The Standar Model of Particle Physics
Lecture IV

The Standard Model in the LHC hera

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Maria Laach School, Bautzen, September 2011

Outline of Lecture IV

- Standard Model processes as background to new physics:
  - $\longrightarrow$ new physics searches at hadron colliders: structure of hadronic processes, most important building blocks;
  - $\longrightarrow$ theoretical prediction dominated by QCD effects;
  - $\longrightarrow$ high accuracy in theoretical predictions needed: challenges;
  - $\longrightarrow$ recent developments and existing tools;
  - $\longrightarrow$ milestone examples.

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

$\longrightarrow$ . . .

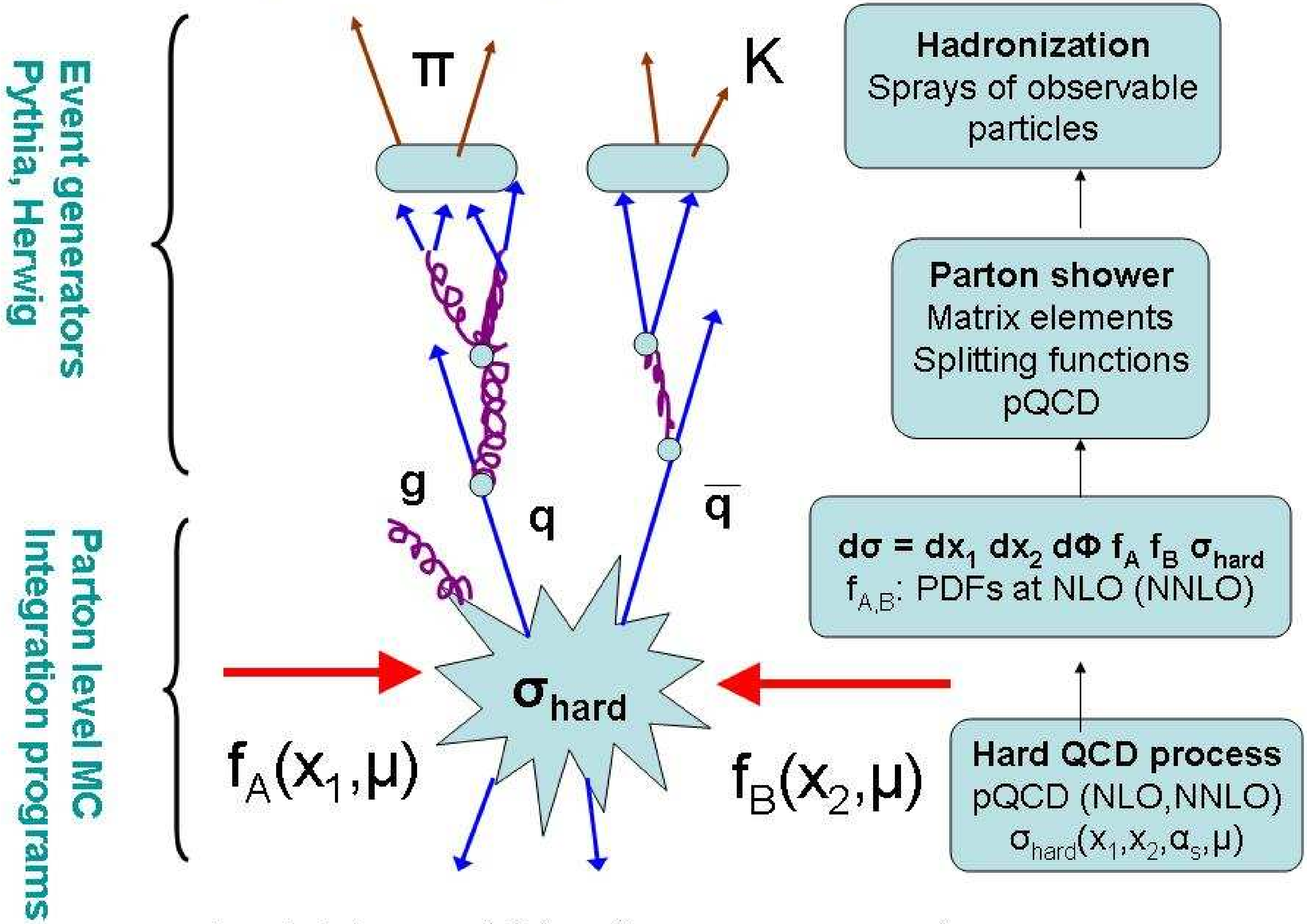
all characterized by: large multiplicity and many massive particles.

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

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:

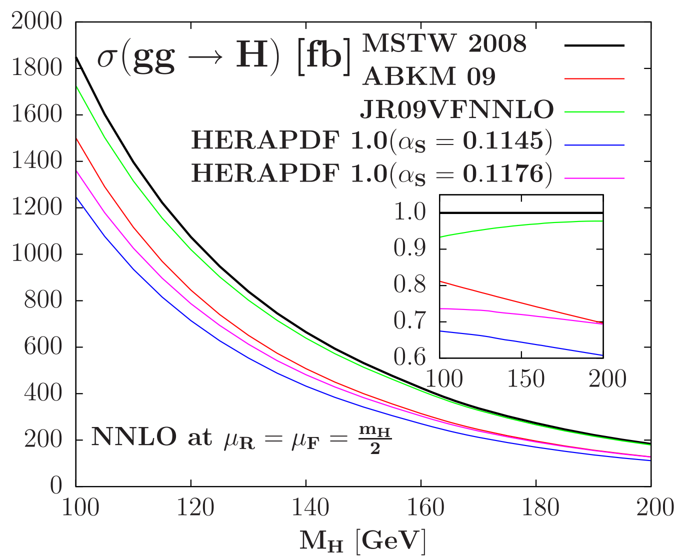
- PDF and $\alpha_s(\mu)$;
- left over scale dependence;
- input parameters.

