HNNLO: a MC program for Higgs boson production at hadron colliders

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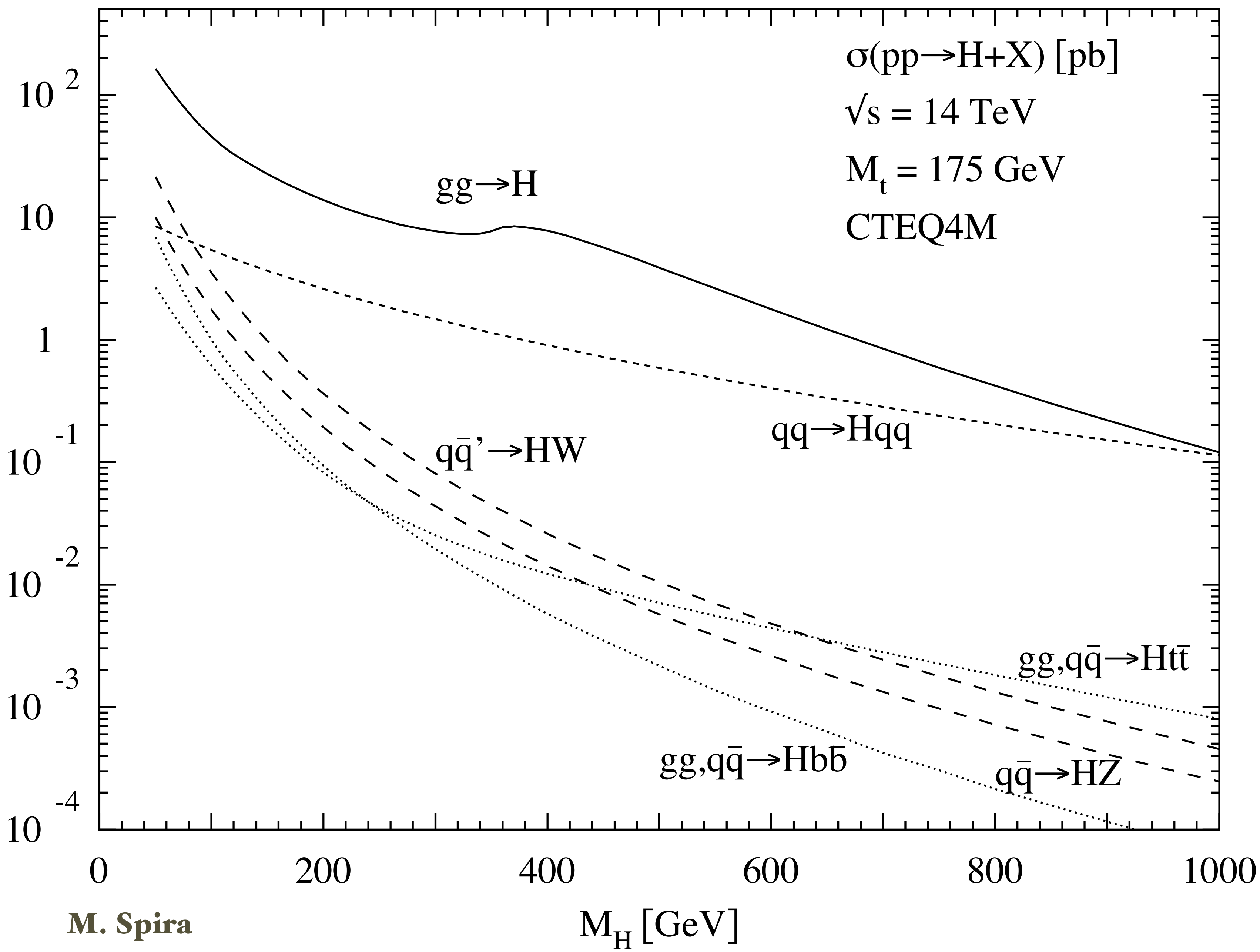
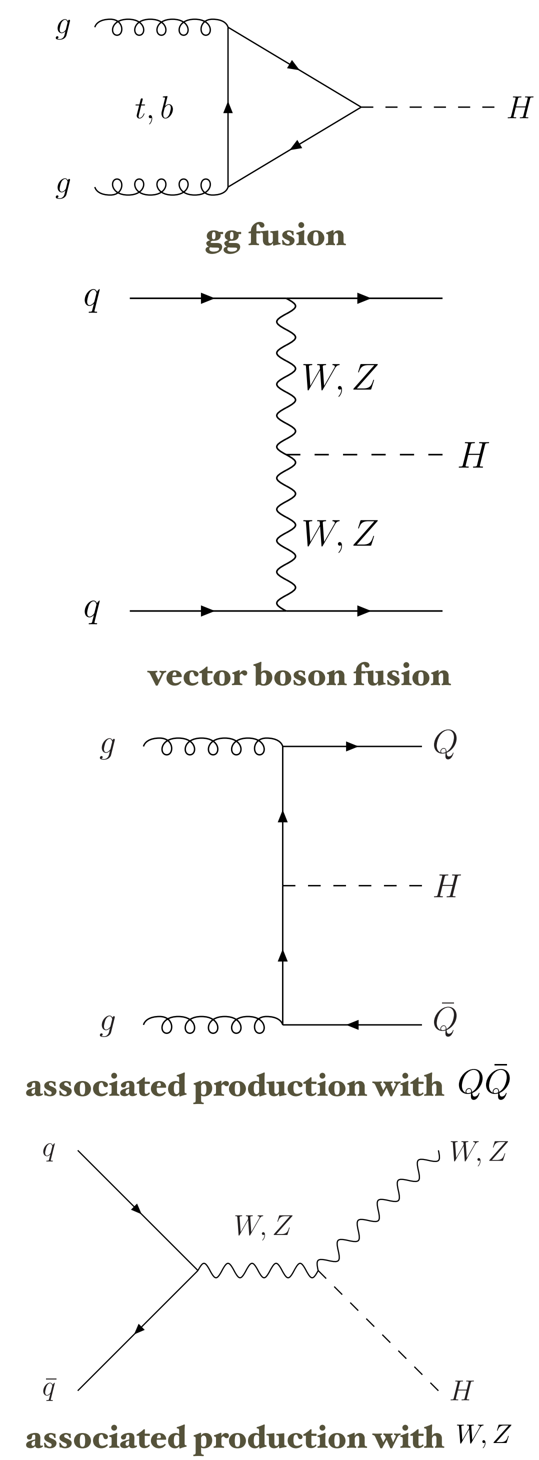
RADCOR 2007

