Higgs Boson Phenomenology
Lecture III

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Outline of Lecture III

- Looking for a SM Higgs boson at hadron colliders:

  $\longrightarrow$ parton level production processes;
  $\longrightarrow$ Tevatron Higgs physics program;
  $\longrightarrow$ LHC Higgs physics program.

- Structure of hadronic processes: most important building blocks.

  ($\hookrightarrow$ see John Campbell's lectures)

- How can a theorist do a good job?

  $\longrightarrow$ understand hadronic environment;
  $\longrightarrow$ understand experimental measurements;
  $\longrightarrow$ understand the systematic of the theoretical errors.

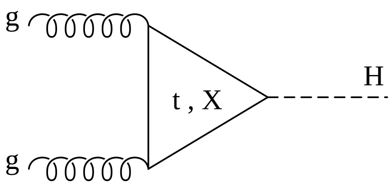
- Examples from Higgs physics:

  $\longrightarrow$ $gg \to H$: a tutorial in itself!
  $\longrightarrow$ overview of inclusive theoretical predictions;
  $\longrightarrow$ ongoing studies for exclusive channels.

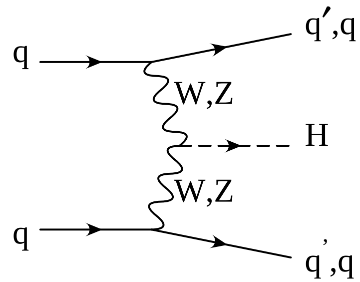
- What we haven't discussed ...

$p\bar{p}, pp$ colliders: SM Higgs production modes

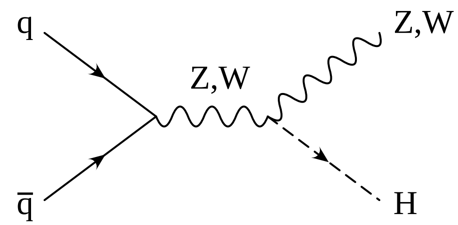
$gg \to H$



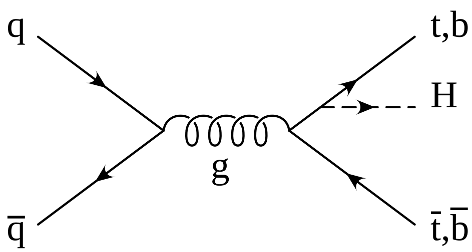
$qq \to qqH$

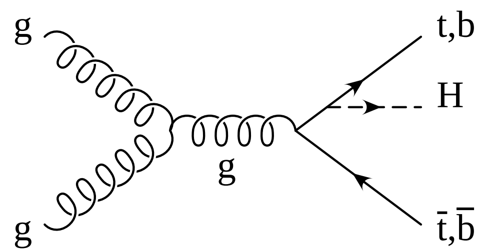


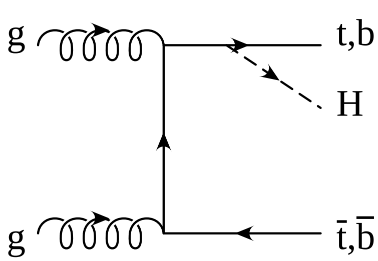
$qq \to WH, ZH$

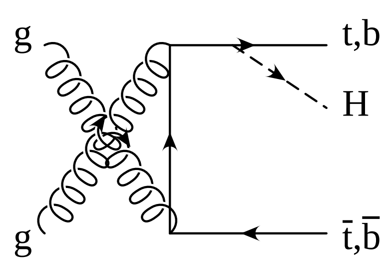


$q\bar{q}, gg \to t\bar{t}H, b\bar{b}H$

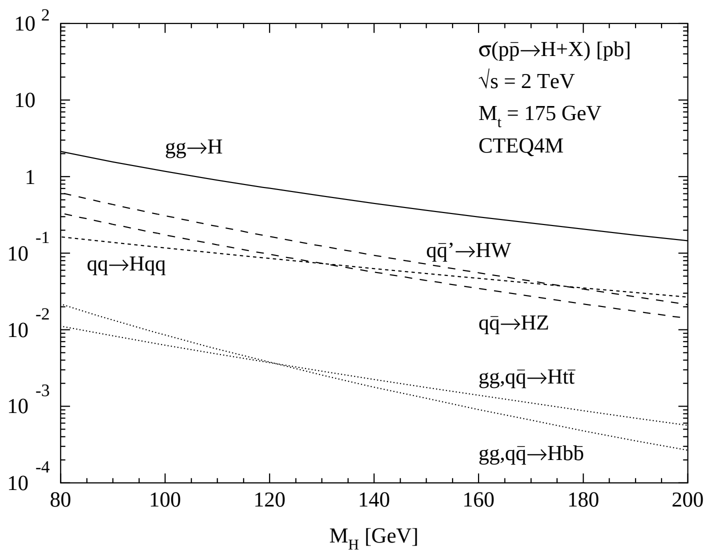


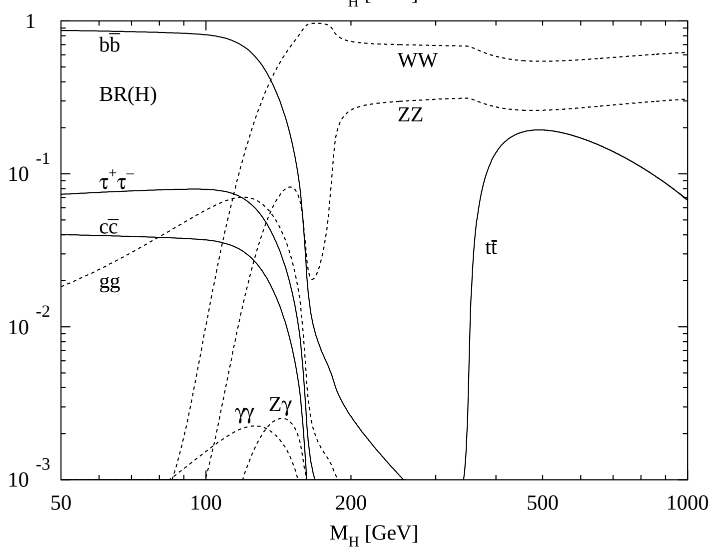






Tevatron: great potential for a light SM-like Higgs boson





(M. Spira, Fortsch.Phys. 46 (1998) 203)

Lower mass region:

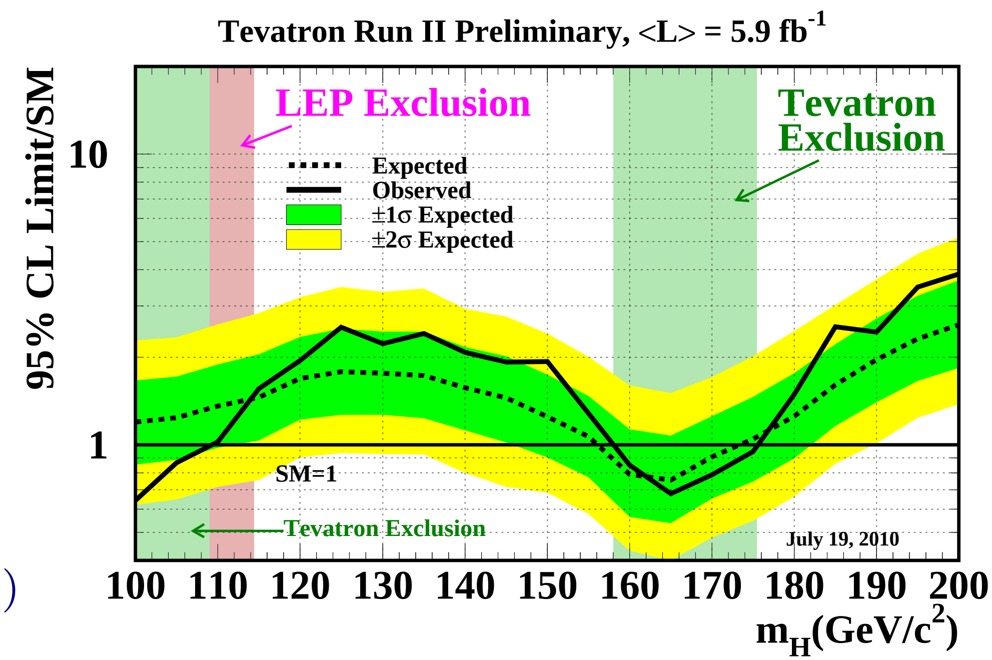
$$q\bar{q}' \to WH, H \to b\bar{b}$$

Higher mass region:

