The Higgs in the Standard Model: 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)$\times$U(1) gauge invariant way:

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

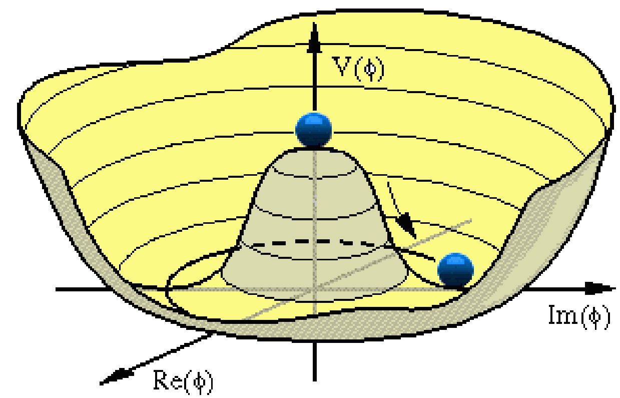
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

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

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

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

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



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

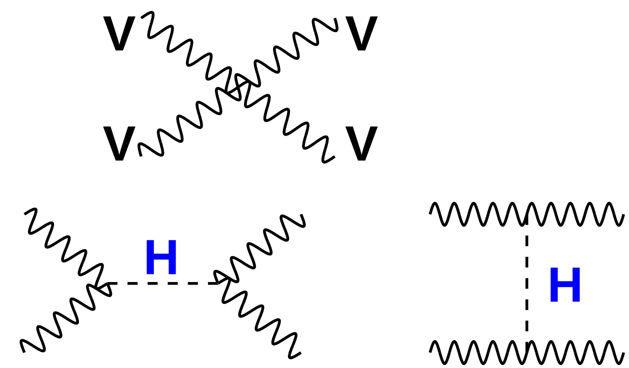
Theory constraints from energy/M_H range up to which the SM is valid

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

$$|A_0(VV \to VV)| \xrightarrow{s \gg M_H^2} \frac{M_H^2}{8\pi v^2} < \frac{1}{2}$$
$$\Rightarrow M_H \lesssim 710 \text{ GeV}$$

(OK with lattice: $M_H \lesssim 650$ GeV)

$$|A_0(VV \to VV)| \xrightarrow{s \ll M_H^2} \frac{s}{32\pi v^2} < \frac{1}{2}$$
$$\Rightarrow \sqrt{s} \lesssim 1.2 \text{ TeV}$$



- **Triviality and stability bounds:**

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

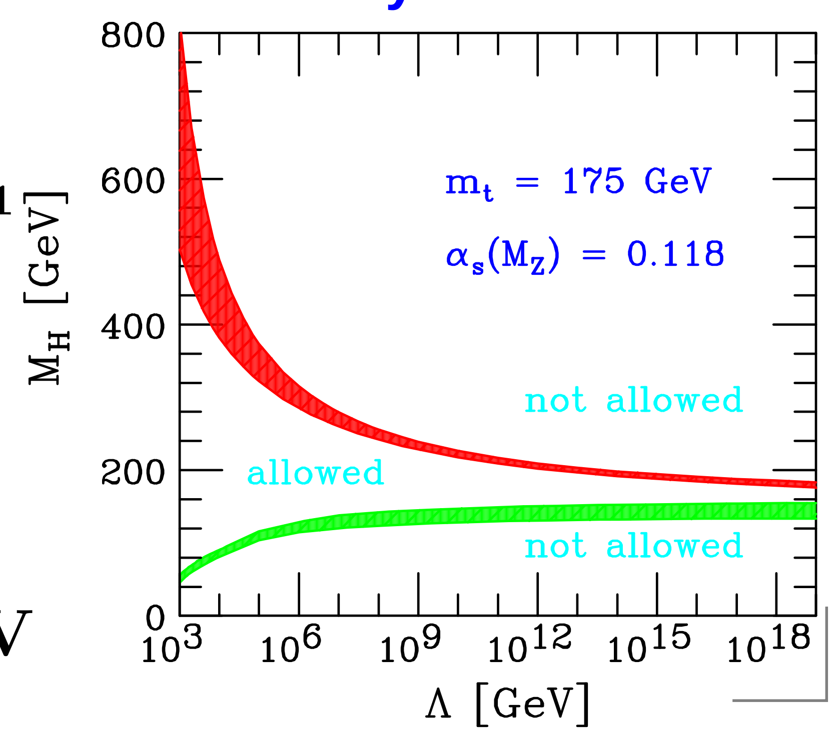
$\lambda \gg 1$ coupling blows up (Landau pole)

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

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

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

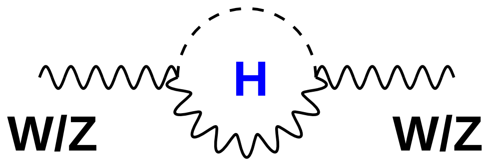
Hambye+Riesselman



1. The Higgs in the SM: constraints on M_H

Indirect constraints from high–precision data

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**

New Gfitter: $M_H \lesssim 153$ **GeV@95%CL**

?What top mass should be in the fit?

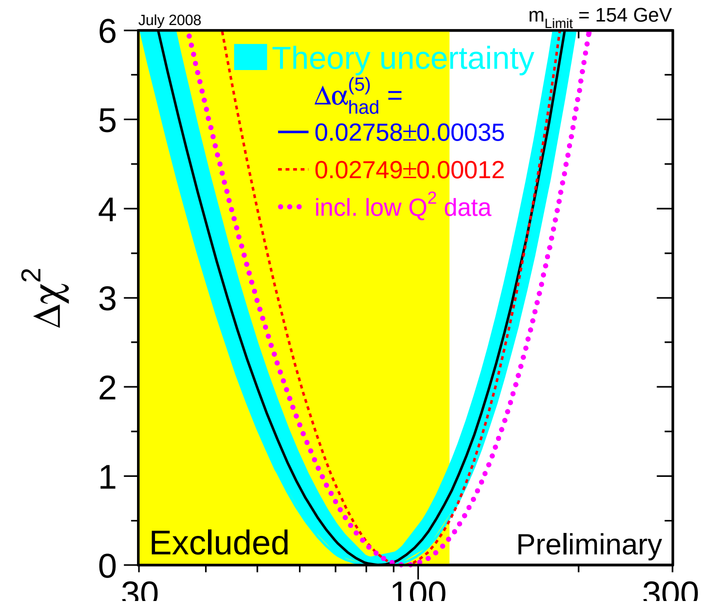
High precision data: on–shell mass

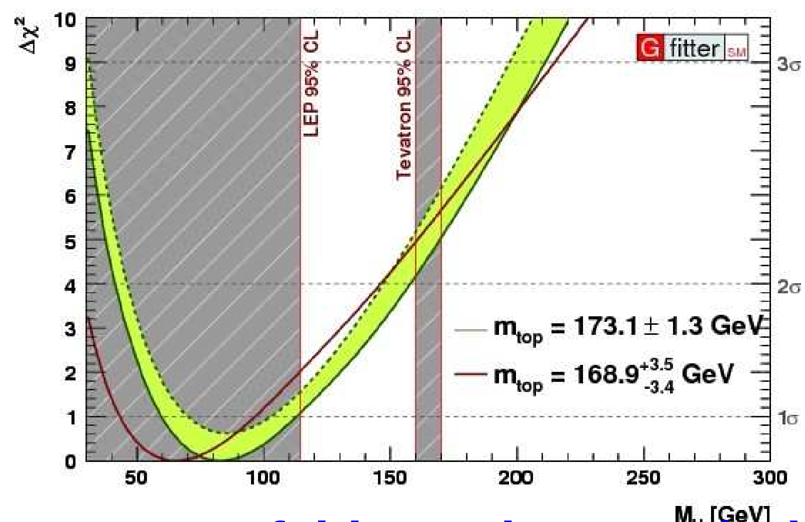
Tevatron: OS, $\overline{\rm MS}$ **mass? 10 GeV diff.**

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

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

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





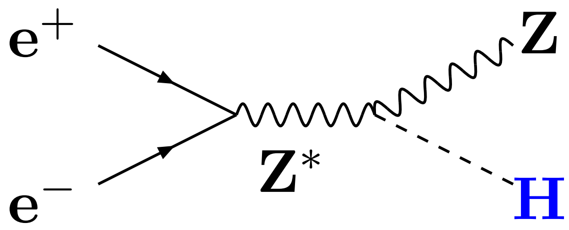
Langerfeld, Moch, Uwer (09).

