

Theoretical aspects of Higgs physics

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- EWSB and the Higgs
- The standard Higgs at hadron colliders
- The Higgs sector in the MSSM
- Measurement of the Higgs
- Conclusion

1. EWSB and the Higgs

To generate particle masses in an $SU(2) \times U(1)$ gauge invariant way:
introduce a doublet of scalar fields $\Phi = (\Phi^+, \Phi^0)$ with $\langle 0 | \Phi^0 | 0 \rangle \neq 0$

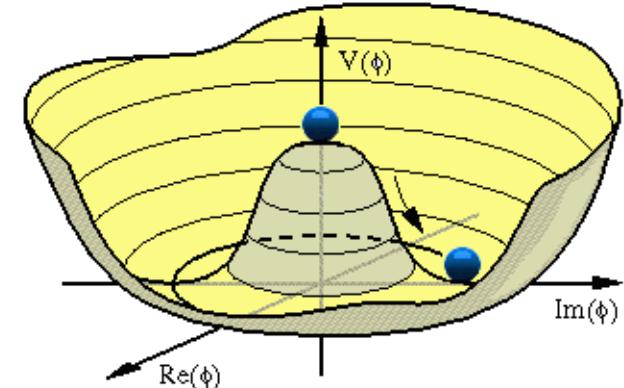
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

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

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

For fermion masses, use same Φ :

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



Residual dof corresponds to spin-0 H particle.

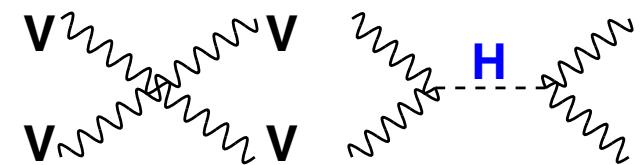
- The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers.
- Masses and self-couplings from V : $M_H^2 = 2\lambda v^2$, $g_{H^3} = 3 \frac{M_H^2}{M_V^2}$, ...
- Higgs couplings \propto particle masses: $g_{Hff} = \frac{m_f}{v}$, $g_{HVV} = 2 \frac{M_V}{v}$

The Higgs unitarizes the theory:

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

including H with couplings as predicted:

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



Once M_H known, all properties of the Higgs are fixed.

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 $\Lambda = M_{NP} \sim M_{Pl}$

$$\Delta M_H^2 \equiv - \text{H} \quad \text{---} \quad \begin{array}{c} f \\ \circlearrowleft \\ \circlearrowright \end{array} \quad \text{---} \quad \text{H} \quad \propto \Lambda^2 \approx (10^{18} \text{ GeV})^2$$

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 $M_h \lesssim 130 \text{ GeV}$ and $M_{H,H^\pm} \approx M_A \lesssim \text{TeV}$

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

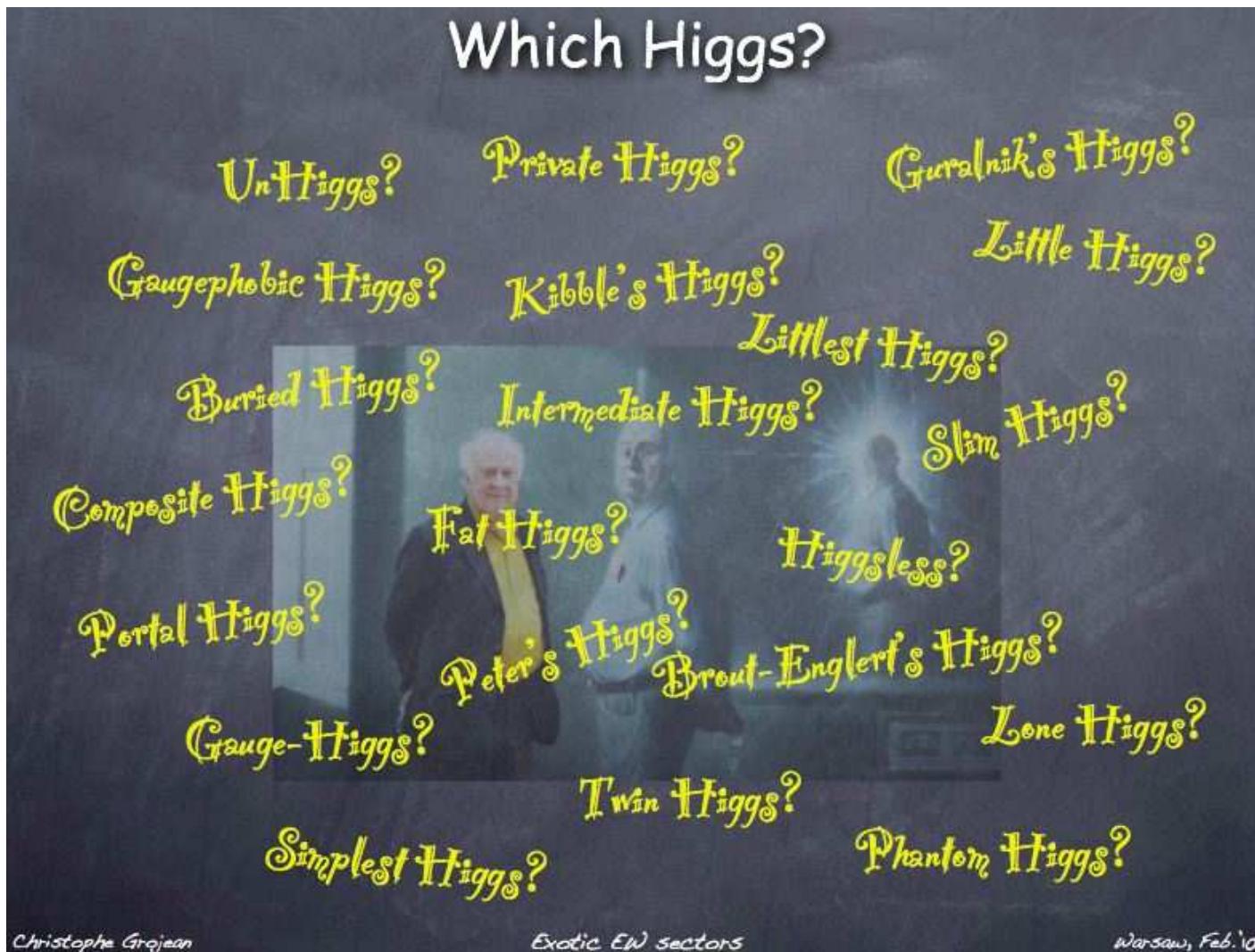
- in most cases: SM-like Higgs sector but properties possibly affected
- but in some cases, there might be no Higgs at all (Higgsless models)....

Strong interactions/compositeness: 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 colliders: decays

