Higgs

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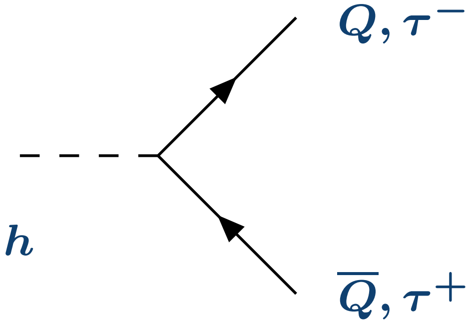
- **Higgs Phenomenon**
- **Higgs in the Standard Model**
- **Bounds on Higgs mass from theory**
    - **Unitarity**
    - **Landau pole**
    - **Perturbativity**
- **Bounds on Higgs mass from experiments**
- **Higgs Decays**
- **Higgs Production**

Higgs Decay

Higgs Decay



$$\frac{m_f}{v}, \qquad f = Q, \tau$$

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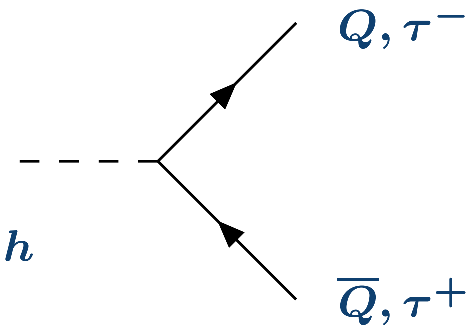

$$\Gamma = \frac{N_c \alpha_{em}}{8 M_W^2 \sin^2\theta_W} m_f^2 m_h \beta(m_f)$$

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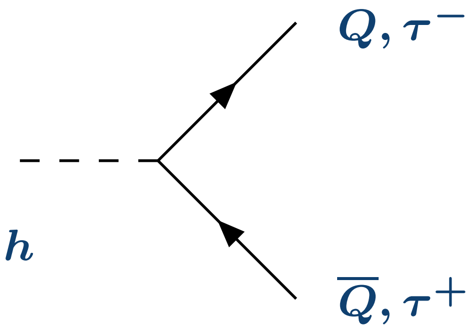

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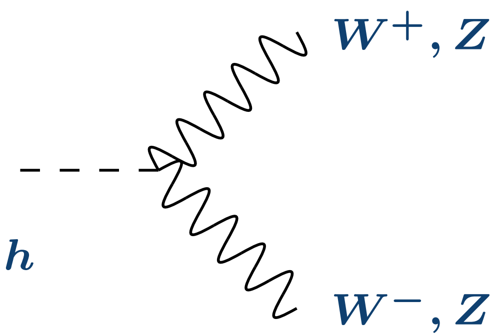

$\frac{m_V^2}{v} g^{\mu\nu}$, $\qquad V = W^\pm, Z$

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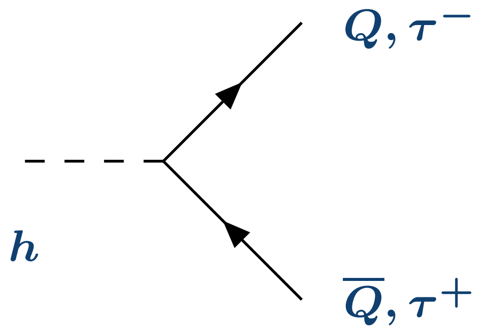

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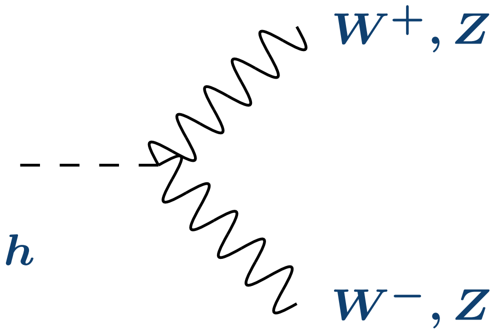
$$\Gamma_W = \frac{\alpha_{em} m_h^3}{16 M_W^2 \sin^2\theta_W} \left(1 - \frac{4M_W^2}{m_h^2} + \frac{3}{4}\left(\frac{4M_W^2}{m_h^2}\right)^2\right) \beta(M_W)$$

$$\Gamma_Z = \frac{\alpha_{em} m_h^3}{32 M_W^2 \sin^2\theta_W} \left(1 - \frac{4M_Z^2}{m_h^2} + \frac{3}{4}\left(\frac{4M_Z^2}{m_h^2}\right)^2\right) \beta(M_Z)$$

$$\beta(m) = \sqrt{1 - 4m^2/m_h^2}$$



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Higgs Decay to gluons

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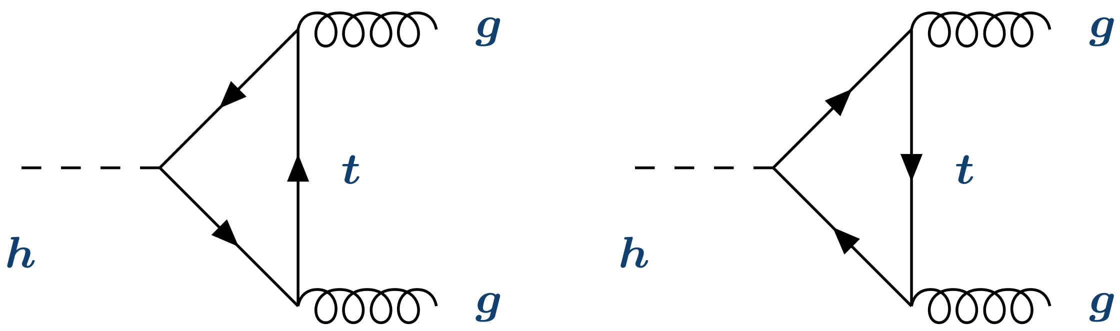

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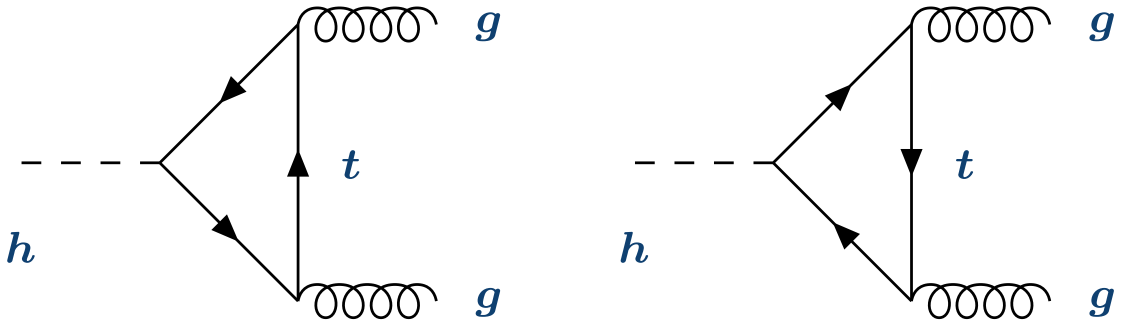

Higgs decay to pair of gluons can be described by an effective Lagrangian

$$\mathcal{L} = -\frac{g^2}{2M_W}\frac{\alpha_s}{12\pi}\, I\, G^a_{\mu\nu}G^{a\mu\nu}h\,,$$

where

$$I = 3\sum_q \Big(2\tau_q + \tau_q(4\tau_q - 1)f(\tau_q)\Big)\,, \qquad \tau_q = \frac{4m_q^2}{m_h^2}$$

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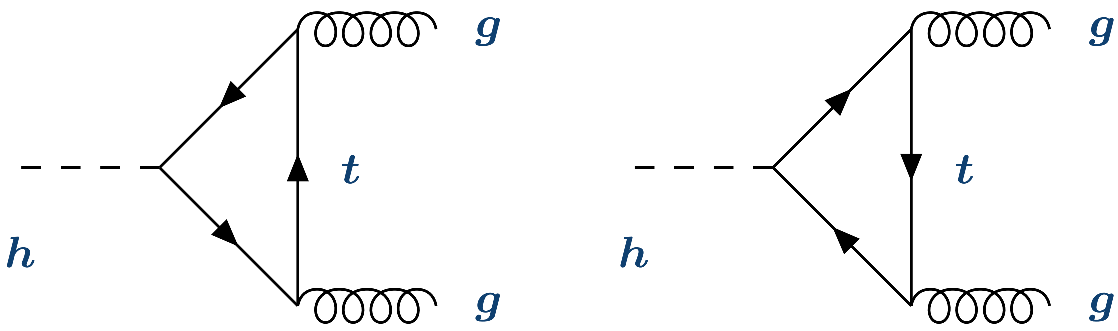

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$$\begin{aligned} f(\lambda) &= -2\left(\sin^{-1}\frac{1}{\sqrt{\lambda}}\right)^2 && \text{for} \quad \lambda > \frac{1}{4} \\ &= \frac{1}{2}\left(\log\frac{\eta^+}{\eta^-}\right)^2 - \frac{\pi^2}{2} + i\pi\log\frac{\eta^+}{\eta^-} && \text{for} \quad \lambda < \frac{1}{4} \end{aligned}$$

where $\eta^{\pm} = 1/2 \pm \sqrt{1/4 - \lambda}$.

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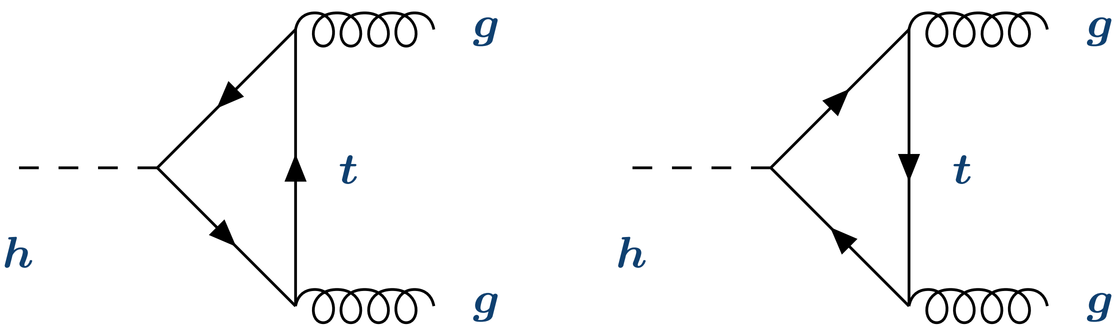

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$$\Gamma_g = \frac{g^2\alpha_s^2(m_h)}{288\pi^3}\frac{m_h^3}{m_W^2}|I|^2\,, \qquad \alpha_s = \frac{g_s^2}{4\pi}$$

Higgs Decay to photons

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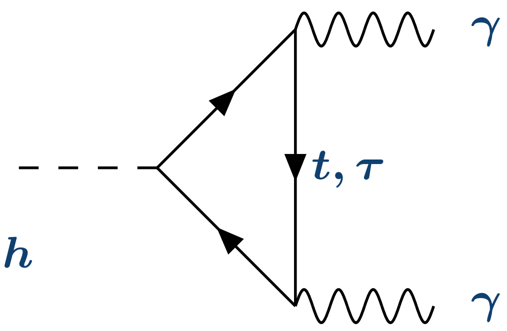

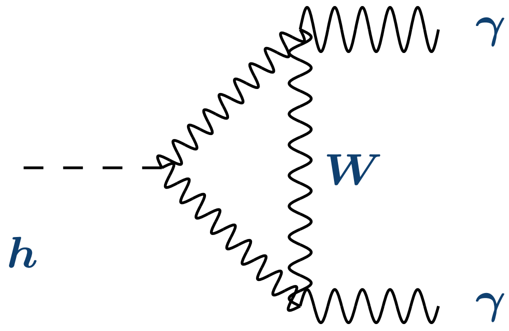

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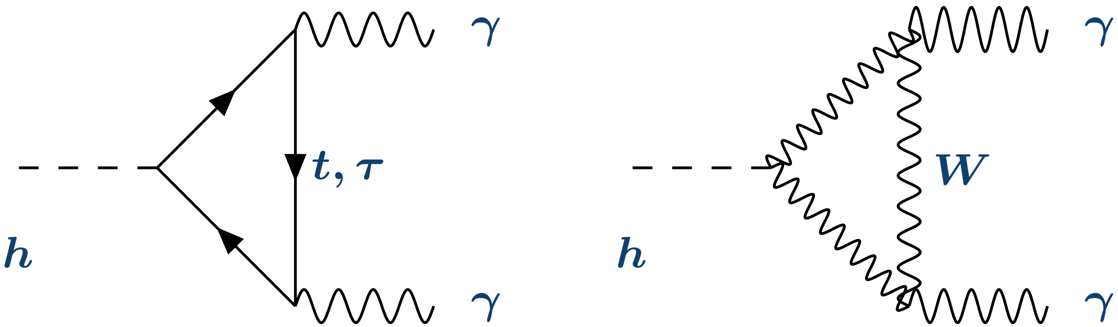

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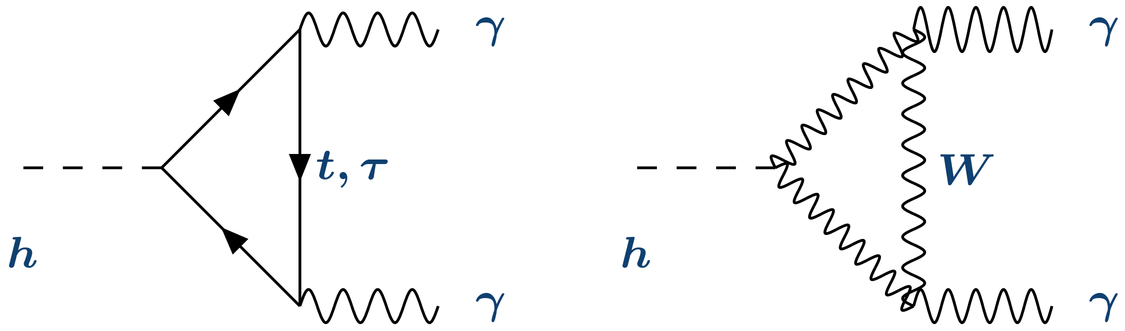

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Higgs Decay

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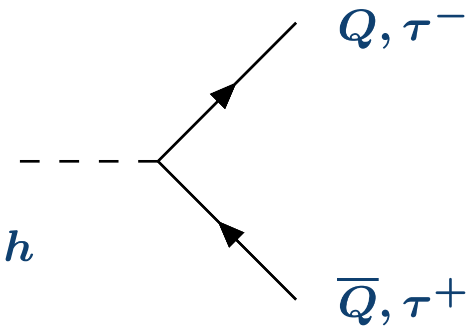

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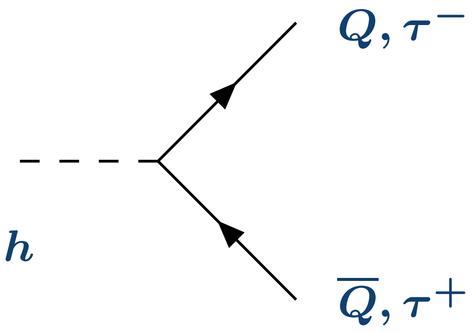

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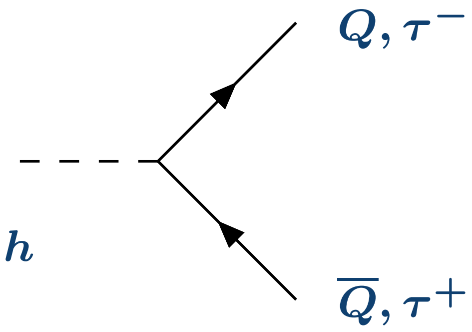

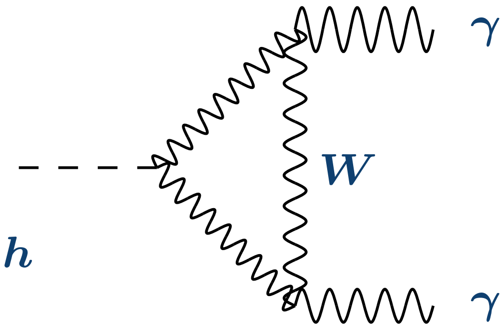

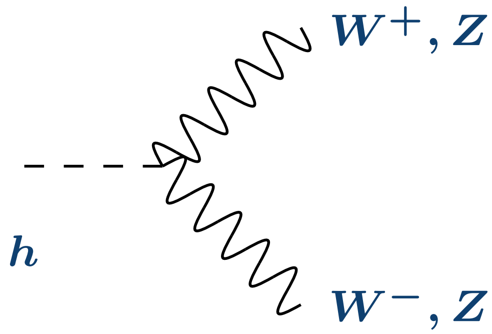

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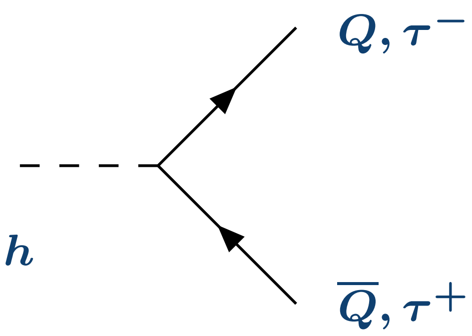

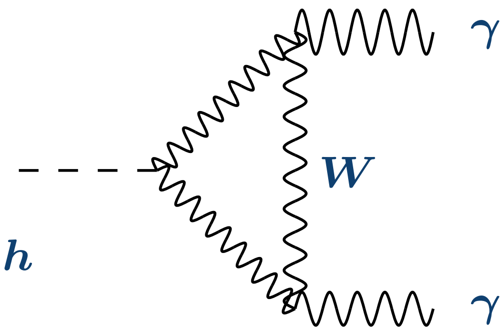

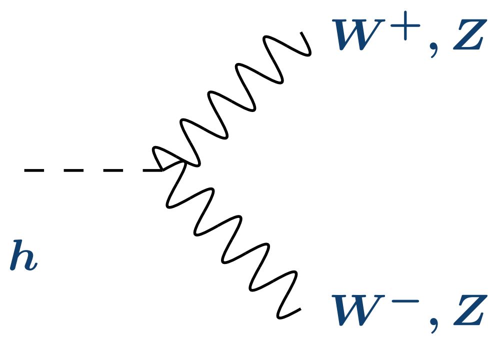

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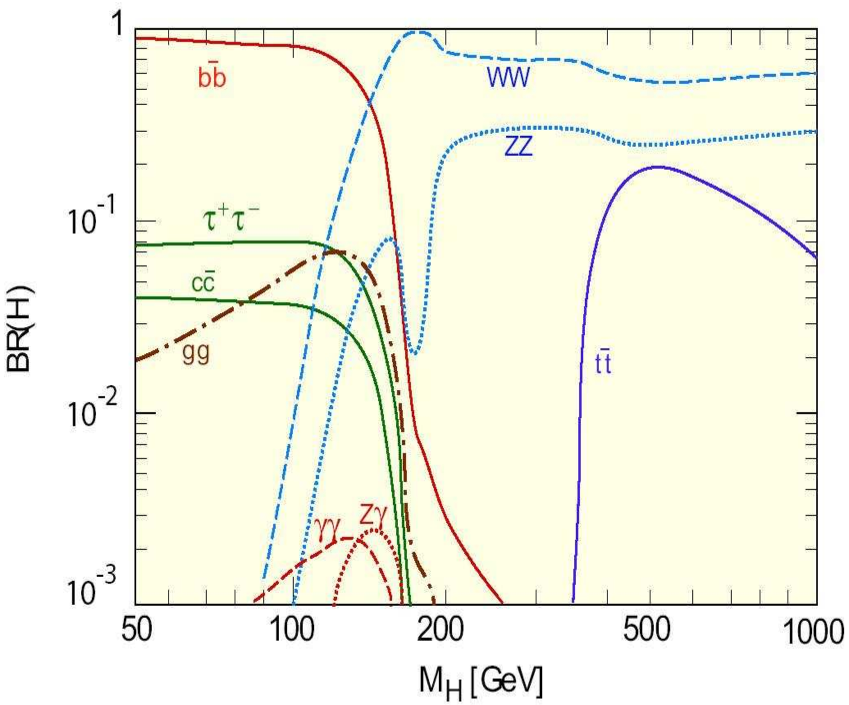

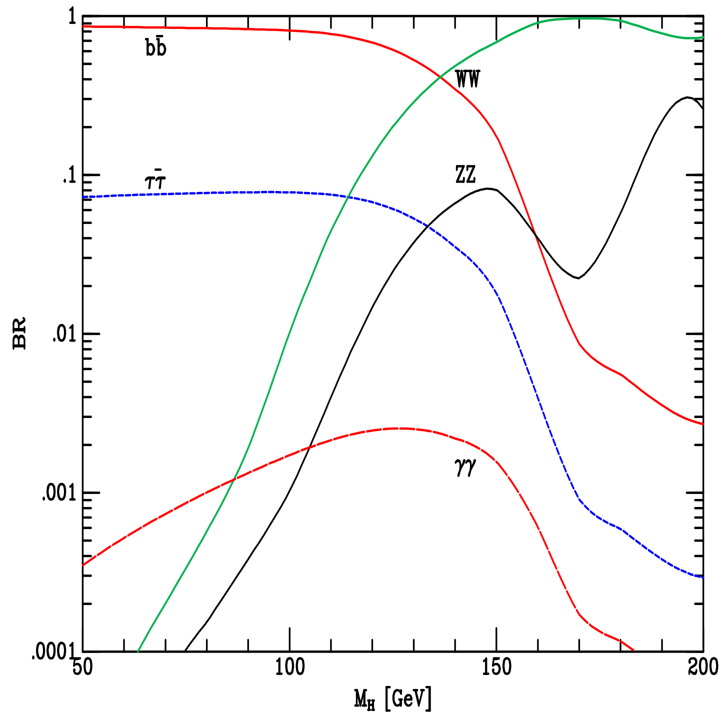

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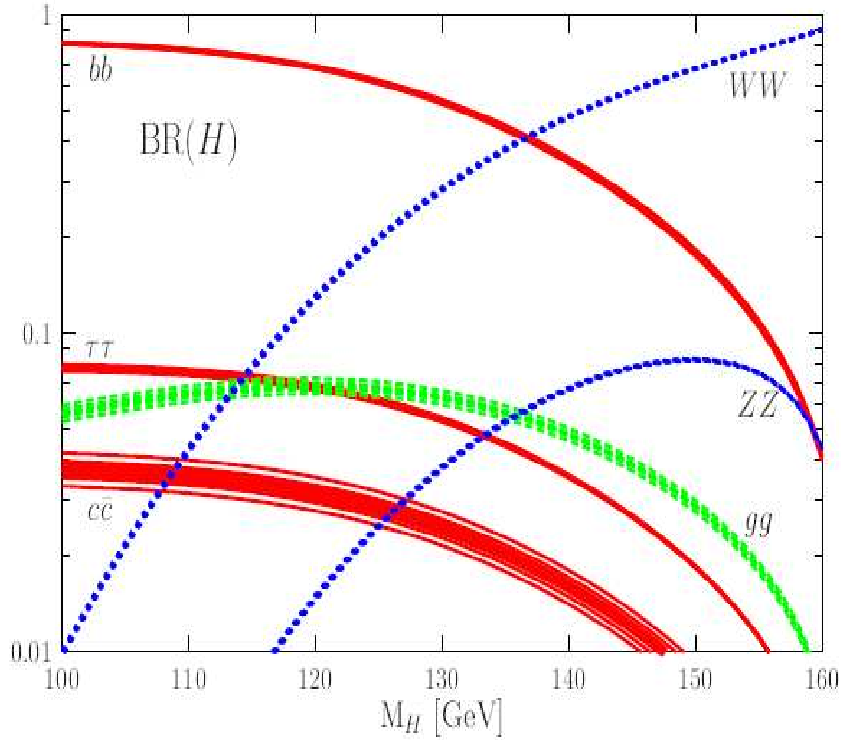

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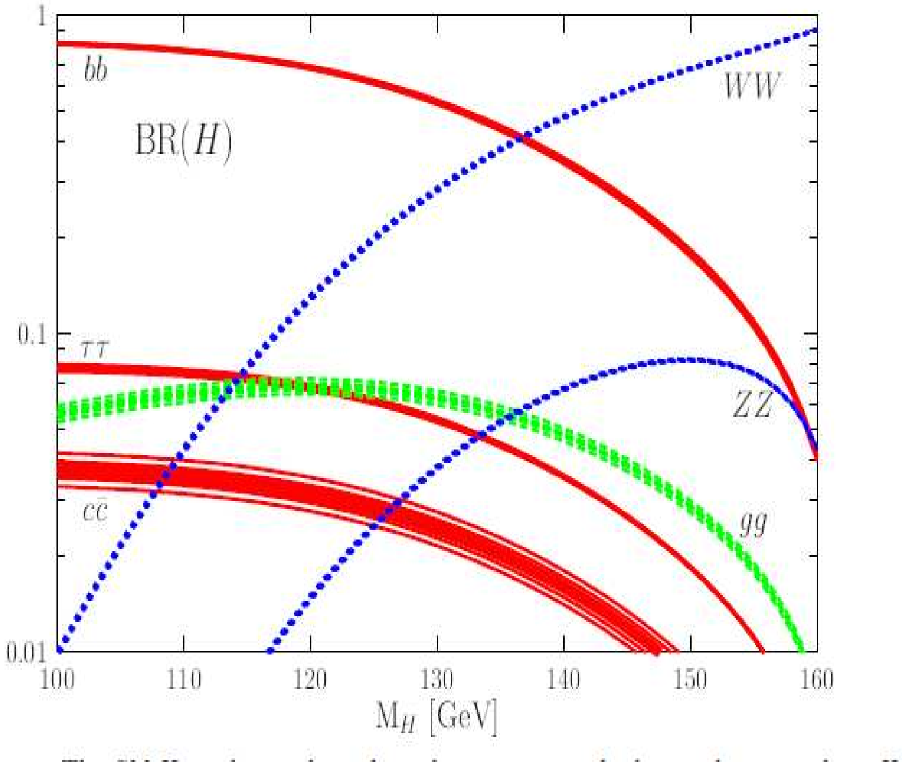

Decay rates are proportional to coupling constants and the massies:

- Strong coupling constant ($\alpha_s(M_Z) = 0.1172 \pm 0.002$)
- Quark masses ($m_t = 178 \pm 4.3\ GeV, m_b = 4.88 \pm 0.07\ GeV$ and $m_c = 1.64 \pm 0.07\ GeV$)

Higgs Production $P_1 + P_2 \to h + X$

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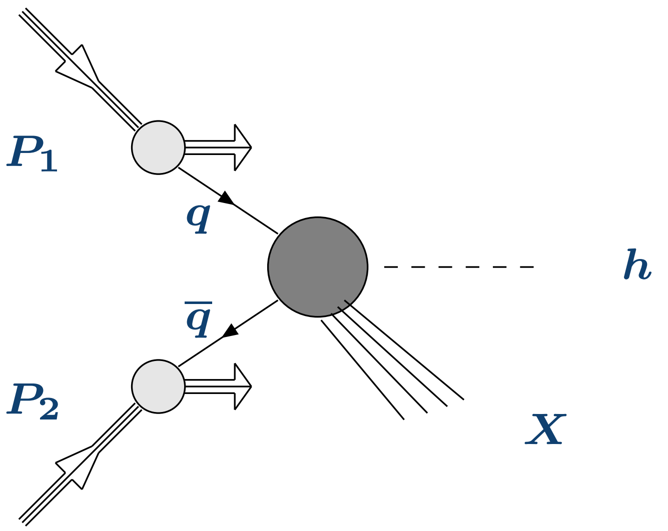

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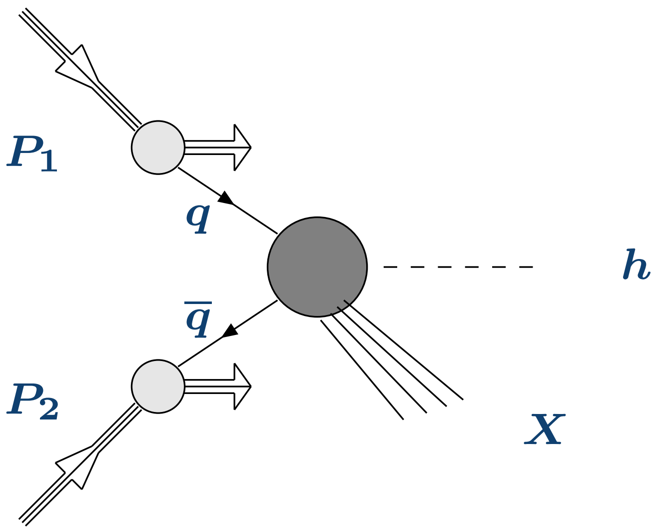

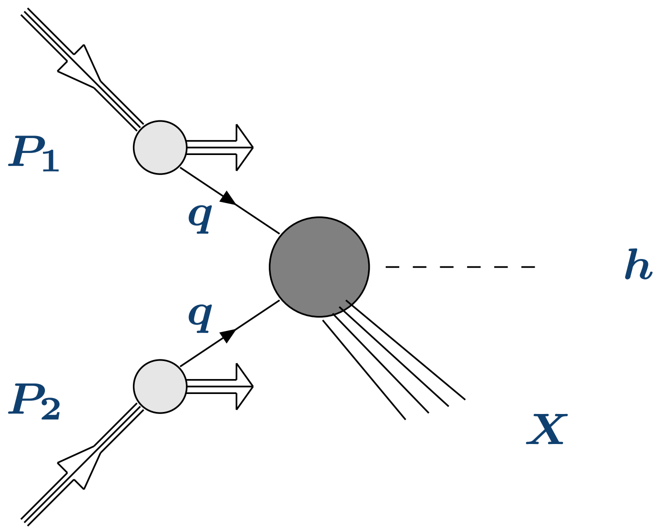

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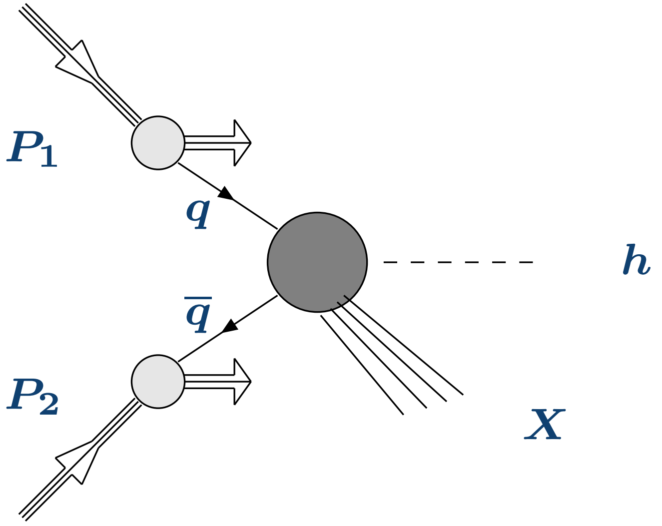

