Higgs Boson Physics, Part IV

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Outline of Part IV

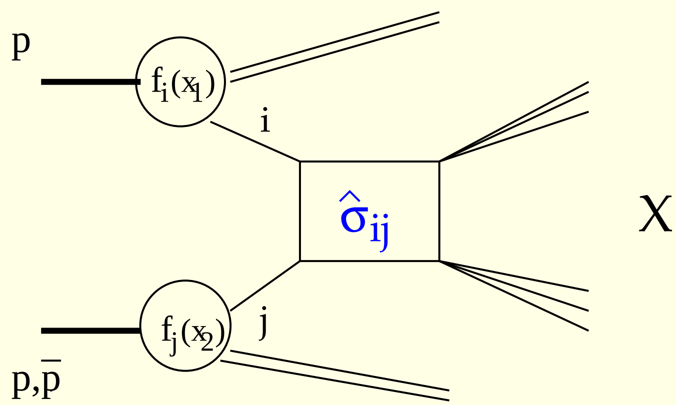
- The current status of theoretical predictions in Higgs physics: How does theory compare to experiments?
- Highlights from the theoretical activity of the last few years:
  $\longrightarrow$ $gg \to H$: gluon-gluon fusion calculated at NNLO in QCD, consolidating the reliability of a very difficult theoretical prediction.
  $\longrightarrow$ $q\bar{q}, gg \to t\bar{t}H$ calculated at NLO in QCD, stabilizing an important theoretical prediction for Higgs discovery in the (most interesting) low mass region.
  $\longrightarrow$ $q\bar{q}, gg \to b\bar{b}H$, $bg \to bH$, $b\bar{b} \to H$: now available including NLO (NNLO) QCD corrections, which clarify a very controversial theoretical scenario.
- Final Overview

Understanding the current status of theoretical predictions

or

How theory can compare to experiments

The basic picture of a $p\bar{p}, pp \rightarrow X$ high energy process ...



where the short and long distance part of the QCD interactions can be factorized and the cross section for $pp, p\bar{p} \rightarrow X$ can be calculated as:

$$\sigma(pp, p\bar{p} \rightarrow X) = \sum_{ij} \int dx_1 dx_2 f_i{}^p(x_1) f_j{}^{p,\bar{p}}(x_2) \hat{\sigma}(ij \rightarrow X)$$

$\longrightarrow$ $ij \rightarrow$ quarks or gluons (partons)

$\longrightarrow$ $f_i^p(x)$, $f_i^{p,\bar{p}}(x)$: Parton Distributions Functions: probability densities (probability of finding parton i in p or $\bar{p}$ with a fraction x of the original hadron momentum)

$\longrightarrow$ $\hat{\sigma}(ij \rightarrow X)$: partonic cross section

. . . is complicated by the presence of interactions

$\longrightarrow$ Focus on strong interactions, dominant at hadron colliders

$\longrightarrow$ In the $ij \to X$ process, initial and final state partons radiate and absorb gluons/quarks:

How to calculate the physical cross section?

$\longrightarrow$ Due to the very same interactions: the strong coupling constant ($\alpha_s = g_s^2/4\pi$) becomes a function of the energy scale (Q^2), such that

$$\alpha_s(Q^2) \to 0 \quad \text{for large scales } Q^2 \quad : \quad \text{running coupling}$$

$$\Downarrow$$

we can calculate $\hat{\sigma}(ij \to X)$ perturbatively

$$\hat{\sigma}(ij \to X) = \alpha_s^k \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)} \alpha_s^m$$

n=0 : Leading Order (LO), or tree level or Born level

n=1 : Next to Leading Order (NLO), include $O(\alpha_s)$ corrections

. . . . . .

Perturbative approach and scale dependence

$\longrightarrow$ At each order in α_s the expression of $\hat{\sigma}(ij \to X)$ contains infinities that are canceled by a subtraction procedure: renormalization.

$\longrightarrow$ A remnant of the subtraction point is left at each perturbative order as a renormalization scale dependence (μ_R)

$$\hat{\sigma}(ij \to X) = \alpha_s^k(\mu_R) \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)}(\mu_R, Q^2)\alpha_s^m(\mu_R)$$

$\longrightarrow$ A similar approach introduces a subtraction point dependence in the initial state parton densities: factorization scale dependence (μ_F)

Setting $\boxed{\mu_R = \mu_F = \mu}$:

$$\sigma(pp, p\bar{p} \to X) = \sum_{ij} \int dx_1 dx_2 f_i^p(x_1, \mu) f_j^{p,\bar{p}}(x_2, \mu) \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)}(\mu, Q^2)\alpha_s^{m+k}(\mu)$$

The theoretical error is systematically organized as an expansion in α_s

Ex.: General structure of a NLO calculation

NLO total cross section:

$$\sigma^{NLO}_{p\bar{p},pp} = \sum_{i,j} \int dx_1 dx_2 \mathcal{F}_i^p(x_1,\mu_F)\mathcal{F}_j^{\bar{p},p}(x_2,\mu_F)\hat{\sigma}^{NLO}_{ij}(x_1,x_2,\mu_R,\mu_F)$$

where

$$\hat{\sigma}^{NLO}_{ij} = \hat{\sigma}^{LO}_{ij} + \frac{\alpha_s}{4\pi}\delta\hat{\sigma}^{NLO}_{ij}$$

NLO corrections made of:

$$\delta\hat{\sigma}^{NLO}_{ij} = \hat{\sigma}^{ij}_{virt} + \hat{\sigma}^{ij}_{real}$$

- $\hat{\sigma}^{ij}_{virt}$: one loop virtual corrections.
- $\hat{\sigma}^{ij}_{real}$: one gluon/quark real emission.
- use $\alpha_s^{NLO}(\mu)$ and match with NLO PDF's.

$\longrightarrow$ renormalize UV divergences ($d=4-2\epsilon_{UV}$)

$\longrightarrow$ cancel IR divergences in $\hat{\sigma}_{virt} + \hat{\sigma}_{real}$ ($d=4-2\epsilon_{IR}$)

$\longrightarrow$ check μ-dependence of $\sigma^{NLO}_{p\bar{p},pp}$ (μ_R,μ_F)

Some important facts ...

- In hadronic production modes QCD effects can be very large.
- Tree level or Leading Order (LO) cross sections normally have very large uncertainties due to:
  - ▷ renormalization/factorization scale dependence
  - ▷ uncertainties from PDF's
- Differential cross sections very sensitive to higher order QCD corrections.
- Main modes have very large QCD background. Realistic studies, including higher order QCD corrections, are vital to a correct estimate of the background.

$$\Downarrow$$

Crucial to know Higher Order QCD corrections

Some References for Part IV

State-of-the-art of QCD predictions for Higgs production at Hadron Colliders.

process	$\sigma_{NLO,NNLO}$ by
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO) V.Ravindran *et al.*, NPB 665 (2003) (NNLO) S.Catani *et al.* JHEP 0307 (2003) (NNLL), G.Bozzi *et al.*, PLB 564 (2003)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991) O.Brien, A.Djouadi, R.Harlander, PLB 579 (2004) (NNLO)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003)
$q\bar{q}, gg \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 67,68 (2003)
$q\bar{q}, gg \to b\bar{b}H$	S.Dittmaier, M.Krämer, M.Spira, hep-ph/0309204 S.Dawson *et al.*, PRD 69 (2004)
$gb(\bar{b}) \to b(\bar{b})H$	J.Cambell *et al.*, PRD 67 (2003)
$b\bar{b}H$	D.A.Dicus *et al.* PRD 59 (1999); C.Balasz *et al.*, PRD 60 (1999). R.Harlander, W.Kilgore, PRD 68 (2003) (NNLO)

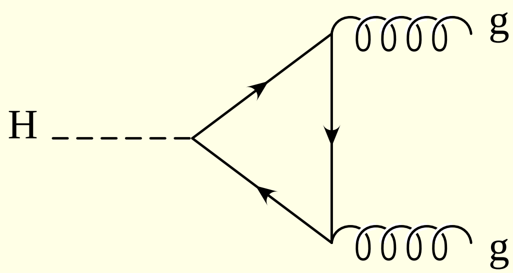
Highlights of recent theoretical activity

- ▷ $H \longrightarrow gg$ at NNLO+NNLL
- ▷ $p\bar{p}, pp \longrightarrow t\bar{t}H$ at NLO
- ▷ $p\bar{p}, pp \longrightarrow b\bar{b}H$ at NLO

Apologies for what will be omitted ...

Preliminaries : Higher order corrections $\Gamma(H \to gg)$

Start from tree level:



$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \sum_q A_q^H(\tau_q) \right|^2$$

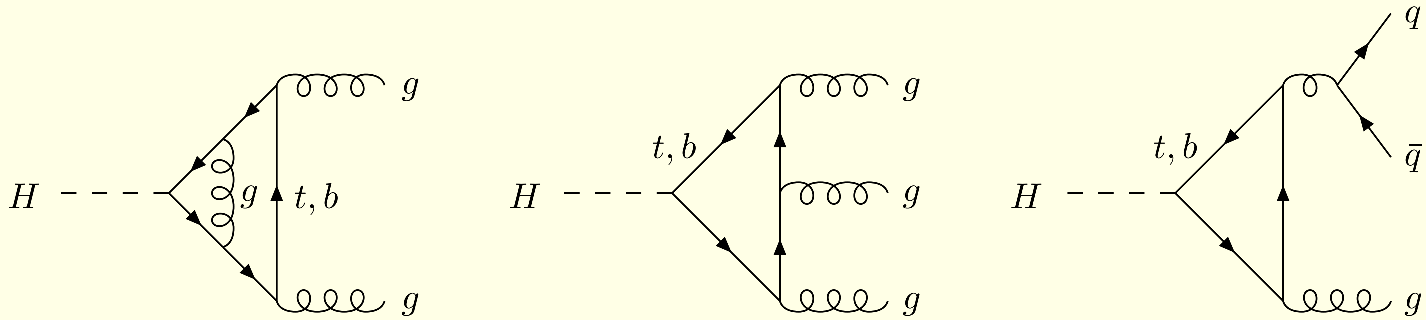
where $\tau_q = 4m_q^2/M_H^2$ and

$$A_q^H(\tau) = \frac{3}{2}\tau \left[1 + (1-\tau) f(\tau)\right]$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

Main contribution from top quark $\longrightarrow$ optimal situation to use Low Energy Theorems to add higher order corrections.

QCD corrections dominant:



Difficult task since decay is already a loop effect.

