Higher Order Tools, part II

Laura Reina

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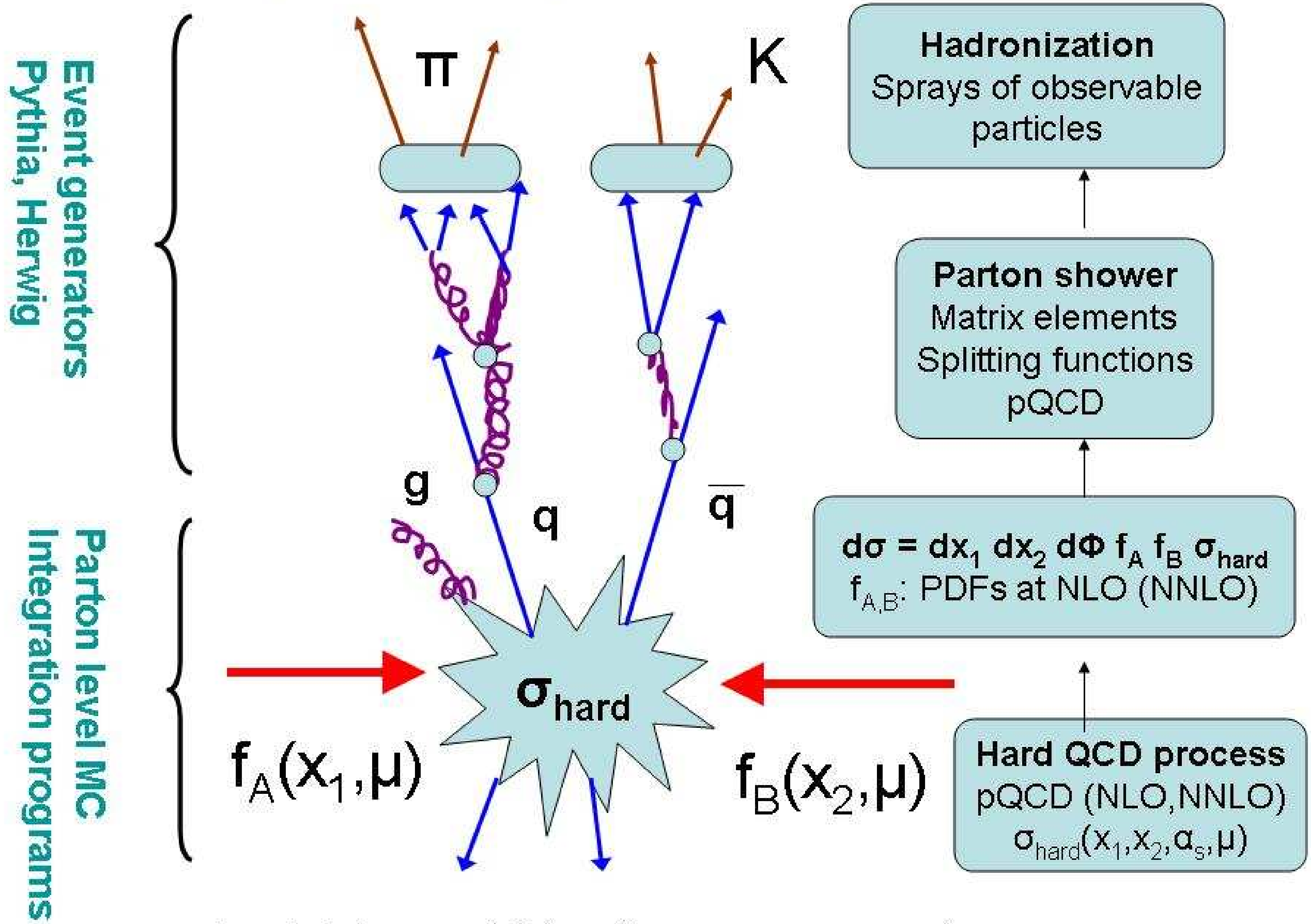
Introduction and Outline

- The reach of the Tevatron and the incredible physics potential of the LHC rely on our ability of providing very accurate QCD predictions. This is very challenging.
- How do we expect to compare with data?
  $\longrightarrow$ Need precise description of hard QCD production as well as a method to interface with the final hadronic states that are measured, accurately.
- Status of NLO QCD calculations for hadron collider physics: what has been done and what are the challenges.
- Having a NLO parton-level calculation, what do we do?
  $\longrightarrow$ Monte Carlo (MC) vs analytic integration over phase space.
  $\longrightarrow$ Parton level MC's vs Shower MC's event generators.
  $\longrightarrow$ Matching with exact NLO QCD calculations.

Anatomy of a QCD prediction at hadron colliders



+ underlying event, interactions among remnants

Hard cross sections: pushing the loop order, why?

LO calculations in QCD can be only used to get a feeling of the order of magnitude, or qualitatively discriminate between different models.

Exact NLO or NNLO calculations of σ_{hard} needed to:

$\longrightarrow$ have accurate and reliable predictions of parton-level observables, like total and differential cross-sections (scale-dependence issue, see "NLO QCD calculations, part I");

$\longrightarrow$ test the convergence of the perturbative series associated to a given physical observable;

$\longrightarrow$ start to correctly reproduce the kinematic of a given process, in particular in peripheral regions of phase space where the LO kinematic may be unnecessarily degenerate;

$\longrightarrow$ provide non trivial jet structure in jet production cross sections.

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.

Recently completed NLO calculations: all backgrounds to HIggs and New Physics searches!

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)

Intrinsic limitations of parton-level MC programs:

$\longrightarrow$ no resummation of large corrections (soft, collinear, threshold) arising at phase space boundaries;

$\longrightarrow$ only one additional parton;

$\longrightarrow$ not a good description of more exclusive observables;

$\longrightarrow$ event weights may be negative;

$\longrightarrow$ only parton level events: no hadronization, no underlying event structure, no simulation of detector effects.

$\Downarrow$

Some of these limitations are overcome by a

Shower MC Event Generators

generate real events, i.e. physical, measurable hadrons, with a correct description of their multiplicity, kinematics and flavor composition.

First step: Shower MC Event Generators

($\longrightarrow$ see S. Mrenna's lectures)

In a nutshell:

After having generated a parton-level configuration at tree level, initial and final state parton emission is controlled by a showering algorithm, a numerical Markov-like evolution which implements the QCD dynamics under certain approximations.

More specifically:

- $\longrightarrow$ probabilities for parton radiation implement soft and collinear leading logarithms, plus some sub-leading classes of logarithms;
  ($\longrightarrow$ see "Higher Order Tools, part I")
- $\longrightarrow$ radiation probabilities are unitarized by the inclusion of Sudakov-like forms factors, i.e. the cross section is dictated by the core matrix element of a given process;
- $\longrightarrow$ an IR cutoff scheme is used;
- $\longrightarrow$ hadronization is added.

Among the most famous: Herwig, Pythia, Sherpa, ...

Pros:

$\longrightarrow$ model realistic events, from the perturbative regime at high energies ($\gg \Lambda_{QCD}$) to the non-perturbative one ($\simeq \Lambda_{QCD}$);

$\longrightarrow$ allows for formation of hadrons and hadron decays;

$\longrightarrow$ include a description of the underlying structure of the event;

$\longrightarrow$ allow realistic detector simulations.

