QCD predictions for Higgs physics

Laura Reina

Higgs Physics at the Tevatron and LHC, the QCD Issues
FNAL, November 09

- Introduction: Why/Where precision is needed.
- Overview of existing results.
- Answering questions (by examples).
- Conclusions and Outlook.

- The Tevatron is breaking new ground and meeting new challenges: exploring the Higgs low mass region, possible $2\sigma - 3\sigma$ evidence.

  (⟶ see E. James's and M. Verzocchi's talks at this meeting)

- The LHC will cover the whole Higgs mass range and with high luminosity will have access to Higgs-boson precision physics.

  (⟶ see J. Qian's and A. Korytov's talks at this meeting)

- Using the SM as a "template", we can test our ability to pinpoint the properties of to-be-discovered scalar and pseudoscalar particles:

  ▷ identify main sources of systematic uncertainty;

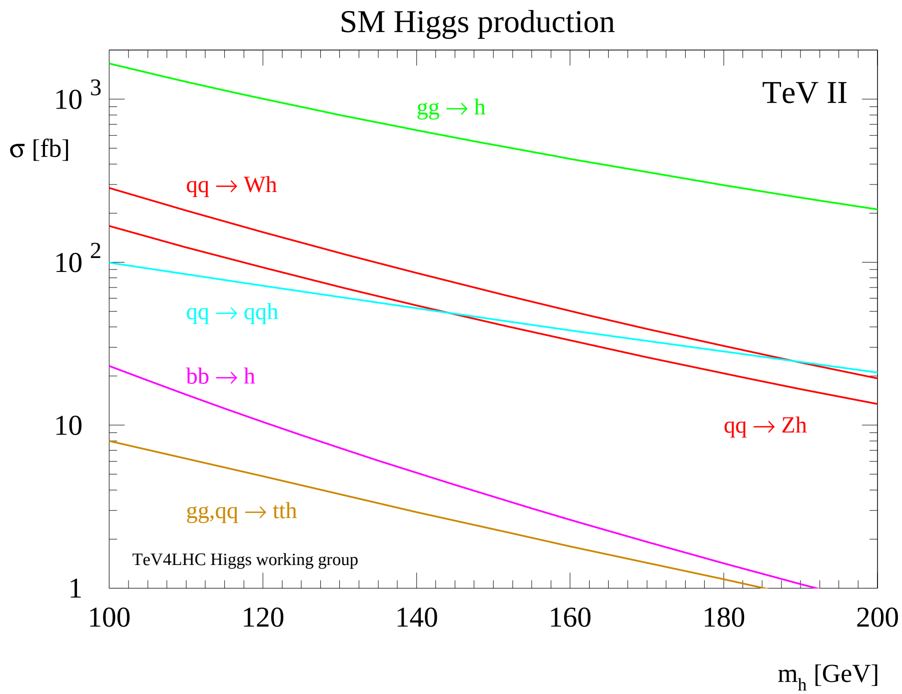
  ▷ work at reducing them, both theoretically and experimentally.

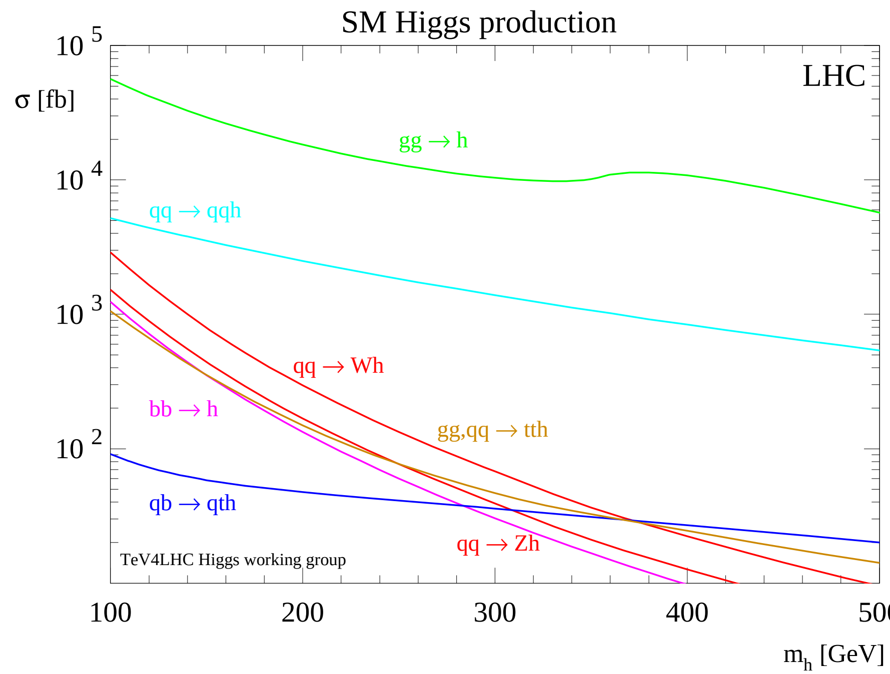
- Building on solid SM ground, start exploring beyond SM scenarios in as much generality as possible, looking for most distinctive patterns and signatures of various realizations of EWSB.

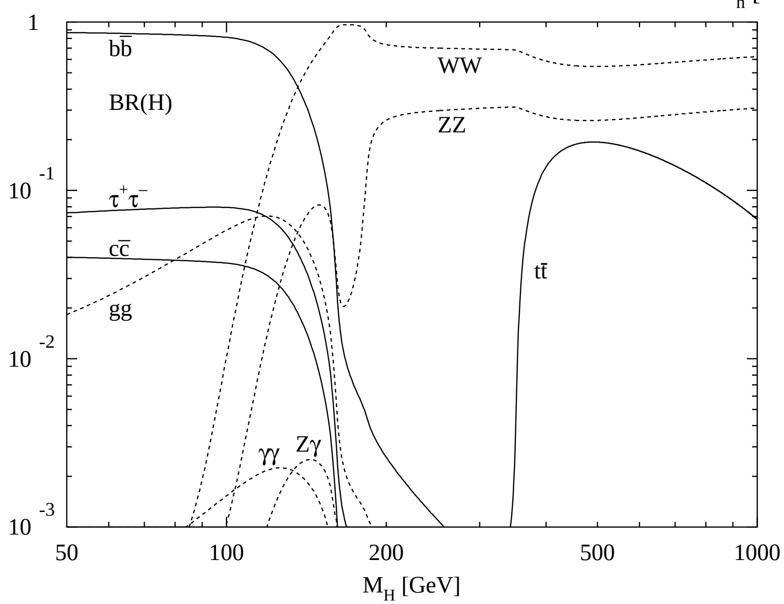
Why/Where precision is needed

- The incredible physics potential of the Tevatron and LHC for Higgs-boson physics relies on our ability of providing very accurate QCD predictions (including interplay with EW corrections):
  $\longrightarrow$ Discovery: precise prediction of signals/backgrounds;
  $\longrightarrow$ Identification: precise extraction of parameters (α_s, m_t, M_H, $y_{t,b}$, M_X, y_X, ...);
  $\longrightarrow$ Precision: $\sigma_{W/Z}$ as parton luminosity monitors (PDF's), ...

- Higgs-boson physics has been an incredible playground for QCD calculations of the last decade. Many important developments came to address processes with:
  $\longrightarrow$ poorly convergent perturbative corrections (Ex.: $gg \rightarrow H$)
  $\longrightarrow$ several massive particles (Ex.: $Ht\bar{t}/Hb\bar{b}$, $W/Zb\bar{b}$, $t\bar{t}b\bar{b}$, ...)
  $\longrightarrow$ high multiplicity (Ex.: VVV, $V+3j$, $t\bar{t}b\bar{b}$, ...)







