Higgs Physics:
status and perspectives.

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1. The Higgs in the Standard Model
2. Higgs decays
3. The Higgs at the Tevatron: predictions and uncertainties
4. The Higgs at the LHC
5. Conclusion

1. The Higgs in the SM: EWSB

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

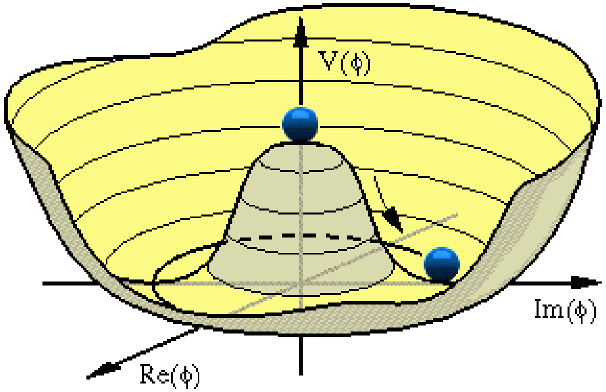
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

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

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

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

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



The residual degree corresponds to the spin–zero Higgs particle, H.

- **The 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:** $g_{Hff} = \frac{m_f}{v},\ g_{HVV} = 2\frac{M_V^2}{v}$

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

1. The Higgs in the SM: constraints on M_H

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

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

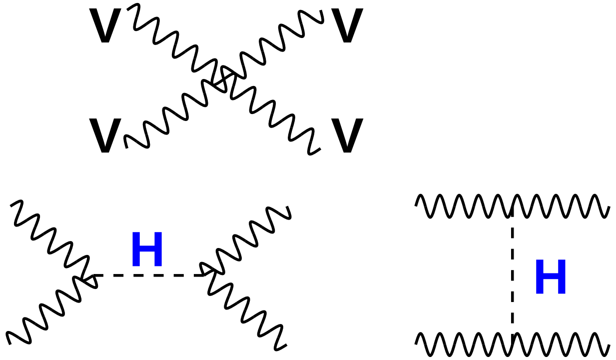
$$|A_0(VV \to VV)| \xrightarrow{s \gg M_H^2} \frac{M_H^2}{8\pi v^2} < \frac{1}{2}$$

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

(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:**

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

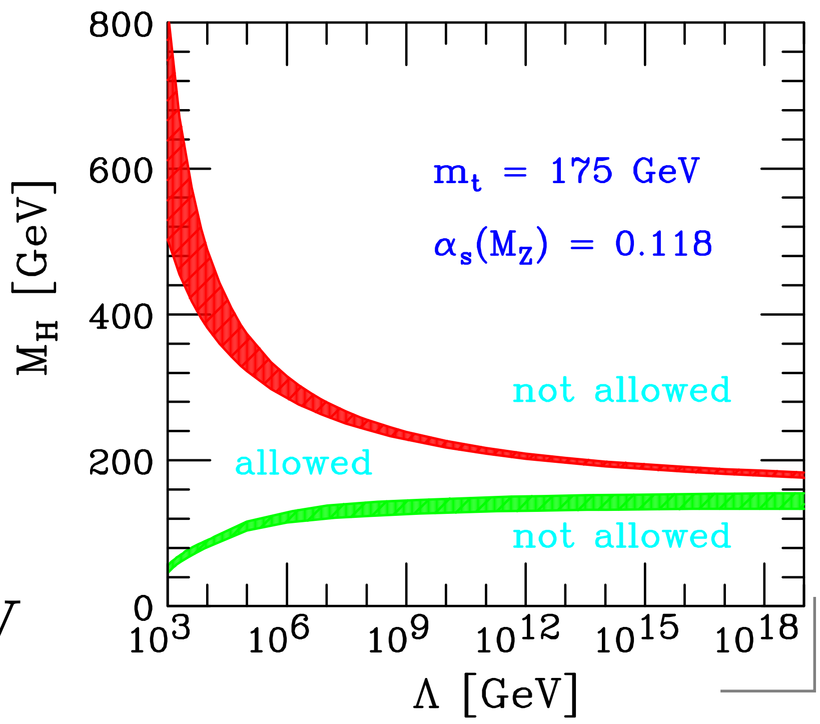
$\lambda \gg 1$ coupling blows up (Landau pole)

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

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

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

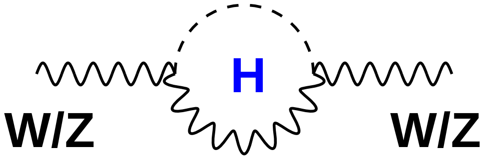
Hambye+Riesselman



1. The Higgs in the SM: constraints on $\mathrm{M_H}$

Indirect constraints from high–precision data

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

one obtains $\mathrm{M_H} = 87^{+35}_{-26}$ GeV, or

$\mathrm{M_H} \lesssim 157$ GeV at 95% CL

New Gfitter: $\mathrm{M_H} \lesssim 153$ GeV@95%CL

?What top mass should be in the fit?

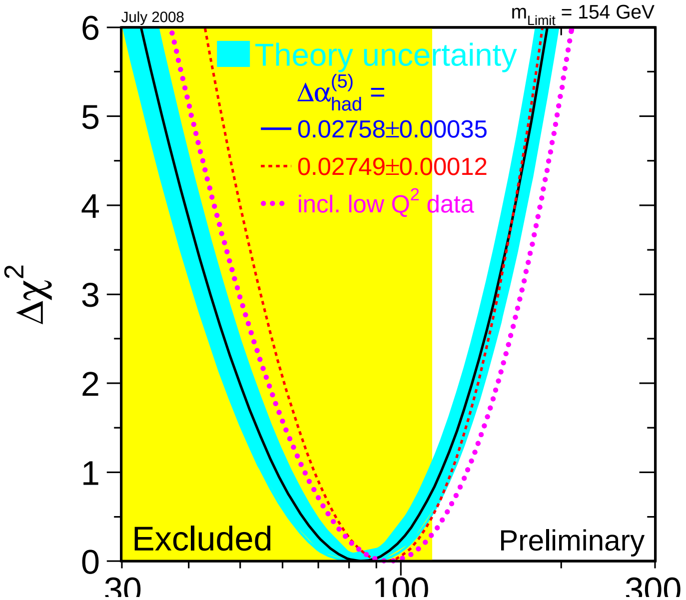
High precision data: on–shell mass

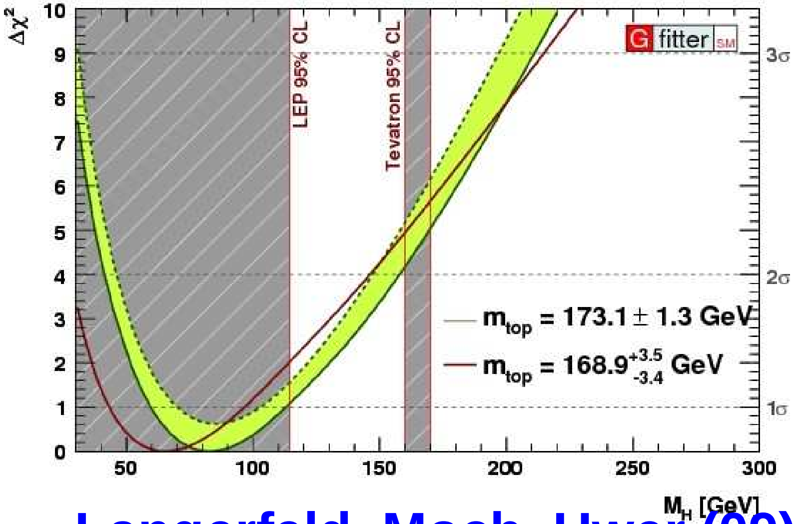
Tevatron: OS, $\overline{\mathrm{MS}}$ mass? 10 GeV diff.

$$\mathrm{m_t^{OS}} = \mathrm{m_t^{\overline{MS}}}(\mu)\left(1 - \frac{\alpha_s}{\pi}\left[\frac{4}{3} + \log\frac{\mu^2}{\mathrm{m_t^2}} + ..\right]\right)$$

$\overline{\mathrm{MS}}$ top mass from NNLO $\sigma(\mathrm{p\bar{p}} \to \mathrm{t\bar{t}})$

convert to $\mathrm{m_t^{pole}} \approx 169 \pm 3.5$ GeV





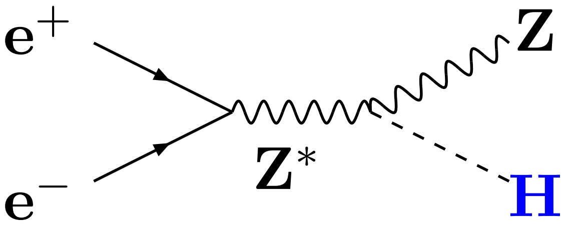
Langerfeld, Moch, Uwer (09).