Cons:

$\longrightarrow$ based on LO matrix elements, in general of $2 \to 1$ or $2 \to 2$ processes;

$\longrightarrow$ shower based on collinear kinematic: high p_T effects are not properly modelled.

$\longrightarrow$ shower only include resummation of leading and some subleading logarithms (Sudakov form factor);

How to improve Shower Monte Carlo's?

The real problem is the collinear approximation.

Think of the LHC: huge energy available $\longrightarrow$ easy to get large-angle hard emission.

Two possible approaches:

- Matrix Element Corrections: apply the showering algorithm after having computed as many as possible real emission matrix elements.

S. Catani, F. Krauss, R. Kuhn, B.R. Webber, JHEP 0111 (2001) 063

L. Lonnblad, JHEP 0205 (2002) 045

- NLO+Parton Shower: apply the showering algorithm to the exact NLO matrix elements.

S. Frixione, B.R. Webber, JHEP 0206 (2002) 029
S. Frixione, P. Nason, B.R. Webber, JHEP 0308 (2003) 007

Z. Nagy, D. Soper JHEP 0510 (2005) 024

Next step: NLO corrections matched with Shower MC

(MC@NLO, S. Frixione, P. Nason, B.R. Webber)

(POWHEG, C. Oleari, P. Nason)

- Based on the full NLO matrix element for the hard process.
- Double counting is avoided by identifying the analytic form of the approximation used by the shower MC to describe real emission and the leading order virtual corrections, and subtracting them from the NLO matrix elements.

  Example: in MC@NLO NLO cross sections are calculated as

$$\mathcal{F}_{\mathrm{MC@NLO}} = \sum_{a,b} \int dx_1 dx_2 d\phi_{n+1} f_a(x_1) f_b(x_2) \times$$

$$\left[\mathcal{F}_{\mathrm{MC}}^{(2\to n+1)} \left(\mathcal{M}_{ab}^{(r)} - \mathcal{M}_{ab}^{\mathrm{MC}}\right) + \mathcal{F}_{\mathrm{MC}}^{(2\to n)} \left(\mathcal{M}_{ab}^{(b,v,c)} - \mathcal{M}_{ab}^{(c.t.)} + \mathcal{M}_{ab}^{\mathrm{MC}}\right)\right]$$

  where the MC counterterms are:

$$\mathcal{M}_{\mathcal{F}(ab)}^{\mathrm{MC}} = \mathcal{F}_{\mathrm{MC}}^{(2\to n)} \mathcal{M}_{ab}^{(b)} + \mathcal{O}(\alpha_s^2 \alpha_s^b)$$

  only two types from initial-state and final-state branching, both calculated.

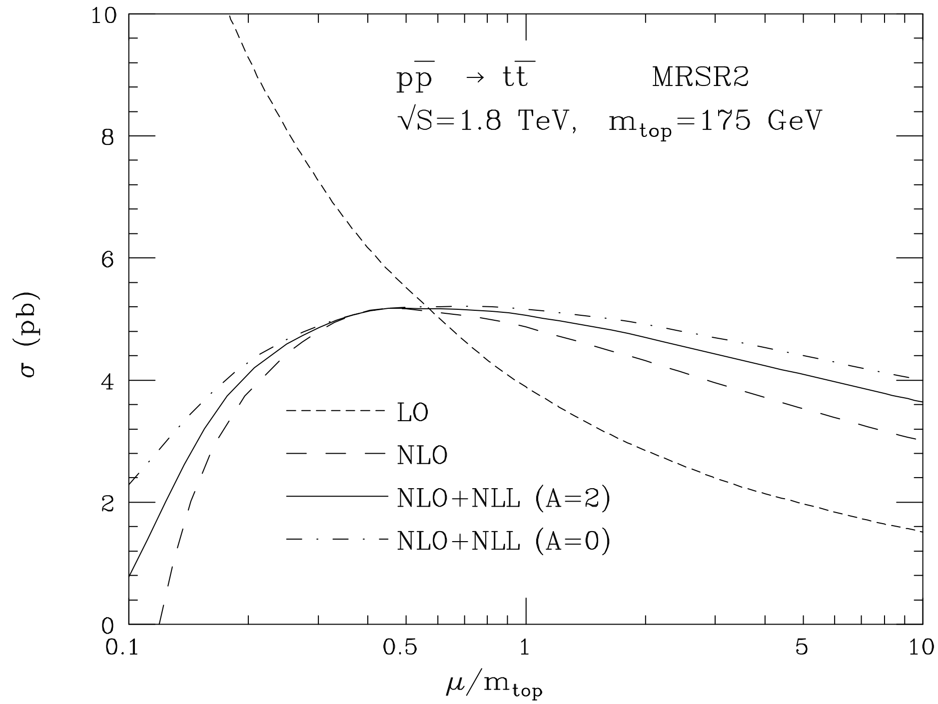
Processes implemented:

- W/Z boson production (MC@NLO, POWHEG);
- WW, ZZ, WZ boson pair production (MC@NLO, POWHEG);
- $Q\bar{Q}$ heavy quark production (MC@NLO, POWHEG);
- single-top production (MC@NLO);
- $gg \to H$ inclusive Higgs boson production (MC@NLO, POWHEG);
- $W/Zb\bar{b}$ production (MC@NLO, POWHEG);
- ...

Crucial improvements:

- the inclusion of NLO corrections in the shower MC properly includes the NLO K-factors and reduce the systematic uncertainty due to renormalization and factorization scale variations;
- the higher order corrections generated by the shower MC improve the description of NLO distributions.

Example 1: $\boxed{p\bar{p} \to t\bar{t}}$, very reduced scale dependence.



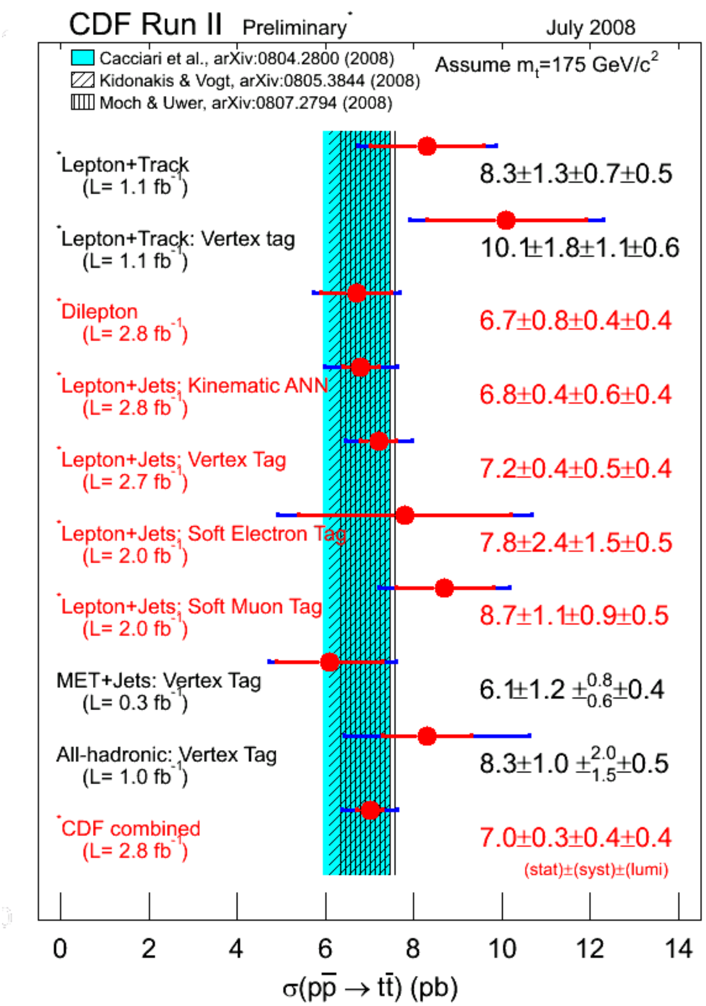
(R. Bonciani, S. Catani, M. Mangano, P. Nason, NPB 529 (1998) 424)

