Standard and Supersymmetric Higgs Production at the Large Hadron Collider

Robert Harlander

Bergische Universität Wuppertal

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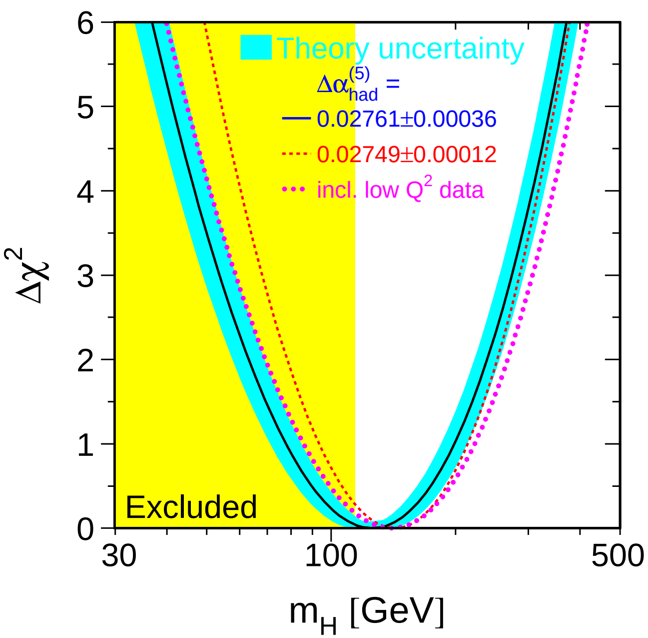
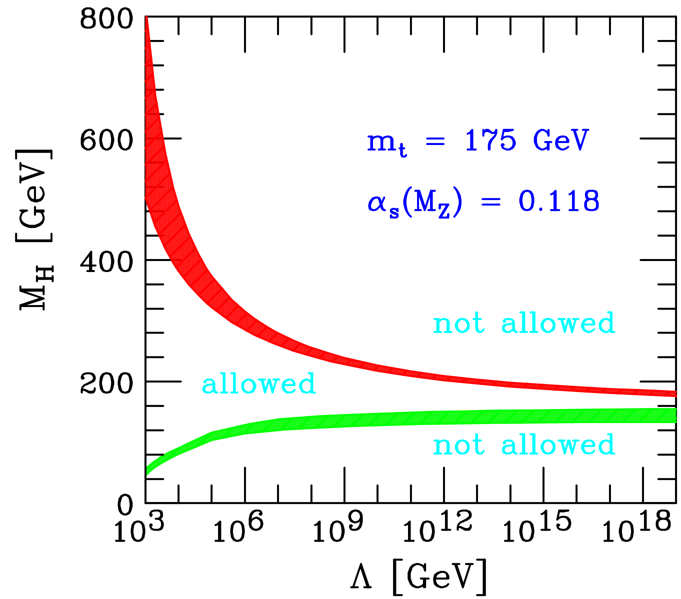
Bhubaneshwar, India, January 5, 2006

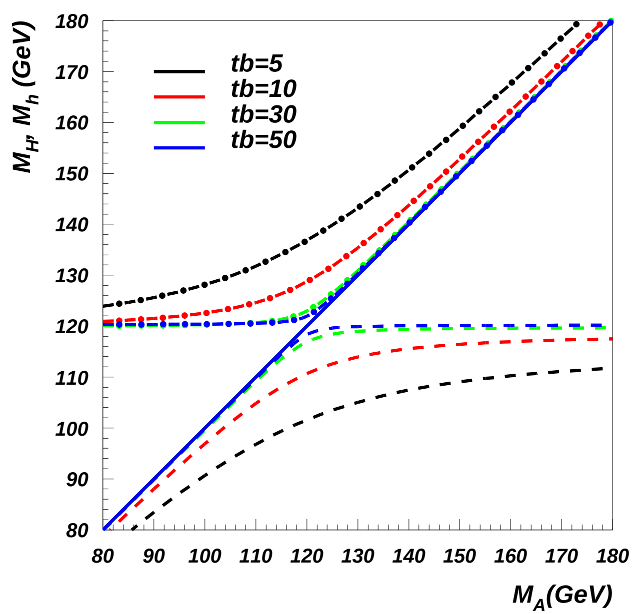
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

BERGISCHE UNIVERSITÄT WUPPERTAL

Where is the Higgs boson?

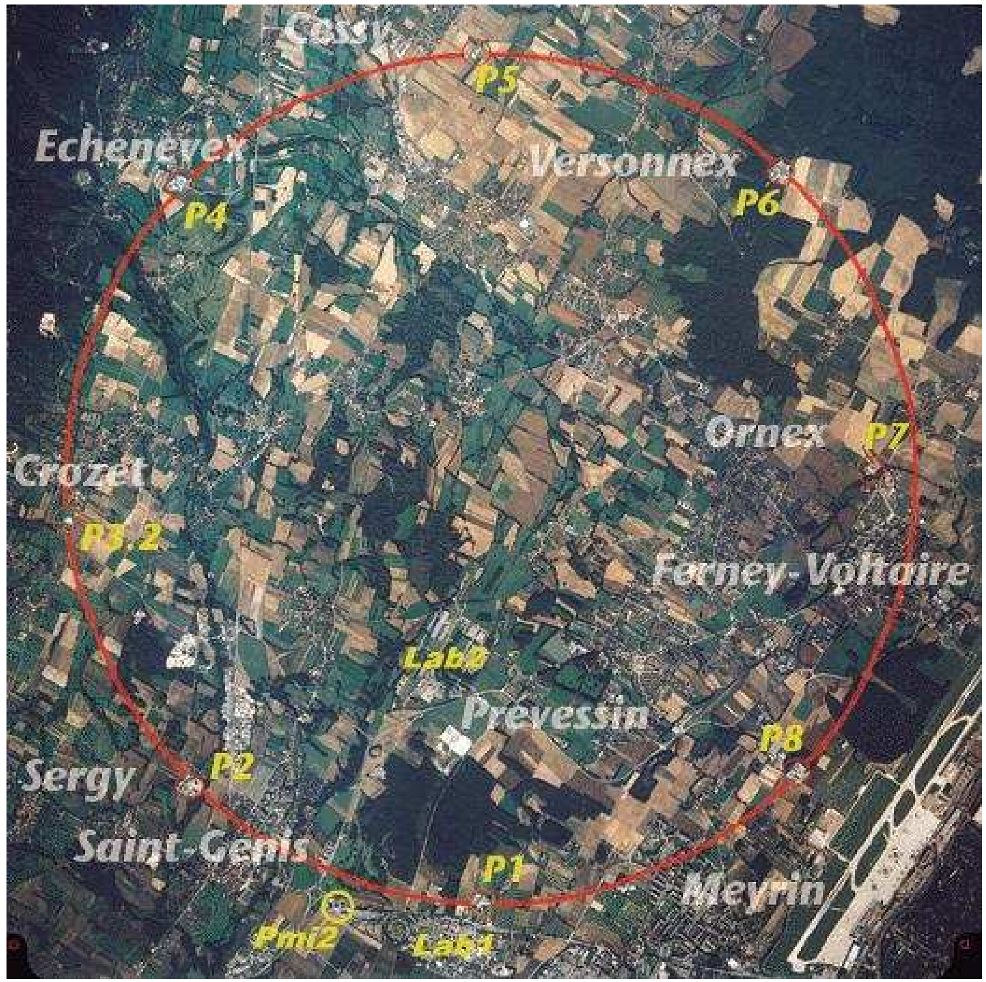




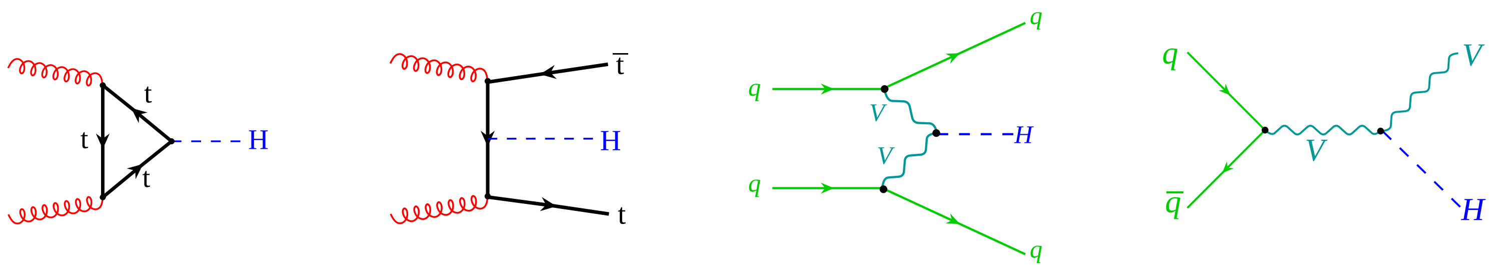


Large Hadron Collider

proton →← proton



$pp \to H$ at 14 TeV



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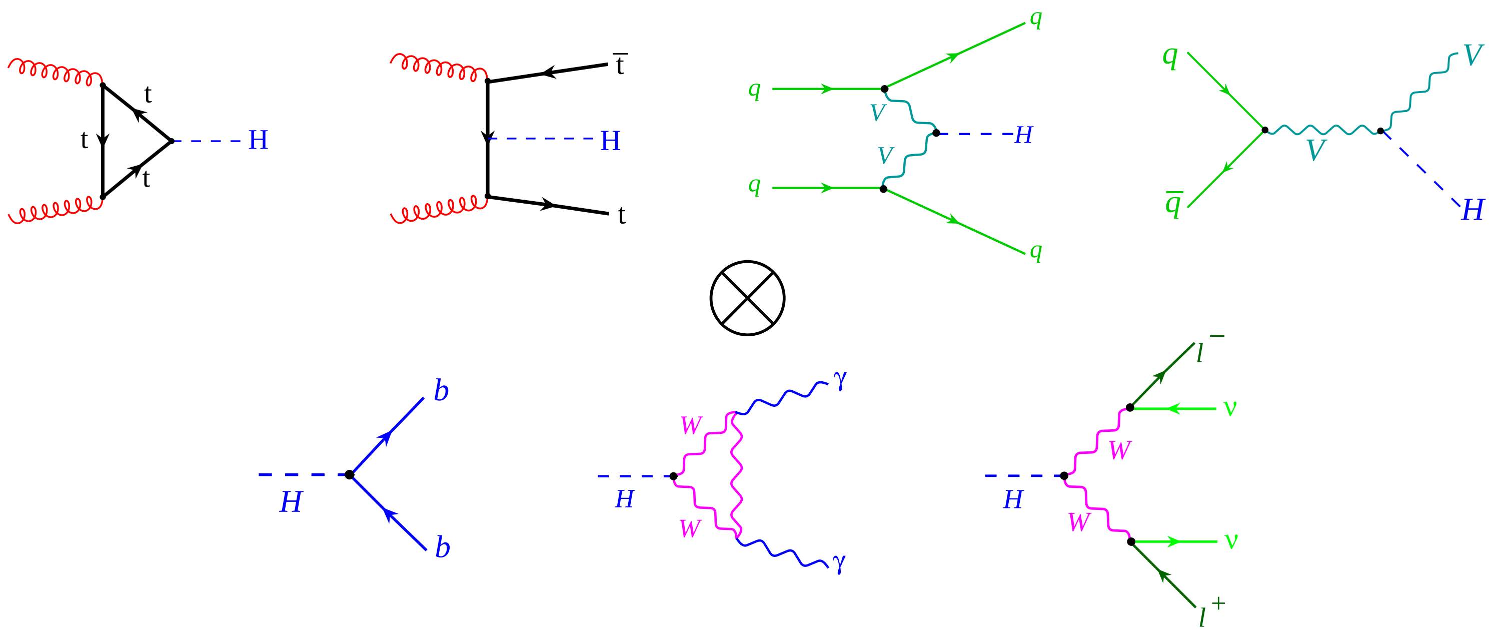

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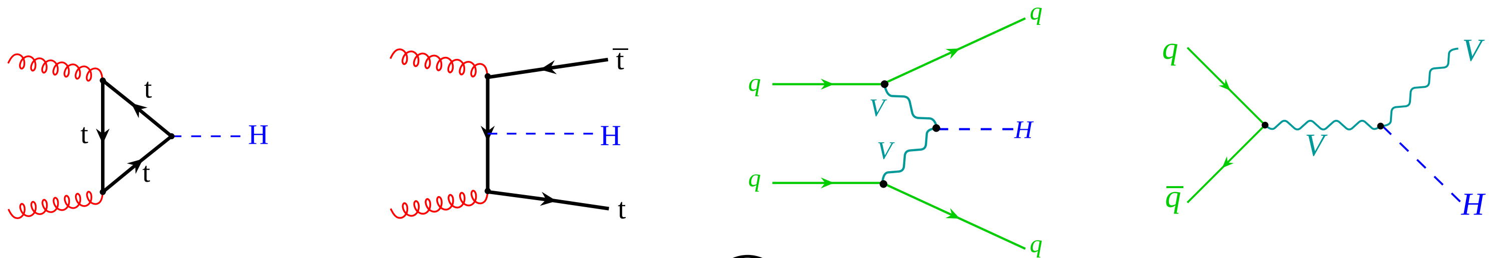
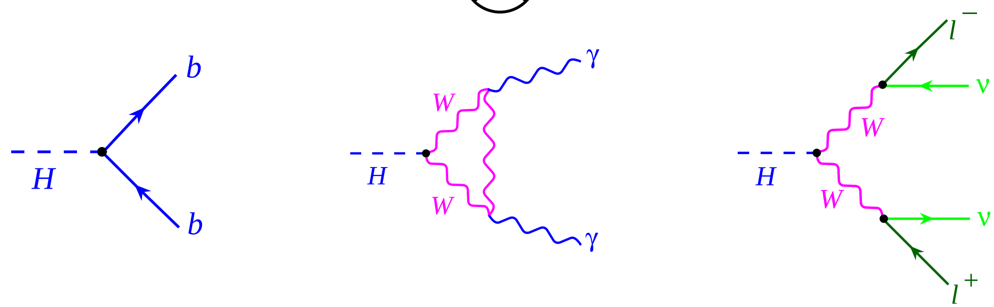
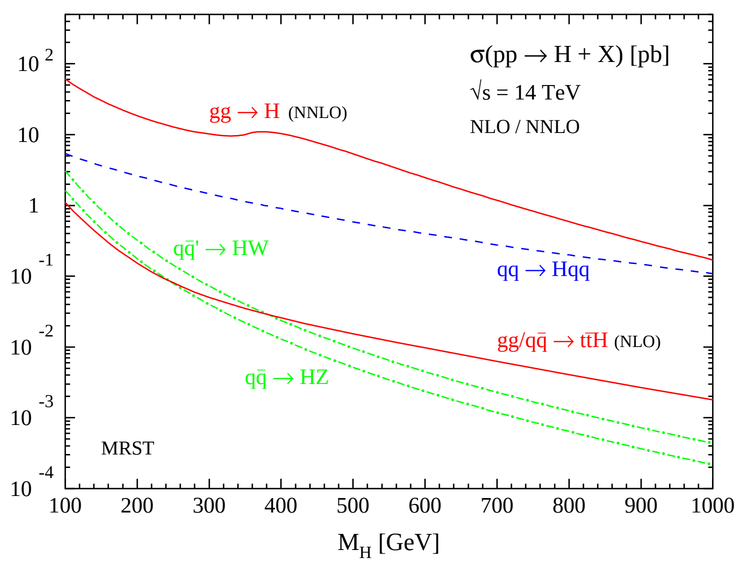


$\otimes$





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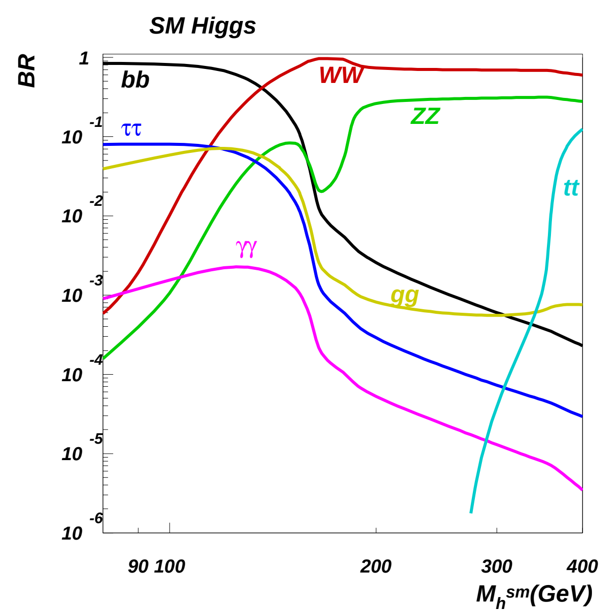
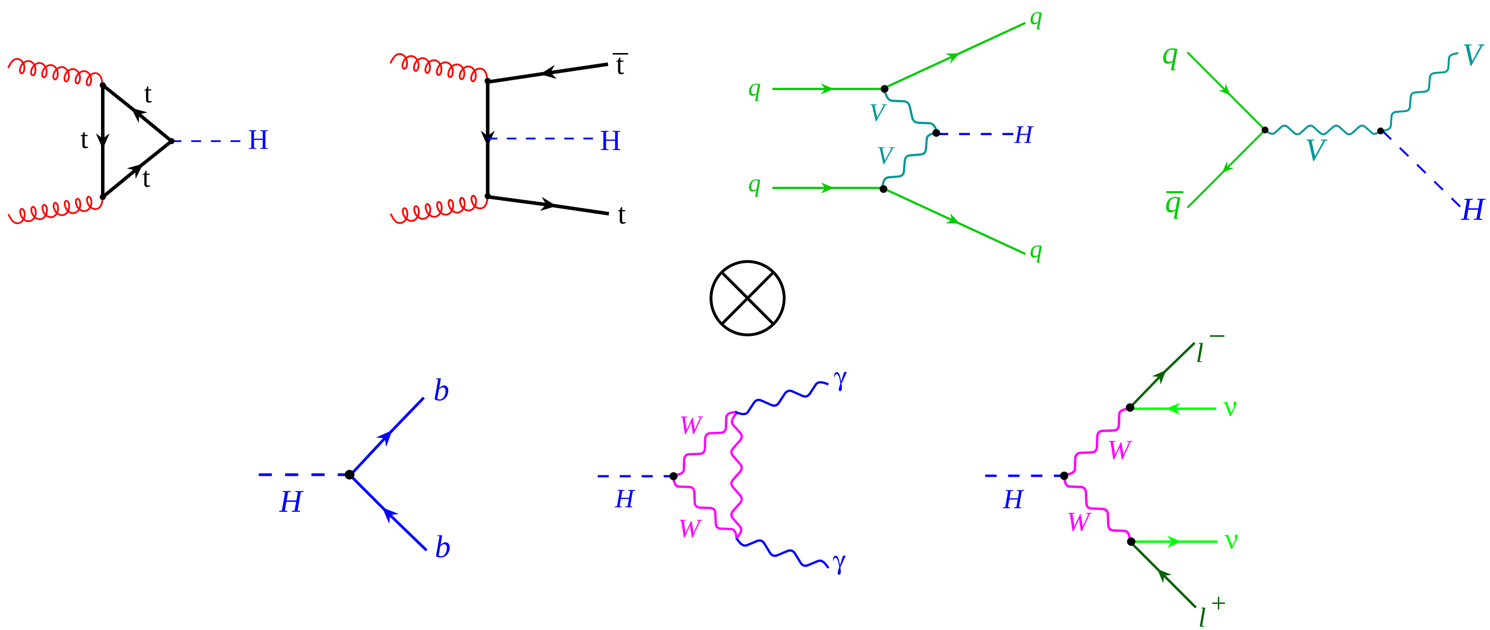


