Interpreting Collider Data

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Prologue

- Progress in Particle Physics has been mainly theory driven for the past few decades. Based on first principles,
  $\longrightarrow$ enormous amount of scenarios of new physics (NP) beyond the Standard Model (BSM) have been proposed;
  $\longrightarrow$ very interesting phenomenology at TeV scale have been predicted.

- For the first time in so long, the Tevatron and the Large Hadron Collider (LHC) are testing new ground and will answer the most fundamental open questions of Particle Physics:
  $\longrightarrow$ Electroweak symmetry breaking (EWSB): Higgs mechanism?
  $\longrightarrow$ New Physics in the TeV range?

- The reach of the Tevatron and the incredible physics potential of the LHC rely on our ability to interpret the data. Success will depend on,
  $\longrightarrow$ very accurate predictions (signal/backgr, PDF, masses, couplings);
  $\longrightarrow$ validation of tools and techniques (ex: Monte Carlo simulations);
  $\longrightarrow$ broad selection of models, leading to robust across-model predictions;
  $\longrightarrow$ new strategies (boosted kinematics, jet sub-structure, ...).

What can we expect?

We do not have much experience in testing the unknown. For the past few decades, everything has been falling into place where we expected it to be.

New Physics may look like:

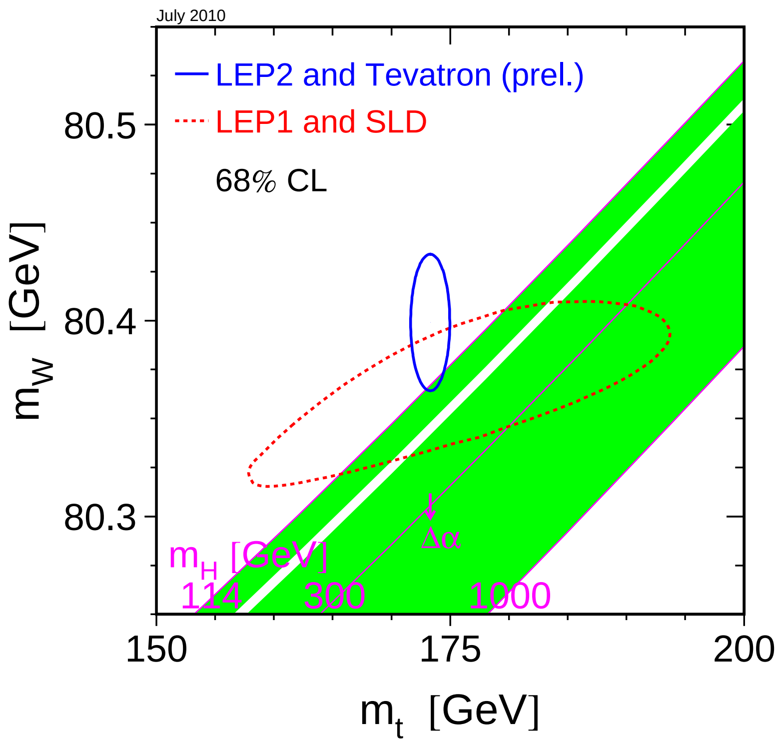
$\longrightarrow$ indirect evidence from precision measurement (theory driven);

$\longrightarrow$ mass peaks (data driven);

$\longrightarrow$ deviations in shapes of kinematical distributions (theory driven).

Higgs boson searches offer an excellent template:

- $\triangleright$ all previous scenarios are contemplated;
- $\triangleright$ has been thoroughly studied at both the Tevatron and the LHC;
- $\triangleright$ both signal and background are predicted with high theoretical accuracy;
- $\triangleright$ we can identify the main sources of systematic uncertainty and work at reducing them, both theoretically and experimentally.



From EW precision fits:

$$m_W = 80.399 \pm 0.023 \text{ GeV}$$

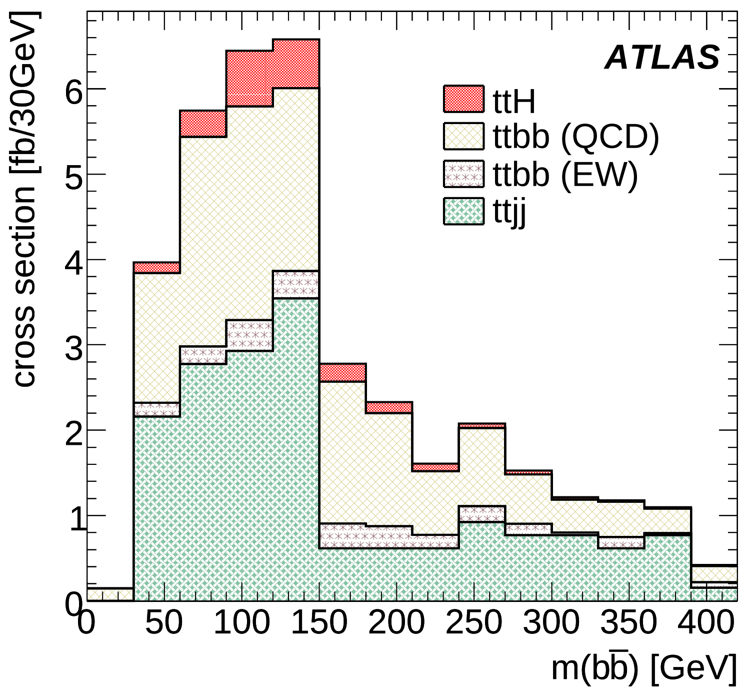
$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 89^{+35}_{-26} \text{ GeV}$$

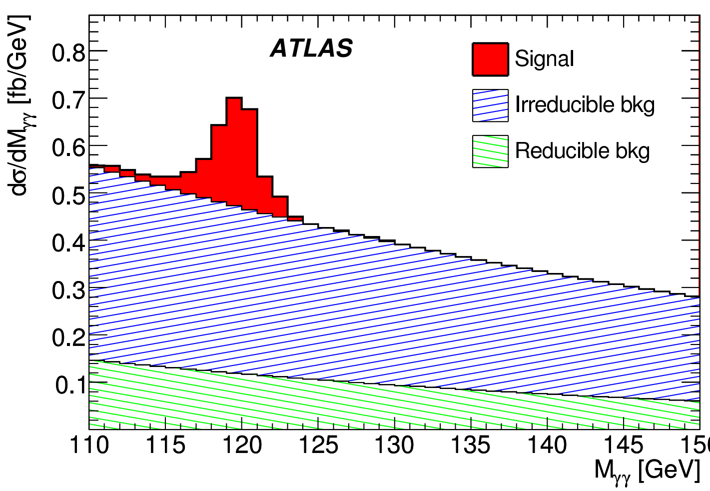
$$M_H < 158\,(185) \text{ GeV}$$

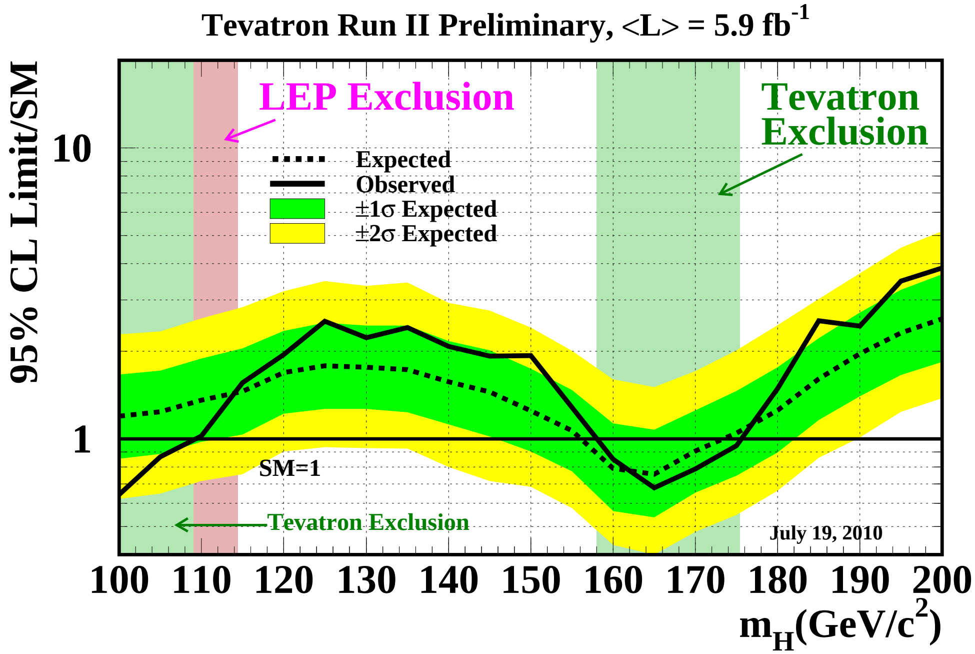
$t\bar{t}H \to b\bar{b}$



Or direct searches:

