

Inclusive Higgs Cross-Sections at the LHC

Robert Harlander

Institut für Theoretische Teilchenphysik

Universität Karlsruhe, Germany

Outline

● Higgs Cross Sections:

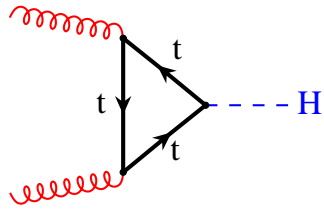
- Gluon Fusion (NNLO, Standard Model, MSSM)
- $H + b\bar{b}$ (and $H + t\bar{t}$)
- Higgs Strahlung (NNLO + EW)

● Not covered:

- Weak Boson Fusion (→ D. Zeppenfeld)
- Distributions (→ M. Grazzini, K. Melnikov, ...)
- Backgrounds (→ T. Binoth, K. Ellis, ...)
- ...

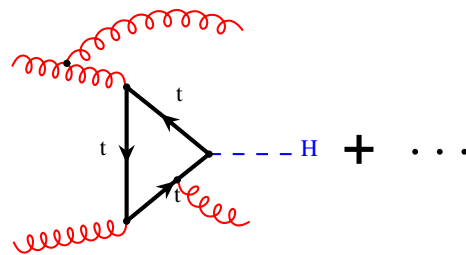
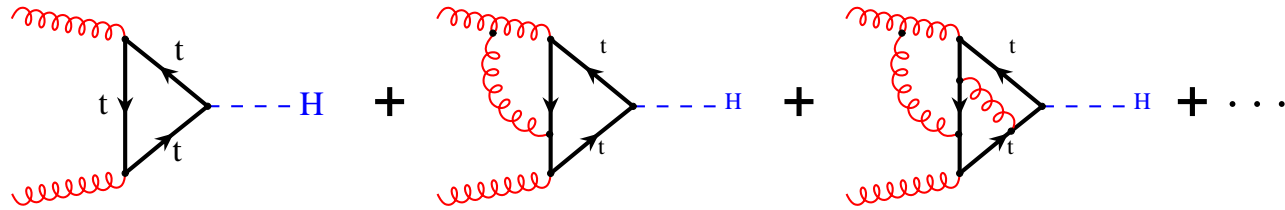
Gluon Fusion

● Standard Model



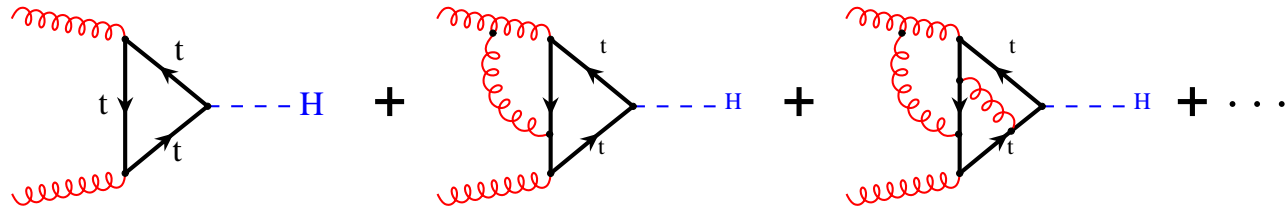
Gluon Fusion

Standard Model



Gluon Fusion

● Standard Model



heavy top limit:

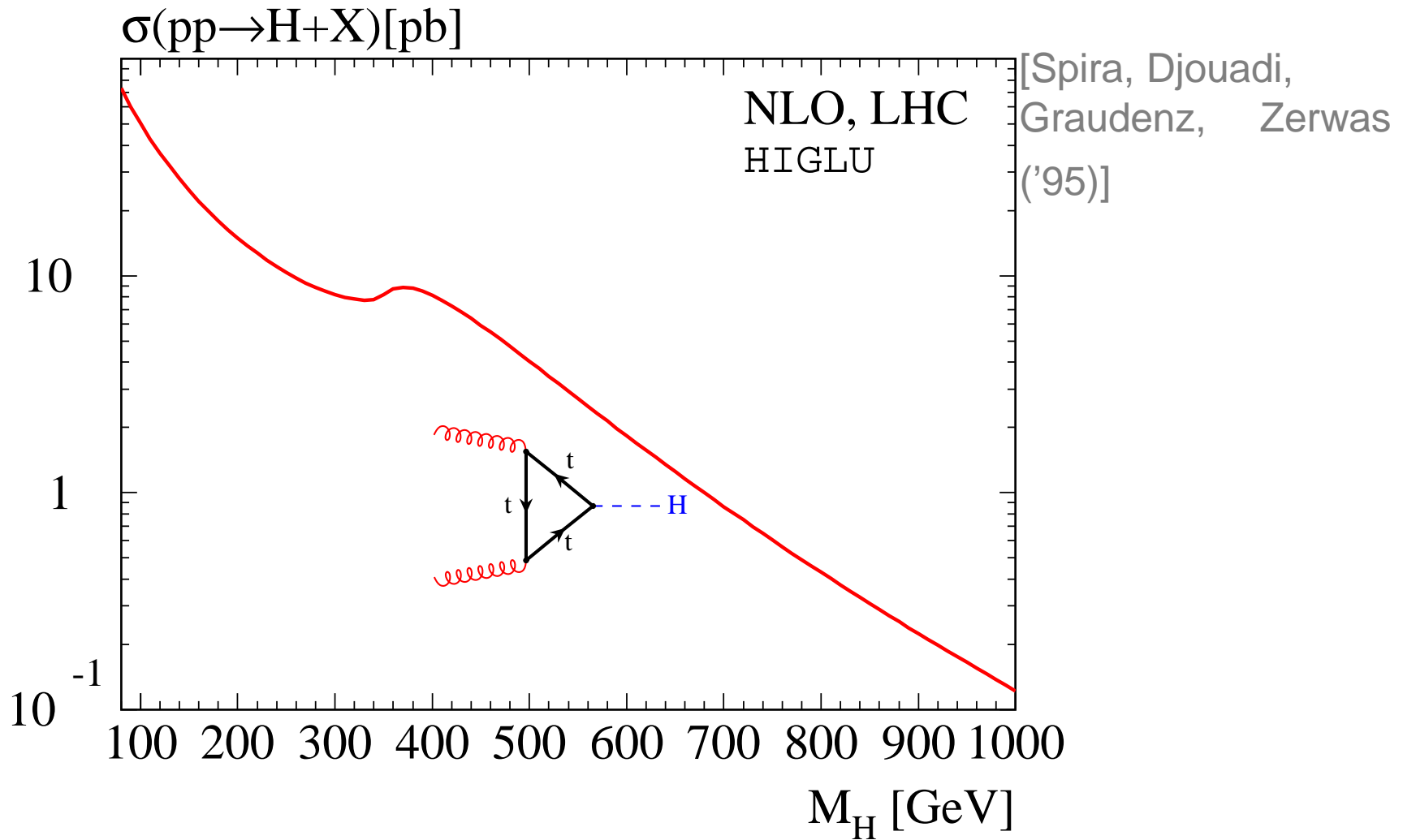
$$\lim_{m_t \rightarrow \infty} \rightarrow C(\alpha_s) \cdot \left(\text{Diagram 1} + \text{Diagram 2} + \dots \right)$$

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

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

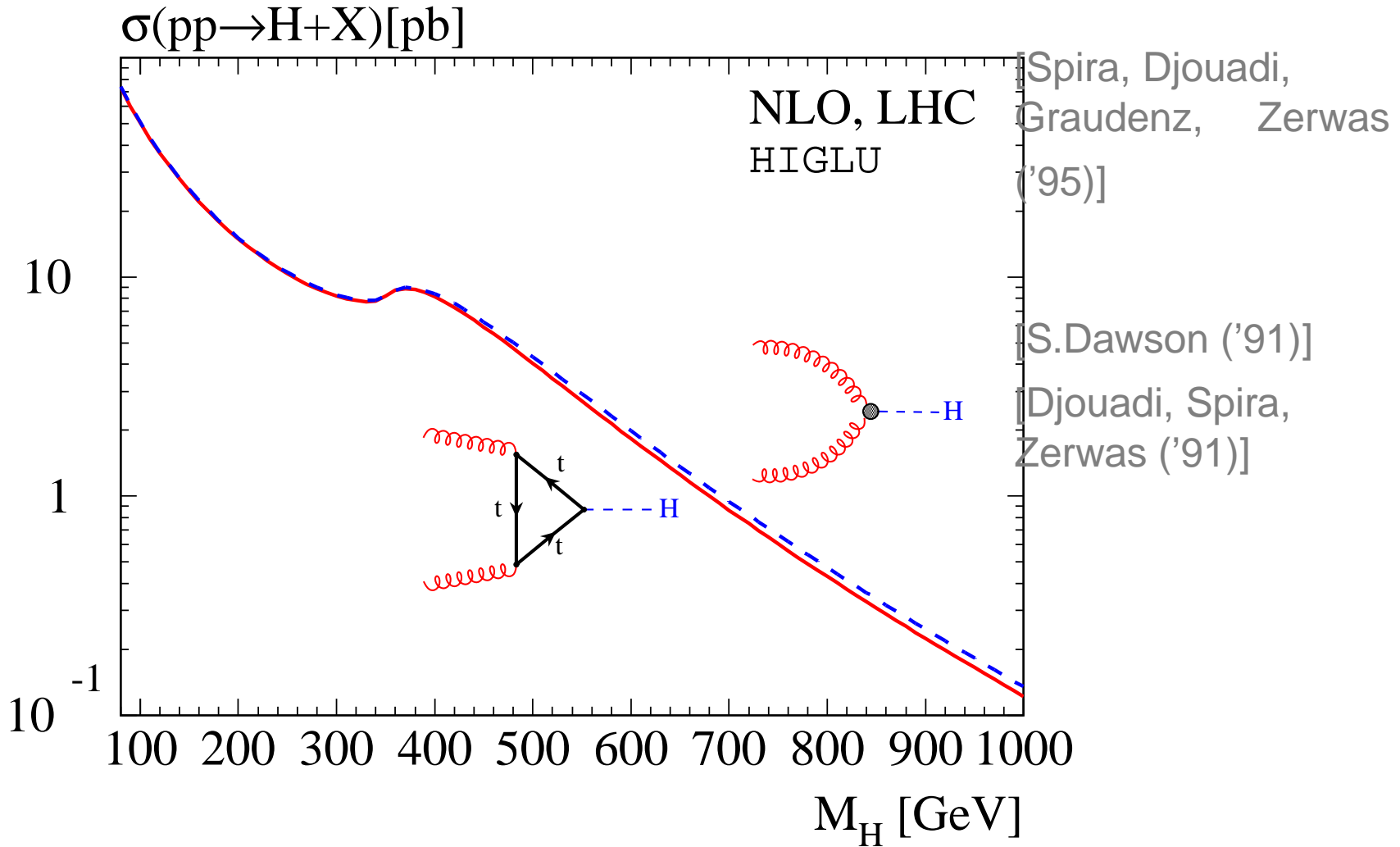
Heavy top limit

(no bottom loops)

