The Higgs: a (tentative) roadmap...

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1. EWSB and Higgs particles

2. The Higgs at the Tevatron and the lHC

3. Implications of a Higgs discovery

4. What if the Higgs is not found (soon)?

5. Perspectives

1. EWSB and Higgs particles

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

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

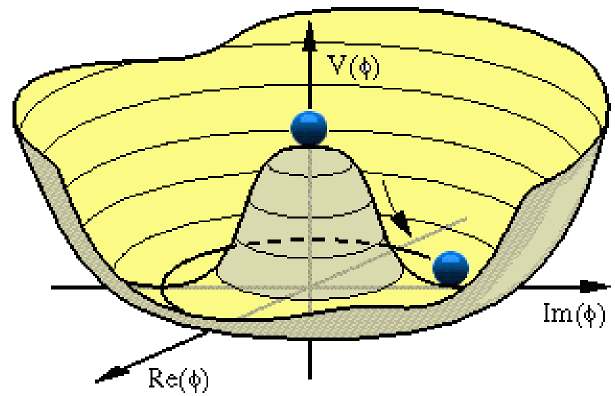
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

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

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

For fermion masses, use same Φ**:**

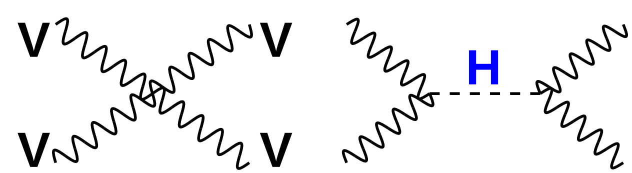
$\mathcal{L}_{Yuk} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R + \ldots$



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...**

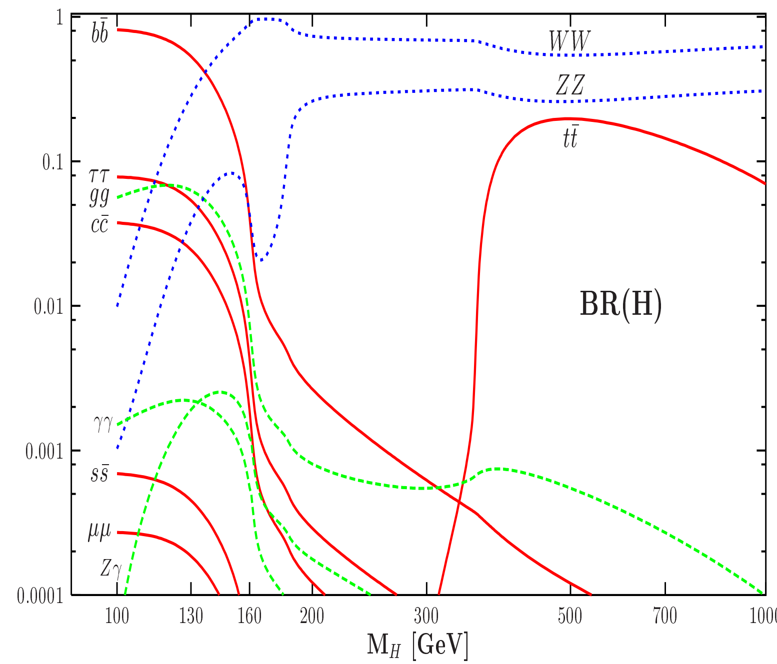
1. EWSB and Higgs particles

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

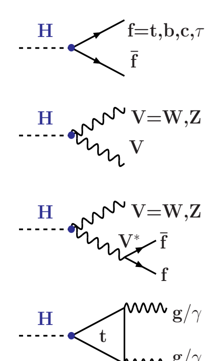
Once M_H known, all properties of the Higgs are fixed (modulo QCD).

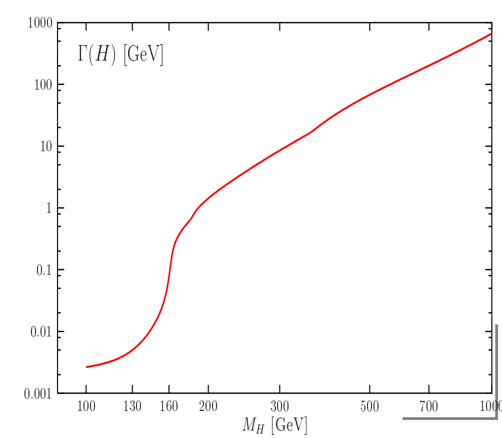
Example: Higgs decays in the SM

- **As $g_{HPP} \propto m_P$, H will decay into heaviest particle phase-space allowed:**
- $M_H \lesssim 130$ GeV, $H \to b\bar{b}$
  – $H \to cc, \tau^+\tau^-, gg = \mathcal{O}(\text{few}\,\%)$
  – $H \to \gamma\gamma, Z\gamma = \mathcal{O}(0.1\%)$
- $M_H \gtrsim 130$ GeV, $H \to WW, ZZ$
  – below threshold decays possible
  – above threshold: B(WW)=$\frac{2}{3}$, B(ZZ)=$\frac{1}{3}$
  – decays into $t\bar{t}$ for heavy Higgs
- **Total Higgs decay width:**
  – very small for a light Higgs
  – comparable to mass for heavy Higgs



HDECAY: Kalinowski, Spira, AD $\Rightarrow$

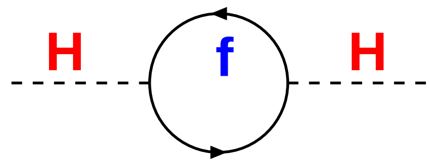




1. EWSB and Higgs particles

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 $M_h \lesssim 130\ \mathrm{GeV}$ 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)....

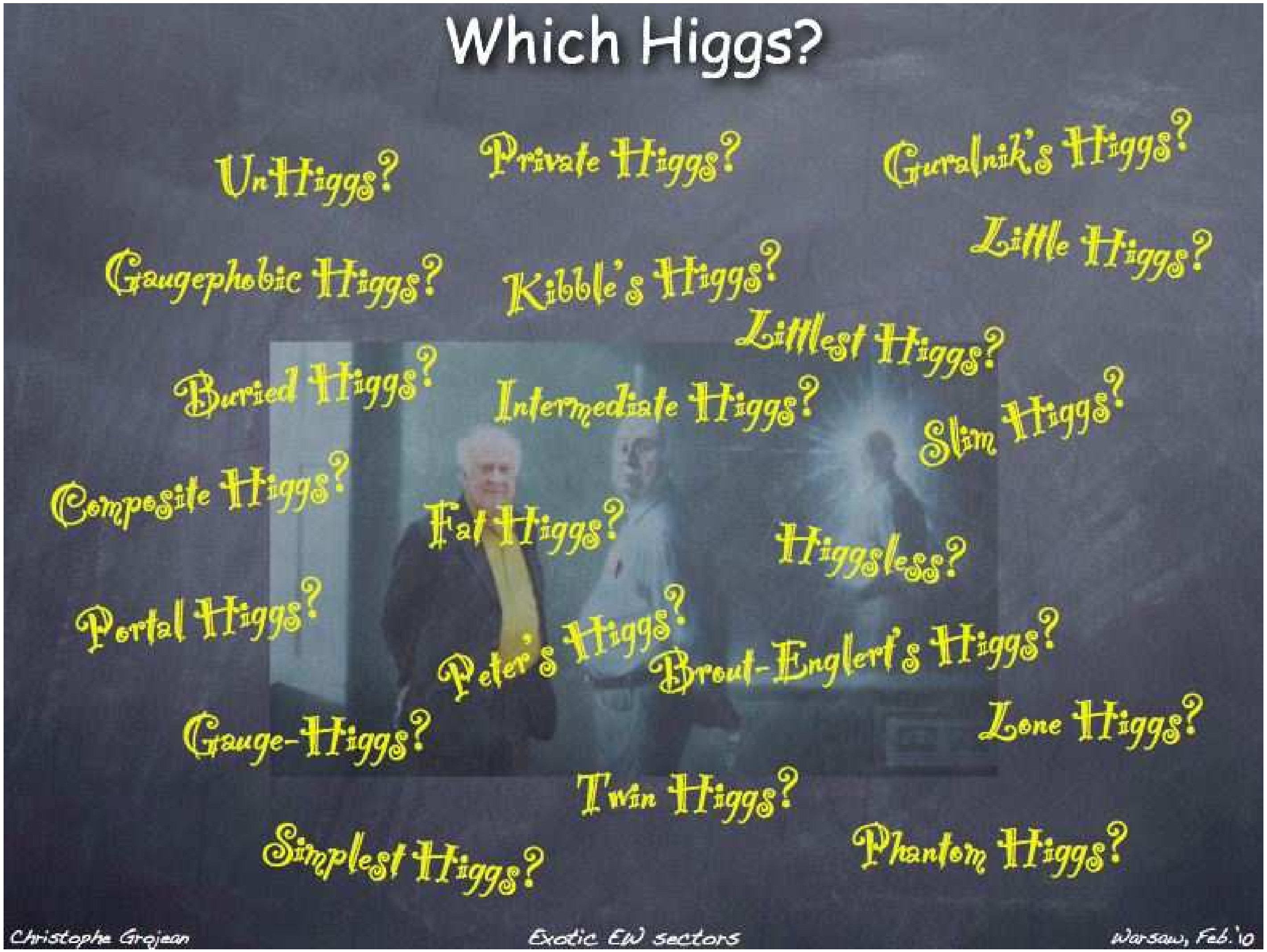
Strong interactions/compositness: the Higgs is not an elementary scalar.

