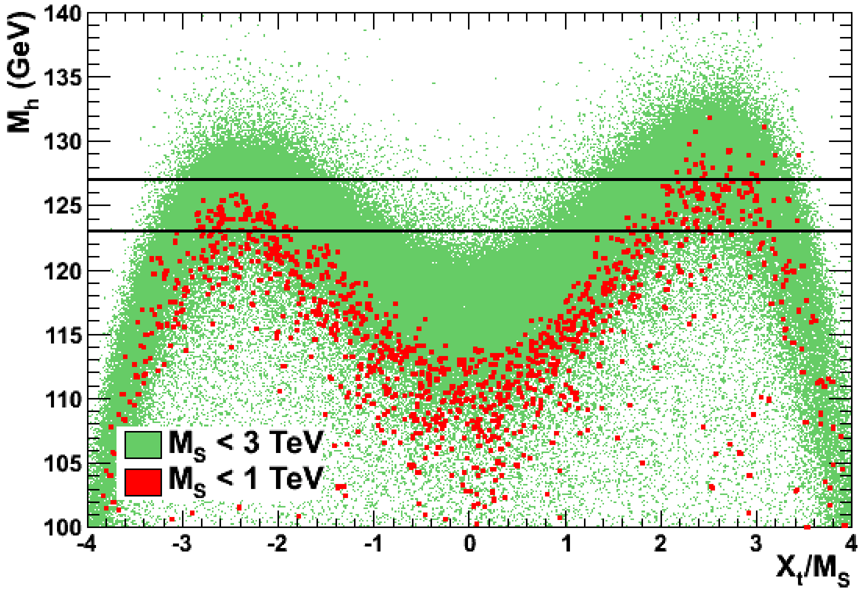
Carena+Heinemeyer+Wagner+Weiglein

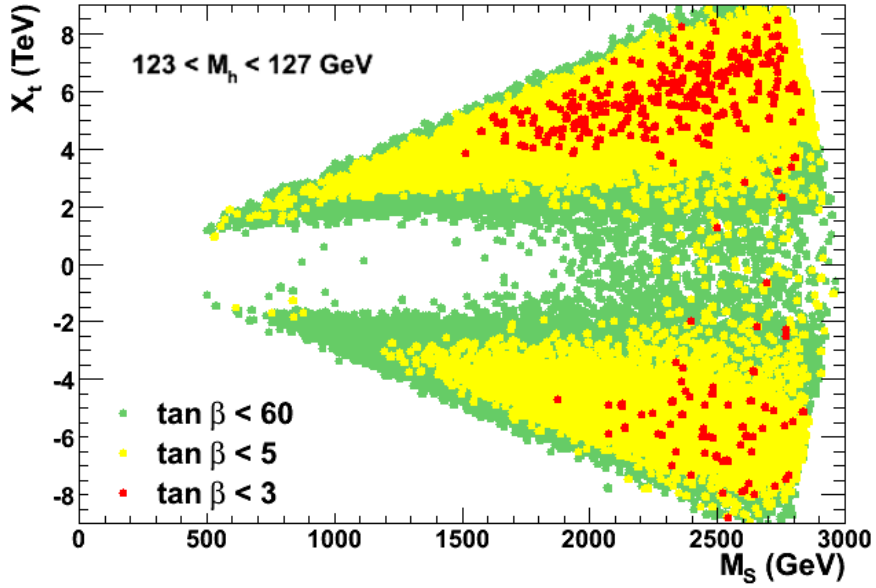
– small $\alpha_{\rm eff}$ scenario with $\mathrm{g_{hbb}} \approx 0$: ruled out by LHC/Tevatron data.

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

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

– max and no-mix need to be updated!





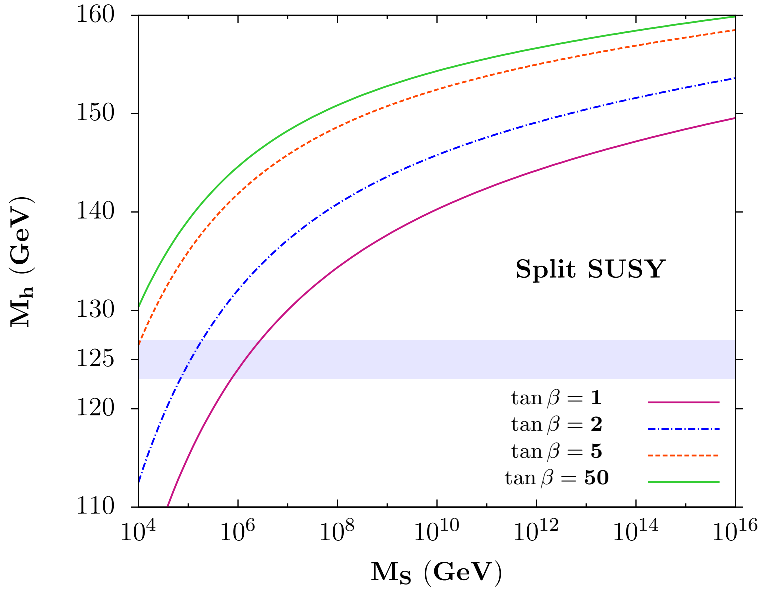
4. Implications of Higgs discovery: high scale SUSY

