Inclusive Higgs Cross-Sections at the LHC

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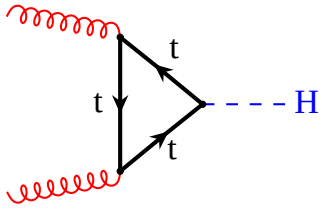
Outline

- Higgs Cross Sections:
  - Gluon Fusion (NNLO, Standard Model, MSSM)
  - $H + b\bar{b}$ (and $H + t\bar{t}$)
  - Higgs Strahlung (NNLO + EW)

- Not covered:
  - Weak Boson Fusion ($\longrightarrow$ D. Zeppenfeld)
  - Distributions ($\longrightarrow$ M. Grazzini, K. Melnikov, ...)
  - Backgrounds ($\longrightarrow$ T. Binoth, K. Ellis, ...)
  - ...

Gluon Fusion

- Standard Model



Gluon Fusion

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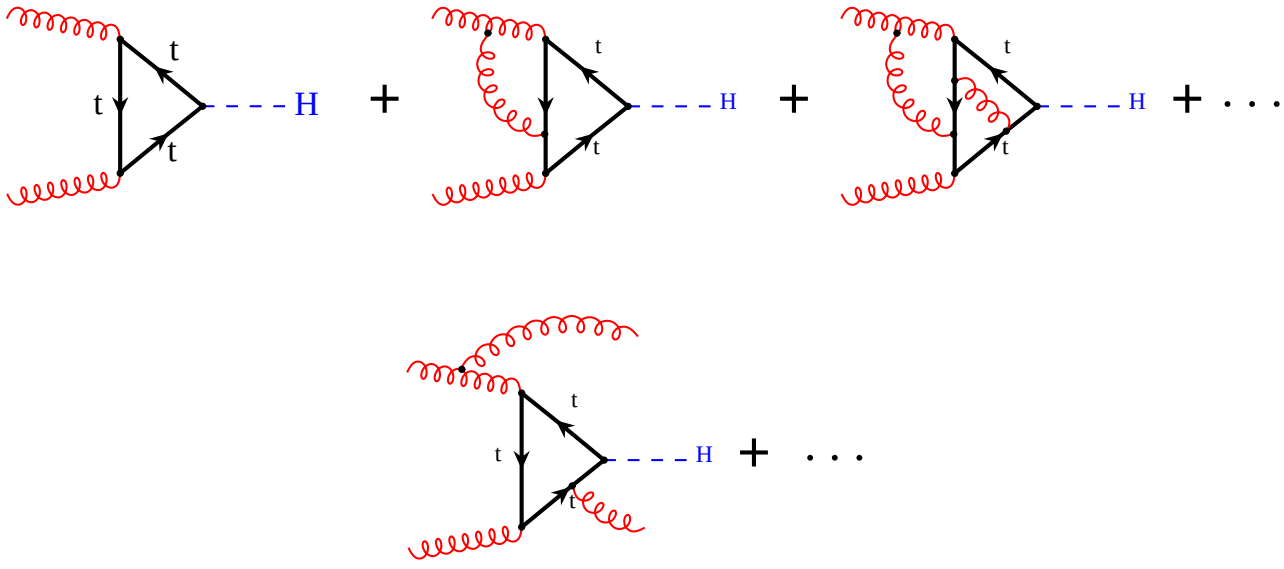

Gluon Fusion

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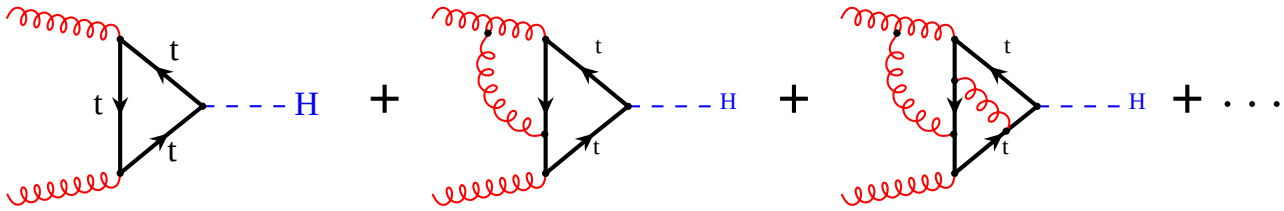
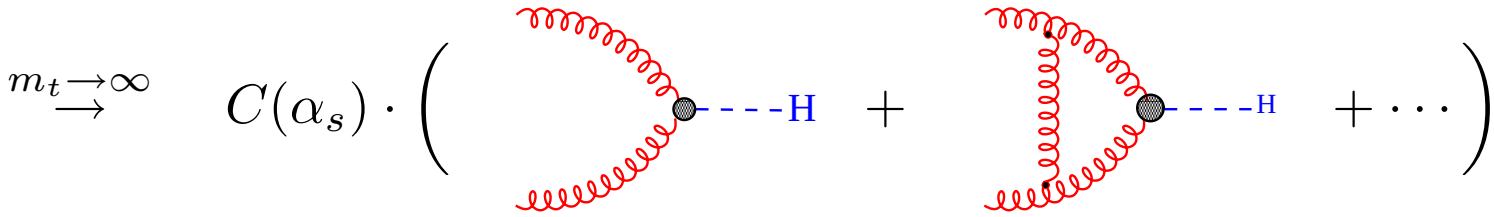


heavy top limit:

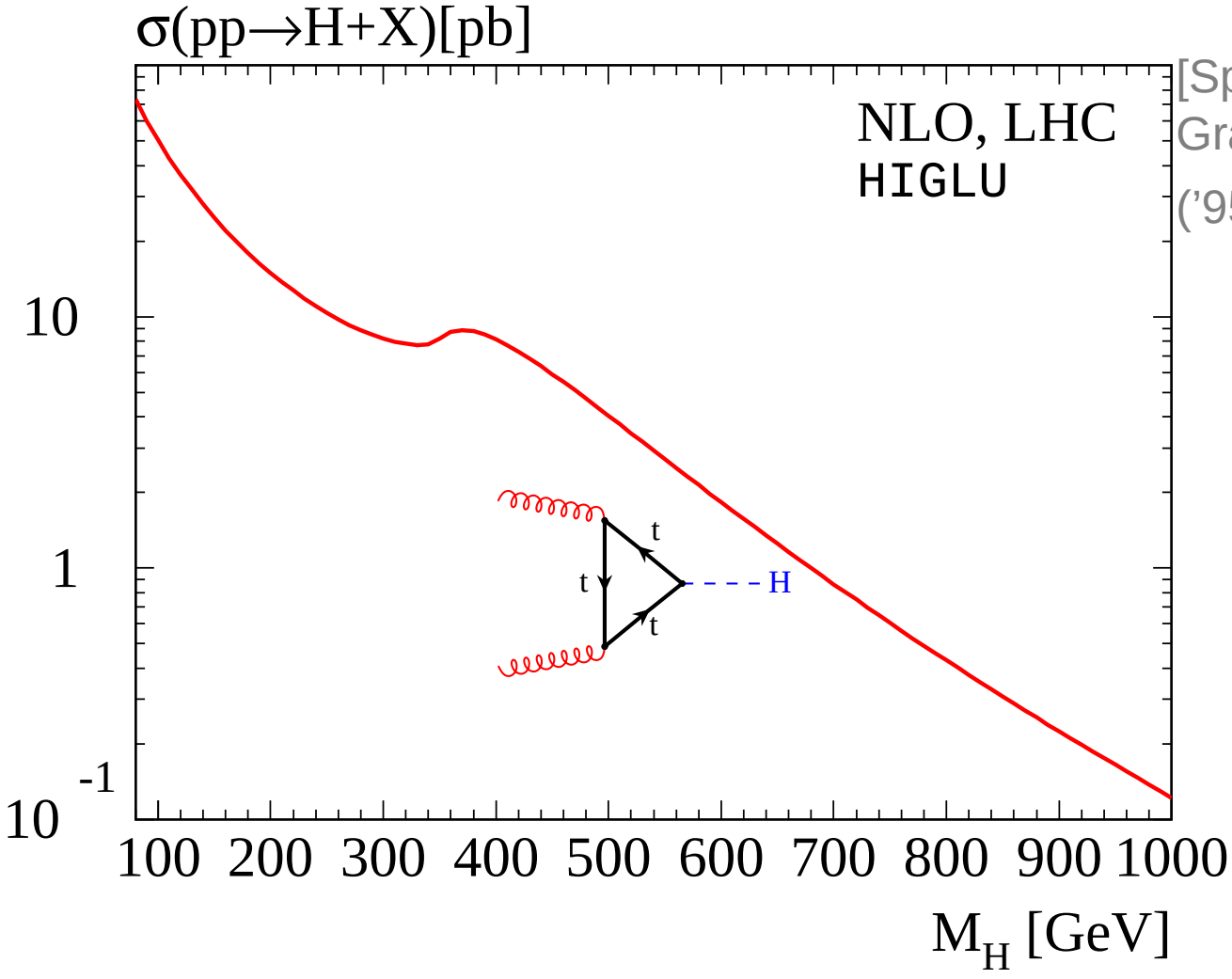


$$\sigma^{\infty} \equiv \frac{\sigma^{(0)}(m_t)}{\sigma^{(0)}(m_t \to \infty)} \cdot \sigma(m_t \to \infty)$$

$C(\alpha_s)$: [Chetyrkin, Kniehl, Steinhauser ('97)]
[Krämer, Laenen, Spira ('98)]

Heavy top limit

(no bottom loops)



[Spira, Djouadi, Graudenz, Zerwas ('95)]