$$gg \to H, H \to W^+W^-$$

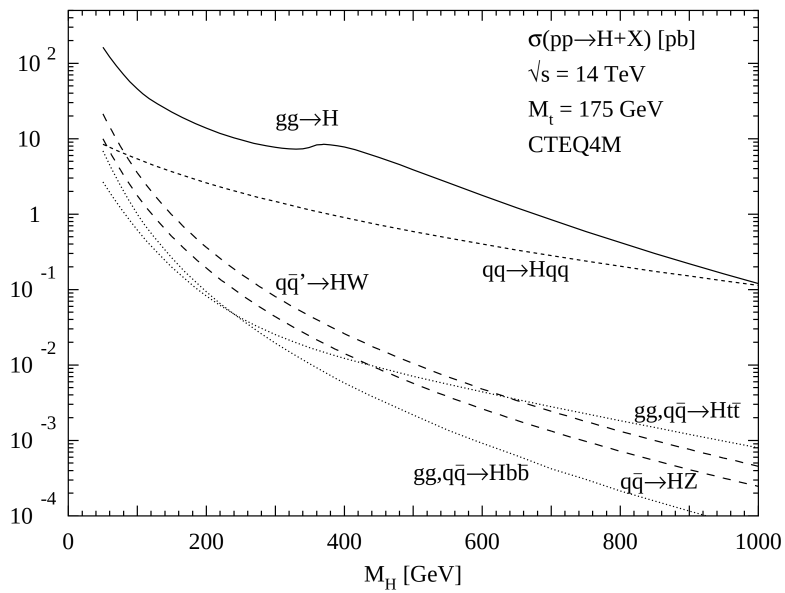
(smaller impact:

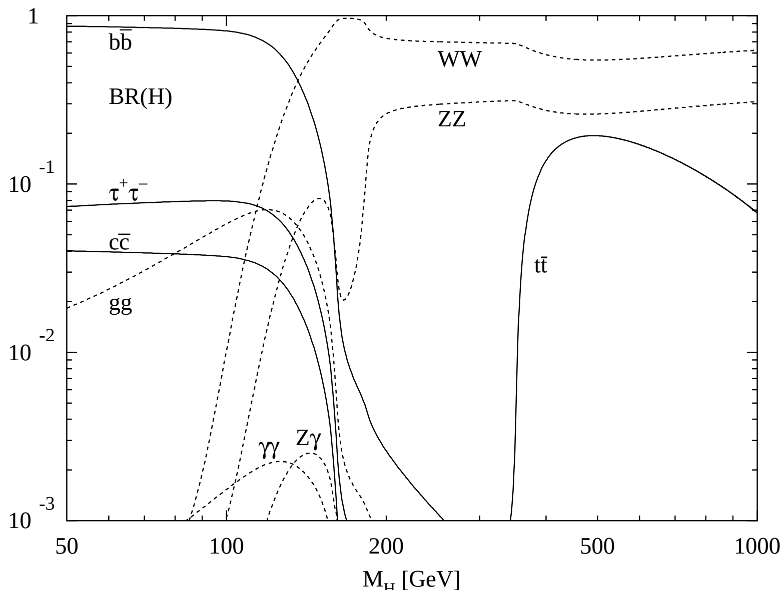
$$q\bar{q} \to q'\bar{q}'H,\ q\bar{q}, gg \to t\bar{t}H)$$



↪ Exclusion region very important for LHC search strategies.

LHC: entire SM Higgs-boson mass range accessible





(M. Spira, Fortsch.Phys. 46 (1998) 203)

Many channels have been studied:

Below 130-140 GeV:

$gg \to H\,,\; H \to \gamma\gamma, WW, ZZ$

$qq \to qqH\,,\; H \to \gamma\gamma, WW, ZZ, \tau\tau$

$q\bar{q}, gg \to t\bar{t}H\,,\; H \to \gamma\gamma, b\bar{b}, \tau\tau$

$q\bar{q}' \to WH\,,\; H \to \gamma\gamma, b\bar{b}$

Above 130-140 GeV:

$gg \to H\,,\; H \to WW, ZZ$

$qq \to qqH\,,\; H \to \gamma\gamma, WW, ZZ$

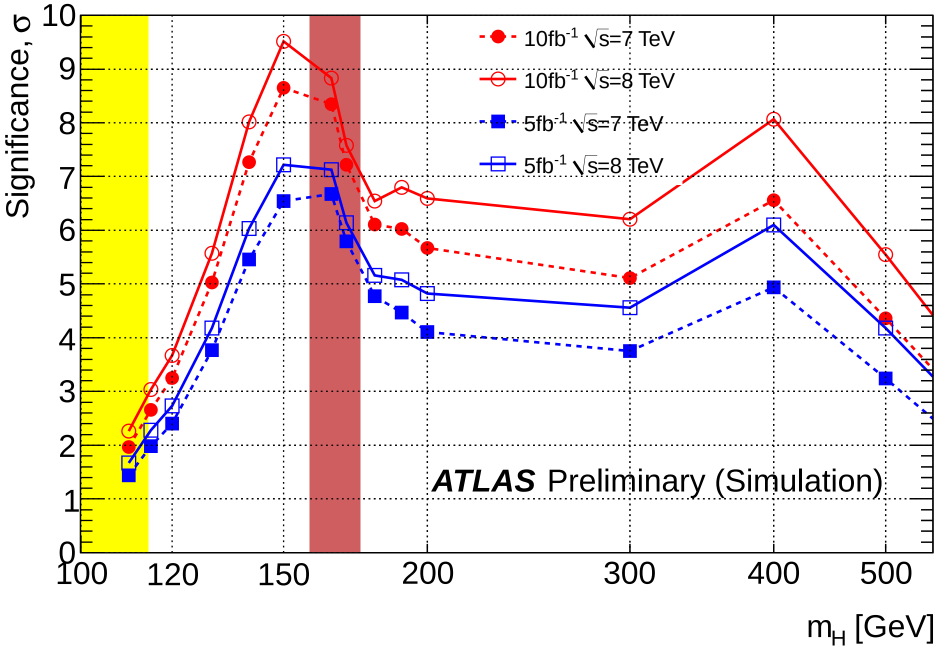
$q\bar{q}, gg \to t\bar{t}H\,,\; H \to \gamma\gamma, WW$

