Theoretical aspects of Higgs physics

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- **EWSB and the Higgs**
- **The standard Higgs at the LHC**
- **The Higgs sector in the MSSM**
- **Measurement of the Higgs**
- **Conclusion**

1. EWSB and the Higgs

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** $\langle 0|\Phi^0|0\rangle \neq 0$

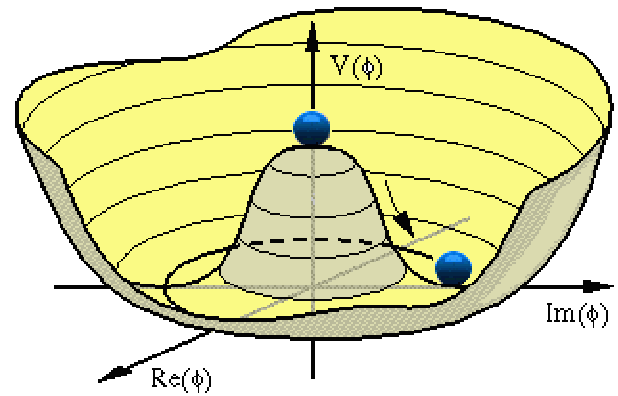
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

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

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

For fermion masses, use **same** Φ**:**

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

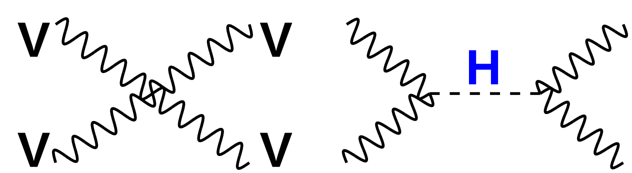


Residual dof corresponds to spin–0 H particle.

- **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:

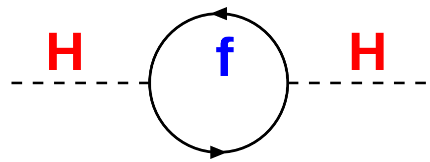
$|A_0| \propto M_H^2/v^2 \Rightarrow$ **the theory is unitary but needs** $M_H \lesssim 700$ **GeV...**

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

1. EWSB and the Higgs

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)....

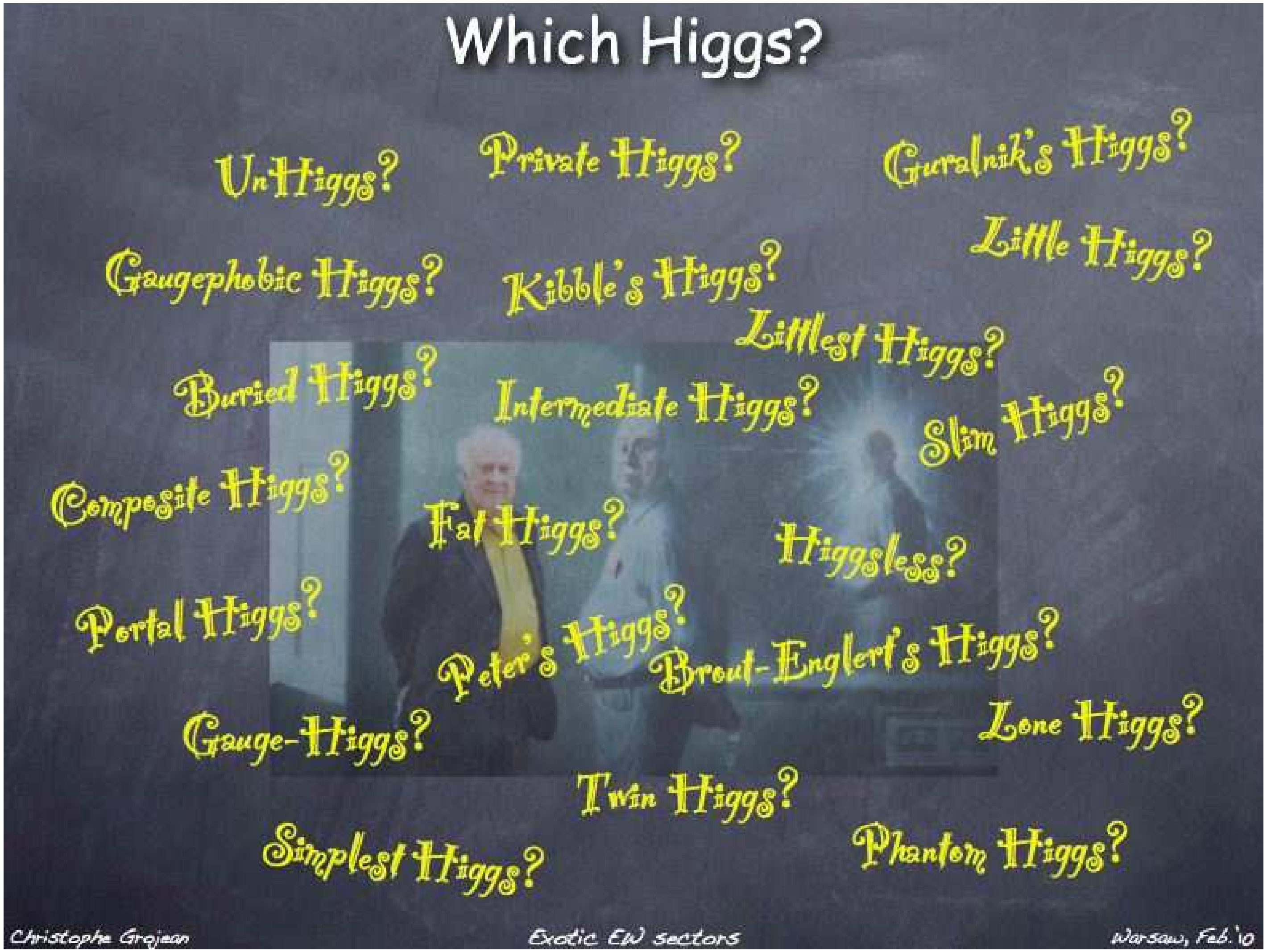
Strong interactions/compositness: the Higgs is not an elementary scalar.

– 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 the Higgs

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



Which scenario chosen by Nature? The LHC supposed to tell!

2. The standard Higgs at the LHC: decays

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

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

First: Higgs decays in the SM

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

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

  – $\mathrm{H \to \gamma\gamma, Z\gamma} = \mathcal{O}(0.1\%)$
- $\mathrm{M_H} \gtrsim 130$ **GeV**, $\mathrm{H \to WW, ZZ}$

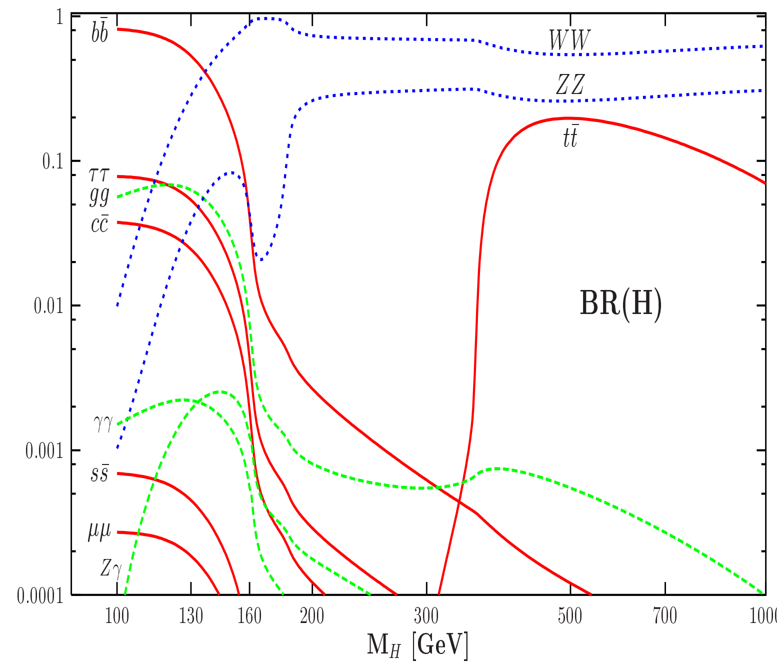
  – below threshold decays possible

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

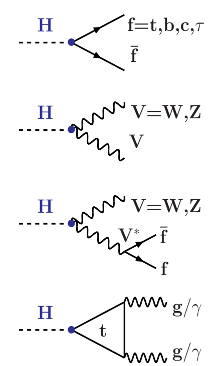
  – decays into $\mathrm{t\bar{t}}$ for heavy Higgs
- **Total Higgs decay width:**

