Higher order corrections to Higgs boson production at the LHC

Robert Harlander

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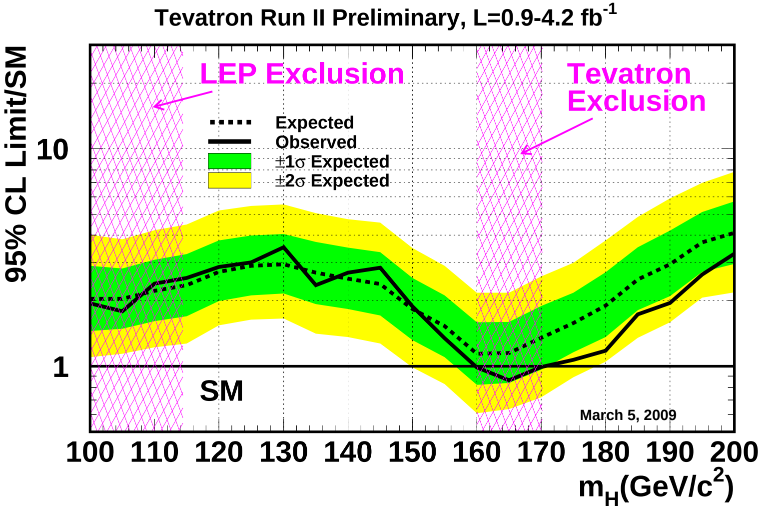
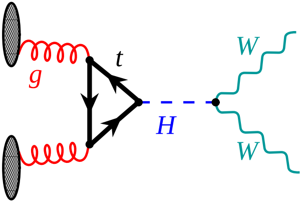
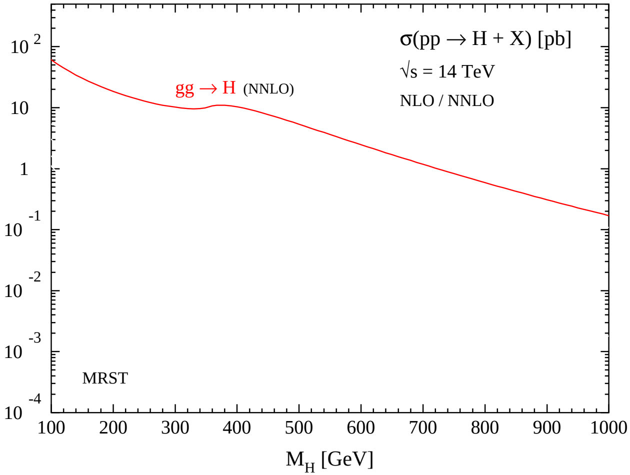
Higgs search at the Tevatron

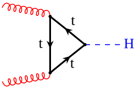


Gluon fusion



Higgs cross sections





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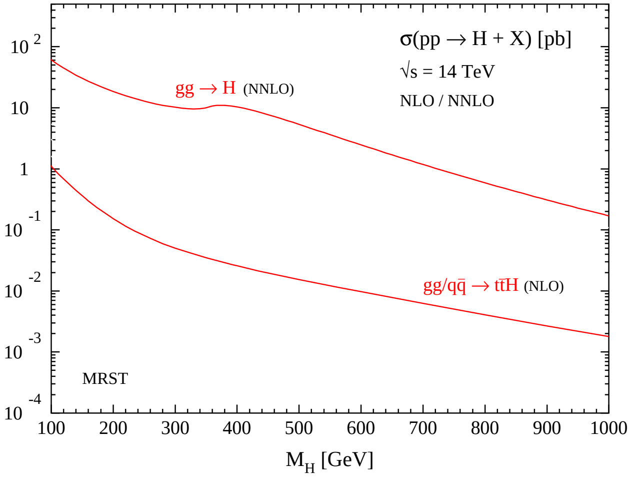

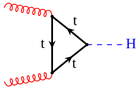

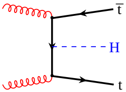

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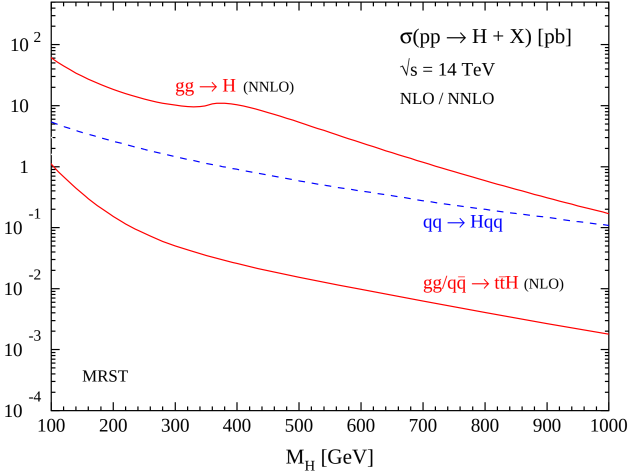

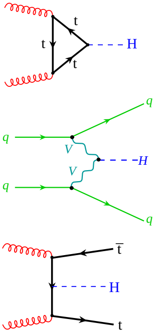

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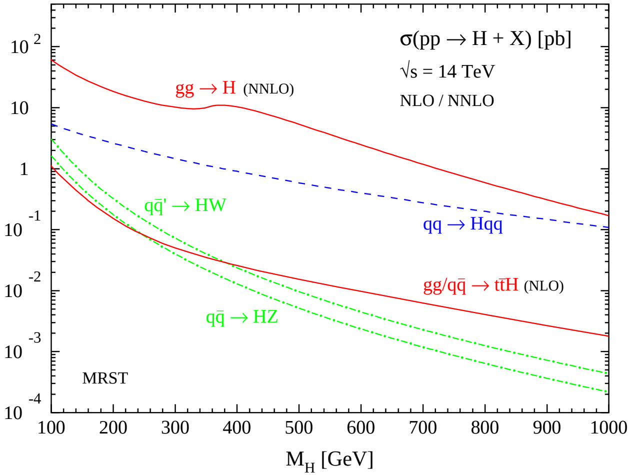

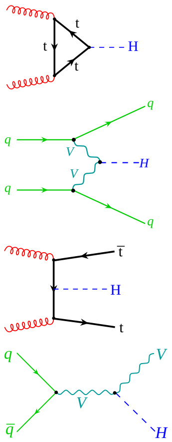

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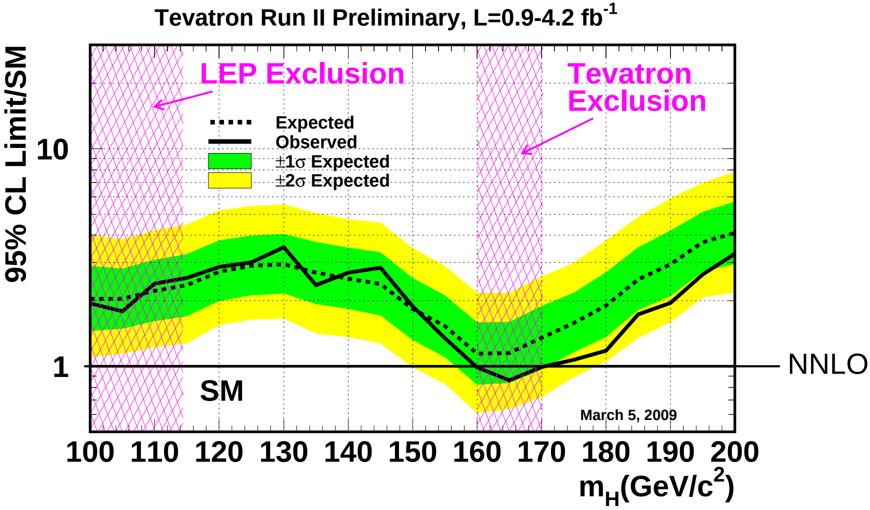

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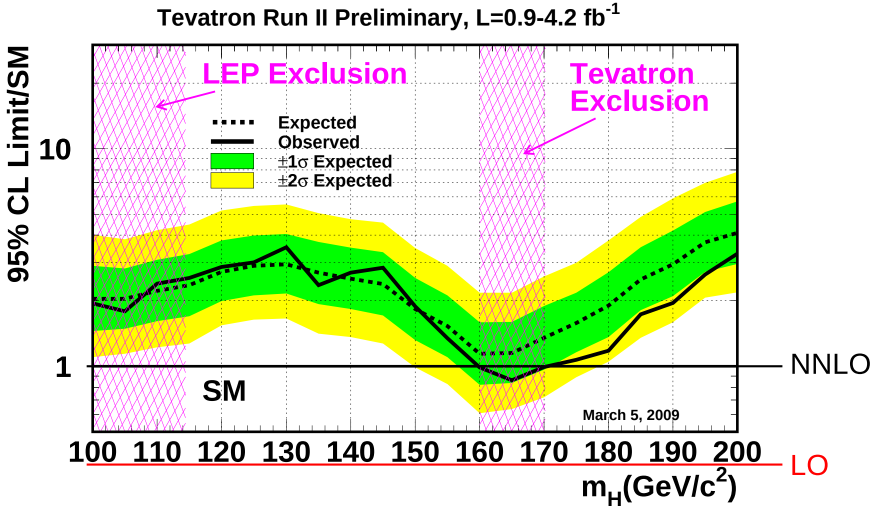