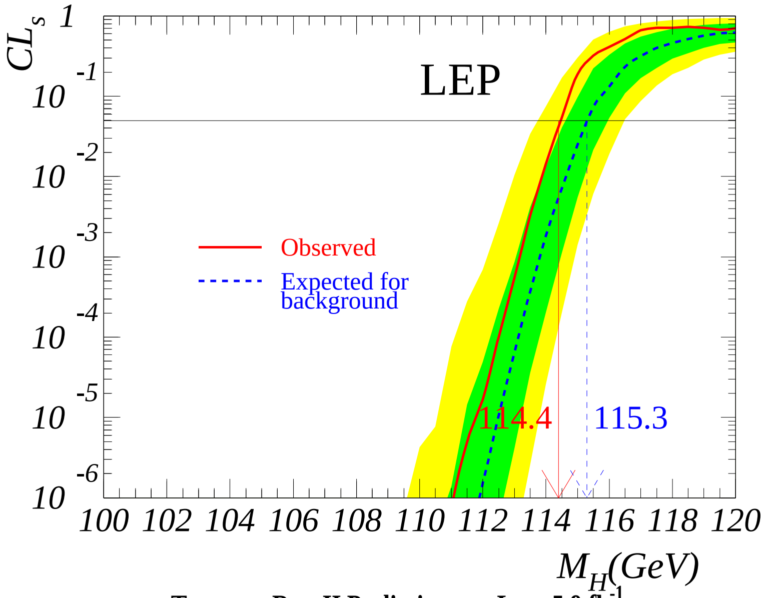
1. The Higgs in the SM: constraints on M_H

Constraints from Higgs non–observation at colliders (LEP/Tevatron).

- **Direct searches at LEP:**

H looked for in $e^+e^- \to ZH$



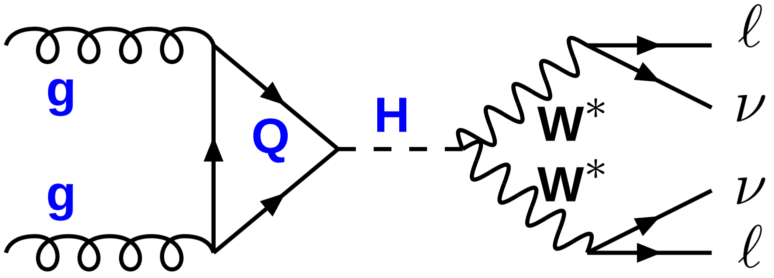


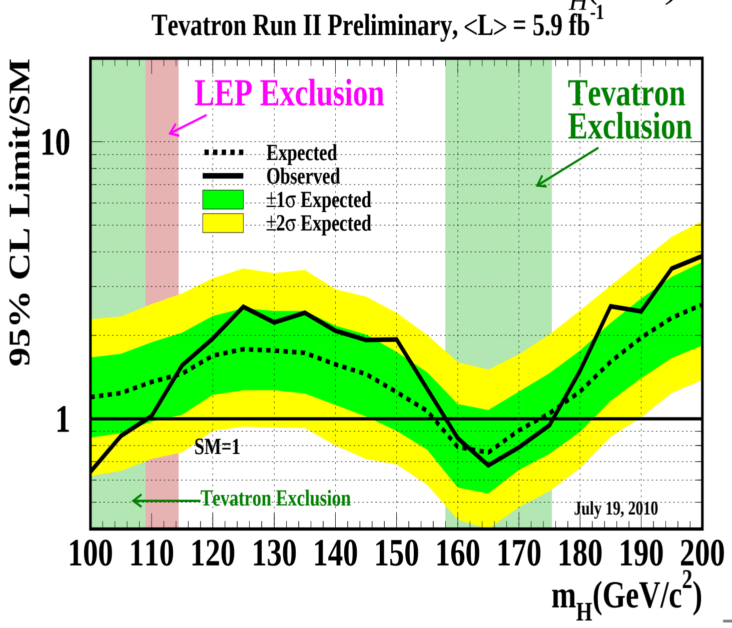
We have a limit at 95% CL:

$$M_H > 114.4 \text{ GeV}$$

- **New results from the Tevatron:**

Mainly: $gg \to H \to WW \to \ell\ell\nu\nu$





exclude $M_H = 158 - 175$ GeV

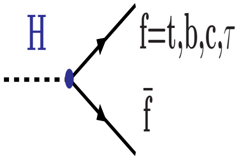
(to be discussed in detail later).

2. Higgs decays

Higgs couplings proportional to particle masses: once M_H is fixed,

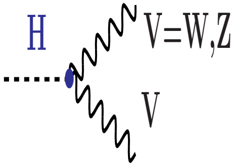
- **the profile of the Higgs boson is determined and its decays fixed,**
- **the Higgs has tendancy to decay into heaviest available particle.**

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

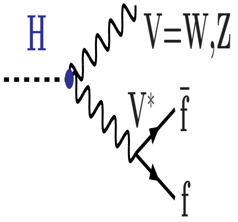


- **only** $b\bar{b}, c\bar{c}, \tau^+\tau^-, \mu^+\mu^-$ **and eventually** $t\bar{t}$
- **QCD RC very large** $\Rightarrow m_b^{\overline{MS}}(M_H^2) \sim 3\,\mathrm{GeV}$.
- **also direct QCD (3-loops) and EW (1-loop).**

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

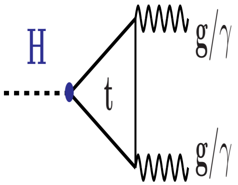


- **above** $2M_Z$ **th. dominant: BR(WW)=**$\frac{2}{3}$**, BR(ZZ)=**$\frac{1}{3}$
- $M_H \gg M_V$: **very large** $\Gamma_{VV} \propto M_H^3$ $(\Gamma_{tt} \propto M_H)$
- **below th. decays possible/important** $(m_b \ll M_V)$**!**



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

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



2. Higgs decays: branching ratios

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

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

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

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

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

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

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

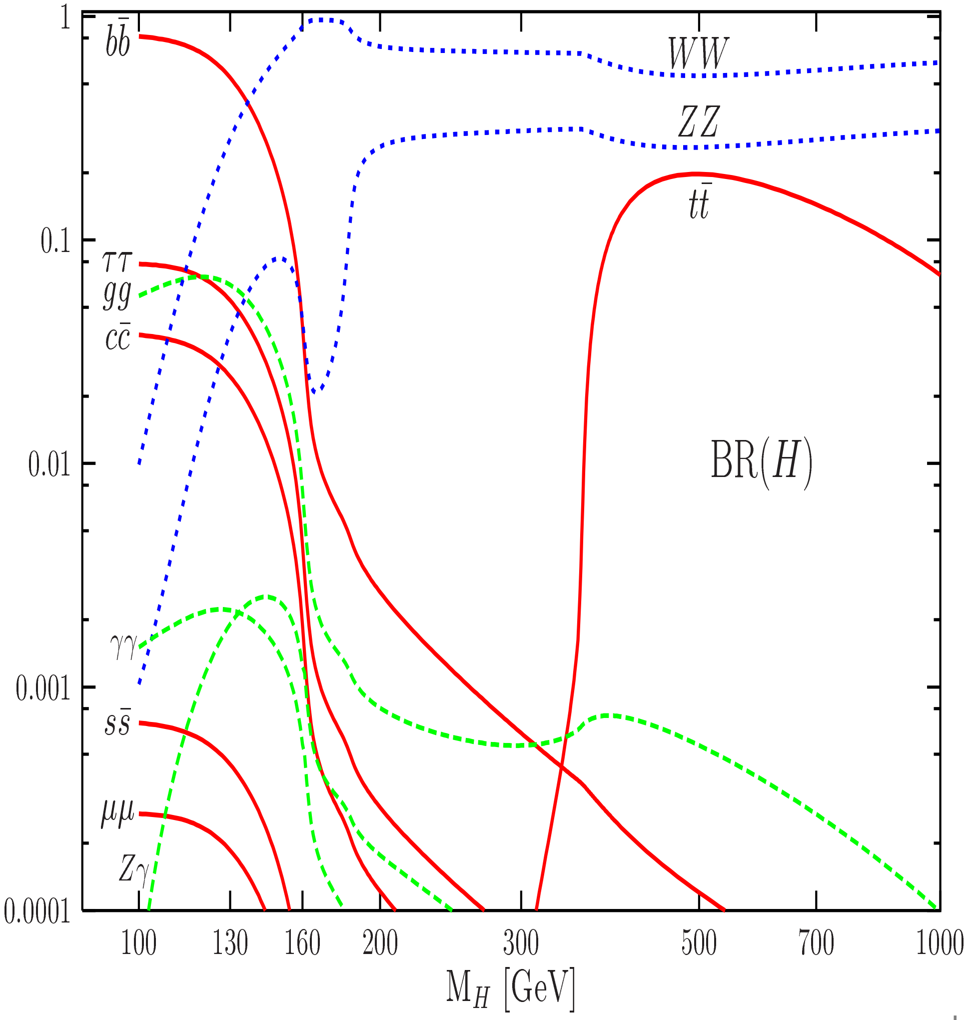
– $\mathrm{H} \to \mathbf{WW}, \mathbf{ZZ}$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