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

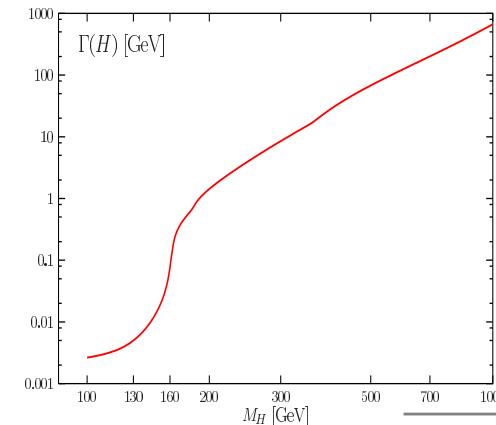
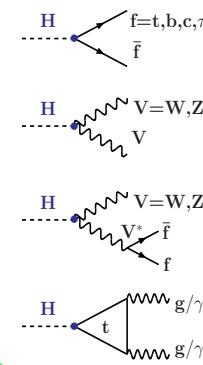
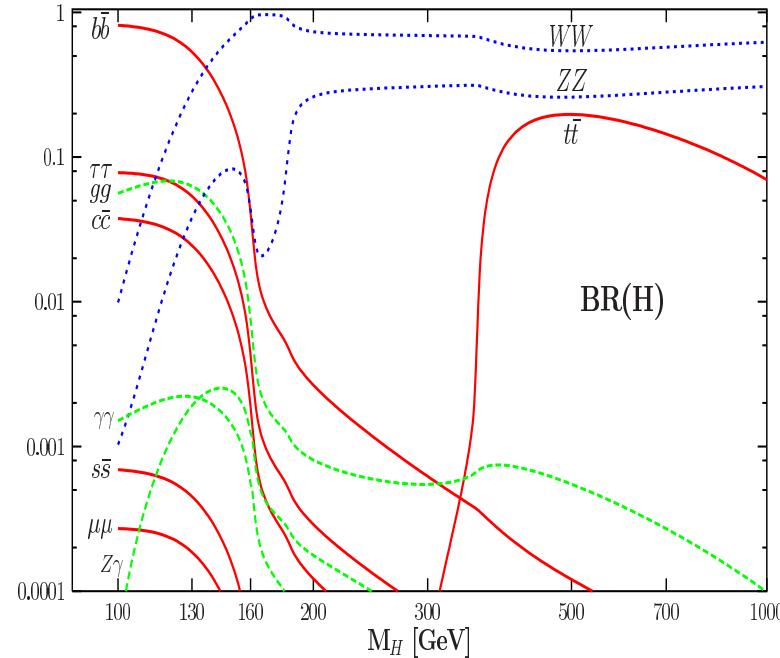
Once M_H known, all properties of the Higgs are fixed (modulo QCD).

First: Higgs decays in the SM

- As $g_{HPP} \propto m_P$, H will decay into heaviest particle phase-space allowed:

- $M_H \lesssim 130 \text{ GeV}$, $H \rightarrow b\bar{b}$
 - $H \rightarrow cc, \tau^+\tau^-, gg = \mathcal{O}(\text{few \%})$
 - $H \rightarrow \gamma\gamma, Z\gamma = \mathcal{O}(0.1\%)$
- $M_H \gtrsim 130 \text{ GeV}$, $H \rightarrow WW, ZZ$
 - 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

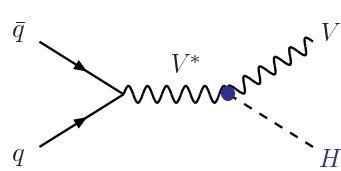
HDECAY \Rightarrow



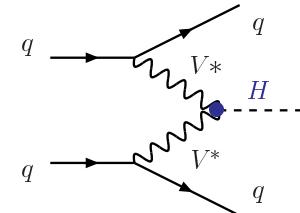
2. The standard Higgs at colliders: production

Main Higgs production channels

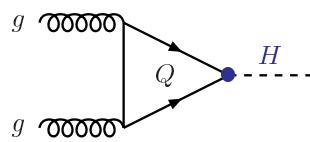
Higgs-strahlung



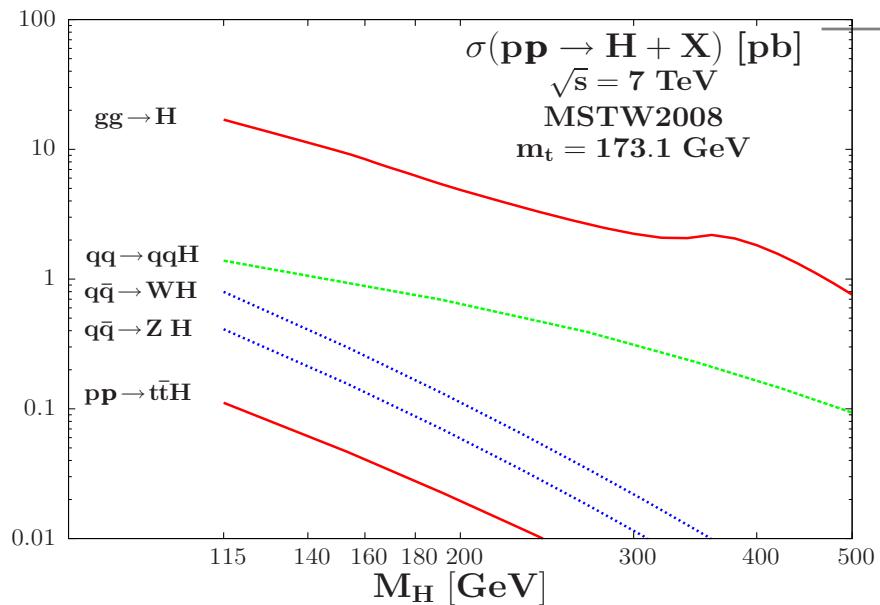
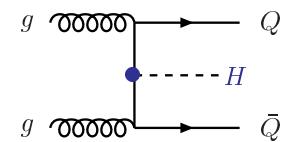
Vector boson fusion



gluon-gluon fusion



in association with $Q\bar{Q}$



Large production cross sections

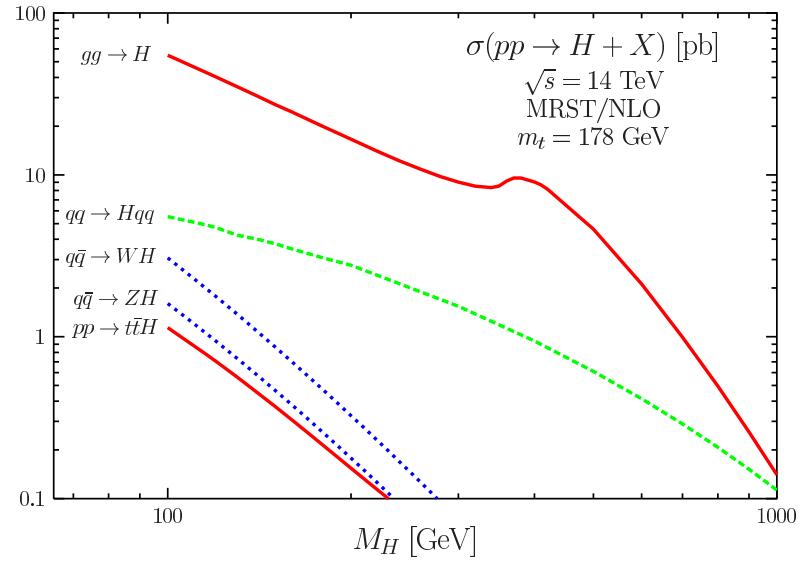
with $gg \rightarrow H$ by far dominant process

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

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

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

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

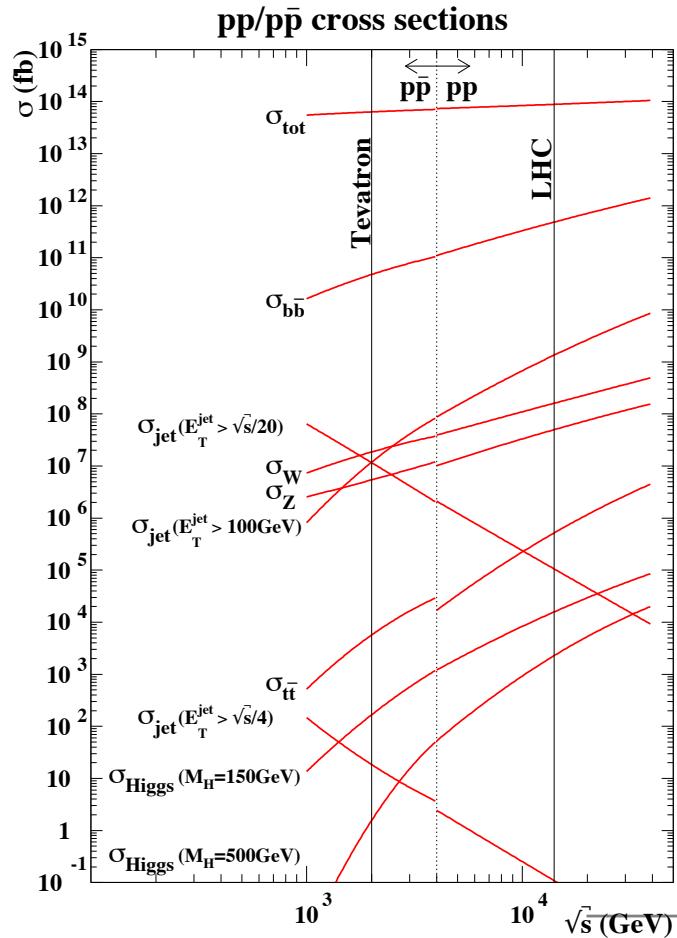
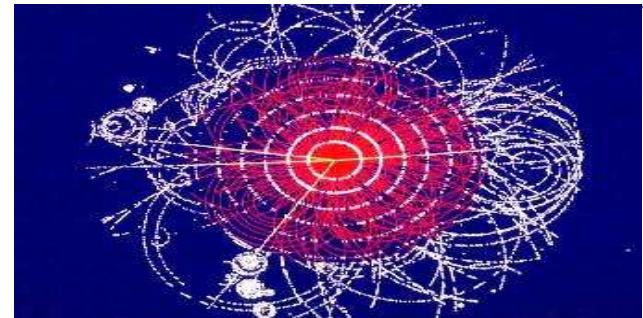