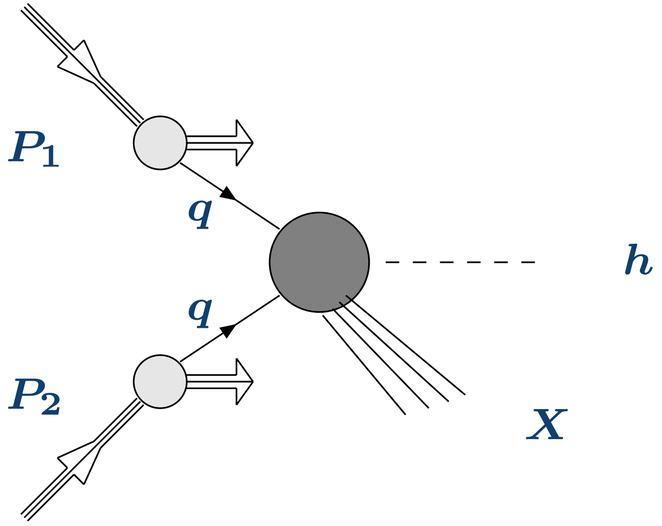

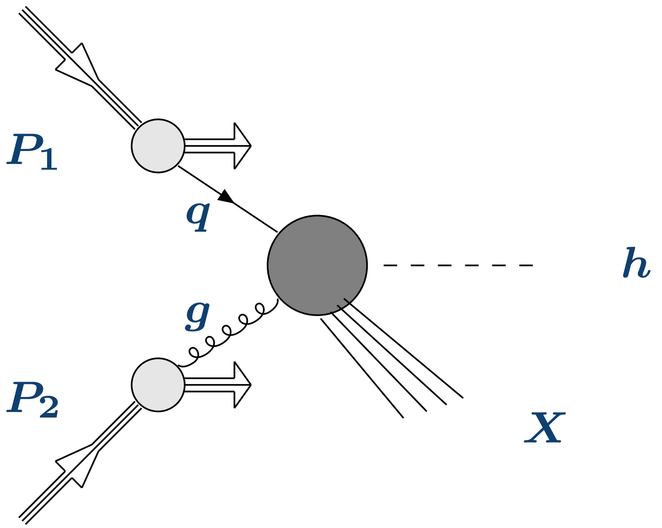

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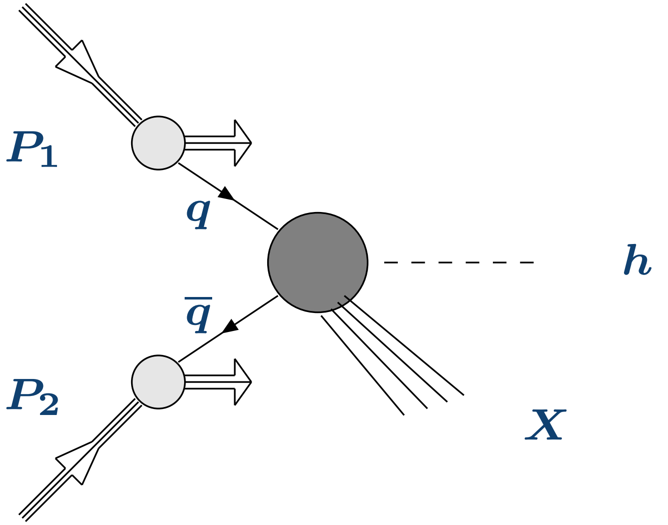
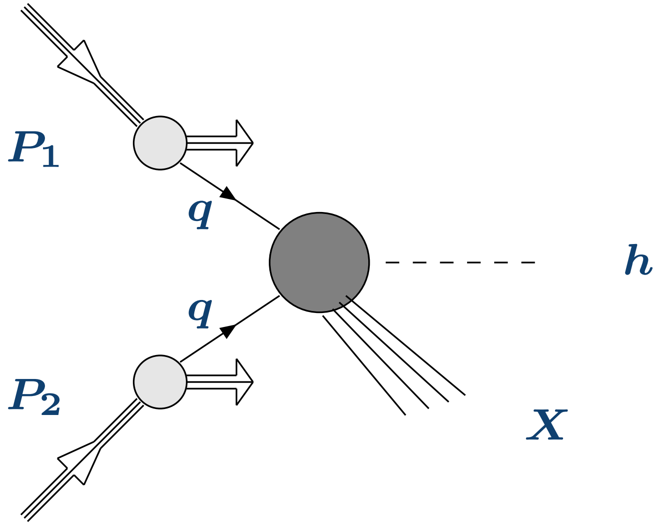
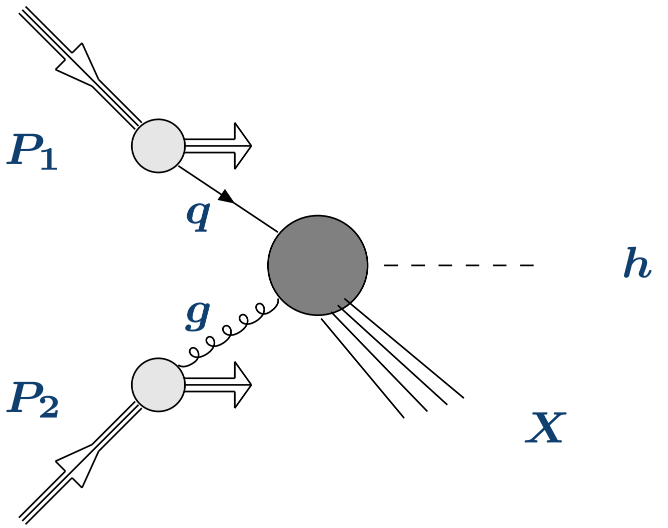
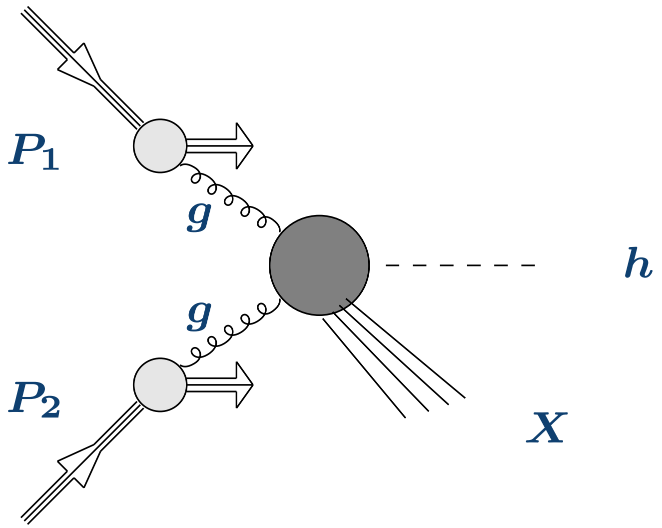
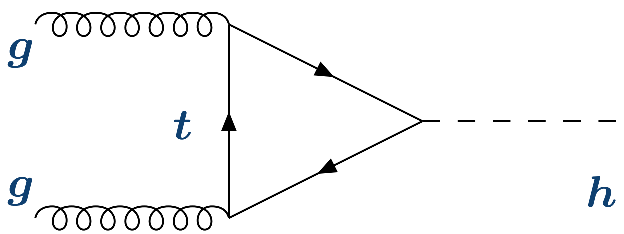


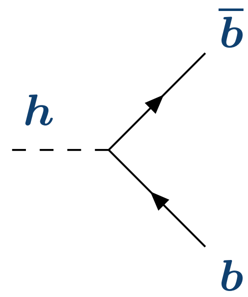


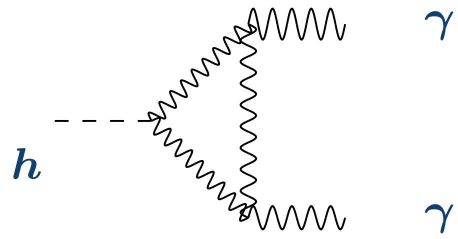




Gluon fusion







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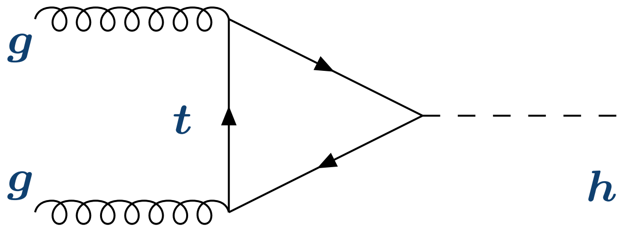

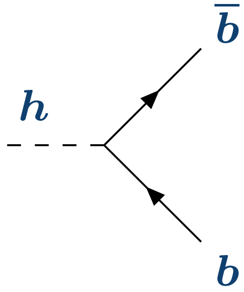

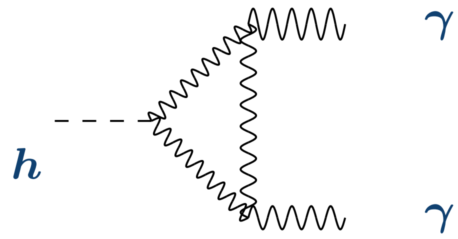

- Inclusive Higgs production

$$g + g \to h \to b\overline{b}, \tau\overline{\tau}, WW, ZZ, \gamma\gamma$$

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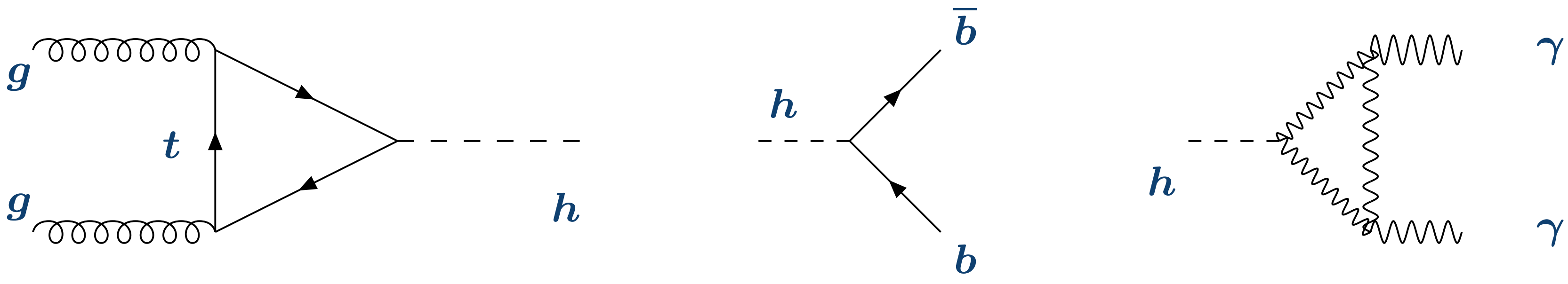

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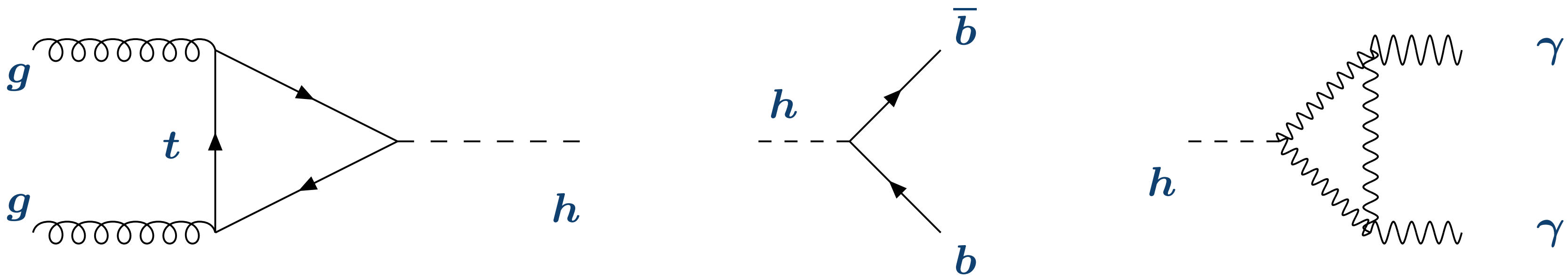

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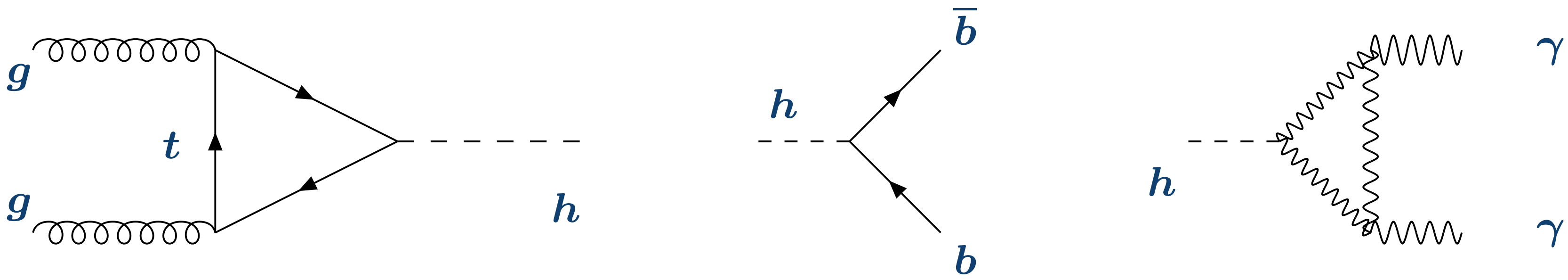

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$$g + g \to h \to W^+W^-/ZZ/\gamma\gamma$$

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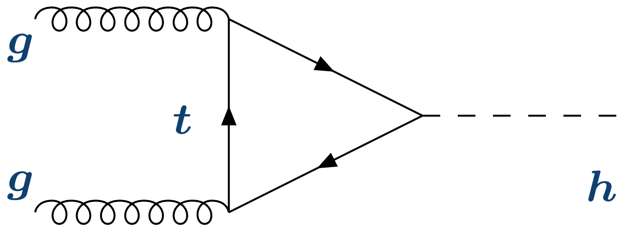
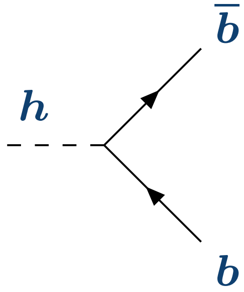
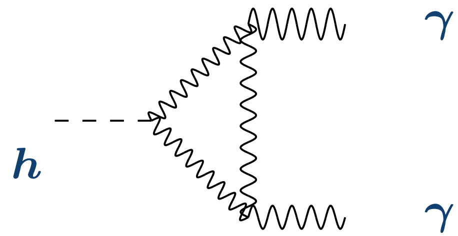
Gluon fusion







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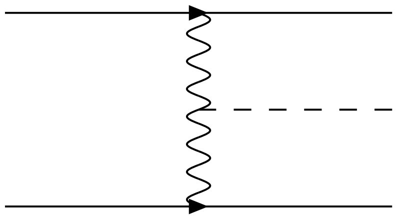
- Ideal discovery mode.

Vector Boson Fusion



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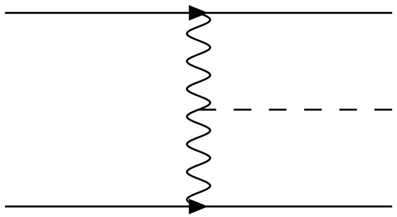

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$$h \rightarrow \tau^+ + \tau^-$$

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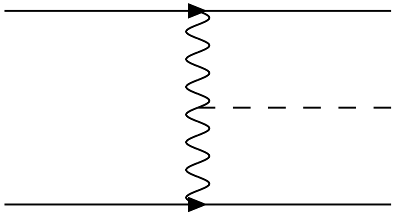

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- No color exchange due to t channel process.
- Signal is
  a) two jets with one in the forward and the other in the backward direction and
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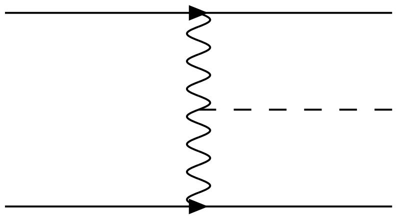
- Background is very less

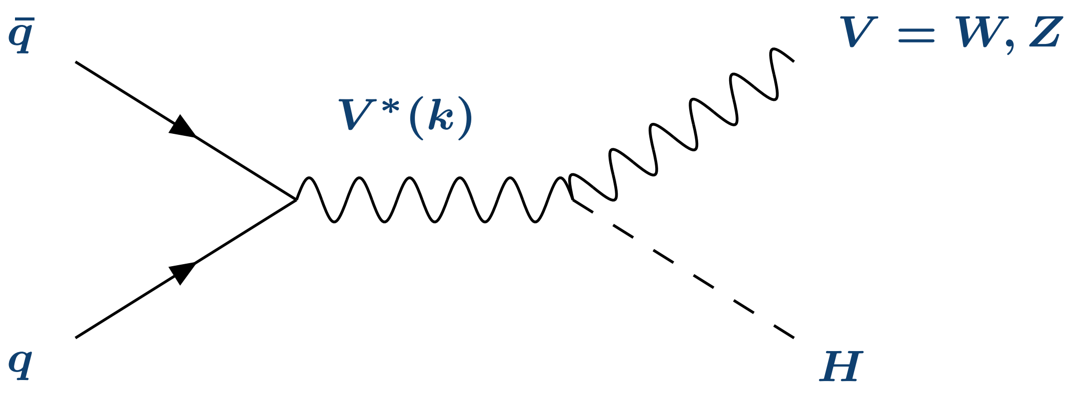
Vector Boson Fusion



$$q + q' \rightarrow \quad (V + V) \quad \rightarrow \qquad h + q + q'$$
$$h \rightarrow \tau^+ + \tau^-$$

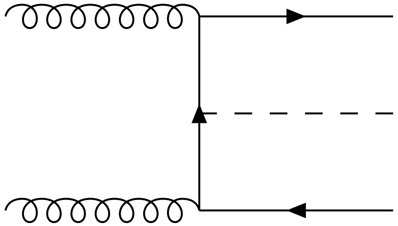
- No color exchange due to t channel process.
- Signal is
  a) two jets with one in the forward and the other in the backward direction and
  b) jet veto in the central region.
- Background is very less
- Good discovery channel.

Higgs Strahlung



- If $m_h < 200\ GeV$, W boson with Higgs is one of the most promising channel at Tevatron.
- $W \rightarrow l + \nu$ and $h \rightarrow (W^+W^-)/\bar{b}b$
- At LHC, the cross section is small

Associated production with tops



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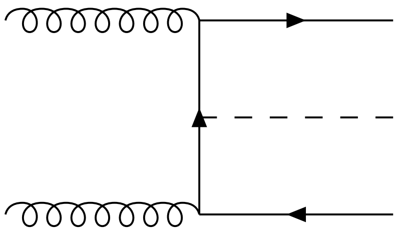

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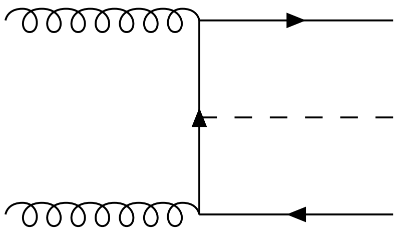

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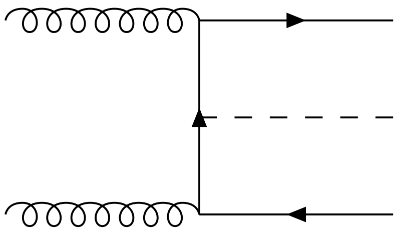

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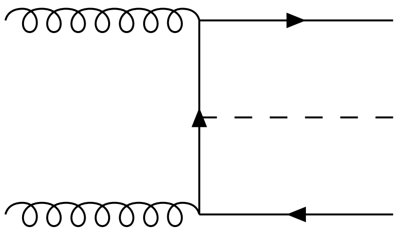

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- Large luminosity is requied to increase the sensitivity.

Parton Model

Bjorken, Feynman

$$P_1 + P_2 \rightarrow higgs + X$$

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$$2S\, d\sigma^{P_1 P_2}\left(\tau, m_h^2\right) = \sum_{ab} \quad f_a\left(\tau\right) \quad \otimes \quad f_b\left(\tau\right) \quad \otimes \quad 2\hat{s}\, d\hat{\sigma}^{ab}\left(\tau, m_h^2\right), \qquad \tau = \frac{m_h^2}{S}$$

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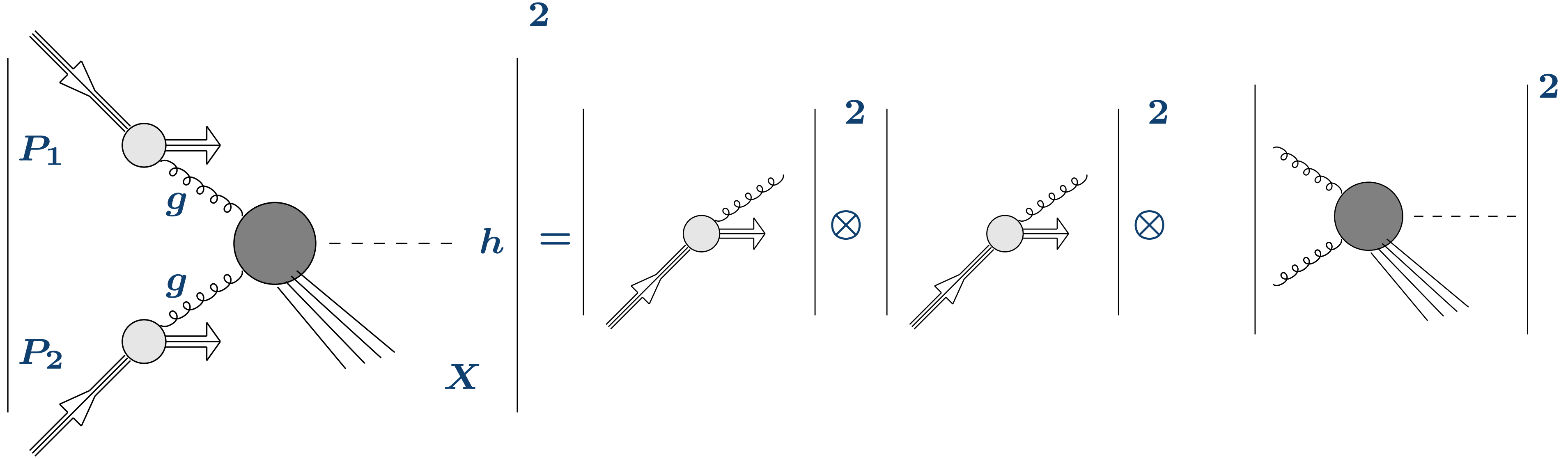

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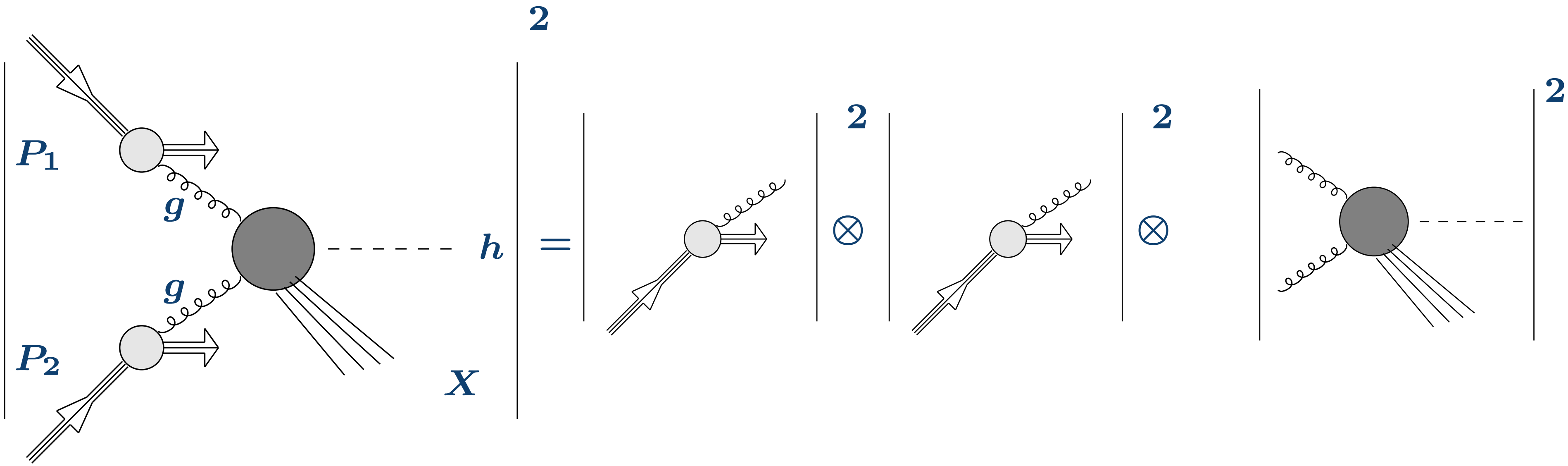

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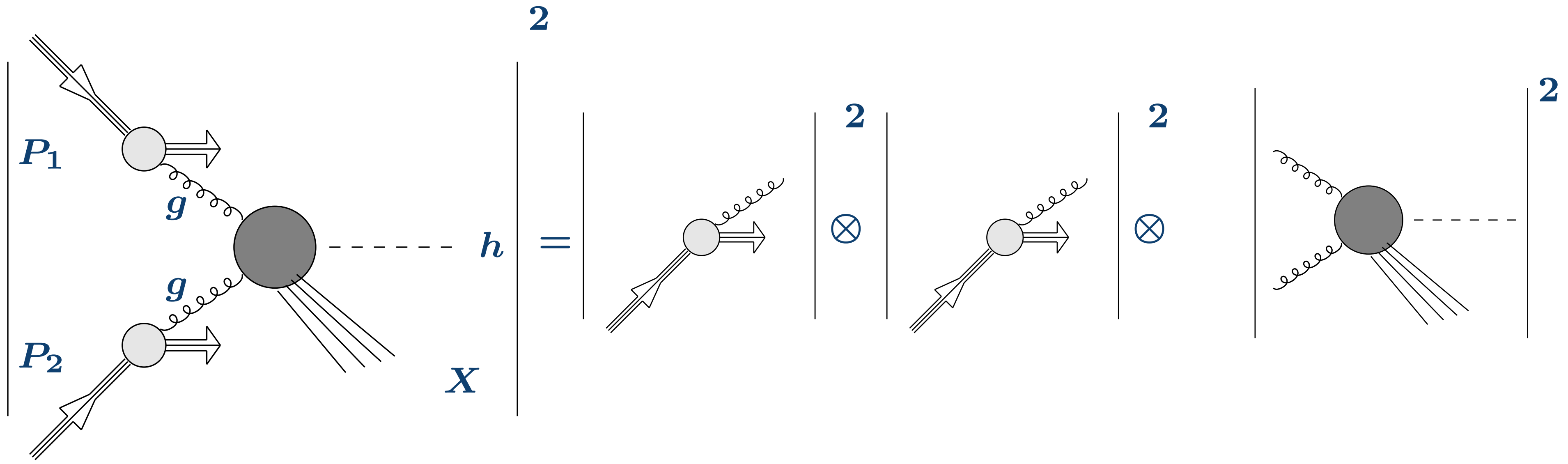

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- $\hat{\sigma}_{ab}$ are the partonic cross sections.
- Perturbatively calculable.

Renormalisation Group Invariance

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$$2S\, d\sigma^{P_1 P_2}\left(\tau, m_H^2\right) = \sum_{ab} \int_{\tau}^{1} \frac{dx}{x} \Phi_{ab}\left(x, \mu_F\right) 2\hat{s}\, d\hat{\sigma}^{ab}\left(\frac{\tau}{x}, m_H^2, \mu_F\right)$$

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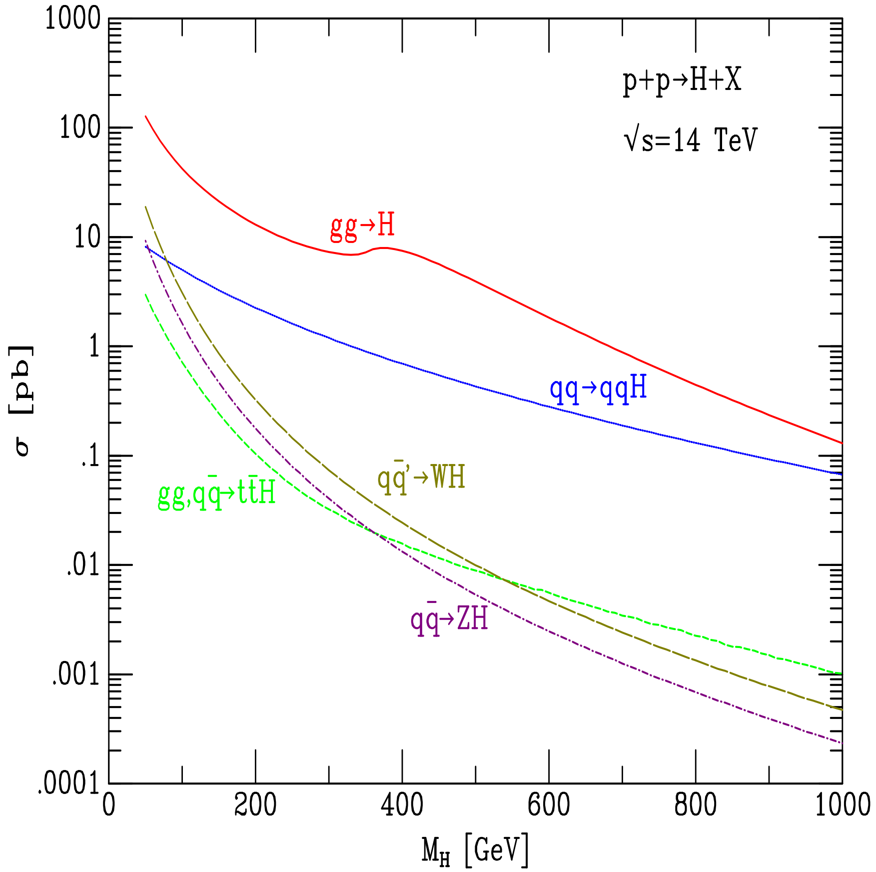
More and more terms in the perturbative expansion can reduce the scale uncertainty

Example: Higgs Production



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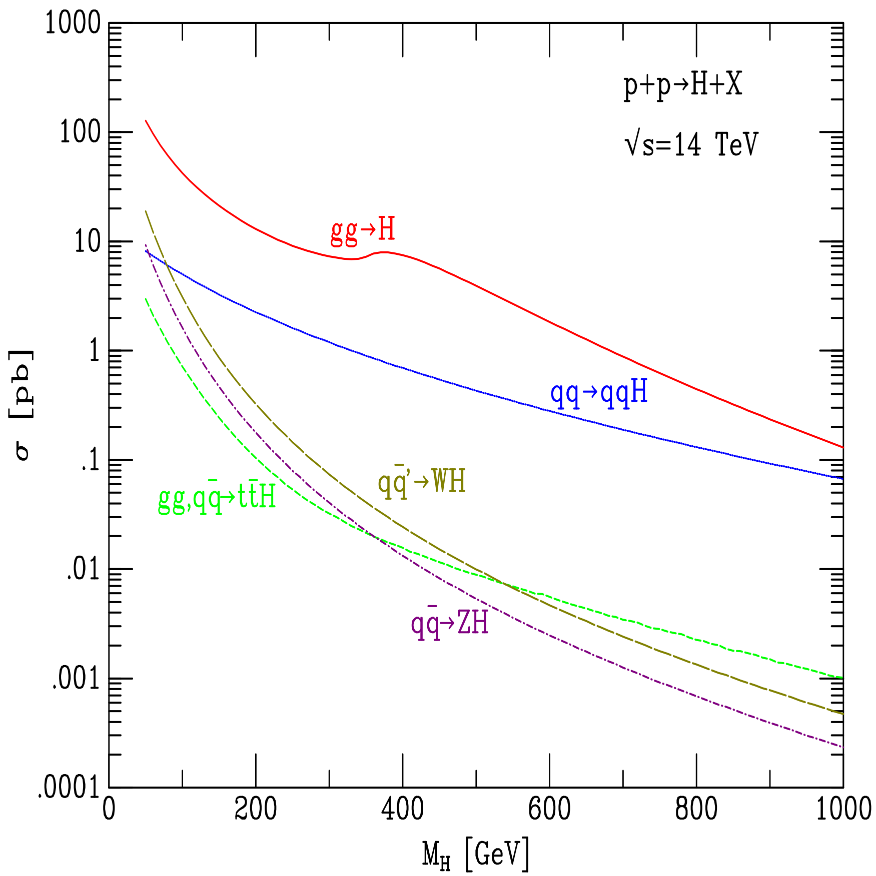