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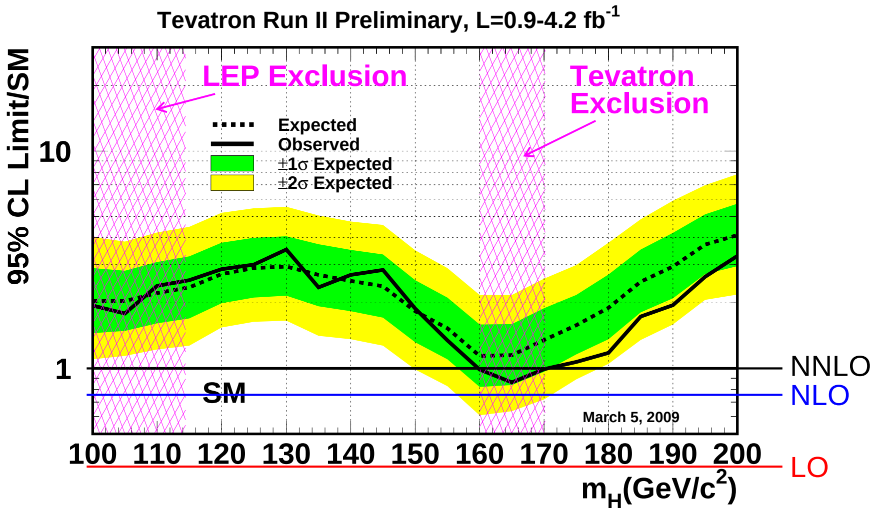

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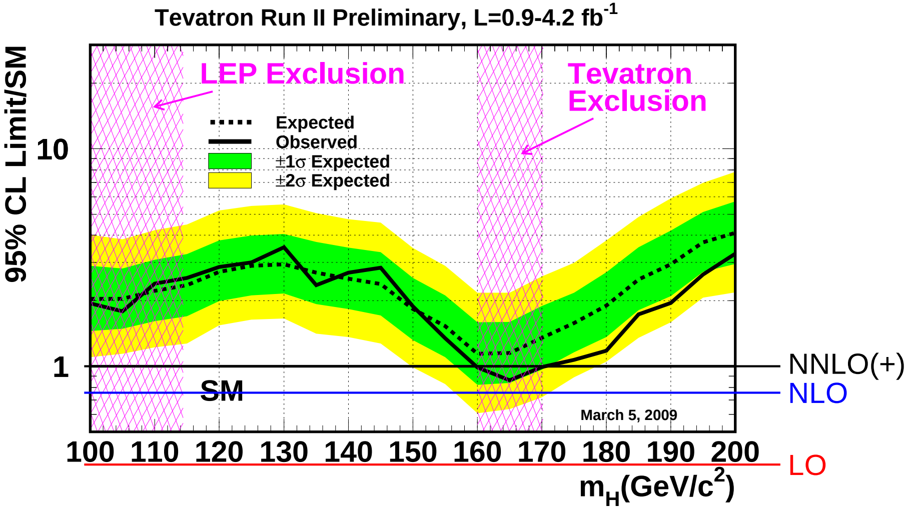
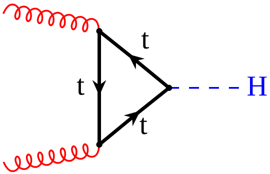


Gluon Fusion



- dominant production mode
- sensitive to heavy particle spectrum

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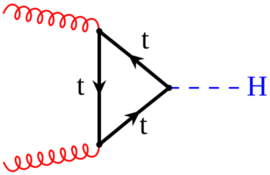

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- $H \rightarrow b\bar{b}$ decay mode not usable for discovery
- LO is 1-loop $\quad\rightarrow\quad$ radiative corrections difficult
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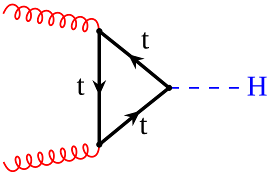

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- $H \to b\bar{b}$ decay mode not usable for discovery
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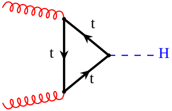
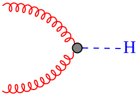
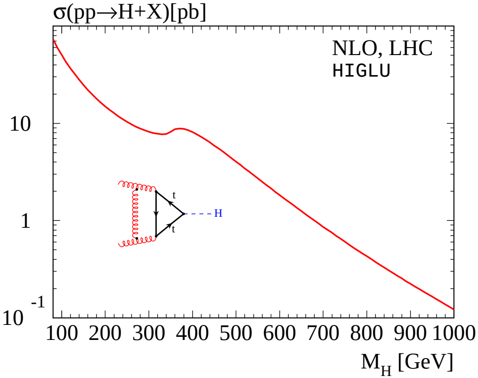
Gluon fusion

- effective theory for $m_t \gg M_H$:



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





$$\sigma_{\infty}^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}(m_t) \left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}} \right)_{m_t \to \infty}$$

Gluon fusion

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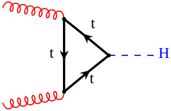
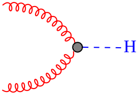
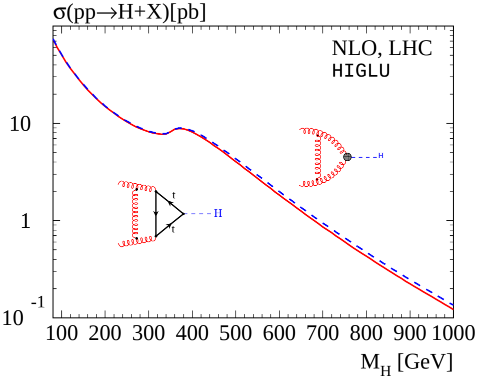


$\overset{m_t \gg M_H}{\longrightarrow}$ $C(m_t, \alpha_s) \times$





$$\sigma_\infty^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}(m_t) \left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}} \right)_{m_t \to \infty}$$

[Krämer, Laenen, Spira ’96]

Gluon fusion

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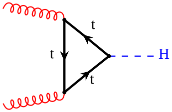

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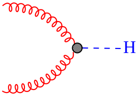

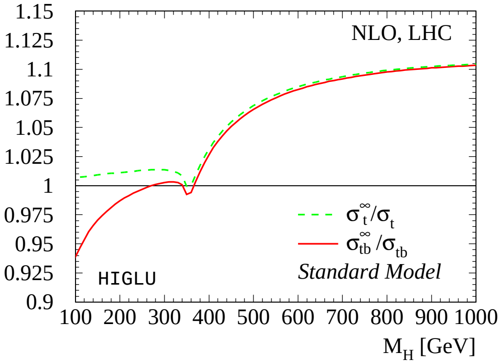

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[Krämer, Laenen, Spira ’96]

Reason? Still debated!

Test: subleading terms in $1/m_t$

$$\hat{\sigma} = \sum_n \left(\frac{m_H^2}{4m_t^2} \right)^n \hat{\sigma}_n$$

- NLO: [Dawson, Kauffman '93]

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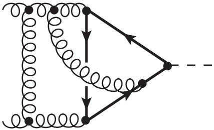

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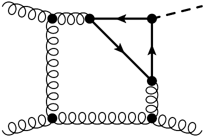

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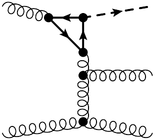

114

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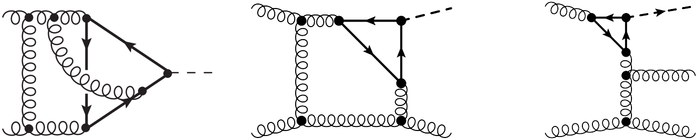


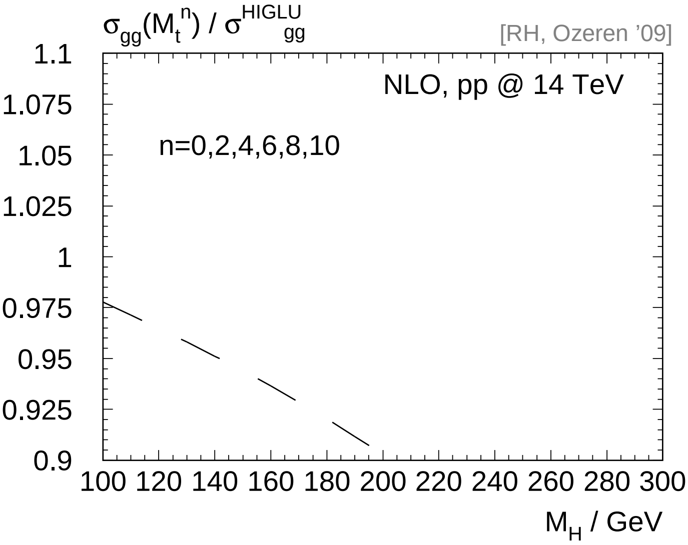
623 327 114

$\rightarrow$ calculate by asymptotic expansions

virtual: [RH, Ozeren '09], [Pak, Rogal, Steinhauser '09]

full: [RH, Ozeren '09]