2. The standard Higgs at colliders: challenges

⇒ 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: $H \rightarrow \gamma\gamma, VV \rightarrow \ell$
 - 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 $gg \rightarrow H$ case



2. The standard Higgs at 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+EWⁱ: a few %

Distributions: two programs^j

^aGeorgi+Glashow+Machacek+Nanopoulos

^bSpira+Graudenz+Zerwas+AD (exact)

^cSpira+Zerwas+AD; Dawson (EFT)

^dHarlander+Kilgore, Anastasiou+Melnikov

Ravindran+Smith+van Neerven

^eCatani+de Florian+Grazzini+Nason

^fMoch+Vogt; Ahrens et al.

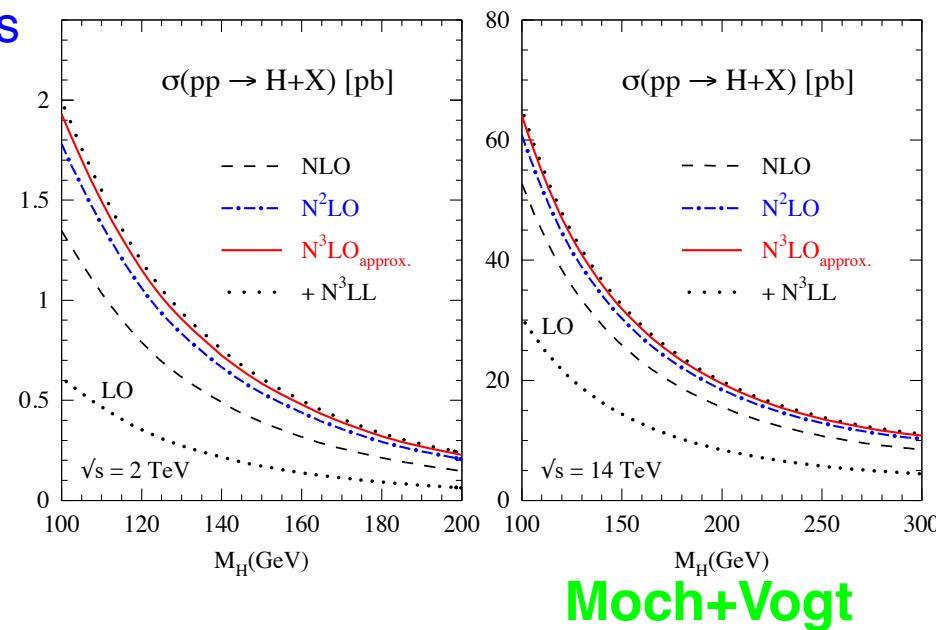
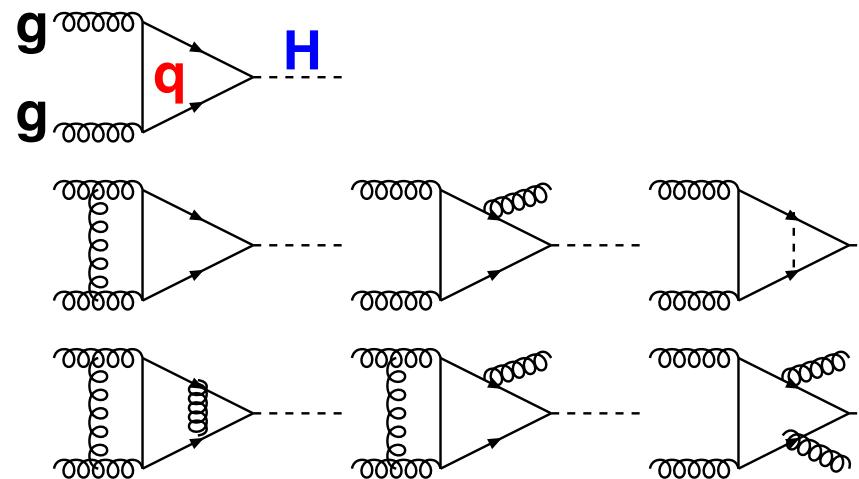
^gGambino+AD; Degrassi et al.

^hActis+Passarino+Sturm+Uccirati

ⁱAnastasiou+Boughezal+Pietriello

^jAnastasiou et al.; Grazzini

The $\sigma_{gg \rightarrow H}^{\text{theory}}$ long story (70s–now) ...



2. The standard Higgs at colliders: uncertainties

Despite of that, the $gg \rightarrow H$ 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 IHC: $\mu_0 = \frac{1}{2}M_H$, $\kappa = 2 \Rightarrow \Delta_{\text{scale}} \approx 10\%$

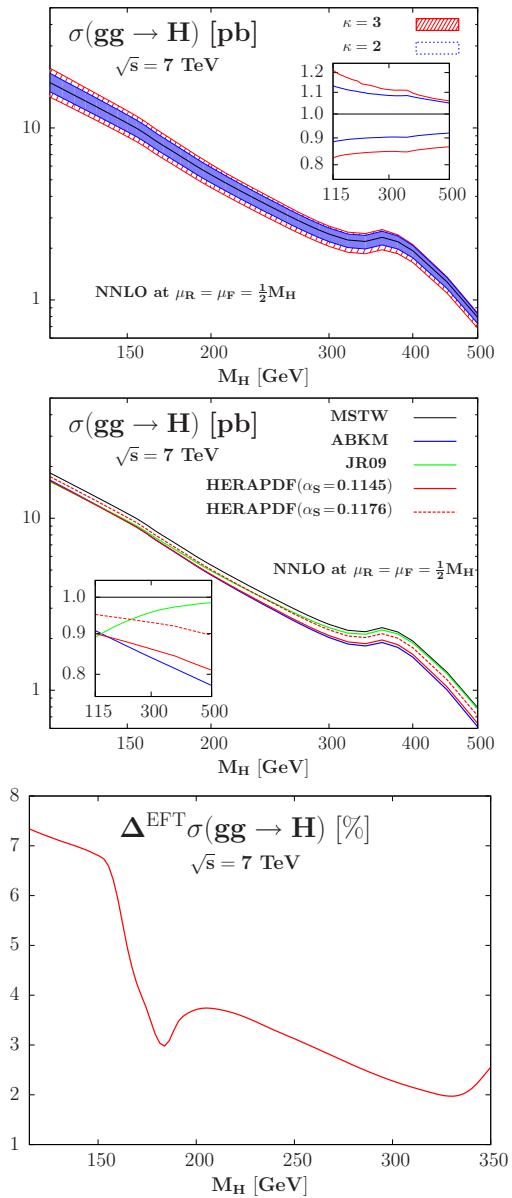
- gluon PDF+associated α_s uncertainties:
 gluon PDF at high-x less constrained by data
 α_s uncertainty (WA, DIS?) affects $\sigma \propto \alpha_s^2$
 \Rightarrow large discrepancy between NNLO PDFs
 PDF4LHC recommend: $\Delta_{\text{pdf}} \approx 10\% @ \text{IHC}$