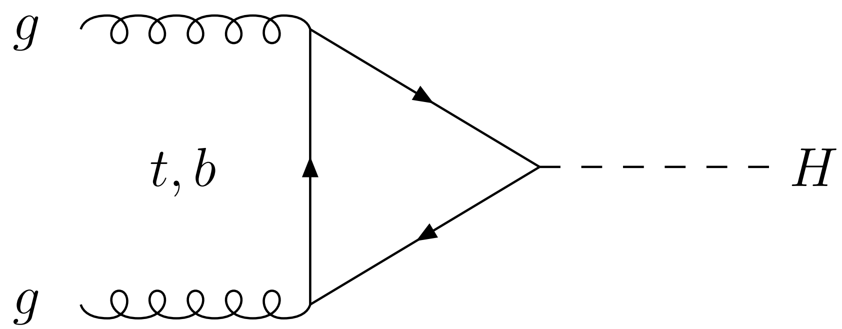
Higgs production at the LHC





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

S. Catani, D. De Florian, P. Nason, MG (2003)

Effects of soft-gluon resummation: additional +6 %

EW two-loop effects also known (+5-8 %)

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 the $H \to \gamma\gamma$ and $H \to WW$ decays

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

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)

For a generic $pp \to F + X$ process:

- At NLO we need a LO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$

  - the counterterm $d\sigma^{CT}_{LO}$ requires the resummation coefficients $A^{(1)}, B^{(1)}$ and the one loop anomalous dimensions

  - the general form of $\mathcal{H}^{F(1)}$ is known

D. de Florian, MG (2000)
G. Bozzi, S. Catani, D. de Florian, MG (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$

  - the counterterm $d\sigma^{CT}_{NLO}$ depends also on the resummation coefficients $A^{(2)}, B^{(2)}$ and on the two loop anomalous dimensions

  - the general form of $\mathcal{H}^{F(2)}$ is not known.....
  ....but we have computed $\mathcal{H}^{H(2)}$ for Higgs production !

S. Catani, MG (2007)

→ **since H+1 jet is known to NLO we have all the necessary ingredients to go to NNLO**

.....and now results.......