Overview

- Cross sections: Importance of higher orders
- Distributions and Cuts
- Backgrounds
- Supersymmetry

Higgs search



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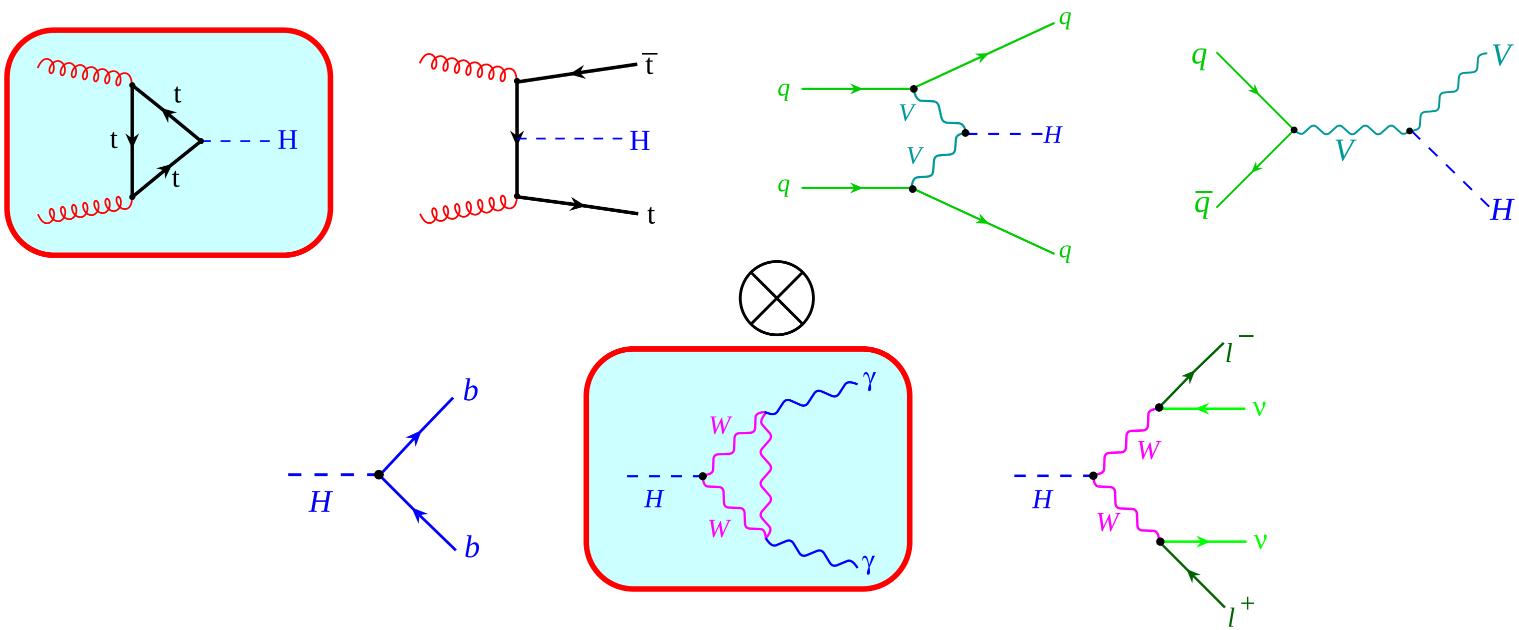
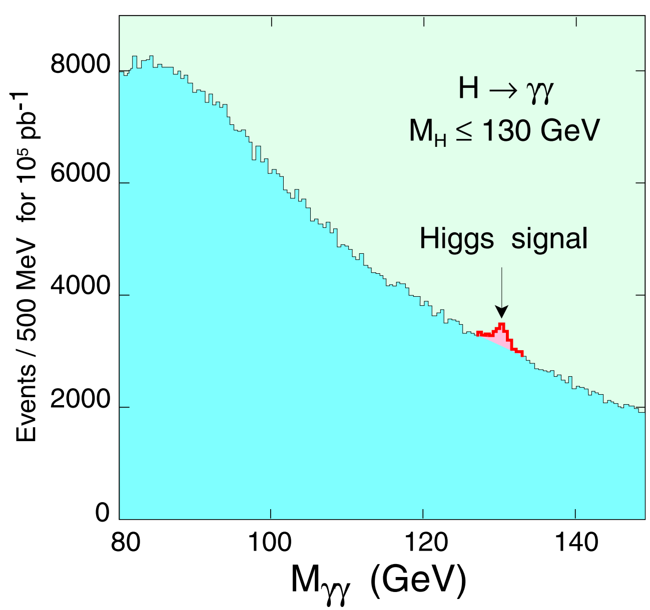
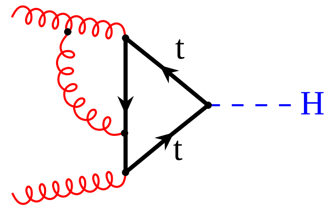
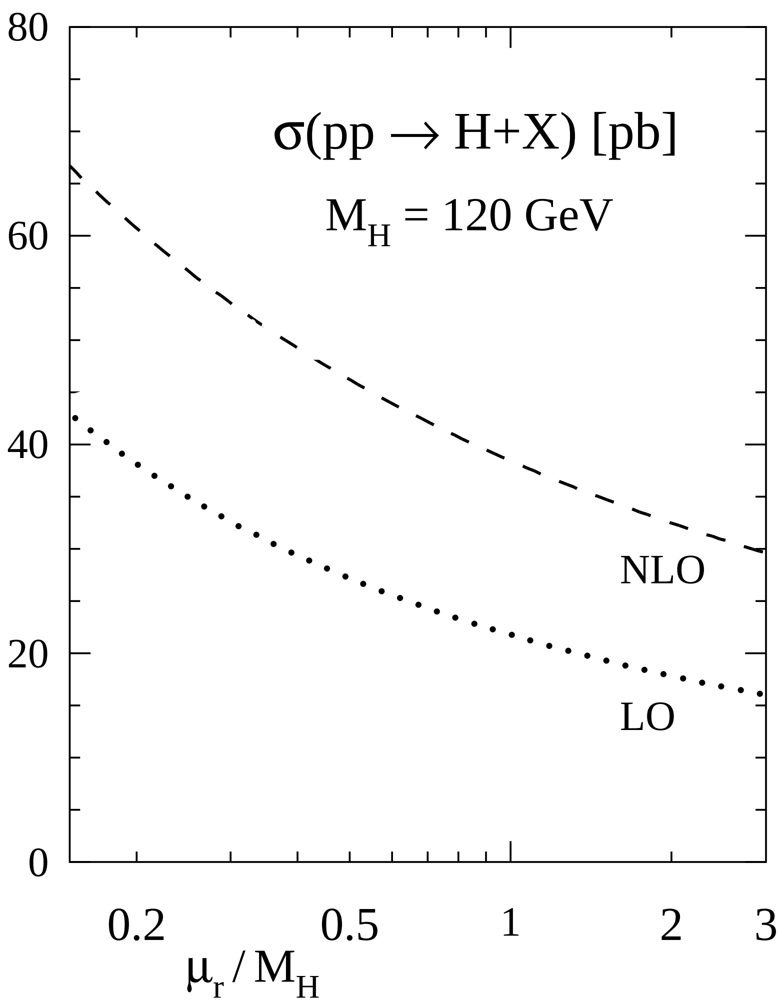




Gluon fusion





[Dawson ’91]

[Djouadi, Graudenz, Spira, Zerwas ’91,’93]

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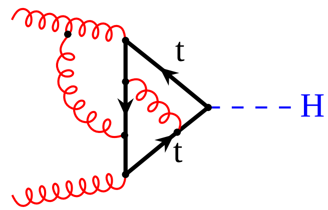

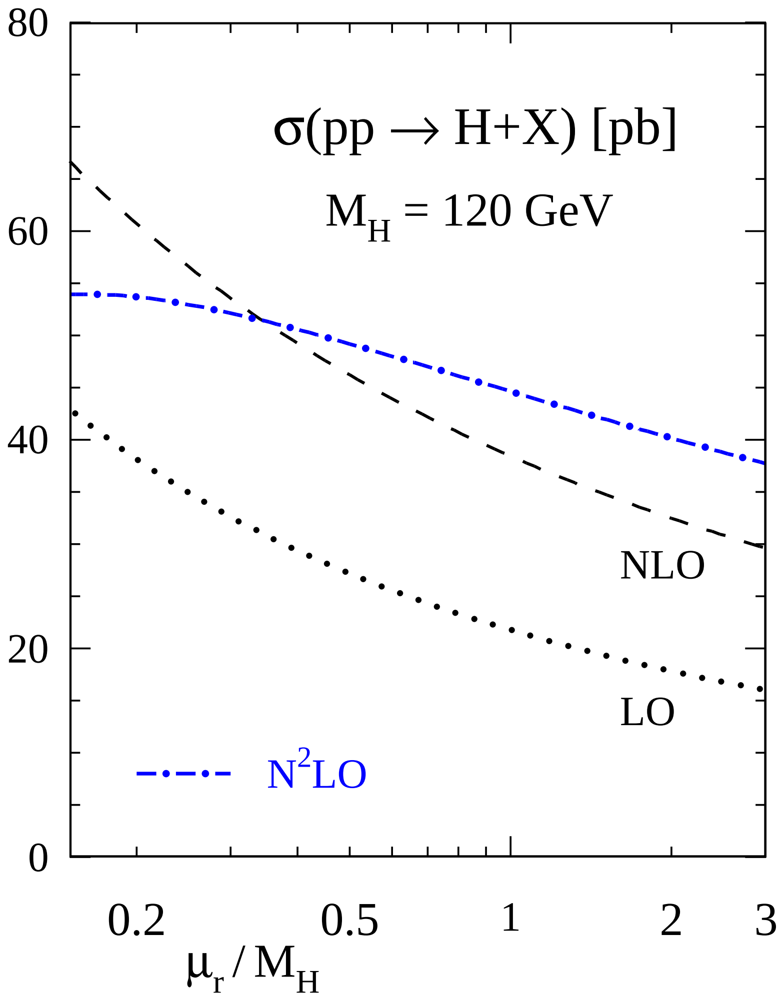

[R.H., Kilgore ’02]
[Anastasiou, Melnikov ’02]
[Ravindran, Smith, v.Neerven ’03]

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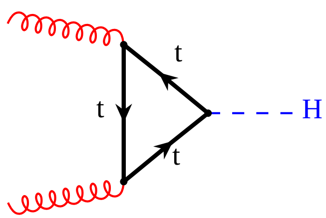
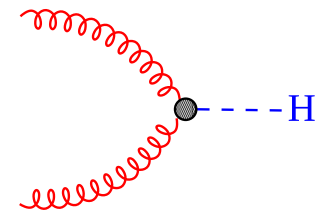
Side remark

- effective theory for $m_t \gg M_H$:



$\overset{m_t \gg M_H}{\longrightarrow}$ $C(m_t, \alpha_s) \times$



$C(m_t, \alpha_s)$: [Chetyrkin, Kniehl, Steinhauser '96]
[Krämer, Laenen, Spira '96]

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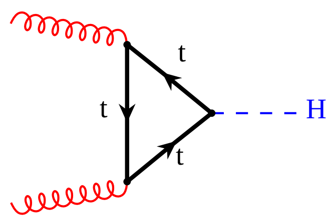

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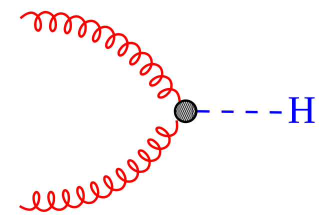

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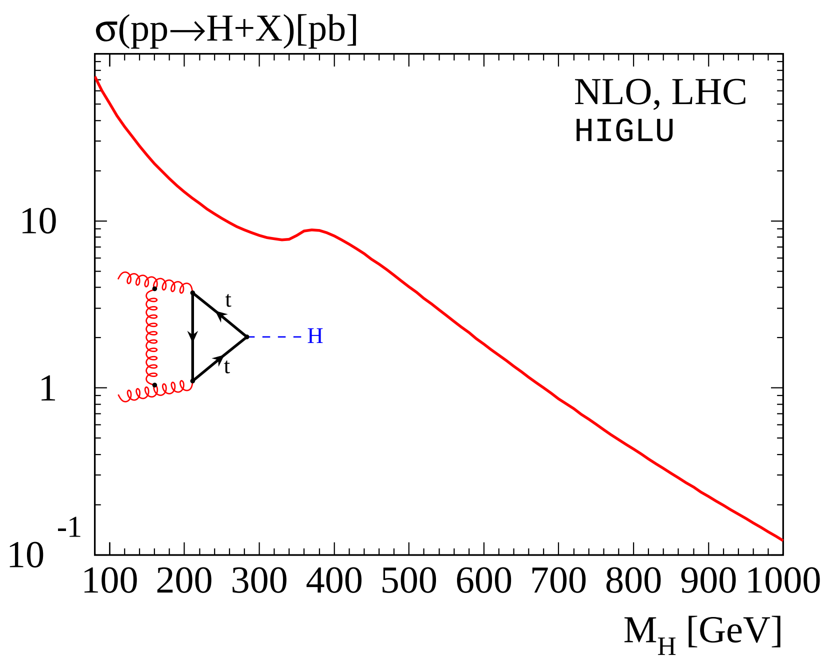

[Spira, Djouadi,
Graudenz, Zerwas (’95)]

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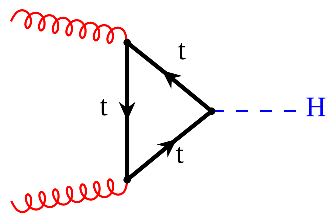

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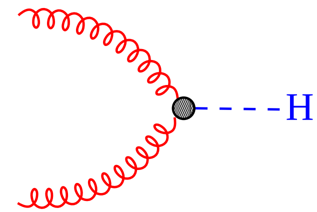

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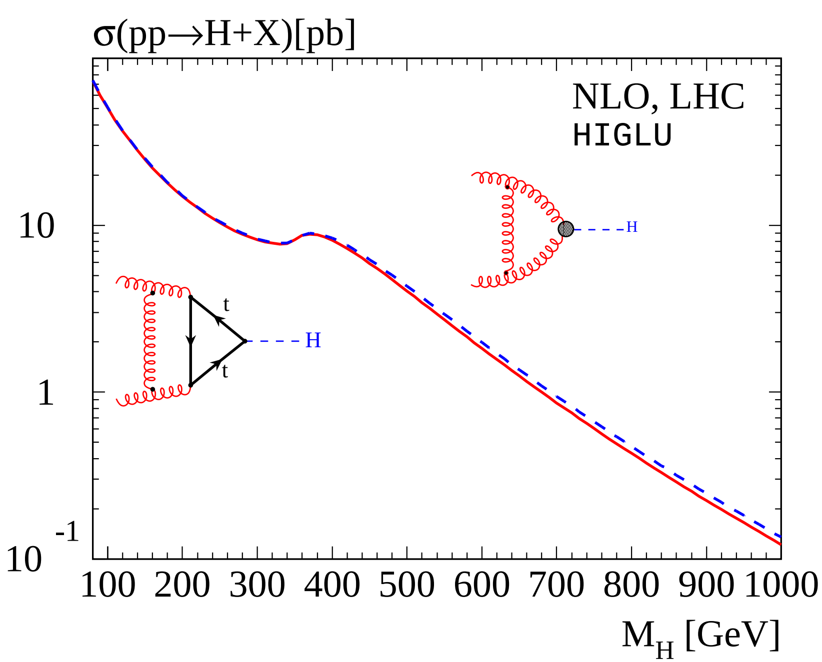

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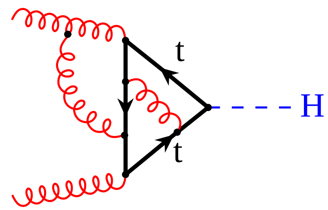

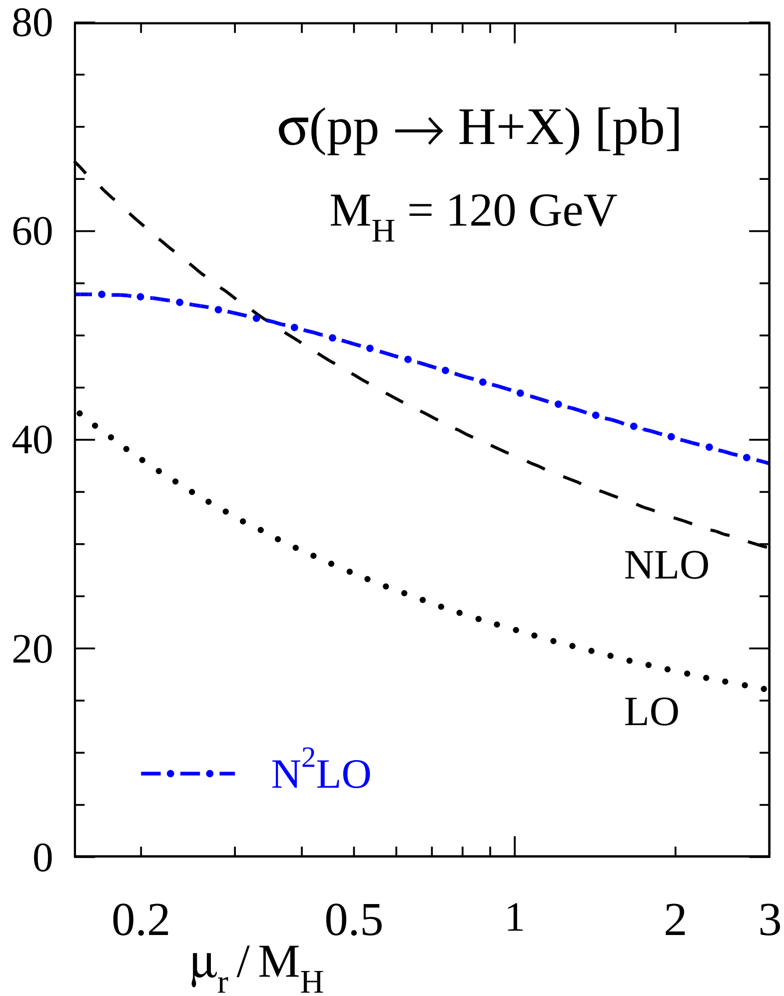

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Algorithms

- Expansion + Inversion [R.H., Kilgore '02], [R.H., P. Kant '05]

$$f(x,a) = \frac{1}{x}\log(1-ax) + \frac{1}{ax}\mathrm{Li}_2(ax)\,,$$

$$\int_0^1 f(x,a)\,\mathrm{d}x = \,?$$

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$$= -\mathrm{Li}_2(a) + \frac{1}{a}\,\mathrm{Li}_3(a)$$