$M_h < 130 - 140 \longrightarrow$ most difficult

Need precise theoretical understanding of both signal and background

State of the art of QCD calculations

for hadronic processes

Relative order	$2 \to 1$	$2 \to 2$	$2 \to 3$	$2 \to 4$	$2 \to 5$	$2 \to 6$
1	LO					
α_s	NLO	LO				
α_s^2	NNLO	NLO	LO			
α_s^3		NNLO	NLO	LO		
α_s^4			NNLO	NLO	LO	
α_s^5				NNLO	NLO	LO

(from N. Glover)

Green light $\longrightarrow$ Done

Red light $\longrightarrow$ Still work in progress

NLO: $V + b\bar{b}/t\bar{t}$, $VV + j$, VVV, $H + 2j$, $t\bar{t} + j$, $V + 3j$, $t\bar{t}b\bar{b}$, ...

NNLO: $q\bar{q}, gg \to Q\bar{Q}$ (Czakon, Mitov, Moch: analytical for $m_Q^2 \ll s$, exact numerical estimate (06-08)), $q\bar{q} \to W^+W^-$ (Chachamis,Czakon:at $O(m_W^2/s)$ (08))

(plus: NNLO splitting functions (Moch,Vermaseren,Vogt (04))).

Why pushing the Loop Order ...

- Stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales. First reliable normalization of total cross-sections and distributions.

- Physics richness: more channels and more partons in final state, i.e. more structure to better model (in perturbative region):
  $\longrightarrow$ differential cross-sections, exclusive observables;
  $\longrightarrow$ jet formation/merging and hadronization;
  $\longrightarrow$ initial state radiation.

- First step towards matching with algorithms that resum particular sets of large corrections in the perturbative expansion: resummed calculations, parton shower Monte Carlo programs.

Main challenges . . .

- Multiplicity and Massiveness of final state: complex events leads to complex calculations. For a $2 \to N$ process one needs:

  $\longrightarrow$ calculation of the $2 \to N+1$ (NLO) or $2 \to N+2$ real corrections;

  $\longrightarrow$ calculation of the 1-loop (NLO) or 2-loop (NNLO) $2 \to N$ virtual corrections.

- Flexibility of NLO/NNLO calculations via Automation:

  $\longrightarrow$ algorithms suitable for automation are more efficient and force the adoption of standards;

  $\longrightarrow$ faster response to experimental needs (think to the impact of projects like MCFM).

- Matching to Parton Shower Monte Carlos at NLO.

  $\longrightarrow$ instead of correcting NLO parton level calculation to match the hadron level, shower with NLO precision!

NLO: challenges have largely been faced and enormous progress has been made

- several independent codes based on traditional FD's approach
- several NLO processes collected and viable in MFCM (→ interfaced with FROOT) [Campbell, Ellis]
- Enormous progress towards automation:
  - → Virtual corrections: new techniques based on unitarity methods and recursion relations
    - ▷ BlackHat [Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre]
    - ▷ Rocket+MCFM [Ellis, Giele, Kunszt, Melnikov, Zanderighi]
    - ▷ HELAC+CutTools [Bevilacqua, Czakon, van Harmeren, Papadopoulos, Pittau, Worek]
  - → Real corrections: based on Catani-Seymour Dipole subtraction or FKS subtraction
    - ▷ Sherpa [Gleisberg, Krauss]
    - ▷ Madgraph (MadDipole) [Frederix, Gehrmann, Greiner]
    - ▷ Madgraph (MadFKS) [Hasegawa, Moch, Uwer]

- interface to parton shower well advanced:
  - ▷ MC@NLO [Frixione, Webber, Nason, Frederix, Maltoni, Stelzer]
  - ▷ POWHEG [Nason, Oleari, Alioli, Re]

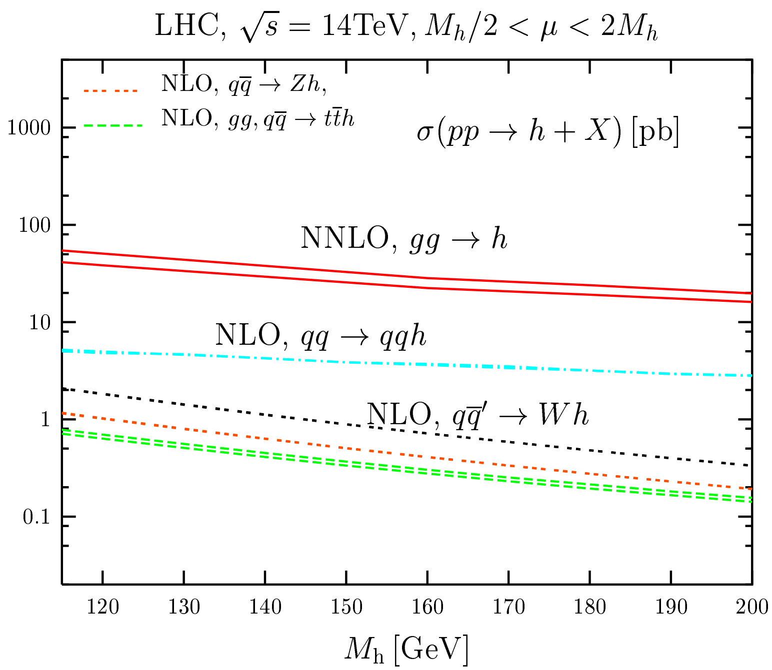
When is NLO not enough?

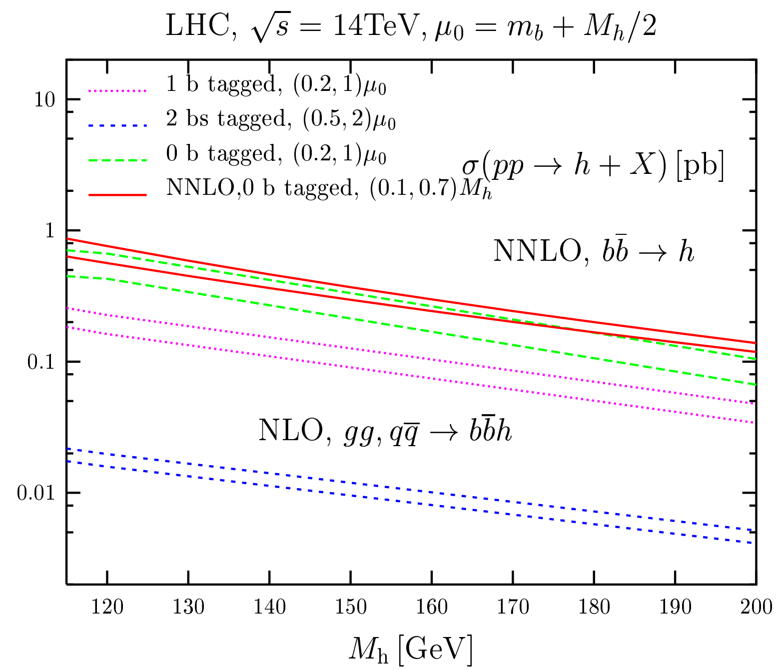
- When NLO corrections are large, to tests the convergence of the perturbative expansion. This may happen when:
  - → processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
  - → new parton level subprocesses first appear at NLO;
  - → new dynamics first appear at NLO;
  - → ...
- When truly high precision is needed (very often the case!).
- When a really reliable error estimate is needed.