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

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

1. EWSB and Higgs particles

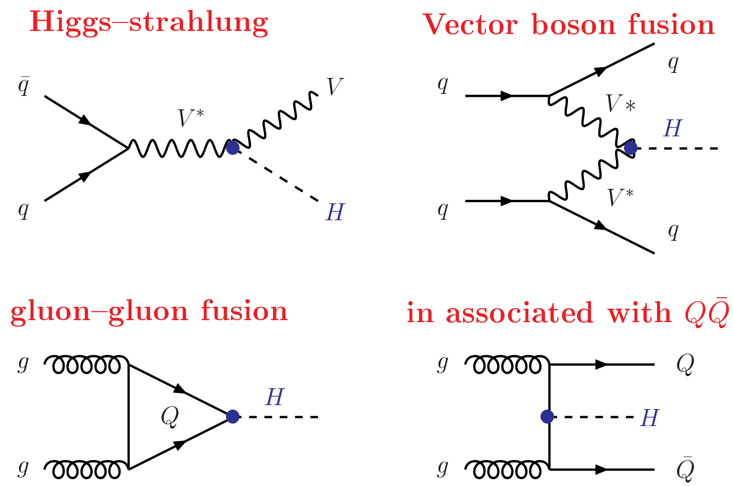
and along the avenues, many possible streets, paths, corners...

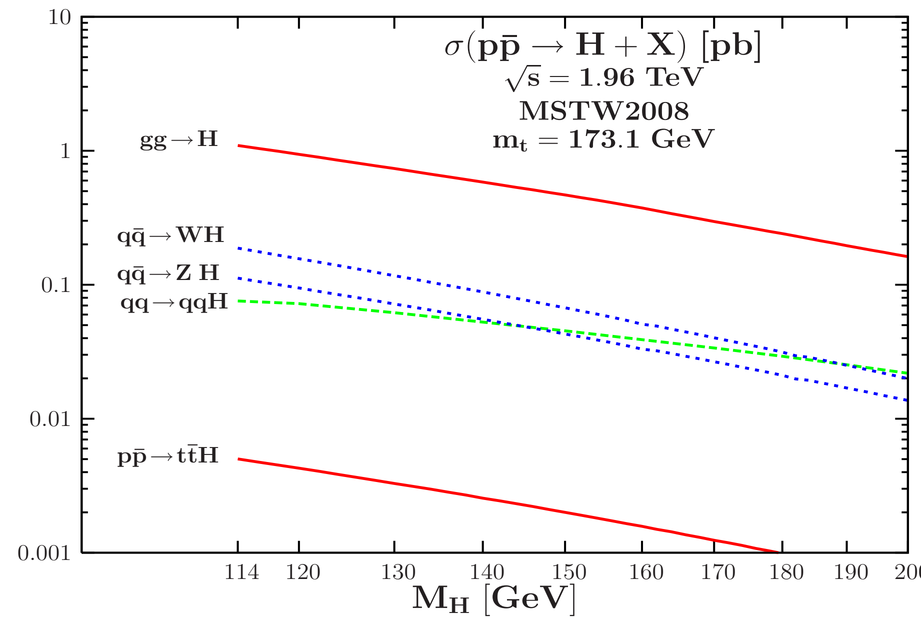


Which scenario chosen by Nature? The LHC will/should tell!

2. The Higgs at hadron colliders

Main Higgs production channels





Large production cross sections

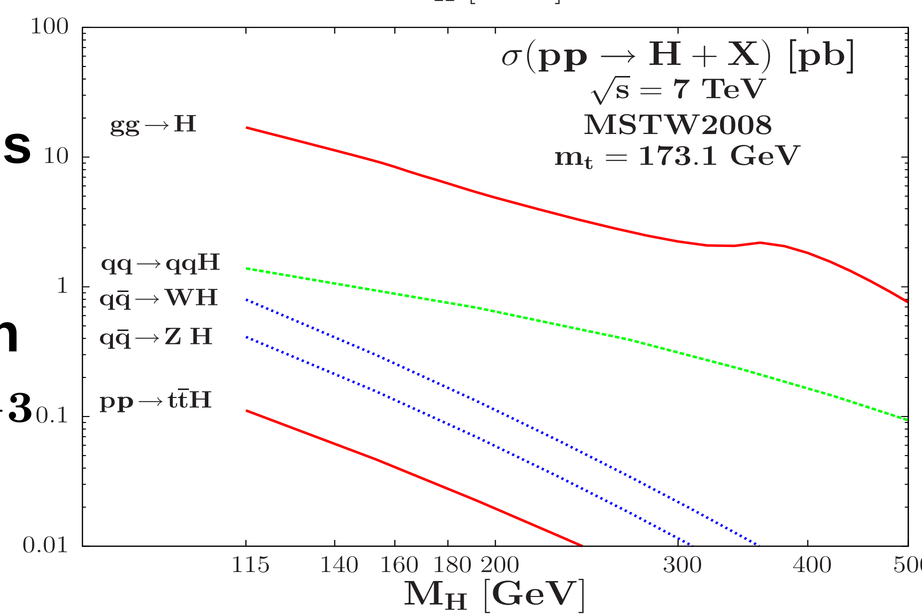
with gg$\longrightarrow$ H by far dominant process

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

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

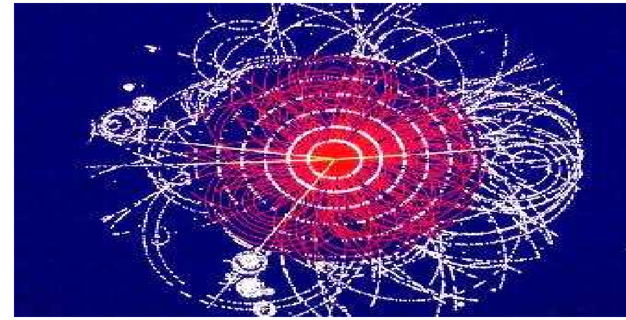
but eg BR(H$\longrightarrow \gamma\gamma, ZZ \longrightarrow 4\ell) \approx 10^{-3}$

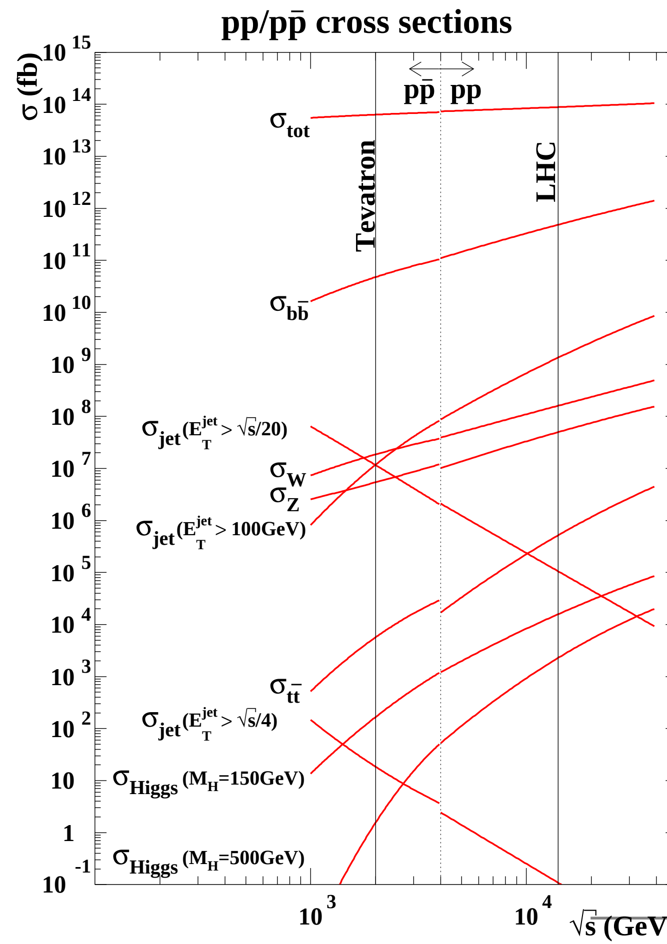
... a small # of events at the end...



2. The Higgs at hadron colliders

$\Rightarrow$ **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: $H \to \gamma\gamma, VV \to \ell$

– 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!)

