NNLO predictions for the Higgs boson signal in the WW and ZZ decay modes

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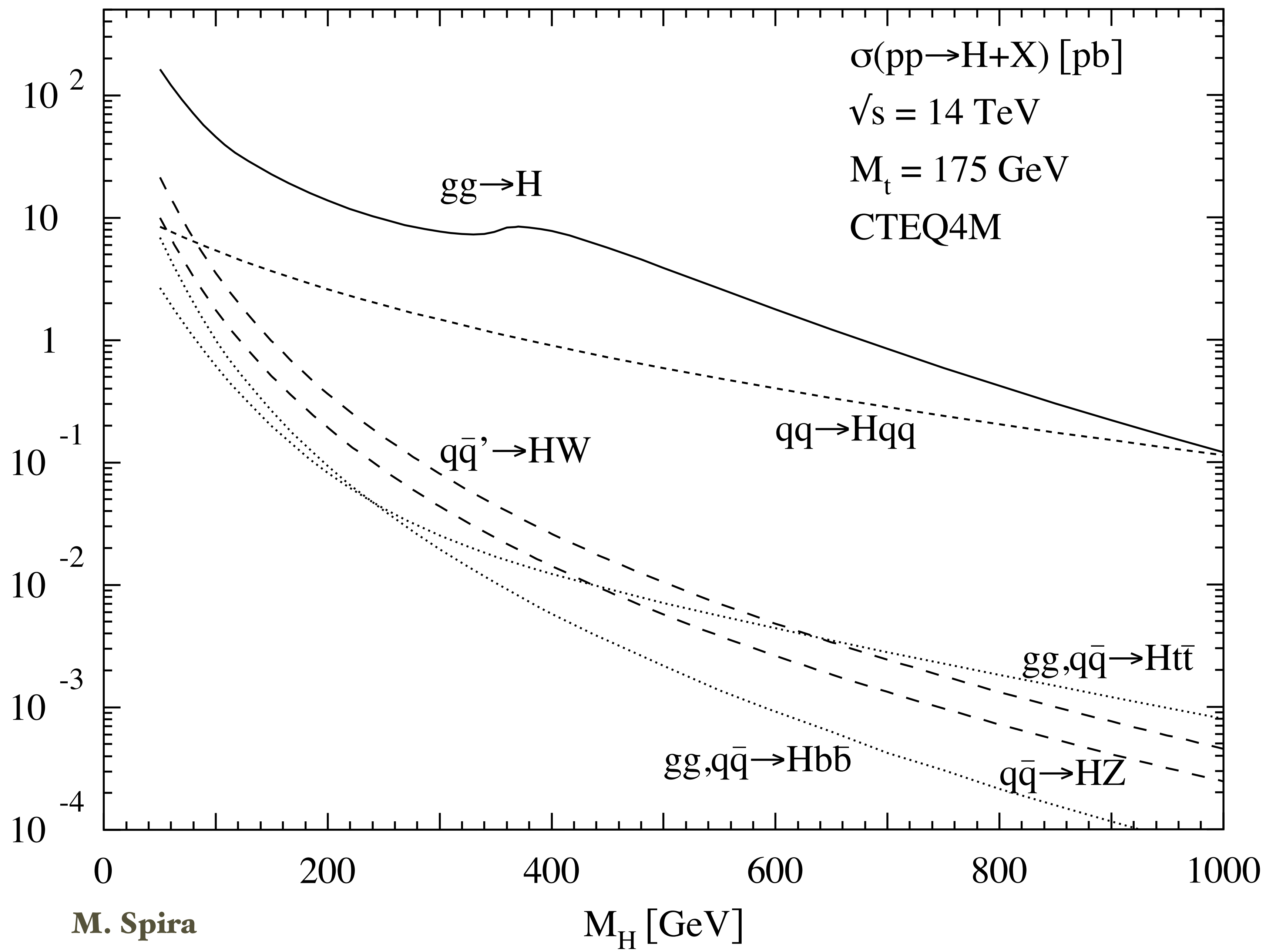
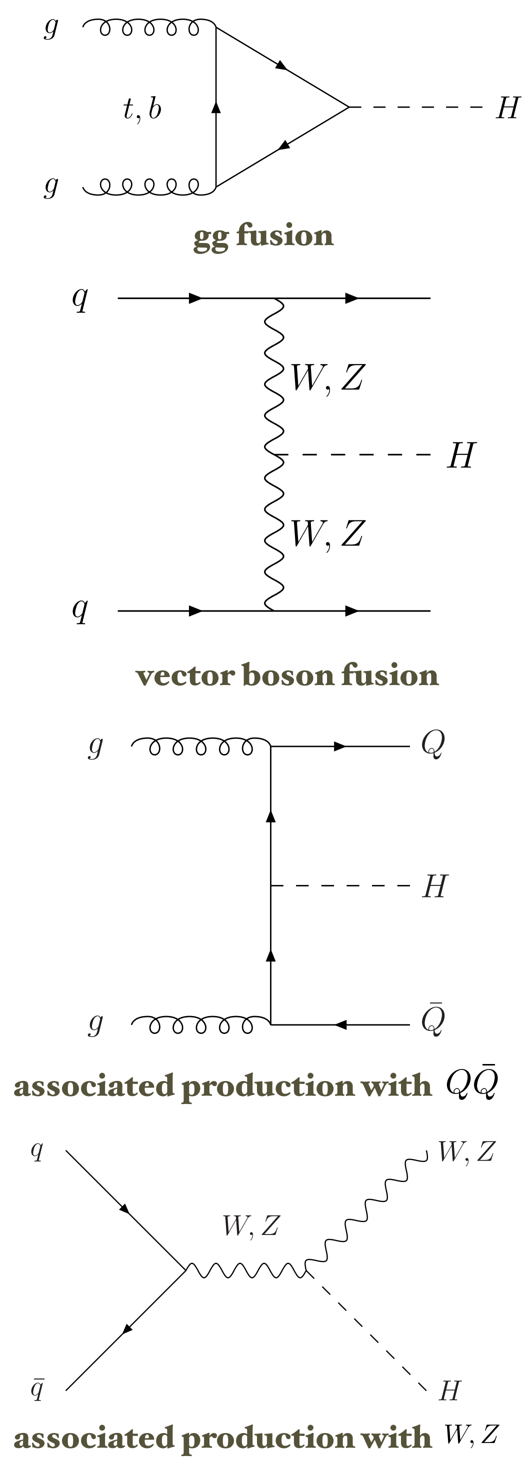
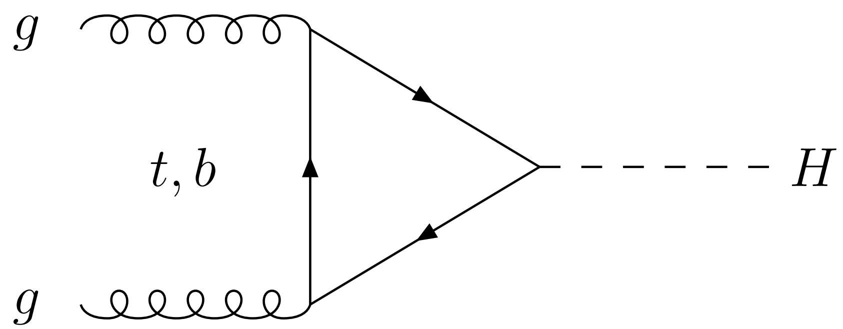
Introduction