Expansion & Inversion

Expansion: $\int_0^1 \mathrm{d}x\, f_{\rm exp}(x,a) = 1 + a\,\frac{13}{36} + a^2\,\frac{809}{4050} + a^3\,\frac{1927}{14700} + a^4\,\frac{234314}{2480625} + a^5\,\frac{7803574}{108056025} + \ldots$

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$$+ a^{30}\,\frac{3492364666716354224912772379903992428467656921752535 04}{554843371877223465430704764794692375739961430895541081 25} + \ldots$$

$$+ a^{40}\,\frac{61113456056322311744870175064504244192595167719946035127265078613639168}{14745493454562605394456699787099536537401020068836289098341590591777721875} + \ldots$$

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$$+ \ldots$$

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$$+ \ldots$$

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$$+ a^{30}\,\frac{34923646667163542249127723799039924284676569217525350 4}{55484337187722346543070476479469237573996143089554108125} + \ldots$$

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$$+ \ldots$$

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$$+ \ldots$$

Expansion & Inversion

$$\frac{809}{4050} + a^{3}\frac{1927}{14700} + a^{4}\frac{234314}{2480625} + a^{5}\frac{7803574}{108056025} + \ldots$$

$$\frac{29609234432}{189271817625} + \ldots$$

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$$\frac{0175064504244192595167719946035127265078613639168}{99787099536537401020068836289098341590591777721875} + \ldots$$

$$\frac{9274633011959191579658481277324946765508662514142950473189880368104925081944850737235101650589750429 9}{8450019860548032984785987565671211465903567266917977858035684466127039882827658570376152784851514702}$$

Expansion & Inversion

$$- \, a^5 \frac{7803574}{108056025} + \ldots$$

$$\frac{504}{8125} + \ldots$$

$$\frac{35127265078613639168}{9098341590591777721875} + \ldots$$

$$\frac{24946765508662514142950473189880368104925081944850737235101650589750429946517469801770049189096743846}{67121146590356726691797785803568446612703988282765857037615278485151470216338228550227166109933811546}$$

Expansion & Inversion

$$\frac{98803681049250819448507372351016505897504299465174698017700491890967438460589585811161362548515272025}{35684466127039882827658570376152784851514702163382285502271661099338115463236231206966125740312425543}$$

Expansion & Inversion

$$\frac{1016505897504299465174698017700491890967438460589585811161362548515272020257024}{1527848515147021633822855022716610993381154632362312069661257403124255431443 75} + \ldots$$

Expansion & Inversion

$$\frac{98803681049250819448507372351016505897504299465174698017700491890967438460589585811161362548515272025}{35684466127039882827658570376152784851514702163382285502271661099338115463236231206966125740312425543}$$

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$$+ a^{20}\,\frac{22177065823518334551926296609234432}{197020007032219396569654189271817625} + \ldots$$

$$+ a^{30}\,\frac{34923646667163542249127723799039924284676569217525 3504}{55484337187722346543070476479469237573996143089554108125} + \ldots$$

$$+ a^{40}\,\frac{6111345605632231174487017506450424419259516771994603512726507861363 9168}{1474549345456260539445669978709953653740102006883628909834159059177 7721875} + \ldots$$

$$+ \ldots$$

$$+ a^{100}\,\frac{458368735977822033131927463301195919157965848127732494676550866251414295047 31\ldots}{12361295730895994540334845001986054803298478598756567121146590356726691797785 8\ldots}$$

$$+ \ldots$$

Inversion: $$\rightarrow \quad \mathrm{Li}_2(1-a^2)\ , \quad \mathrm{Li}_2\left(\frac{1-a}{1+a}\right)\ , \quad \mathrm{Li}_3(1-a)\ , \ldots$$

Algorithms

- Expansion + Inversion [R.H., Kilgore ’02], [R.H., P. Kant ’05]

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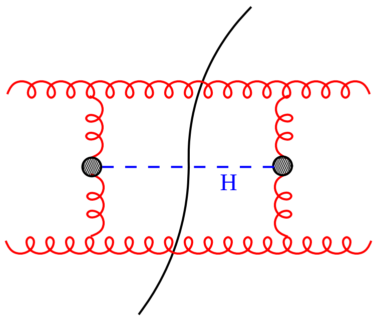

$$\delta(p^2 - m^2) \rightarrow \frac{1}{2\pi i}\left[\frac{1}{p^2 - m^2 - i\epsilon} - \frac{1}{p^2 - m^2 + i\epsilon}\right]$$

$\rightarrow$ use multi-loop techniques for phase space integrals!

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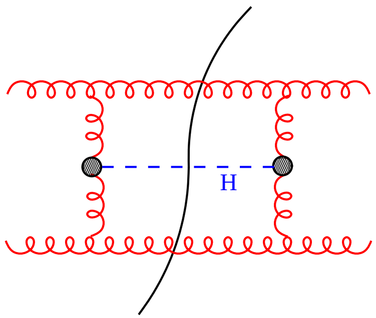

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distributions: $\delta\Big(f(p)\Big)$

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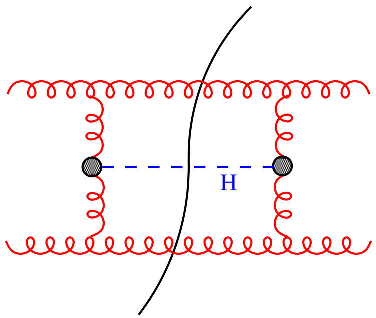

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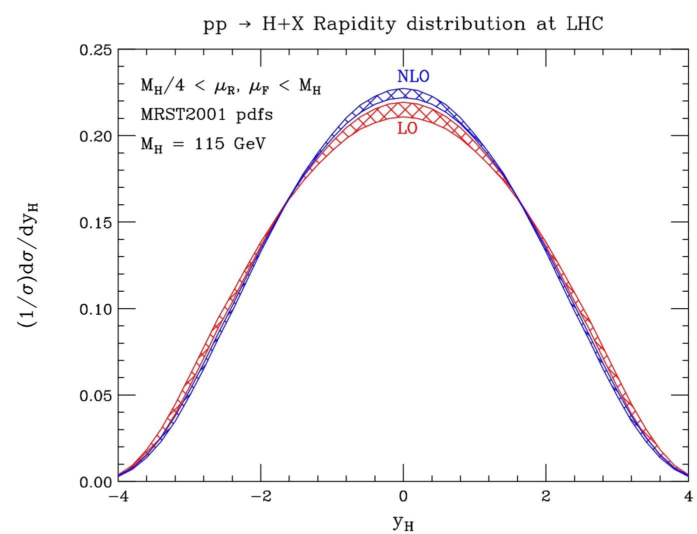
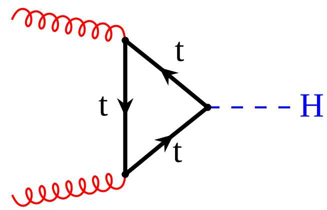
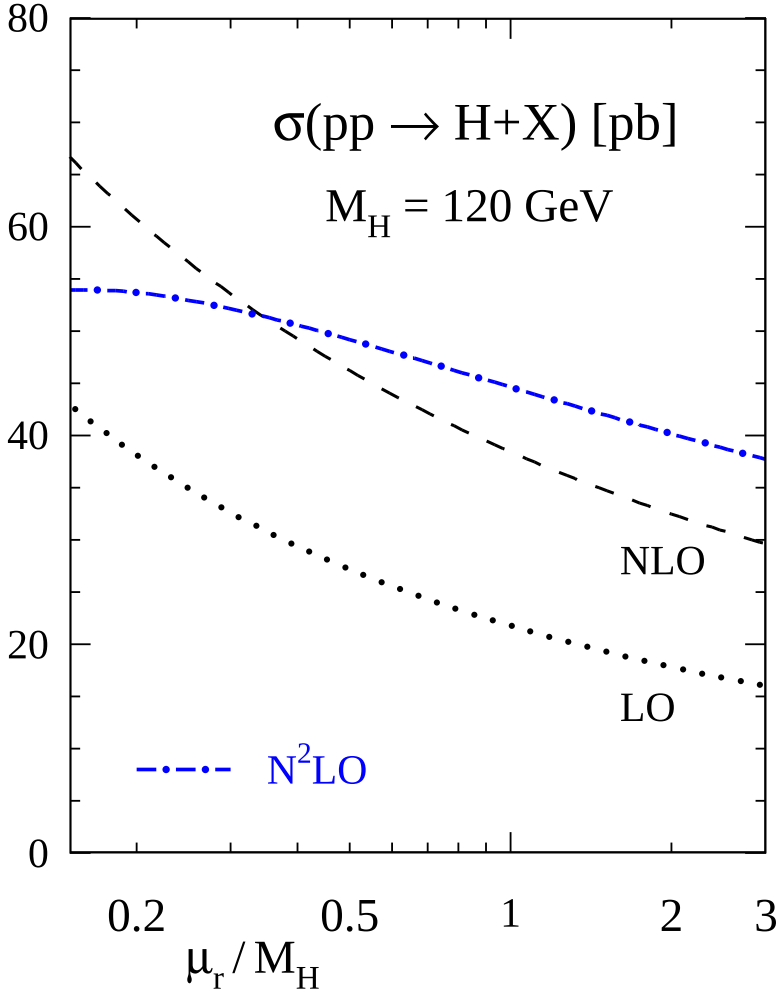
NLO rapidity:
[Anastasiou, Dixon, Melnikov '02]



Gluon fusion





[R.H., Kilgore '02]

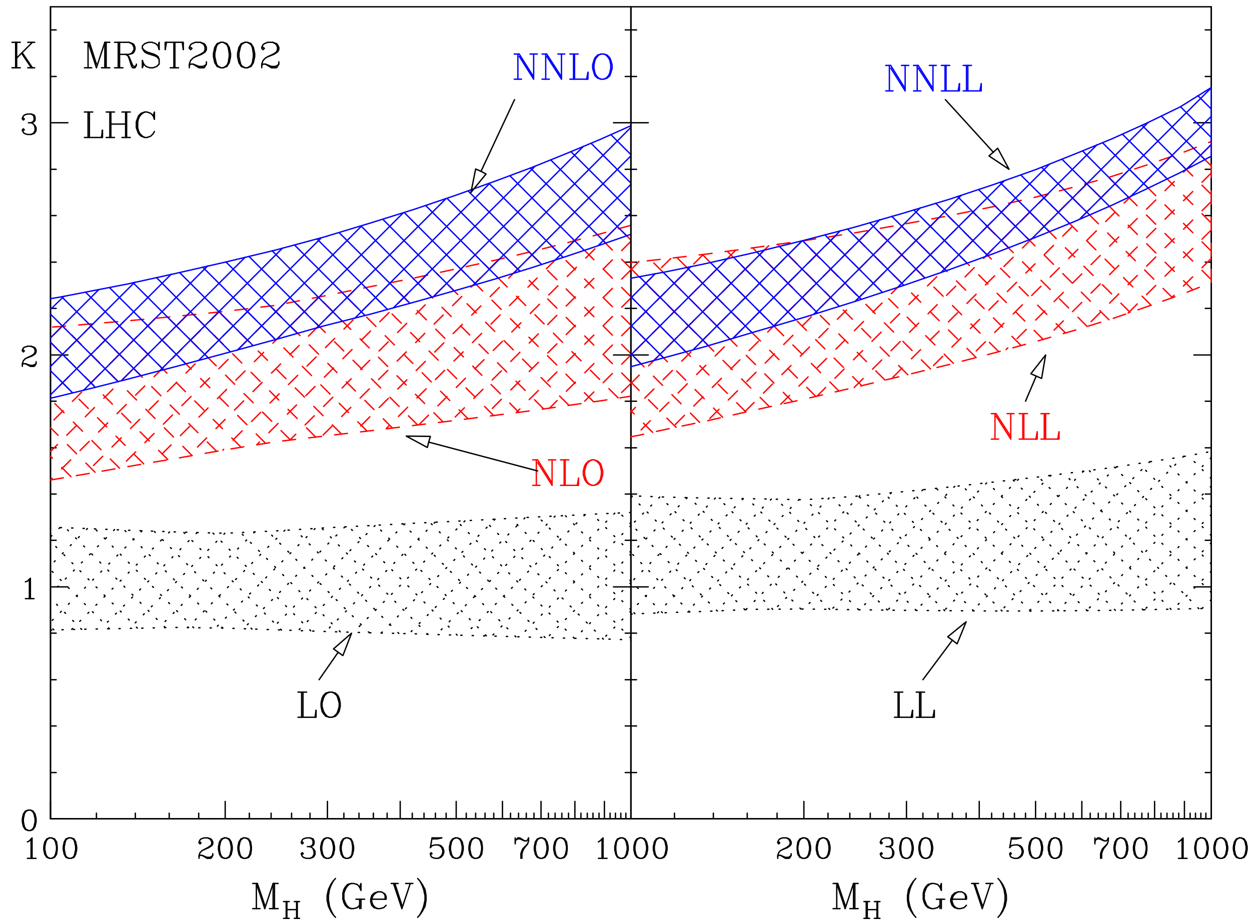
[Anastasiou, Melnikov '02]

[Ravindran, Smith, v.Neerven '03]

[Dawson '91]

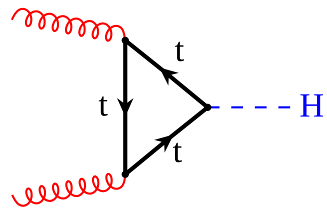
[Djouadi, Graudenz, Spira, Zerwas '91,'93]

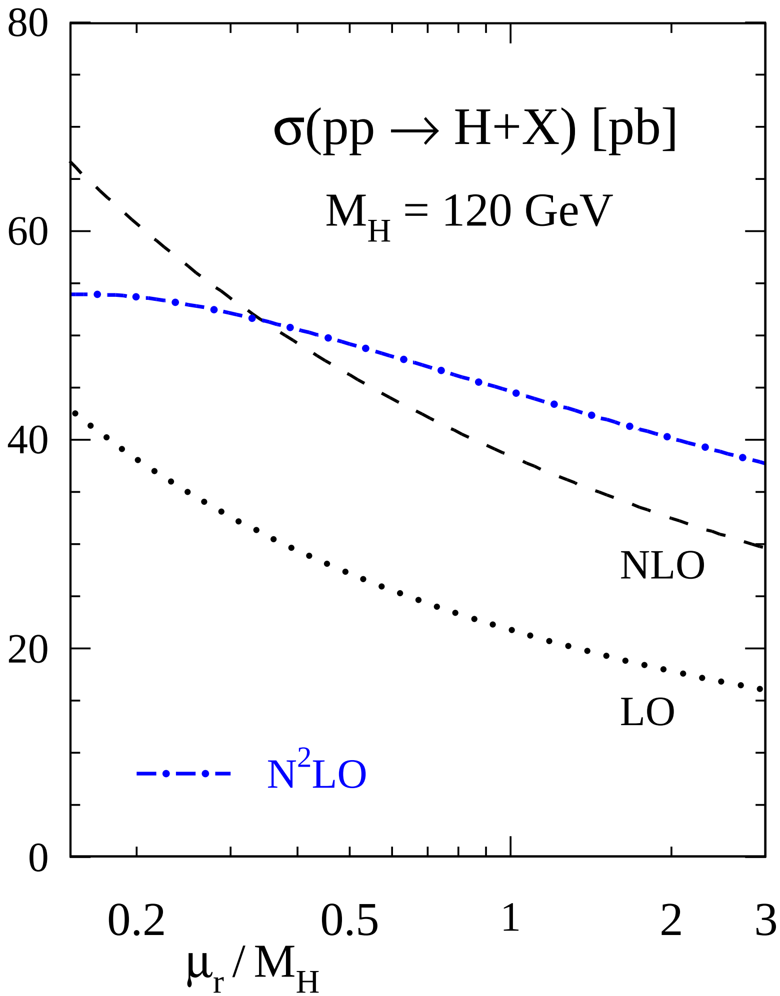
Resummation



[Catani, de Florian, Grazzini, Nason ’03]

Gluon fusion





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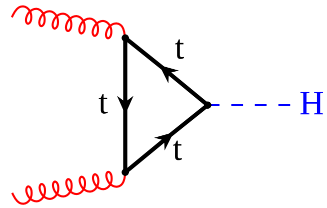

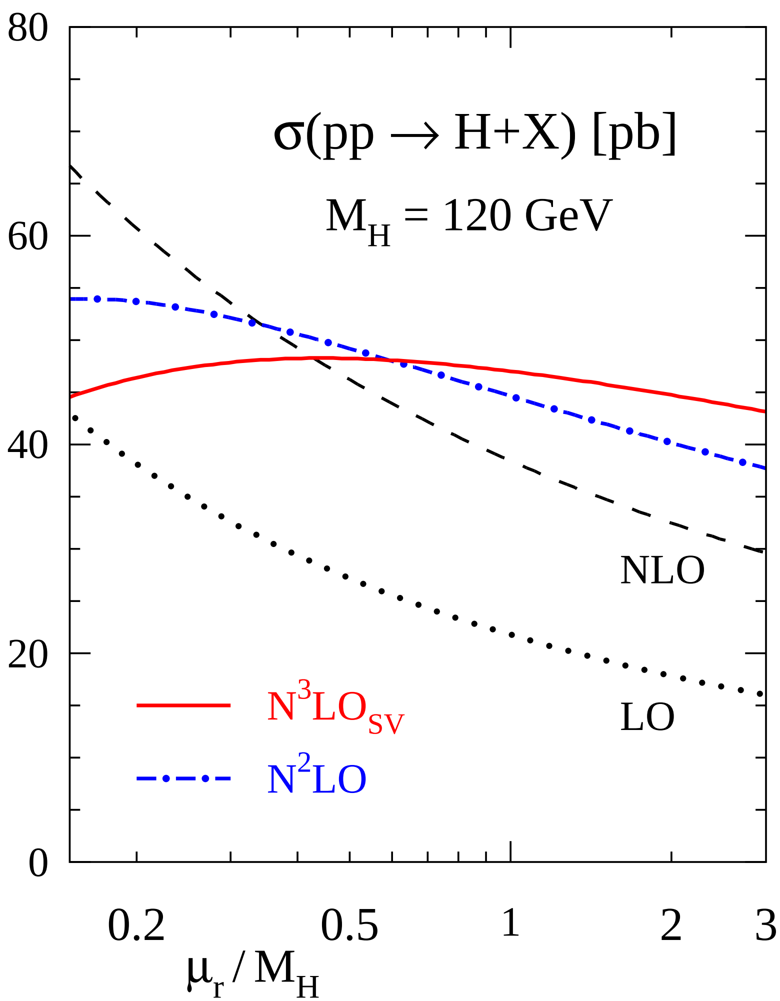

[Moch, Vogt ’05]