Convergence of $1/m_t$ expansion at NLO



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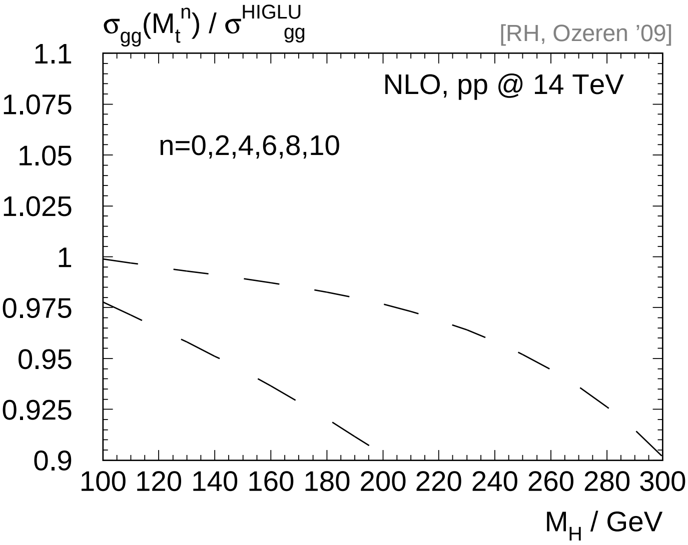

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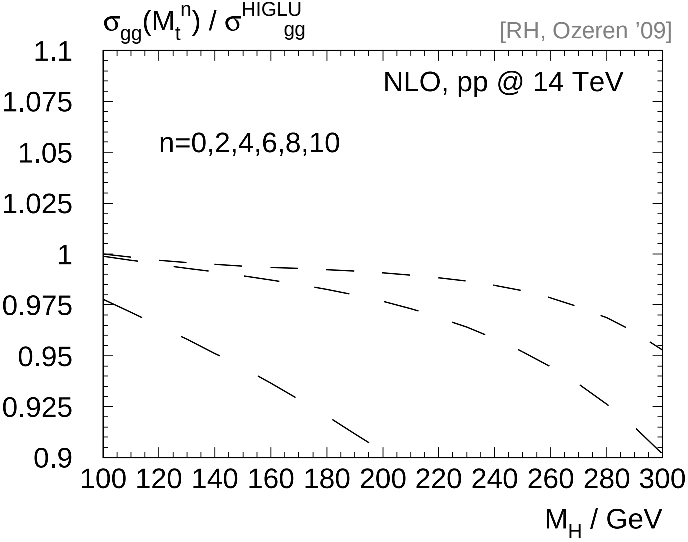

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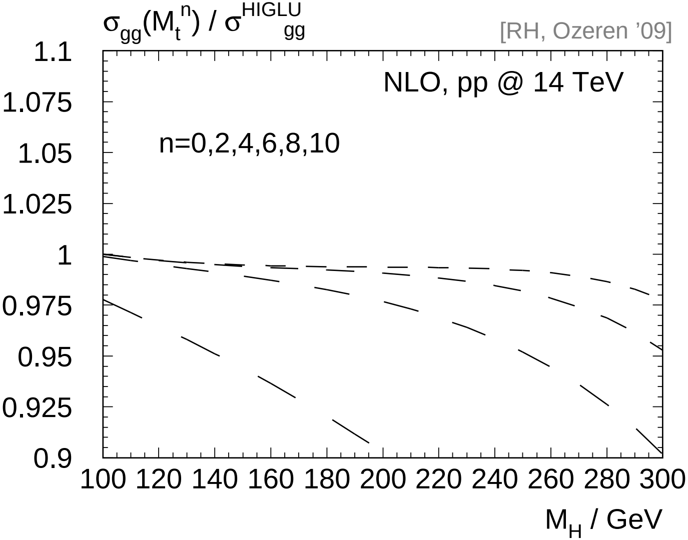

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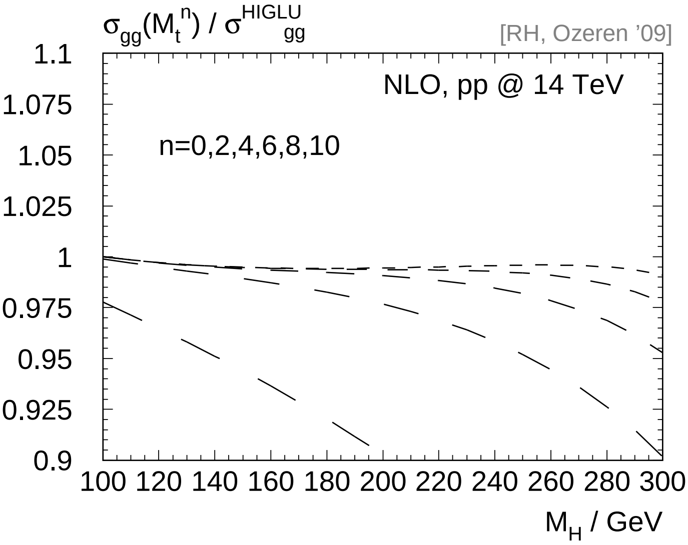

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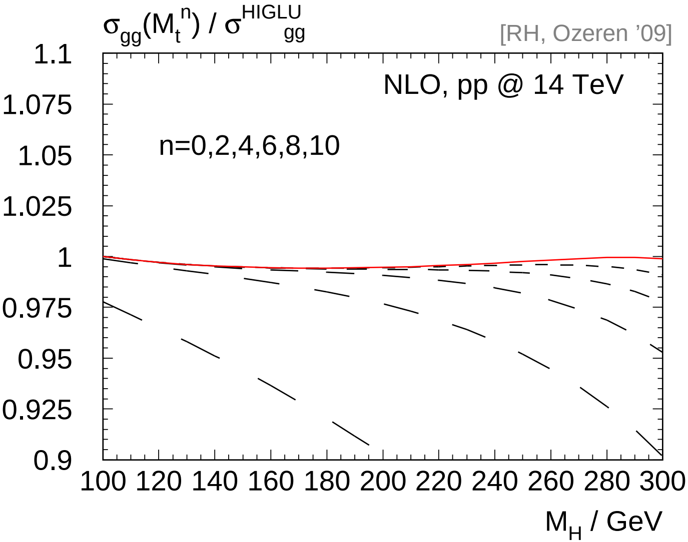

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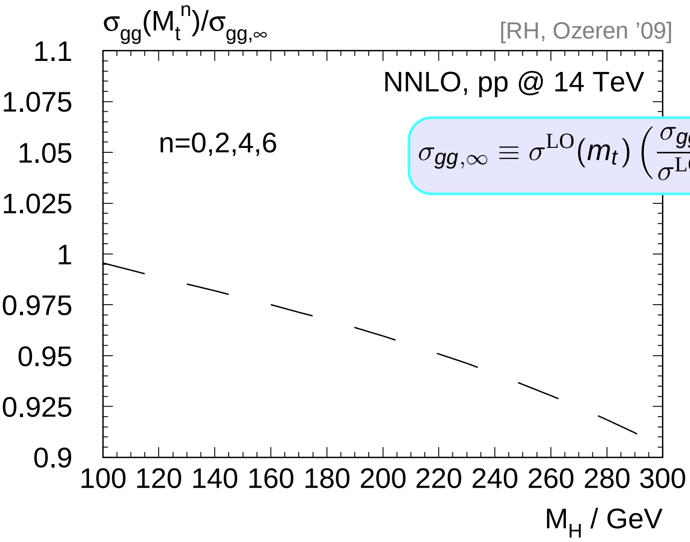

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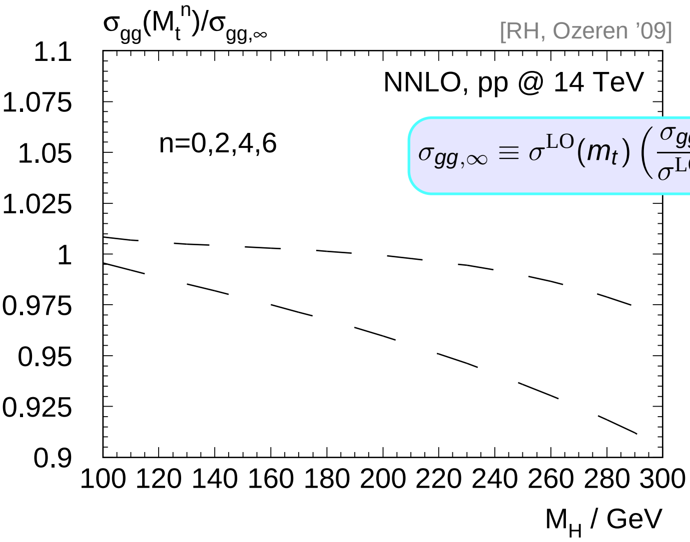