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



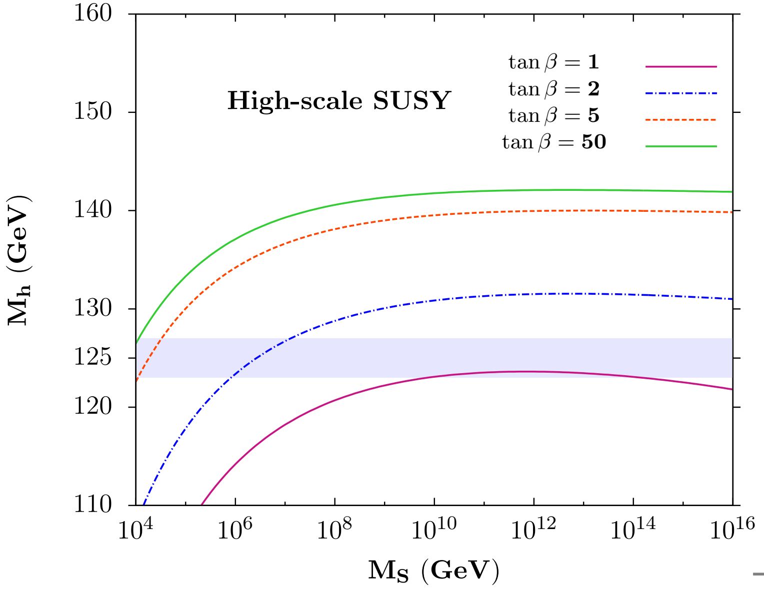
- **SUSY broken at the GUT scale...**

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 $\mathrm{M_{GUT}} \approx 10^{16}$ GeV

– universal soft terms emerge if the interactions are “flavor–blind”

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

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

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

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

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

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

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**: $m_0 = A_0$

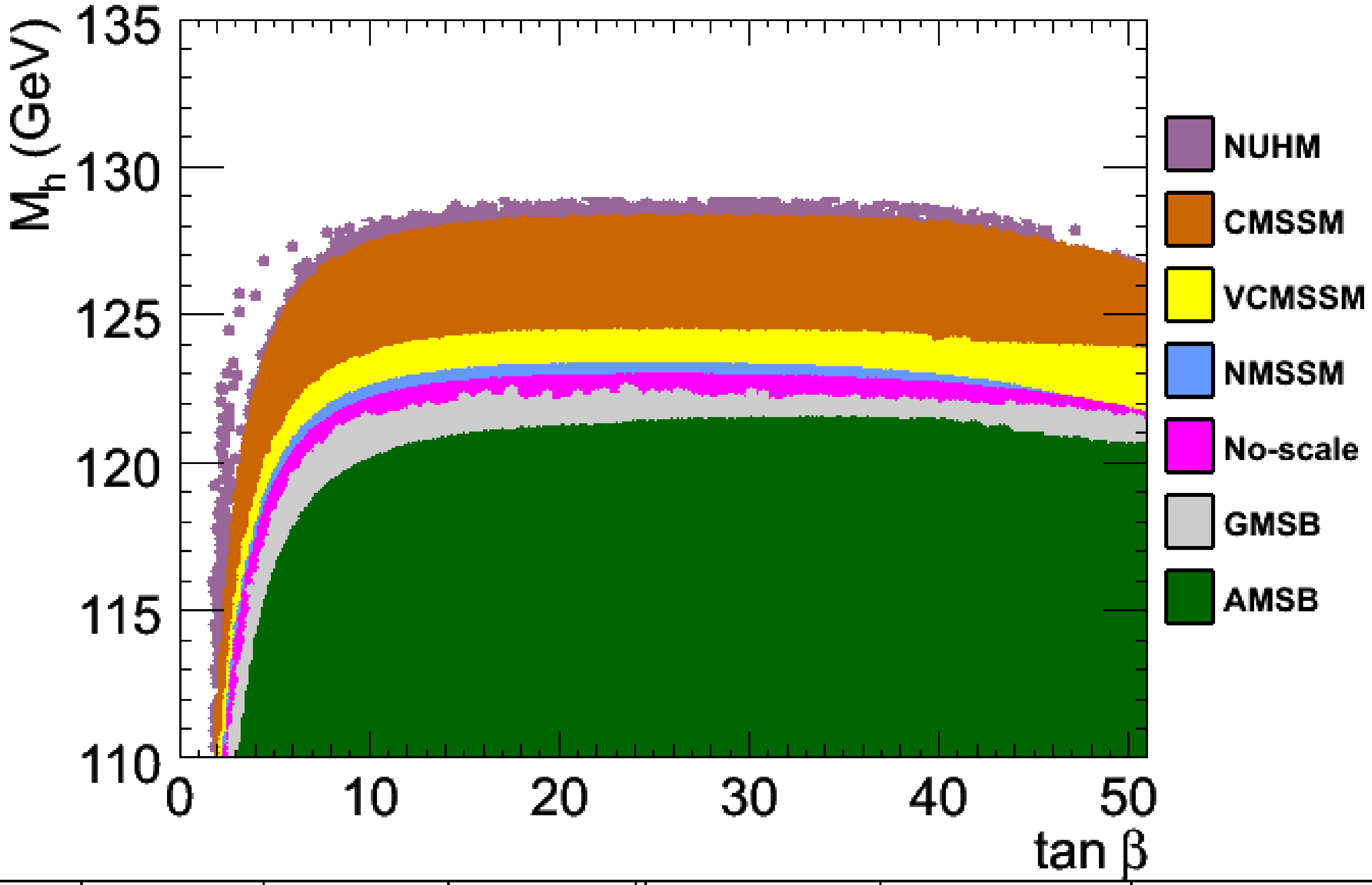
as well as as the less constrained non–universal Higgs mass model:

- **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 $\gamma\gamma, 4\ell^{\pm}, \mathrm{b\bar{b}}$ rates?

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

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

- **$\mathrm{M_H = 119}$ GeV would have been a boring value: everybody OK..**
- **$\mathrm{M_H = 145}$ GeV would be a devastating value: mass extinction..**
- **$\mathrm{M_H \approx 125}$ 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:

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

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