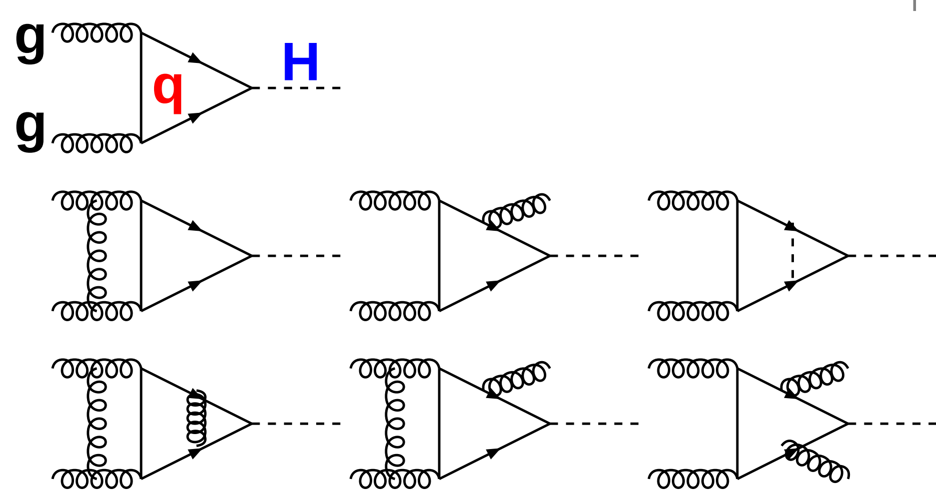
For a flavor of how it is complicated from the theory side: a look at the $gg \to H$ case

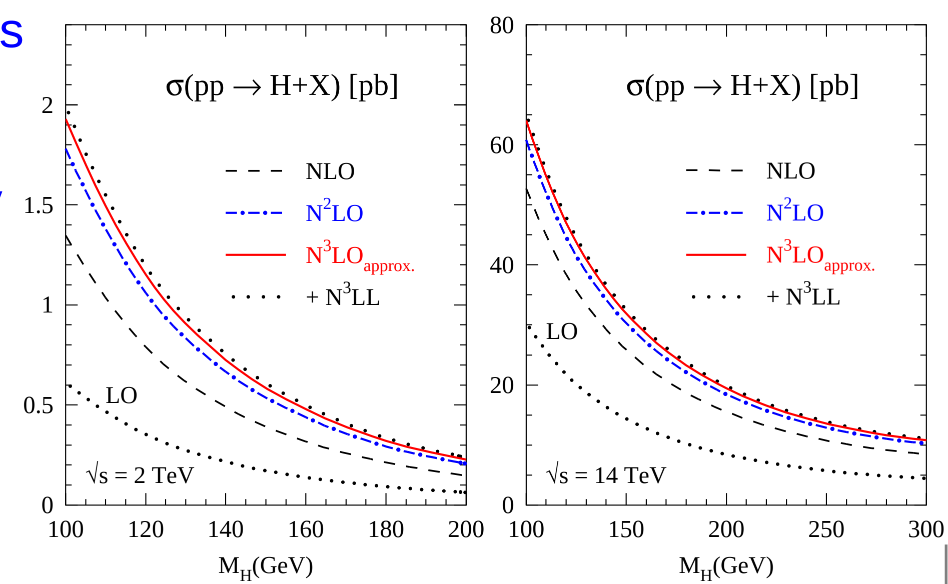
2. The Higgs at hadron colliders

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]

[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 $\sigma_{gg\to H}^{\rm theory}$ long story (70s–now) ...





Moch+Vogt

2. The Higgs at hadron colliders

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

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

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

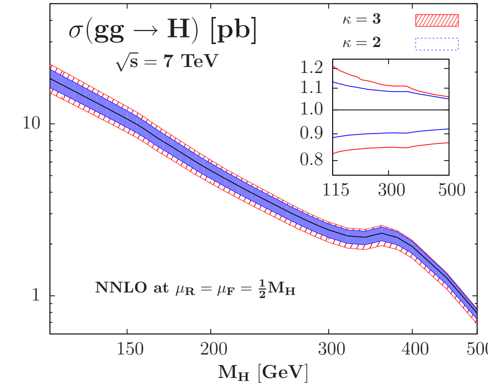
- **Uncertainty from EFT approach at NNLO**

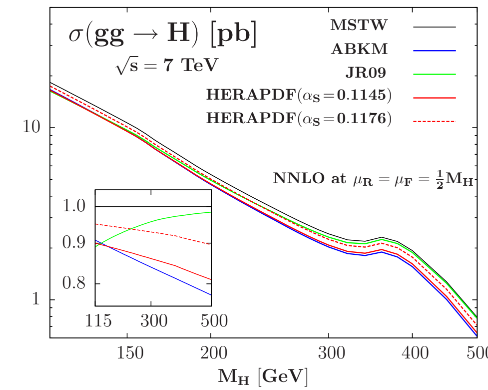
$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
but not above and not b ($\approx 10\%$), W/Z loops
Estimate from (exact) NLO: $\Delta_{\rm EFT} \approx 5\%$

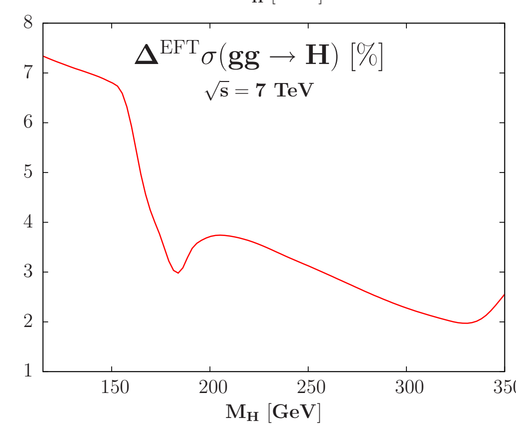
- **Include ΔBR(H$\longrightarrow$X) of at most few %**

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

LHC-HxsWG; Baglio+AD $\Rightarrow$







2. The Higgs at hadron colliders

Expectations for the future:

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

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

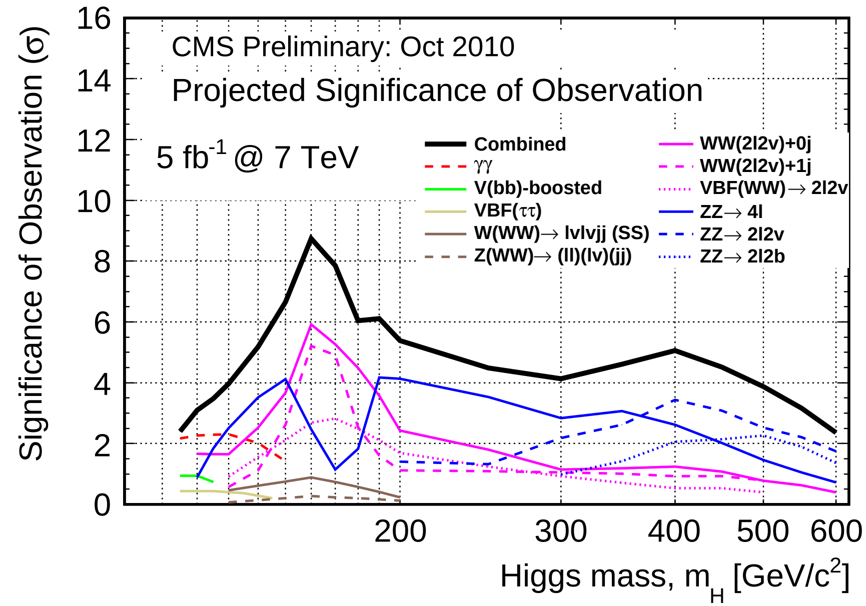
95%CL sensitivity for $M_H \lesssim$600 GeV

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

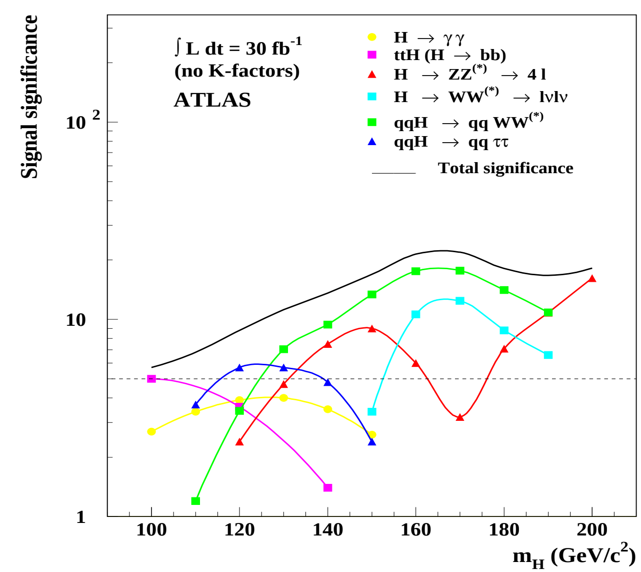
Still $HV \to b\bar{b}\ell X @ M_H \lesssim$130 GeV!

