The Higgs at the Tevatron: Predictions and Uncertainties

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1. The Higgs in the Sm

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

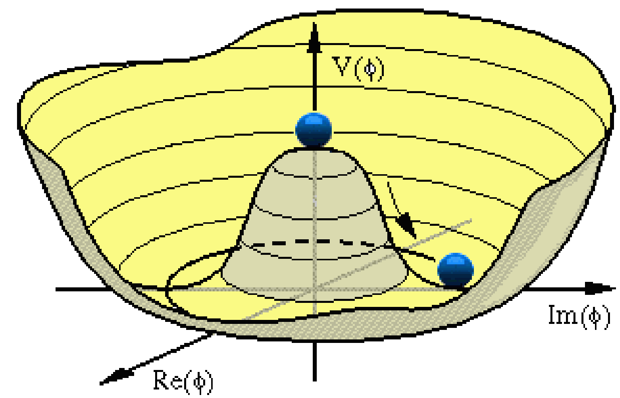
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

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

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

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

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



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 : $M_H^2 = 2\lambda v^2,\ g_{H^3} = 3\frac{M_H^2}{v}, \dots$
- **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

- **Indirect constraints:**

H contributes to RC to W/Z masses:

Fit the EW precision measurements:

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

$M_H \lesssim 157$ **GeV at 95% CL**

- **Direct searches at LEP:**

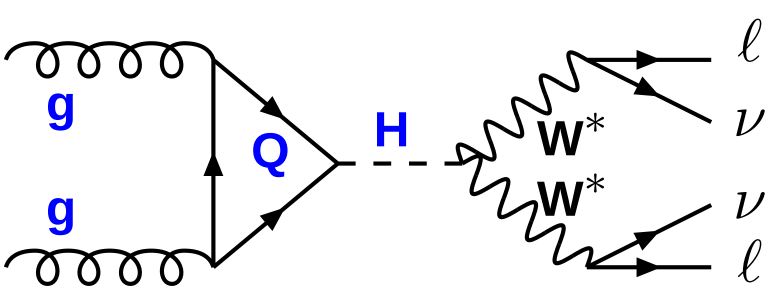
H looked for in $e^+e^- \to ZH$

We have a limit at 95% CL:

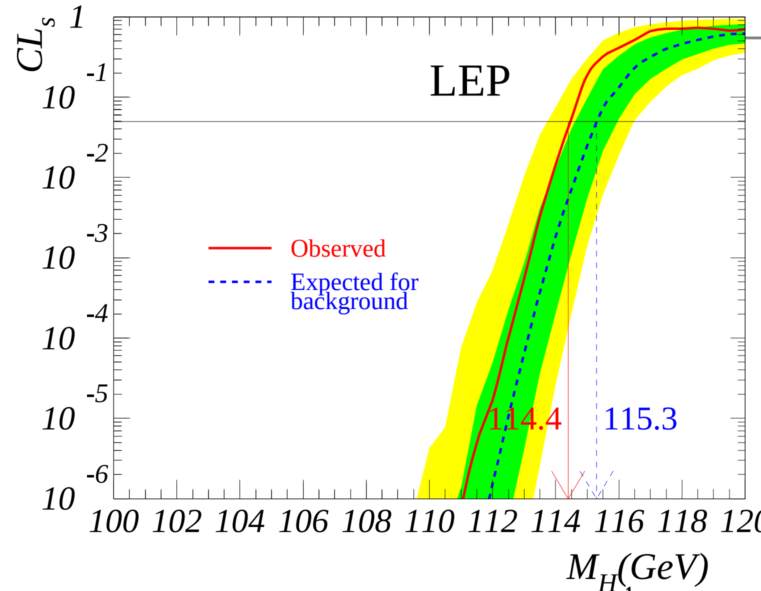
$M_H > 114.4$ **GeV**

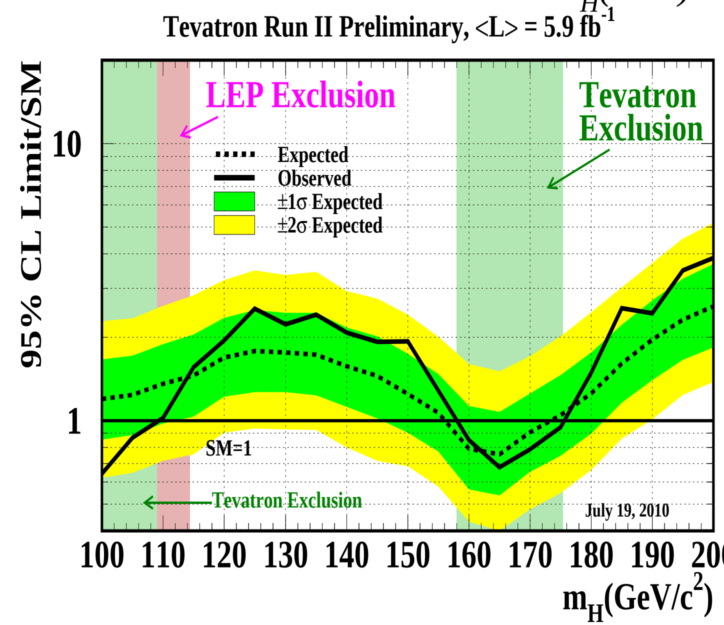
- **New results from the Tevatron:**

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



exclude $M_H = 158 - 175$ GeV





2. Higgs decays: branching ratios

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

- **'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** $\gtrsim 2\mathrm{M_W}$