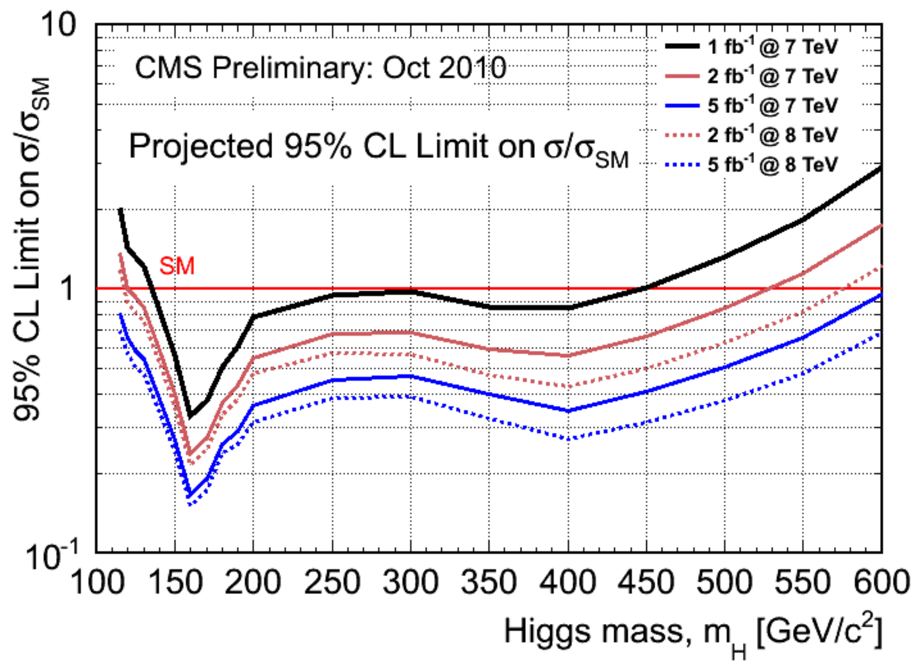
$q\bar{q}' \to WH\,,\; H \to WW$

With $\sqrt{s} = 7$ TeV and a few fb^{-1} ...

Combining only $H \to W^+W^-$, $H \to ZZ$, $H \to \gamma\gamma$, ATLAS and CMS indicate that,

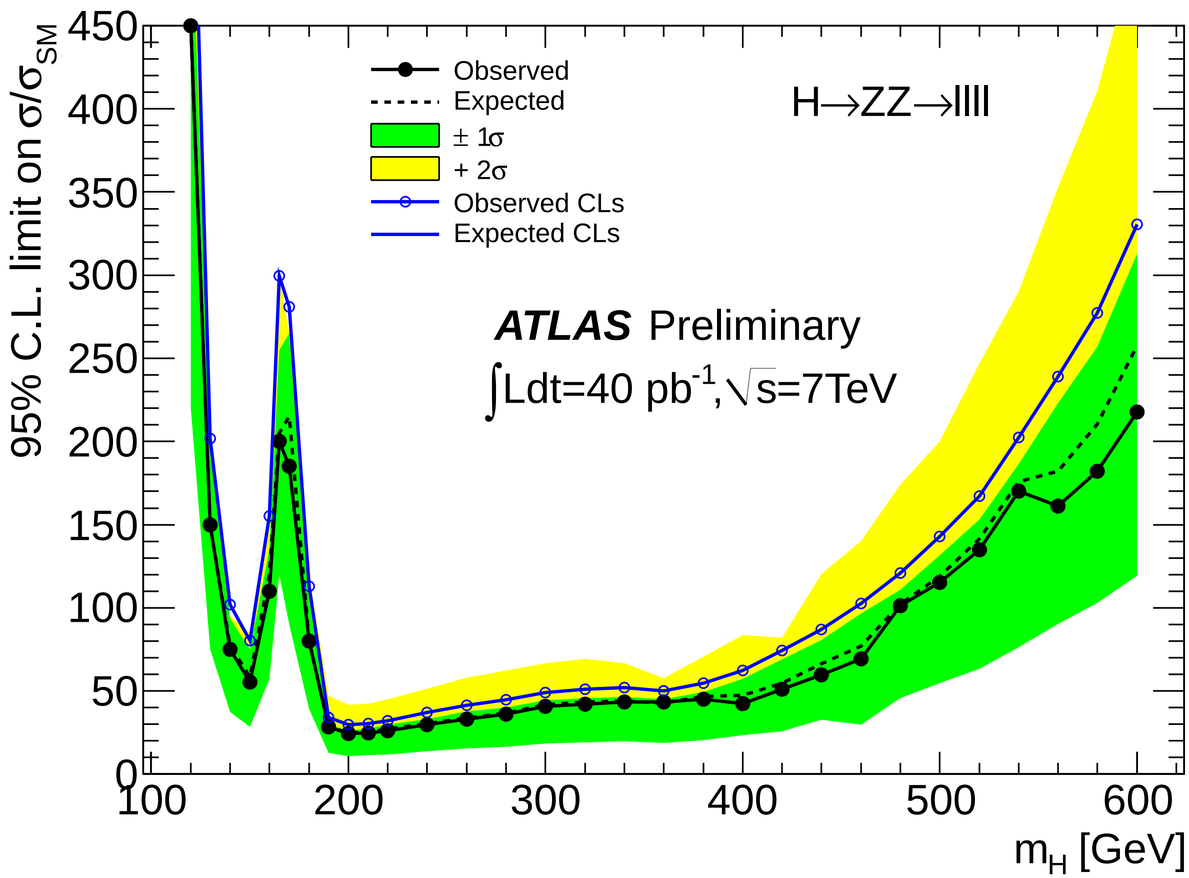
- if no signal, the SM Higgs can be excluded up to 500 GeV;
- a 5σ significance for a SM Higgs in the $140 - 170$ GeV mass range;
- in the low mass region ($\hookleftarrow$ new strategies, new ideas).





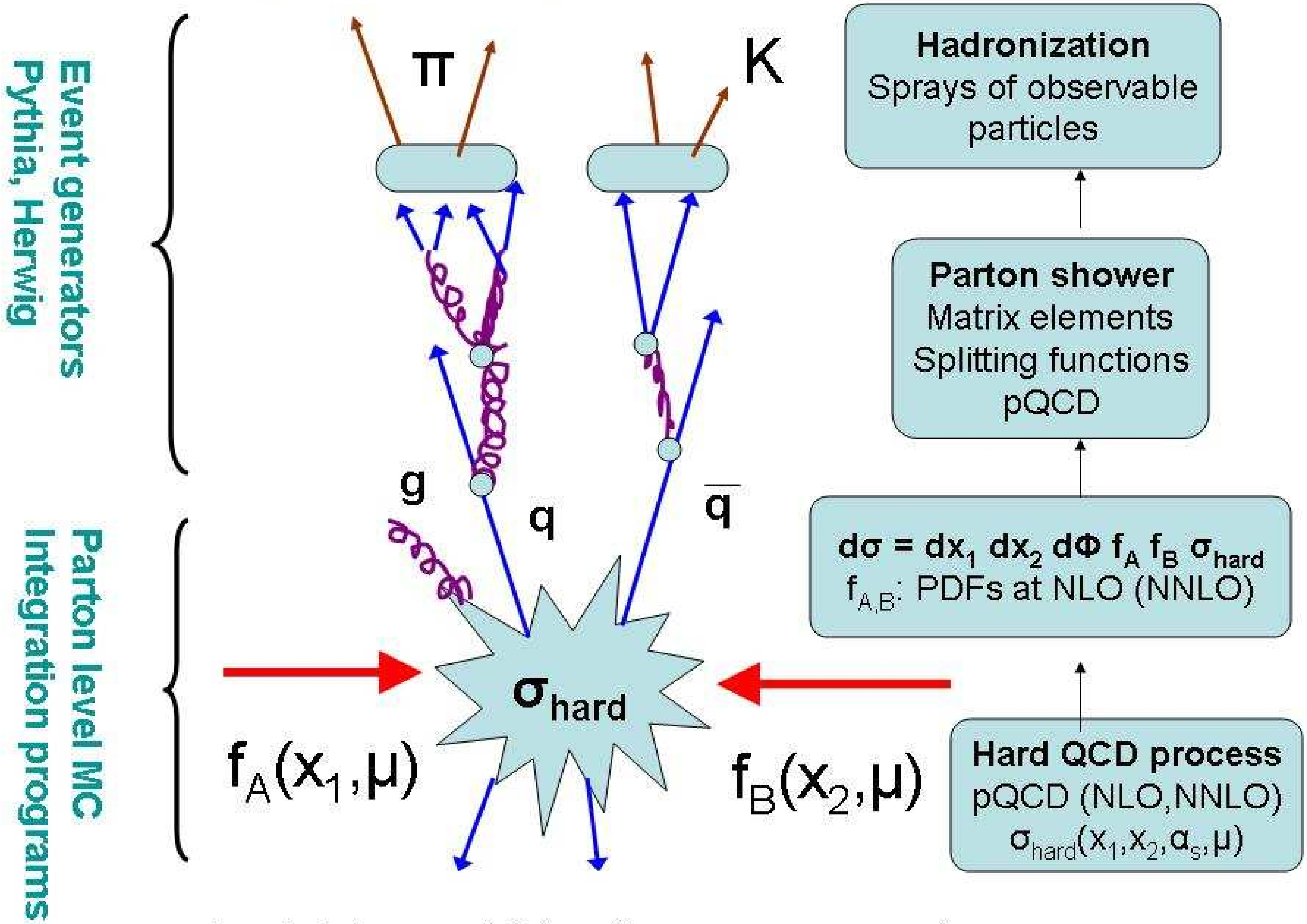
where also $WH, H \to b\bar{b}$ (highly boosted) and VBF with $H \to \tau\tau$ were used.