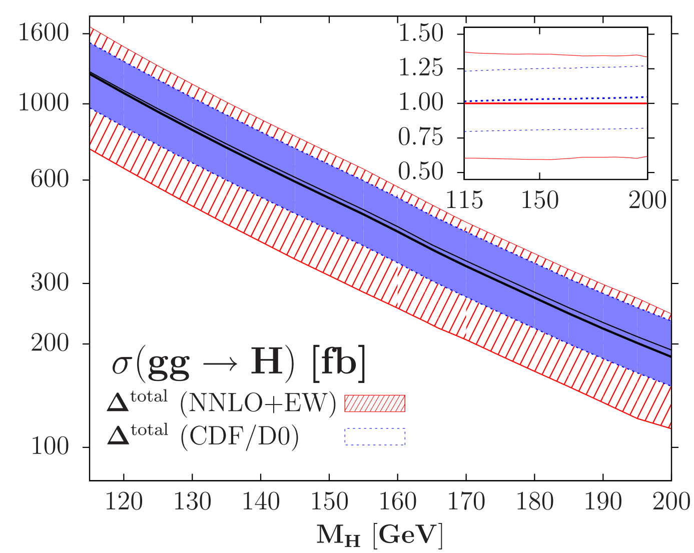
Systematic error from PDFs: need care ...

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

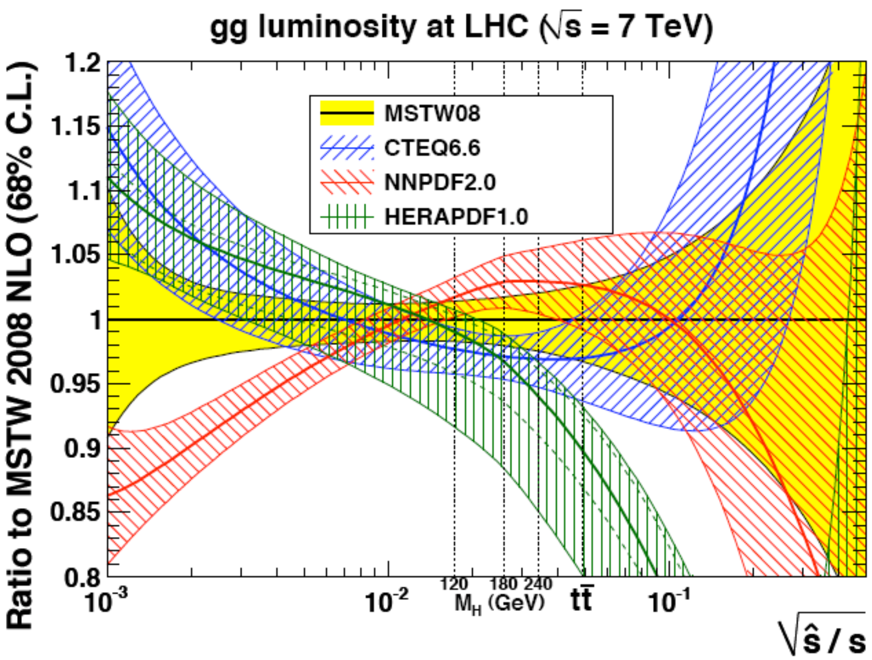
Example: Tevatron bound has been questioned with the claim that the error from PDF's has been largely underestimated

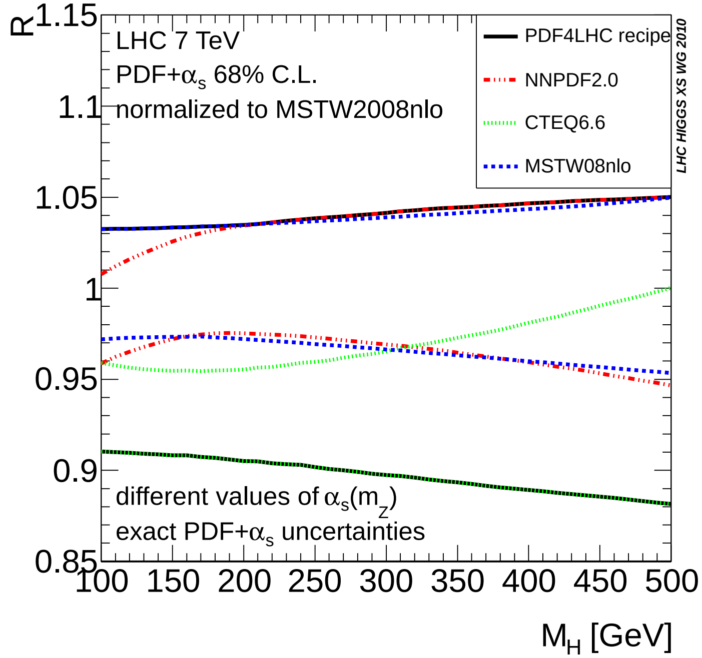




(Baglio, Djouadi, Ferrag, Godbole, arXiv:1101.1832)

PDF4LHC: problem carefully studied 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.

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.