Large gluon luminosity → gg fusion is the dominant production channel over the whole range of M_H

gg fusion



The Higgs coupling is proportional to the quark mass → top-loop dominates

NLO QCD corrections to the total rate computed more than 15 years ago and found to be large

A. Djouadi, D. Graudenz, M. Spira, P. Zerwas (1991)

They increase the LO result by about 80-100 % !

They are well approximated by the large- m_{top} limit (differences range from 1 to 4 % for $M_H < 200$ GeV)

S.Dawson (1991)
M.Kramer, E. Laenen, M.Spira(1998)

NNLO corrections to $\sigma_H^{\rm tot}$ computed in the large m_{top} limit

S. Catani, D. De Florian, MG (2001)
R.Harlander, W.B. Kilgore (2001,2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

Effect ranges from 15 to 20 % for $M_H < 200$ GeV

Effects of soft-gluon resummation: additional +6 %
Nicely confirmed by computation of soft terms at N^3LO

S. Catani, D. De Florian, P. Nason, MG (2003)
S. Moch, A. Vogt (2006)

EW two-loop effects also known

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)

Up to now only total cross sections but....more exclusive observables are needed !

- H+ 1 jet: NLO corrections known

D. de Florian, Z. Kunszt, MG (1999)
J. Campbell, K.Ellis (MCFM)

- H+ 2 jet: NLO corrections recently computed

J. Campbell, K.Ellis, G. Zanderighi (2006)

→ background for VBF

All these predictions are obtained in the large-m_{top} limit

→ (it is a good approximation for small transverse momenta of the accompanying jets)

Del Duca et al. (2001)

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NNLO corrections to $gg \to H$ computed for arbitrary cuts for $H \to \gamma\gamma$ → FEHIP

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It was the first fully exclusive NNLO calculation for a physically interesting process but....

If you are interested in distributions you need to do a single run for each bin

→ requires a lot of CPU time !

The optimal solution would be to have a *parton-level event generator*

With such a program one can apply arbitrary cuts and obtain the desired distributions in the form of bin histograms

→ this is what is typically done at NLO with the *subtraction method*

Quite an amount of work has been done in the last few years towards a general extension of the subtraction method to NNLO

D. Kosower (1998,2003,2005)
S. Weinzierl (2003)
S. Frixione, MG (2004)
A. & T. Gehrmann, N. Glover (2005)
G, Somogyi, Z. Trocsanyi, V. Del Duca (2005, 2007)

Up to now results obtained for $e^+e^- \to 2$ jets

A. & T. Gehrmann, N. Glover (2004)
S. Weinzierl (2006)

and now for $e^+e^- \to 3$ jets

A. & T. Gehrmann, N. Glover, G. Heinrich (2007)

NEW:

HNNLO

S. Catani, MG (2007)

We propose a new version of the subtraction method to compute higher order QCD corrections to a specific class of processes in hadron collisions (vector boson, Higgs boson production, vector boson pairs......)