However, full massive calculation of $\Gamma(H \to gg(q), q\bar{q}g)$ agrees with $m_t \gg M_H$ result at 10%

$$\Gamma(H \to gg(q), q\bar{q}g) = \Gamma_{LO}(\alpha_s^{(N_L)}(M_H)) \left[1 + E^{(N_L)} \frac{\alpha_s^{(N_L)}}{\pi}\right]$$

$$E^{(N_L)} \stackrel{M_H^2 \ll 4m_q^2}{\longrightarrow} \frac{95}{4} - \frac{7}{6} N_L$$

Dominant soft/collinear radiation do not resolve the Higgs boson coupling to gluons $\longrightarrow$ QCD corrections are just a (big) rescaling factor

Low-energy theorems, in a nutshell.

- Observing that:

  In the $p_H \to 0$ limit: the interactions of a Higgs boson with the SM particles arise by substituting

$$M_i \longrightarrow M_i \left(1 + \frac{H}{v}\right) \quad (i = f, W, Z)$$

  In practice: Higgs taken on shell ($p_H^2 = M_H^2$), and limit $p_H \to 0$ is limit of small Higgs masses (e.g.: $M_H^2 \ll 4m_t^2$).

- Then

$$\lim_{p_H \to 0} \mathcal{A}(X \to Y + H) = \frac{1}{v} \sum_i M_i \frac{\partial}{\partial M_i} \mathcal{A}(X \to Y)$$

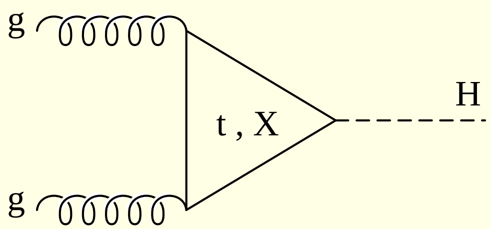
  very convenient!

- Equivalent to an Effective Theory described by:

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v} (1 + O(\alpha_s))$$

  including higher order QCD corrections.

$gg \to H$, the leading production mode

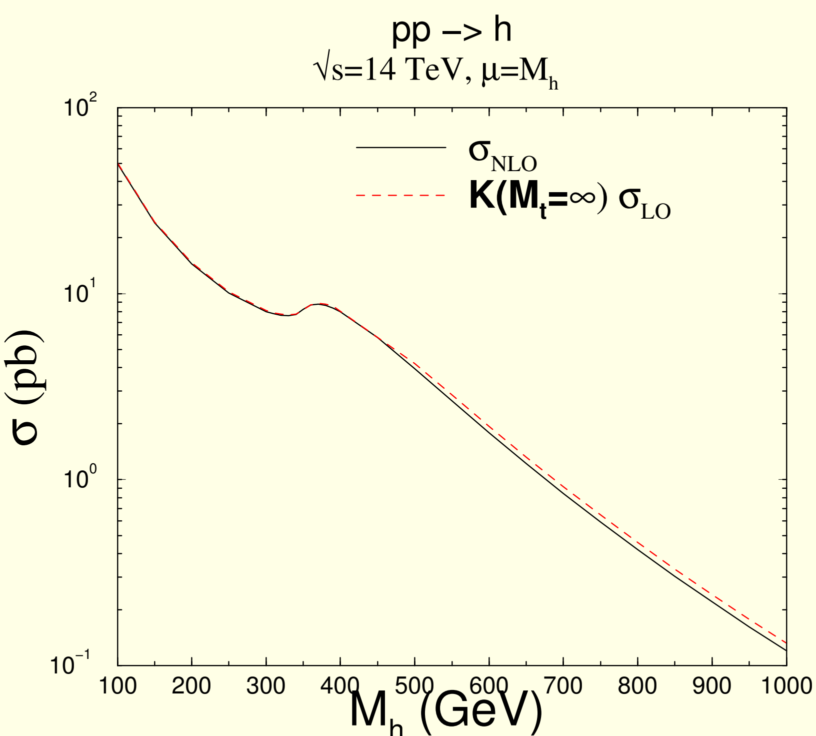


$$\sigma_{LO} = \frac{G_F \alpha_s(\mu)^2}{288\sqrt{2}\pi} \left| \sum_q A_q^H(\tau_q) \right|^2$$

$$\tau_q = 4m_q^2/M_H^2$$

$$A_q^H(\tau_q) \to 1 \ \text{for} \ \tau_q \to \infty$$

NLO QCD corrections calculated exactly and in the $m_t \to \infty$ limit.



where the K-factor is defined as:

$$K(m_t = \infty) = \lim_{m_t \to \infty} K = \lim_{m_t \to \infty} \frac{\sigma_{NLO}}{\sigma_{LO}}$$

perfect agreement even for $M_H \gg m_t$

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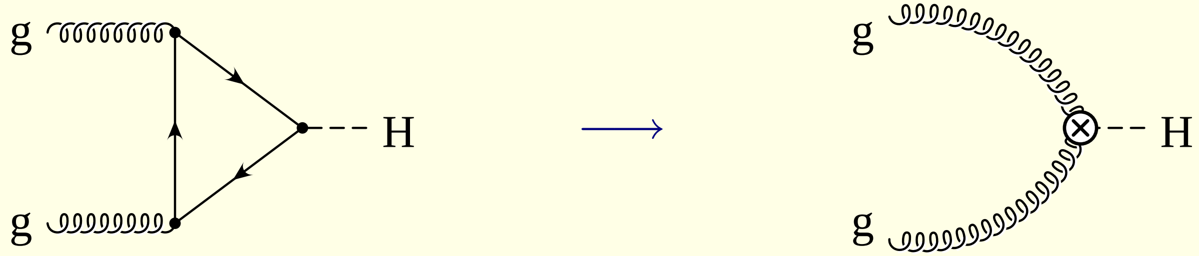
soft radiation dominates

As for $H \to gg$, this suggest to use at NNLO:

$\longrightarrow$ low energy theorems $(m_t \to \infty)$



$$\Downarrow$$

$$\mathcal{L}_{eff} = \frac{H}{4v} C(\alpha_s) G^{a\mu\nu} G^a_{\mu\nu}$$

where, including NLO and NNLO QCD corrections:

$$C(\alpha_s) = \frac{1}{3}\frac{\alpha_s}{\pi}\left[1 + c_1 \frac{\alpha_s}{\pi} + c_2 \left(\frac{\alpha_s}{\pi}\right)^2 + \cdots\right]$$

This reduces by one the order of loops.

Ex.: at NNLO

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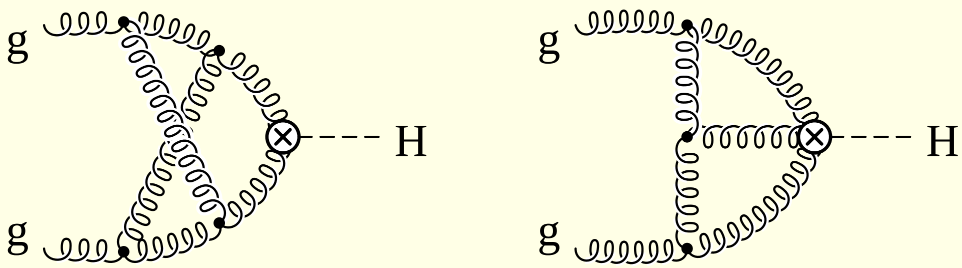
calculates 2-loop diagrams

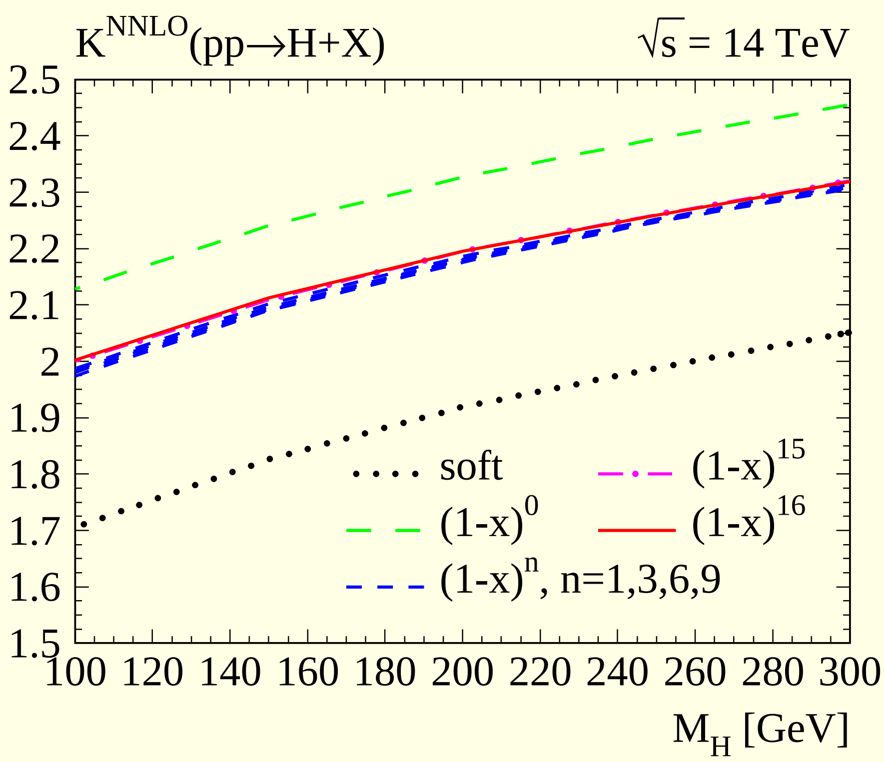


⟶ soft limit ($x = M_H^2/\hat{s} \to 1$), where

$$\hat{\sigma}_{ij} = \sum_{n\geq 0} \left(\frac{\alpha_s}{\pi}\right)^n \hat{\sigma}_{ij}^{(n)}$$

is calculated as an expansion around the soft limit:

$$\hat{\sigma}_{ij}^{(n)} = \underbrace{a^{(n)}\delta(1-x) + \sum_{k=0}^{2n-1} b_k^{(n)} \left[\frac{\ln^k(1-x)}{1-x}\right]_+}_{\text{purely soft terms}} + \underbrace{\sum_{l=0}^{\infty}\sum_{k=0}^{2n-1} c_{lk}^{(n)}(1-x)^l \ln^k(1-x)}_{\text{collinear+hard terms}}$$



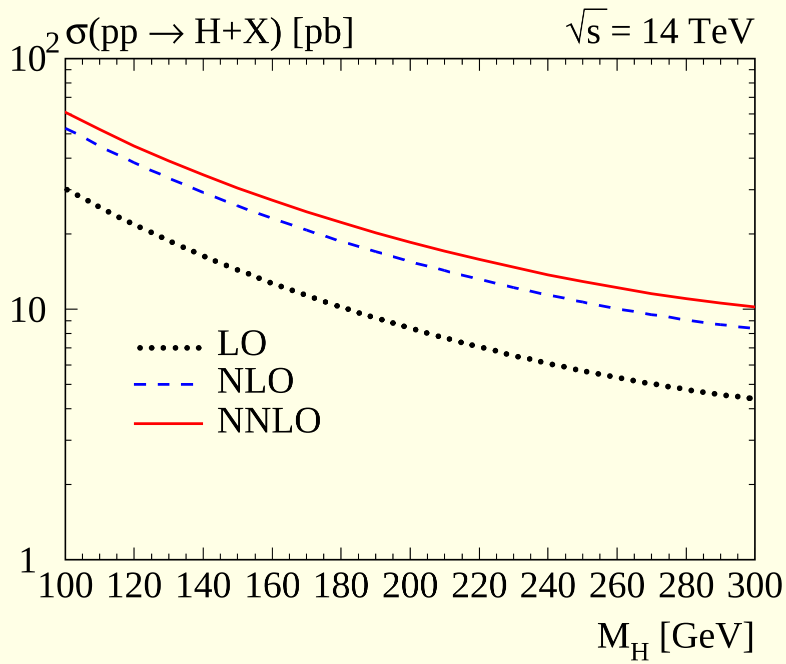
NNLO ⟶ $a^{(2)}$, $b_k^{(2)}$, $c_{lk}^{(2)}$
(for $l \geq 0$ and $k = 0, \ldots, 3$).