[R.H., Kilgore ’02]

[Anastasiou, Melnikov ’02]

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Importance of higher orders

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  $\longrightarrow$ scale dependence

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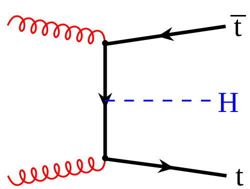

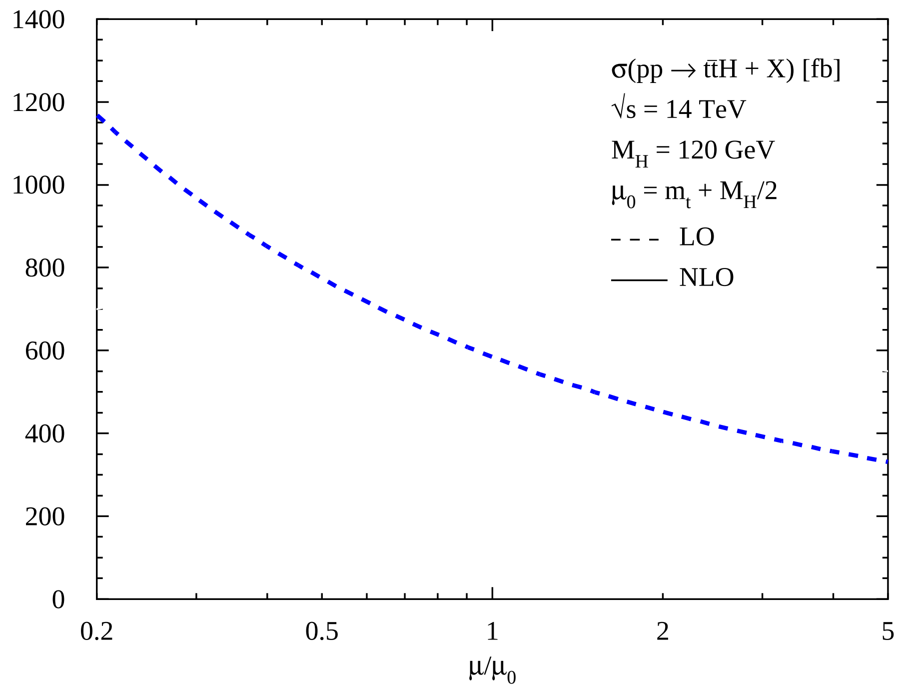

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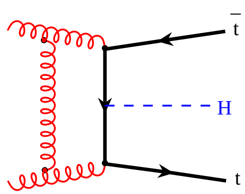
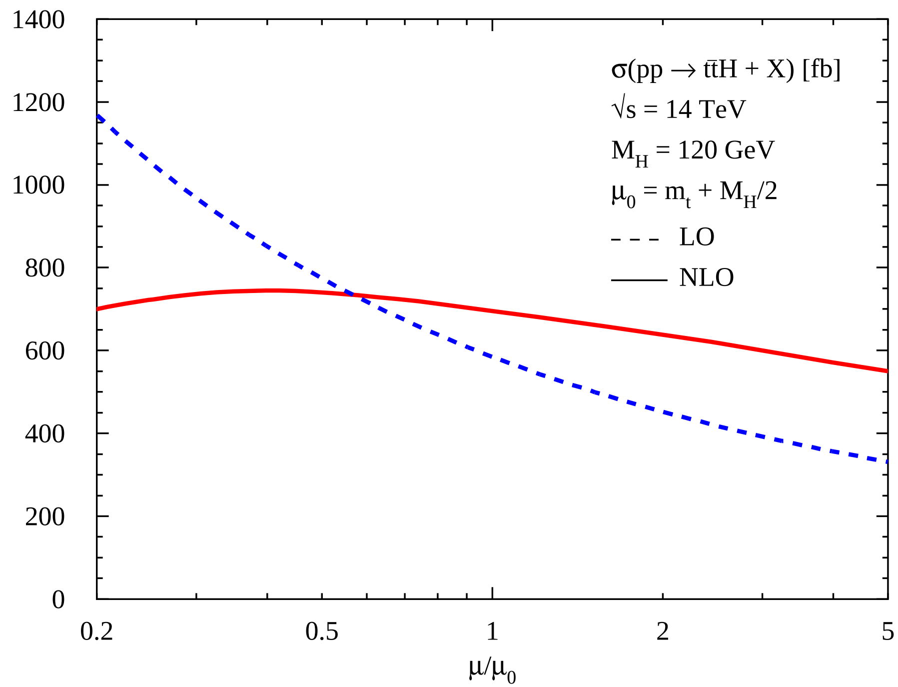
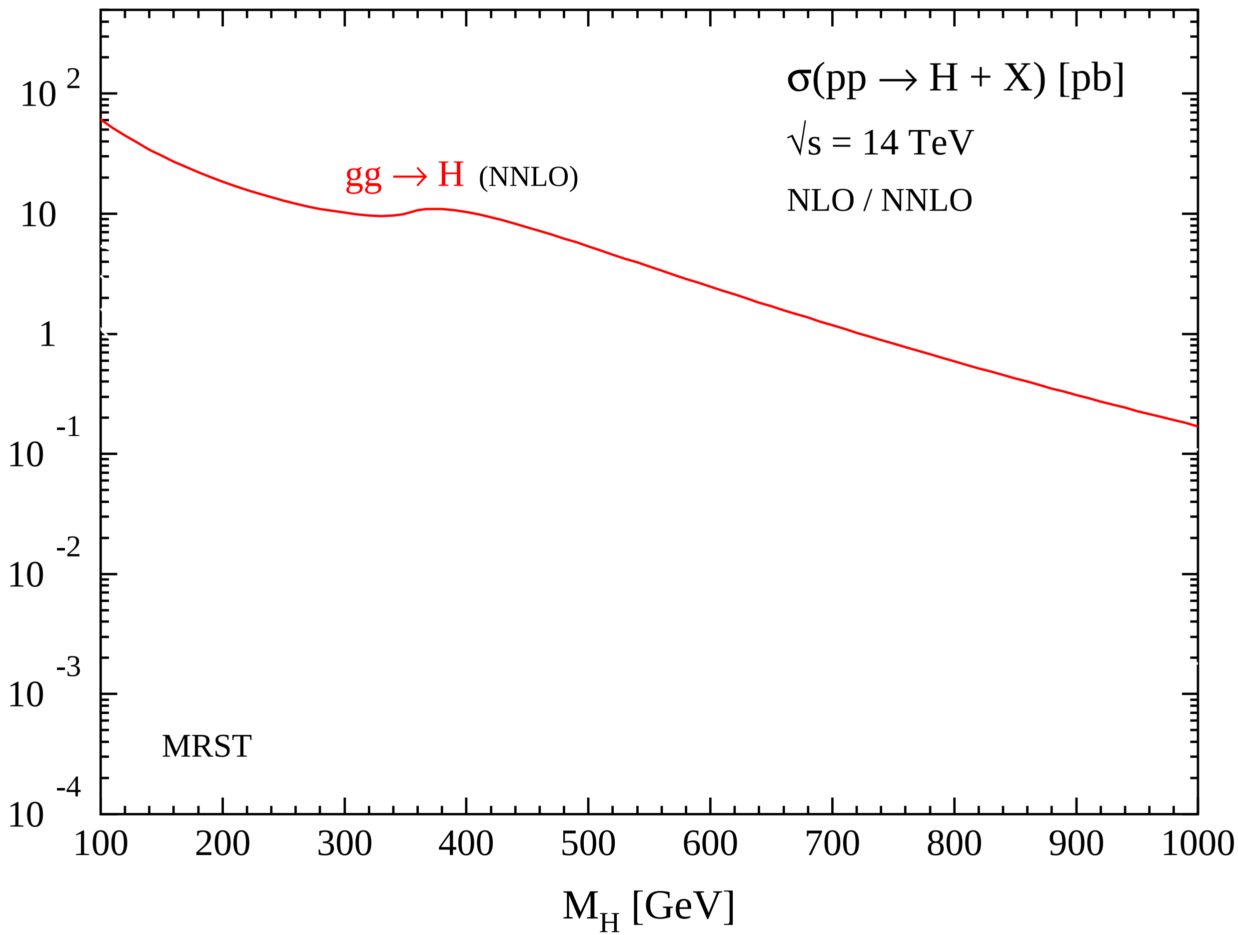


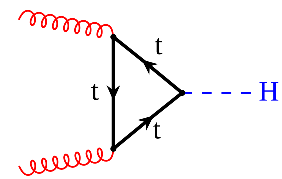


[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas ’01]

[Dawson, Reina, Wackeroth, Orr, Jackson ’01-’03]

Cross sections





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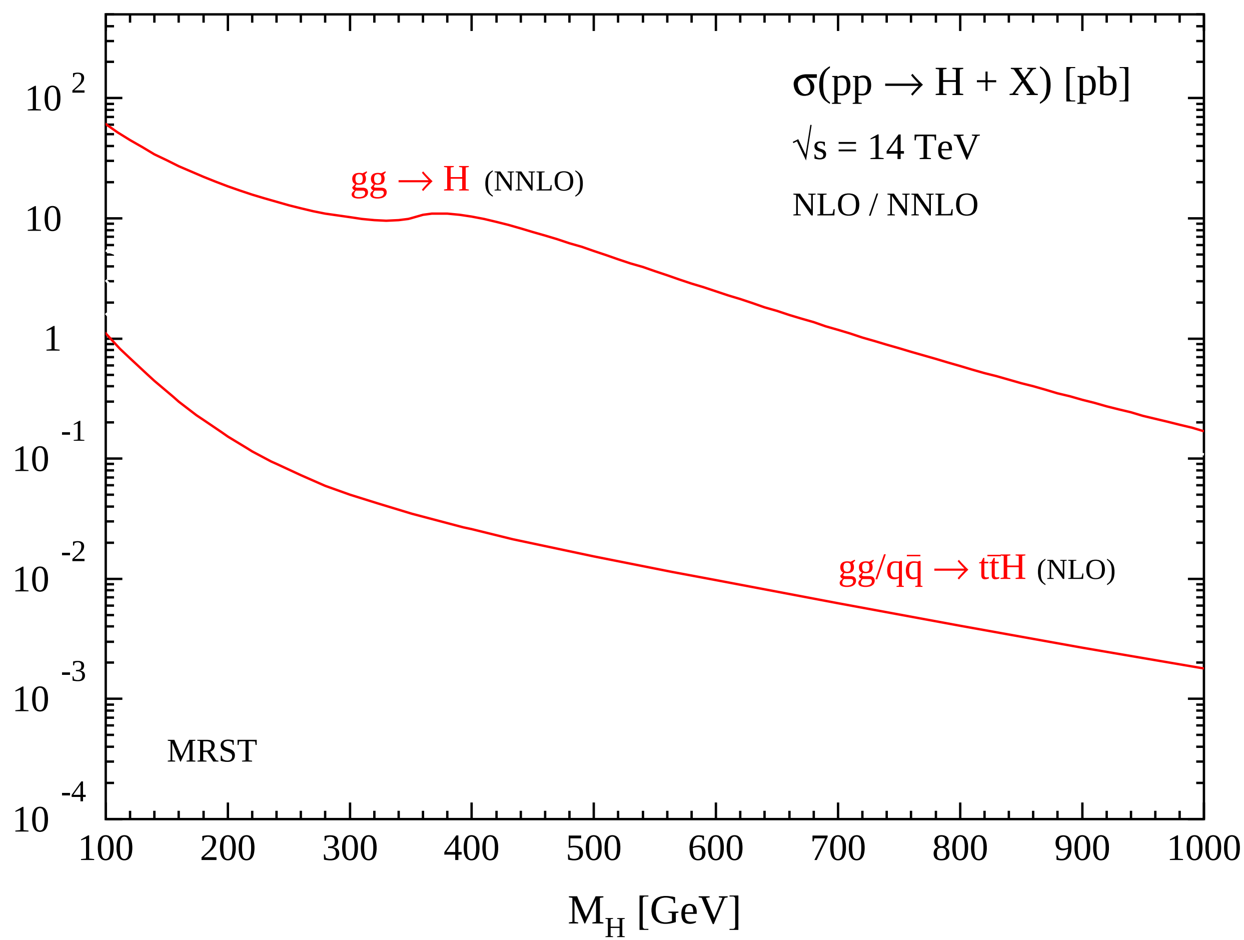

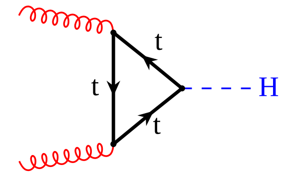

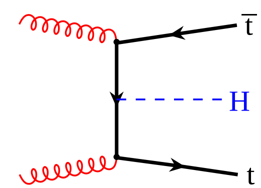

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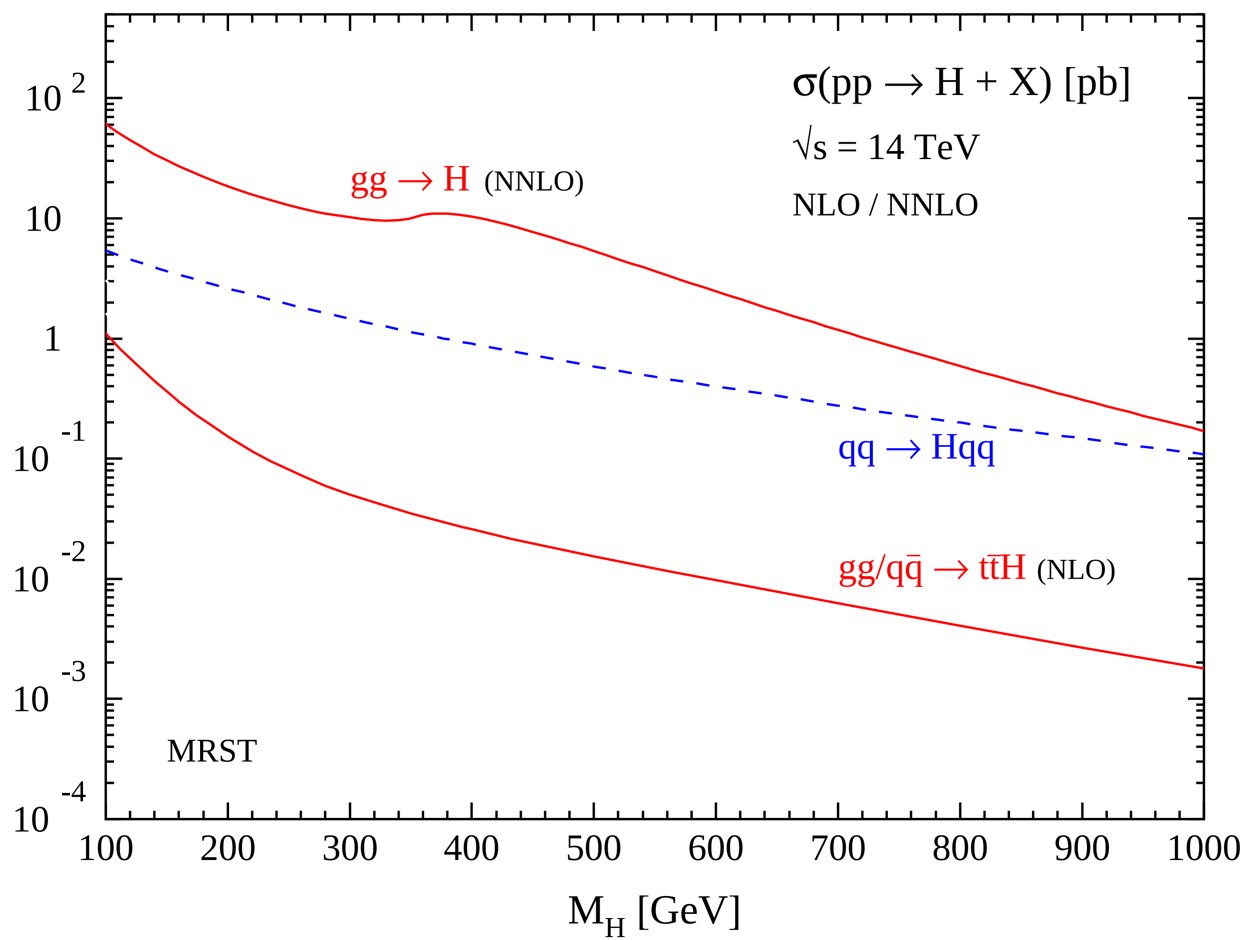