We compute the NNLO corrections to $gg \to H$ implementing them in a fully exclusive parton level generator including all the relevant decay modes

→ ecompasses previous calculations in a single stand-alone numerical code
it makes possible to apply arbitrary cuts

Strategy: start from NLO calculation of H+jet(s) and observe that as soon as the transverse momentum of the Higgs $q_T \neq 0$ one can write:

$$d\sigma^{H}_{(N)NLO}|_{q_T \neq 0} = d\sigma^{H+\text{jets}}_{(N)LO}$$

Define a counterterm to deal with singular behaviour at $q_T \to 0$

But.....

the singular behaviour of $d\sigma^{H+\mathrm{jet(s)}}_{(N)LO}$ is well known from the resummation program of large logarithmic contributions at small transverse momenta

G. Parisi, R. Petronzio (1979)
J. Collins, D.E. Soper, G. Sterman (1985)
S. Catani, D. de Florian, MG (2000)

→ choose $d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^{H}(q_T/Q)$

where $$\Sigma^H(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{H(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$$

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Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^H_{(N)NLO} = \mathcal{H}^H_{(N)NLO} \otimes d\sigma^H_{LO} + [d\sigma^{H+\mathrm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^H$ can be computed in QCD perturbation theory

$$\mathcal{H}^H = 1 + \left(\frac{\alpha_S}{\pi}\right)\mathcal{H}^{H(1)} + \left(\frac{\alpha_S}{\pi}\right)^2\mathcal{H}^{H(2)} + \ldots\ldots$$

Note that:

- The counterterm $d\sigma^{CT}$ regularizes the singular behaviour of the *sum* of the *double-real* and *real-virtual* contribution
- The form of the counterterm is arbitrary: only its $q_T \to 0$ limit is fixed
- Once a form of the counterterm is chosen, the hard function $\mathcal{H}^H$ is uniquely identified ➡ **we choose the form used in our resummation work**

G. Bozzi, S. Catani, D. de Florian, MG (2005)

- At NLO (NNLO) the physical information of the *one-loop* (*two-loop*) contribution is contained in the coefficient $\mathcal{H}^{H(1)}$ ($\mathcal{H}^{H(2)}$)
- Due to the simplicity of the LO process, jets appear only in $d\sigma^{H+\mathrm{jet(s)}}_{(N)LO}$