Data!



↪ see talks by John Conway (CMS) and Chris Lester (ATLAS).

Anatomy of a QCD prediction at hadron colliders



+ underlying event, interactions among remnants

Schematically ...

The hard cross section is calculated 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
......

and convoluted with initial state parton densities at the same order.

Renormalization and factorization scale dependence left at any fixed order.
Setting $\boxed{\mu_R = \mu_F = \mu}$:

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

Systematic theoretical error from:

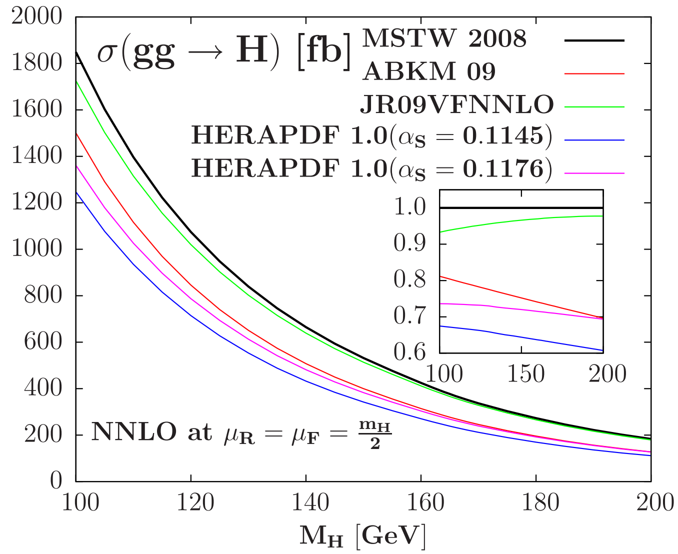
- PDF and $\alpha_s(\mu)$;
- left over scale dependence;
- input parameters.

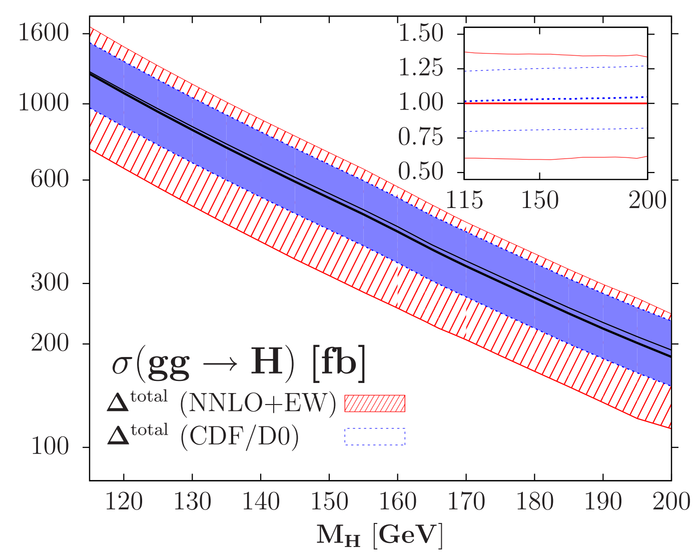
Systematic error from PDFs: need care . . .

Several PDF sets (CTEQ, MSTW, NNPDF, . . .) allow to estimate the error from α_s and error obtained by varying the inputs used in the PDF fit within their experimental error.

However: results obtained using different sets of PDF differ by much more than the respective internal errors $\longrightarrow$ difference from parametrization

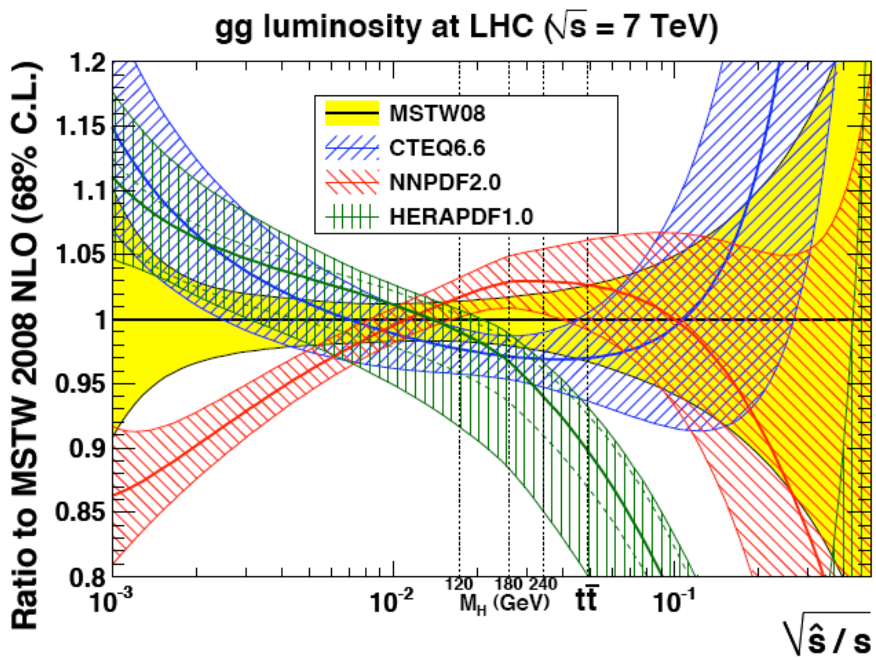
Example: Tevatron bound has been questioned with the claim that the error from PDF's has been largely underestimated

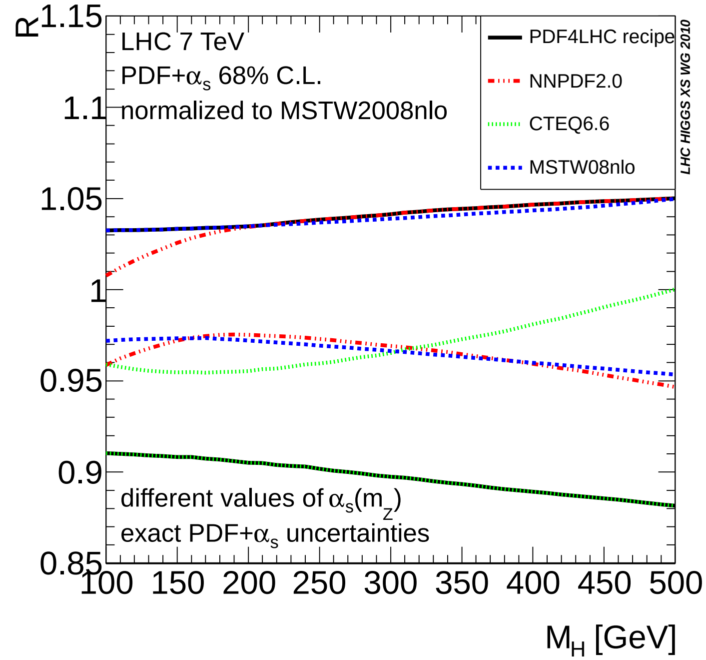




(Baglio, Djouadi, Ferrag, Godbole, arXiv:1101.1832)