Higgs process	$\sigma_{NLO,NNLO}$ (QCD only)
$gg \to H$	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), NPB 737 (2006) (NNLL) C.Anastasiou, R.Boughezal, F.Petriello, JHEP (2008) (QCD+EW)
$q\bar{q} \to (W,Z)H$	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, PRD 70 (2004) S.Dawson *et al.*, PRD 69 (2004), PRL 94 (2005)
$gb(\bar{b}) \to b(\bar{b})H$	J.Campbell *et al.*, PRD 67 (2003)
$b\bar{b} \to (b\bar{b})H$	D.A.Dicus *et al.* PRD 59 (1999); C.Balasz *et al.*, PRD 60 (1999). R.Harlander, W.Kilgore, PRD 68 (2003) (NNLO)

SM Higgs-boson production: theoretical precision at a glance . . .

QCD predictions for total hadronic cross sections of Higgs-boson production processes (μ_R/μ_F scale dependence only, PDF's uncertainties not included)





Still, much more to do: study the effect of QCD corrections on distributions, exclusive channels, background processes, . . .

NLO: Recently completed calculations (since Les Houches 2005): all relevant to Higgs-boson physics!

Process ($V \in \{Z, W, \gamma\}$)	Calculated by
$pp \to V$+2 jets(b)	Campbell,Ellis,Maltoni,Willenbrock (06)
$pp \to Vb\bar{b}$	Febres Cordero,Reina,Wackeroth (07-08)
$pp \to VV$+jet	Dittmaier,Kallweit,Uwer (WW+jet) (07)
	Campbell,Ellis,Zanderighi (WW+jet+decay) (07)
	Binoth,Karg,Kauer,Sanguinetti (09)
$pp \to VV$+2 jets	Bozzi,Jäger,Oleari,Zeppenfeld (via WBF) (06-07)
$pp \to VVV$	Lazopoulos,Melnikov,Petriello (ZZZ) (07)
	Binoth,Ossola,Papadopoulos,Pittau (WWZ,WZZ,WWW) (08)
	Hankele,Zeppenfeld ($WWZ \to$ 6 leptons, full spin correlation) (07)
$pp \to H$+2 jets	Campbell,Ellis,Zanderighi (NLO QCD to gg channel)(06)
	Ciccolini,Denner,Dittmaier (NLO QCD+EW to WBF channel) (07)
$pp \to H$+3 jets	Figy,Hankele,Zeppenfeld (large N_c) (07)
$pp \to t\bar{t}$+jet	Dittmaier,Uwer,Weinzierl (07), Ellis,Giele,Kunszt (08)
$pp \to t\bar{t}Z$	Lazopoulos,Melnikov,Petriello (08)
$gg \to WW$	Binoth,Ciccolini,Kauer,Kramer (06)
$gg \to HH, HHH$	Binoth,Karg,Kauer,Rückl (06)
$pp \to t\bar{t}\,b\bar{b}$	Bredenstein et al., Bevilacqua et al. (09)
$pp \to V$+3jets	Berger et al., Ellis et al. (09)

Still, many questions were raised at this workshop . . .

- What theory uncertainties should be included as acceptance uncertainties when setting limits on a cross section?
- Should the factorization/renormalization scales be varied separately or together?
- How are these higher order predictions related to the LO event generators that one most often uses?
- How to deal with higher order differential distributions?
- Using NLO (NNLO) calculations to provide best LO (NLO) estimates for multi-parton final states: best scale choice? impact of jet choice?
- What is the impact of jet vetoing on the theoretical uncertainty for a signal/background cross section?
- How to handle the uncertainty on processes that can be calculated using a Fixed or Variable Flavor Scheme (FFS/VFS)?
- Many more on Joey's list!

No unique or simple answer . . .

Some guiding principles:

- reduce the dependence on unphysical scales (renorm./fact. scale);
- have the perturbative expansion of physical observables (inclusive σ, distributions, . . .) to show a well behaved convergence.

Several possible steps:

- add enough higher order corrections (NLO, NNLO) till: scale dependence improves, no large next order corrections expected;
- look for recurrent large contributions that may spoil convergence;
- find the best expansion parameter (α_s, α_s times large logarithms, . . .);
- using scaling properties, resum large scale dependent corrections;
- find the best choice of unphysical scales to avoid generating large logarithmic corrections at all orders;
- study the effect of cuts and vetos.

Interesting to look at some examples,
right from Higgs physics.

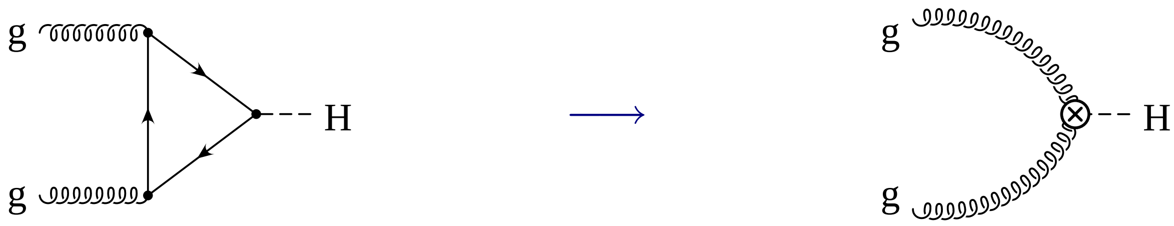
Ex. 1: $gg \to H$, main production mode (with $H \to \gamma\gamma, W^+W^-, ZZ$)

... large K-factors, scale dependence, resummations, and more.

NLO QCD corrections calculated exactly and in the $m_t \to \infty$ limit: perfect agreement even for $M_H >> m_t$.

