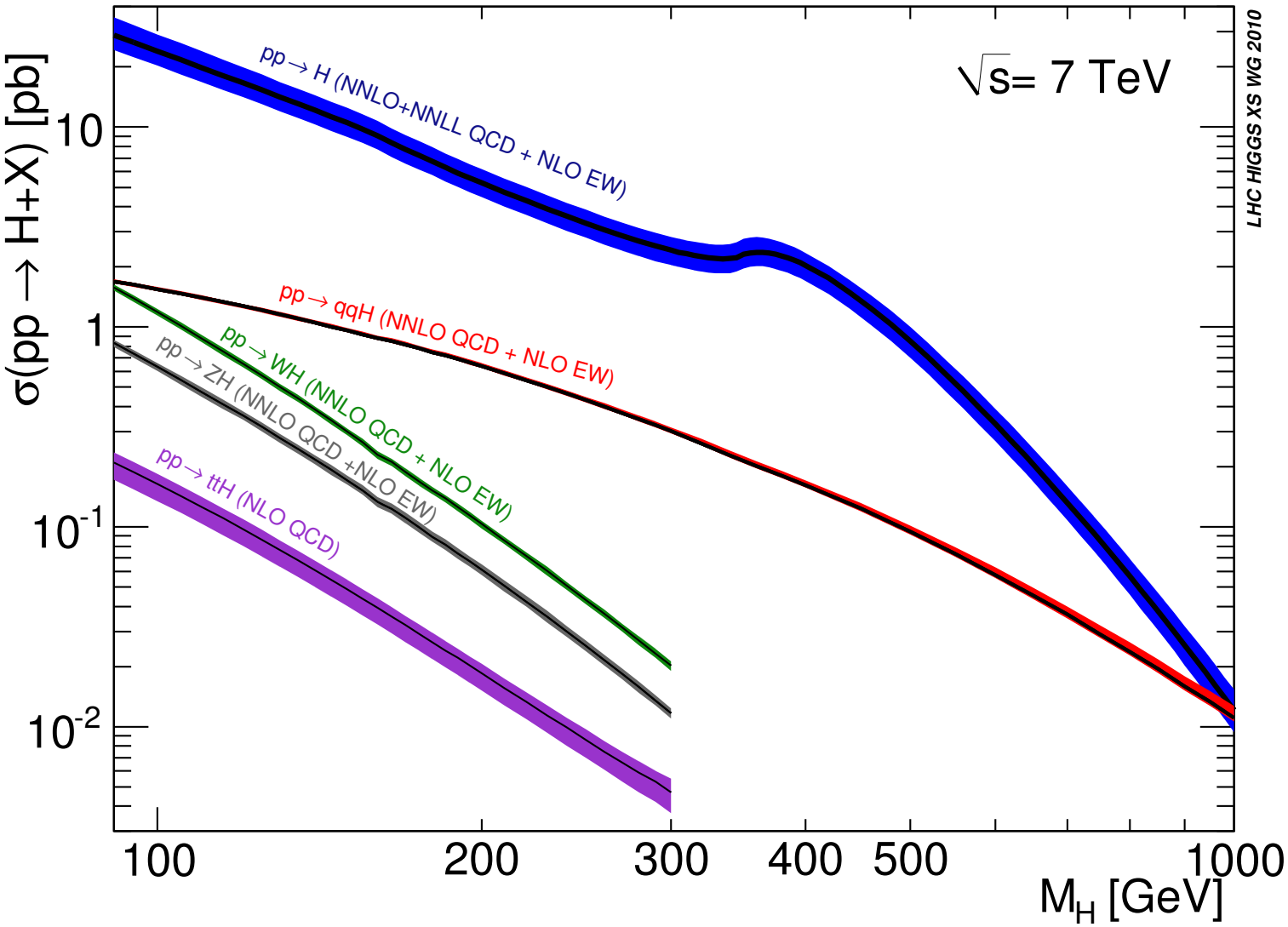
Inclusive Higgs Cross Sections — Channel by Channel —

Robert Harlander

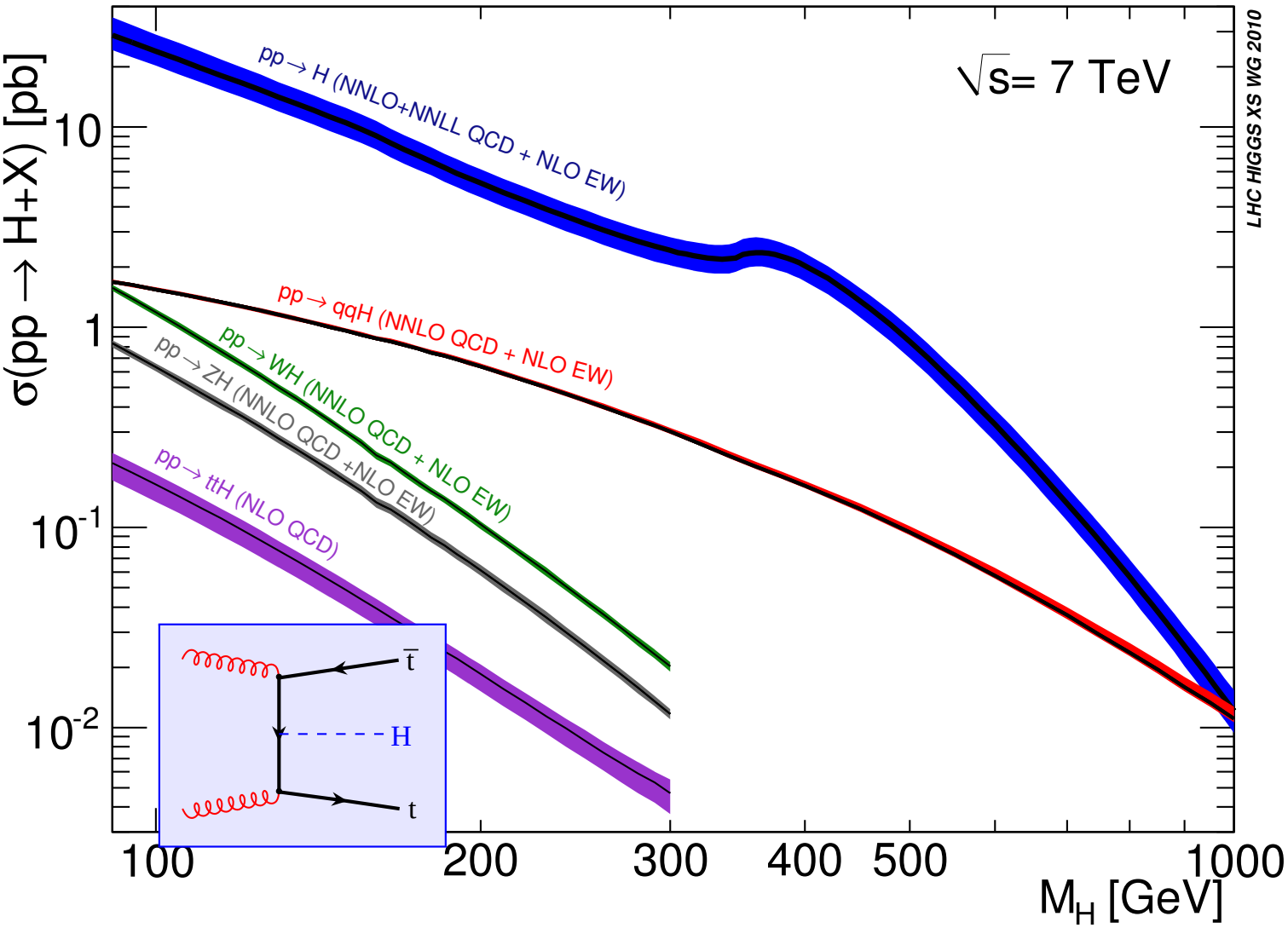
BU Wuppertal

Phenomenology Workshop
Zürich (Jan 9-11, 2012)

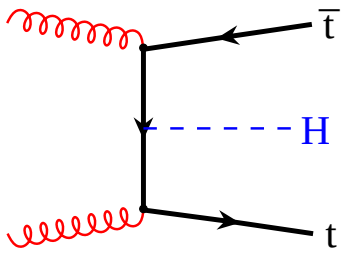
Inclusive Higgs Cross Sections

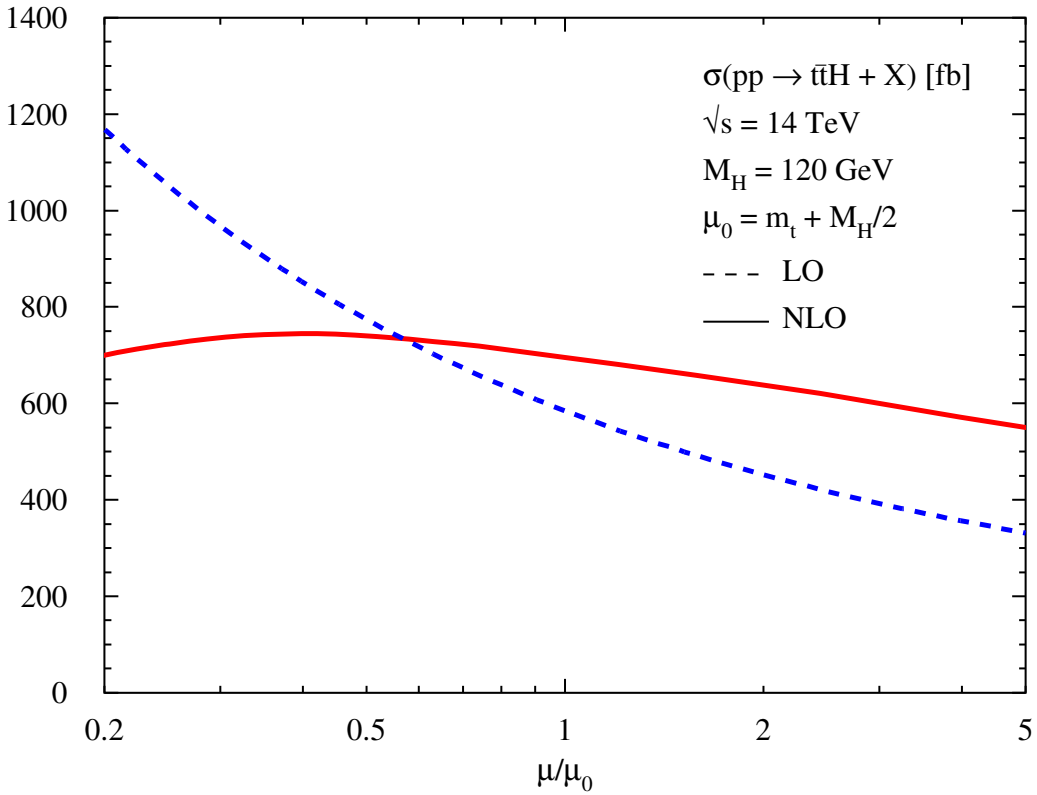


$pp \to t\bar{t}H$


σ(pp → H+X) [pb]
10
1
10^-1
10^-2
√s= 7 TeV
LHC HIGGS XS WG 2010
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
t̄
H
t
100
200
300
400
500
1000
M_H [GeV]

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

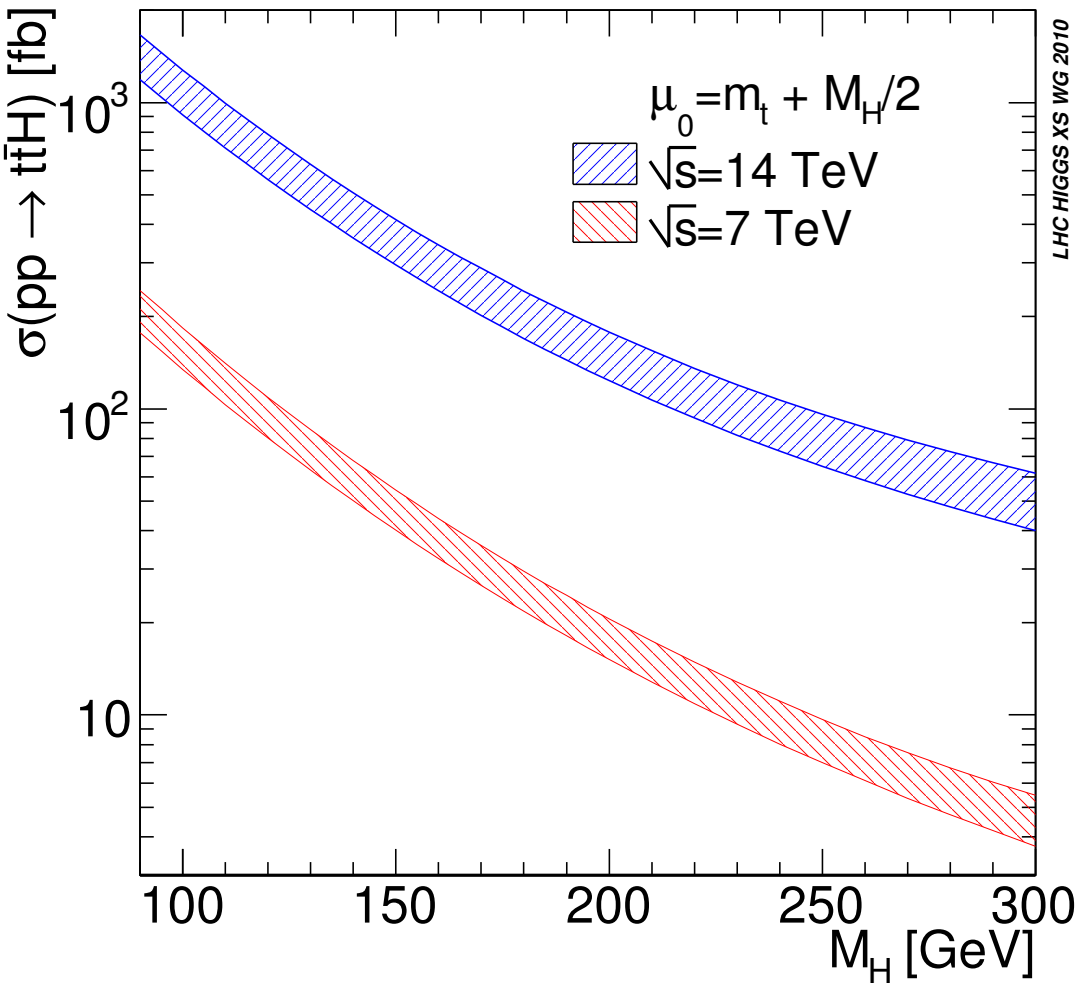




[Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01]

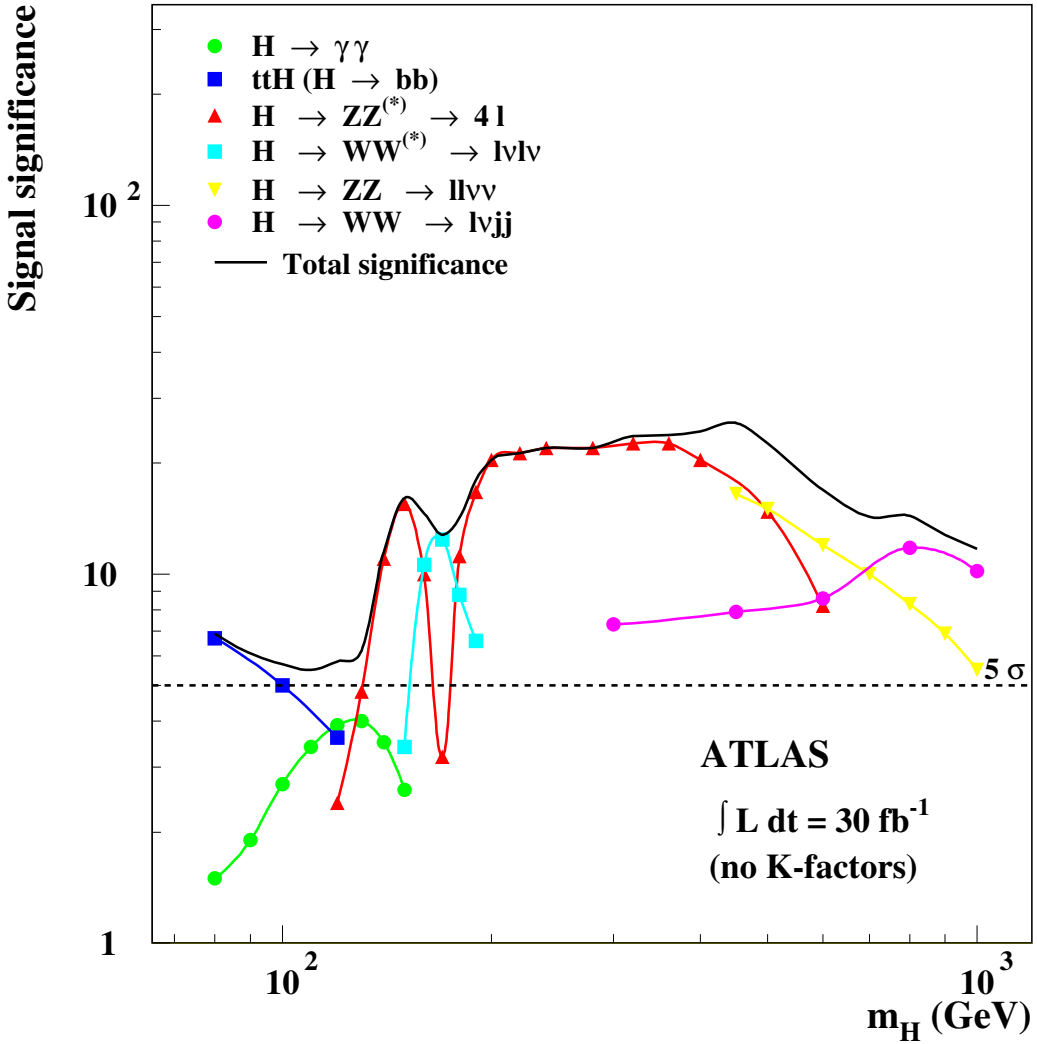
[Dawson, Reina, Wackeroth, Orr, Jackson '01-'03]

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


σ(pp → tt̄H) [fb]
10³
10²
10
100
150
200
250
300
M_H [GeV]
μ_0=m_t + M_H/2
√s=14 TeV
√s=7 TeV
LHC HIGGS XS WG 2010