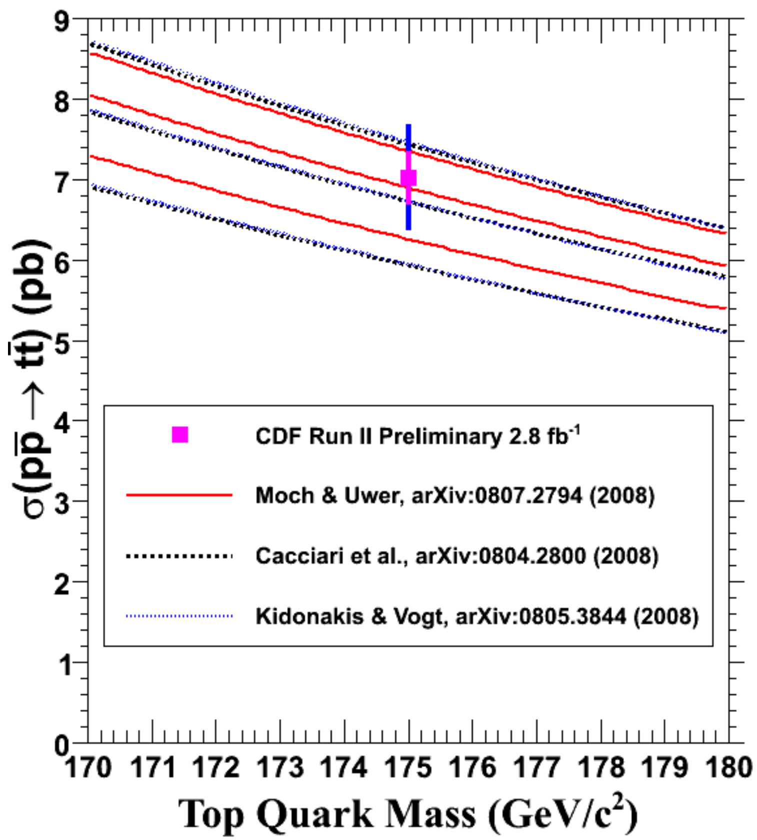
Tevatron: radiative corrections are large in the region near threshold ($\hat{s} = 4m_t^2$).
Calculation refined to resum higher order corrections due to soft gluon radiation

NLO $\longrightarrow$ scale uncertainty $\simeq \pm 10\%$

NNL $\longrightarrow$ Next-to-Leading Logarithms, scale uncertainty $\simeq \pm 5\%$

comparing to experimental results . . .

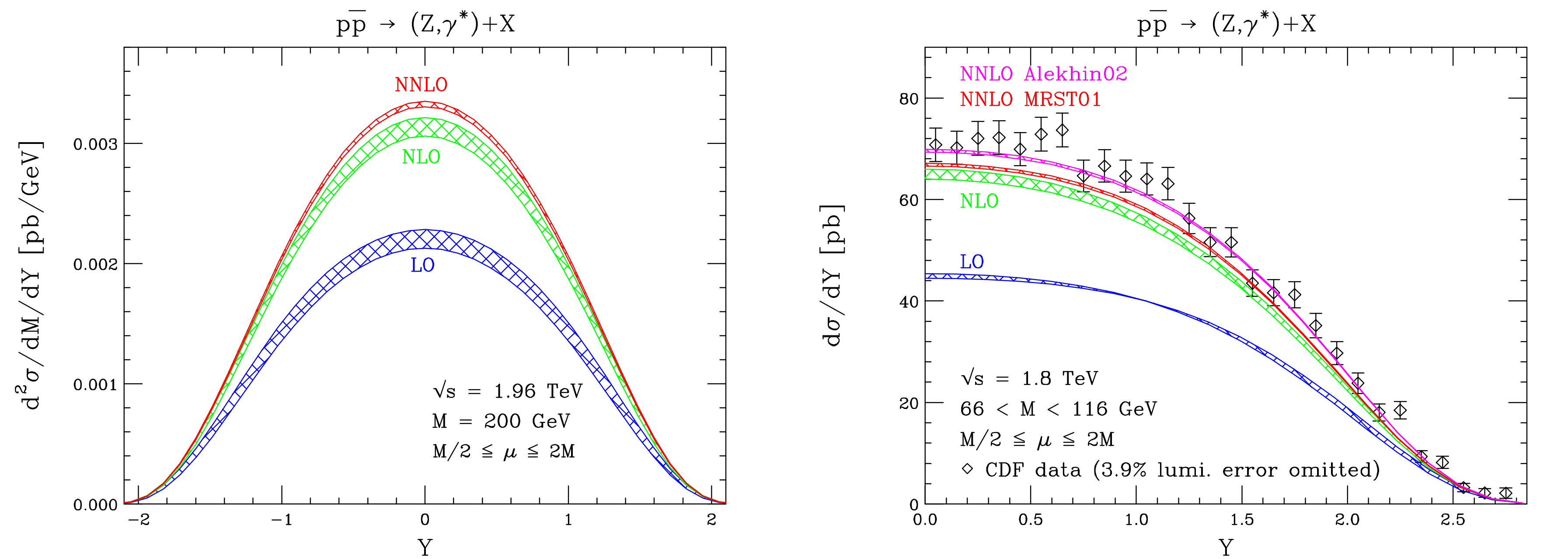




NLO and resummation of soft corrections crucial to match the $t\bar{t}$ cross-section measurement so closely.

Example 2: W/Z production at the Tevatron, testing PDF's at NNLO.

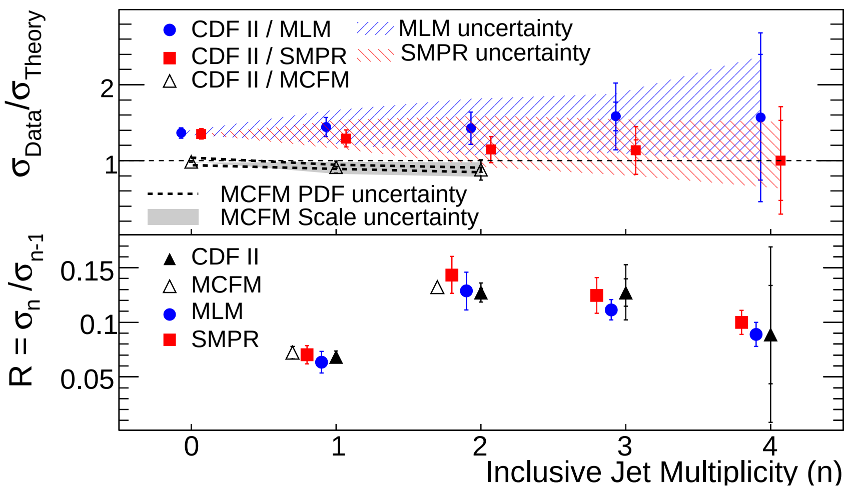
Rapidity distributions of the Z boson calculated at NNLO:



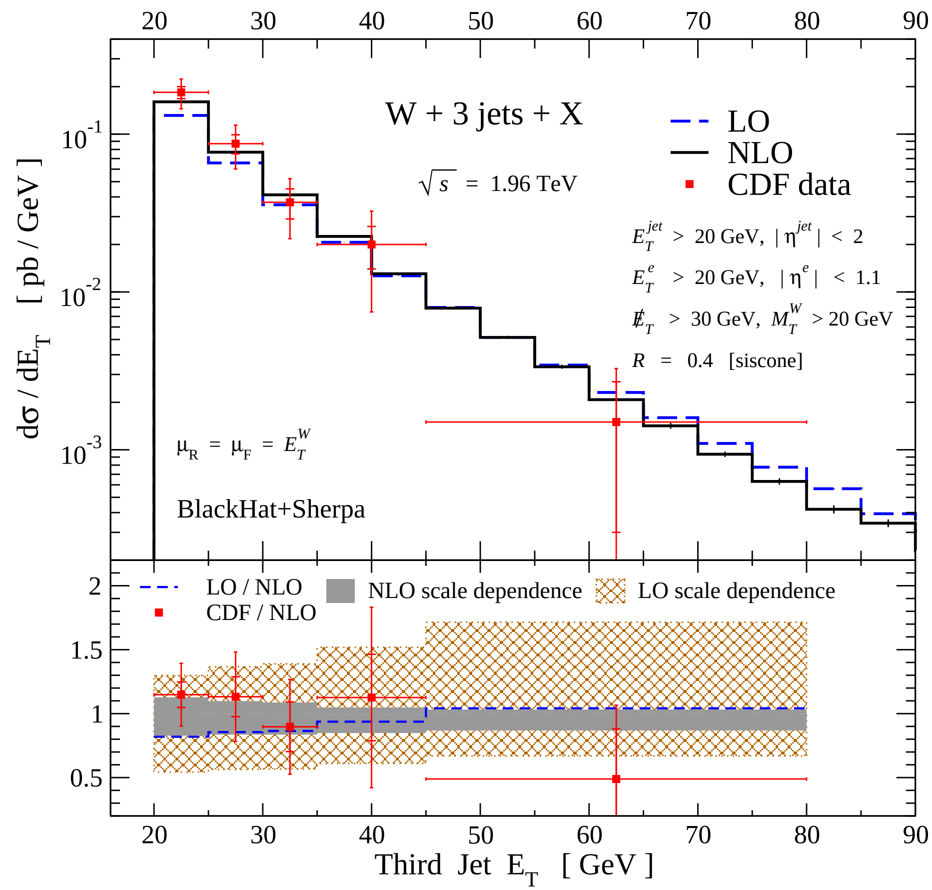
(C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello, PRL 91 (2003) 182002)

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

Example 3: W+jets production at the Tevatron, where progress has been most impressive!



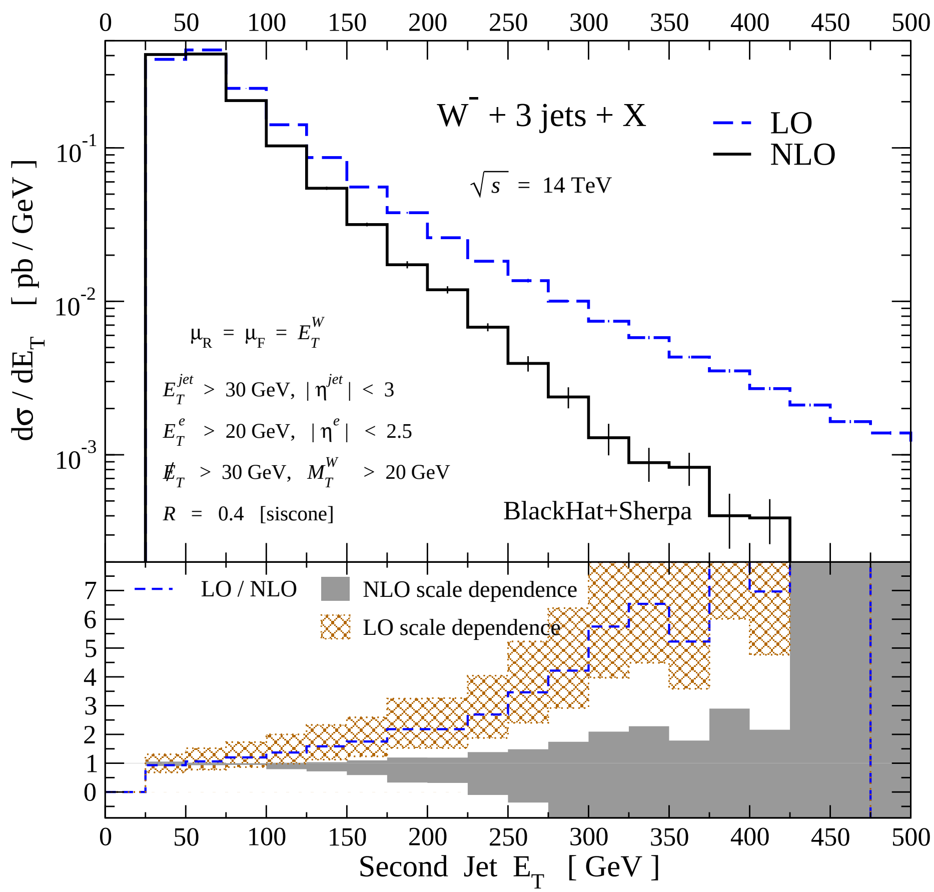
(CDF collaboration, arXiv:0711.4044)