1. The Higgs in the SM: constraints on M_H

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

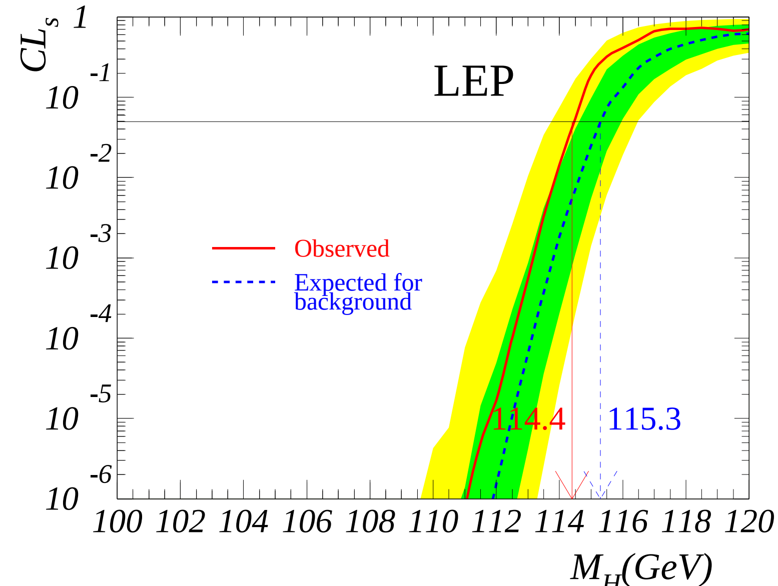
- **Direct searches at LEP:**

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



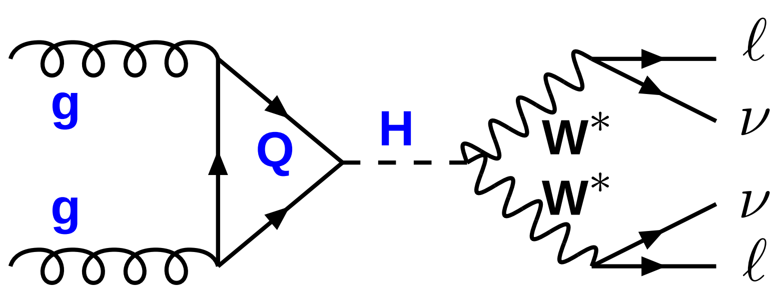
We have a limit at 95% CL:

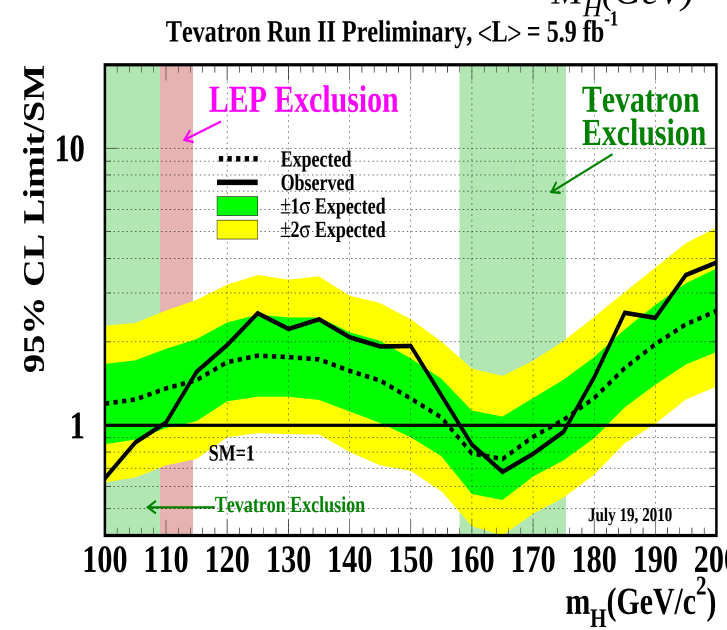
$$M_H > 114.4 \text{ GeV}$$



- **New results from the Tevatron:**

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





exclude $M_H = 158 - 175$ GeV

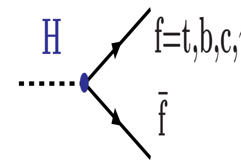
(to be discussed in detail later).

2. Higgs decays

Higgs couplings proportional to particle masses: once $\mathrm{M_H}$ is fixed,

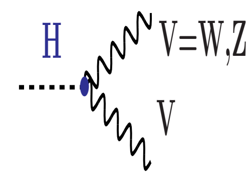
- the profile of the Higgs boson is determined and its decays fixed,
- the Higgs has tendancy to decay into heaviest available particle.

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

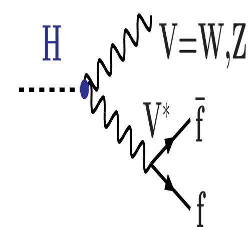


- only $\mathrm{b\bar{b}}, \mathrm{c\bar{c}}, \tau^+\tau^-, \mu^+\mu^-$ and eventually $\mathrm{t\bar{t}}$
- QCD RC very large $\Rightarrow \mathrm{m_b^{\overline{MS}}(M_H^2)} \sim 3\,\mathrm{GeV}$.
- also direct QCD (3-loops) and EW (1-loop).

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

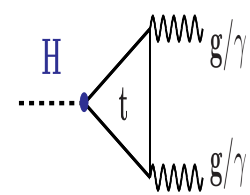


- above $2\mathrm{M_Z}$ th. dominant: BR(WW)=$\frac{2}{3}$, BR(ZZ)=$\frac{1}{3}$
- $\mathrm{M_H} \gg \mathrm{M_V}$: very large $\Gamma_\mathrm{VV} \propto \mathrm{M_H^3}$ $(\Gamma_\mathrm{tt} \propto \mathrm{M_H})$
- below th. decays possible/important $(\mathrm{m_b} \ll \mathrm{M_V})$!