$$\Downarrow$$

Dominant soft dynamics do not resolve the Higgs boson coupling to gluons



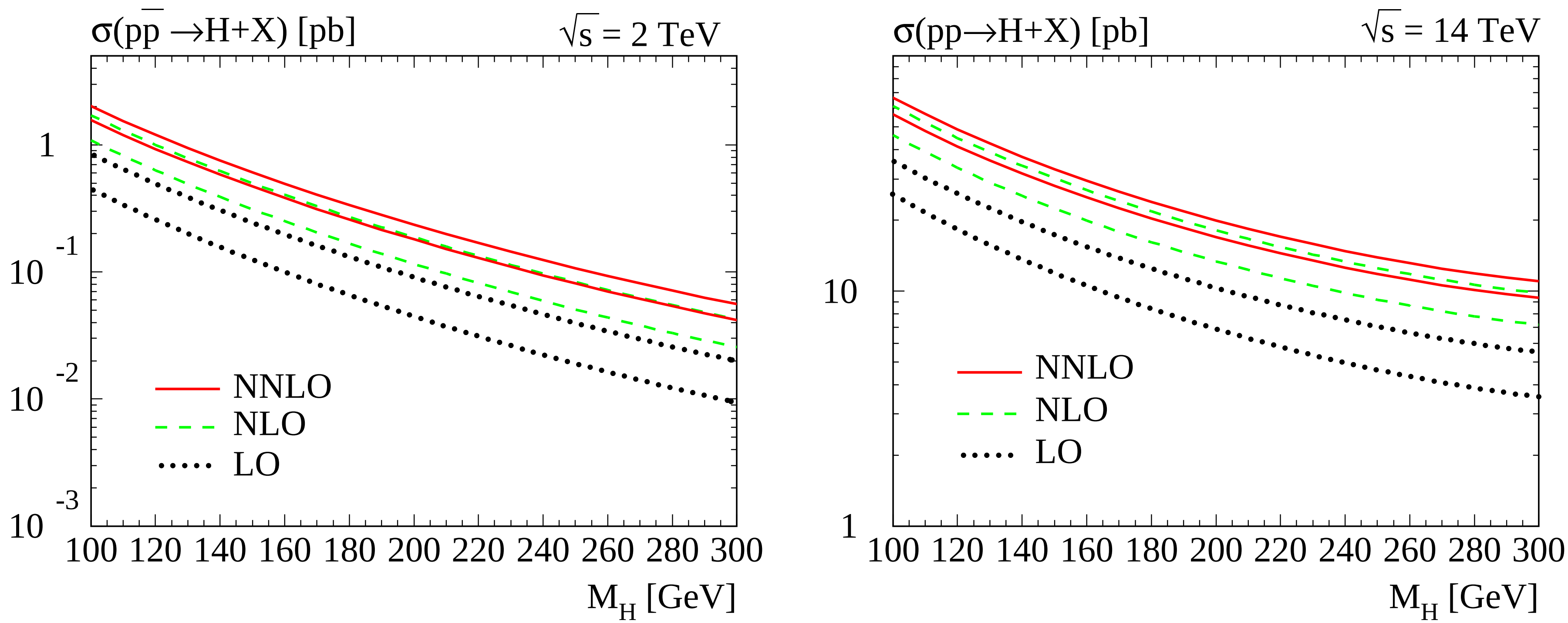
$$\Downarrow$$

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

where, including NLO and NNLO QCD corrections:

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

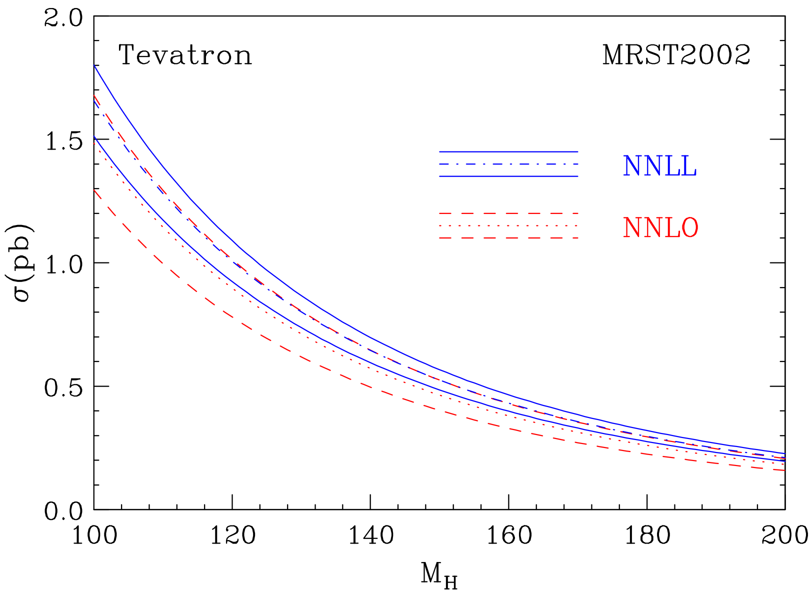
Fixed order NNLO:

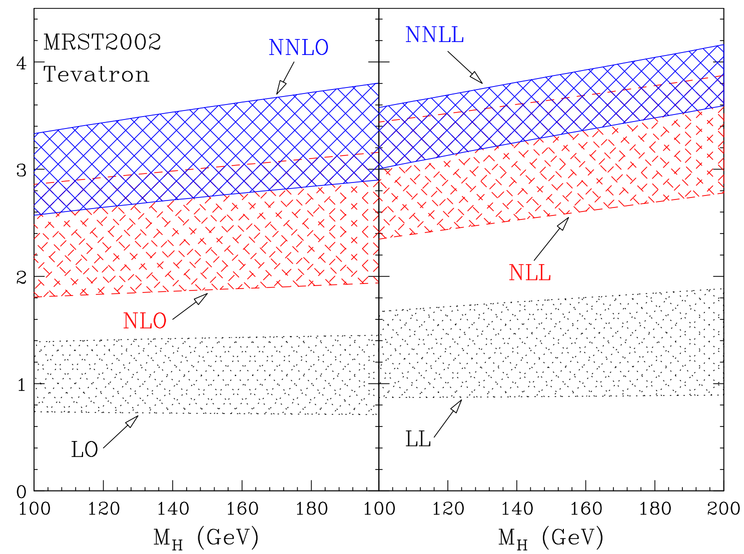


[Harlander,Kilgore (02)]

- very large corrections in going LO → NLO (K=1.7-1.9) → NNLO (K=2-2.2);
- perturbative convergence LO → NLO (70%) → NNLO (30%): residual 15% theoretical uncertainty.
- Tevatron case: still some tension.

Resumming effects of soft radiation . . .





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

Theoretical uncertainty reduced to:

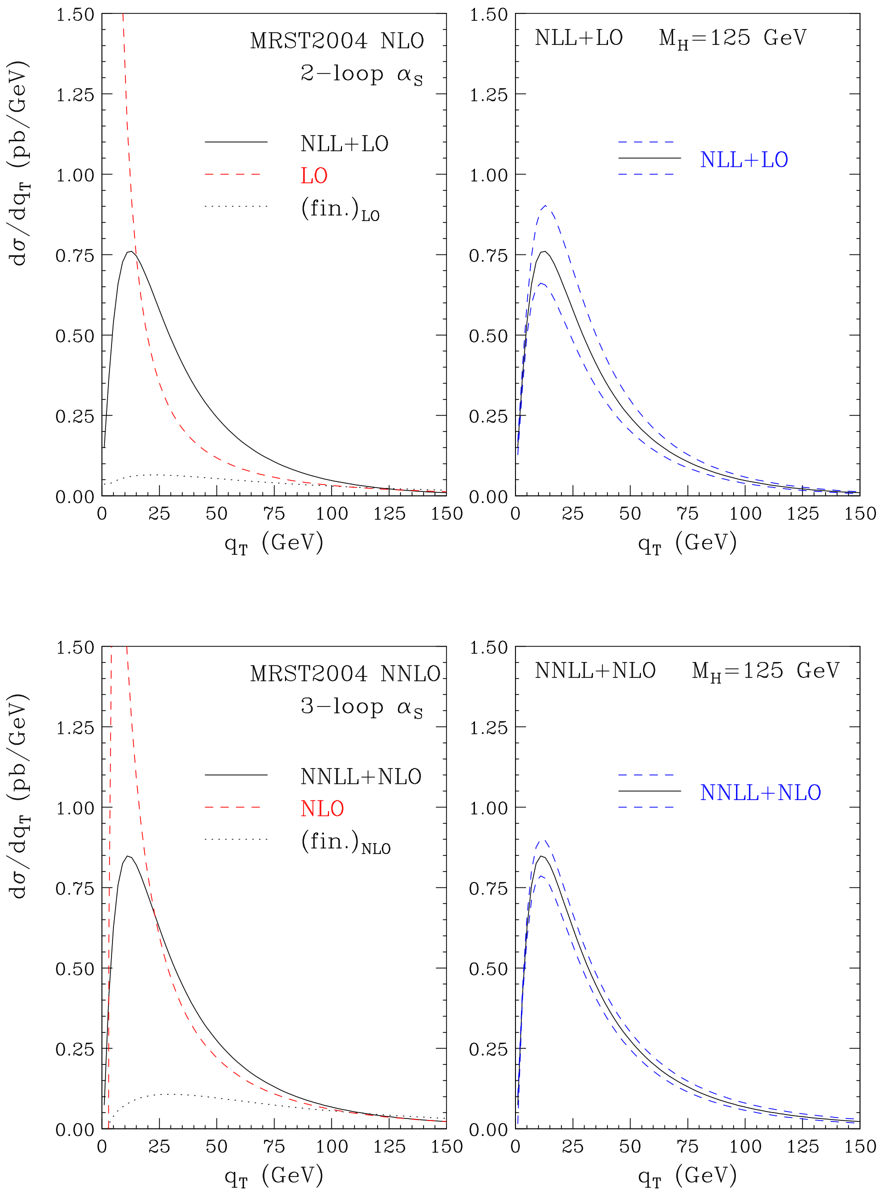
⟶ $\simeq$ 10% perturbative uncertainty, including the $m_t \to \infty$ approximation.