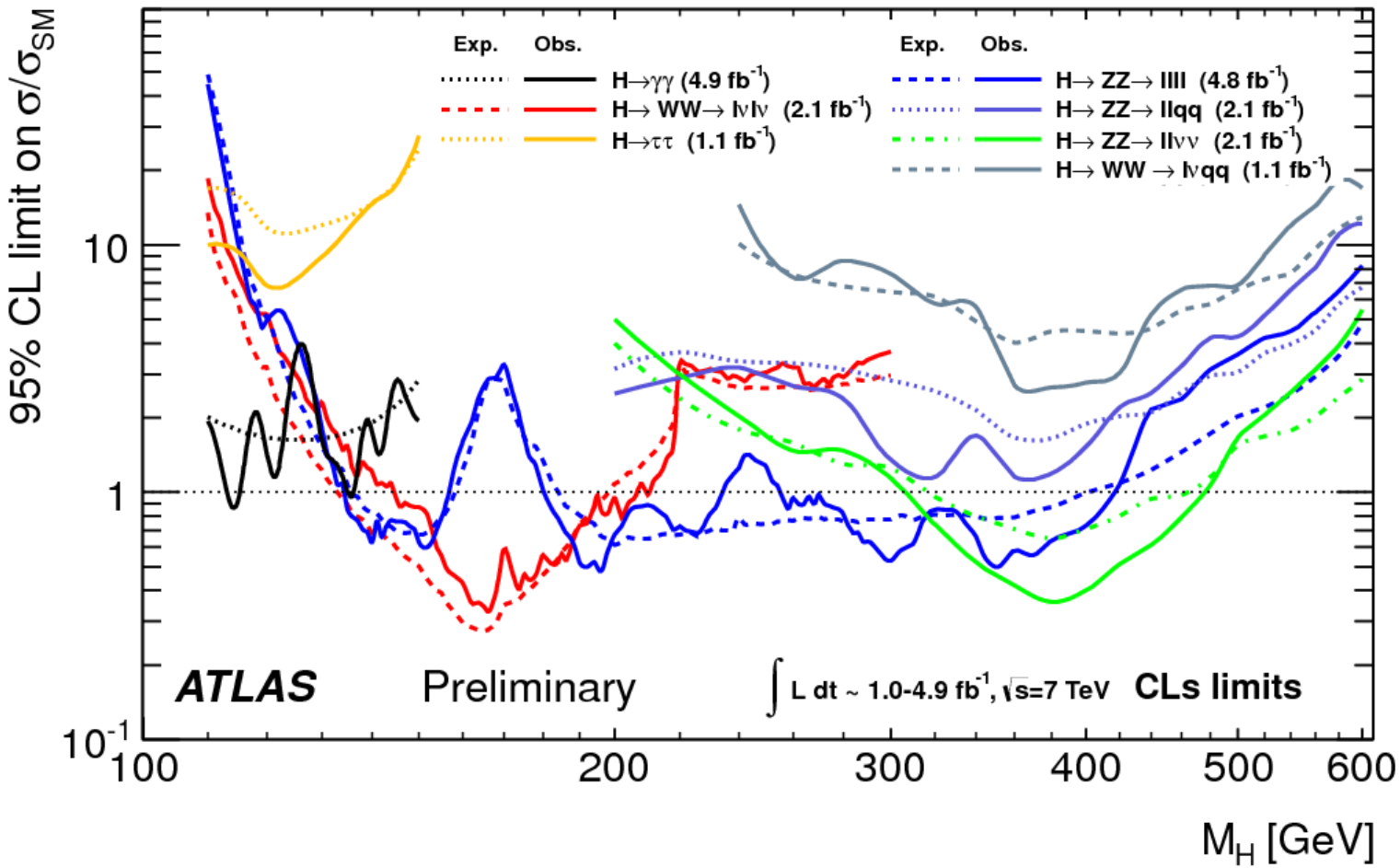
Discovery potential

Channel by channel



Exclusion

Channel by channel



$t\bar{t}H$: Backgrounds at NLO

- $t\bar{t}j$

  [Dittmaier, Uwer, Weinzierl '07],

  [Kardos, Papadopoulos, Trocsanyi '11],

  [Melnikov, Scharf, Schulze '11]
- $t\bar{t}Z$

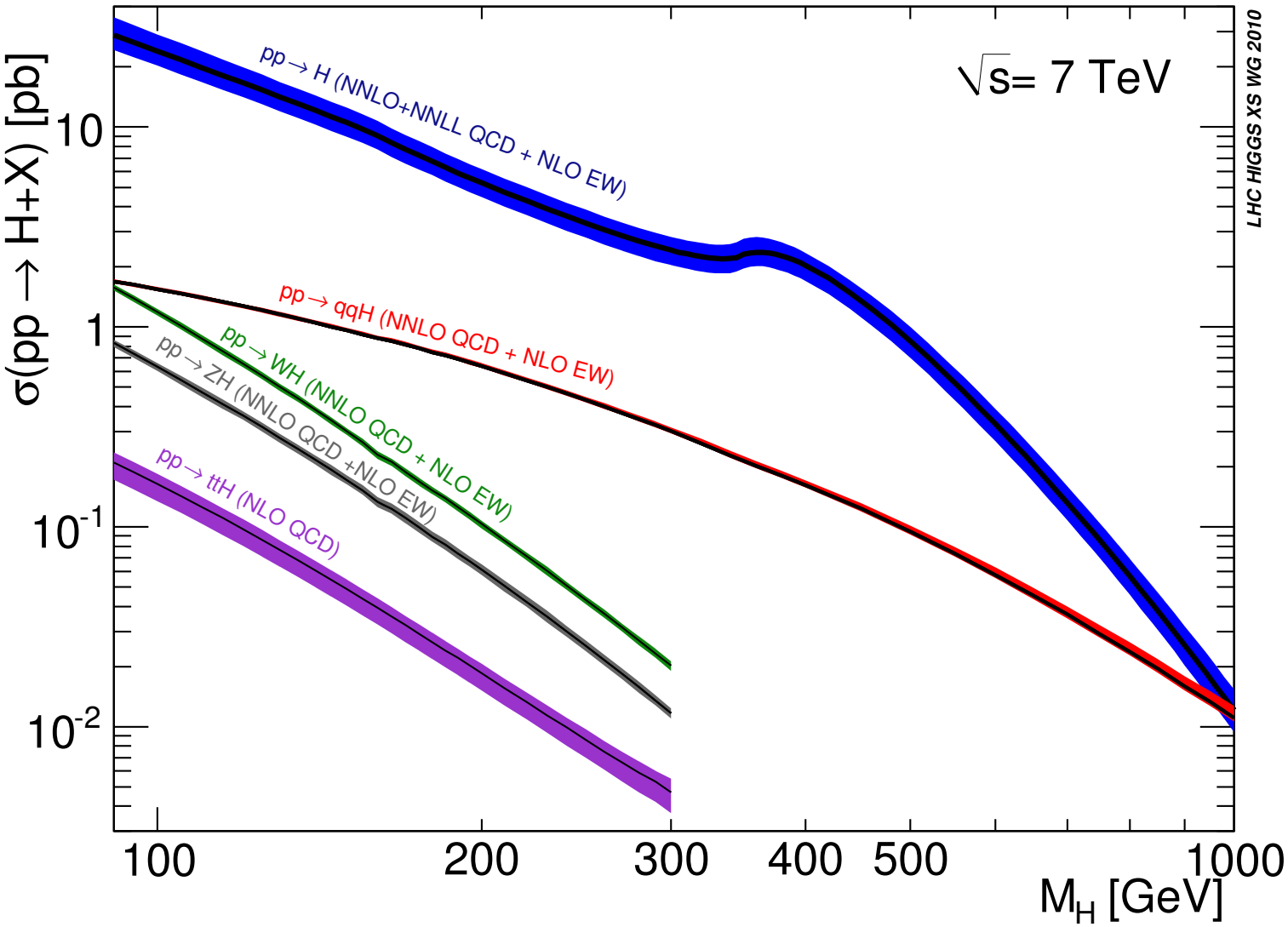
  [Lazopoulos, McElmurry, Melnikov, Petriello '08]
- $t\bar{t}jj$

  [Bevilacqua, Czakon, Papadopoulos, Worek '10]
- $t\bar{t}b\bar{b}$

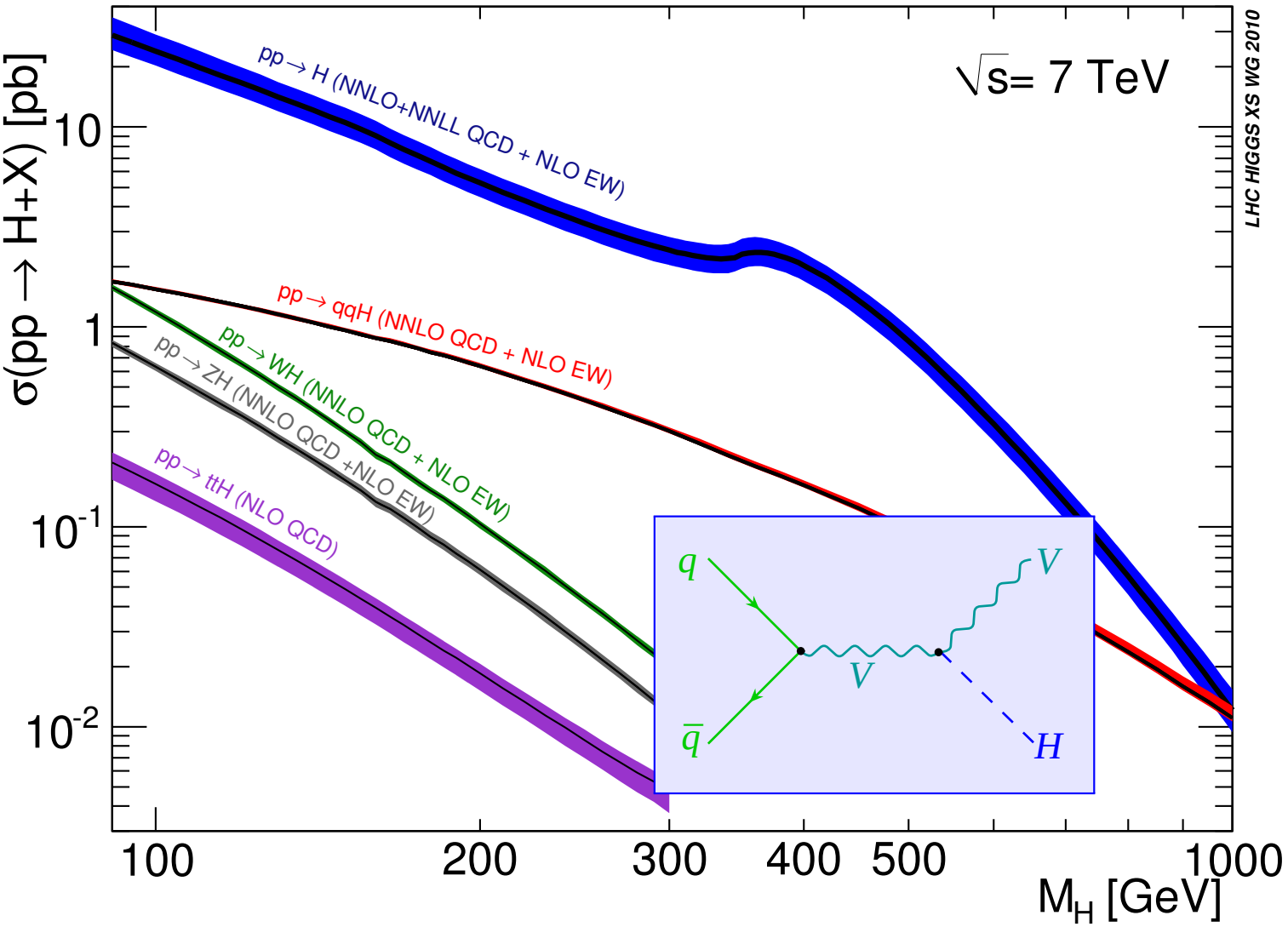
  [Bredenstein, Denner, Dittmaier, Pozzorini '09],

  [Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09]
- ...

Inclusive Higgs Cross Sections

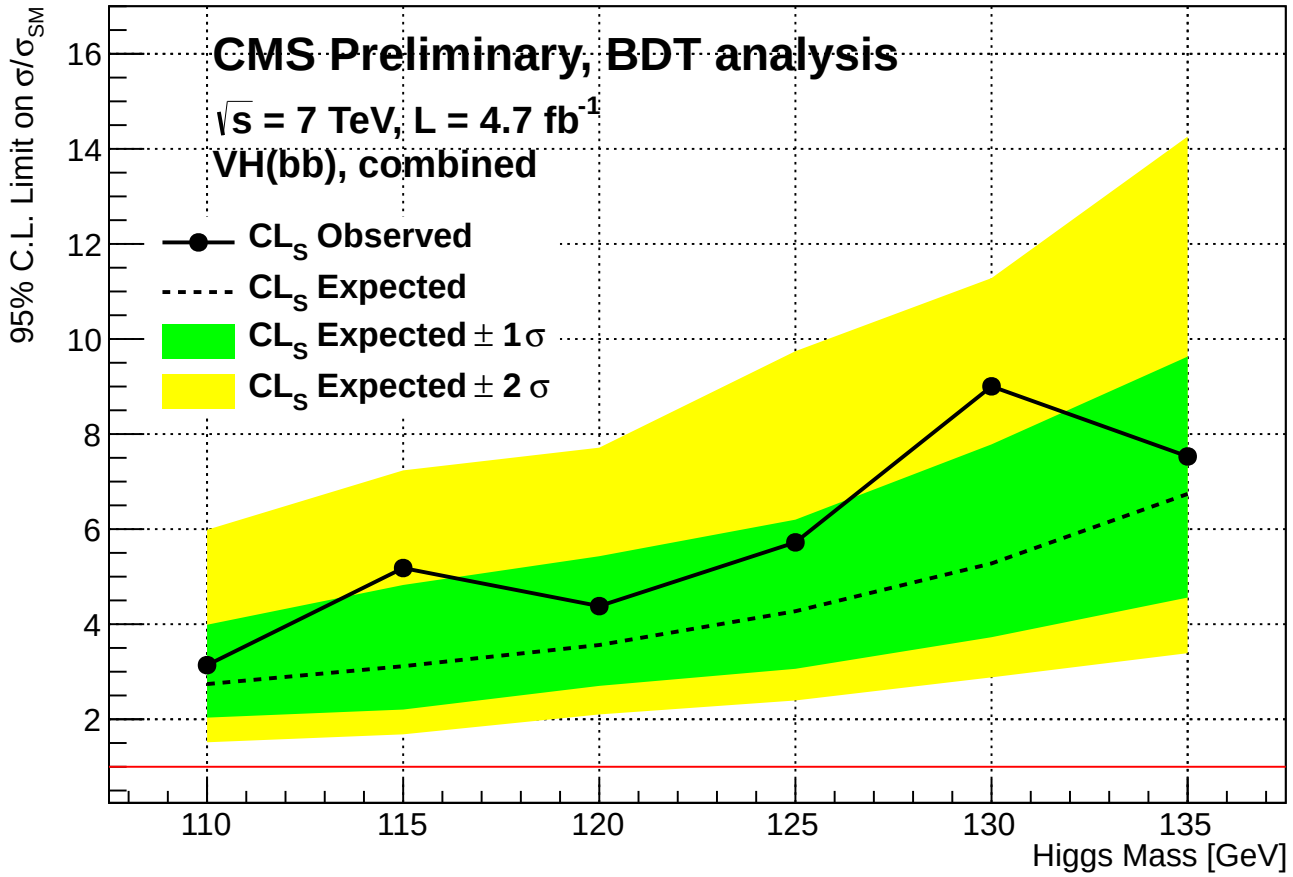


Higgs Strahlung

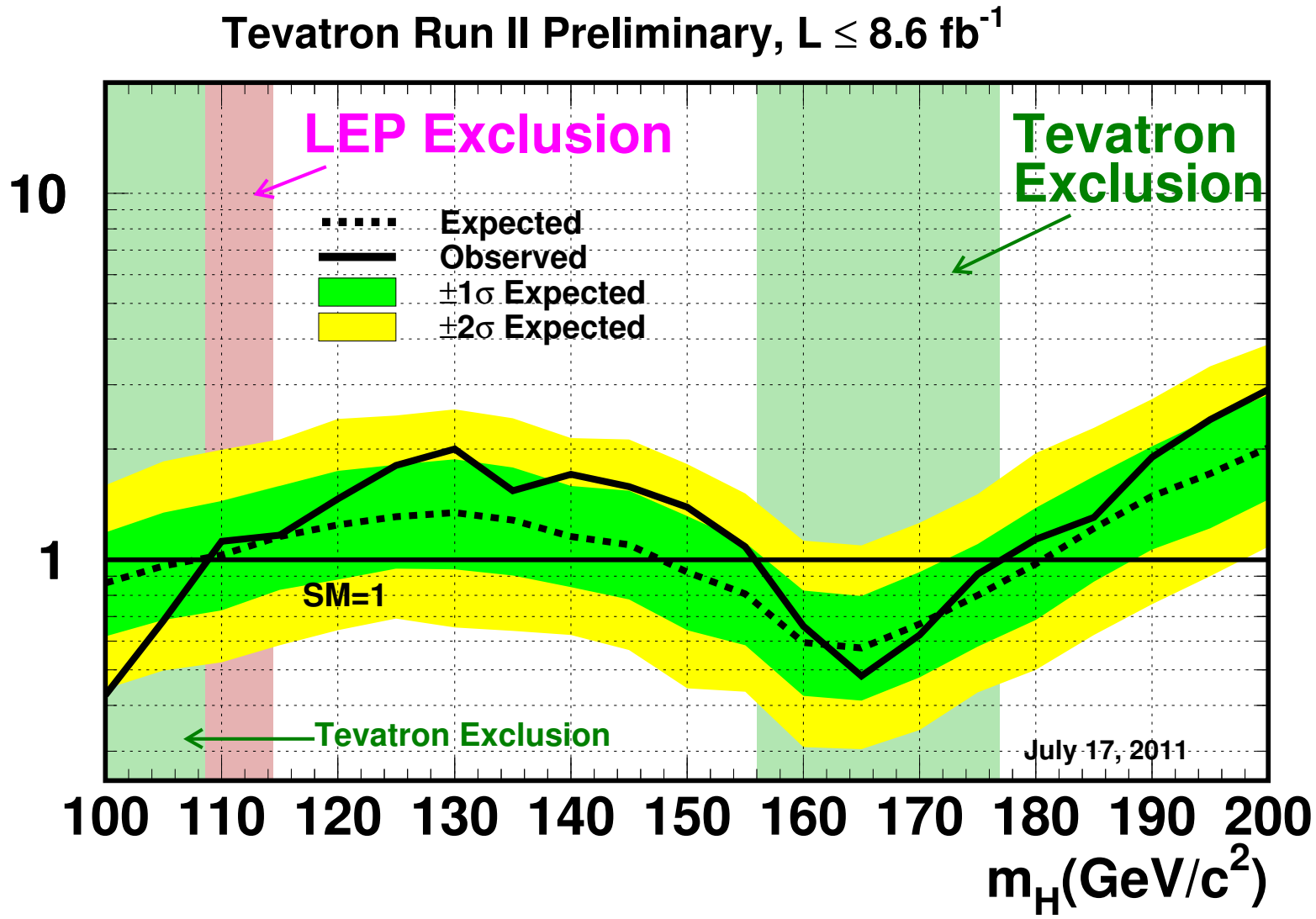


Higgs-Strahlung

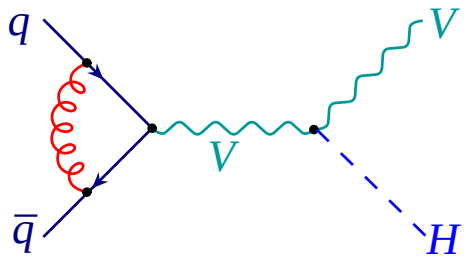
$$pp \to (H \to b\bar{b}) + (V \to \{\mu\bar{\mu}, e\bar{e}, \nu\bar{\nu}, \mu\nu_\mu, e\nu_e\})$$