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

- **Total Higgs decay width:**

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

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



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

2. Higgs decays: total width

Total decay width: $\Gamma_{\rm H} \equiv \sum_{\rm X} \Gamma({\rm H} \to {\rm X})$

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

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– $\rm H \to WW^*, ZZ^*$ **up to** $\gtrsim \rm 2M_W$

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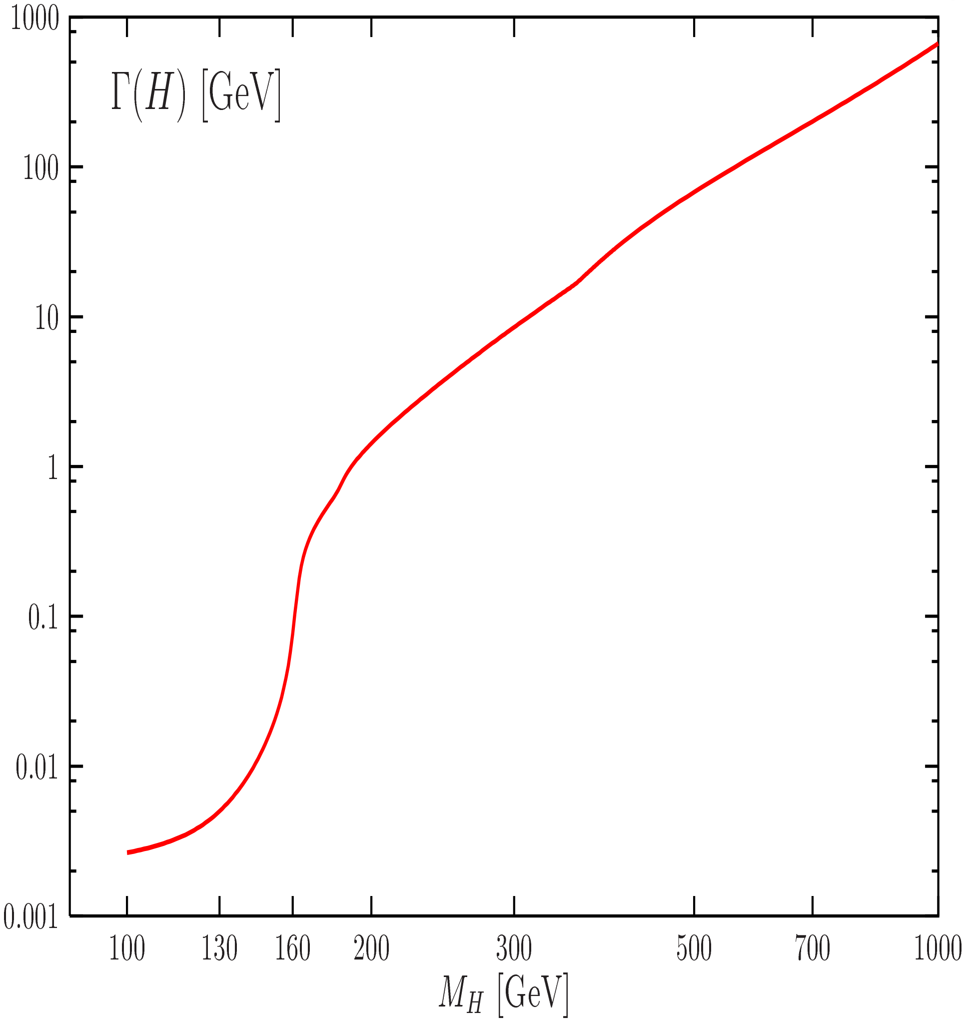


HDECAY: AD, Kalinowski, Spira (95–10). Includes all relevant higher orders.

2. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

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

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

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

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

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

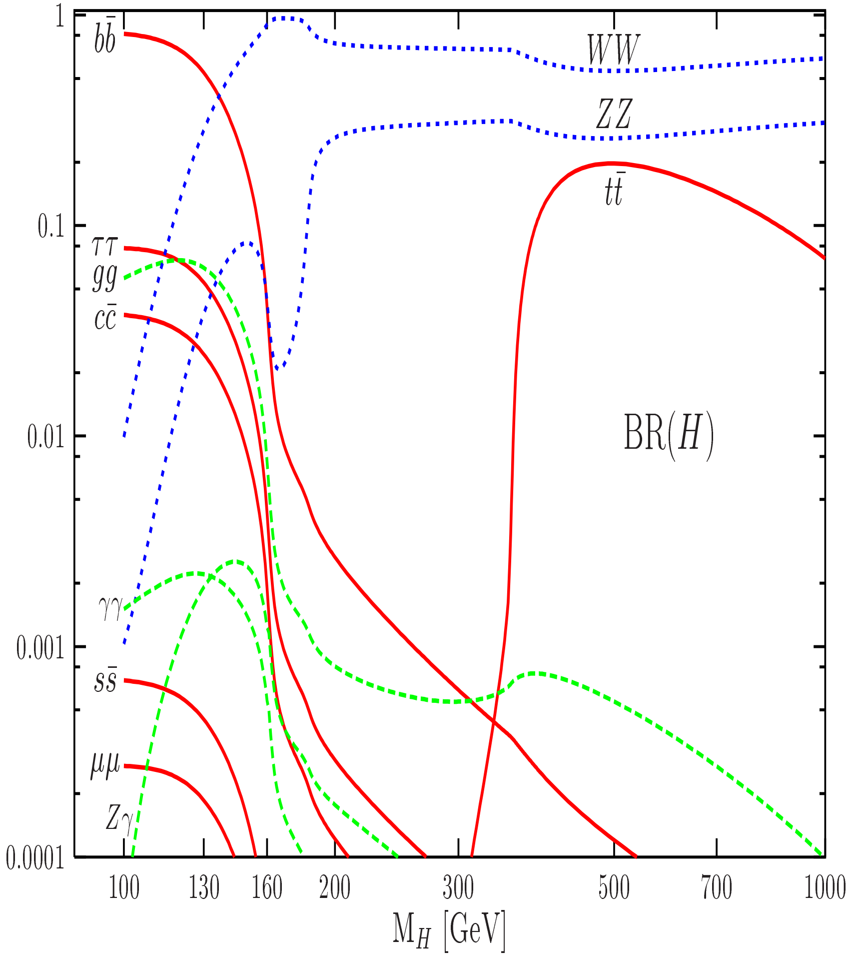
$\mathbf{\alpha_s(M_Z^2) = 0.1171 \pm 0.0028}$ **@NNLO**

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

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

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

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



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

(QCD effects appear at high orders).