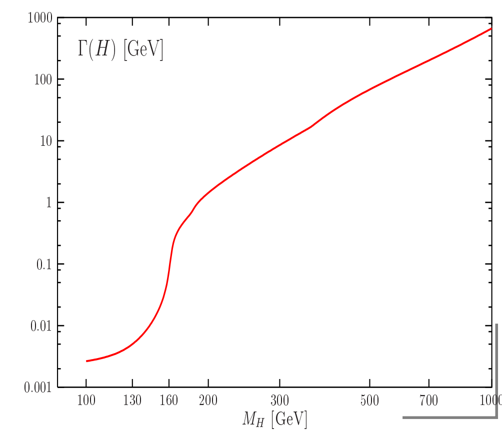
  – very small for a light Higgs

  – comparable to mass for heavy Higgs



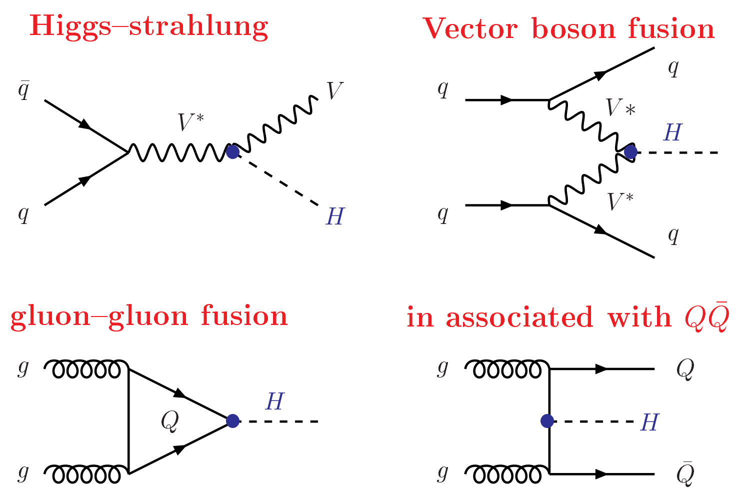
HDECAY ⇒

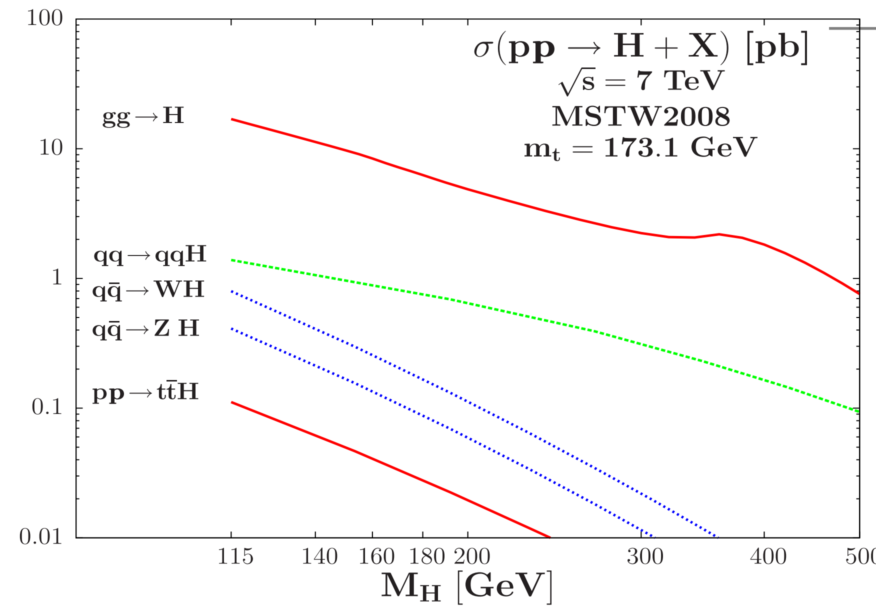




2. The standard Higgs at the LHC: production

Main Higgs production channels





Large production cross sections

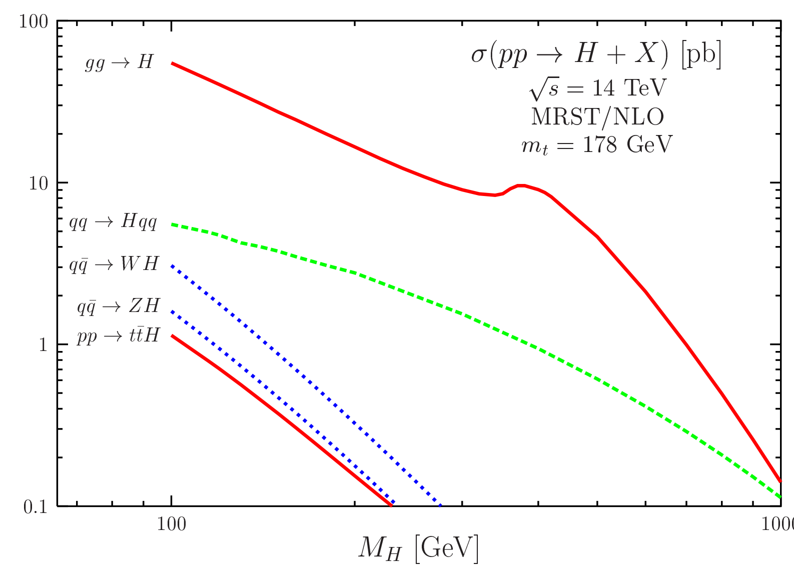
with gg$\longrightarrow$ H by far dominant process

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

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

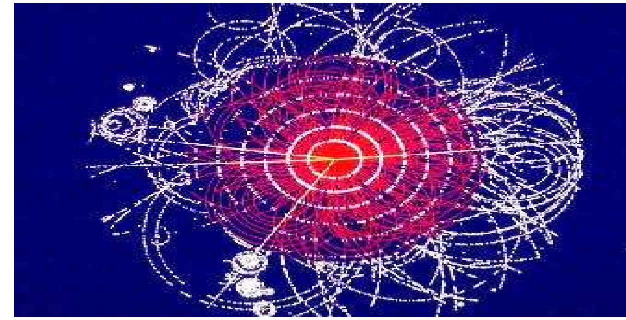
but eg BR(H$\to \gamma\gamma, ZZ \to 4\ell) \approx 10^{-3}$

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



2. The standard Higgs at the LHC: challenges

$\Rightarrow$ **an extremely challenging task!**



- **Huge cross sections for QCD processes**
- **Small cross sections for EW Higgs signal**

  S/B $\gtrsim 10^{10} \Rightarrow$ a needle in a haystack!
- **Need some strong selection criteria:**

– trigger: get rid of uninteresting events...

– select clean channels: $\mathrm{H} \to \gamma\gamma, \mathrm{VV} \to \ell$

– use specific kinematic features of Higgs

- **Combine # decay/production channels**

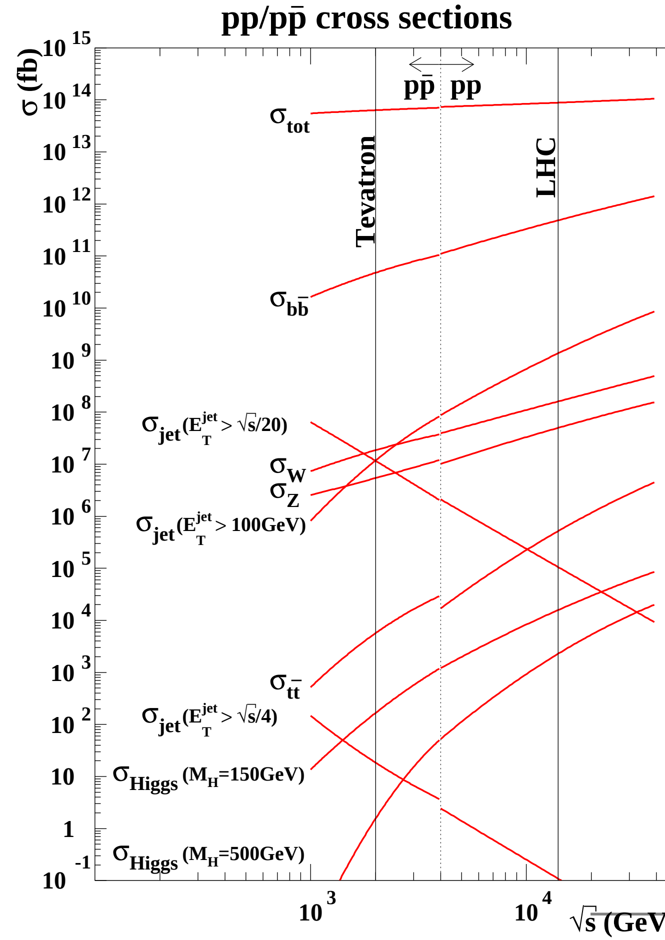
(and eventually several experiments...)

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

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

- **Gigantic experimental + theoretical efforts**

(more than 30 years of very hard work!)