⟶ $\simeq$ 10% (estimated) from NNLO PDF's (now existing!).

But . . . recent update shows that: Going from MRST2002 to MSTW2008 greatly affects the Tevatron/LHC cross section: from 9%/30% ($M_H = 115$ GeV) to -9%/+9% ($M_H = 200/300$ GeV) !

[De Florian,Grazzini (09)]

Resumming effects of soft radiation for q_T^H spectrum ...



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 $\ln(M_H^2/q_T^2)$

residual uncertainty:

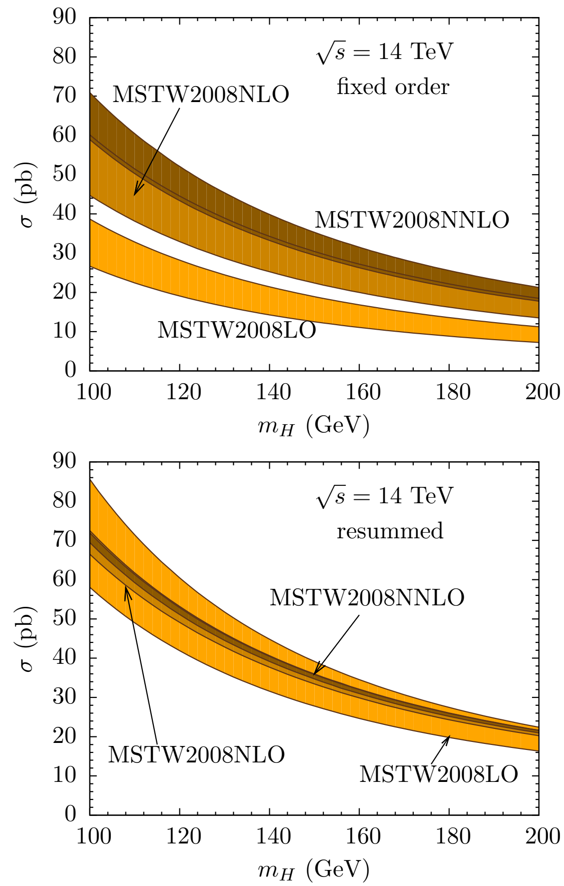
LO-NLL: 15-20%

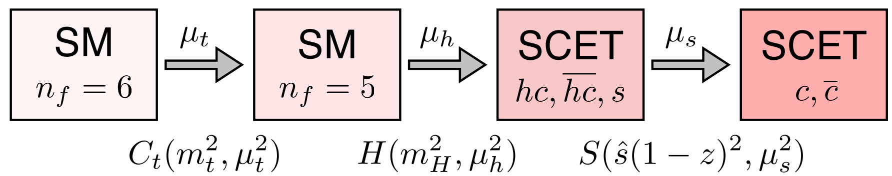
NLO-NNLL: 8-20%

[Bozzi,Catani,De Florian,Grazzini (04-08)]

Large K factors interpreted in SCET ...

... as mainly due to large $(\alpha_s C_A \pi)^n$ terms arising from double logarithmic terms in the gluon form factor. They can be resummed using effective theory techniques.





$$G_{\mu\nu} G^{\mu\nu} \longleftrightarrow \text{SCET operators}$$

→ improved convergence

→ sizable effects: 13% (Tevatron), 8% (LHC)

[Ahrens,Becher,Neubert,Yang (09)]

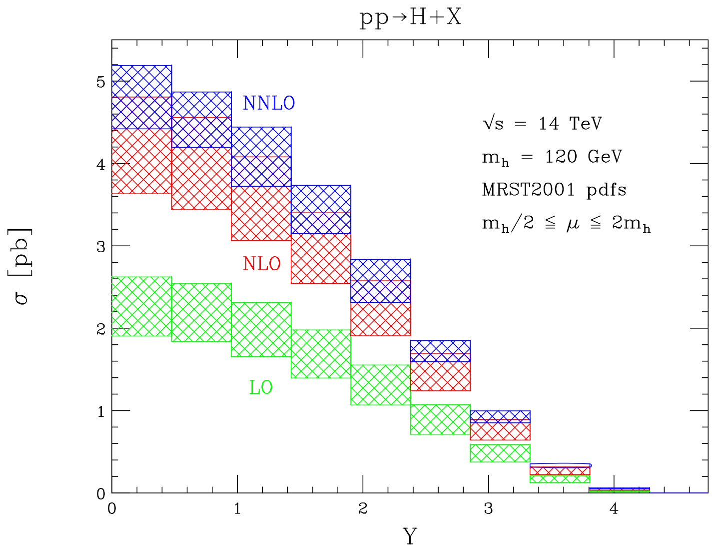
Exclusive NNLO results: $gg \to H$, $H \to \gamma\gamma, WW, ZZ$

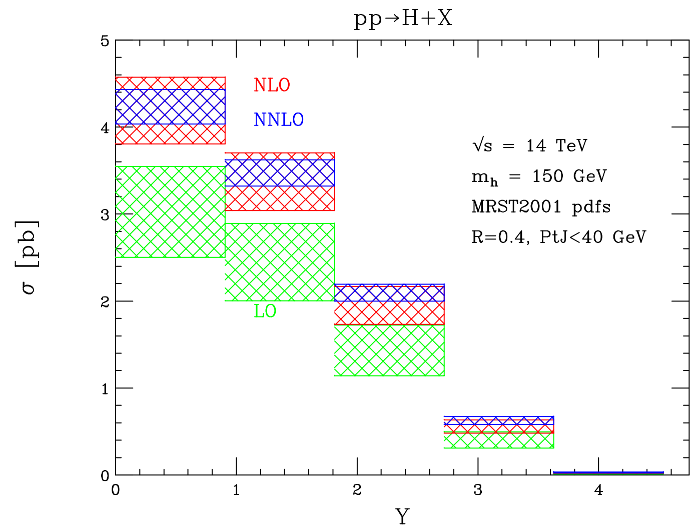
Extension of (IR safe) subtraction method to NNLO

$\longrightarrow$ HNNLO[Catani,Grazzini (05)]

$\longrightarrow$ FEHiP [Anastasiou,Melnikov,Petriello (05)]

Essential tools to reliably implement experimental cuts/vetos.