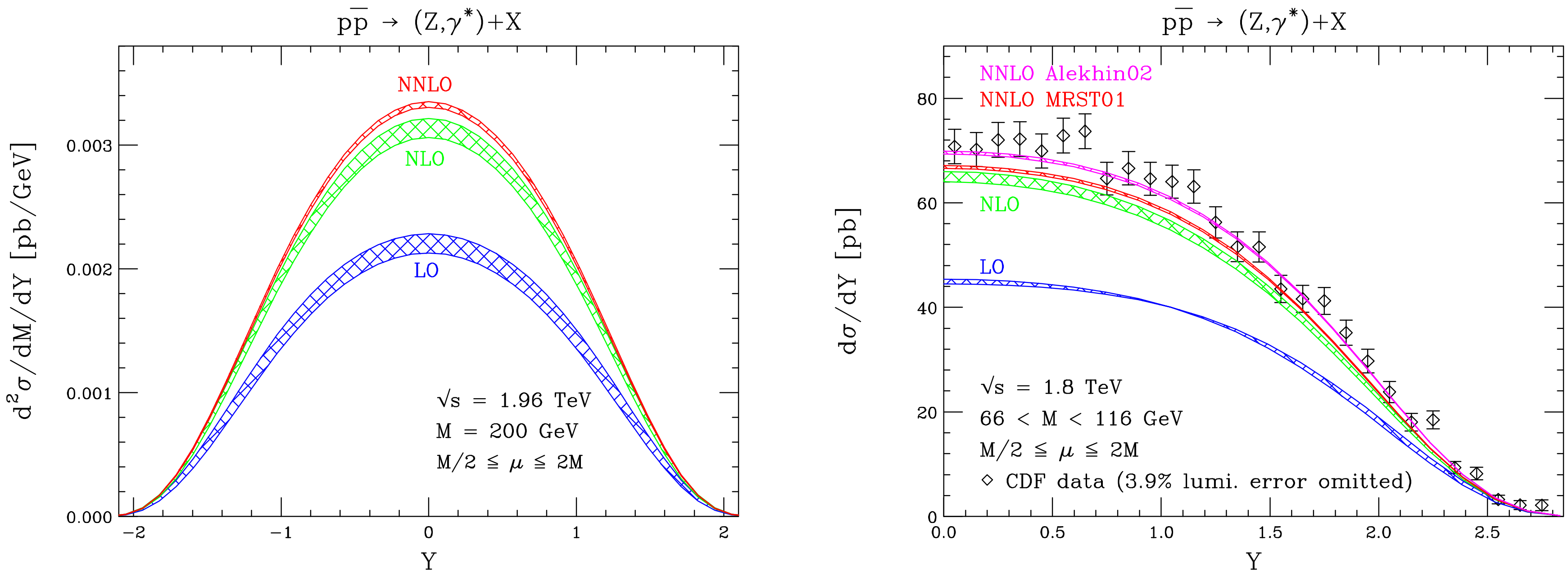
Several possible steps:

- 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.

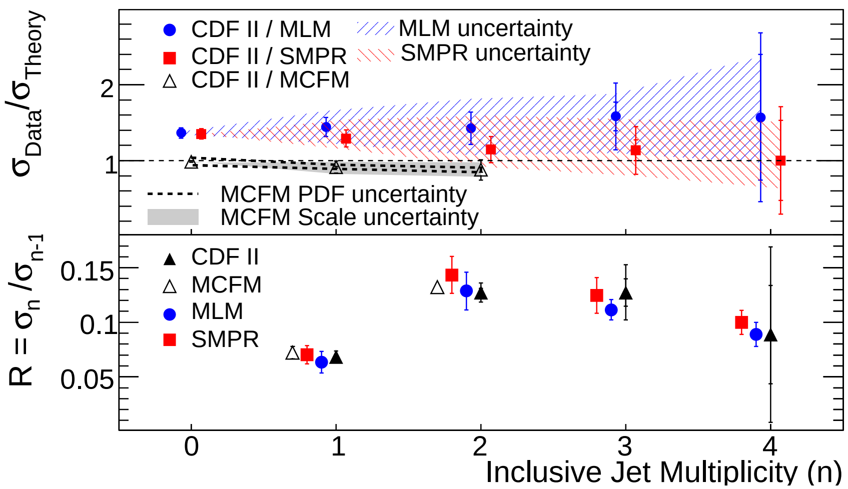
Rapidity distributions of the Z boson calculated at NNLO:



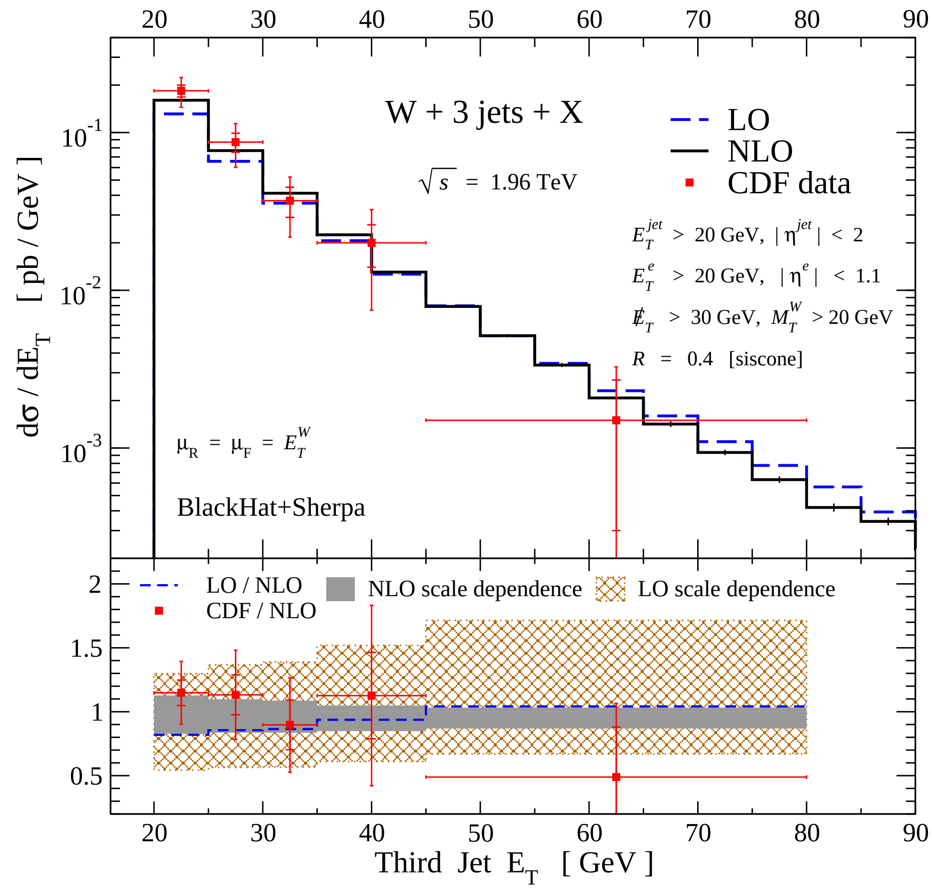
(C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello, PRL 91 (2003) 182002)

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

Ex. 2: W+jets production at the Tevatron, where progress has been most impressive!