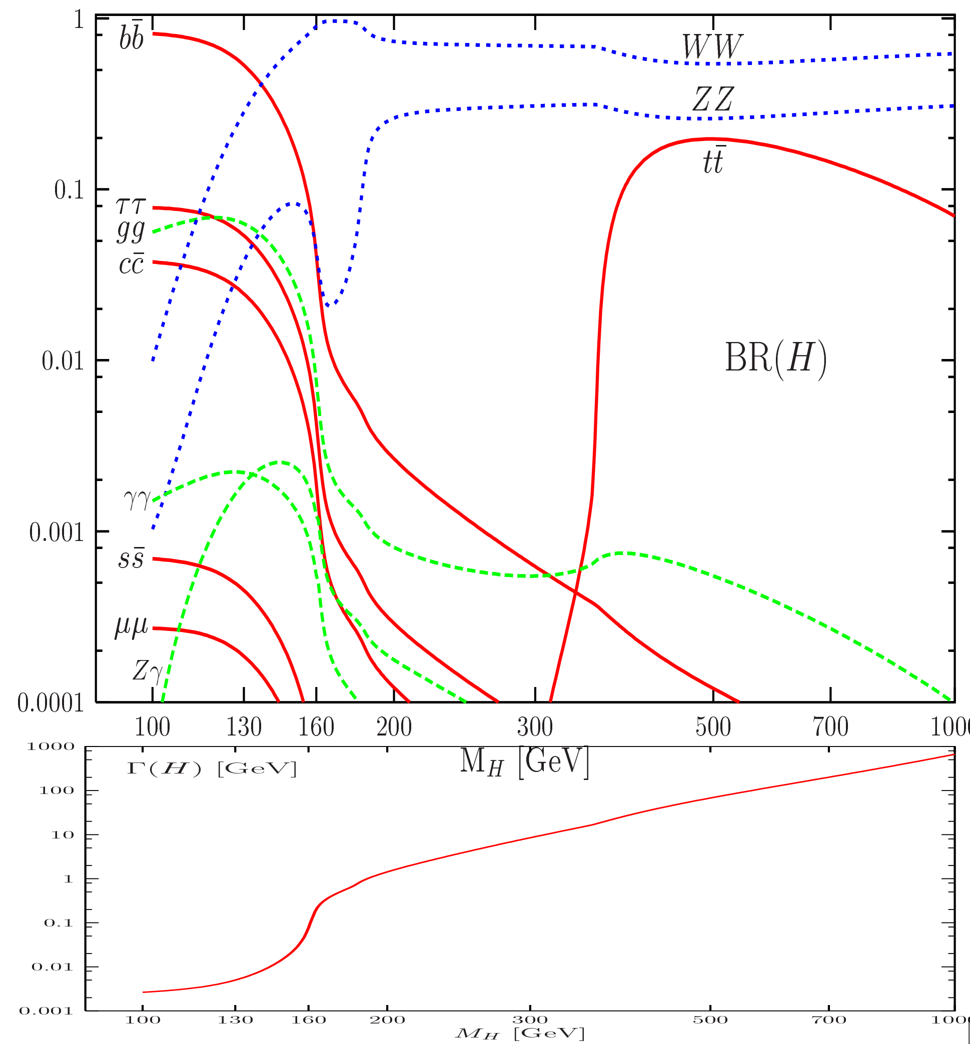
– $\mathrm{H} \to \mathbf{WW}, \mathbf{ZZ}$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

– $\mathrm{H} \to \mathrm{t\bar{t}}$ **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: theory uncertainties

However: there are theoretical uncertainties....

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

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

– $\overline{m}_b(M_b) = 4.19^{+0.018}_{-0.06}$ **GeV**

– $\overline{m}_c(M_c) = 1.27^{+0.07}_{-0.09}$ **GeV**

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

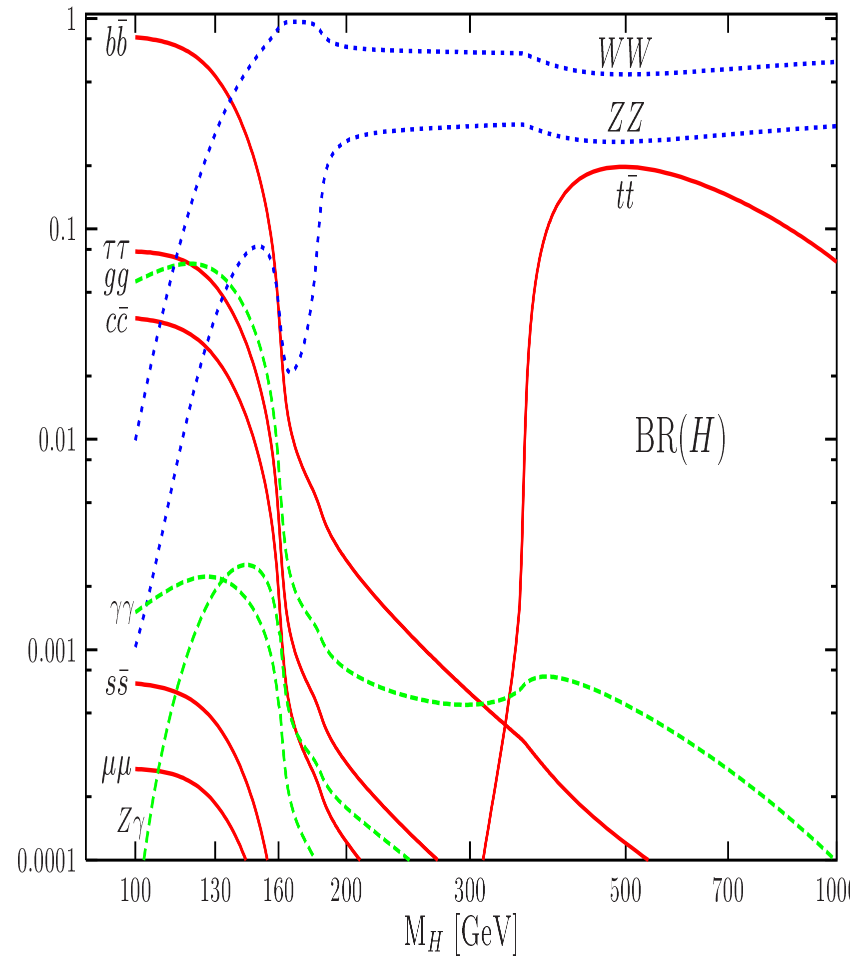
$\alpha_s(M_Z^2) = 0.1171 \pm 0.0014$ **@NNLO**

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

$$\frac{1}{2}M_H \le \mu \le 2M_H$$

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

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



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

(QCD effects appear at high orders).

2. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

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

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

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

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

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

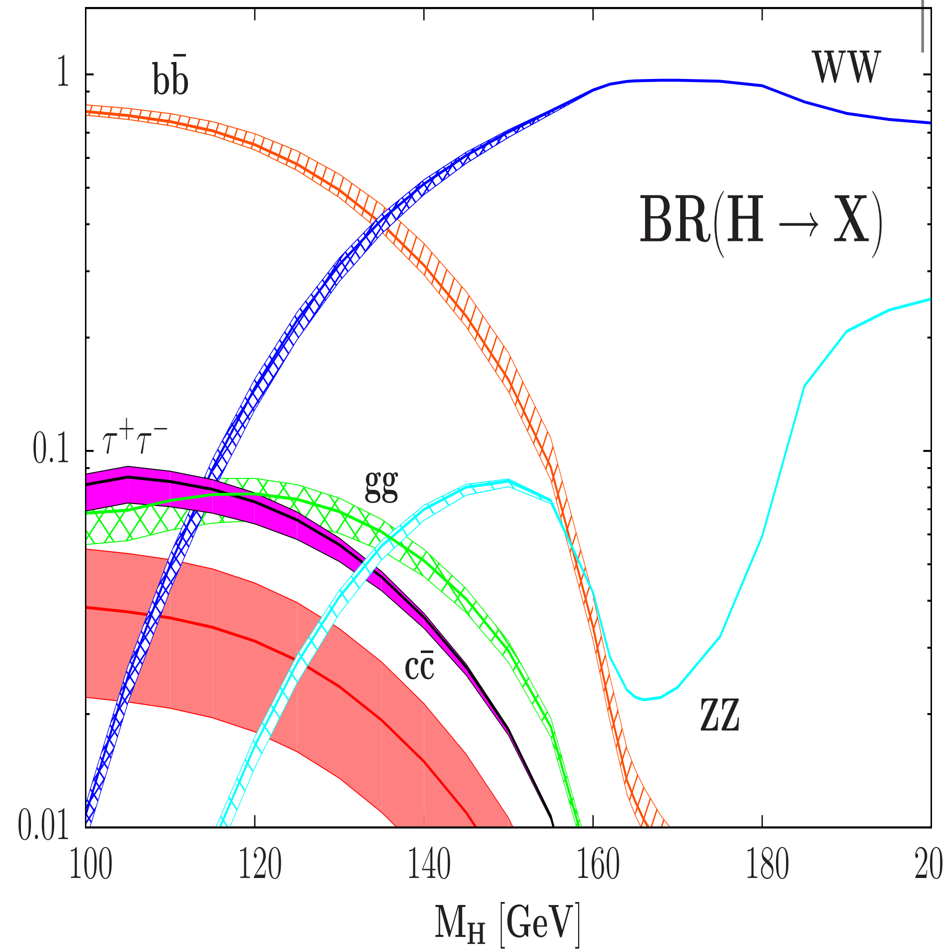
$\alpha_s(M_Z^2) = 0.1171 \pm 0.0028$ **@NNLO**

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

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

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

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



Baglio,AD

Include all items ⇒ large uncertainties!

esp. for $M_h \approx$120–150 GeV: 5–10% for $H \to b\bar{b}$ and $H \to WW^*$

3. The Higgs at the Tevatron

• $M_H \gtrsim 140$ GeV : $gg \to H$

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

LO[a] already at one loop

exact NLO[b] : $K \approx 2$ (1.7)

EFT NLO[c]: good approx.

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

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

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

exact NLO EW[g]: $\approx \pm$ 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)

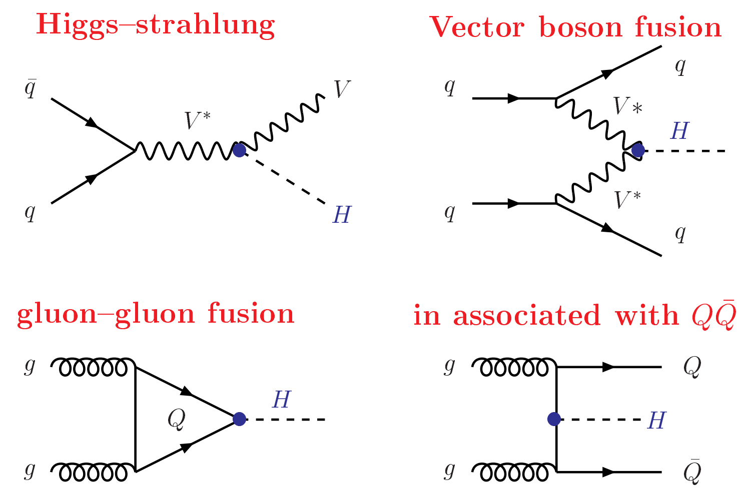
[d] Harlander+Kilgore, Anastasiou+Melnikov Ravindran+Smith+van Neerven