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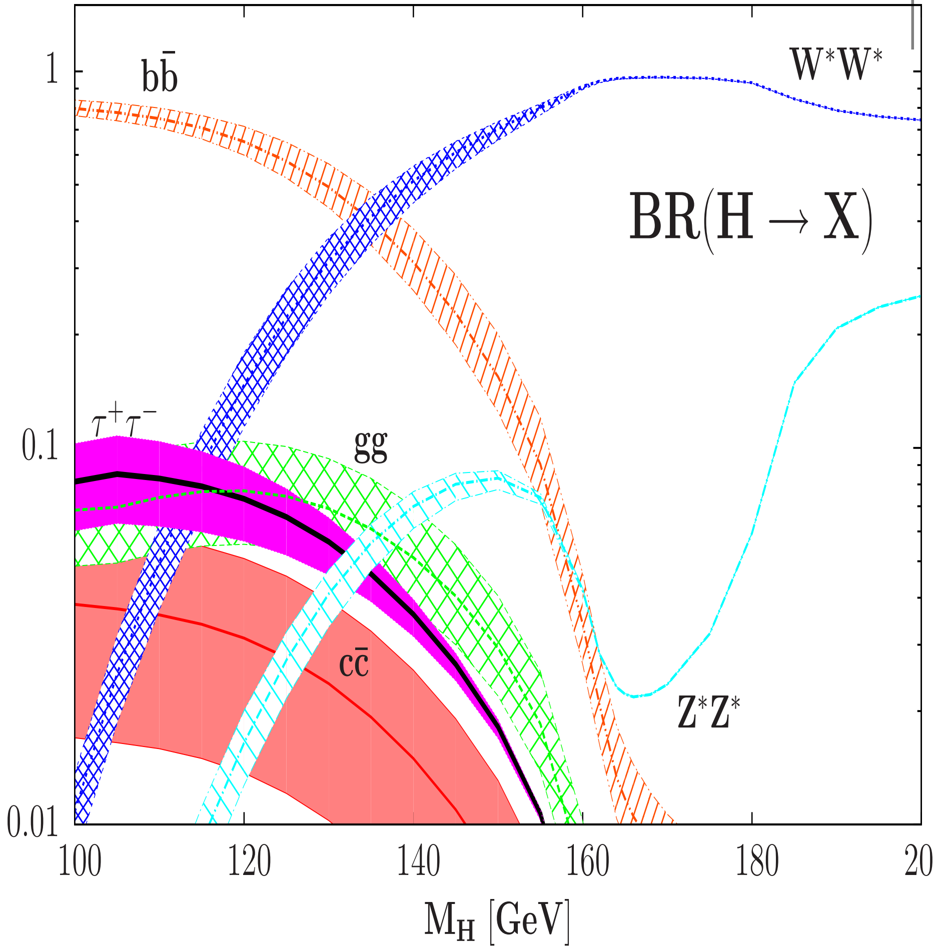


Baglio,AD

Include all items ⇒ large uncertainties!

esp. for M_h ≈120–150 GeV: 10–30% for $H \to b\bar{b}$ and $H \to WW^*$

3. The Higgs at the Tevatron

- **$M_H \gtrsim 140$ GeV : gg → H**

(with $H \to W^* W^* \to \ell\ell\nu\nu$)

LO[a] already at one loop

exact NLO[b] : K ≈2 (1.7)

EFT NLO[c]: good approx.

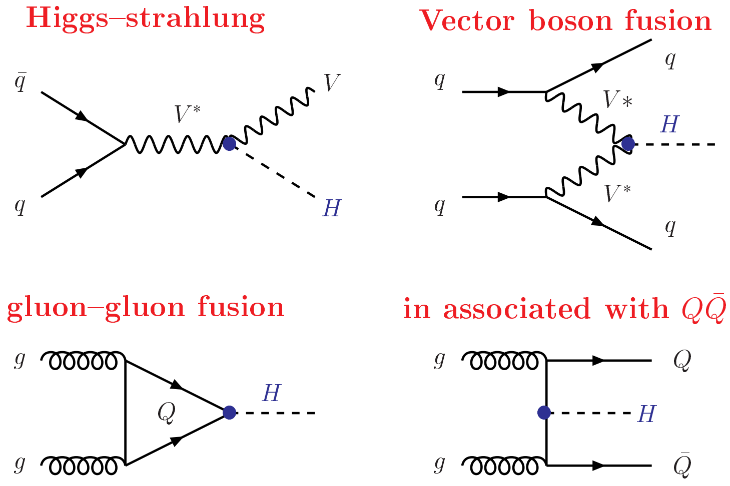
QCD: EFT NNLO[d]: K ≈3 (2)

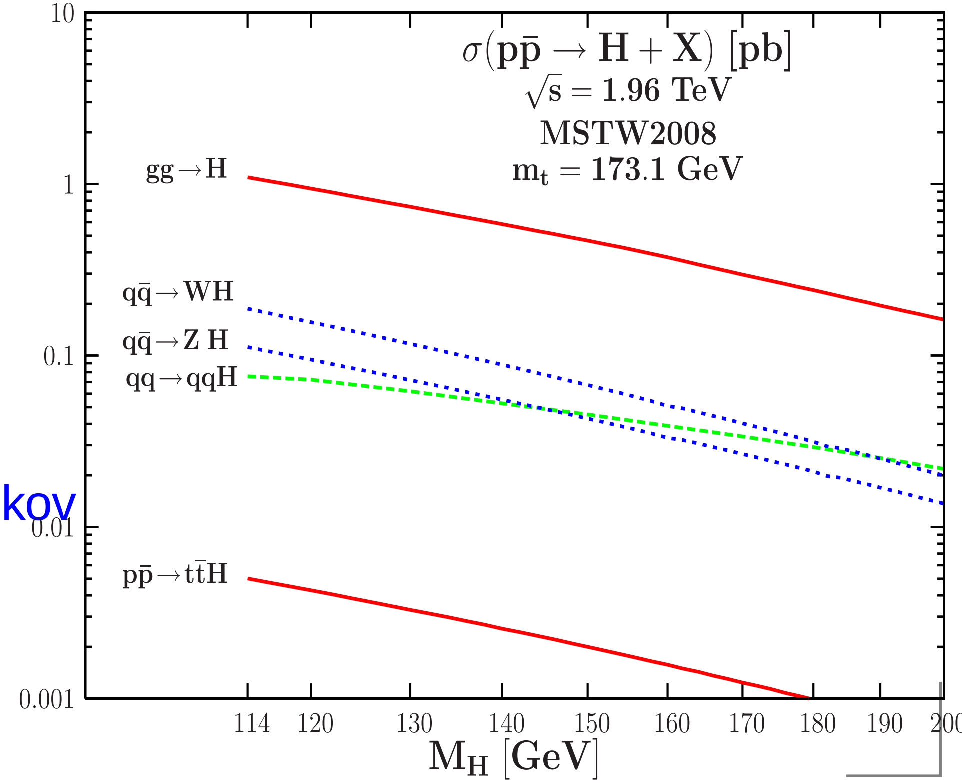
EFT NNLL[e]: ≈ +10% (5%)

EFT NLO EW[f]: ≈ ± very small

exact NLO EW[g]: ≈ ± a few %

EFT NNLO QCD+EW[h]: a few %





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[a] Georgi et al., Ellis et al, Wilczek
[b] Spira+AD+Graudenz+Zerwas (exact)
[c] AD, Spira, Zerwas; Dawson (EFT)
[d] Harlander+Kilgore, Anastasiou+Melnikov
Ravindran+Smith+van Neerven
[e] Catani+de Florian+Grazzini+Nason
[f] AD,Gambino; Degrassi et al.
[g] Actis+Passarino+Sturm+Uccirati
[h] Anastasiou+Boughezal+Pietriello

3. Higgs at the Tevatron: production

- $\mathbf{M_H \lesssim 140\ GeV\ :\ q\bar{q} \to HV}$

$\mathbf{q\bar{q} \to HW \to b\bar{b}\ell\nu}$
$\mathbf{q\bar{q} \to HZ \to b\bar{b}\ell\ell, b\bar{b}\nu\bar{\nu}}$
$\mathbf{q\bar{q} \to HW \to \ell\ell\ell\nu\nu\nu}$

LO[a]: $\equiv \sigma(\mathrm{V}^*) \times \mathrm{BR}(\mathrm{V}^* \to \mathrm{VH})$

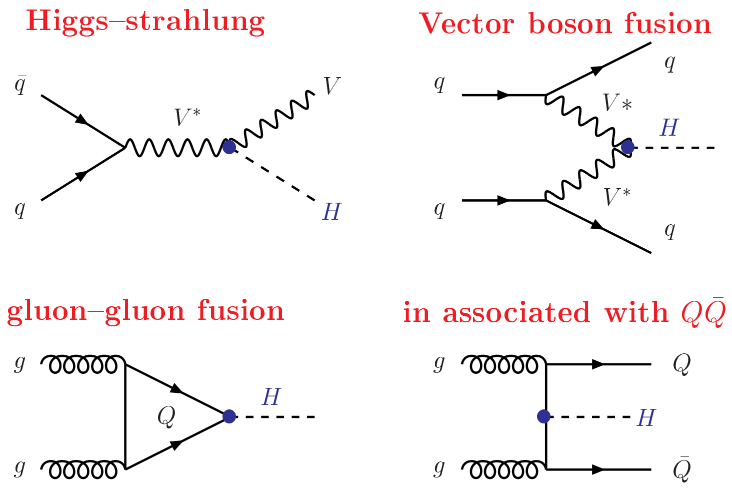
exact NLO QCD[b] : $\mathrm{K} \approx$ **1.4**