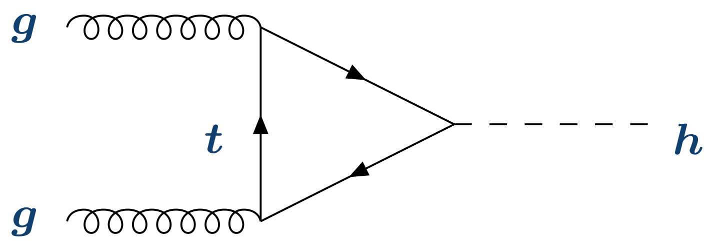

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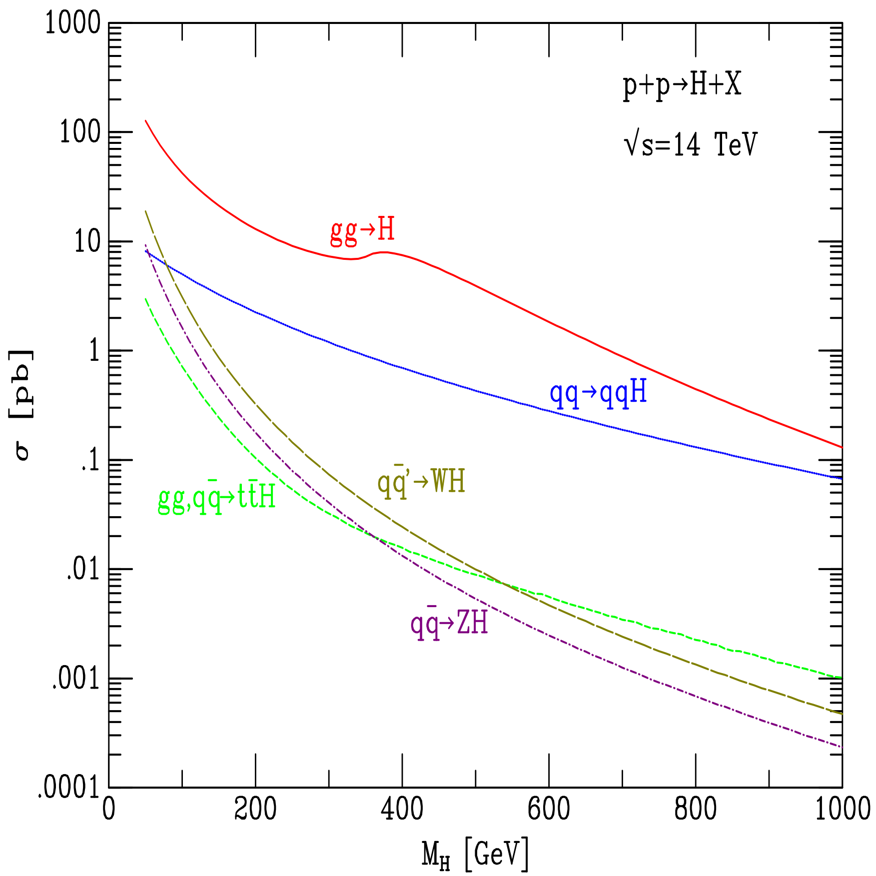

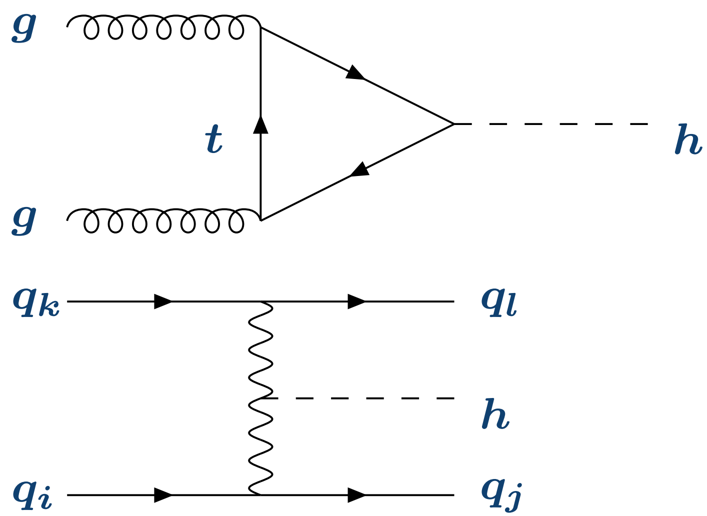

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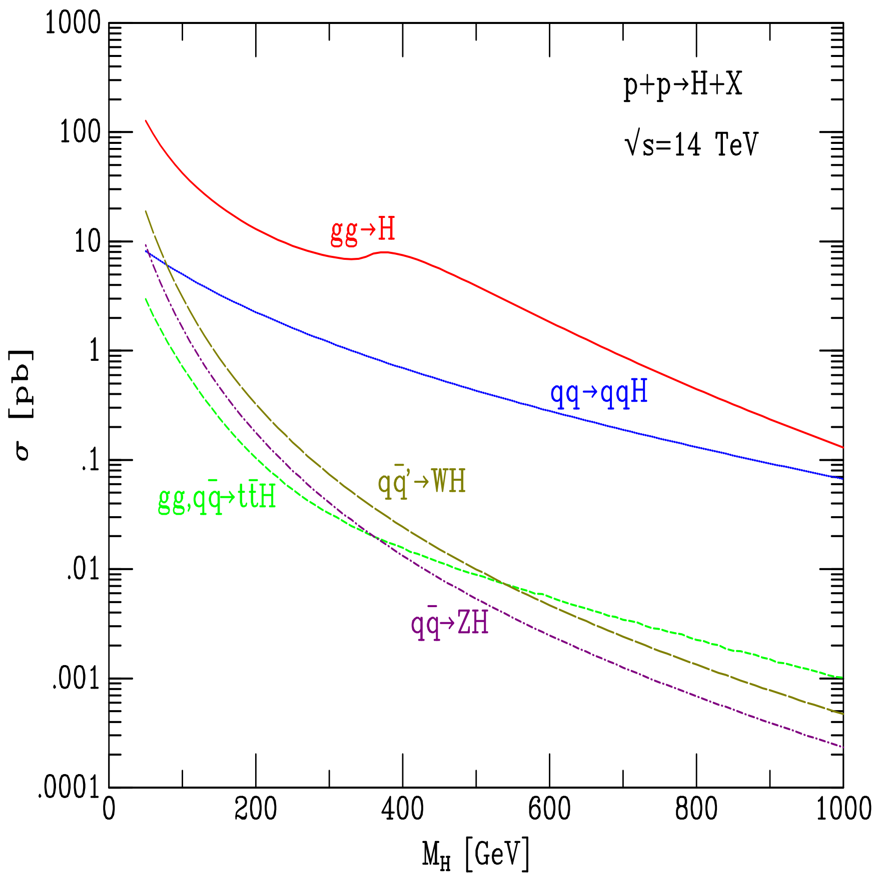

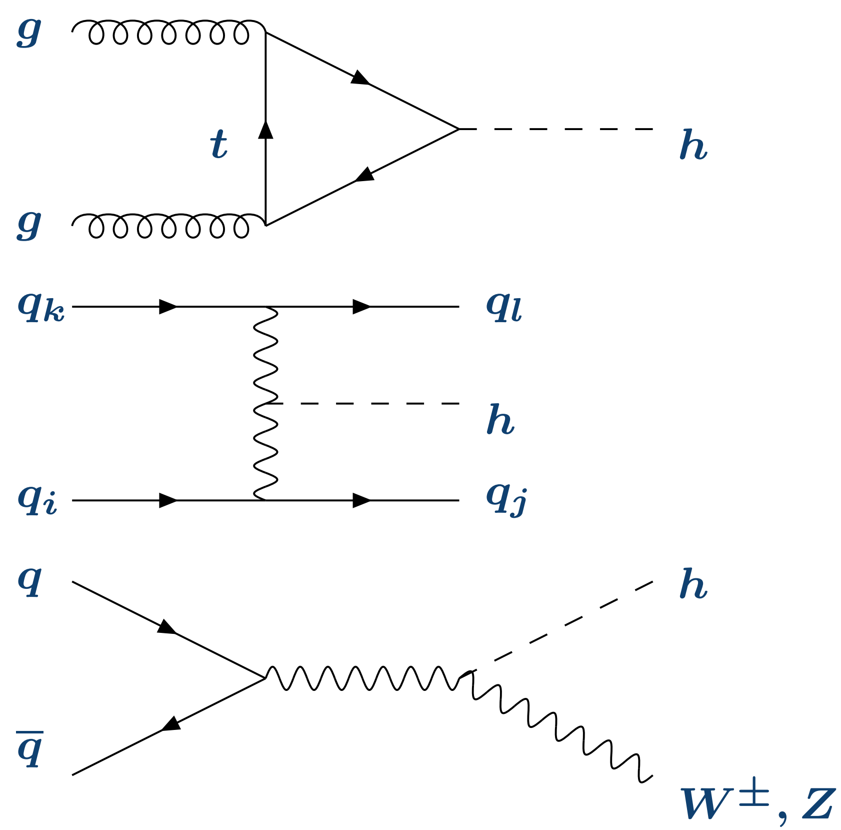

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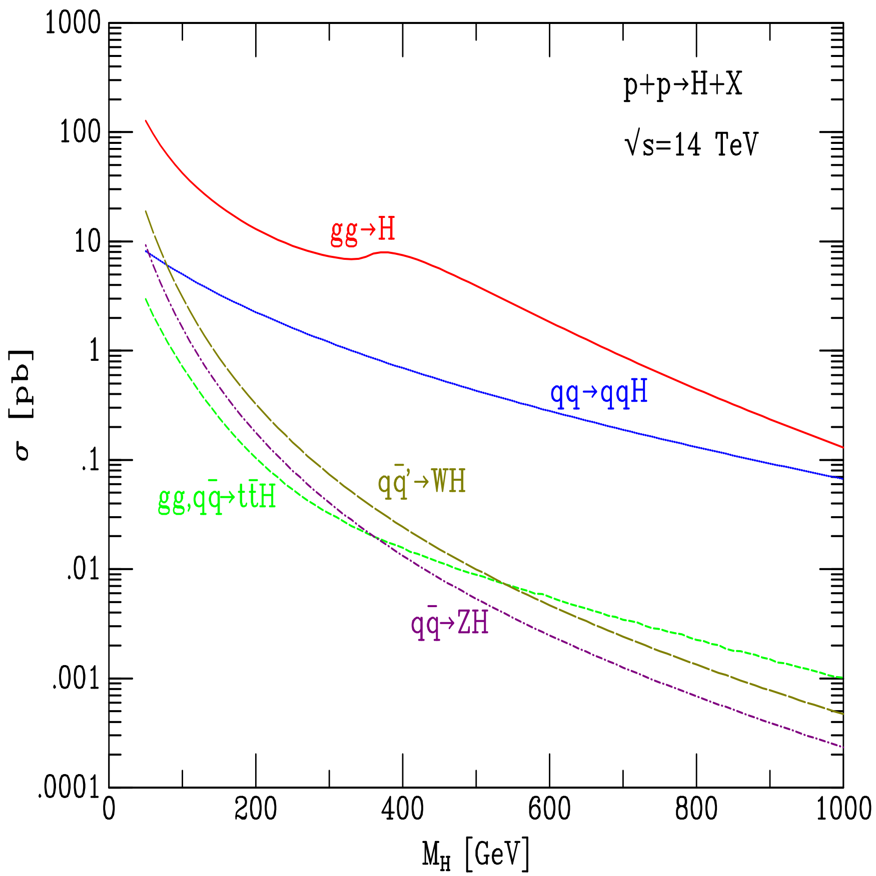

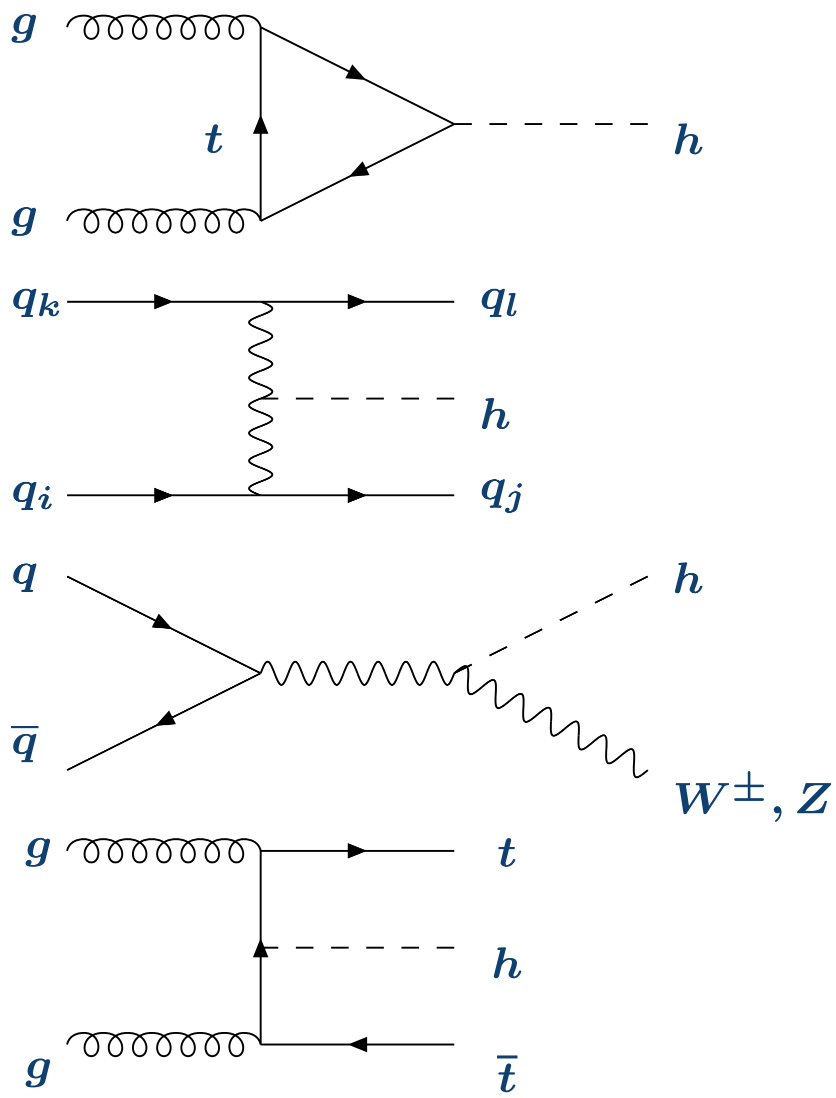

Haber

Higgs production at Leading Order(LO)

Hinchcliff, many others

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$$2S\, d\sigma^{PP}(x, m_h) = \int_x^1 \frac{dz}{z} \Phi_{gg}^{(0)}(z, m_h, \mu_F)\, 2\hat{s}\, d\hat{\sigma}_{gg}^{(0)}\left(\frac{x}{z}, m_h^2, \mu_R\right) + \cdots$$

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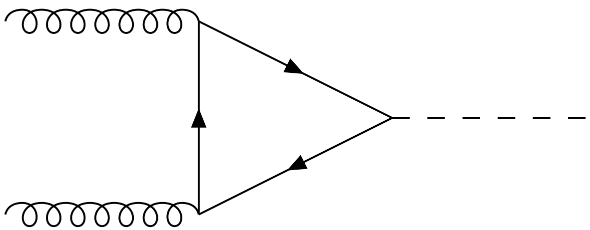

$$N = \frac{\sigma_{LO}^{PP}(\mu_F = \mu_R = \mu)}{\sigma_{LO}^{PP}(\mu_F = \mu_R = \mu_0)}$$

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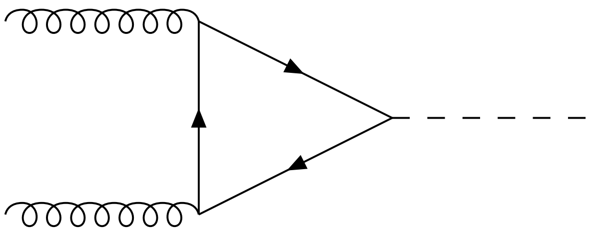

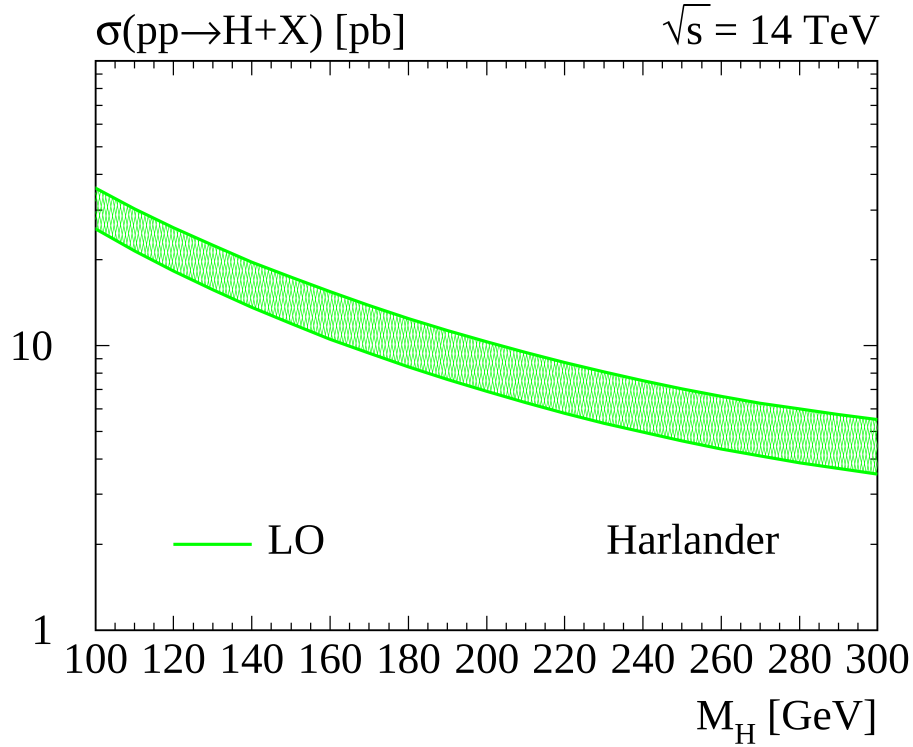

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Higgs production at NLO

$Djouadi, Spira, Zerwas, Dawson$

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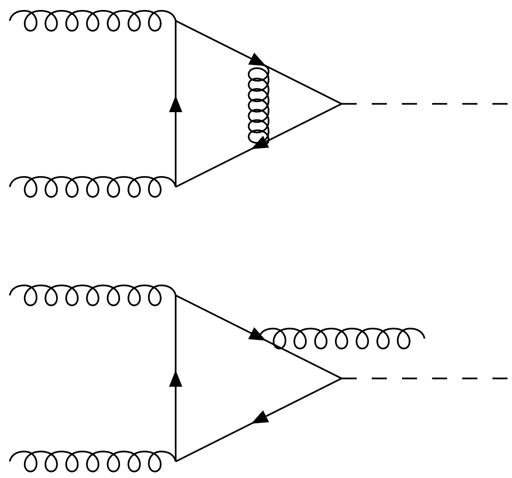

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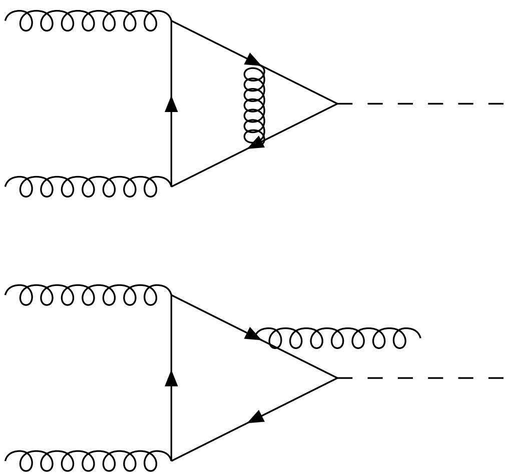

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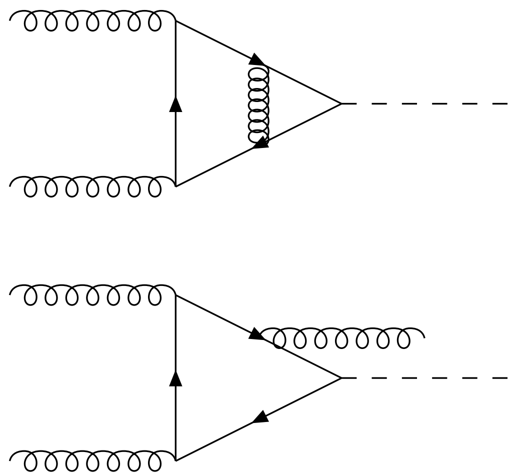

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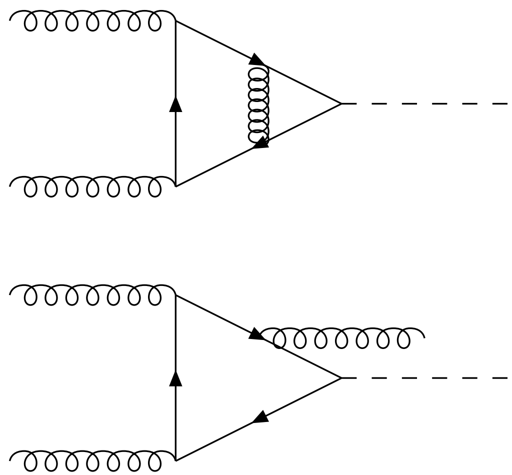

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- Collinear mass factorisation is done in $\overline{MS}$ scheme.

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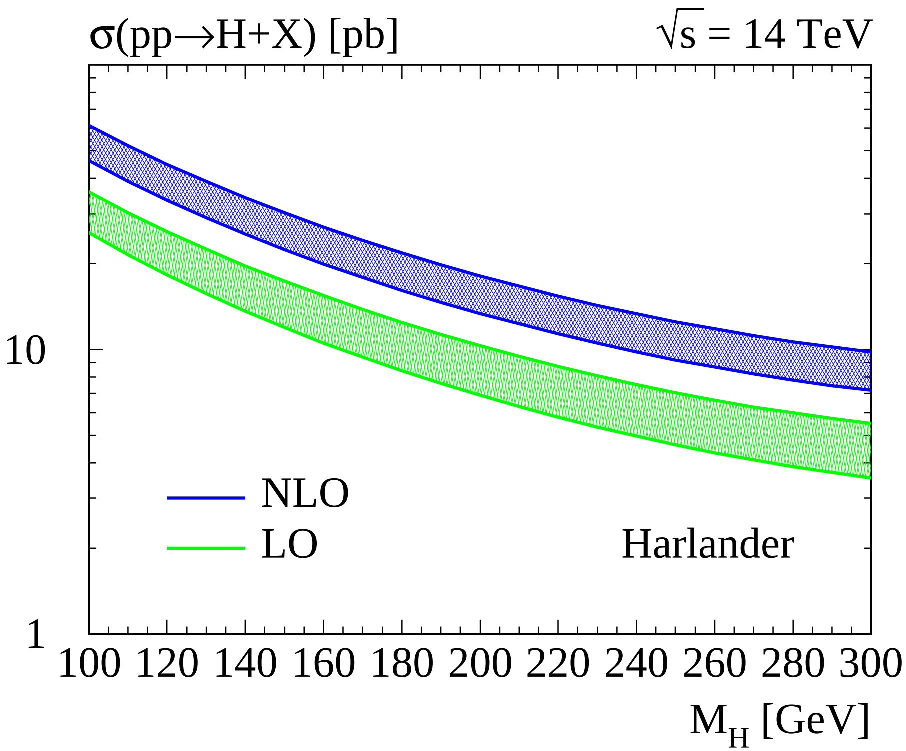

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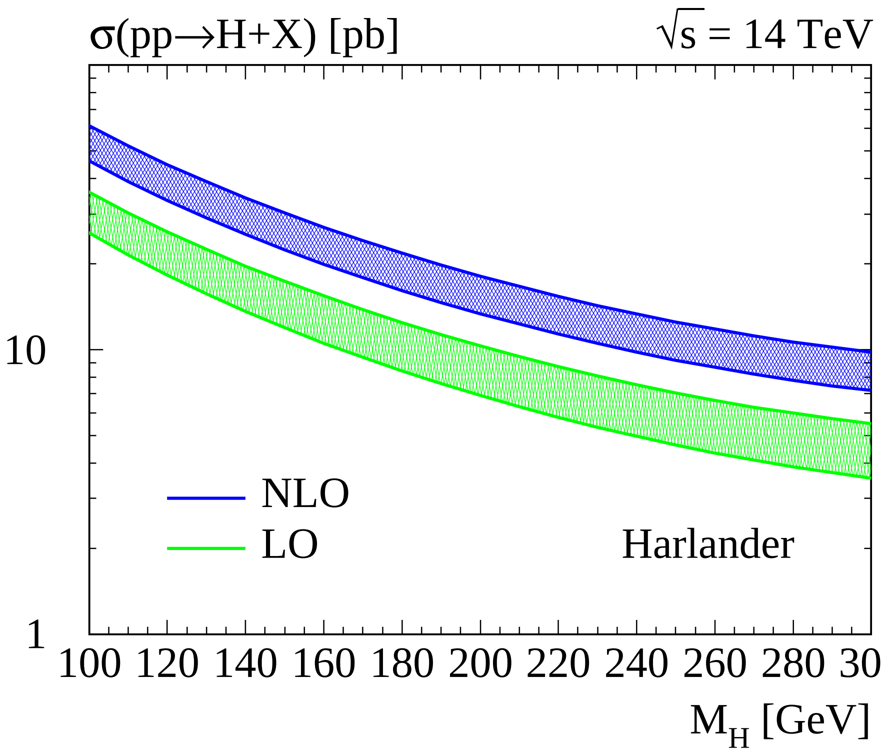

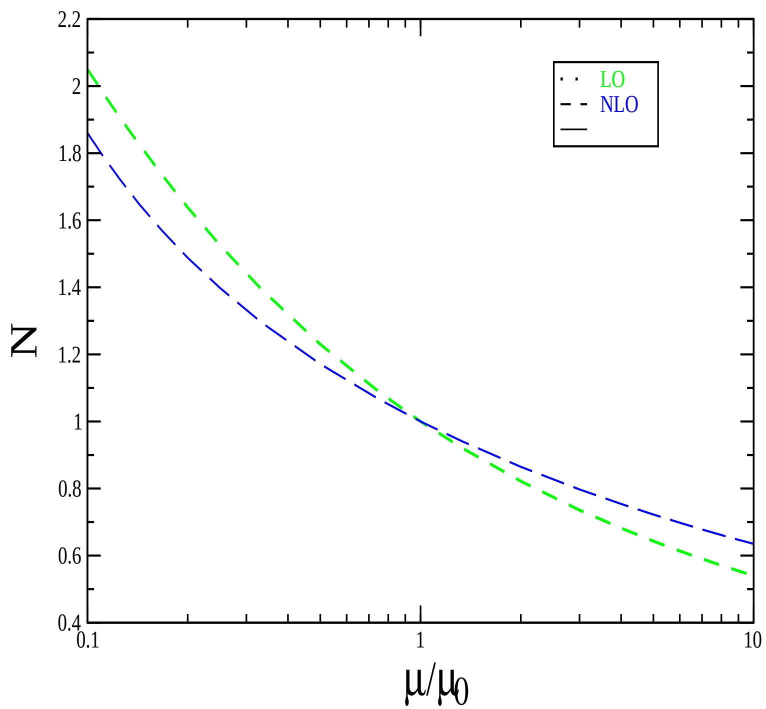

- Scale uncertainity is not improved much
- Even NLO is unreliable and calls for NNLO

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- With present technology it is impossible to compute NNLO contributions to Higgs production with the heavy quarks.

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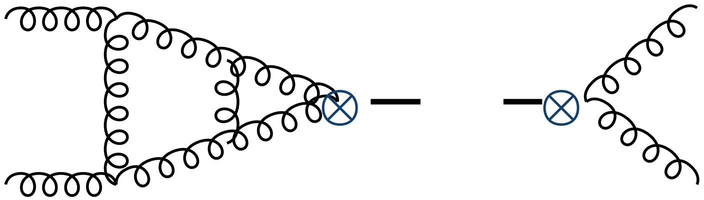
- S_{eff} NLO agrees with exact NLO within 5% to 10% level.

Processes at NNLO

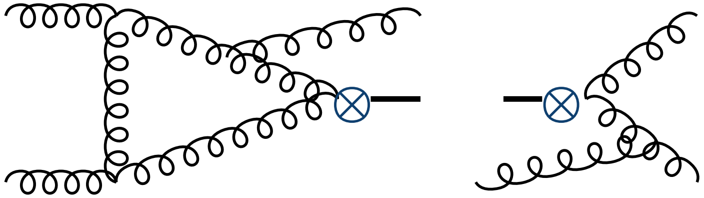
Harlander, Kilgore, Anastasiou, Melnikov, van Neerven, Smith, V.Ravindran

Double Virtual:



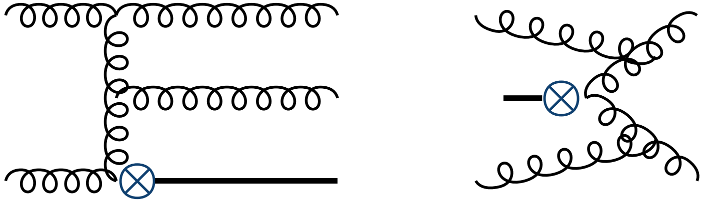
+ 148 terms;

Real Virtual:



+ 635 terms;

Double Real:



+ 594 terms.