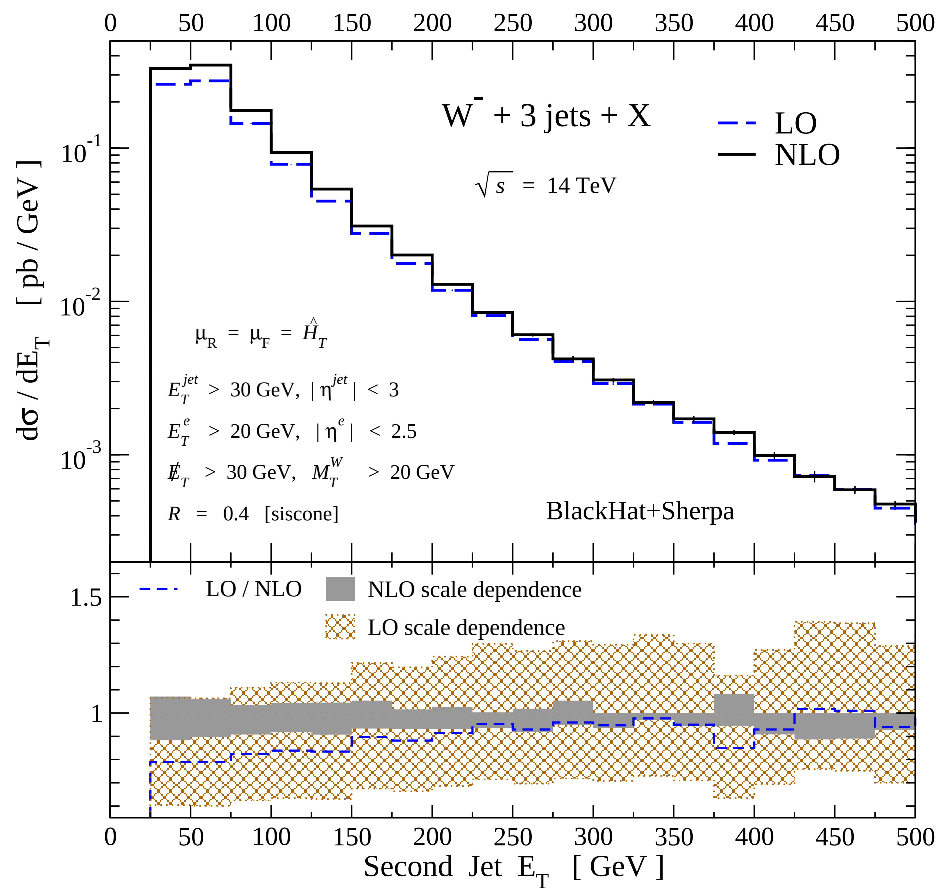


(Berger et al., arXiv:0907.1984)

- 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 . . .



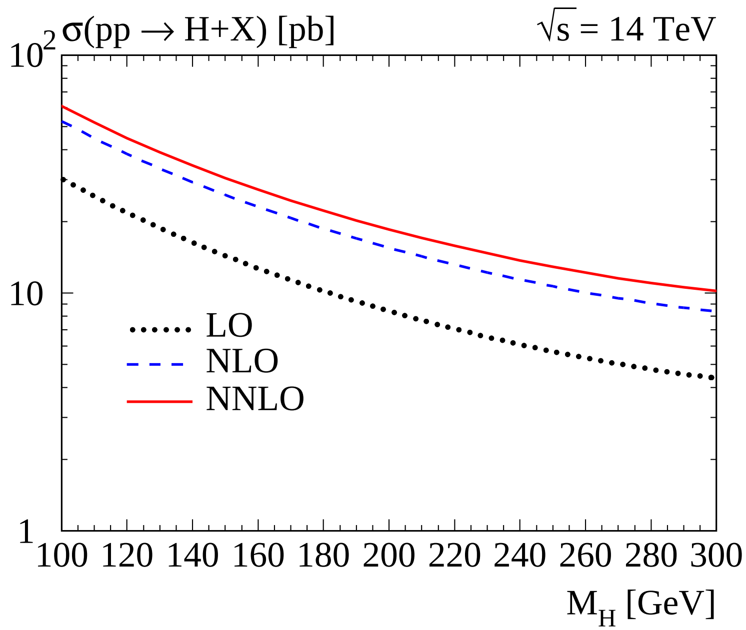


(Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Kosower, Maitre, arXiv:0907.1984)

“Wrong” scale choice leads to enhanced unphysical instabilities

Example 4: $\boxed{gg \to H}$, stability at NNLO.

(R. Harlander, W. Kilgore, PRL 88 (2002) 201801)



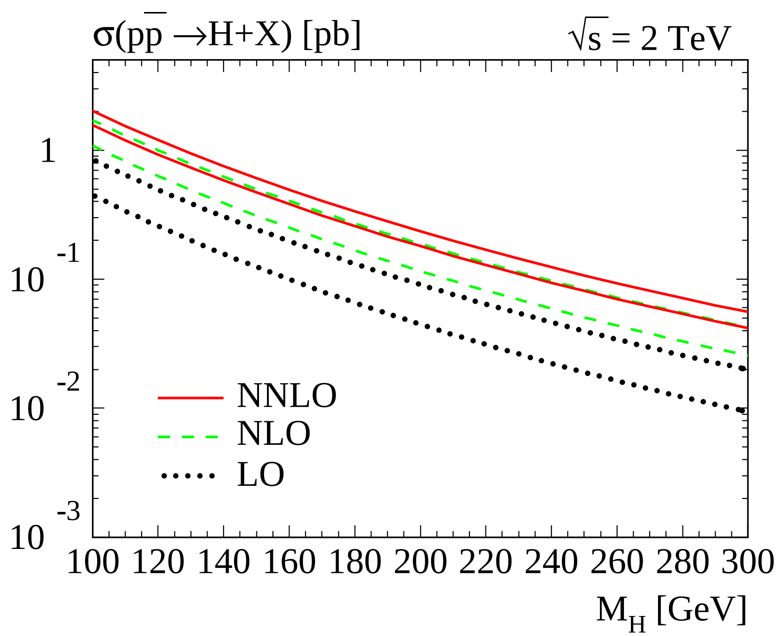
convergence in going:

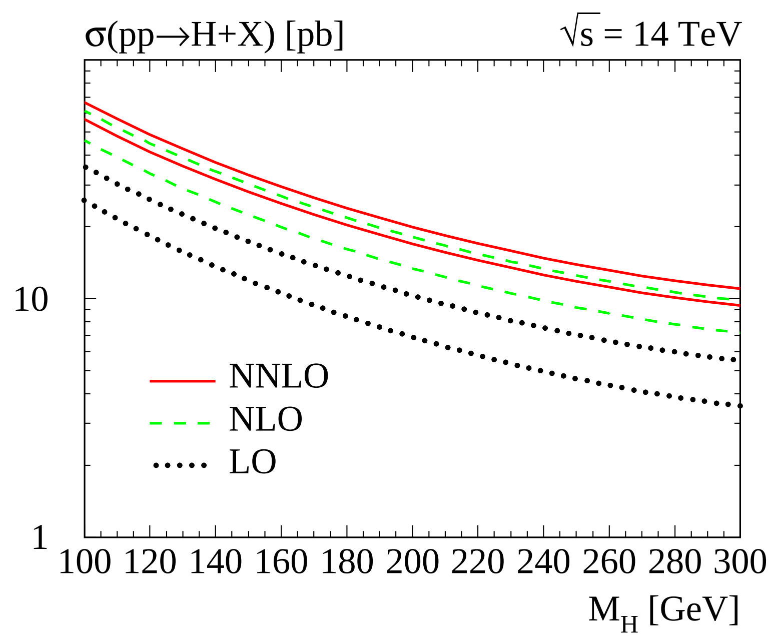
LO $\longrightarrow$ NLO $\longrightarrow$ NNLO

Confirmed by the full

scale dependence:

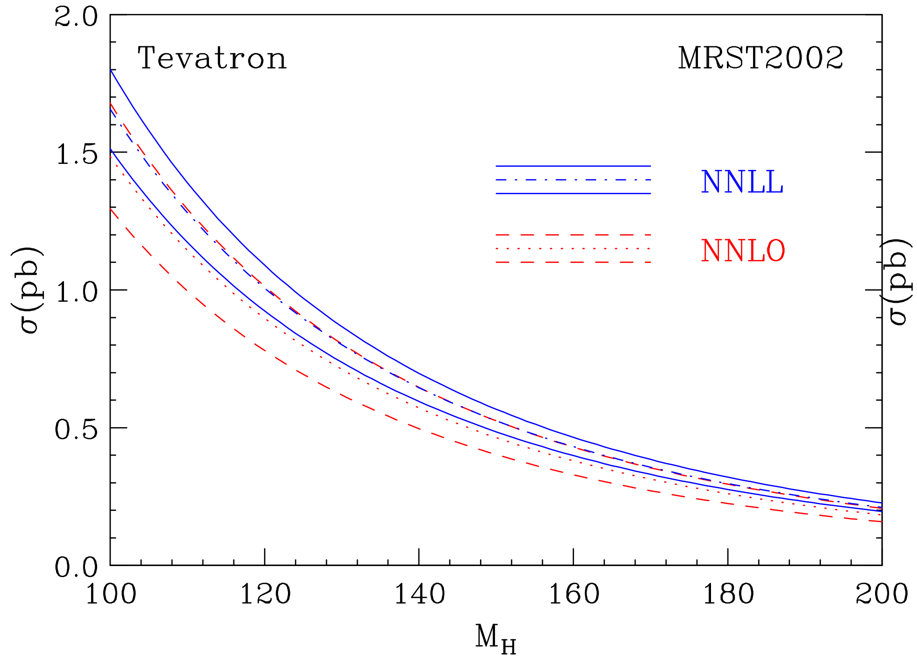
$\Downarrow$

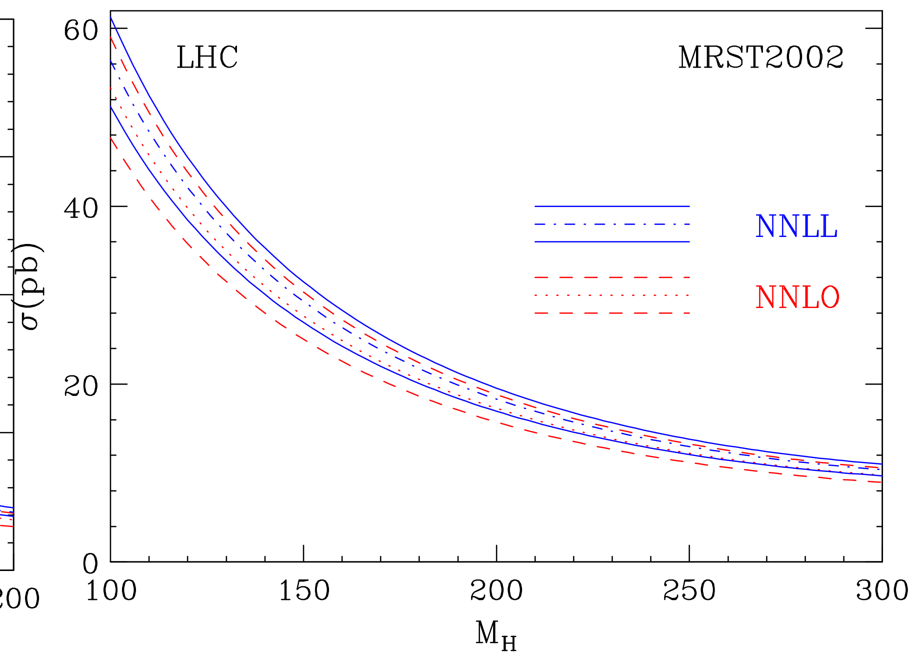




Further improvement: resumming soft logarithms.

(→ see G. Sterman's lectures)





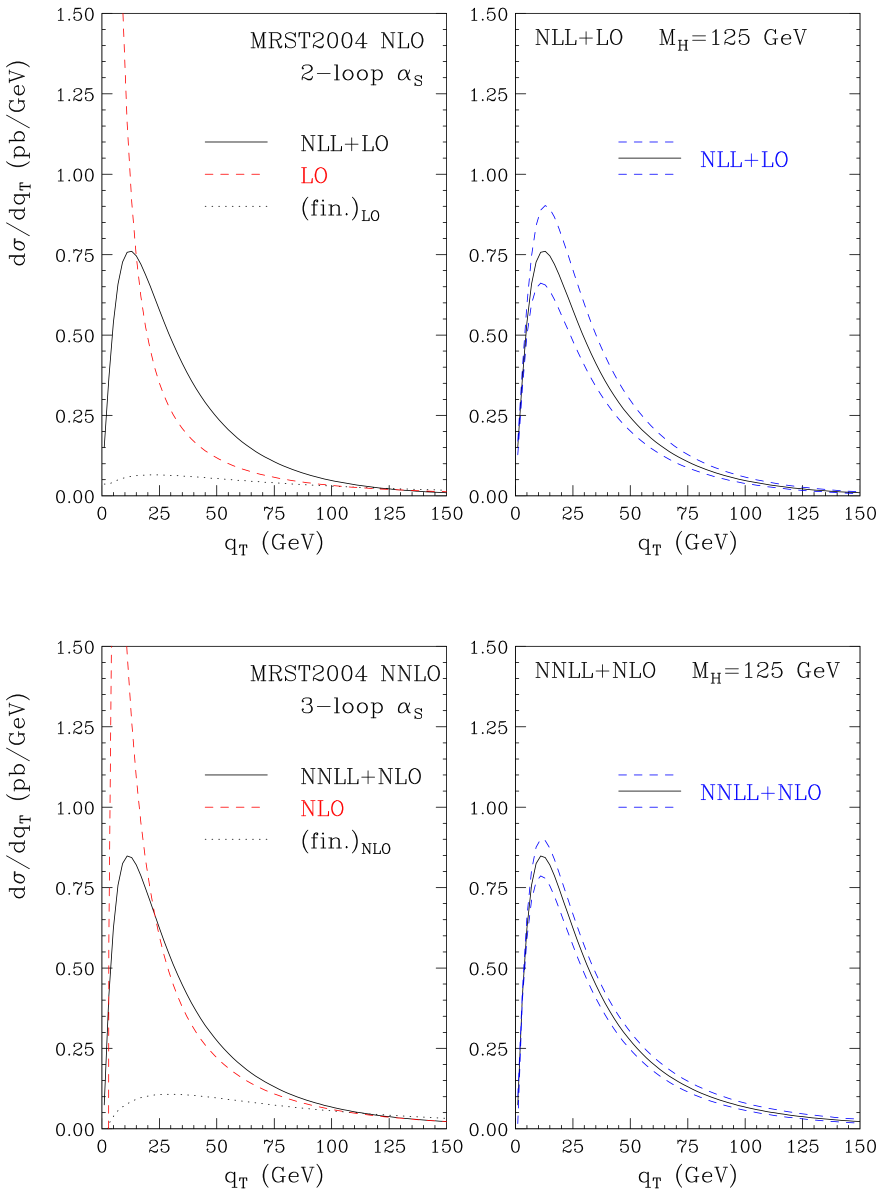
(S. Catani, D. de Florian, M. Grazzini, P. Nason, JHEP 0307 (2003) 028)

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.