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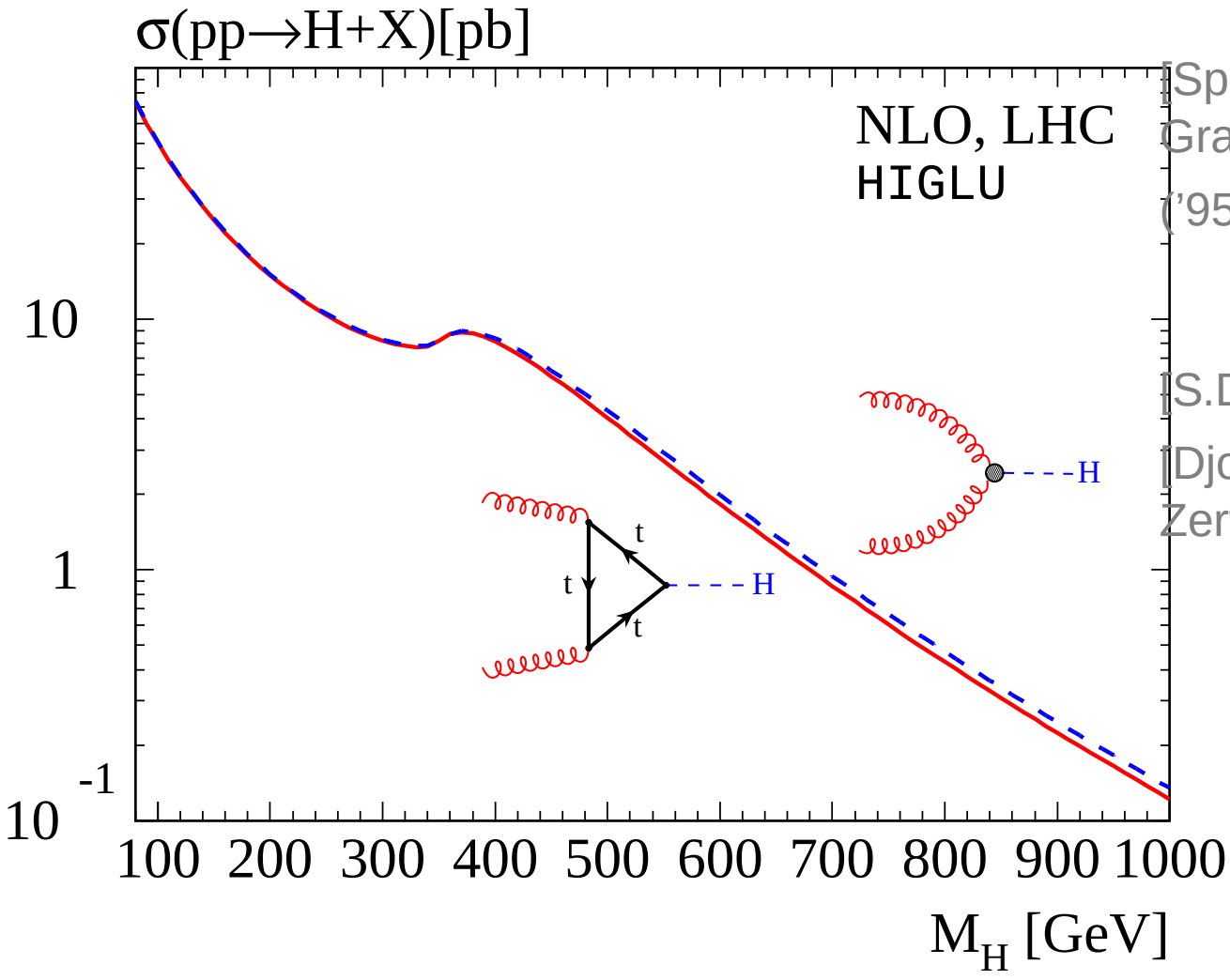
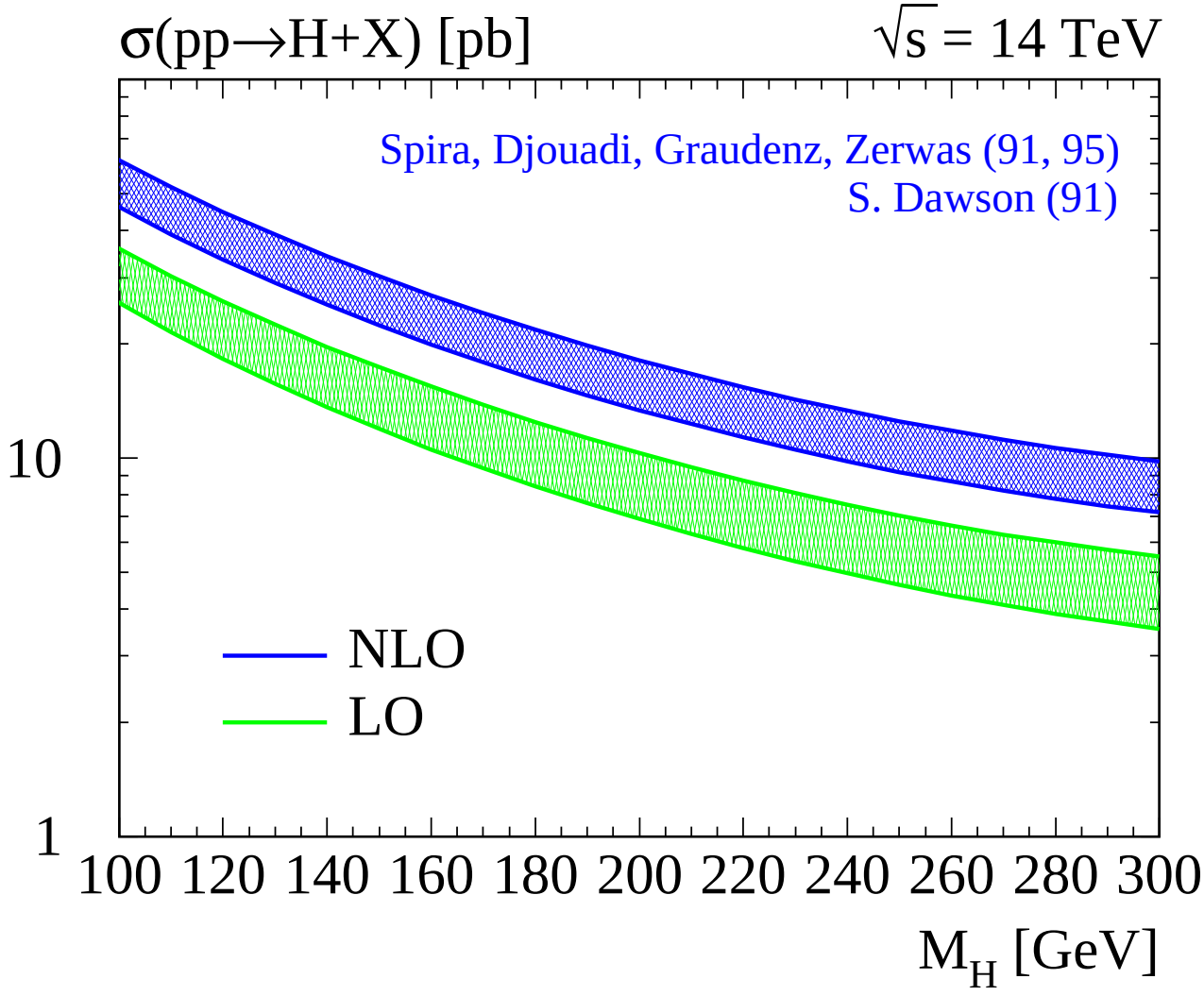


[Spira, Djouadi, Graudenz, Zerwas ('95)]

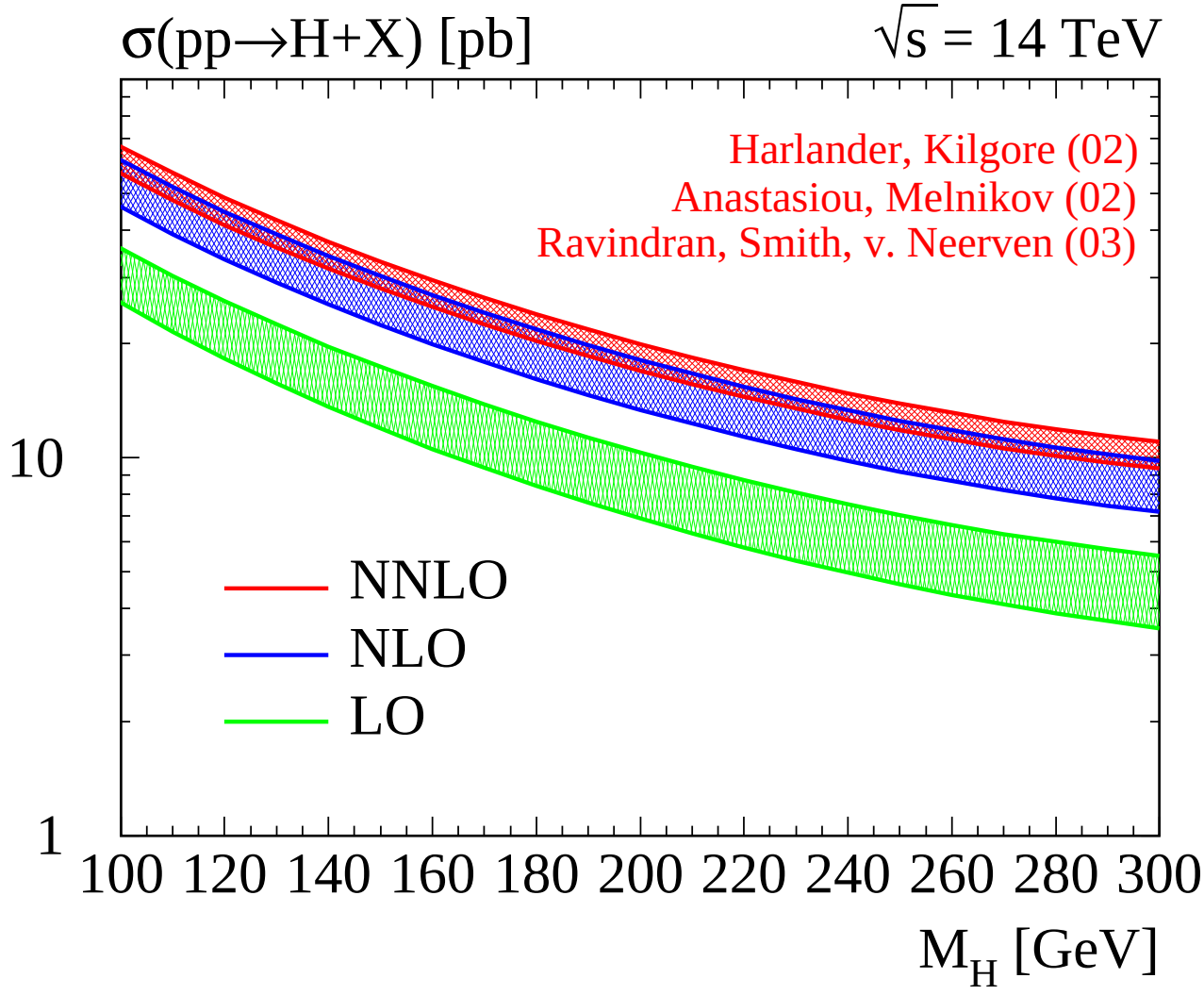
[S.Dawson ('91)]

[Djouadi, Spira, Zerwas ('91)]