PDF4LHC: problem carefully studies for LHC physics





(Forte, Huston, Mazumdar, Thorne, Vicini, arXiv:1101.0593)

- NLO: use sets that perform a global fit to all available collider data: CTEQ(6.6), MSTW(2008), NNPDF(2.0). Estimate the error from PDF using the envelope prescription.
- NNLO: use MSTW(2008), normalized to a more conservative error i.e. multiplied by (NLO envelope error/NLO MSTW2008 error).

Hard cross sections: pushing the loop order, why?

- 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:

  $\longrightarrow$ resummed calculations (e.g. soft/collinear logs, kinematic logs);
  $\longrightarrow$ parton shower Monte Carlo programs (e.g. PYTHIA, HERWIG).

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 ($\rightarrow$ interfaced with FROOT) [Campbell, Ellis]
- Enormous progress towards automation:

  $\rightarrow$ Virtual corrections: new techniques based on unitarity methods and recursion relations

  - ▷ BlackHat [Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre]
  - ▷ Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi]
  - ▷ HELAC+CutTools,Samurai [Bevilacqua, Czakon, van Harmeren, Papadopoulos, Pittau,Worek; Mastrolia, Ossola, Reiter, Tramontano]

  $\rightarrow$ Real corrections: based on Catani-Seymour Dipole subtraction or FKS subtraction

  - ▷ Sherpa [Gleisberg, Krauss]
  - ▷ Madgraph (AutoDipole) [Hasegawa, Moch, Uwer]
  - ▷ Madgraph (MadDipole) [Frederix, Gehrmann, Greiner]
  - ▷ Madgraph (MadFKS) [Frederix,Frixione, Maltoni, Stelzer]

- virtual+real:
  - ▷ MadLoop+MadFKS [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]
- 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.

Important questions arise when interpreting data . . .

- 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 algorithm choice?
- What is the impact of jet vetoing on the theoretical uncertainty for a signal/background cross section?
- What theory uncertainties should be included as acceptance uncertainties when setting limits on a cross section?
- Many more!

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.

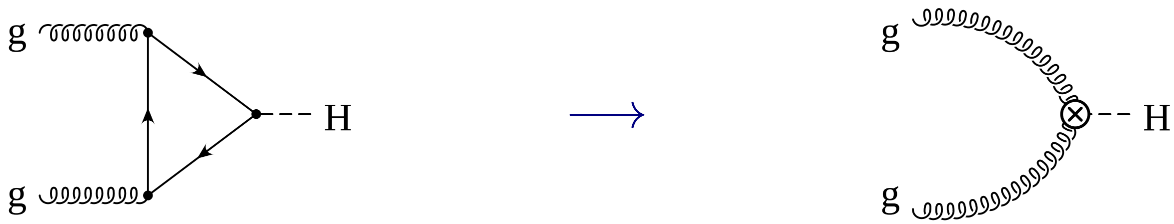
A tutorial: $gg \to H$, main production mode

... 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



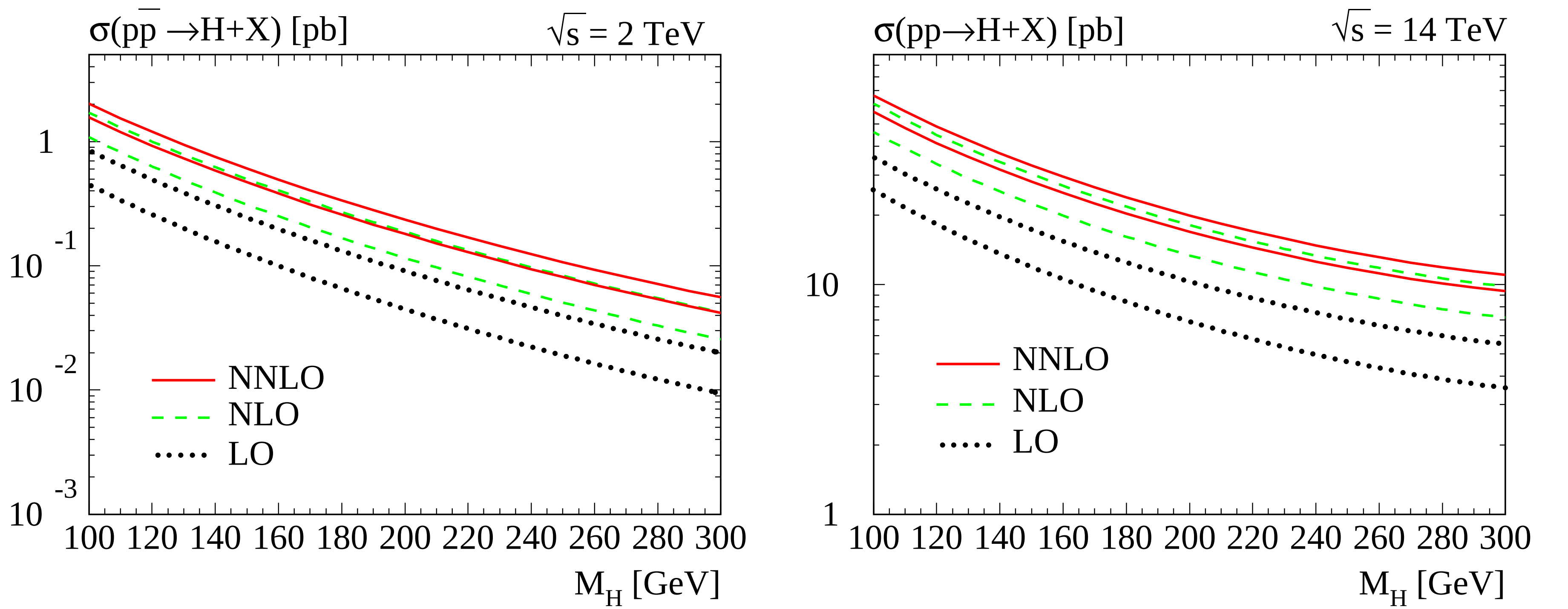
$$\Downarrow$$

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

where, including NLO and NNLO QCD corrections:

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

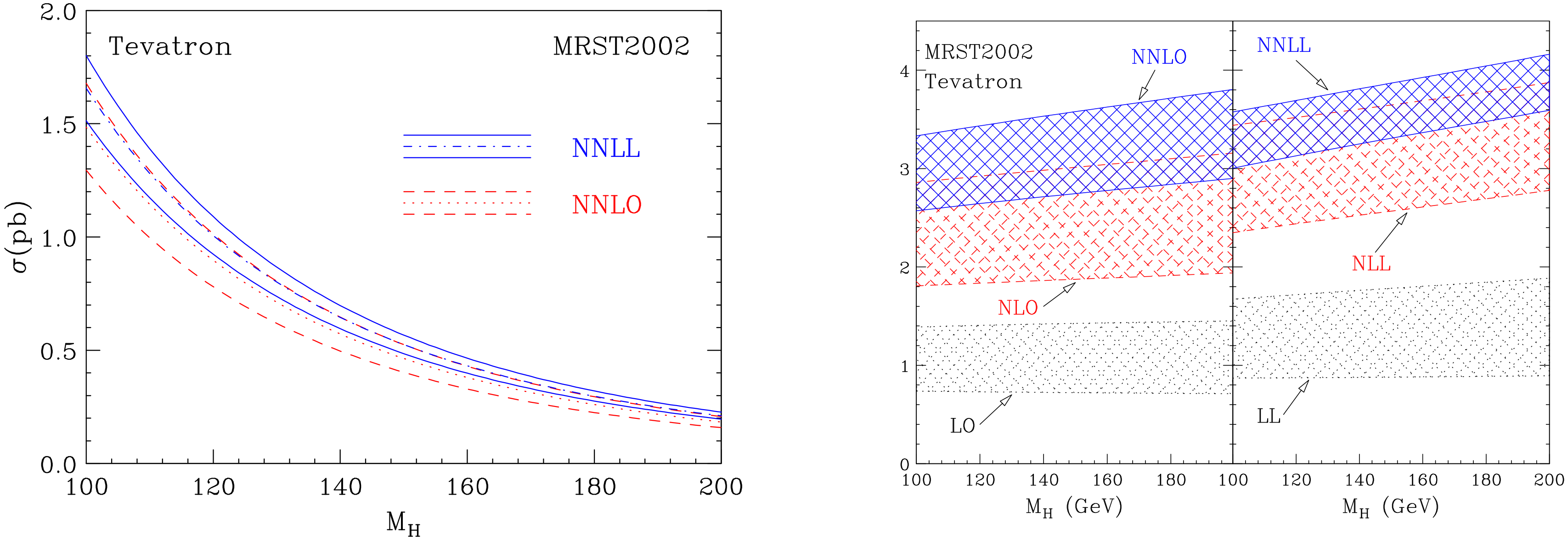
Fixed order NNLO:



[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:

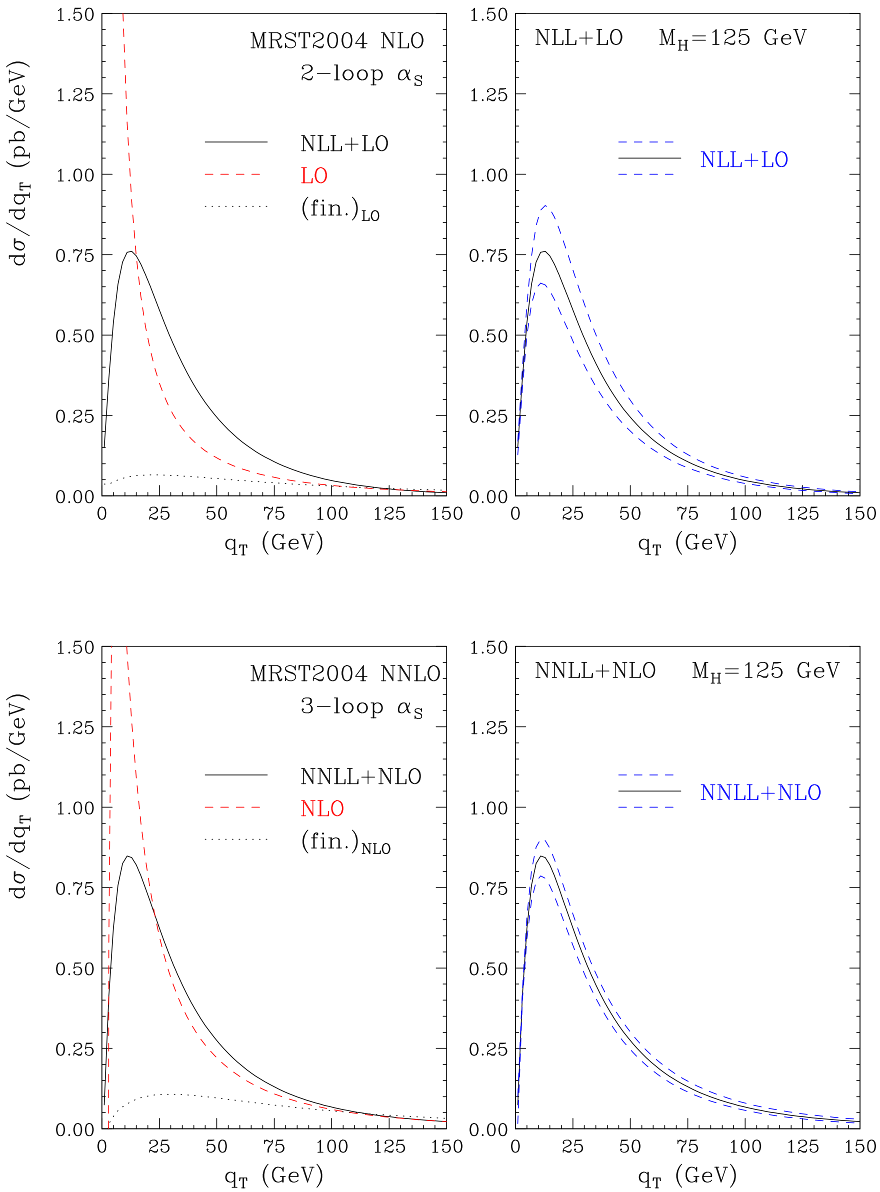
$\longrightarrow$ $\simeq$ 10% perturbative uncertainty, including the $m_t \to \infty$ approximation.

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

But . . . <u>let us remember</u> that: going from MRST2002 to MSTW2008 greatly affected 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)]

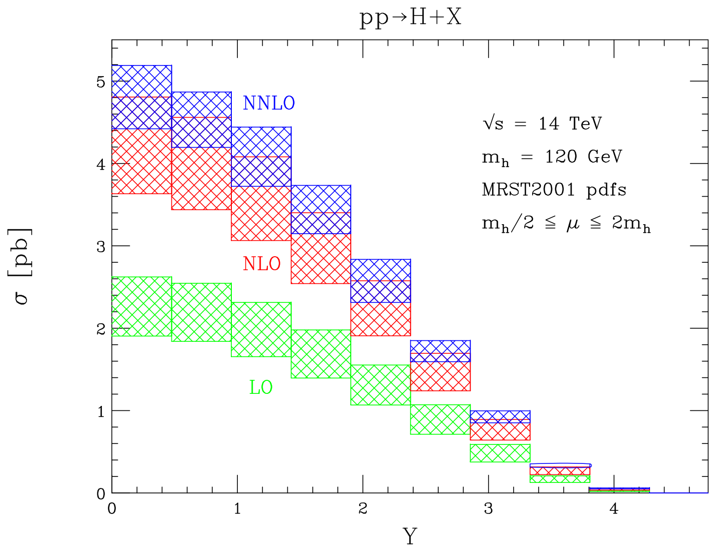
Exclusive NNLO results: $gg \to H$, $H \to \gamma\gamma, WW, ZZ$

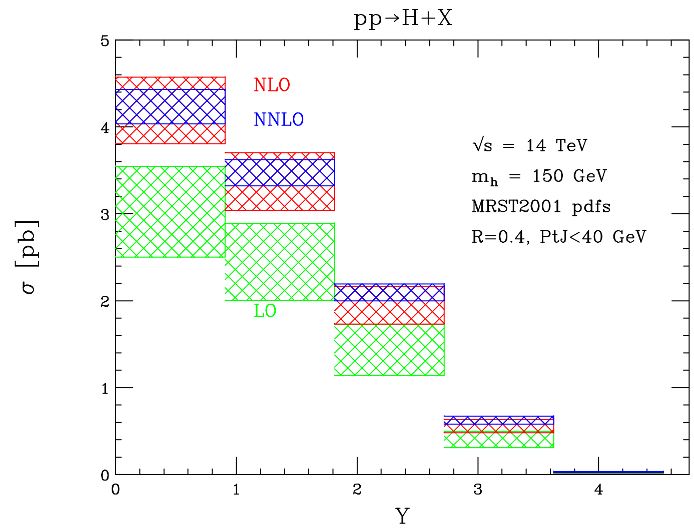
Extension of (IR safe) subtraction method to NNLO

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

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

Essential tools to reliably implement experimental cuts/vetos.



