

# Higgs production

## — Higher orders and finite top mass effects —

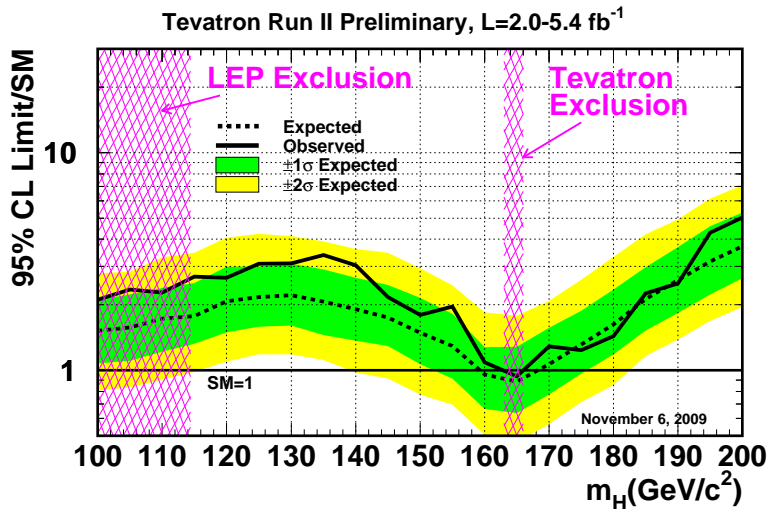
Robert Harlander

Bergische Universität Wuppertal

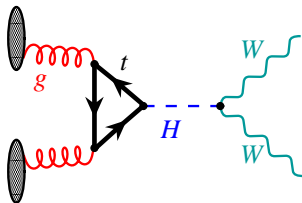
Rencontres de Moriond  
EW Interactions and Unified Theories  
La Thuile, Italy (March 6-13, 2010)

*Supported by: BMBF, DFG, Helmholtz Alliance "Physics at the Terascale"*

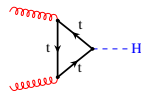
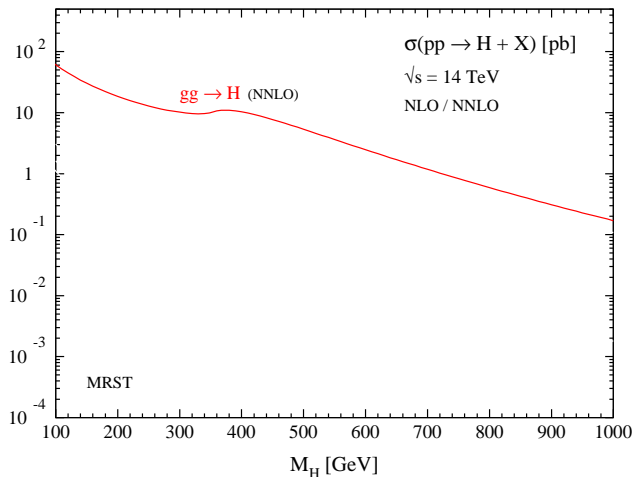
# Higgs search at the Tevatron



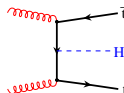
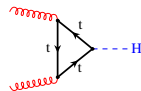
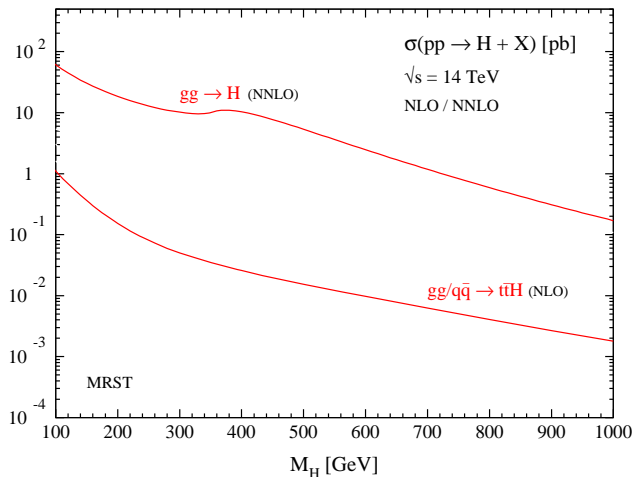
# Gluon fusion



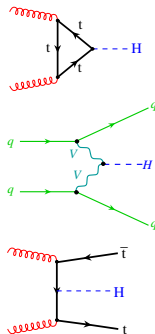
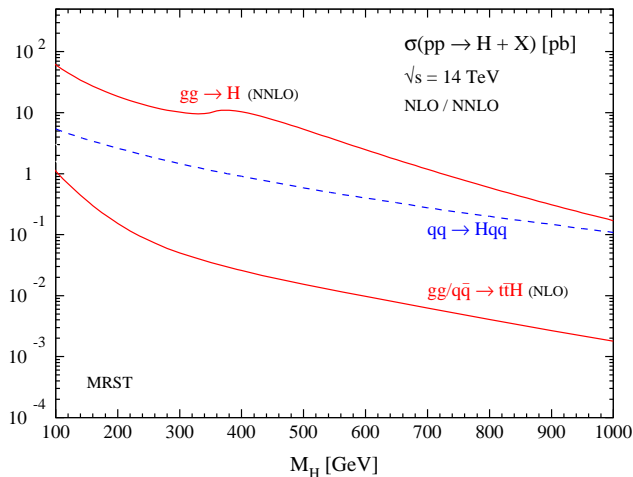
# Higgs cross sections



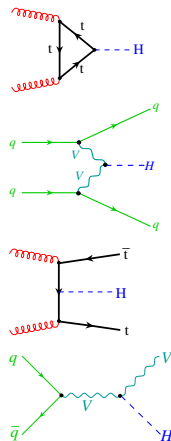
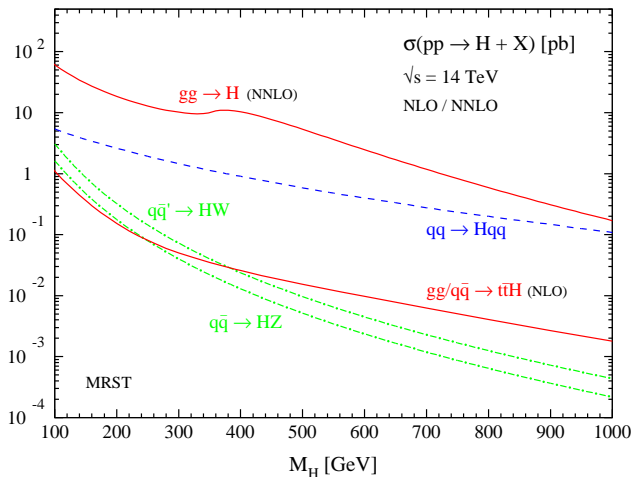
# Higgs cross sections