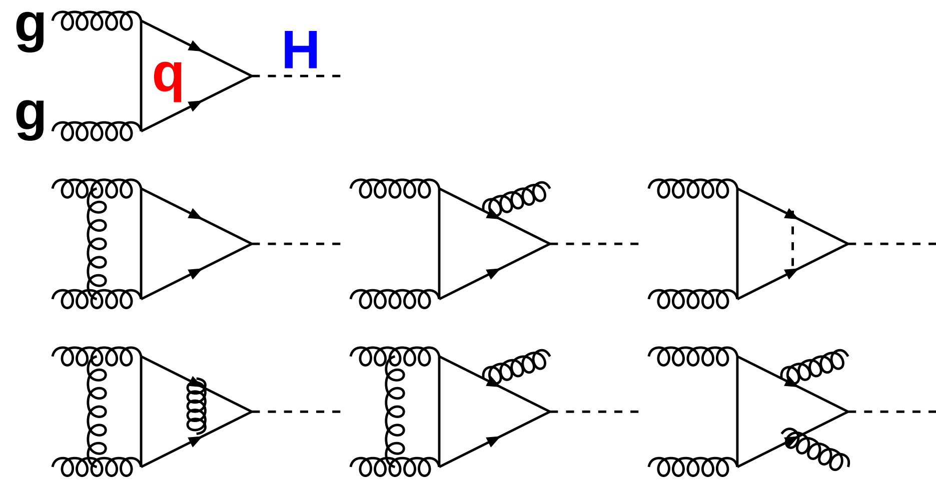
For a flavor of how it is complicated from the theory side: a look at the $\mathrm{gg} \to \mathrm{H}$ case

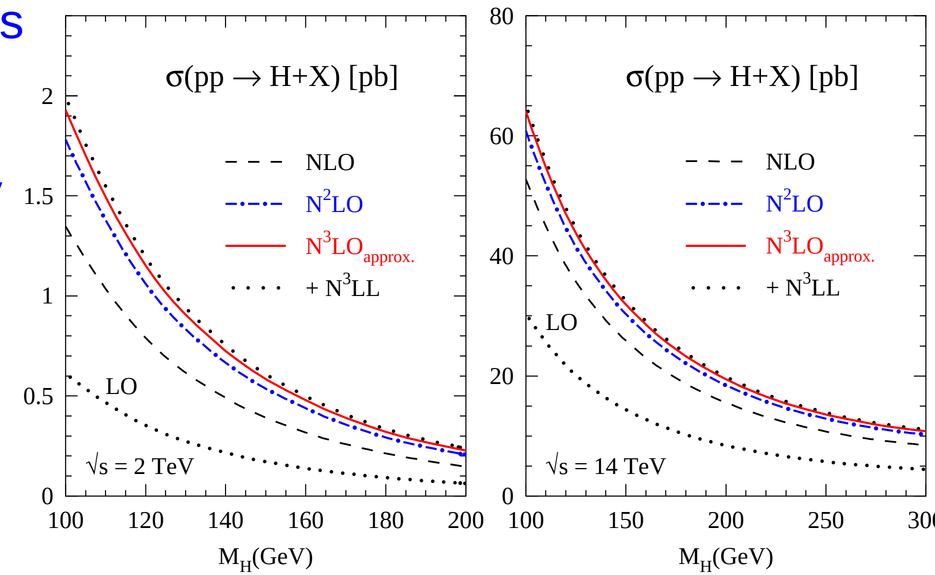
2. The Higgs at the LHC: gg fusion

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





Moch+Vogt

2. The Higgs at the LHC: uncertainties

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

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

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

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

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

- **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

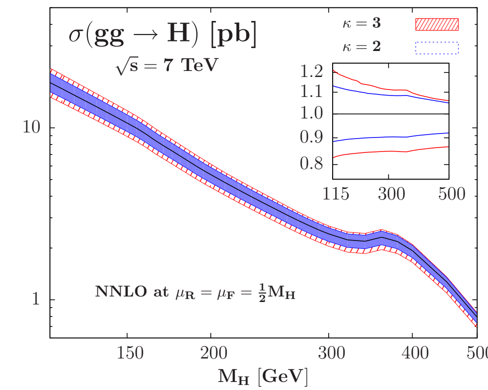
- **Uncertainty from EFT approach at NNLO**

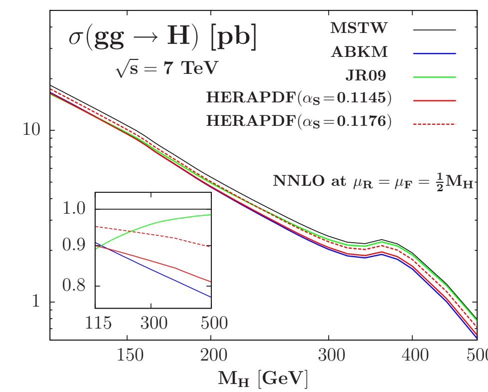
$m_{\rm loop} \gg M_H$ good for top if $M_H \lesssim 2m_t$
but not above and not b ($\approx 10\%$), W/Z loops
Estimate from (exact) NLO: $\Delta_{\rm EFT} \approx 5\%$

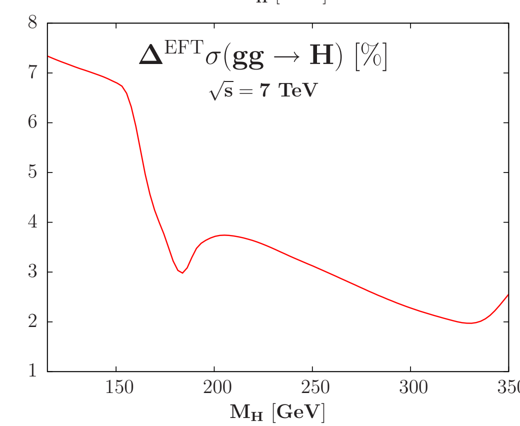
- **Include ΔBR(H$\longrightarrow$X) of at most few %**

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

LHC-HxsWG; Baglio+AD $\Rightarrow$



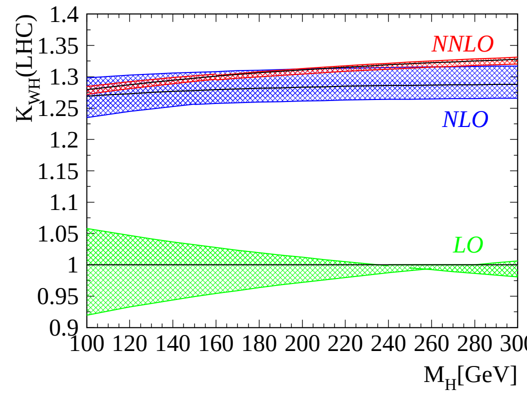




2. The Higgs at the LHC: other channels

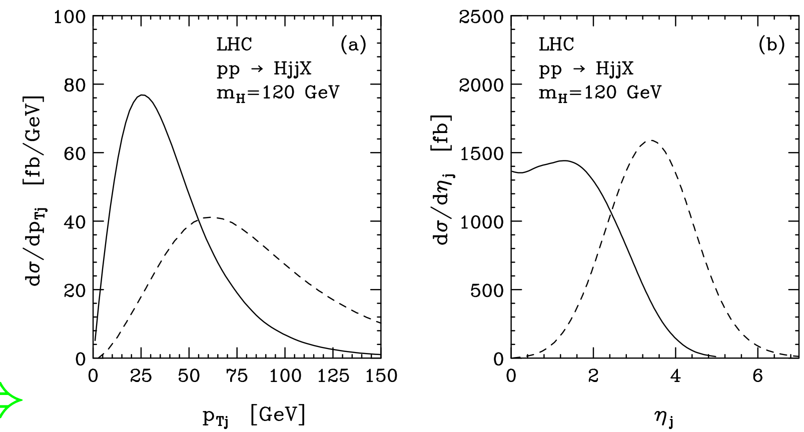
- **Higgs–strahlung: $q\bar{q} \to VH$**
- – Drell–Yan with $V^* \to VH$ decays
- – RC known at NNLO, rather moderate
- – $\ell\nu b\bar{b}$ main mode@Tevatron for light H
- – resurrected at LHC with boosted jets

Brein, AD, Harlander $\Rightarrow$



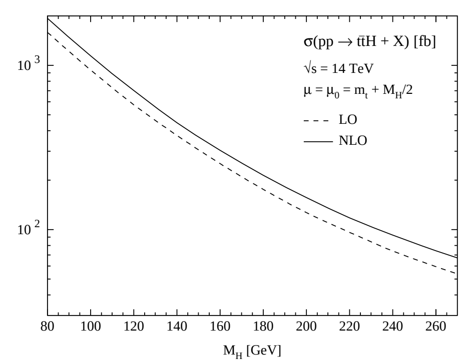
- **vector boson fusion: $qq \to Hqq$**
- – large cross section at high $\sqrt{s}$
- – p_T^{high} forward jets, central jeto veto, ..
- – TH clean (small RC) but ggH contam.
- – many H decay channels observable.