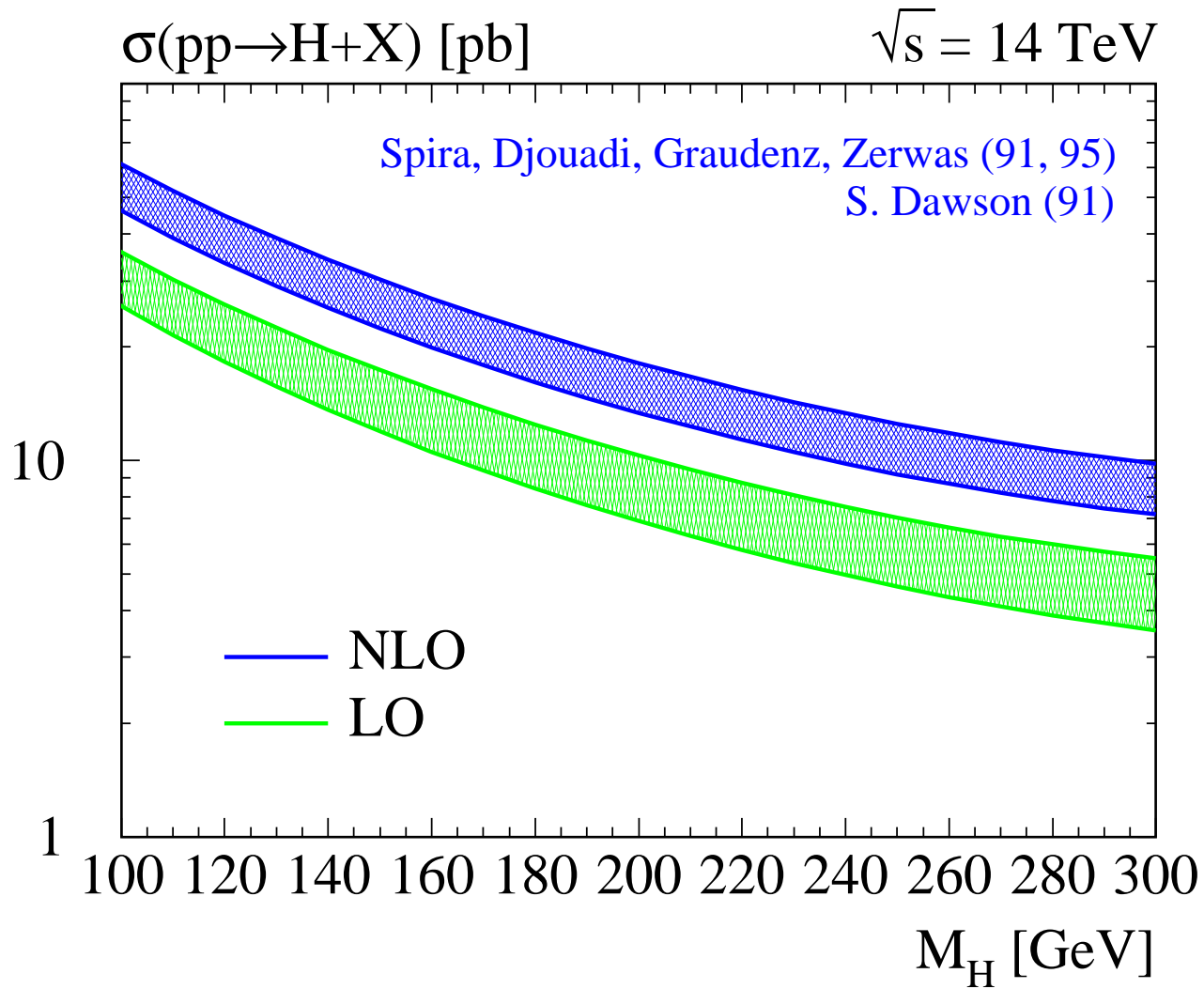


Heavy top limit

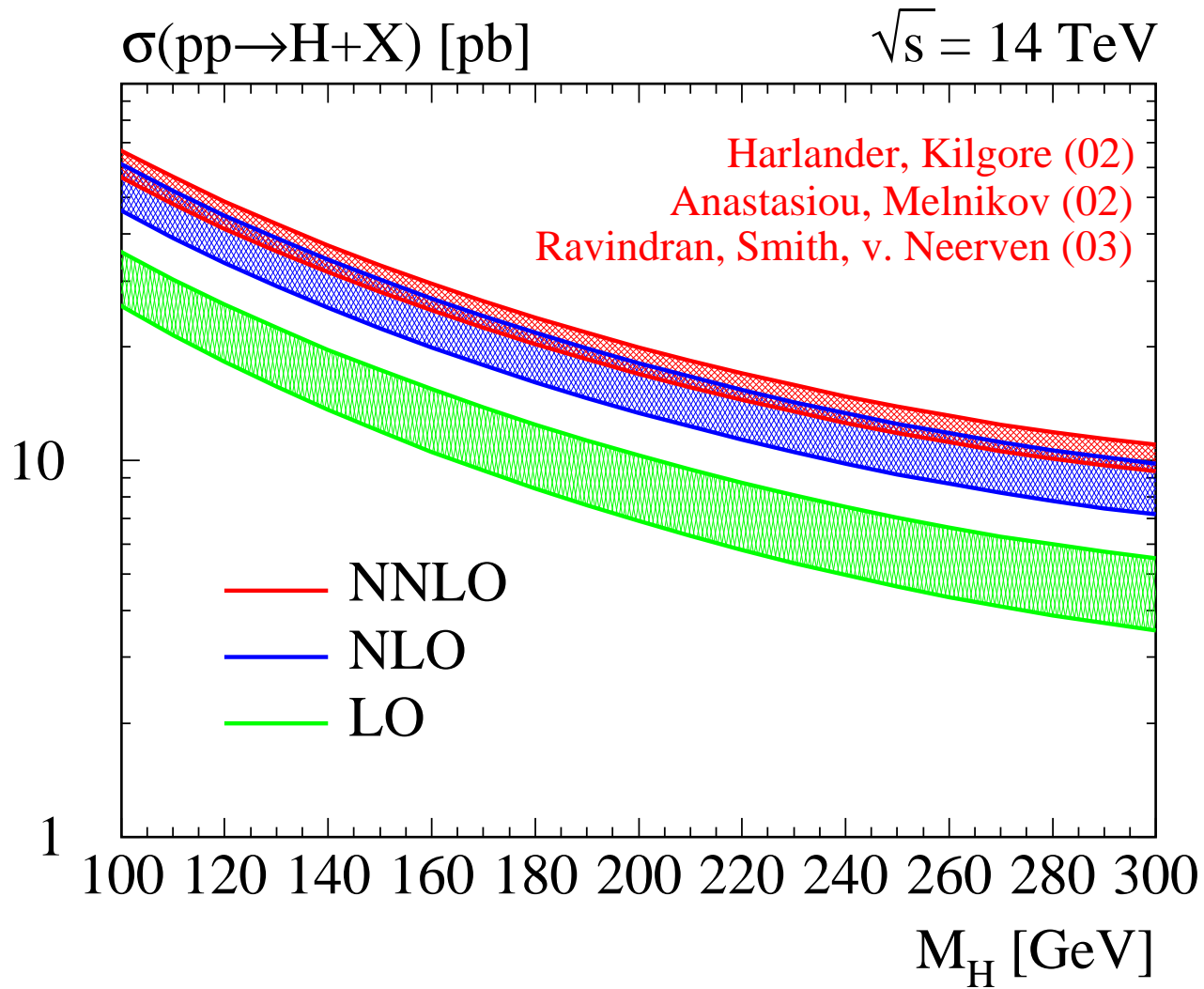
(no bottom loops)



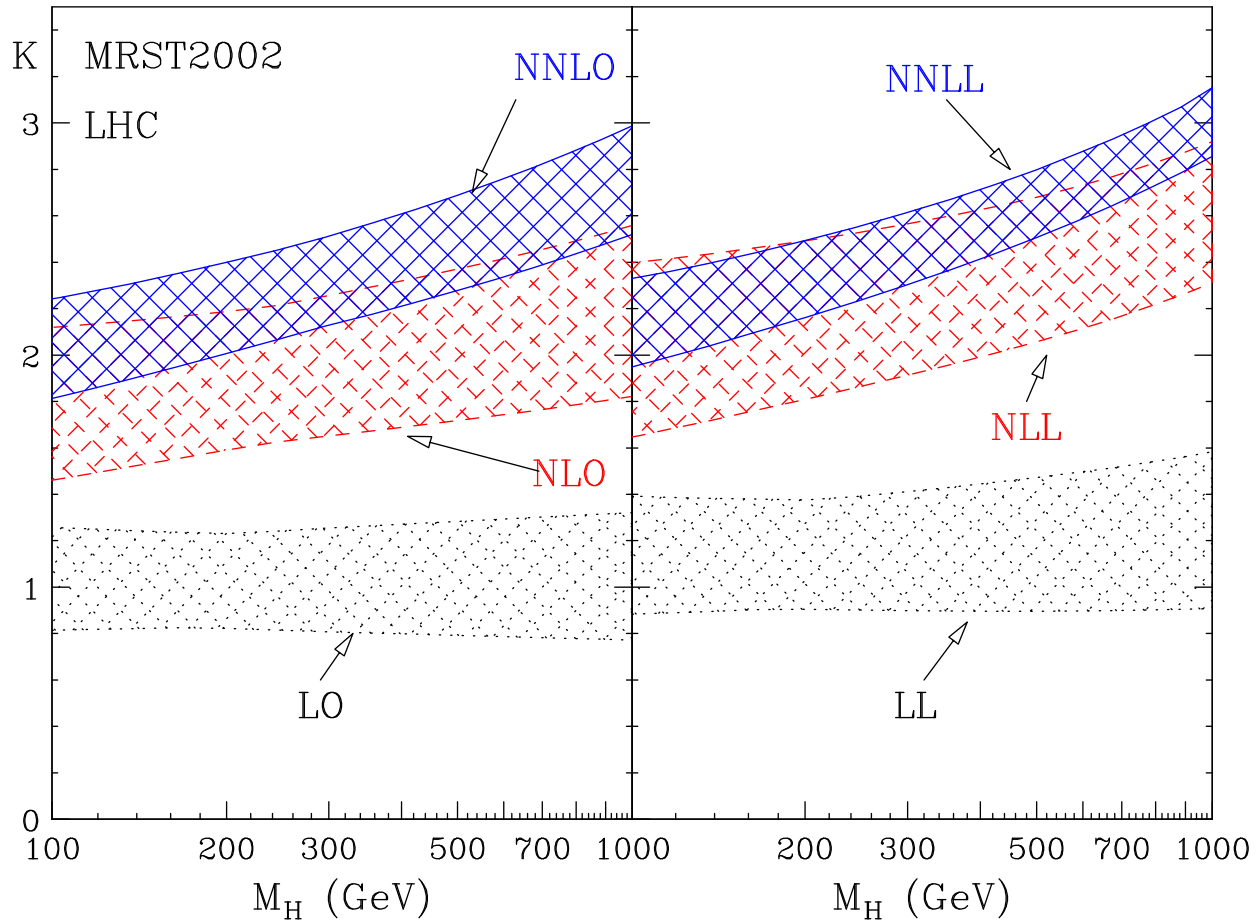
Cross section



Cross section



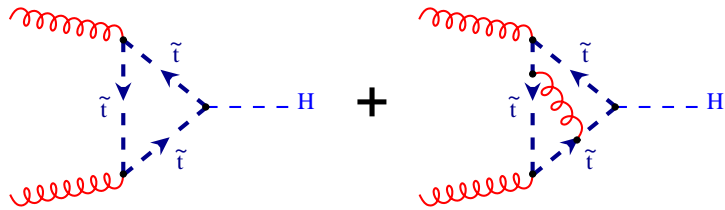
Resummation



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

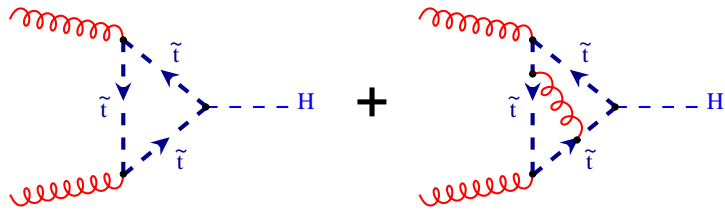
Gluon Fusion

● SUSY: Squarks



Gluon Fusion

SUSY: Squarks



heavy stop limit:

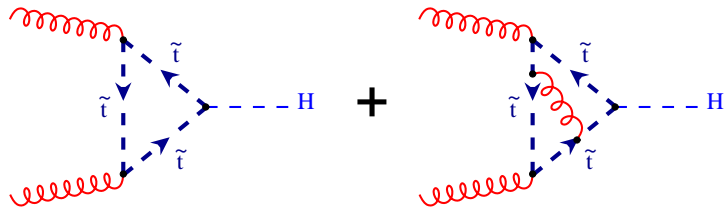
$$\rightarrow \tilde{C}(\alpha_s) \cdot \left(\text{[Diagram 1]} + \text{[Diagram 2]} + \dots \right)$$

The equation shows the heavy stop limit of the gluon fusion process. The coefficient $\tilde{C}(\alpha_s)$ is circled in blue. The diagrams in the parentheses are the same as those shown above, representing the leading-order and next-to-leading-order contributions in the heavy stop limit.

[Dawson, Djouadi, Spira ('96)]

Gluon Fusion

SUSY: Squarks



heavy stop limit:

$$\rightarrow \tilde{C}(\alpha_s) \cdot \left(\text{diagram 1} + \text{diagram 2} + \dots \right)$$

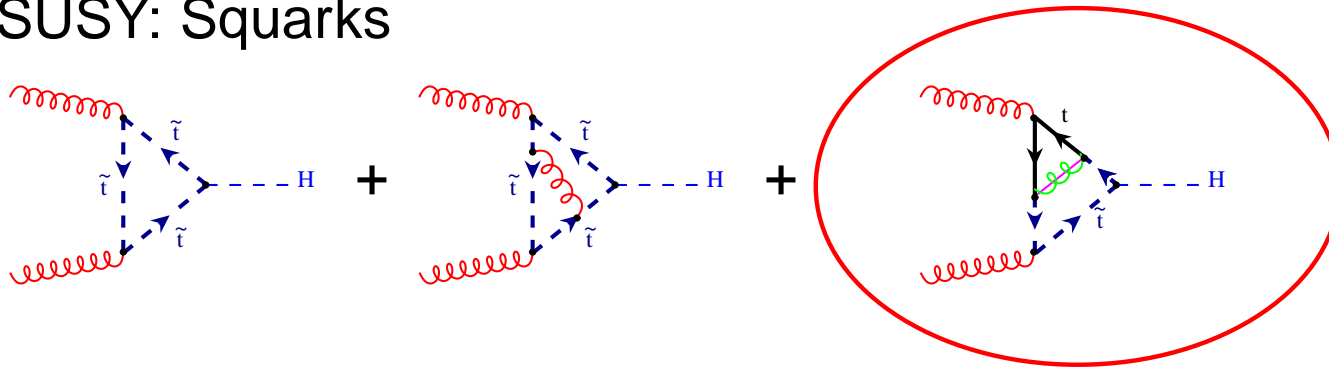
The equation shows the heavy stop limit of the gluon fusion process. The coefficient $\tilde{C}(\alpha_s)$ is circled in blue. The diagrams in parentheses represent the leading-order and higher-order terms in the expansion.

[Dawson, Djouadi, Spira ('96)]

but: not SUSY!

Gluon Fusion

SUSY: Squarks



heavy stop limit:

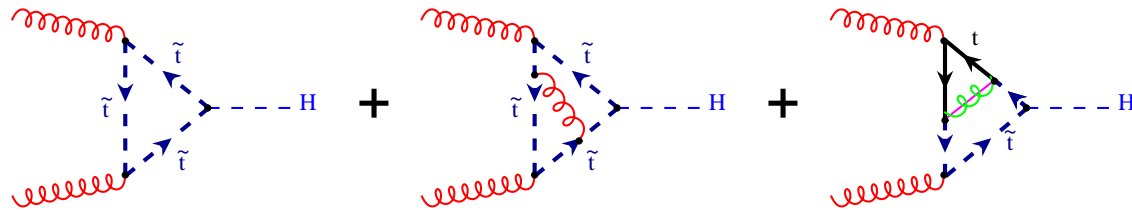
$$\rightarrow \tilde{C}(\alpha_s) \cdot \left(\text{tree-level diagrams} + \dots \right)$$

[Dawson, Djouadi, Spira ('96)]

but: not SUSY!

Gluon Fusion

● SUSY: Squarks + Gluinos



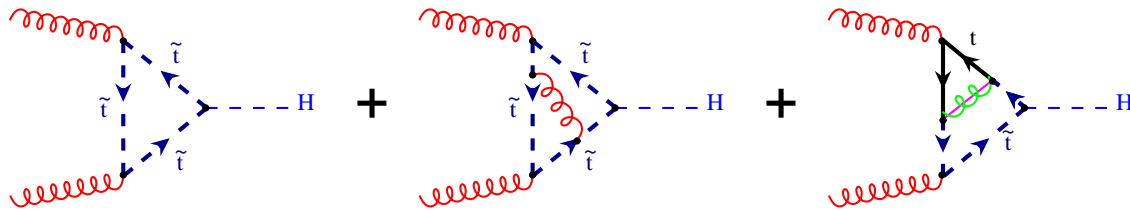
heavy top/stop/gluino limit: [R.H., Steinhauser ('03)]

$$\rightarrow \tilde{C}(\alpha_s) \cdot \left(\text{Diagram 1} + \text{Diagram 2} + \dots \right)$$

The equation shows the heavy top/stop/gluino limit of the gluon fusion process. It is represented as a coefficient $\tilde{C}(\alpha_s)$ multiplied by a sum of diagrams. The first two diagrams are shown: a top squark loop with a gluino exchange and a top squark loop with a top quark exchange. The sum is enclosed in large parentheses, followed by an ellipsis indicating other diagrams.

Gluon Fusion

SUSY: Squarks + Gluinos



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

$$\rightarrow \tilde{C}(\alpha_s) \cdot \left(\text{diagram 1} + \text{diagram 2} + \dots \right)$$

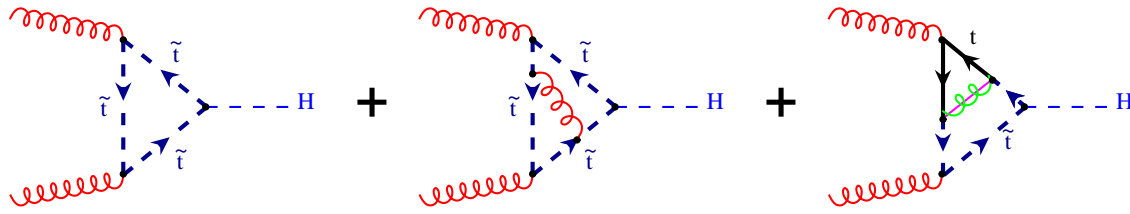
The equation shows the heavy top/stop/gluino limit. The coefficient $\tilde{C}(\alpha_s)$ is multiplied by a sum of diagrams. The first diagram is a top quark loop with a stop squark exchange. The second diagram is a top quark loop with a gluino exchange. The sum is followed by an ellipsis, indicating higher-order terms.

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

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

Gluon Fusion

● SUSY: Squarks + Gluinos



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

$$\rightarrow \tilde{C}(\alpha_s) \cdot \left(\text{diagram 1} + \text{diagram 2} + \dots \right)$$

The equation shows the heavy top/stop/gluino limit. The coefficient $\tilde{C}(\alpha_s)$ is multiplied by a sum of diagrams. The first diagram is a top quark loop with a top squark (\tilde{t}) exchange. The second diagram is a top quark loop with a top squark (\tilde{t}) exchange and a gluino (\tilde{g}) loop. The sum is followed by an ellipsis, indicating higher-order terms.

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

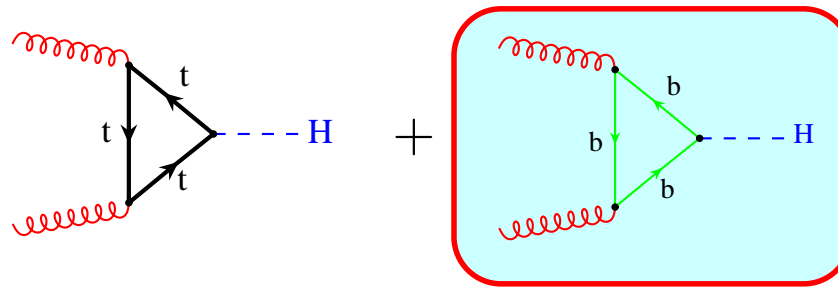
$$\Rightarrow \tilde{C}(\alpha_s) = \tilde{C}(\alpha_s, m_t/m_{\tilde{t}}, m_{\tilde{t}}/m_{\tilde{g}})$$

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

Gluon Fusion

- SUSY: bottom quarks

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



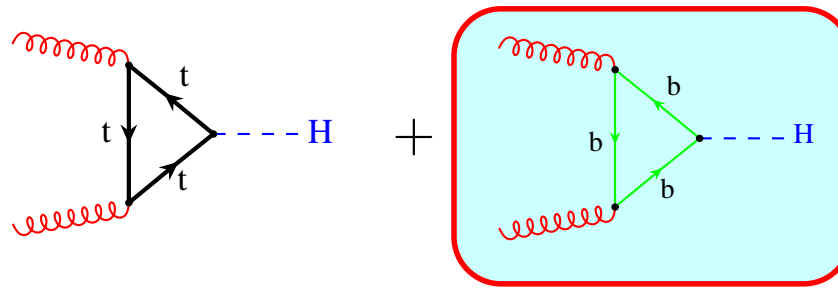
NLO: [Spira, Djouadi, Graudenz, Zerwas ('95)]

NNLO: "heavy bottom"?