➡ cuts on the jets can be effectively accounted for through a (N)LO calculation

S. Catani, D. de Florian, MG (2001)

LHC

Results: $gg \to H \to \gamma\gamma$

S. Catani, MG (2007)

Use cuts as in CMS TDR

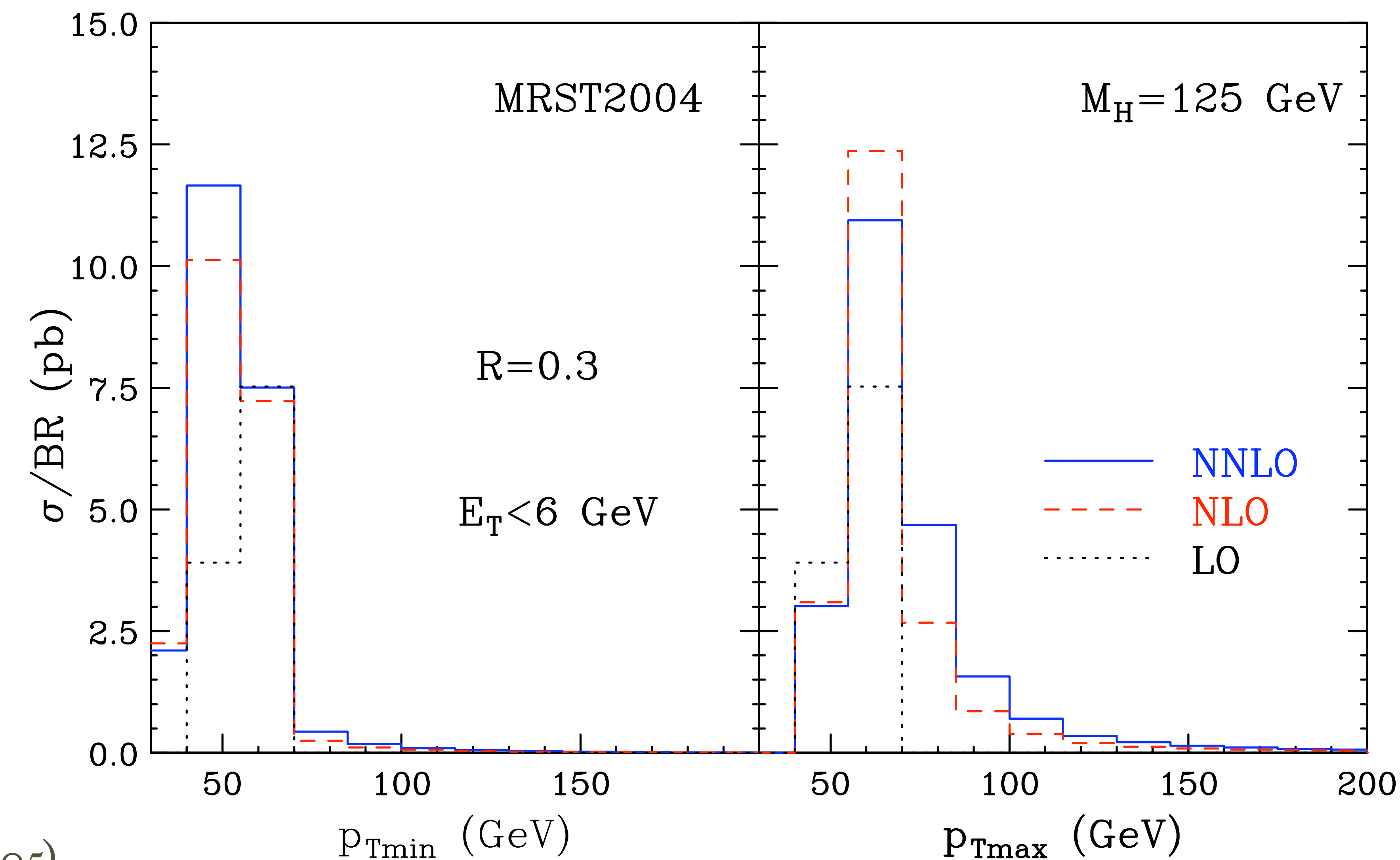
$p_T^{\min} > 35$ GeV

$p_T^{\max} > 40$ GeV

$|y| < 2.5$

Photons should be isolated: total transverse energy in a cone of radius $R = 0.3$ should be smaller than 6 GeV

corresponding distributions



note perturbative instability when $p_T \to M_H/2$

We find good agreement with FEHIP

Anastasiou et al. (2005)

Results: $gg \to H \to WW \to l\nu l\nu$

MG (2007)

Use *preselection cuts* as in Davatz. et al (2003)

see also C.Anastasiou, G. Dissertori, F. Stockli (2007)