Zeppenfeld et al. $\Rightarrow$



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

Beenakker et al. $\Rightarrow$



2. The Higgs at the LHC: expectations

Expectations for 2012 and beyond:

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

5σ discovery for $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

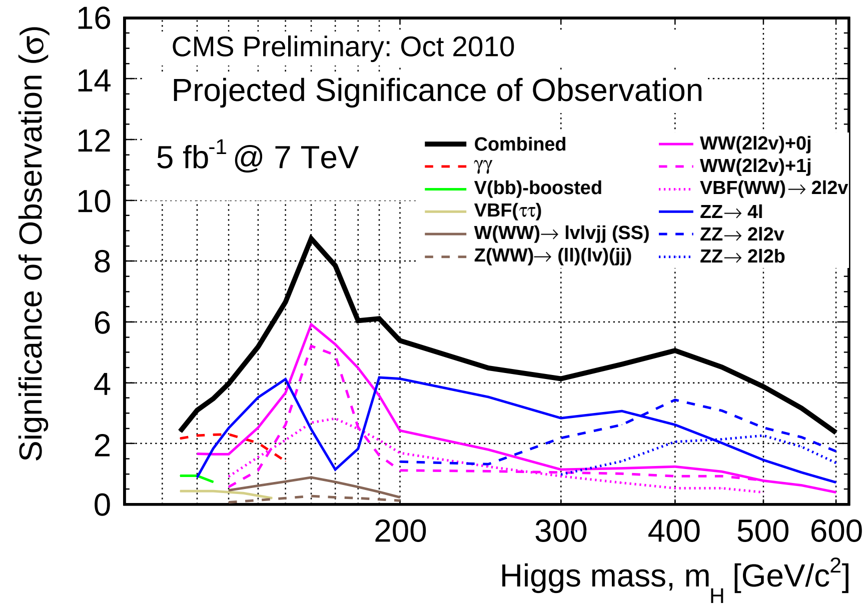
$gg\to H\to ZZ\to 4\ell, 2\ell 2\nu, 2\ell 2b$

$gg\to H\to\tau\tau+0,1$ jets

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

– at lHC with jet substructure

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

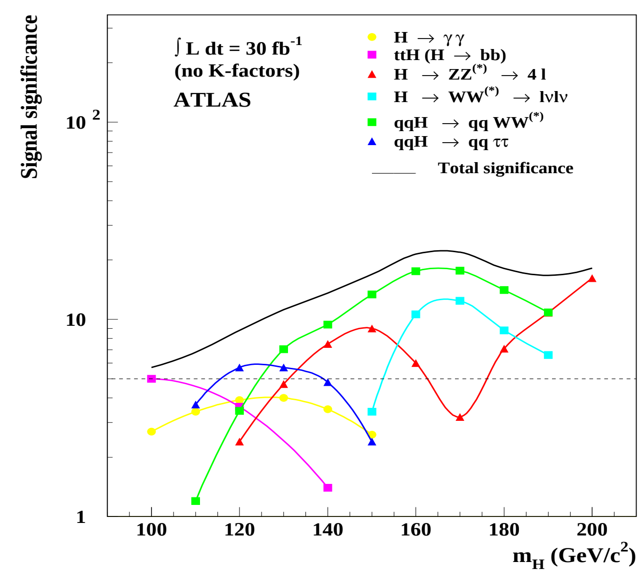


Full LHC: same as lHC plus some others

– 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?



3. MSSM Higgs at the LHC

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

After EWSB (which can be made radiative: more elegant than in SM):

Three dof to make $\mathbf{W_L^\pm, Z_L} \Rightarrow$ **5 physical states left out:** $\mathbf{h, H, A, H^\pm}$

Only two free parameters at tree–level: $\tan\beta, \mathbf{M_A}$ **but rad. cor. important**

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

– Couplings of $\mathrm{h, H}$ **to VV are suppressed; no AVV couplings (CP).**

– For $\tan\beta \gg 1$**: couplings to b (t) quarks enhanced (suppressed).**

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\sin\alpha}{\cos\beta} \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\frac{\sin\alpha}{\sin\beta} \to 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A	$1/\tan\beta$	$\tan\beta$	0

In the decoupling limit: MSSM reduces to SM but with a light SM Higgs.

Haber

At tan$\beta \gg$1, one SM–like and two CP–odd like Higgses with cplg to b,τ

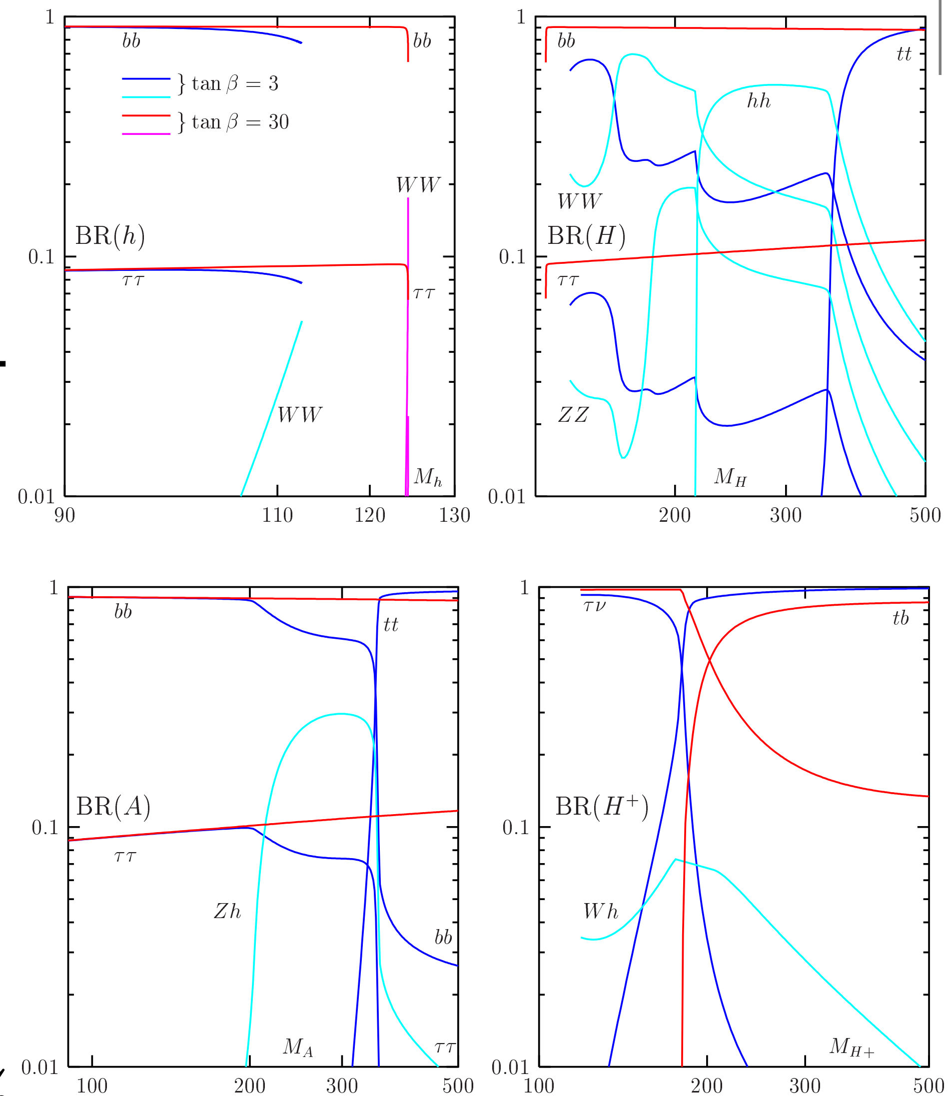
$$\mathbf{M_A \le M_h^{max} \Rightarrow h \equiv A, H \equiv H_{SM}}\ ,\ \mathbf{M_A \ge M_h^{max} \Rightarrow H \equiv A, h \equiv H_{SM}}$$

3. MSSM Higgs at the LHC

Higgs decays in the MSSM:

General features:

- h: same as $\mathrm{H_{SM}}$ in general (esp. in decoupling limit) if not $\mathrm{h} \to \mathrm{b\bar{b}}, \tau^+\tau^-$ enhanced for tanβ >1
- A: only $\mathrm{b\bar{b}}, \tau^+\tau^-$ and $\mathrm{t\bar{t}}$ decays (no VV decays, hZ suppressed).
- H: same as A in general; tan$\beta \gg$1 $\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ decays suppressed.
- $\mathrm{H^{\pm}}$: $\tau\nu$ and tb decays (depending if $\mathrm{M_{H^{\pm}}} <$ or $>$ $\mathrm{m_t}$).