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

- Include $\Delta \text{BR}(H \rightarrow X)$ of at most few %

total $\Delta \sigma_{gg \rightarrow H \rightarrow X}^{\text{NNLO}} \approx 15-20\% @ \text{IHC}$

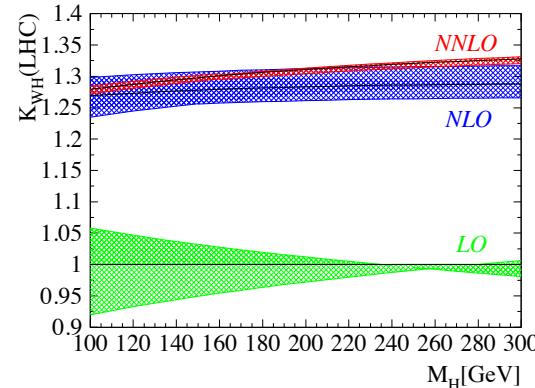
LHC-HxsWG; Baglio+AD \Rightarrow



2. The standard Higgs at colliders: other channels

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

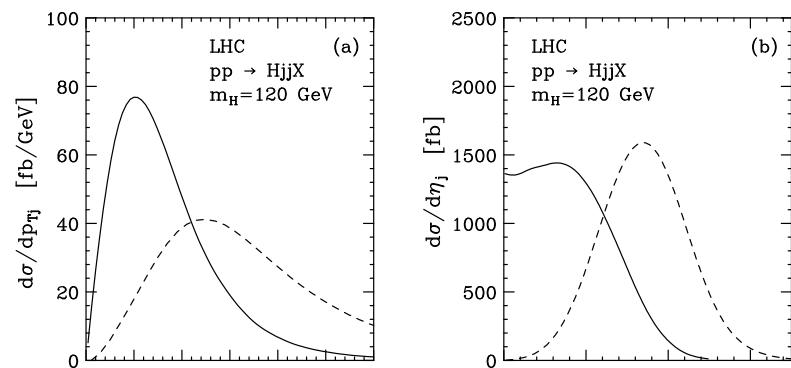
Brein, AD, Harlander \Rightarrow



- **vector boson fusion:** $qq \rightarrow Hqq$

- large cross section at high \sqrt{s}
- p_T^{high} forward jets, central jet veto, ..
- TH clean (small RC) but ggH contam.
- many H decay channels observable.

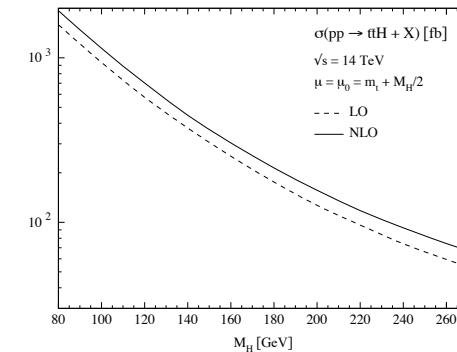
Zeppenfeld et al. \Rightarrow



- **Associated ttH production** $pp \rightarrow t\bar{t}H$

- complicated process but probes g_{Htt}
- small cross section but small RC too
- too large bkg for $H \rightarrow bb$; boosted jets?

Beenakker et al. \Rightarrow



2. The Higgs at the LHC: expectations vs life

Slide from pre-history: expectations

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

5 σ discovery for $M_H \approx 130\text{--}200\text{ GeV}$

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

$gg \rightarrow H \rightarrow \gamma\gamma$ ($M_H \lesssim 130\text{ GeV}$)

$gg \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\nu + 0, 1\text{ jets}$

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

$gg \rightarrow H \rightarrow \tau\tau + 0, 1\text{ jets}$

$q\bar{q} \rightarrow VH \rightarrow Vbb\bar{b}$

– at IHC with jet substructure

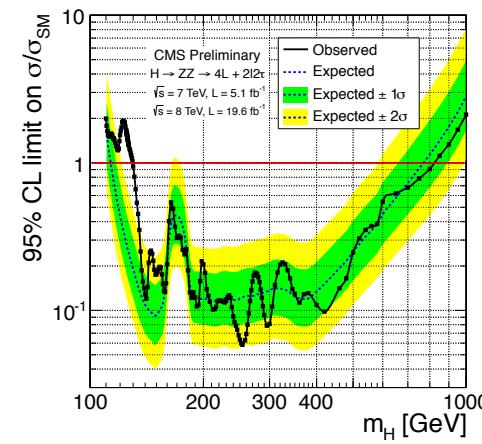
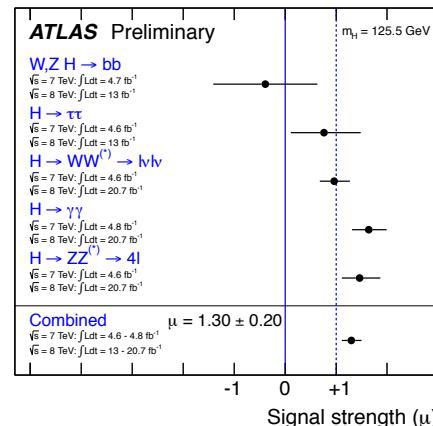
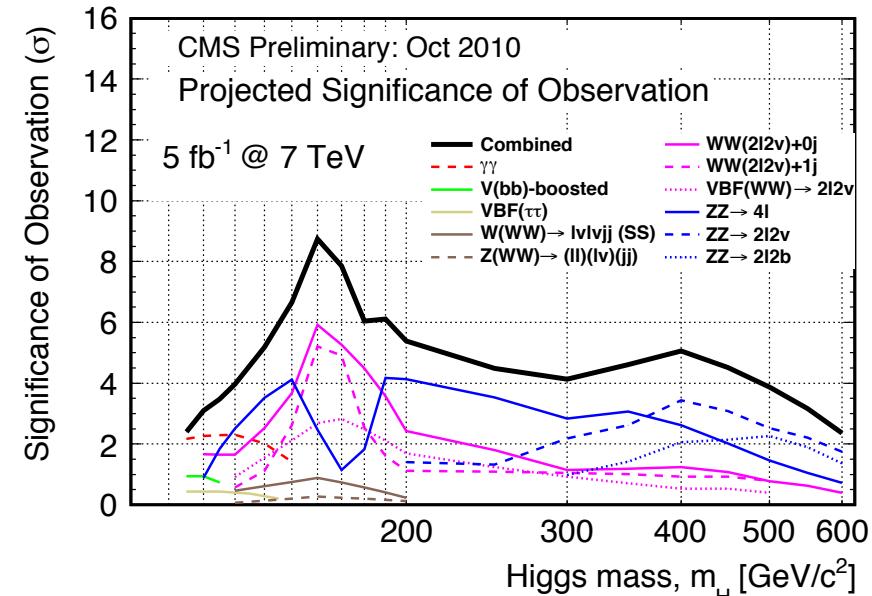
– also at Tevatron in $Wh \rightarrow \ell\nu b\bar{b}$

great help from VBF in many modes:

$qqH \rightarrow \tau\tau, \gamma\gamma, WW^*, ZZ^*$

Compare to the situation as by now:

Mission $(\frac{1}{2})$ accomplit!



3. MSSM Higgs at the LHC

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

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 tree-level: $\tan\beta, M_A$ but rad. cor. important

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

- Couplings of h, H to VV are suppressed; no AVV couplings (CP).
- For $\tan\beta \gg 1$: couplings to b (t) quarks enhanced (suppressed).

