Higgs production at hadron colliders: selected results

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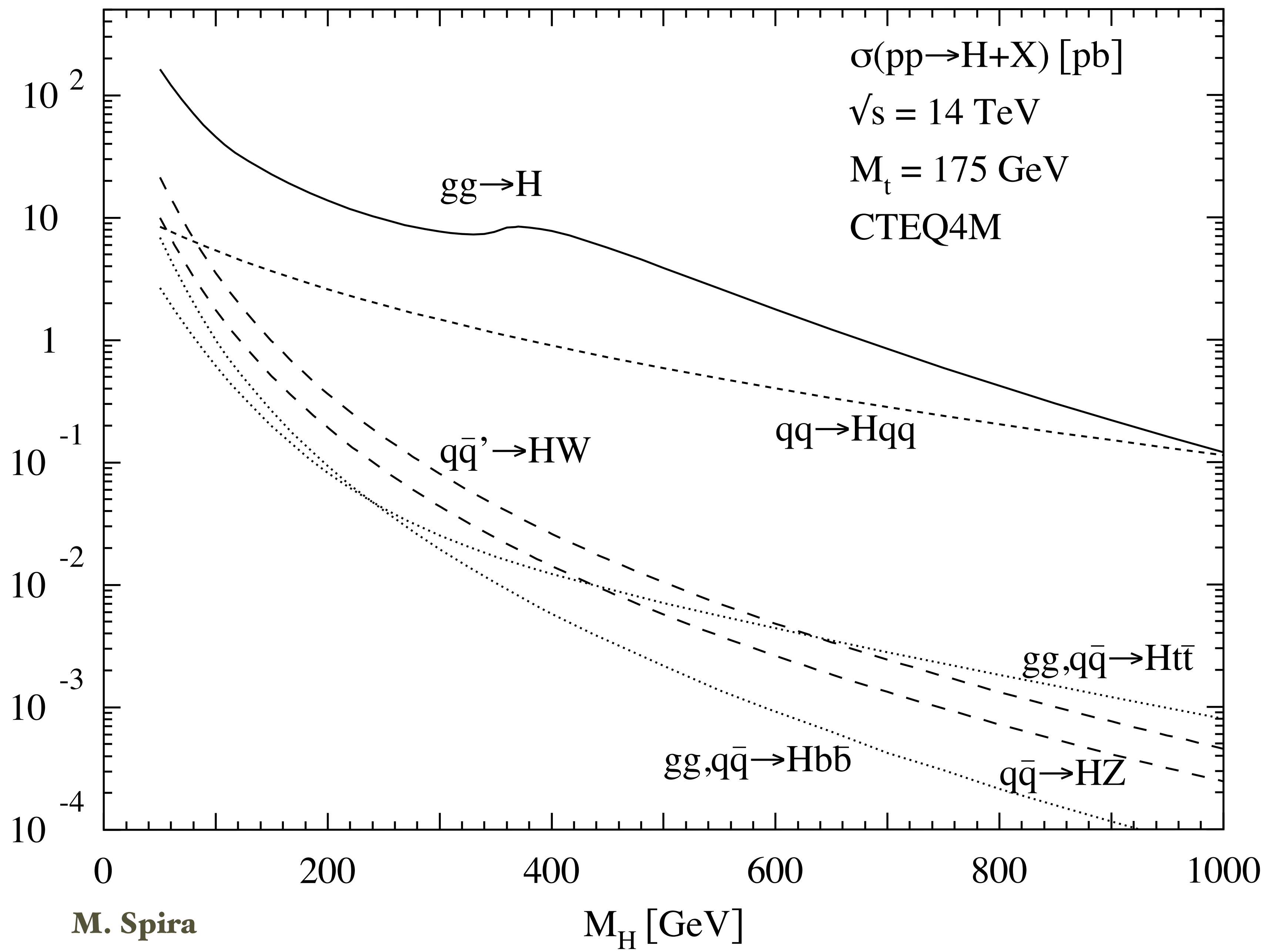
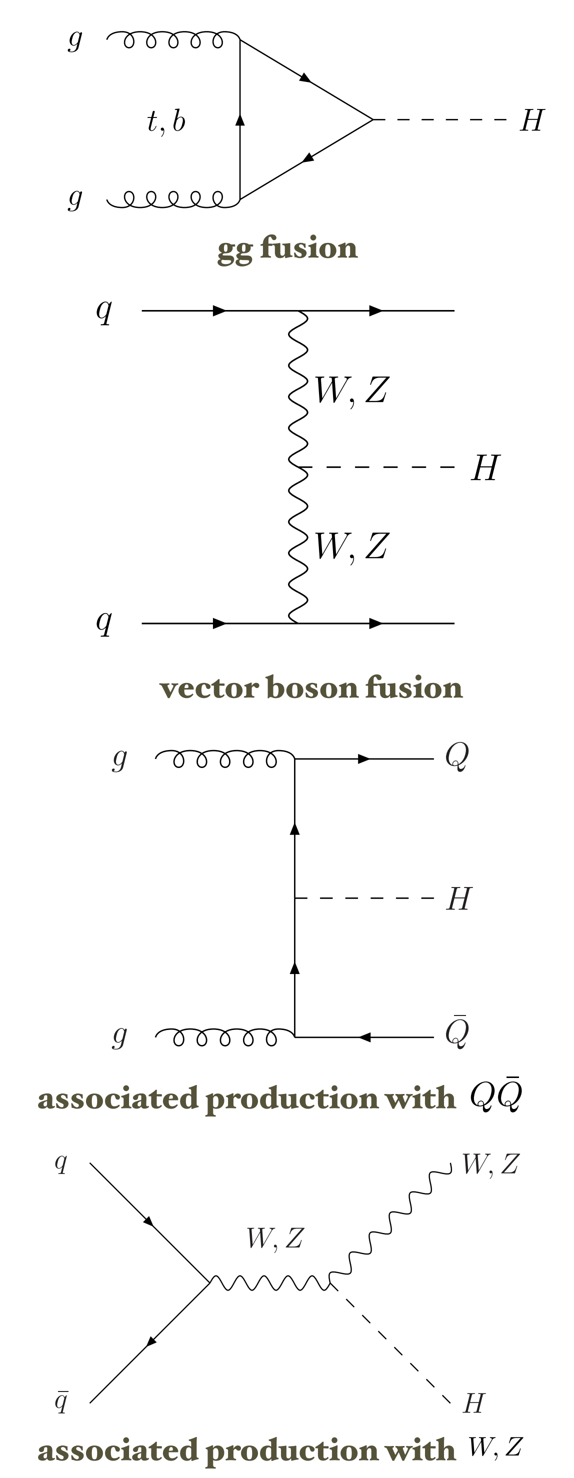
Outline