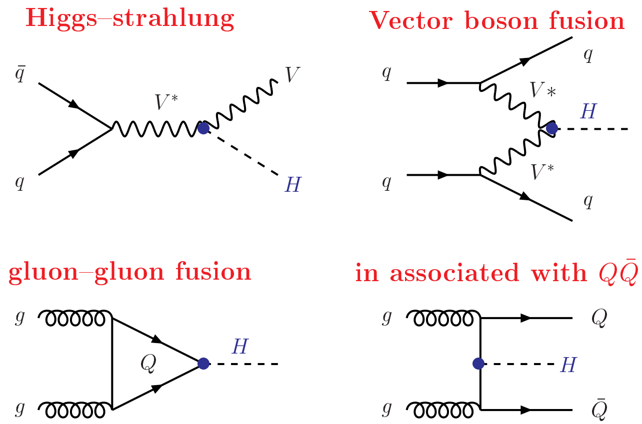
Possible new effects from SUSY!!

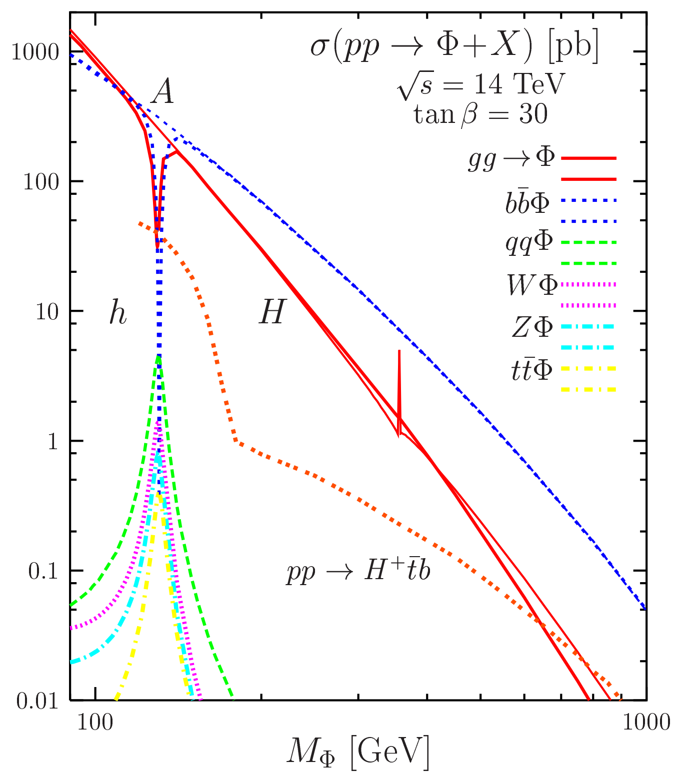
For tan$\beta \gg$1, only decays into b/τ:
BR: $\Phi \to \mathrm{b\bar{b}} \approx 90\%$, $\Phi \to \tau\tau \approx 10\%$

For tan$\beta \approx$1, other channels need to be considered too!

3. MSSM Higgs at the LHC

SM production mechanisms





What is different in MSSM

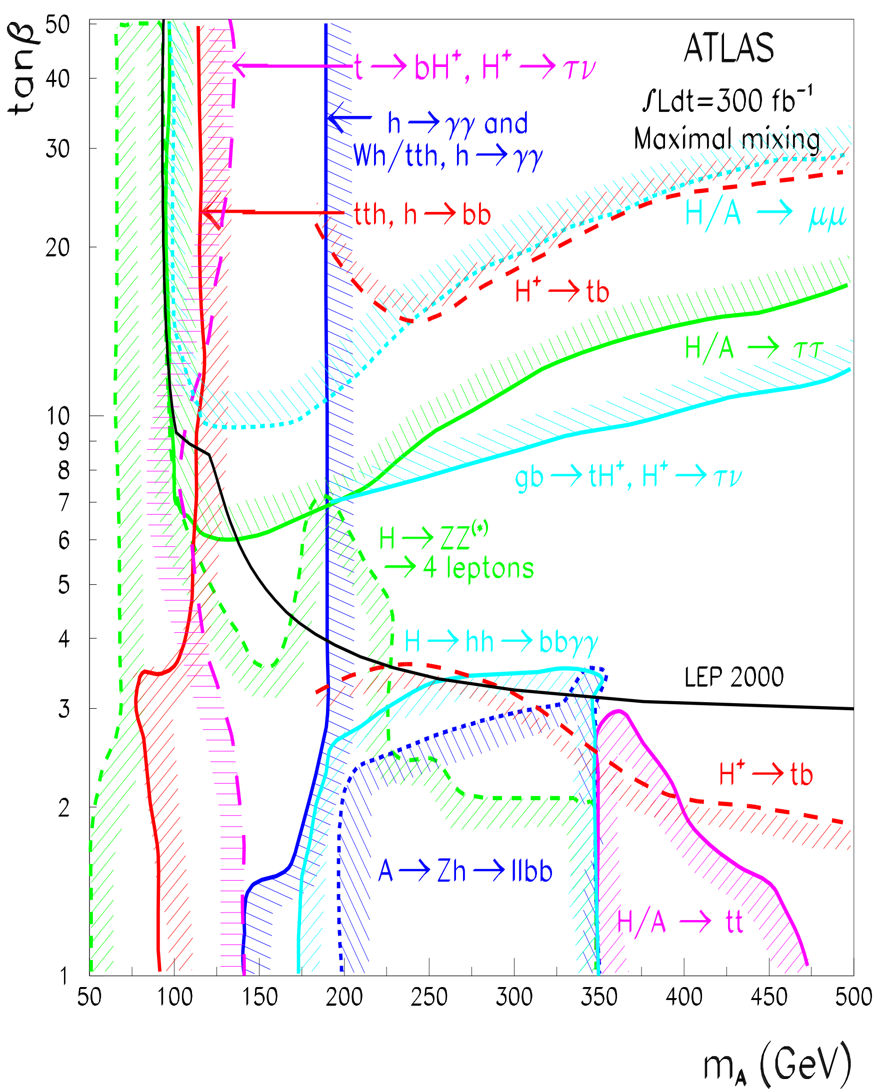
- **All work for CP–even h,H bosons.**
  - **in ΦV, $qq\Phi$ h/H complementary**
  - **additional mechanism: qq $\to$ A+h/H**
- **For $gg \to \Phi$ and $pp \to QQ\Phi$**
  - **include the contr. of b–quarks**
  - **dominant contr. at high tanβ!**
- **For pseudoscalar A boson:**
  - **CP: no ΦA and qqA processes**
  - **$gg \to A$ and $pp \to bbA$ dominant.**
- **For charged Higgs boson:**
  - **$M_H \lesssim m_t$: $pp \to t\bar{t}$ with $t \to H^+b$**
  - **$M_H \gtrsim m_t$: continuum $pp \to t\bar{b}H^-$**

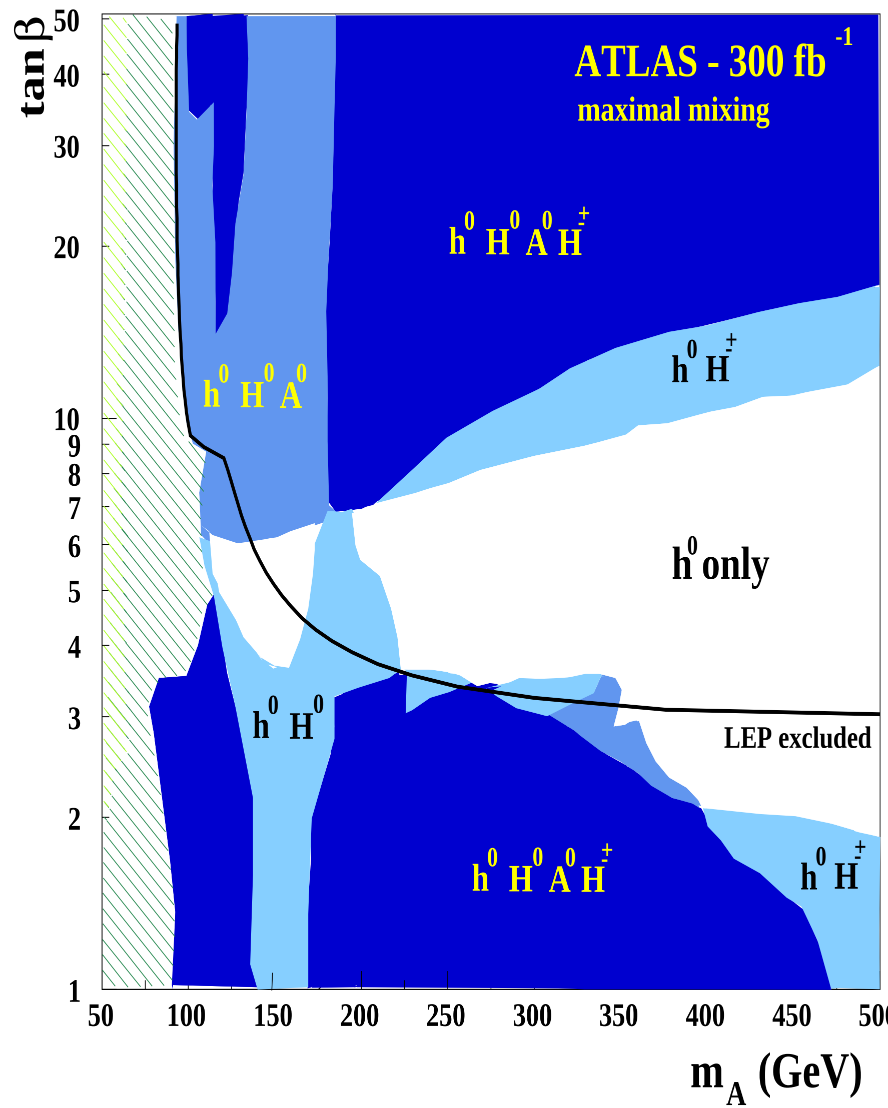
At high tanβ values:

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

3. MSSM Higgs at the LHC

Slightly outdated but still telling...