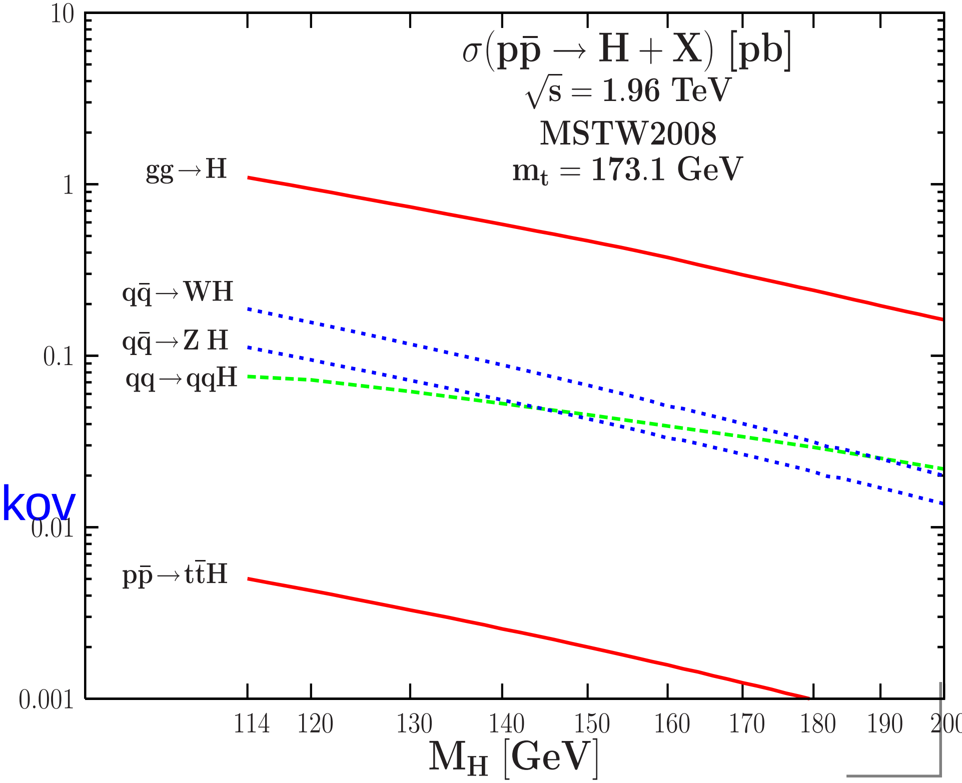
[e] Catani+de Florian+Grazzini+Nason

[f] AD,Gambino; Degrassi et al.

[g] Actis+Passarino+Sturm+Uccirati

[h] Anastasiou+Boughezal+Pietriello





3. Higgs at the Tevatron: production

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

$q\bar{q} \to HW \to b\bar{b}\ell\nu$

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

$q\bar{q} \to HW \to \ell\ell\ell\nu\nu\nu$

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

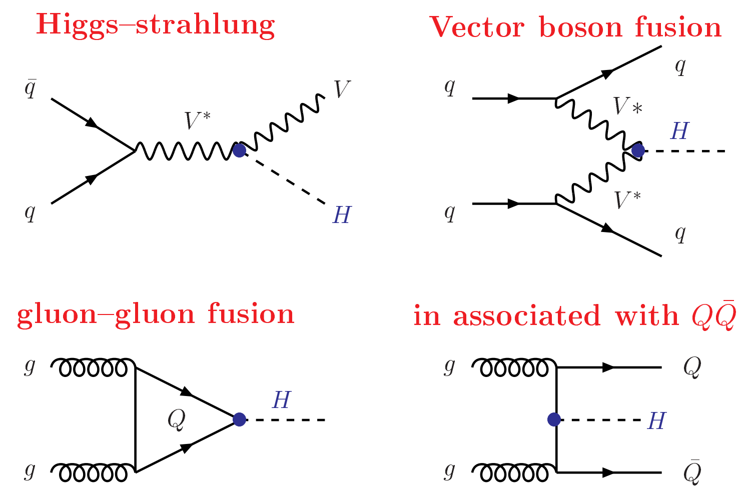
exact NLO QCD[b] : $K \approx 1.4$

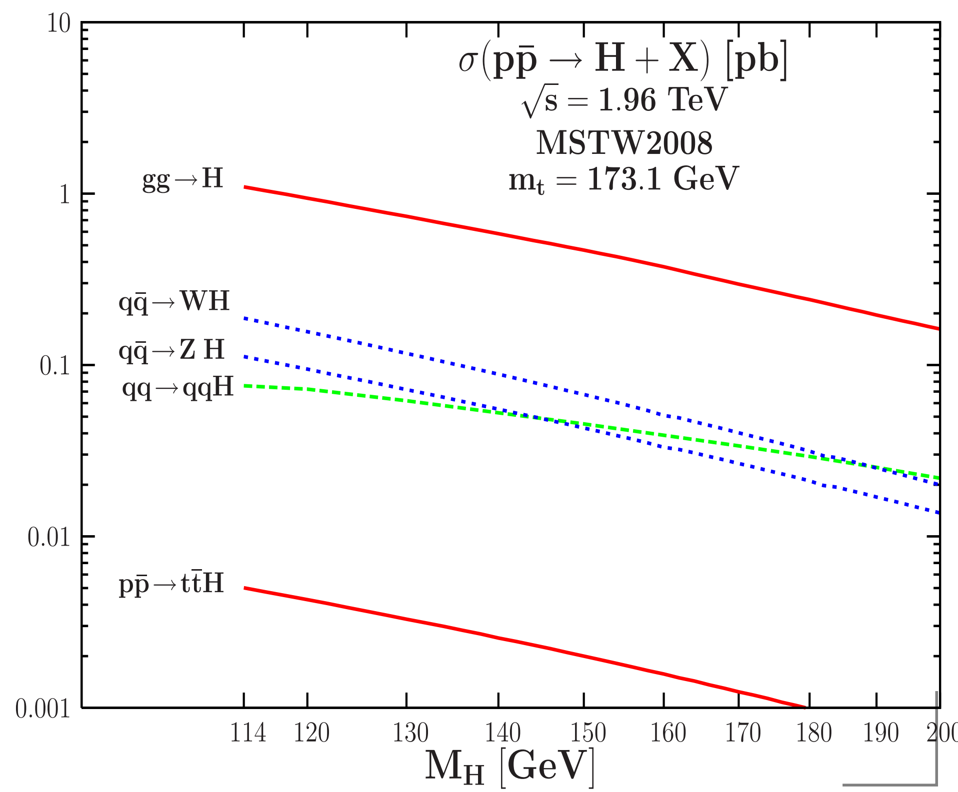
exact NNLO QCD[c]: $K \approx 1.5$

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

In practice combine ggH+HZ/HW

- $p\bar{p} \to Hqq$: bkg. too high.
- $p\bar{p} \to Ht\bar{t}$: 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 $\sigma_{\rm LO} \approx \sigma_{\rm NLO} \approx \sigma_{\rm NNLO}$.