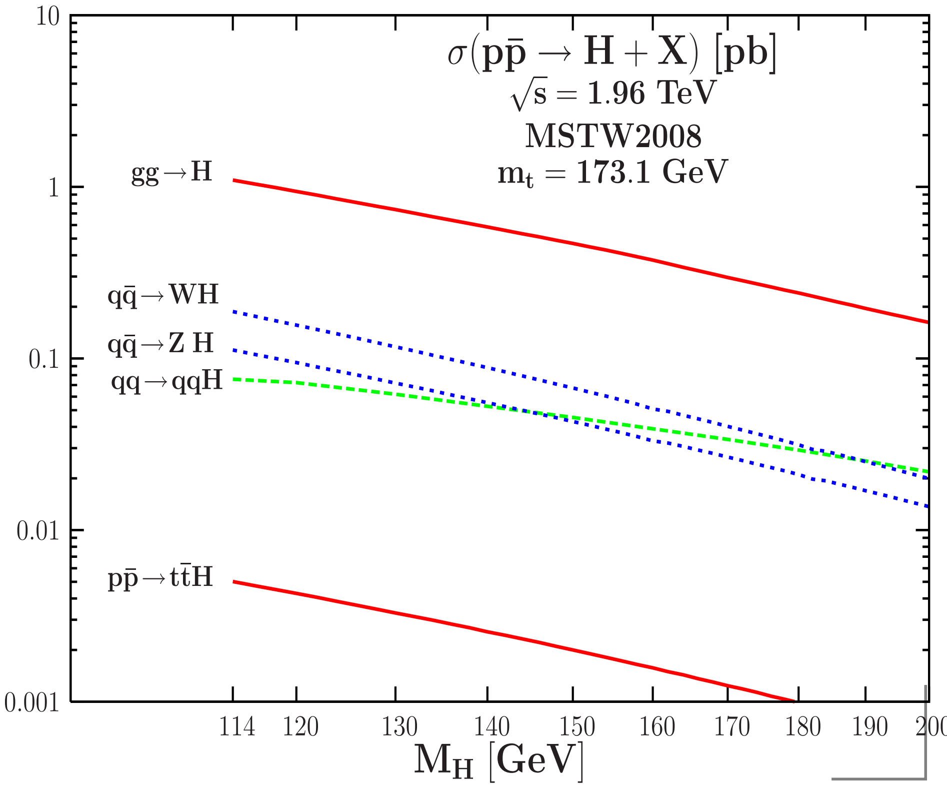
exact NNLO QCD[c]: $\mathrm{K} \approx$ **1.5**

exact NLO EW[d] :$\approx -$**5%**

In practice combine ggH+HZ/HW

- $\mathbf{p\bar{p} \to Hqq}$: **bkg. too high.**
- $\mathbf{p\bar{p} \to Ht\bar{t}}$: **rates too low.**





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[a] Glashow, Nanopoulos,Yildiz
[b] Altarelli et al; Han, Willenbrock
[c] Hamberg+van Neerven+Matsuura; Brein+AD+Harlander
[d] Ciccolini+Dittmaier+Krämer

3. Higgs at Tevatron: focus on gg→H

- **The K factors are extraordinarily large:**

good: this is what makes the Tevatron sensitive to the SM Higgs!

bad: perturbation theory almost jeopardized as $\sigma_{\mathbf{LO}} \approx \sigma_{\mathbf{NLO}} \approx \sigma_{\mathbf{NNLO}}$.

uggly: higher order (HO) corrections might be very important...

- **NNLL corrections known only for inclusive cross section $\sigma_{\mathbf{tot}}$:**

– $\sigma_{\mathbf{cuts}}$ used experimentally is known only at NNLO[a]: stick to NNLO.

– NNLL corrections mimicked by using central scale $\mu_0 = \frac{1}{2}\mathrm{M_H}$.

– in fact, NNLO only in EFT approach (no b-loop); exact only at NLO[b].

– K in $\sigma_{\mathbf{tot}}$ and $\sigma_{\mathbf{cuts}}$ different[c] by $\approx$ 25%: $\mathbf{K^{nnlo}_{cuts}}$=2.6 vs $\mathbf{K^{nnlo}_{tot}}$ =3.3.

- **Other remarks:**

– Starting point of calculation: HIGLU (M. Spira) based on Ref. [b].

– Recent update[d] for $\mathrm{gg} \to \mathrm{H}$ (2009) but not for $\mathrm{p\bar{p}} \to \mathrm{HV}$ (2004).

– Distributions not discussed, see Ref. [c]; no background neither.

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[a] Catani+Grazzini (HNNLO), Anastasiou+Melnikov+Petriello (FEHIP)

[b] Spira+AD+Graudenz+Zerwas (exact NLO)

[c] Anastasiou, Dissertori, Grazzini, Stökli, Webber (2009)

[d] de Florian+Grazzini; Anastasiou+Boughezal+Pietriello

3. Higgs at Tevatron: higher orders and scale variation

Higher orders (HO) guessed by varying

μ_R, μ_F **arround central scale** $\mu_0 = \frac{1}{2} M_H$:

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

(only a guess, not a true measure!)

In general, when small HO, $\kappa = 2$ **enough**

(this is the case for $q\bar{q} \to HV$ **e.g.).**

Here: $K_{HO} \approx 3$ **and PTh almost ruined.**

HO beyond NNLO might be still large:

$\Rightarrow$ **guess scale domain from** σ_{NLO}

For σ_{NLO} **band to catch** σ_{NNLO} **value**

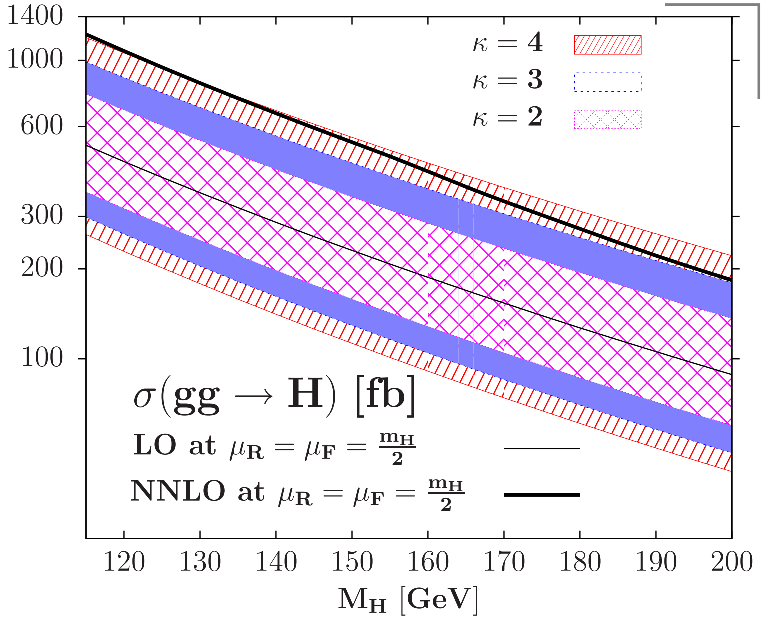
$\Rightarrow$ **one needs at least $\kappa = 3$**

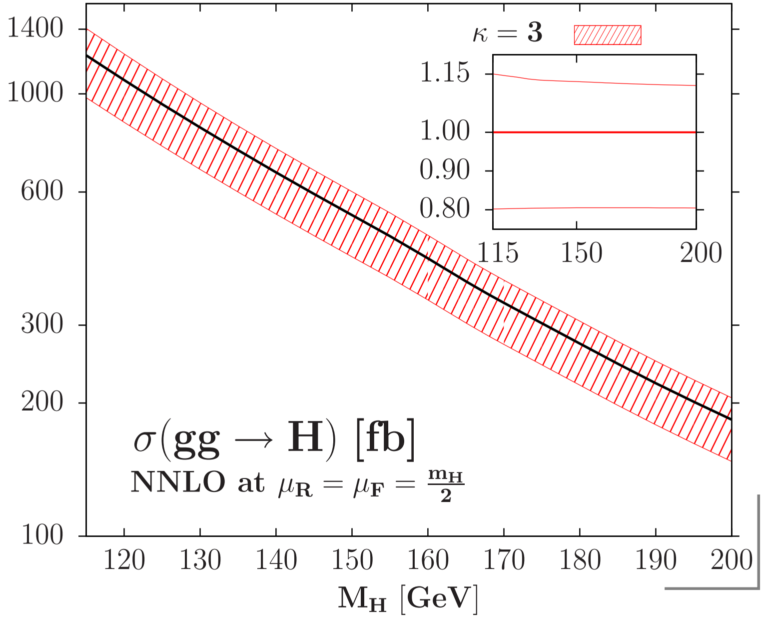
Apply variation with $\kappa = 3$ **for** σ_{NNLO}

$\approx 20\%$ **scale uncertainty on** σ_{NNLO}

(compared to $\approx 10\%$ **for** σ_{NNLL}**+**$\kappa = 2$**)**

compensates for 30% diff. K_{cuts} vs K_{tot}.