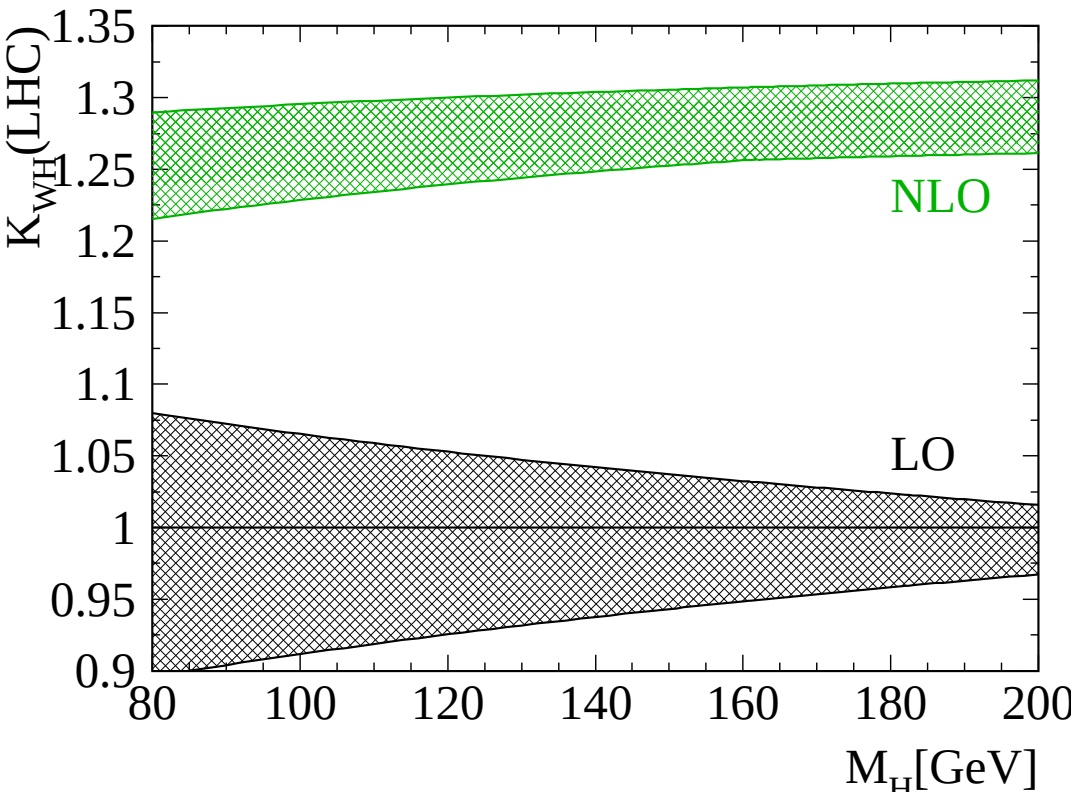


Tevatron exclusion



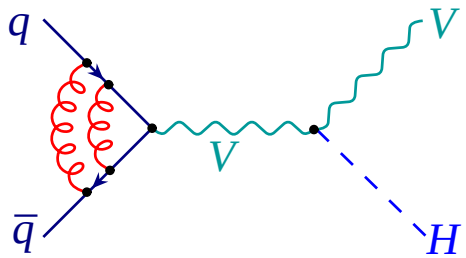
Higgs Strahlung

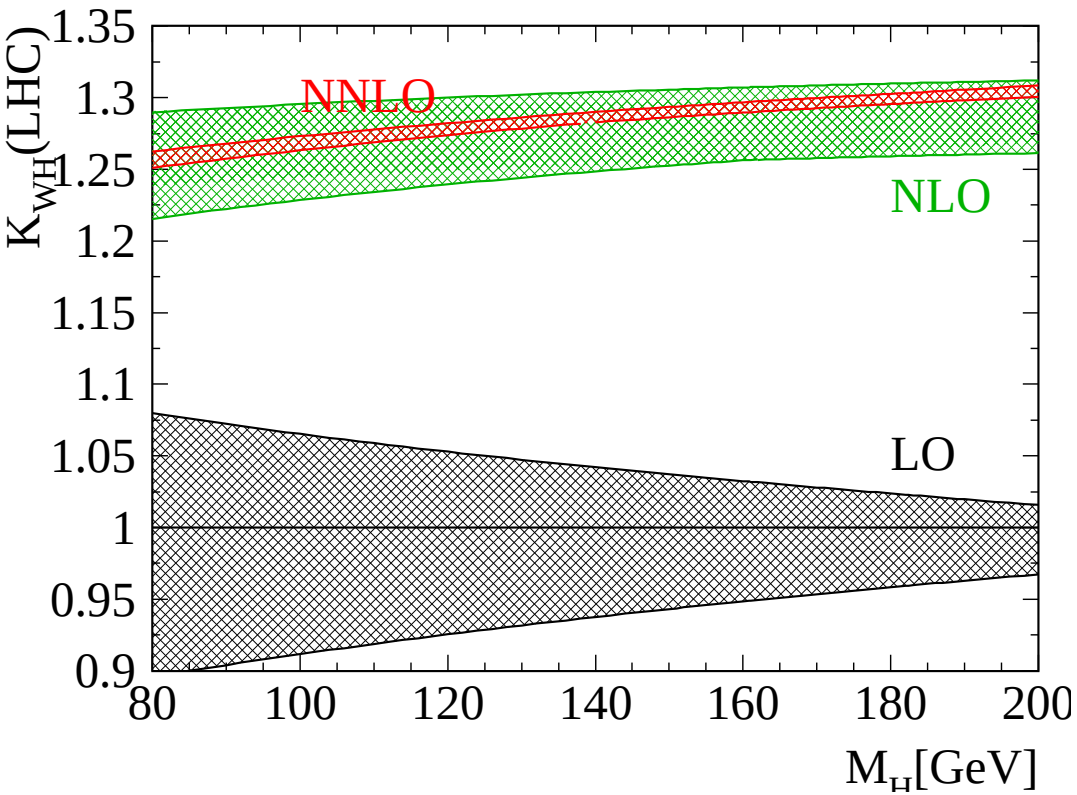




[Han, Willenbrock '90]

Higgs Strahlung



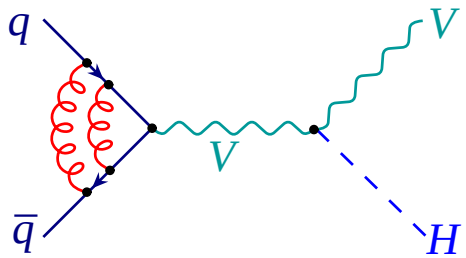


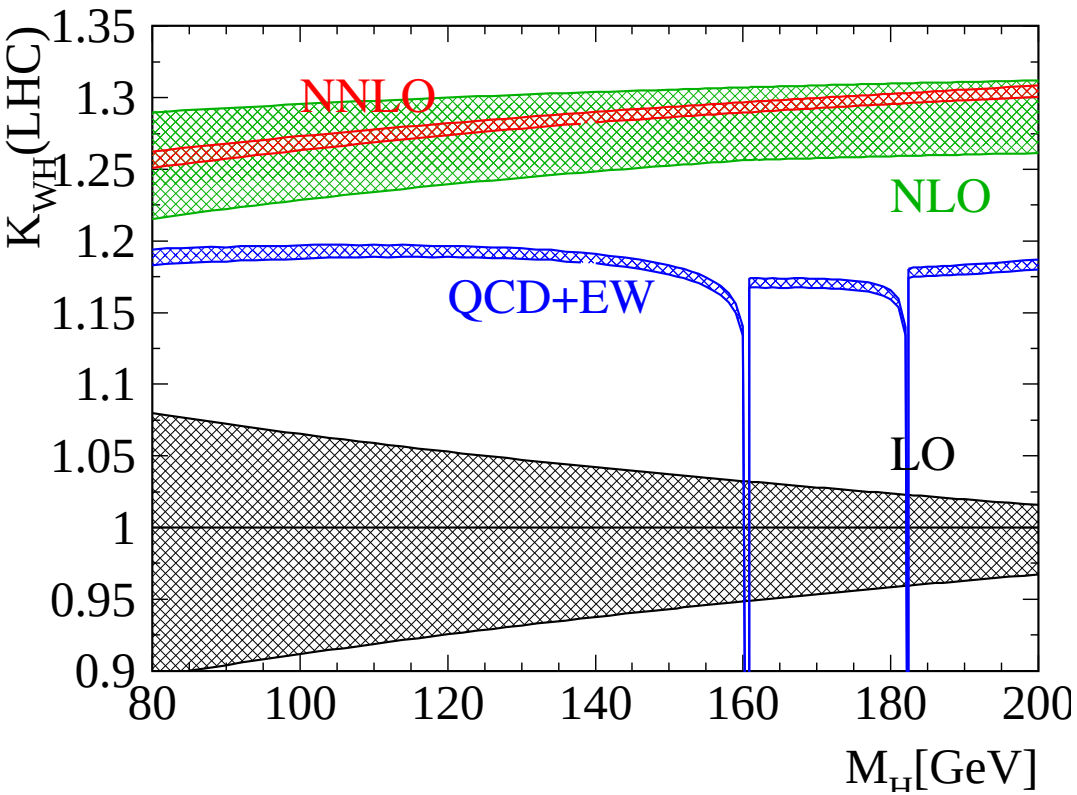
[Brein, Djouadi, R.H. '03]

[Hamberg, v. Neerven, Matsuura '91]

[Han, Willenbrock '90]

Higgs Strahlung





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[Hamberg, v. Neerven, Matsuura '91]

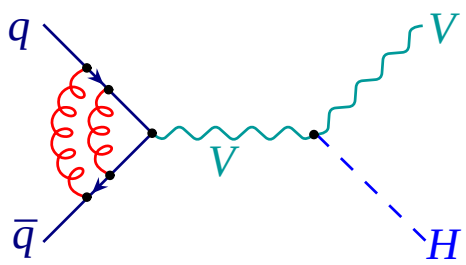
[Han, Willenbrock '90]

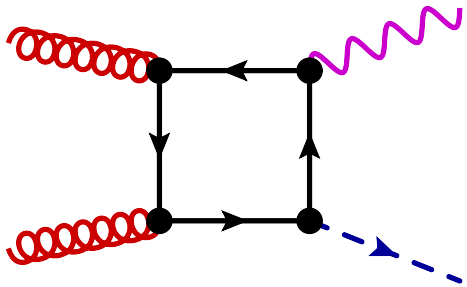
[Ciccolini, Dittmaier, Krämer '03]

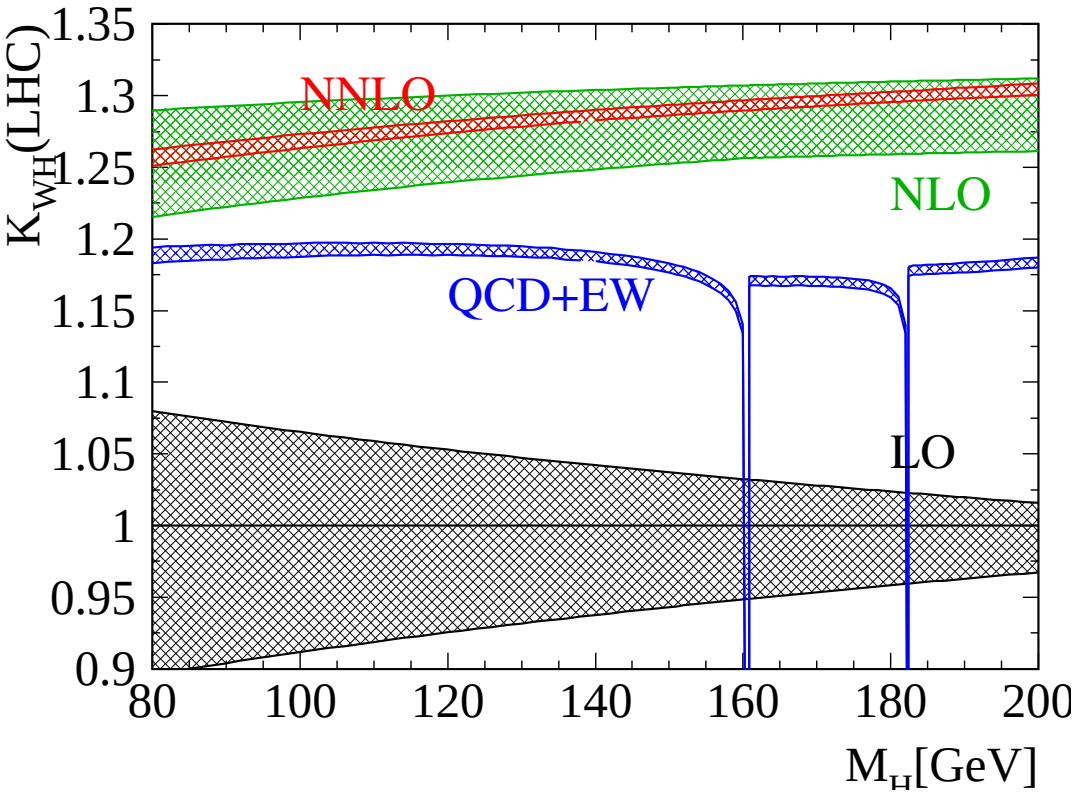
[Denner, Dittmaier, Kallweit, Mück '11]

→ HAWK

Higgs Strahlung







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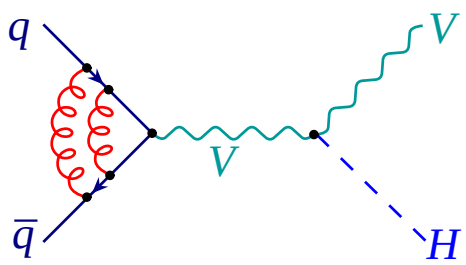

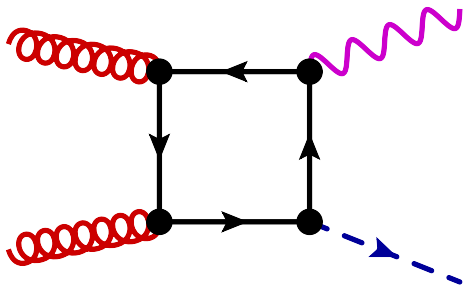

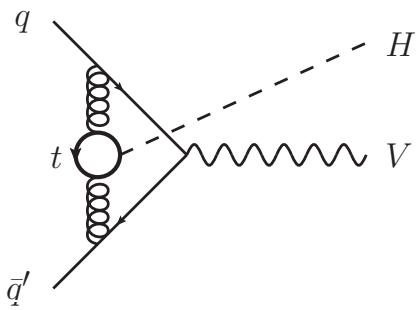

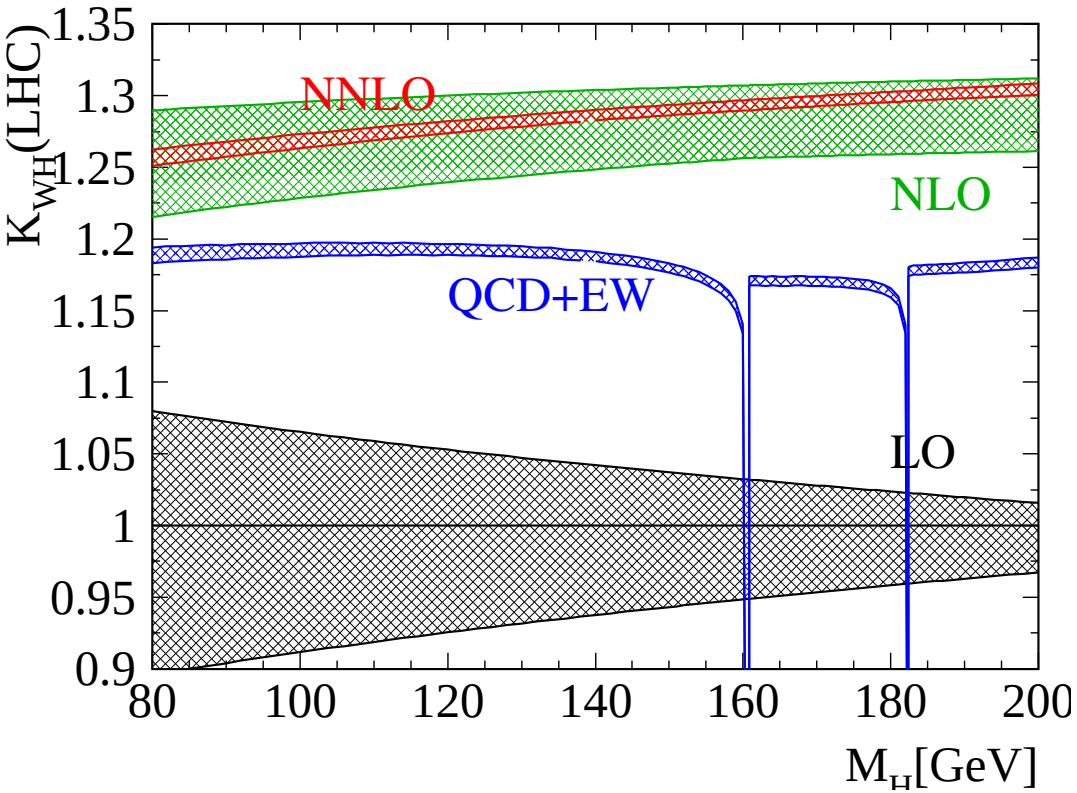

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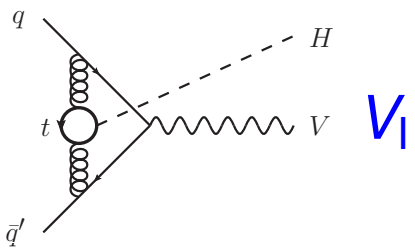
→ HAWK