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

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

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

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

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

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

• **Other remarks:**

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

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

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

[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** $\mu_0 = \frac{1}{2} M_H$:

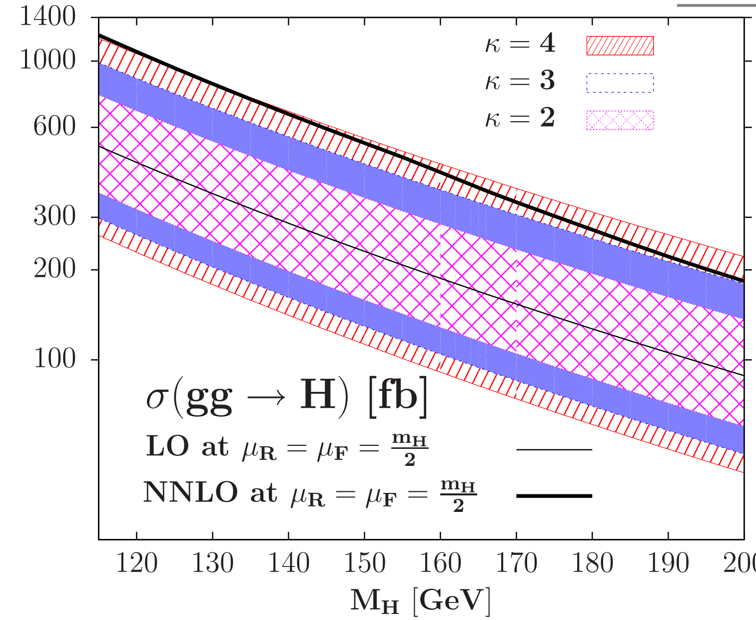
$$\mu_0/\kappa \leq \mu_R, \mu_F \leq \kappa\mu_0$$

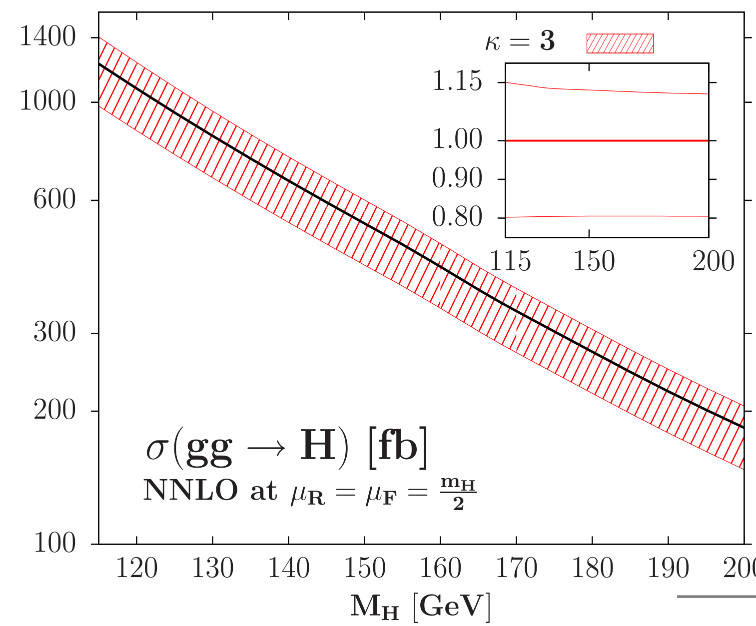
(only a guess, not a true measure!)
In general, when small HO, $\kappa = 2$ **enough**
(this is the case for $q\bar{q} \to HV$ **e.g.).**