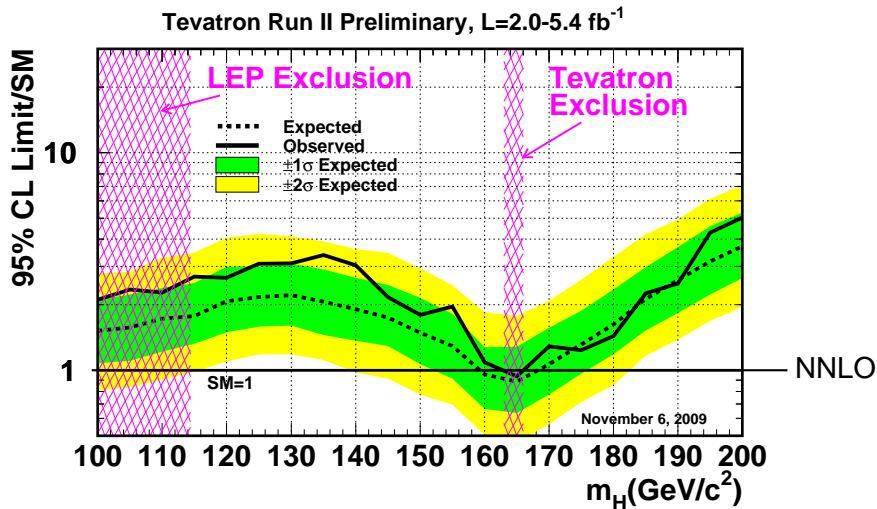
# Higgs cross sections



# Higgs cross sections

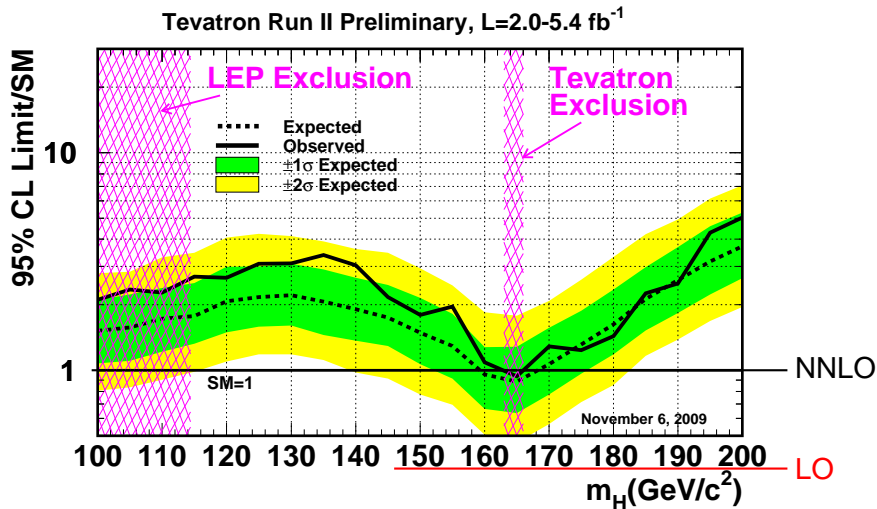


# Higgs search at the Tevatron

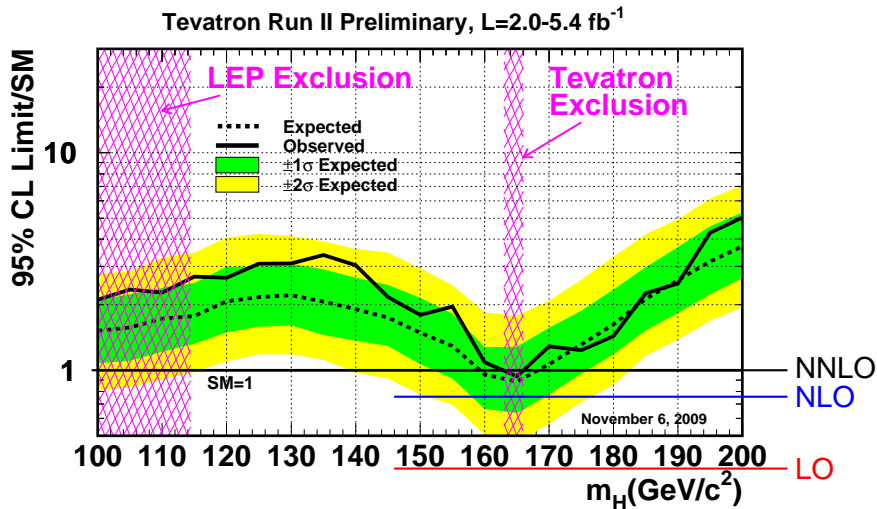




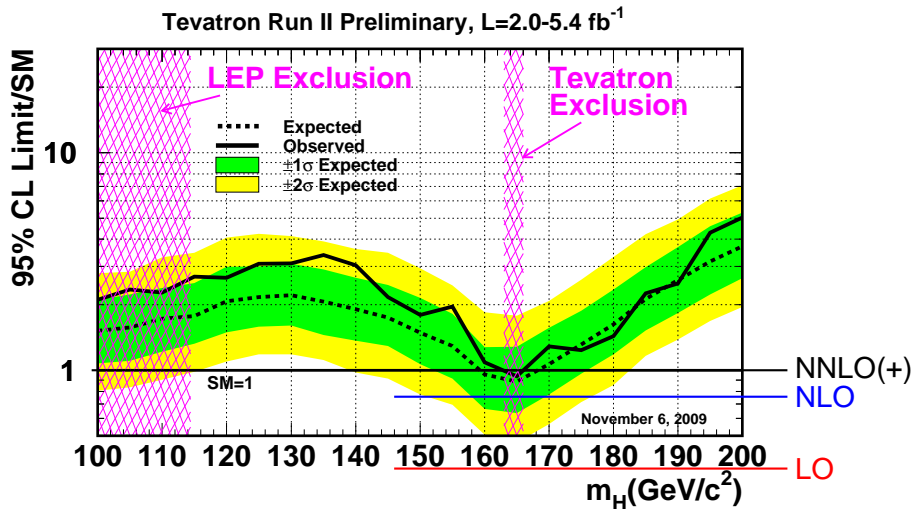
# Higgs search at the Tevatron



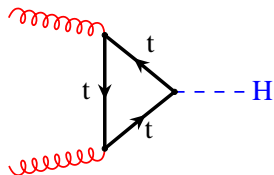
# Higgs search at the Tevatron



# Higgs search at the Tevatron

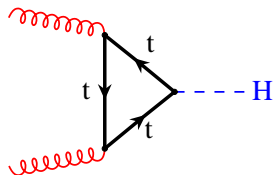


# Gluon Fusion



- dominant production mode
- sensitive to heavy particle spectrum

# Gluon Fusion

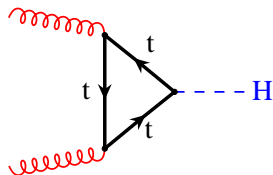


- dominant production mode
- sensitive to heavy particle spectrum

but

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

# Gluon Fusion



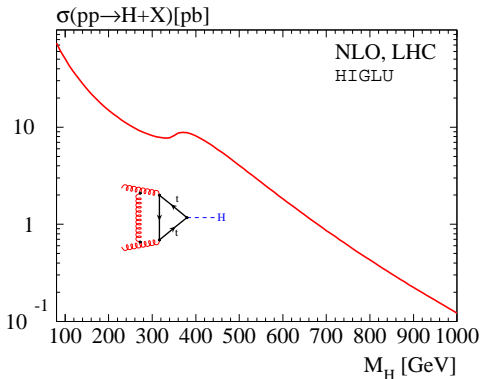
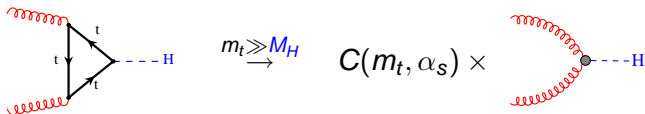
- dominant production mode
- sensitive to heavy particle spectrum

but

- $H \rightarrow b\bar{b}$  decay mode not usable for discovery
- LO is 1-loop  $\rightarrow$  radiative corrections difficult — really?
- depends on Yukawa coupling

# Gluon fusion

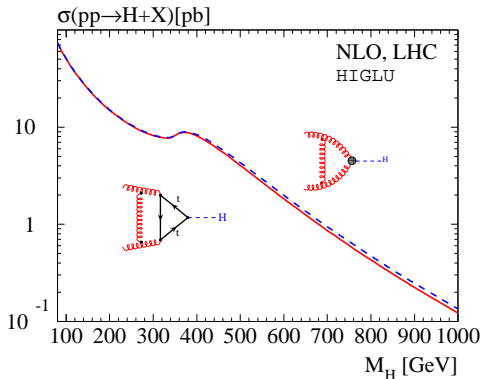
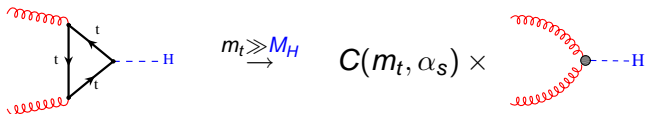
- effective theory for  $m_t \gg M_H$ :



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

# Gluon fusion

- effective theory for  $m_t \gg M_H$ :



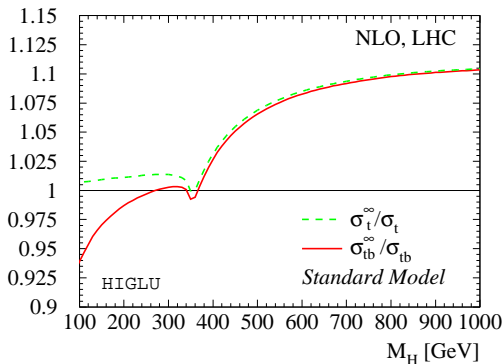
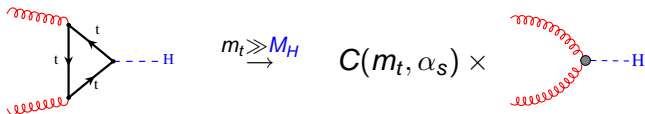
$$\sigma_{\infty}^{\text{HO}} \equiv \sigma^{\text{LO}}(m_t) \left( \frac{\sigma^{\text{HO}}}{\sigma^{\text{LO}}} \right)_{m_t \rightarrow \infty}$$

[Krämer, Laenen, Spira '96]



# Gluon fusion

- effective theory for  $m_t \gg M_H$ :



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

[Krämer, Laenen, Spira '96]  
Reason? Still debated!

# Test: subleading terms in $1/m_t$

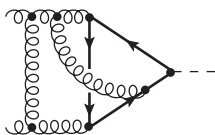
$$\hat{\sigma} = \sum_n \left( \frac{m_H^2}{4m_t^2} \right)^n \hat{\sigma}_n$$

- **NLO:** [Dawson, Kauffman '93]

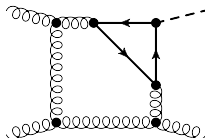
# Test: subleading terms in $1/m_t$

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

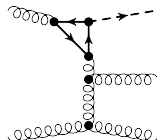
- **NLO:** [Dawson, Kauffman '93]
- **NNLO:**



623



327



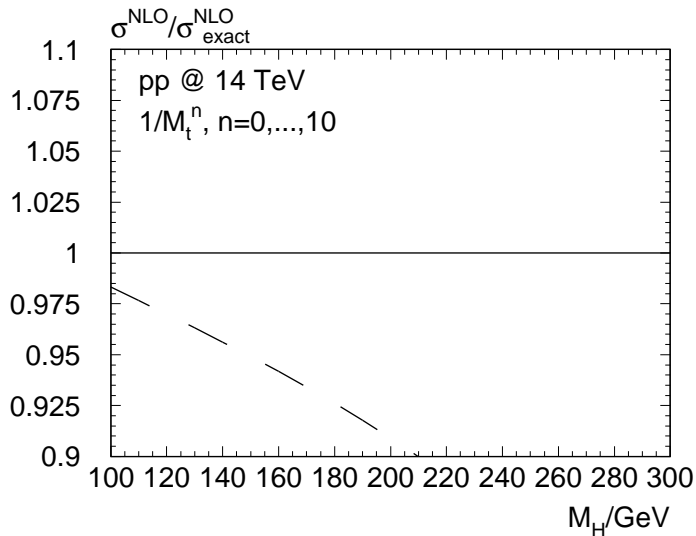
114

[RH, Ozeren '09]