4. Measurement of Higgs properties

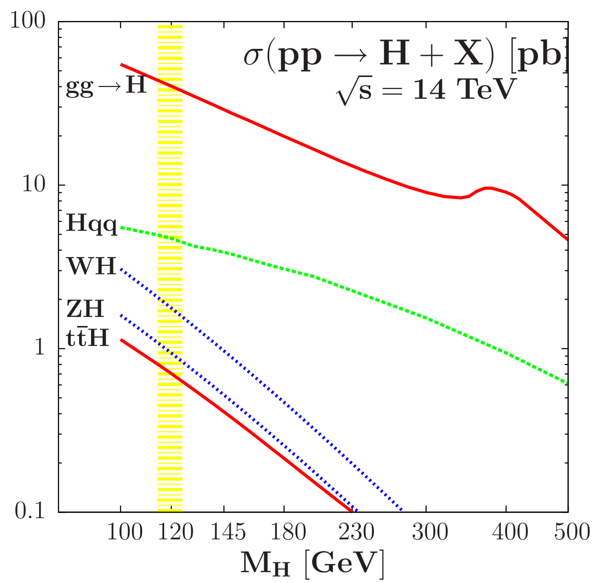
Once the Higgs is found (even if nothing else): would HEP be "closed"?

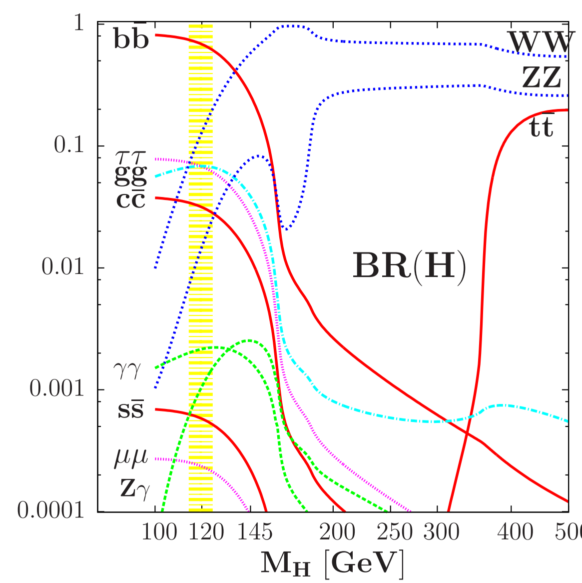
No! Need to check that H is indeed responsible of sEWSB (and SM-like?)

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 $M_H \approx$ 120–130 GeV as all production/decay channels useful!





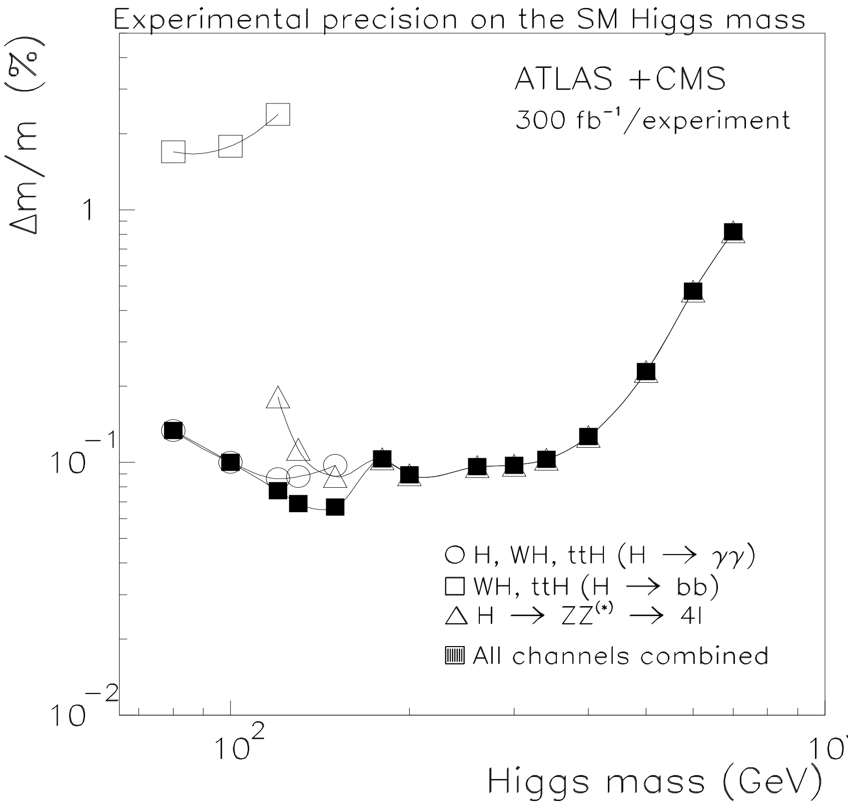
4. Higgs properties: mass and width

Higgs boson mass from:

– $H \to \gamma\gamma$ for $M_H \lesssim 130$ GeV

– $H \to ZZ \to 4\ell^{\pm}$ beyond

Final $\Delta M_H/M_H \sim 0.1\%$ to 1%.

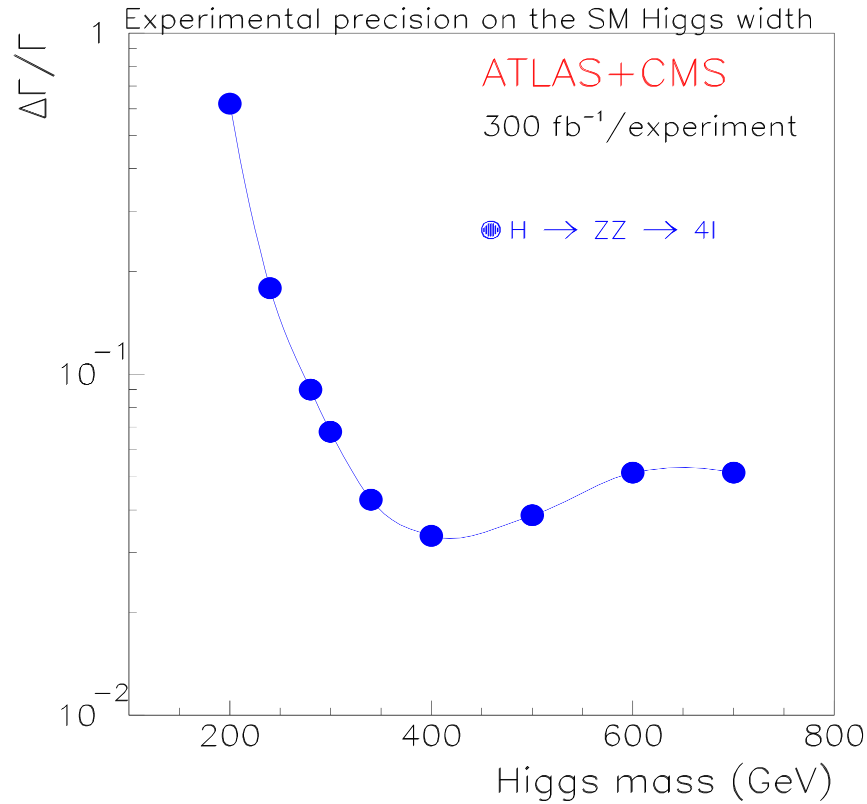


Higgs boson total width:

– Too small for $M_H \lesssim 2M_Z$

– $H \to ZZ \to 4\ell^{\pm}$ beyond

Final $\Delta\Gamma_H/\Gamma_H \sim$ a few %



Mass precisely measured but total width out of reach (invisible decays?)

4. Higgs properties: J^{PC} numbers

- **Higgs spin:**

$H \to \gamma\gamma$: rules out J=1 and fixes C=+.