3. Higgs at Tevatron: PDFs and α_s

PDF uncertainties estimated using the 2x20 MSTW PDF sets including errors.
$\Rightarrow$ 5–10% PDF error (idem for CTEQ)

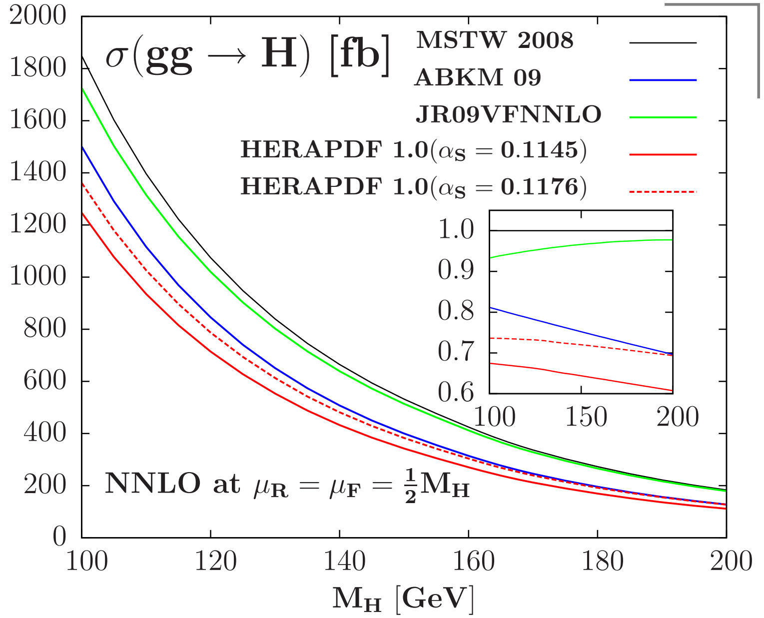
However, also other sets: HERA, ABKM, JR, which are also at NNLO, so let us try:

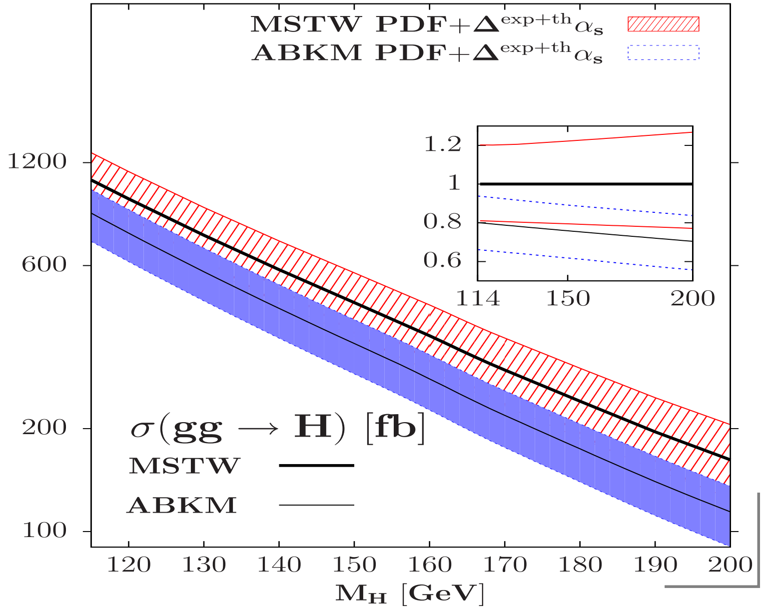
$\Rightarrow$ very large differences!!

(# is also a measure of the PDF error...)
Pb: $\sigma_{\rm LO} = \mathcal{O}(\alpha_s^2)$,.., $\sigma_{\rm NNLO} = \mathcal{O}(\alpha_s^4)$
and $\alpha_s(M_Z^2)$=0.1171$\pm$0.0034 (90%CL)

MSTW has new set up with $\Delta^{\rm exp}\alpha_s$ in.

Not enough: also $\Delta^{\rm th}\alpha_s \approx 0.003$ (NLO)
Include all: PDF+$\Delta^{\rm exp}\alpha_s \oplus$PDF+$\Delta^{\rm th}\alpha_s$
MSTW/ABKM now consistent (not HERA!).
But total PDF error is now $\gtrsim$ 15% !
(compared with $\approx$ 5% for PDF alone)





3. Higgs at Tevatron: EFT approach at NNLO

To simplify (hard!) NNLO calculation

EFT approach where $\mathrm{M_{loop}} \gg \mathrm{M_H}$

Good for t–loop (see R. Harlander)

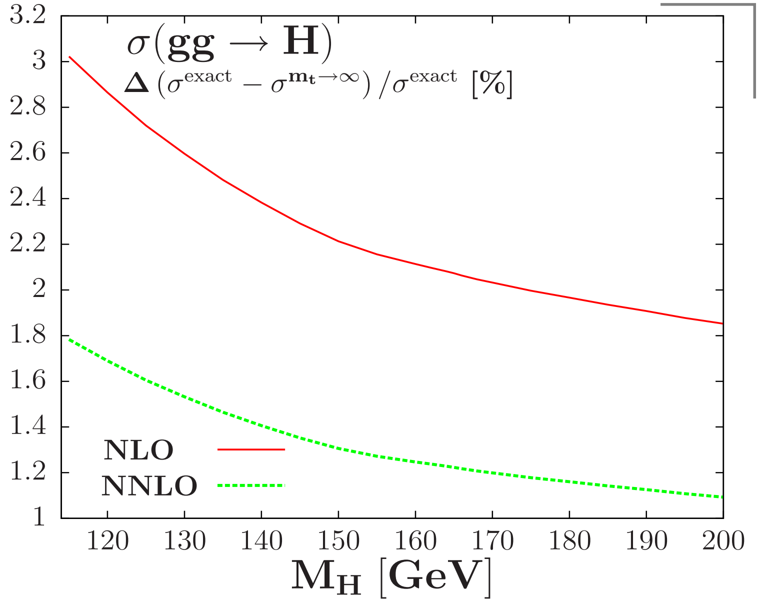
Not good for b–loop ($\approx$ 10% at LO)

Estimate error from NLO (known exactly)

$$\Delta_{\mathrm{b}}^{\mathrm{NNLO}} : \frac{\sigma^{\mathrm{NLO}}_{\mathrm{exact}} - \sigma^{\mathrm{NLO}}_{\mathrm{EFT}}}{\sigma^{\mathrm{NLO}}_{\mathrm{exact}}} \times \frac{\mathrm{K_{NLO}}}{\mathrm{K_{NNLO}}}$$

In addition: $\mathrm{m_b^{pole}}$ or $\mathrm{m_b^{\overline{MS}}(m_b)}$?

Uncertainty of a few percent...