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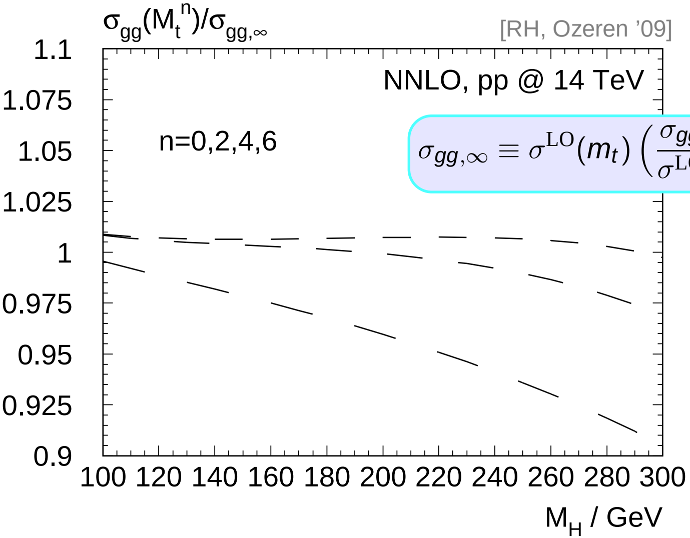

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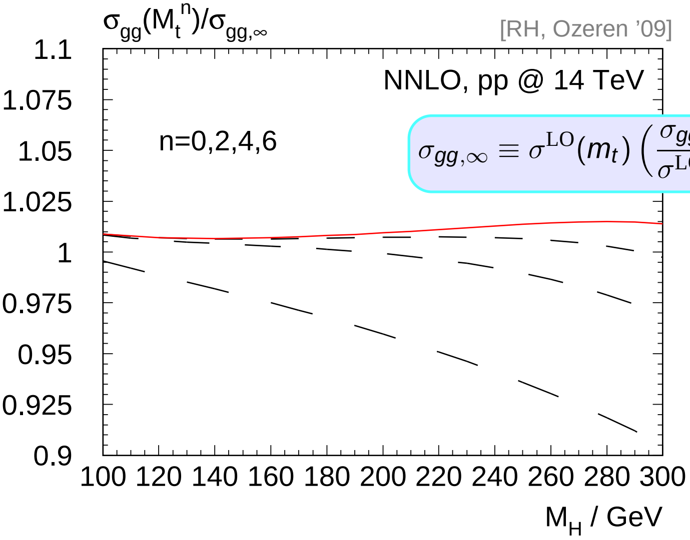

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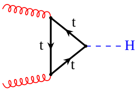
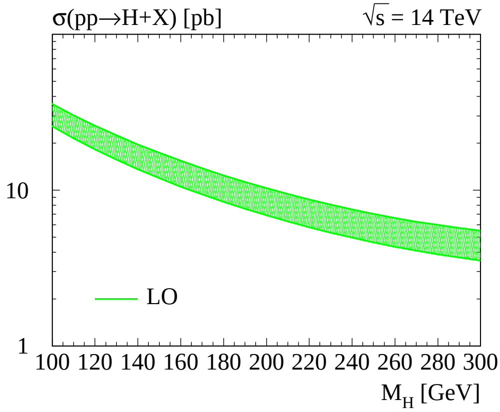
Gluon fusion: theory prediction





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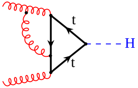
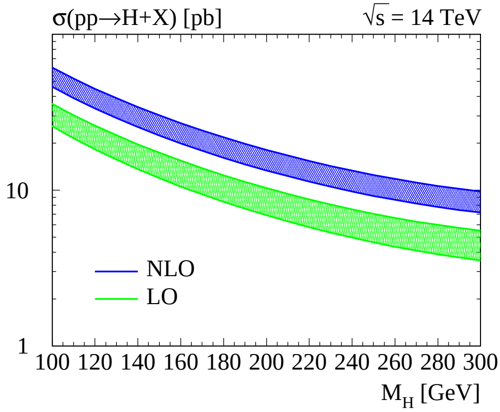
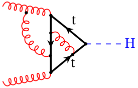
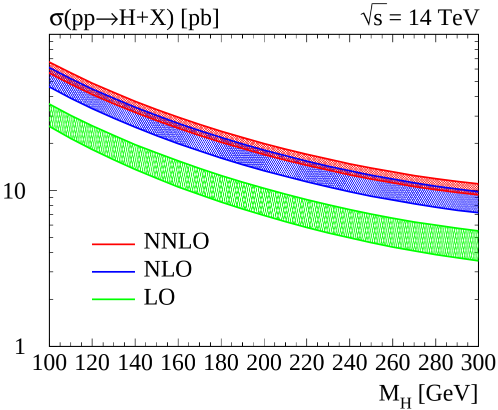




[Spira, Djouadi, Graudenz, Zerwas ’91/’93]

[Dawson ’91]





[R.H., Kilgore '02]

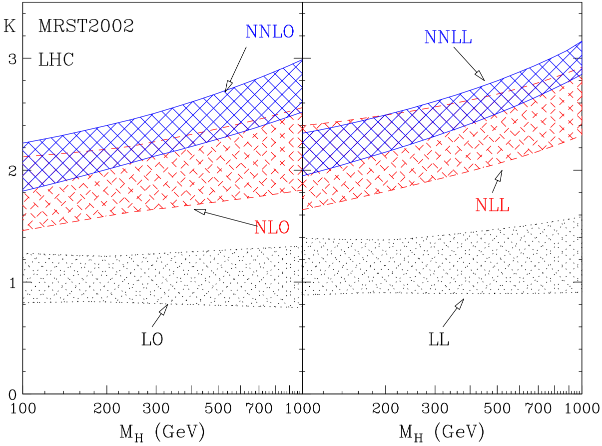
[Anastasiou, Melnikov '02]

[Ravindran, Smith, v. Neerven '03]

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

[Dawson '91]

Soft gluon resummation



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

Gluon Fusion: Latest developments

Resumming $(C_A \pi \alpha_s)^n$ from $\ln(-\mu^2/m_H^2) = \ln(\mu^2/m_H^2) + i\pi$

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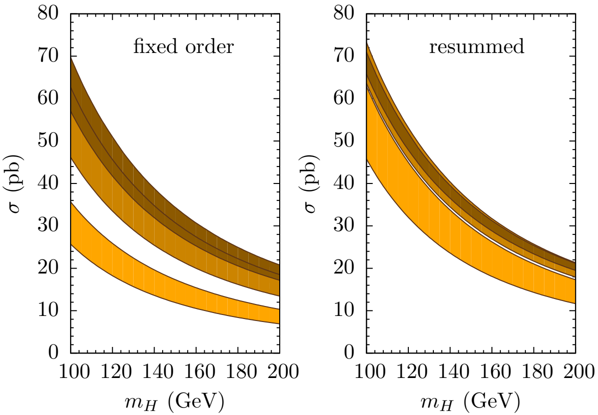

$$\alpha_s(\mu^2) \to \alpha_s(-m_H^2)$$
$$\approx (0.9 + 0.2i)\,\alpha_s(m_H^2)$$

[Ahrens, Becher, Neubert, Yang '08]

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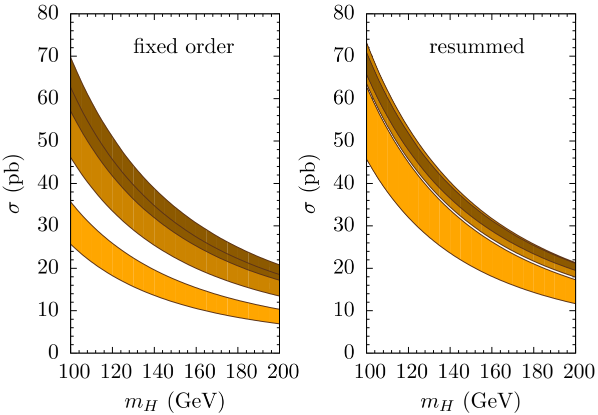