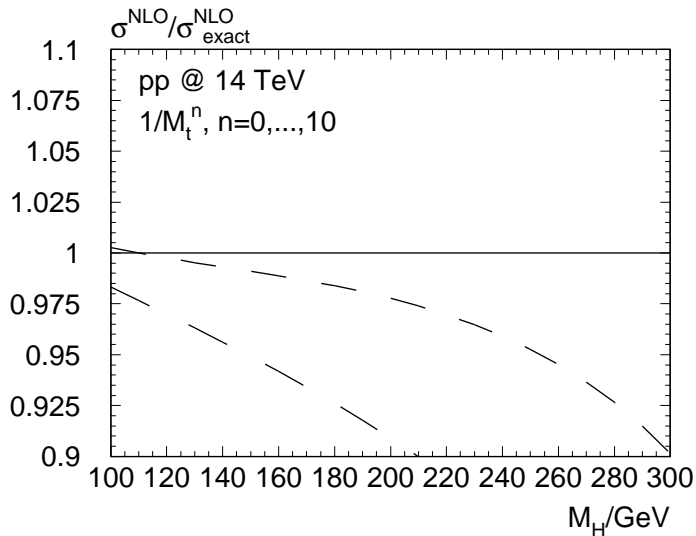
[RH, Mantler, Marzani, Ozeren '09]

[Pak, Rogal, Steinhauser '09]

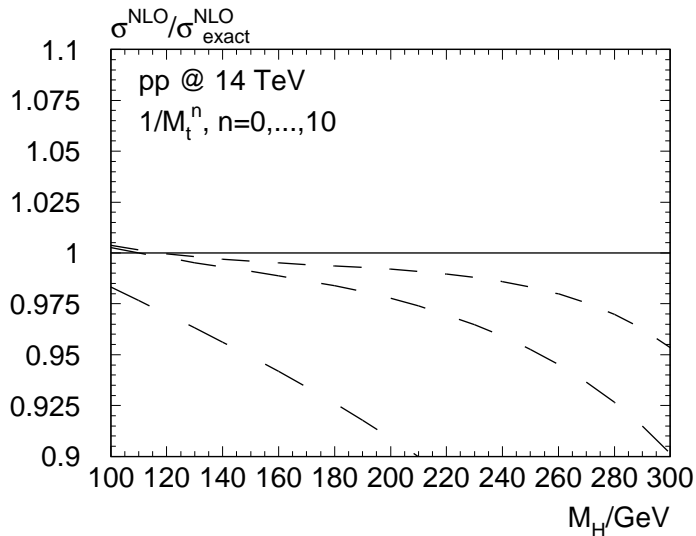
# Convergence of $1/m_t$ expansion at NLO



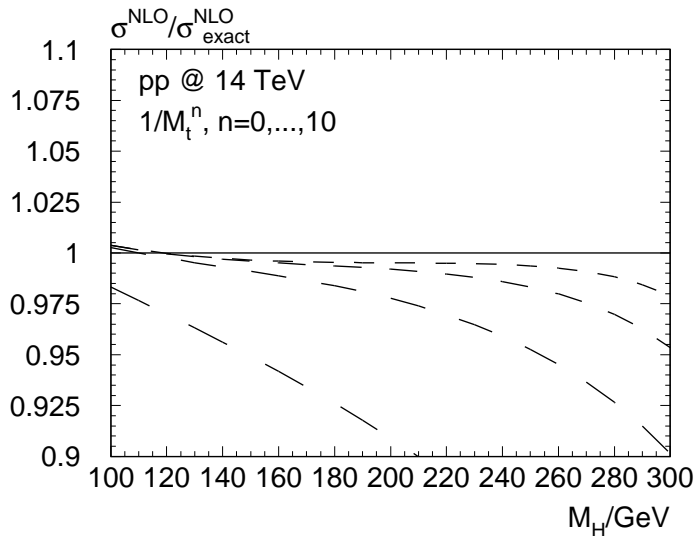
# Convergence of $1/m_t$ expansion at NLO



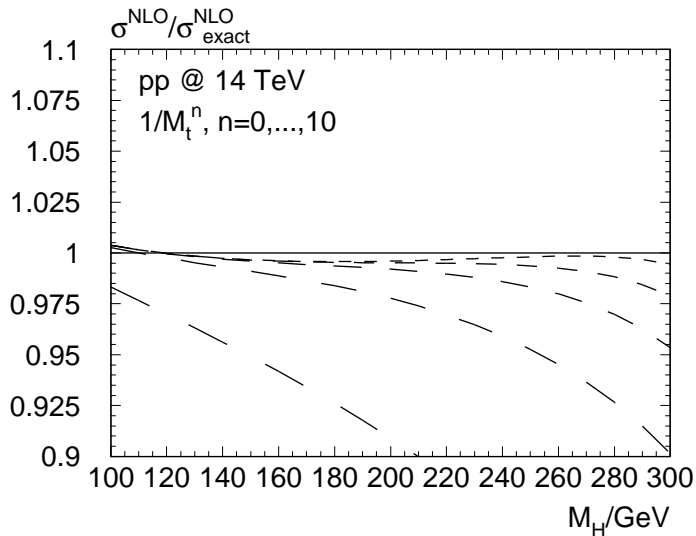
# Convergence of $1/m_t$ expansion at NLO



# Convergence of $1/m_t$ expansion at NLO

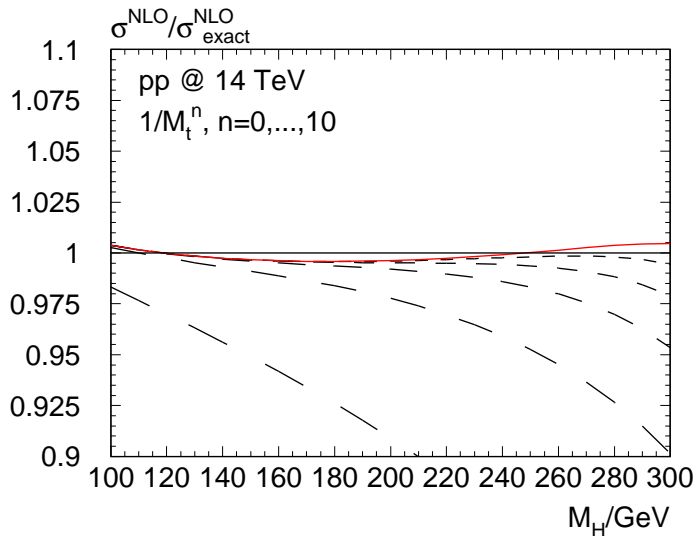


# Convergence of $1/m_t$ expansion at NLO

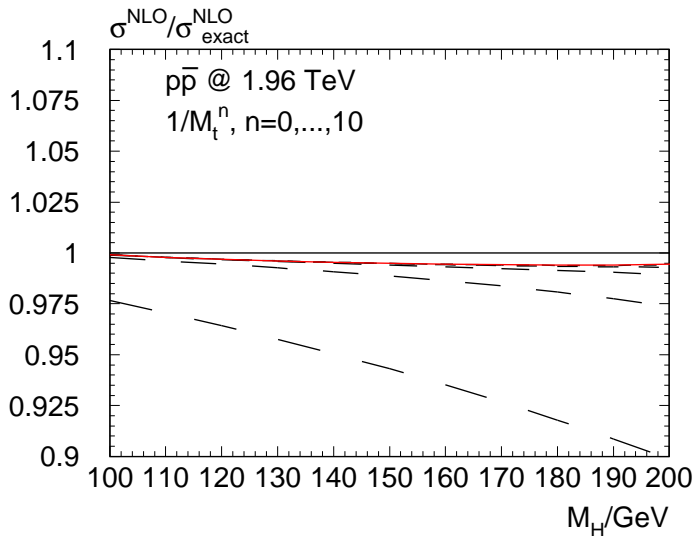




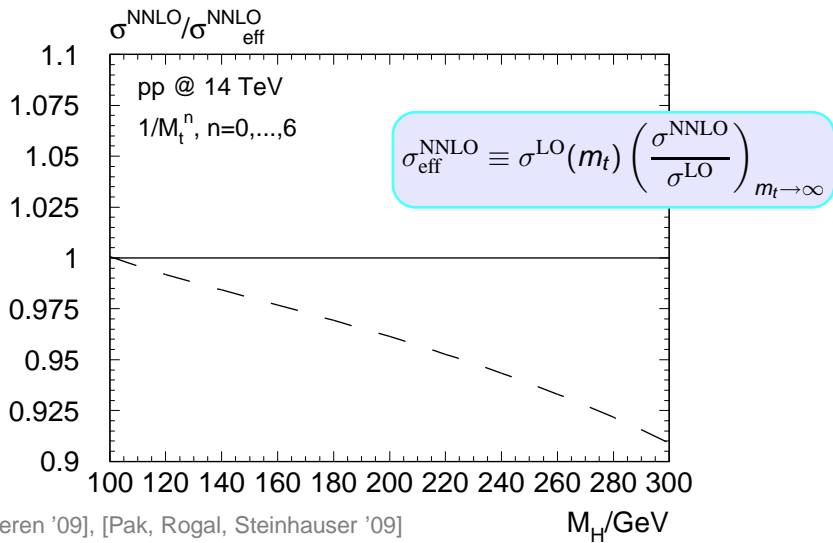
# Convergence of $1/m_t$ expansion at NLO