Gluon Fusion

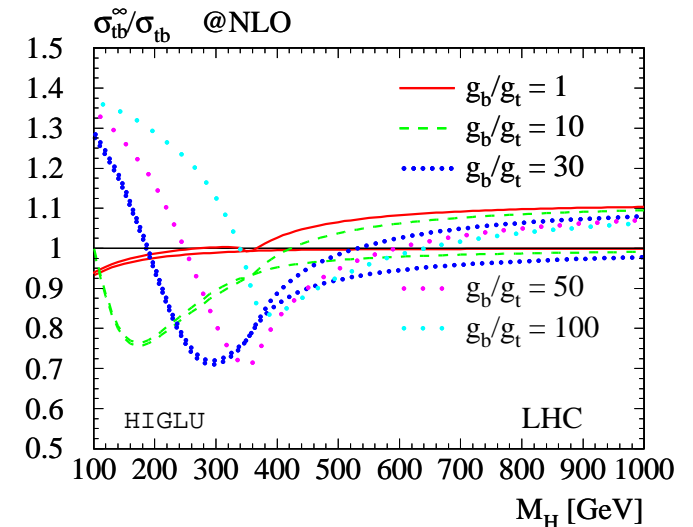
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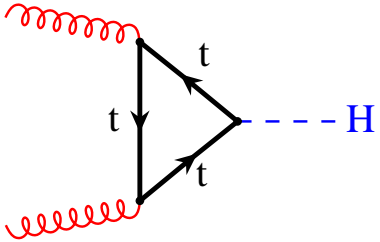
NLO: [Spira, Djouadi, Graudenz, Zerwas ('95)]

NNLO: “heavy bottom”?

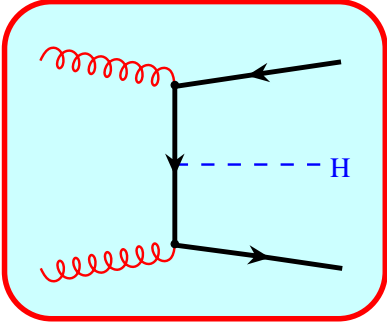


$$gg \rightarrow t\bar{t}H$$

instead of virtual:

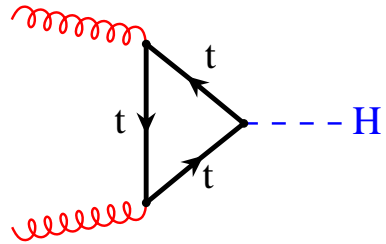


consider real tops:

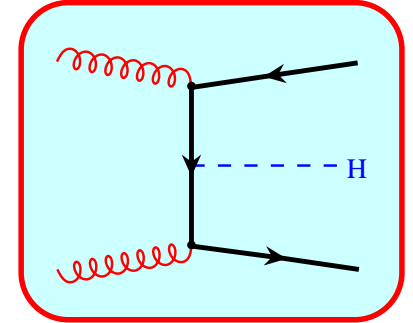


$$gg \rightarrow t\bar{t}H$$

instead of virtual:



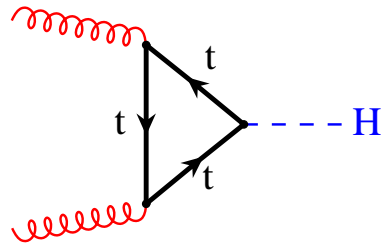
consider real tops:



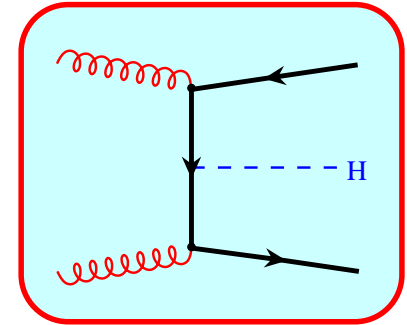
- supplementary mode at small M_H
- measurement of top Yukawa coupling

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

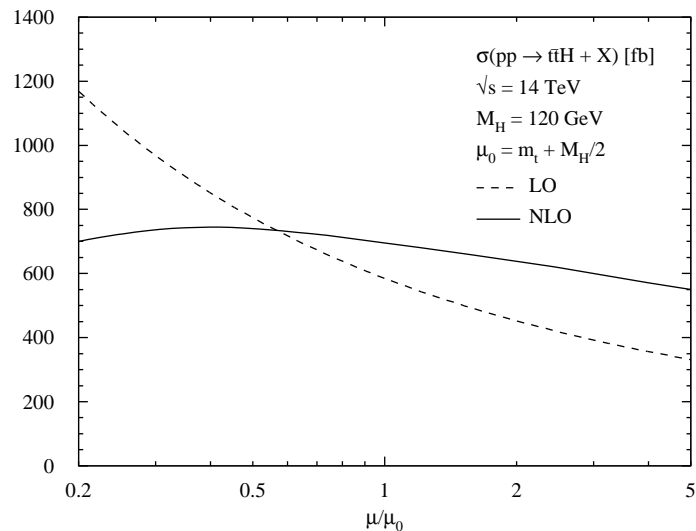
instead of virtual:



consider real tops:



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



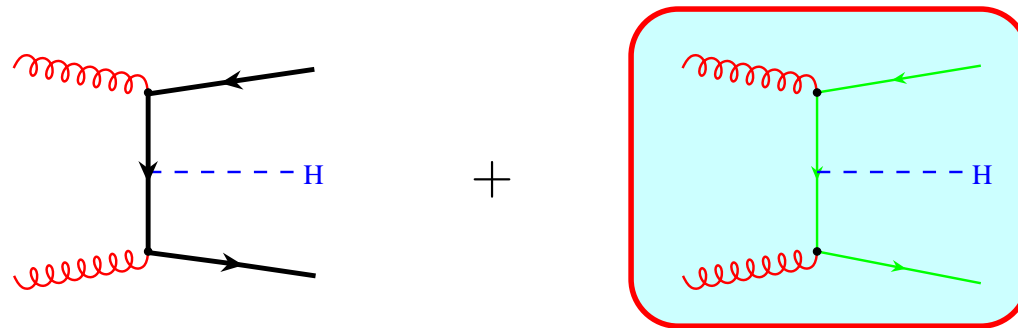
[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas ('01)]

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

SUSY again...

● modified Yukawas:

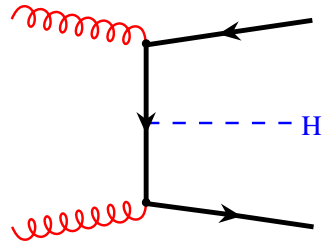
$$\frac{\lambda_b}{\lambda_t} = \frac{m_b}{m_t} \cdot \frac{v_u}{v_d} = \frac{m_b}{m_t} \cdot \tan \beta$$



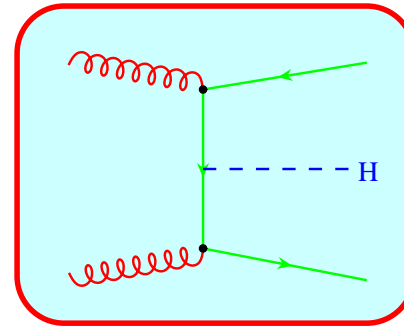
SUSY again...

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+



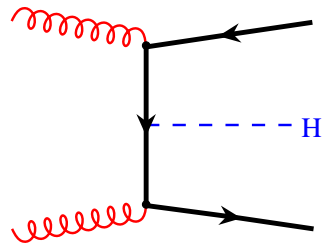
● collinear logarithms:

$$\sim \alpha_s \ln(m_b/M_H)$$

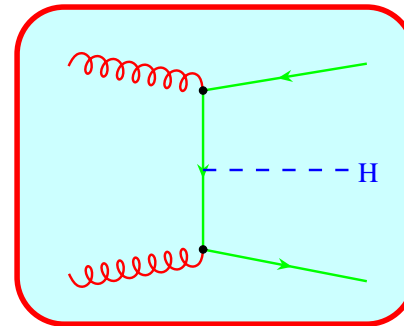
SUSY again...

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+

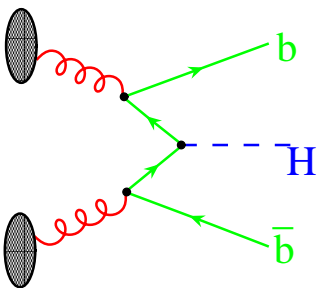


● collinear logarithms:

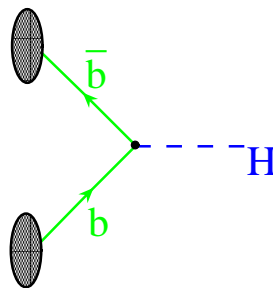
$$\sim \alpha_s \ln(m_b/M_H)$$

● resummation:

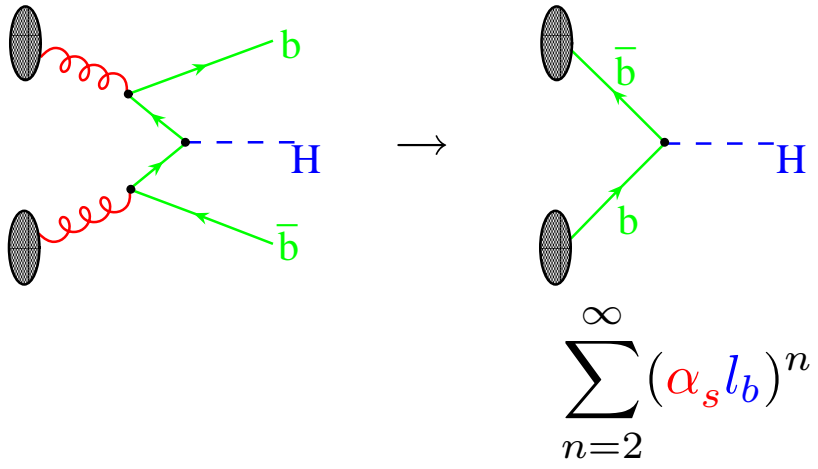
bottom parton densities



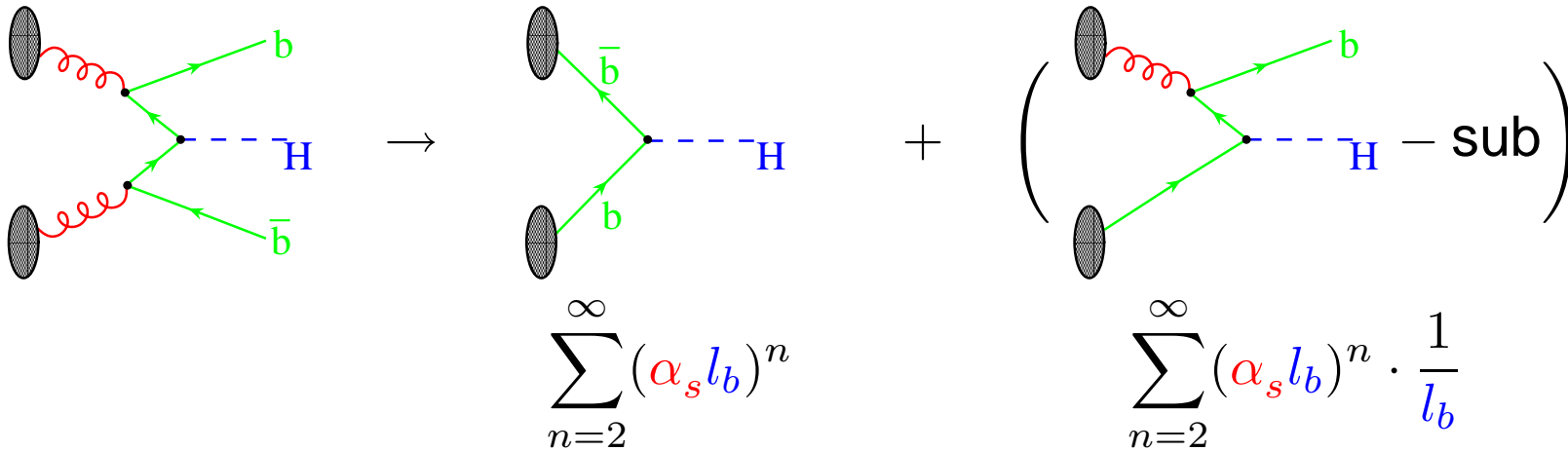
→



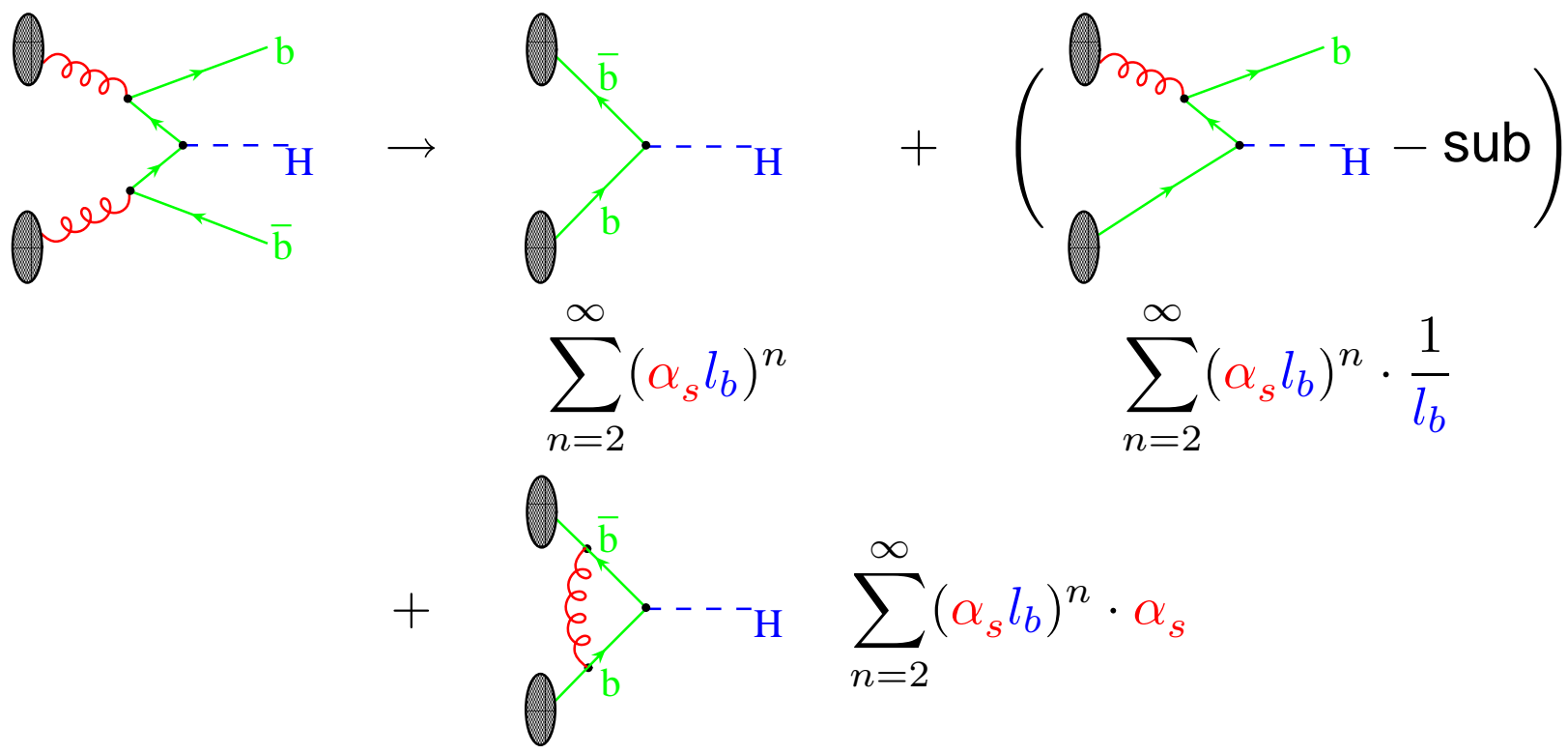
$pp \rightarrow H b \bar{b}$



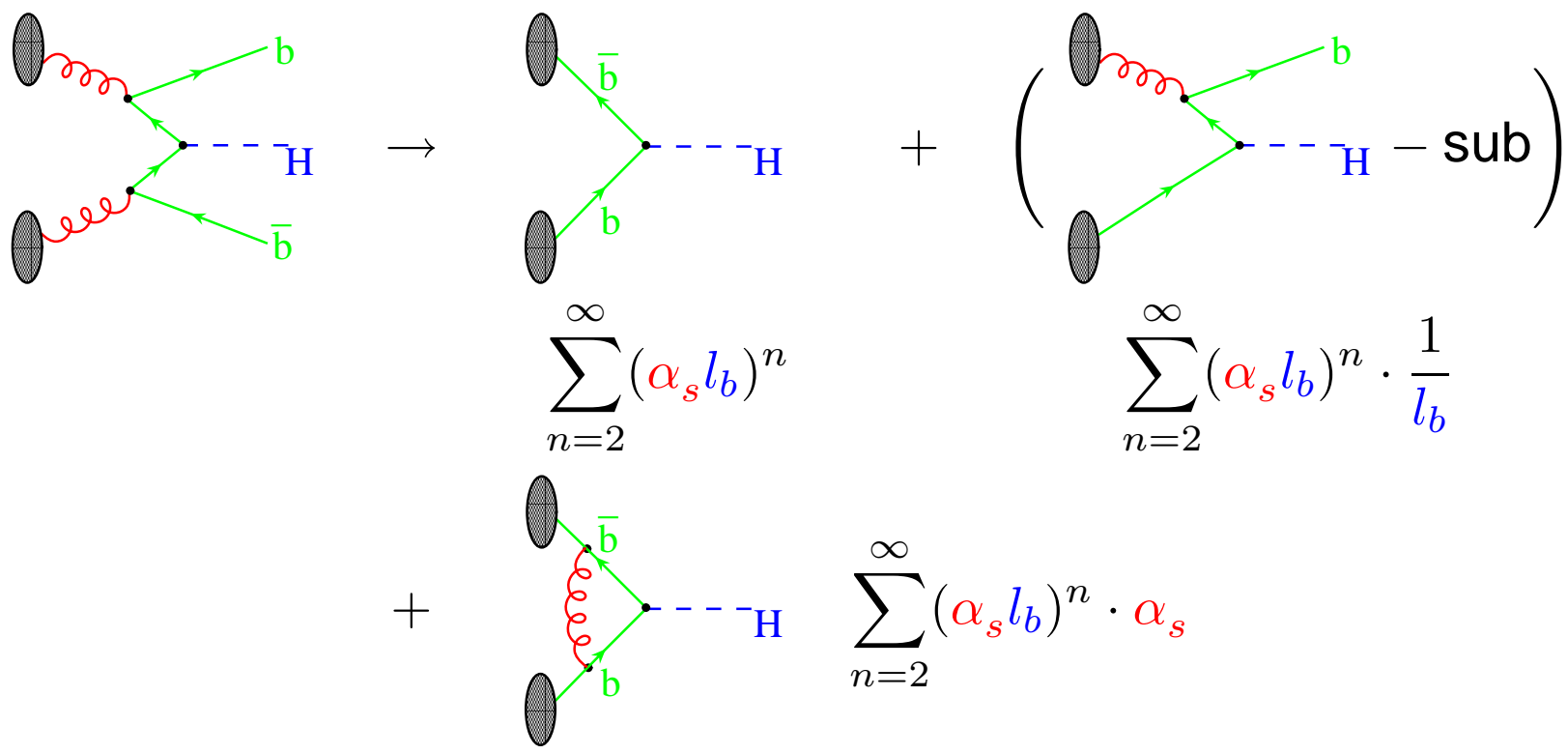
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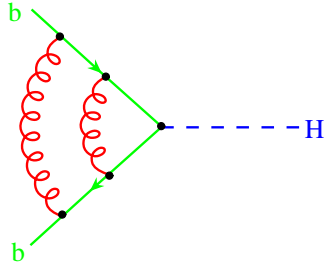
$pp \rightarrow H b \bar{b}$



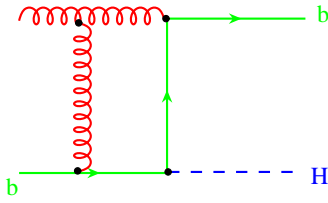
NLO:
$$\sigma(b\bar{b} \rightarrow H) = \sum_{n=0}^{\infty} (\alpha_s l_b)^n \alpha_s^2 \left[c_{n0} l_b^2 + c_{n1} l_b \right]$$

[Maltoni, Sullivan, Willenbrock ('03)]

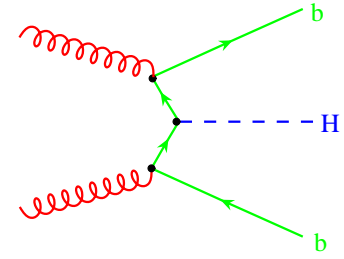
$b\bar{b} \rightarrow H$ @ NNLO



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

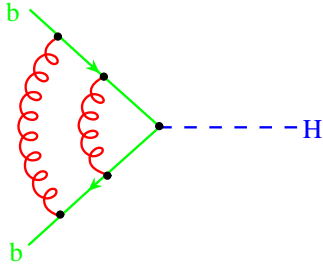


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \alpha_s \frac{1}{l_b}$$

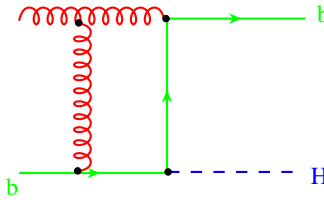


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \frac{1}{l_b^2}$$

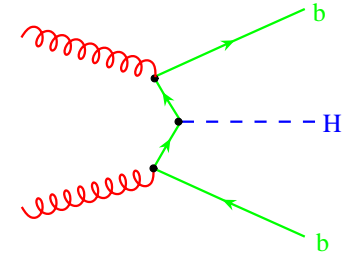
$b\bar{b} \rightarrow H$ @ NNLO



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



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

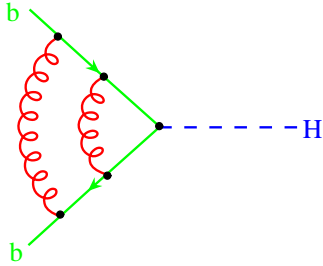


$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \frac{1}{l_b^2}$$

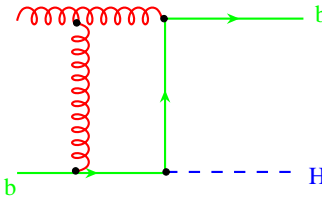
NNLO:
$$\sigma(b\bar{b} \rightarrow H) = \sum_{n=0}^{\infty} (\alpha_s l_b)^n \alpha_s^2 \left[c_{n0} l_b^2 + c_{n1} l_b + c_{n0} \right]$$