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Message: π^2 is large

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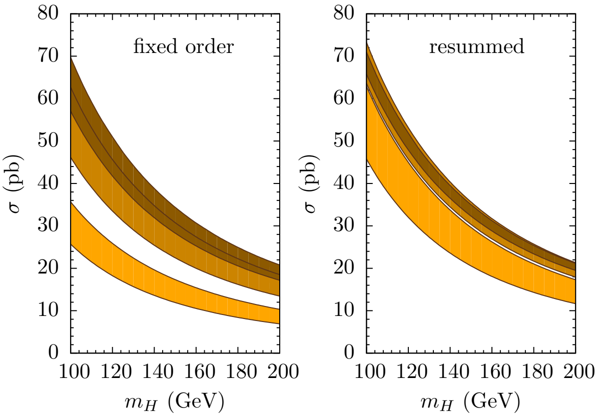

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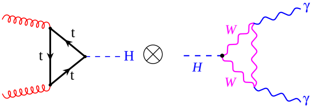
[Ahrens, Becher, Neubert, Yang '08]

Message: π^2 is large but some π^2's are larger than others

NNLO with cuts

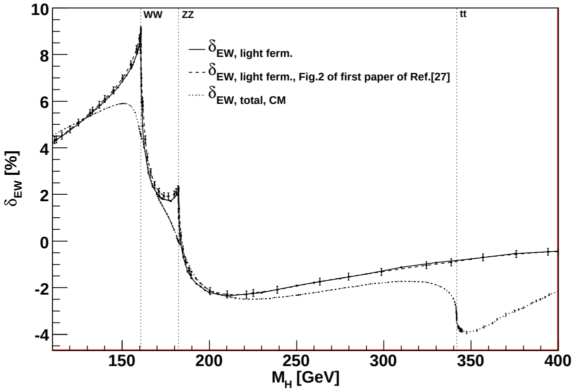


m_h	$\sigma^{\text{cut}}_{\text{NNLO}}/\sigma^{\text{inc}}_{\text{NNLO}}$	$K^{(2)}_{\text{cut}}/K^{(2)}_{\text{inc}}$
110	0.590	0.981
115	0.597	0.968
120	0.603	0.953
125	0.627	0.970
130	0.656	1.00
135	0.652	0.98

[Anastasiou, Melnikov, Petriello ’05]

but: can depend strongly on cuts (jet-veto etc.) [Anastasiou et al. ’07]
in particular $gg \to H \to WW \to l\nu l\nu$ [Dittmar, Dreiner ’97]

Gluon fusion: Electro-weak corrections



[Actis, Passarino, Sturm, Uccirati '08]

partial:

[Aglietti, Bonciani, Degrassi, Vicini '04]

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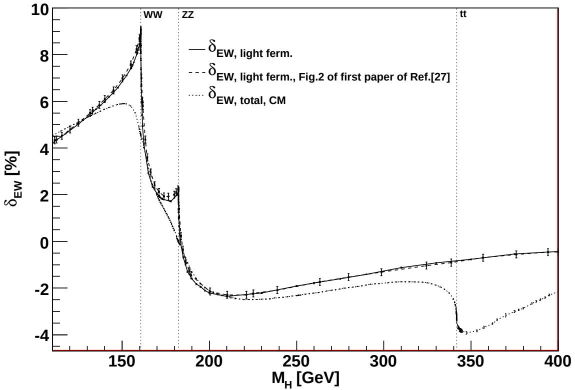

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mixed EW/QCD?

→ do they factorize? (remember LEP?)

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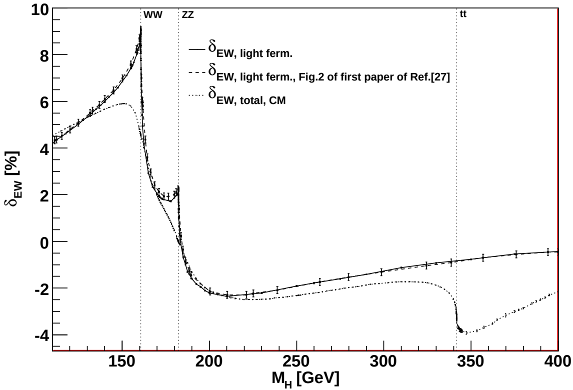

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$\rightarrow$ do they factorize? (remember LEP?)

limit $M_H \ll M_W$ [Anastasiou, Boughezal, Petriello '08]

Latest compilations[1]

- NLO [Dawson '91], [Spira, Djouadi, Graudenz, Zerwas '91-'95]
  $\longrightarrow$ +110% of LO

[1] Numbers to be confirmed.

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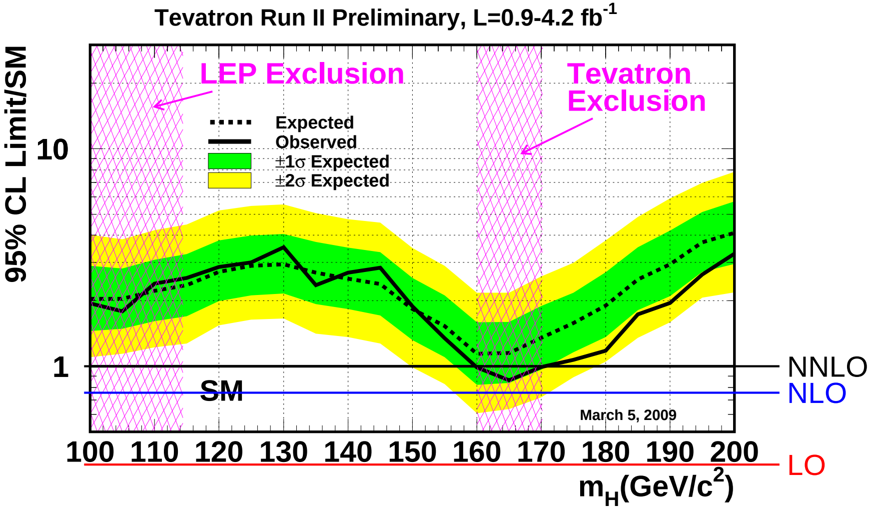
- PDFs: MRST2006 $\rightarrow$ MSTW2008 $\rightarrow$ -13% (!)

[1] Numbers to be confirmed.

Higgs search at the Tevatron



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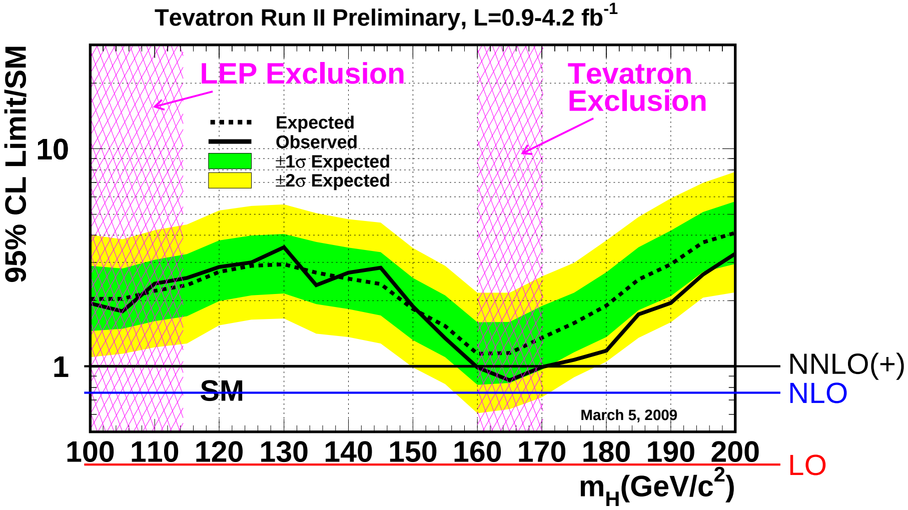