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)]

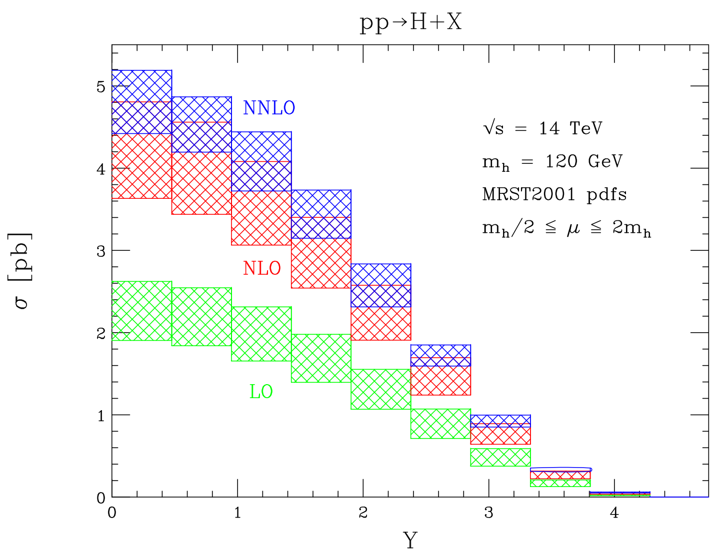
Exclusive NNLO results: $gg \to H$, $H \to \gamma\gamma, WW, ZZ$

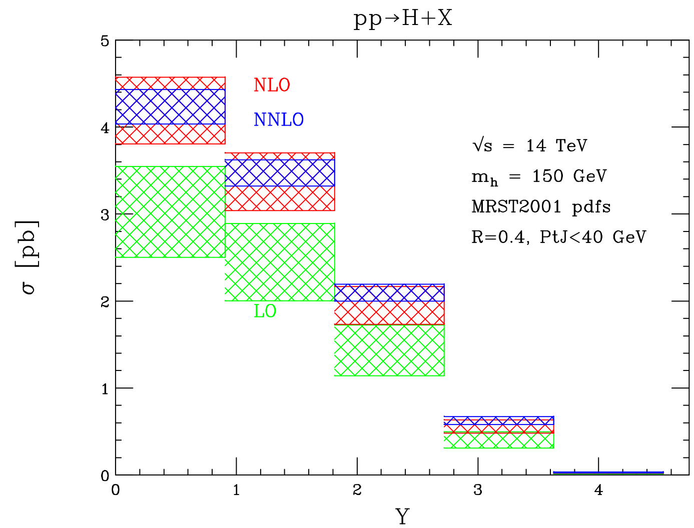
Extension of (IR safe) subtraction method to NNLO

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

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

Essential tools to reliably implement experimental cuts/vetos.



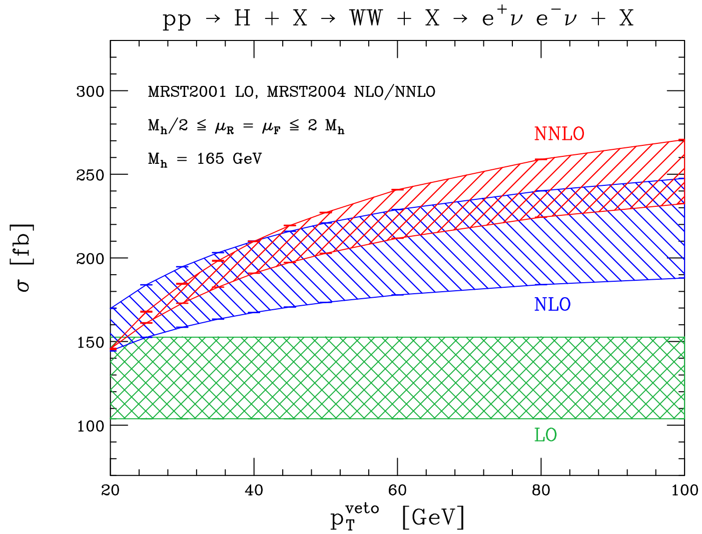


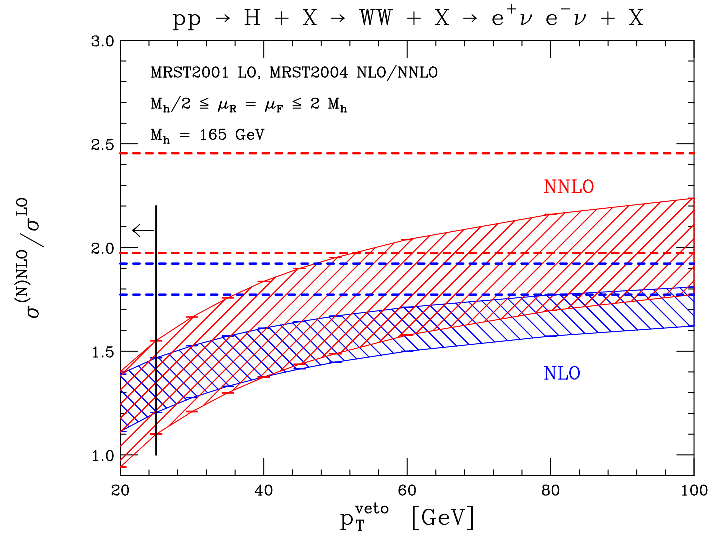
[Anastasiou,Melnikov,Petriello (05)]

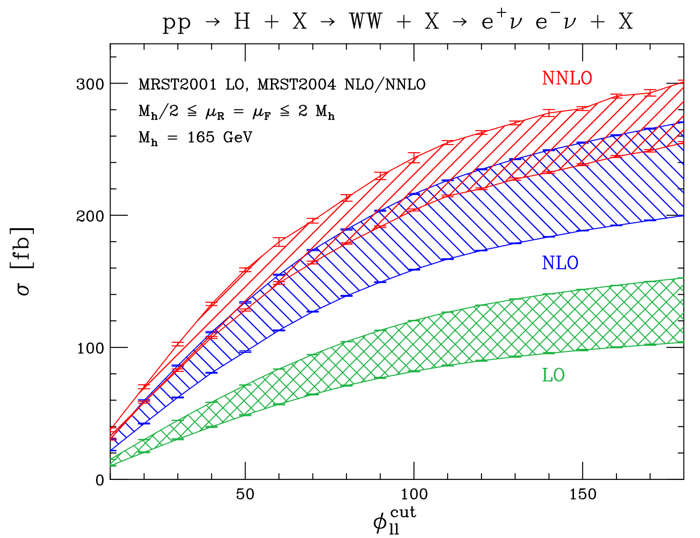
jet veto (to enhance $H \to WW$ signal with respect to $t\bar{t}$ background) seems to improve perturbative stability of y-distribution $\longrightarrow$ jet veto is removing non-NNLO contributions.