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

$$M_A \leq M_h^{\max} \Rightarrow h \equiv A, H \equiv H_{\text{SM}}, M_A \geq M_h^{\max} \Rightarrow H \equiv A, h \equiv H_{\text{SM}}$$

3. MSSM Higgs at the LHC

Higgs decays in the MSSM:

General features:

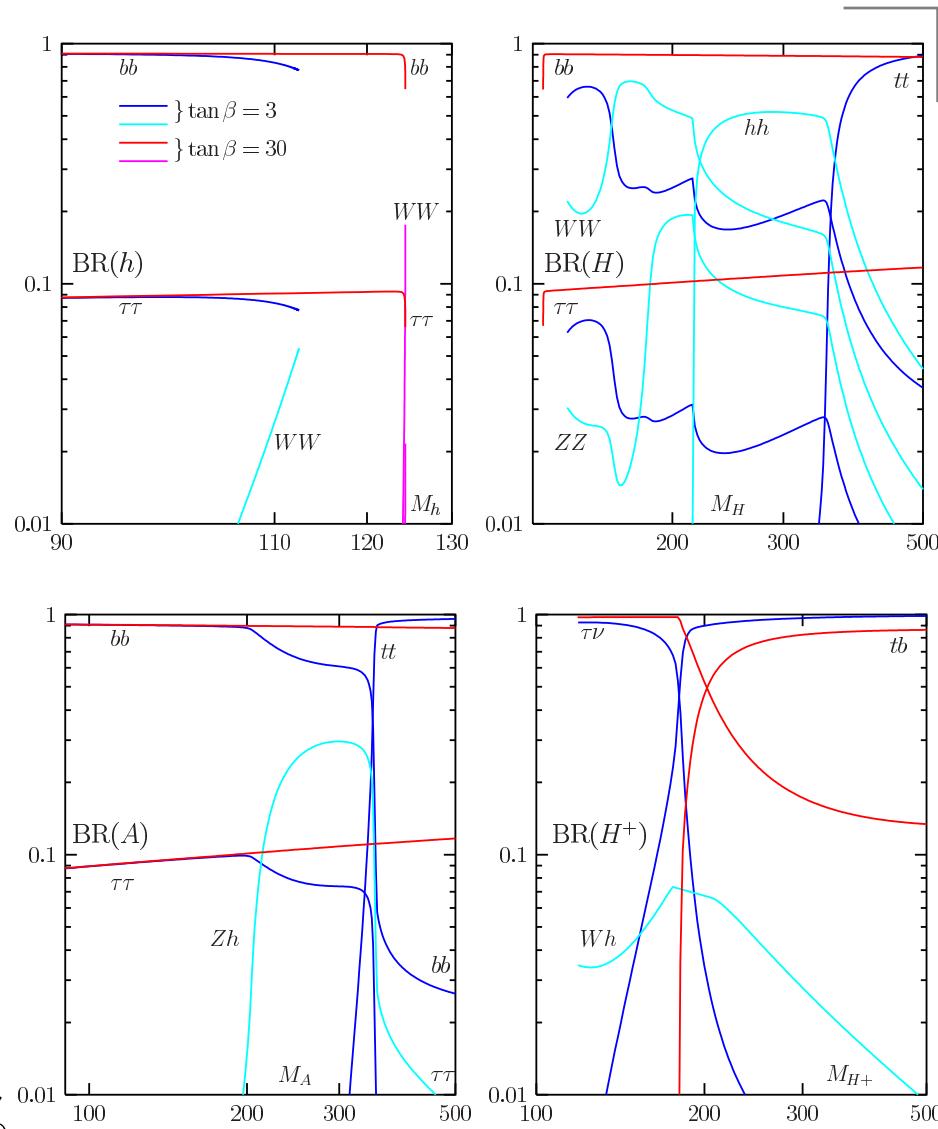
- h : same as H_{SM} in general
(esp. in decoupling limit) if not
 $h \rightarrow b\bar{b}, \tau^+\tau^-$ enhanced for $\tan\beta > 1$
- A : only $b\bar{b}, \tau^+\tau^-$ and $t\bar{t}$ decays
(no VV decays, hZ suppressed).
- H : same as A in general; $\tan\beta \gg 1$
 WW, ZZ, hh decays suppressed.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

Possible new effects from SUSY!!

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

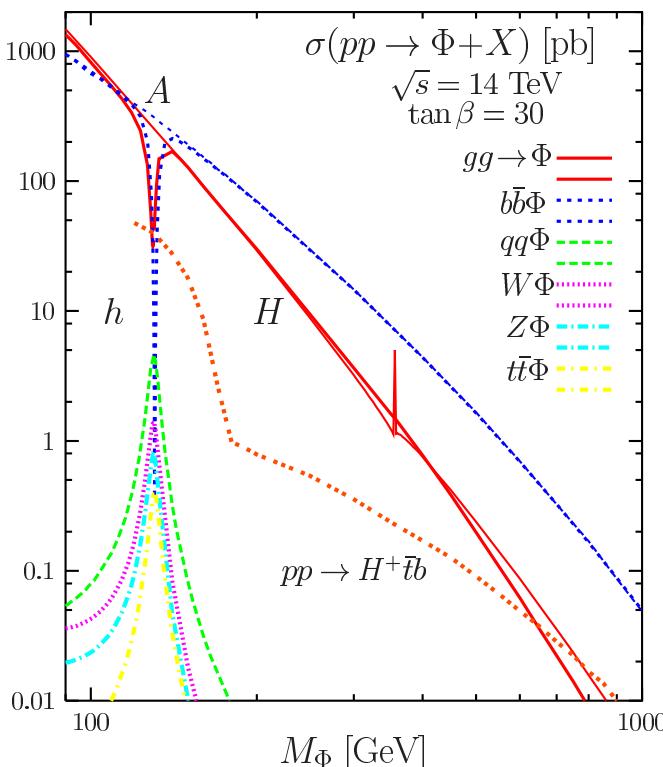
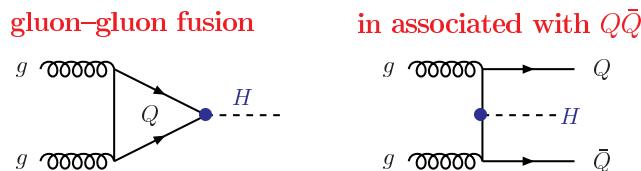
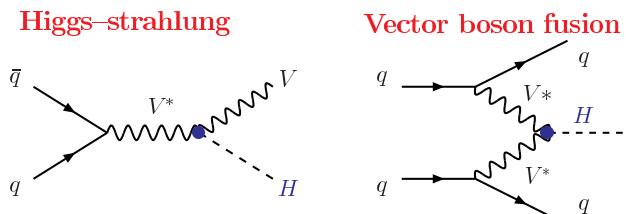
BR: $\Phi \rightarrow b\bar{b} \approx 90\%$, $\Phi \rightarrow \tau\tau \approx 10\%$