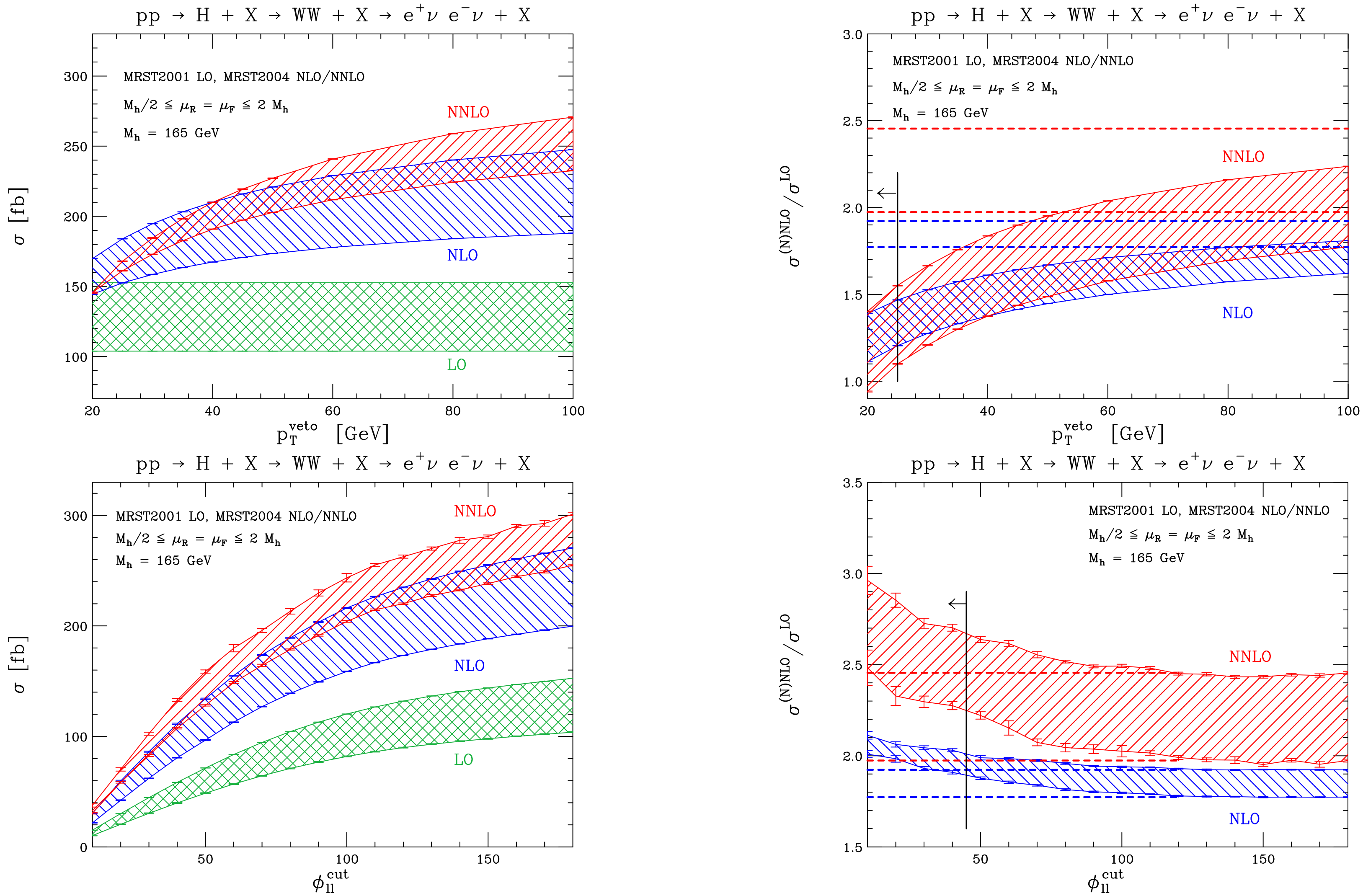


[Anastasiou,Melnikov,Petriello (05)]

jet veto (to enhance $H \to WW$ signal with respect to $t\bar{t}$ background) seems to improve perturbative stability of y-distribution $\longrightarrow$ jet veto is removing non-NNLO contributions.

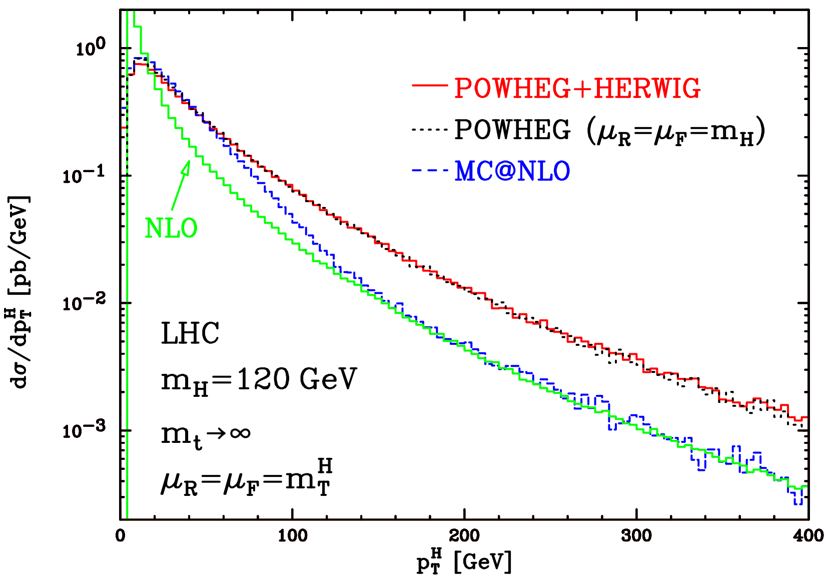
Full fledged $(gg \to) H \to W^+W^- \to l^+\nu l^-\bar{\nu}$

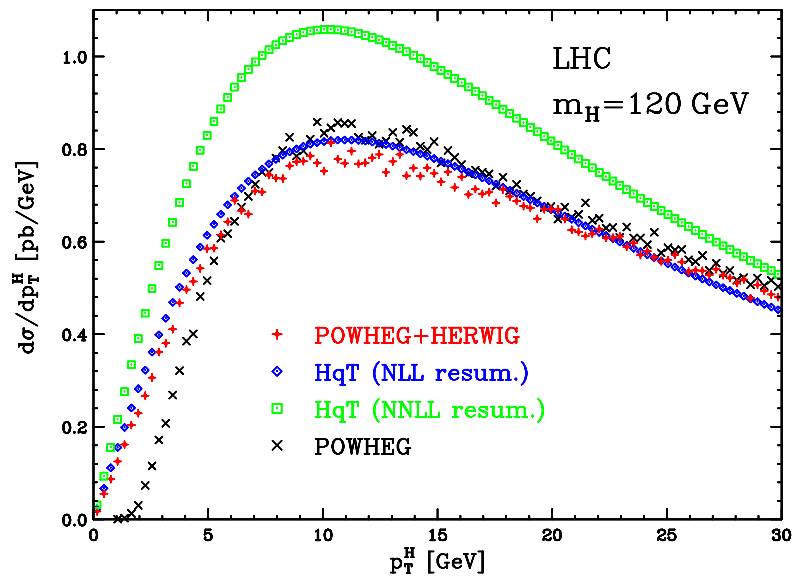
The magnitude of higher order corrections varies significantly with the signal selection cuts.