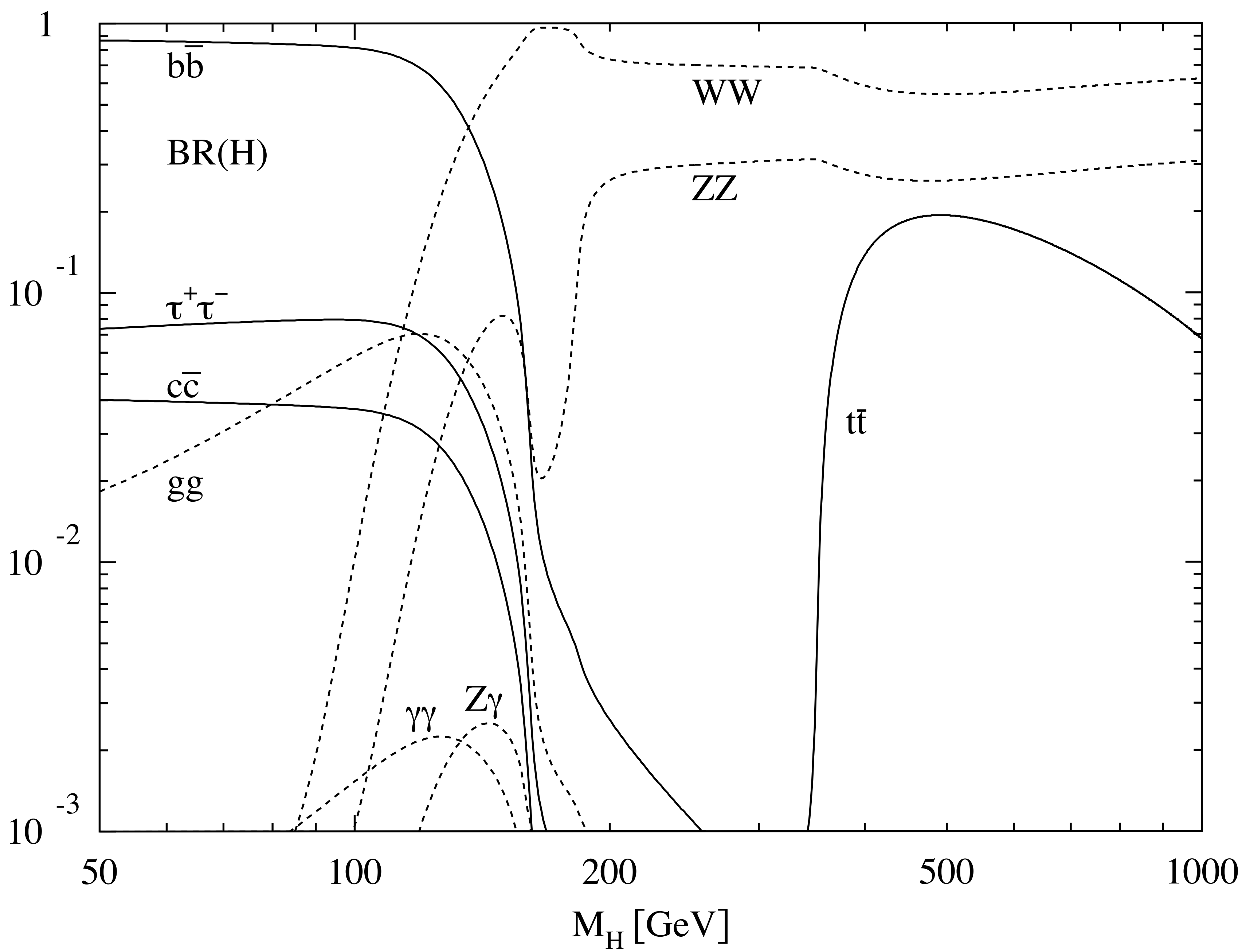
- Introduction
- Higgs search at hadron colliders: gg fusion
- Theoretical predictions
  - HNNLO
  - Transverse momentum resummation
- Conclusions