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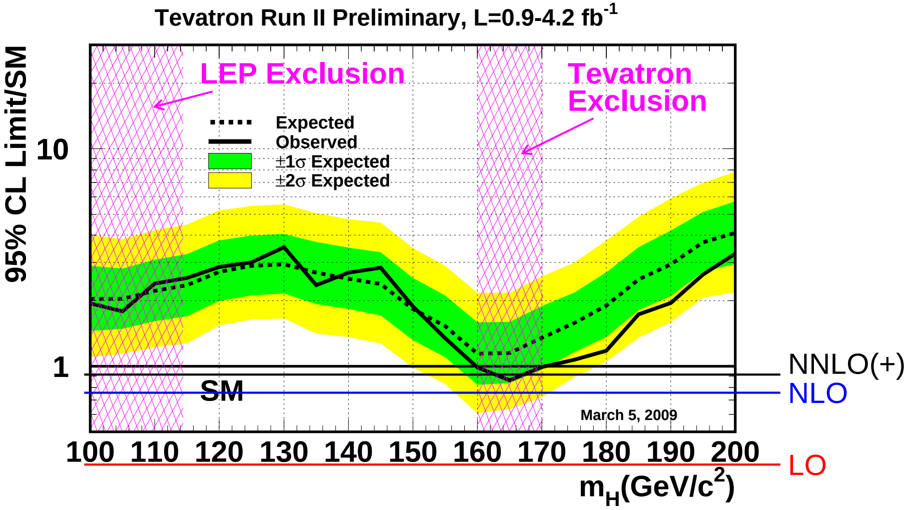
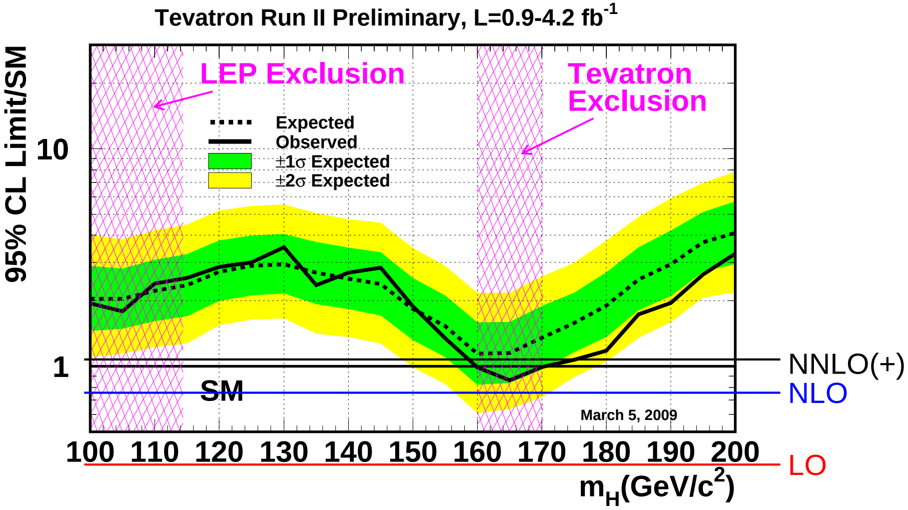
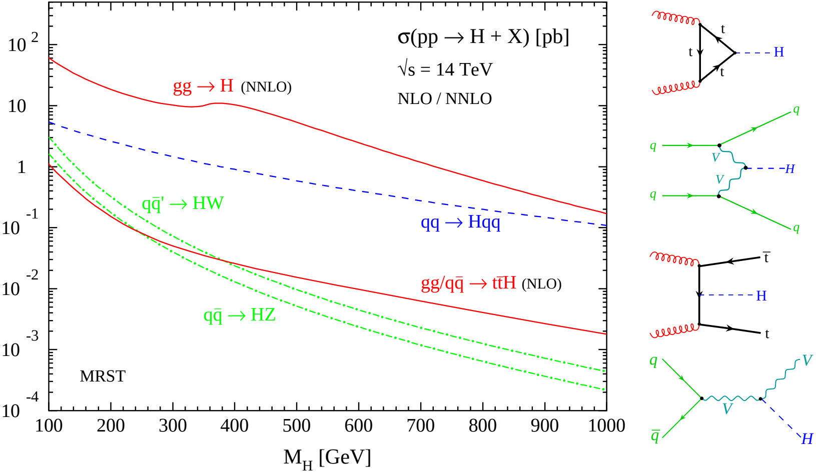


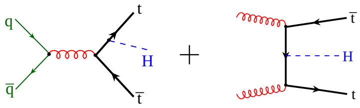
Higgs search at the Tevatron



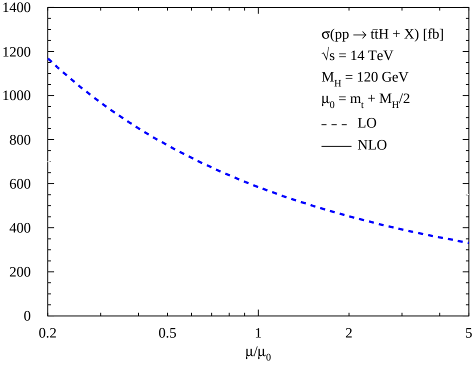
Higgs cross sections



ttH at NLO



33%   67% $\sim \alpha_s^2$



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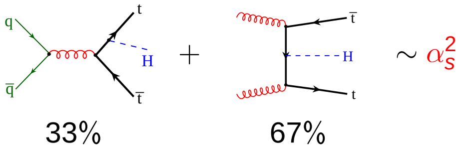
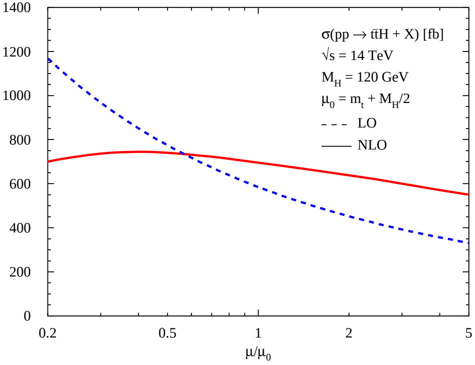
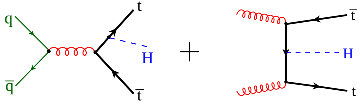




[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01]

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

ttH at NLO



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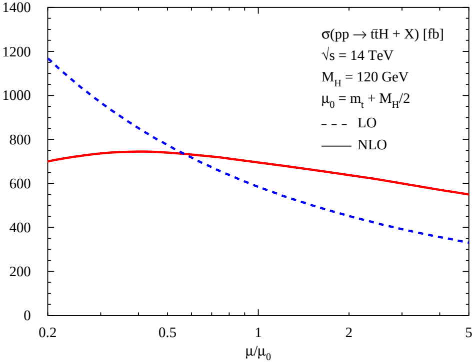

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→ no longer a discovery channel

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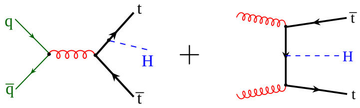

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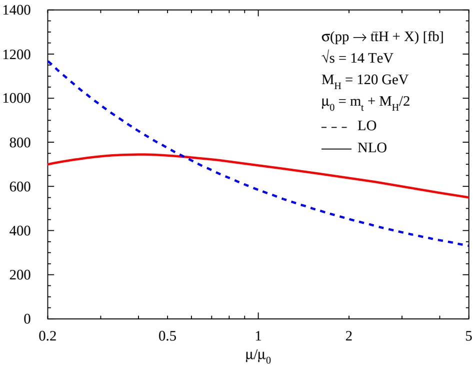

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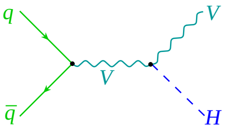
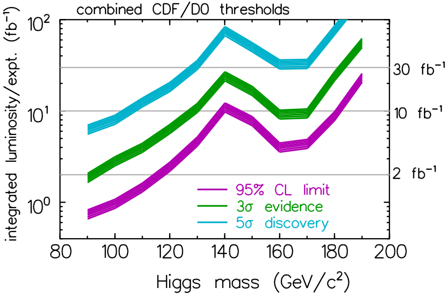
… but we have seen channels come and go…

Higgs Strahlung





[Tev Higgs WG '00]

- used to be
  - main search mode for Tevatron

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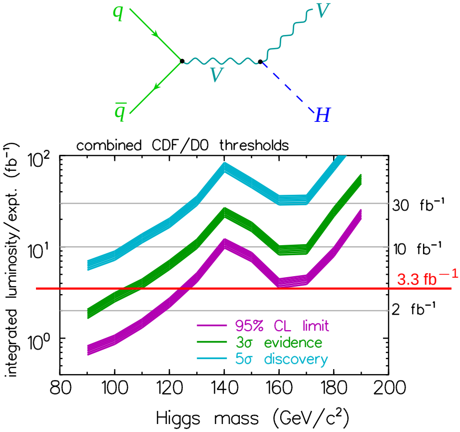

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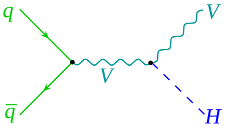

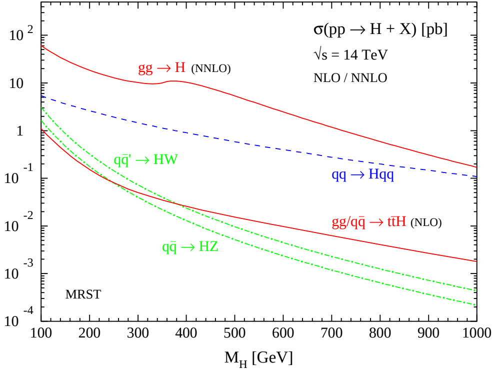

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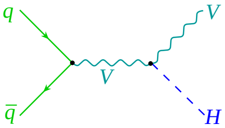
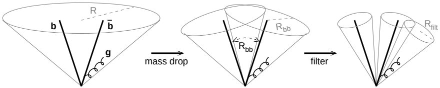


- used to be
  - main search mode for Tevatron
  - considered useless for Higgs search at LHC
- use jet sub-structure:

  [Butterworth *et al.* 08]

  promising for $M_H \approx 120$ GeV



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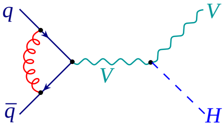