# Convergence of $1/m_t$ expansion at NLO



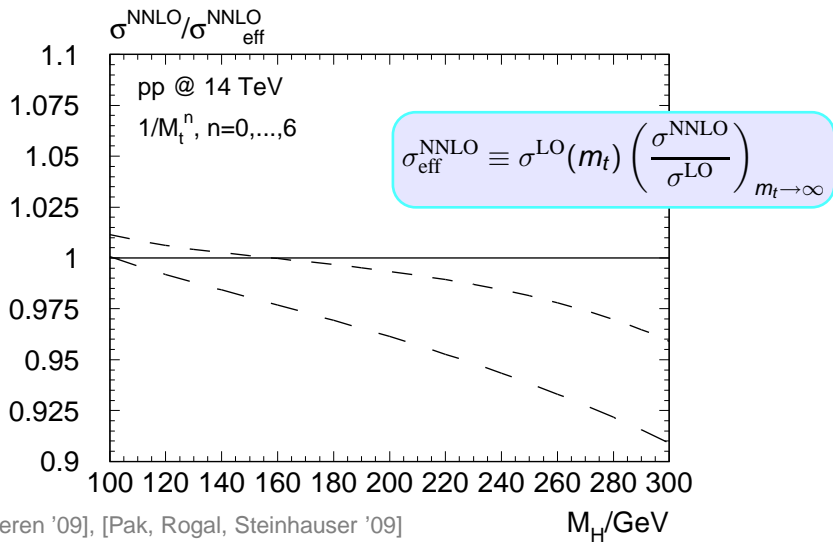
# Convergence of $1/m_t$ expansion at NNLO



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

[RH, Mantler, Marzani, Ozeren '09]

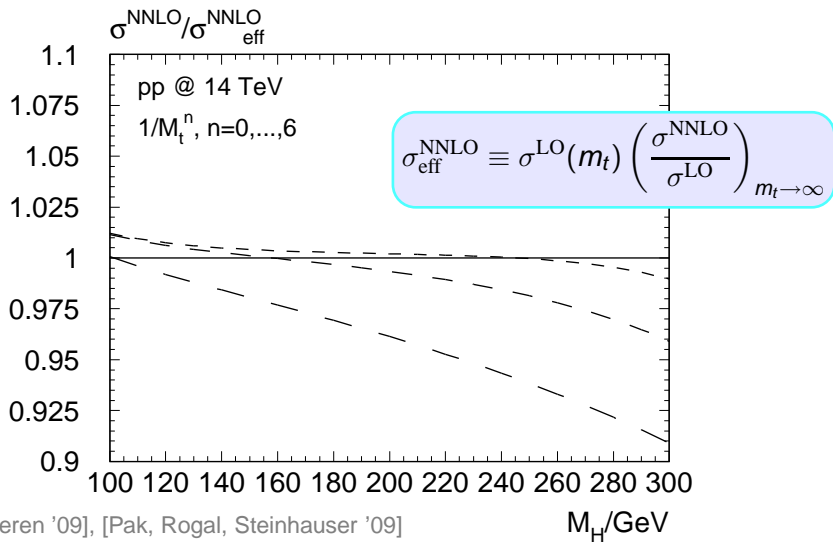
# Convergence of $1/m_t$ expansion at NNLO



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

[RH, Mantler, Marzani, Ozeren '09]

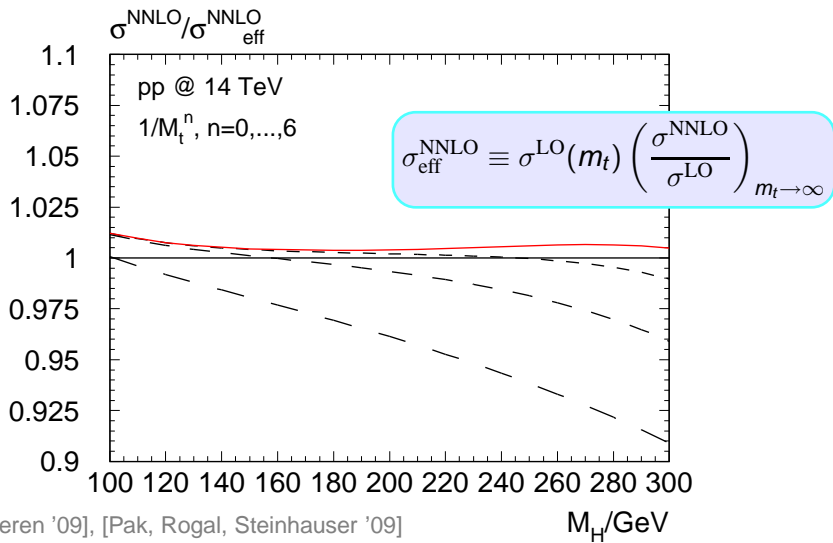
# Convergence of $1/m_t$ expansion at NNLO



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

[RH, Mantler, Marzani, Ozeren '09]

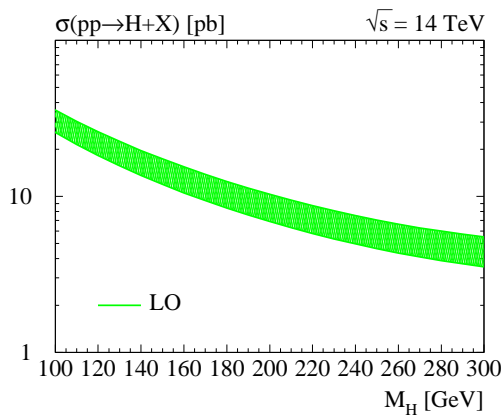
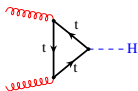
# Convergence of $1/m_t$ expansion at NNLO



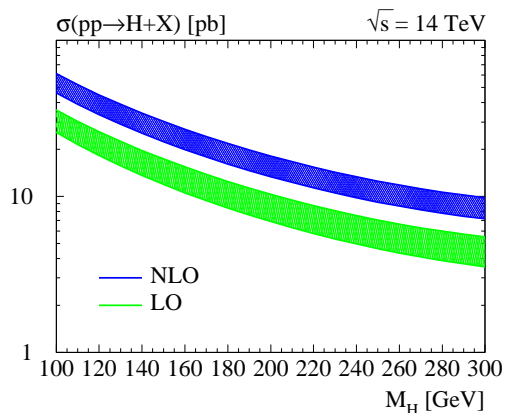
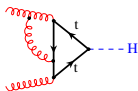
[RH, Ozeren '09], [Pak, Rogal, Steinhauser '09]

[RH, Mantler, Marzani, Ozeren '09]

# Gluon fusion: theory prediction



# Gluon fusion: theory prediction

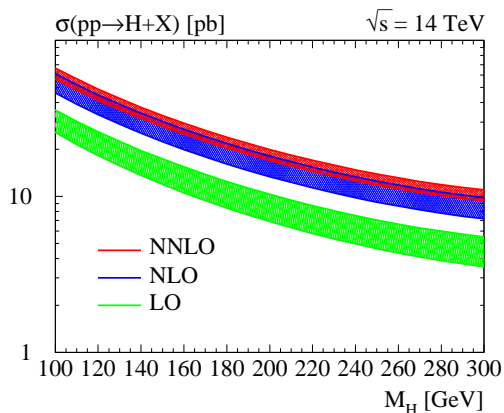
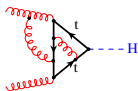


[Spira, Djouadi, Graudenz,  
Zerwas '91/'93]

[Dawson '91]

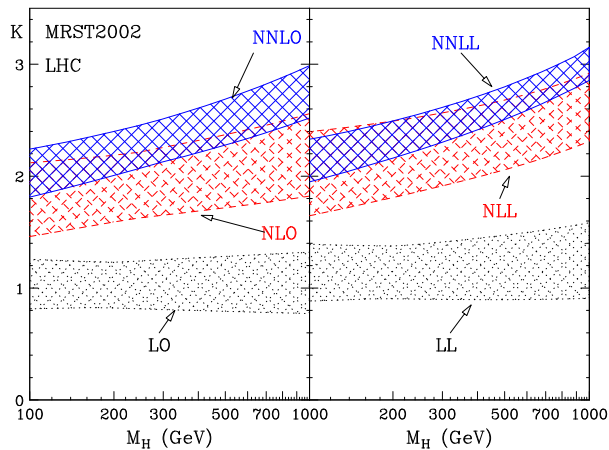


# Gluon fusion: theory prediction



- [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)]

# Resumming $\pi^2$

$$\ln\left(-\mu^2/M_H^2\right) = i\pi \quad \text{for} \quad \mu^2 = M_H^2$$

# Resumming $\pi^2$

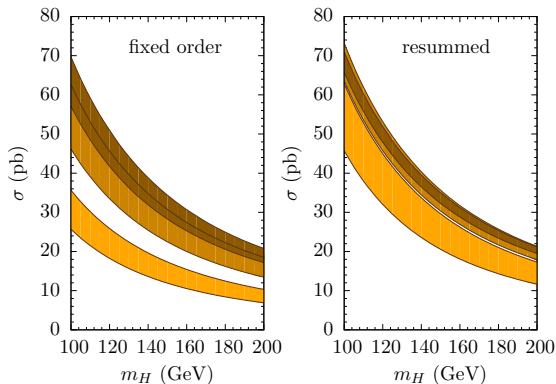
$$\ln\left(-\mu^2/M_H^2\right) = 0 \quad \text{for} \quad \mu^2 = -M_H^2$$

# Resumming $\pi^2$

$$\ln\left(-\mu^2/M_H^2\right) = 0 \quad \text{for} \quad \mu^2 = -M_H^2 \quad \Rightarrow \quad \alpha_s(-M_H^2)$$

# Resumming $\pi^2$

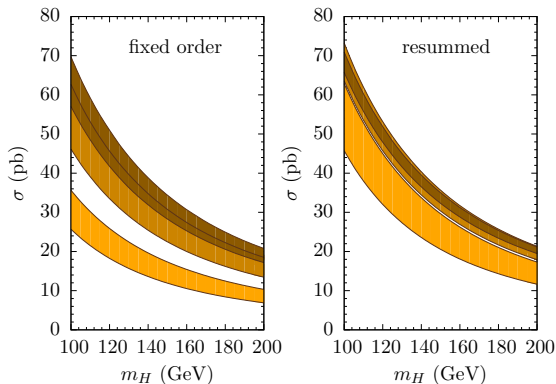
$$\ln\left(-\mu^2/M_H^2\right) = 0 \quad \text{for} \quad \mu^2 = -M_H^2 \quad \Rightarrow \quad \alpha_s(-M_H^2)$$