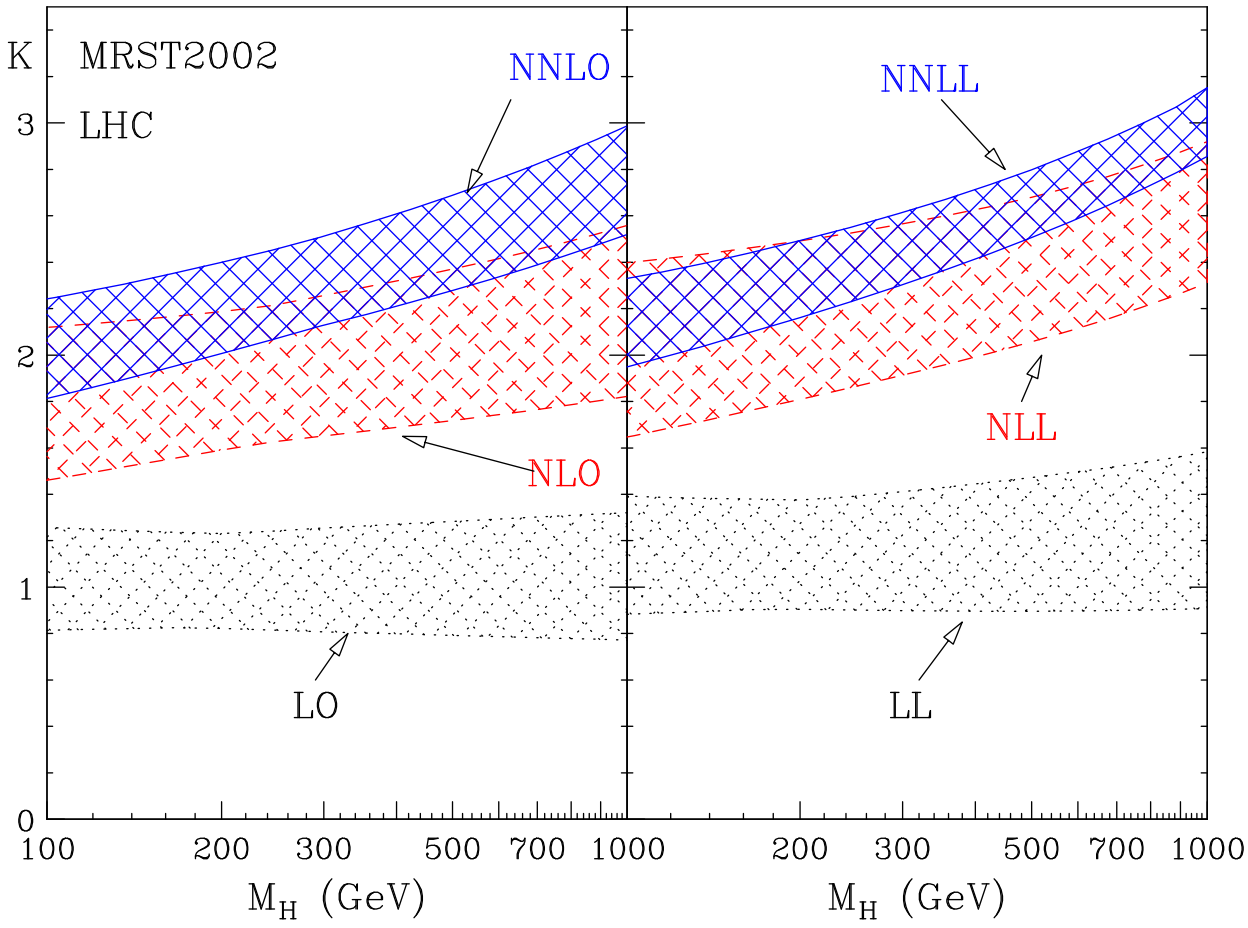
Cross section



Cross section



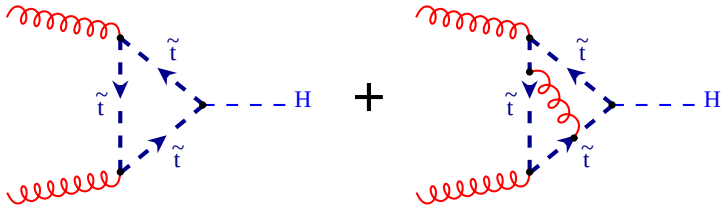
Resummation



[Catani, de Florian, Grazzini, Nason ('03)]

Gluon Fusion

- SUSY: Squarks



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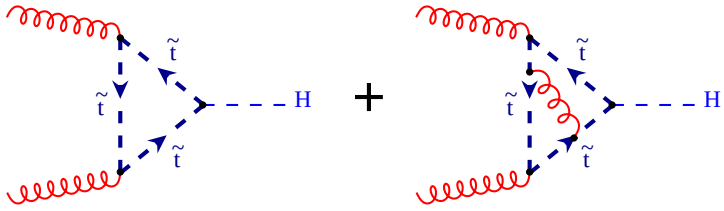

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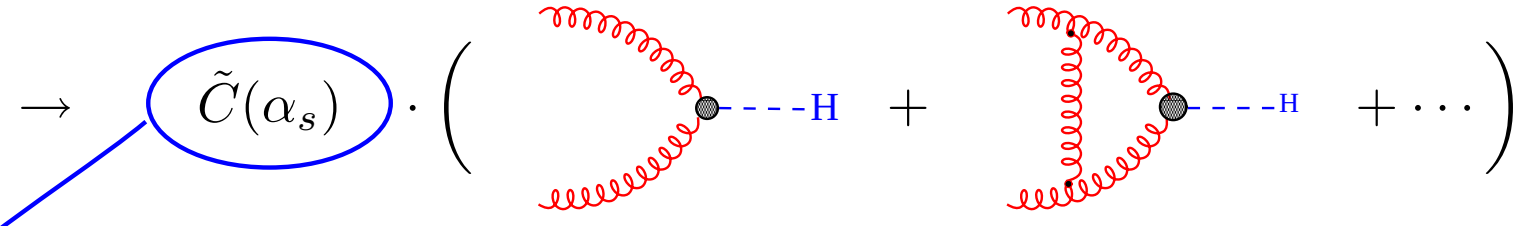

[Dawson, Djouadi, Spira ('96)]

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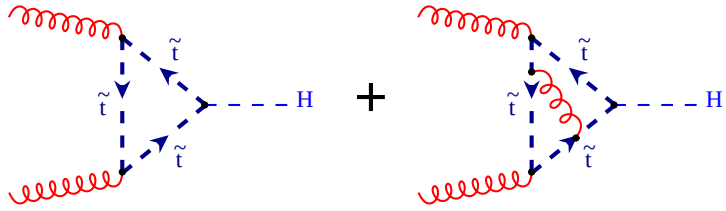

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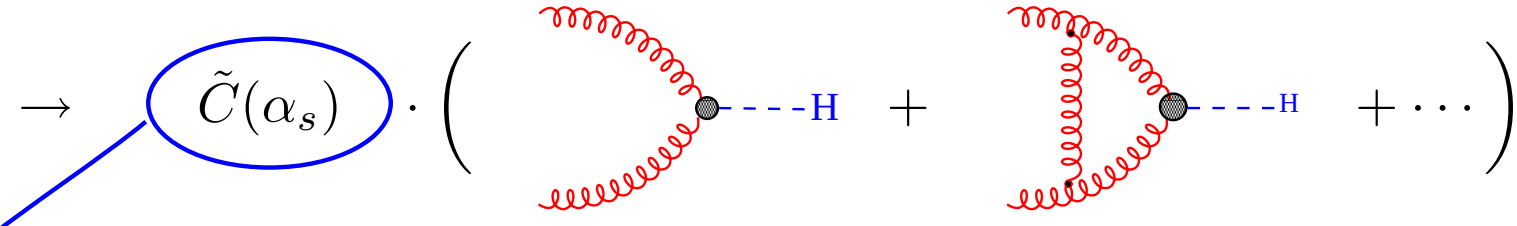

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but: not SUSY!

Gluon Fusion

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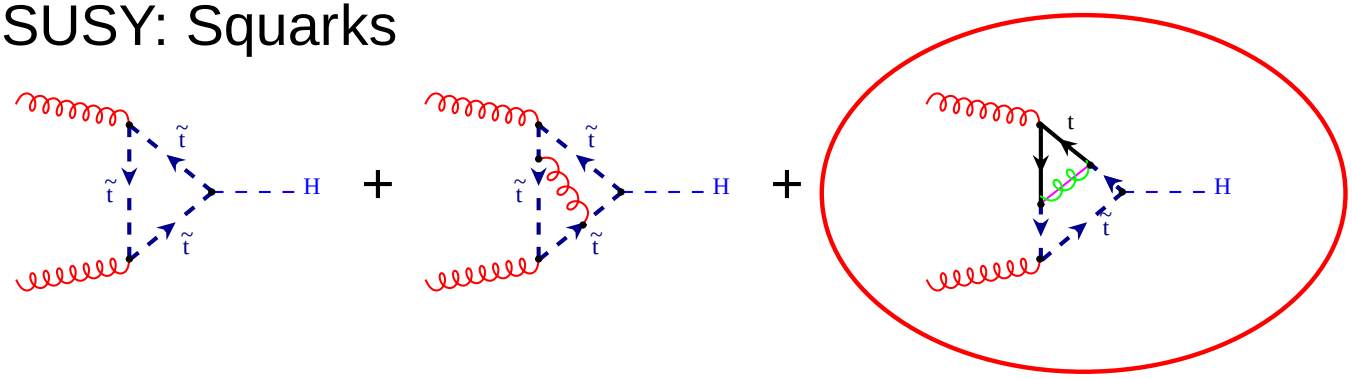

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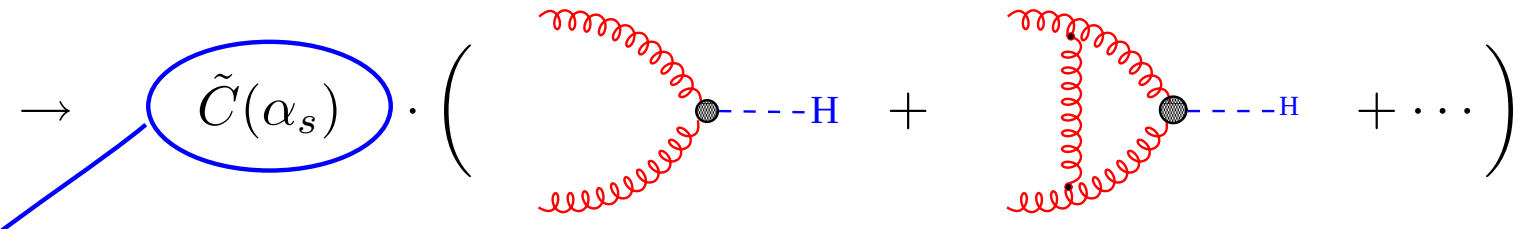

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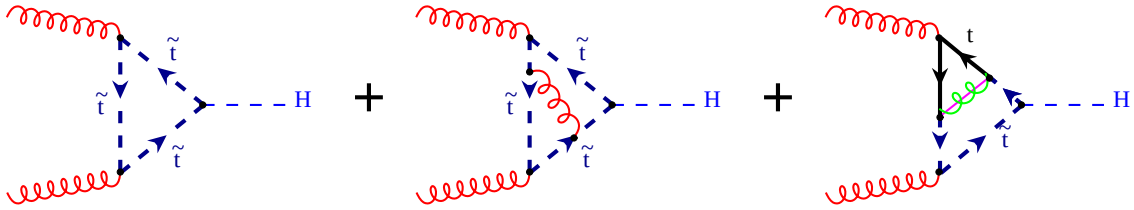
Gluon Fusion

- SUSY: Squarks + Gluinos

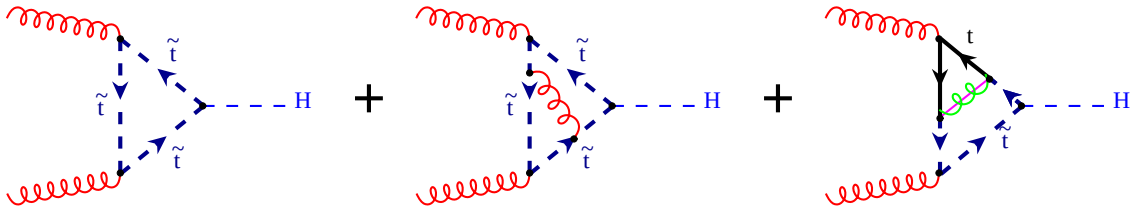


heavy top/stop/gluino limit: [R.H., Steinhauser ('03)]

$$\rightarrow \quad \tilde{C}(\alpha_s) \cdot \Bigg(\quad + \quad + \cdots \Bigg)$$