An example: $gg \to H \to \gamma\gamma$

Use cuts as in CMS TDR

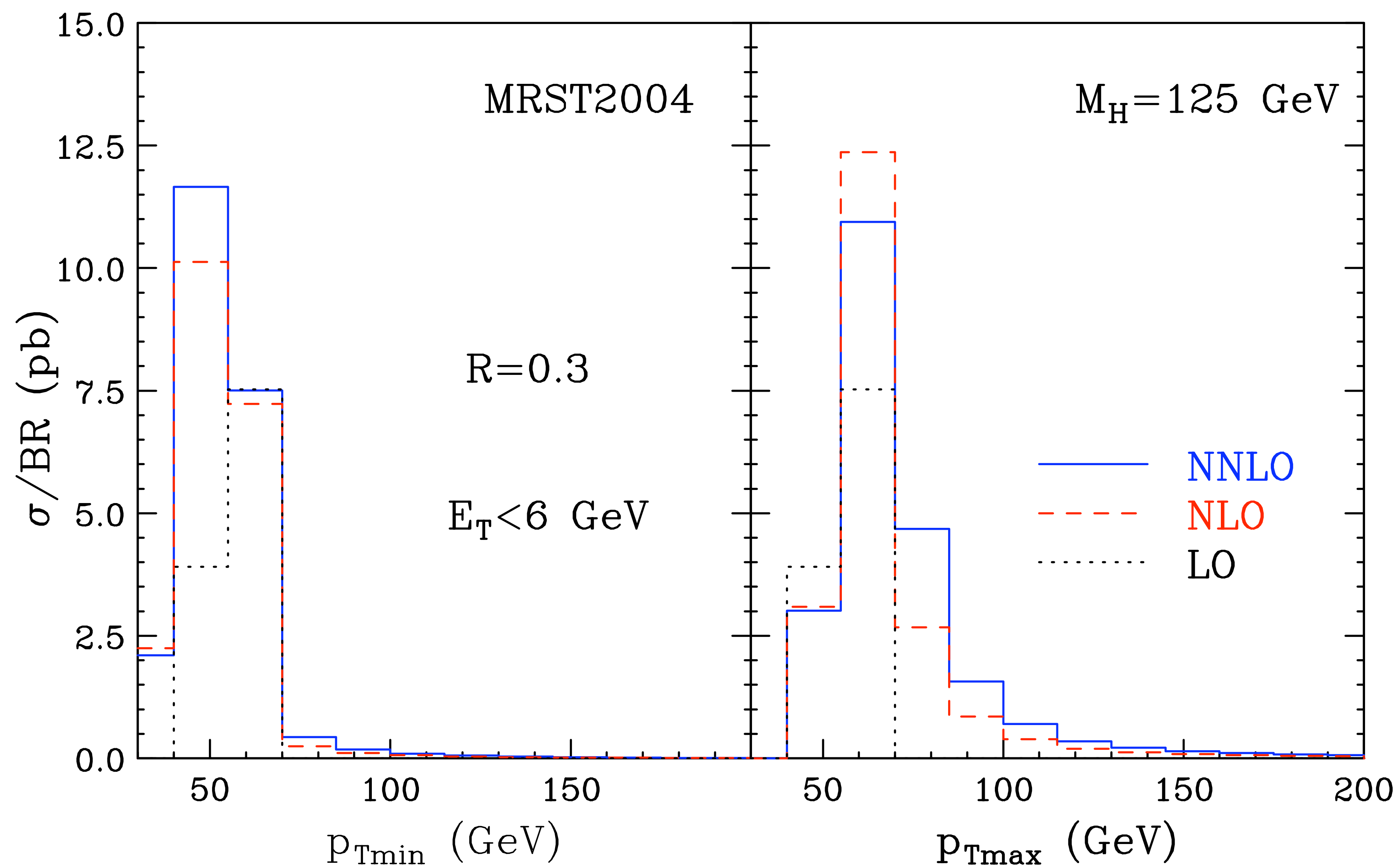
$p_T^{\rm min} > 35$ GeV

$p_T^{\rm max} > 40$ 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

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$p_T^{\max} > 40$ GeV

$|y| < 2.5$

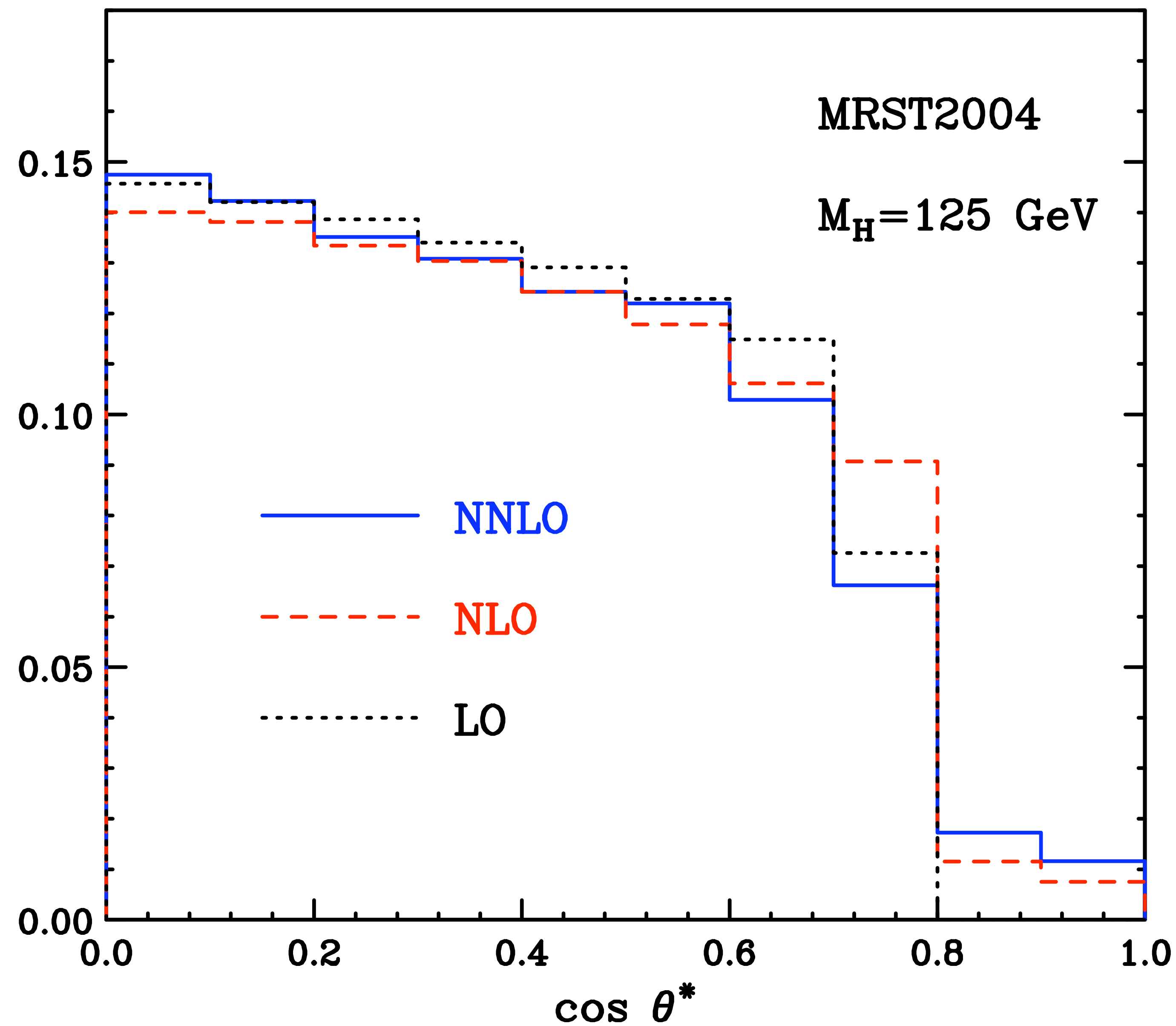
Photons should be isolated: total transverse energy in a cone of radius $R = 0.3$ should be smaller than 6 GeV

define $\cos\theta^*$ **distribution**

θ^* **polar angle of one of the photons in the Higgs rest frame (used by ATLAS)**

note upper bound on $\cos\theta^*$ at LO

- again perturbative instability beyond LO !