[Ahrens, Becher, Neubert,  
Yang 08]

# Resumming $\pi^2$

$$\ln\left(-\mu^2/M_H^2\right) = 0 \quad \text{for} \quad \mu^2 = -M_H^2 \quad \Rightarrow \quad \alpha_s(-M_H^2)$$

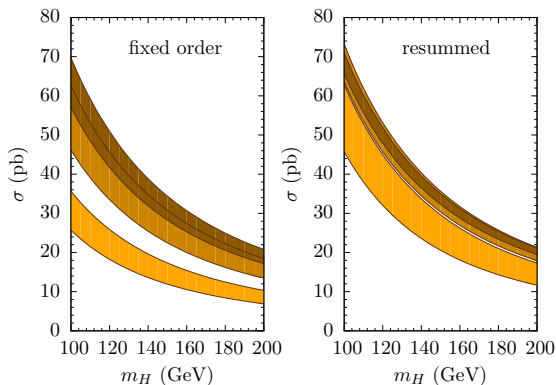


[Ahrens, Becher, Neubert,  
Yang 08]

**Claim:**  $\pi^2$  is large

# Resumming $\pi^2$

$$\ln\left(-\mu^2/M_H^2\right) = 0 \quad \text{for} \quad \mu^2 = -M_H^2 \quad \Rightarrow \quad \alpha_s(-M_H^2)$$

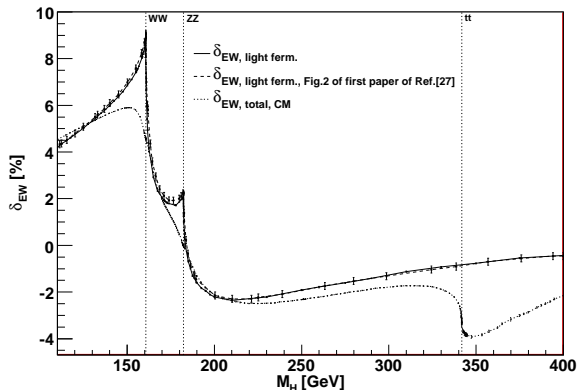


[Ahrens, Becher, Neubert,  
Yang 08]

**Claim:**  $\pi^2$  is large but some  $\pi^2$ 's are larger than others!



# Gluon fusion: Electro-weak corrections



[Actis, Passarino, Sturm,  
Uccirati '08]

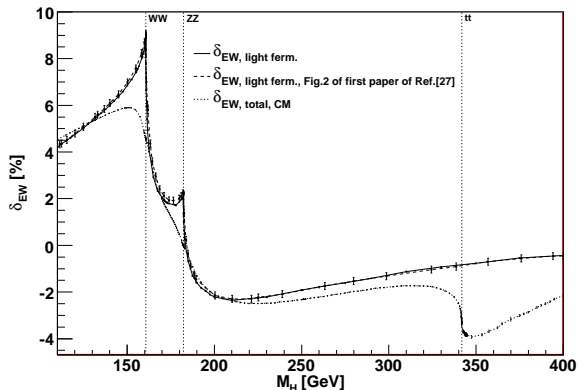
partial:

[Aglietti, Bonciani,  
Degrassi, Vicini '04]

[Degrassi, Maltoni '04]

[Djouadi, Gambino '94]

# Gluon fusion: Electro-weak corrections



[Actis, Passarino, Sturm,  
Uccirati '08]

partial:

[Aglietti, Bonciani,  
Degrassi, Vicini '04]

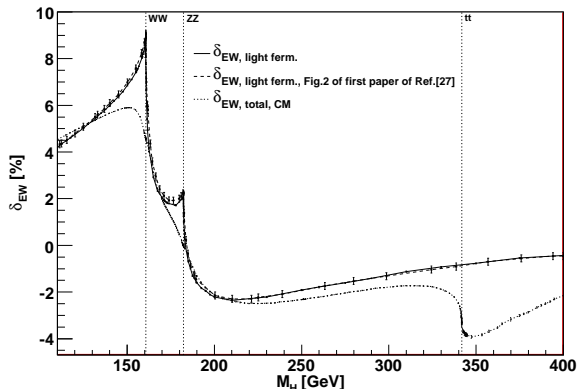
[Degrassi, Maltoni '04]

[Djouadi, Gambino '94]

mixed EW/QCD?

→ do they factorize? (remember LEP?)

# Gluon fusion: Electro-weak corrections



[Actis, Passarino, Sturm,  
Uccirati '08]

partial:

[Aglietti, Bonciani,  
Degrassi, Vicini '04]

[Degrassi, Maltoni '04]

[Djouadi, Gambino '94]

mixed EW/QCD?

→ do they factorize? (remember LEP?)

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

# Latest compilations<sup>1</sup>

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

---

<sup>1</sup>Inofficial numbers.

# Latest compilations<sup>1</sup>

- NLO [Dawson '91], [Spira, Djouadi, Graudenz, Zerwas '91-'95]  
→ +110% of LO
- NNLO [RH, Kilgore '02], [Anastasiou, Melnikov '02]  
→ +60% of LO (30% of NLO)

---

<sup>1</sup>Inofficial numbers.

# Latest compilations<sup>1</sup>

- NLO [Dawson '91], [Spira, Djouadi, Graudenz, Zerwas '91-'95]  
→ +110% of LO
- NNLO [RH, Kilgore '02], [Anastasiou, Melnikov '02]  
→ +60% of LO (30% of NLO)
- soft gluon resummation (or  $\mu_F = \mu_R = m_H/2$ ) → +11%  
[Catani, de Florian, Grazzini, Nason '03]

---

<sup>1</sup>Inofficial numbers.

# Latest compilations<sup>1</sup>

- NLO [Dawson '91], [Spira, Djouadi, Graudenz, Zerwas '91-'95]  
→ +110% of LO
- NNLO [RH, Kilgore '02], [Anastasiou, Melnikov '02]  
→ +60% of LO (30% of NLO)
- soft gluon resummation (or  $\mu_F = \mu_R = m_H/2$ ) → +11%  
[Catani, de Florian, Grazzini, Nason '03]
- electro-weak → +6% of LO [Actis, Passarino, Sturm, Uccirati '08]

---

<sup>1</sup>Inofficial numbers.

# Latest compilations<sup>1</sup>

- NLO [Dawson '91], [Spira, Djouadi, Graudenz, Zerwas '91-'95]  
→ +110% of LO
- NNLO [RH, Kilgore '02], [Anastasiou, Melnikov '02]  
→ +60% of LO (30% of NLO)
- soft gluon resummation (or  $\mu_F = \mu_R = m_H/2$ ) → +11%  
[Catani, de Florian, Grazzini, Nason '03]
- electro-weak → +6% of LO [Actis, Passarino, Sturm, Uccirati '08]
- $\pi^2$  resummation *not* included

---

<sup>1</sup>Inofficial numbers.



# Latest compilations<sup>1</sup>

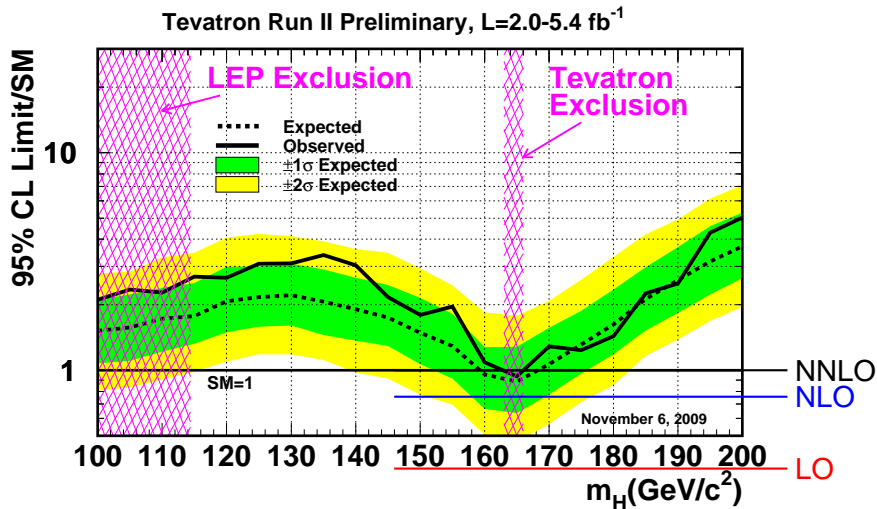
- NLO [Dawson '91], [Spira, Djouadi, Graudenz, Zerwas '91-'95]  
→ +110% of LO
- NNLO [RH, Kilgore '02], [Anastasiou, Melnikov '02]  
→ +60% of LO (30% of NLO)
- soft gluon resummation (or  $\mu_F = \mu_R = m_H/2$ ) → +11%  
[Catani, de Florian, Grazzini, Nason '03]
- electro-weak → +6% of LO [Actis, Passarino, Sturm, Uccirati '08]
- $\pi^2$  resummation *not* included
- PDFs: MRST2006 → MSTW2008 → -13% (!)