In addition:

$$q + g \to h + X(q, \overline{q}, g) \qquad q_i + q_j(\overline{q}_j) \to h + X(q, \overline{q}, g)$$

Scale dependence at LHC

Harlander, Kilgore, Anastasiou, Melnikov, van Neerven, Smith, V.Ravindran

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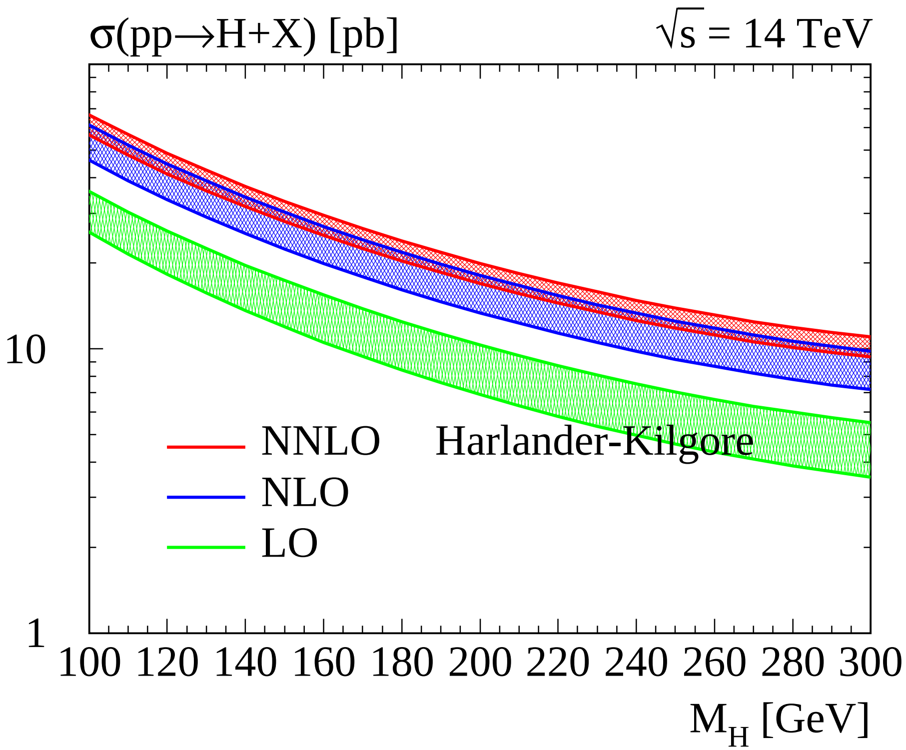

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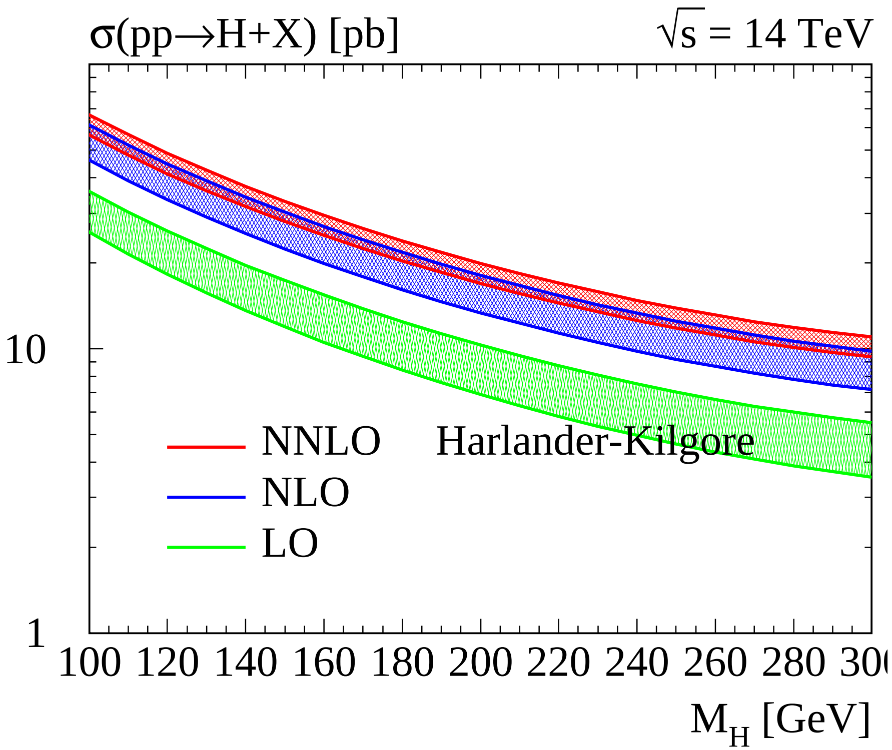

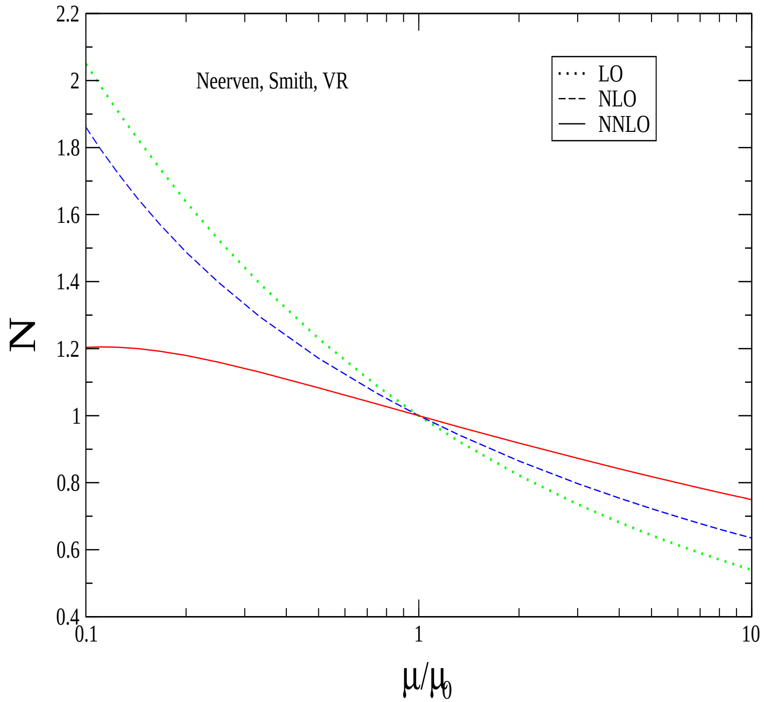

- NNLO result reduces scale dependence considerably

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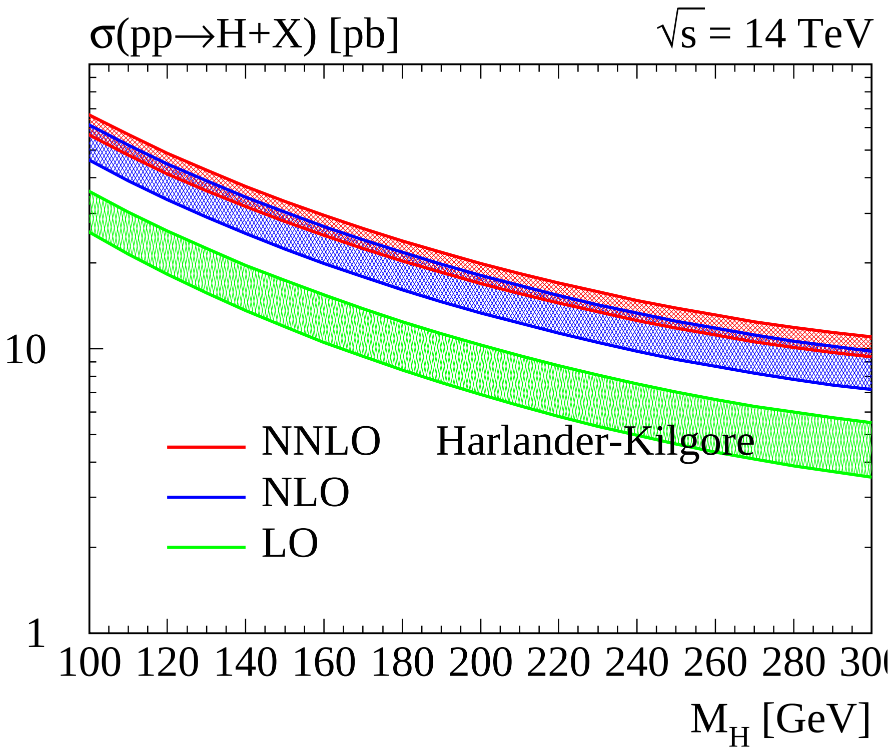
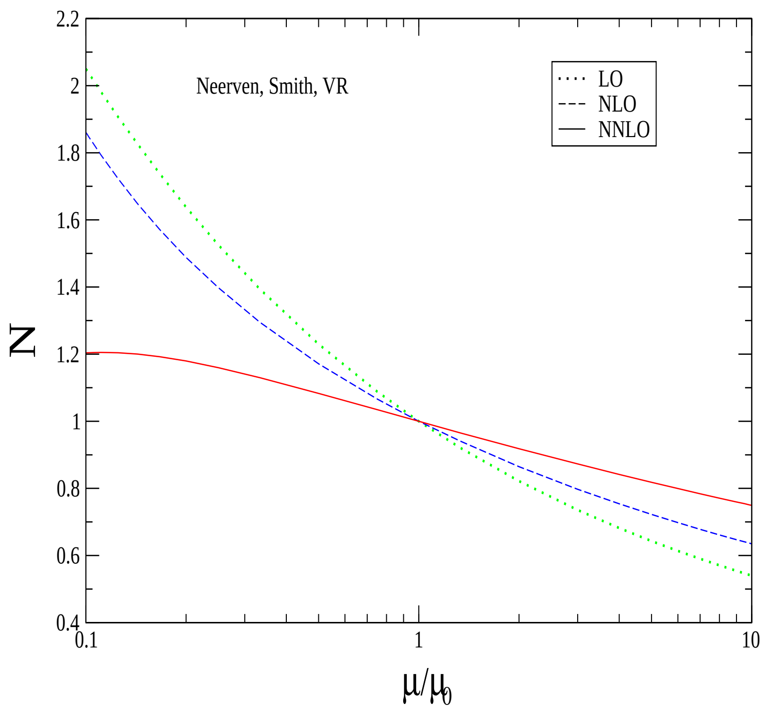
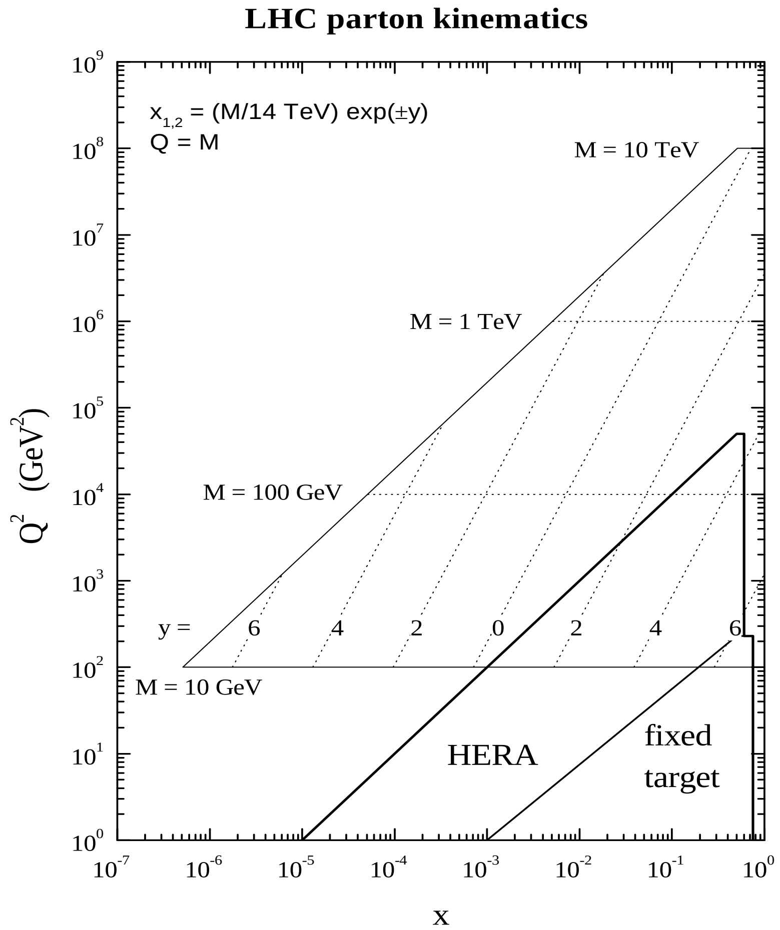


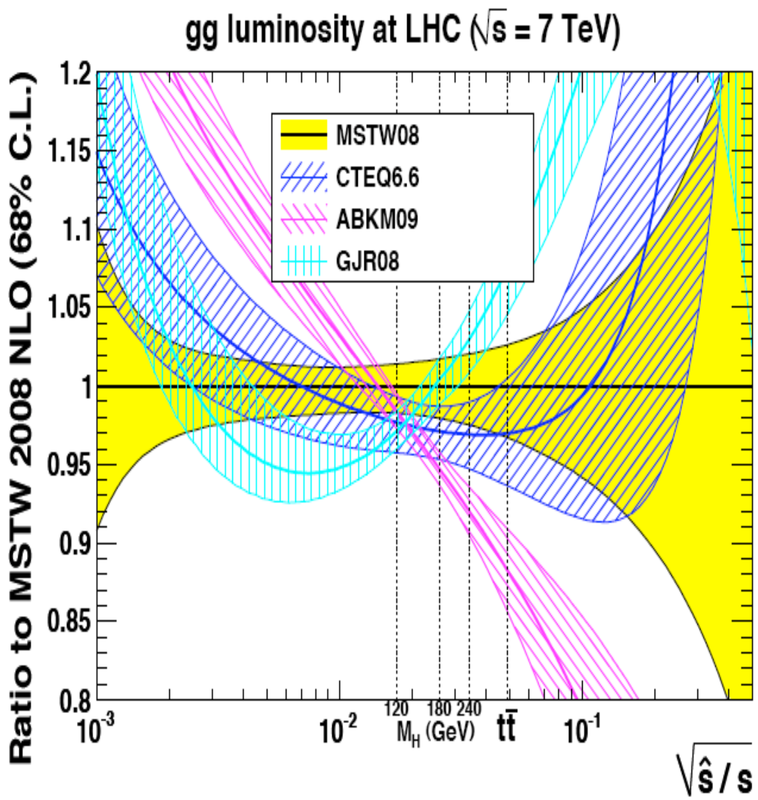


- NNLO result reduces scale dependence considerably
- Good News!

PDFs for LHC

[CTEQ,MSTW,ABKM,ABM,NNPDF]





PDFs for LHC

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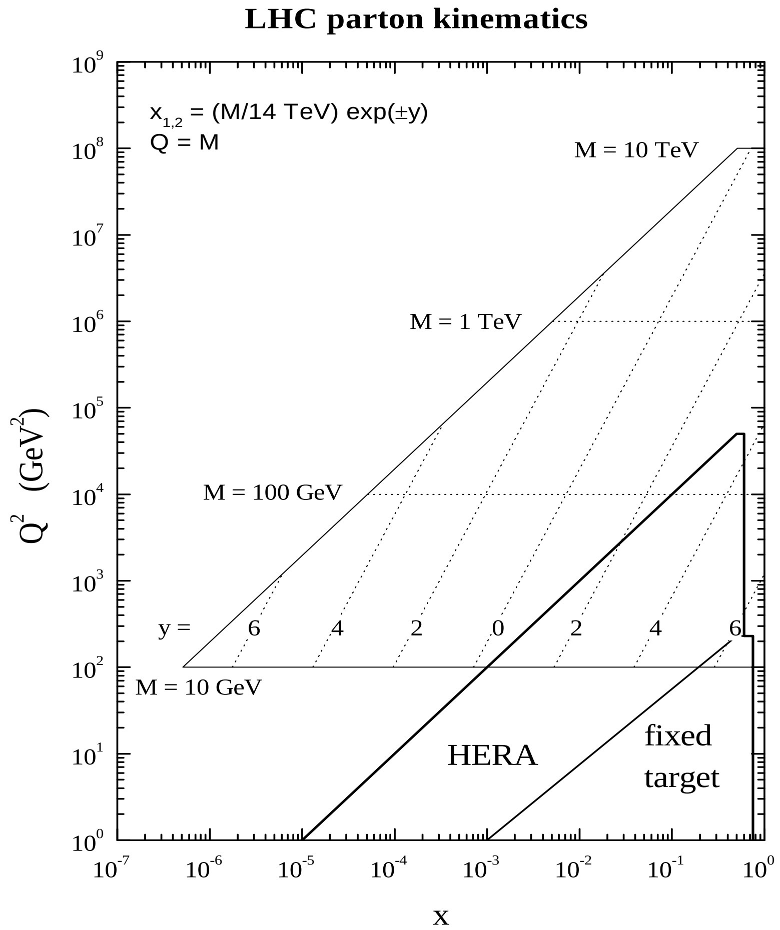

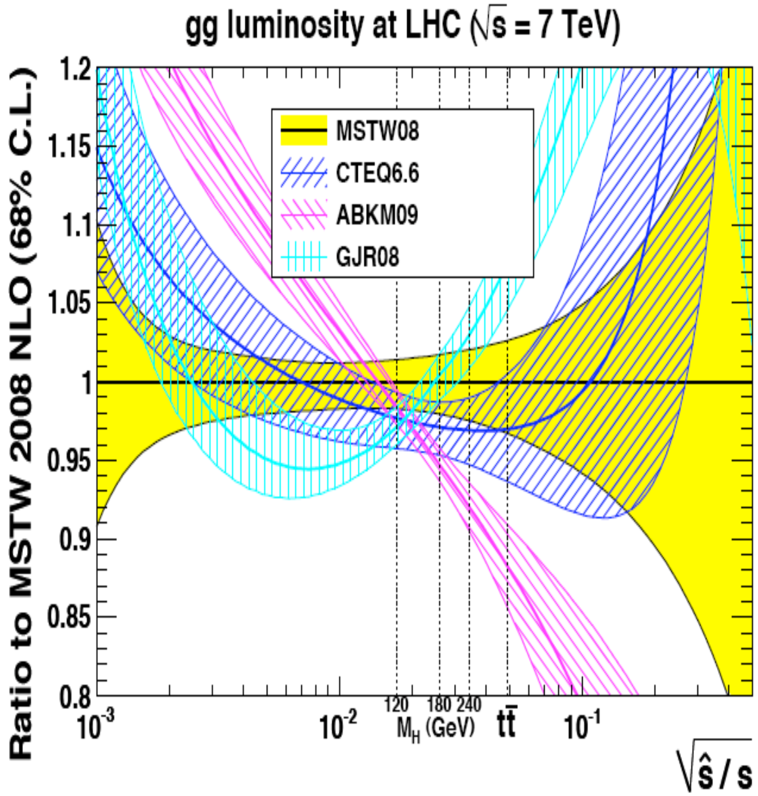

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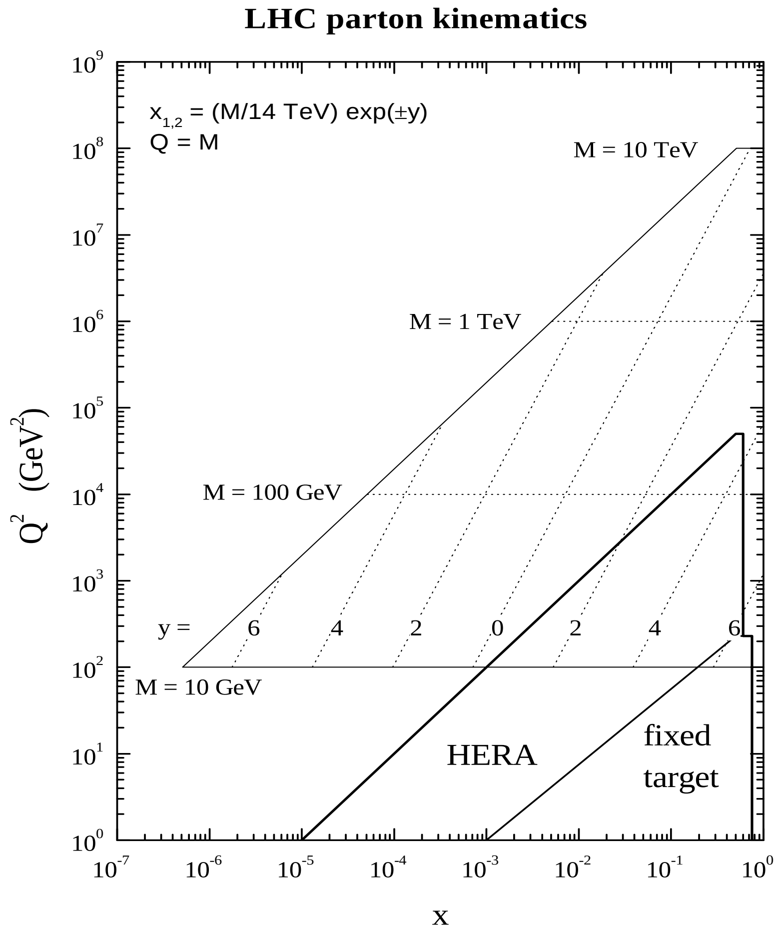

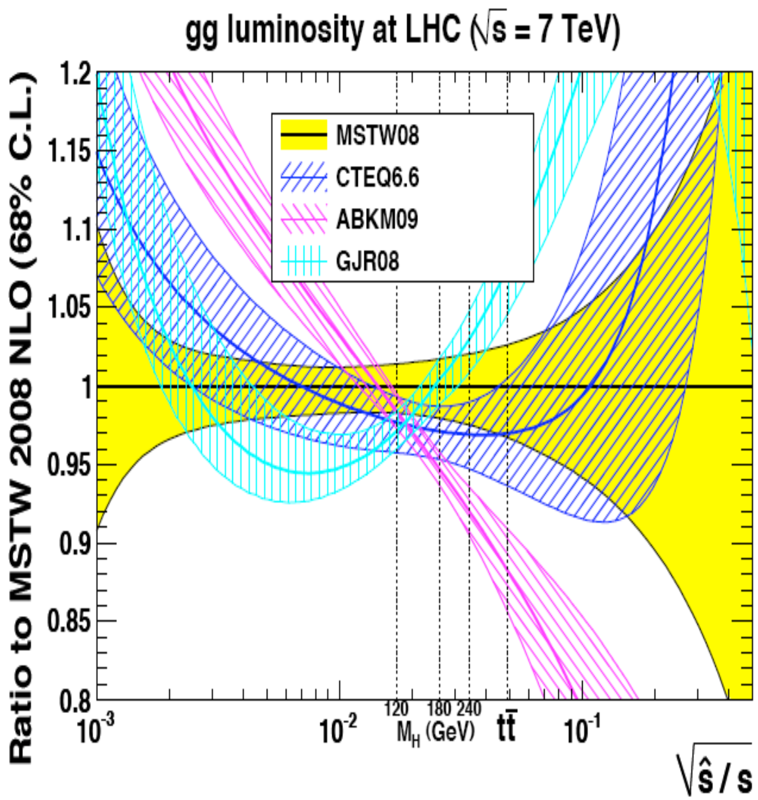

• CTEQ, MSTW, ABM and NNPDF come with different PDF sets with different choices of α_s, m_c, m_b • Choice of PDF set can bring in significant uncertainty of the order 10 to 20%

NNLO QCD corrected Higgs Cross section at $\sqrt{S} = 14$ TeV

$m_H/2 < \mu_F = \mu_R < 2m_H$

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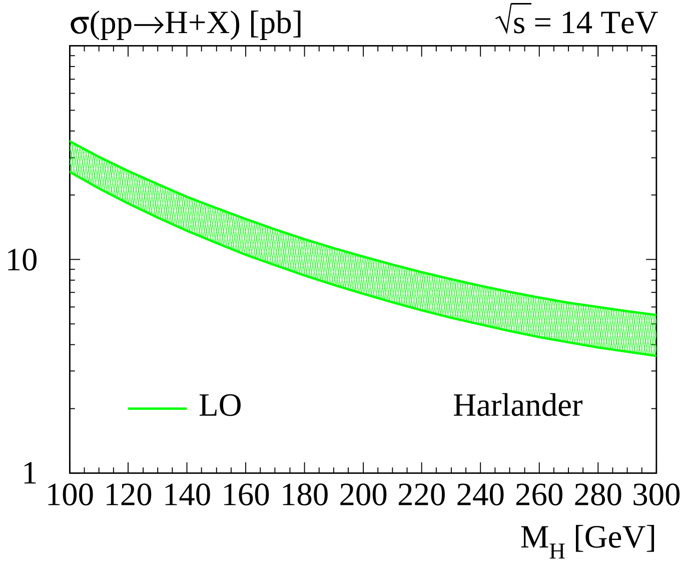

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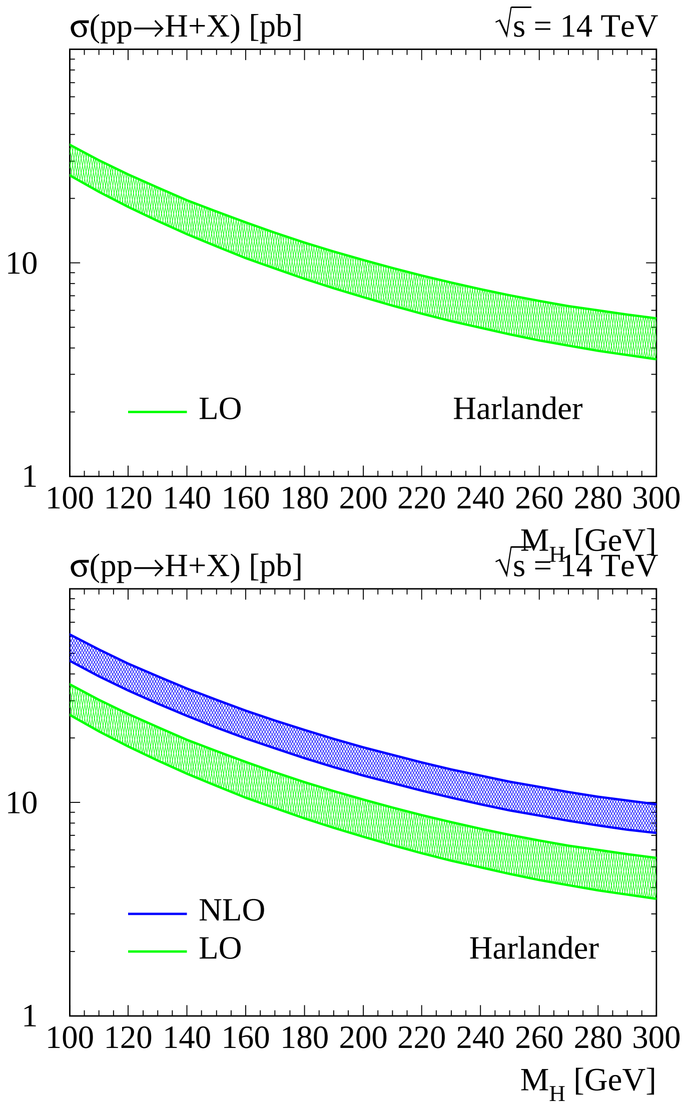

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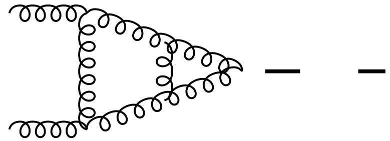

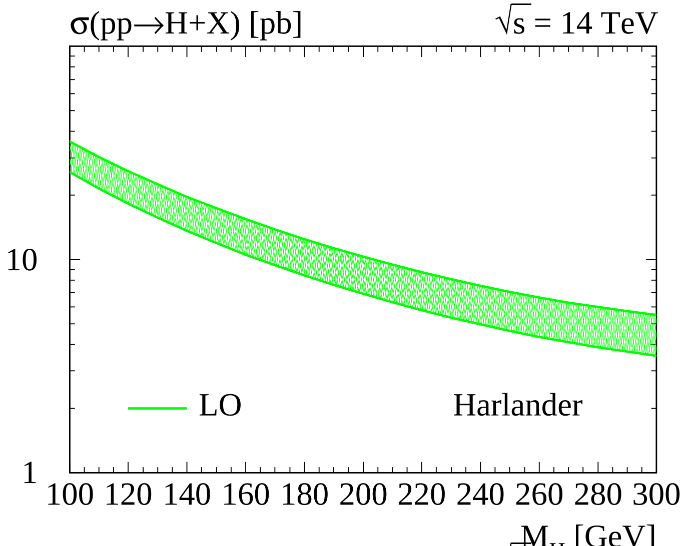

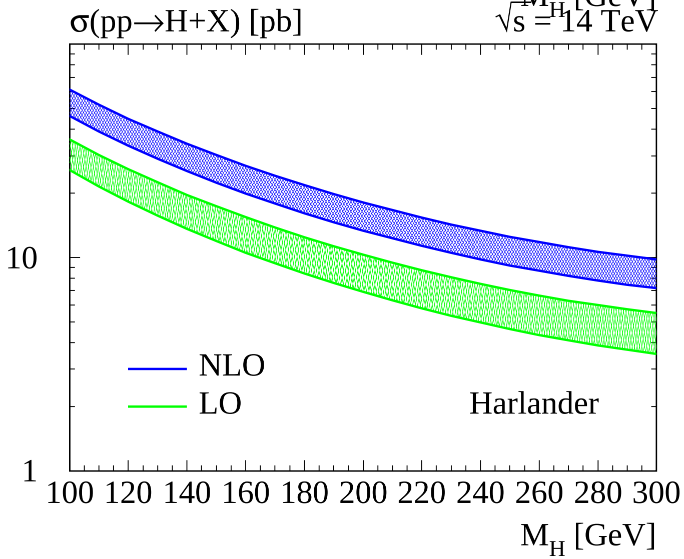

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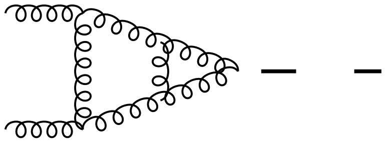
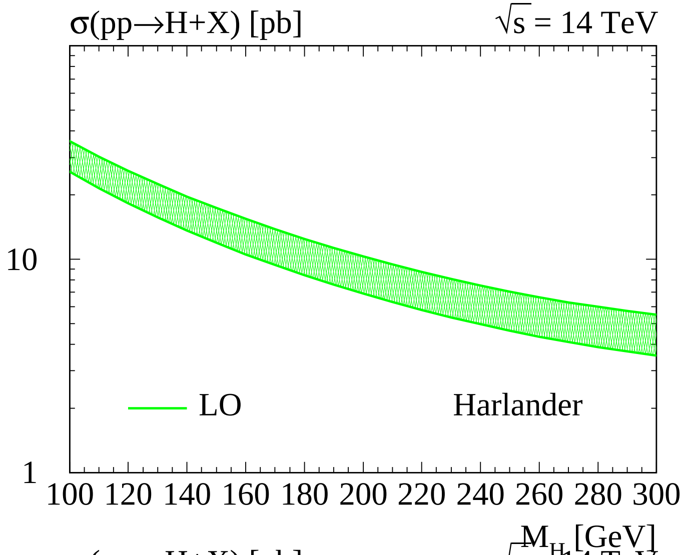
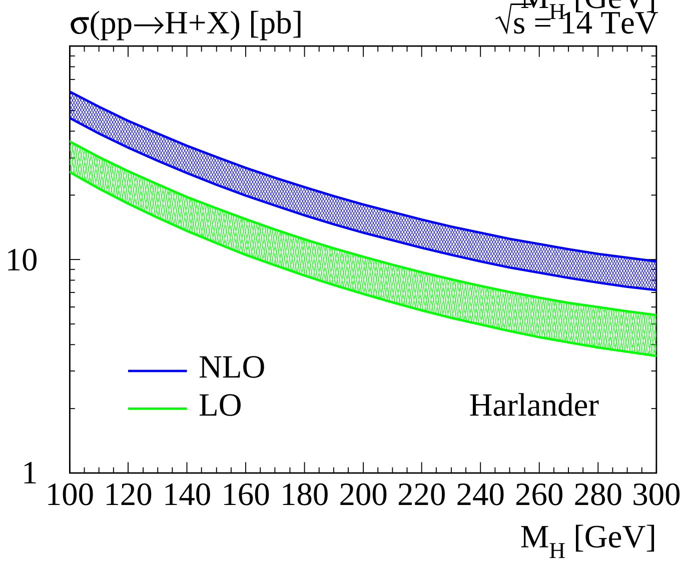
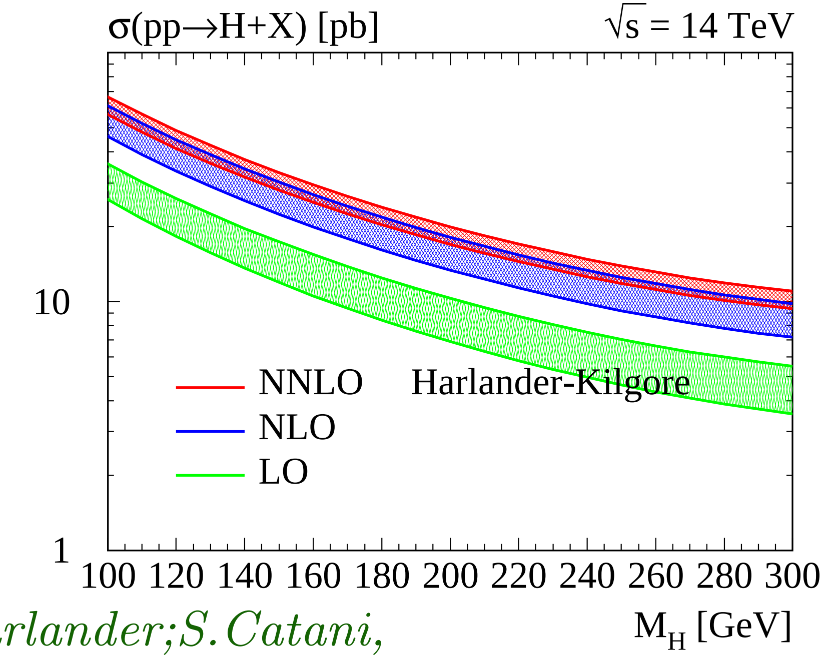


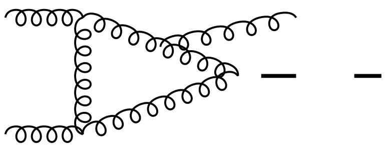


A.Djouadi,D.Grandenz,M.Spira,P.Zerwas





R.Harlander;S.Catani,
D.DeFlorian,M.Grazzini;
R.Harlander,B.Kilgore;C.Anastasiou,Melnikov;
VR,J.Smith,W.L.van Neerven



Soft gluons dominates!