$H \to \gamma\gamma$



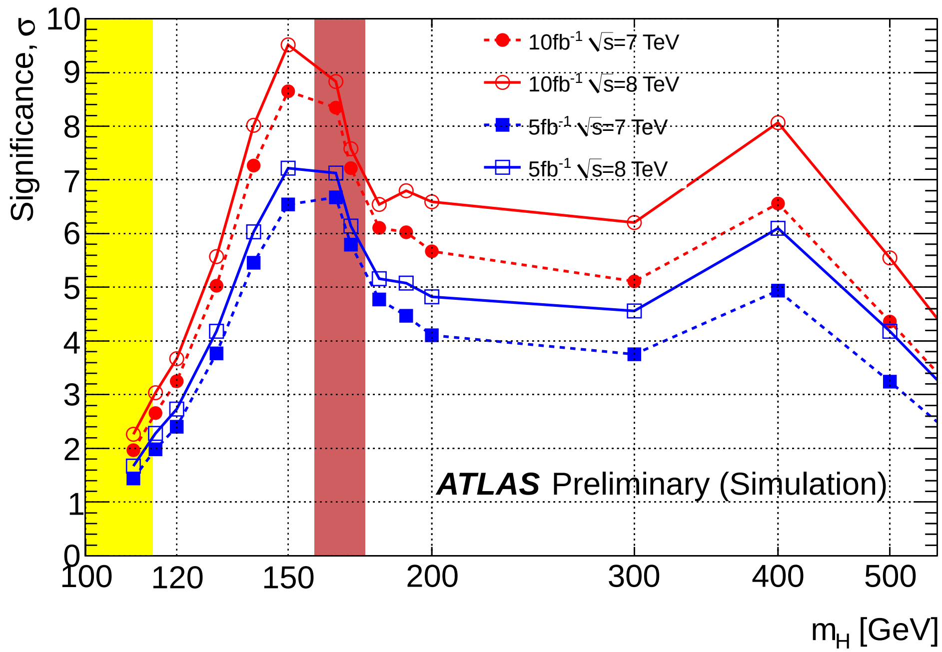


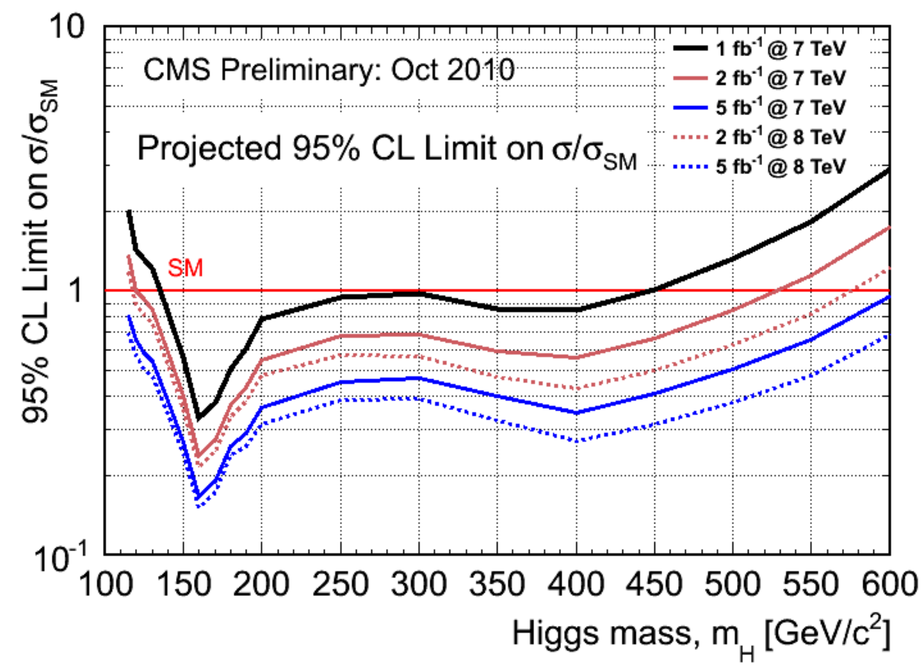
plus exclusion limits (95% c.l.):

$$M_H > 114.4 \text{ GeV (LEP)}$$

$$M_H \neq 158 - 173 \text{ GeV (Tevatron)}$$

LHC with $\sqrt{s} = 7$ TeV and a few fb^{-1}:





Beyond Higgs boson physics . . .

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

$\hookrightarrow$ "Signatures of new physics at the LHC" (SLAC)

Typical signatures will have: jets+$\not{E}_T$ (+leptons)

Main Standard Model irreducible/reducible backgrounds:

$\longrightarrow$ $W/Z + n-$jets

$\longrightarrow$ $W/Z + b-$jets

$\longrightarrow$ $t\bar{t}$+jets

$\longrightarrow$ . . .

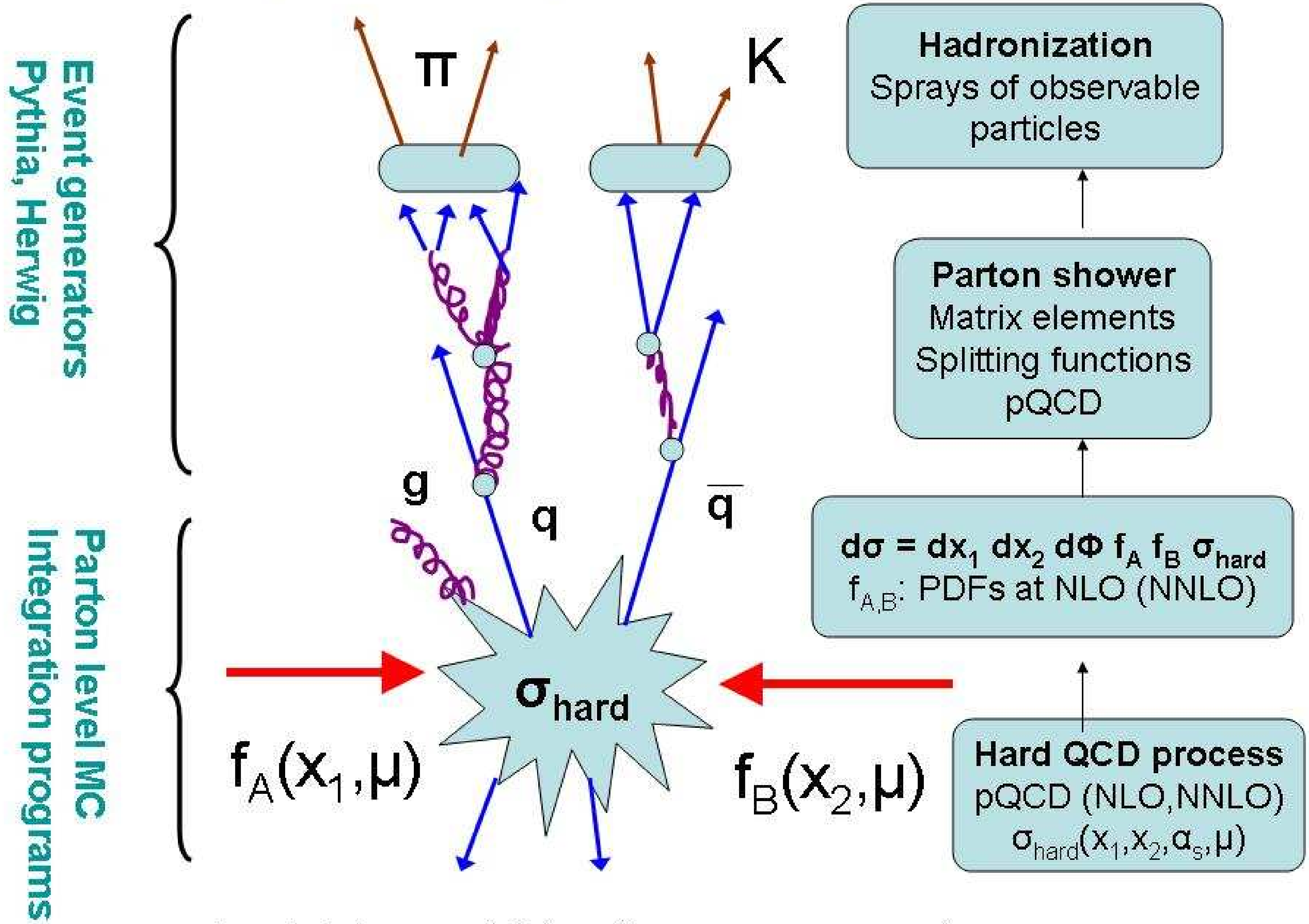
all characterized by: large multiplicity and many massive particles.