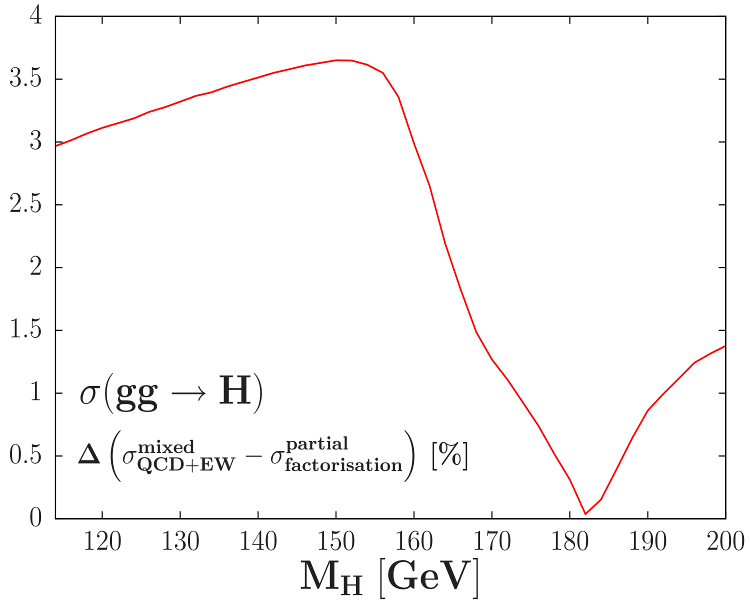
Mixed EW+QCD RadCor at NNLO:

EFT approach with $\mathrm{M_{W/Z}} \gg \mathrm{M_H}$

Contrib. $\equiv$ to EW NLO in $\#$ schemes

$$\Delta_{\mathrm{EW}}^{\mathrm{NNLO}} : \frac{\sigma^{\mathrm{NLO-EW}}_{\mathrm{complete\ factor.}} - \sigma^{\mathrm{NLO-EW}}_{\mathrm{partial\ factor.}}}{\sigma^{\mathrm{NLO-EW}}_{\mathrm{complete\ factor.}}}$$

Uncertainty of a few percent ($\lesssim$ 3.5%)



3. Higgs at Tevatron: combination

Next very important issue: how to combine these theoretical errors?

– add scale and PDF not in quadrature!

(no stat ground; both have flat prior!)

Reasonable way: calculate $\frac{\max}{\min}\sigma(\mu_{\rm F/R})$ and apply on them PDF+$\Delta^{\rm ex+th}\alpha_s$ errors

In $gg \to H$:≈ ±40% total uncertainty

much larger than assumed by CDF/D0

In $p\bar{p} \to HV$:≈ ±10% uncertainty

smaller than gg→H but x2 CDF/D0 error.

Don't forget the error on the Higgs BR's!

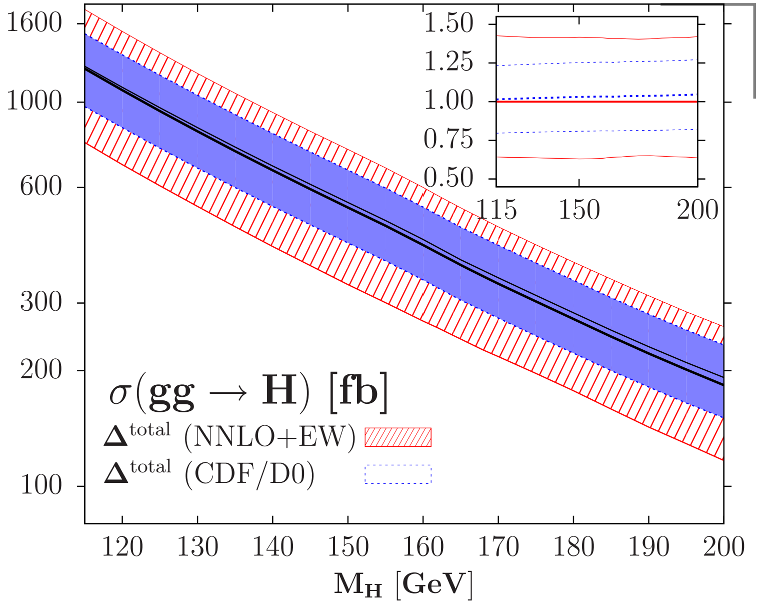
(to be added linearly to those on σ)

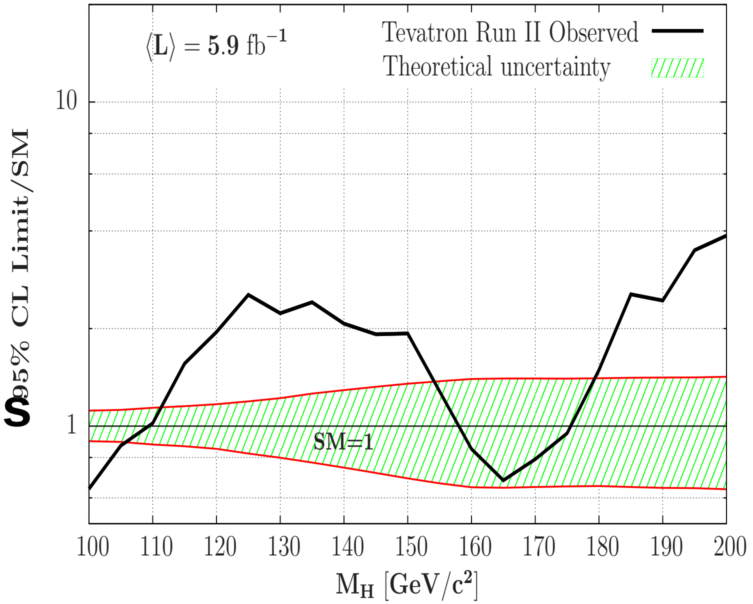
Combination of all channels:

– assume same acceptance for all channels

– CDF/D0 theory error has no effect ....

No Higgs mass is excluded with errors!





4. The Higgs at the ℓHC

ℓHC: $\sqrt{s}=7$ TeV, $\int\mathcal{L}=1$ fb^{-1}

Same production as at Tevatron:

– rates $\approx$ 10 times higher

– much larger backgrounds

– much lower luminosity: $1\,\text{fb}^{-1}$

Only: $gg \to H \to W^*W^* \to \ell\ell\nu\nu$

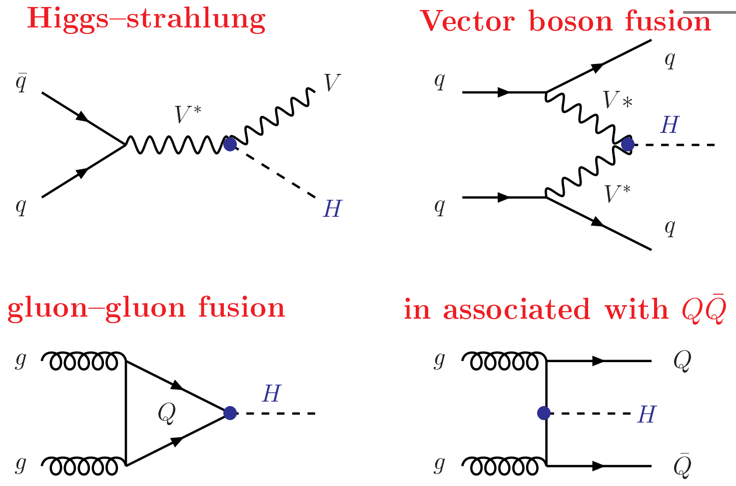
($\approx$ 200 of Higgs signal events)

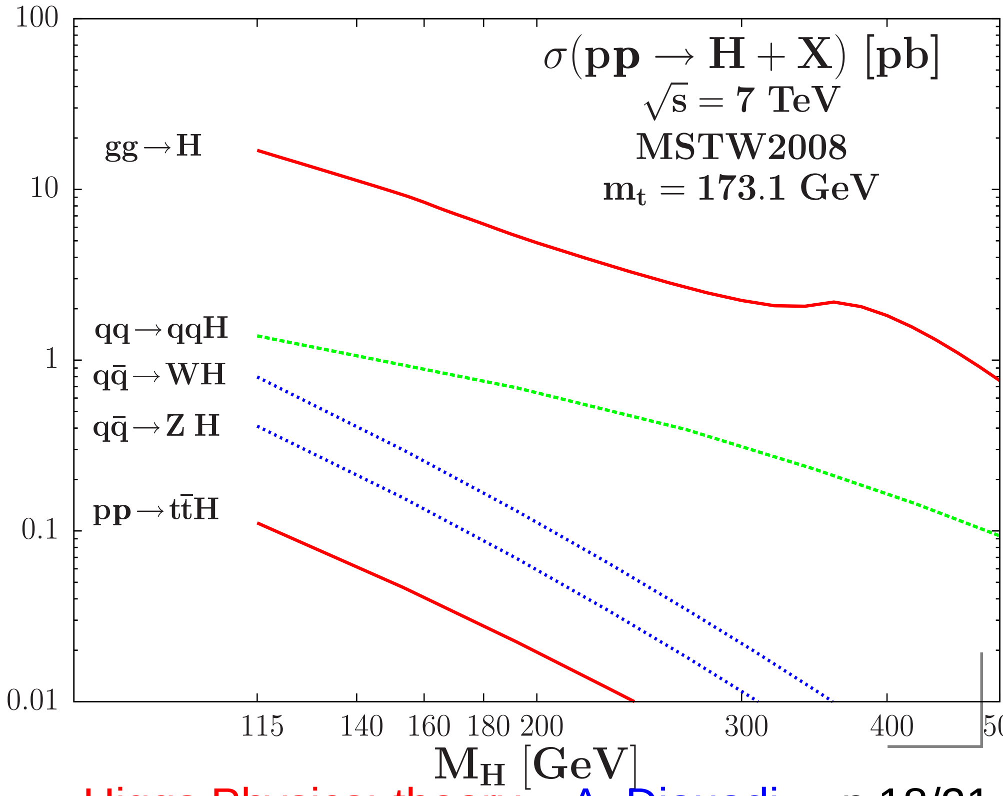
– Hqq, Htt hopeless

– to much bckg from Wbb,Zbb (?)