Higgs production at the LHC





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



Key point:
enormous QCD background

$$\sigma(gg \to H \to b\bar{b}) \sim 20\ pb$$

$$\sigma(b\bar{b}) \sim 500\ \mu b$$

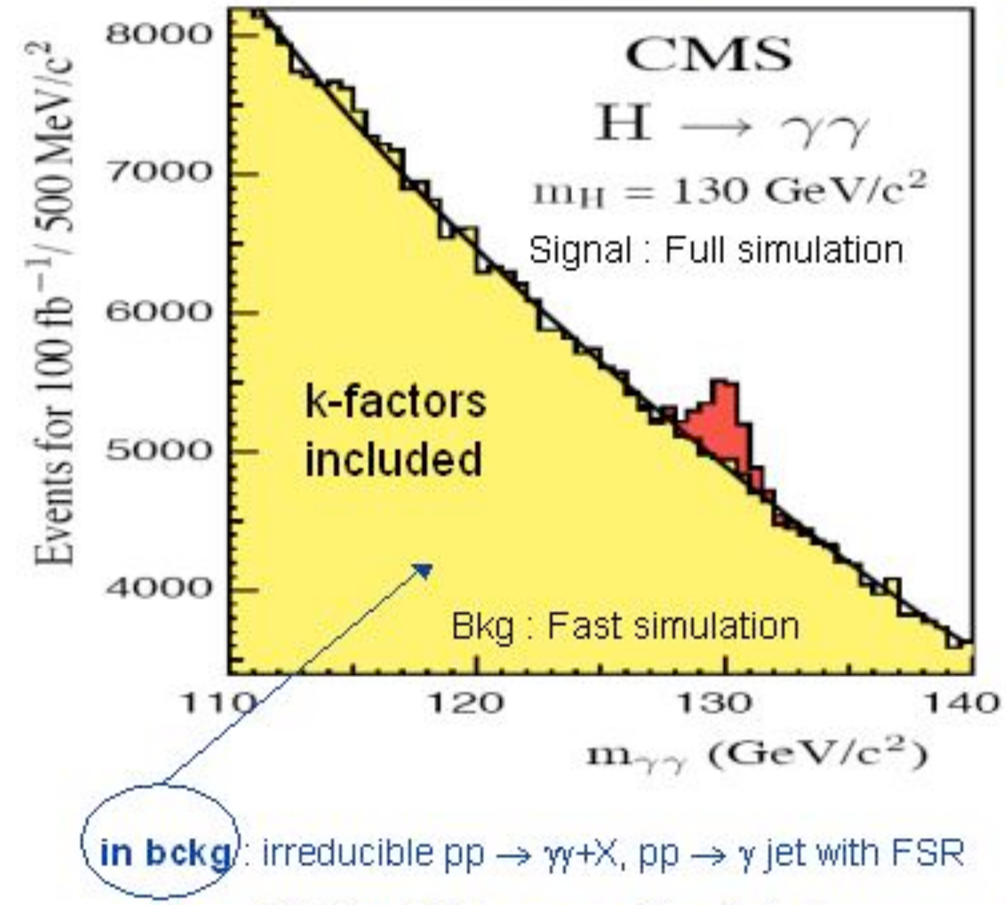
No chance to look at fully hadronic final states