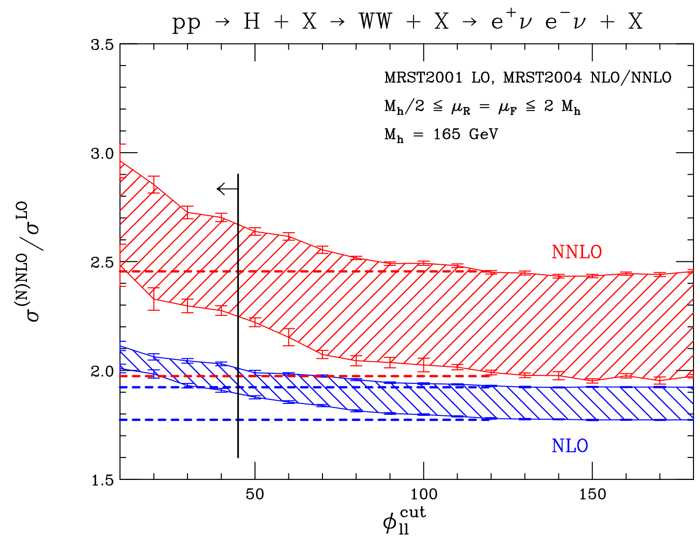
Full fledged $(gg \to) H \to W^+W^- \to l^+\nu l^-\bar{\nu}$

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



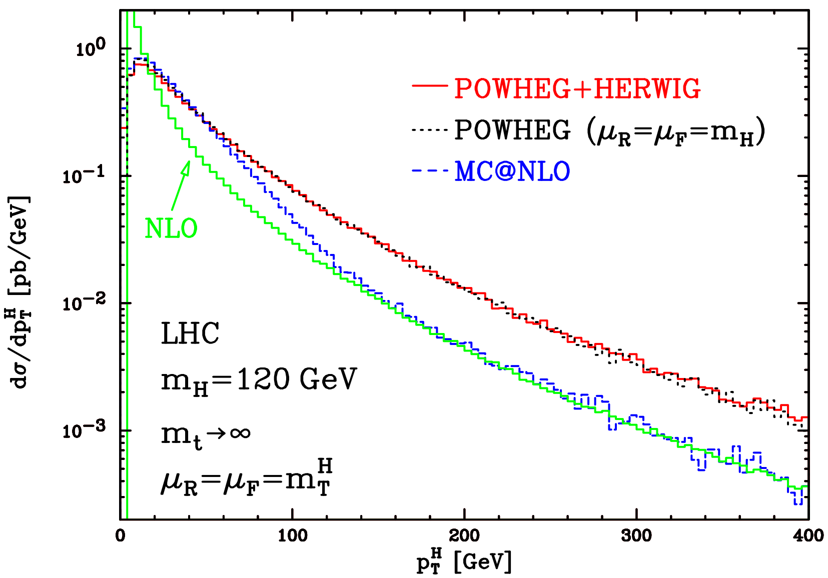


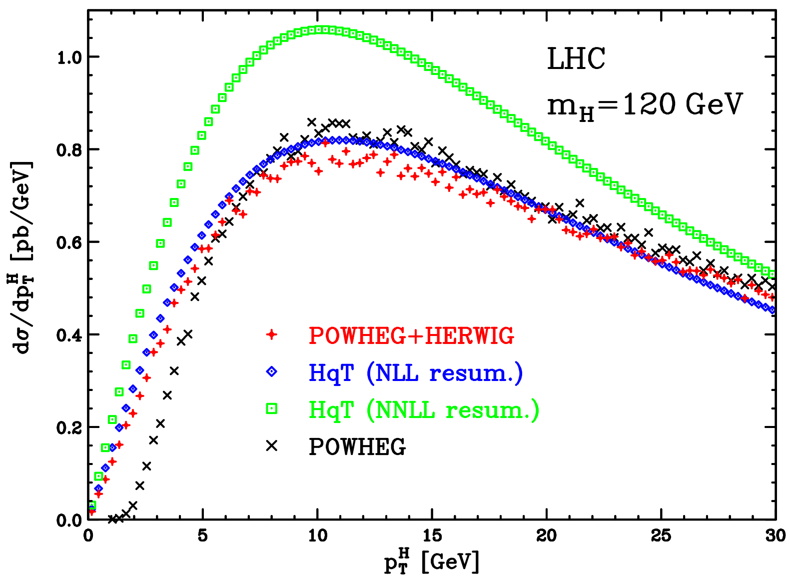




[Anastasiou,Dissertori,Stöckli (07)]

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





[Nason, Oleari, Alioli, Re]

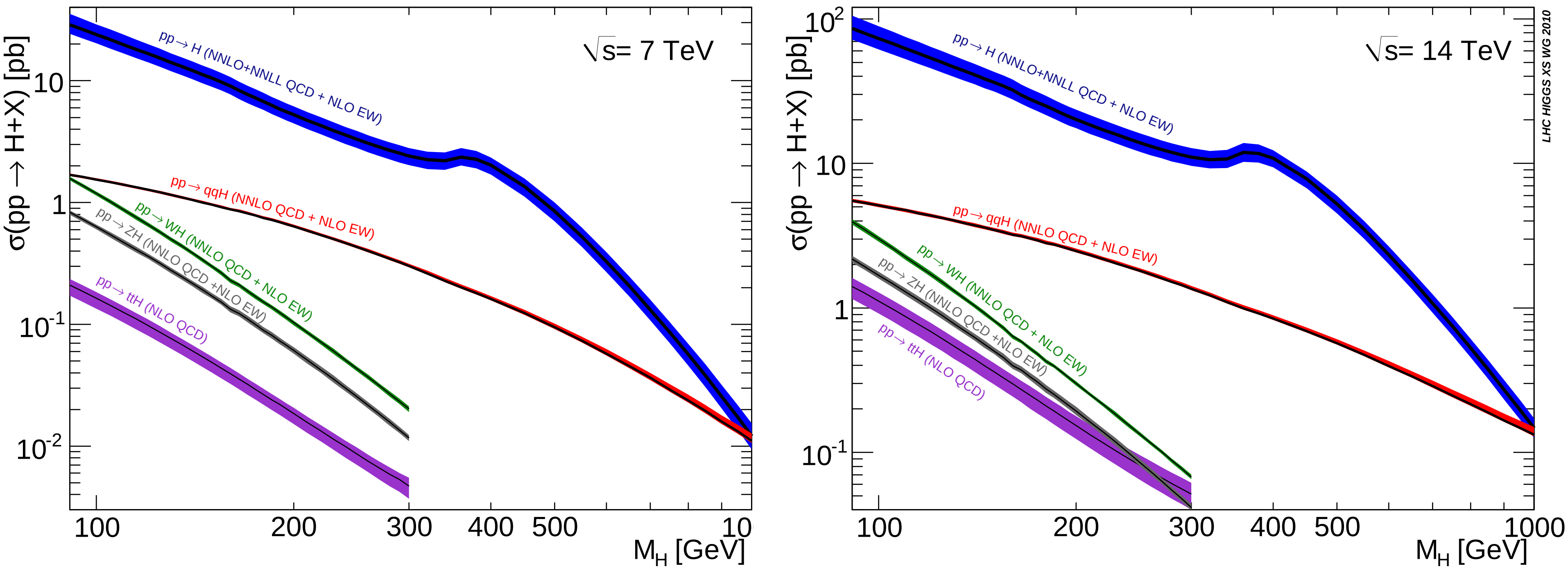
→ general good agreement with PYTHIA;

→ comparison MC@NLO vs POWHEG understood;

→ comparison with resummed NLL results under control.

→ rescale effects using NNLL/NLL knowledge.

Example 5: Higgs production at the LHC, overview.



(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.

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), 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)

Conclusions

- Parton-level NLO QCD calculations have reached a mature stage: results available for all $2 \to 2$ and $2 \to 3$, and for some $2 \to 4$ processes of interest at hadron colliders.
- Partial/full NNLO corrections or resummed NLL or NNLL corrections are available for several processes.
- The incredible activity of the last few years has brought major progress on two crucial aspects of NLO calculations:

  $\longrightarrow$ automatization: providing NLO QCD calculations for multi-leg ($2 \to 4$ or more) seems more at reach;

  $\longrightarrow$ interfacing of parton-level NLO calculations with MC shower event generators.

- Continuing progress will put us in a good position to fully explore the physics potential of the LHC.