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

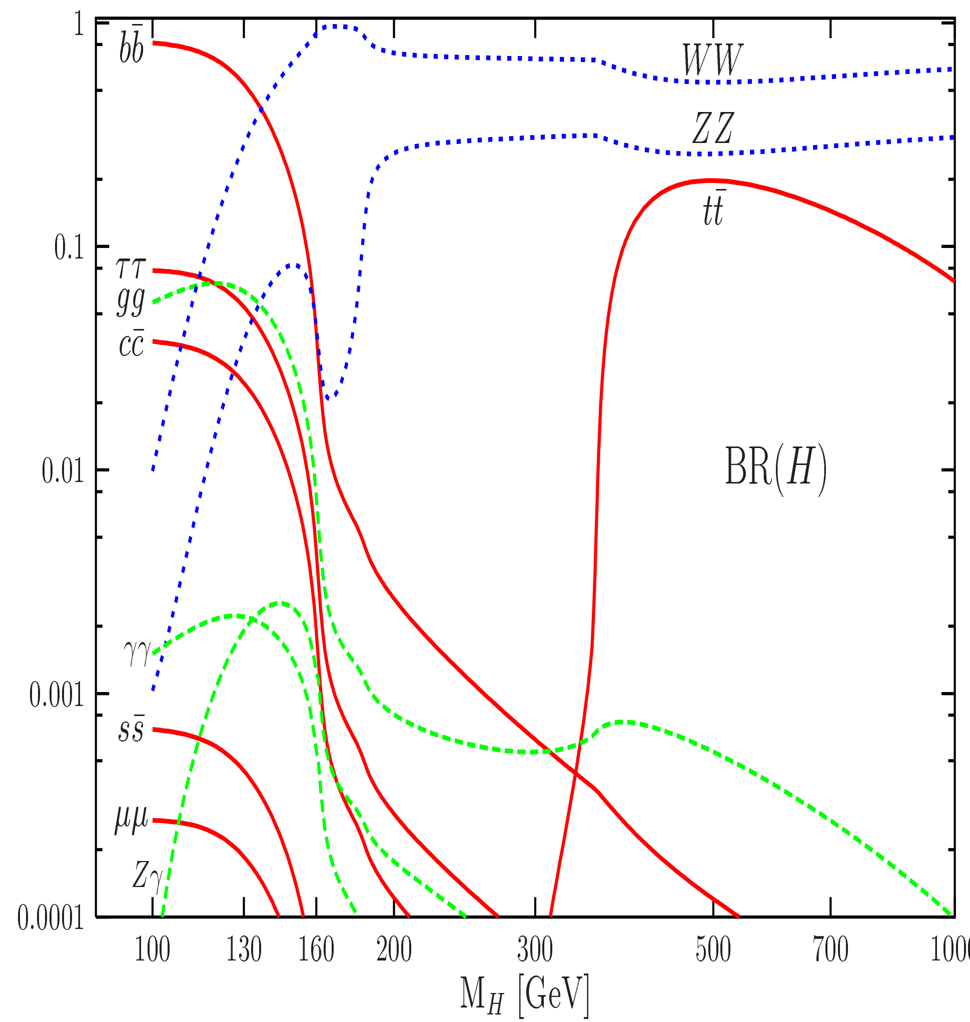
- heavy particles do not decouple! mainly t(W) loops
- $\mathrm{H \to gg}$: large (#2) RC; reverse of $\mathrm{gg \to H}$!
- $\mathrm{H} \to \gamma\gamma$: much smaller ($\propto \alpha^2/\alpha_s^2$) but clean!



2. Higgs decays: branching ratios

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

- **'Low mass range', $M_H \lesssim 130$ GeV:**
  - $H \to b\bar{b}$ dominant, BR = 60–90%
  - $H \to \tau^+\tau^-, c\bar{c}, gg$ BR= a few %
  - $H \to \gamma\gamma, \gamma Z$, BR = a few permille.
- **'High mass range', $M_H \gtrsim 130$ GeV:**
  - $H \to WW^*, ZZ^*$ up to $\gtrsim 2M_W$
  - $H \to WW, ZZ$ above (BR $\to \frac{2}{3}, \frac{1}{3}$)
  - $H \to t\bar{t}$ for high M_H; BR $\lesssim 20\%$.
- **Total Higgs decay width:**
  - $\mathcal{O}$(MeV) for $M_H \sim 100$ GeV (small)
  - $\mathcal{O}$(TeV) for $M_H \sim 1$ TeV (obese).



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

2. Higgs decays: total width

Total decay width: $\Gamma_H \equiv \sum_X \Gamma(H \to X)$

- **'Low mass range', $M_H \lesssim 130$ GeV:**
- $H \to b\bar{b}$ **dominant, BR = 60–90%**
- $H \to \tau^+\tau^-, c\bar{c}, gg$ **BR= a few %**
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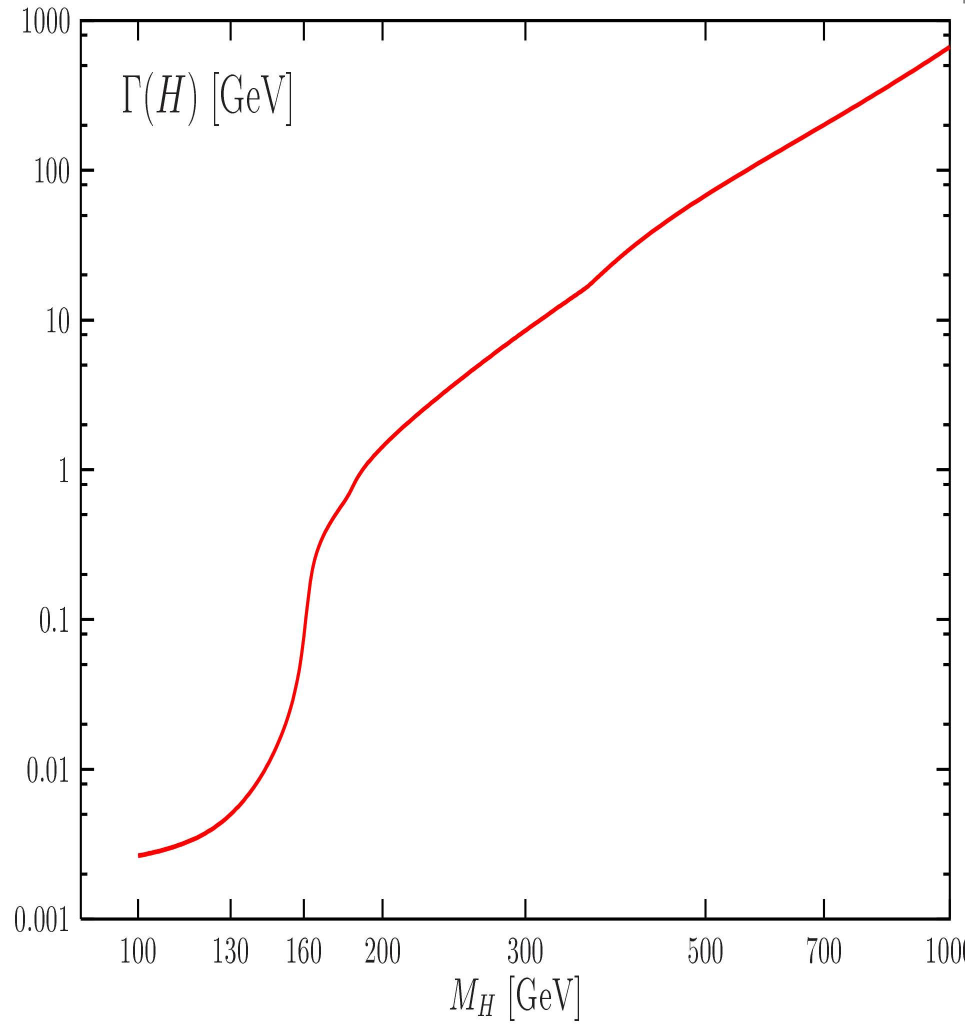


HDECAY: AD, Kalinowski, Spira (95–10). Includes all relevant higher orders.

2. Higgs decays: theory uncertainties

However: there are theoretical uncertainties....