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_{NNL0} **value**

$$\Rightarrow \text{one needs at least } \kappa = 3$$

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}**.**





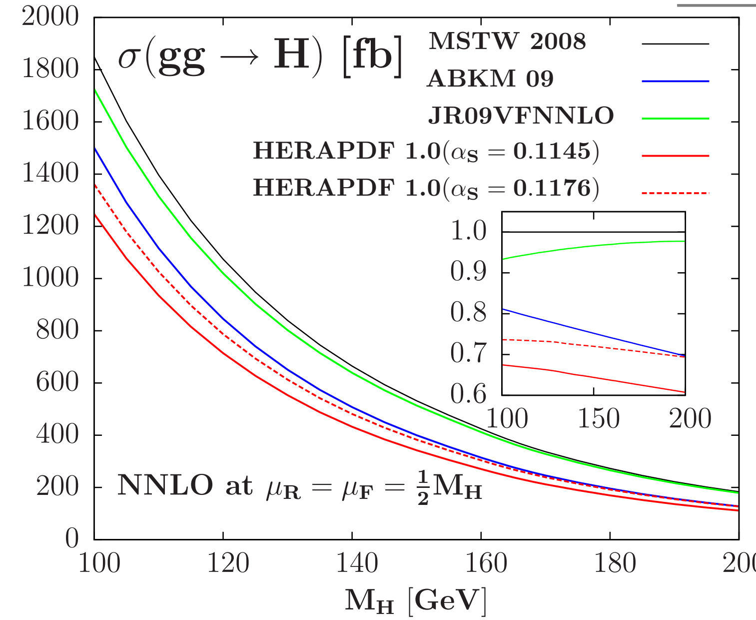
3. Higgs at Tevatron: PDFs and α_s

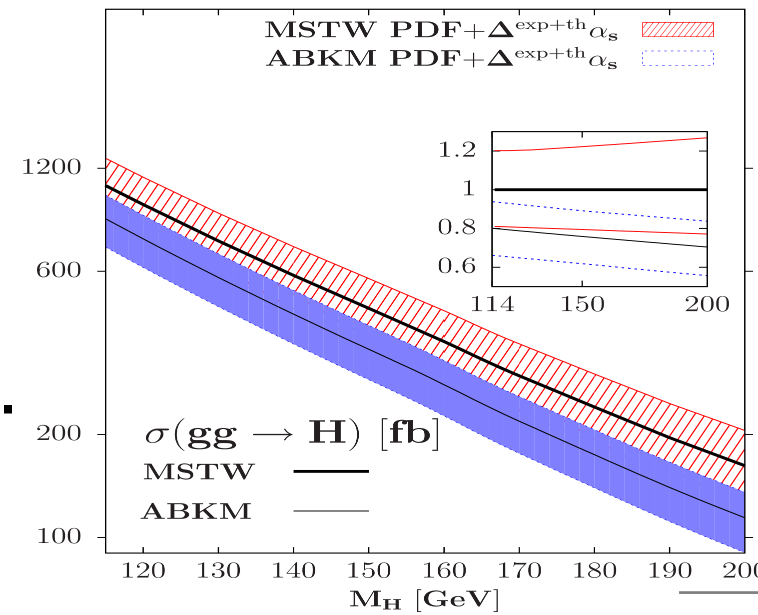
PDF uncertainties estimated using the 2x20 MSTW PDF sets including errors.
$\Rightarrow$ 5–10% PDF error (idem for CTEQ)

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 $M_{loop} \gg M_H$

Good for t–loop (see R. Harlander)

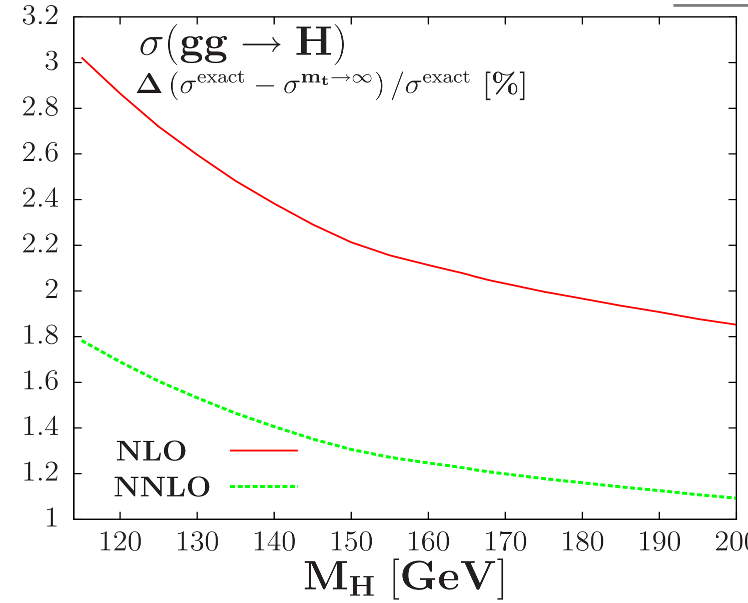
Not good for b–loop ($\approx$ 10% at LO)

Estimate error from NLO (known exactly)

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

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

Uncertainty of a few percent...



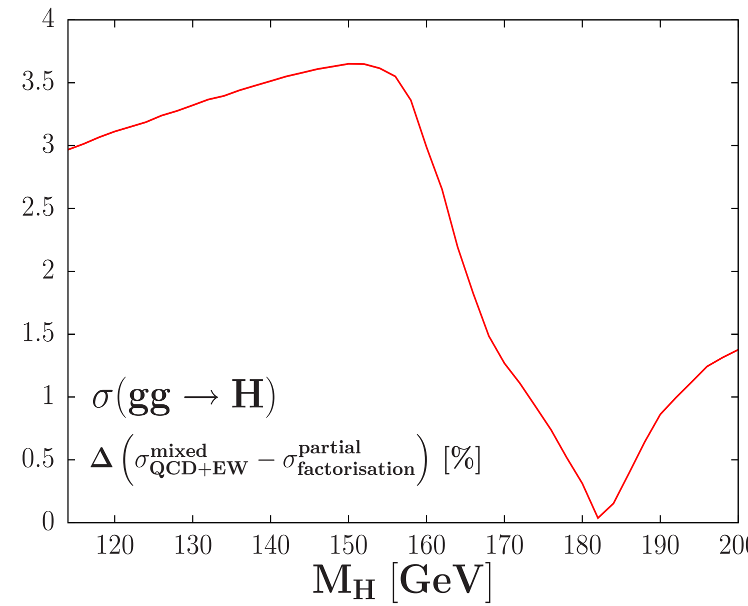
Mixed EW+QCD RadCor at NNLO:

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

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

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

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 $\frac{\max}{\min}\sigma(\mu_{F/R})$

and apply on them PDF+$\Delta^{\rm ex+th}\alpha_s$ errors

In $gg \to H$:$\approx \pm$40% total uncertainty

much larger than assumed by CDF/D0

In $p\bar{p} \to HV$:$\approx \pm$10% uncertainty

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

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

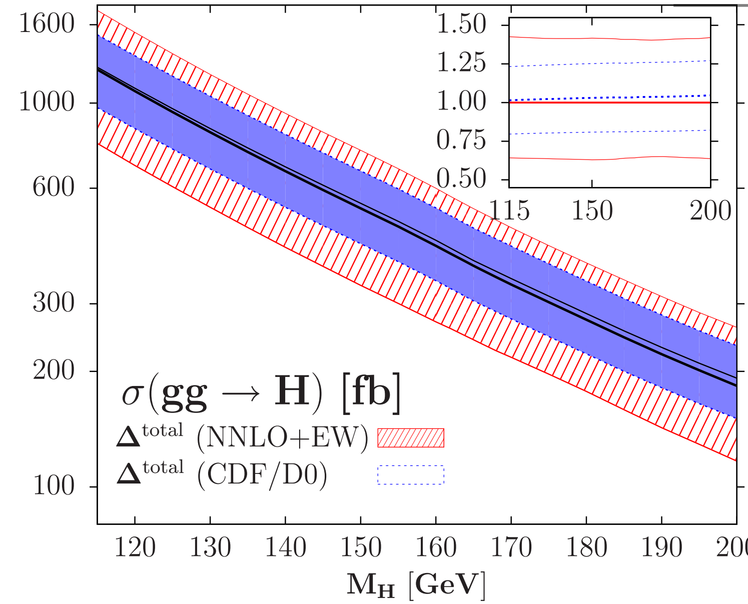
(to be added to those on σ)