A reliable quantitative description of strong dynamics in high energy collisions remains as a crucial technical challenge

which has been

largely faced during the last decade.

Anatomy of a QCD prediction at hadron colliders



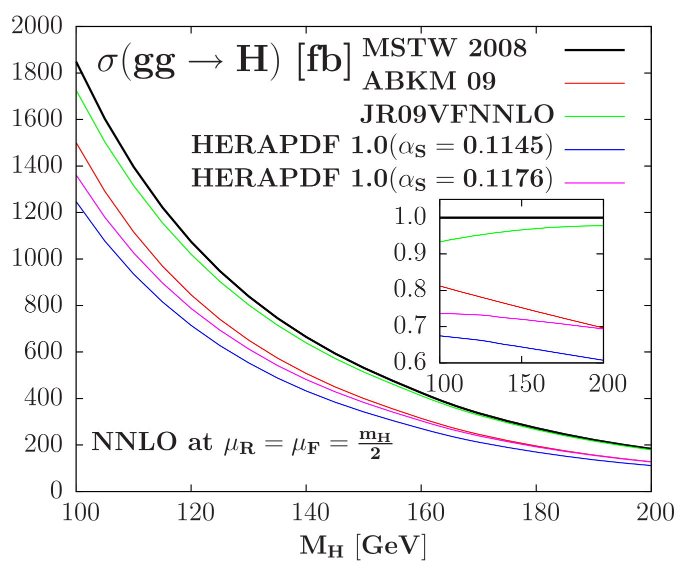
+ underlying event, interactions among remnants

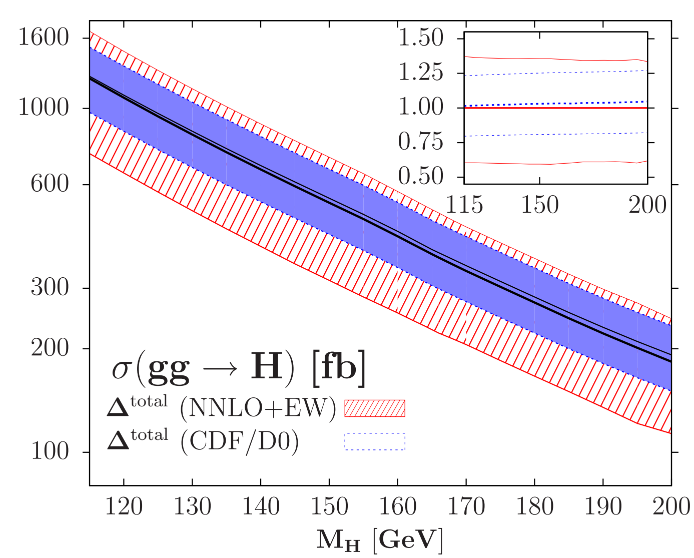
Systematic error from PDFs: need care . . .

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

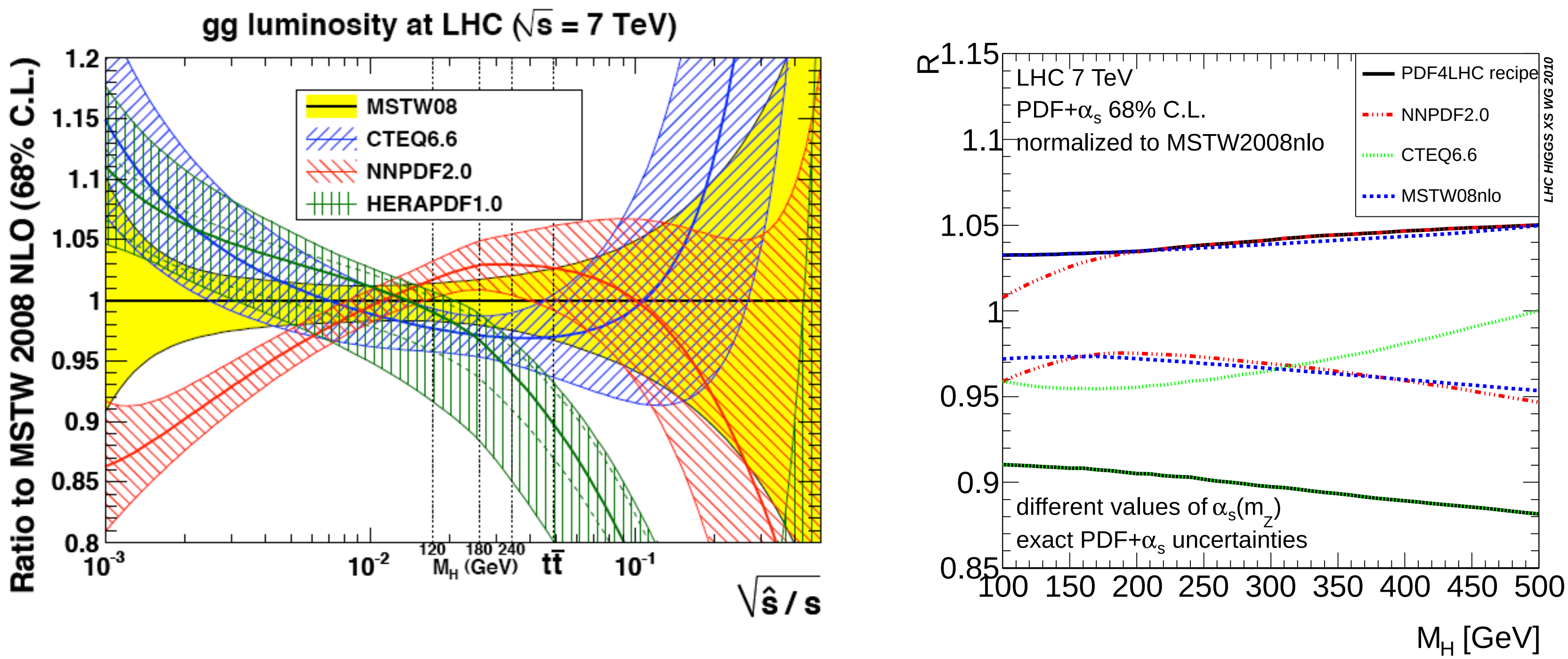
Example: Tevatron bound has been questioned with the claim that the error from PDF's has been largely underestimated





(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: 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 ($\rightarrow$ 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 . . .

- 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?
- 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.

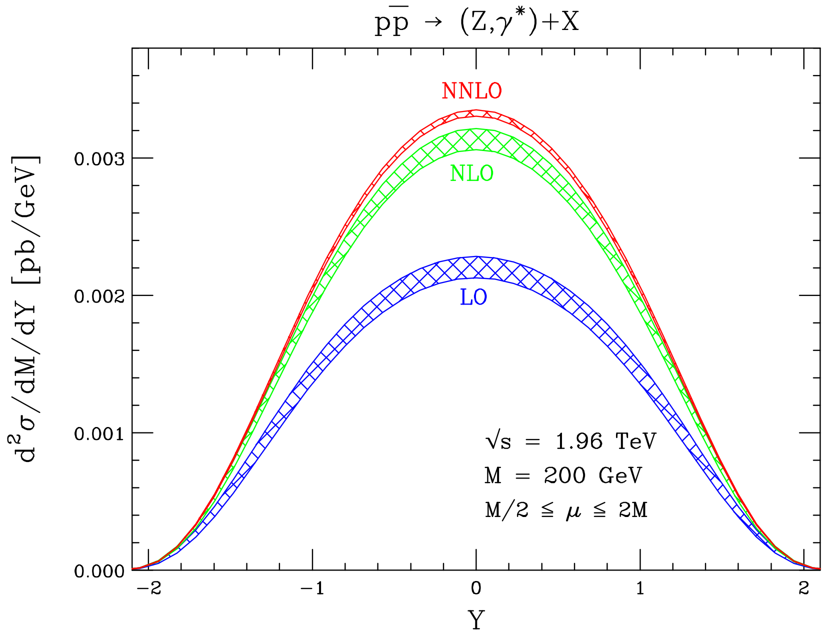
Several possible steps:

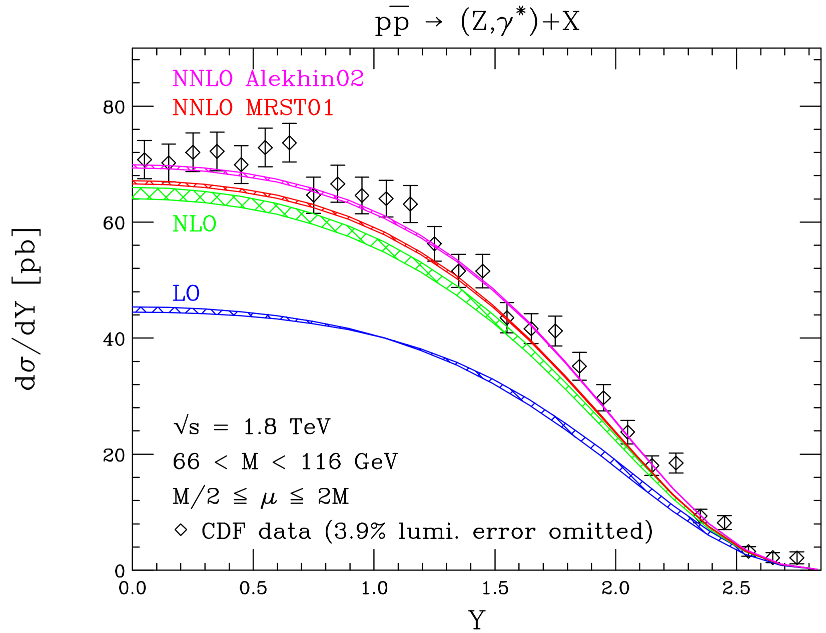
- add enough higher order corrections (NLO, NNLO) till: scale dependence improves, no large next order corrections expected;
- look for recurrent large contributions that may spoil convergence;
- find the best expansion parameter (α_s, α_s times large logarithms, . . .);
- using scaling properties, resum 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.

Interesting to look at some examples

Ex. 1: W/Z production at the Tevatron, testing PDF's at NNLO.

Rapidity distributions of the Z boson calculated at NNLO:





(C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello, PRL 91 (2003) 182002)

- W/Z production processes are standard candles at hadron colliders.
- Testing NNLO PDF's: parton-parton luminosity monitor, detector calibration.

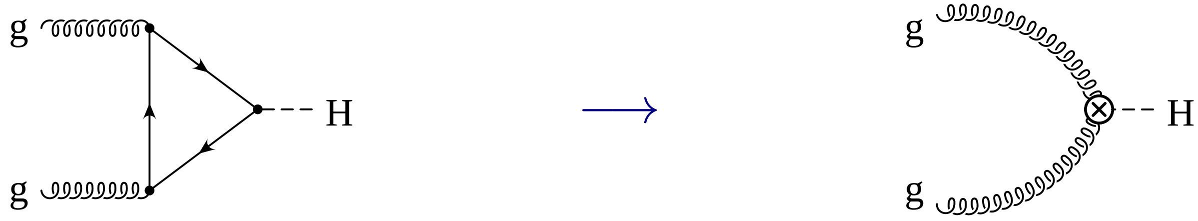
Ex. 2: $gg \to H$, main production mode (with $H \to \gamma\gamma, W^+W^-, ZZ$)

... 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



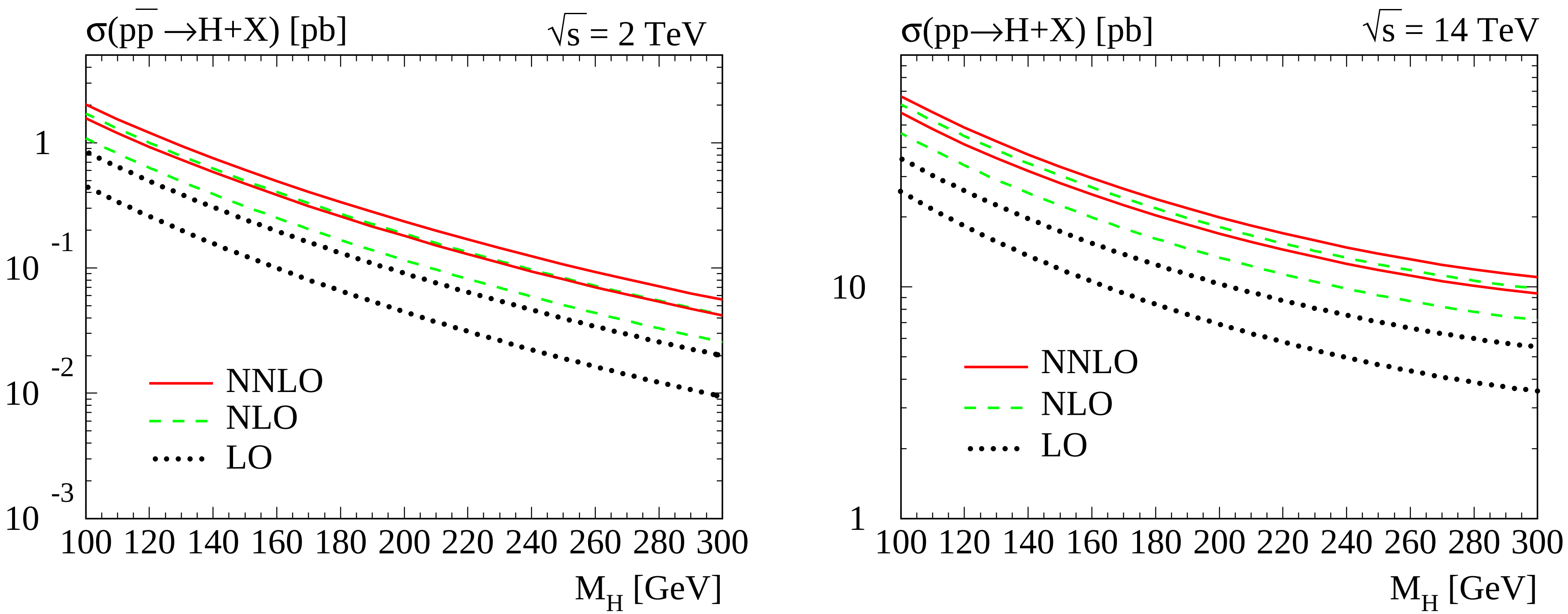
$$\Downarrow$$

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

where, including NLO and NNLO QCD corrections:

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

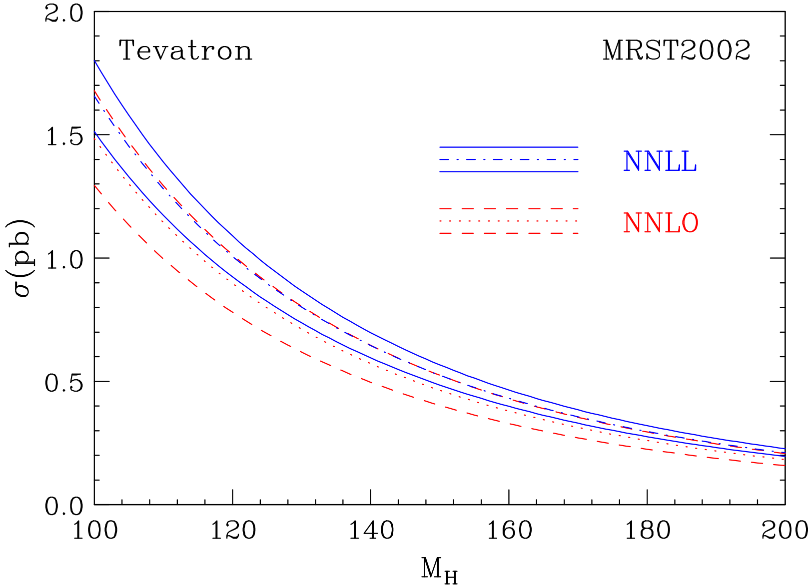
Fixed order NNLO:

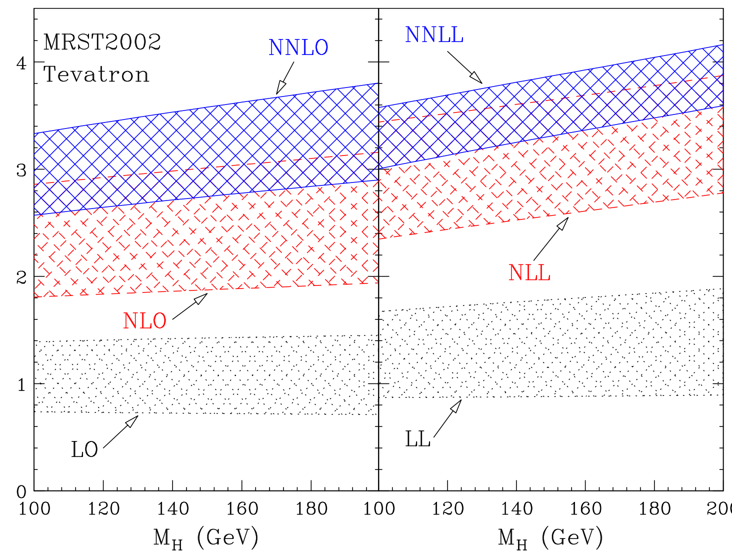


[Harlander,Kilgore (02)]

- 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:

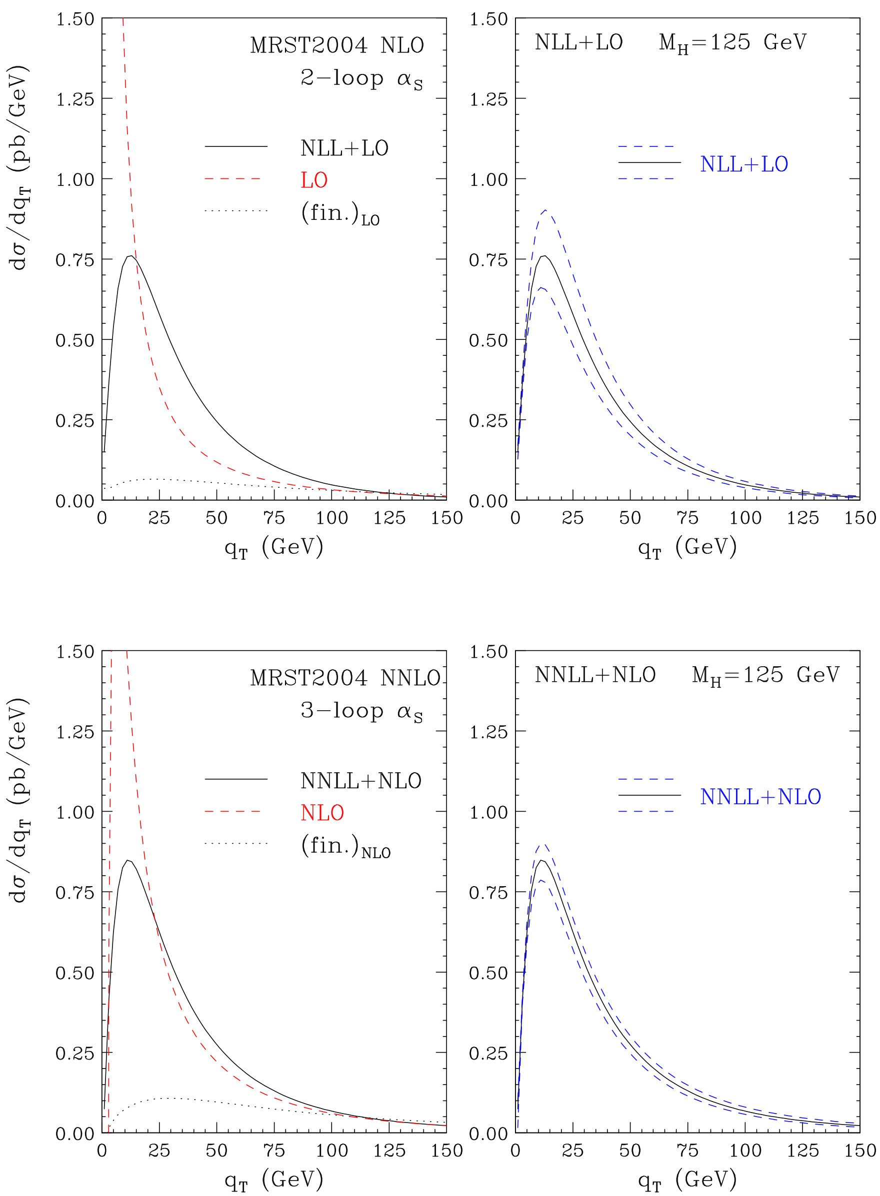
$\longrightarrow$ $\simeq 10\%$ perturbative uncertainty, including the $m_t \to \infty$ approximation.

$\longrightarrow$ $\simeq 10\%$ (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)]

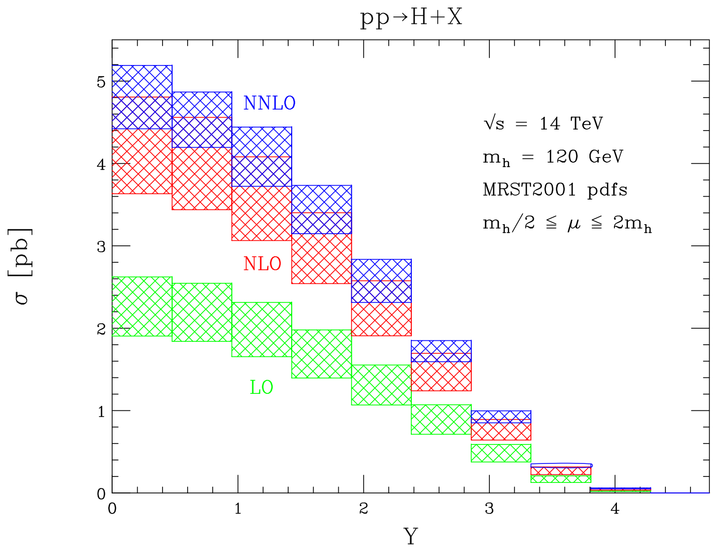
Exclusive NNLO results: $gg \to H$, $H \to \gamma\gamma, WW, ZZ$

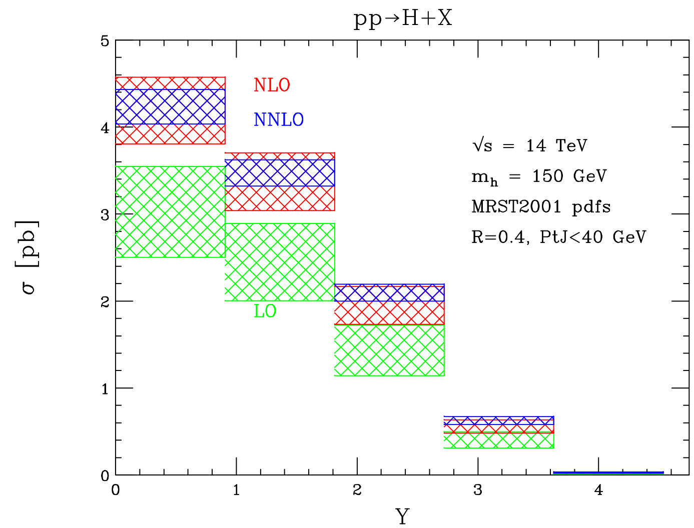
Extension of (IR safe) subtraction method to NNLO

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

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

Essential tools to reliably implement experimental cuts/vetos.