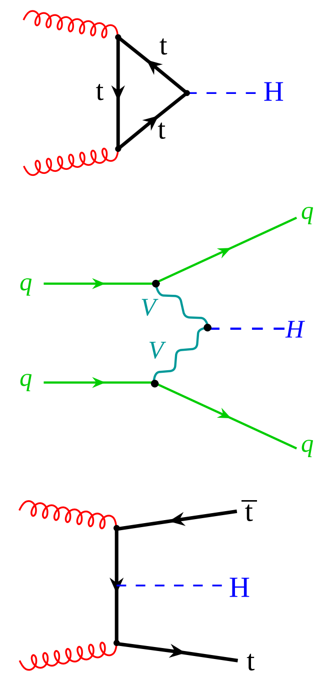

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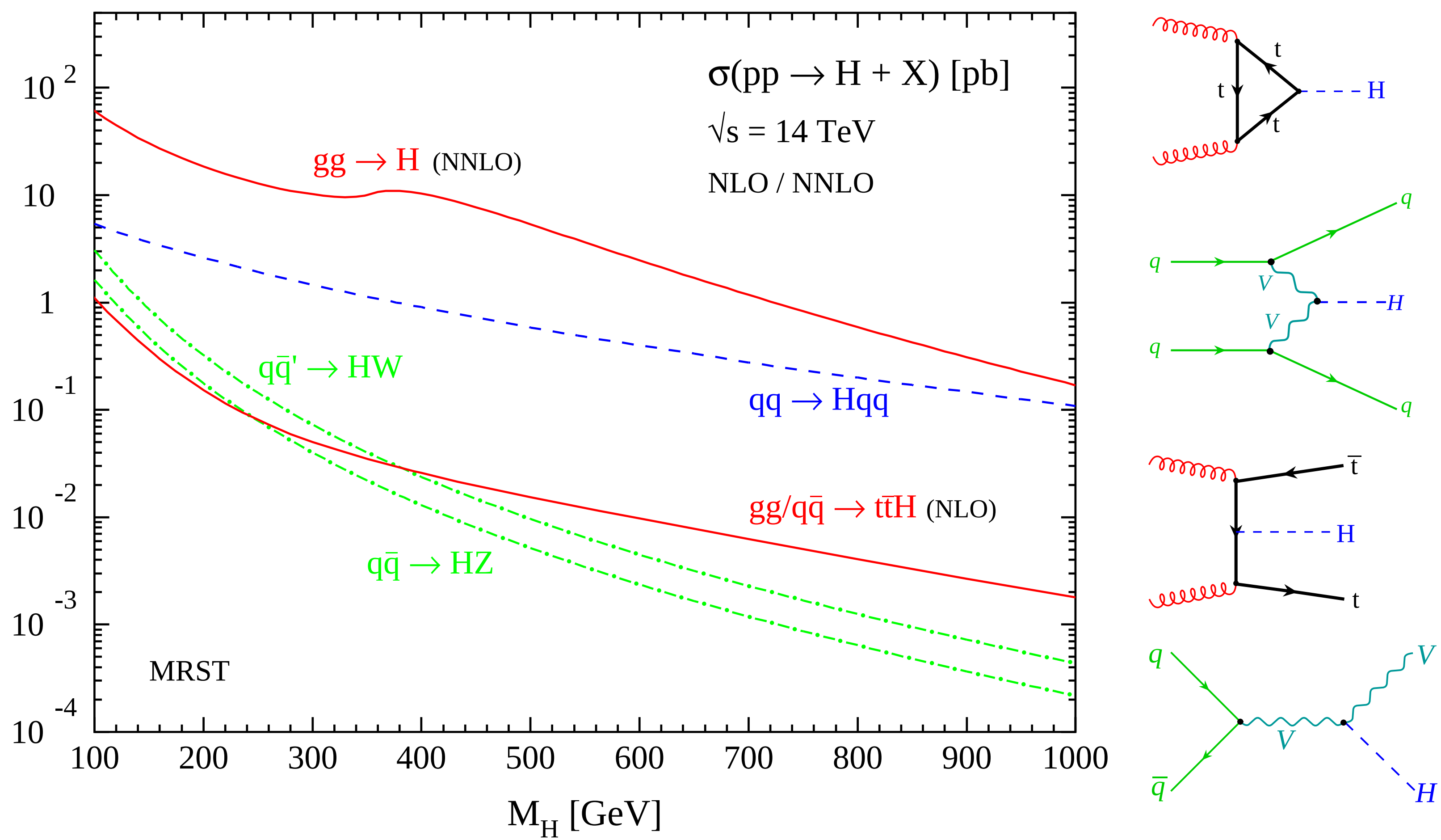

Distributions and Cuts

- so far, fully inclusive cross sections: $\int \mathrm{d}\sigma(H + \text{anything})$

Distributions and Cuts

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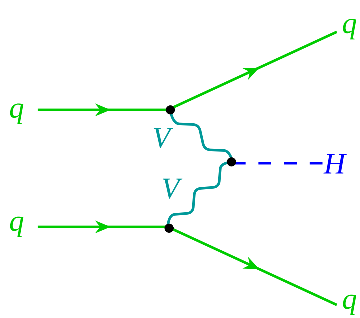
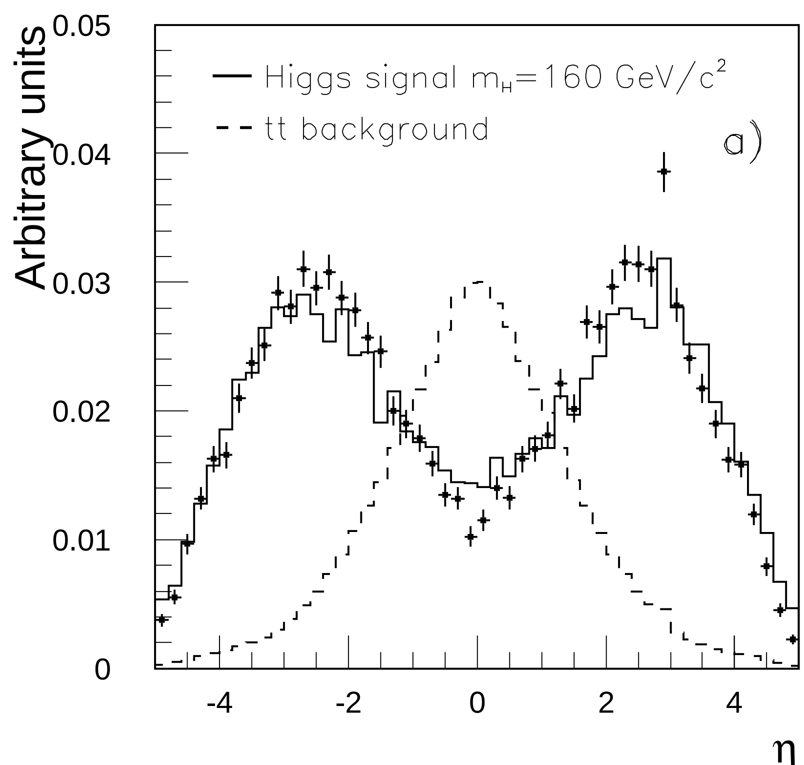
- reduce background, e.g.





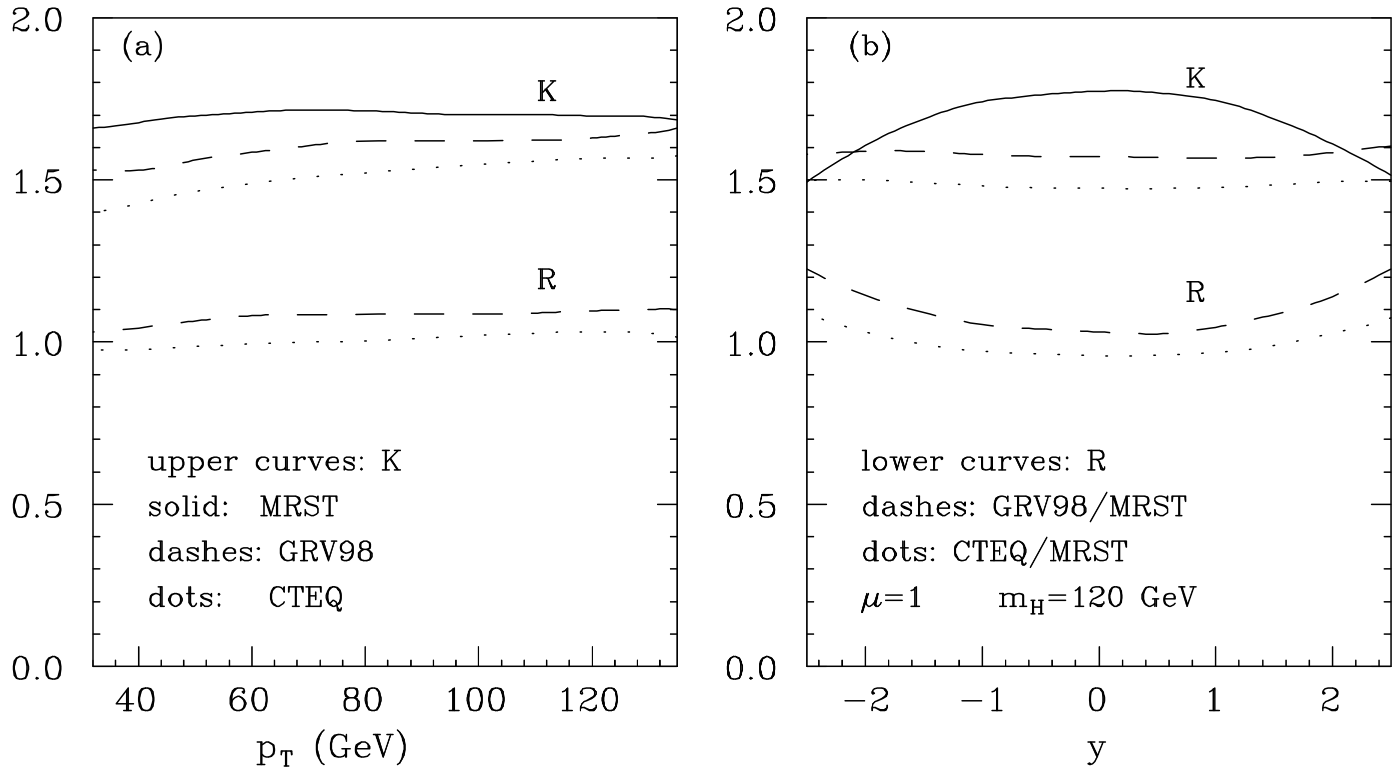
→ talk by Zeppenfeld

Distributions and Cuts

- so far, fully inclusive cross sections: $\int \mathrm{d}\sigma(H + \text{anything})$
- reduce background, e.g.
- there are no 4π detectors!

$K(p_T, y) \approx K_{\text{tot}}$?

$M_H = 120\,\text{GeV}$ from [de Florian, Grazzini, Kunszt '99]

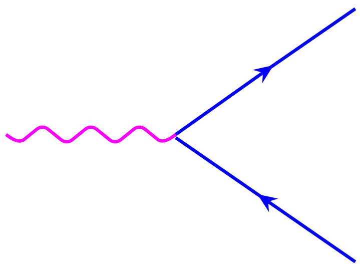


see also [Glosser, Schmidt '02]
[Ravindran, Smith, v.Neerven '02]

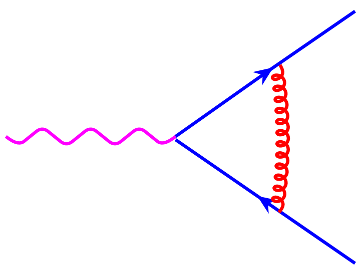
Higher orders with Cuts

Consider $Z \to 2$ jets: inclusive

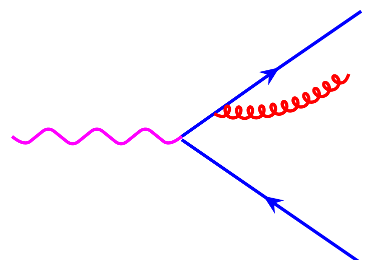
LO:



NLO:



$+ \int$



$$\frac{A}{\epsilon} + B \qquad -\frac{A}{\epsilon} + C \qquad = \qquad B + C$$

Higher orders with Cuts

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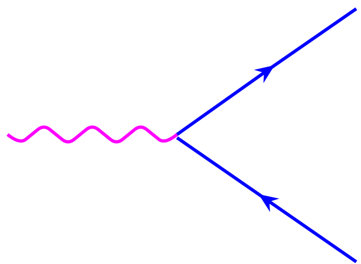
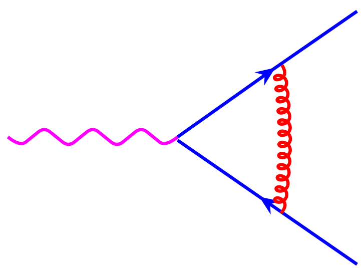
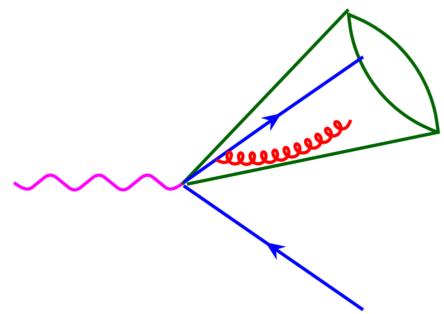


NLO:

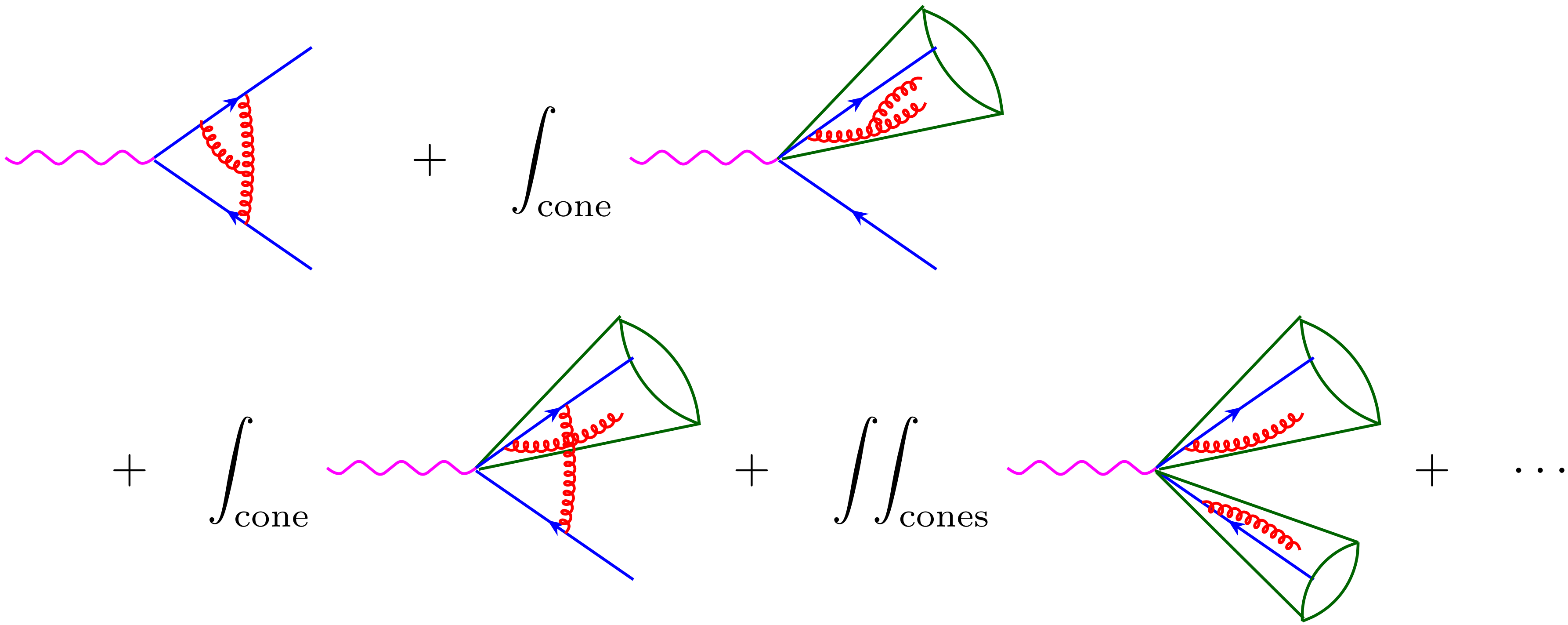


$+ \quad \int_{\text{cone}}$



$$\frac{A}{\epsilon} + B \qquad\qquad -\frac{A}{\epsilon} + C_{\text{cut}} \quad = \quad B + C_{\text{cut}}$$

Exclusive at NNLO

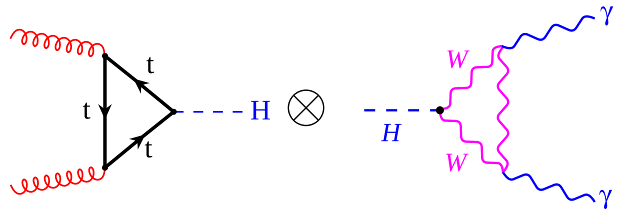


Very active field:

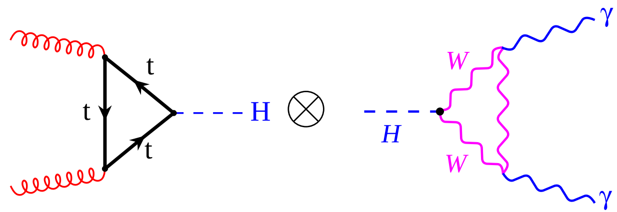
[Anastasiou, Melnikov, Petriello], [Gehrmann, G.-de Ridder, Glover],

[Grazzini, Frixione], [Kilgore], [Kosower], [Somogyi, Trocsanyi, Del Duca], [Weinzierl]

NNLO with cuts



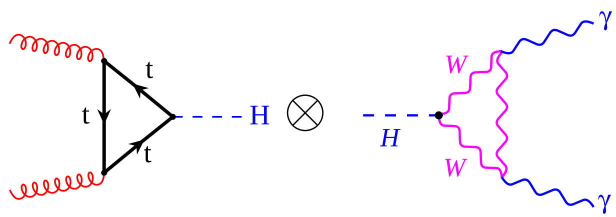
NNLO with cuts

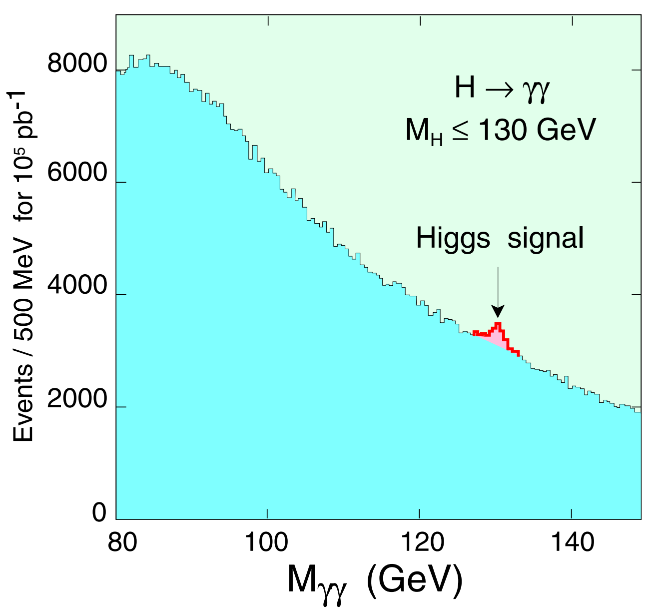


m_h	$\sigma^{\rm cut}_{\rm NNLO}/\sigma^{\rm inc}_{\rm NNLO}$	$K^{(2)}_{\rm cut}/K^{(2)}_{\rm inc}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

[Anastasiou, Melnikov, Petriello ’05]

Backgrounds





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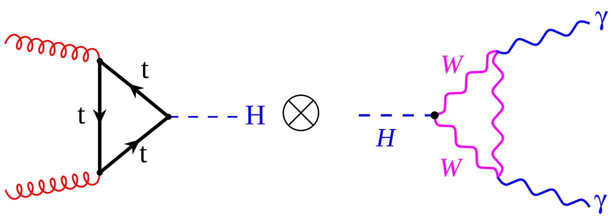
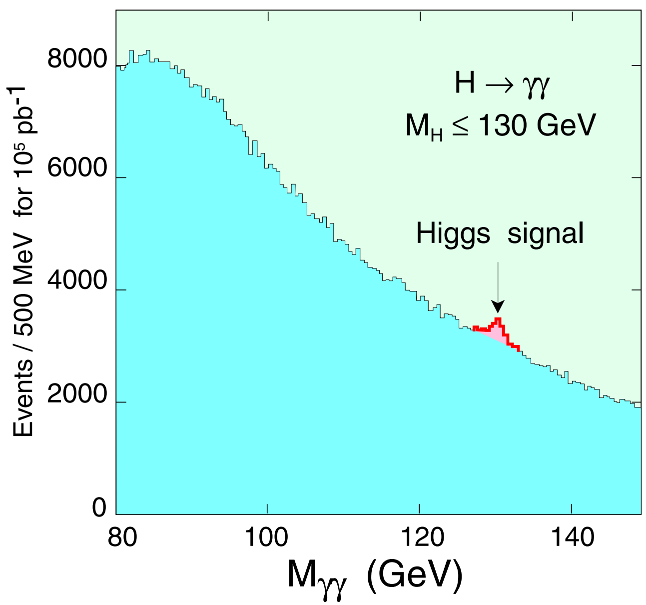
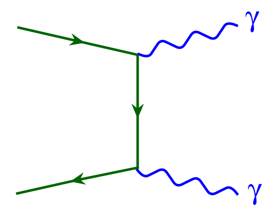




vs.