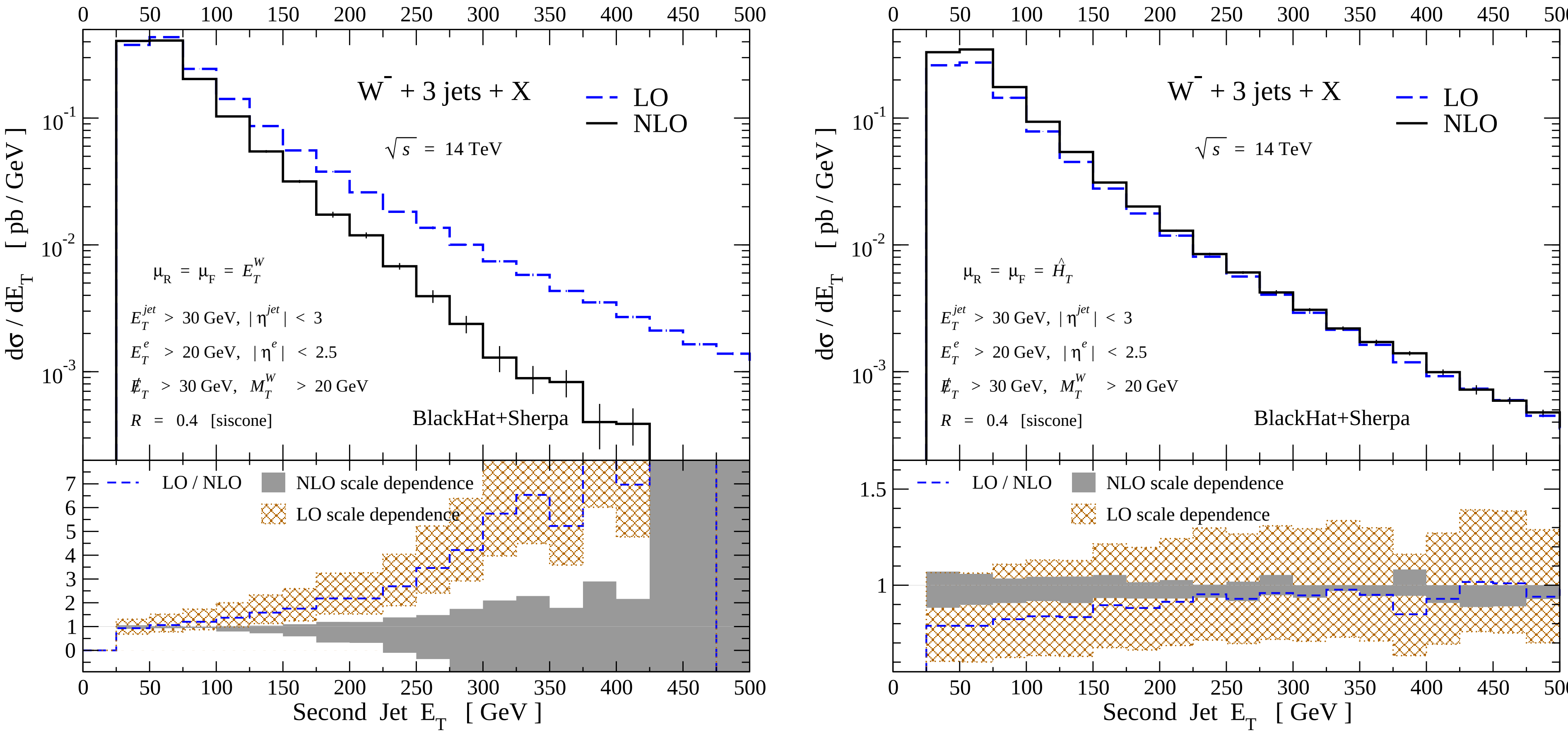
(CDF collaboration, arXiv:0711.4044)



(Berger et al., arXiv:0907.1984)

- much reduced systematics at NLC
- only up to $W + 2j$ available in ’07
- today $W + 3j$ and $W + 4j$ available at NLO.

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

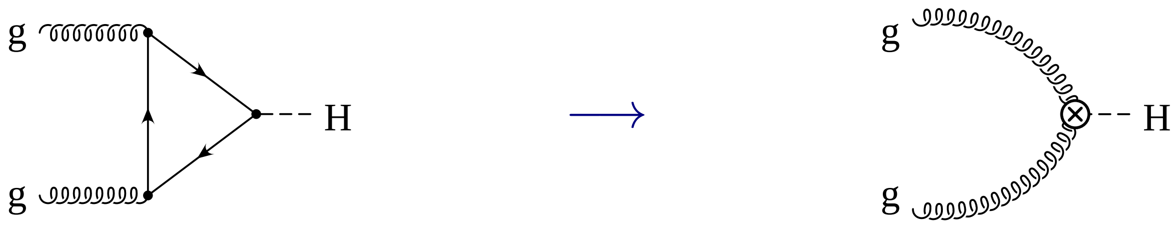
Ex. 3: $gg \to H$, main production mode (with $H \to \gamma\gamma, W^+W^-, ZZ$)