Gluon Fusion

- SUSY: Squarks + Gluinos



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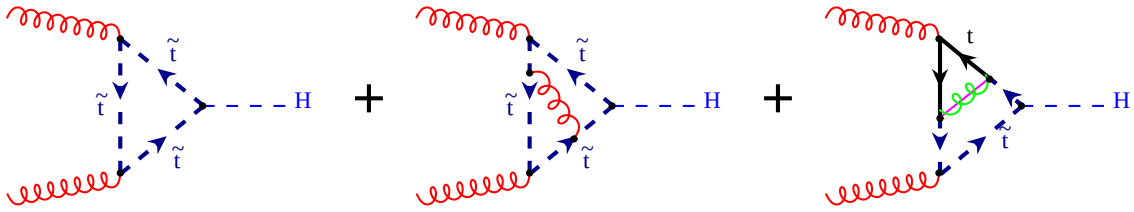
$$m_t,\ m_{\tilde{t}},\ m_{\tilde{g}} \gg M_H$$

$$\Rightarrow \quad \tilde{C}(\alpha_s) = \tilde{C}(\alpha_s, m_t/m_{\tilde{t}}, m_{\tilde{t}}/m_{\tilde{g}})$$

Gluon Fusion

- SUSY: Squarks + Gluinos



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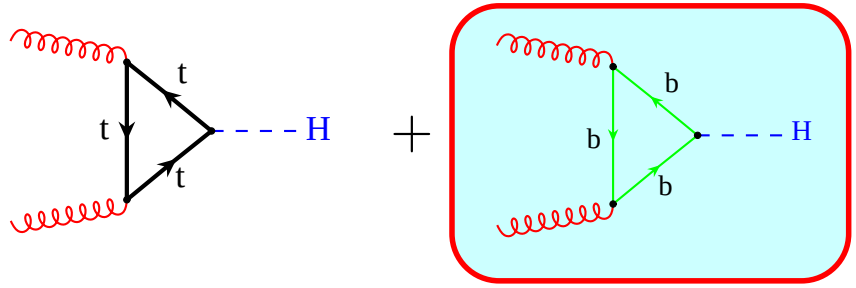
$$\Rightarrow \quad \tilde{C}(\alpha_s) = \tilde{C}(\alpha_s, m_t/m_{\tilde{t}}, m_{\tilde{t}}/m_{\tilde{g}})$$

in particular: $\tilde{C}(\alpha_s) \sim \ln(m_{\tilde{g}})$ for $m_{\tilde{g}} \to \infty$

Gluon Fusion

- SUSY: bottom quarks

$$\frac{\lambda_b}{\lambda_t} = \frac{m_b}{m_t} \cdot \frac{v_u}{v_d} = \frac{m_b}{m_t} \cdot \tan\beta$$



NLO: [Spira, Djouadi, Graudenz, Zerwas ('95)]

NNLO: "heavy bottom"?

Gluon Fusion

- SUSY: bottom quarks

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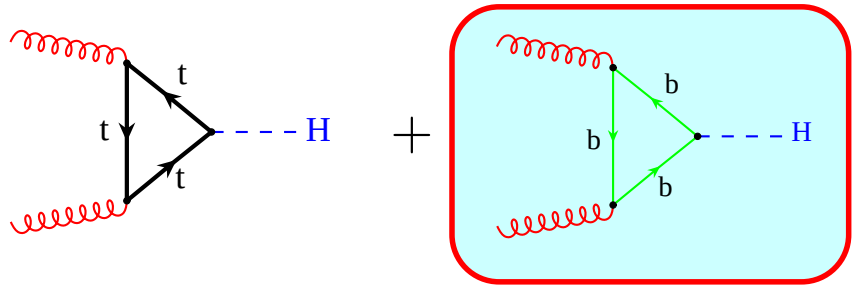

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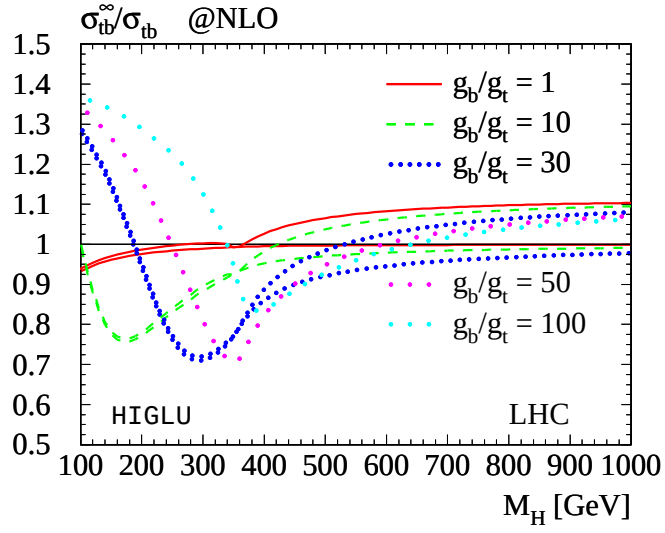
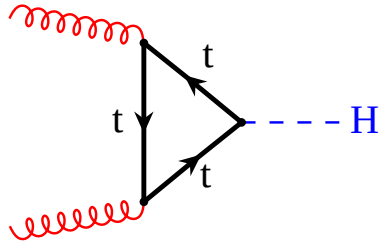
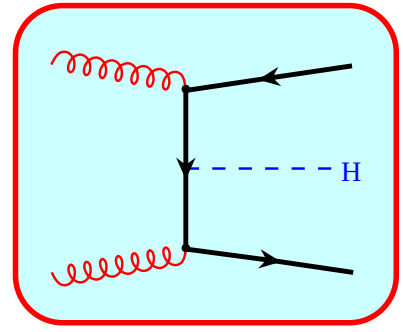


$gg \to t\bar{t}H$

instead of virtual:



consider real tops:



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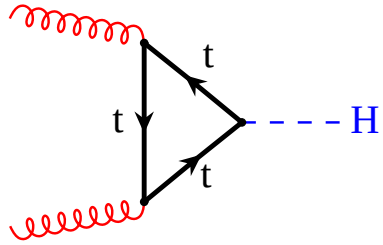

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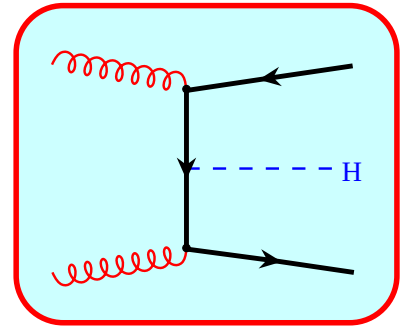

- supplementary mode at small M_H
- measurement of top Yukawa coupling

$gg \to t\bar{t}H$

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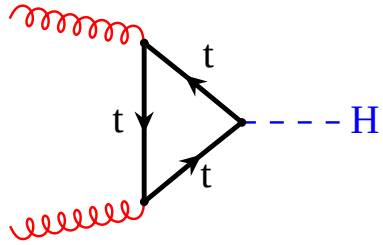

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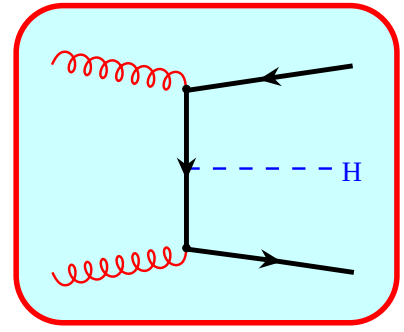

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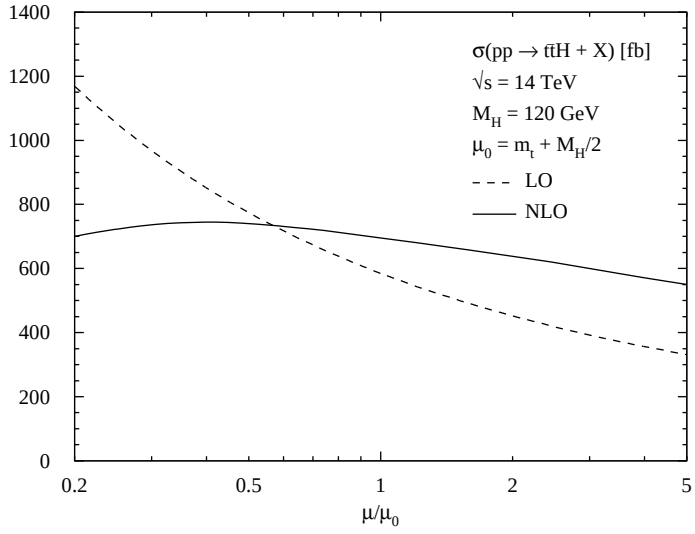


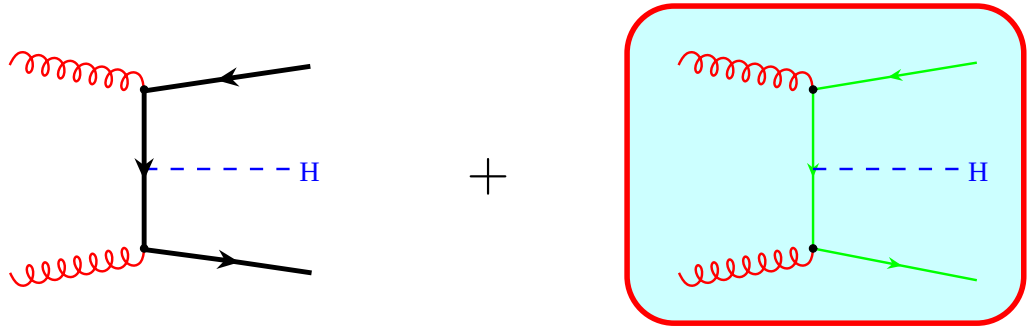
[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas ('01)]

[Dawson, Reina, Wackeroth, Orr, Jackson ('01-'03)]

SUSY again...

- modified Yukawas:

$$\frac{\lambda_b}{\lambda_t} = \frac{m_b}{m_t} \cdot \frac{v_u}{v_d} = \frac{m_b}{m_t} \cdot \tan\beta$$



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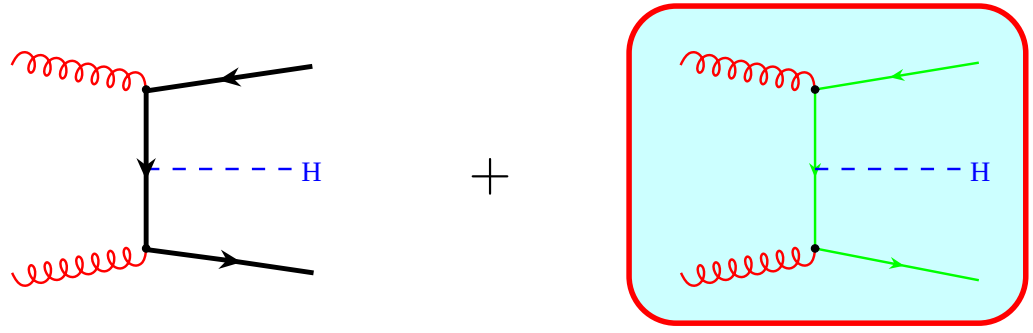

- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H)$

SUSY again...