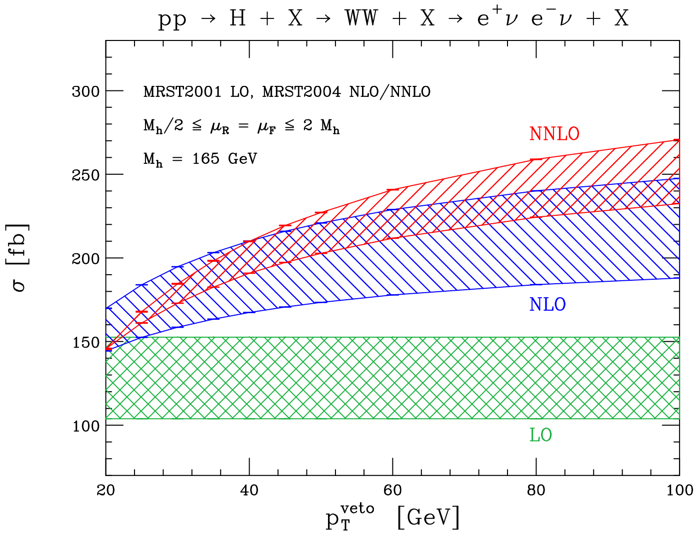


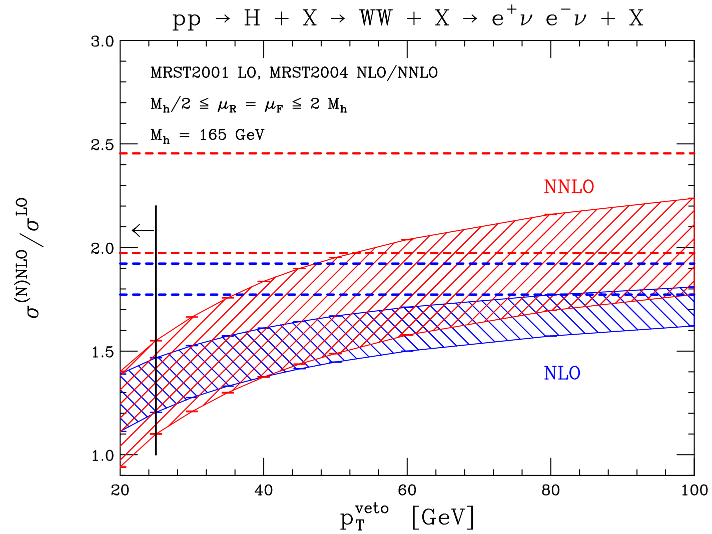
[Anastasiou,Melnikov,Petriello (05)]

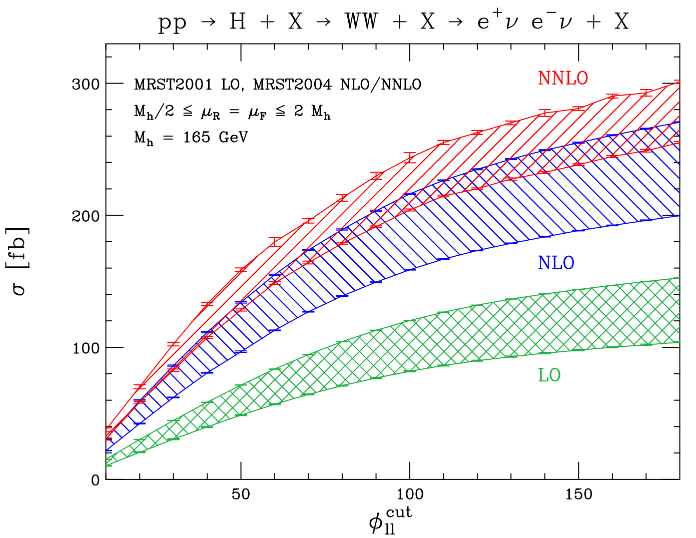
jet veto (to enhance $H \to WW$ signal with respect to $t\bar{t}$ background) seems to improve perturbative stability of y-distribution $\longrightarrow$ jet veto is removing non-NNLO contributions.

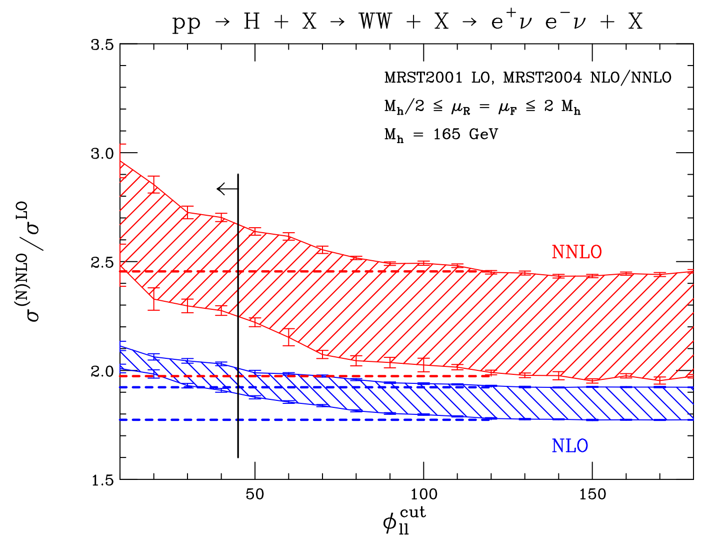
Full fledged $(gg \to)H \to W^+W^- \to l^+\nu l^-\bar{\nu}$

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



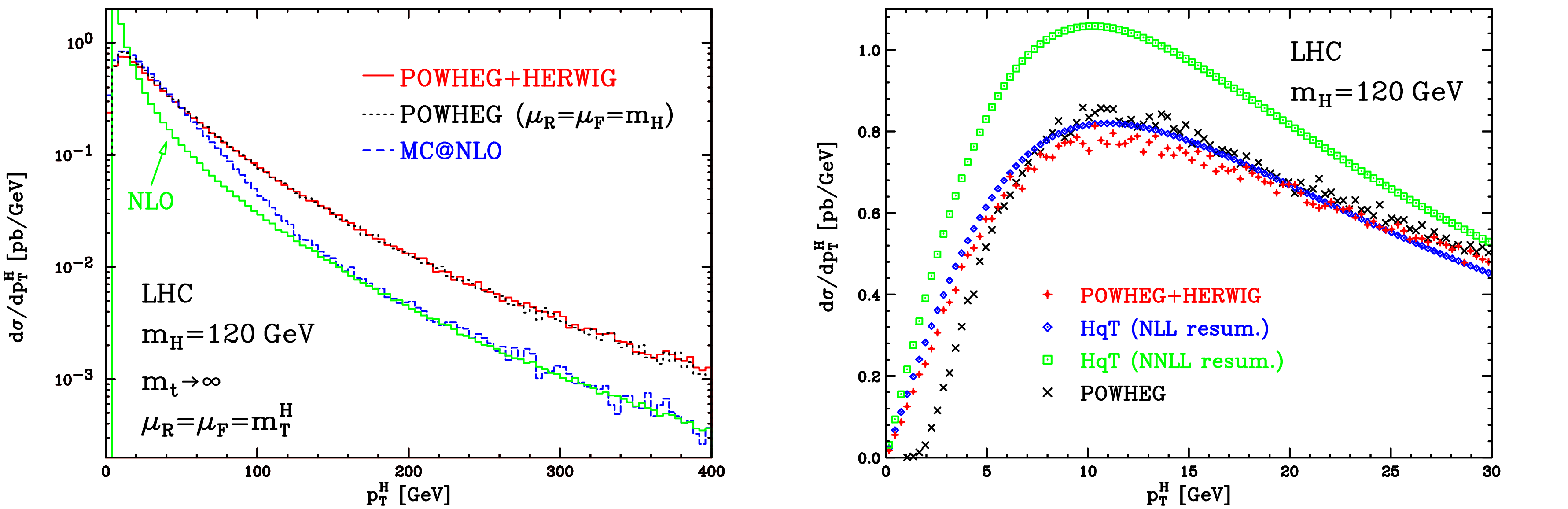






[Anastasiou,Dissertori,Stöckli (07)]