S.Catani, P.Nason, M.Grazzini, D.DeFlorian; R.Harlander, B.Kilgore; E.Laenen, L.Magnea, Moch, Vogt, VR

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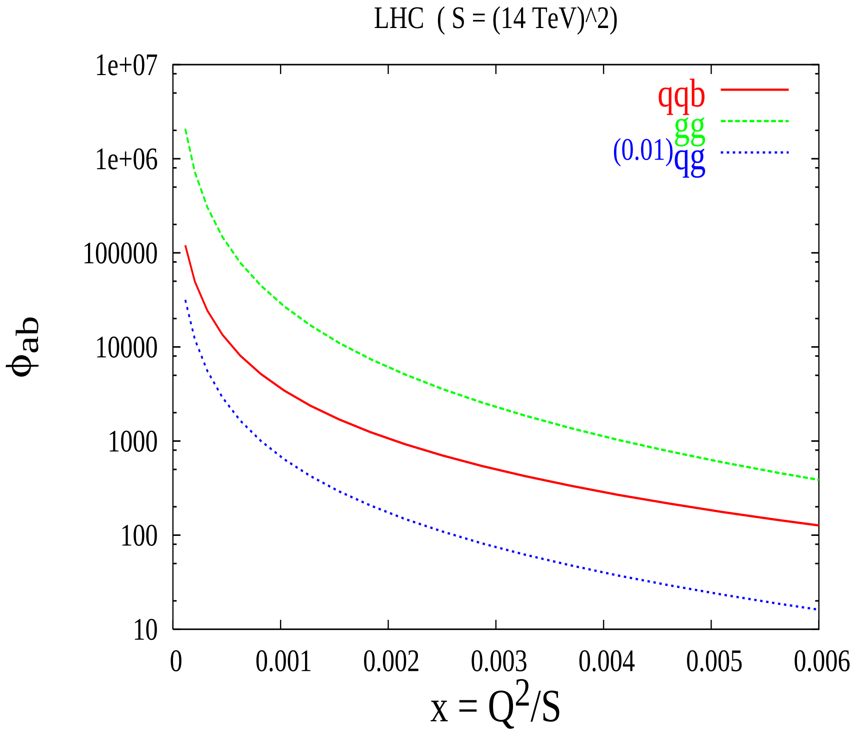

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S.Catani, D.DeFlorian, P.Nason, M.Grazzini

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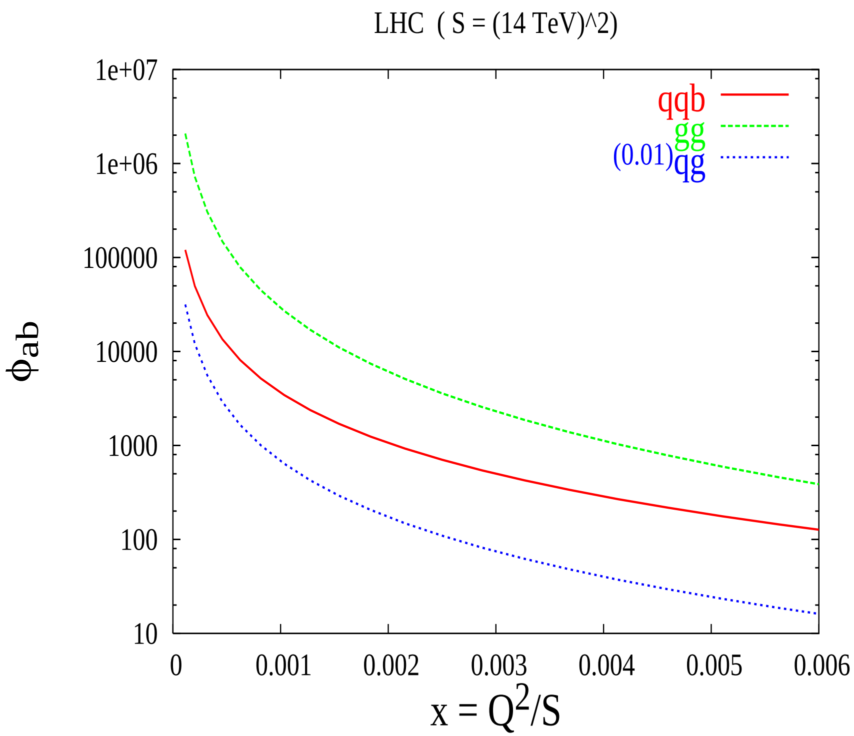

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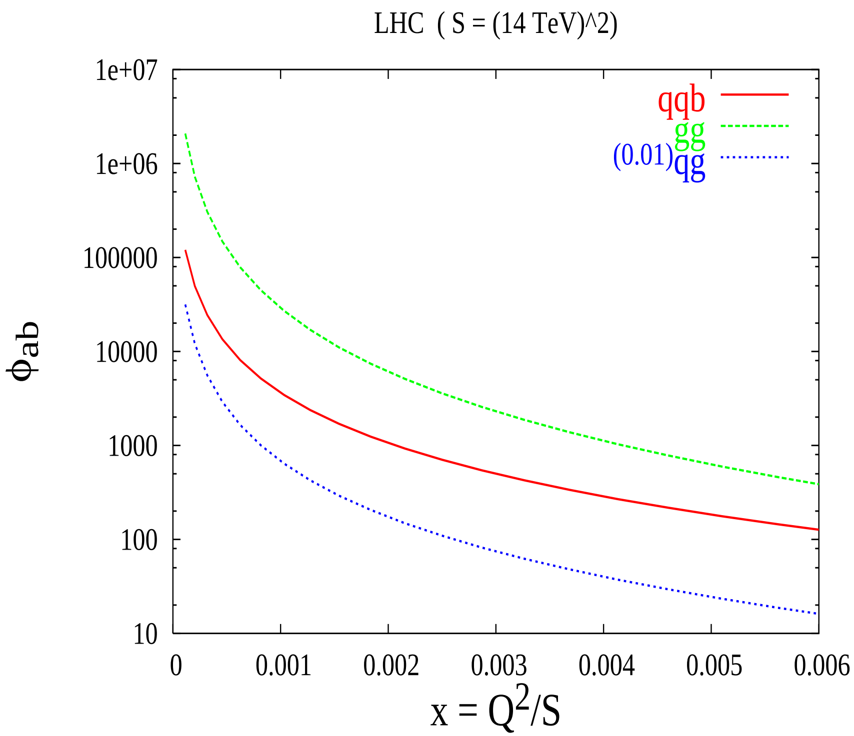

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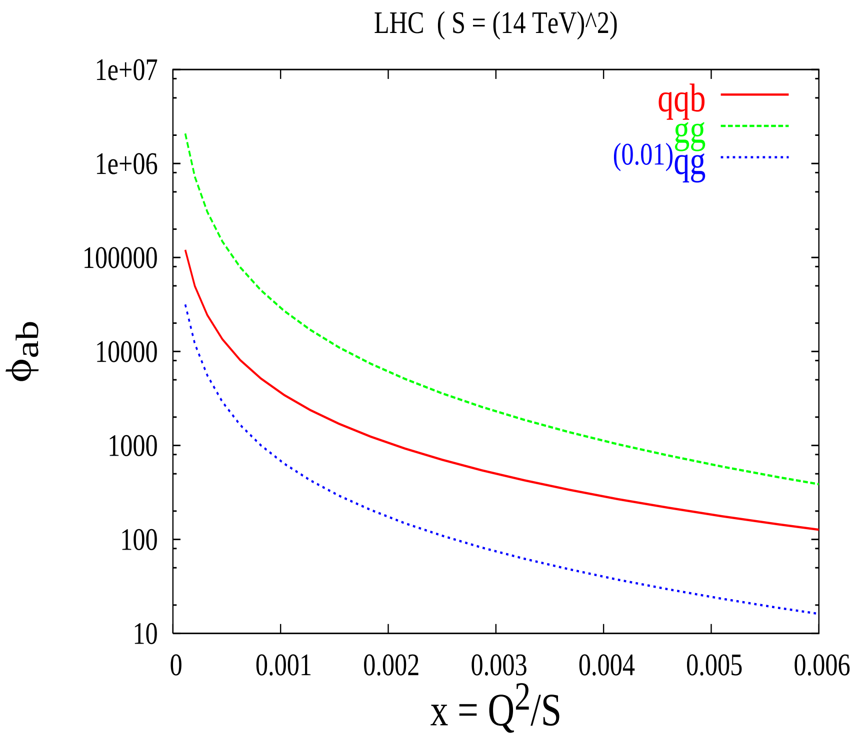

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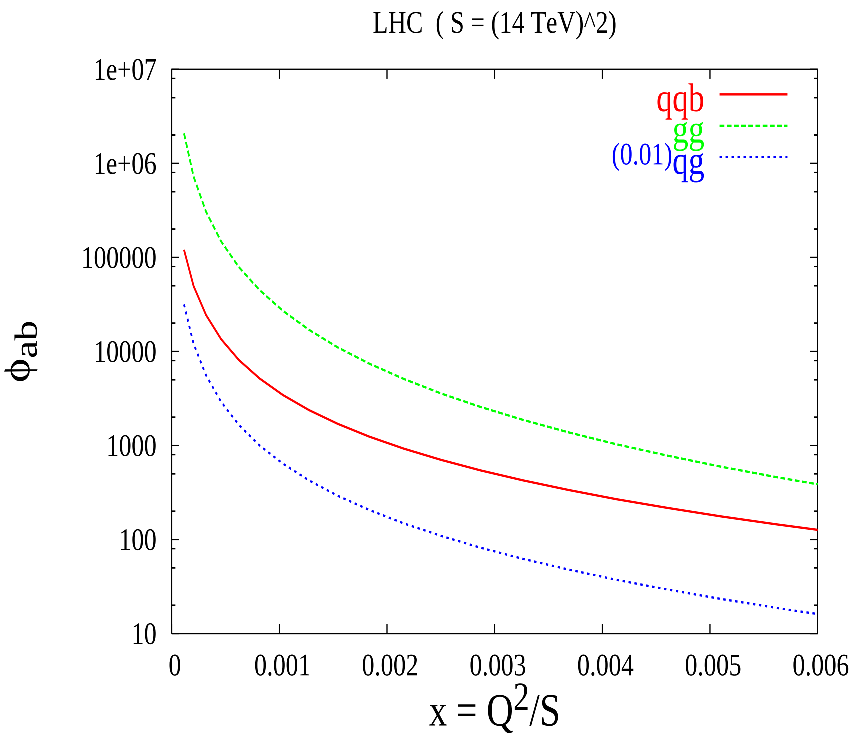

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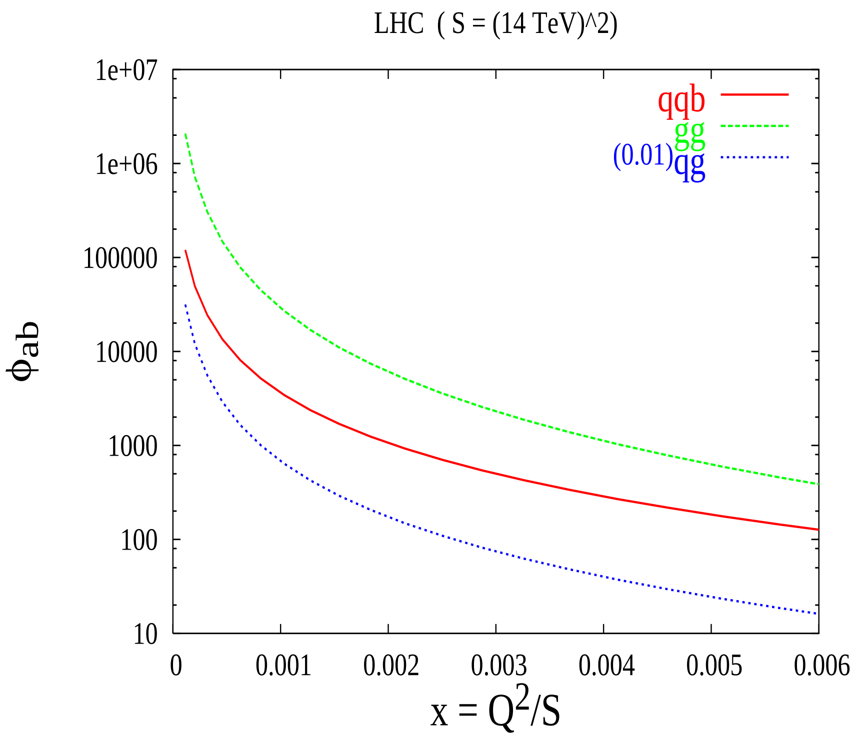

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Soft+Virtual part of N^3LO and NNLL resummation

$G.Sterman;S.Catani,P.Nason,M.Grazzini,D.DeFlorian;R.Harlander,$
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$$d\hat{\sigma}(z) = \mathcal{C}^{(0)}(z) + \sum_{i=1}^{\infty}(1-z)^i \mathcal{C}^{(i)} \qquad\qquad z = \frac{x}{\tau}$$

Soft+Virtual part of N^3LO and NNLL resummation

$G.Sterman; S.Catani, P.Nason, M.Grazzini, D.DeFlorian; R.Harlander, B.Kilgore; E.Laenen, L.Magnea; Moch, Vogt, VR$

- Expand the partonic cross section around $x = \tau$ or $z = \frac{x}{\tau} = 1$.

$$d\hat{\sigma}(z) = \mathcal{C}^{(0)}(z) + \sum_{i=1}^{\infty} (1-z)^i \mathcal{C}^{(i)} \qquad z = \frac{x}{\tau}$$

- $\mathcal{C}^{(0)}$:

$$\mathcal{C}^{(0)} = \mathcal{C}_0^{\delta}\, \delta(1-z) + \sum_{k=0}^{\infty} \mathcal{C}_0^{(k)} \left(\frac{\log^k(1-z)}{(1-z)} \right)_+$$

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- $\mathcal{C}_0^{(i)}$ will be pure constants such as $\zeta(2), \zeta(3)$.

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  OR

  Extract from "Form factors and DGLAP kernels" using

  1) Factorisation theorem   2) Renormalisation Group Invariance
  3) Sudakov Resummation

Factorisation of Soft and Collinear partons

G.Sterman, S.Catani

Factorisation of Soft and Collinear partons

$G.Sterman, S.Catani$

$$\begin{aligned}\Delta(z,Q^2) &= \delta(1-z)+\alpha_s(Q^2)\left(a_{11}\delta(1-z)+\frac{a_{12}}{(1-z)_+}+a_{13}\left(\frac{\log(1-z)}{1-z}\right)_+\right.\\ &\left.+R_1(z)\right)+\alpha_s^2(Q^2)\left(\cdots+\cdots+\cdots+R_2(z)\right)+\cdots\end{aligned}$$

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$R_i(z)$ are regular as $z \to 1$

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Soft distribution functions factorise

$$\Delta(z,Q^2) = S(z,Q^2,\mu_R^2) \otimes \Big(\delta(1-z) + \alpha_s(Q^2)\tilde{R}_1(z,Q^2,\mu_R^2) + \alpha_s^2(Q^2)\tilde{R}_2(z,Q^2,\mu_R^2) + \cdots\Big)$$

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$$\left. + R_1(z)\right) + \alpha_s^2(Q^2)\left(\cdots + \cdots + \cdots + R_2(z)\right) + \cdots$$

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Soft contribution exponentiates

$$S(z,Q^2,\mu_R^2) = \mathcal{C}\exp\left(\Psi(z,Q^2,\mu_R^2)\right) \qquad \Psi(z,Q^2,\mu_R^2) \quad is\text{"finite distribution"}$$

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$$\mathcal{C}e^{f(z)} = \delta(1-z) + \frac{1}{1!}f(z) + \frac{1}{2!}f(z)\otimes f(z) + \frac{1}{3!}f(z)\otimes f(z)\otimes f(z) + \cdots.$$

Soft plus Virtual part at N^3LO_{pSV} for Higgs Production

$S.Moch, A.Vogt; E.Laenen, L.Magnea; VR$

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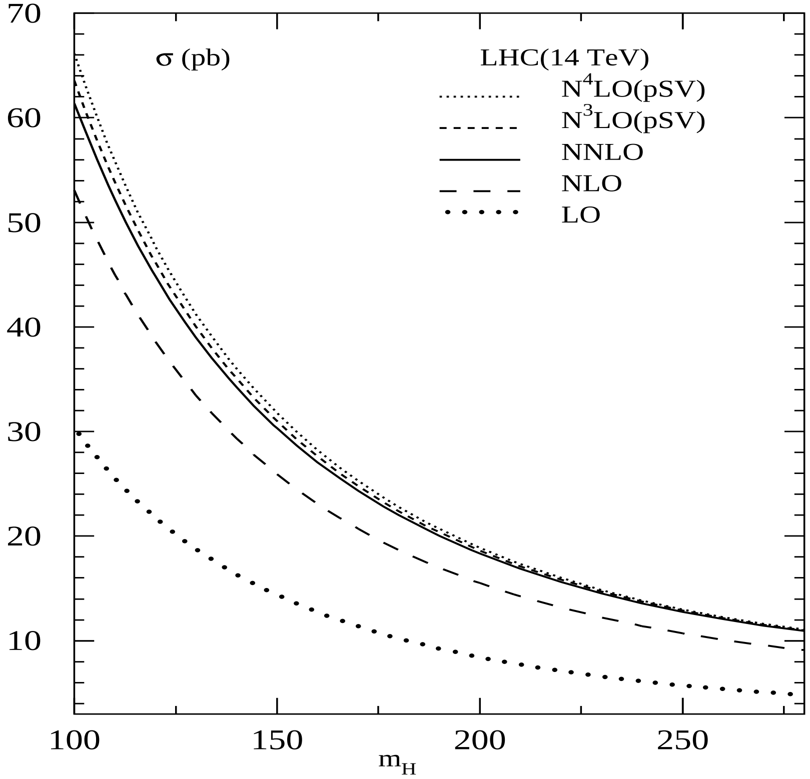
$$2S\, d\sigma^{P_1P_2}(\tau, m_H) = \sum_{ab}\int_\tau^1 \frac{dx}{x}\Phi_{ab}(x)\, 2\hat{s}\, d\hat{\sigma}^{ab}\left(\frac{\tau}{x}, m_H\right) \qquad \tau = \frac{m_H^2}{S}$$



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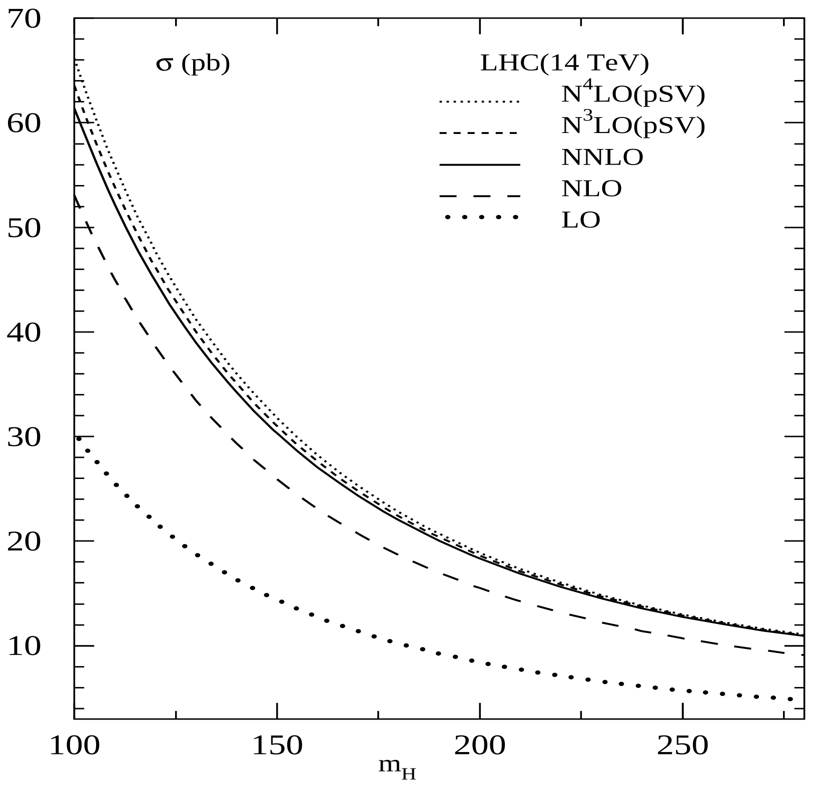

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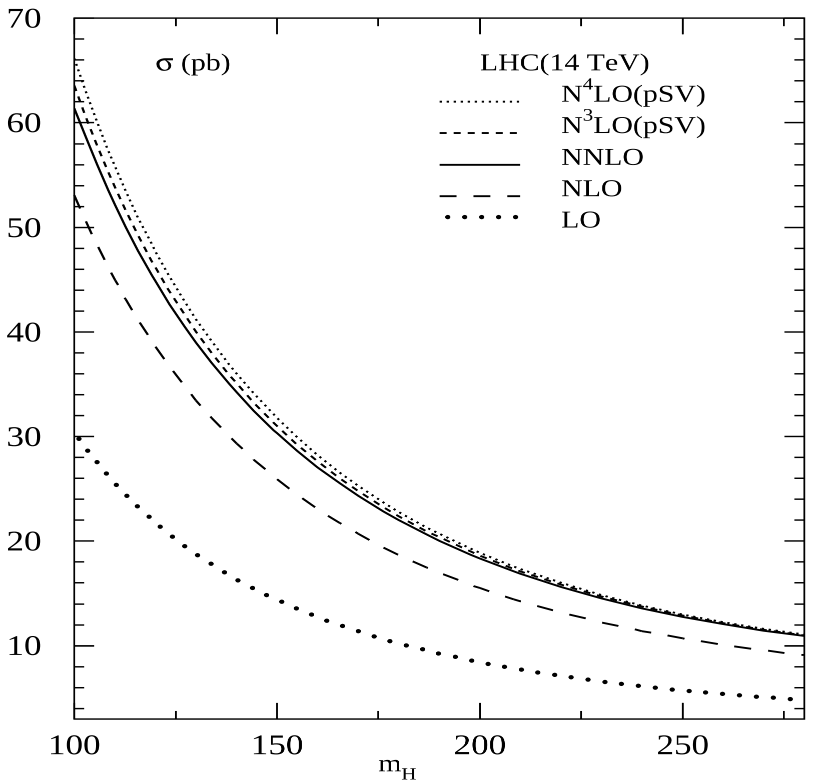

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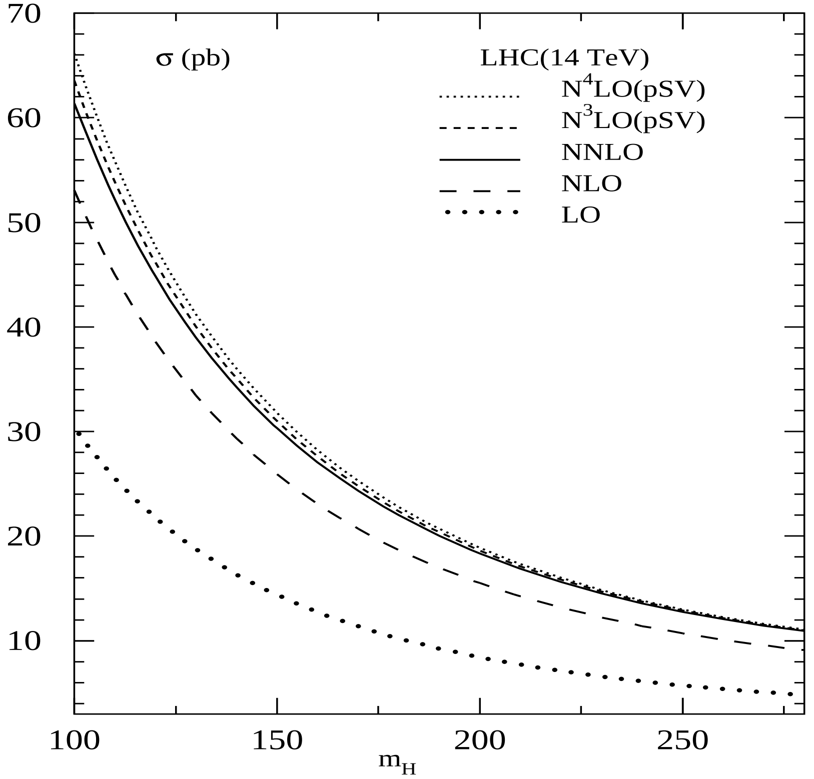

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$$\mathcal{D}_j \qquad j = 5, 4, 3, 2, 1, 0$$

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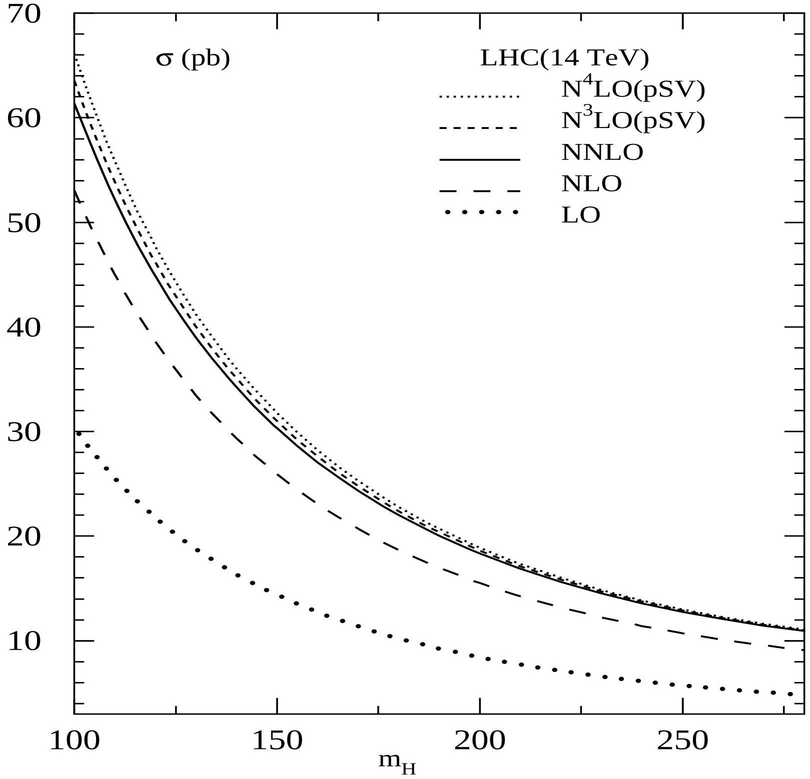

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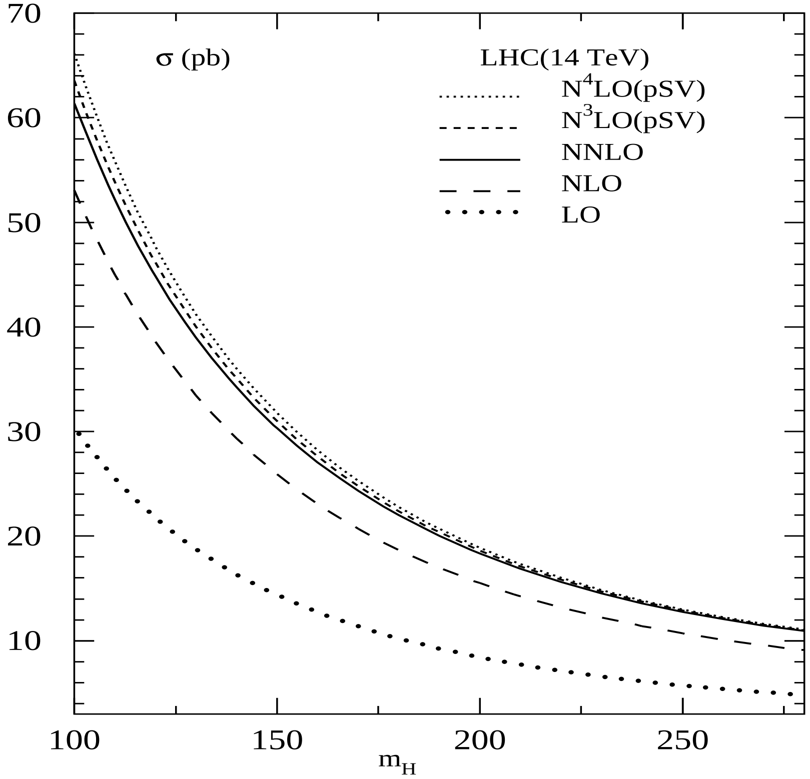

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- They contribute bulk of the cross section

Soft gluon Resummation beyond $NNLL$ for Higgs production

S.Catani, P.Nason, D.DeFlorian, M.Grazzini; S.Moch, A.Vogt; E.Laenen, L.Magnea

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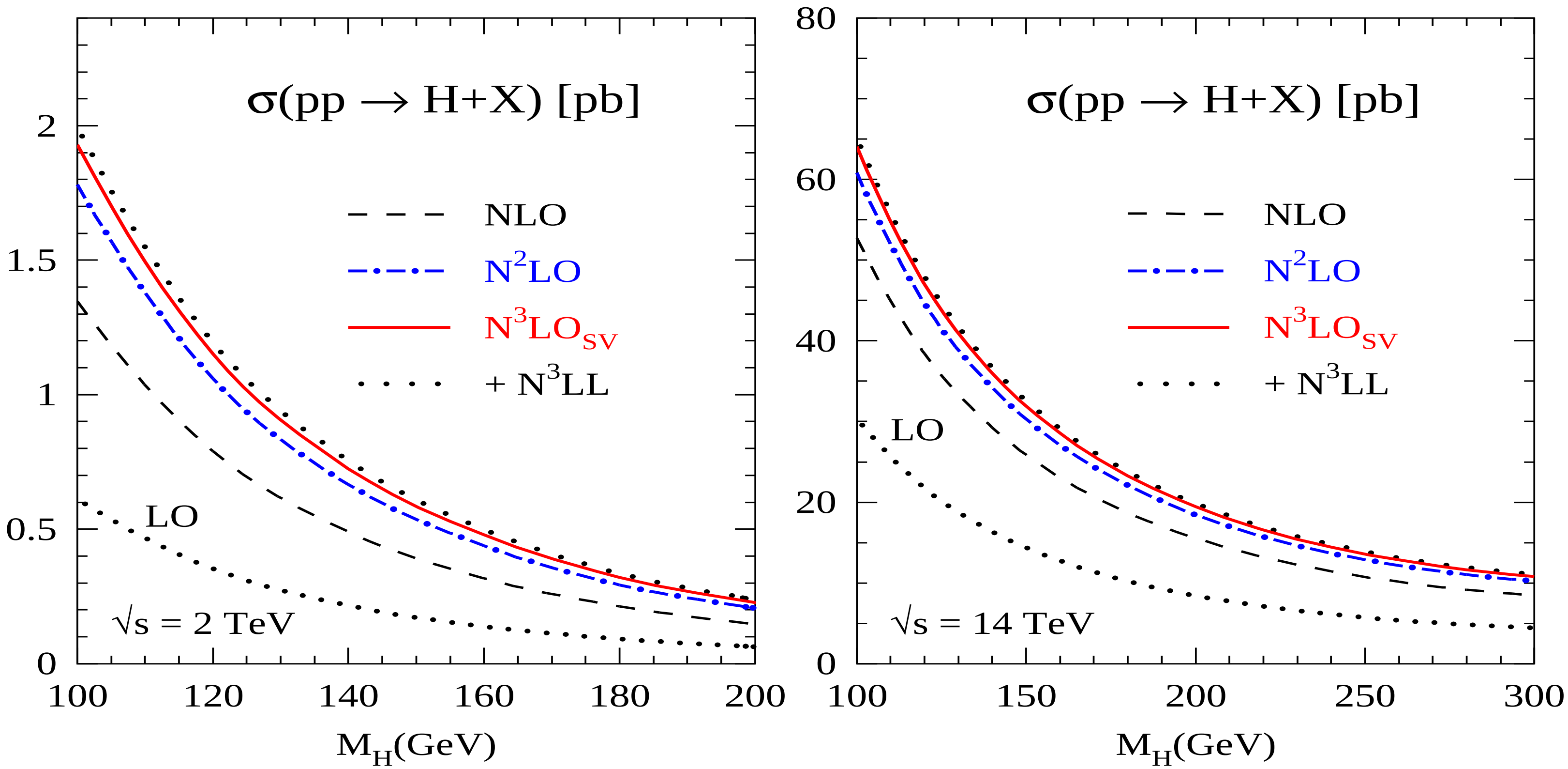

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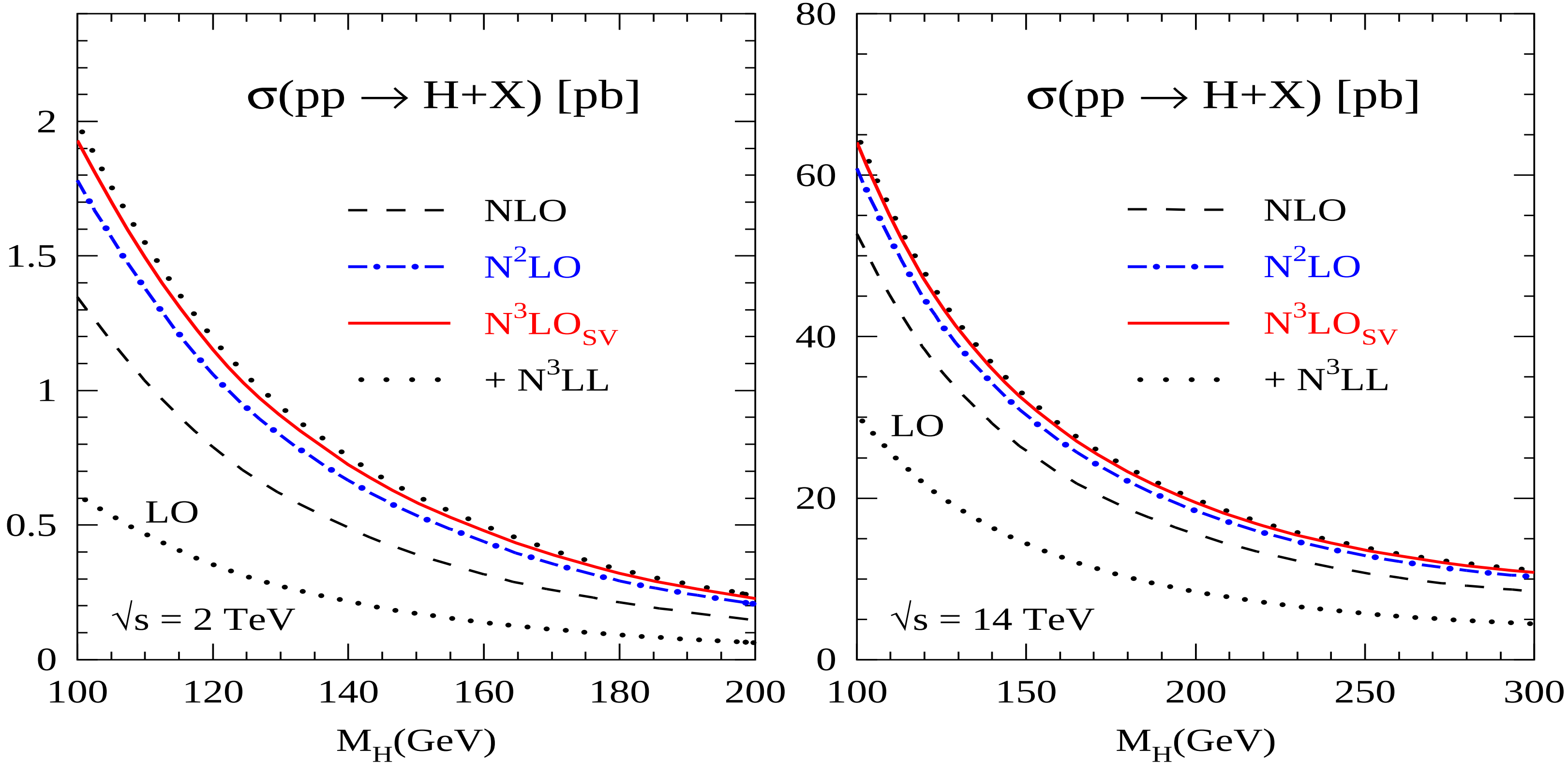

- N^3LL resummation exponents are available now.