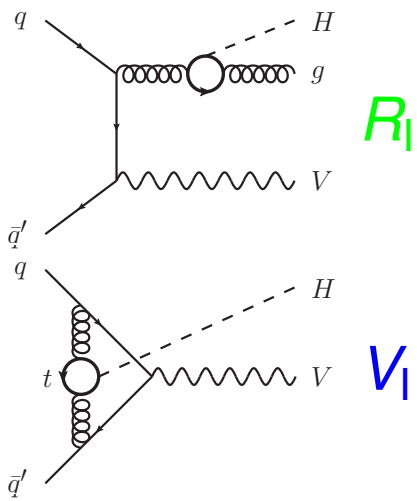
Higgs Strahlung

Top induced terms: *WH*



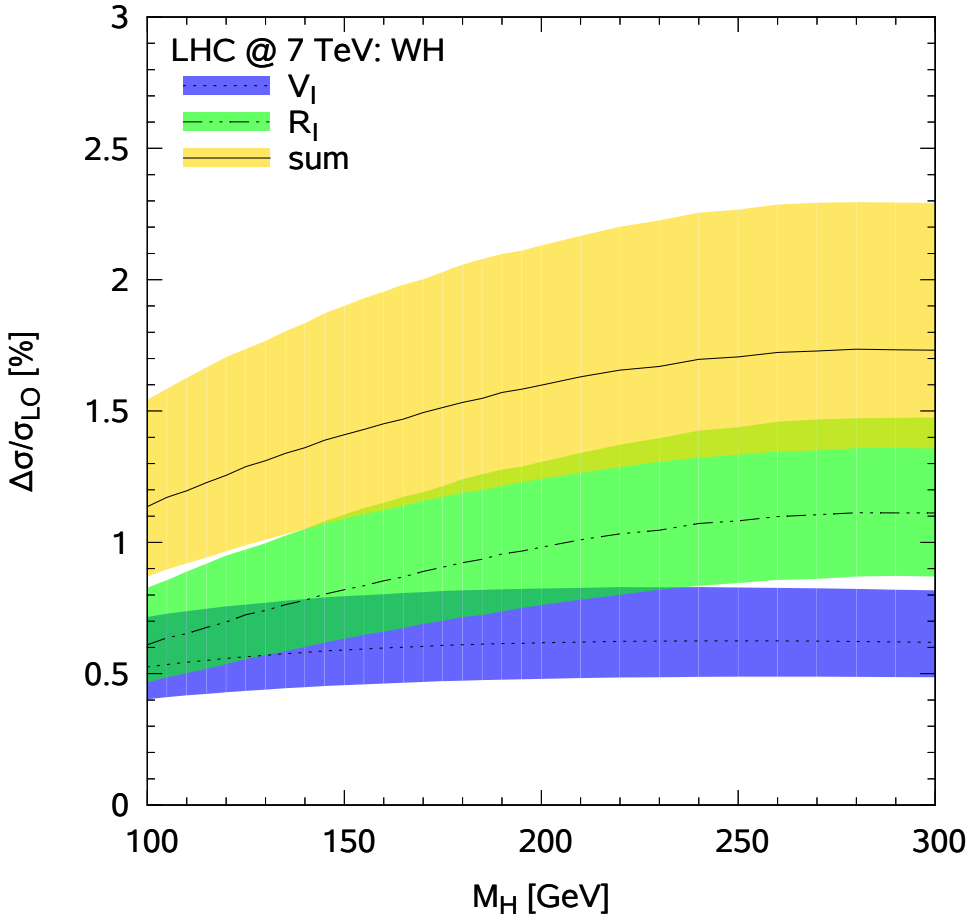
Higgs Strahlung

Top induced terms: *WH*

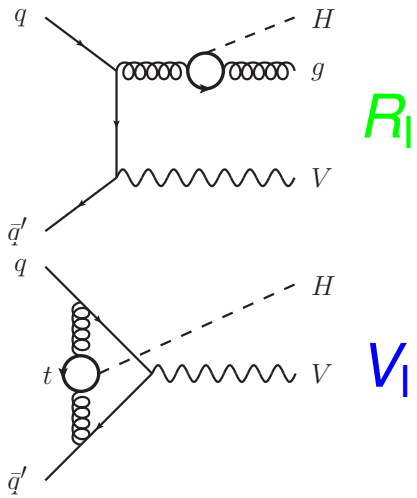


Higgs Strahlung

Top induced terms: *WH*

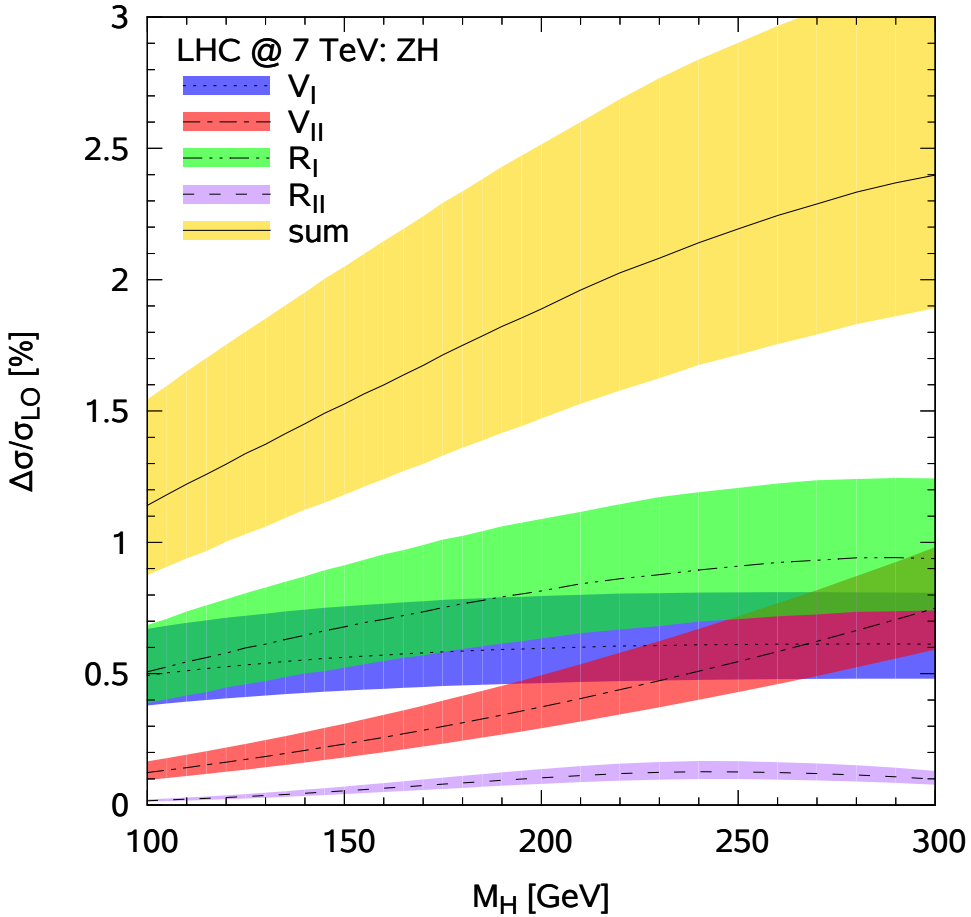


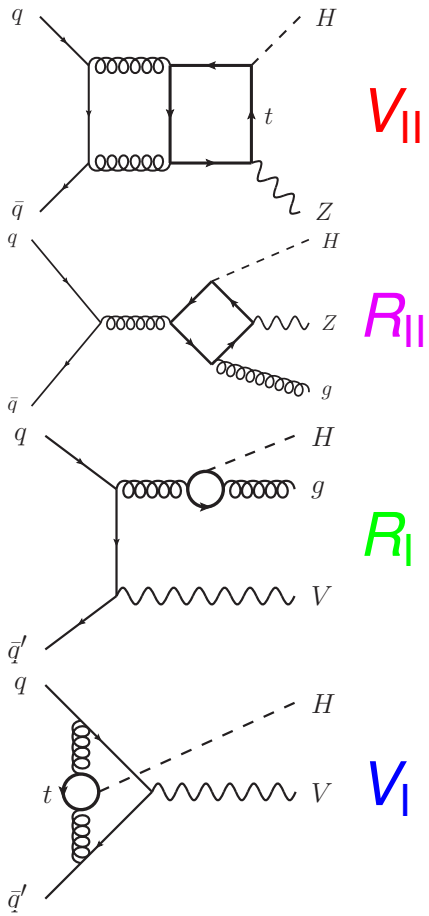
[Brein, RH, Wiesemann, Zirke '11]



Higgs Strahlung

Top induced terms: *ZH*

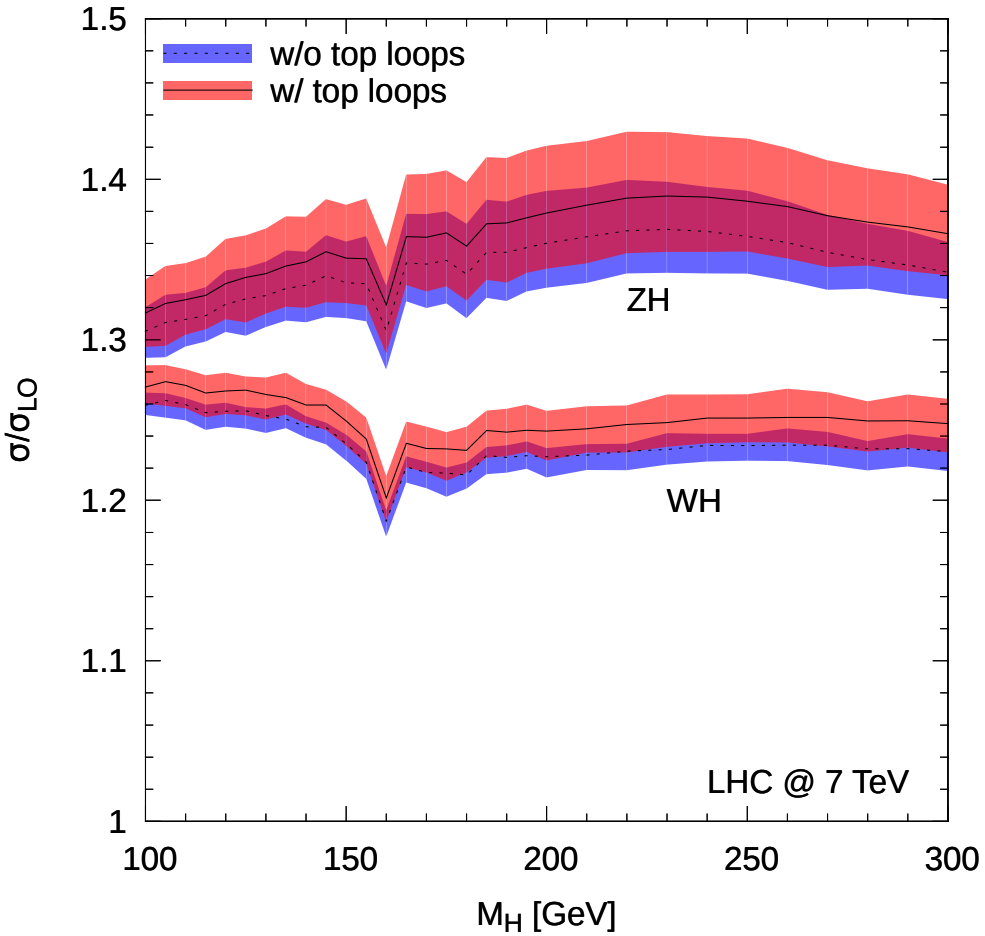




[Brein, RH, Wiesemann, Zirke '11]

Higgs Strahlung

Top induced terms



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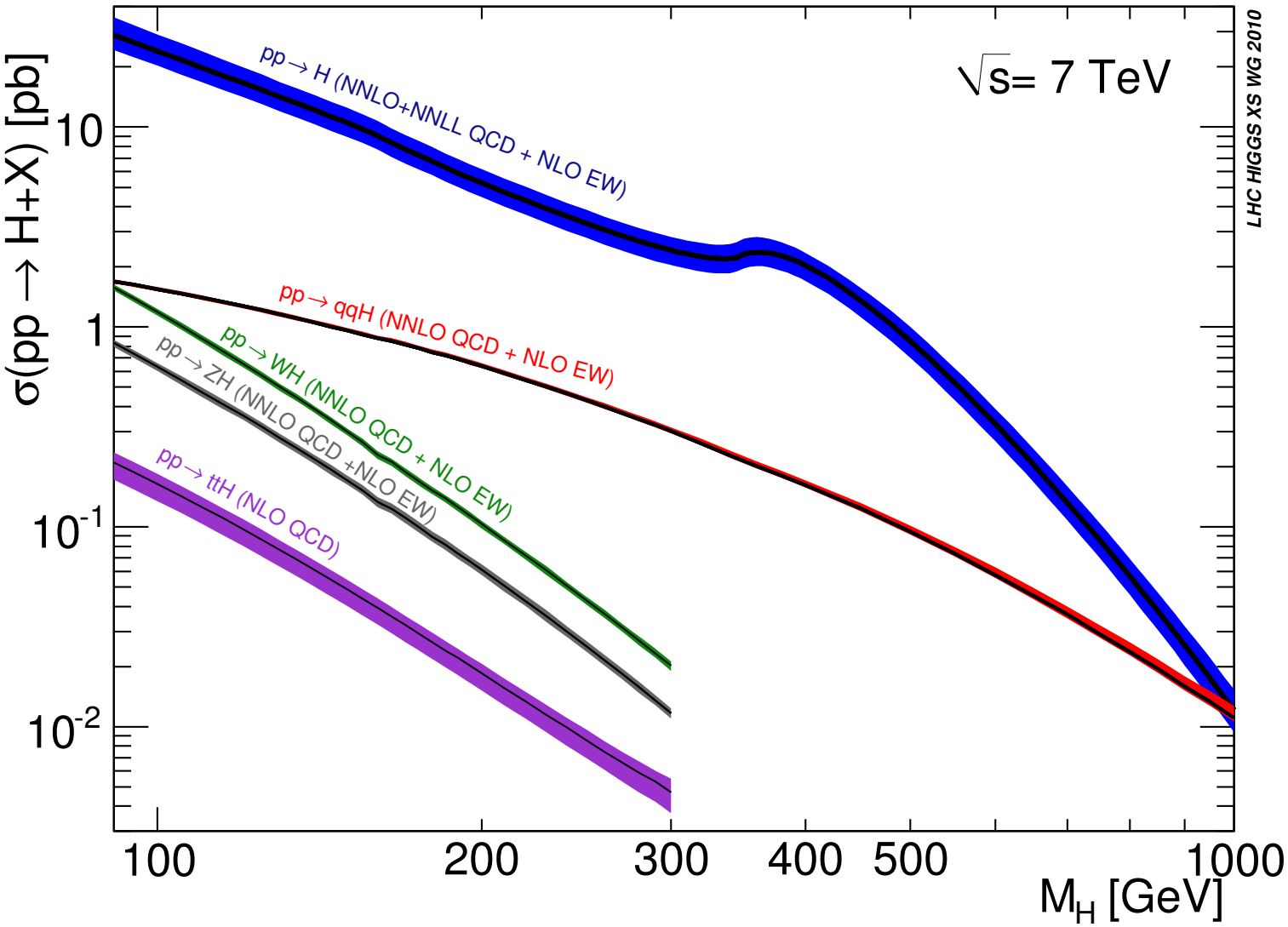
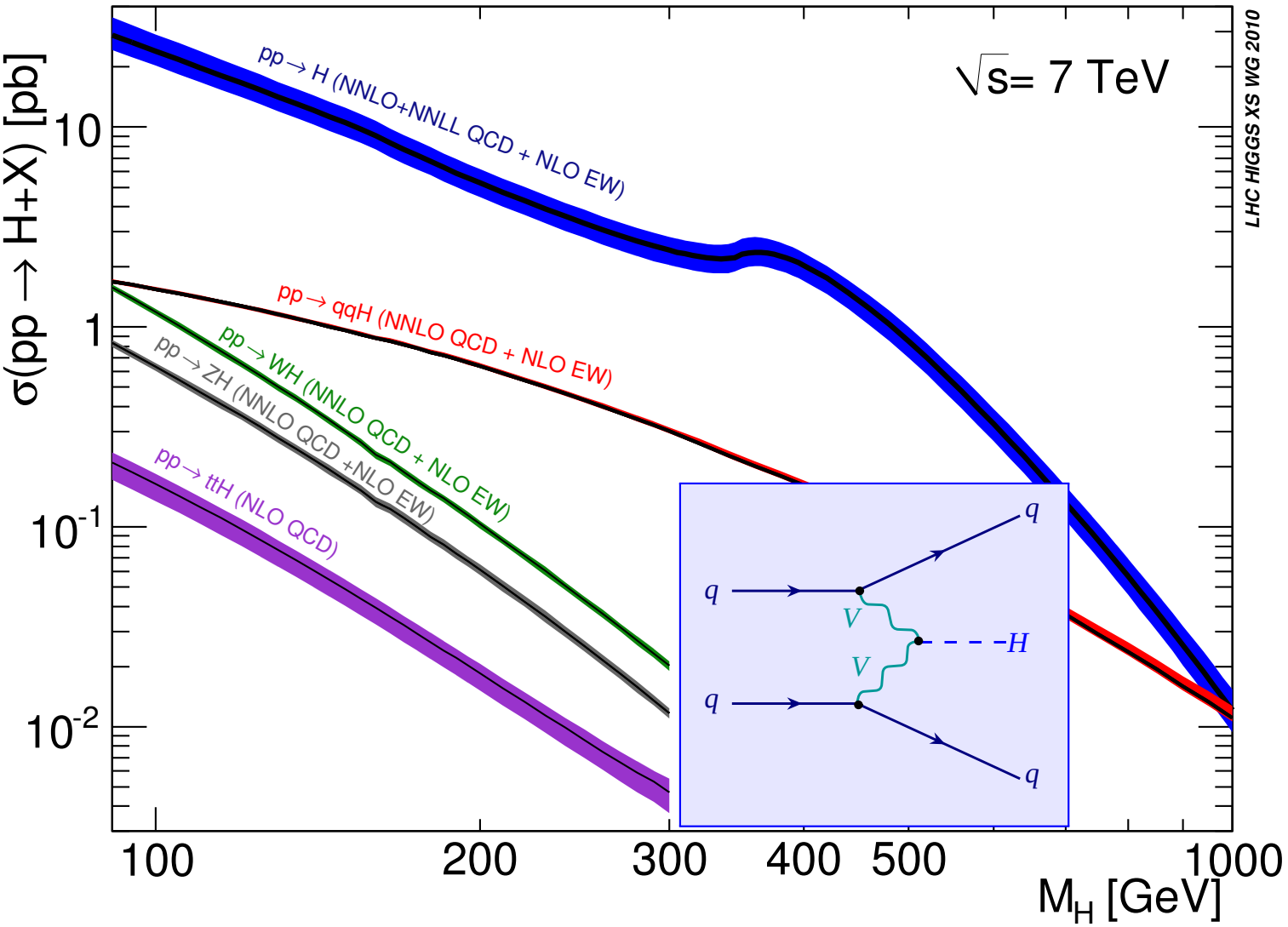
Inclusive Higgs Cross Sections

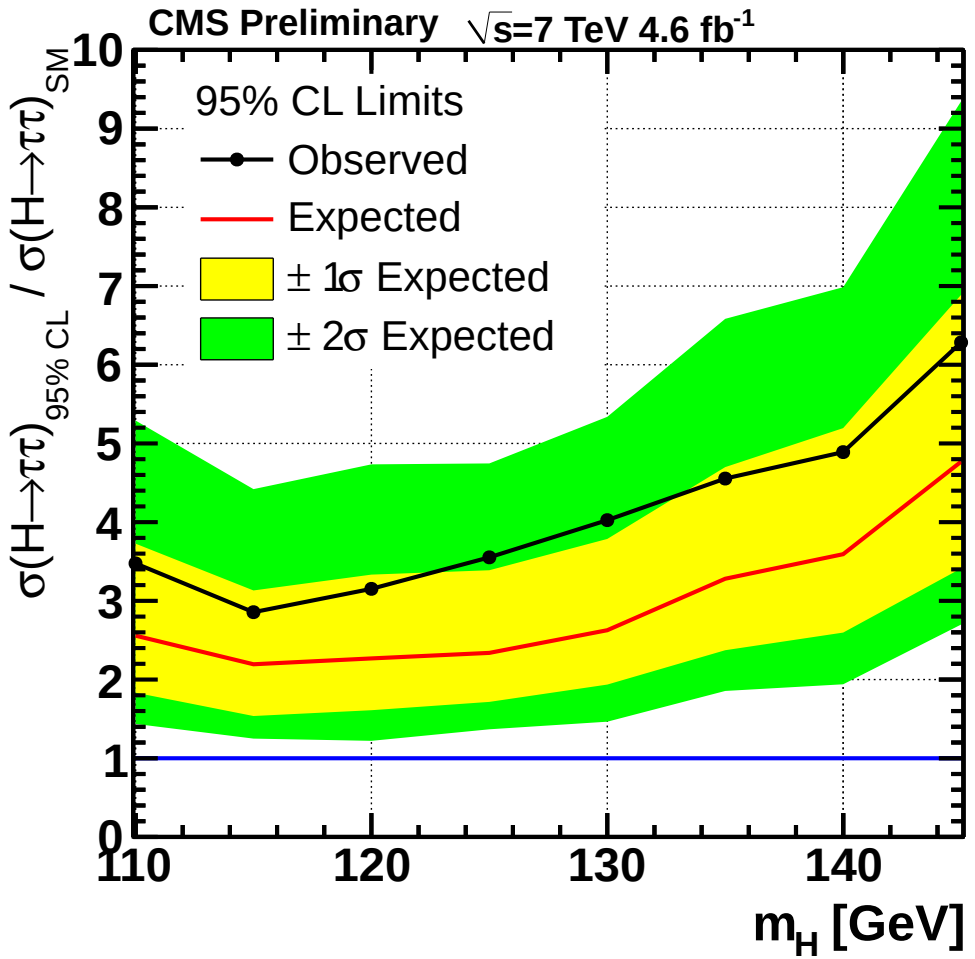


Weak Boson Fusion

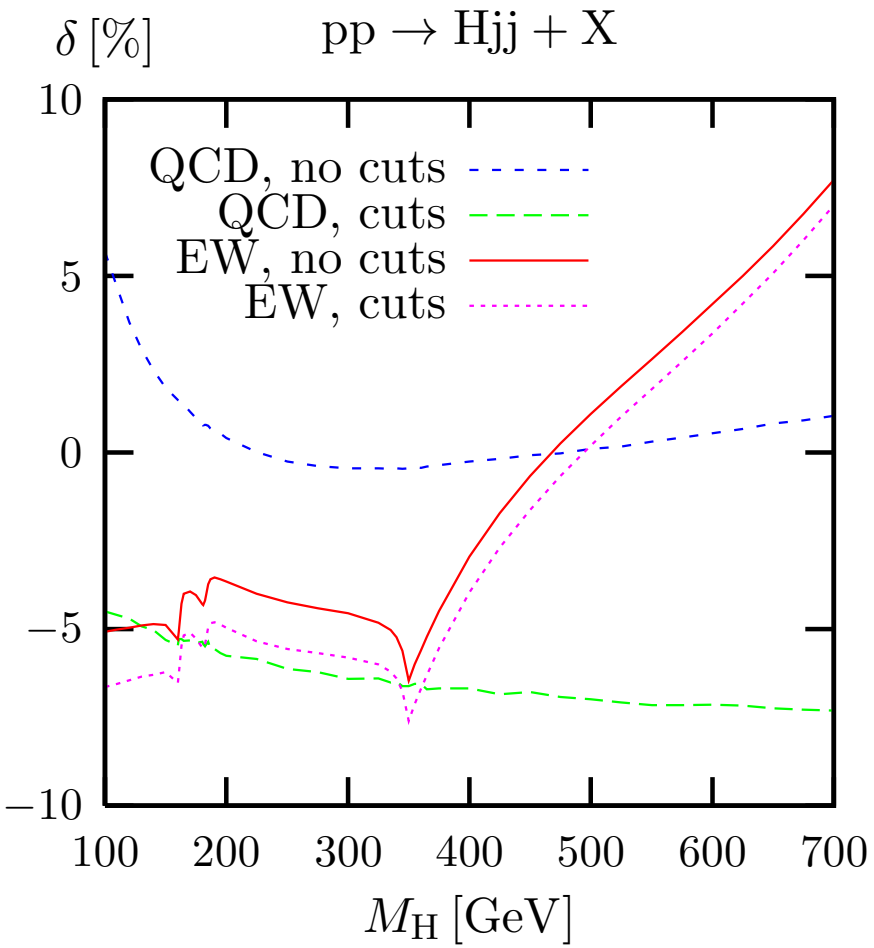


Weak Boson Fusion

$H \to \tau\tau$



WBF: QCD+EW corrections



- NLO QCD
  [Figy, Oleari, Zeppenfeld '03],
  → VBFNLO
- NLO QCD+EW
  [Ciccolini, Denner, Dittmaier '08]
  → HAWK
- EW+SUSY
  [Figy, Palmer, Weiglein '10]