Full LHC: same as lHC plus some others

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

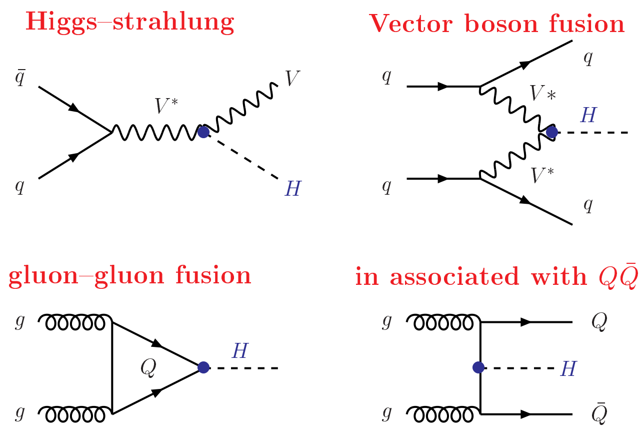
– VH$\to$Vbb with jet substructure tech.

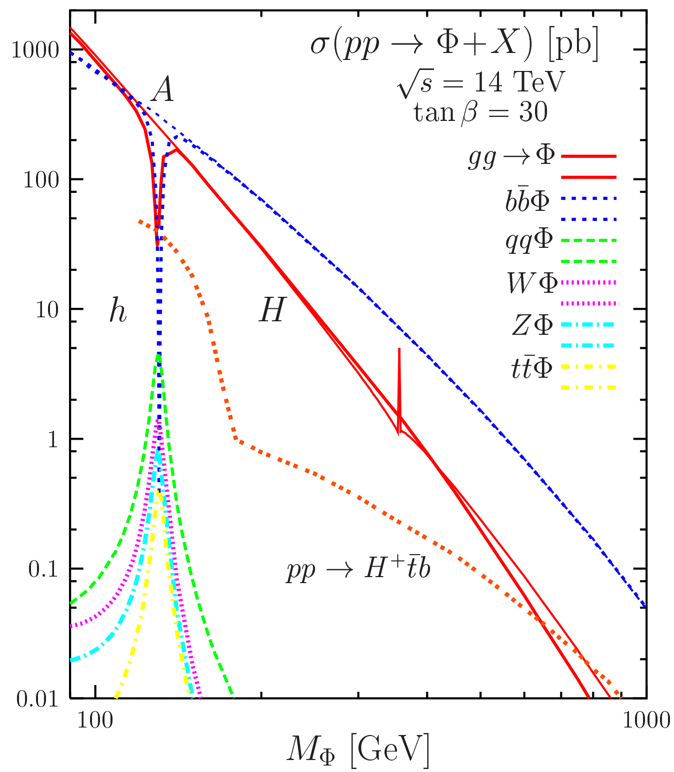
– ttH: H$\to\gamma\gamma$ bonus, H$\to b\bar{b}$ hopeless?



2. The Higgs at hadron colliders

Higgs production in the MSSM





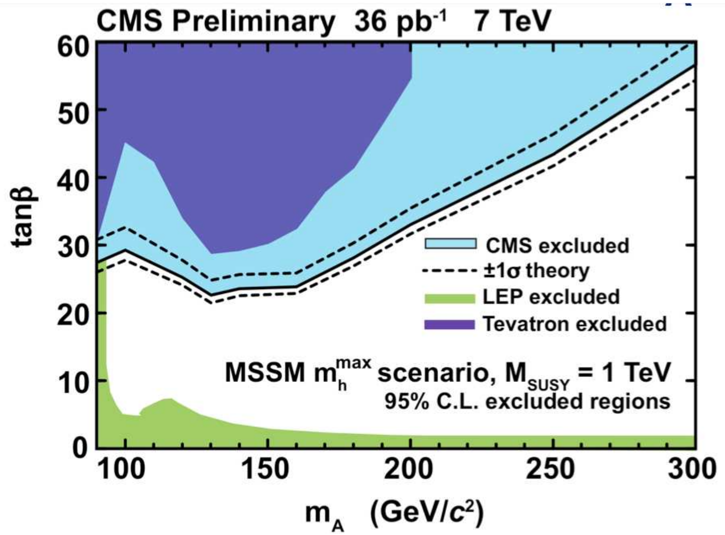
What is different from the SM
(assuming heavy sparticles)

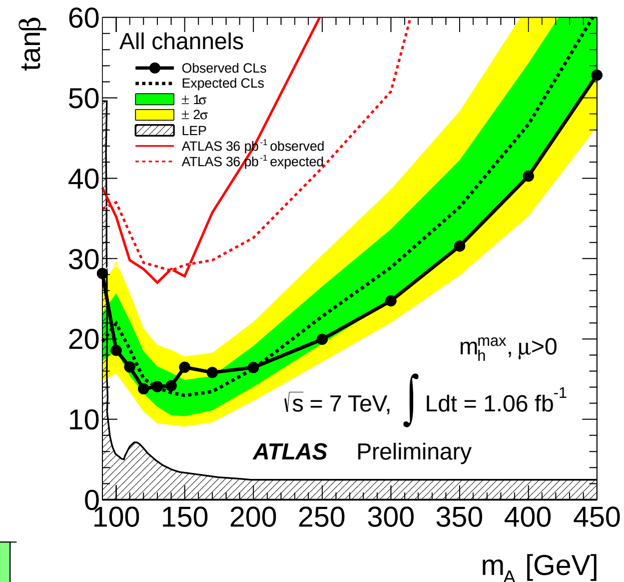
- **All work for CP–even h,H bosons.**
- **– rates suppressed except for $\mathrm{H_{SM}}$**
- **– CP: no AV and qqA processes**
- **– additional mechanism: qq $\longrightarrow$ A+h/H**
- **For $\Phi = \mathrm{h/H, A}$ dominant processes:**
- **– $\mathrm{gg} \to \Phi$ with contribution of b–quarks**
- **– $\mathrm{gg} \to \Phi \mathrm{b\bar{b}}$ or equivalent $\mathrm{b\bar{b}} \to \Phi$**
  (both enhanced by a power $\tan^2\beta$)
- **For charged Higgs boson:**
- **– $\mathrm{M_H} \lesssim \mathrm{m_t}$: $\mathrm{pp} \longrightarrow \mathrm{t\bar{t}}$ with $\mathrm{t} \to \mathrm{H^+b}$**
- **– $\mathrm{M_H} \gtrsim \mathrm{m_t}$: continuum $\mathrm{pp} \longrightarrow \mathrm{t\bar{b}H^-}$**

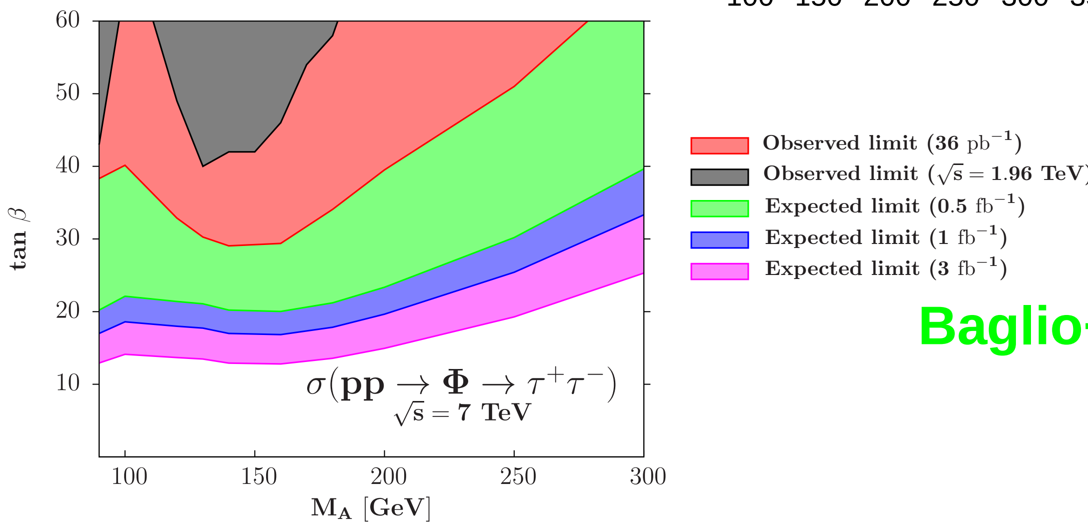
Now@lHC for high tanβ values:

- **– h/H as in SM with $\mathrm{M_h}$ =115–130 GeV**
- **– H/h and A in $\mathrm{gg, b\bar{b}} \to \Phi \longrightarrow \tau^+\tau^-$**
- **– $\mathrm{H^\pm}$ in $\mathrm{t} \to \mathrm{H^+b}$ with $\mathrm{H^+} \to \tau^+\nu$**

2. The Higgs at hadron colliders







Baglio+AD

3. Implications of a Higgs discovery

Let us assume for some time that a Higgs particle has been observed by the ATLAS and CMS collaborations (un sympa. cadeau de Noel?)...

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CMS–HIG–11–666

CERN–PH–EP–2011–042
2011/08/22

We finally got the damn Higgs particle in CMS!
..... and it weights 145 GeV...