⇓

Remarkable convergence

Confirmed by exact calculation.

Dramatically improved perturbative behavior



convergence in going:

LO $\longrightarrow$ NLO $\longrightarrow$ NNLO

Confirmed by the full

μ_R/μ_F dependence:

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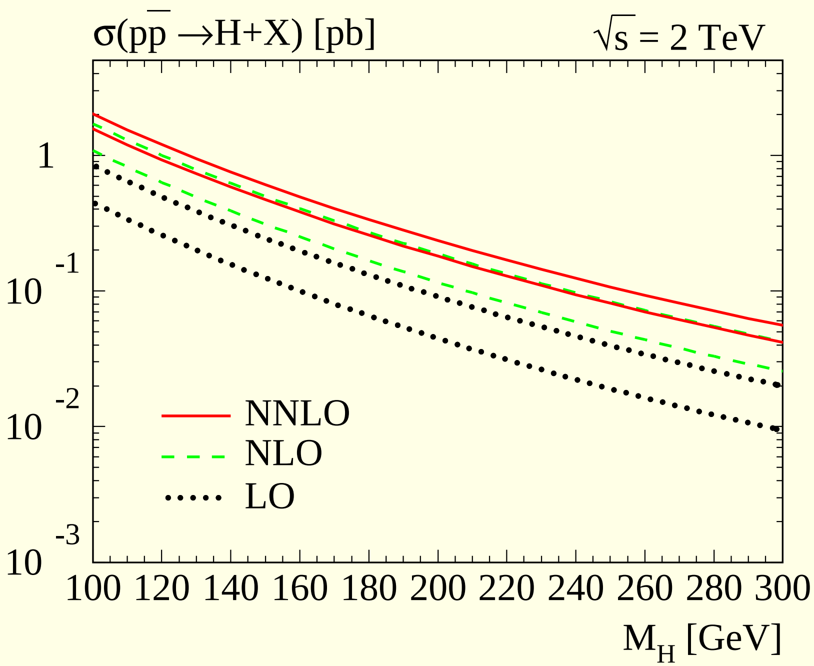
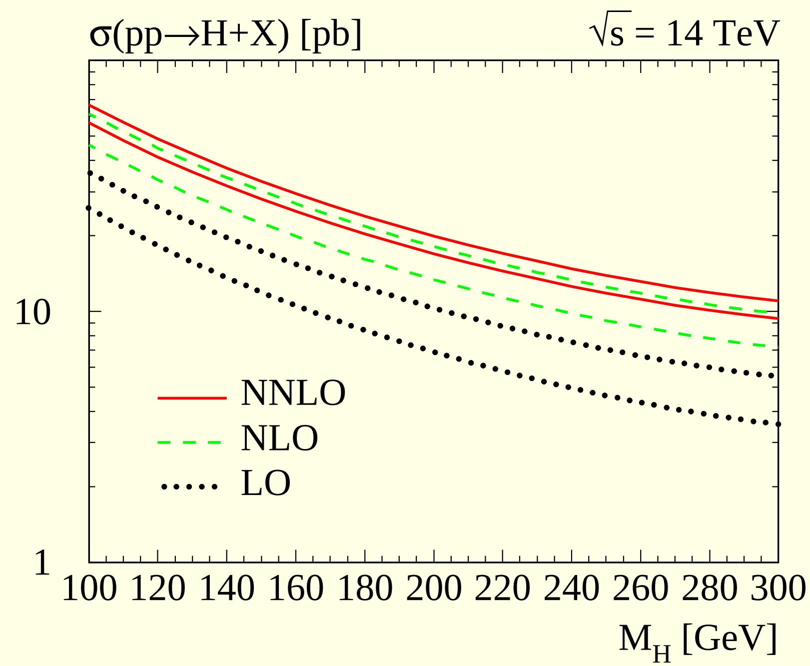
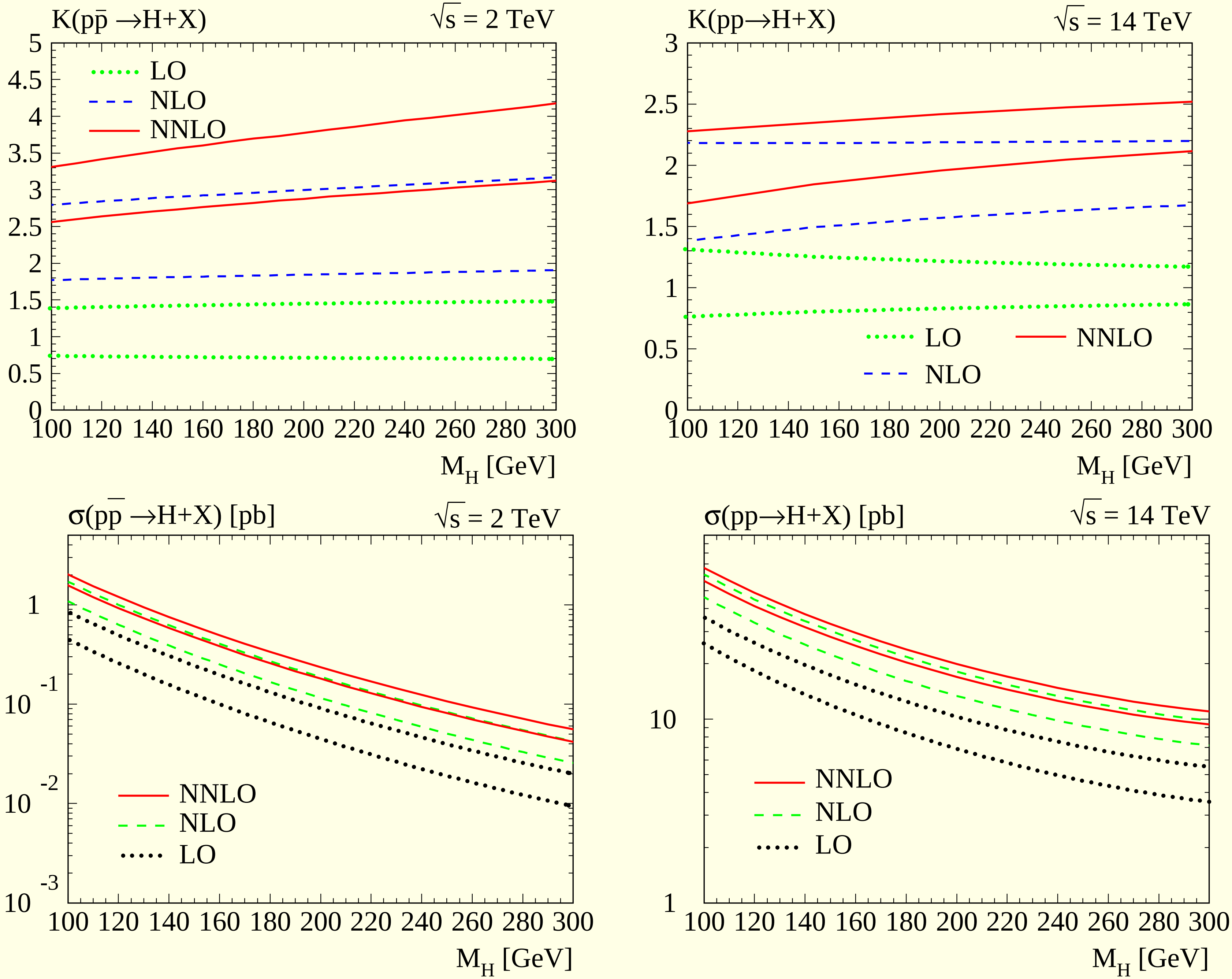
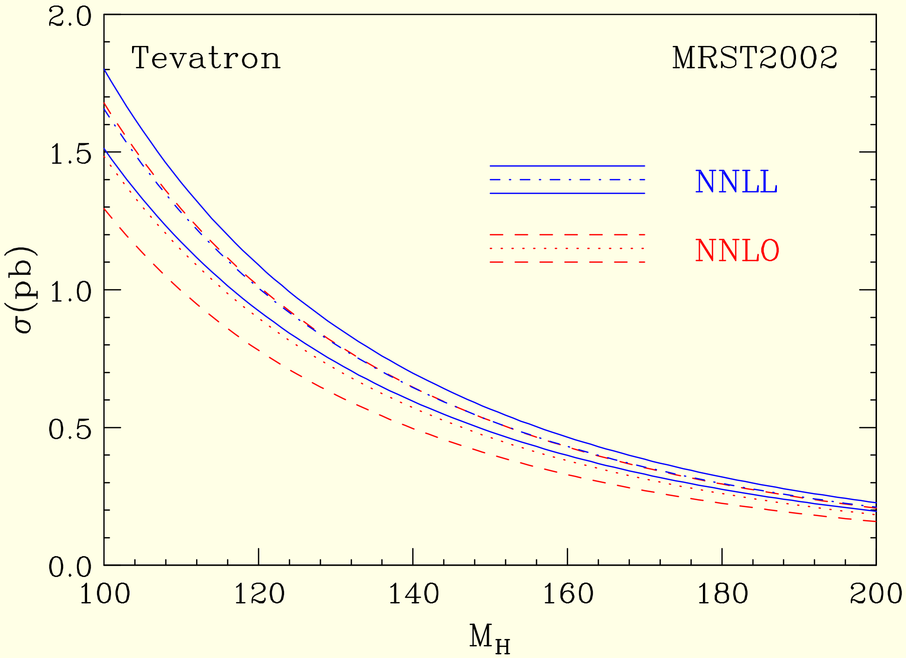