WBF: BNLO corrections

- gluon fusion/WBF interference

  [Andersen, Binoth, Heinrich, Smillie '07], [Andersen, Smillie '08]
  [Bredenstein, Hagiwara, Jäger '08]

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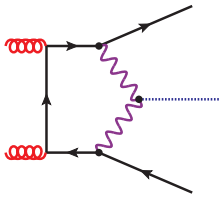

part of NNLO

WBF: BNLO corrections

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  [Andersen, Binoth, Heinrich, Smillie '07], [Andersen, Smillie '08]
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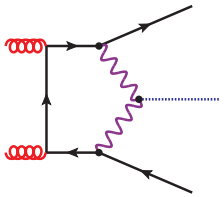
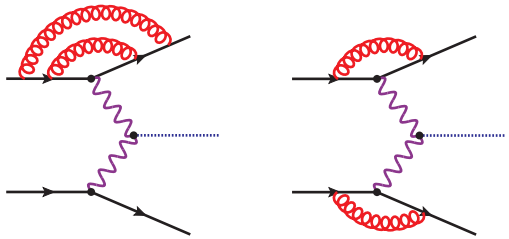


part of NNLO

- DIS-like NNLO (inclusive)



+ a few others [Bolzoni, Maltoni, Moch, Zaro '11]

WBF: BNLO corrections

- gluon fusion/WBF interference

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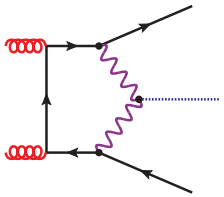
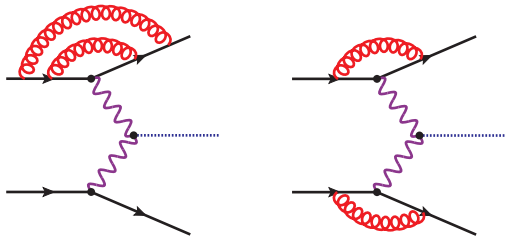


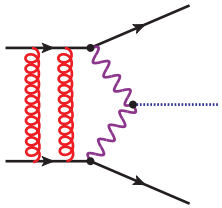
part of NNLO

- DIS-like NNLO (inclusive)

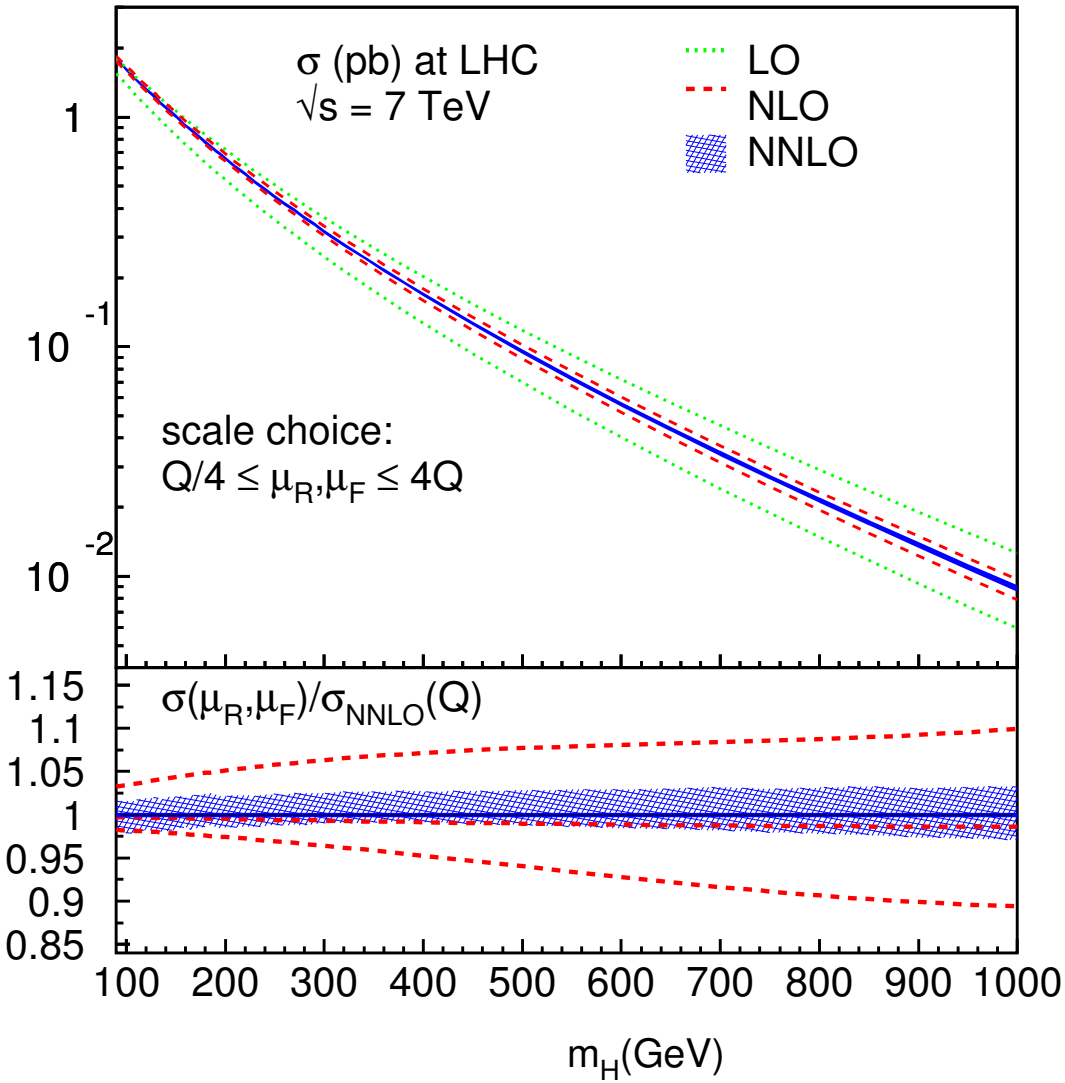


+ a few others [Bolzoni, Maltoni, Moch, Zaro '11]

- missing:

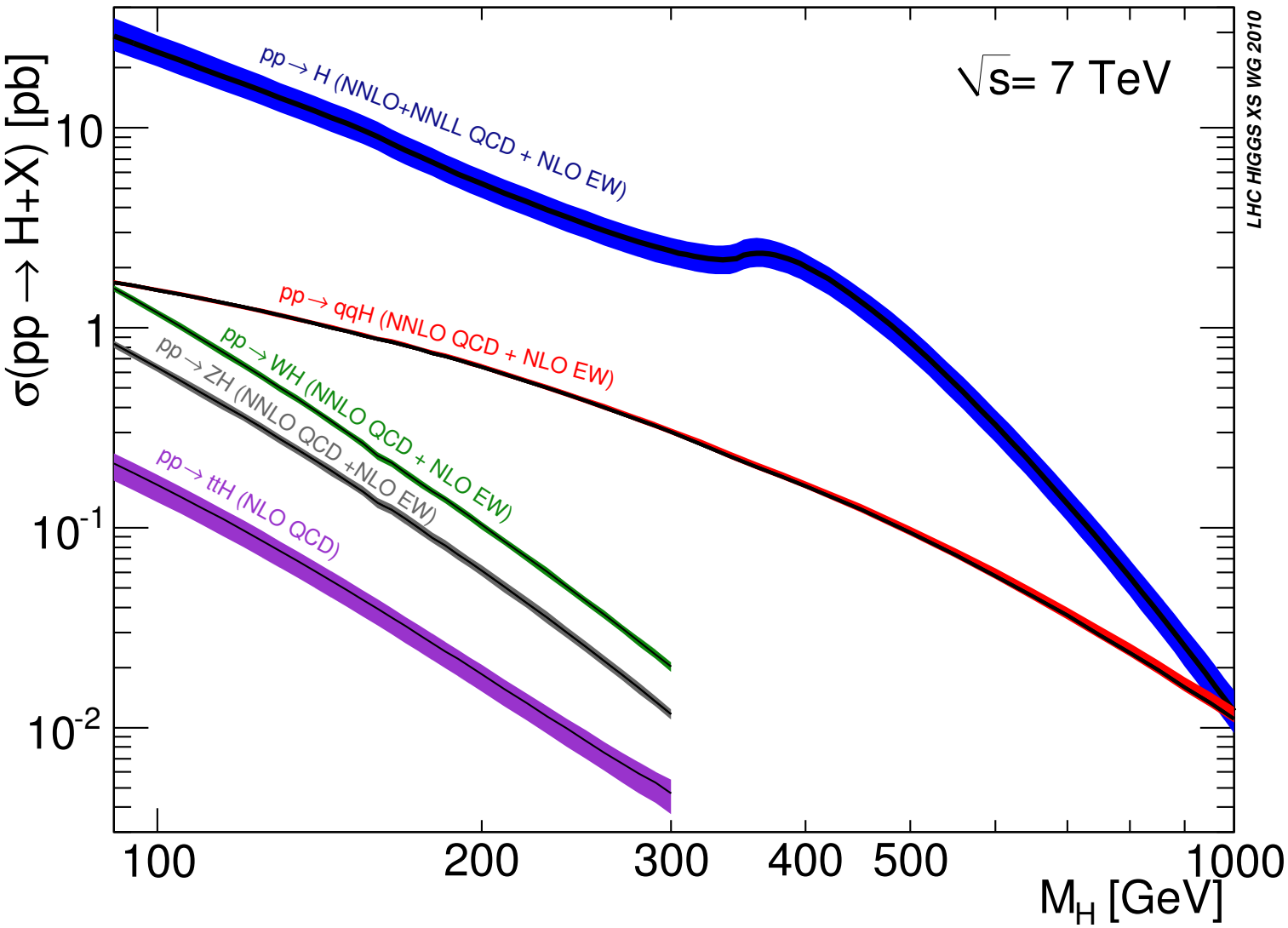


WBF

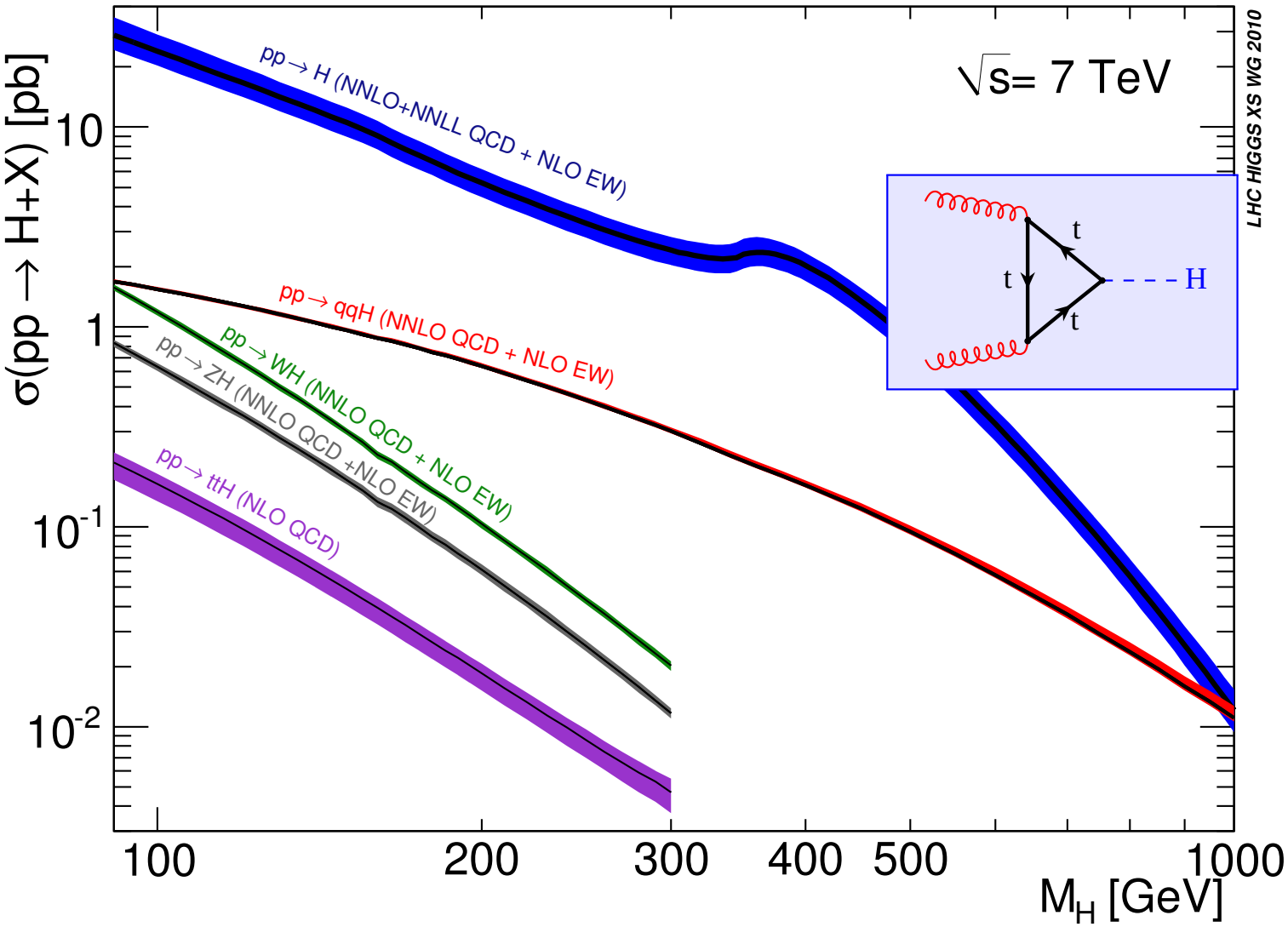


[Bolzoni, Maltoni, Moch, Zaro '11]