An example: $gg \to H \to WW \to l\nu l\nu$

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

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

$p_T^l > 20$ GeV

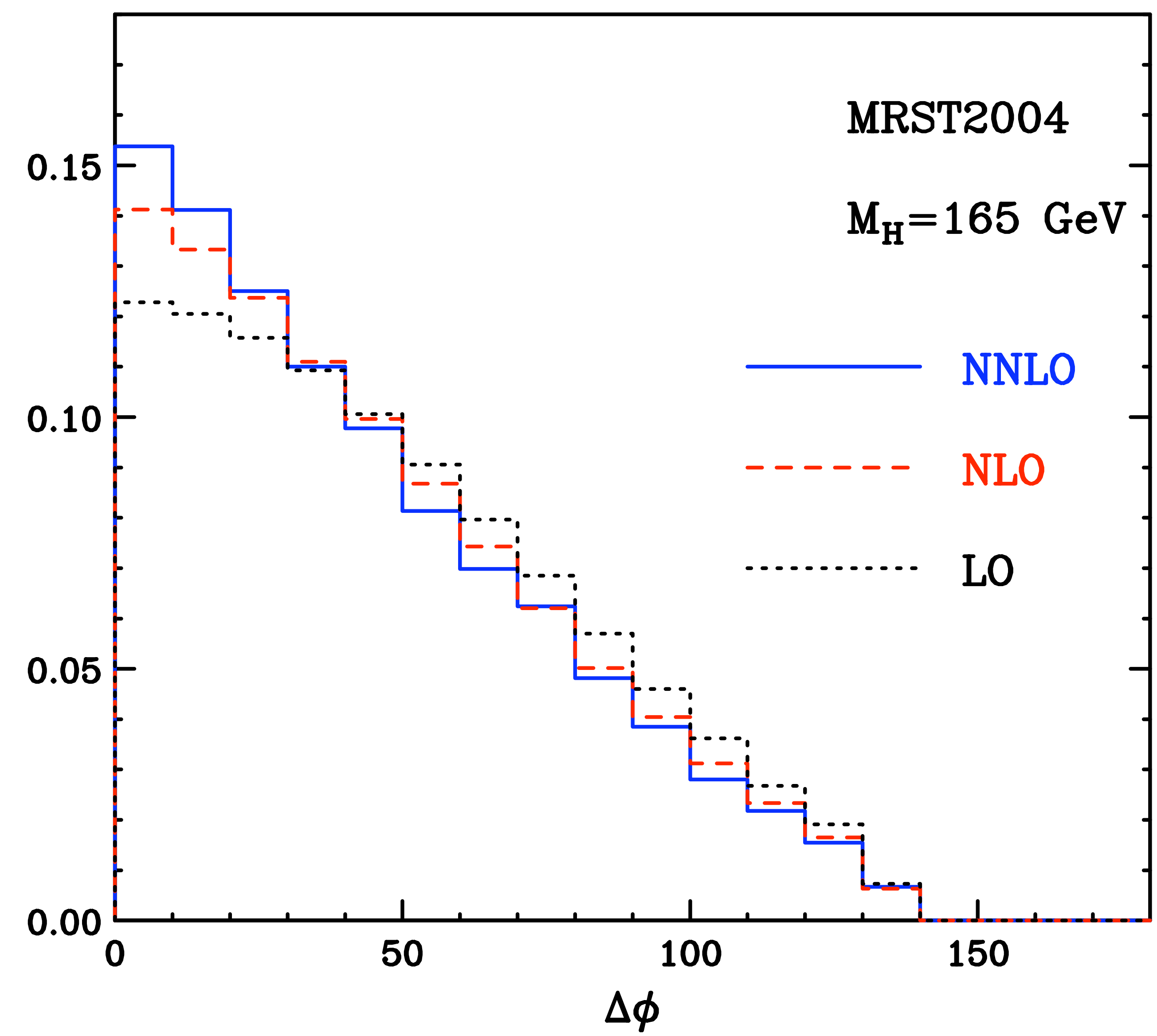
$|y_l| < 2$

$p_T^{\text{miss}} > 20$ 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

An example: $gg \to H \to WW \to l\nu l\nu$

Use now selection cuts as in Davatz. et al (2003)

$p_T^{\min} > 25$ GeV

$m_{ll} < 35$ GeV

$35 \text{ GeV} < p_T^{\max} < 50 \text{ GeV}$

$|y_l| < 2$

$p_T^{\text{miss}} > 20$ GeV

$\Delta\phi < 45^o$

$\mu_F = \mu_R = M_H$

Effect of a jet veto on top of the leptonic cuts →

p_T^{veto} (GeV)	σ_{NLO} (fb)	σ_{NNLO} (fb)
no veto	21.26 ± 0.05	22.21 ± 0.32
40	18.62 ± 0.05	17.38 ± 0.34
30	17.18 ± 0.05	15.74 ± 0.35
20	14.42 ± 0.05	11.31 ± 0.38

Summary

- I have presented an extension of the subtraction method to compute NNLO corrections to 2->1 processes in hadron collisions
- The method has been applied to Higgs boson production in hadron collision and is implemented in the MC program HNNLO
- It computes Higgs production in pp or $p\bar{p}$ collisions in the large-m_{top} limit at LO, NLO and NNLO
- It implements $H \to \gamma\gamma$ and $H \to WW \to l\nu l\nu$ decay modes
- I presented the first results: more to come !
- Public version can be downloaded from

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