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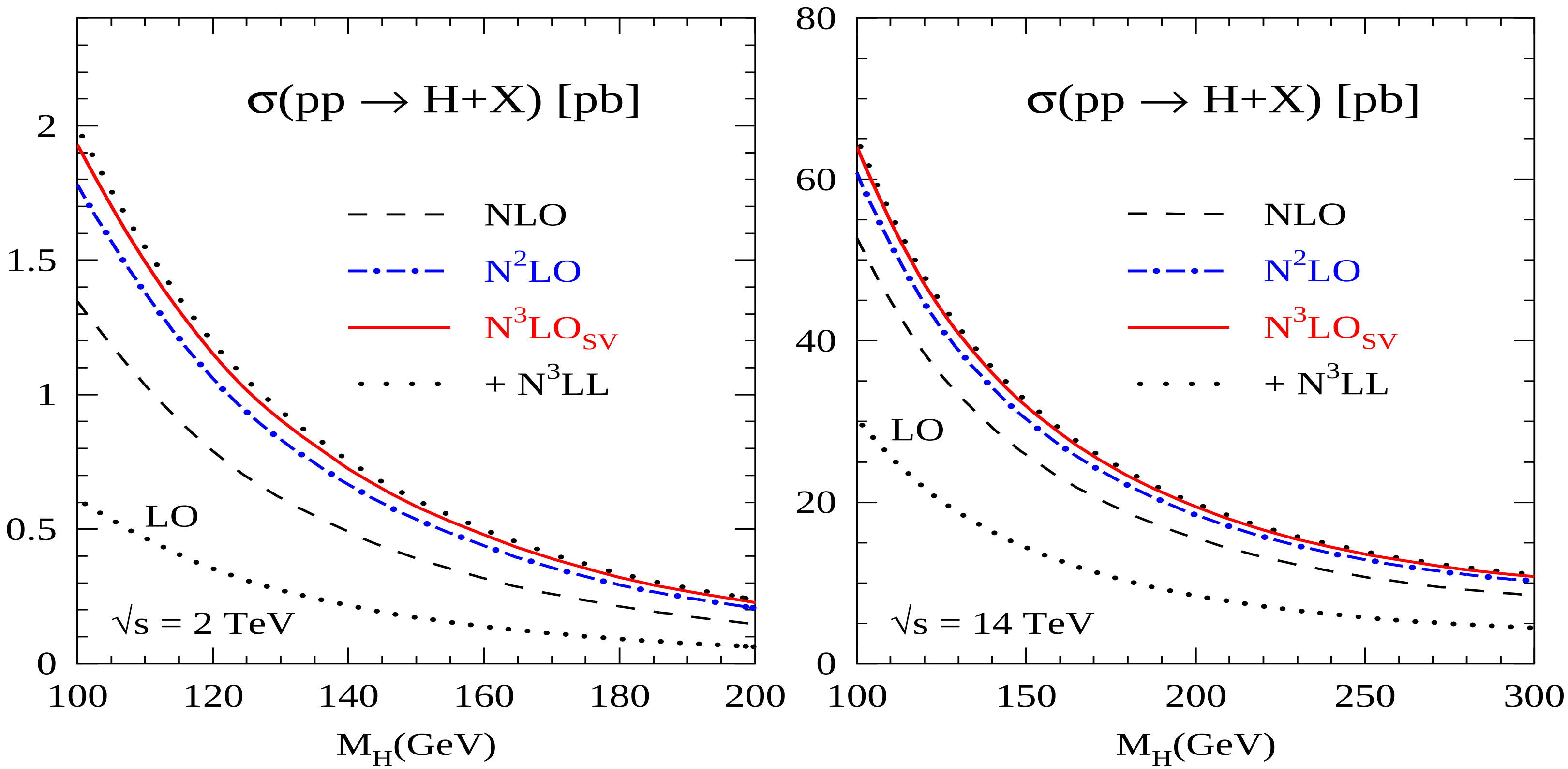

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- N^3LL resummation does not change the picture much. Fixed order N^3LO_{pSV} is very close to the N^3LL resummed result.

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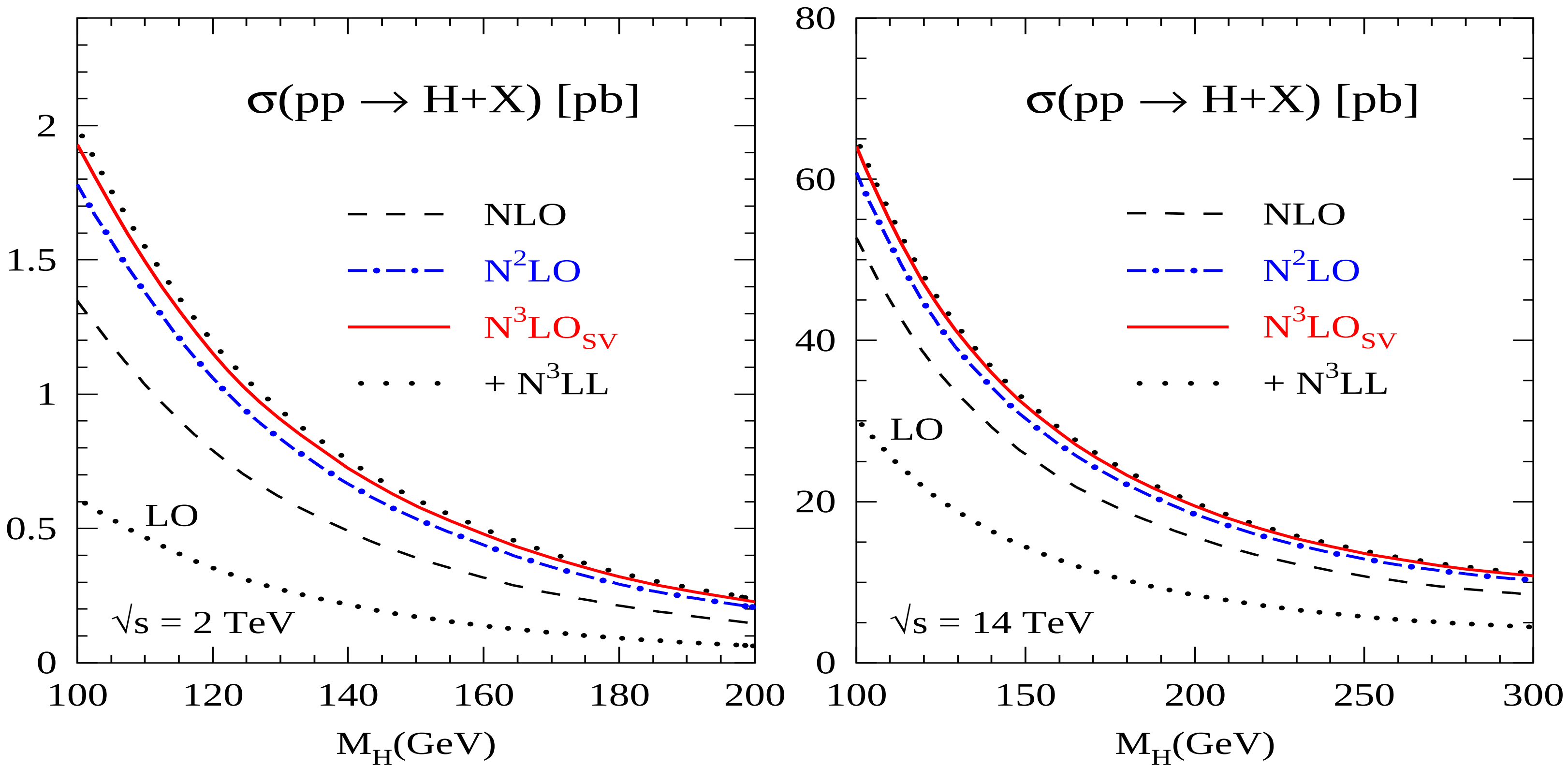

- N^3LL resummation exponents are available now.
- N^3LL resummation does not change the picture much. Fixed order N^3LO_{pSV} is very close to the N^3LL resummed result.
- Since QCD corrections can reduce the scale uncertainties only to $10\% - 20\%$, contributions from electroweak sector is also important.

2-loop Electroweak, Mixed QCD and Electroweak, b quark contributions:

U.Aglietti et al;G.Degrassi,F.Maltoni;G.Passarino et al;Anastasiou et al;W.Keung,F.Petriello,O.Brein

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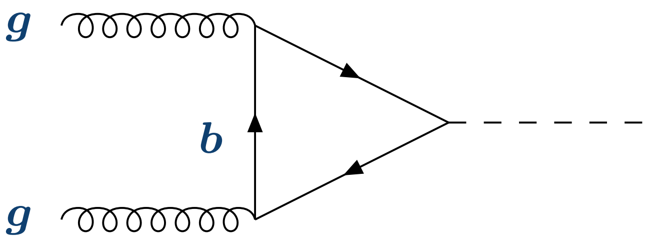

H "interferece" with "t" loop + NLO QCD

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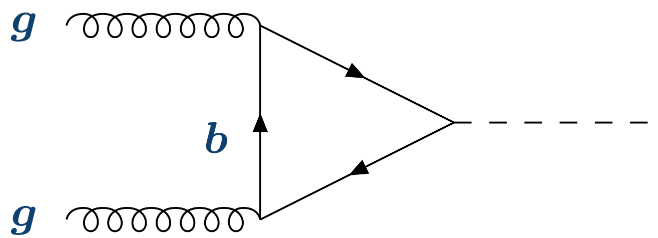

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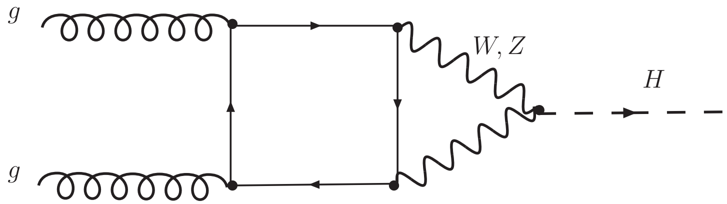
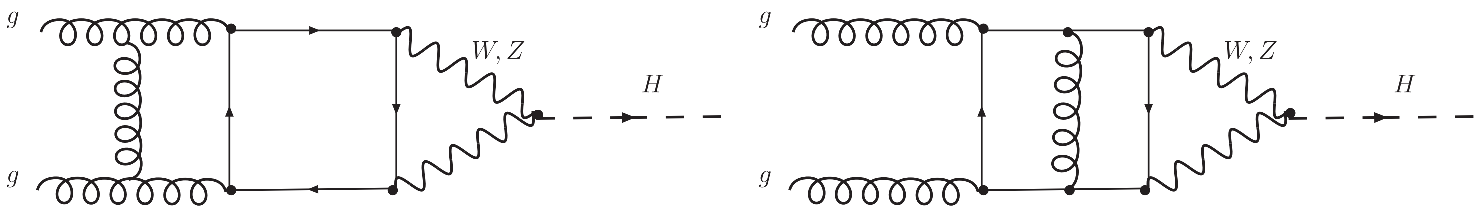
Pure QCD processes interference with Electroweak Processes:





Electroweak: $5\%(m_H = 120$ Gev) and -2% ($m_H = 300$GeV); b quark loops contribute $5 - 6\%$ at $m_H = 120$ GeV at LHC

Renormalisation group improved result

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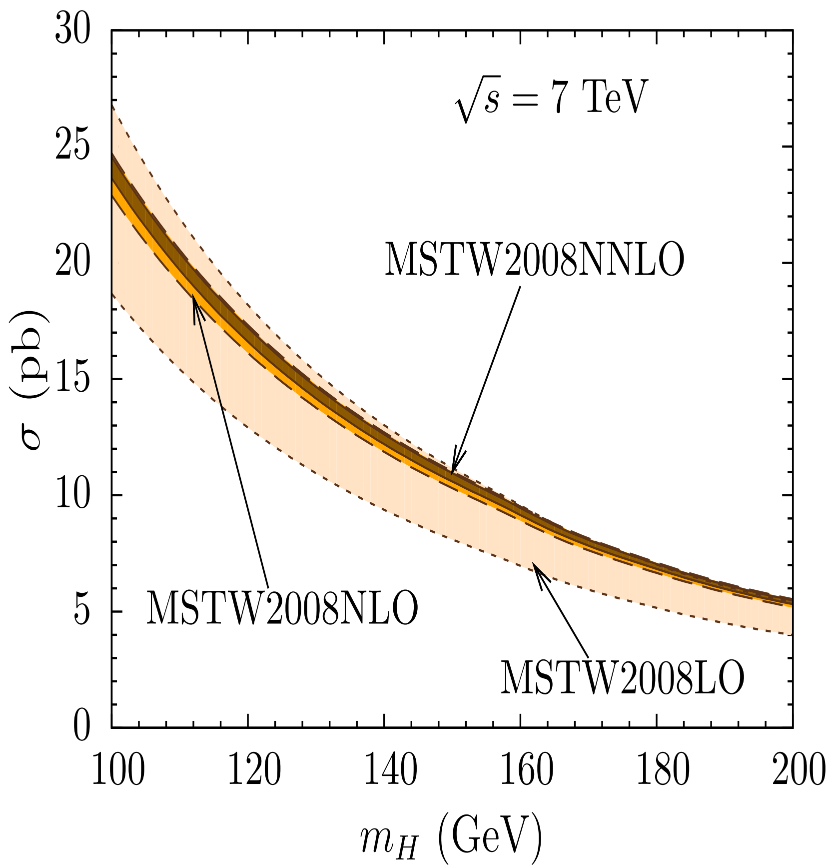

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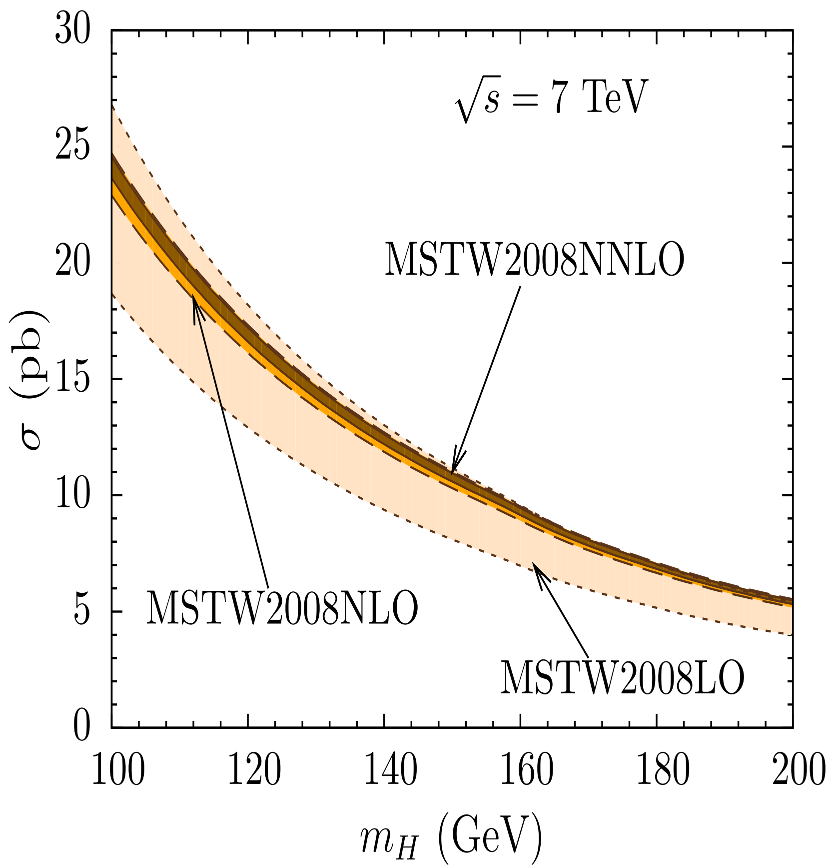

- *Ahrens, Becher, Neubert, Yang*: NLO with exact top quark mass contributions, NNLO in the large top quark mass limit, EW corrections given by Passarino et al and **use exact solutions to the RG equations of soft,collinear and hard pieces** of the cross section.

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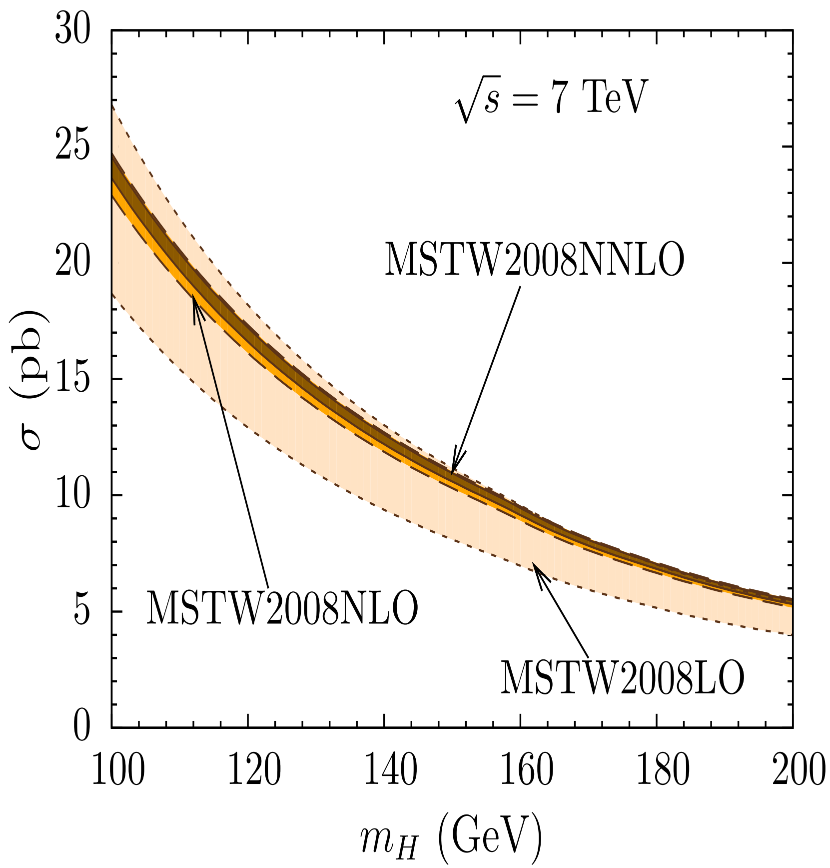

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Good perturbative stability from LO onwards, I believe that this is the most reliable approach

Soft gluons at N^3LO_{pSV} for Higgs production ($8\ TeV$)

$VR,\ J.\ Smith$

$$R = \frac{\sigma_{N^iLO}(\mu)}{\sigma_{N^iLO}(\mu_0)}$$

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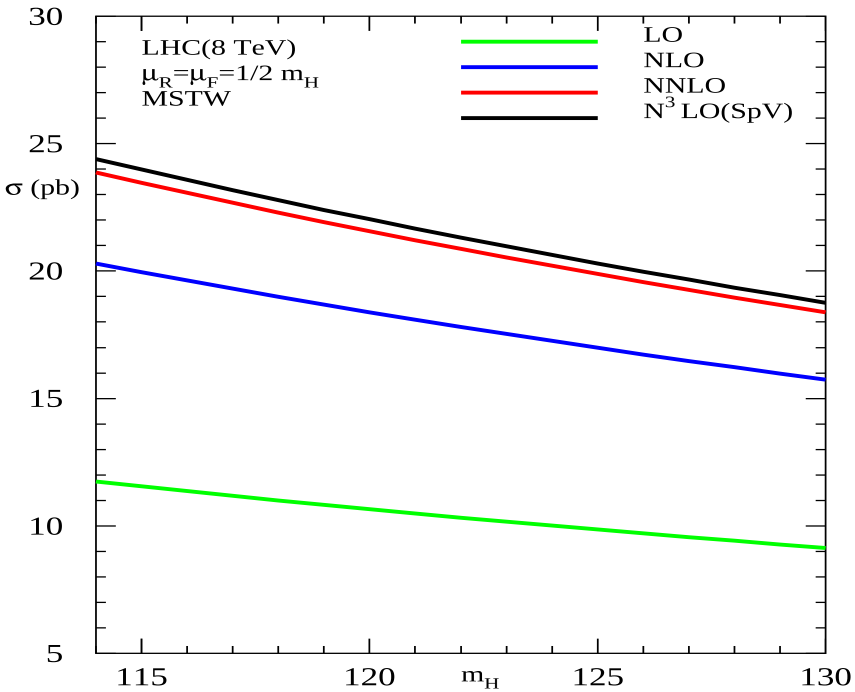

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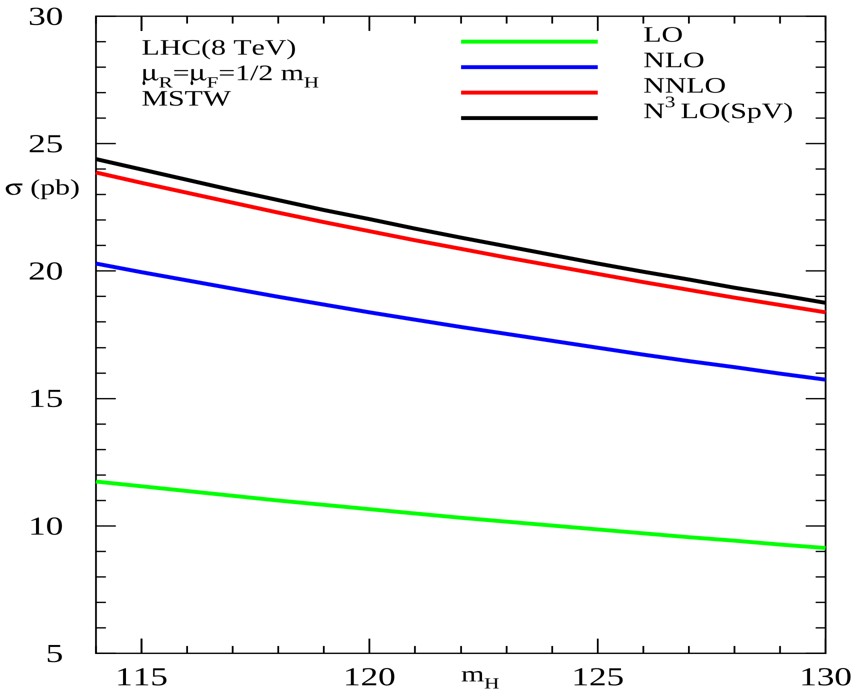

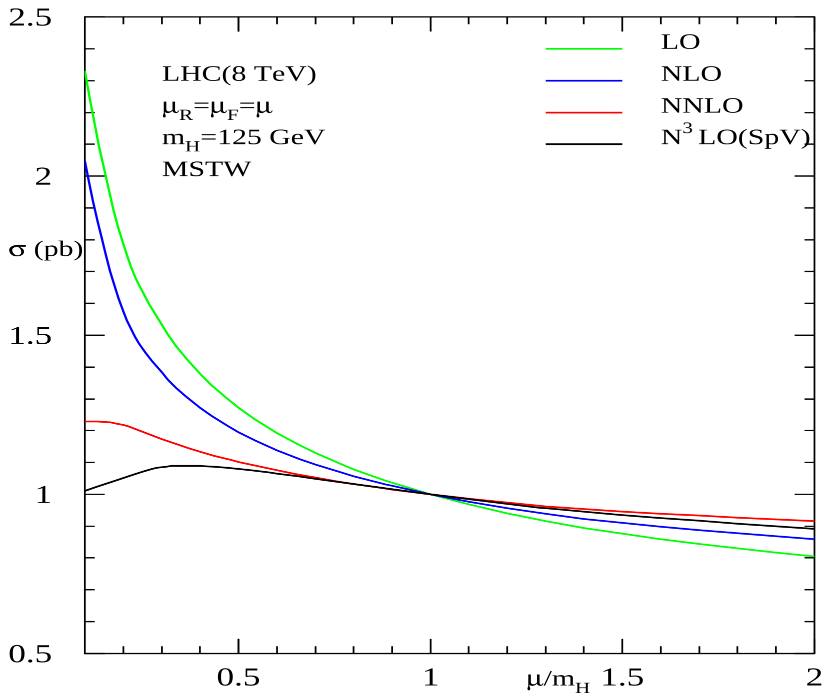

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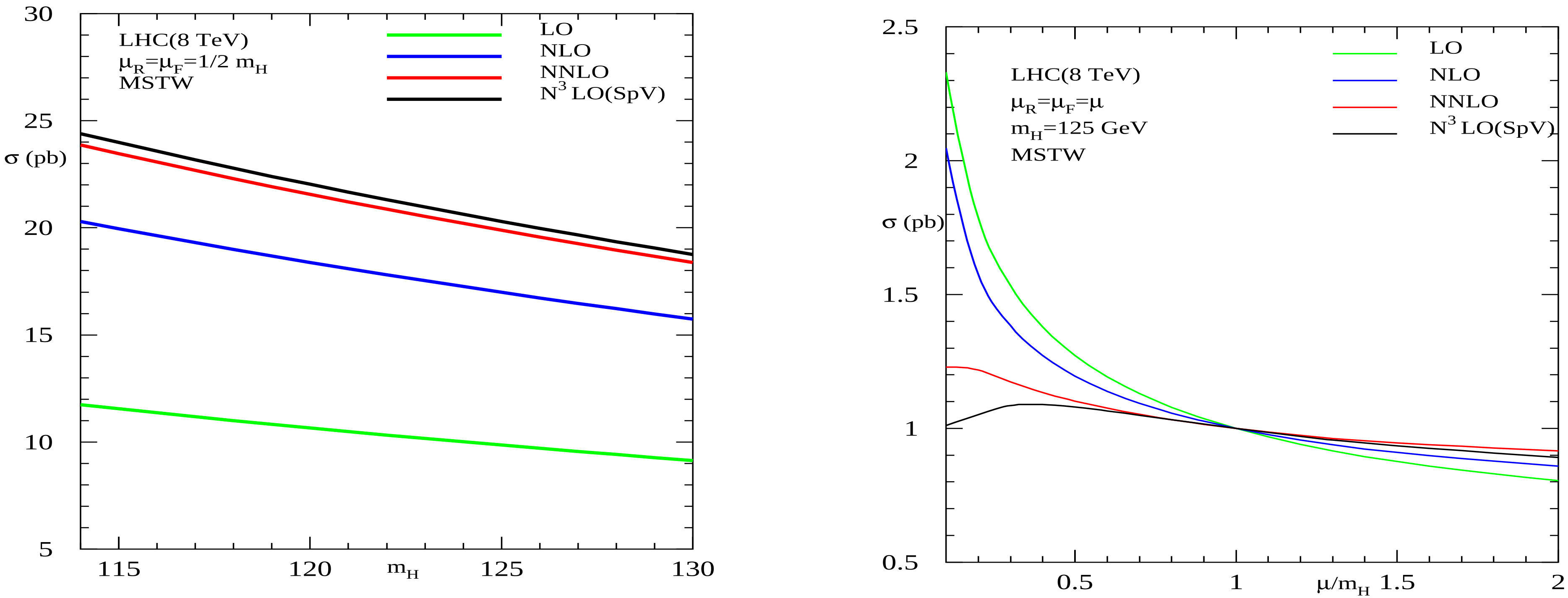

- Scale uncertainty goes down a lot
- Additional $7-9\%$ increase in cross section due to N^3LO soft gluons.