... 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



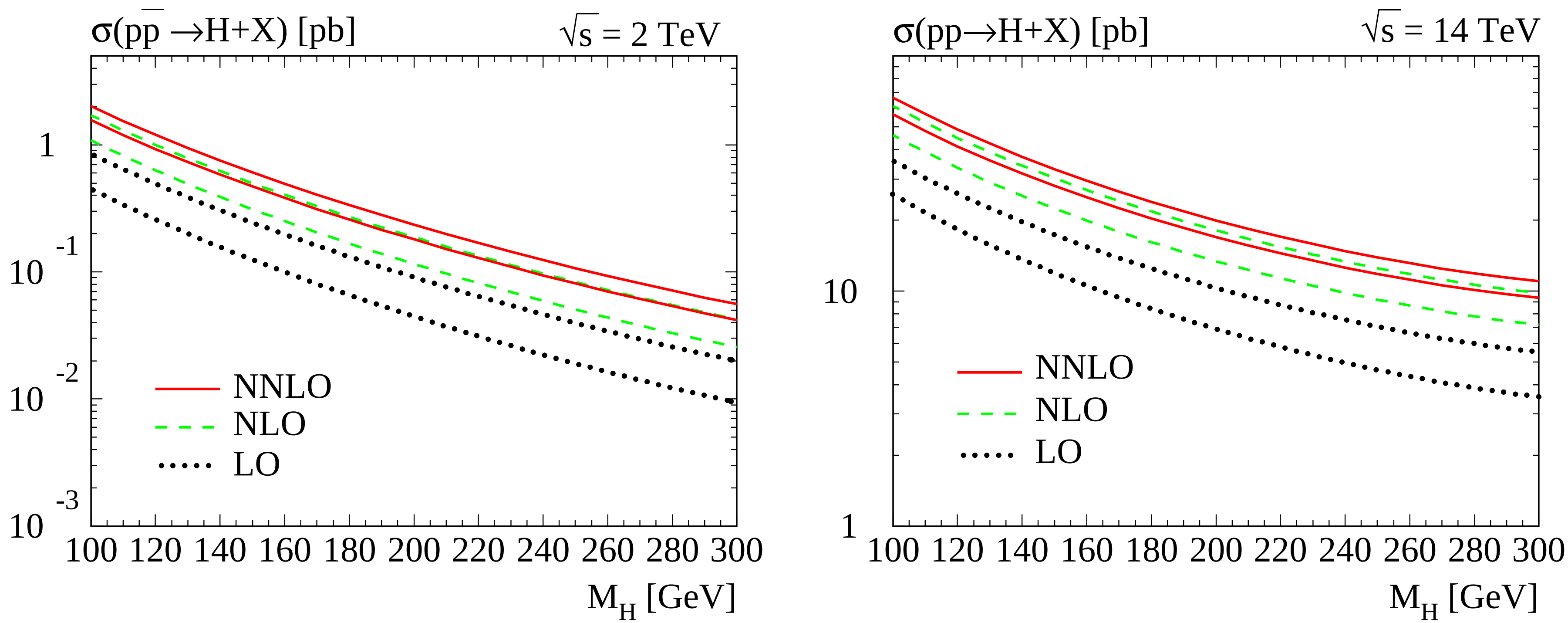
$$\Downarrow$$

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

where, including NLO and NNLO QCD corrections:

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

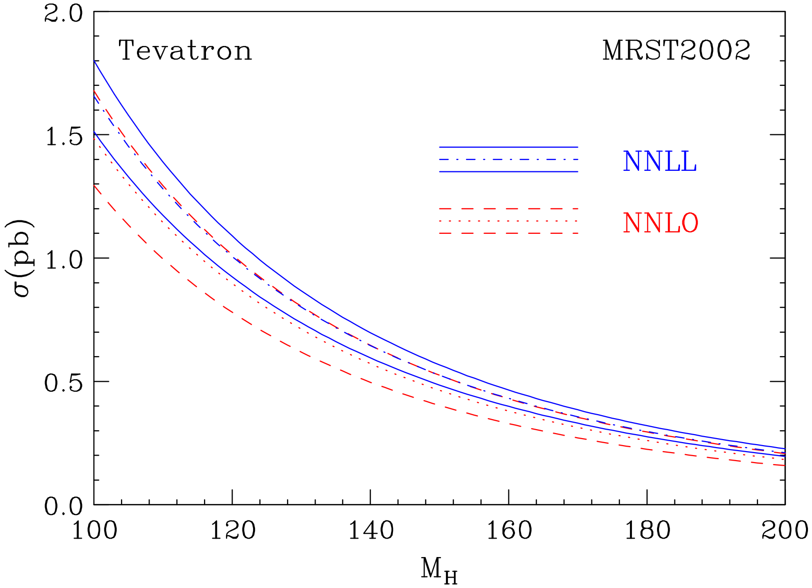
Fixed order NNLO:

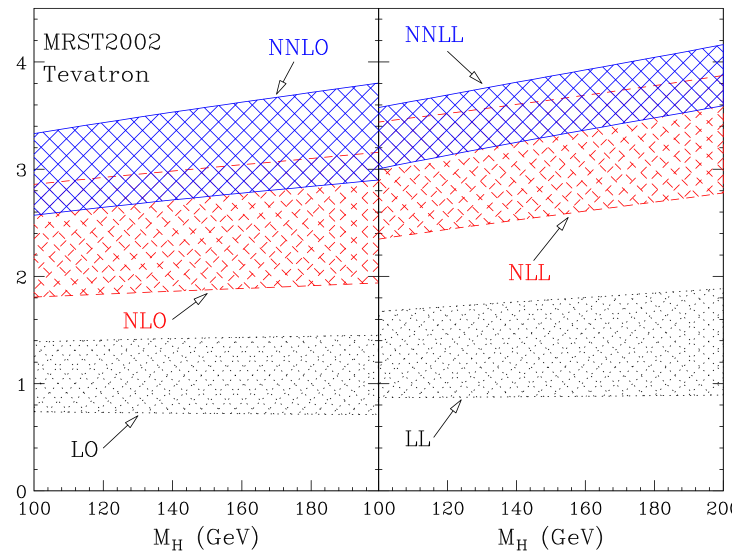


[Harlander,Kilgore (02)]

- 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:

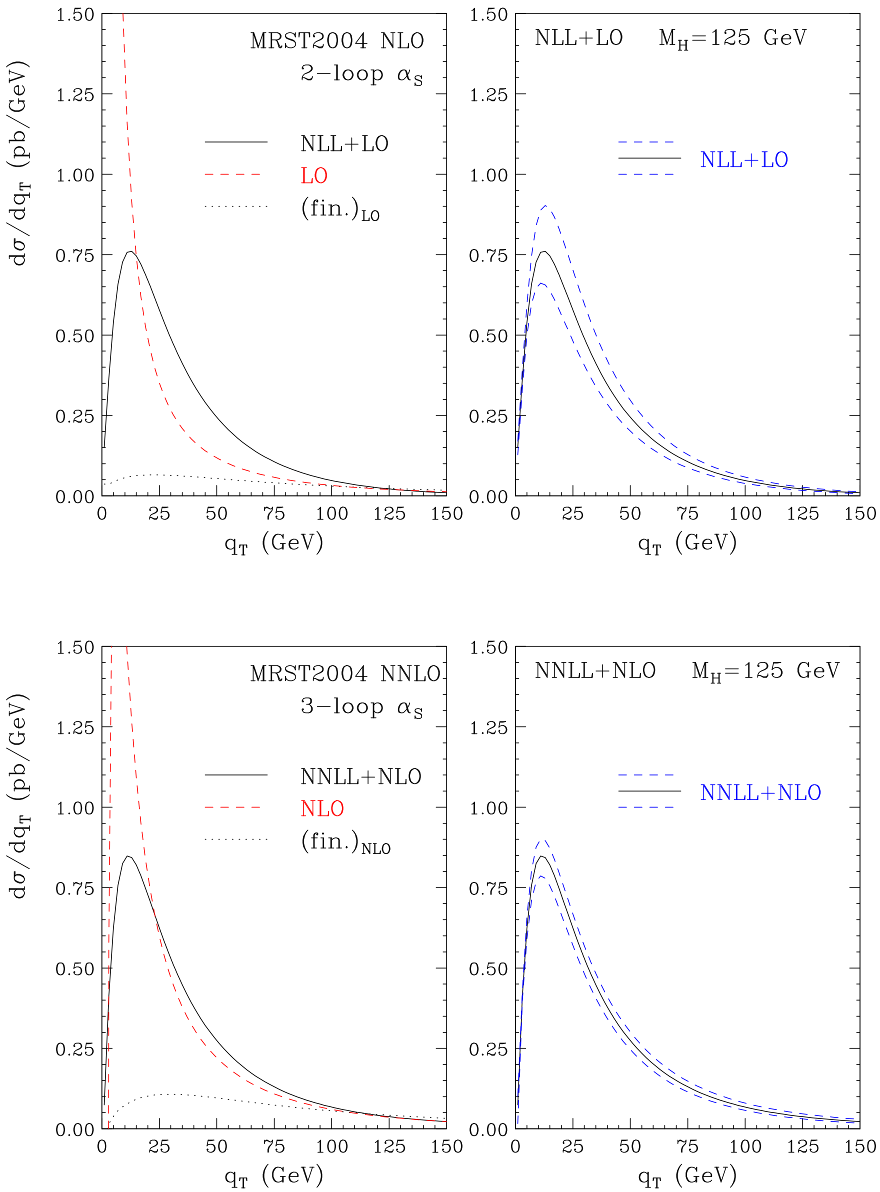
$\longrightarrow$ $\simeq$ 10% perturbative uncertainty, including the $m_t \to \infty$ approximation.

$\longrightarrow$ $\simeq$ 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)]

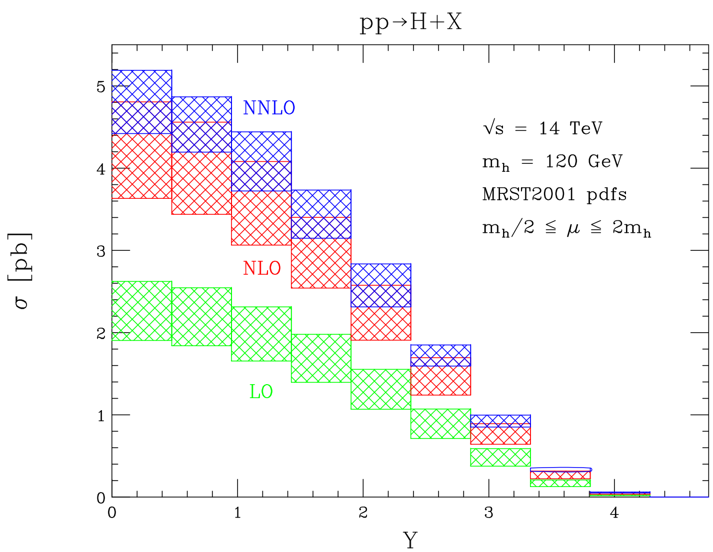
Exclusive NNLO results: $gg \to H$, $H \to \gamma\gamma, WW, ZZ$

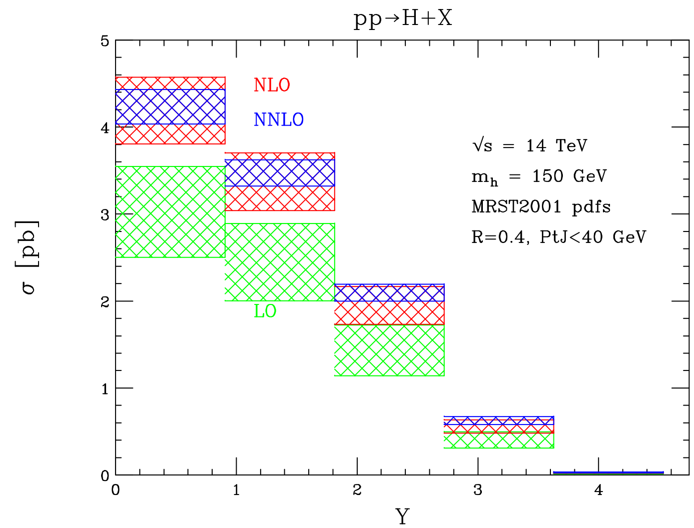
Extension of (IR safe) subtraction method to NNLO

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

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

Essential tools to reliably implement experimental cuts/vetos.