Compared to the Tevatron case:

- **Smaller HO: $K_{\rm NNLO}=2,5$**
- **Scale: κ=2 enough $\Rightarrow$ 15%**
- **PDF errors smaller, $\approx$10%**
- **Again 5% error from EFT**
- **Include error on BR(H$\to$WW)**





4. The Higgs at the ℓHC

ℓHC: $\sqrt{s}=7$ TeV, $\int\mathcal{L}=1$ fb^{-1}

Same production as at Tevatron:

– rates ≈ 10 times higher

– much larger backgrounds

– much lower luminosity: $1\,\mathrm{fb}^{-1}$

Only: $gg \to H \to W^*W^* \to \ell\ell\nu\nu$

(≈ 200 of Higgs signal events)

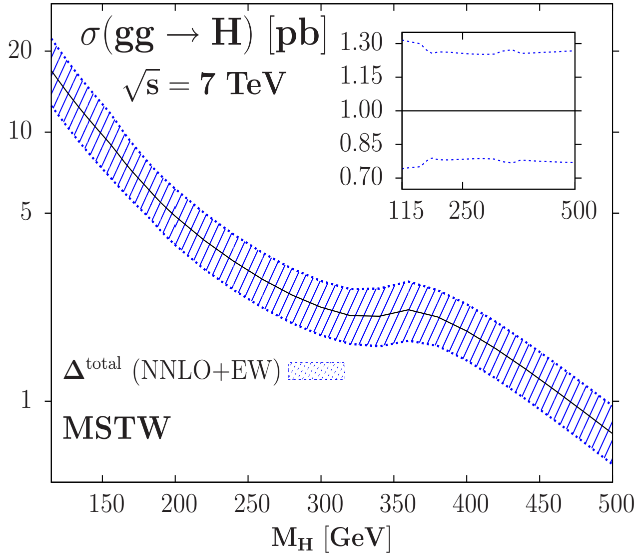
Compared to the Tevatron case:

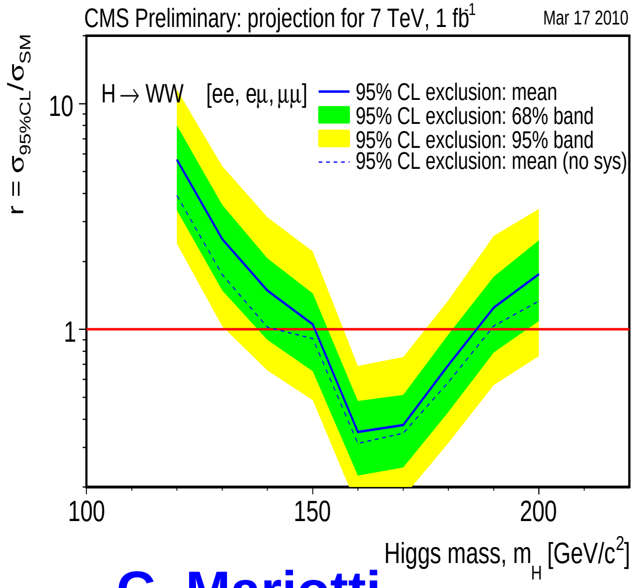
- **Smaller HO: $K_{\rm NNLO}=2,5$**
- **Scale: κ=2 enough ⇒ 15%**
- **PDF errors smaller, ≈10%**
- **Again 5% error from EFT**
- **Include error on BR($H \to WW$)**

Combined uncertainty ≈ ±30%

excludes $M_H \approx 150-190$ GeV

Baglio+AD





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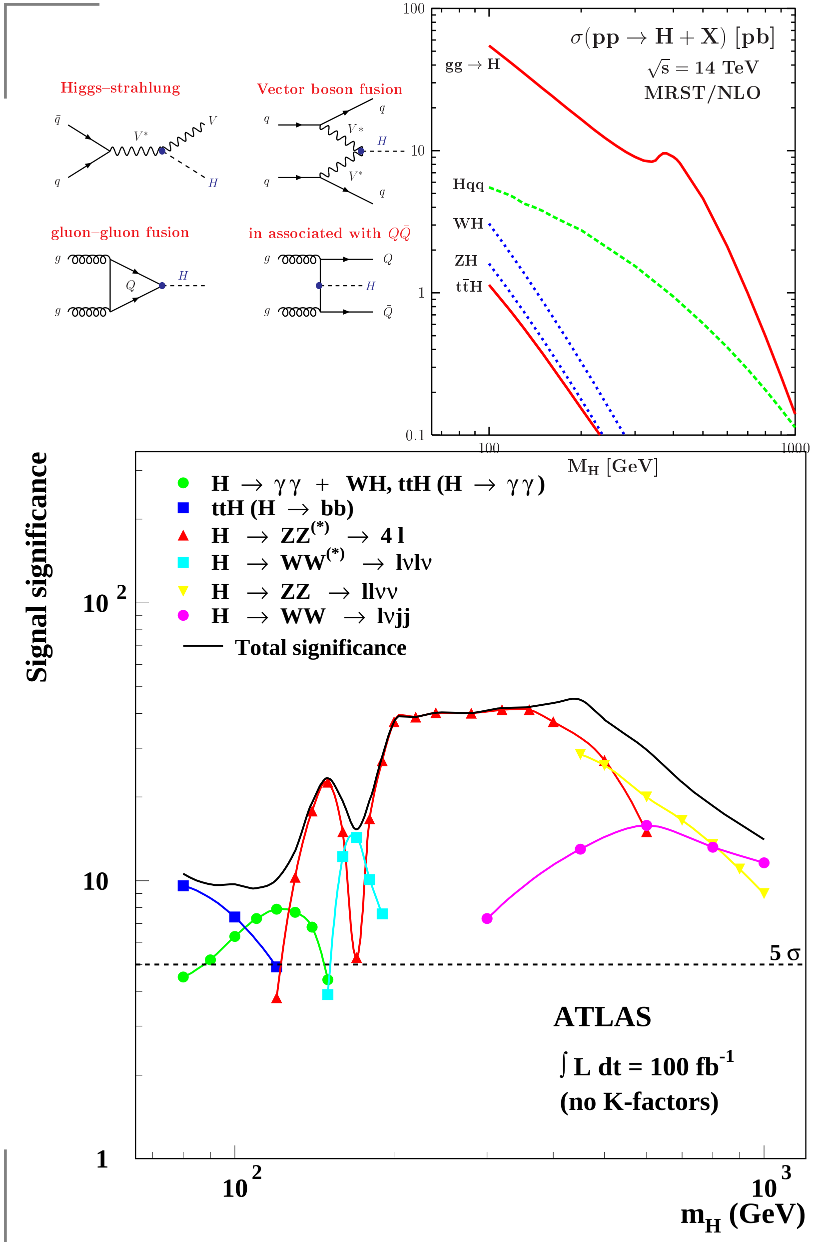
4. The Higgs at the (full) LHC



LHC: $\sqrt{s}=7+7=14$ TeV $\Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \sim 5$ TeV

$\mathcal{L} \sim 10$ fb^{-1} first years and 100 fb^{-1} later

gluon–gluon fusion:

$gg \to \tau\tau, b\bar{b}, t\bar{t}$ hopeless

$gg \to H \to \gamma\gamma$ (below $M_H \approx$ 150 GeV)

$gg \to H \to ZZ^* \to 4\ell$ (130–500 GeV)

$gg \to H \to WW \to \ell\nu\ell\nu$ (130–200 GeV

$H \to ZZ, WW \to jj + \ell$ (above 500 GeV

Vector boson fusion:

S/B $\sim$ 1 after standard VBF cuts

$pp \to H \to \tau\tau, \gamma\gamma, ZZ^*, WW^*$

Association with top pairs:

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

Association with W,Z:

jet substructure; measurements?

Only question: when?

5. Conclusion

The LHC will tell.