The CMS collaboration

Abstract

A measurement of W^+W^- production in pp collisions at $\sqrt{s} = 7$ TeV and a search for the Higgs boson by the CMS collaboration are reported. The W^+W^- candidates are selected in events with two leptons, either electrons or muons. The measurement is performed using LHC data recorded with the CMS detector, corresponding to an integrated luminosity of 5 fb^{-1}. The pp $\to$ W^+W^- cross section is measured to be 41.1$\pm$5.3 (stat)$\pm$.8 (syst)$\pm$2.5 (lumi) pb. Something looks fishy there and it looks like there is a 5σ excess above the standard model prediction. Some of us therefore think that we have finally found the Higgs boso with a 145 GeV mass (why 145? why not? it looks like a good number..) and, before the signal disappears, we are drinking champagne. More information will be given after we finish with the hang–over...

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ATLAS–HIG–11–111

CERN–PH–EP–2011–043
2011/08/22

And the verdict is: YES, the Higgs indeed exists!
..... and it came across our detector...

The ATLAS collaboration

Abstract

A measurement of $pp \to ZZ$ production in pp collisions at $\sqrt{s} = 7$ TeV and a search for the Higgs boson by the ATLAS collaboration are reported. The ZZ candidates are selected in events with four leptons, either electrons or muons. The measurement is performed using LHC data recorded with the ATLAS detector, corresponding to an integrated luminosity of 5 fb^{-1}. Many signal peaks show up in the 4ℓ mass range between 120 and 150 GeV and, despite of the fact that we do not understand all backgrounds, we conclude that the siginificant excess of events can be attributed to the unfamous Higgs particle (that half of the collaboration does not believe in...). As in the case of our CMS collegues, we are heavily celebrating and not yet in a state to give you more information. So please "stay tuned"...

What would be the implications for high–energy particle physics?

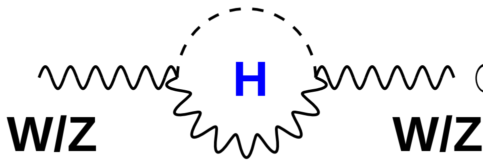
For illustration, take the examples of a mass $M_H \approx 115-145$ GeV (with cross section/decay rates compatible with SM, say up to $\approx$ 30%)

3. Implications of a Higgs discovery

A triumph for the SM and high-energy physics!

Indirect constraints from high–precision electroweak data[a] $\Rightarrow$ update summer 2011

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

$$M_H \lesssim 161 \text{ GeV at 95\% CL}$$

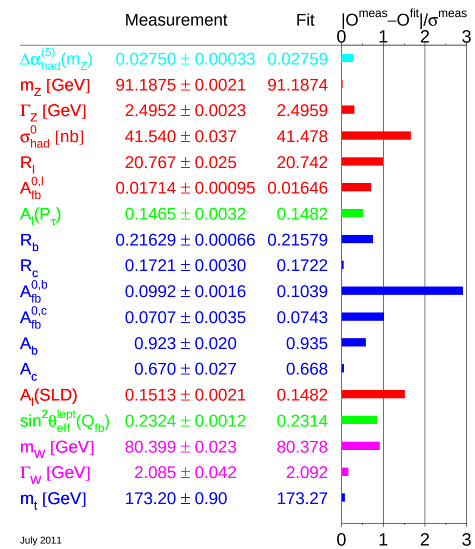
compared with "observed" $M_H = 145$ GeV

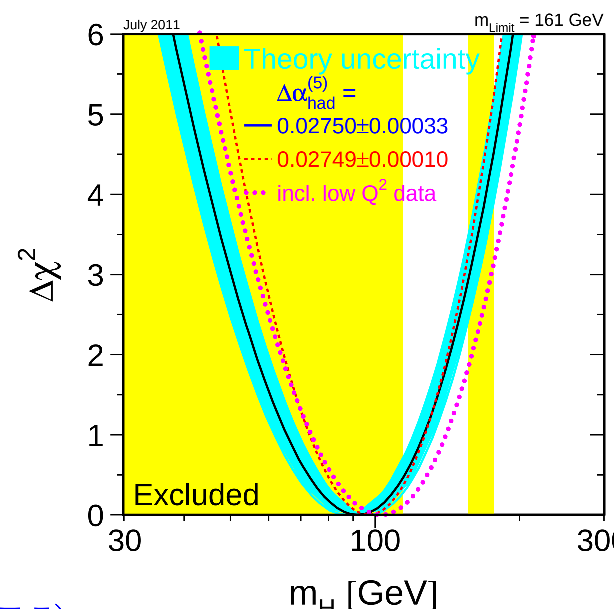
A very non–trivial check of SM consistency!

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....

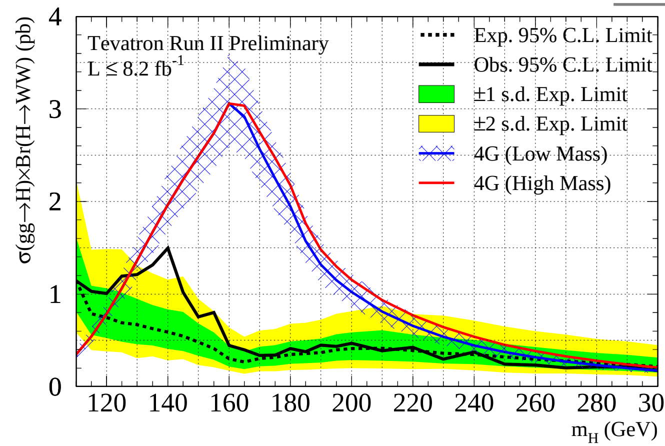




[a] Still some problems with A_{FB}^{b} (LEP), A_{FB}^{t} (TeV) and $g-2$...

3. Implications of a Higgs discovery

The SM particle spectrum is now complete....



Not only we observed the last missing piece, we made sure that there is no 4th generation fermions which get masses through H field[a]:

completion of LEP/SLC job with light νs...

If $M_H \gtrsim 130$GeV, SM extrapolable to M_{GUT}

Triviality/stability bounds on $\lambda = \frac{M_h^2}{2v^2}$:

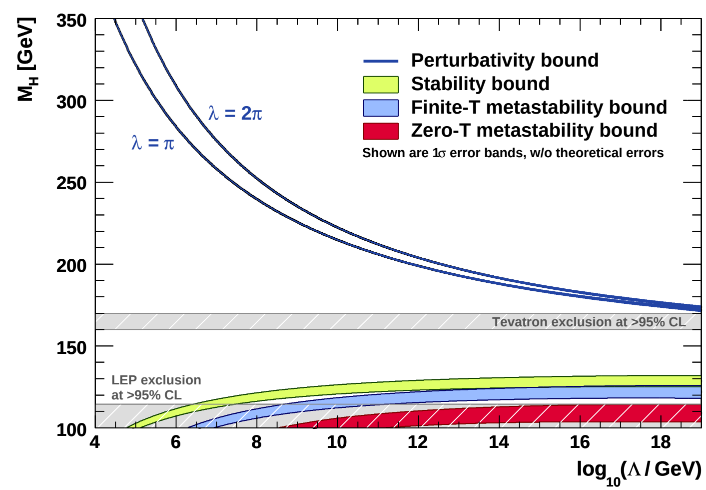
$\lambda \gg 1$ coupling blows up (Landau pole)

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

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

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

with $M_H \approx 145$ GeV SM OK up to M_{GUT}[b]



Ellis et al. ⇒

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[a] Constraint to be updated as EW corrections found to be large: Passarino et al...

[b] Still some efforts for ν masses, gauge coupling unification, dark matter,...

3. Implications of a Higgs discovery

Simple models for low–energy supersymmetry dead or alive...

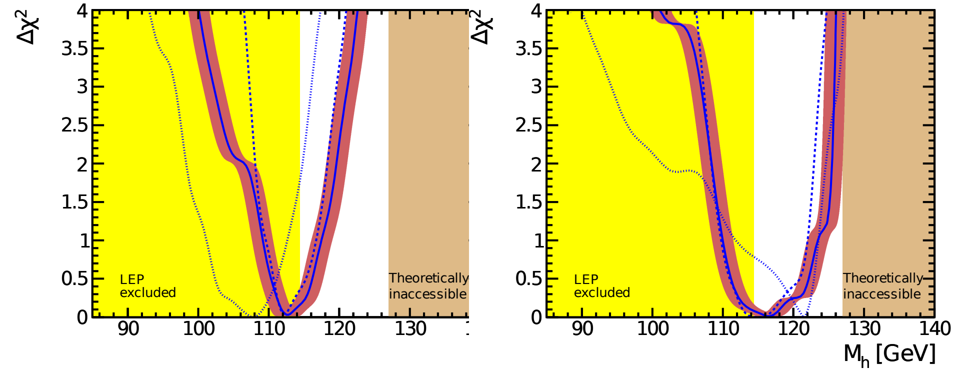
- **Constrained SUSY models:**

CMSSM : $M_h \lesssim 120$ GeV

NUHMSSM: $M_h \lesssim 130$ GeV

out if the Higgs is too heavy....