[Anastasiou, Boughezal, Petriello '09], [de Florian, Grazzini '09]

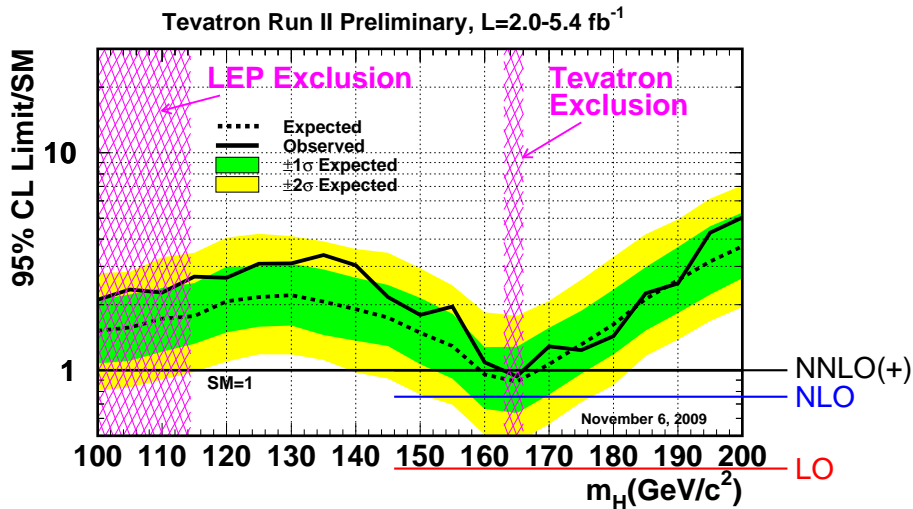
---

<sup>1</sup>Inofficial numbers.

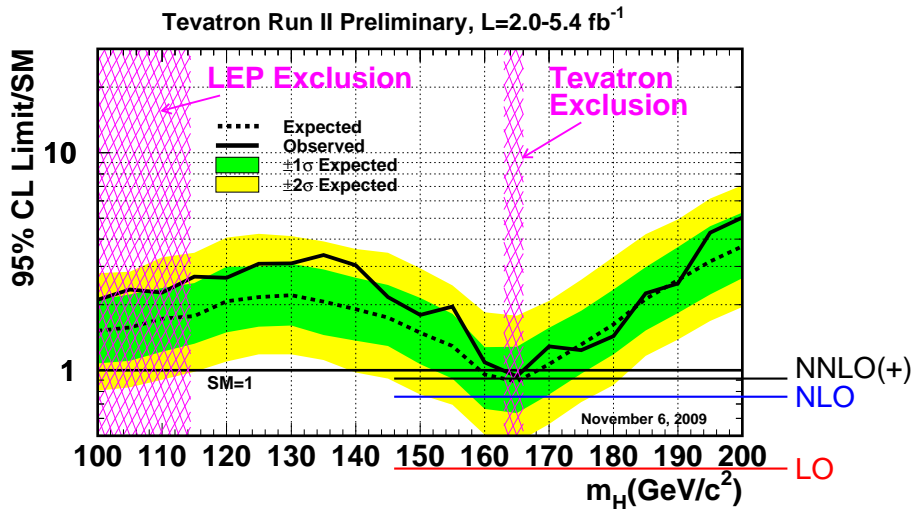
# Higgs search at the Tevatron



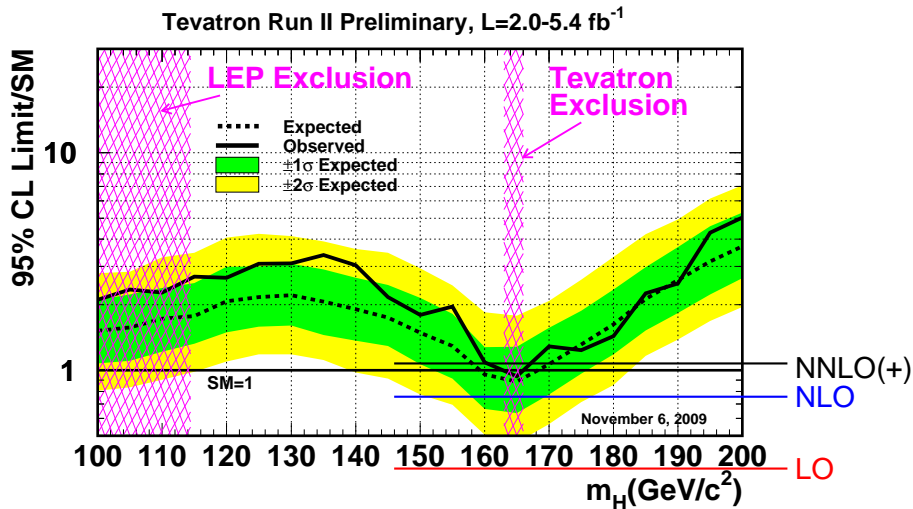
# Higgs search at the Tevatron

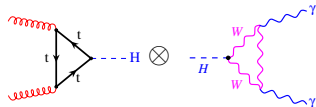


# Higgs search at the Tevatron



# Higgs search at the Tevatron





$m_h$	$\sigma_{\text{NNLO}}^{\text{cut}} / \sigma_{\text{NNLO}}^{\text{inc}}$	$K_{\text{cut}}^{(2)} / K_{\text{inc}}^{(2)}$
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

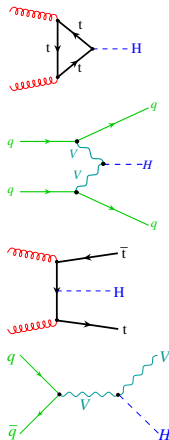
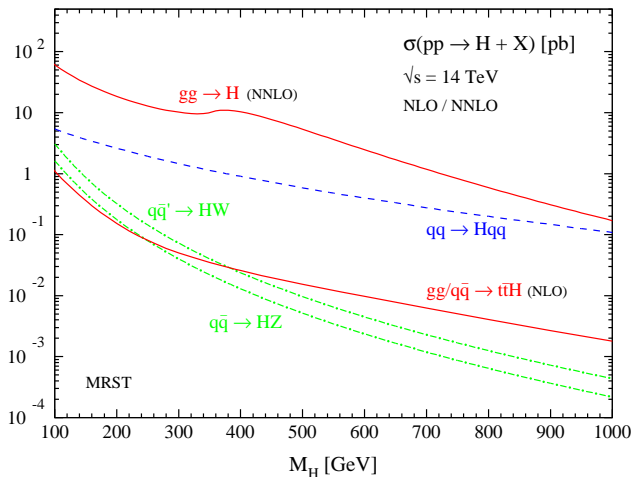
[Anastasiou, Melnikov, Petriello '05]

[Catani, Grazzini '08]

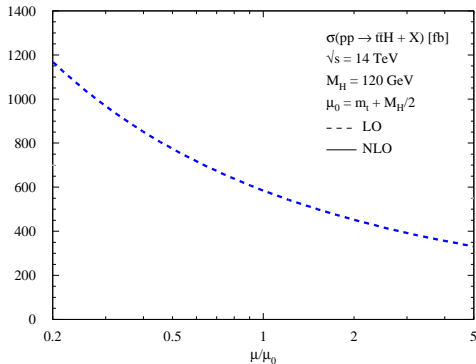
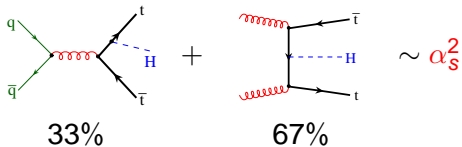
**but:** can depend strongly on cuts (jet-veto etc.) [Anastasiou et al. '07]

in particular  $gg \rightarrow H \rightarrow WW \rightarrow l\nu l\nu$  [Dittmar, Dreiner '97]

# Higgs cross sections

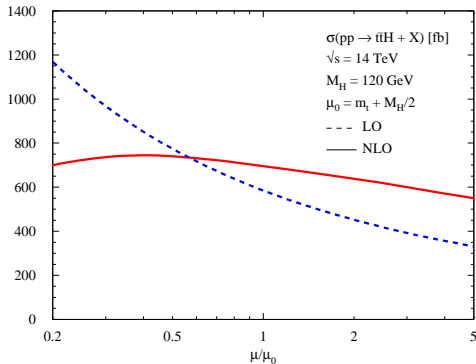
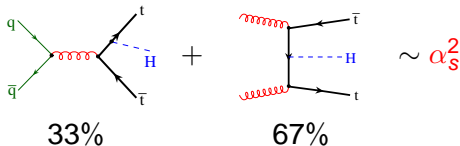


# $t\bar{t}H$ at NLO





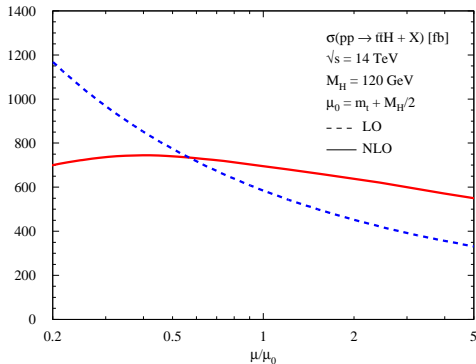
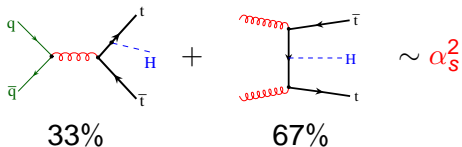
# $t\bar{t}H$ at NLO



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

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

# $t\bar{t}H$ at NLO

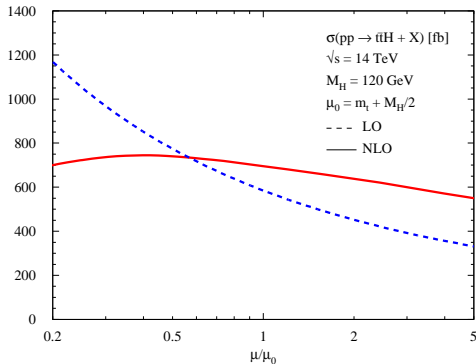
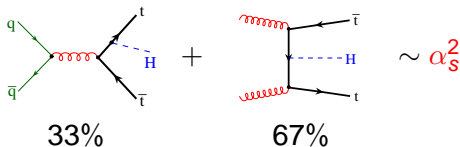


[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01]

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

→ no longer a discovery channel

# $t\bar{t}H$ at NLO



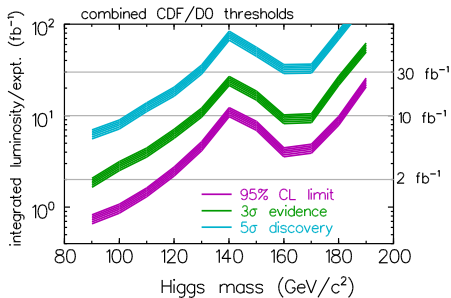
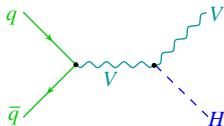
[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01]

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

→ no longer a discovery channel

... but we have seen channels come and go...