Total cross section for Higgs production at $\sqrt{s} = 8$ TeV

J.Smith, V. Ravindran

Cross sections (in pb) at the LHC ($\mu_F = \mu_R = m_H$) with $\sqrt{s} = 8$ TeV, using the MSTW2008 parton densities.

$$\sigma^{best} = \sigma^{NNLO} + \sigma^{NNLL} + \sigma^{EW} + \sigma^{tb}$$

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m_H	σ^{best}	PDF	Scale
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115	23.46	$^{+0.59}_{-0.74}$	$^{+2.04}_{-2.18}$
116	23.07	$^{+0.58}_{-0.73}$	$^{+2.00}_{-2.14}$
117	22.68	$^{+0.57}_{-0.72}$	$^{+1.96}_{-2.11}$
118	22.30	$^{+0.56}_{-0.71}$	$^{+1.92}_{-2.07}$
119	21.93	$^{+0.55}_{-0.69}$	$^{+1.88}_{-2.03}$
120	21.57	$^{+0.54}_{-0.68}$	$^{+1.85}_{-2.00}$
121	21.21	$^{+0.53}_{-0.67}$	$^{+1.81}_{-1.97}$
122	20.87	$^{+0.53}_{-0.66}$	$^{+1.78}_{-1.93}$
123	20.53	$^{+0.52}_{-0.65}$	$^{+1.75}_{-1.90}$
124	20.20	$^{+0.51}_{-0.64}$	$^{+1.71}_{-1.87}$
125	19.88	$^{+0.50}_{-0.63}$	$^{+1.68}_{-1.84}$
126	19.57	$^{+0.50}_{-0.62}$	$^{+1.65}_{-1.81}$
127	19.26	$^{+0.49}_{-0.61}$	$^{+1.62}_{-1.78}$
128	18.96	$^{+0.48}_{-0.60}$	$^{+1.59}_{-1.75}$
129	18.66	$^{+0.48}_{-0.59}$	$^{+1.57}_{-1.73}$
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118	22.30	$^{+0.56}_{-0.71}$	$^{+1.92}_{-2.07}$
119	21.93	$^{+0.55}_{-0.69}$	$^{+1.88}_{-2.03}$
120	21.57	$^{+0.54}_{-0.68}$	$^{+1.85}_{-2.00}$
121	21.21	$^{+0.53}_{-0.67}$	$^{+1.81}_{-1.97}$
122	20.87	$^{+0.53}_{-0.66}$	$^{+1.78}_{-1.93}$
123	20.53	$^{+0.52}_{-0.65}$	$^{+1.75}_{-1.90}$
124	20.20	$^{+0.51}_{-0.64}$	$^{+1.71}_{-1.87}$
125	19.88	$^{+0.50}_{-0.63}$	$^{+1.68}_{-1.84}$
126	19.57	$^{+0.50}_{-0.62}$	$^{+1.65}_{-1.81}$
127	19.26	$^{+0.49}_{-0.61}$	$^{+1.62}_{-1.78}$
128	18.96	$^{+0.48}_{-0.60}$	$^{+1.59}_{-1.75}$
129	18.66	$^{+0.48}_{-0.59}$	$^{+1.57}_{-1.73}$
130	18.38	$^{+0.47}_{-0.58}$	$^{+1.54}_{-1.70}$

- NNLO QCD corrections contributes bulk of the cross section

Total cross section for Higgs production at $\sqrt{s} = 8$ TeV

J.Smith, V. Ravindran

Cross sections (in pb) at the LHC ($\mu_F = \mu_R = m_H$) with $\sqrt{s} = 8$ TeV, using the MSTW2008 parton densities.

$$\sigma^{best} = \sigma^{NNLO} + \sigma^{NNLL} + \sigma^{EW} + \sigma^{tb}$$

m_H	σ^{best}	PDF	Scale
114	23.87	$^{+0.60}_{-0.76}$	$^{+2.08}_{-2.22}$
115	23.46	$^{+0.59}_{-0.74}$	$^{+2.04}_{-2.18}$
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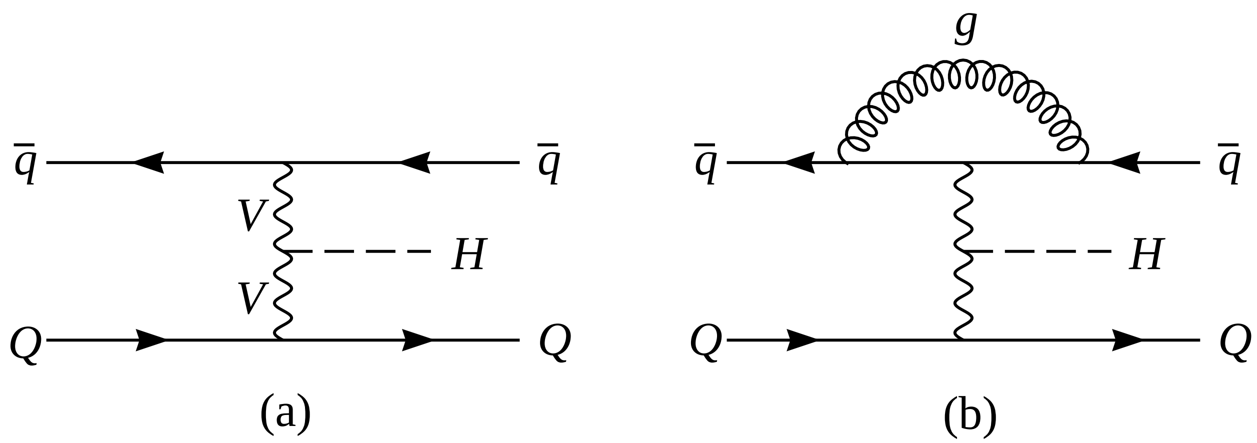
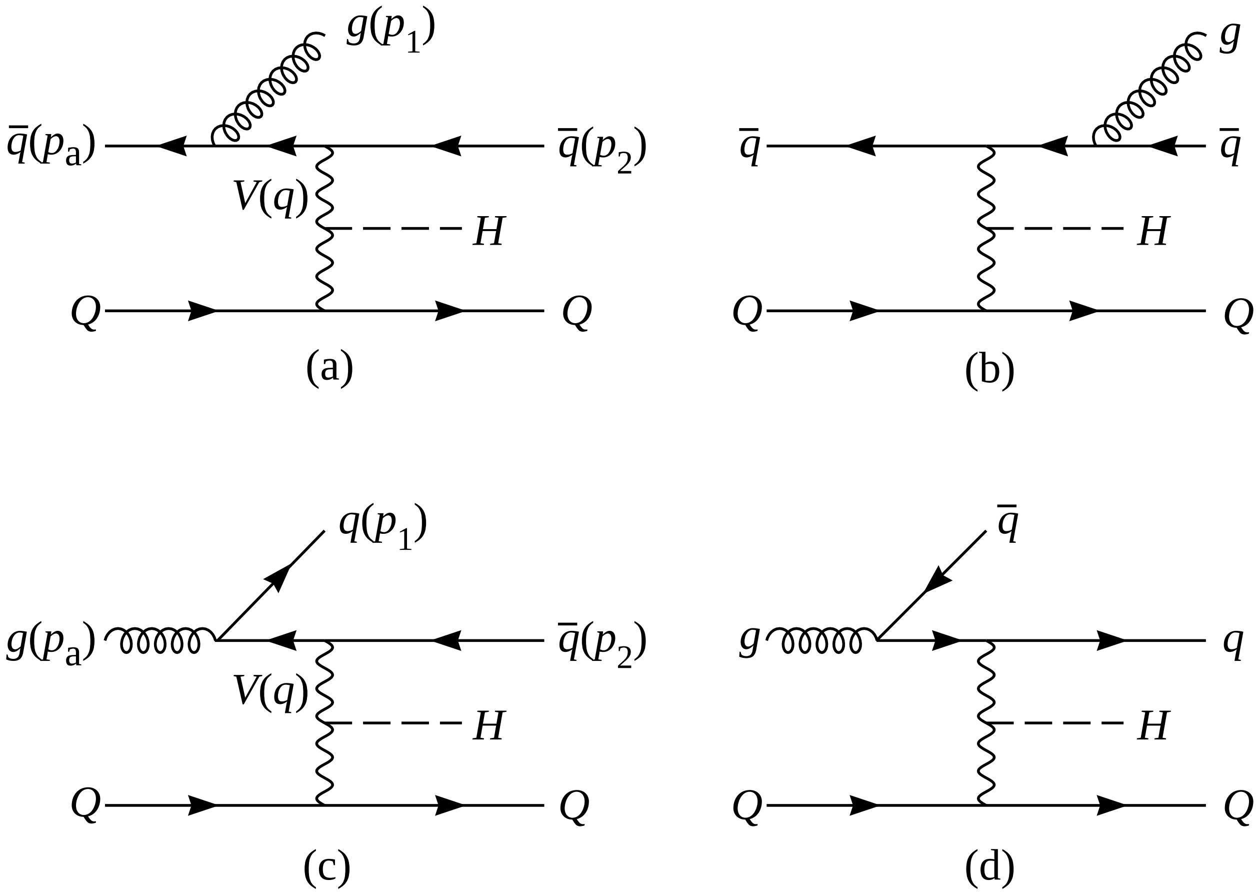
- Mixed electroweak and b quark contributions account for $5 - 10\%$
- $NNLL$ resummations are accounted for through $\mu_R = \mu_F = m_H$
- Scale uncertainty is around $\pm 8\%$ for $m_H = 113 - 130$ GeV.
- PDF uncertainty is around $\pm 3\%$ at $m_H = 113 - 130$ GeV.

Higgs from Weak-Boson Fusion(WBF) at LHC



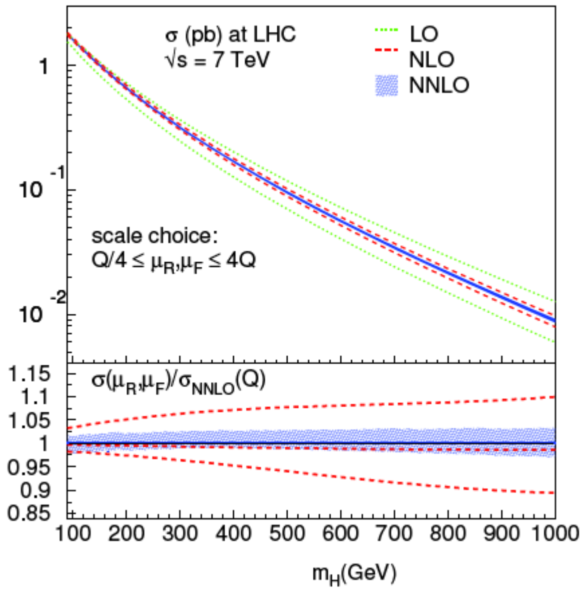
- This is a promising channel for the discovery
- A clean channel to measure $H \to b\bar{b},\ \tau^+, \tau^-, WW, \gamma\gamma, invisible$
- It will be a clean experimental obervation with a statistical accuracy ranging from 5% to 10%.
- So precise measurement of Higgs coupling to various SM particles is possible only if the theoretical error is well below 10%.
- Need to include higher order corrections to WBF processes

Typical QCD corrections to WBF



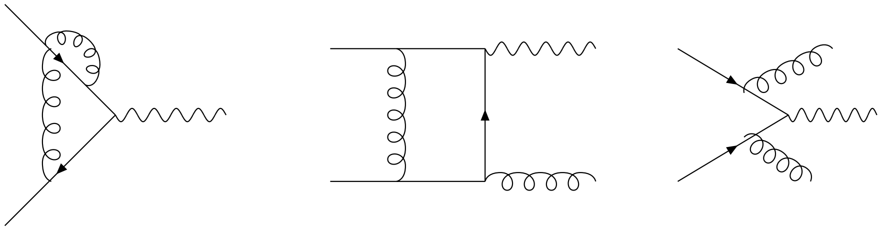
- Virtual corrections, real emissions due to gluons
- Gluon initiated processes
- No color exchange, hence computations are relatively easy

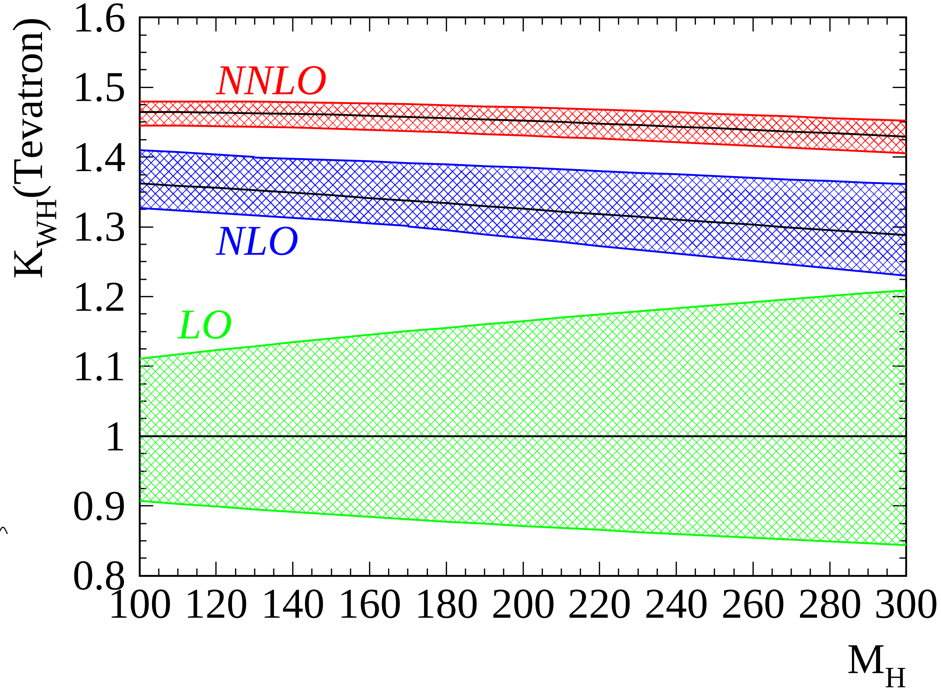
Results



- NLO QCD is by Figy, Oleari, Zeppenfeld
- NLO QCD+EW by Ciccolini,Denner, Dittmaier
- NLO SUSY by Figy,Palmer, Weiglein
- Beyond NLO: gluon fusion/WBF, Anderson,Binoth, Heinrich,Smillie, Brendenstein, Hagiwara, Jager Gluon Induced WBF: Harlander, Vollinga, Weber, DIS-like NNLO, Bolzoni, Maltoni, Moch, Zaro

Higgs strahlung at $NNLO$

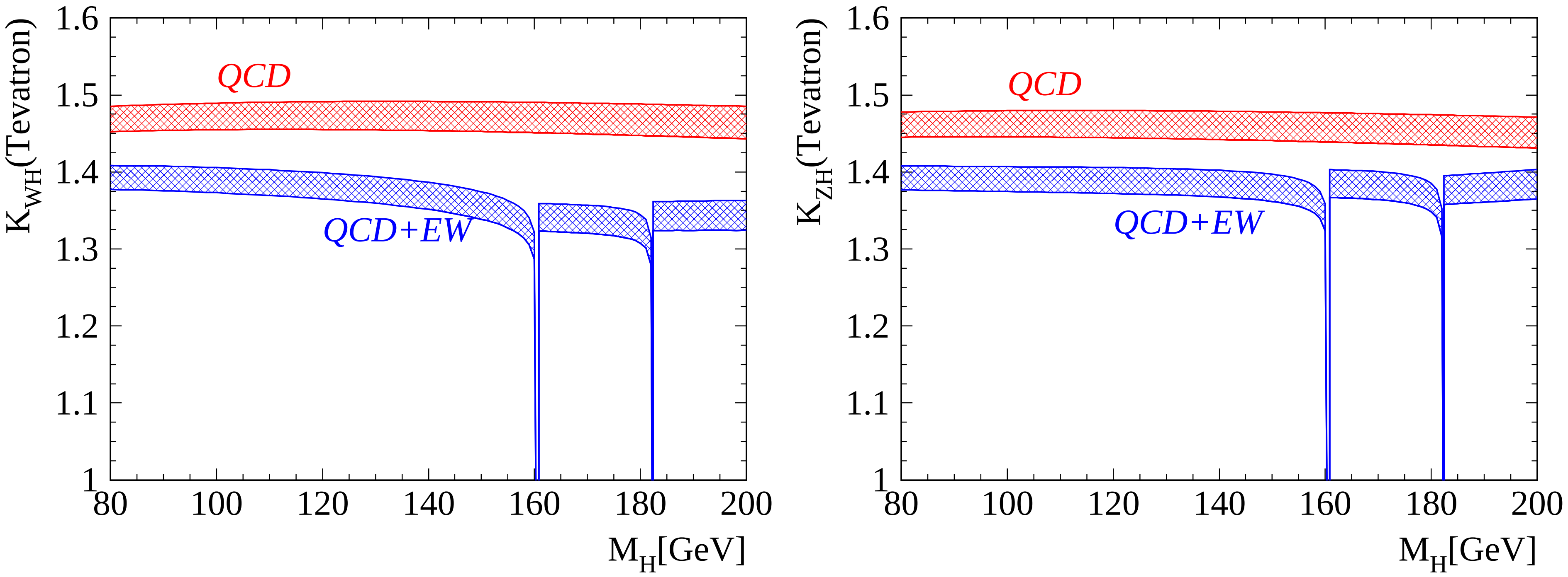




- The corrections are $\mathbf{3\%}$ at LHC and $\mathbf{10\%}$ at Tevatron
- Scale uncertainity is around $\mathbf{10\%}$ at NLO level
- NNLO reduces it to $\mathbf{2-3\%}$ at NLO level

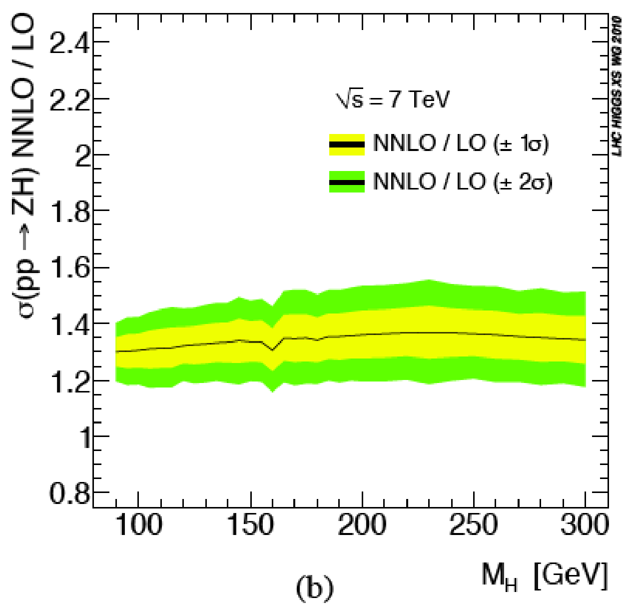
QCD+Electroweak

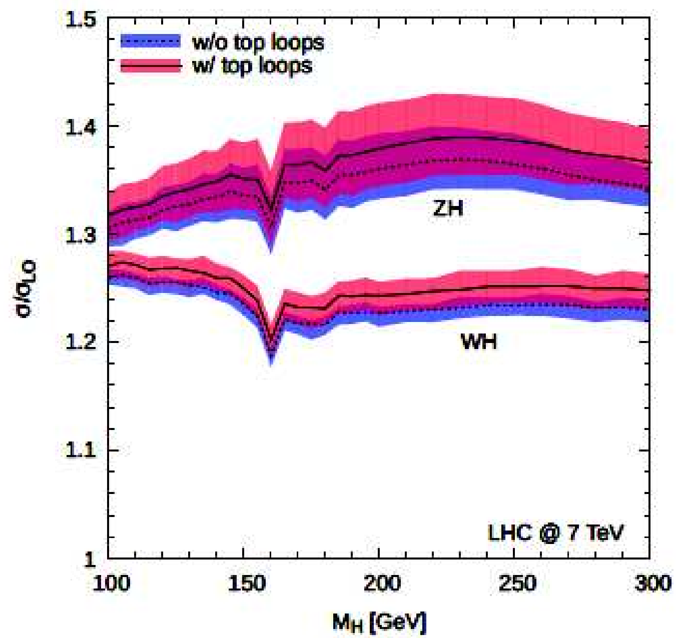
- NNLO QCD corrections are comparable to electtrowead corrections
- Electro weak corrections has opposite sign



QCD+Electroweak

NLO: Han, Willenbrock , NNLO: Brein, Djouadi, Harlander EW: Ciccolini, Dittmaier, Kramer





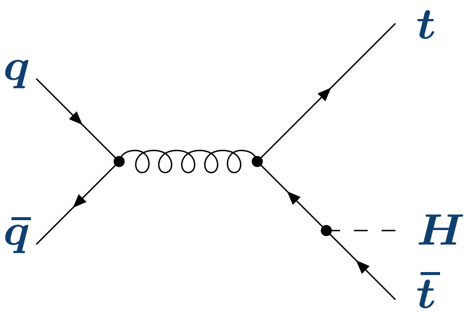
Associated Production of Higgs with tops

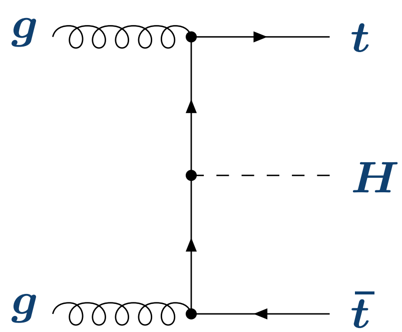
Processes:

$$p\,\bar{p}\,/p\,p \to t + \bar{t} + H$$

Sub processes(leading order(LO)):

$$q\,\bar{q}\ \to t + \bar{t} + H$$
$$g\,\bar{g}\ \to t + \bar{t} + H$$

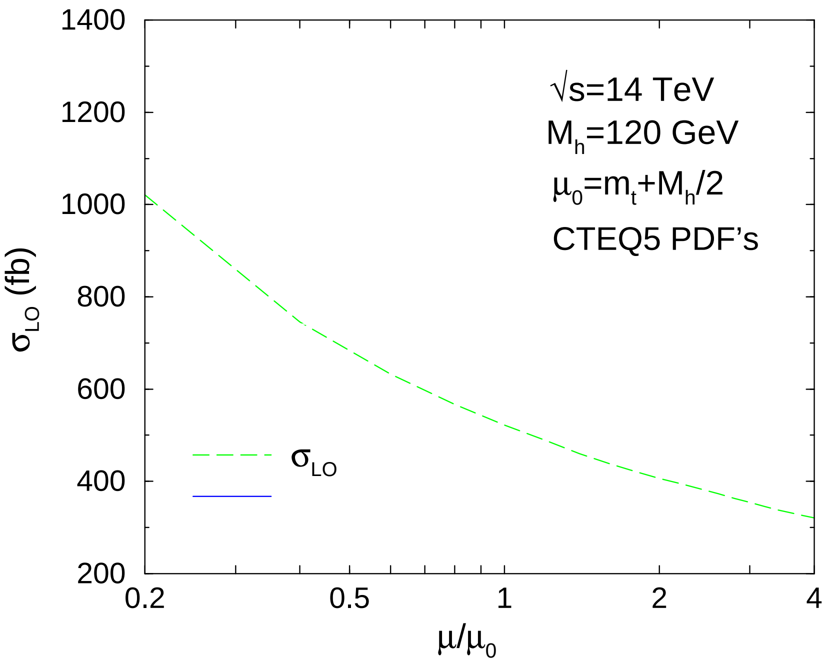




- Rate will be very small! BUT ...
- At Tevatron, these are clean events for Higgs mass below $140\ GeV$
- At LHC, these are clean events for Higgs mass below $125\ GeV$
- Fine determination of Top-Yukawa coupling is possible

Why NLO?

- Theoretical Uncertainties in the LO cross section is large:



$$\sigma^{P_1,P_2} \sim \left(\frac{\alpha_s(\mu_R)}{4\pi}\right)^2 \Phi_{ab}(\hat{s},\mu_F)$$

- a) Renormalization scale through strong coupling constant $\alpha_s(\mu_R)$

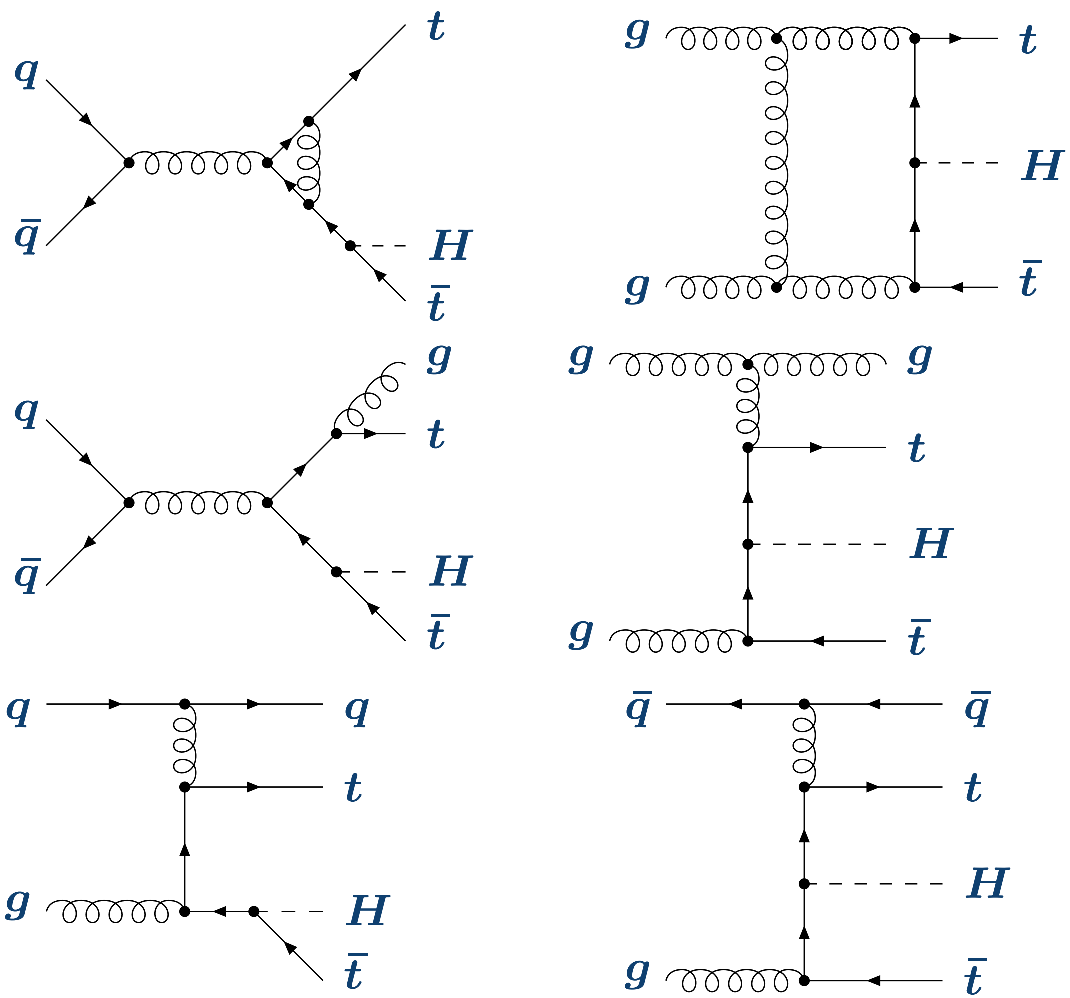
  b) Factorisation scale μ_F through parton distribution functions

  c)Various parton densities themselves

- Uncertainity: $100\% \quad - \quad 200\%$

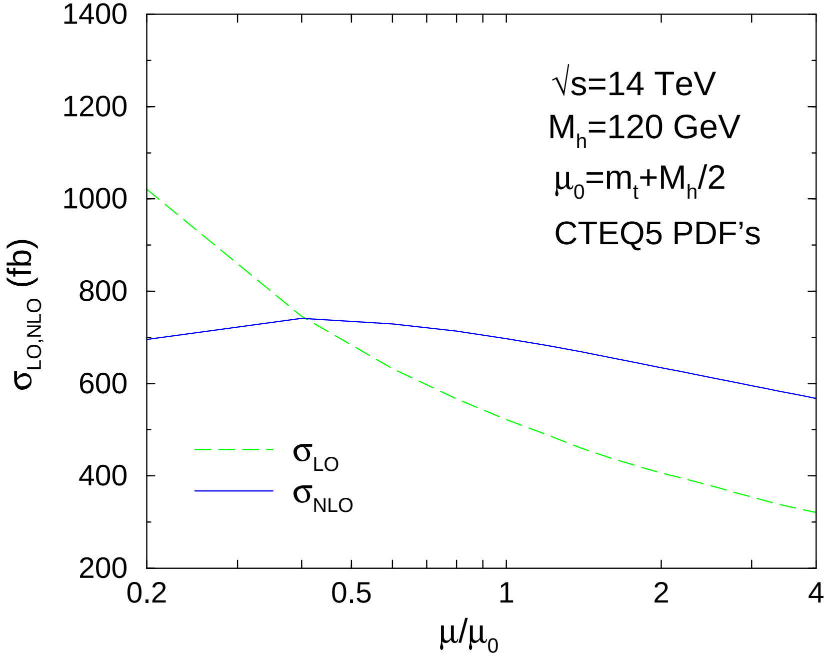
NLO processes

Next to Leading order QCD corrections:



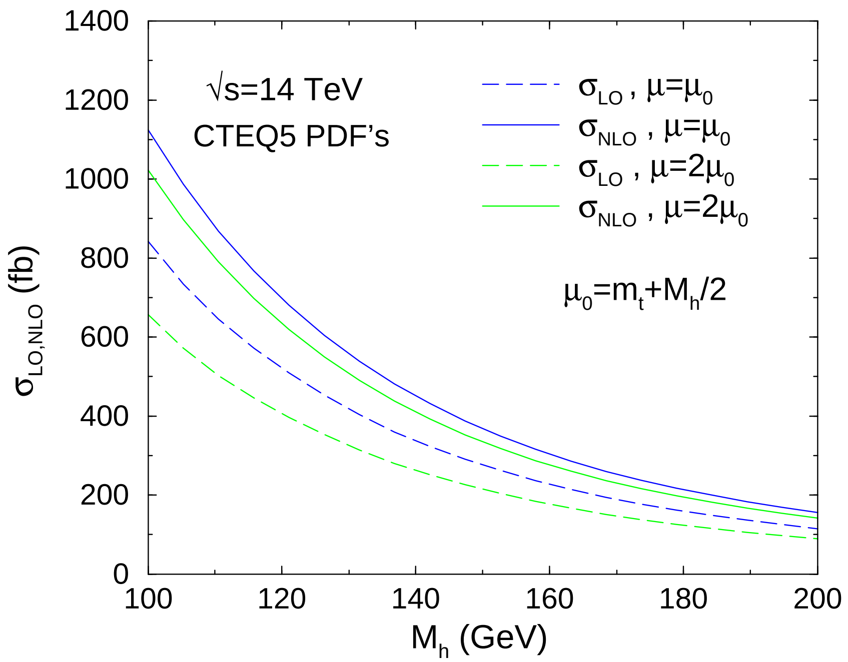
Scale dependence on σ_{NLO} at LHC

Beenakker, Dittmaier, Kramer, Plumper, Spira, Zerwas; Dawson, Reina, Wackeroth, Orr, Jackson NLO+PS: Frederix, Frixione, Hirschi, Maltoni, Pittau, Torielli-aMC@NLO; Garzelli, Kardos, Papadopoulos, Troosanyi, PowHel



- $\mu_0 = m_t + M_h/2$ and $\mu = 2m_t + M_h$.
- LO theoretical uncertainty is 100% to 200% With NLO, Scale uncertainty reduces 10%, PDF uncertainty to 7% Total theoretical uncertainty reduces substantially to 15% to 20%
- $\sigma^{NLO}(g + g \to t + \bar{t} + h)$ is stable under scale $\sigma^{NLO}(q + g \to t + \bar{t} + h)$ is very sensitive to scale

Total cross section at LHC



- $\sigma^{NLO}(g+g\to t+\bar{t}+h)$ is dominant
- $\sigma^{NLO}(q+\bar{q}\to t+\bar{t}+h)$ and $\sigma^{NLO}(q+g\to t+\bar{t}+h)$ are less dominant

ICHEP 2010: Tevatron updates

ICHEP: Data of $\mathbf{5.9}\ \boldsymbol{fb^{-1}}$ at CDF and $\mathbf{6.7}\ \boldsymbol{fb^{-1}}$ at D0 exclude Higgs of mass in $\mathbf{158} < \boldsymbol{m_H} < \mathbf{175}\ \boldsymbol{GeV/c^2}$.

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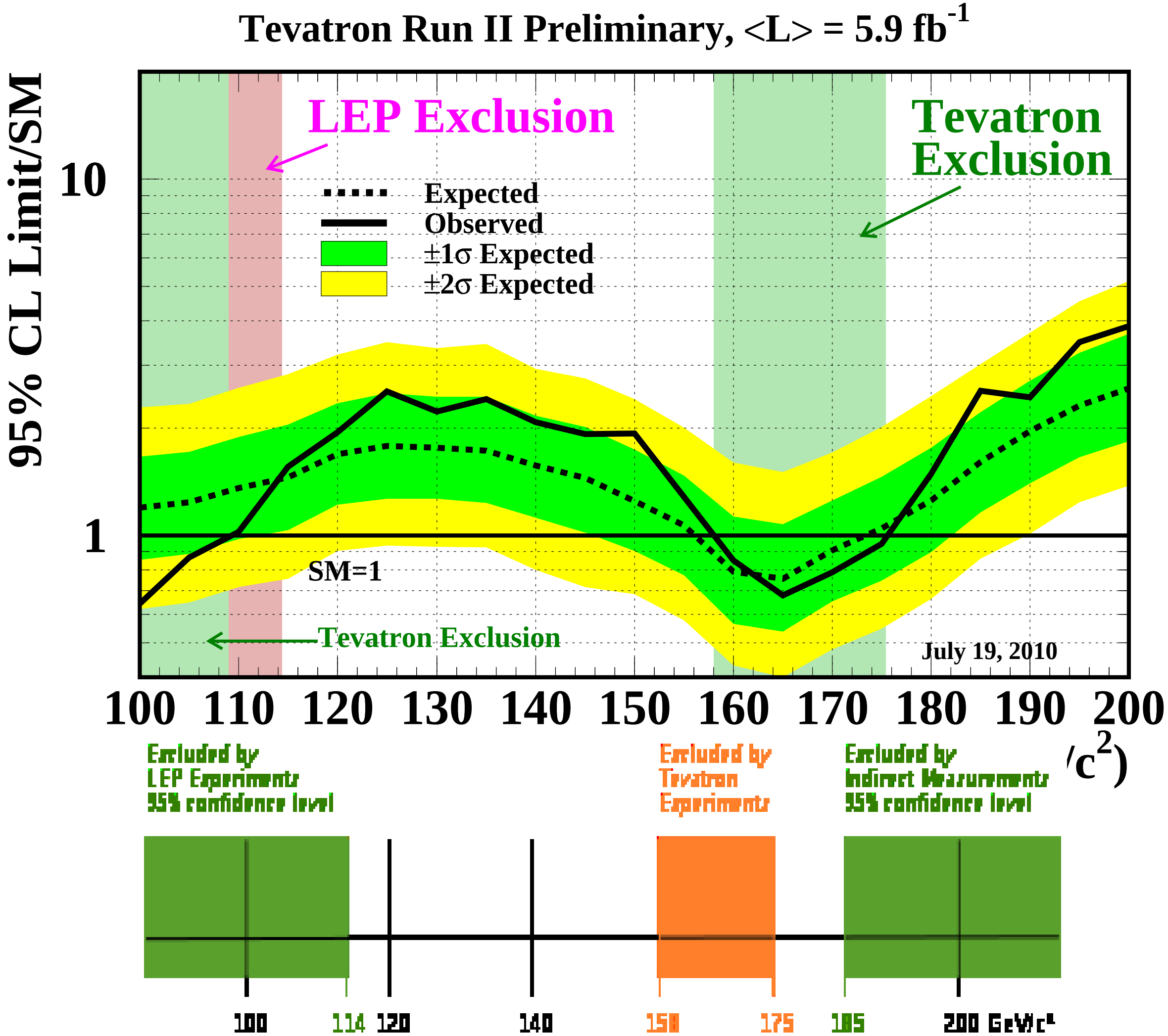

Winter 2011: Combined Tevatron updates

Data of $8.3 fb^{-1}$ exclude Higgs of mass in $158 < m_H < 173\ GeV/c^2$ at 95% CL.