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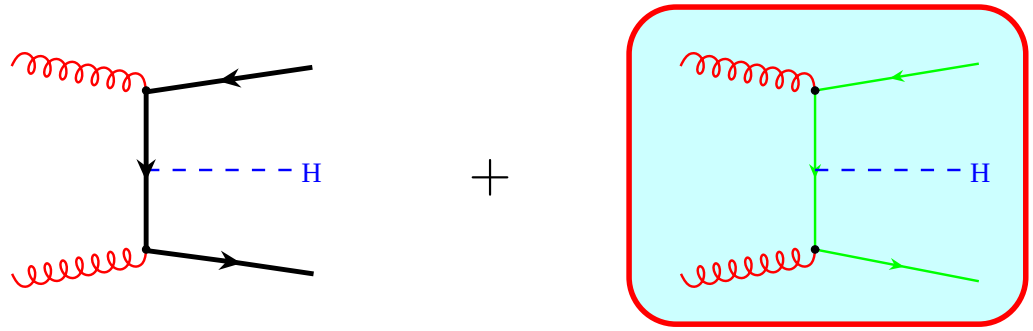
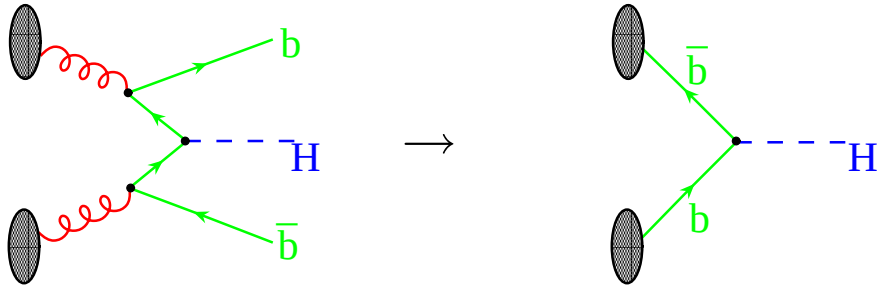
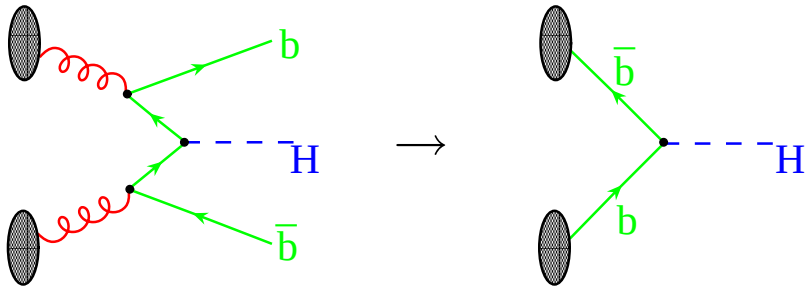


- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H)$
- resummation: bottom parton densities

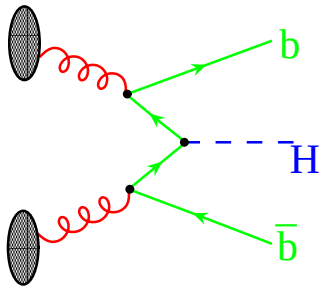


$pp \longrightarrow Hb\bar{b}$

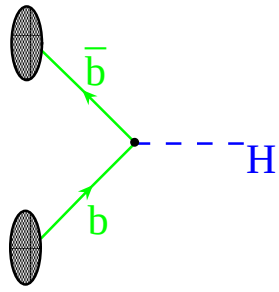


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n$$

$pp \longrightarrow Hb\bar{b}$



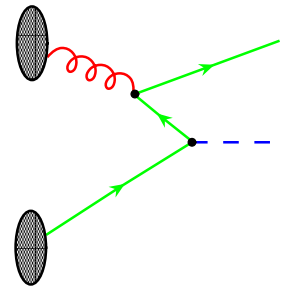
$\longrightarrow$



$$\sum_{n=2}^{\infty}(\alpha_s l_b)^n$$

$+$

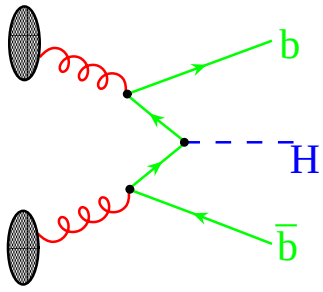
$\Bigg($



$-$ sub $\Bigg)$

$$\sum_{n=2}^{\infty}(\alpha_s l_b)^n \cdot \frac{1}{l_b}$$

$pp \to Hb\bar{b}$



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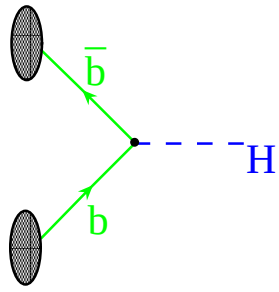

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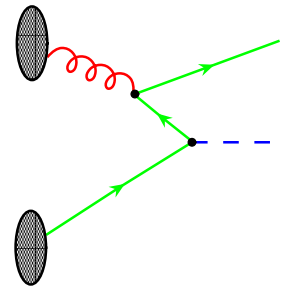

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$\sum_{n=2}^{\infty}(\alpha_s l_b)^n \cdot \frac{1}{l_b}$

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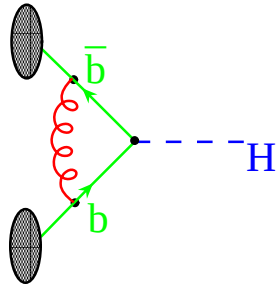
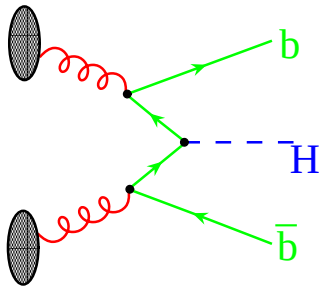


$\sum_{n=2}^{\infty}(\alpha_s l_b)^n \cdot \alpha_s$

$pp \to Hb\bar{b}$



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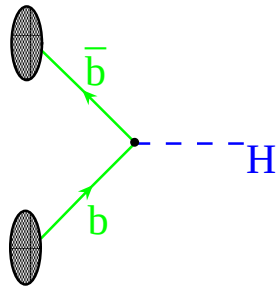

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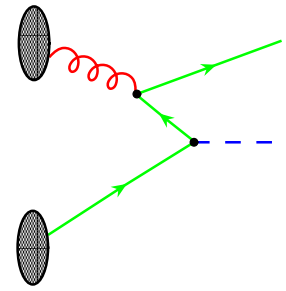

$-$ sub $\Big)$

$\sum_{n=2}^{\infty}(\alpha_s l_b)^n \cdot \frac{1}{l_b}$

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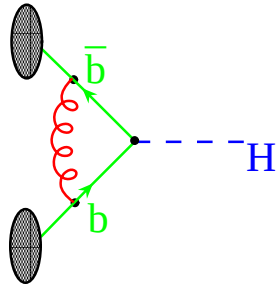
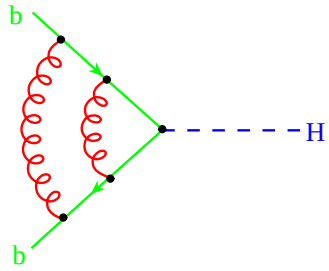


$\sum_{n=2}^{\infty}(\alpha_s l_b)^n \cdot \alpha_s$

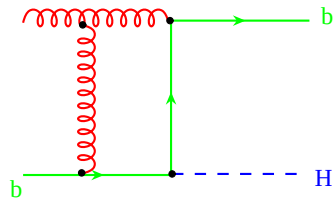
NLO: $\sigma(b\bar{b} \to H) = \sum_{n=0}^{\infty} (\alpha_s l_b)^n \; \alpha_s^2 \Big[\; c_{n0} \, {l_b}^2 \; + \; c_{n1} \, l_b \Big]$

[Maltoni, Sullivan, Willenbrock ('03)]

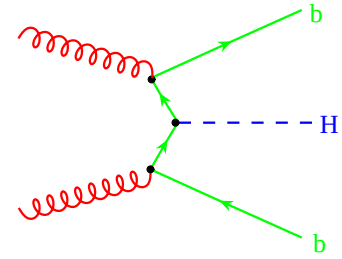
$b\bar{b} \to H$ @ NNLO



$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s^2$$

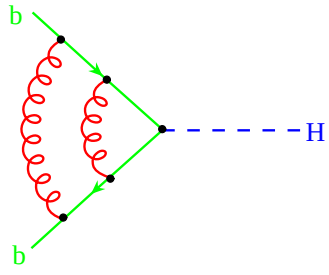


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s \frac{1}{l_b}$$

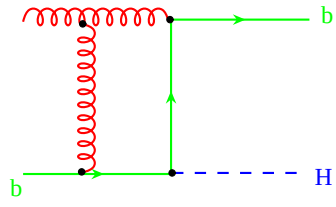


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \frac{1}{{l_b}^2}$$

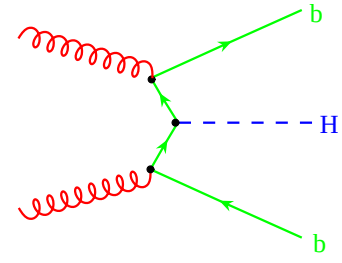
$b\bar{b} \to H$ @ NNLO



$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s^2$$



$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s \frac{1}{l_b}$$

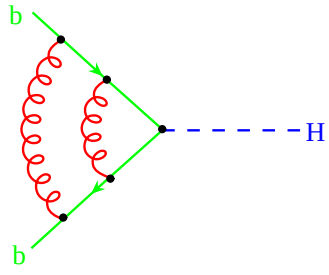


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \frac{1}{{l_b}^2}$$

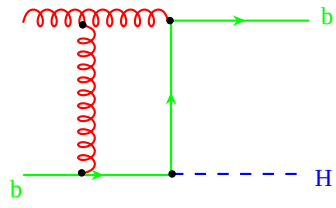
NNLO: $$\sigma(b\bar{b} \to H) = \sum_{n=0}^{\infty} (\alpha_s l_b)^n \, \alpha_s^2 \left[c_{n0} \, {l_b}^2 + c_{n1} \, l_b + c_{n0} \right]$$

[R.H., Kilgore ('03)]