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



3. MSSM Higgs at the LHC

SM production mechanisms



LHC–Fr. Annecy, 04/04/2013

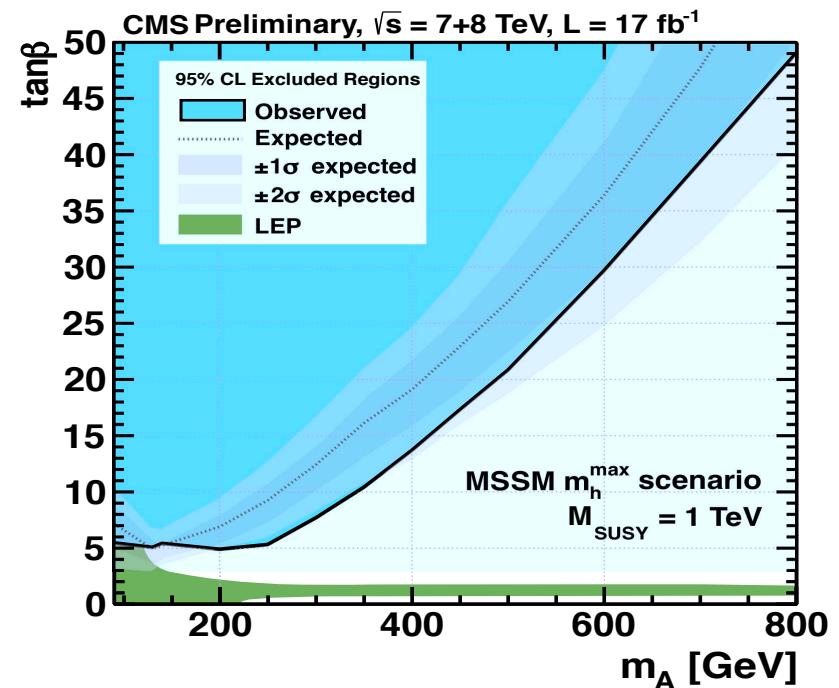
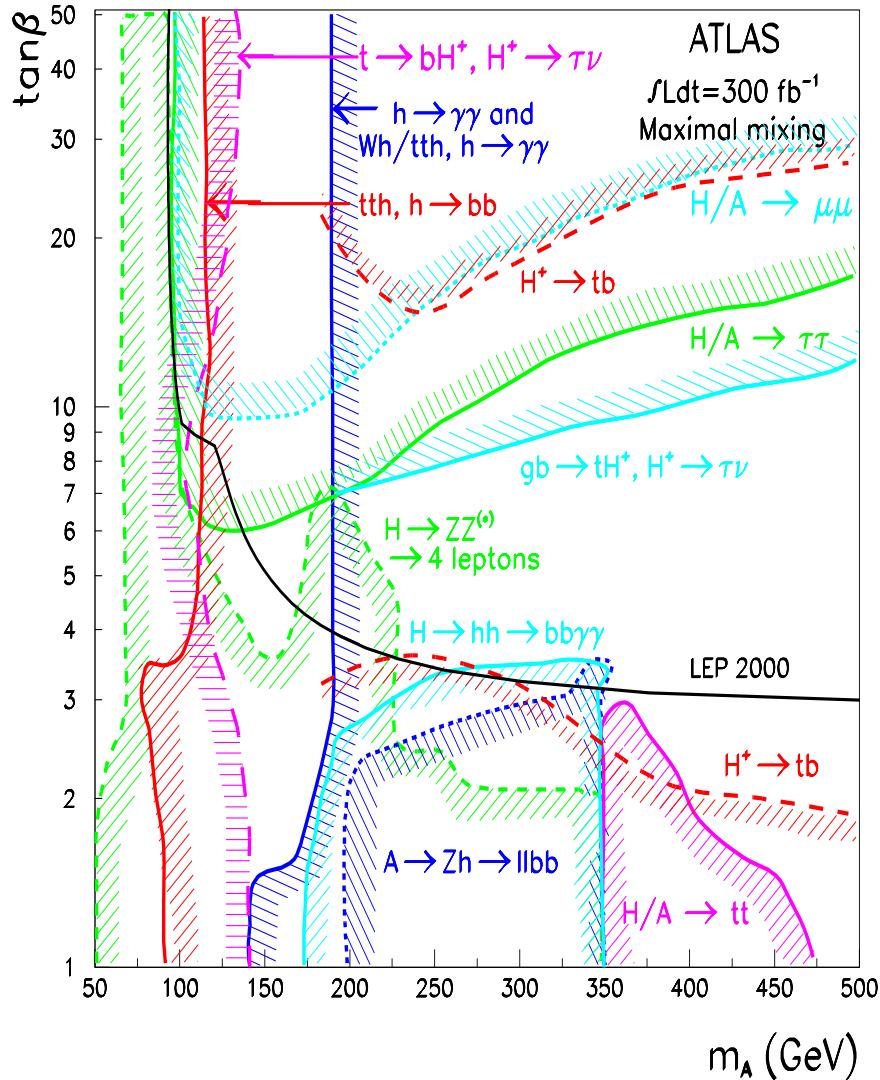
What is different in MSSM

- All work for CP-even h, H bosons.
 - in ΦV , $q\bar{q}\Phi$ h/H complementary
 - additional mechanism: $q\bar{q} \rightarrow A+h/H$
 - For $gg \rightarrow \Phi$ and $pp \rightarrow QQ\Phi$
 - include the contr. of b-quarks
 - dominant contr. at high $\tan\beta$!
 - For pseudoscalar A boson:
 - CP: no ΦA and $q\bar{q}A$ processes
 - $gg \rightarrow A$ and $pp \rightarrow b\bar{b}A$ dominant.
 - For charged Higgs boson:
 - $M_H \lesssim m_t$: $pp \rightarrow t\bar{t}$ with $t \rightarrow H^+ b$
 - $M_H \gtrsim m_t$: continuum $pp \rightarrow t\bar{b}H^-$
- At high $\tan\beta$ values:
- h as in SM with $M_h = 115 - 130 \text{ GeV}$
 - dominant channel: $gg, b\bar{b} \rightarrow \Phi \rightarrow \tau\tau$

3. MSSM Higgs at the LHC

Avant...

... Après..



4. Measurement of Higgs properties

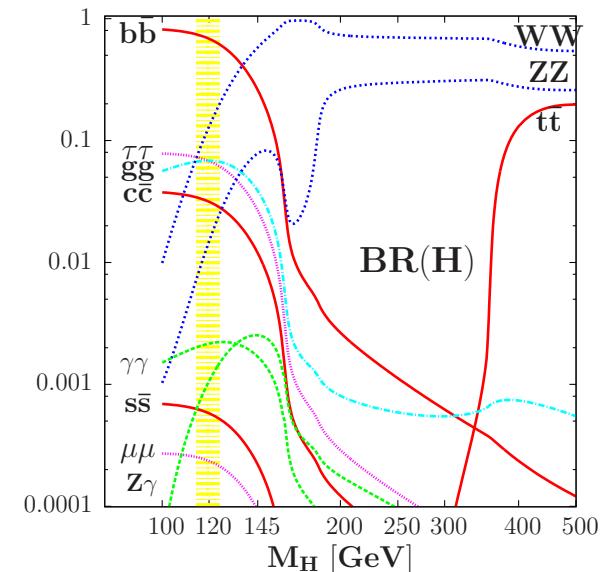
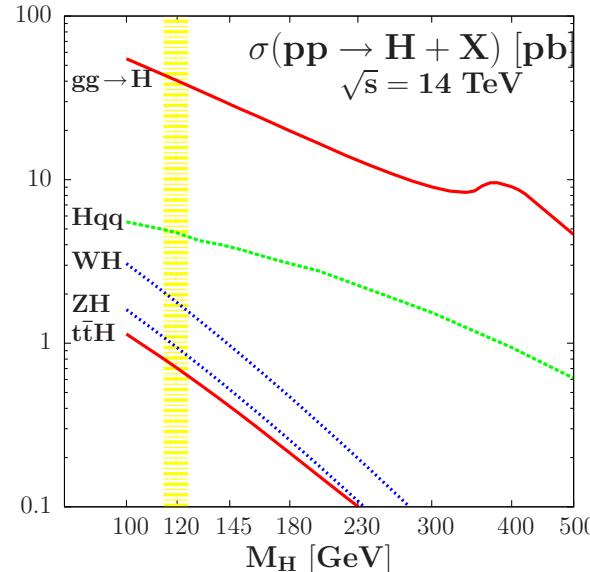
Now that the Higgs is found (nothing else yet): would HEP be “closed”?

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 $M_H \approx 120\text{--}130 \text{ GeV}$ as all production/decay channels useful!



4. Higgs properties: J^{PC}

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

- not spin-1: Landau–Yang
- could be spin-2 like graviton?
 - miracle that couplings fit that of H,
 - “prima facie” evidence against it:

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

many th. analyses (no suspense).