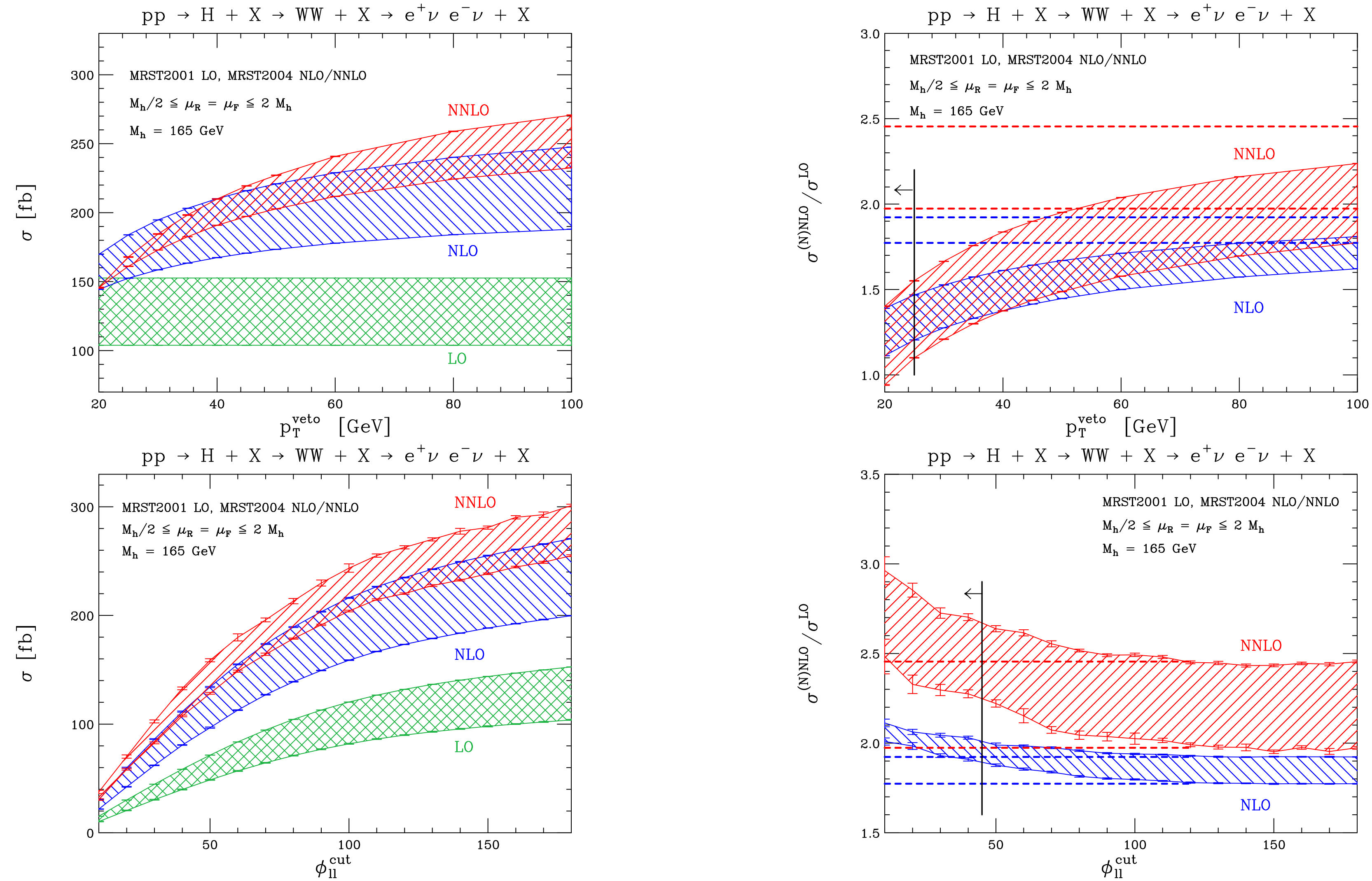


[Anastasiou,Melnikov,Petriello (05)]

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.

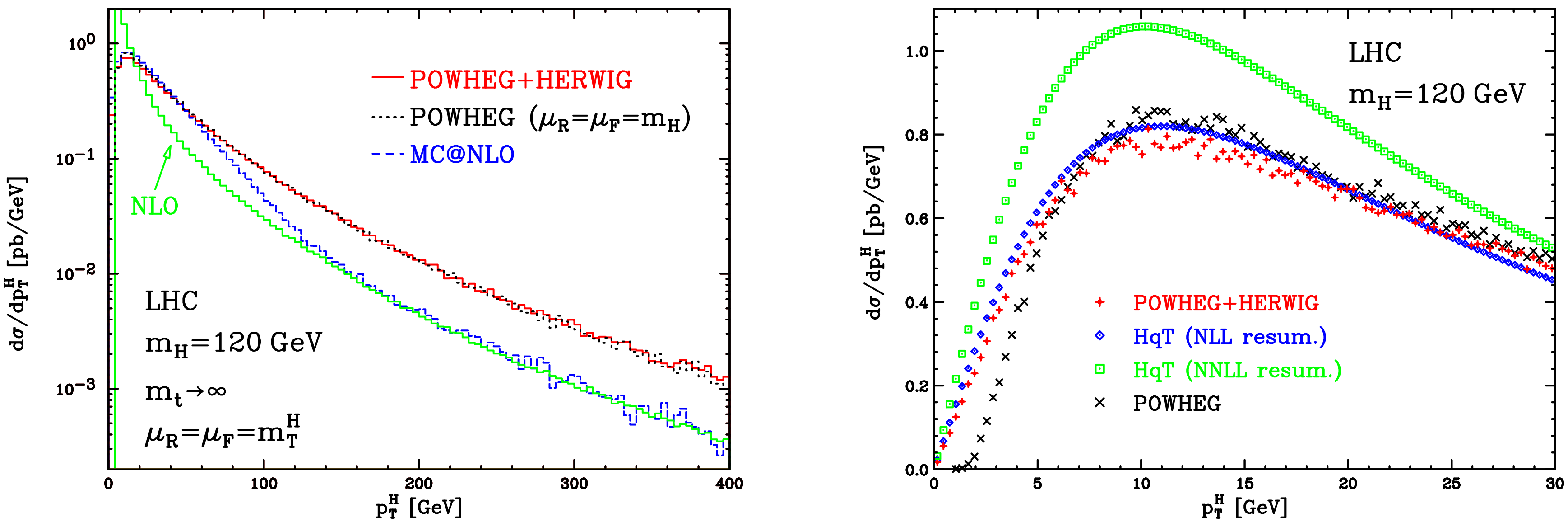
Full fledged $(gg \to)H \to W^+W^- \to l^+\nu l^-\bar{\nu}$

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



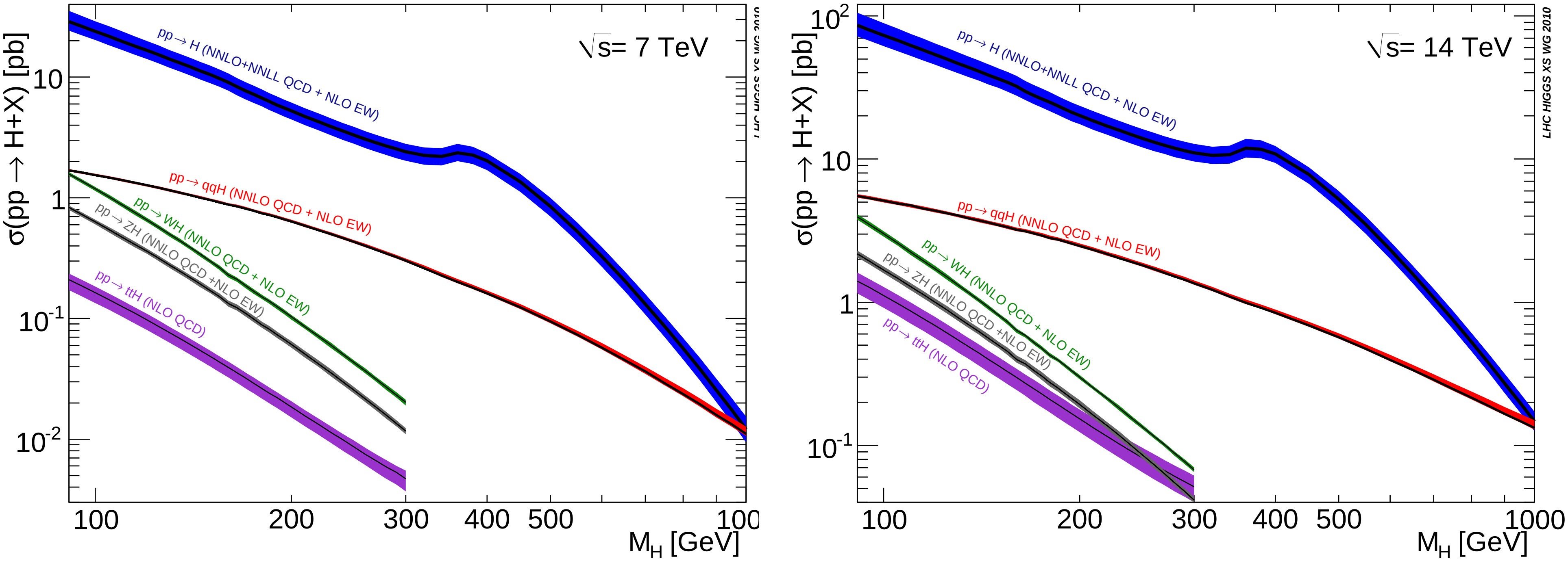
[Nason, Oleari, Alioli, Re]

$\rightarrow$ general good agreement with PYTHIA;