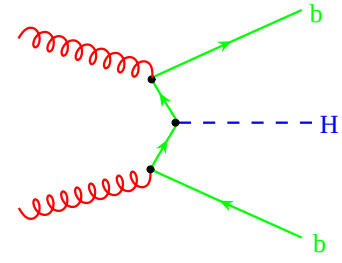
$b\bar{b} \to H$ @ NNLO



$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s^2$$



$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s \frac{1}{l_b}$$



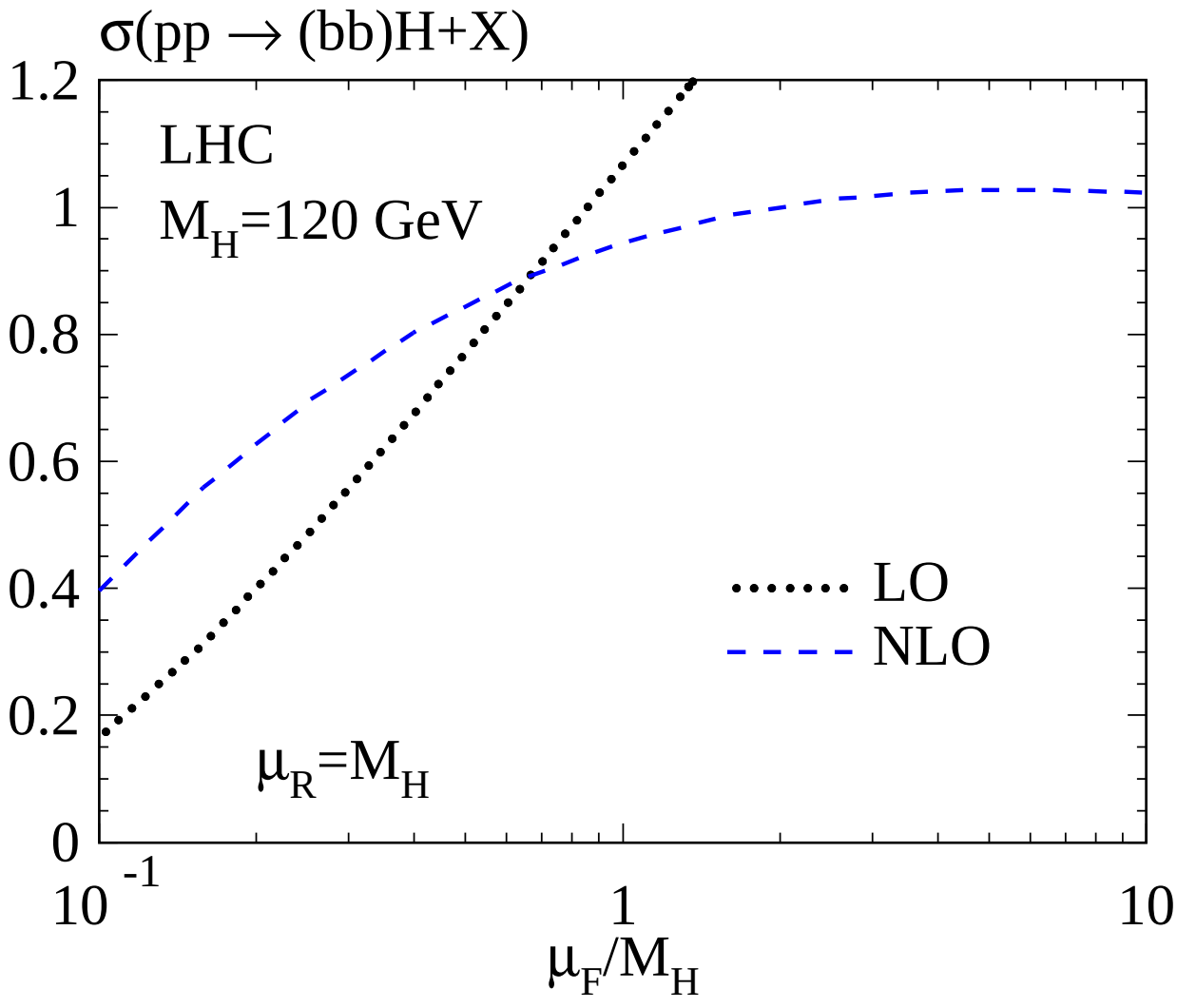
$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \frac{1}{{l_b}^2}$$

NNLO: $$\sigma(b\bar{b} \to H) = \sum_{n=0}^{\infty} (\alpha_s l_b)^n \, \alpha_s^2 \Big\{ \Big[\, c_{n0} \, {l_b}^2 \, + \, c_{n1} \, l_b \, + \, c_{n0} \Big]$$

[R.H., Kilgore ('03)]

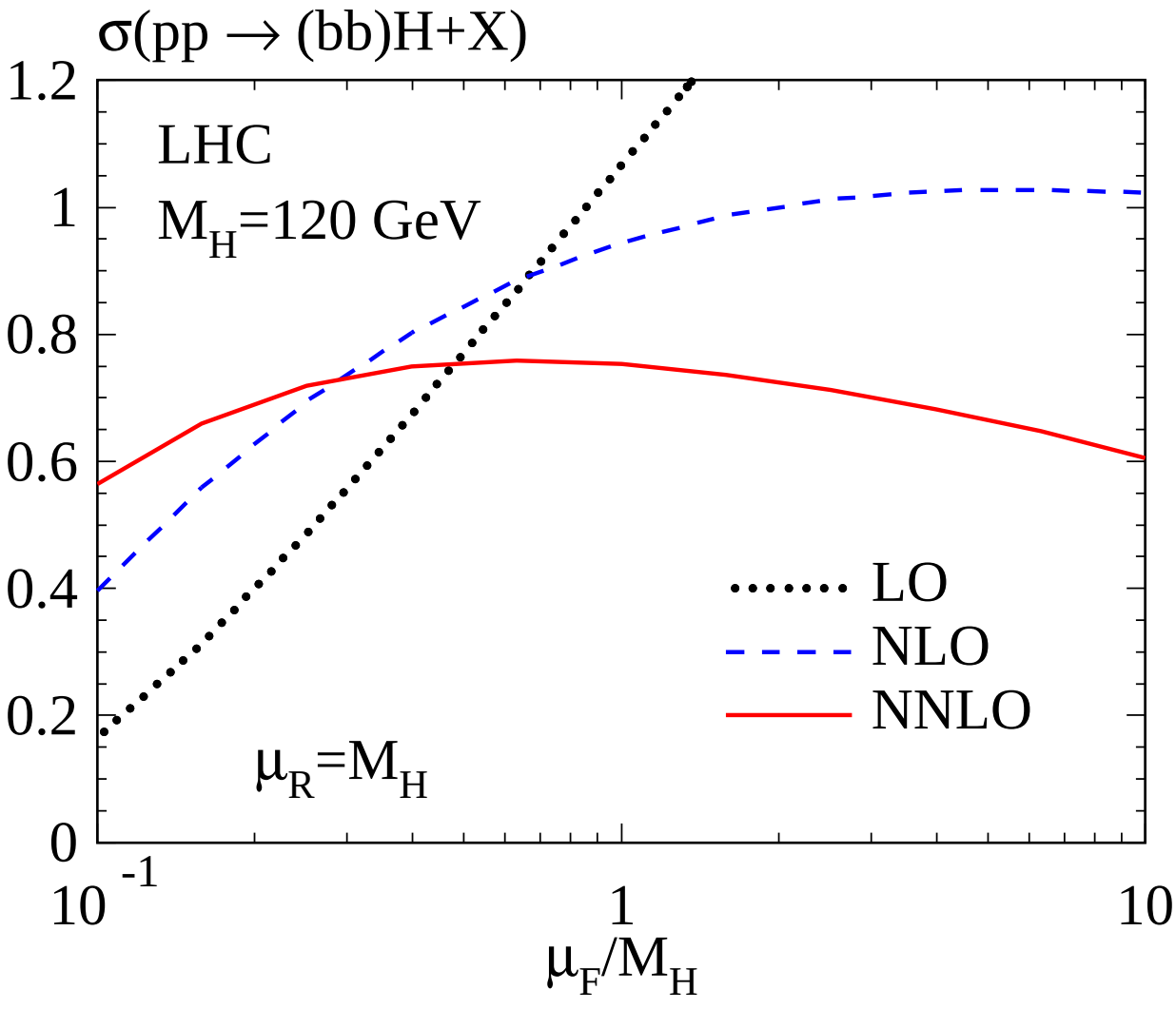
higher orders: $$+ d_{n3}\alpha_s^3 + d_{n4}\alpha_s^4 + \ldots \Big\}$$

$b\bar{b} \to H$



[Maltoni, Sullivan, Willenbrock ('03)]

$b\bar{b} \to H$



[Maltoni, Sullivan, Willenbrock ('03)]

[R.H., Kilgore ('03)]

$b\bar{b} \to H$ vs. $gg \to b\bar{b}H$

- $gg \to b\bar{b}H$ @ NLO: [Dittmaier, Krämer, Spira ('03)]
  [Dawson, Jackson, Reina, Wackeroth ('03)]