$p_T^l > 20$ GeV

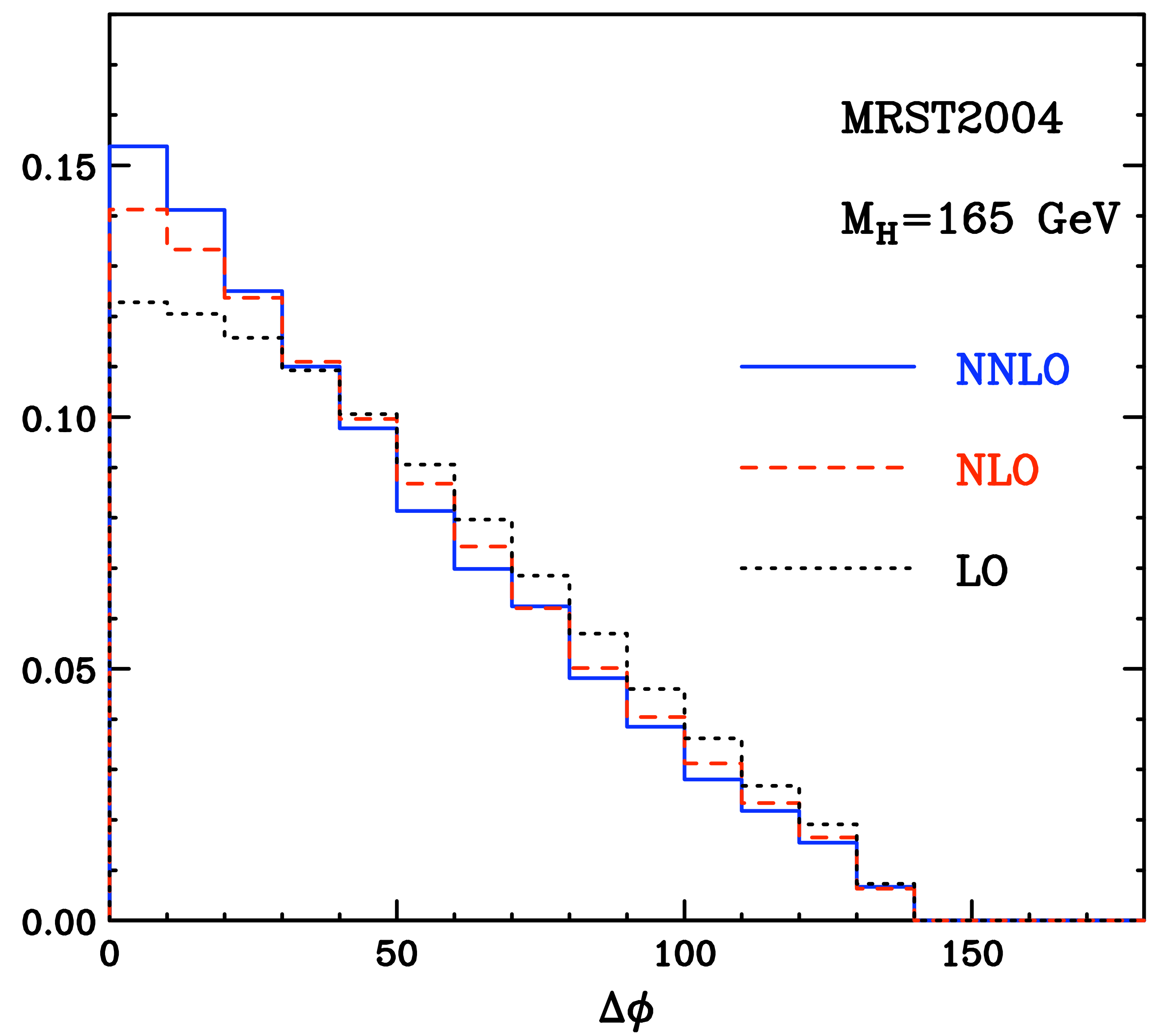
$|y_l| < 2$

$p_T^{miss} > 20$ GeV

$\Delta\phi < 135^o$

$m_{ll} < 80$ GeV

normalized $\Delta\phi$ **distribution**



The distributions appears to be steeper when going from LO to NLO and from NLO to NNLO

Results: $gg \to H \to WW \to l\nu l\nu$

MG (2007)

see also C.Anastasiou, G. Dissertori, F. Stockli (2007)

$p_T^{\rm min} > 25$ GeV $\quad m_{ll} < 35$ GeV $\quad \Delta\phi < 45^o$