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

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

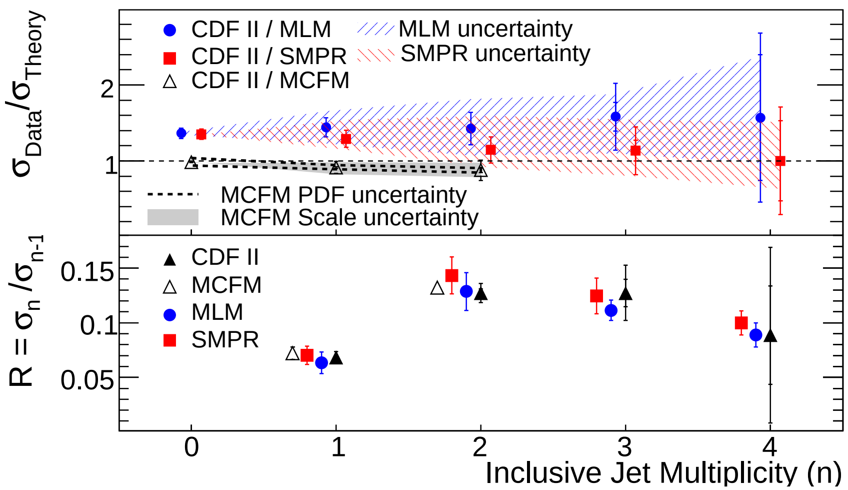
Ex. 3: Inclusive SM Higgs Production: theoretical predictions and their uncertainty



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

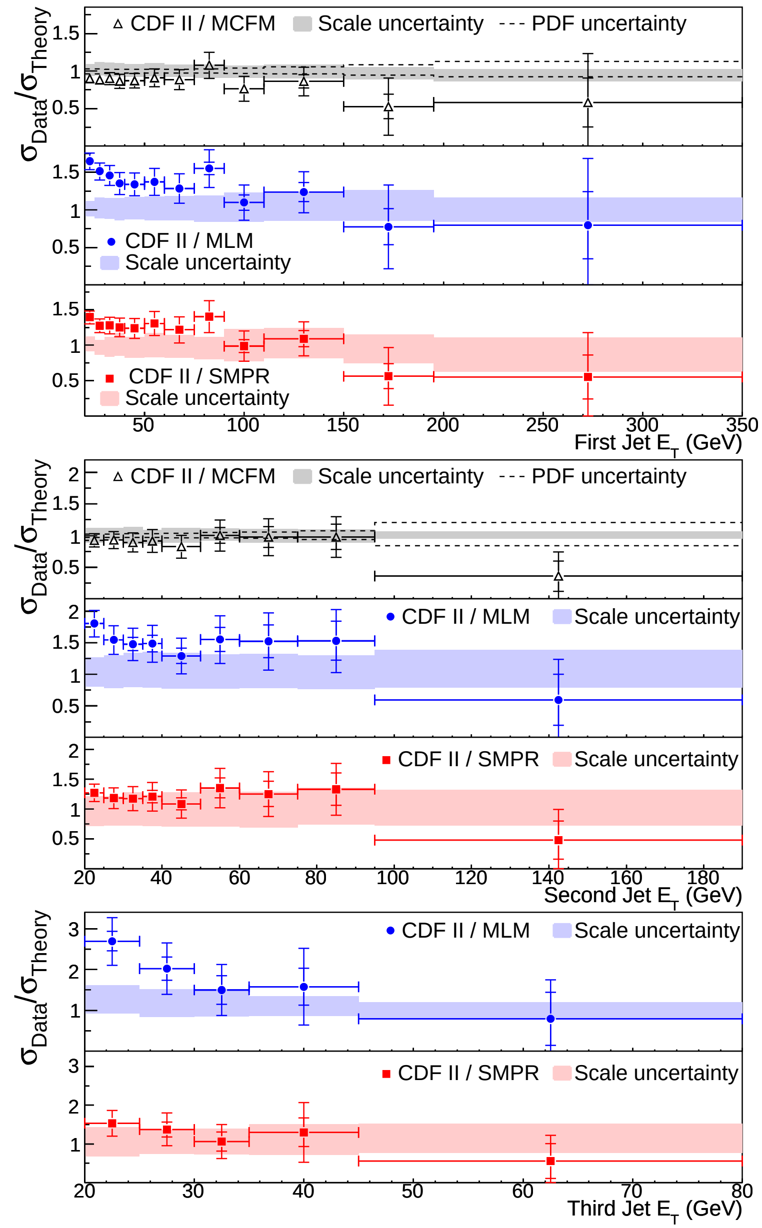
- all orders of calculated higher orders corrections included (tested with all existing calculations);
- theory errors (scales, PDF, α_s, ...) combined according to common recipe.
- Exclusive observables: started in 2011 (meeting at BNL (May 4-6)).

Ex. 4: W+jets production at the Tevatron, where progress has been most impressive!



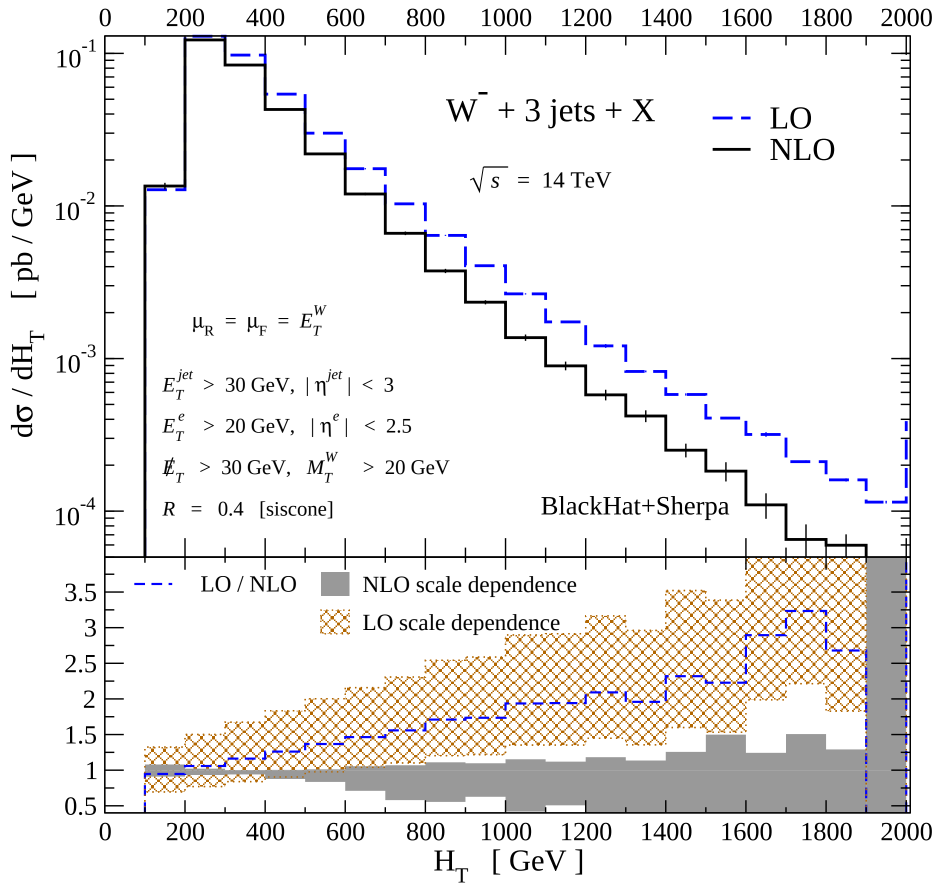
- much reduced systematics at NLO;
- only up to W+2 jet available in '07;
- today $W + 4$ jets available NLO