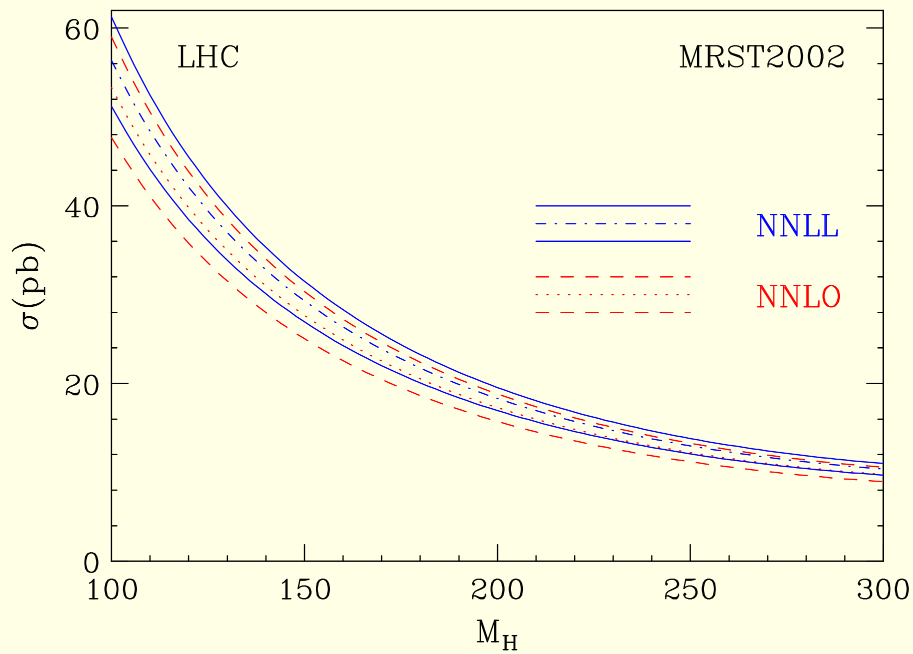


A comment on K-factors . . .



Further improvement: resumming soft logs





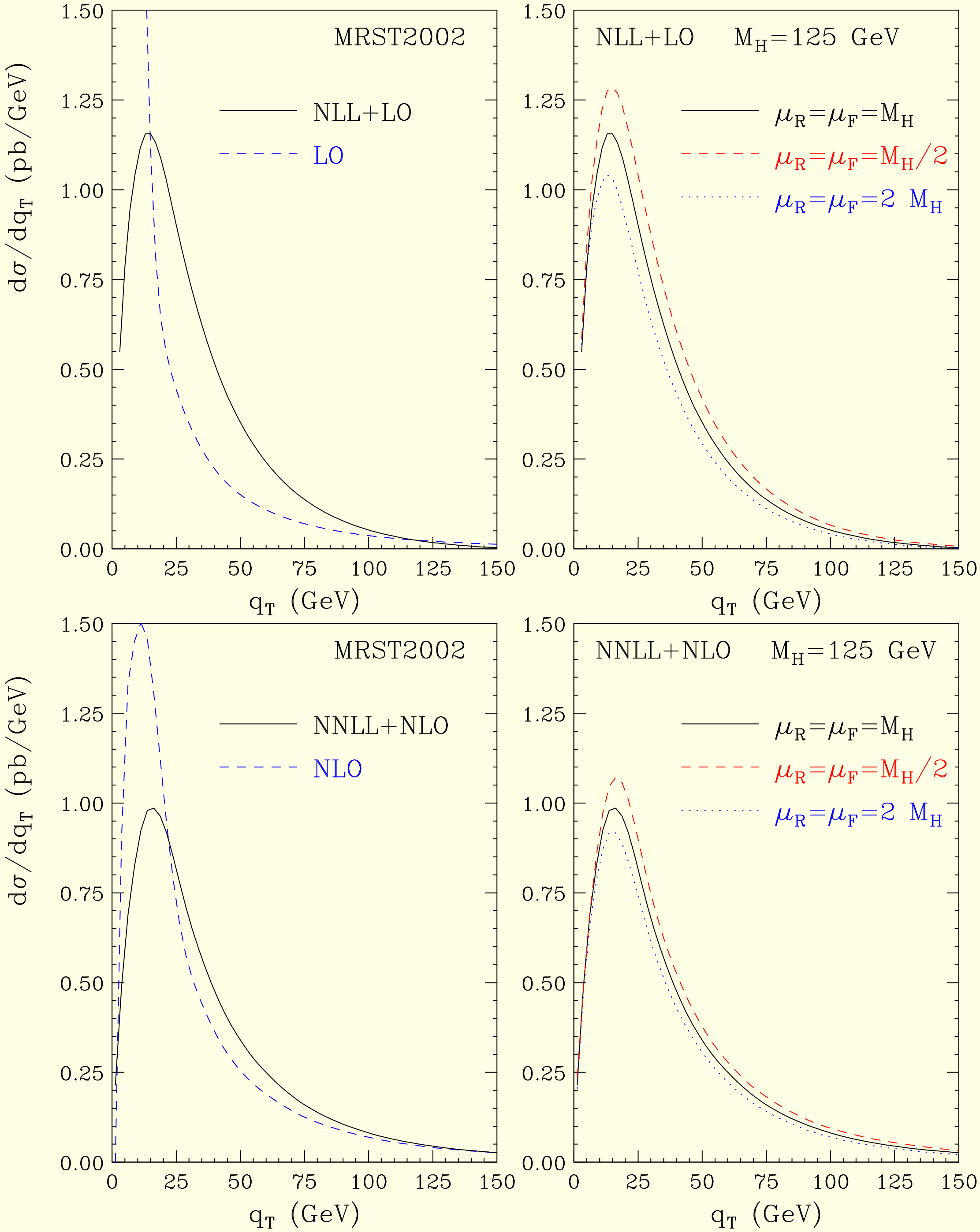
$$\sigma^{(\mathrm{res})}(s, M_H^2) = \underbrace{\sigma^{(\mathrm{SV})}(s, M_H^2)}_{\text{resummed}} + \sigma^{(\mathrm{match})}(s, M_H^2)$$

with **NNLO+NNLL** : Theoretical uncertainty reduced to:

$\longrightarrow$ $\simeq 10\%$ perturbative uncertainty, including the $m_t \to \infty$ approximation.

$\longrightarrow$ $\simeq 10\%$ from (now existing, but still to be tested) NNLO PDF's.

Resummation crucial in transverse momentum distributions



$q_T \longrightarrow$ Higgs boson transverse momentum

large $q_T \xrightarrow{q_T > M_H}$ perturbative expansion in $\alpha_s(\mu)$

small $q_T \xrightarrow{q_T \ll M_H}$ need to resum large $\ln(M_H^2/q_T^2)$

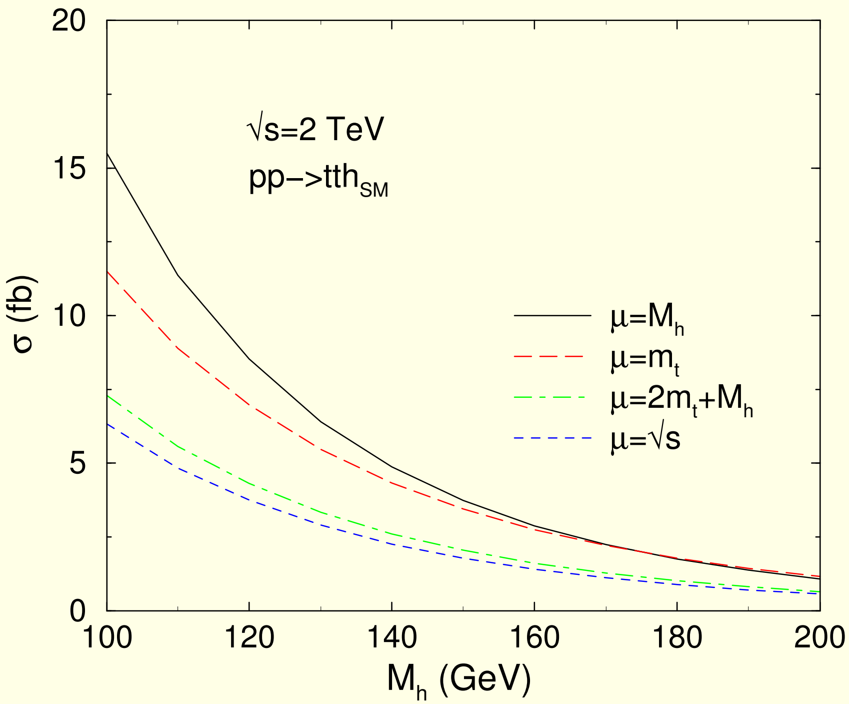
Higgs boson production with Heavy Quarks pairs: $p\bar{p}, pp \to t\bar{t}H, b\bar{b}H$

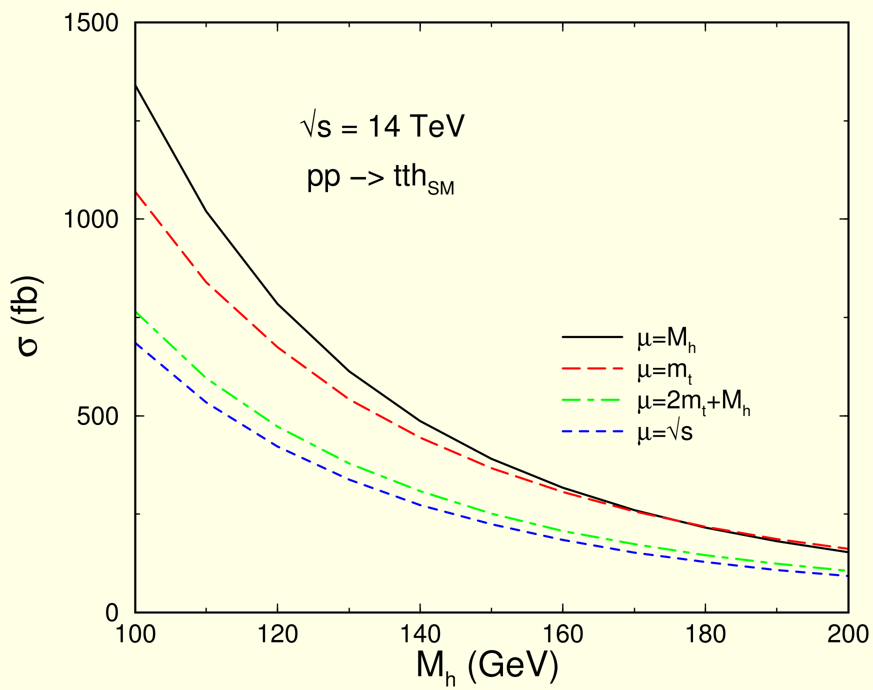
Last NLO calculation to be completed, mainly due to:

$\longrightarrow$ many external particles ($2 \to 3$ process)

$\longrightarrow$ many massive particles

Still, NLO calculation badly needed: very strong μ_R/μ_F dependence at LO.