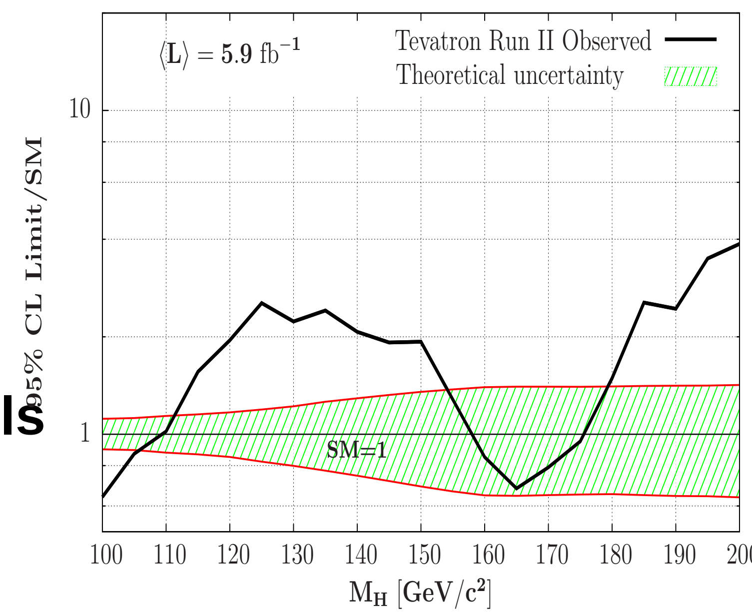
Combination of all channels:

– 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

ℓ**HC:** $\sqrt{s} = 7$ TeV, $\int \mathcal{L} = 1\ \mathrm{fb}^{-1}$

Same production as at Tevatron:

– rates $\approx$ 10 times higher

– much larger backgrounds

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

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

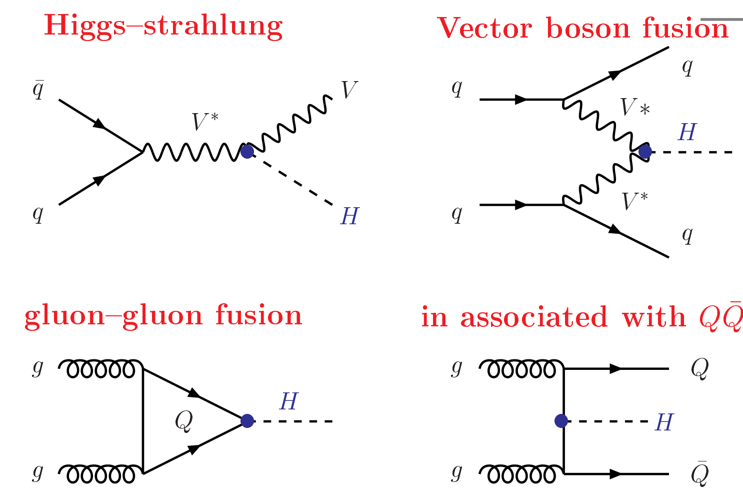
($\approx$ 200 of Higgs signal events)

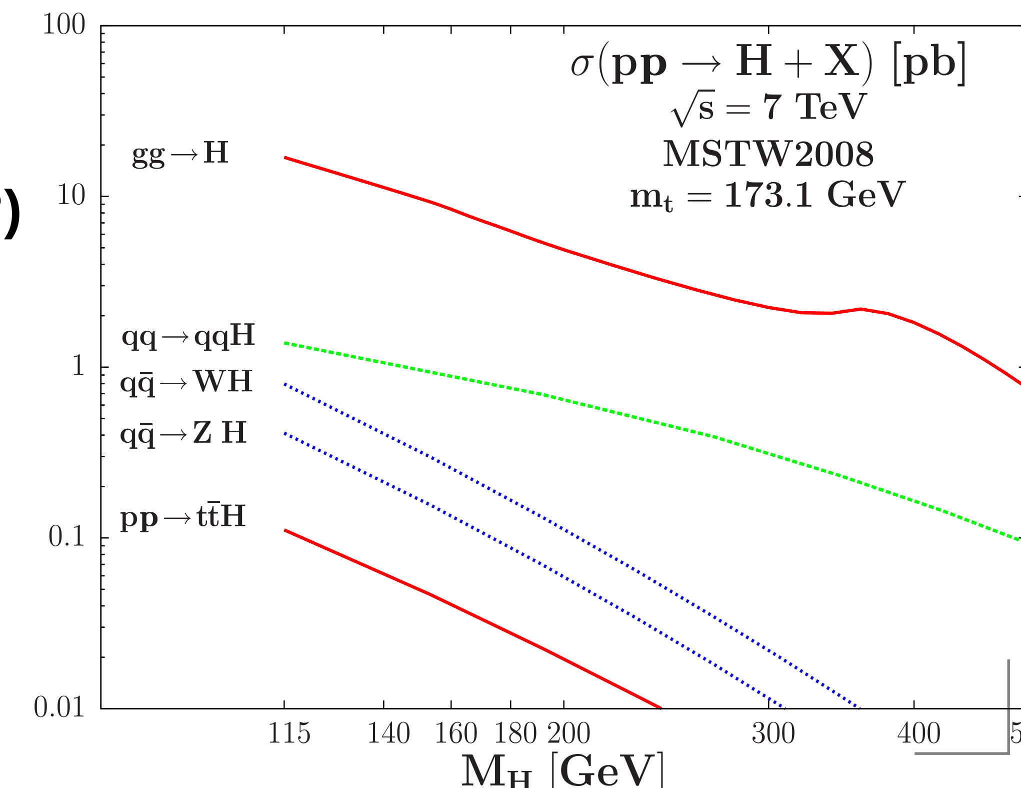
– Hqq, Htt hopeless

– to much bckg from Wbb,Zbb (?)