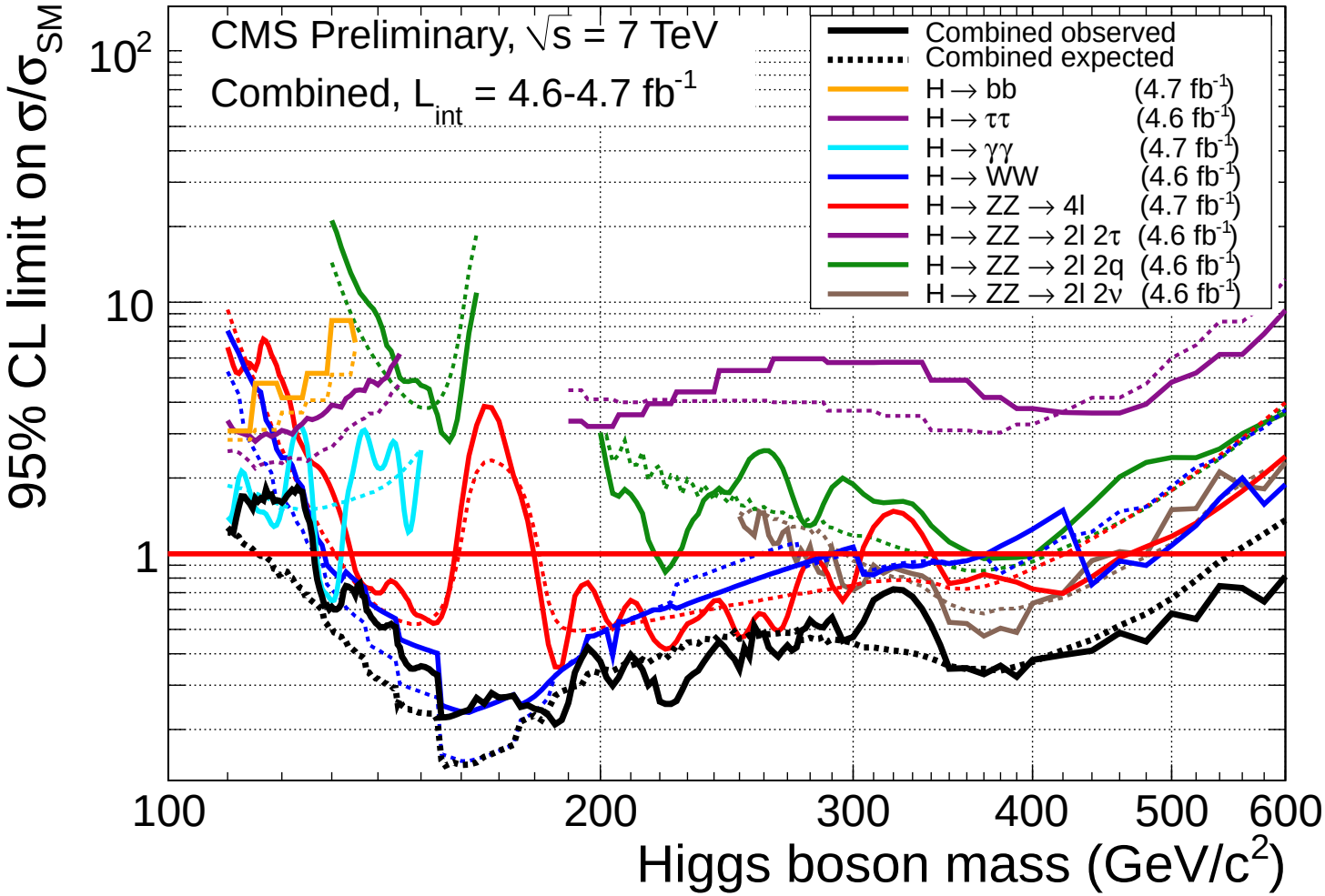
Cross sections



Gluon fusion

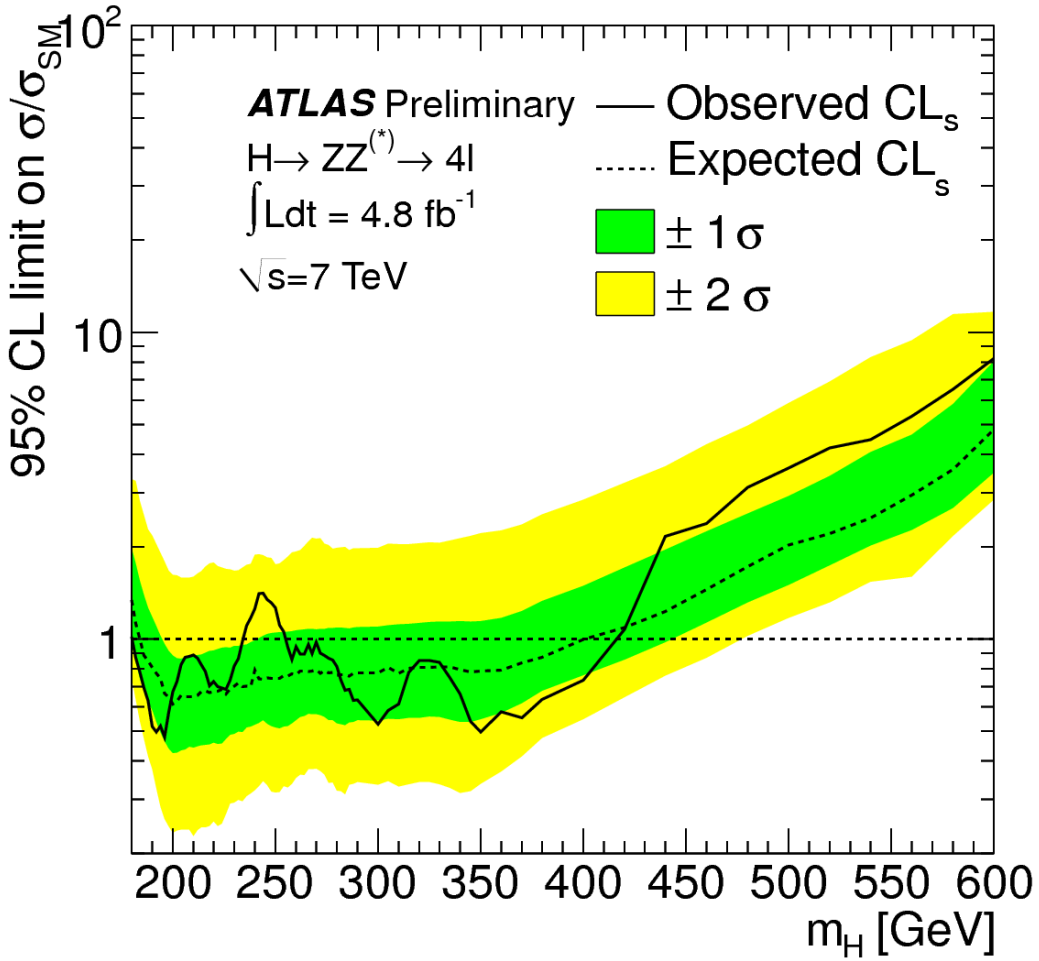


Gluon fusion: search channels



Gluon fusion: $H \to ZZ \to 4l$

High mass region



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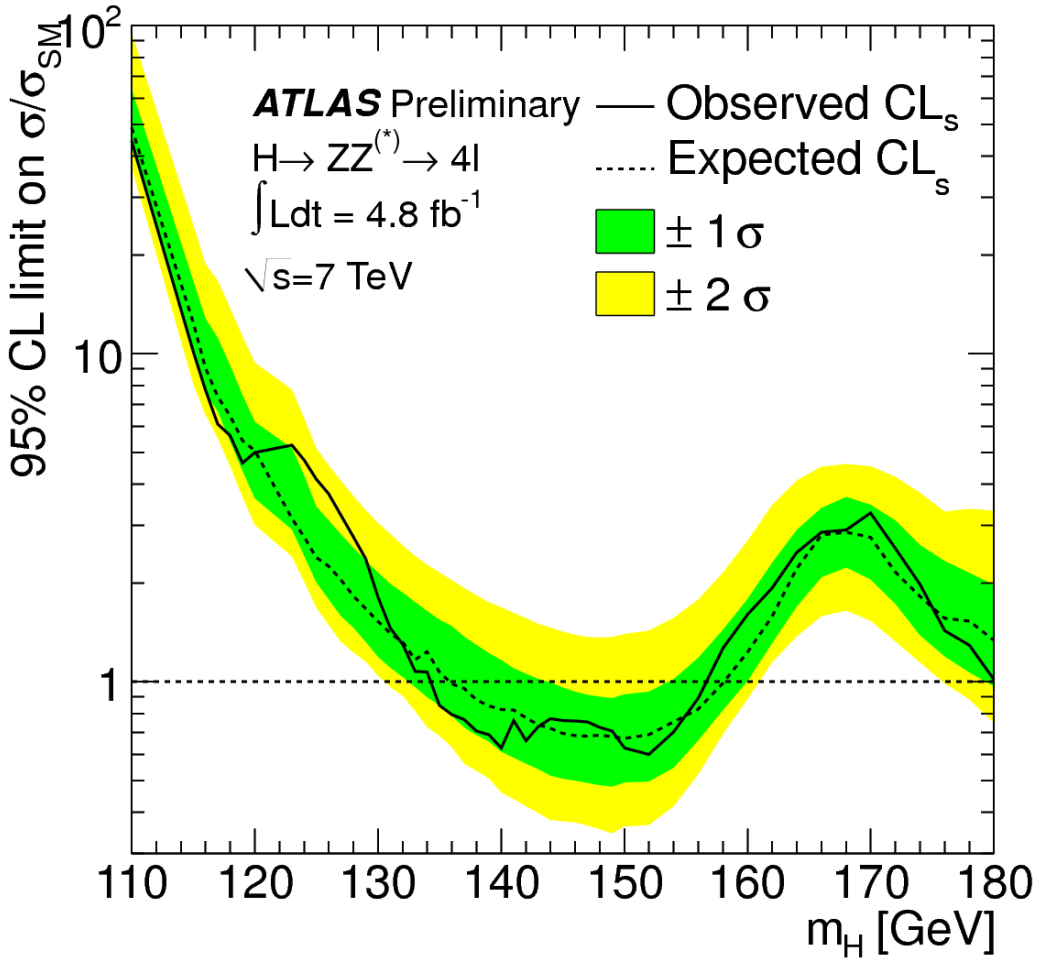
Low mass region



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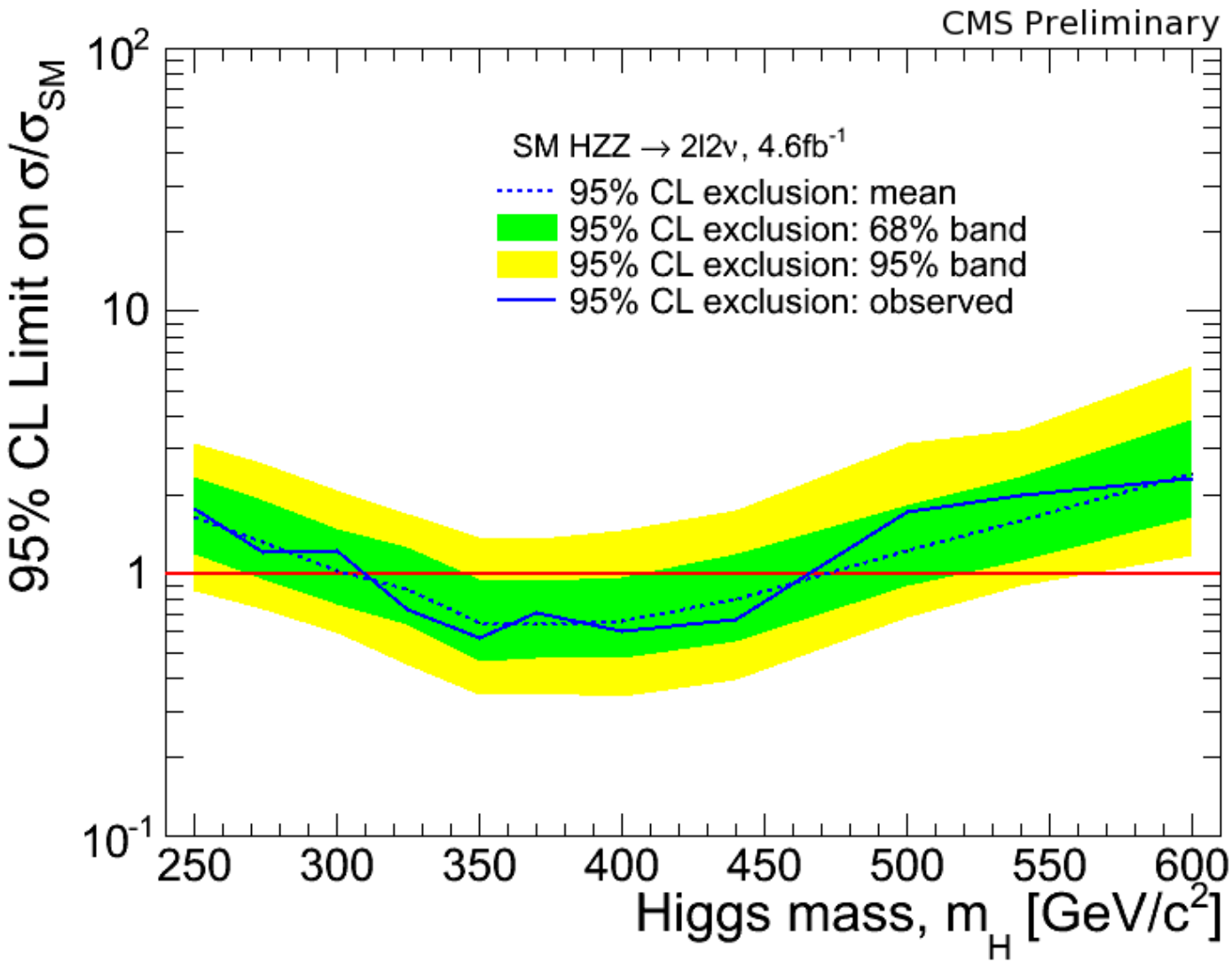
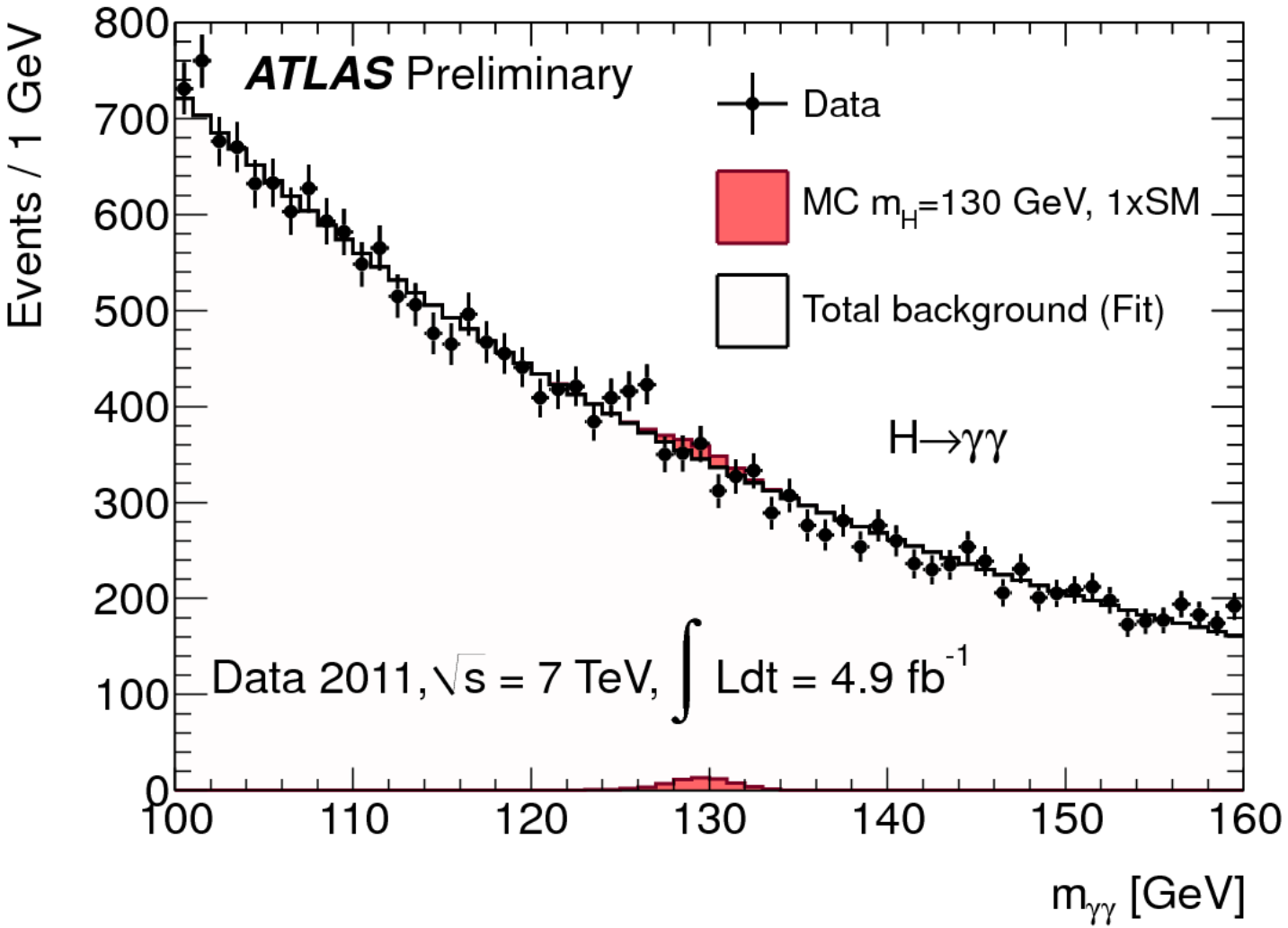
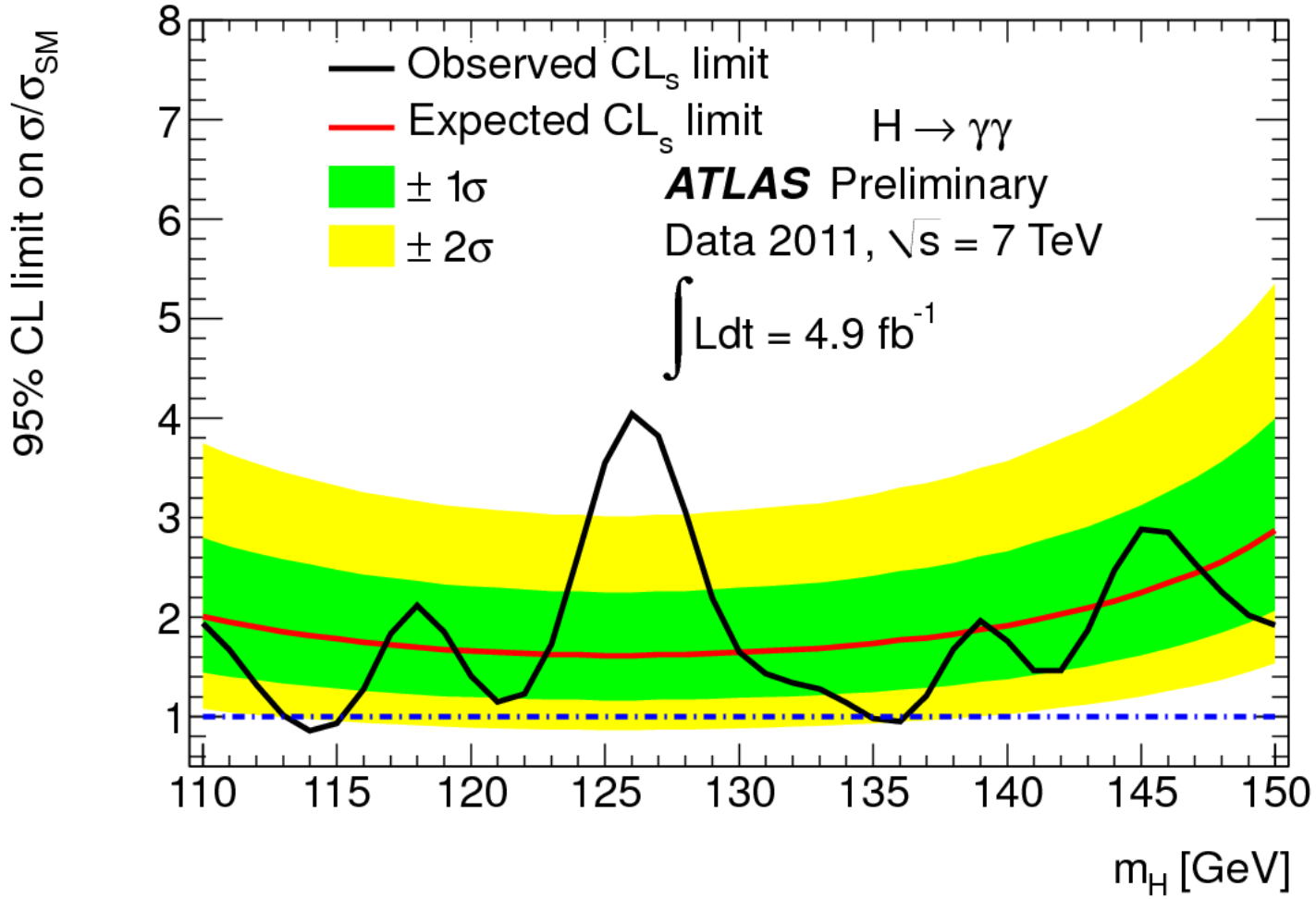


$H \to \gamma\gamma$



$H \to \gamma\gamma$
exclusion limit



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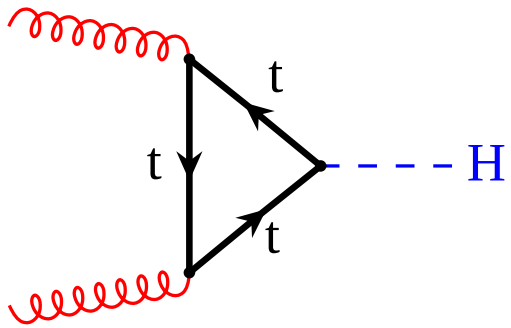

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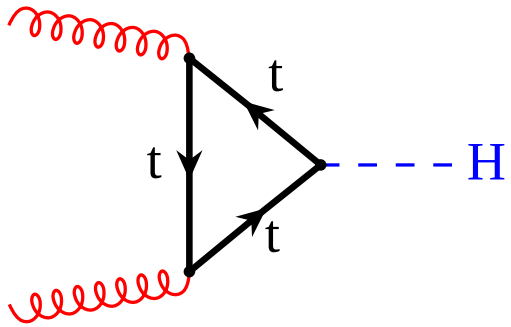
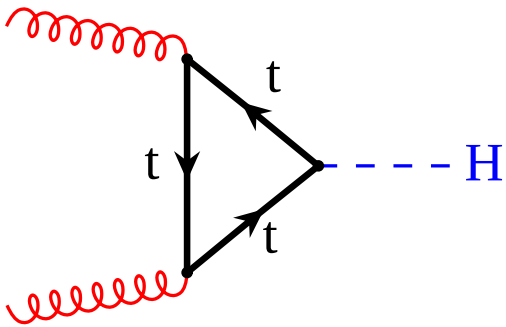