$35\ \text{GeV} < p_T^{\rm max} < 50\ \text{GeV} \quad |y_l| < 2 \quad p_T^{\rm miss} > 20$ GeV

cuts as in Davatz et al. (2003)

Results for $p_T^{\rm veto} = 30$ GeV

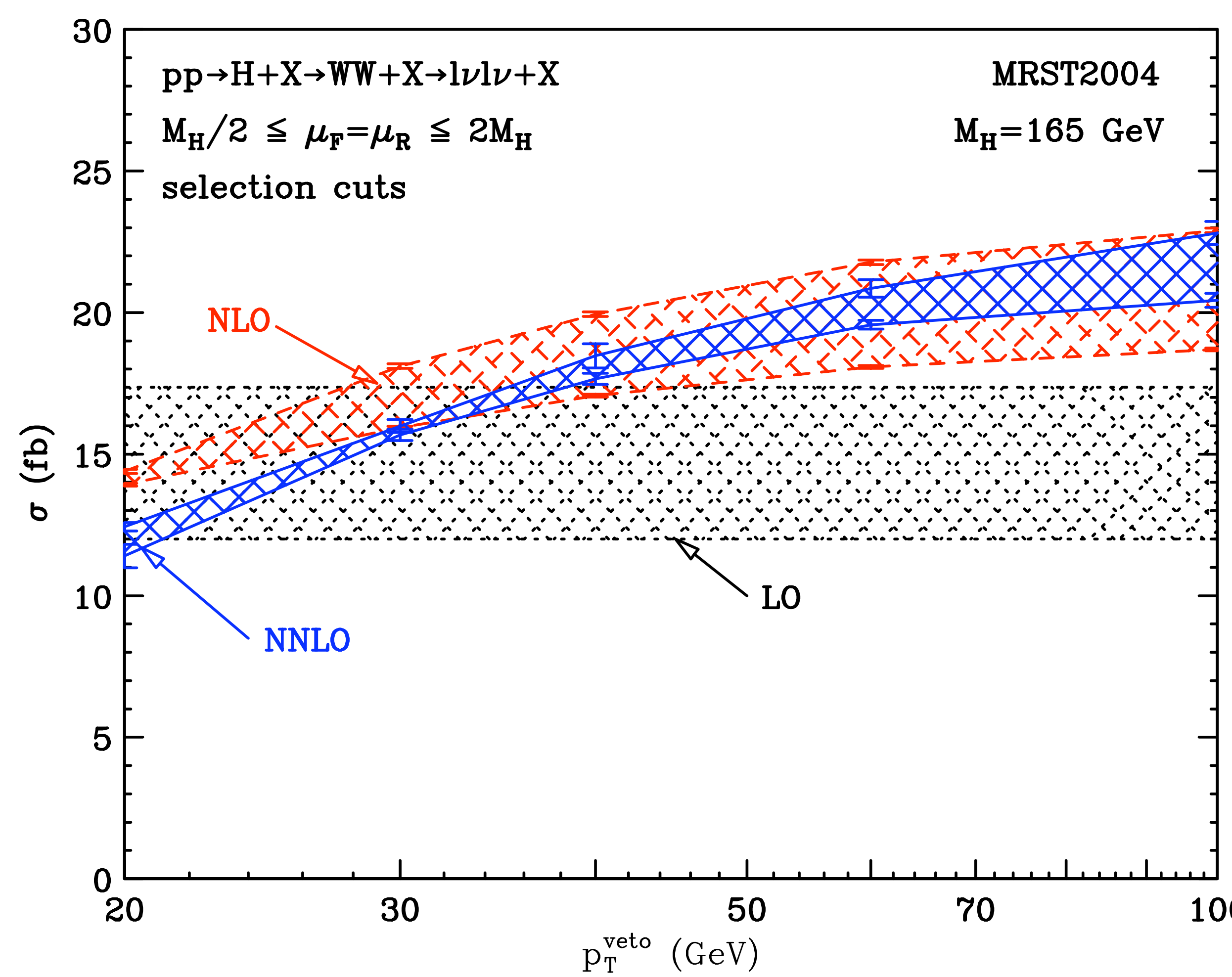
σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_H/2$	17.36 ± 0.02	18.11 ± 0.08	15.70 ± 0.32
$\mu_F = \mu_R = M_H$	14.39 ± 0.02	17.07 ± 0.06	15.99 ± 0.23
$\mu_F = \mu_R = 2M_H$	12.00 ± 0.02	15.94 ± 0.05	15.68 ± 0.20