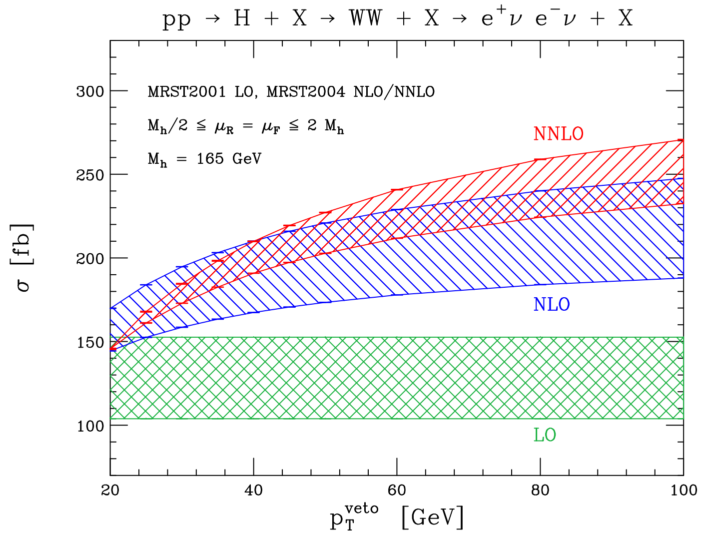


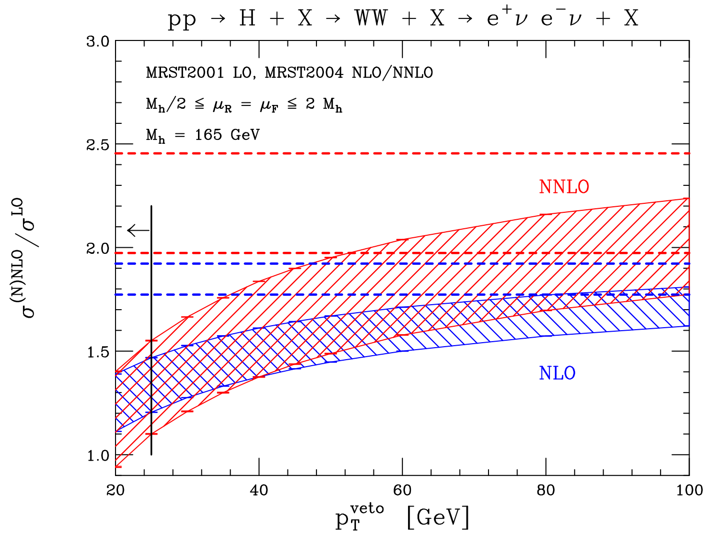
[Anastasiou,Melnikov,Petriello (05)]

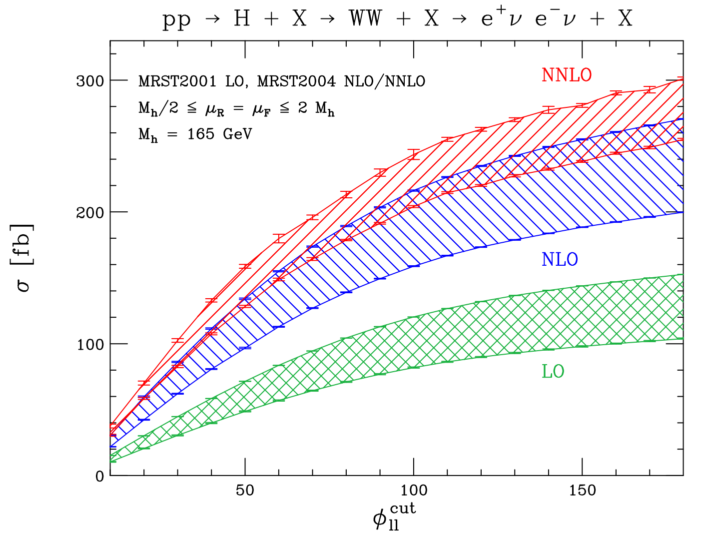
jet veto (to enhance $H \to WW$ signal with respect to $t\bar{t}$ background) seems to improve perturbative stability of y-distribution $\longrightarrow$ jet veto is removing non-NNLO contributions.

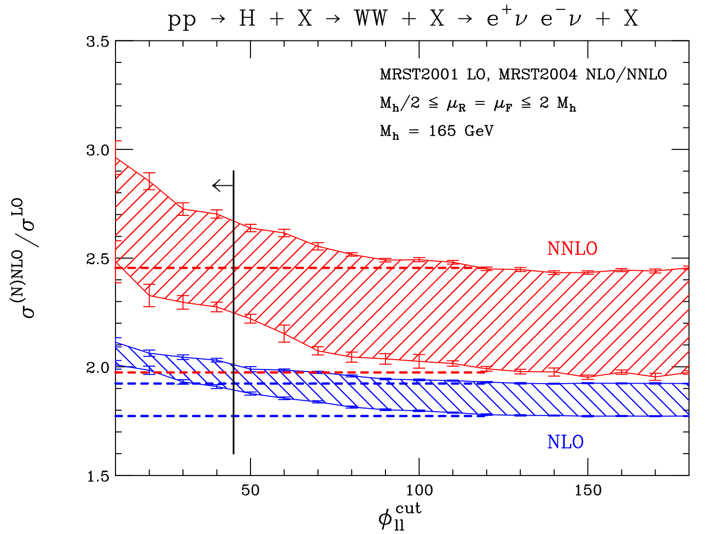
Full fledged $(gg \to) H \to W^+W^- \to l^+\nu l^-\bar{\nu}$