– not generalizable to $H \leftrightarrow gg (g \approx q)$

– other possibility left, ex: J=2 (radion).

- **Higgs parity:**

– $H \to ZZ \to 4\ell^\pm$ rules out CP–odd.

– spin–correlations in $gg \to H \to WW^*$.

But need to check that H is pure CP–even

– challenging precision measurement,

– roughly doable in H$\to$VV$\to$ $4\ell^\pm$ correlations.

– also in $d\Gamma(H \to ZZ^*)/dM_*$

Drawback: If H is mostly CP–even,

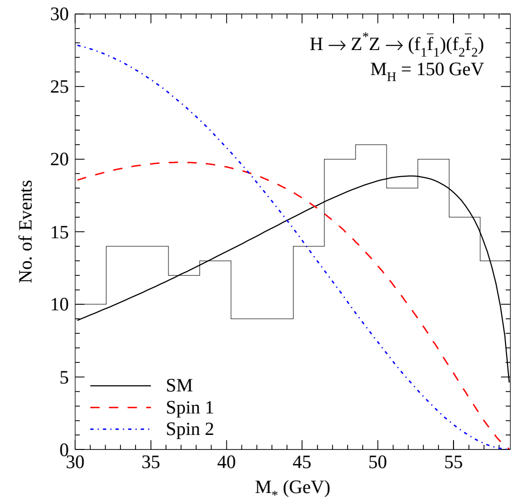
rates for $A \to VV$ are too small...

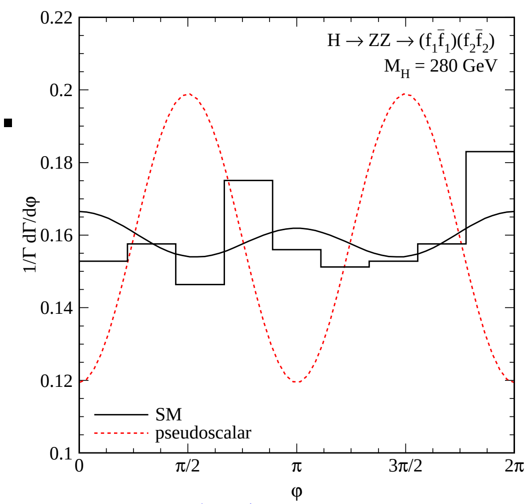
More convincing: look at Hff couplings

Possible but challenging channels:

$gg \to H \to \tau\tau$ or $pp \to t\bar{t}H \to ttbb$

$d\Gamma(H \to ZZ^*)/dM_*$@thresh





$d\Gamma(H \to ZZ)/d\phi$ azimuth

4. Higgs properties: Higgs couplings

● **Look at various H production/decay channels and measure $N_{ev} = \sigma \times BR$**

LHC with $\mathcal{L} = 300$fb^{-1} (more statistics?)

● **Large errors mainly due to:**

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

– theory: PDFs, HO/scale, model dep...

total error about 20–30% in $gg \to H$

contaminates also VBF/HZ (30%)...

$\Rightarrow$ ratios of $\sigma \times BR$: many errors drop out!

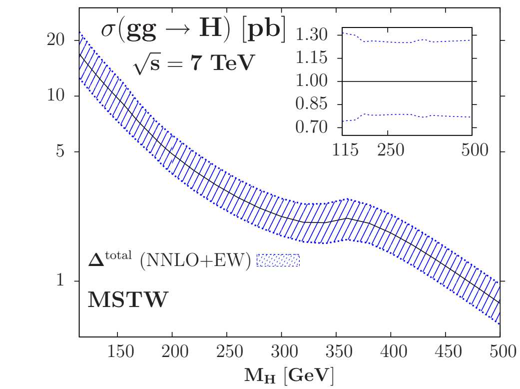
● **One obtains width ratios: Γ_X/Γ_Y**

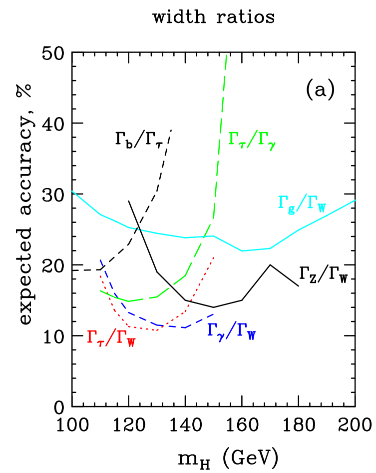
● **Theory assumptions (no invisible, SU(2) invariance, some couplings are known,..)**

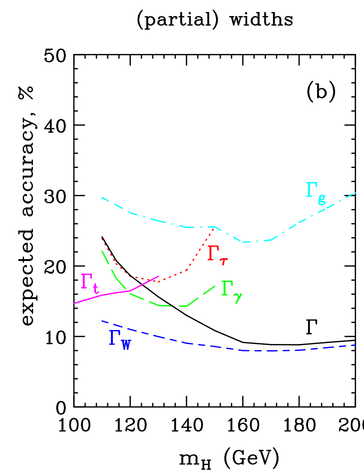
$\Rightarrow$ translate into $\Gamma_X \propto g^2_{HXX}$ with precision: $\Delta g_{HXX} = \frac{1}{2}\frac{(\Delta^{exp}\Gamma + \Delta^{th}\Gamma)}{\Gamma}$

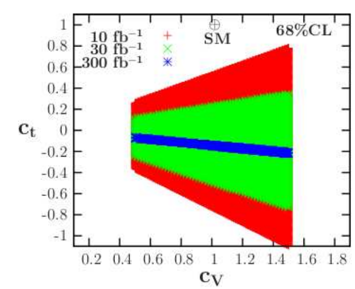
$\Rightarrow$ reasonable precision of order 10%

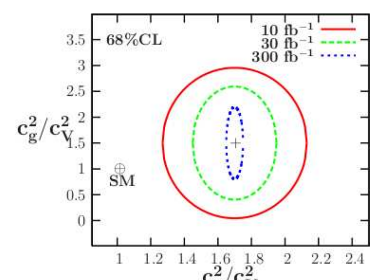
not bad... but is it really enough?











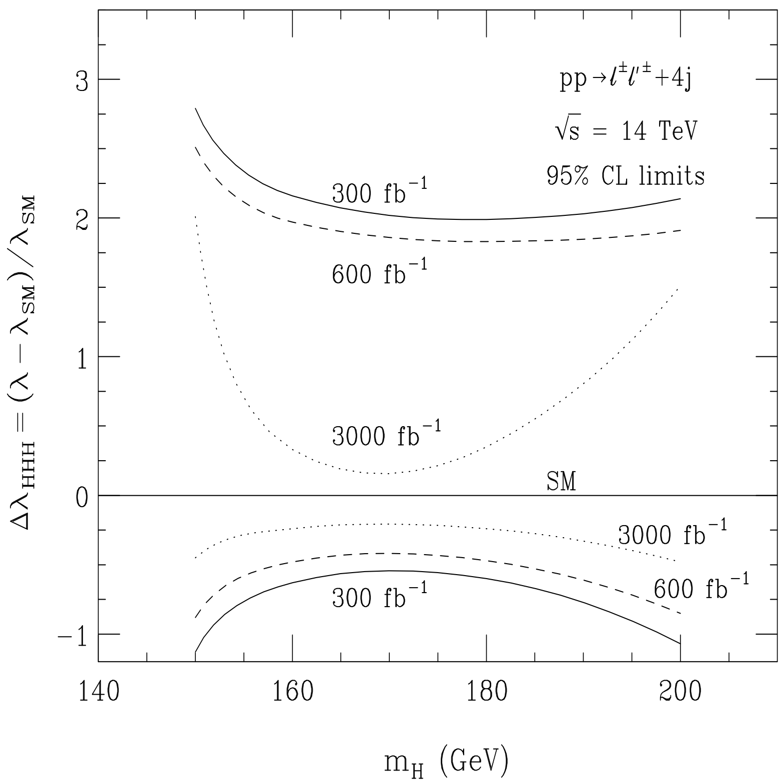
4. Higgs properties: Higgs self-couplings

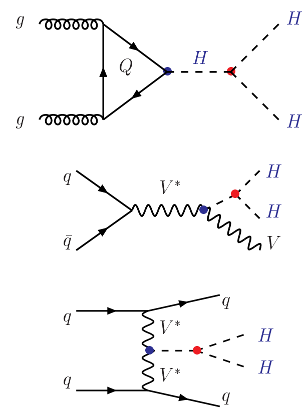
Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to V_H.