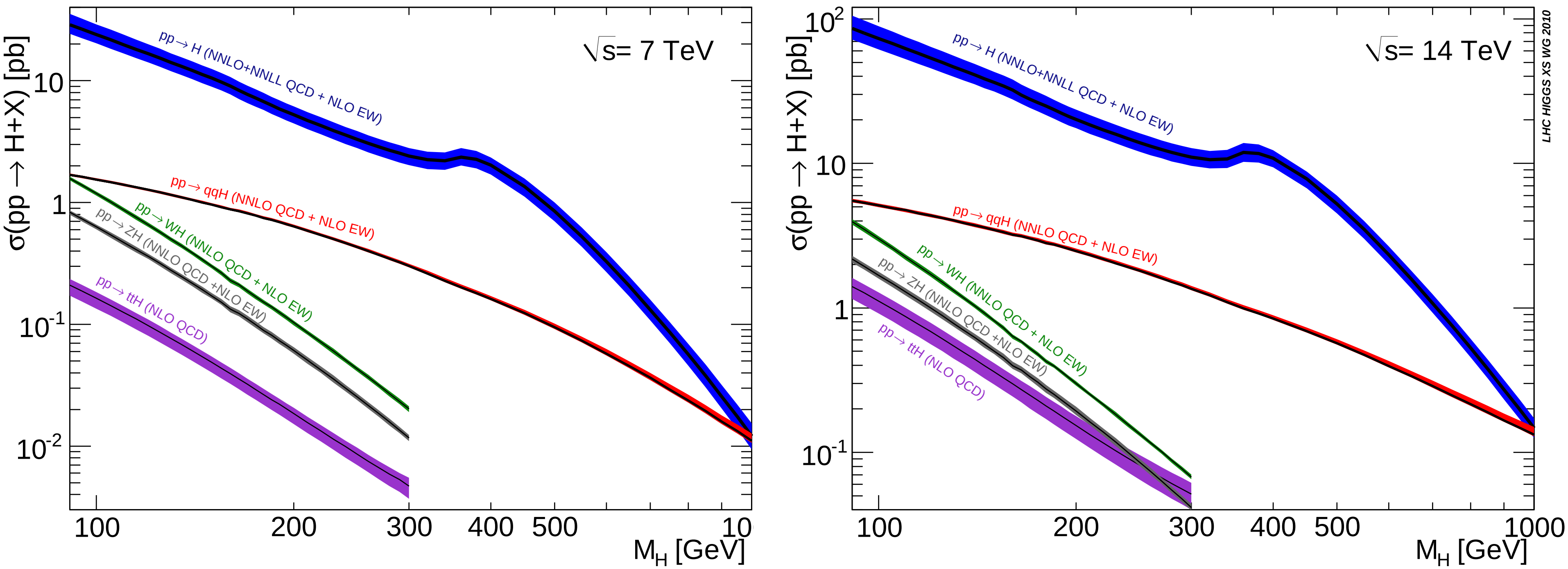
$gg \to H$ implemented in MC@NLO and POWHEG



[Nason, Oleari, Alioli, Re]

- → general good agreement with PYTHIA;
- → comparison MC@NLO vs POWHEG understood;
- → comparison with resummed NLL results under control.
- → rescale effects using NNLL/NLL knowledge.

Inclusive SM Higgs Production: theoretical predictions and their uncertainty



(LHC Higgs Cross Sections Working Group, arXiv:1101.0593 → CERN Yellow Book)

- all orders of calculated higher orders corrections included (tested with all existing calculations);
- theory errors (scales, PDF, α_s, ...) combined according to common recipe.
- Exclusive observables: started in 2011.

References

Higgs process	$\sigma_{NLO,NNLO,NNLL,EW}$
$gg \to H$	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) M.L.Ciccolini, S.Dittmaier, and M.Krämer (2003) (EW) 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) M.L.Ciccolini, A.Denner,S.Dittmaier (2008) (QCD+EW) P.Bolzoni, F.Maltoni, S.O.Moch, and M.Zaro (2010) (NNLO)
$q\bar{q}, gg \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 67,68 (2003)

Towards exclusive studies: including decays, cuts, jet vetos, backgrounds, . . .

- Obtain distibutions from NLO/NNLO/NNLL calculations.
- Study the impact of higher order corrections in the presence of cuts, jet vetos, etc.
- If cuts imposed on decay products, need to include decays and estimate higher order corrections to the new process
  - high multiplicity of final state makes calculation more involved (very few NLO calculations exist)
  - new NLO tools may allow fast progress.
- Interface with NLO Monte Carlo would be best:
  - MC@NLO: $gg \to H$, W/ZH;
  - POWHEG: $gg \to H$, $q\bar{q}'H$.
- Backgrounds need to be calculated with comparable accuracy.

Recently completed NLO calculations: most are relevant backgrounds to Higgs-boson physics!

Process ($V \in \{Z, W, \gamma\}$)	Calculated by
$pp \to V$+2 jets(b)	Campbell,Ellis,Maltoni,Willenbrock (06)
$pp \to V b\bar{b}$	Febres Cordero,Reina,Wackeroth (07-08)
$pp \to W b\bar{b}$	Campbell,Ellis (10)
$pp \to VV$+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)
$pp \to W$+4jets	Berger et al. (10)

We have not disscussed: study of Higgs properties

At the LHC:

- Color and charge will be given by the measurement of a given (production+decay) channel.
- The Higgs boson mass will be measured with 0.1% accuracy in $H \to ZZ^* \to 4l^\pm$, complemented by $H \to \gamma\gamma$ in the low mass region. Above $M_H \simeq 400$ GeV precision deteriorates to $\simeq 1\%$ (lower rates).
- The Higgs boson width can be measured in $H \to ZZ^* \to 4l^\pm$ above $M_H \simeq 200$ GeV. The best accuracy of $\simeq 5\%$ is reached for $M_H \simeq 400$ GeV.
- The Higgs boson spin could be measured through angular correlations between fermions in $H \to VV \to 4f$: need for really high statistics.
- The Higgs boson couplings will be measured combining multiple channels:

$$(\sigma_p(H)\mathrm{Br}(H \to dd))^{exp} = \frac{\sigma_p^{th}(H)}{\Gamma_p^{th}} \frac{\Gamma_d \Gamma_p}{\Gamma_H}$$

Higgs self-couplings will be very hard!

Conclusions and Outlook

- We are living through a new era in Higgs boson physics: looking for direct evidence.
- SM Higgs boson precision physics has given a first coherent set of predictions for inclusive observables: Higgs boson production cross sections and branching ratios.
- Short term: study exclusive observables, including decays, background processes, and experimental cuts.
- Long term: the LHC can carry through a precision program that also include measurements of Higgs boson properties, to identify it:
  - high luminosity required;
  - strategies depend on itermediate discoveries;
  - more sophisticated techniques available by then.