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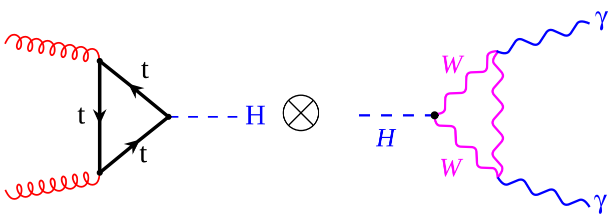

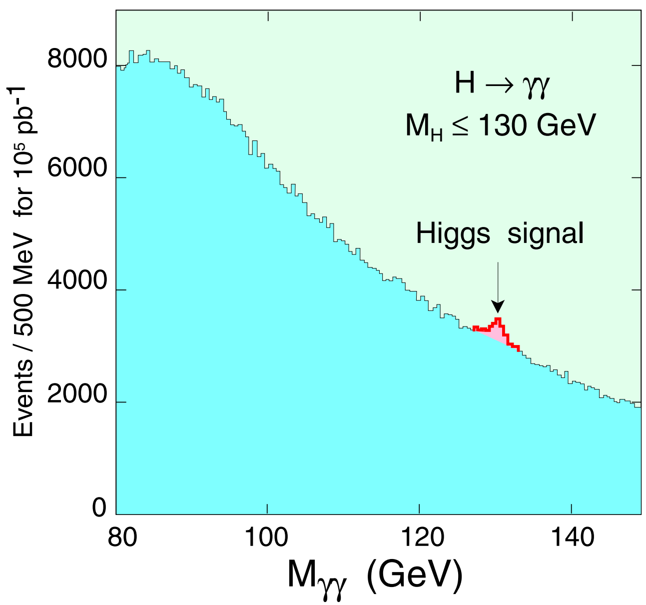

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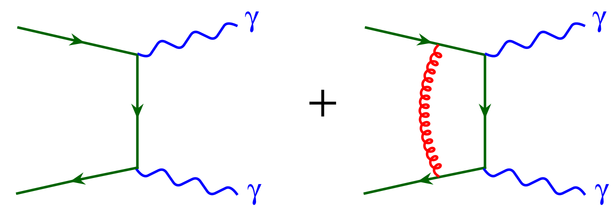
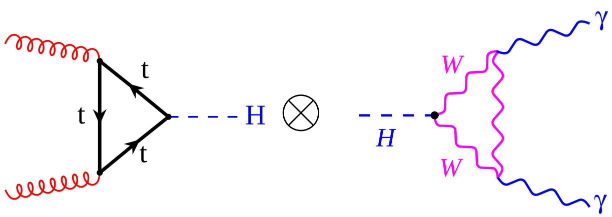
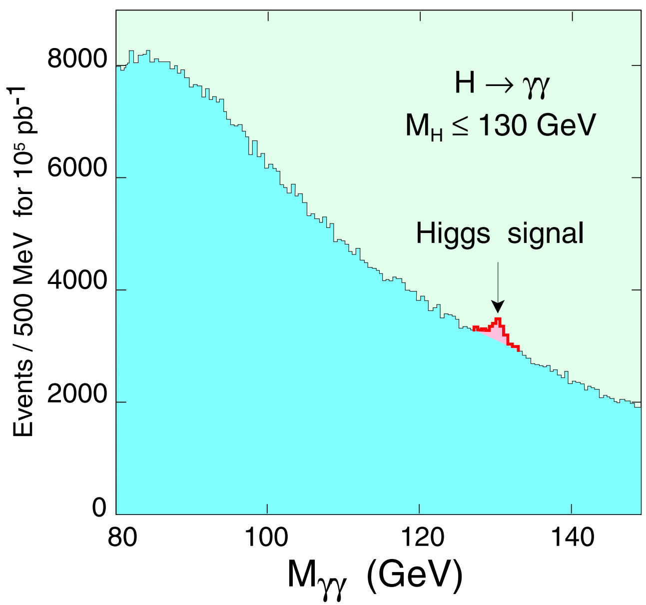


[Binoth, Guillet, Pilon, Werlen '00]

Backgrounds





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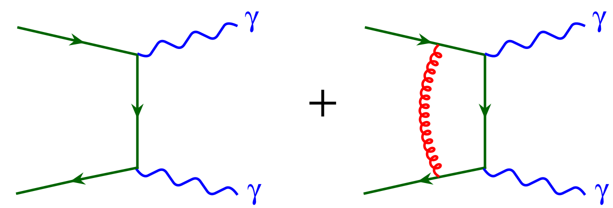
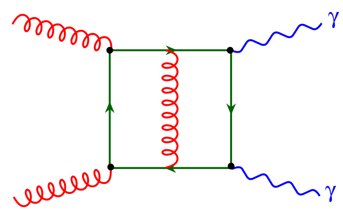
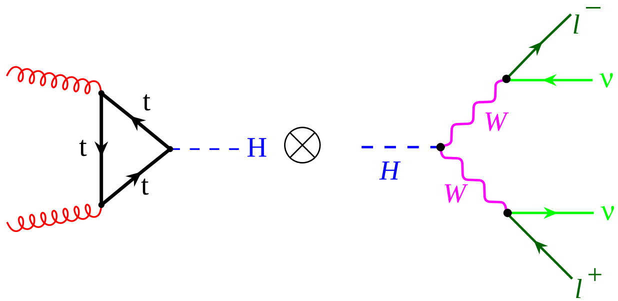


[Binoth, Guillet, Pilon, Werlen ’00]



[Bern, Dixon, Schmidt ’02]

Backgrounds



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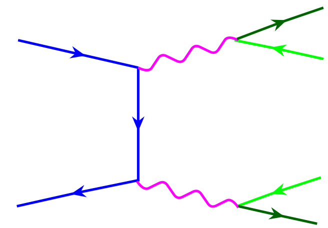
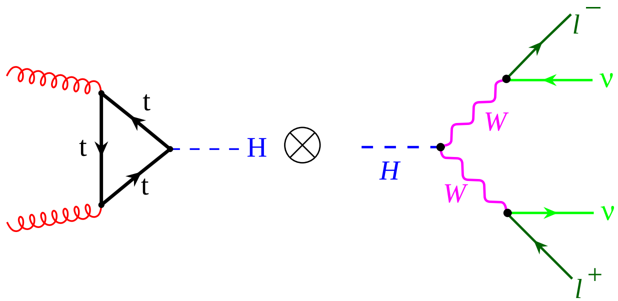


- no mass peak
- angular correlations needed
- NLO: [Ohnemus ’94], [Dixon, Kunszt, Signer ’98]
  [Campbell, Ellis ’99]

Backgrounds



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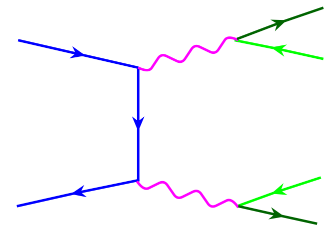

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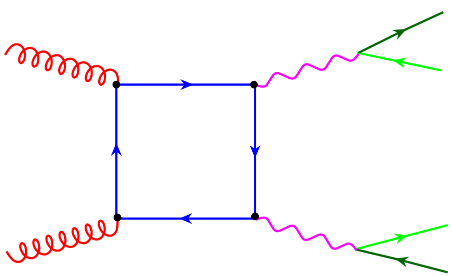
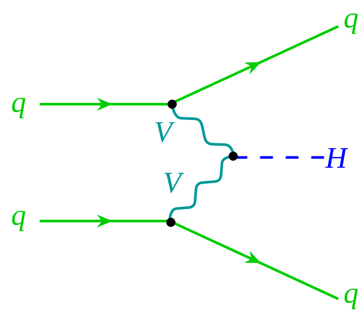


up to 30% of NLO $q\bar{q}$

[Binoth, Cicciolini, Kauer, Krämer ’05]
[Dührssen, Jakobs, Marquard, v.d. Bij ’05]

Backgrounds



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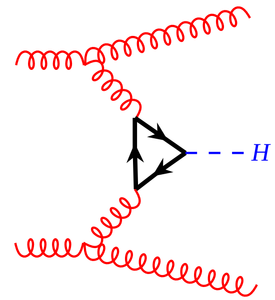

[Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld ’01]

Backgrounds

NLO wishlist...

Single boson	Di-boson	Tri-boson	Heavy flavor
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

[Run II Monte Carlo Workshop, April 2001]

many implemented in MCFM [J.Campbell, K.Ellis]

Effects of Supersymmetry

$$H \quad \leftrightarrow \quad h^0, H^0, A, H^+, H^-$$

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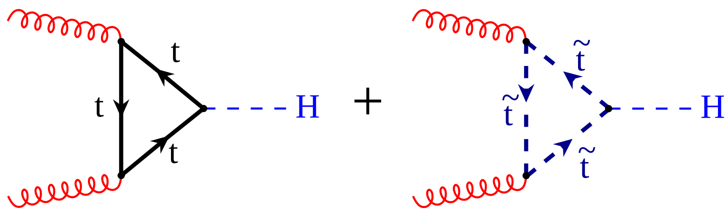

Effects of Supersymmetry

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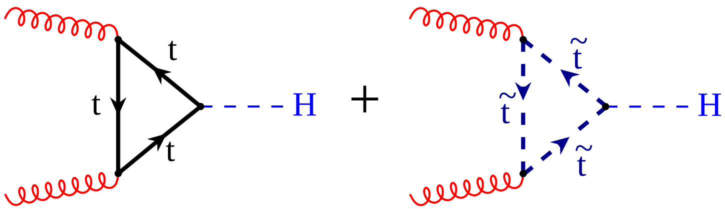
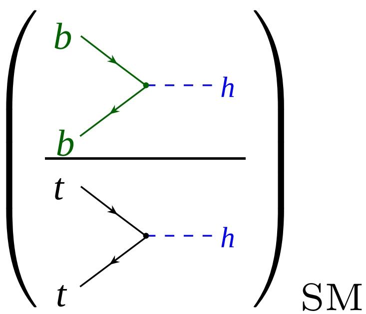
- 

- 

$= \frac{m_b}{m_t}$

Effects of Supersymmetry

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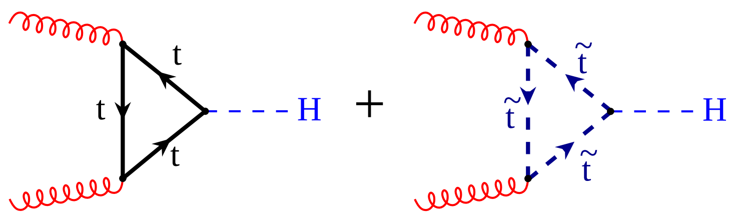
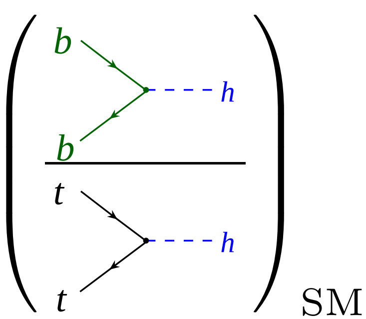
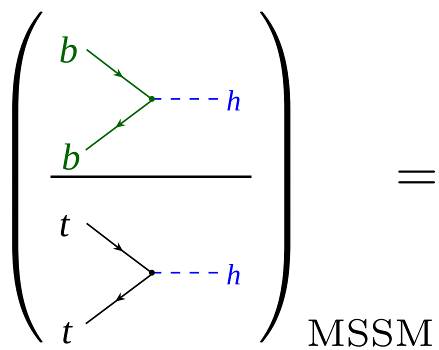
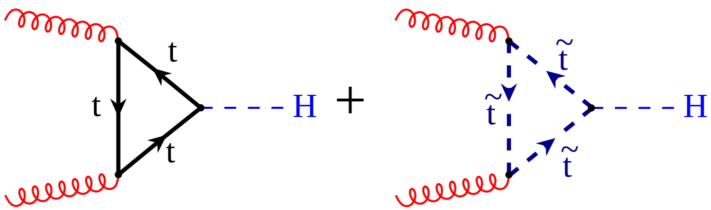
- 

-  $= \frac{m_b}{m_t}$,

 $= \frac{m_b}{m_t} \cdot \tan\beta$

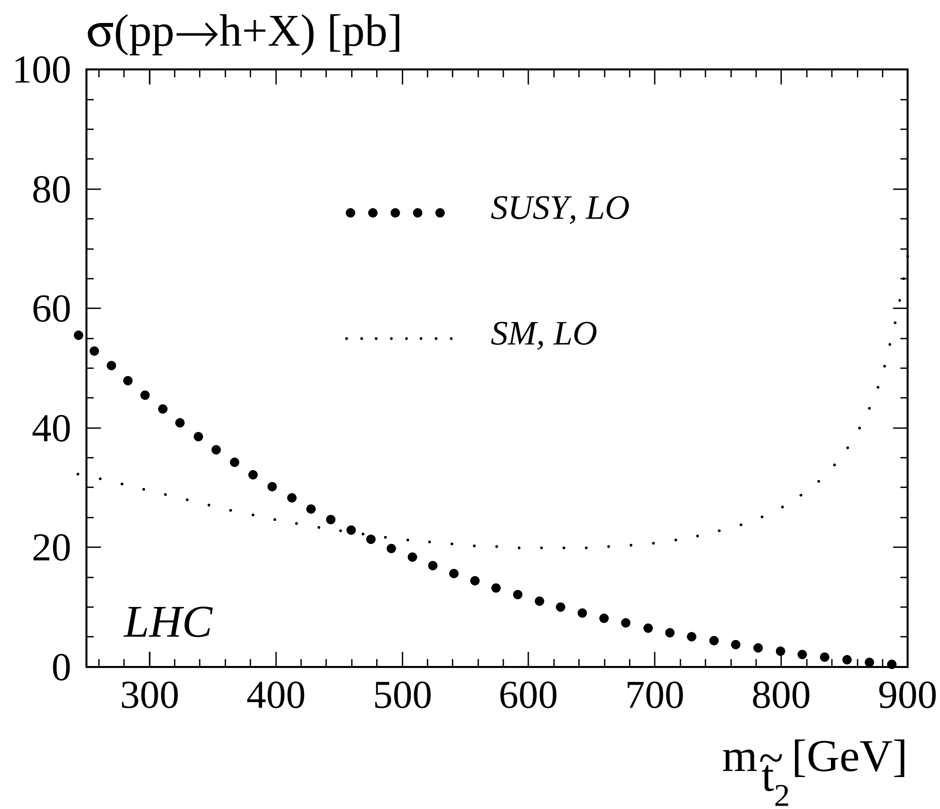
Example: “gluophobic Higgs”

[Djouadi ’98], [Carena *et al.* ’99]



may interfere destructively!

$$m_{\tilde{t}_1} = 200\,\mathrm{GeV}$$
$$m_{\tilde{g}} = 1\,\mathrm{TeV}$$
$$\tan\beta = 10\,, \quad \alpha = 0\,,$$
$$\theta_t = \frac{\pi}{4}$$



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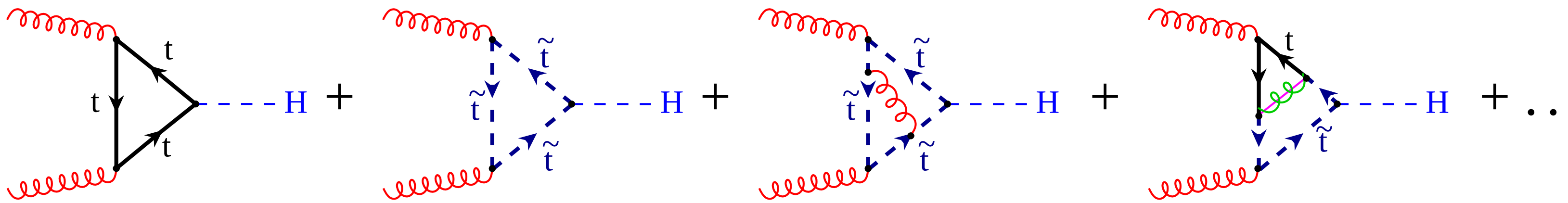