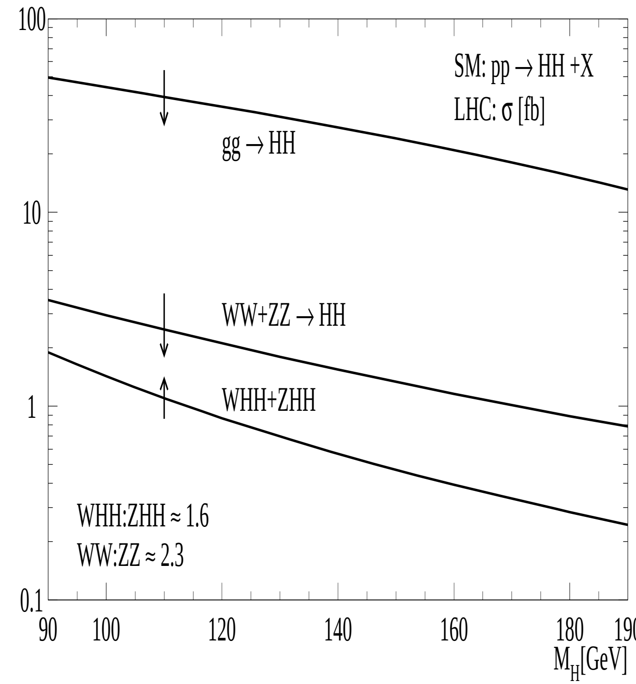
- g_{H^3} **from** $pp \to HH + X \Rightarrow$
- g_{H^4} **from pp→3H+X, hopeless.**

Relevant processes for HH prod:

only $gg \to HHX$ **relevant...**







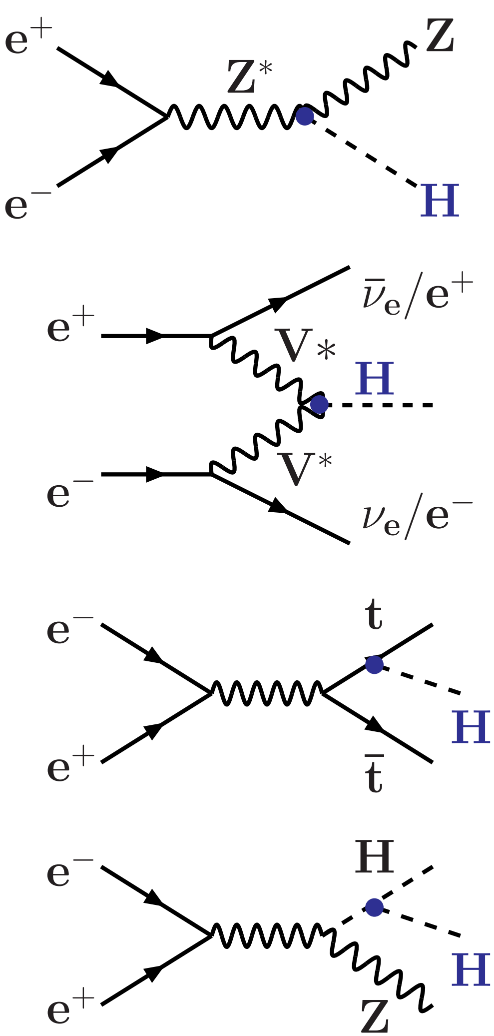
- $H \to \gamma\gamma$ **decay too rare,**
- $H \to b\bar{b}$ **decay not clean**
- $H \to WW$ **at low** M_H**?**

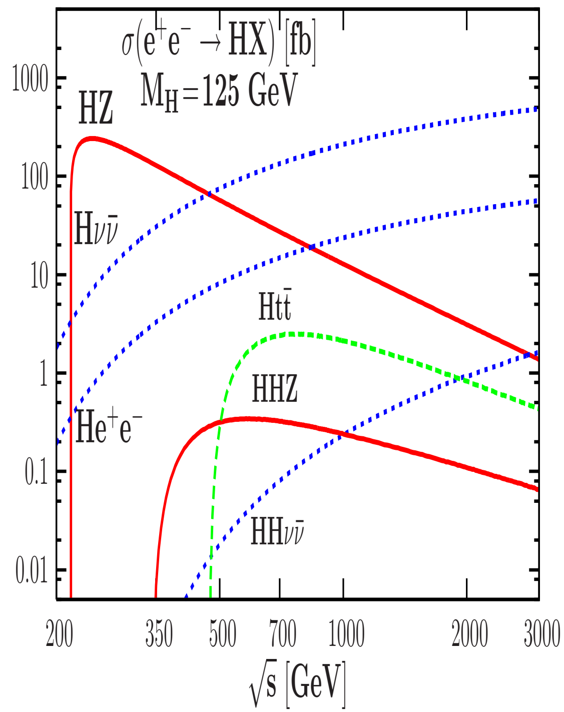
– parton level analysis...

– look for $2\ell^{\pm}, 3\ell^{\pm} + \nu$**+jets+**

– needs very large luminosity.

4. Higgs properties at the LC





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

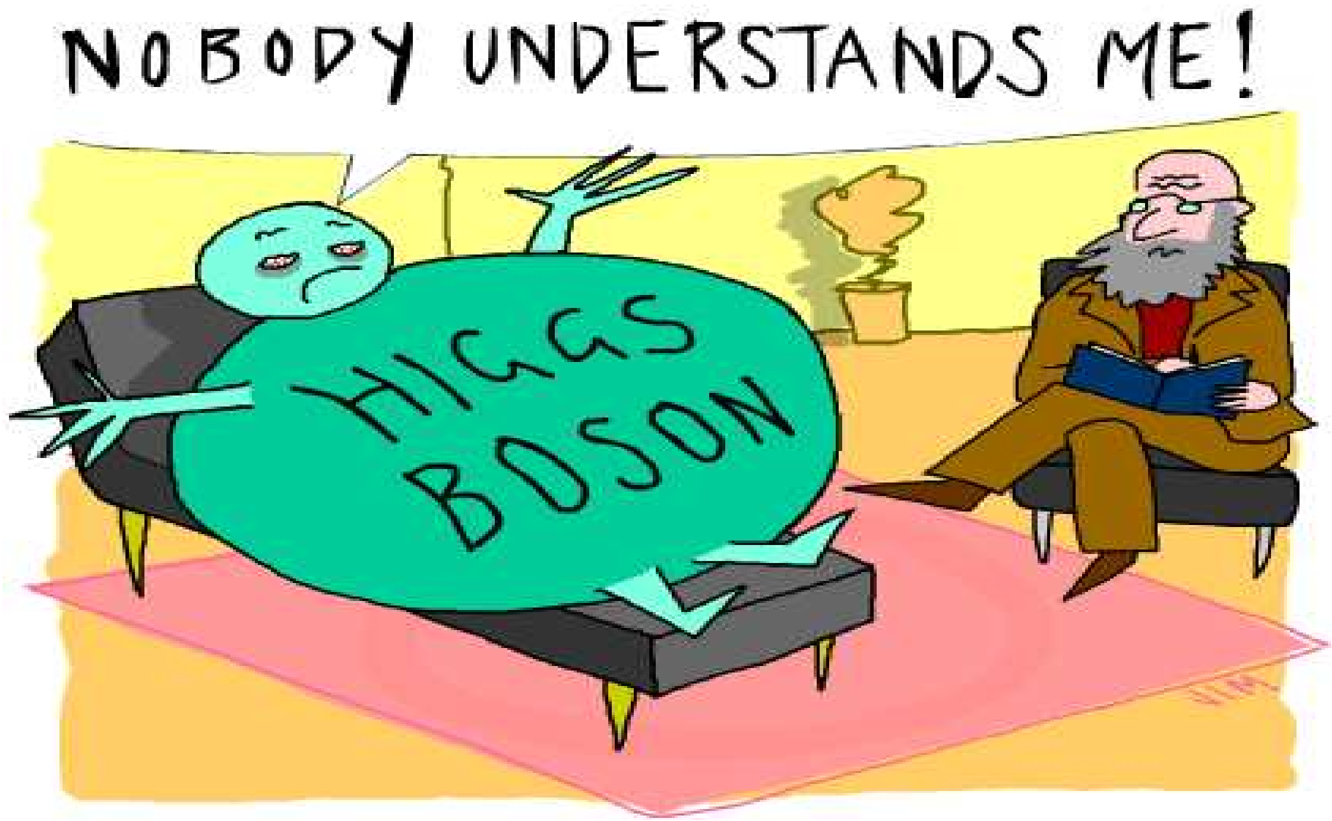
g_{HWW}	± 0.012
g_{HZZ}	± 0.012
g_{Hbb}	± 0.022
g_{Hcc}	± 0.037
$g_{H\tau\tau}$	± 0.033
g_{Htt}	± 0.030
λ_{HHH}	± 0.22
M_H	± 0.0004
Γ_H	± 0.061
CP	± 0.038

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

$\Rightarrow$ Miyamoto

5. Conclusion

So there is still a long way and a lot of work to do before we can claim that we have finally "understood the Higgs boson"...



and an e^+e^- Collider will be an essential instrument/step to get there...