- dominant production mode
- sensitive to heavy particle spectrum

Gluon Fusion



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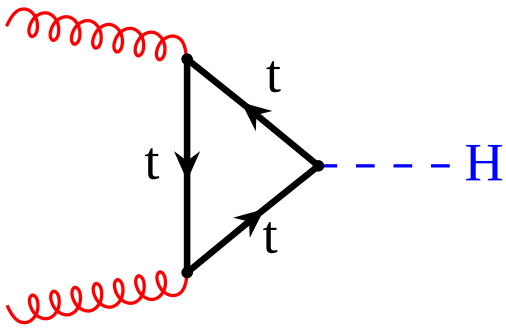
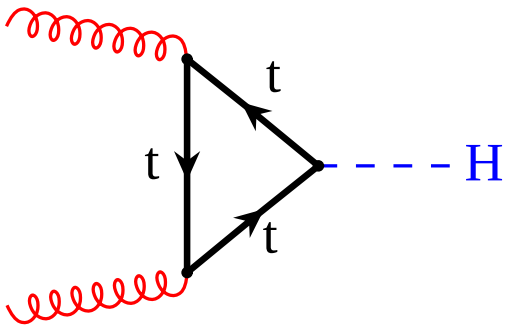


- QCD through NNLO

  [Spira, Djouadi, Graudenz, Zerwas '95], [Dawson '91], [RH, Kilgore '02], [Anastasiou, Melnikov '02], [Ravindran, Smith, v.Neerven '03]

Gluon Fusion



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- resummation of BNNLO effects
  - $\ln^n(1-z)\,, \quad z = M_H^2/\hat{s}$

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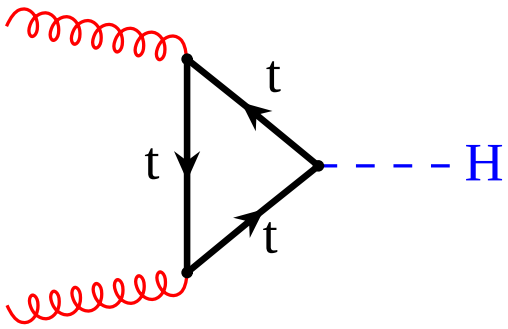
Gluon Fusion



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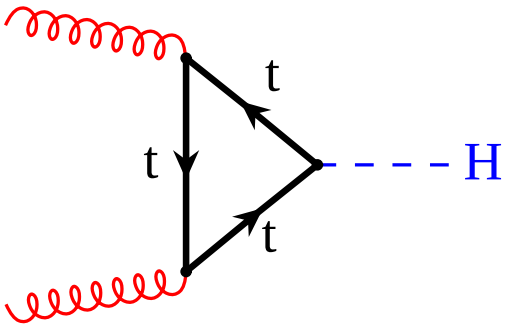

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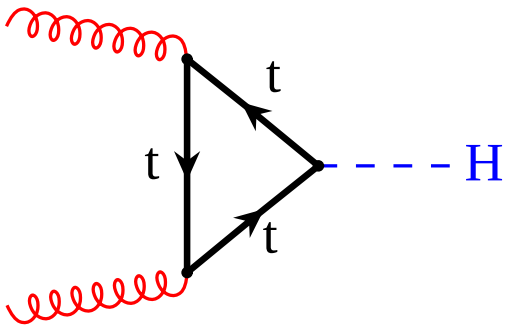

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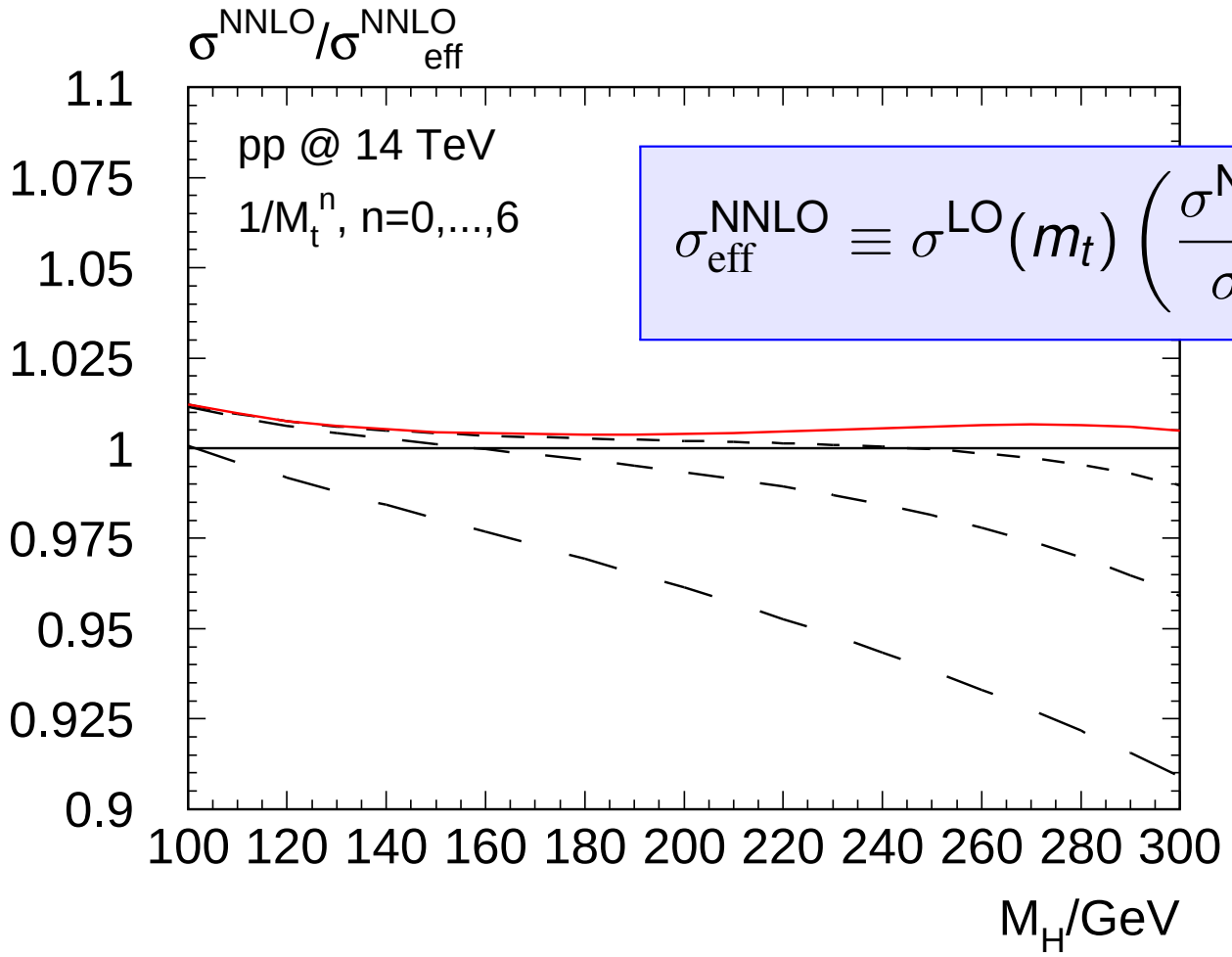
- $1/m_t$ effects

Convergence of $1/m_t$ expansion at NNLO



$$\sigma^{\text{NNLO}}_{\text{eff}} \equiv \sigma^{\text{LO}}(m_t) \left(\frac{\sigma^{\text{NNLO}}}{\sigma^{\text{LO}}} \right)_{m_t \to \infty}$$

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

[RH, Mantler, Marzani, Ozeren '09]

Theory uncertainties

- μ dependence (renormalization/factorization scales)

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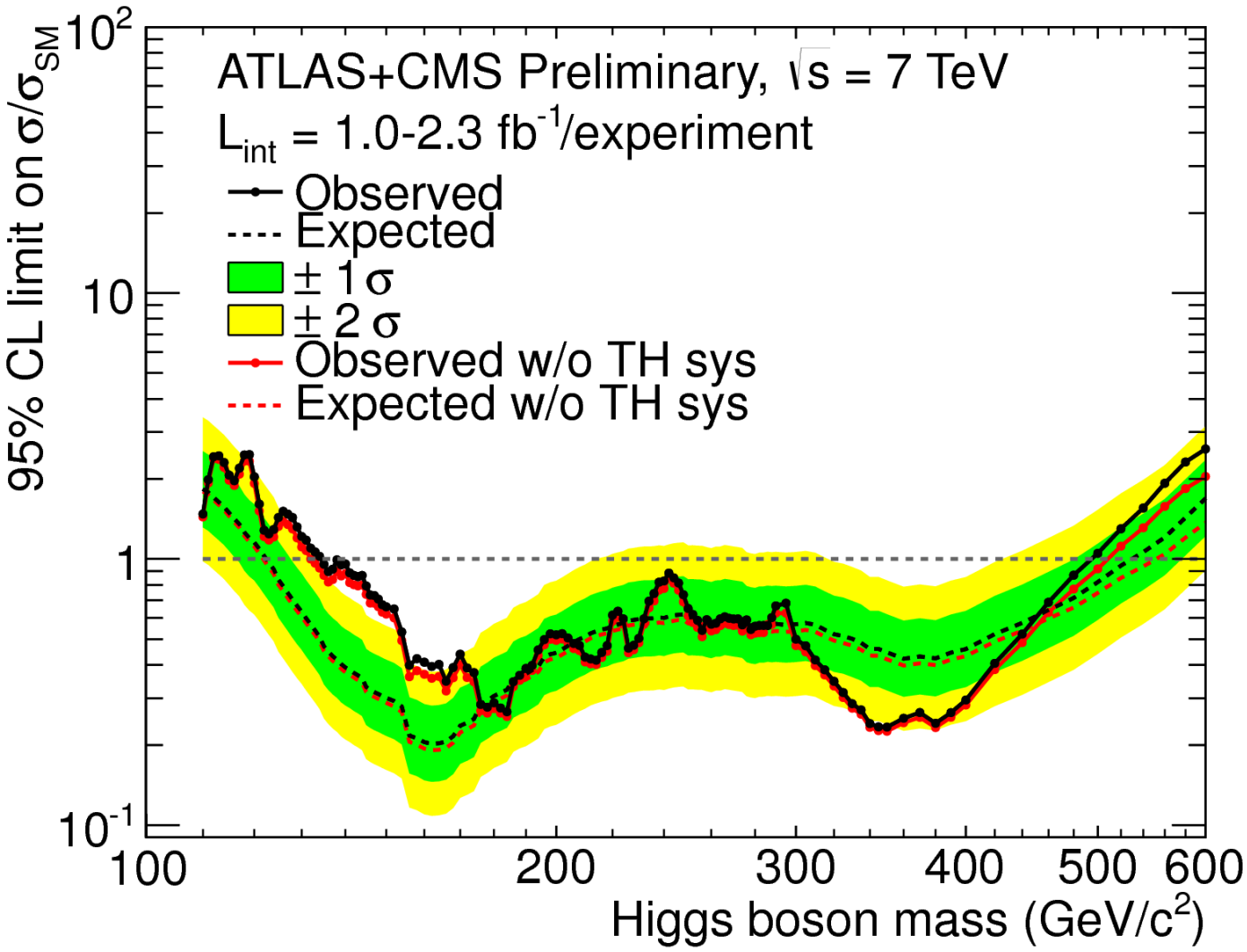
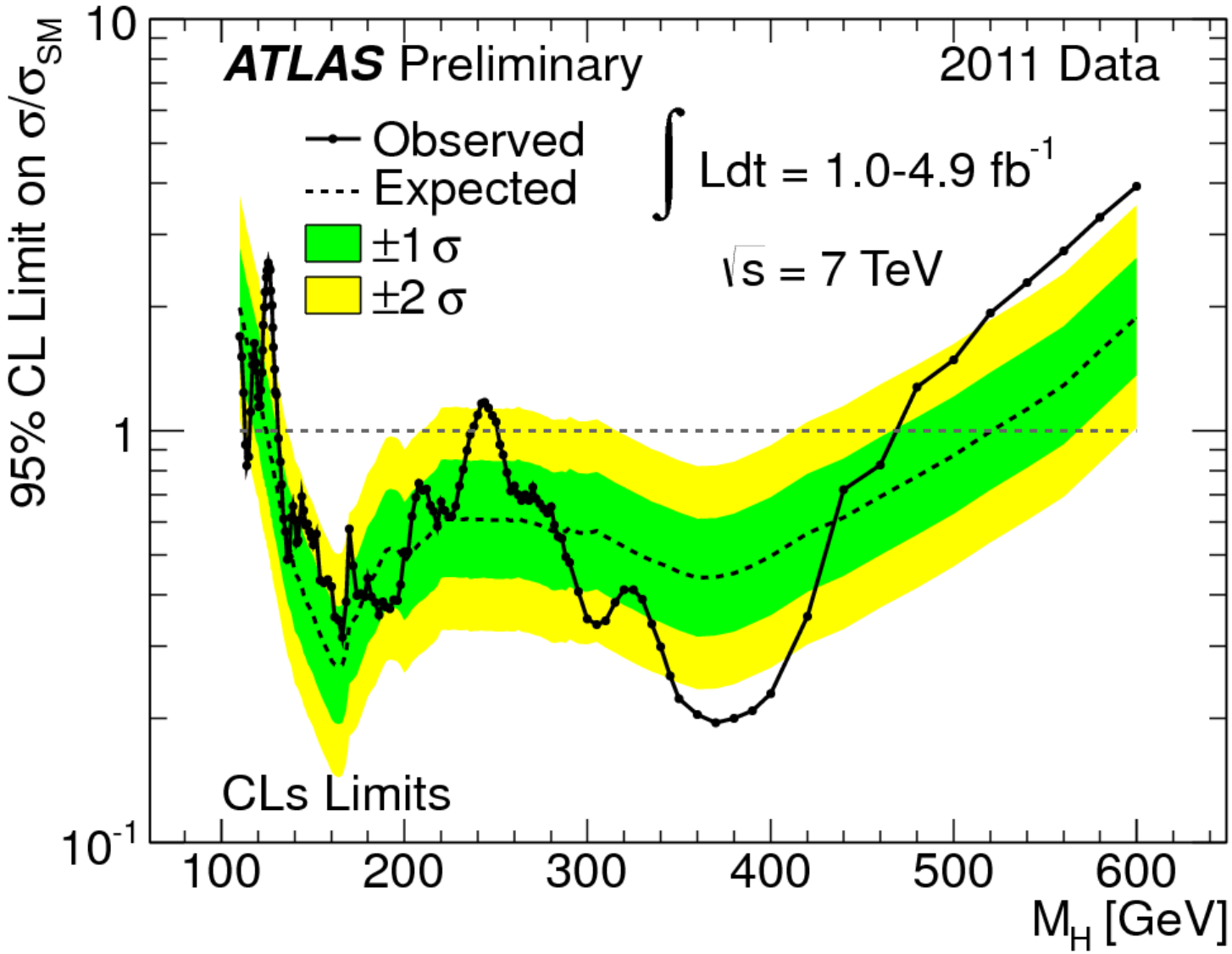
Influence of theory errors



Influence of central value

very roughly. . .



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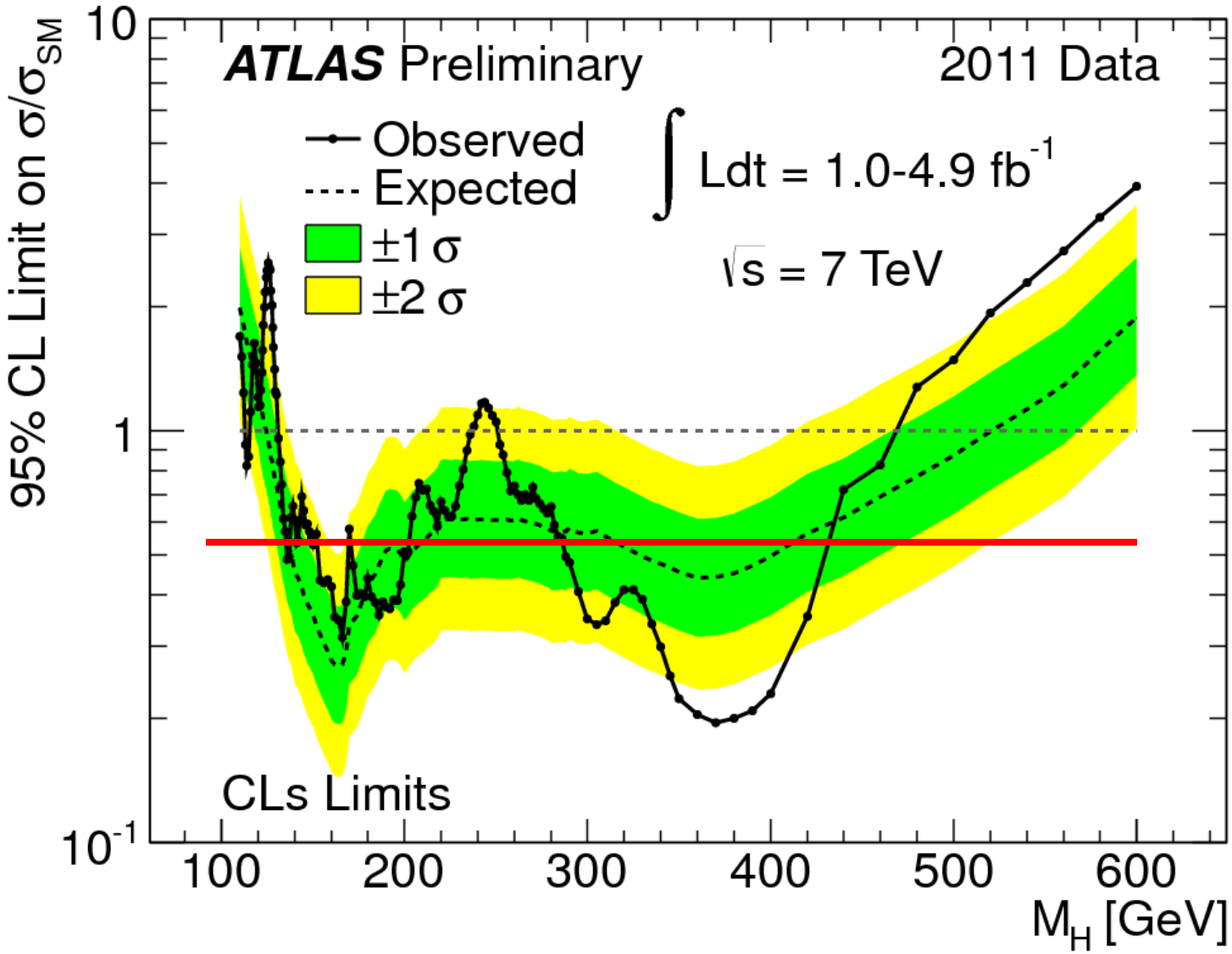
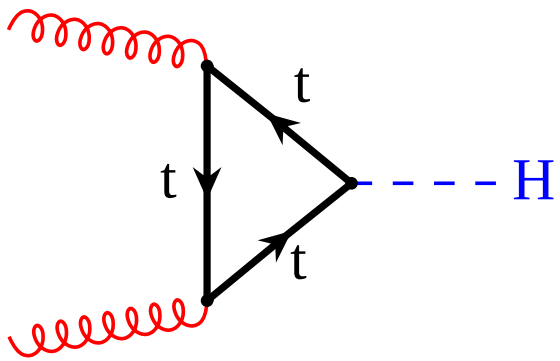


Gluon Fusion

4^{th} generation



- sensitive to heavy particle spectrum

Gluon Fusion

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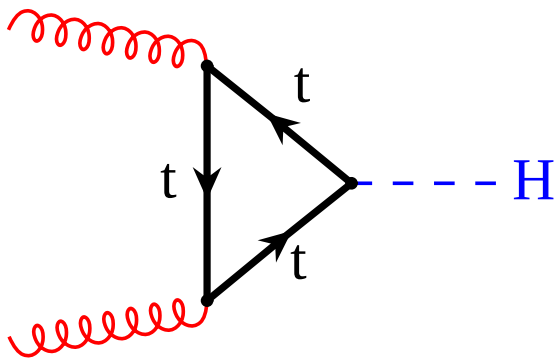
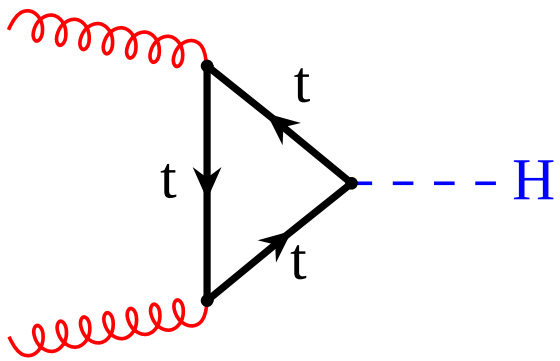