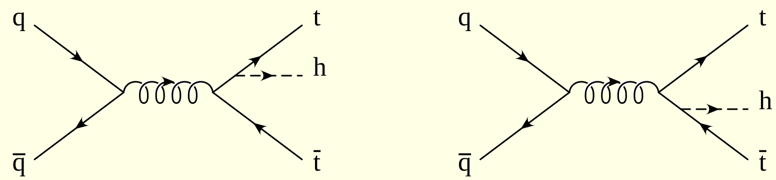




$p\bar{p}, pp \longrightarrow t\bar{t}H$: tree level

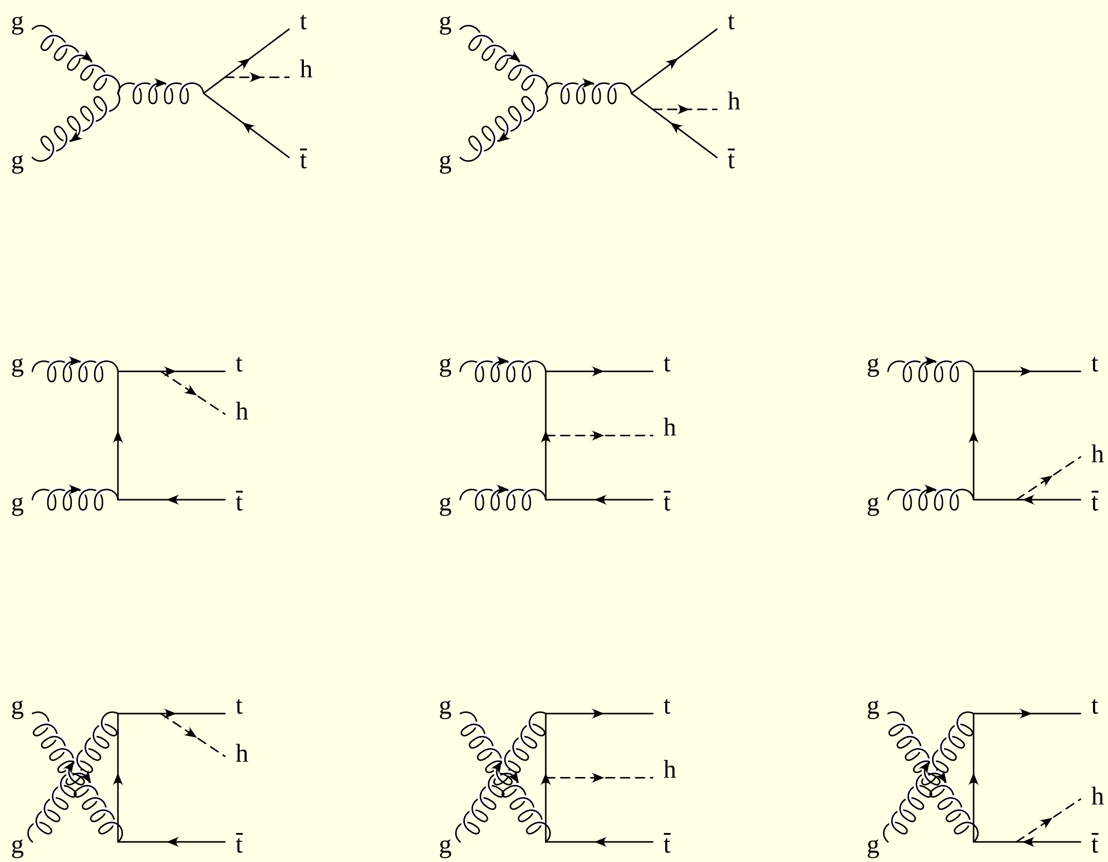
$q\bar{q} \rightarrow t\bar{t}H$

leading contribution at the Tevatron



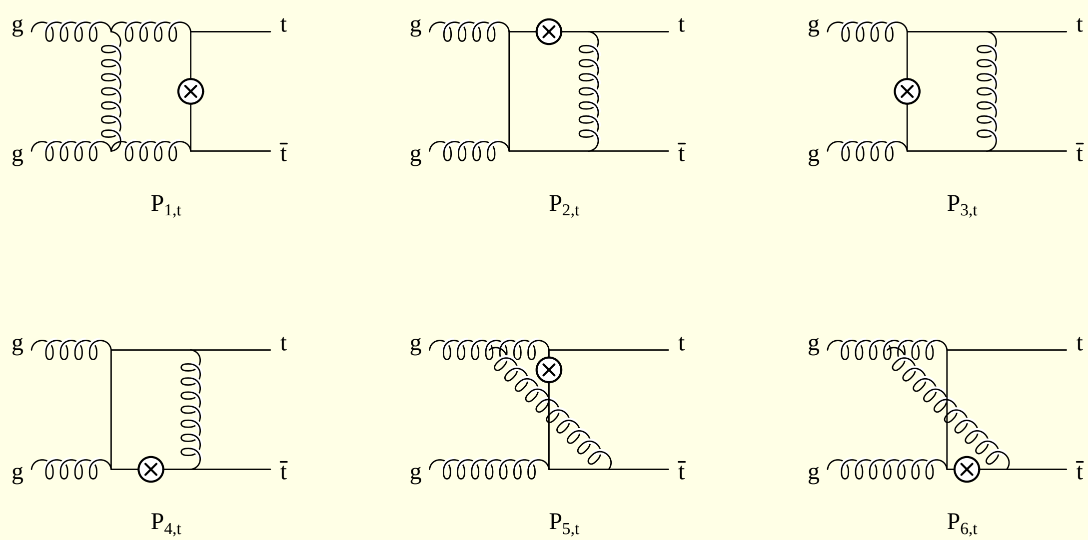
$gg \rightarrow t\bar{t}H$

leading contribution at the LHC

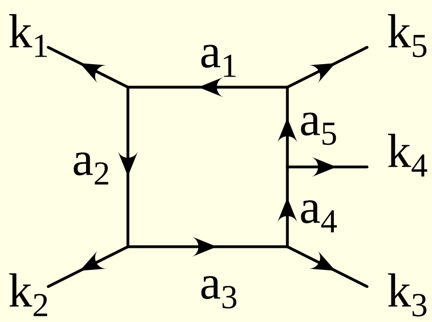


$p\bar{p}, pp \rightarrow Q\bar{Q}H$: $\mathcal{O}(\alpha_s)$ virtual corrections

Main challenge: Pentagon scalar and tensor integrals with several external and internal massive particles



- Scalar pentagon integrals: reduced to linear combination of five box scalar integrals (Z.Bern,L.J.Dixon, D.A.Kosower; A.Denner)
- Tensor pentagon integrals: numerical instabilities (due to Gram determinant spurious singularities) treated both analytically and numerically.



gives origin to scalar integrals of the form:

$$E0 = \frac{1}{16\pi^2}(4\pi\mu^2)^\epsilon \Gamma(3+\epsilon) \int d^5 a_i \frac{\delta(1 - \sum_{i=1}^5 a_i)}{[\mathcal{D}(a_i)]^{3+\epsilon}}$$

where $\mathcal{D}(a_i) = \sum_{i,j=1}^{5} S_{ij} a_i a_j$ $\quad \begin{cases} S_{ij} = \frac{1}{2}(M_i^2 + M_j^2 - p_{ij}) \\ p_{ij} = k_i + k_{i+1} + \cdots + k_{j-1} \end{cases}$

scalar pentagon $\longrightarrow \sum$ scalar boxes

$$I_n = \frac{(-1)^n}{2}\left[\sum_{i=1}^{n} c_i I_{n-1}^{(i)} + (n-5+2\epsilon) c_0 I_n^{6-2\epsilon}\right]$$

$$\Downarrow$$

$$E0 = -\frac{1}{2}\left[\sum_{i=1}^{5} c_i D0^{(i)} + 2\epsilon c_0 E0^{6-2\epsilon}\right]$$

Pentagon tensor integrals, e.g.:

$$\begin{aligned} E_1^{\mu} &= E_1^{(1)} p_1^{\mu} + E_1^{(2)} p_2^{\mu} + E_1^{(3)} p_3^{\mu} + E_1^{(4)} p_4^{\mu} \\ E_2^{\mu\nu} &= E_2^{(11)} p_1^{\mu} p_1^{\nu} + \ldots + E_2^{(12)} (p_1^{\mu} p_2^{\nu} + p_1^{\nu} p_2^{\mu}) + \ldots \\ E_3^{\mu\nu\rho} &= \ldots \end{aligned}$$

$E_{1,2,3}^{(i)} \longrightarrow$ determined through Passarino-Veltman reduction:
proportional to inverse powers of the full Gram determinant (GD)

$$GD(p_1 + p_2 \to p_3 + p_4 + p_5) = \det(p_i \cdot p_j) \simeq f(E_3, E_4, \sin\theta_3, \sin\theta_4, \sin\phi_4)$$

$\boxed{GD \to 0}$ when two momenta become degenerate: spurious divergences.

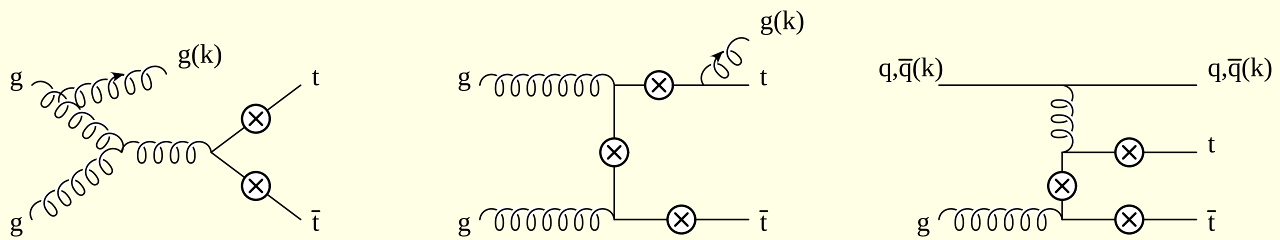
We use two methods:

$\longrightarrow$ Kinematic cuts to avoid numerical instabilities and extrapolation to the unsafe region using several algorithms.

$\longrightarrow$ Eliminate all pentagon tensor integrals at the level of the amplitude square.