Buchmuller et al. $\Rightarrow$



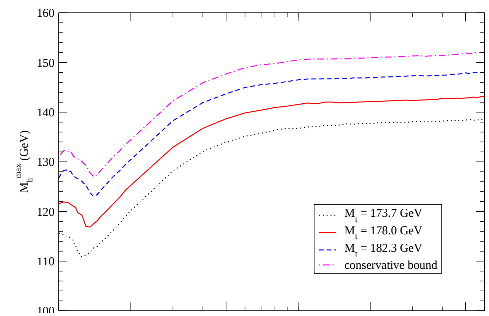
- **Phenomenological MSSM OK?**

if all parameters are (very) tuned

maximum-maximorum $M_h \approx 140$GeV

right in the allowed mass range..

Allanach et al. $\Rightarrow$

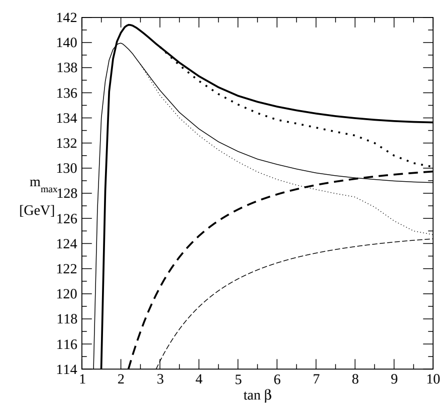


- **Extensions of the MSSM?**

ex. NMSSM: one extra singlet Higgs

maximum mass $M_h^{max} \approx 142$ GeV

Ellwanger et al. $\Rightarrow$



Note: check that observed state is h!

3. Implications of a Higgs discovery

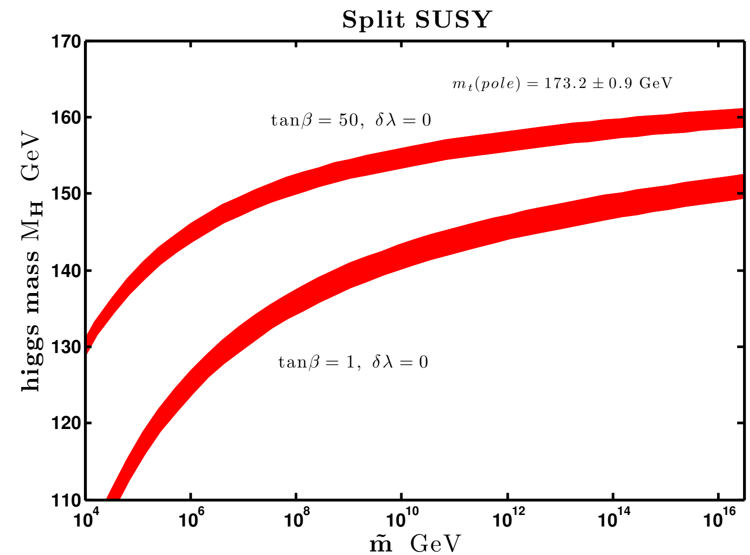
... strong constraints if the scale of SUSY breaking is very high...

- **Split SUSY: allow fine–tuning**

scalars (including H_2) at high scale
gauginos–higgsinos at weak scale
(unification+DM solutions still OK)

$$M_H \propto \log(\tilde{m}/M_W) \gtrsim 145 \text{ GeV}$$

Bernal, Slavich, AD
Giudice, Feldman, ... $\Rightarrow$



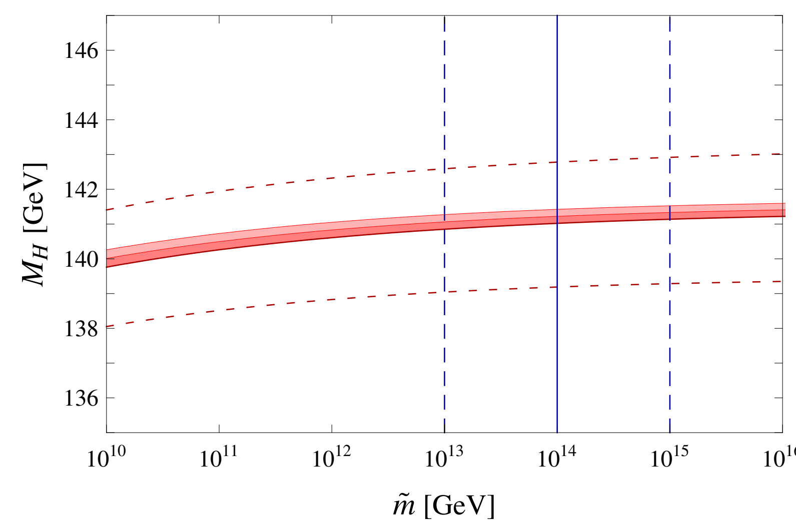
- **SUSY broken at the GUT scale...**

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 $M_H = 141 \pm 2$ GeV ...

Hall+Nomura $\Rightarrow$



A scenario that might be good for string theory, but probably not for HEP...

3. Implications of a Higgs discovery

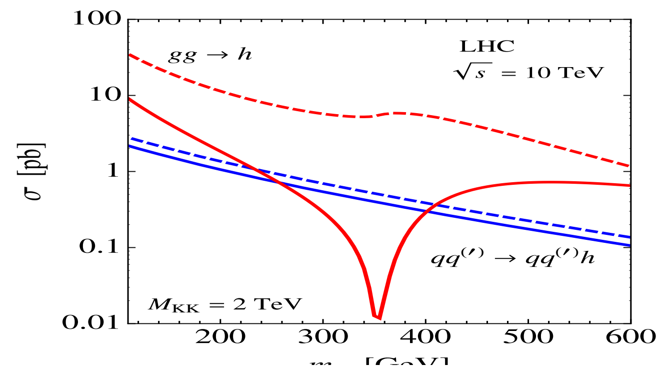
What about alternative New Physics scenarios?

A few examples:

- **In ED scenarios:**

– Higgsless models ruled out...
– some properties could be altered
(KK or new states might contribute..)

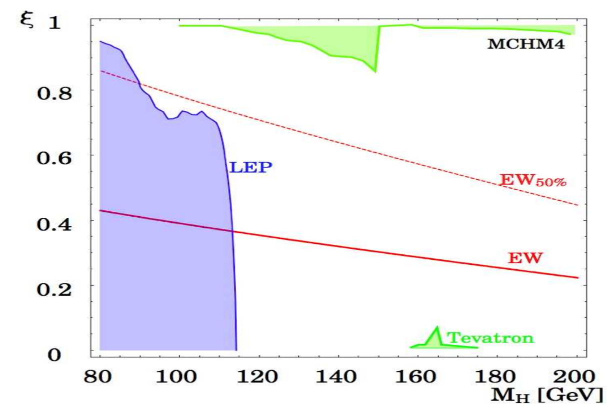
Moreau, AD; Casagrande et al. $\Rightarrow$



- **Composite Higgs: rates altered**

MCHM4: $g_{Hpp} \to g_{Hpp}\sqrt{1-\xi}$
EWPT prefer low $\xi = \frac{f}{v}$ **close to SM**
easy to check unless $\xi \approx 0$ **(SM)...**

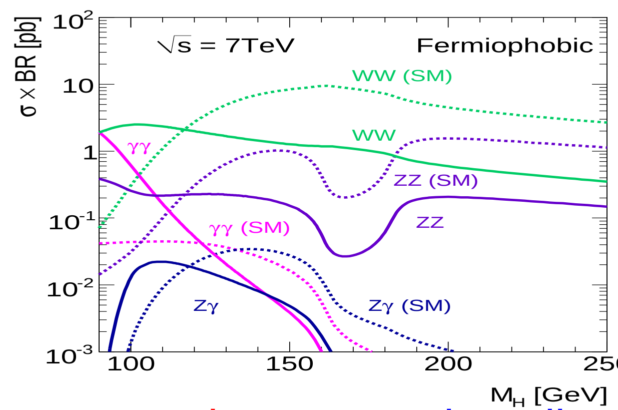
Espinosa, Grojean, Muhlleitner $\Rightarrow$



- **Many other scenarios can be checked:**

fermiophobic: $pp \to Hqq \to \gamma\gamma qq$
gauge–phobic: $gg \to H \to \tau^+\tau^-$
4th generation with $pp \to H \to NN$

Dittmaier et al. LHC-HxsWG $\Rightarrow$



4. What if the Higgs is not found?

In the SM at the early stage lHC: get back to the theory predicton?

We might have been too optimistic with the cross section prediction

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

and we should maybe be more conservative about the uncertainty?

Scale uncertainty, κ=4 leads to a $\approx$ 20% error...