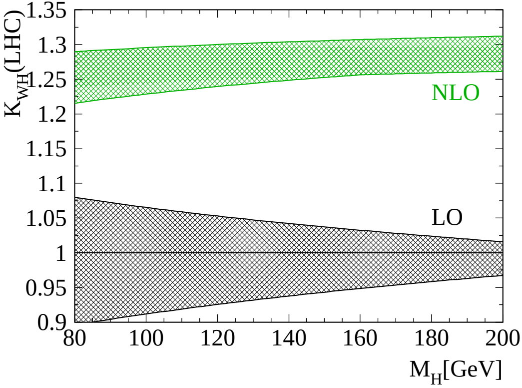

[Han, Willenbrock '90]

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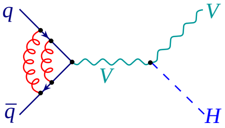

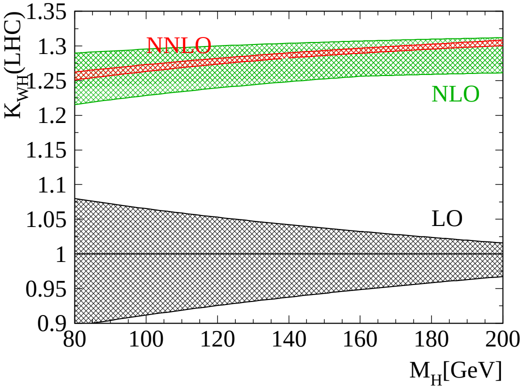

[Brein, Djouadi, R.H. ’03]

[Han, Willenbrock ’90]

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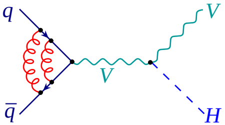
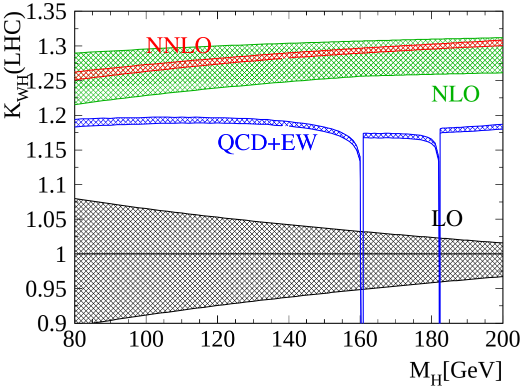


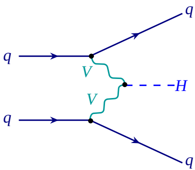


[Brein, Djouadi, R.H. '03]

[Han, Willenbrock '90]

[Ciccolini, Dittmaier, Krämer '03]

Weak Boson Fusion



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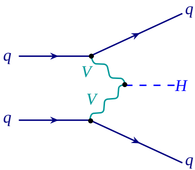

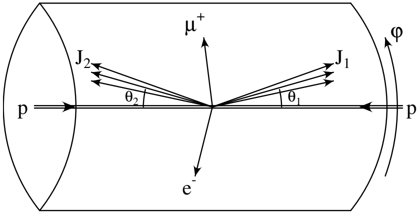

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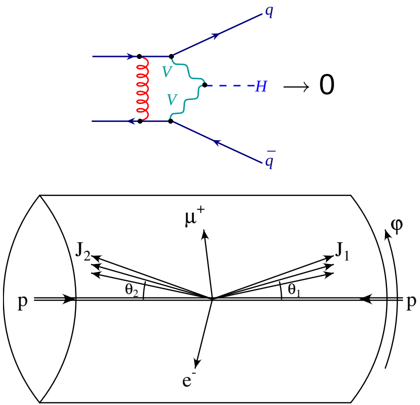
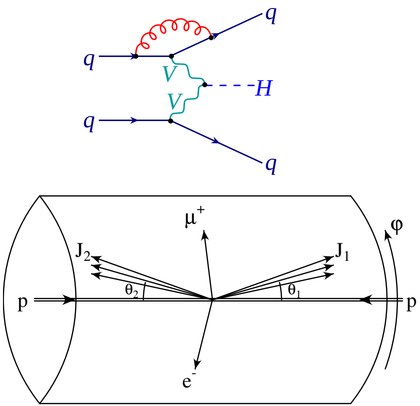
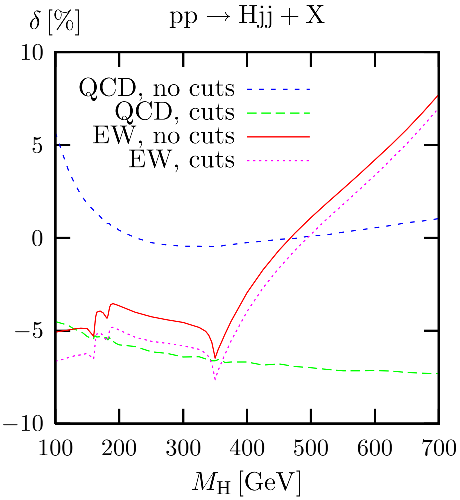




NLO QCD: [Figy, Oleari, Zeppenfeld ’03]

+ EW: [Ciccolini, Denner, Dittmaier ’08]

WBF: QCD+EW corrections

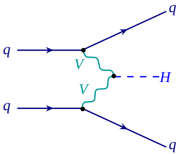


[Ciccolini, Denner, Dittmaier ’08]

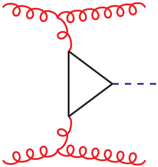
WBF: other corrections

- mixed QCD/EW [Bredenstein, Hagiwara, Jäger ’08]
- gluon fusion/WBF interference [Andersen, Binoth, Heinrich, Smillie ’07]
- gluon induced WBF [R.H., Vollinga, Weber ’08]

Weak Boson Fusion



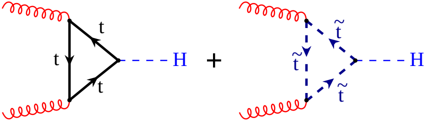
vs.



- $gg \to H$+2 jets: [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld '01]
- NLO for $m_t \to \infty$: [Campbell, Ellis, Zanderighi '06]
- $gg \to H + n$ jets: [Andersen, Del Duca, White '08]
- appropriate cuts allow distinction

Effects of SUSY

[Djouadi 98], [Carena *et al.* 99]



may interfere destructively!

Effects of SUSY

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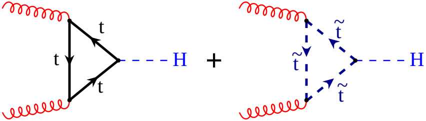
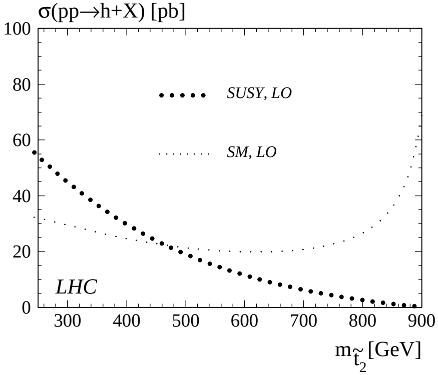


may interfere destructively!

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



[R.H., Steinhauser '04],
[Anastasiou *et al.* '06/'08]
[Mühlleitner, Rzehak, Spira '07/'08]
[Aglietti, Bonciani, Degrassi, Vicini '06]
[Degrassi, Slavich '08]

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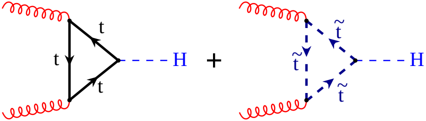

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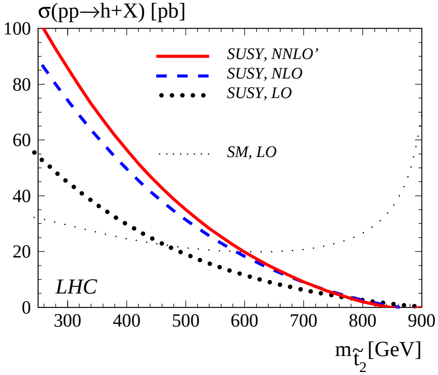

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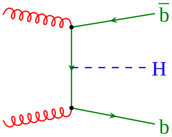
$H/A + b\bar{b}$



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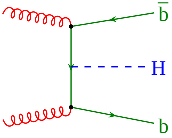
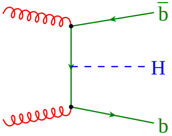
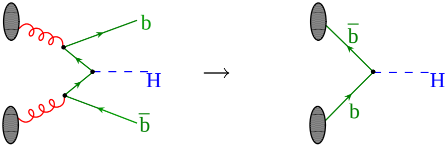


- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$

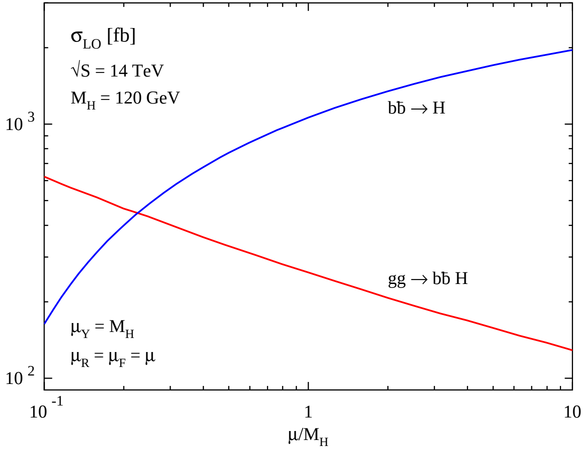
$H/A + b\bar{b}$



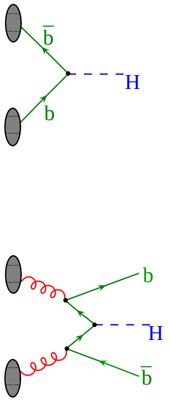
- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$
- resummation: bottom quarks as partons



4-FNS vs. 5-FNS

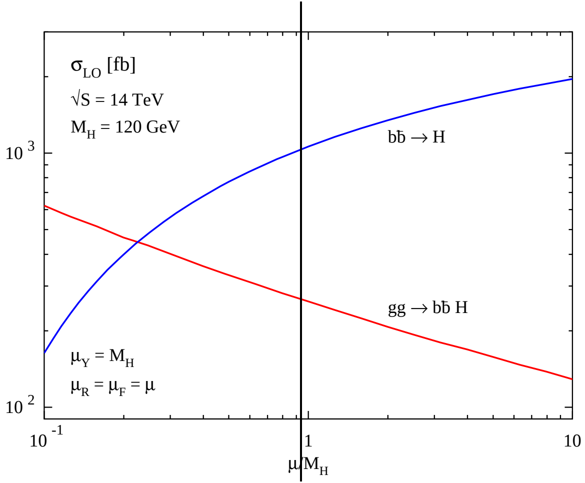


σLO [fb]
√S = 14 TeV
MH = 120 GeV
bb̄ → H
gg → bb̄ H
μY = MH
μR = μF = μ
10 3
10 2
10 -1
1
10
μ/MH

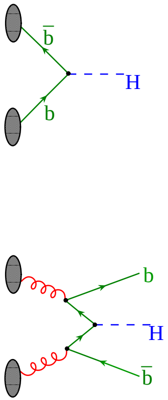


b̄
b
H
b
H
b̄

4-FNS vs. 5-FNS

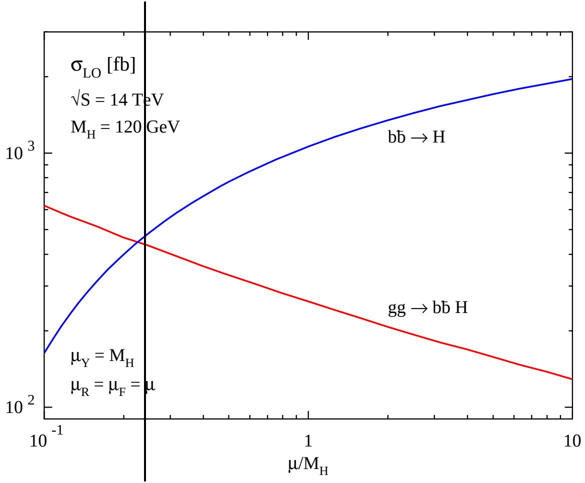


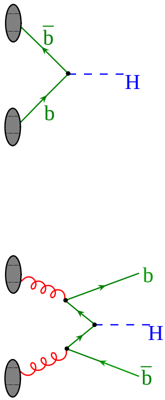
σ_{LO} [fb]
$\sqrt{S}$ = 14 TeV
M_H = 120 GeV
$b\bar{b} \to H$
$gg \to b\bar{b}H$
$\mu_Y = M_H$
$\mu_R = \mu_F = \mu$
10^3
10^2
10^{-1}
1
10
μ/M_H



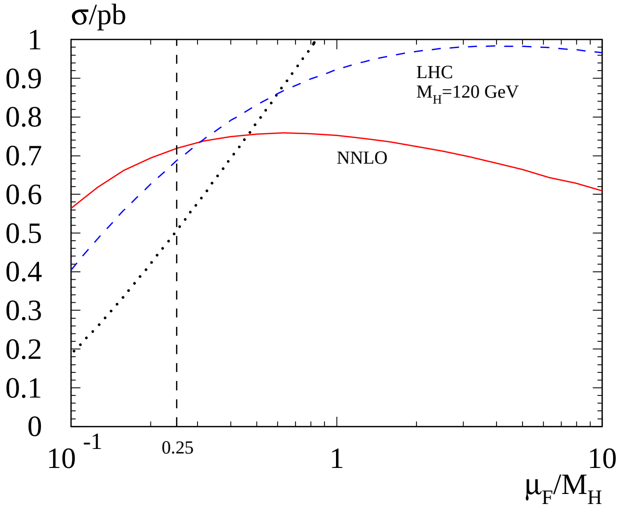
$\bar{b}$
b
H
b
H
$\bar{b}$

4-FNS vs. 5-FNS


σ_LO [fb]
√S = 14 TeV
M_H = 120 GeV
bb̄ → H
gg → bb̄ H
μ_Y = M_H
μ_R = μ_F = μ
10^3
10^2
10^-1
1
10
μ/M_H

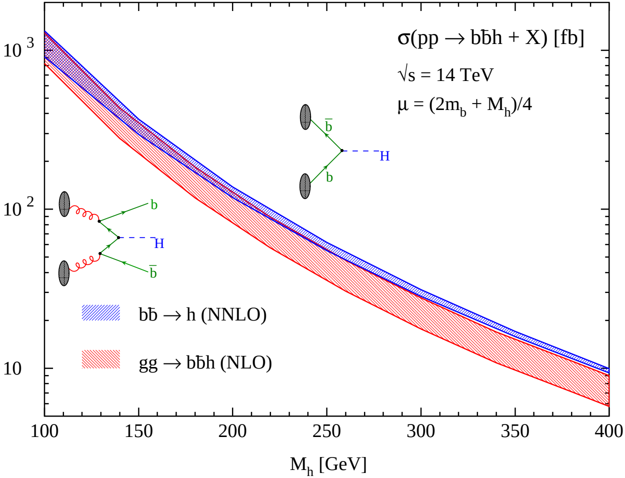

b̄
b
H
b
H
b̄

5-FNS at NNLO



bbh@nnlo: [RH, Kilgore '03]

$pp \to H + b\bar{b}$



electro-weak: [Dittmaier, Krämer, Mück, Schlüter '06]

Background processes: Les Houches '05 wishlist

Reaction	background for	existing calculations
$\mathrm{pp} \to VVj$	$\mathrm{t\bar{t}H}$, new physics	$\mathrm{WW}j$: Dittmaier, Kallweit, Uwer '07 $\mathrm{WW}j$: Campbell, R.K.Ellis, Zanderighi '07 $\mathrm{WW}j$: Binoth, Guillet, Karg, Kauer, Sanguinetti (in progress)
$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	$\mathrm{t\bar{t}H}$	this talk
$\mathrm{pp} \to \mathrm{t\bar{t}}jj$	$\mathrm{t\bar{t}H}$	–
$\mathrm{pp} \to VV\mathrm{b\bar{b}}$	VBF$\to \mathrm{H} \to VV$, $\mathrm{t\bar{t}}$, NP	–
$\mathrm{pp} \to VVjj$	VBF$\to \mathrm{H} \to VV$	VBF: Jäger, Oleari, Zeppenfeld '06 + Bozzi '07
$\mathrm{pp} \to Vjjj$	new physics	amplitudes: Berger et al. '08, R.K.Ellis et al. '08
$\mathrm{pp} \to VVV$	SUSY trilepton signal	ZZZ: Lazopoulos, Melnikov, Petriello '07 WWZ: Hankele, Zeppenfeld '07 VVV: Binoth, Ossola, Papadopoulos, Pittau '08

- NLO for $2 \to 3$ processes established
- very few calculations for $2 \to 4$, no complete calculation for pp process
  $\mathrm{e^+e^+} \to 4f$ (EW) Denner et al. '05 , $\mathrm{e^+e^+} \to \mathrm{HH}\nu\bar{\nu}$ (EW) Boudjema et al. '05
  $\gamma\gamma \to \mathrm{t\bar{t}b\bar{b}}$ (QCD) Lei et al. '07, $\mathrm{u\bar{u}} \to \mathrm{s\bar{s}b\bar{b}}$ (QCD) Binoth et al. '08

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- control non-perturbative uncertainties?
  PDFs, underlying event, ...