- sensitive to heavy particle spectrum

$$\sigma \overset{m_t \gg M_H}{\longrightarrow} \frac{\pi}{256\sqrt{2}} \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{y_t}{m_t}\right)^2$$

Gluon Fusion

4th generation



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$$\sigma \overset{m_t \gg M_H}{\to} \frac{\pi}{256\sqrt{2}} \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{y_t}{m_t} + \frac{y_{t'}}{m_{t'}} + \frac{y_{b'}}{m_{b'}}\right)^2$$

Gluon Fusion

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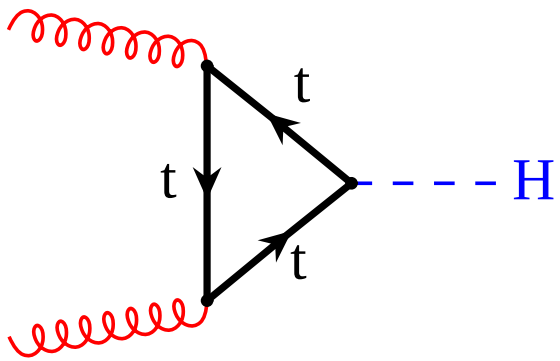

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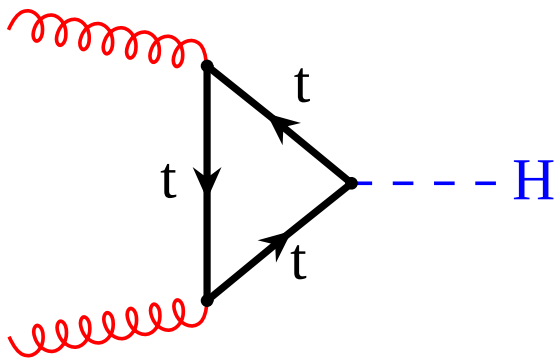

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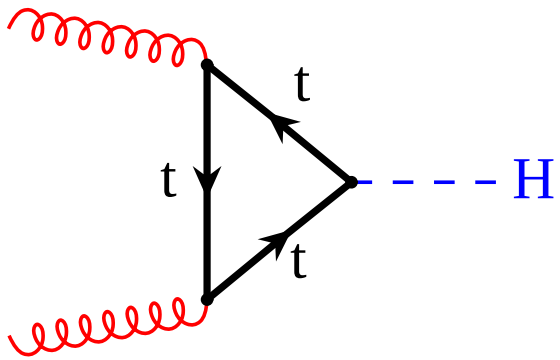
NNLO: [Anastasiou, Buehler, Furlan, Herzog, Lazopoulos '11]

EW: [Passarino, Sturm, Uccirati '11], [Denner *et al.* '11]

Gluon Fusion

Supersymmetry



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Gluon Fusion

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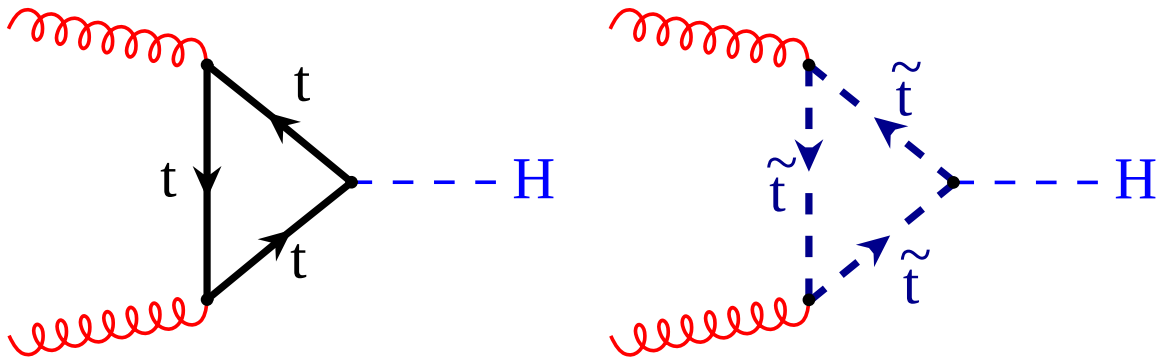

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Gluon Fusion

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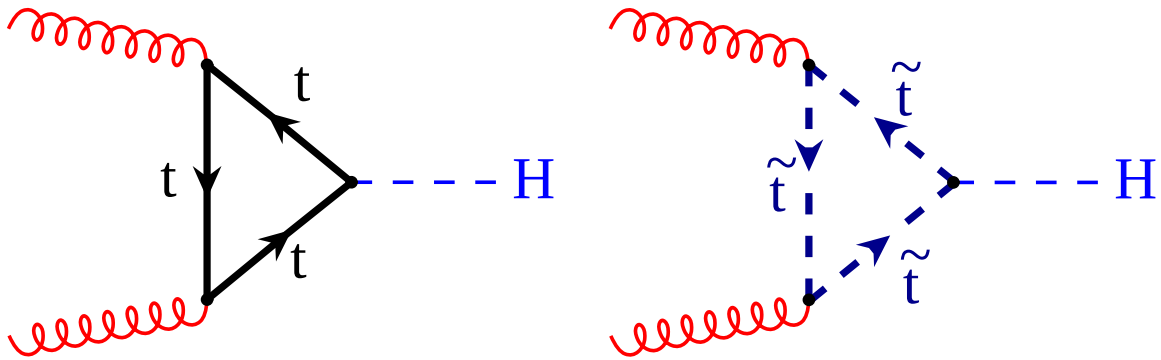

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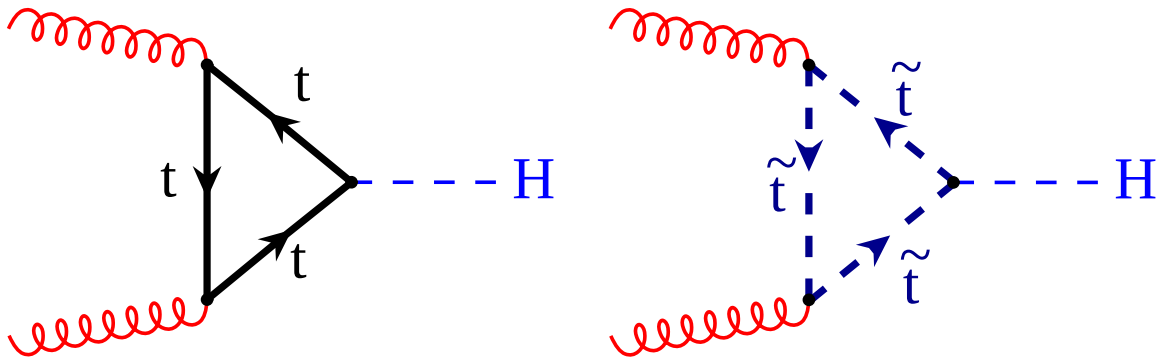

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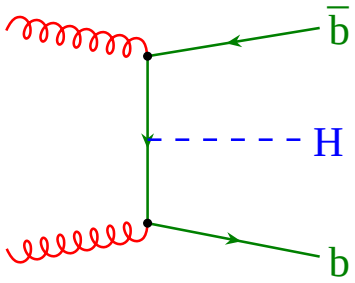
NLO: [RH, Steinhauser '04], [Anastasiou, Beerli, Daleo '08 + Bucherer, Kunszt '06], [Mühlleitner, Rzehak, Spira '07/'08], [Aglietti, Bonciani, Degrassi, Vicini '06], [RH, Hofmann, Mantler '11], [Degrassi, Slavich '08/'10 + Bagnasci, Vicini '11]

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



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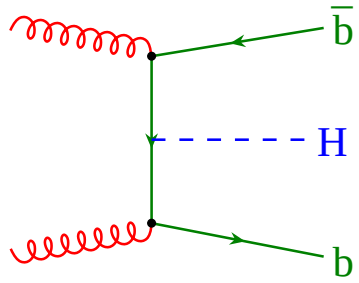

- collinear logarithms: $\sim \alpha_s \ln(m_b/M_H) \sim \alpha_s \ln(5/200)$

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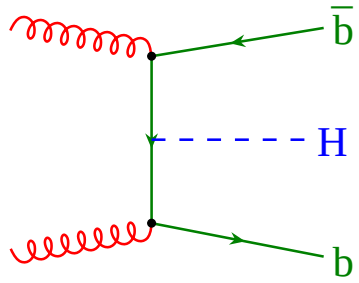

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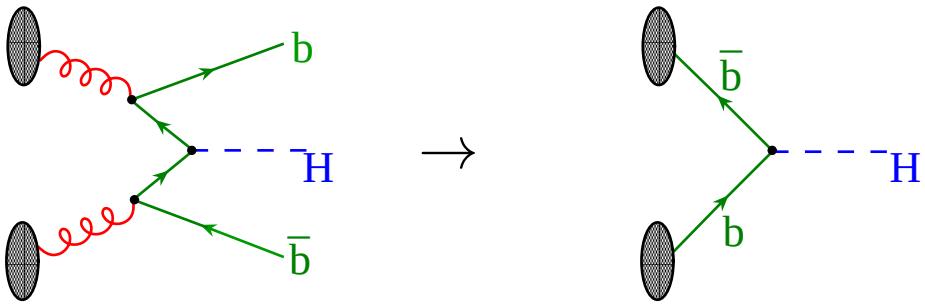
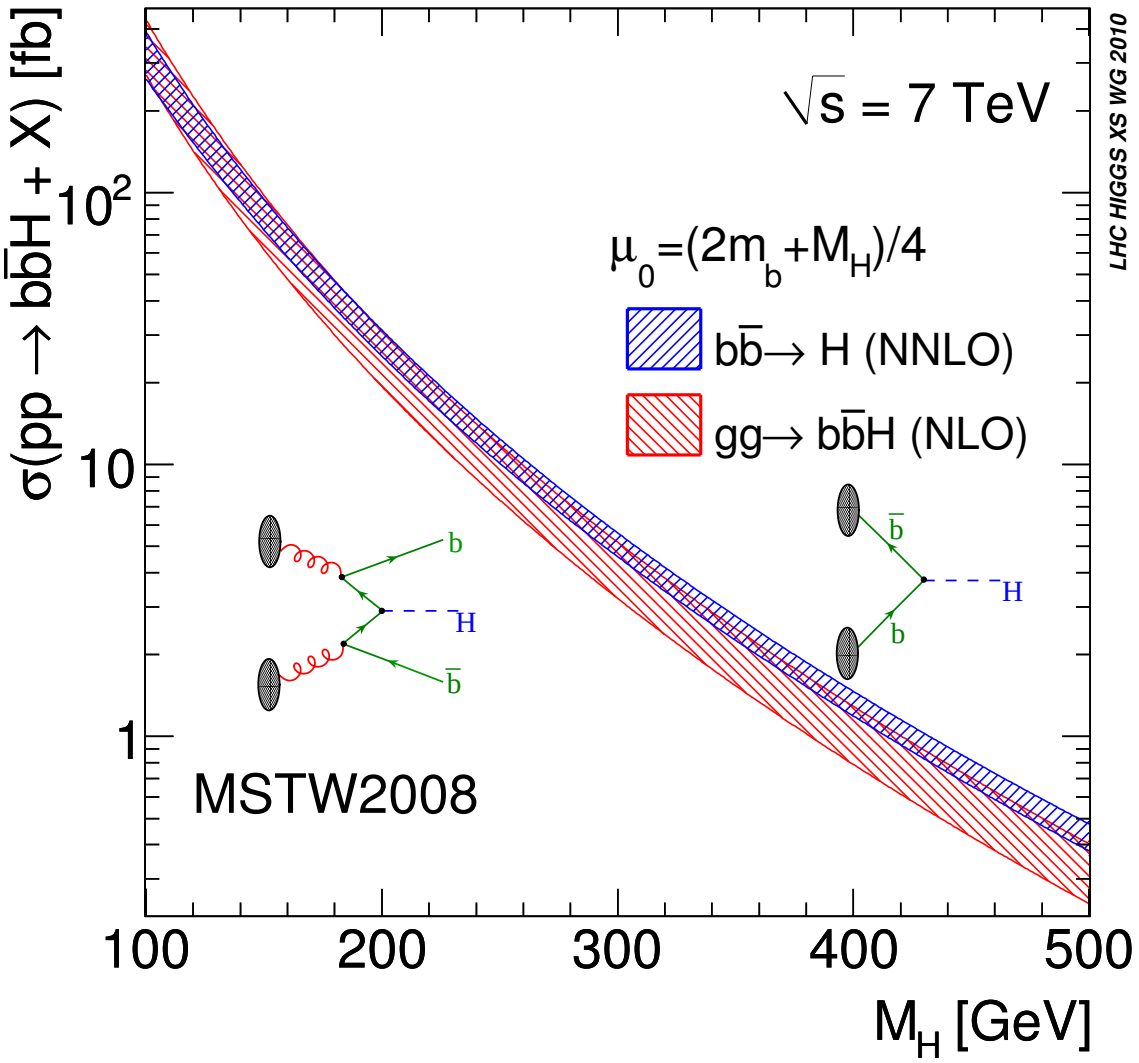


$pp \to H + b\bar{b}$



[RH, Kilgore '03]

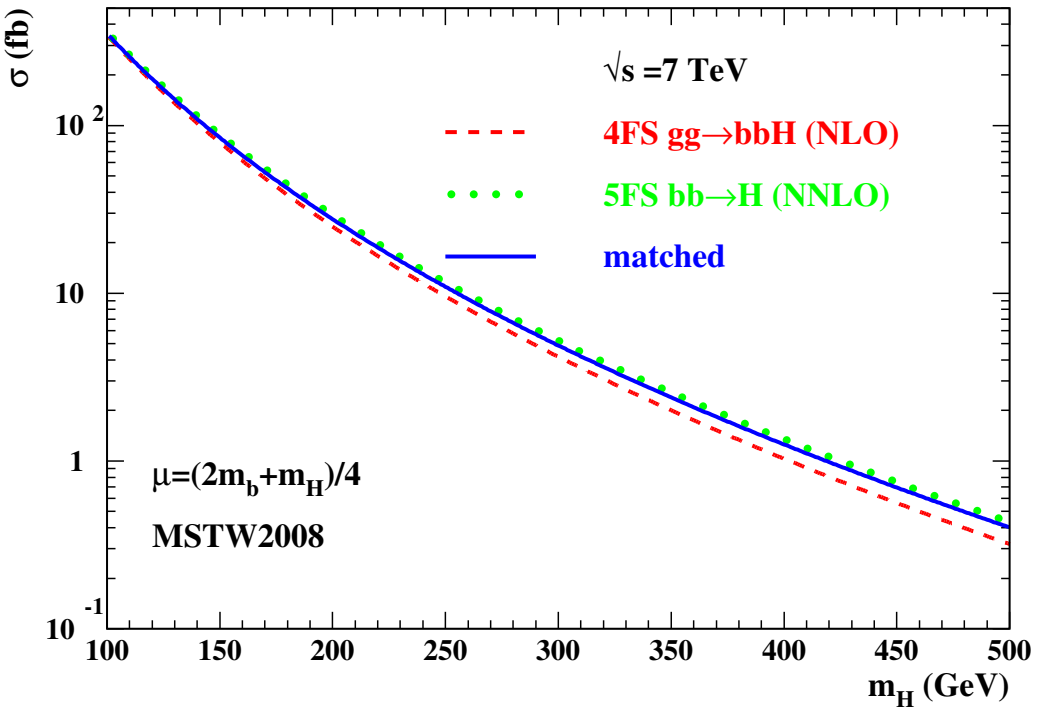
[Dittmaier, Krämer, Spira '04]

[Dawson, Jackson, Reina, Wackeroth '04]

electro-weak:

[Dittmaier, Krämer, Mück, Schlüter '06]

Santander matching



[R.H., Krämer, Schumacher '11]

$$\sigma = \frac{\sigma_{\rm 4FS} + w\sigma_{\rm 5FS}}{1+w}$$

$$\Delta\sigma = \frac{\Delta\sigma_{\rm 4FS} + w\Delta\sigma_{\rm 5FS}}{1+w}$$

$$w = \ln\frac{m_H}{m_b} - 2$$

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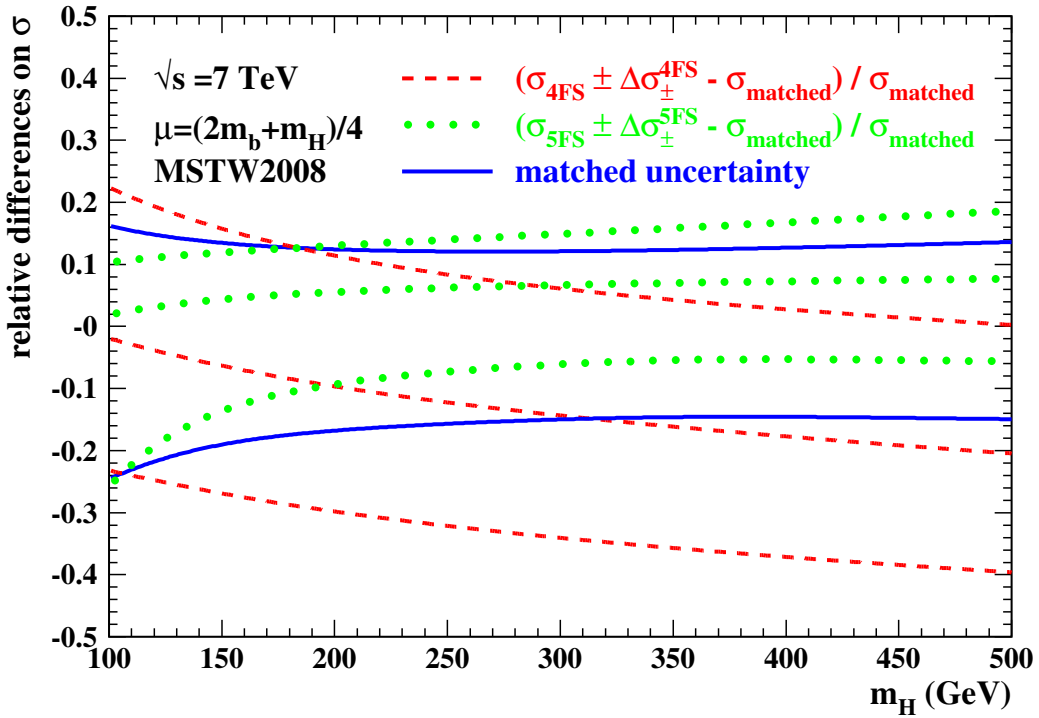

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Conclusions

- inclusive cross sections for Standard Model Higgs production known through NNLO QCD + NLO EW (except $t\bar{t}H$) + BNNLO

  higlu, ggh@nnlo, bbh@nnlo, vh@nnlo, vbfnnlo, ihixs, ...

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- most important BSM scenarios covered

Conclusions

- inclusive cross sections for Standard Model Higgs production known through NNLO QCD + NLO EW (except $t\bar{t}H$) + BNNLO

  higlu, ggh@nnlo, bbh@nnlo, vh@nnlo, vbfnnlo, ihixs, ...
- strong influence on exclusion limits
- uncertainties will be very important for measurements
- most important BSM scenarios covered
- Higgs physics could soon be precision physics!