➡ **Impact of higher order corrections strongly reduced by selection cuts**

The NNLO band overlaps with the NLO one for $p_T^{\rm veto} \gtrsim 30$ GeV

The bands do not overlap for $p_T^{\rm veto} \lesssim 30$ GeV

NNLO efficiencies found in good agreement with MC@NLO



Anastasiou et al. (2008)

Results: $gg \to H \to ZZ \to e^+e^-e^+e^-$

MG (2007)

Inclusive cross sections:

σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_H/2$	2.457 ± 0.001	4.387 ± 0.006	4.82 ± 0.03
$\mu_F = \mu_R = M_H$	2.000 ± 0.001	3.738 ± 0.004	4.52 ± 0.02
$\mu_F = \mu_R = 2M_H$	1.642 ± 0.001	3.227 ± 0.003	4.17 ± 0.01

$K_{NLO} = 1.87$ $K_{NNLO} = 2.26$

Consider the *selection cuts* as in the CMS TDR: $|y| < 2.5$

$p_{T1} > 30$ GeV $p_{T2} > 25$ GeV $p_{T3} > 15$ GeV $p_{T4} > 7$ GeV

Isolation: total transverse energy in a cone of radius R=0.2 around each lepton should fulfill $E_T < 0.05\ p_T$

For each e^+e^- pair, find the closest (m_1) and next to closest (m_2) to m_Z

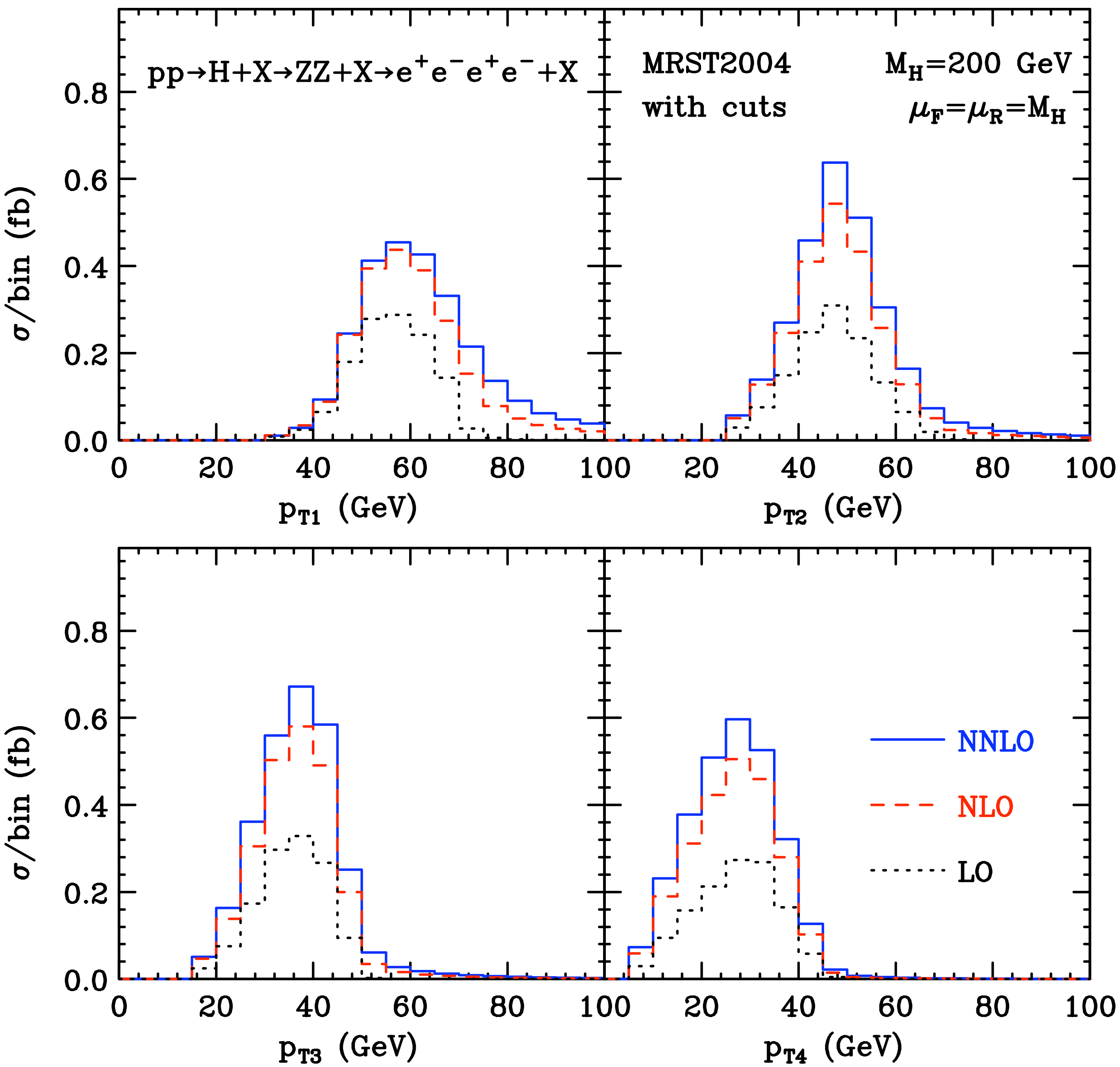
➡ $81\ \text{GeV} < m_1 < 101\ \text{GeV}$ and $40\ \text{GeV} < m_2 < 110\ \text{GeV}$

The corresponding cross sections are:

σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_H/2$	1.541 ± 0.002	2.764 ± 0.005	2.966 ± 0.023
$\mu_F = \mu_R = M_H$	1.264 ± 0.001	2.360 ± 0.003	2.805 ± 0.015
$\mu_F = \mu_R = 2M_H$	1.047 ± 0.001	2.044 ± 0.003	2.609 ± 0.010

$$K_{NLO} = 1.87$$

$$K_{NNLO} = 2.22$$



→ in this case the cuts are mild and do not change significantly the impact of higher order corrections

Note that at LO

$$p_{T1}, p_{T2} < M_H/2$$

$$p_{T3} < M_H/3 \quad p_{T4} < M_H/4$$

Behaviour at the kinematical boundary is smooth

→ No instabilities beyond LO

TEVATRON

Results: $gg \to H \to WW \to l\nu l\nu$

I consider $M_H = 160$ GeV → The inclusive K-factors are:

$K_{NLO} = 2.42 \quad K_{NNLO} = 3.31$

I use the cuts from the CDF paper PRL 97 (2006) 081802

Trigger: Select events with $WW \to e^+e^-\nu\bar{\nu}, \mu^+\mu^-\nu\bar{\nu}, e^\pm\mu^\mp\nu\bar{\nu}$

and one of the following signatures:

- a central electron with $|\eta| < 1.1$ and $E_T > 18$ GeV
- a forward electron with $1.2 < |\eta| < 2$ with $E_T > 20$ GeV and $\not{E}_T > 15$ GeV
- a central muon with $|\eta| < 1$ and $p_T > 18$ GeV

Trigger efficiency is $\epsilon = 88\,\%$ at LO

Selection cuts for $M_H = 160$ GeV*:*

- $p_{T1} > 20$ GeV $\quad p_{T2} > 10$ GeV $\quad \not{E}_T > 40$ GeV
- Isolation: energy in a cone of radius R=0.4 around each lepton should fulfill $E < 0.1\ p_T$
- If $\not{E}_T < 50$ GeV ➡ $\Delta\phi(\not{E}_T, p) > 20^o$ for each lepton or jet
- $16 \text{ GeV} < m_{ll} < 75$ GeV
- Count jets with $E_T > 15$ GeV and $|\eta| < 2.5$