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

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

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

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

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

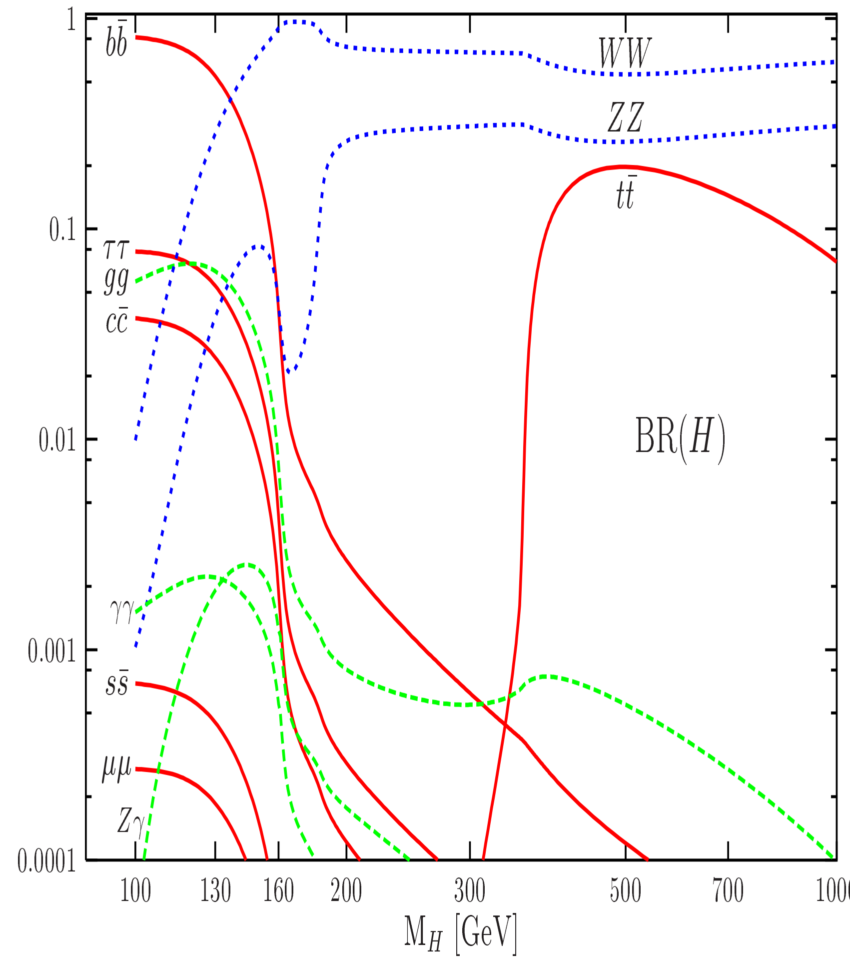
$\alpha_s(M_Z^2) = 0.1171 \pm 0.0028$ **@NNLO**

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

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

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

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



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

(QCD effects appear at high orders).

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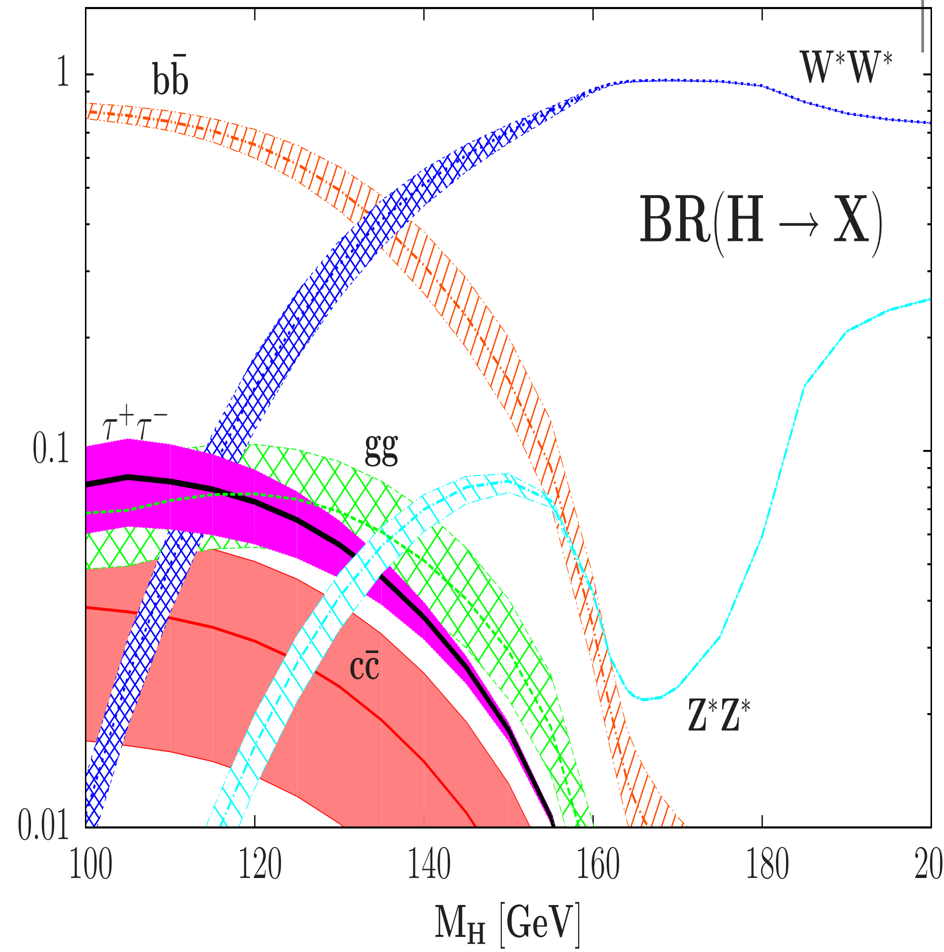


Baglio,AD

Include all items $\Rightarrow$ large uncertainties!

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

3. The Higgs at the Tevatron

• $\mathbf{M_H \gtrsim 140\ GeV:\ gg \to H}$

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

LO[a] already at one loop

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

EFT NLO[c]: good approx.

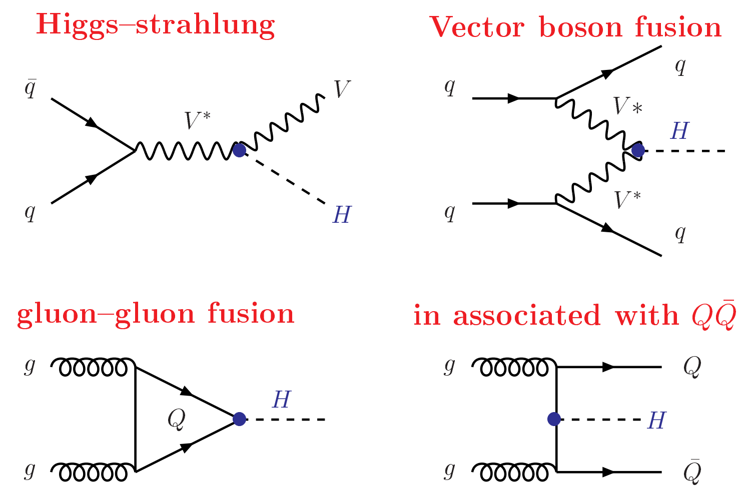
QCD: EFT NNLO[d]: $\mathrm{K} \approx$3 (2)