PDFs: using another set, σ might be lower by $\approx$ 20%

Also a slightly larger EFT uncertainty, say $\approx$ 10%

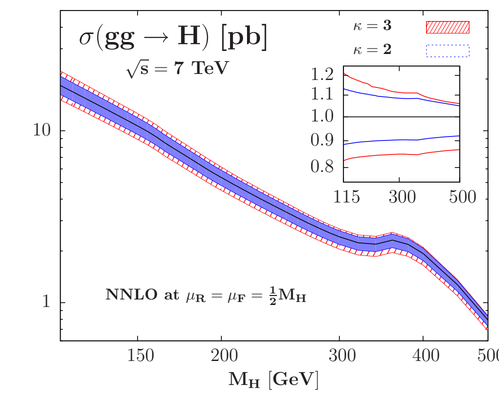
$\Rightarrow$ a total uncertainty of 50% on the cross section

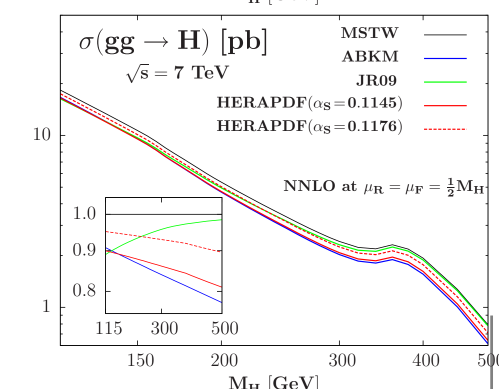
$\equiv$ a possible reduction of expected rate by factor 2

(maybe do the same excercice on the backgrounds!!)

Might save the day until next year (end of lHC run?)...

But not more: at some point H should be observed!





4. What if the Higgs is not found?

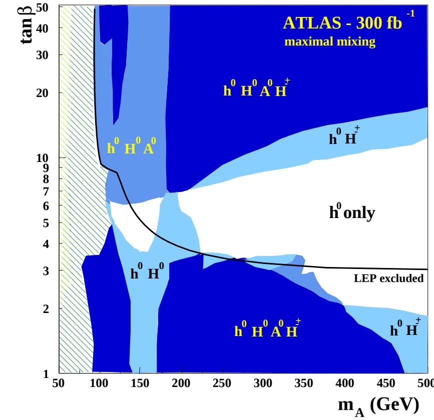
In SUSY theories, there are several possibilites for early non–observation

- **We are not yet in the decoupling limit:**

– suppressd VV couplings for both h and H

– for $\tan\beta \gtrsim 1$, BR(VV/bb) suppressed/enhanced

$\Rightarrow$ discovery needs larger luminosity/energy



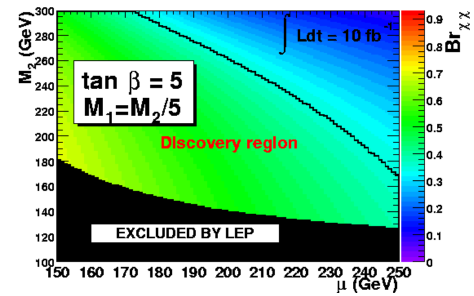
- **We have large invisible Higgs decays:**

– in MSSM, $h \to \chi\chi$ decays still possible

(in non–universal scenarios in particular)

– in RpV models, Higgs$\to$ JJ decays large

but new (SUSY) states might be observable...



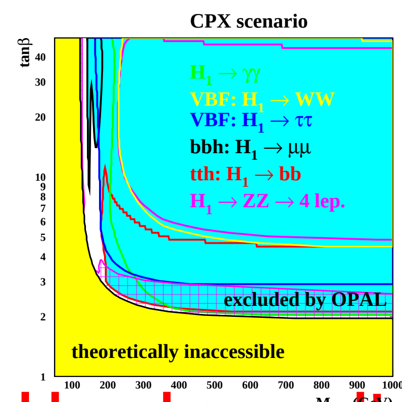
- **We have new/complicated Higgs decays:**

– in CPV scenarios, very light Higgs H_1

– in the NMSSM, a very light CP–odd A_1

$\Rightarrow$ dominant H$\to H_1H_1, A_1A_1 \to 4b$ decays

but instead other Higgses could be detected ...



But at some point, at least one Higgs or a sparticle should be observed!

4. What if the Higgs is not found?

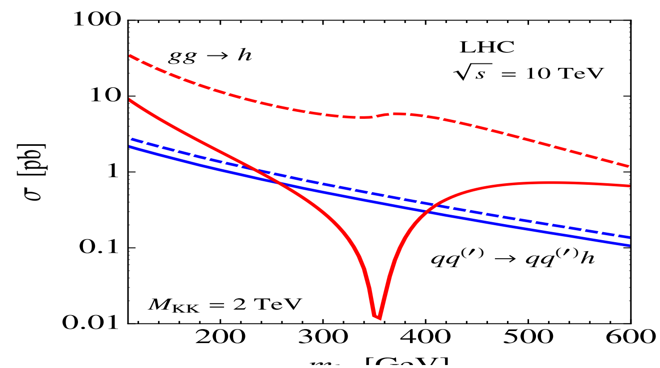
Couplings strongly suppressed in alternative New Physics scenarios?

A few examples where this could occur:

- **In ED scenarios:**

– HVV couplings suppressed
– production rates could be altered
(KK or new states might contribute..)

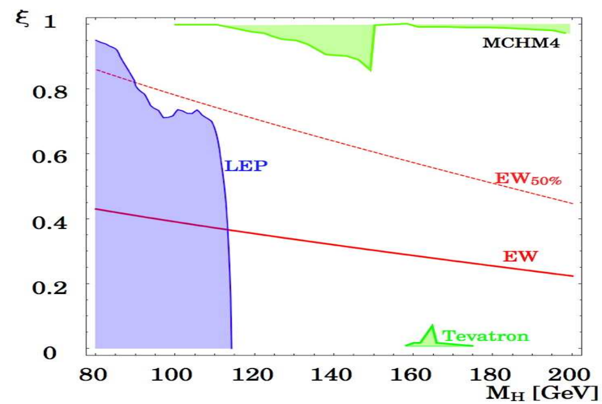
Moreau, AD; Casagrande et al. $\Rightarrow$



- **Composite Higgs: rates altered**

MCHM4: $g_{\rm Hpp} \to g_{\rm Hpp}\sqrt{1-\xi}$
EWPT prefer low $\xi = \frac{f}{v}$ close to SM
but possibility of large ξ not out...

Espinosa, Grojean, Muhlleitner $\Rightarrow$



- **Many other scenarios are possible:**

fermiophobic: $\rm pp \to Hqq \to \gamma\gamma qq$
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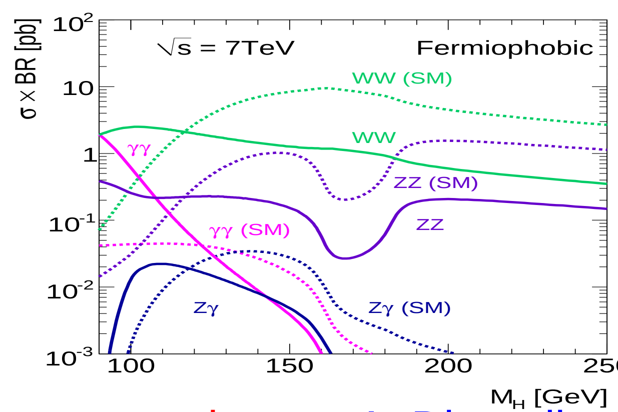
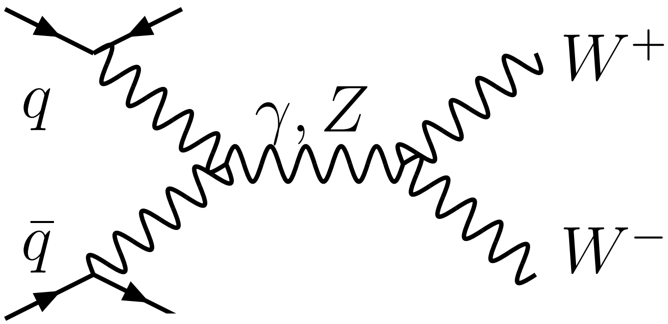
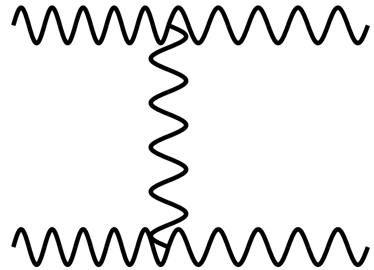


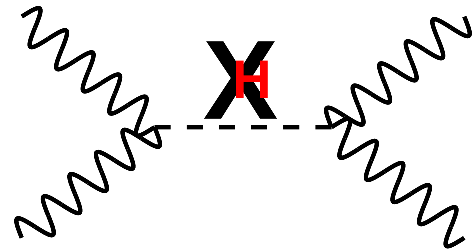
4. What if the Higgs is not found?