$b\bar{b} \to H$ vs. $gg \to b\bar{b}H$

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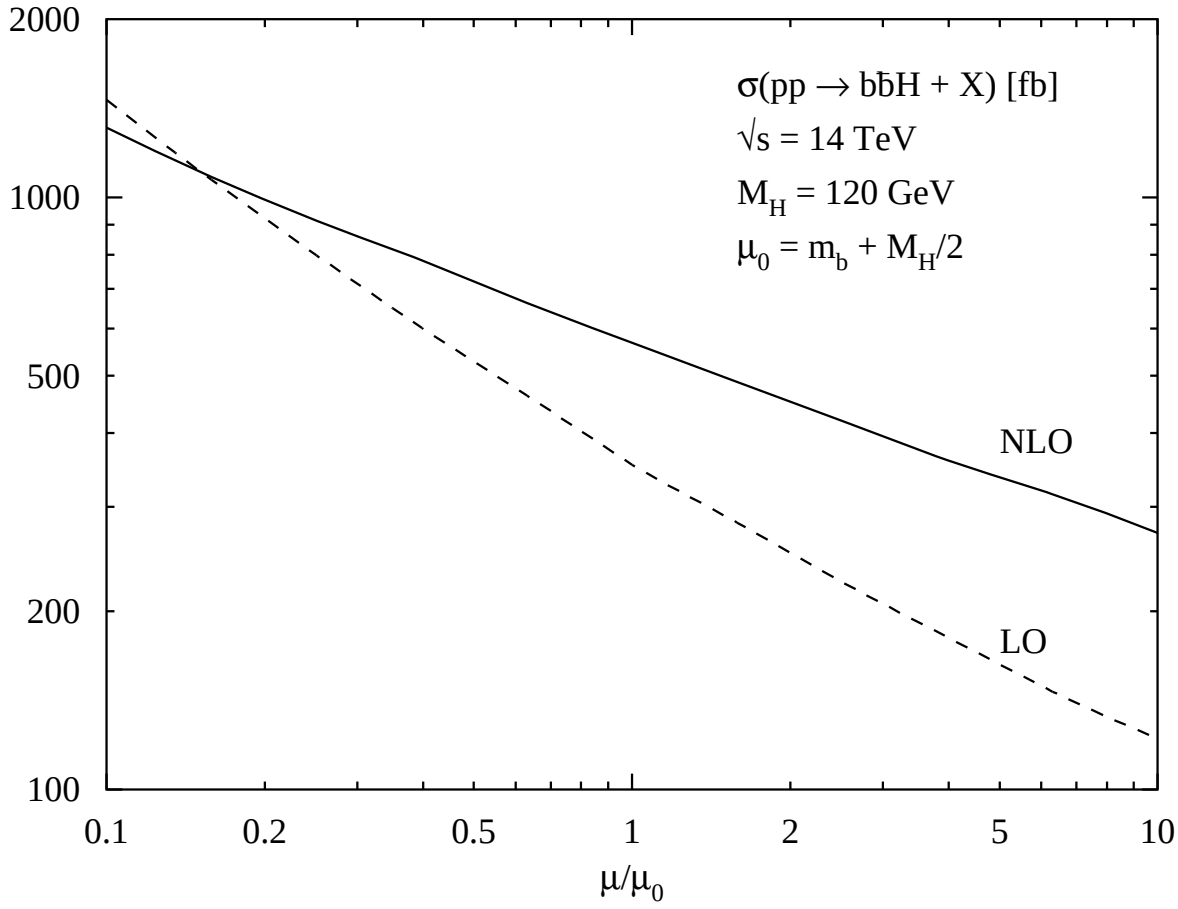
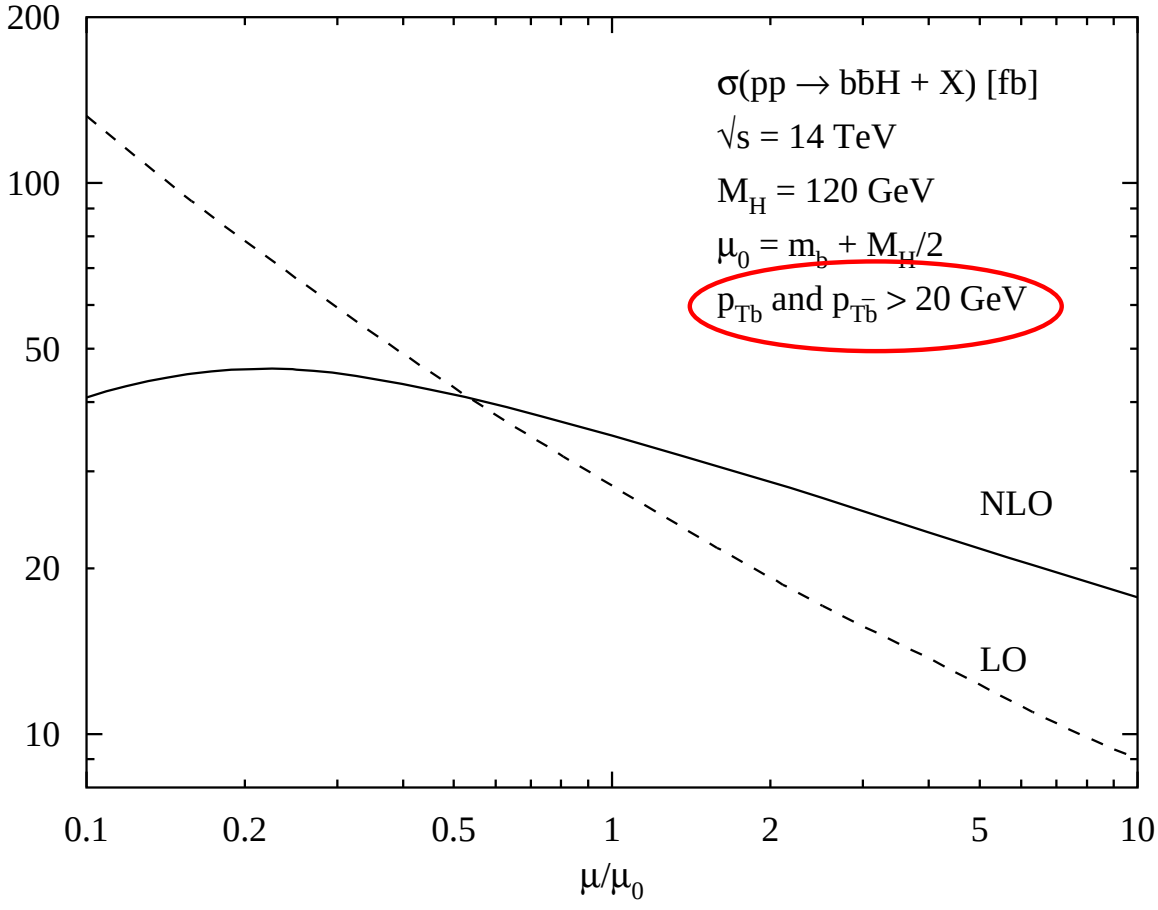


note the log scale

$b\bar{b} \to H$ vs. $gg \to b\bar{b}H$

- $gg \to b\bar{b}H$ @ NLO: [Dittmaier, Krämer, Spira ('03)] [Dawson, Jackson, Reina, Wackeroth ('03)]



note the log scale

$b\bar{b} \to H$ vs. $gg \to b\bar{b}H$

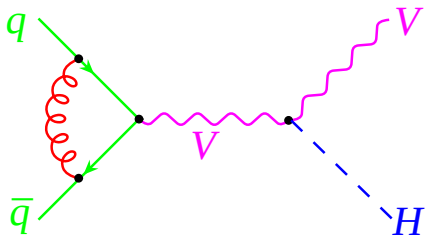
	$gg \to b\bar{b}H$	$b\bar{b} \to H$
Tevatron	$8.0^{+3.1}_{-2.4}$ fb	$10.5^{+0.3}_{-1.1}$ fb
LHC	$7.3^{+2.0}_{-1.6} \cdot 10^2$ fb	$7.2^{+0.4}_{-1.6} \cdot 10^2$ fb

$b\bar{b} \to H$ vs. $gg \to b\bar{b}H$

	$gg \to b\bar{b}H$	$b\bar{b} \to H$
Tevatron	$8.0^{+3.1}_{-2.4}$ fb	$10.5^{+0.3}_{-1.1}$ fb
LHC	$7.3^{+2.0}_{-1.6} \cdot 10^2$ fb	$7.2^{+0.4}_{-1.6} \cdot 10^2$ fb

- total rate for $b\bar{b} \to H$ under control
- bottom quark densities are very useful tool
- discussions on factorization scale are settling

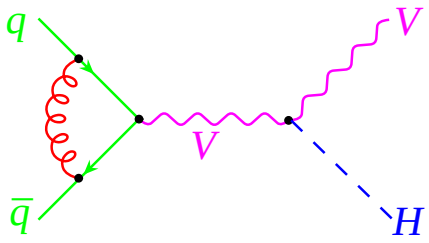
Higgs Strahlung



$\sim$ Drell-Yan! [Han, Willenbrock ('90)]

$\approx +30\%$

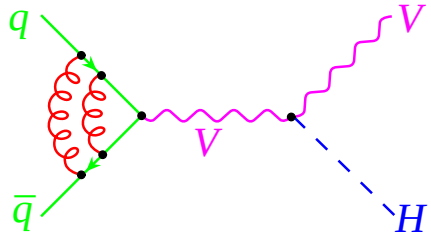
Higgs Strahlung



$\sim$ Drell-Yan! [Han, Willenbrock ('90)]

$\approx +30\%$

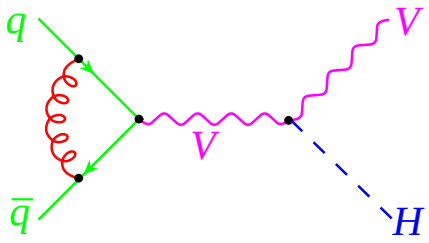
even NNLO:



[Hamberg, Matsuura, v.Neerven ('91)]

[R.H., Kilgore ('02)]

Higgs Strahlung



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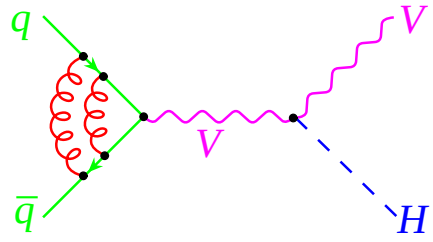
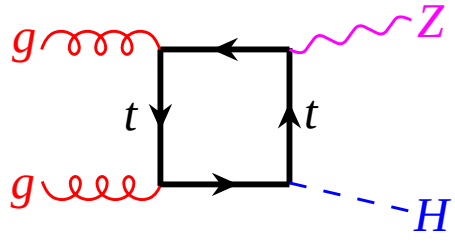


[Hamberg, Matsuura, v.Neerven ('91)]

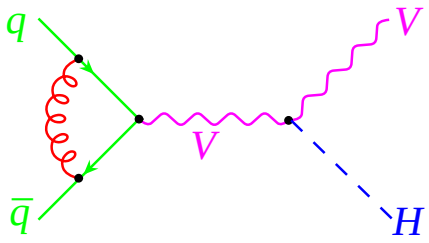
[R.H., Kilgore ('02)]

for $H + Z$: +



[Barger *et al.* ('86)]
[Dicus, Kao ('88)]
[Kniehl ('90)]

Higgs Strahlung



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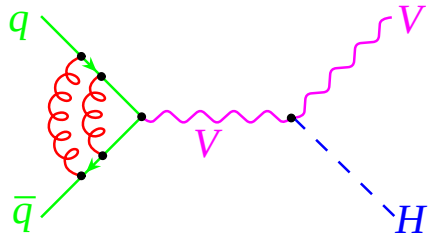
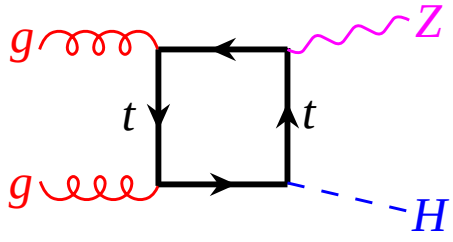
$\approx +30\%$

even NNLO:



[Hamberg, Matsuura, v.Neerven ('91)]

[R.H., Kilgore ('02)]