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

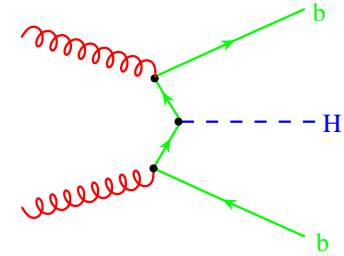
$b\bar{b} \rightarrow H$ @ NNLO



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



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



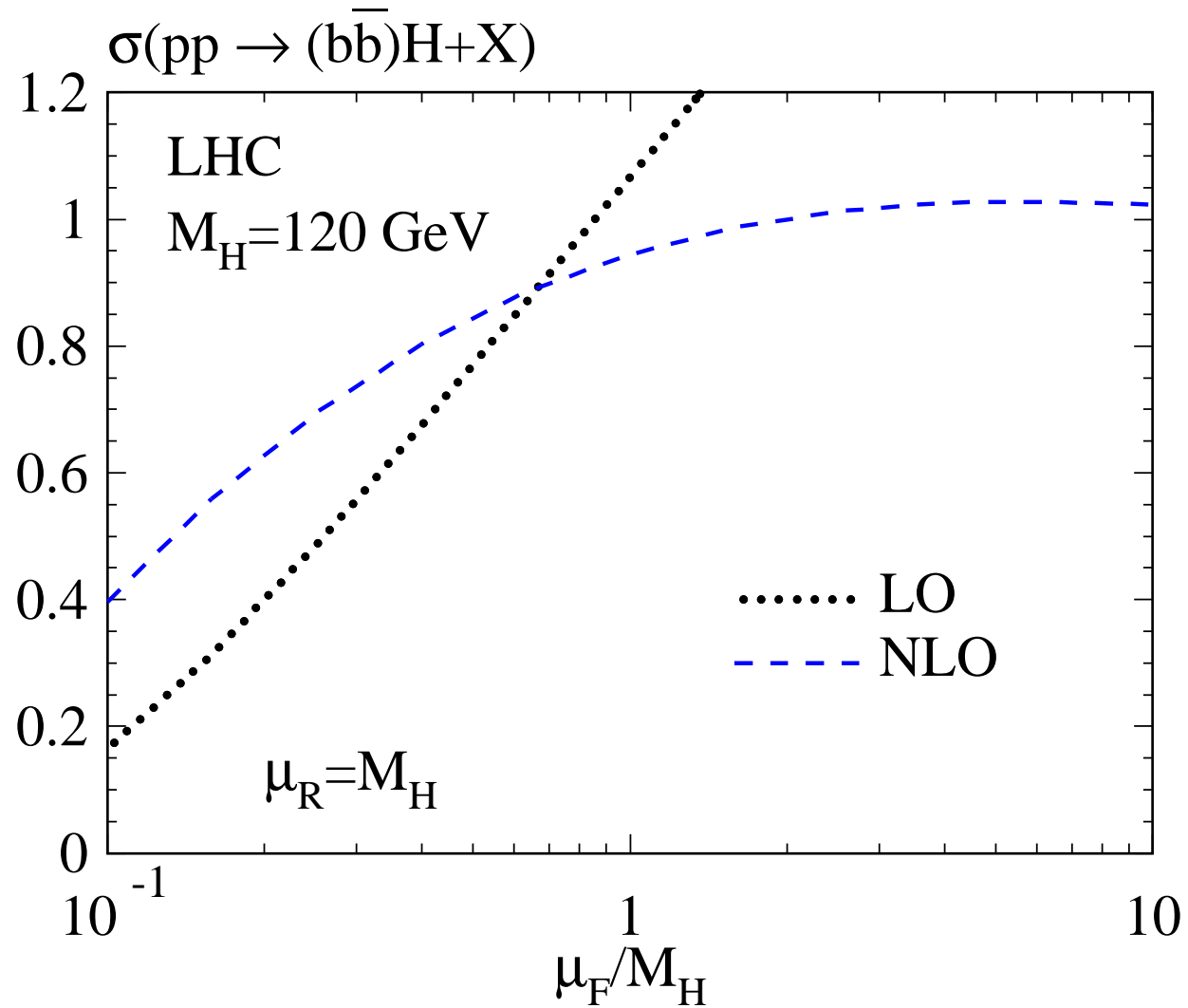
$$\sum_{n=2}^{\infty} (\alpha_s l_b)^n \cdot \frac{1}{l_b^2}$$

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

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

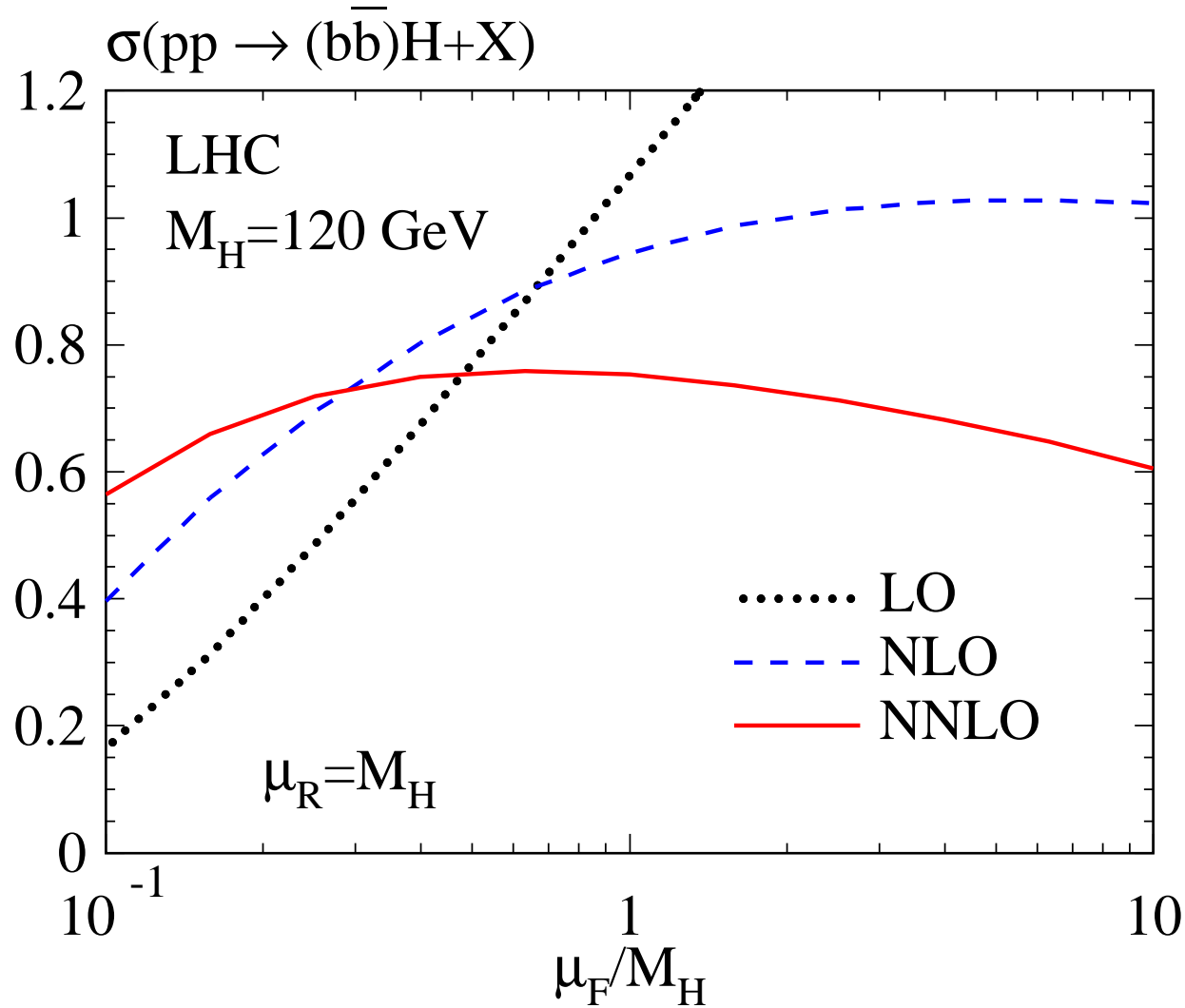
$$\text{higher orders: } \left. + d_{n3} \alpha_s^3 + d_{n4} \alpha_s^4 + \dots \right\}$$

$$b\bar{b} \rightarrow H$$



[Maltoni, Sullivan,
Willenbrock ('03)]

$$b\bar{b} \rightarrow H$$



[Maltoni, Sullivan,
Willenbrock ('03)]

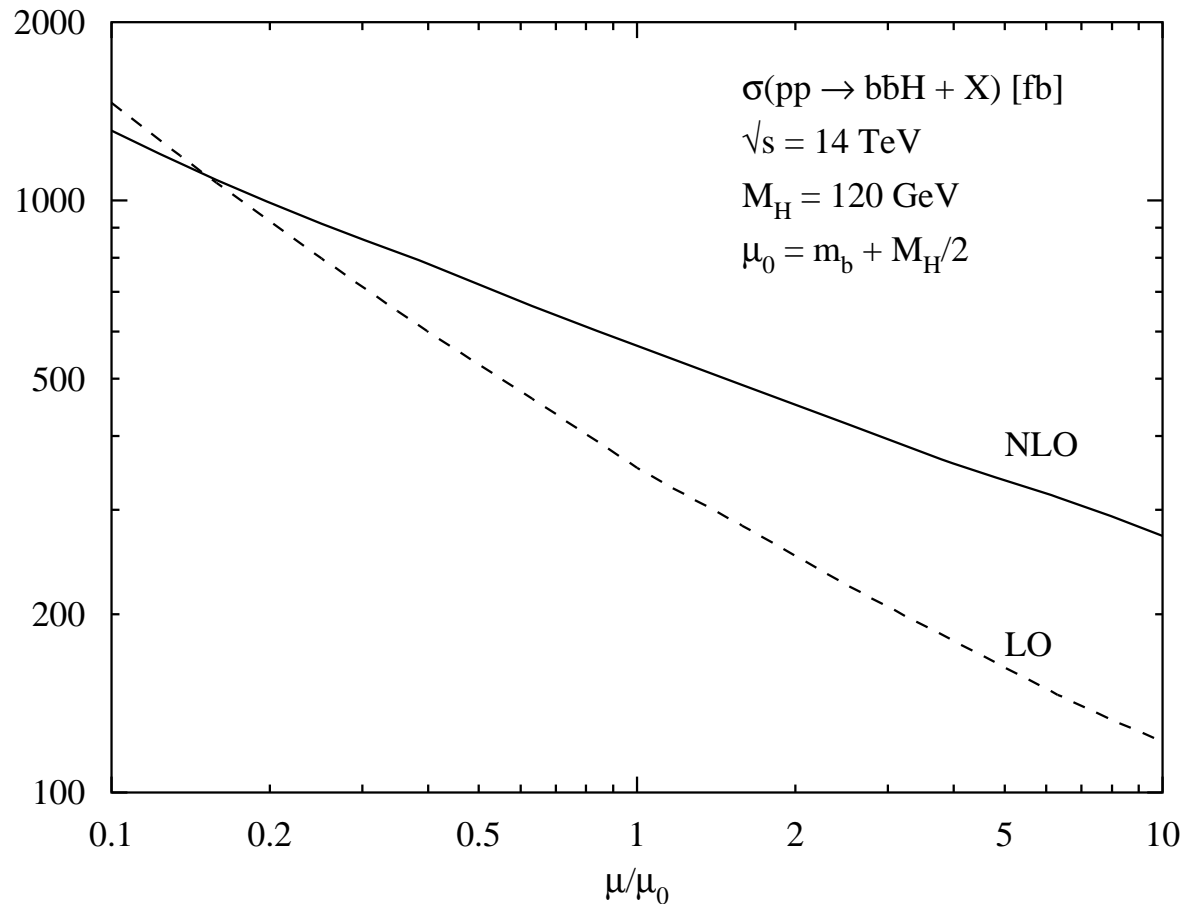
[R.H., Kilgore ('03)]