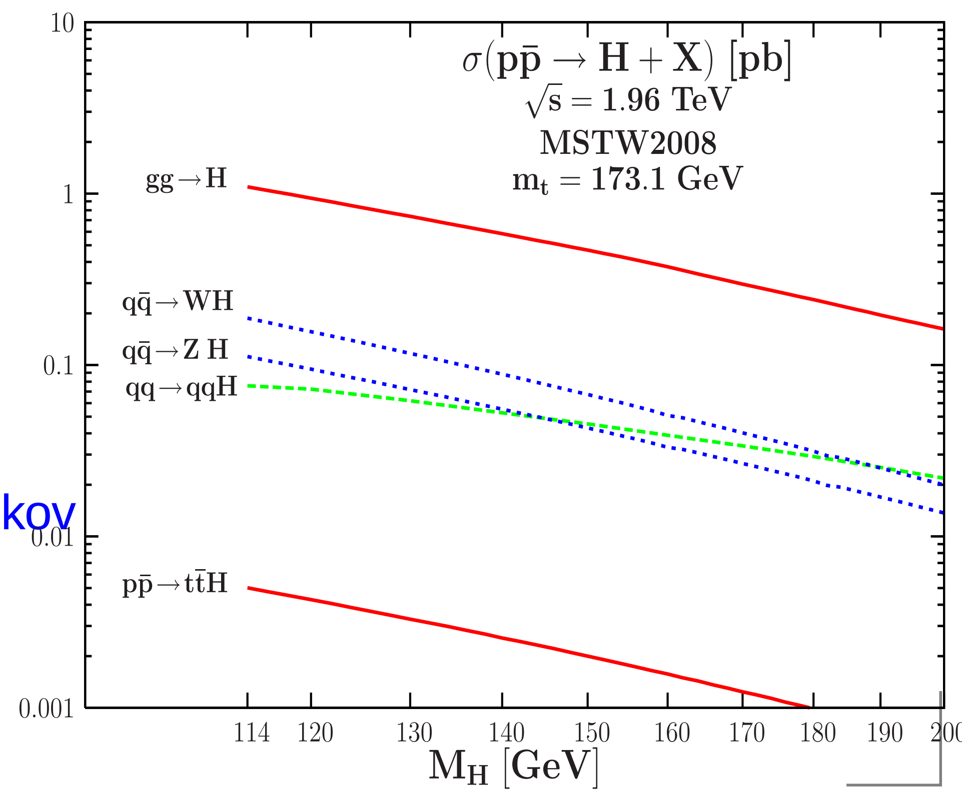
EFT NNLL[e]: $\approx +$10% (5%)

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

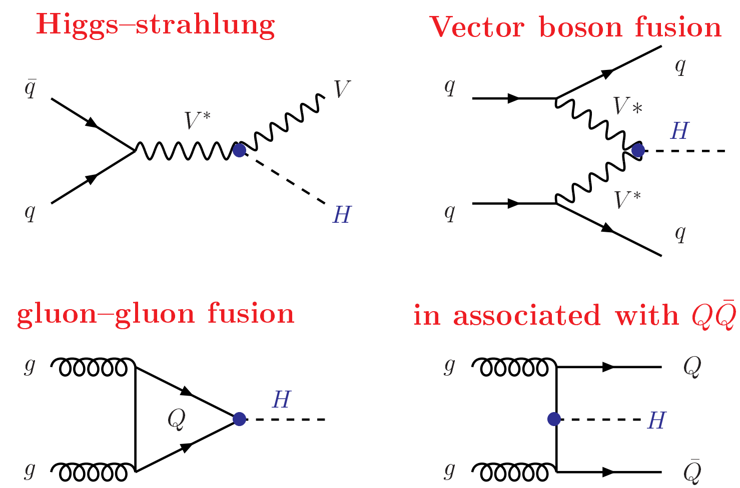
exact NLO QCD[b] : $K \approx$1.4

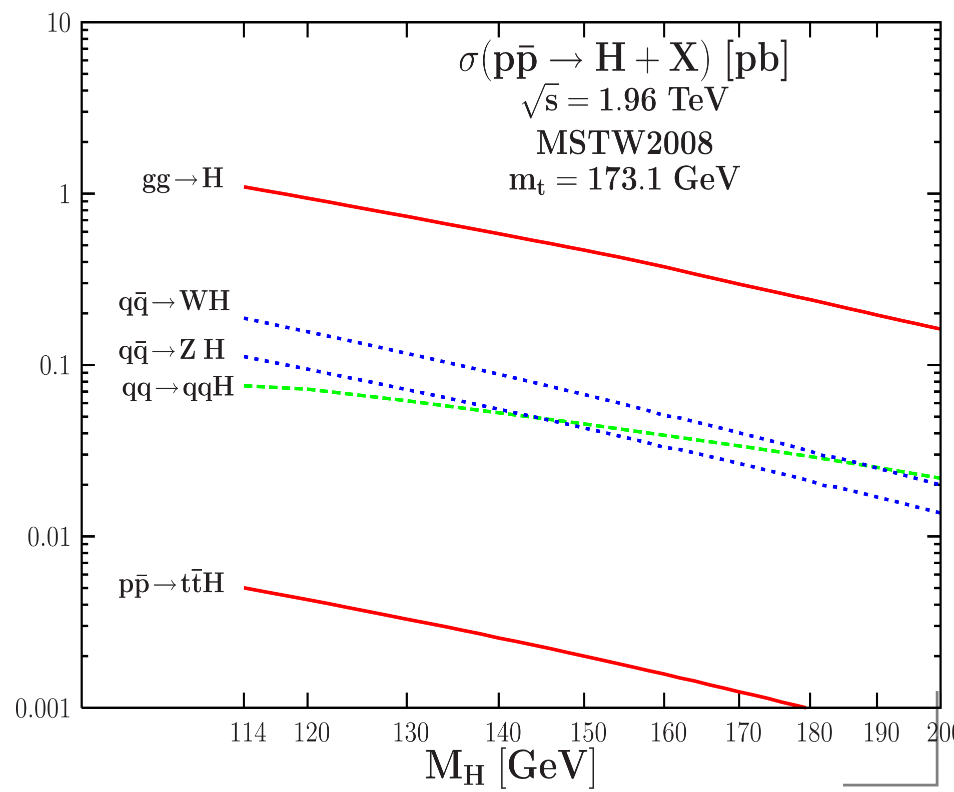
exact NNLO QCD[c]: $K \approx$1.5

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.





[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 updates[d] for $gg \to H$ (2009) but not for $p\bar{p} \to HV$ (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; Ahrens et al;

3. Higgs at Tevatron: higher orders and scale variation

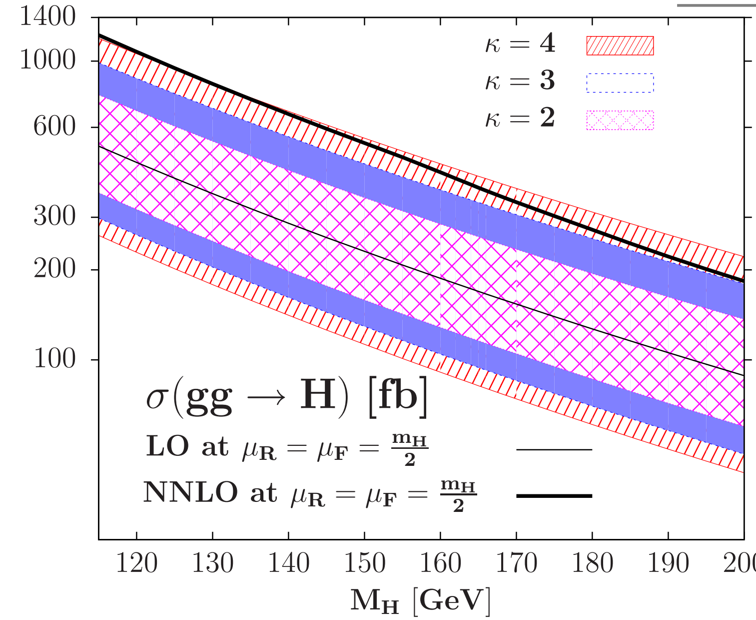
Higher orders (HO) guessed by varying
μ_R, μ_F arround central scale $\mu_0 = \frac{1}{2} M_H$:

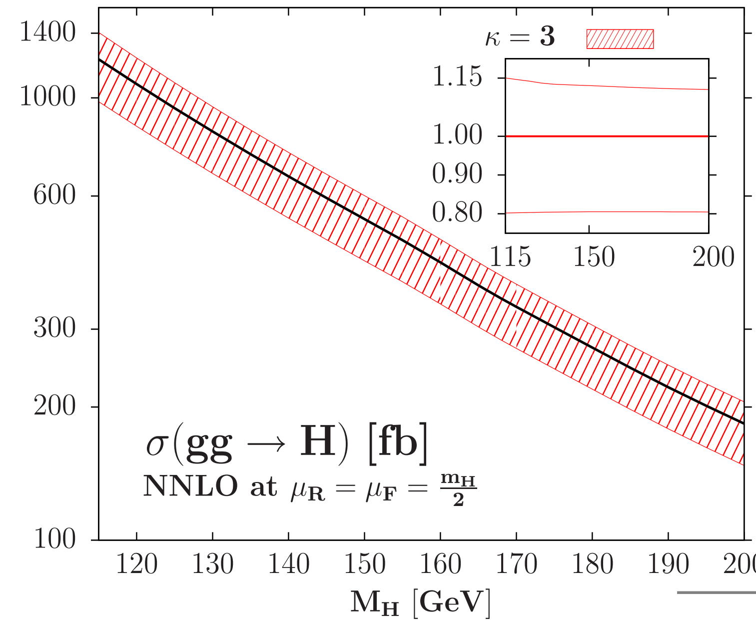
$$\mu_0/\kappa \leq \mu_R, \mu_F \leq \kappa\mu_0$$

(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_{LO}
For σ_{LO} band to catch σ_{NNLO} 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)

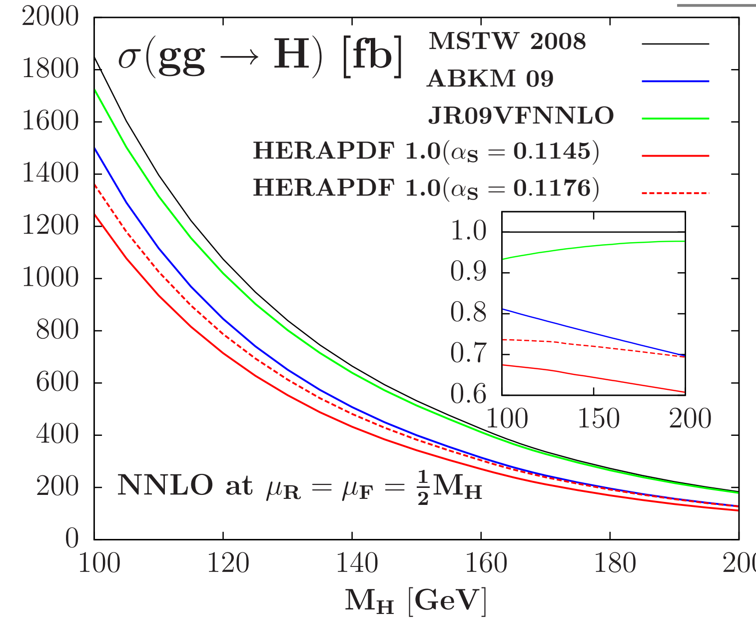
However, also other sets: HERA, ABKM, JR, which are also at NNLO, so let us try:

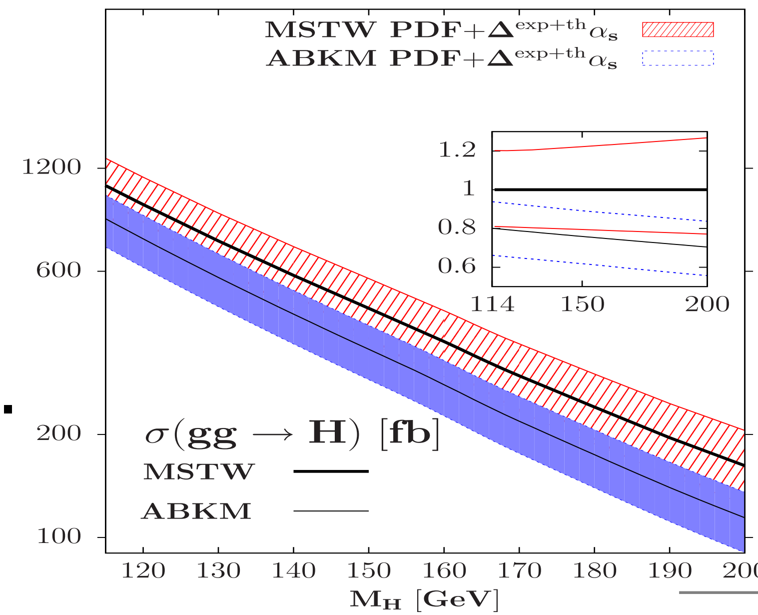
$\Rightarrow$ very large differences!!

(# 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$0.002 (NNLO)
Include all: PDF+$\Delta^{\rm exp}\alpha_s \oplus$PDF+$\Delta^{\rm th}\alpha_s$
MSTW/ABKM now consistent (not HERA!).
But total PDF error is now $\approx$ 15–20% !
(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)

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

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

Uncertainty of a few percent...

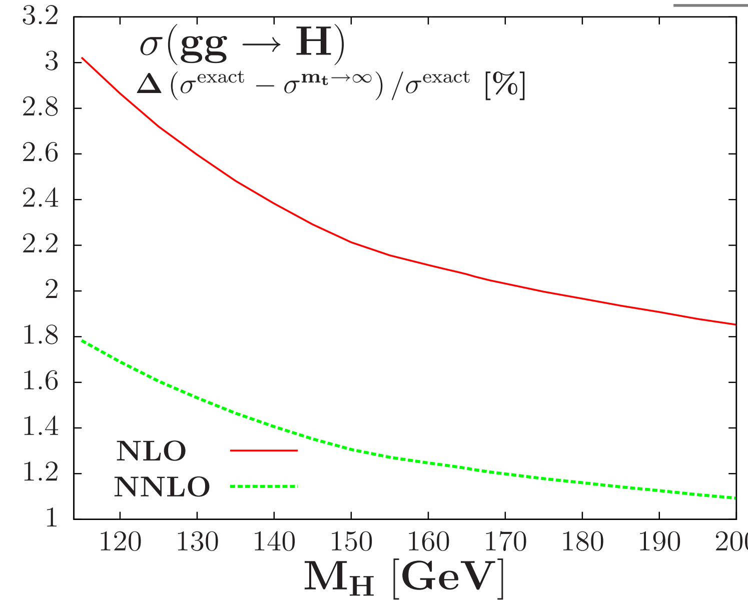
Mixed EW+QCD RadCor at NNLO:

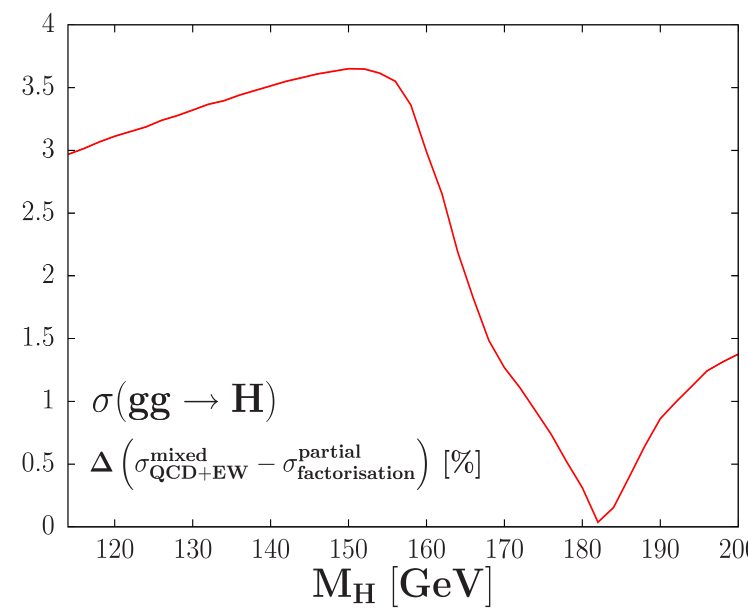
EFT approach with $\mathrm{M_{W/Z}} \gg \mathrm{M_H}$

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

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

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 $^{\max}_{\min}\sigma(\mu_{\mathbf{F/R}})$

and apply on them PDF+$\Delta^{\mathbf{ex+th}}\alpha_{\mathbf{s}}$ errors

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

much larger than assumed by CDF/D0

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

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

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

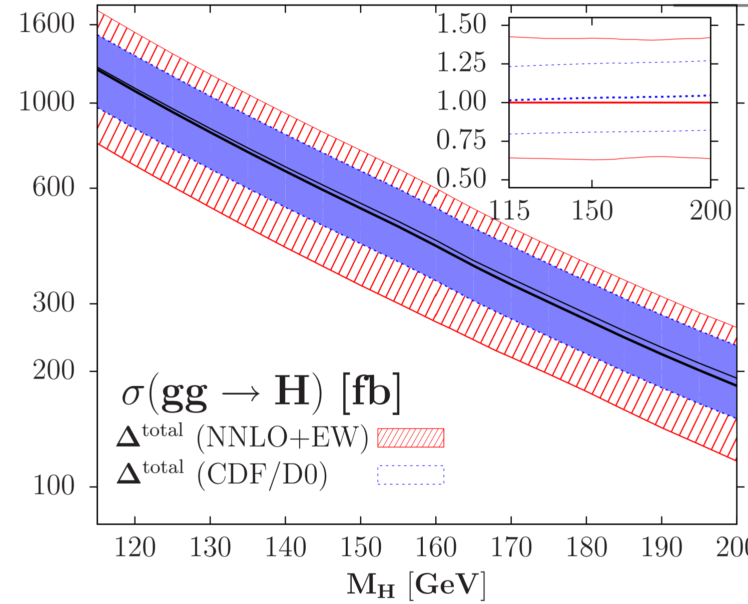
(to be added linearly to those on σ)

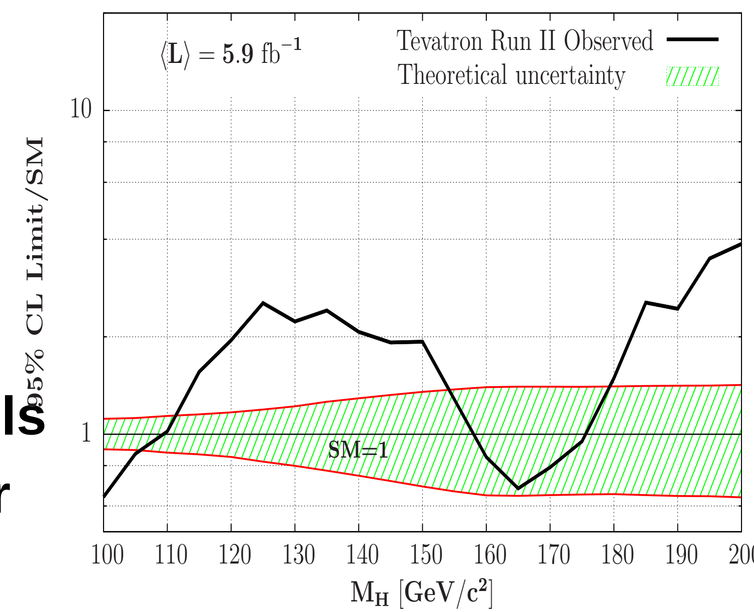
Combination of all channels:

– assume same acceptance for all channels

– assume no effect of CDF/D0 theory error

No Higgs mass is excluded with errors!





4. The Higgs at the ℓHC

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

Same production as at Tevatron:

– rates $\approx$ 10 times higher

– much larger backgrounds

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

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

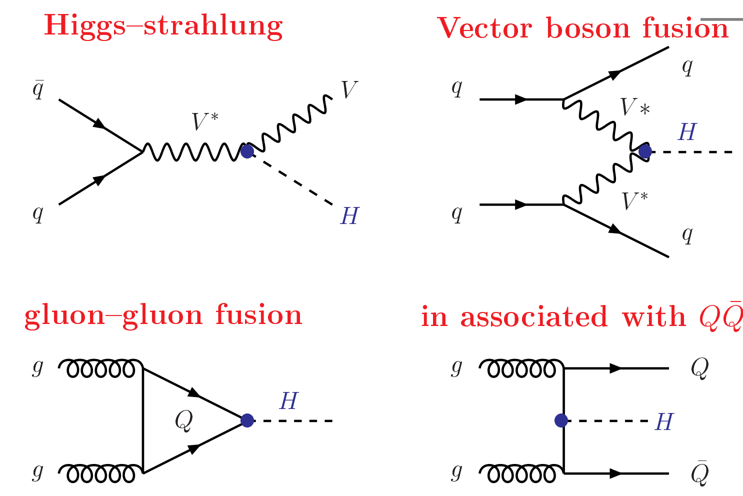
($\approx$ 200 of Higgs signal events)