[R.H., Steinhauser ’04]

$$m_{\tilde{t}_1} = 200\,\text{GeV}$$
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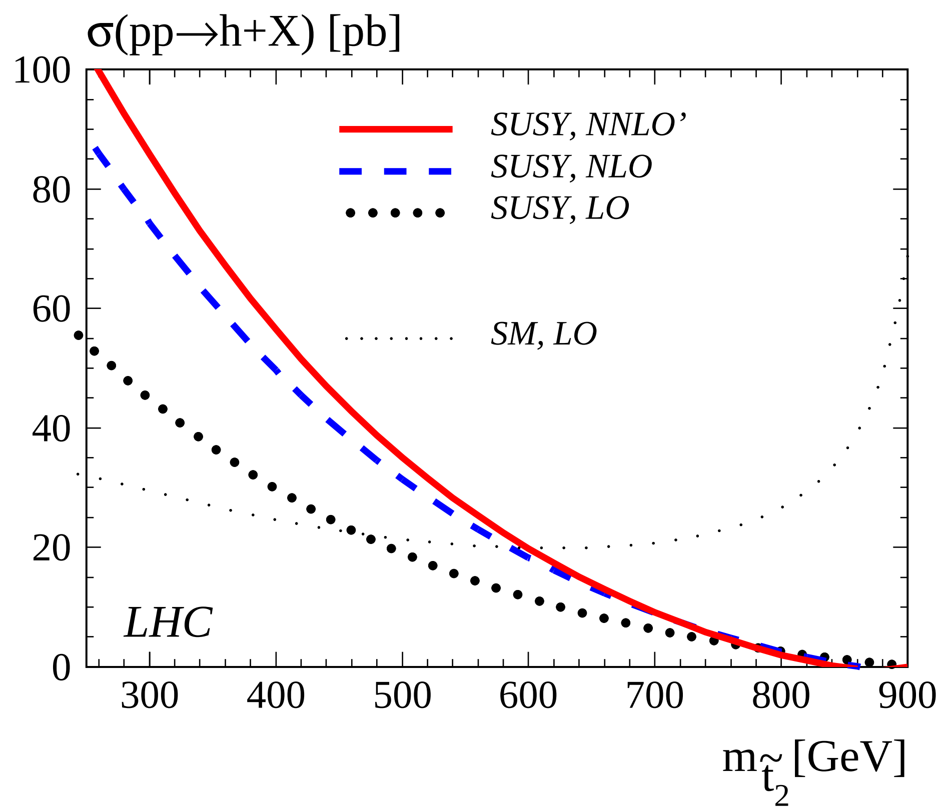
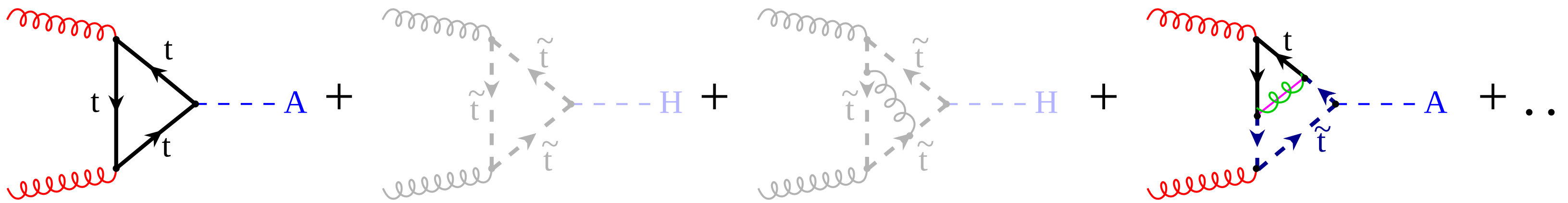


Pseudo-scalar Higgs



[R.H., Hofmann ’05]

Effects of Supersymmetry

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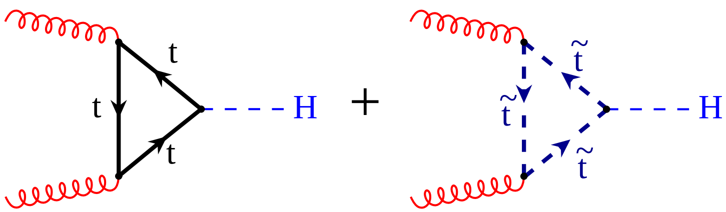
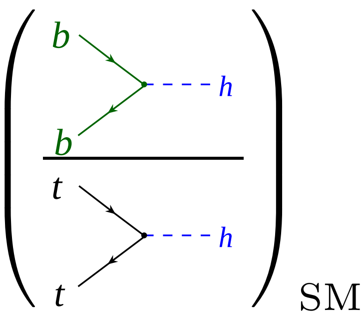
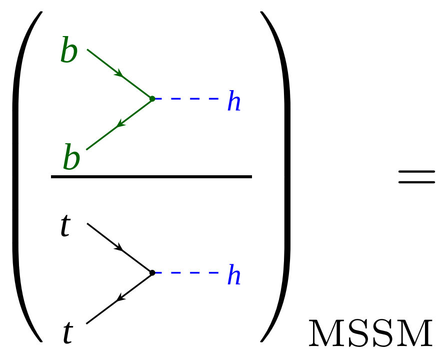
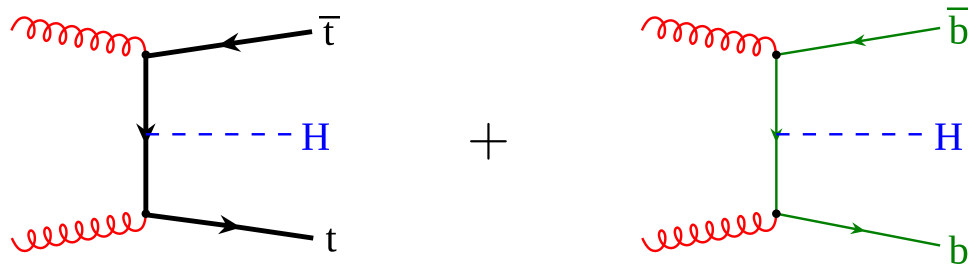
- 

- 

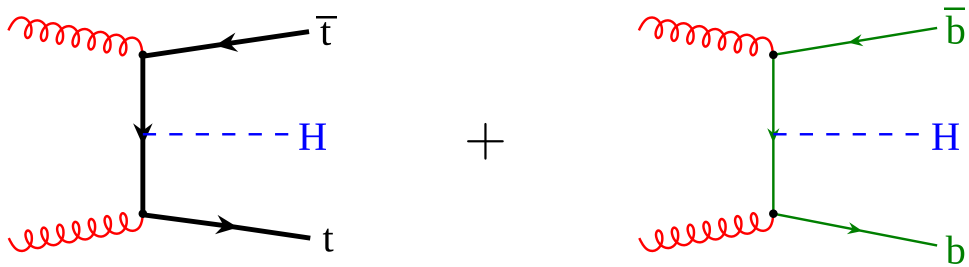
$= \frac{m_b}{m_t}$,


$= \frac{m_b}{m_t} \cdot \tan\beta$

$b\bar{b} \to H$

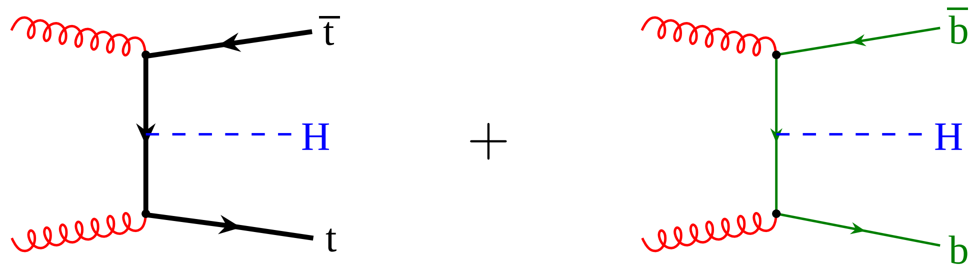


$b\bar{b} \longrightarrow H$

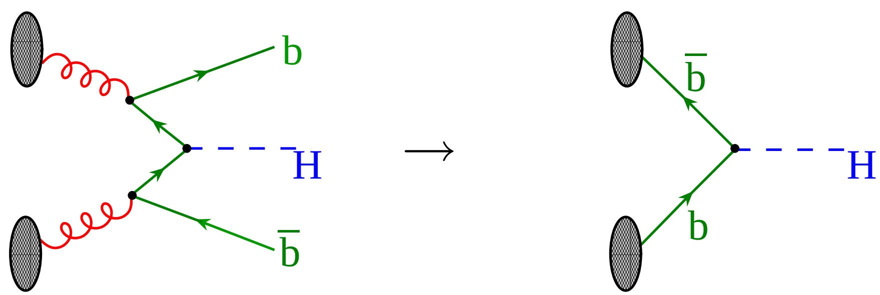


- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$

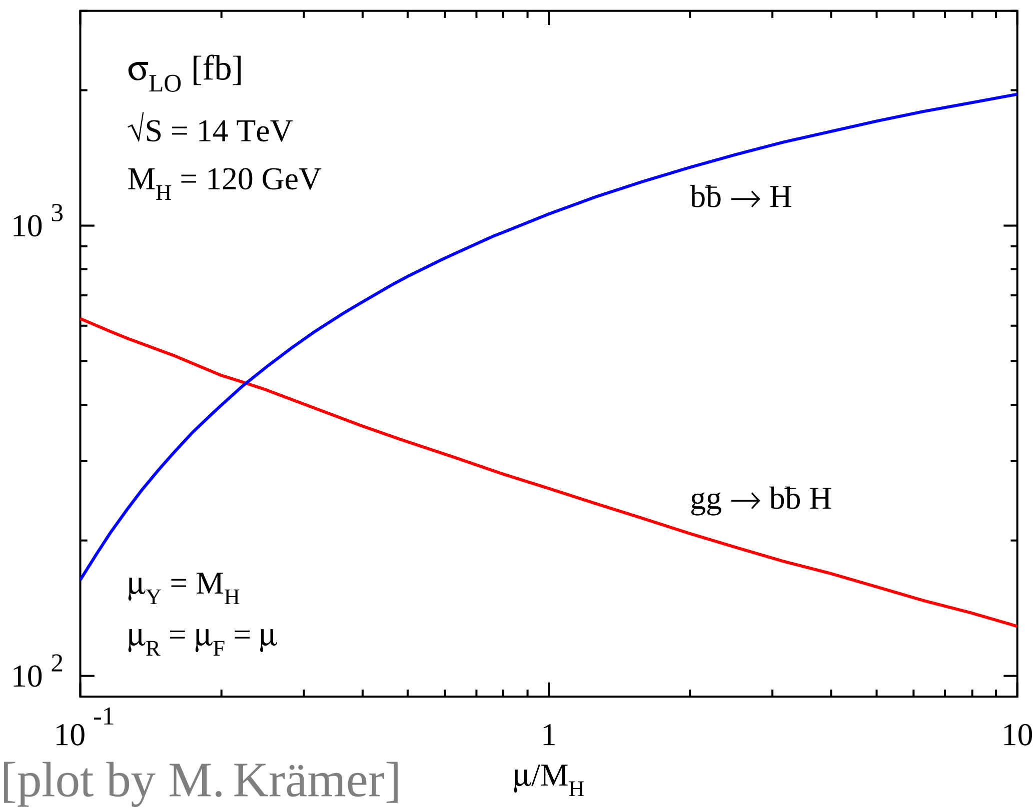
$b\bar{b} \longrightarrow H$



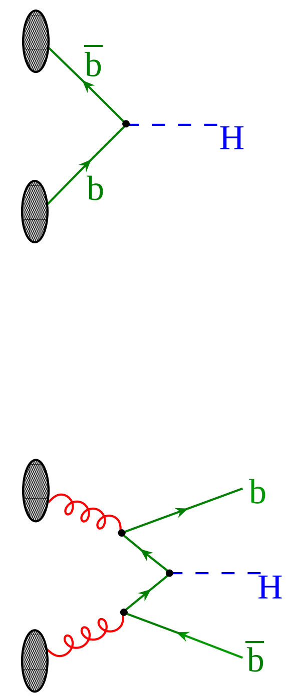
- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$
- resummation: bottom quarks as partons



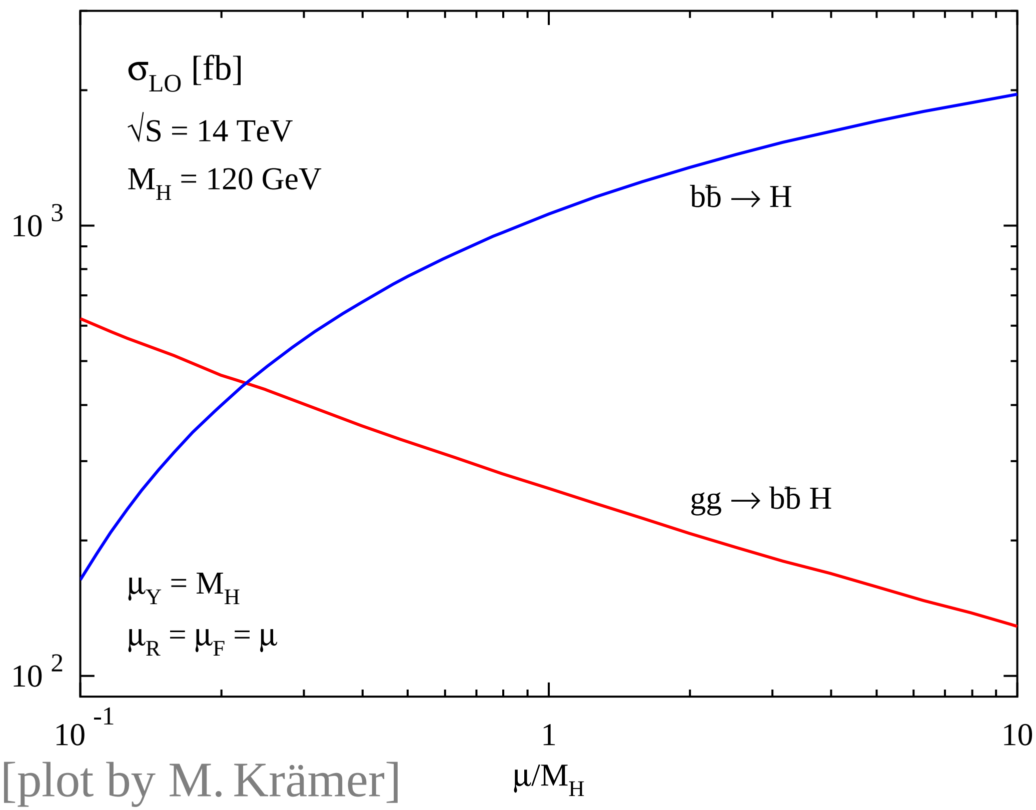
$b\bar{b} \to h$ vs. $gg \to b\bar{b}h$



[plot by M. Krämer]



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



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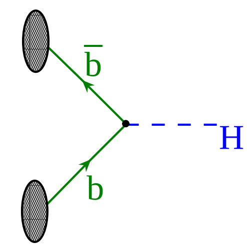
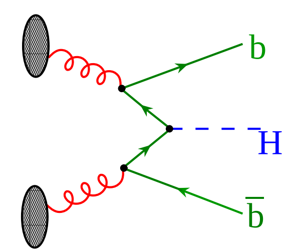
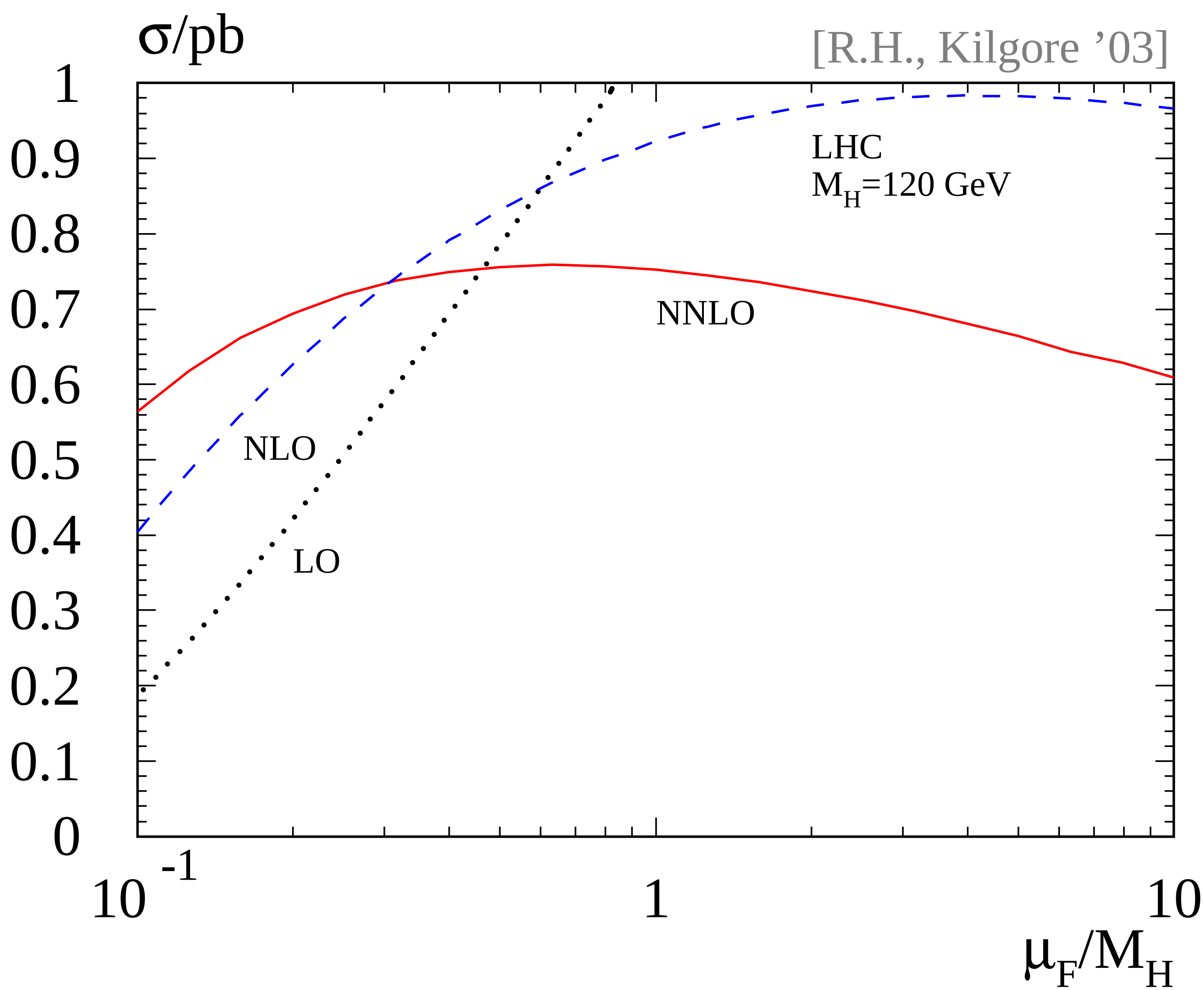