$$b\bar{b} \rightarrow H \quad \text{vs.} \quad gg \rightarrow b\bar{b}H$$

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

$$b\bar{b} \rightarrow H \quad \text{vs.} \quad gg \rightarrow b\bar{b}H$$

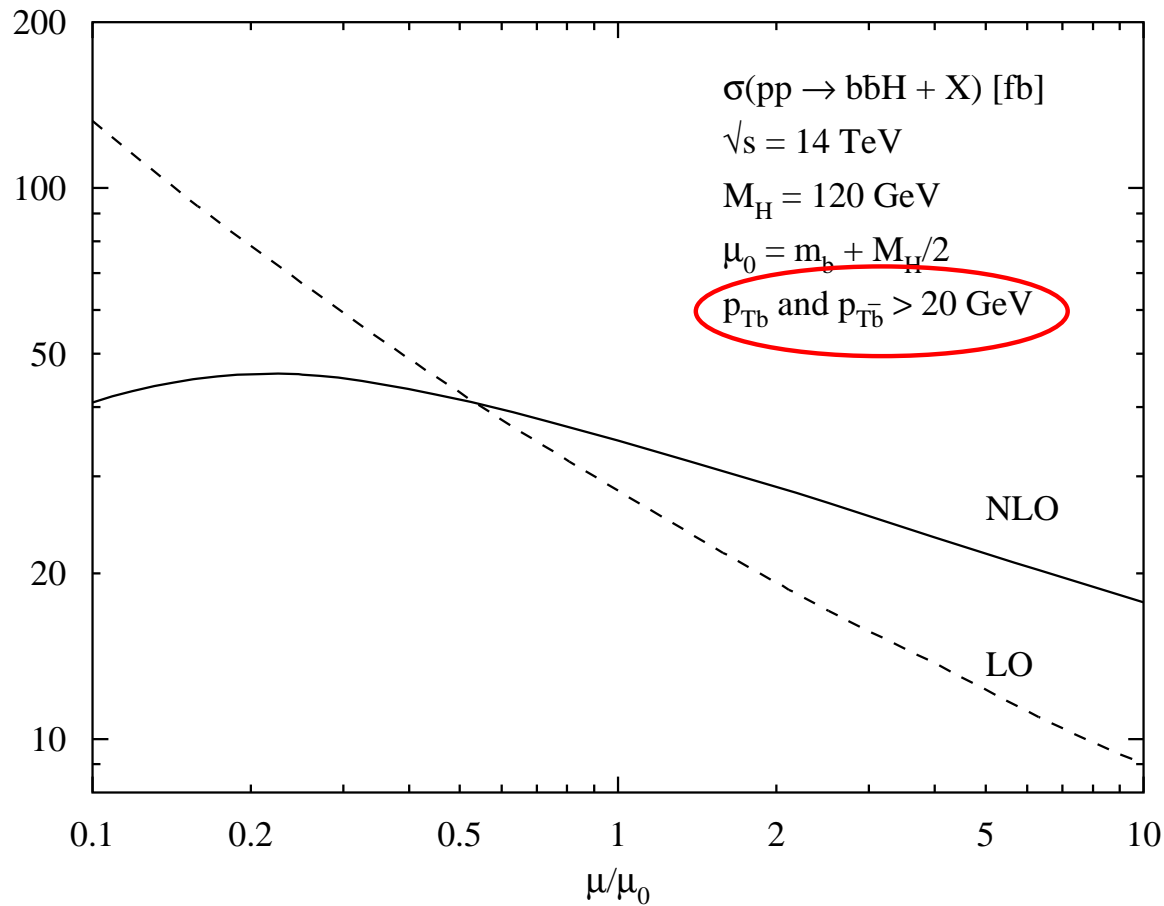
● $gg \rightarrow b\bar{b}H$ @ NLO: [Dittmaier, Krämer, Spira ('03)]
[Dawson, Jackson, Reina, Wackerath ('03)]



note the log scale

$$b\bar{b} \rightarrow H \quad \text{vs.} \quad gg \rightarrow b\bar{b}H$$

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



note the log scale

$$b\bar{b} \rightarrow H \quad \text{vs.} \quad gg \rightarrow b\bar{b}H$$

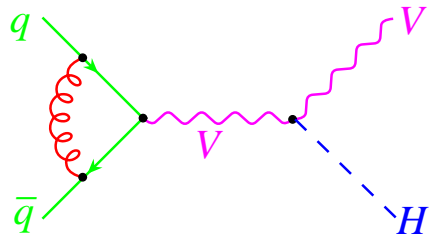
	$gg \rightarrow b\bar{b}H$	$b\bar{b} \rightarrow H$
Tevatron	$8.0^{+3.1}_{-2.4} \text{ fb}$	$10.5^{+0.3}_{-1.1} \text{ fb}$
LHC	$7.3^{+2.0}_{-1.6} \cdot 10^2 \text{ fb}$	$7.2^{+0.4}_{-1.6} \cdot 10^2 \text{ fb}$

$$b\bar{b} \rightarrow H \quad \text{vs.} \quad gg \rightarrow b\bar{b}H$$

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

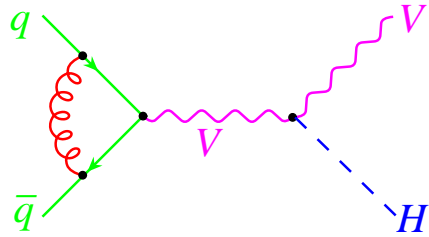
- total rate for $b\bar{b} \rightarrow H$ under control
- bottom quark densities are very useful tool
- discussions on factorization scale are settling

Higgs Strahlung



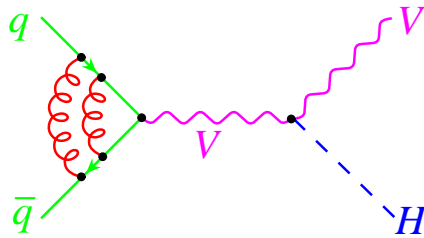
\sim Drell-Yan! [Han, Willenbrock ('90)]
 $\approx +30\%$

Higgs Strahlung



\sim Drell-Yan! [Han, Willenbrock ('90)]
 $\approx +30\%$

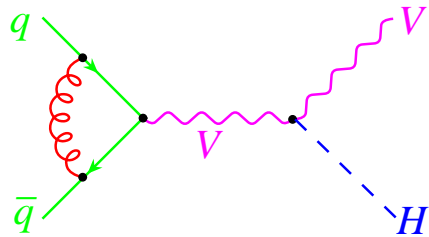
even NNLO:



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

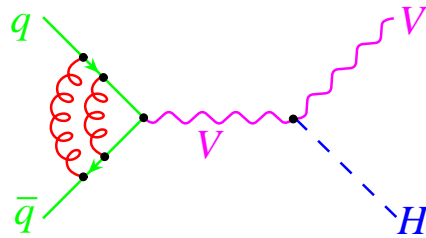
[R.H., Kilgore ('02)]

Higgs Strahlung



~ Drell-Yan! [Han, Willenbrock ('90)]
 $\approx +30\%$

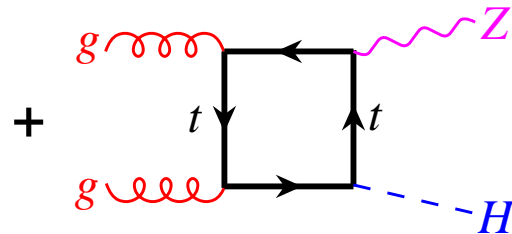
even NNLO:



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

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

for $H + Z$:

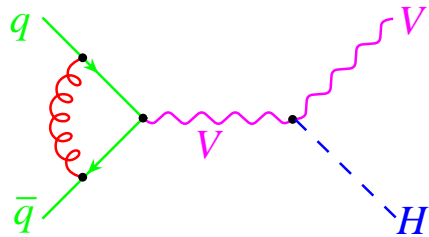


[Barger *et al.* ('86)]

[Dicus, Kao ('88)]

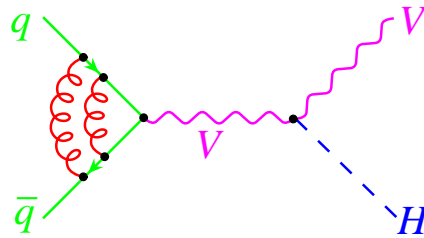
[Kniehl ('90)]

Higgs Strahlung



~ Drell-Yan! [Han, Willenbrock ('90)]
 $\approx +30\%$

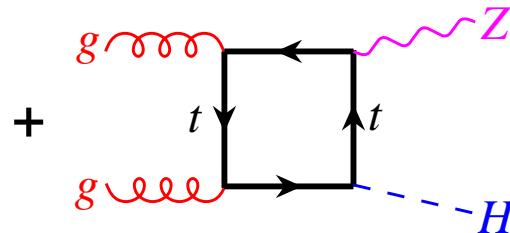
even NNLO:



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

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

for $H + Z$:



[Barger *et al.* ('86)]