Compared to the Tevatron case:

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





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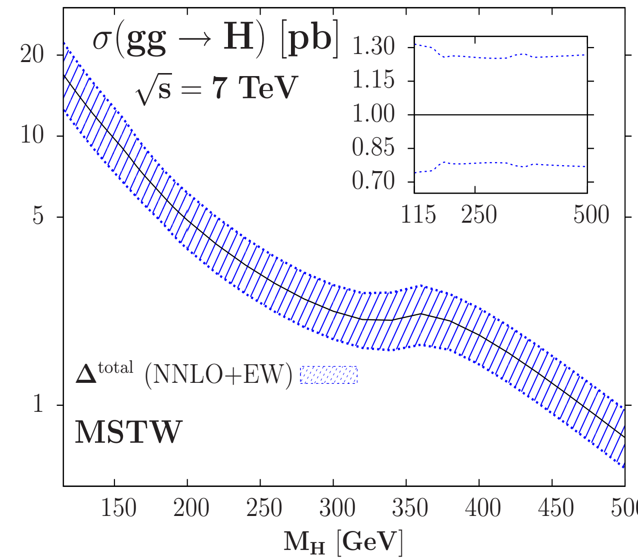
Compared to the Tevatron case:

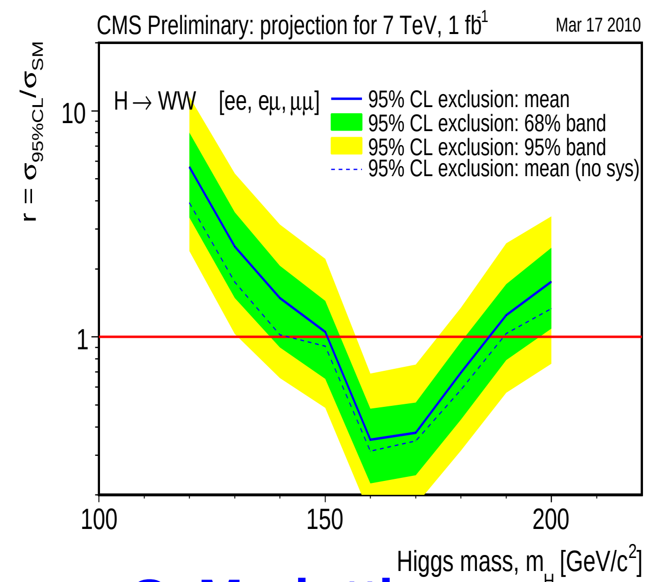
- **Smaller HO: $K_{NNLO} = 2, 5$**
- **Scale: κ=2 enough $\Rightarrow$ 15%**
- **PDF errors smaller, $\approx$10%**
- **Again 5% error from EFT**
- **Include error on BR($H \to WW$)**

Combined uncertainty $\approx \pm$30%

excludes $M_H \approx 150 - 190$ GeV

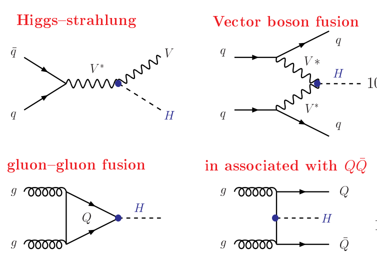
Baglio+AD

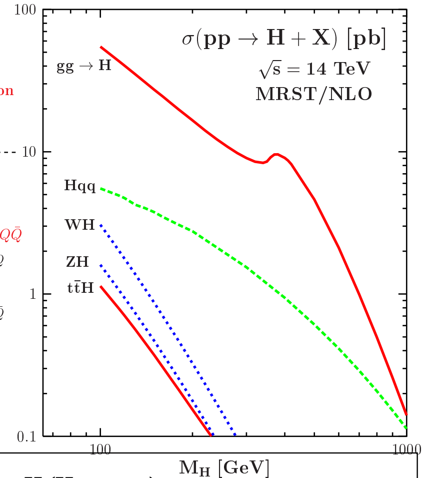


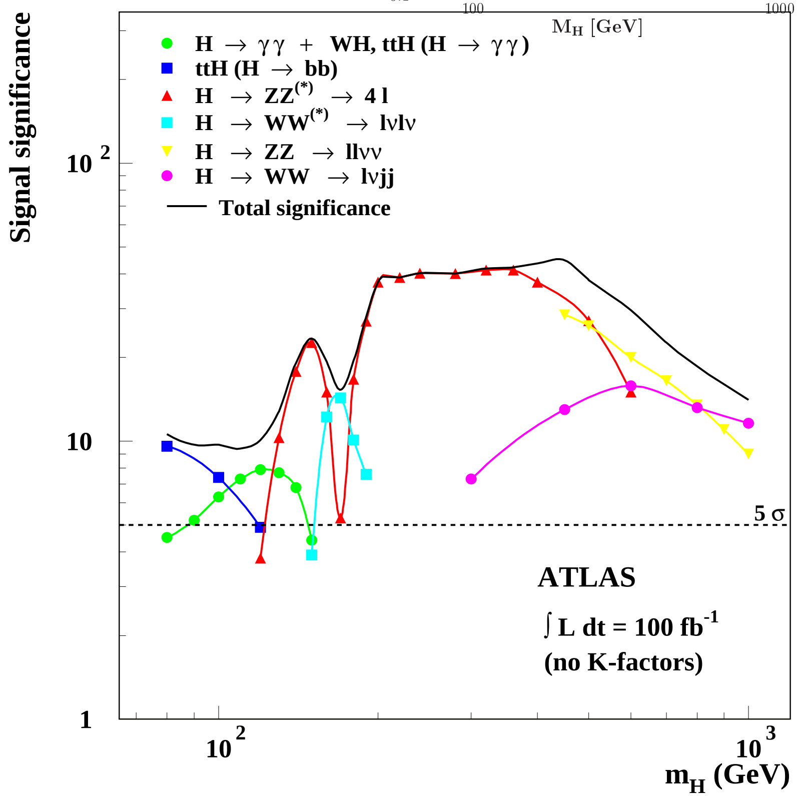


C. Mariotti

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