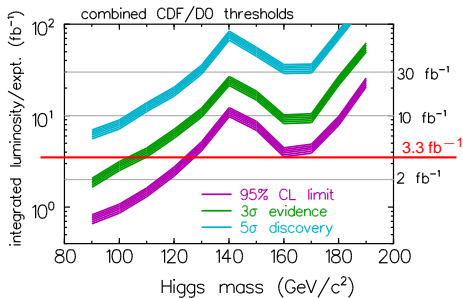
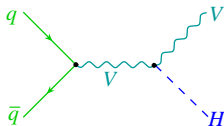
# Higgs Strahlung



[Tev Higgs WG '00]

- used to be
  - main search mode for Tevatron

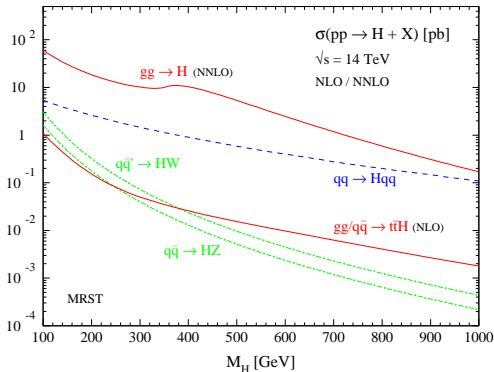
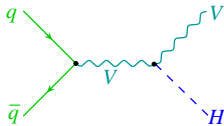
# Higgs Strahlung



[Tev Higgs WG '00]

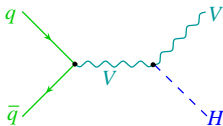
- used to be
  - main search mode for Tevatron

# Higgs Strahlung



- used to be
  - main search mode for Tevatron
  - considered useless for Higgs search at LHC

# Higgs Strahlung

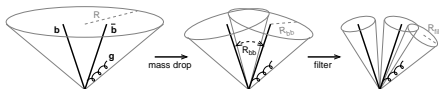


- used to be
  - main search mode for Tevatron
  - considered useless for Higgs search at LHC

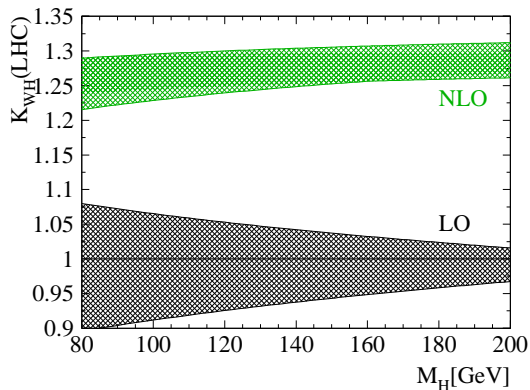
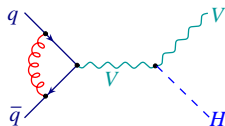
- use jet sub-structure:

[Butterworth *et al.* 08]

promising for  $M_H \approx 120$  GeV



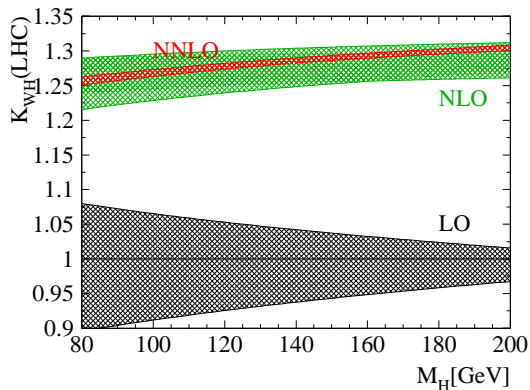
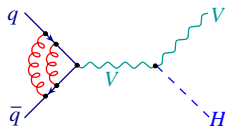
# Higgs Strahlung



[Han, Willenbrock '90]



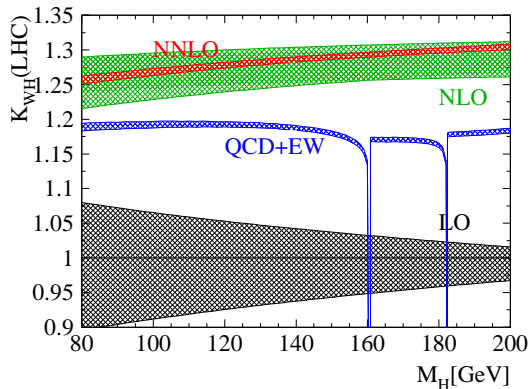
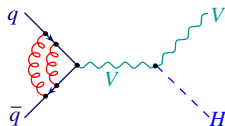
# Higgs Strahlung



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

[Han, Willenbrock '90]

# Higgs Strahlung

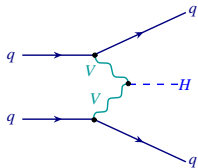


[Brein, Djouadi, R.H. '03]

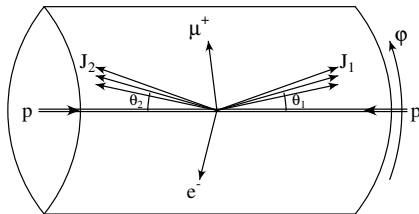
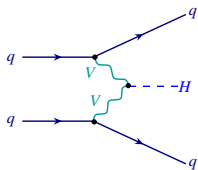
[Han, Willenbrock '90]

[Ciccolini, Dittmaier, Krämer '03]

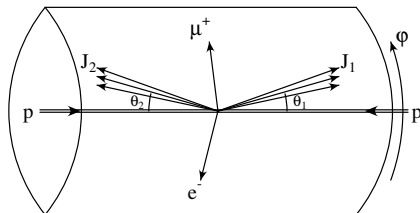
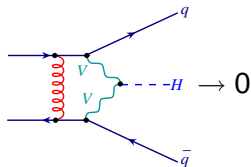
# Weak Boson Fusion



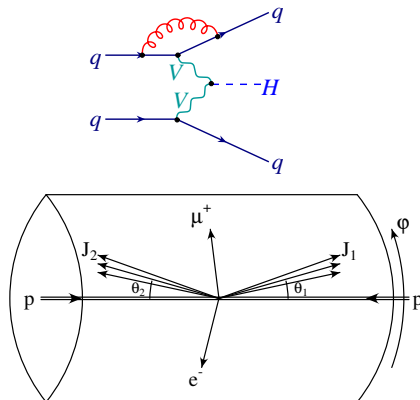
# Weak Boson Fusion



# Weak Boson Fusion



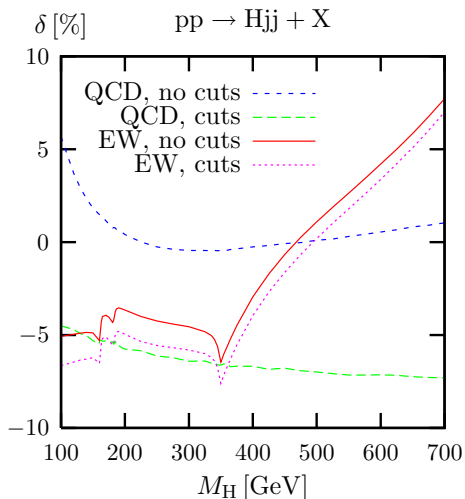
# Weak Boson Fusion



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

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

# WBF: QCD+EW corrections



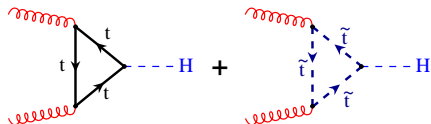
[Ciccolini, Denner, Dittmaier '08]

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



# Effects of SUSY

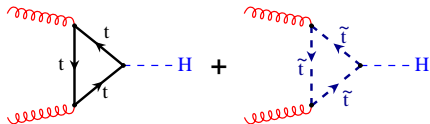
[Djouadi 98], [Carena *et al.* 99]



may interfere destructively!

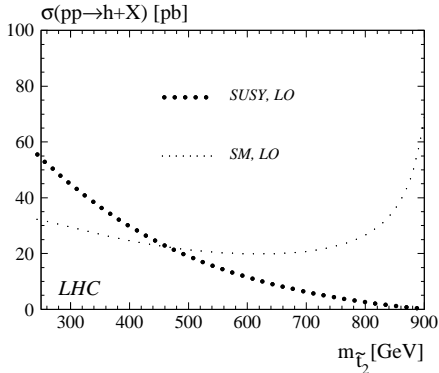
# Effects of SUSY

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



may interfere destructively!

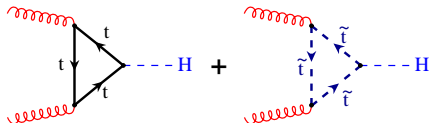
$$\begin{aligned}
 m_{\tilde{t}_1} &= 200 \text{ GeV} \\
 m_{\tilde{g}} &= 1 \text{ TeV} \\
 \tan \beta &= 10, \\
 \alpha &= 0, \\
 \theta_t &= \frac{\pi}{4}
 \end{aligned}$$



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

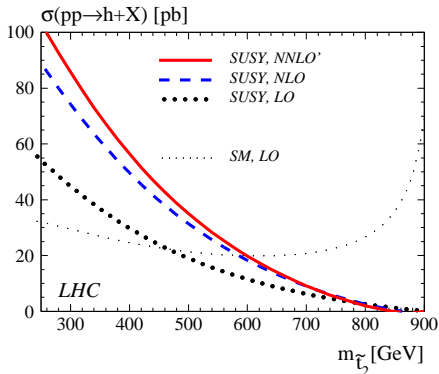
# Effects of SUSY

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

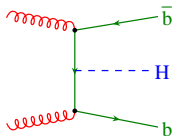


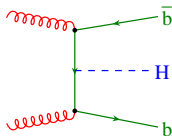
may interfere destructively!