[Anastasiou,Dissertori,Stöckli (07)]

$gg \to H$ implemented in MC@NLO and POWHEG





[Nason, Oleari, Alioli, Re]

$\longrightarrow$ general good agreement with PYTHIA;

$\longrightarrow$ comparison MC@NLO vs POWHEG understood;

$\longrightarrow$ comparison with resummed NLL and NNLL results under control.

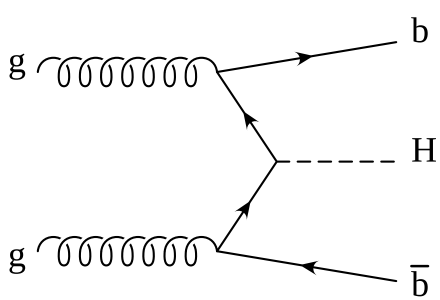
Ex. 2: $p\bar{p}, pp \to b\bar{b}H$: hints of new physics?

4FNS vs 5FNS …

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

- Exclusive modes have smaller cross section, but also smaller background and they measure the bottom-quark Yukawa coupling unambiguously.

- Inclusive modes enhanced by large collinear $\ln(\mu_H^2/m_b^2)$ arising in the PS integration of untagged b-quarks in $gg \to b\bar{b}H$



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

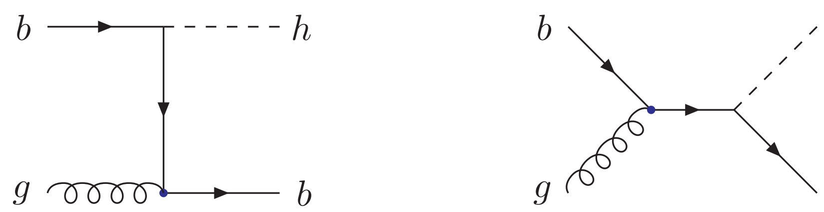
They can be resummed by introducing a b-quark PDF:

$$b(x,\mu) = \frac{\alpha_s(\mu)}{2\pi} \log\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)$$

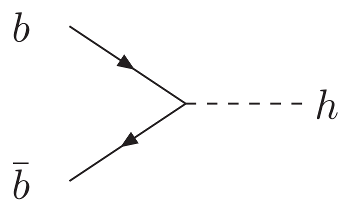
- Semi-inclusive and inclusive cross sections: 2 approaches

$\longrightarrow$ Use $q\bar{q}, gg \rightarrow b\bar{b}h$ (at NLO) $\longrightarrow$ **4FNS**
imposing tagging cuts on only one or no final state b quarks.

$\longrightarrow$ Use b-quark PDF, resumming the large collinear logs $\longrightarrow$ **5FNS**



$\longrightarrow$ **1 b-tag** $(bg \rightarrow bH)$



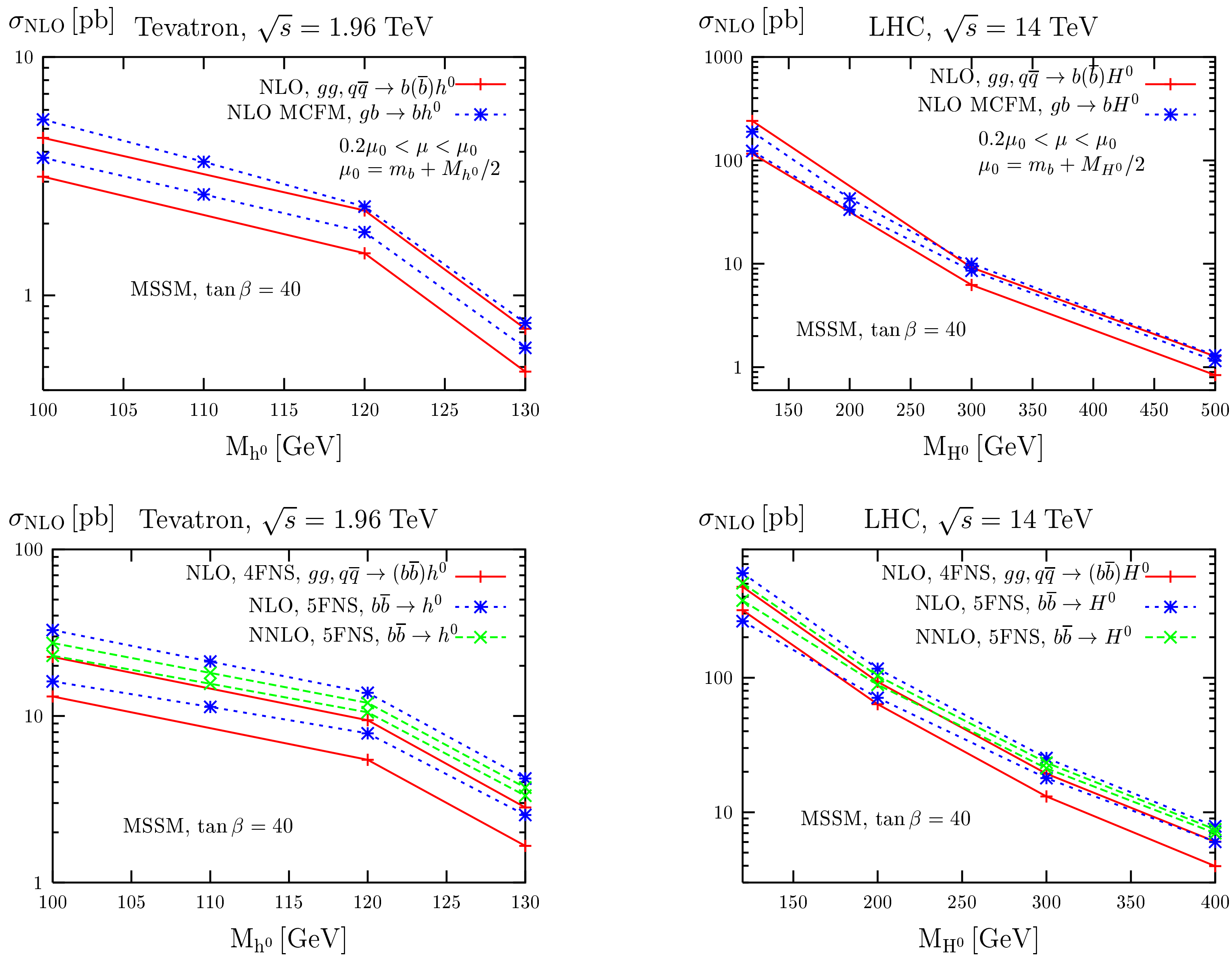
$\longrightarrow$ **0 b-tags** $(b\bar{b} \rightarrow H)$

Perturbative series ordered in Leading and SubLeading powers of $\alpha_s \ln(\mu_H^2/m_b^2)$.