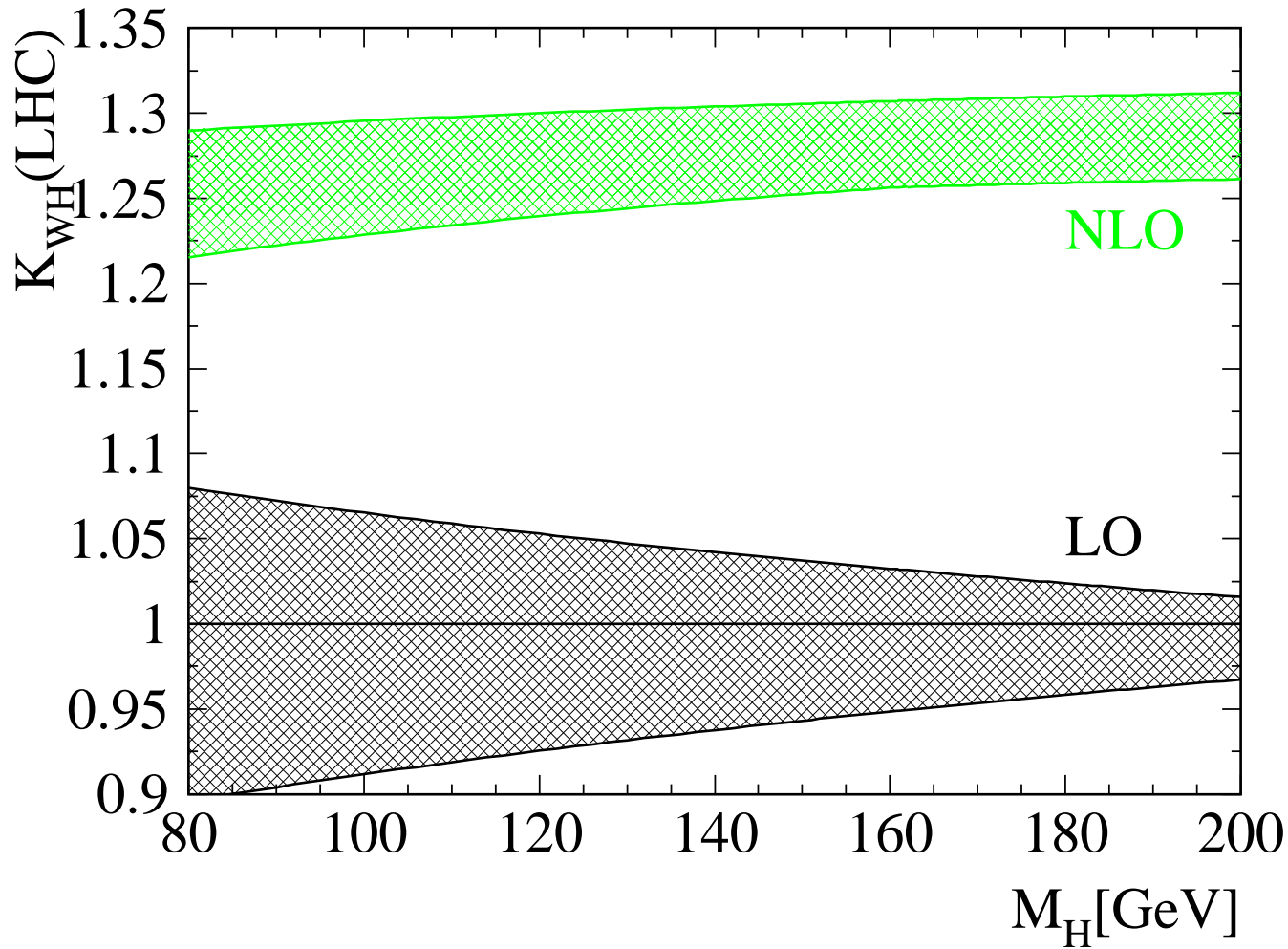
[Dicus, Kao ('88)]

[Kniehl ('90)]

→ **NNLO QCD** [Brein, Djouadi, R.H. ('03)]

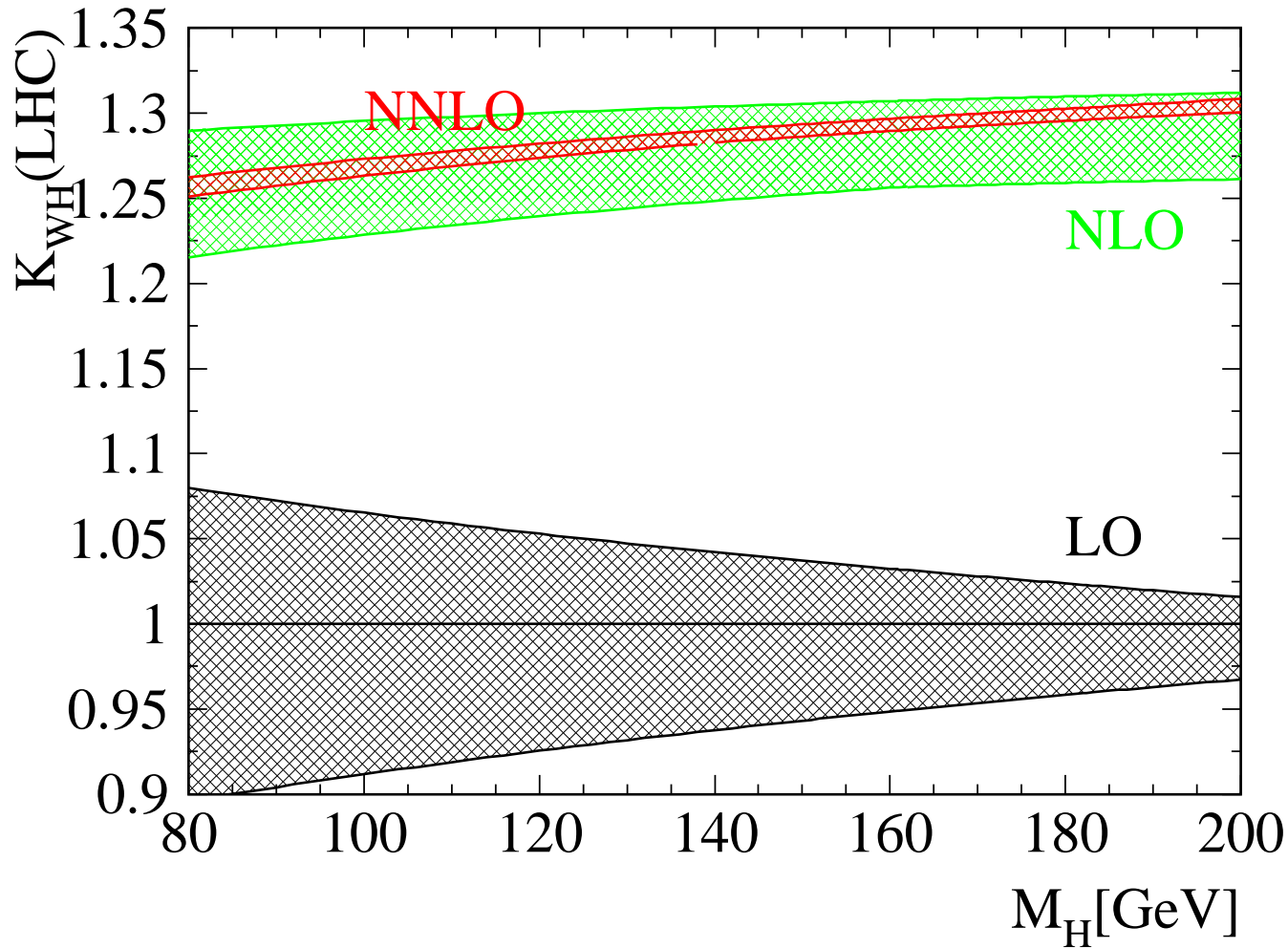
+ **EW** [Ciccolini, Dittmaier, Krämer ('03)]

Higgs Strahlung



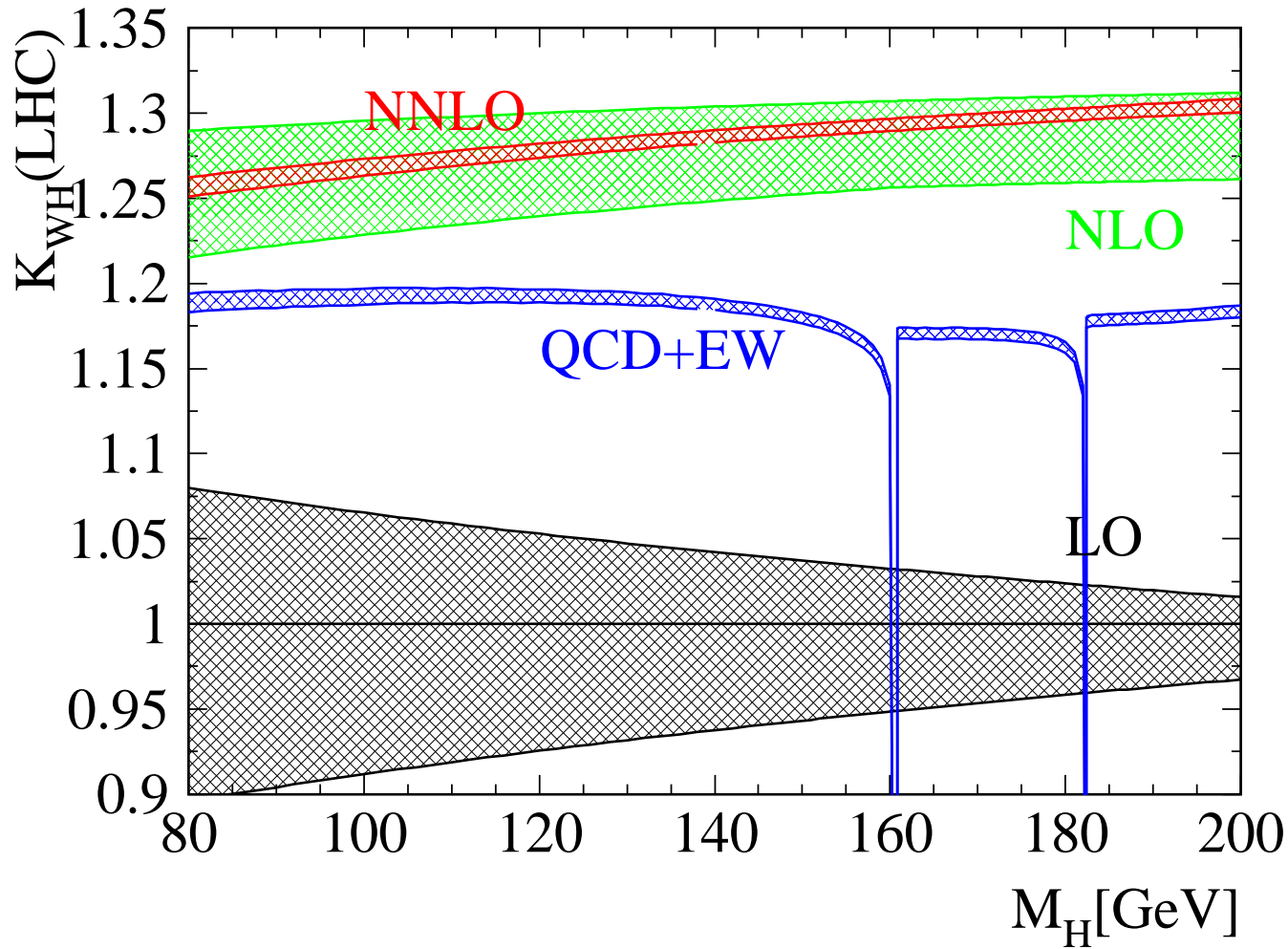
[Han,
Willenbrock ('90)]

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
 - $gg \rightarrow H \rightarrow 15\%$
 - $b\bar{b} \rightarrow H \rightarrow 15\%$
 - Higgs Strahlung $\rightarrow 1\%$ -level
- **NLO results** for
 - $gg \rightarrow t\bar{t}H \rightarrow 10\%$
 - $gg \rightarrow b\bar{b}H \rightarrow ??$
 - Weak Boson Fusion $\rightarrow 10\%$
- **Questions:**
 - need for distributions?
 - need for backgrounds? Theory vs. Data?
 - need for a Monte Carlo?