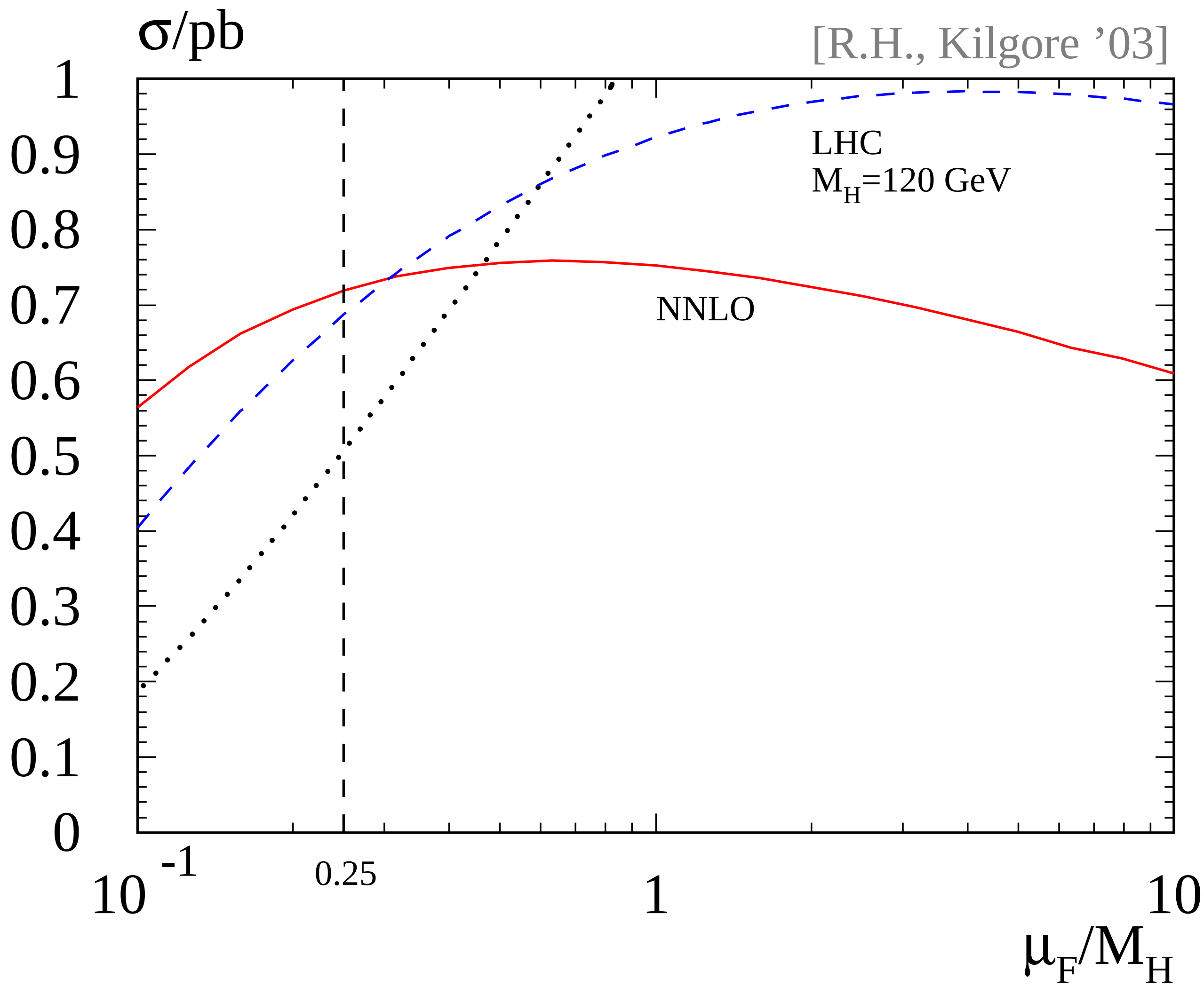
$\mu_F = M_H/4?$

[Boos, Plehn ’04] [Maltoni, Sullivan, Willenbrock ’03]

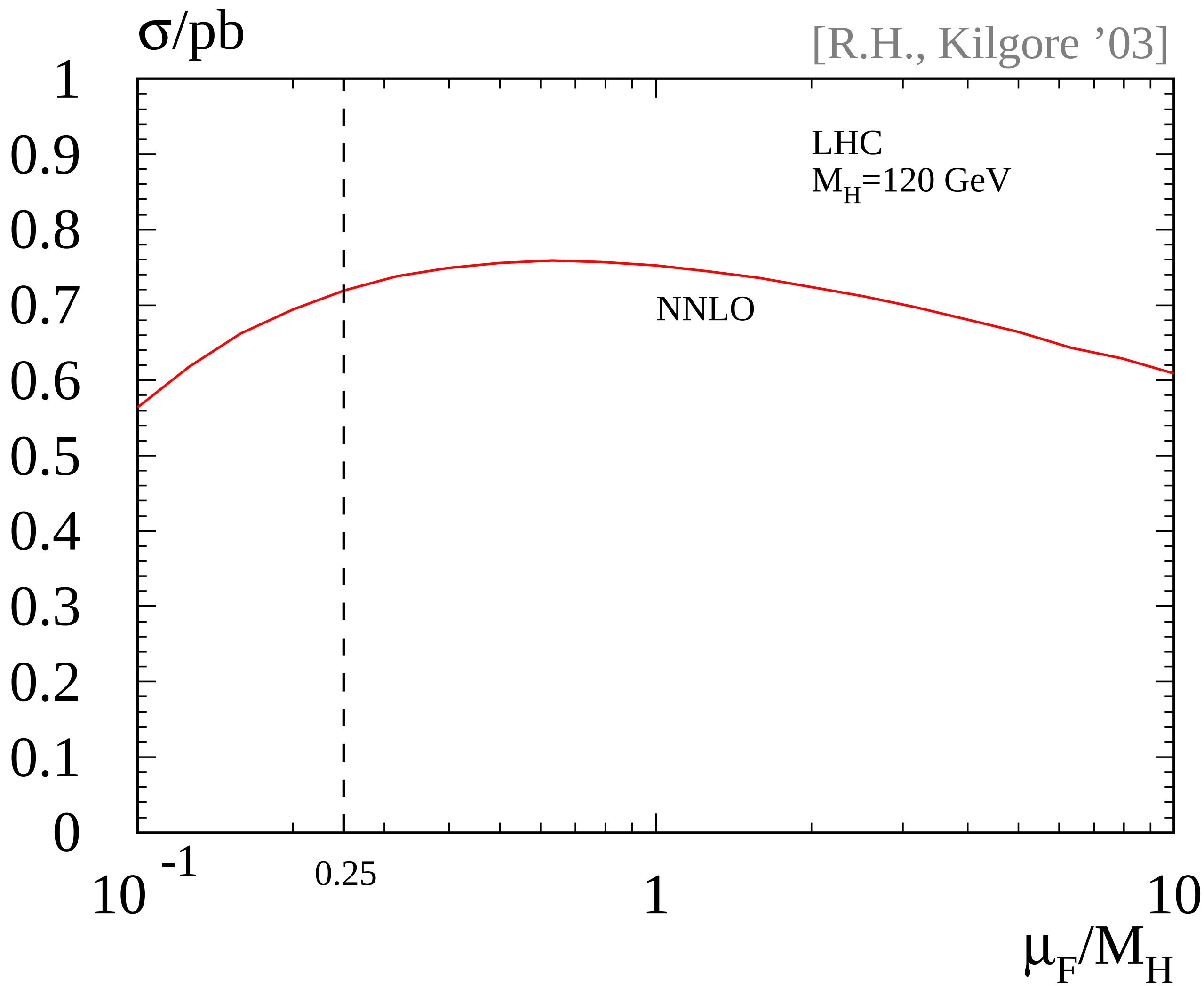
$b\bar{b} \to H$ at NNLO



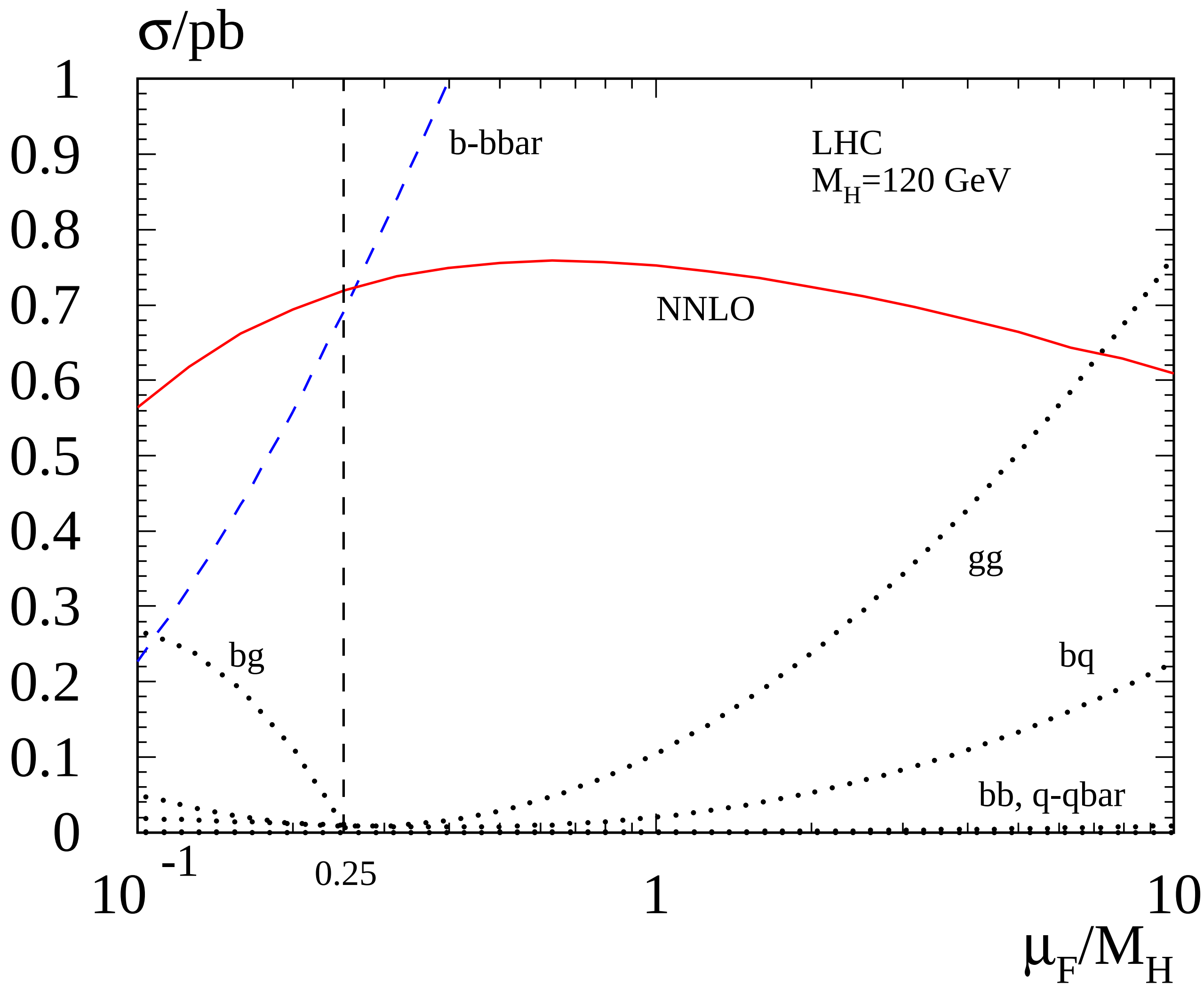
$b\bar{b} \to H$ at NNLO



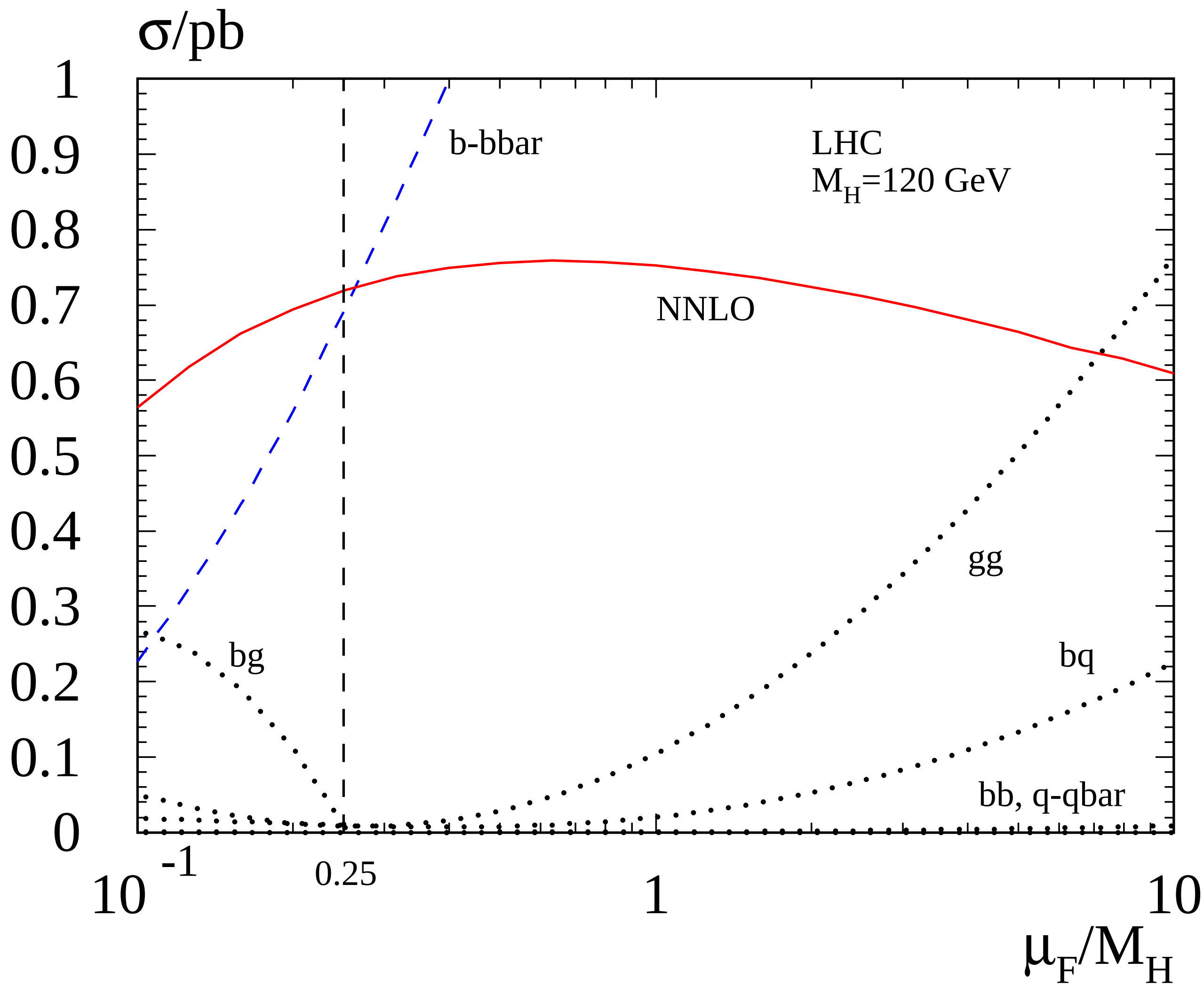
$b\bar{b} \longrightarrow H$ at NNLO



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



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



test: $b\bar{b} \to Z$ at Tevatron [Maltoni, McElmurry, Willenbrock '05]

Conclusions

- Higgs physics very inspiring for theoretical developments

  $\longrightarrow$ phase space integrations, higher order Monte Carlos, ...

- new conceptual understandings

  $\longrightarrow$ bottom densities, higher order SUSY, ...

- higher orders essential

  $\sigma(gg \to H) \approx \sigma_{\rm LO}(1 + 0.7 + 0.3 + \cdots) \approx 2\sigma_{\rm LO}$

- exciting times ahead of us

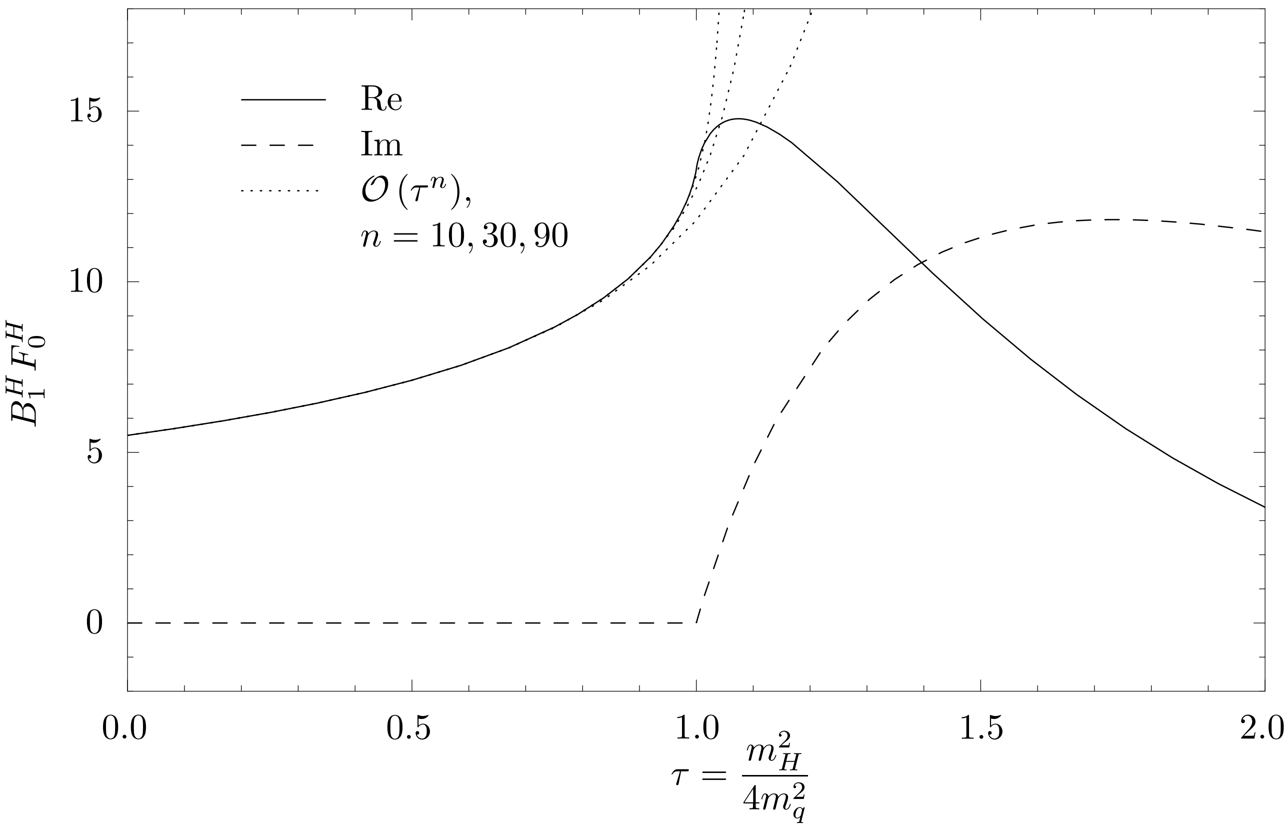
  $\longrightarrow$ (N)NLO era at hadron colliders has begun!

  $\longrightarrow$ Higgs physics with data!

Backup

Example: Virtual $gg \longrightarrow H$ at NLO

[R.H., P. Kant '05]



portable, easy-to-handle analytical result