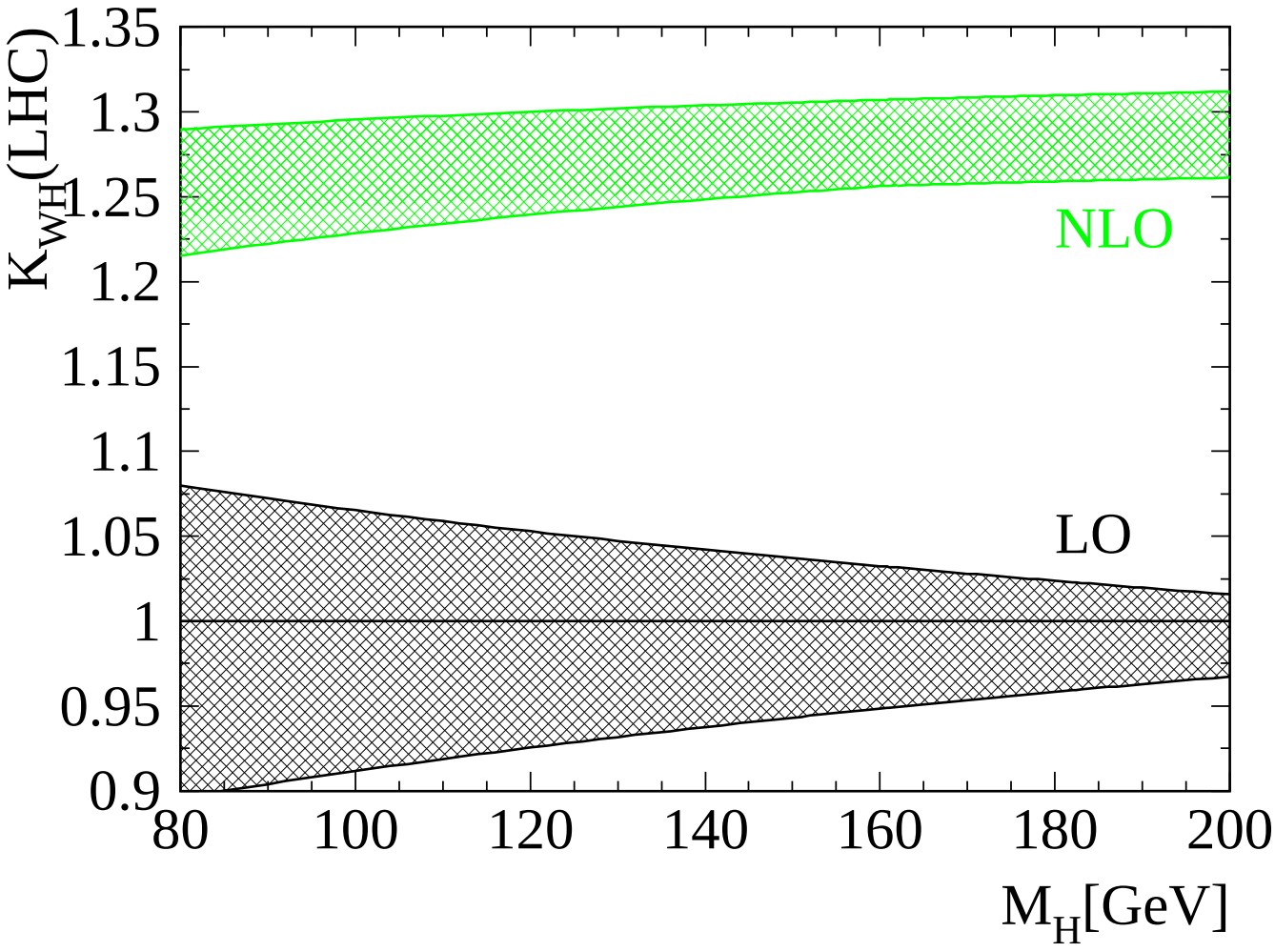
for $H + Z$: + 

[Barger *et al.* ('86)]
[Dicus, Kao ('88)]
[Kniehl ('90)]

$\rightarrow$ NNLO QCD [Brein, Djouadi, R.H. ('03)]

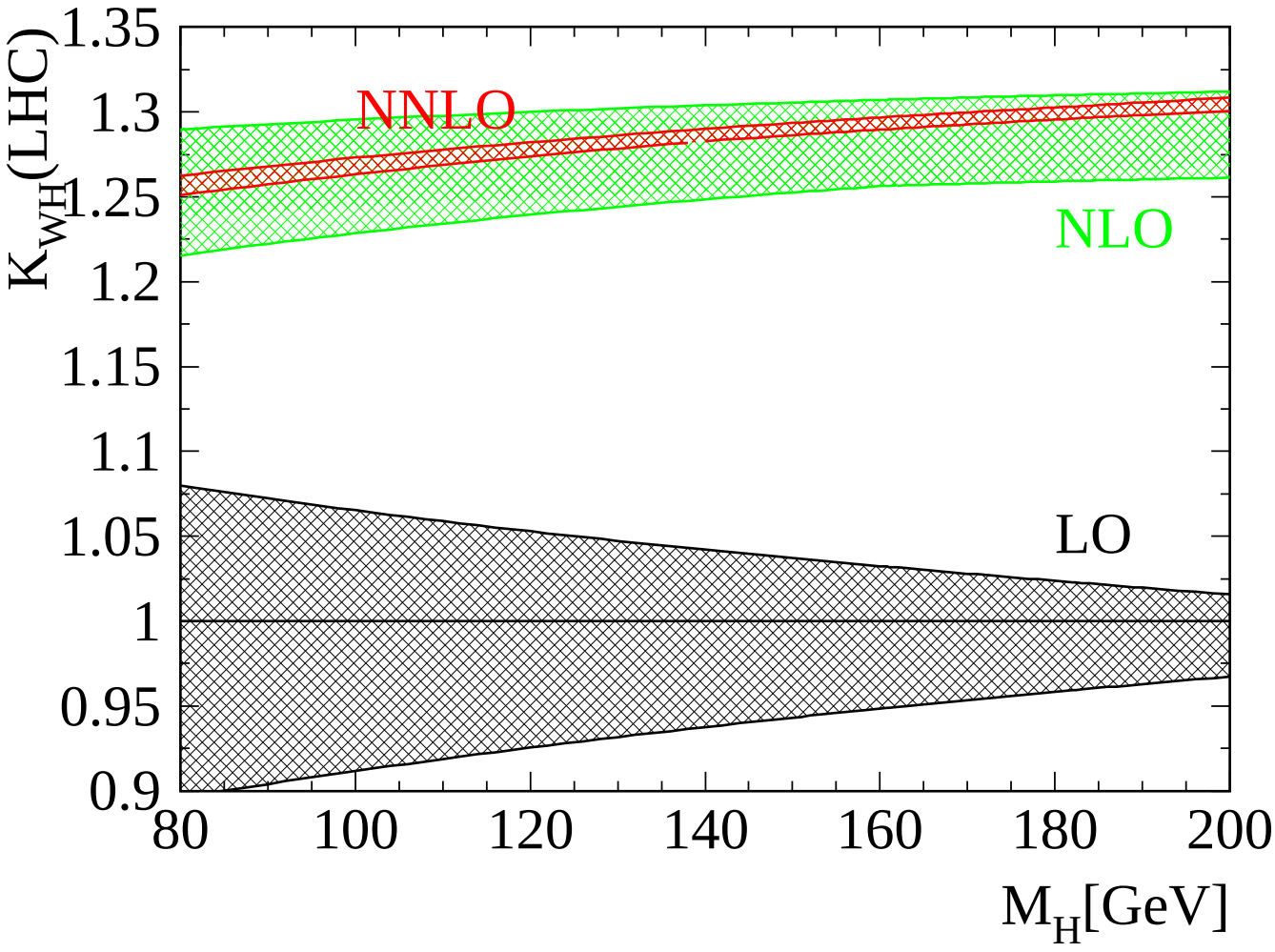
$+$ EW [Ciccolini, Dittmaier, Krämer ('03)]

Higgs Strahlung



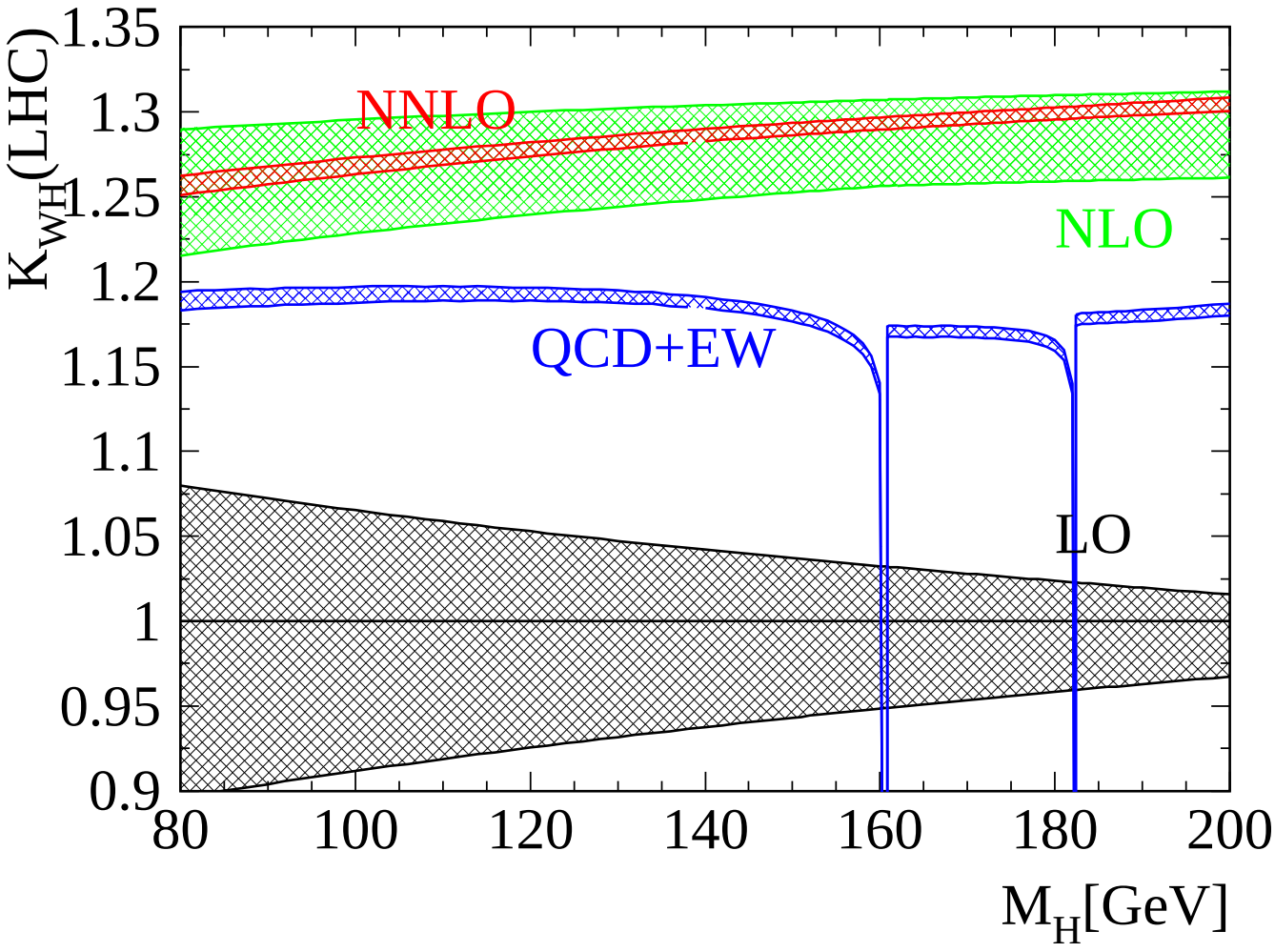
[Han, Willenbrock ('90)]

Higgs Strahlung



[Brein, Djouadi, R.H. ('03)]

Higgs Strahlung



[Brein, Djouadi, R.H. ('03)]

+

[Ciccolini, Dittmaier, Krämer ('03)]

Conclusions

- Inclusive Higgs cross sections under very good theoretical control
- NNLO results for
  - $gg \to H \quad \to 15\%$
  - $b\bar{b} \to H \quad \to 15\%$
  - Higgs Strahlung $\to 1\%$-level
- NLO results for
  - $gg \to t\bar{t}H \quad \to 10\%$
  - $gg \to b\bar{b}H \quad \to ??$
  - Weak Boson Fusion $\to 10\%$
- Questions:
  - need for distributions?
  - need for backgrounds? Theory vs. Data?
  - need for a Monte Carlo?