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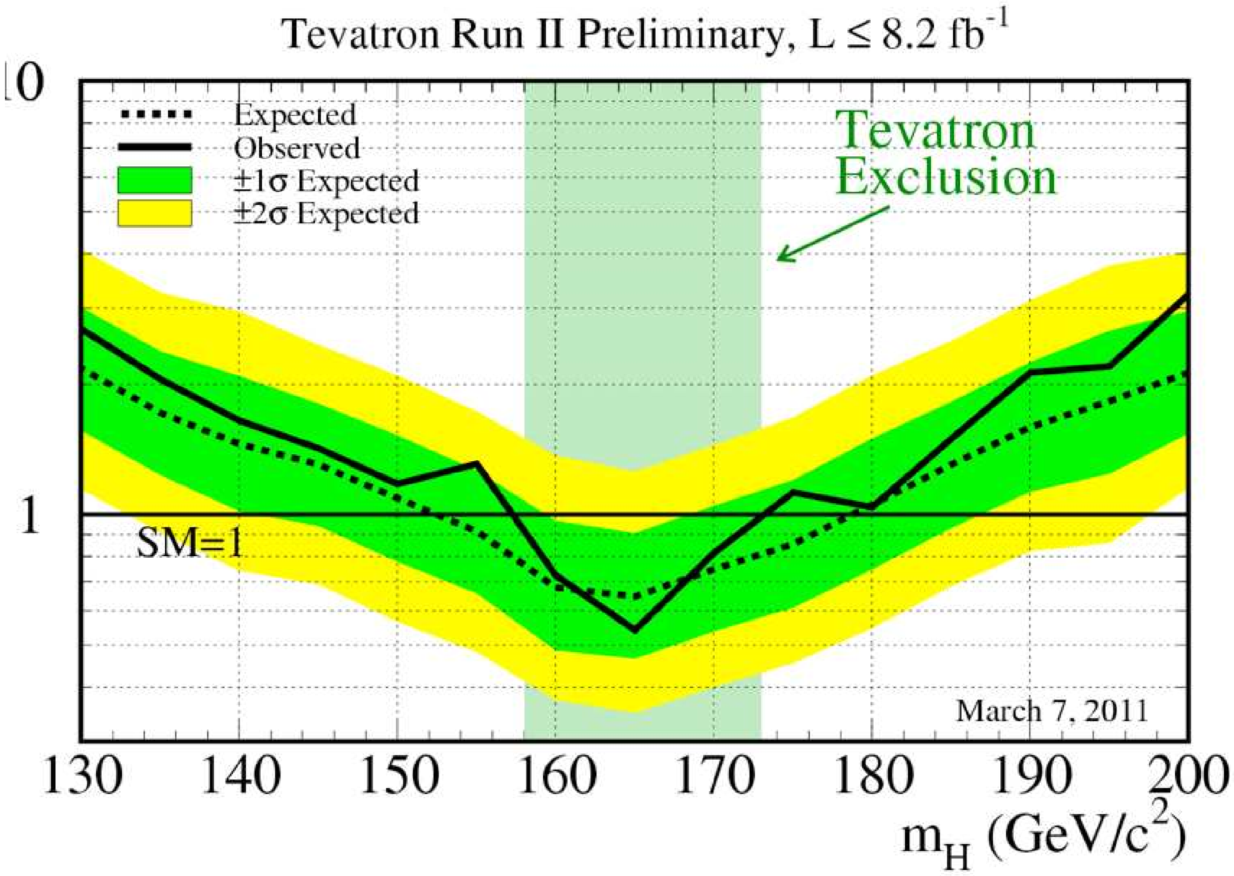

July 2012: Combined Tevatron updates

Data of $\mathbf{10 fb^{-1}}$ exclude Higgs of mass in $\mathbf{100 < m_H < 106, 147 < m_h < 179 \ GeV/c^2}$ at $\mathbf{95\%}$ CL.

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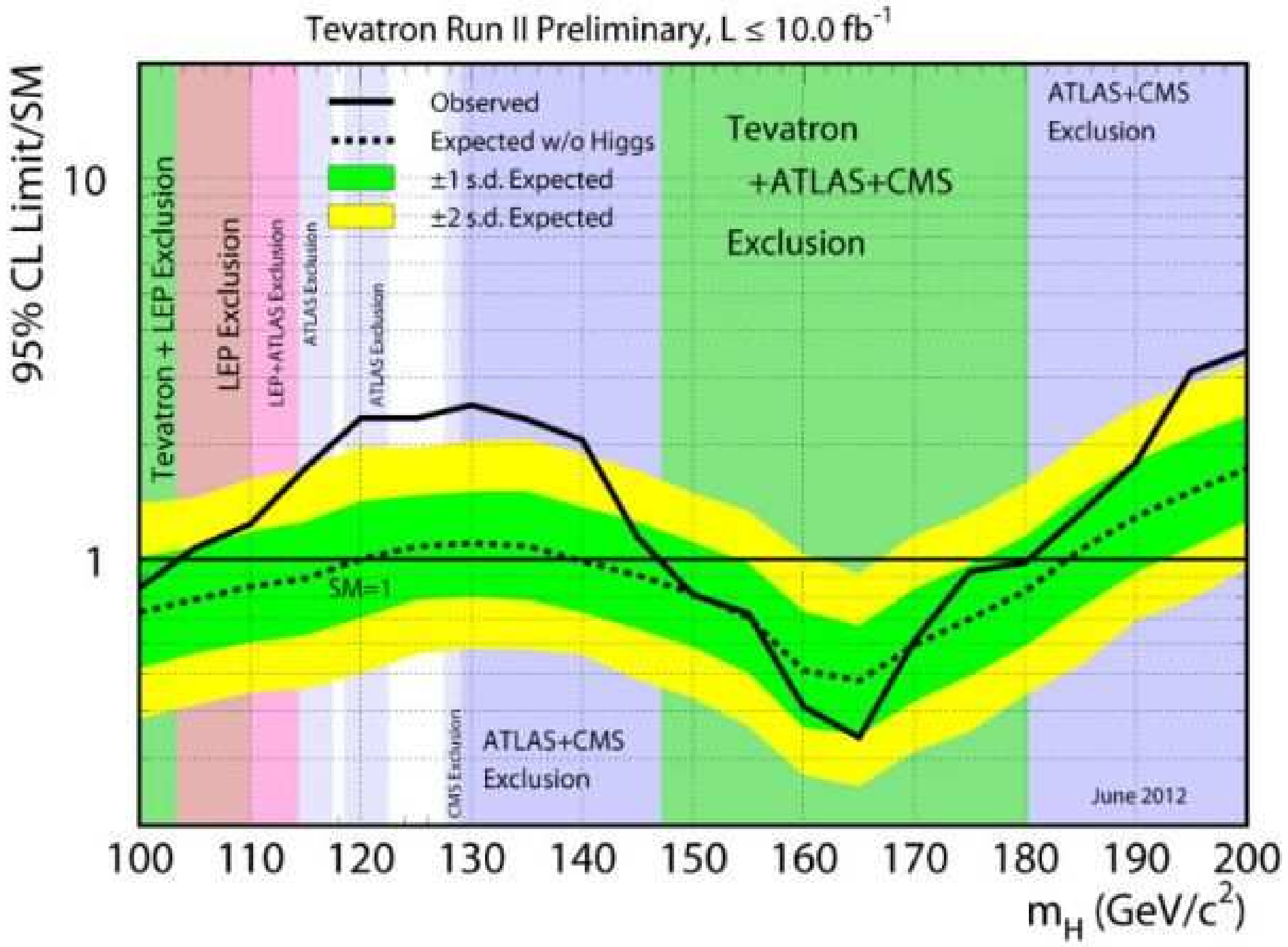

Excess over background in the mass range $115 < m_h < 135 \, GeV/c^2$ with significance of 2.7 sigma (local).

ATLAS results: Moriond EW'2012

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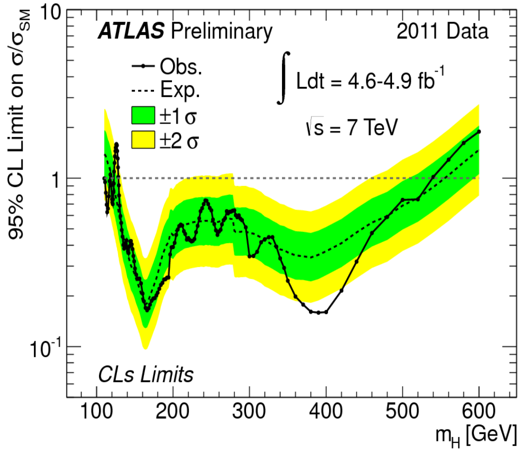

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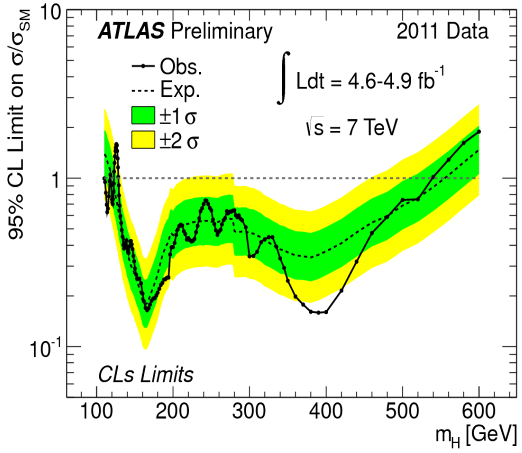

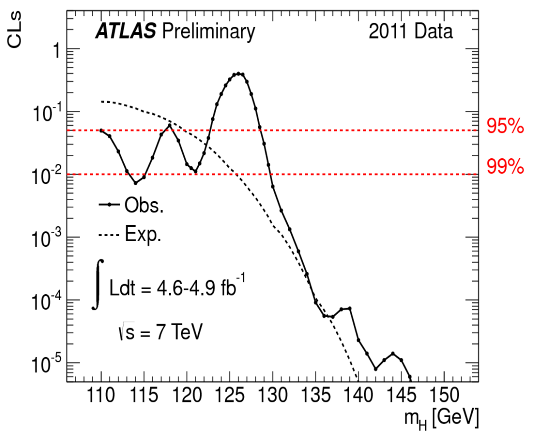

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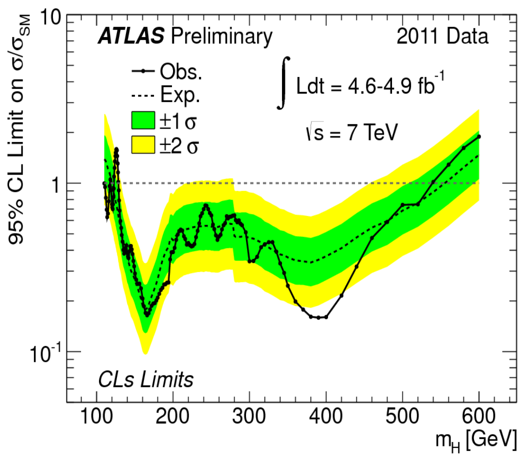

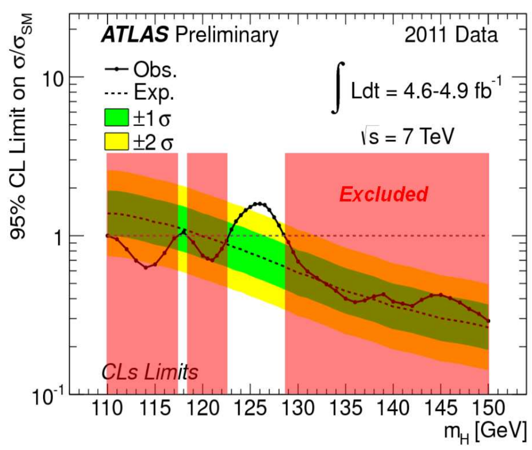

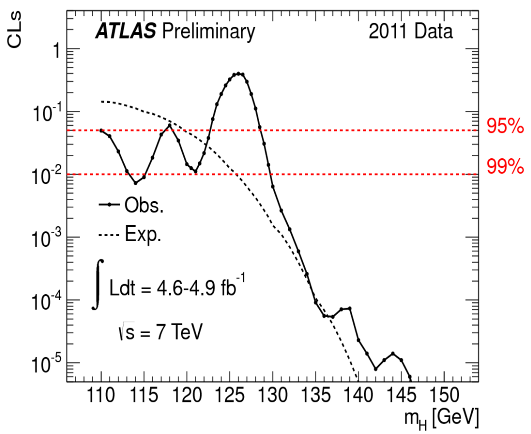

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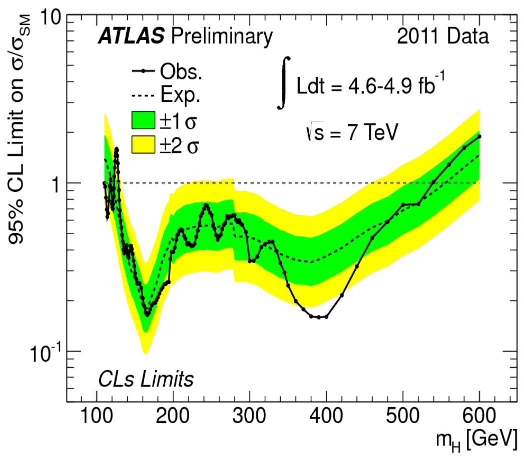

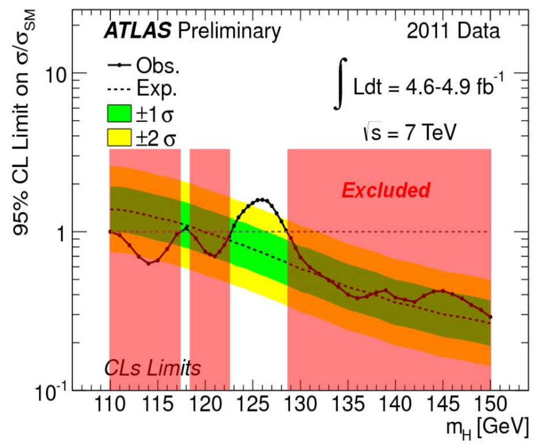

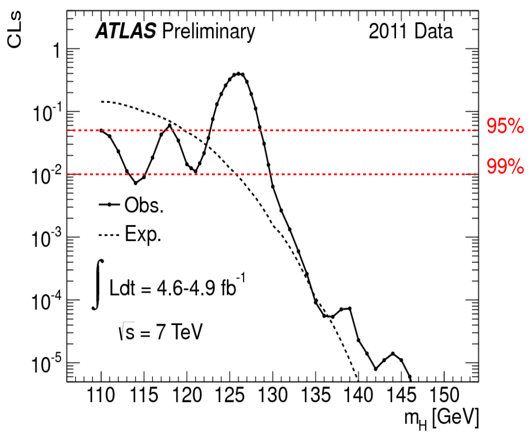

- $\mathbf{95\%}$ exclusion on m_H: $\mathbf{110 - 117,\ 118.5 - 122.5,\ 129 - 539}$ GeV
- $\mathbf{99\%}$ exclusion on m_H: $\mathbf{130 - 486}$ GeV
- $\mathbf{95\%}$ allowed m_H: $\mathbf{117.5 - 118.5,\ 122.5 - 129}$ GeV
- Excess for m_H: $\mathbf{126.5}$ GeV $\mathbf{2.8\sigma}$ local, $\mathbf{1.5\sigma}$ global

CMS results: Moriond EW'2012

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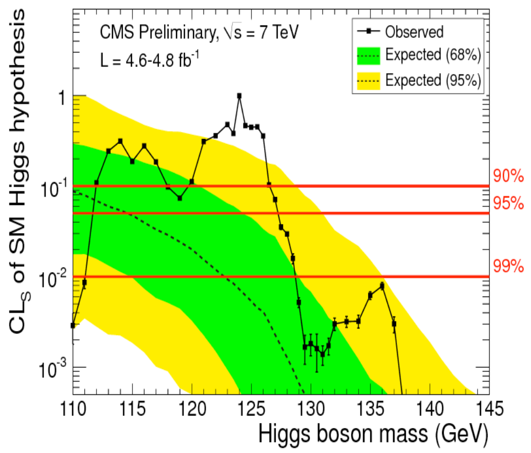

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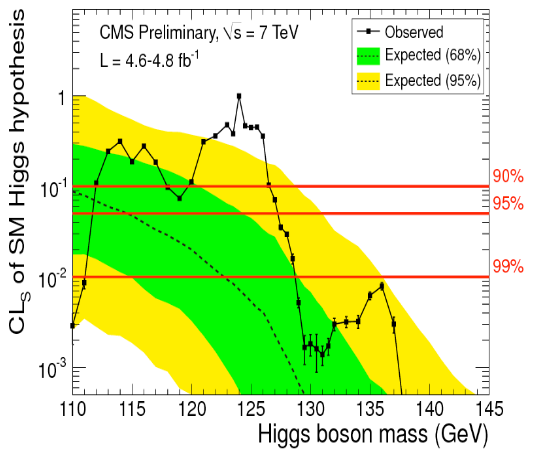

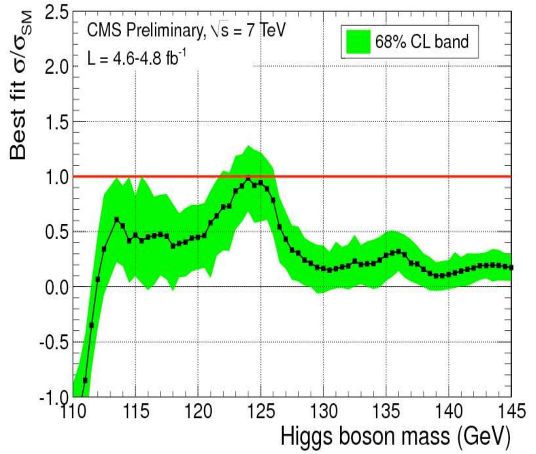

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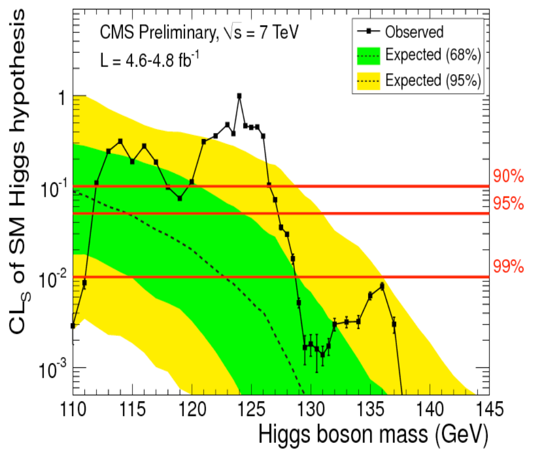

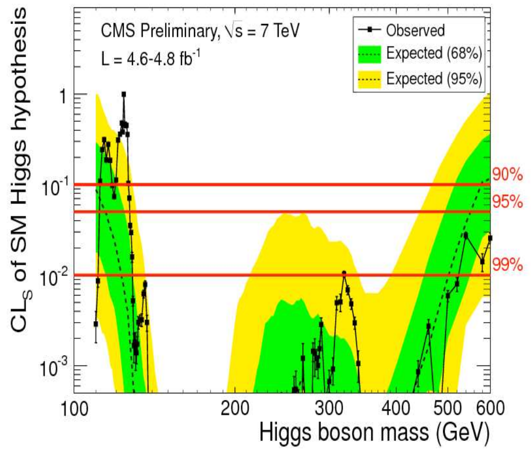

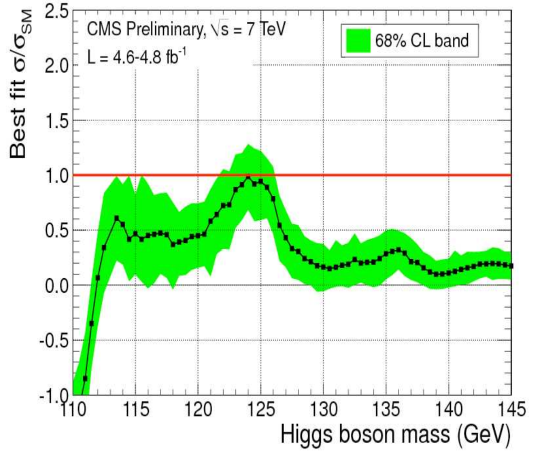

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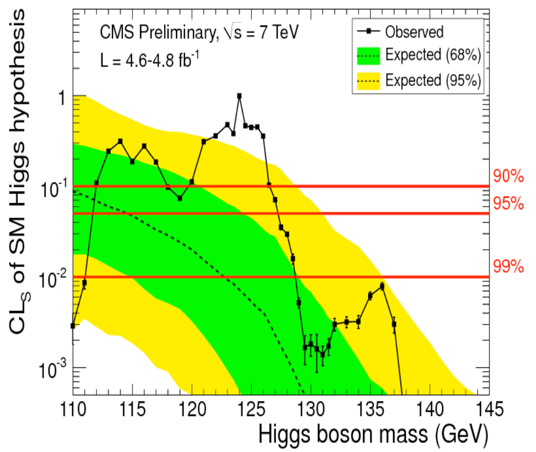

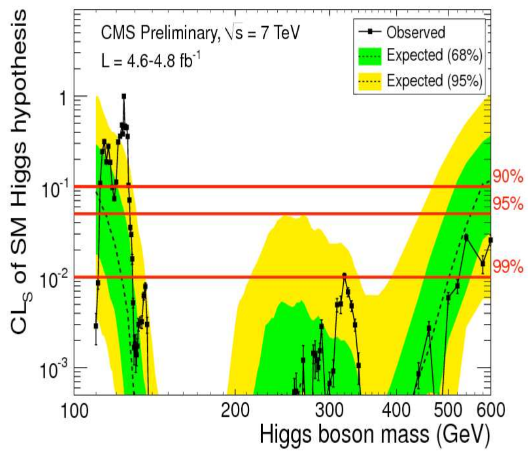

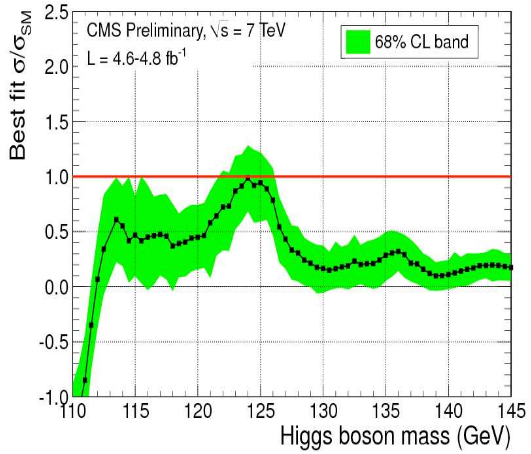

- 95% exclusion on m_H:
  $127 - 600$ GeV
- 99% exclusion on m_H:
  $129 - 525$ GeV
- 95% allowed m_H:
  $114 - 127.5$ GeV
- Excess for m_H:
  125 GeV 2.8σ local,0.8σ global

Theory influence on the rates

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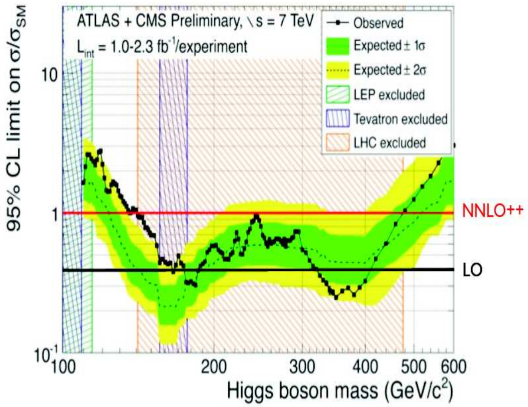
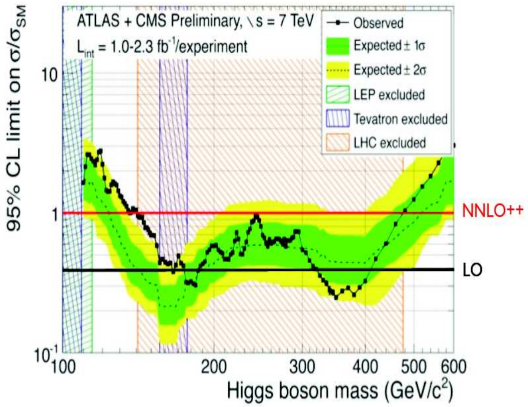
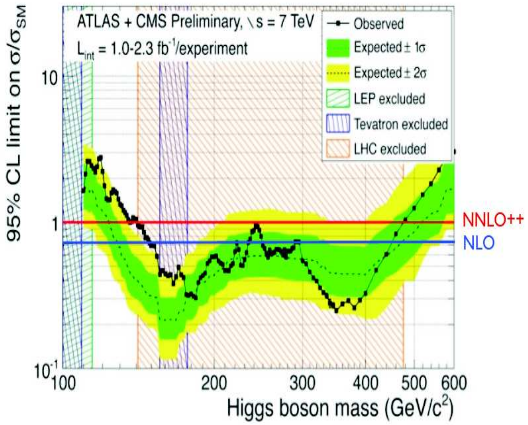


Theory influence on the rates





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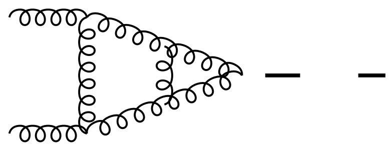

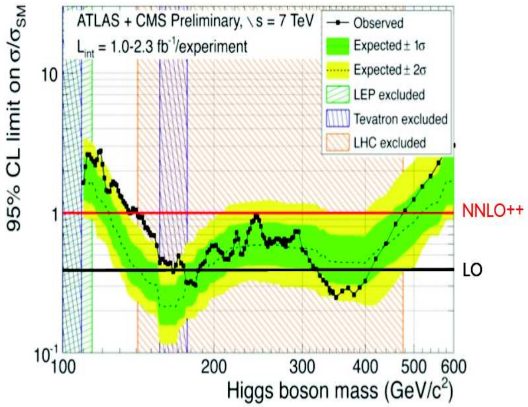

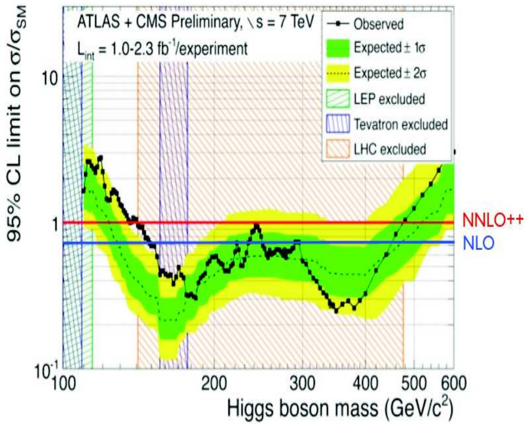

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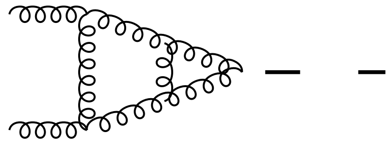

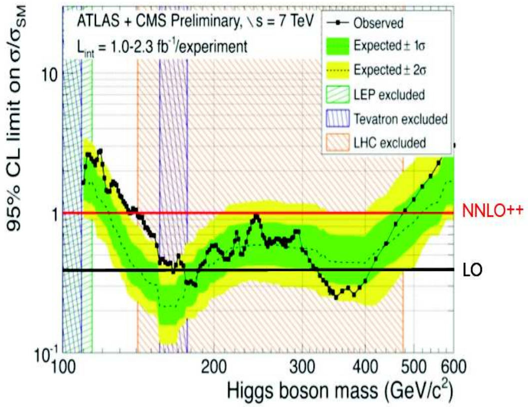

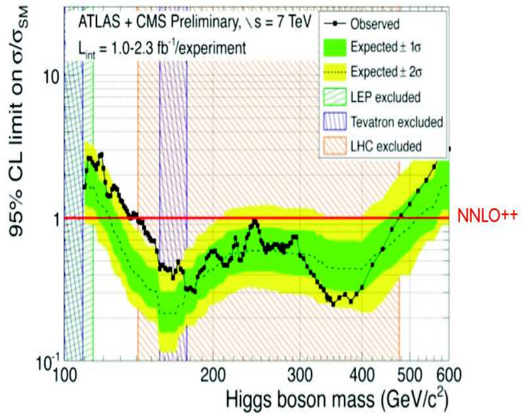

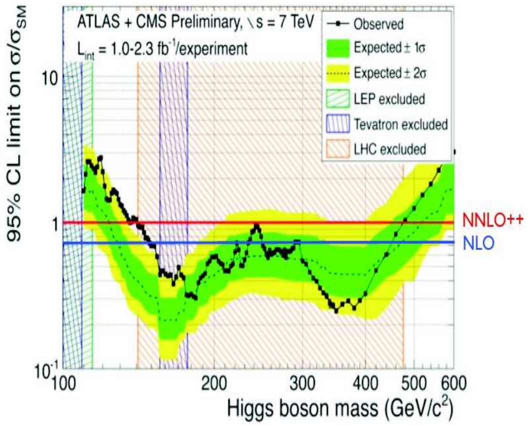

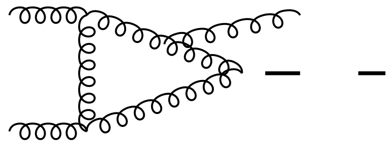

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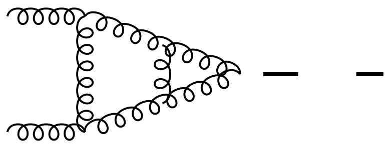

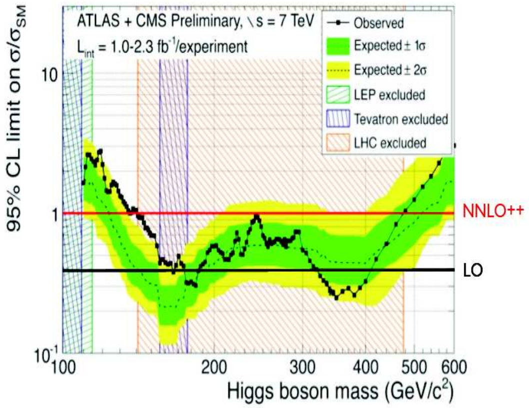

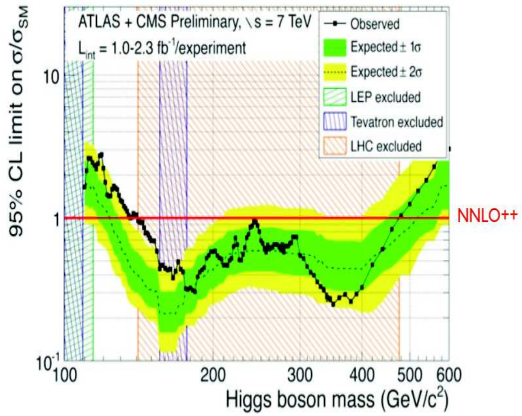

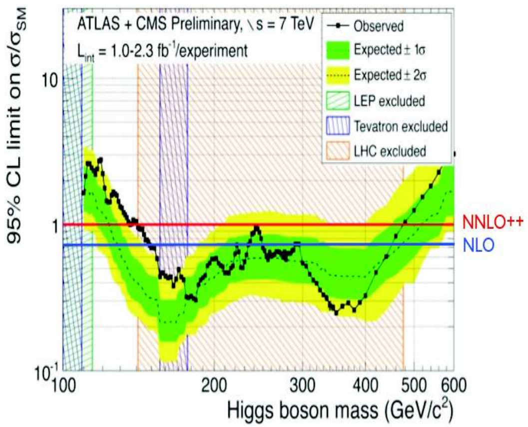

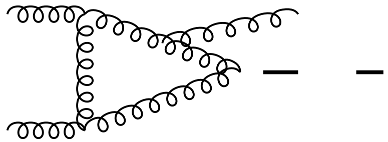

Sub leading corrections due to finite top mass at NNLO are now known and the large top mass limit works well (0.5%) upto $m_H = 300$ GeV.

R.Harlander et al;M. Steinhauser et al

Conclusions

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