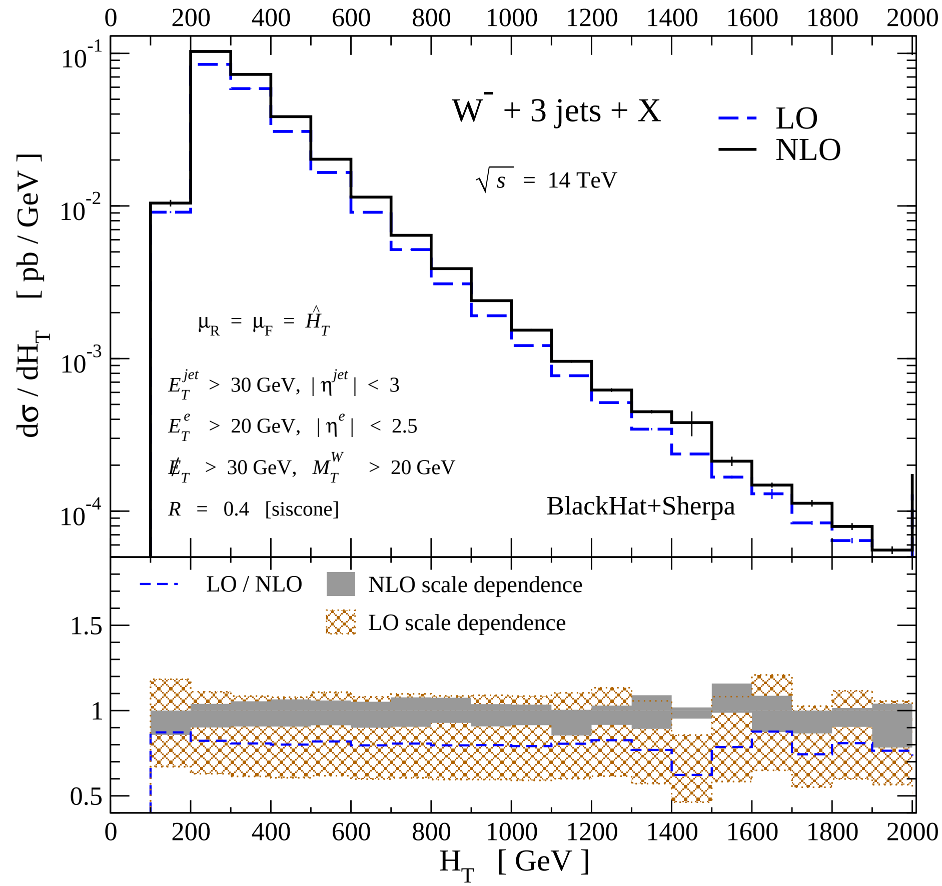
  (see Zvi Bern's talk)



(CDF collaboration, arXiv:0711.4044)

Best scale choice only possible with NLO wisdom . . .





(Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Kosower, Maitre, arXiv:0907.1984)

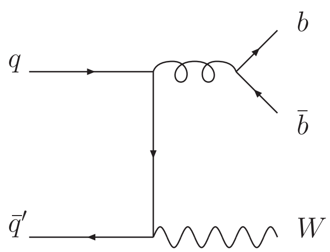
"Wrong" scale choice leads to enhanced unphysical instabilities

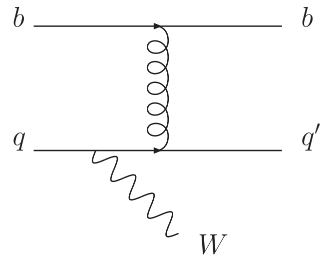
Ex. 5: $W + 1\,b$-jet: crucial background for WH production

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

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

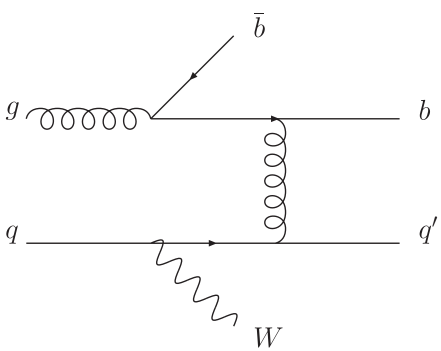
Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:



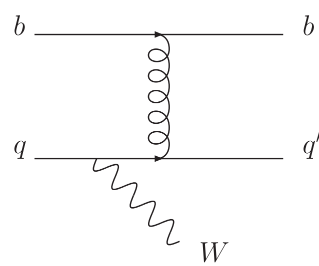


$+ \quad O(\alpha_s)$ corrections

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:



$\longrightarrow$



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

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

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:

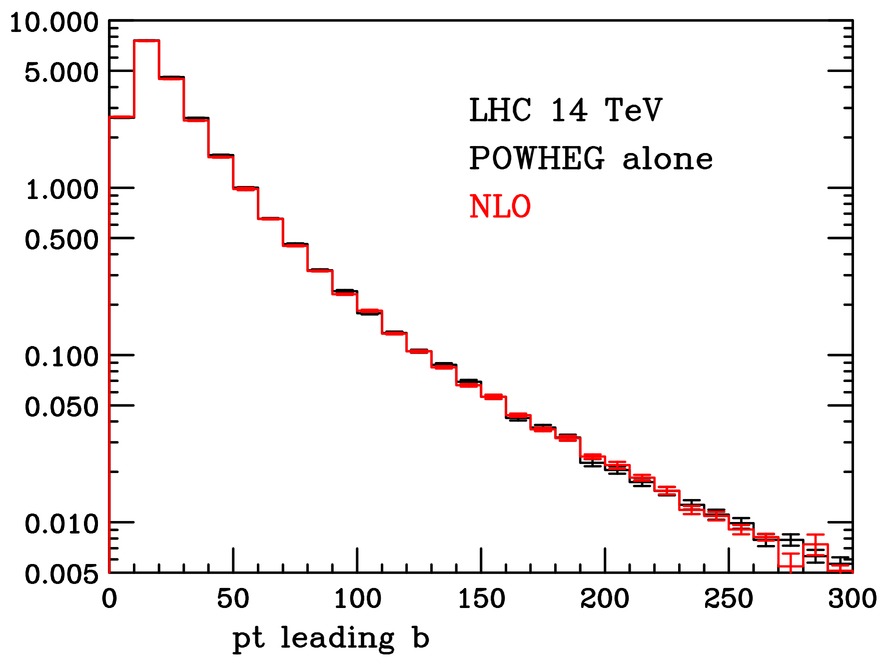
ALPGEN prediction: 0.78 pb

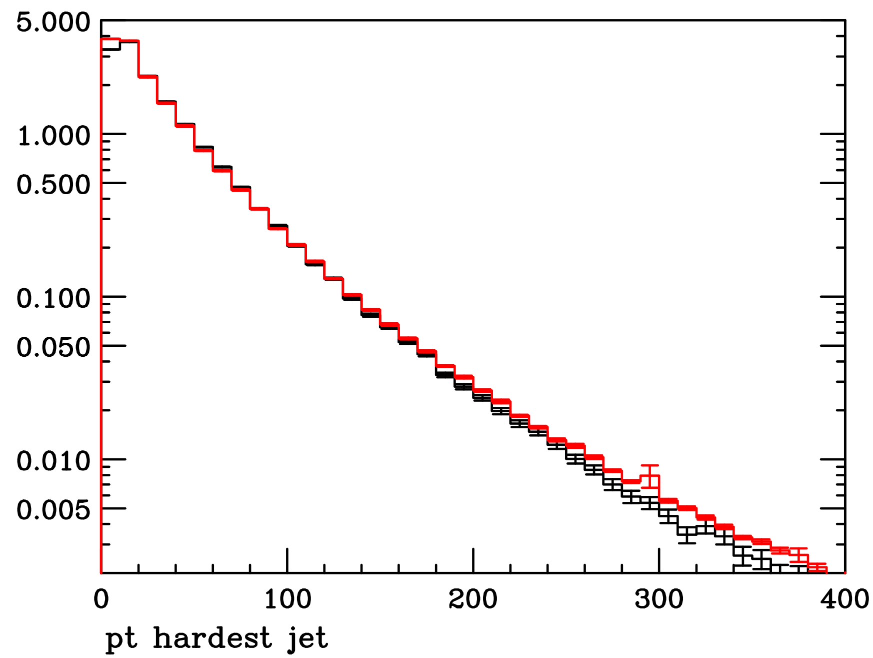
PYTHIA prediction: 1.10 pb

$\longrightarrow$ Now working at comparison with imminent ATLAS measurement.

[Campbell, Caola, Febres Cordero, L.R., Wackeroth]

Further development: $Wb\bar{b}$ implemented in POWHEG and MC@NLO, including $W \to l\nu_l$ decay.





(Oleari, L.R., preliminary)

- implementation ready for release,
- distributed to experimentalists working on WH at the LHC for testing.

Conclusions and Outlook

- With the start of the LHC a new era of interpreting collider data has begun: higher energies, higher precision, higher expectations.
- We understand most aspects of the systematic theoretical error and have developed efficient tools to improve it.
- Theoretical tools and understanding of the experimental environment are far more advanced and mature than ten years ago and are ready to be validated against the LHC data.
- A close interaction between theorists and experimentalists is key to success!
- Claiming new physics will take lots of careful and critical work, but it will be rewarding!