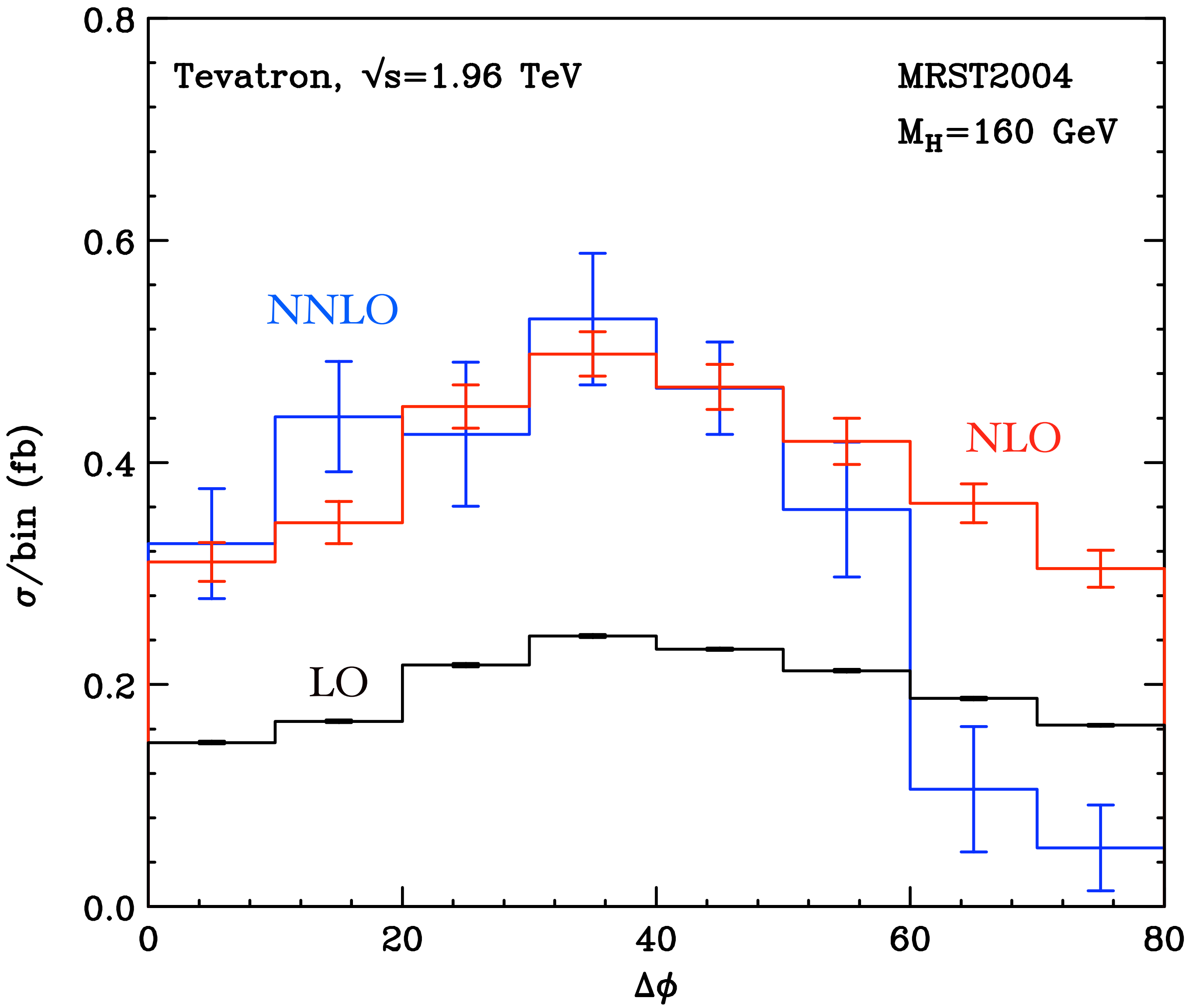
  ➡ Require either no such jet, or one of such jets and $E_T < 55$ GeV or two with $E_T < 40$ GeV (reduces $t\bar{t}$ background)
- Scalar sum of the p_T of the two leptons and $\not{E}_T$ should be smaller than M_H
- Concentrate on small $\Delta\phi$ region: $\Delta\phi < 80^o$

Results

$$\sigma_{LO} = (1.571 \pm 0.003)\ \text{fb}$$

$$\sigma_{NLO} = (3.16 \pm 0.01)\ \text{fb}$$

$$\sigma_{NNLO} = (2.78 \pm 0.17)\ \text{fb}$$



→ $$K_{NLO} = 2.01$$

$$K_{NNLO} = 1.77$$

As for the LHC, the impact of higher order corrections appears to be strongly reduced by the selection cuts

Efficiencies: $\epsilon_{LO} = 33\%$ $\epsilon_{NLO} = 27\%$ $\epsilon_{NNLO} = 18\%$

→ Large theoretical uncertainties that need to be further investigated

Summary

- HNNLO is a numerical program to compute Higgs boson production through gluon fusion in pp or $p\bar{p}$ collisions at LO, NLO, NNLO

- It implements all the relevant decay modes of the Higgs boson:
$H \to \gamma\gamma \quad H \to WW \to l\nu l\nu \quad H \to ZZ \to 4l$

- It allows the user to apply arbitrary cuts on the final state photon/leptons and the associated jet activity, and to obtain the required distributions in the form of bin histograms

- These features should make our program a useful tool for Higgs studies at the Tevatron and the LHC

- Public version can be downloaded from

http://theory.fi.infn.it/grazzini/codes.html