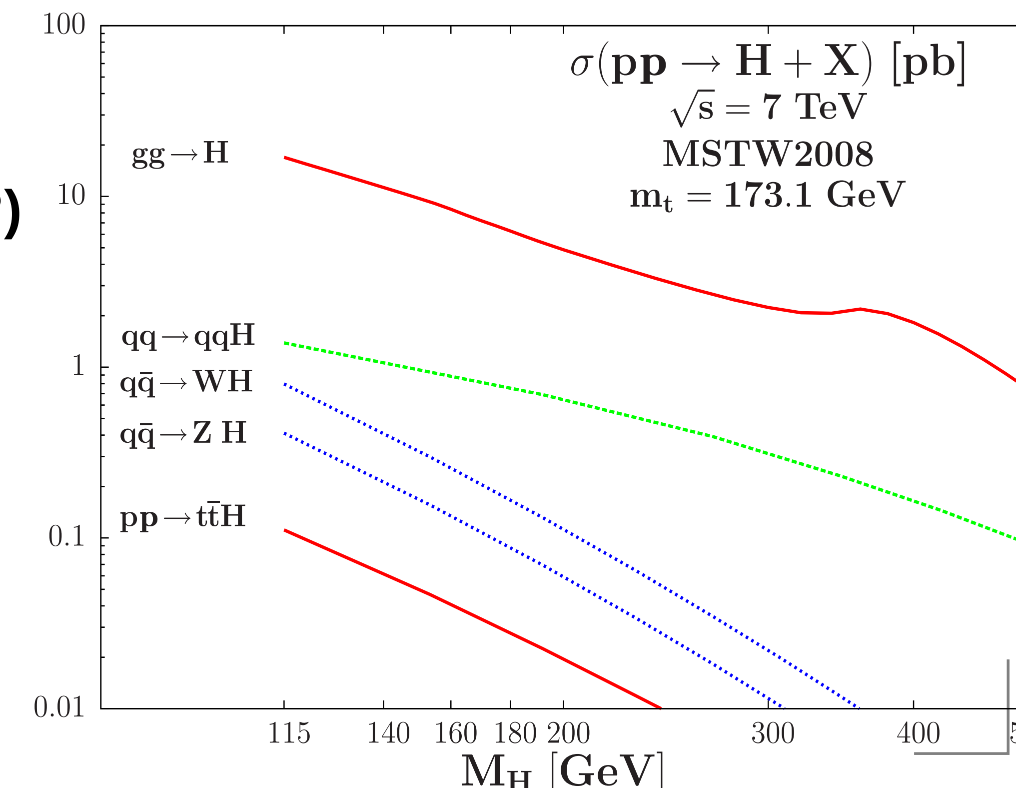
– Hqq, Htt hopeless

– to much bckg from Wbb,Zbb (?)

Compared to the Tevatron case:

- **Smaller HO:** $K_{NNLO} = 2, 5$
- **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 $\approx$ 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)

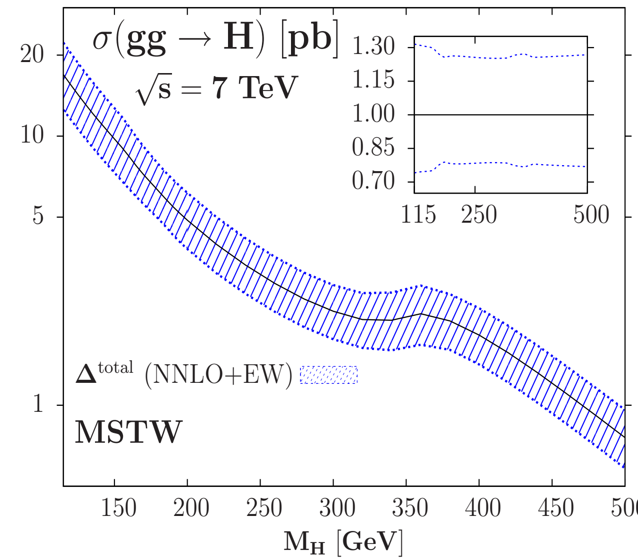
Compared to the Tevatron case:

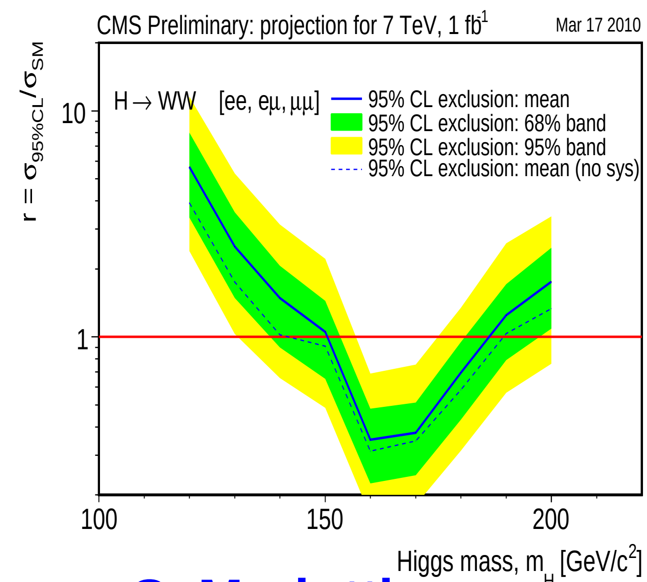
- **Smaller HO: $K_{NNLO} = 2,5$**
- **Scale: κ=2 enough $\Rightarrow$ 15%**
- **PDF errors smaller, $\approx$10%**
- **Again 5% error from EFT**
- **Include error on BR($H \to WW$)**

Combined uncertainty $\approx \pm$30%

excludes $M_H \approx 150-190$ GeV

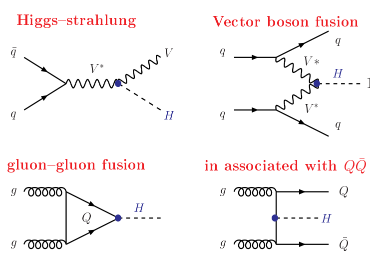
Baglio+AD

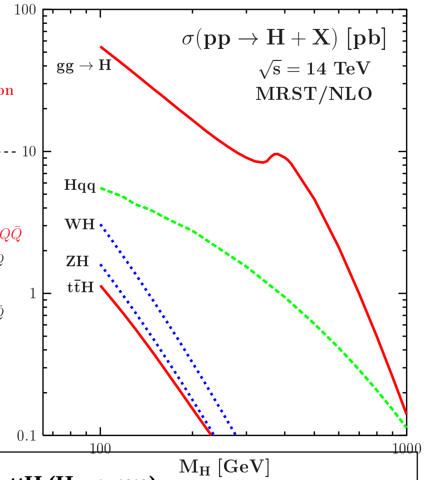


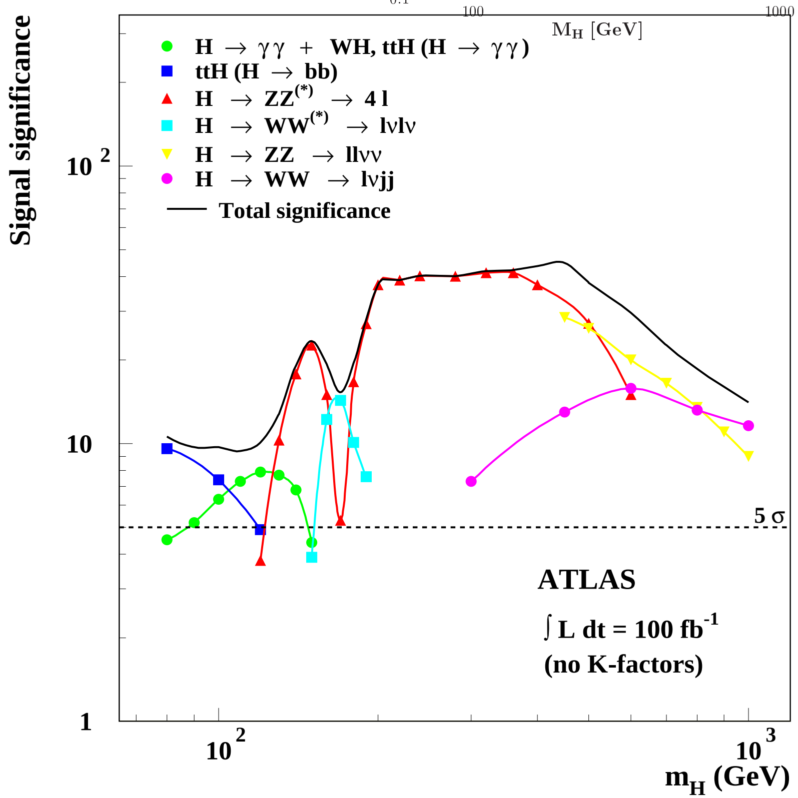


C. Mariotti

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.