$p\bar{p}, pp \to Q\bar{Q}H$: $\mathcal{O}(\alpha_s)$ real corrections

Real gluon emission: IR singularities for $2 \to 4$ process



$+ \cdots$

Phase Space Slicing $\longrightarrow$ isolate the region of the $Q\bar{Q}h + g(q,\bar{q})$ phase space where $s_{ik} \to 0$

$$s_{ik} = 2p_i \cdot k = 2E_i k^0 (1 - \beta_i \cos\theta_{ik})$$

$$\longrightarrow \quad \text{two cut-off method} : \begin{cases} \delta_s & (k^0 < \delta_s \sqrt{s}/2) \\ \delta_c & (1 - \cos\theta_{ik}) < \delta_c) \end{cases}$$

$$\longrightarrow \quad \text{one cut-off method} : s_{min} \quad (s_{ik} < s_{min})$$

- 2CM : L.Bergmann, J.Owens, B.Harris (review), ...
- 1CM : W.Giele, N.Glover, D.A.Kosower, S.Keller, E.Laenen

In the Two Cutoff Method (δ_s,δ_c):

$$\hat{\sigma}_{real}(ij \to Q\bar{Q}H + g) = \hat{\sigma}_{soft} + \hat{\sigma}_{hard/coll} + \hat{\sigma}_{hard/non-coll}$$

where

- $\hat{\sigma}_{soft} \longrightarrow E_g < \frac{\sqrt{s}}{2}\delta_s$
- $\hat{\sigma}_{hard/coll} \longrightarrow E_g > \frac{\sqrt{s}}{2}\delta_s$ and $(1 - \cos\theta_{ig}) < \delta_c$

are computed analytically to extract IR singularities

$$\hat{\sigma}_{soft} \propto \int d(PS_3) \left(\int d(PS_g)_{soft} |\mathcal{A}_{soft}(ij \to Q\bar{Q}H + g|^2 \right)$$

$$\hat{\sigma}_{hard/coll} \propto \int d(PS_3) \left(\int d(PS_g)_{coll} |\mathcal{A}_{coll}(ij \to Q\bar{Q}H + g)|^2 \right)$$

- $\hat{\sigma}_{hard/non-coll} \longrightarrow E_g > \frac{\sqrt{s}}{2}\delta_s$ and $(1 - \cos\theta_{ig}) > \delta_c$

is computed numerically, since IR finite.

In the One Cutoff Method (s_{min}):

$$\hat{\sigma}_{real}(ij \to Q\bar{Q}H + g) = \hat{\sigma}_{ir} + \hat{\sigma}_{hard}$$

where

- $\hat{\sigma}_{ir} \longrightarrow s_{ig} < s_{min}$

is computed analytically to extract IR singularities

$\longrightarrow$ cross all colored particles to final state

$\longrightarrow$ work with color ordered amplitudes: easier matching between soft and collinear region

$\longrightarrow$ crossing functions: to account for difference between i.s. and f.s. collinear singularities

- $\hat{\sigma}_{hard} \longrightarrow s_{ig} > s_{min}$

is computed numerically, since IR finite.

Consider e.g. $gg \to t\bar{t}H + g$:

$$\hat{\sigma}_{real}^{H\to ggt\bar{t}+g} = \int d(PS_5)\overline{\sum}|\mathcal{A}_{real}^{H\to ggt\bar{t}+g}|^2 \ ,$$

where

$$\mathcal{A}_{real}^{H\to ggt\bar{t}+g} = \sum_{\substack{i,j,k=A,B,C\\ i\neq j\neq k}} \mathcal{A}_{ijk}\, T^i\, T^j\, T^k \ .$$

The amplitude square is made of three terms:

$$\overline{\sum}|\mathcal{A}_{real}^{H\to ggt\bar{t}+g}|^2 = \frac{(N^2-1)}{2}\left[\frac{N^2}{4}\sum_{\substack{i,j,k=A,B,C\\ i\neq j\neq k}}|\mathcal{A}_{ijk}|^2\right.$$

$$\left. -\frac{1}{4}\sum_{\substack{i,j,k=A,B,C\\ i\neq j\neq k}}|\mathcal{A}_{ijk}+\mathcal{A}_{ikj}+\mathcal{A}_{kij}|^2+\frac{1}{4}\left(1+\frac{1}{N^2}\right)\left|\sum_{\substack{i,j,k=A,B,C\\ i\neq j\neq k}}\mathcal{A}_{ijk}\right|^2\right]$$

with very definite soft/collinear factorization properties.

Soft singularities $\longrightarrow$ straightforward

How to disentangle soft vs collinear region of PS with one cutoff?

Collinear limit for $ig \to i'$: $s_{ig} \to 0$ $(i = g_1, g_2)$ $\begin{cases} p_i = z p'_i \\ p_g = (1-z) p'_i \end{cases}$

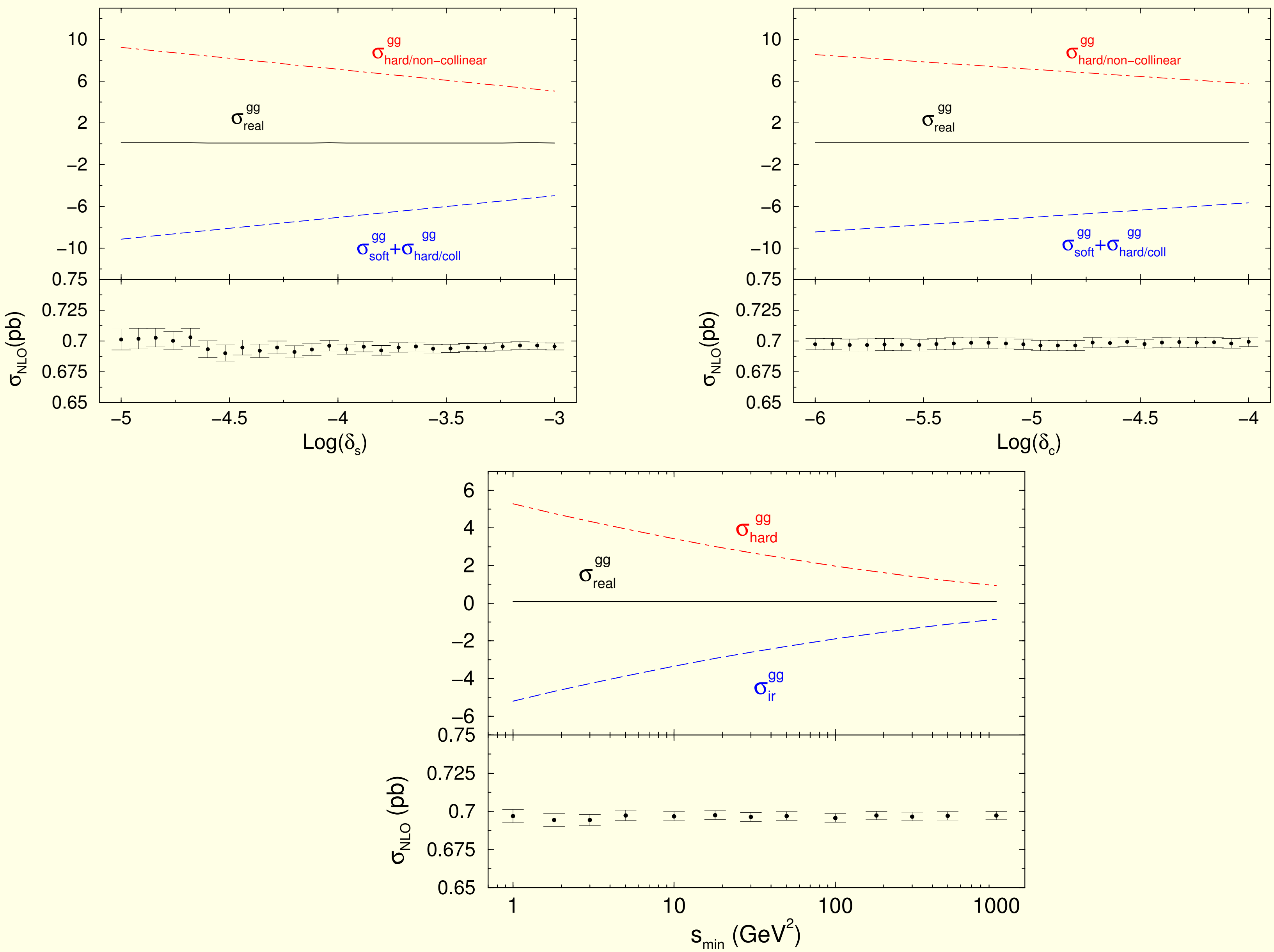
Each $\mathcal{A}_{ijk}$ (or linear combination of) proportional to $(s_{ai} s_{ig} s_{gb})^{-1}$

collinear region $\begin{cases} s_{ig} < s_{min} \\ s_{ai} > s_{min} \longrightarrow z s_{ai'} > s_{min} \longrightarrow z > z_1 = \frac{s_{min}}{s_{ai'}} \\ s_{gb} > s_{min} \longrightarrow (1-z) s_{i'b} > s_{min} \longrightarrow z < 1 - z_2 = 1 - \frac{s_{min}}{s_{i'b}} \end{cases}$

$z_1,\ 1 - z_2 \longrightarrow$ integration boundaries

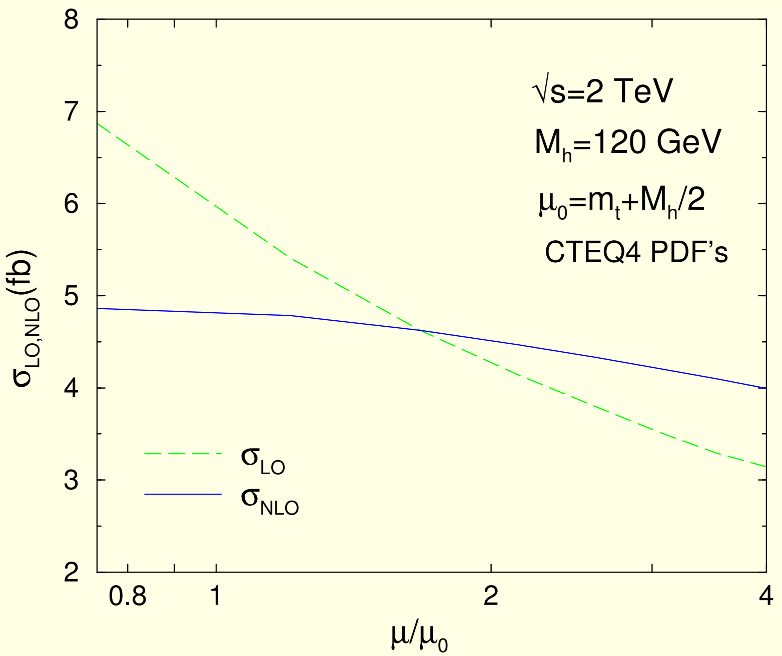
How to match with $\hat{\sigma}_{hard}$? Match each term in $|\mathcal{A}_{real}|^2$ separately.