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



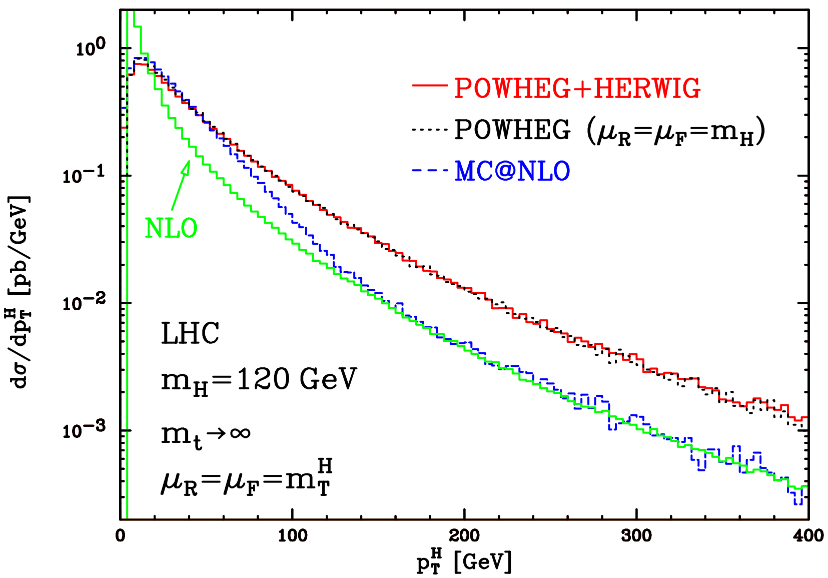


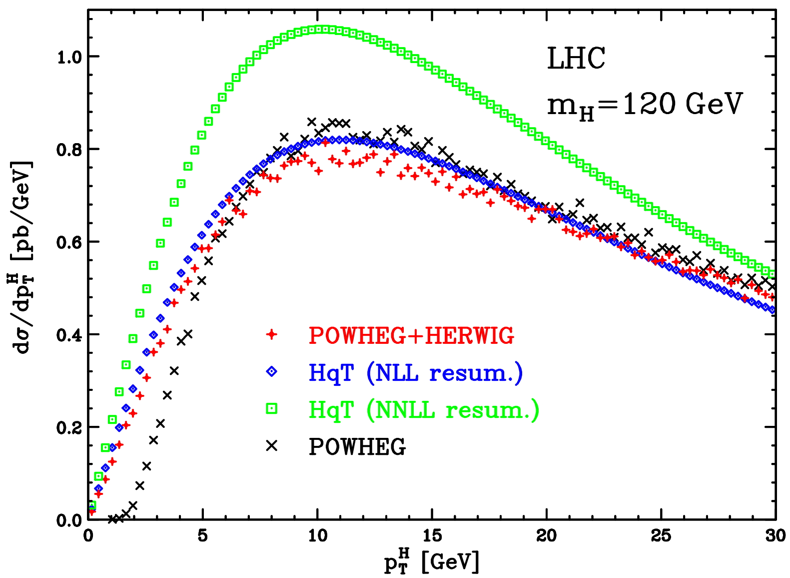




[Anastasiou,Dissertori,Stöckli (07)]

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





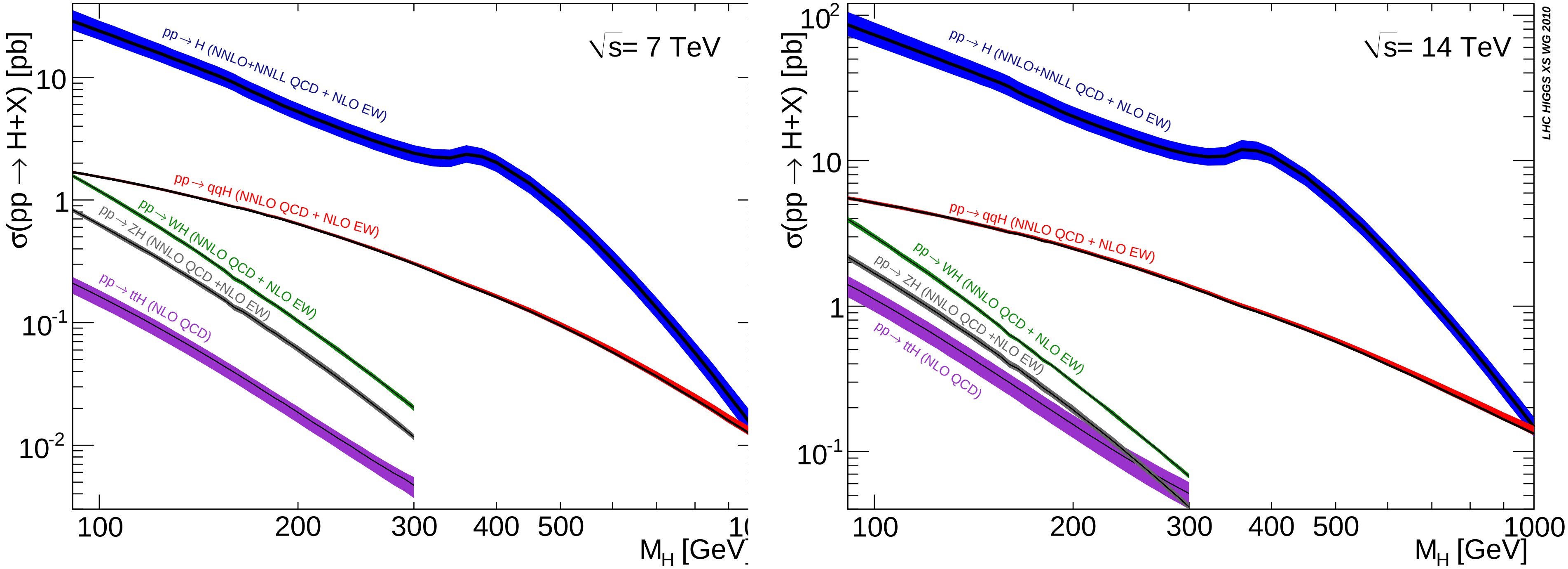
[Nason, Oleari, Alioli, Re]

→ general good agreement with PYTHIA;

→ comparison MC@NLO vs POWHEG understood;

→ comparison with resummed NLL and NNLL results under control.

Ex. 4: 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);
- ↪ common recipe for renormalization+factorization scale dependence;
- ↪ PDF and α_s errors following PDF4LHC prescription (→ see de Florian's talk);
- ↪ all other parametric errors included;
- ↪ theory errors combined according to common recipe.

For $\sqrt{s} = 7$ TeV (from S. Dittmaier's talk, BNL, May 2011)

	M_H	Uncertainties scale	Uncertainties PDF4LHC	NLO/NNLO/NNLO+ QCD	NLO/NNLO/NNLO+ EW
ggF	< 500 GeV	6-10%	8-10%	> 100%	5%
VBF	< 500 GeV	1%	2-7%	5%	5%
WH	< 300 GeV	1%	3-4%	30%	5-10%
ZH	< 300 GeV	1-2%	3-4%	40%	5%
$t\bar{t}H$	< 300 GeV	10%	9%	5%	?

For $\sqrt{s} = 14$ TeV

	M_H	Uncertainties scale	Uncertainties PDF4LHC	NLO/NNLO/NNLO+ QCD	NLO/NNLO/NNLO+ EW
ggF	< 500 GeV	6-14%	7%	> 100%	5%
VBF	< 500 GeV	1%	3-4%	5%	5%
WH	< 300 GeV	1%	3-4%	30%	5-10%
ZH	< 300 GeV	2-4%	3-4%	45%	5%
$t\bar{t}H$	< 300 GeV	10%	9%	15-20%	?