CP: is it CP-even or CP-odd?

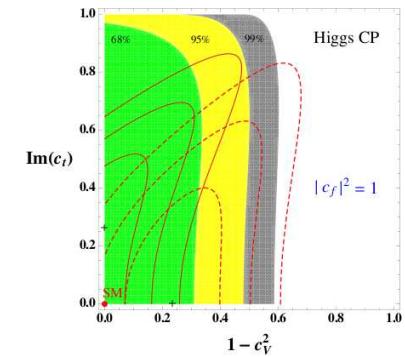
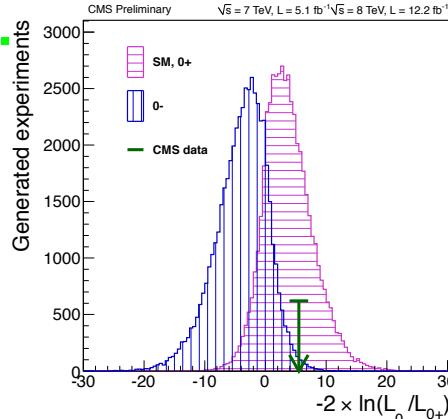
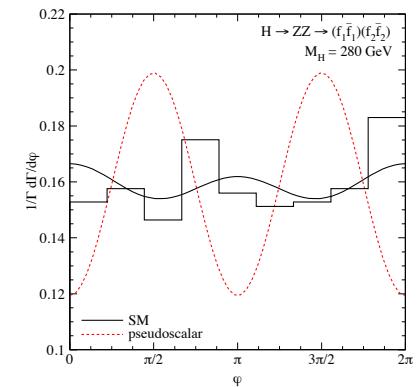
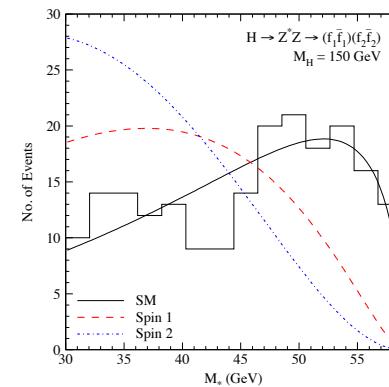
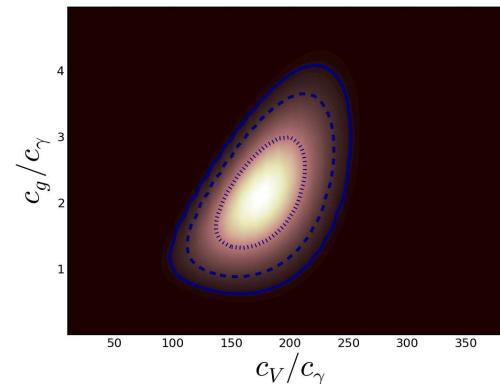
$$HV_\mu V^\mu \text{ vs } H\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma}$$

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

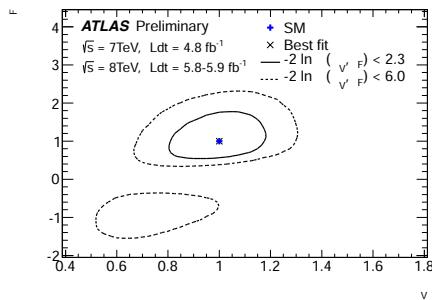
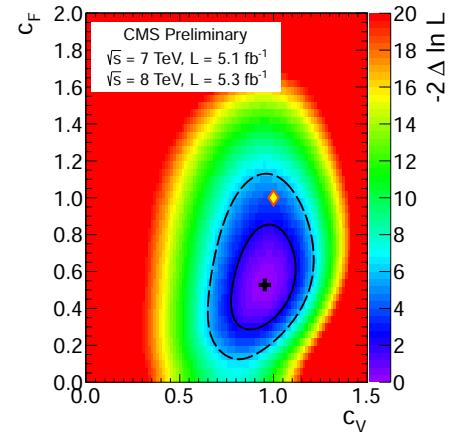
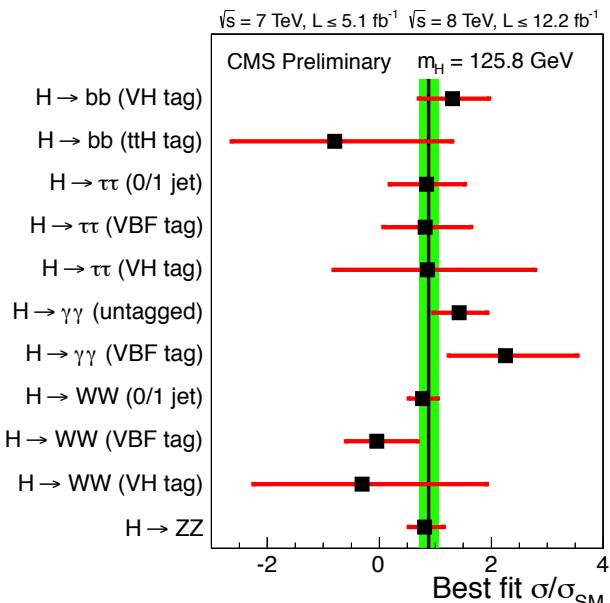
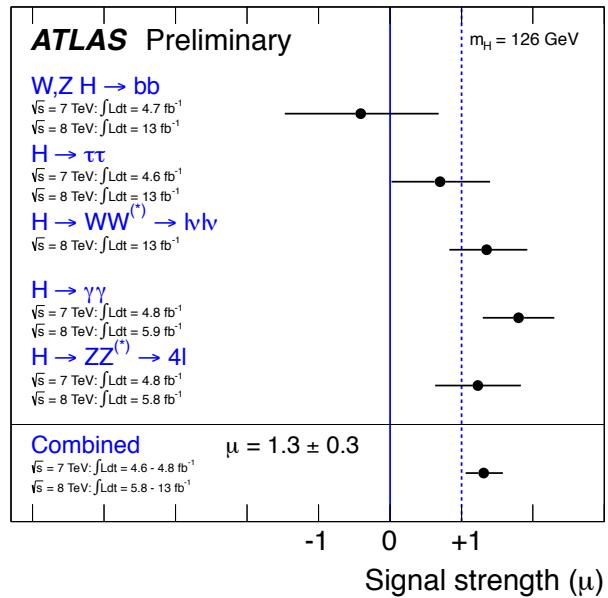
ATLAS/CMS: $\approx 3\sigma$ for CP-even.

Problem: if H is CP mixture, only 0^+ component is projected out!
(or very large 0^- VV loop cplg).

\Rightarrow better probe: $\hat{\mu}_{ZZ} = 1.1 \pm 0.4$!



4. Higgs properties: is it a Higgs?



From ATLAS/CMS results:

Higgs couplings to elementary particles as predicted by Higgs mechanism

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

So, it is not only a “new particle”, the “126 GeV boson”, a “new state”...

IT IS A HIGGS BOSON!

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

To check this you need very precise measurements to see small deviations...