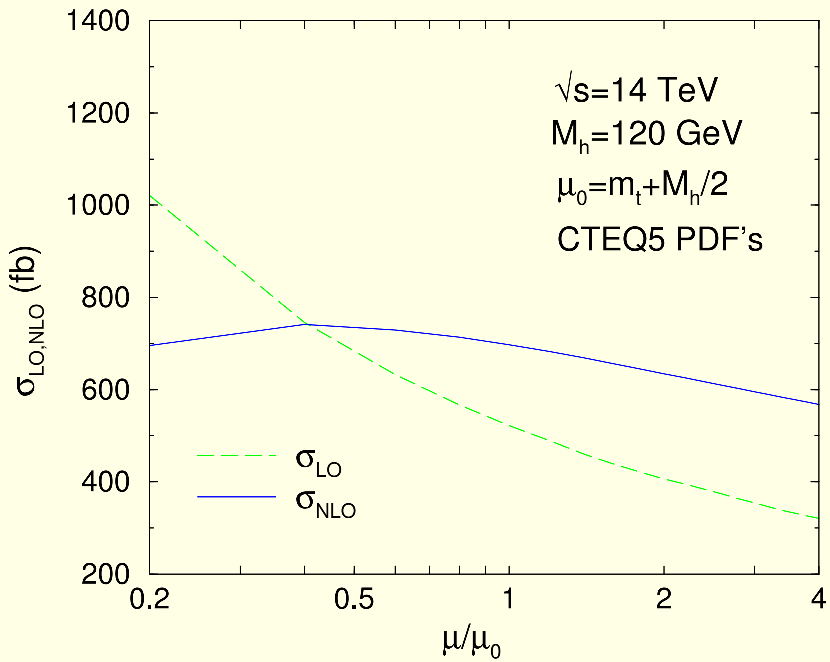
Cross section independent of the unphysical cutoff



(LHC, $M_H = 120$ GeV, $\mu = m_t + M_H/2$)

LHC, $pp \to t\bar{t}H$: NLO cross section





$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} < 1$$

for most values of μ and M_H

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} > 1$$

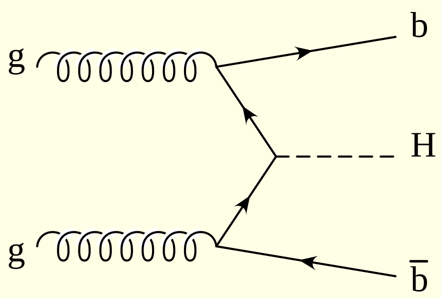
for most values of μ and M_H

Theoretical uncertainty reduced to about 15%

$p\bar{p}, pp \to b\bar{b}H$: exclusive vs inclusive cross section

- b-quarks identification requires tagging (p_T^b and η^b cuts): exclusive (1 b-tag, 2 b-tags) vs inclusive (0 b-tags) cross section.

- Large collinear $\ln(\mu_H^2/m_b^2)$ arise in $gg \to b\bar{b}h$ when final state b-quarks are collinear to initial state gluons



$\longrightarrow$ large collinear logs ($g \to b\bar{b}$) regulated by m_b

- Fully exclusive cross section (2 b-tags):

  $\longrightarrow$ needs $gg \to b\bar{b}h$: two b's in final state

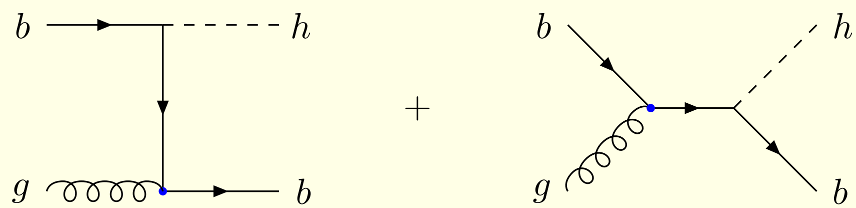
  $\longrightarrow$ has no large logs: p_T^b cut select high p_T b's.

  NLO calculation drastically improves the stability of the cross section.

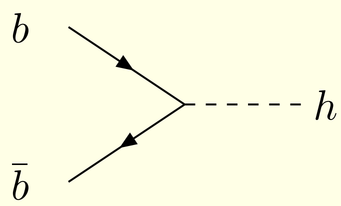
- More inclusive cross sections, two approaches:

$\longrightarrow$ Fixed (or four) flavor number scheme (FFS):
fixed order approach, based on $gg, q\bar{q} \rightarrow b\bar{b}H$ only.

$\longrightarrow$ Variable (or five) flavor number scheme (VFS):
resum large logs in b-quark PDF.



$\longrightarrow$ 1 b-tag



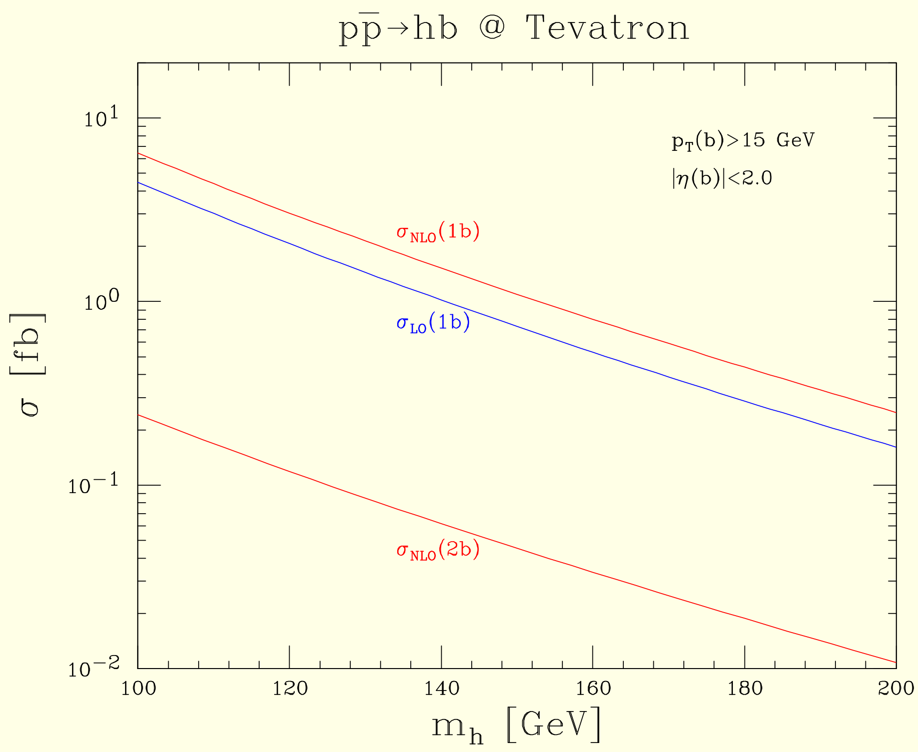
$\longrightarrow$ 0 b-tags

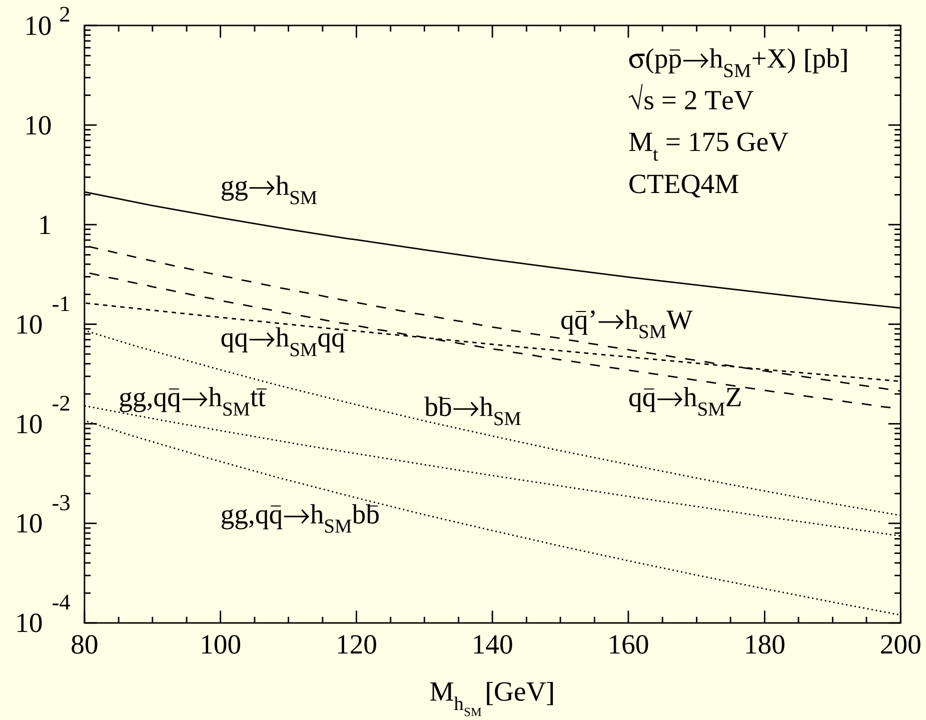
Perturbative series ordered in Leading and SubLeading powers of $\alpha_s \ln(\mu_H^2/m_b^2)$. Need to consider (avoiding double counting)

- ▷ $b\bar{b} \rightarrow H$ (known at NNLO) $\longrightarrow \alpha_s^2 \ln^2(\mu_H^2/m_b^2)$
- ▷ $bg \rightarrow bH$ (known at NLO) $\longrightarrow \alpha_s^2 \ln(\mu_H^2/m_b^2)$
- ▷ $gg \rightarrow b\bar{b}H$ (need LO, known at NLO) $\longrightarrow \alpha_s^2$

Inclusive versus Exclusive modes

▷ More inclusive cross sections are larger.