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

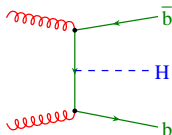


[R.H., Steinhauser '04],  
 [Anastasiou *et al.* '06/'08]  
 [Mühlleitner, Rzehak,  
 Spira '07/'08]  
 [Aglietti, Bonciani,  
 Degrassi, Vicini '06]  
 [Degrassi, Slavich '08]

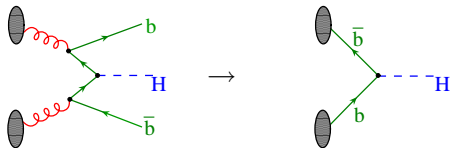




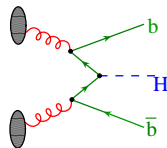
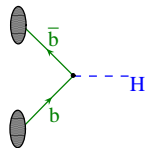
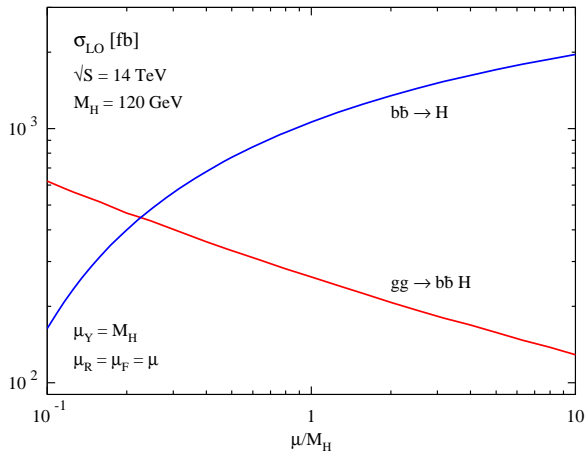
- collinear logarithms:  $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$



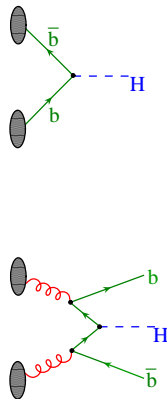
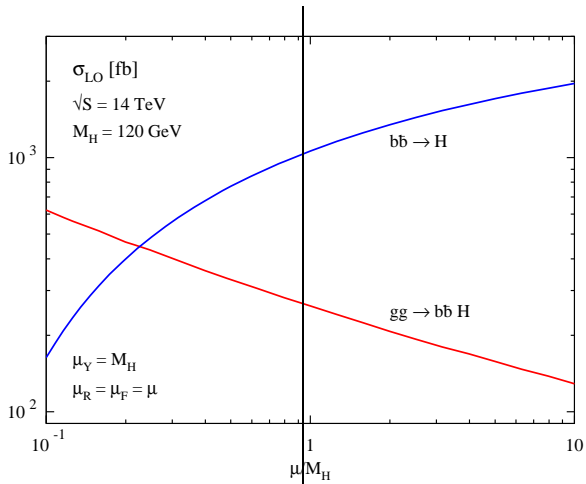
- collinear logarithms:  $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$
- resummation: **bottom quarks as partons**



# 4-FNS vs. 5-FNS

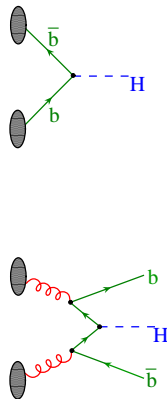
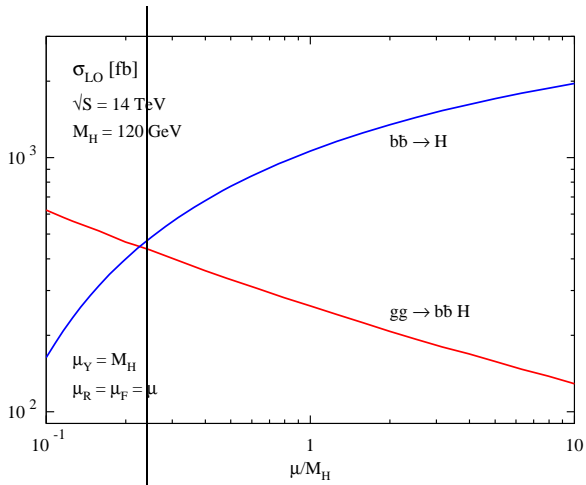


# 4-FNS vs. 5-FNS

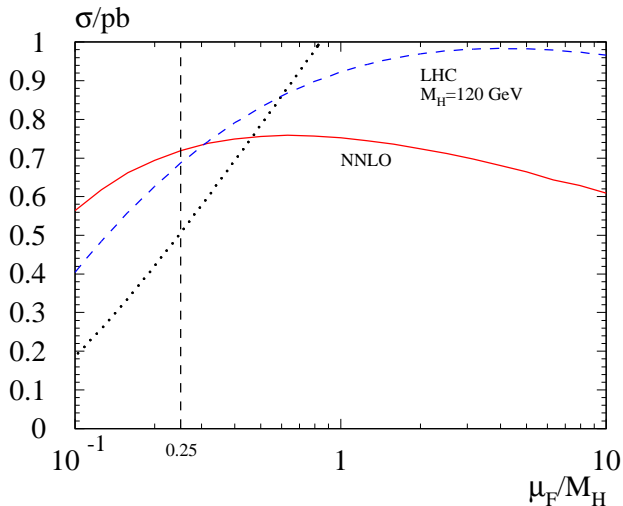




# 4-FNS vs. 5-FNS

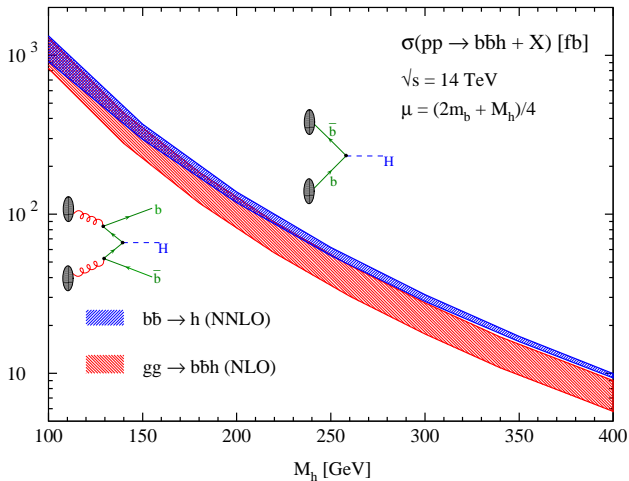


# 5-FNS at NNLO



bbh@nnlo: [RH, Kilgore '03]

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



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

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

- NLO for  $2 \rightarrow 3$  processes established
- very few calculations for  $2 \rightarrow 4$ , no complete calculation for  $pp$  process

$$e^+e^+ \rightarrow 4f \text{ (EW)} \quad \text{Denner et al. '05}, \quad e^+e^+ \rightarrow HH\nu\bar{\nu} \text{ (EW)} \quad \text{Boudjema et al. '05}$$

$$\gamma\gamma \rightarrow t\bar{t}b\bar{b} \text{ (QCD)} \quad \text{Lei et al. '07}, \quad u\bar{u} \rightarrow s\bar{s}b\bar{b} \text{ (QCD)} \quad \text{Binoth et al. '08}$$

- Higgs cross sections under very good theoretical control:  
e.g. **gluon fusion**:
  - inclusive: NNLO QCD + NNLL + EW (+ EW/QCD) + ...  
+ SUSY + ...

- Higgs cross sections under very good theoretical control:  
e.g. **gluon fusion**:
  - inclusive: NNLO QCD + NNLL + EW (+ EW/QCD) + ...  
+ SUSY + ...
  - exclusive NNLO

- Higgs cross sections under very good theoretical control:  
e.g. **gluon fusion**:
  - inclusive: NNLO QCD + NNLL + EW (+ EW/QCD) + ...  
+ SUSY + ...
  - exclusive NNLO
  - heavy top limit tested for inclusive NNLO cross section  
→ validation of higher order results!

- Higgs cross sections under very good theoretical control:  
e.g. **gluon fusion**:
  - inclusive: NNLO QCD + NNLL + EW (+ EW/QCD) + ...  
+ SUSY + ...
  - exclusive NNLO
  - heavy top limit tested for inclusive NNLO cross section  
→ validation of higher order results!
- triggered many theory developments



# Conclusions

- Higgs cross sections under very good theoretical control:  
e.g. **gluon fusion**:
  - inclusive: NNLO QCD + NNLL + EW (+ EW/QCD) + ...  
+ SUSY + ...
  - exclusive NNLO
  - heavy top limit tested for inclusive NNLO cross section  
→ validation of higher order results!
- triggered many theory developments
- (N)NLO Monte Carlos (?)  $\otimes$  Parton Shower?

- Higgs cross sections under very good theoretical control:  
e.g. **gluon fusion**:
  - inclusive: NNLO QCD + NNLL + EW (+ EW/QCD) + ...  
+ SUSY + ...
  - exclusive NNLO
  - heavy top limit tested for inclusive NNLO cross section  
→ validation of higher order results!
- triggered many theory developments
- (N)NLO Monte Carlos (?)  $\otimes$  Parton Shower?
- control non-perturbative uncertainties?  
PDFs, underlying event, ...