$\longrightarrow$ Expect consistence at higher order when comparing $q\bar{q}, gg \rightarrow b\bar{b}H$ (NLO) to

- $b\bar{b} \rightarrow H$ (NNLO) (no b-tag)
  [R.Harlander, W.Kilgore; D.Dicus, T.Stelzer, Z.Sullivan, S.Willenbrock]
- $bg \rightarrow bH$ (NLO) (one b-tag)
  [J.Campbell, R.K.Ellis, F.Maltoni, S.Willenbrock]

Inclusive cross sections in the MSSM: 4FNS vs 5FNS



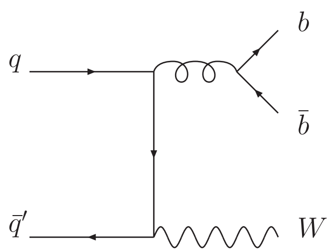
[Dawson, Jackson, L.R., Wackeroth]

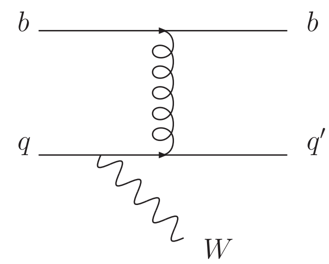
Ex. 3: $W + 1\,b$-jet: crucial background for WH production

Combining 4FNS and 5FNS at NLO: best theoretical prediction

[Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (09)]

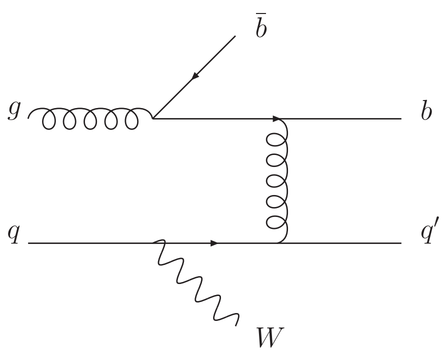
Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:



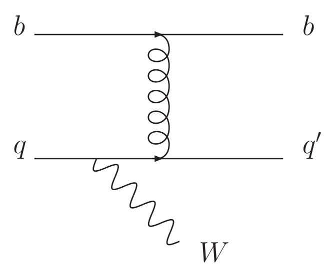


$+ \quad O(\alpha_s)$ corrections

1. $q\bar{q}' \to Wb\bar{b}$ at tree level and one loop ($m_b \neq 0$)
2. $q\bar{q}' \to Wb\bar{b}g$ at tree level ($m_b \neq 0$)
3. $bq \to Wbq'$ at tree level and one loop ($m_b = 0$)
4. $bq \to Wbq'g$ and $bg \to Wbq'\bar{q}$ at tree level ($m_b = 0$)
5. $gq \to Wb\bar{b}q'$ at tree level ($m_b \neq 0$) $\to$ avoiding double counting:



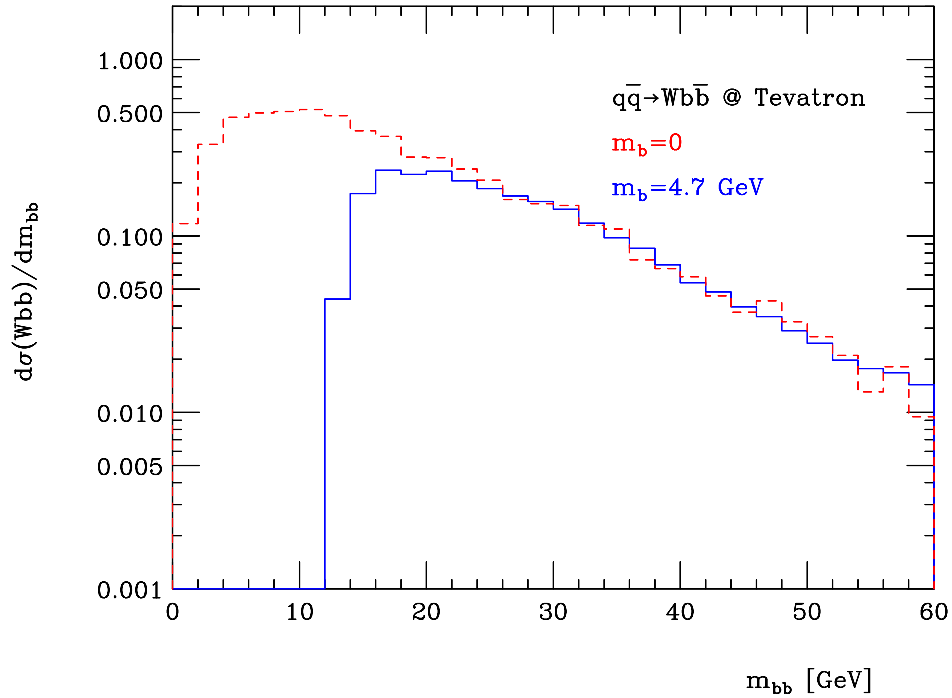
$\longrightarrow$



$$b(x,\mu) = \frac{\alpha_s}{2\pi} \ln\frac{\mu^2}{m_b^2} \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)$$

$\longrightarrow$ indeed: a fully consistent NLO 5FNS calculation (S-ACOT scheme).

- improved scale dependence: NLO corrections to $gq \to Wb\bar{b}q'$ partially included;
- need to keep $m_b \neq 0$ for final state b quarks (one b quark has low p_T)



- four signatures studied: exclusive/inclusive, with single and double-b jets, using $p_T^j > 15$ GeV, $|\eta^j| < 2 - 2.5$, cone algorithm with $\Delta R = 0.7$:
  - $\longrightarrow$ Wb, $W(b\bar{b})$ (exclusive)
  - $\longrightarrow$ Wb and $Wb + j$, $W(b\bar{b})$ and $W(b\bar{b}) + j$ (inclusive)

  which can be combined to obtain different backgrounds, ...
- both contributions play important complementary roles (Tevatron/LHC, inclusive/exclusive);

- NLO results at a glance:

	Exclusive cross sections (pb)	
Collider	Wb	$W(b\bar{b})$
TeV $W^+(=W^-)$	8.02+0.62[-0.05]=8.64	3.73-0.02[-0.02]=3.71
LHC W^+	40.0+48.4[22.6]=88.4	22.7+11.7[11.7]=34.4
LHC W^-	29.8+29.4[12.6]=59.2	17.2+6.5[6.5]=23.7

	Inclusive cross sections (pb)	
Collider	$Wb+X$	$W(b\bar{b})+X$
TeV $W^+(=W^-)$	11.77+2.40[0.77]=14.17	4.17+0.39[0.39]=4.56
LHC W^+	53.6+136.1[68.9]=189.7	25.1+35.9[35.9]=61.0
LHC W^-	39.3+88.2[44.6]=127.5	18.9+23.6[23.6]=42.5

$\longrightarrow$ first number: Processes $1+2$ (pure 4FNS)

$\longrightarrow$ second number: Processes $3+\cdots+5$ (pure 5FNS plus $qg \rightarrow Wb\bar{b}+q'$)

$\longrightarrow$ number in square brackets: Process 5 alone ($qg \rightarrow Wb\bar{b}+q'$)

Comparison with CDF measurement: a puzzle?

CDF Note 9321 (arXiv:0909.1505):

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu) = 2.74 \pm 0.27(\mathrm{stat}) \pm 0.42(\mathrm{syst})\ \mathrm{pb}$$

[Neu, Thomson, Heinrich]

From our $W + 1b$ calculation:

[Campbell, Febres Cordero, L.R.]

$$\sigma_{\mathrm{b-jet}}(W + b\,\mathrm{jets}) \cdot Br(W \to l\nu) = 1.22 \pm 0.14\ \mathrm{pb}$$

For comparison:

ALPGEN prediction: 0.78 pb

PYTHIA prediction: 1.10 pb

Conclusions and Outlook

- Enormous QCD activity for Higgs physics in the past decade: brought incredible progress, raised new questions.
- Now possible to answer questions like:
  - How to reliably estimate the theoretical error?
  - How to use existing NLO/NNLO QCD calculations?
- We have just scratched the surface: More discussion will come through this workshop!