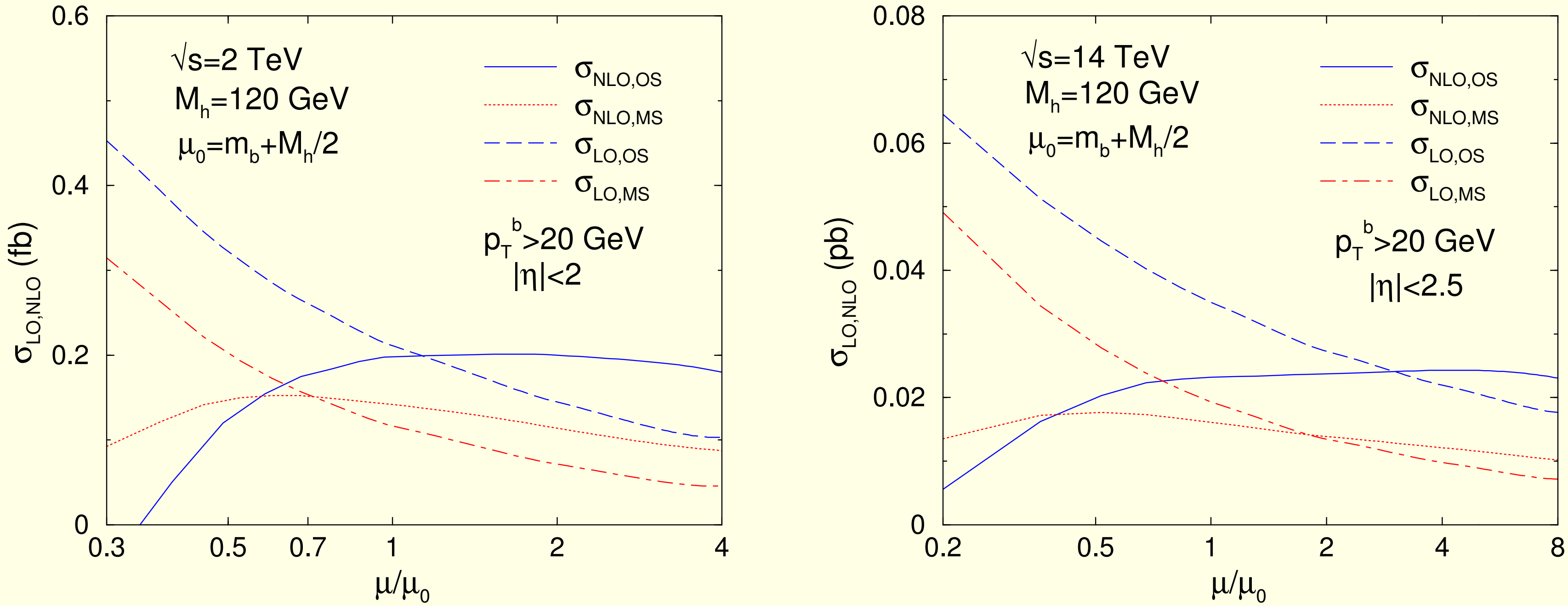


▷ More exclusive modes have much smaller background.

▷ Only exclusive modes probe the $b\bar{b}H$ coupling unambiguously.

Exclusive cross section for $p\bar{p}, pp \to b\bar{b}H$: 2 b-tags

Use high p_T b-quarks to suppress background: need NLO $(q\bar{q})gg \to b\bar{b}H$

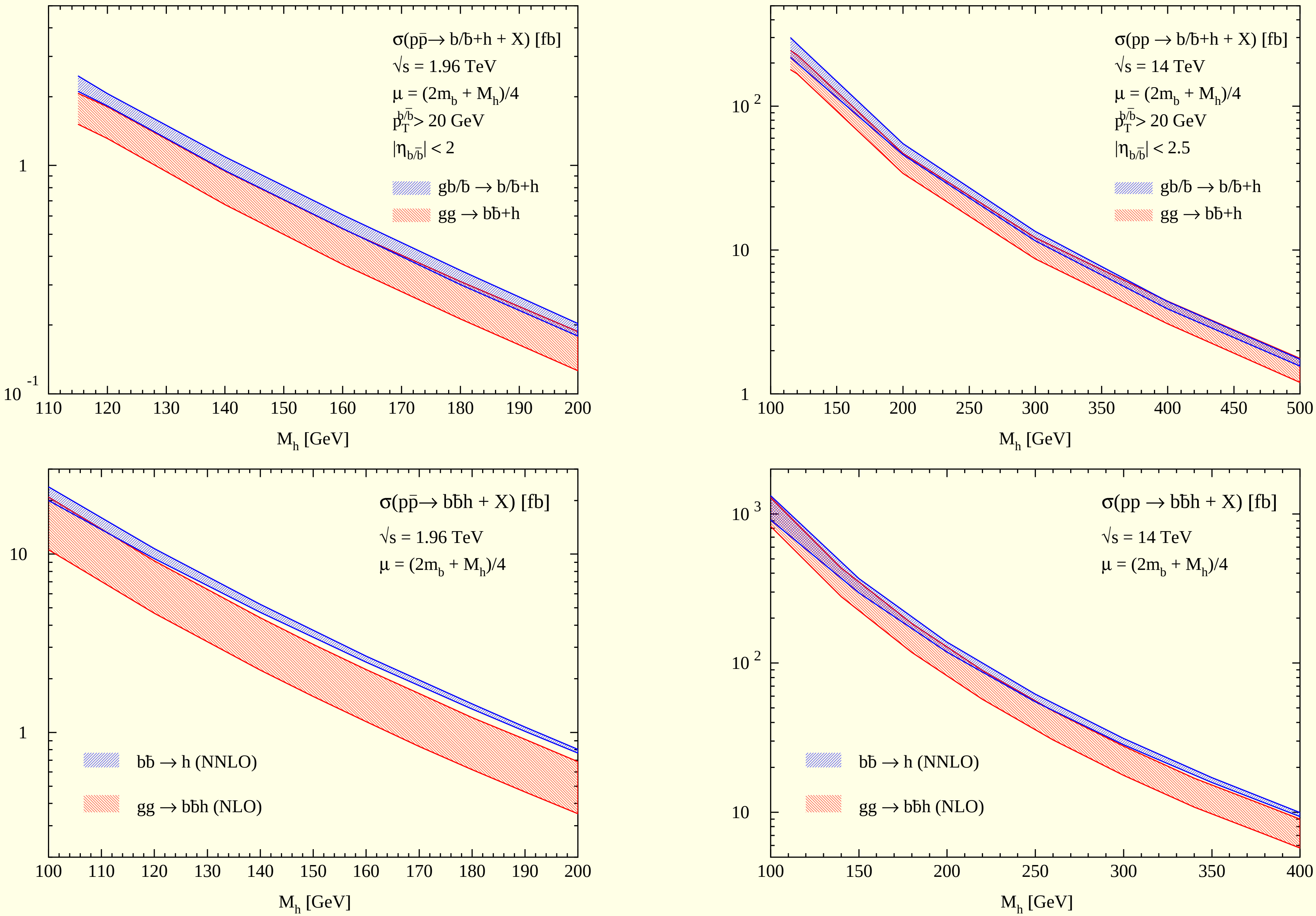


Non trivial dependence on renormalization of $m_b(\mu)$ in bottom quark Yukawa coupling: $\boxed{OS,\overline{MS}} \longrightarrow$ renormalization scheme of $\boxed{y_b = m_b/v}$.

Theoretical uncertainty: 15% (scale dep.), 15% (ren. scheme dep.)

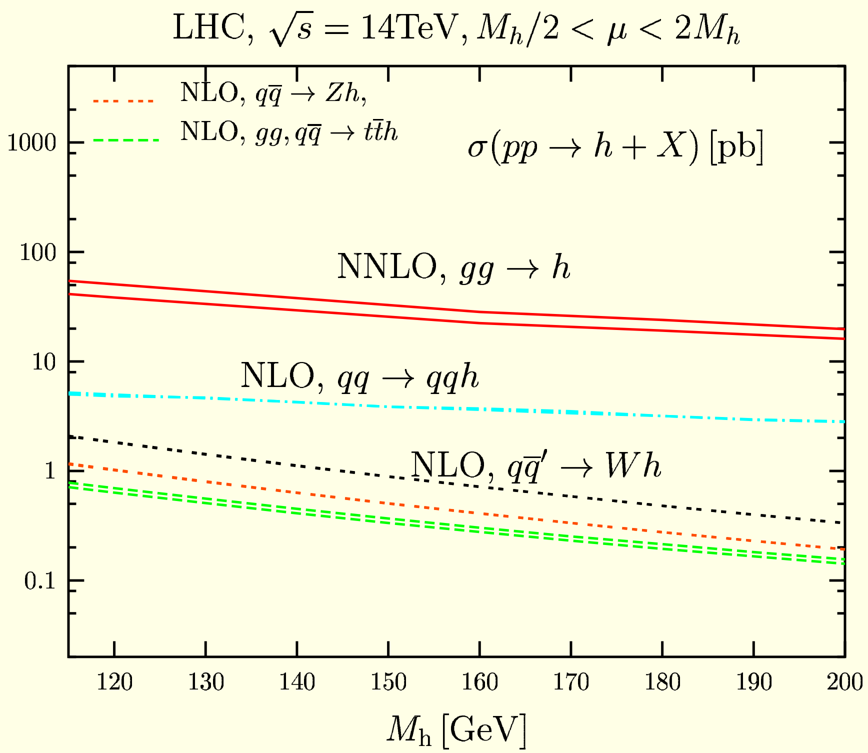
1b-tag and 0b-tag modes: comparison between FFS and VFS

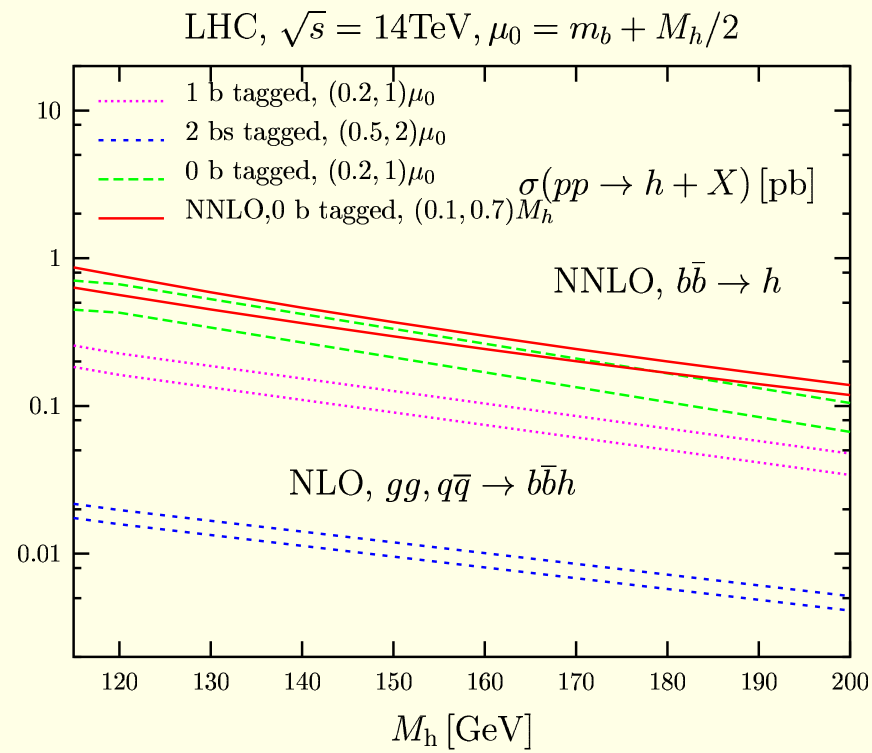
(Les Houches Workshop, 2003-2004)



Overview

QCD predictions for total cross sections to Higgs production processes are under good theoretical control:





Caution:

- ▷ uncertainties only include μ_R/μ_F dependence
- ▷ uncertainties from PDF's are not included (but should improve)