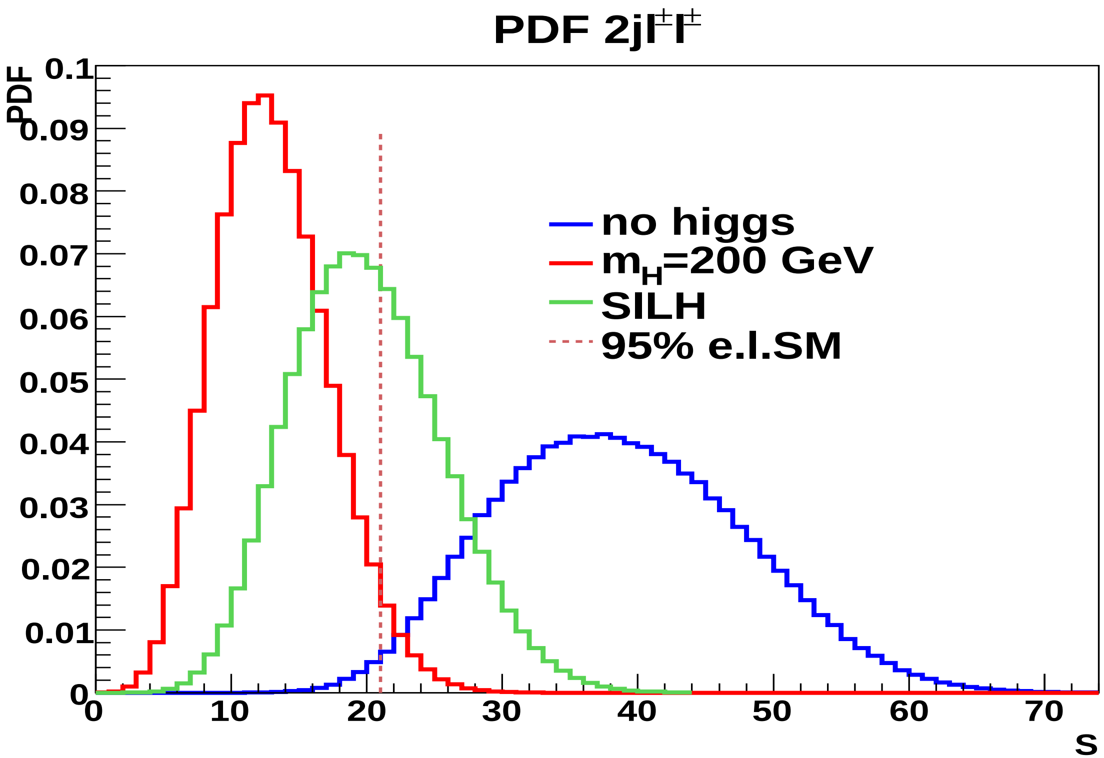
If there is no Higgs boson at all: strongly interacting Higgs sector

WW/ZZ scattering to check it. Largest energy/luminosity needed !









Ballestrero
Franzosi
Maina

5. Perspectives

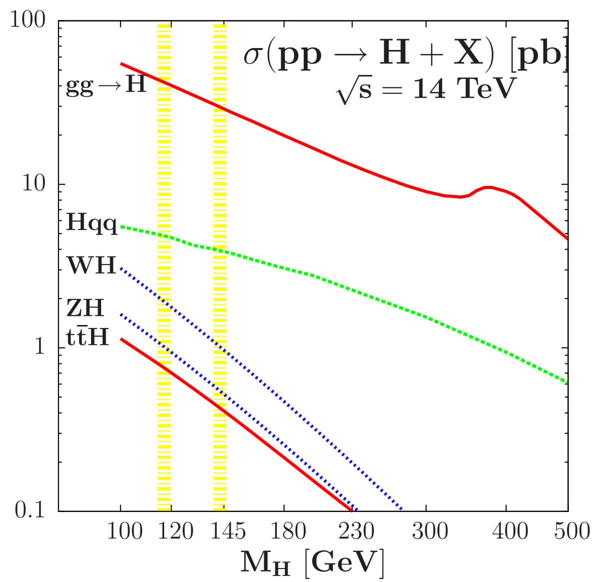
Very soon we will find the Higgs: would particle physics be "closed"?

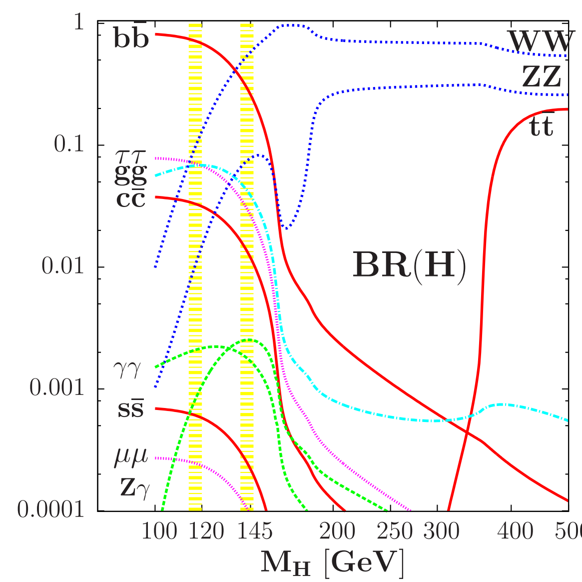
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

Measure its fundamental properties in the most precise way:

- **its mass and total decay width,**
- **its spin–parity quantum numbers and check $J^{PC} = 0^{++}$,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction!),**
- **its self–couplings to reconstruct the potential V_H that makes EWSB.**

Possible for $M_H \approx$ 115–145 GeV as all production/decay channels useful!





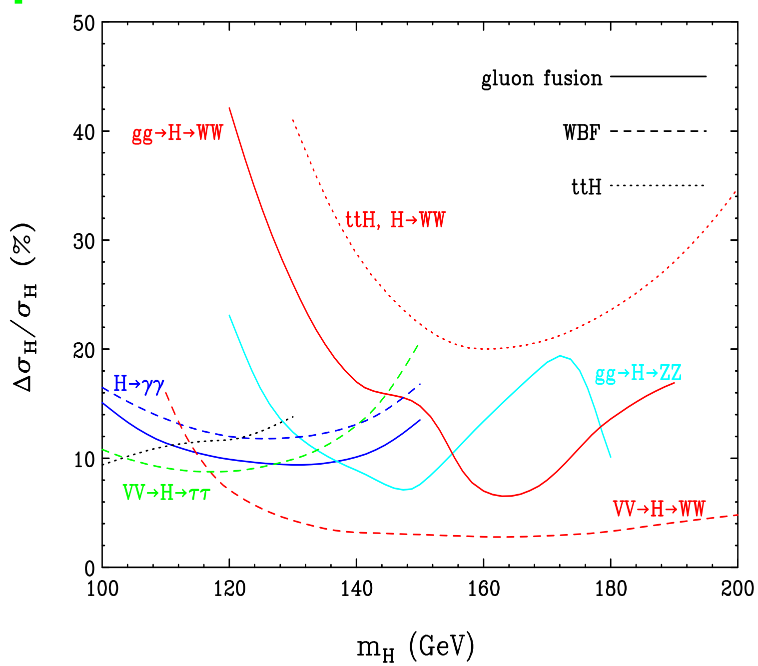
5. Perspectives

Technically a challenging program (even more difficult than discovery?)

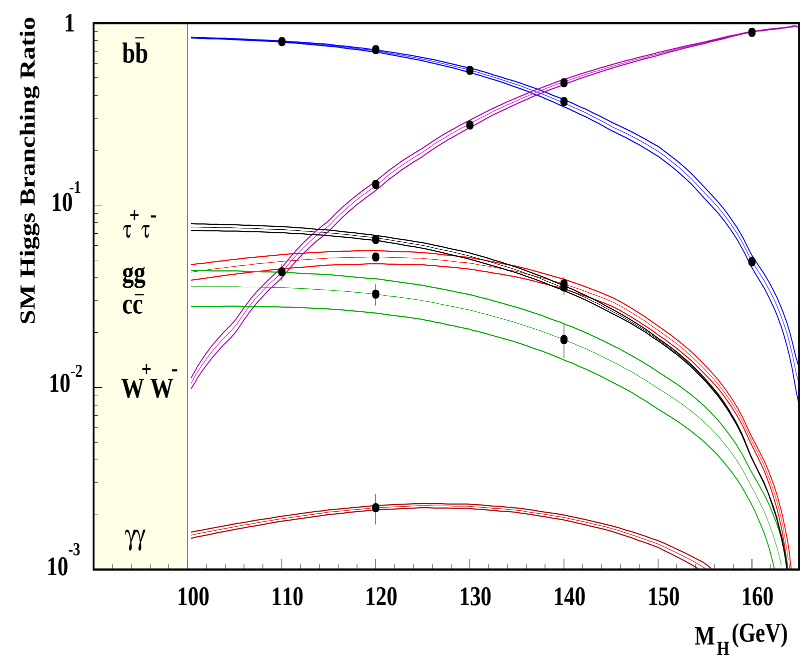
(and more difficult and necessary in some SM extensions...)

- **needs the highest possible energy and luminosity at the LHC**
- **might even need to move to SLHC (in particular for H self–coupling)**
- **even then we will be limited by theoretical/systematical uncertainties**
- **maybe an e^+e^- machine such as ILC or CLIC will be necessary?**

Zeppenfeld et al



TESLA TDR



There is still some work to do and some way to go!