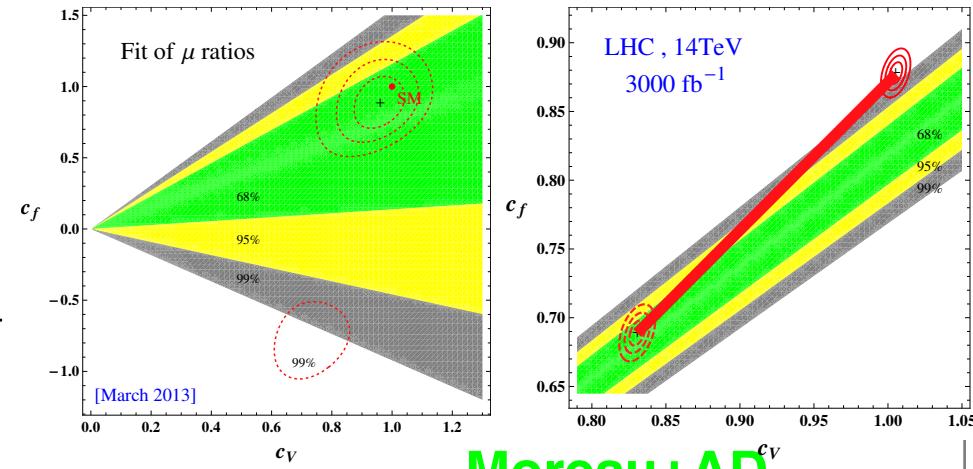
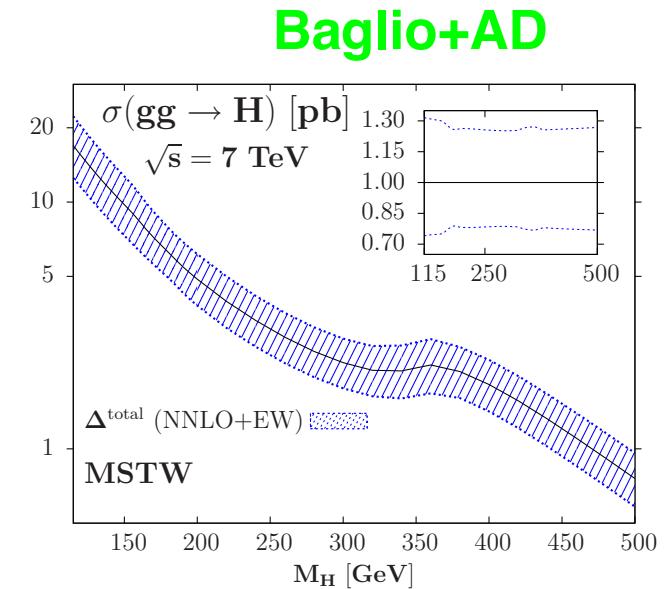
4. Higgs properties: Higgs couplings

- Look at various H production/decay channels and measure $N_{\text{ev}} = \sigma \times \text{BR}$
- But large errors mainly due to:
 - experimental: stats, system., lumi...
 - theory: PDFs, HO/scale, jetology...
 total error about 20–30% in $\text{gg} \rightarrow \text{H}$
 Hjj contaminates VBF (now 30%)..
 ⇒ ratios of $\sigma \times \text{BR}$: many errors out!

Deal with width ratios Γ_X/Γ_Y

- TH on σ and some EX errors
- parametric errors in BRs
- TH ambiguities from Γ_H^{tot}
- Achievable accuracy:
 - now: 20–30% on $\gamma\gamma/\text{VV}, \tau\tau/\text{VV}$
 - future: few % at HL-LHC!

Sufficient to probe BSM physics?



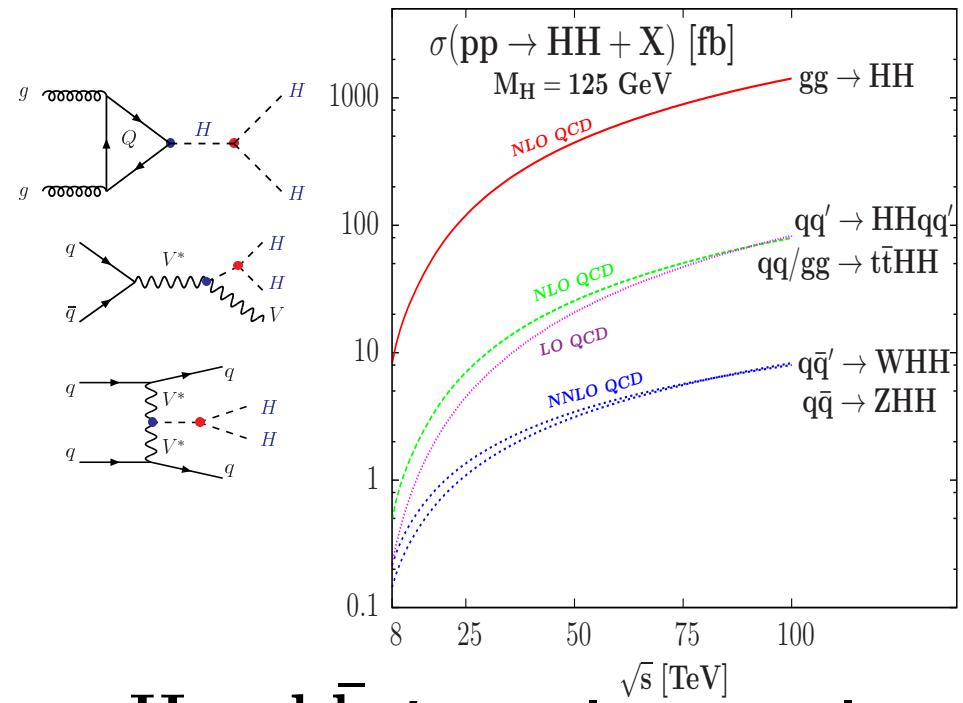
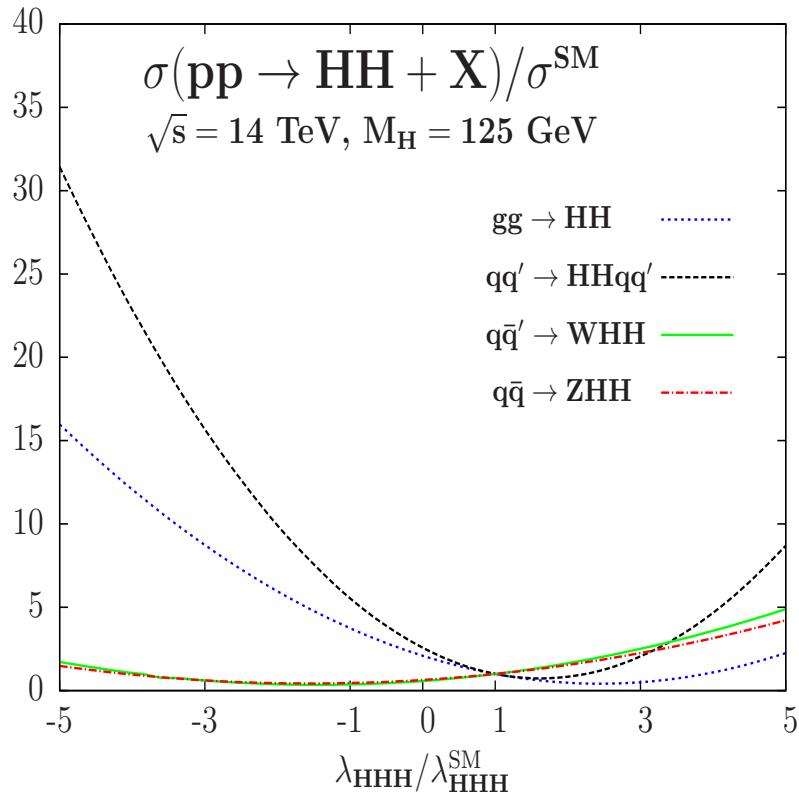
4. Higgs properties: Higgs self-couplings

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

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

Relevant processes for HH prod:

only $gg \rightarrow HHX$ relevant...



- $H \rightarrow b\bar{b}$ decay alone not clean
- $H \rightarrow \gamma\gamma$ decay very rare,
- $H \rightarrow \tau\tau$ would be possible?
- $H \rightarrow WW$ not useful?
 - $b\bar{b}\tau\tau, b\bar{b}\gamma\gamma$ viable?
 - but needs¹ very large luminosity.

5. Conclusion



Now, this is not the end.

It is not even the beginning to the end.

But it is, perhaps, the end of the beginning.

Sir Winston Churchill, November 1942

We hope that **at the end** we finally understand the EWSB mechanism, but there is a long way until then.... and there might be many surprises!

Nobody understands me!