- For $M_H \lesssim 140$ GeV → $H \to \gamma\gamma$ (BR $\sim 10^{-3}$)
- For $140 \lesssim M_H \lesssim 180$ GeV → $H \to WW^* \to l\nu l\nu$
- $M_H > 2M_Z$ → $H \to ZZ \to 4l$ (gold pleated)

$H \rightarrow \gamma\gamma$

Background very large but the narrow width of the Higgs and the excellent mass resolution expected should allow to extract the signal

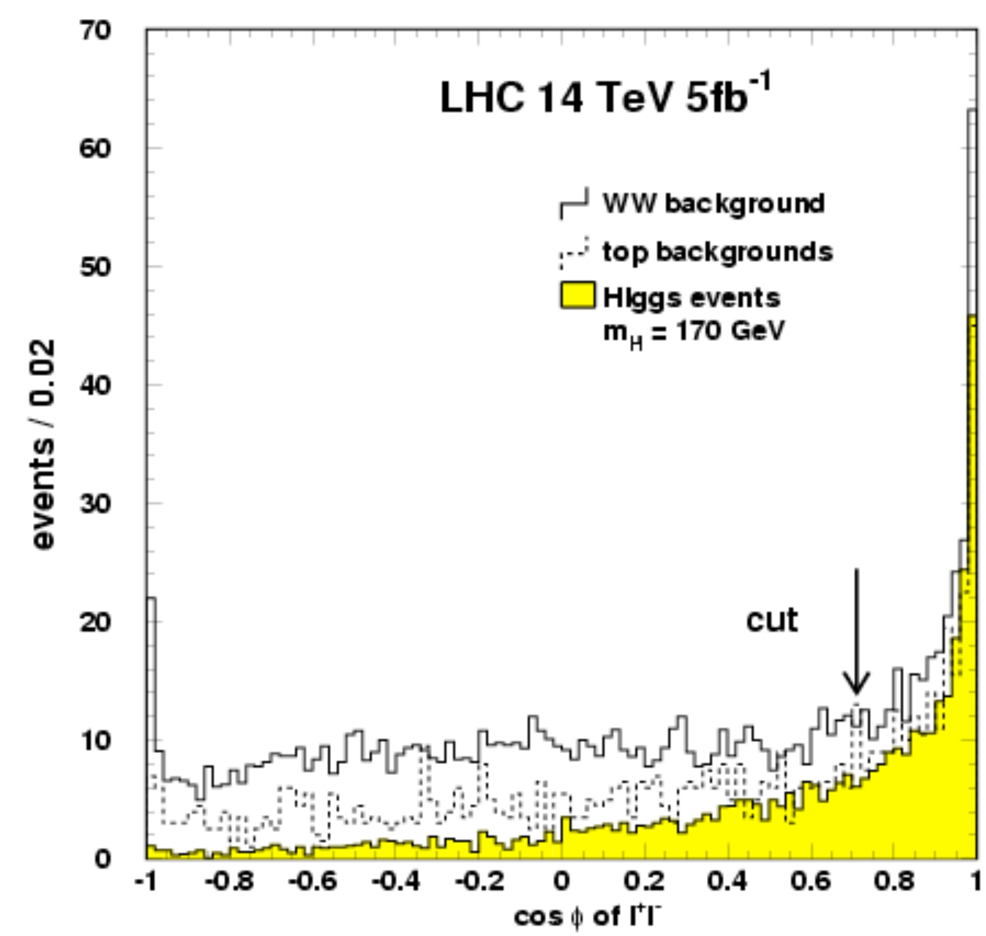
Background measured from sidebands



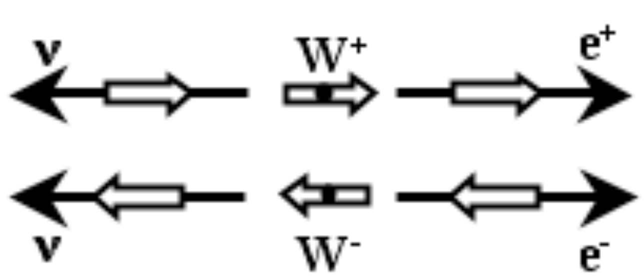
$H \rightarrow WW^* \rightarrow l\nu l\nu$

No mass peak but strong angular correlations between the leptons

M.Dittmar, H.Dreiner (1996)



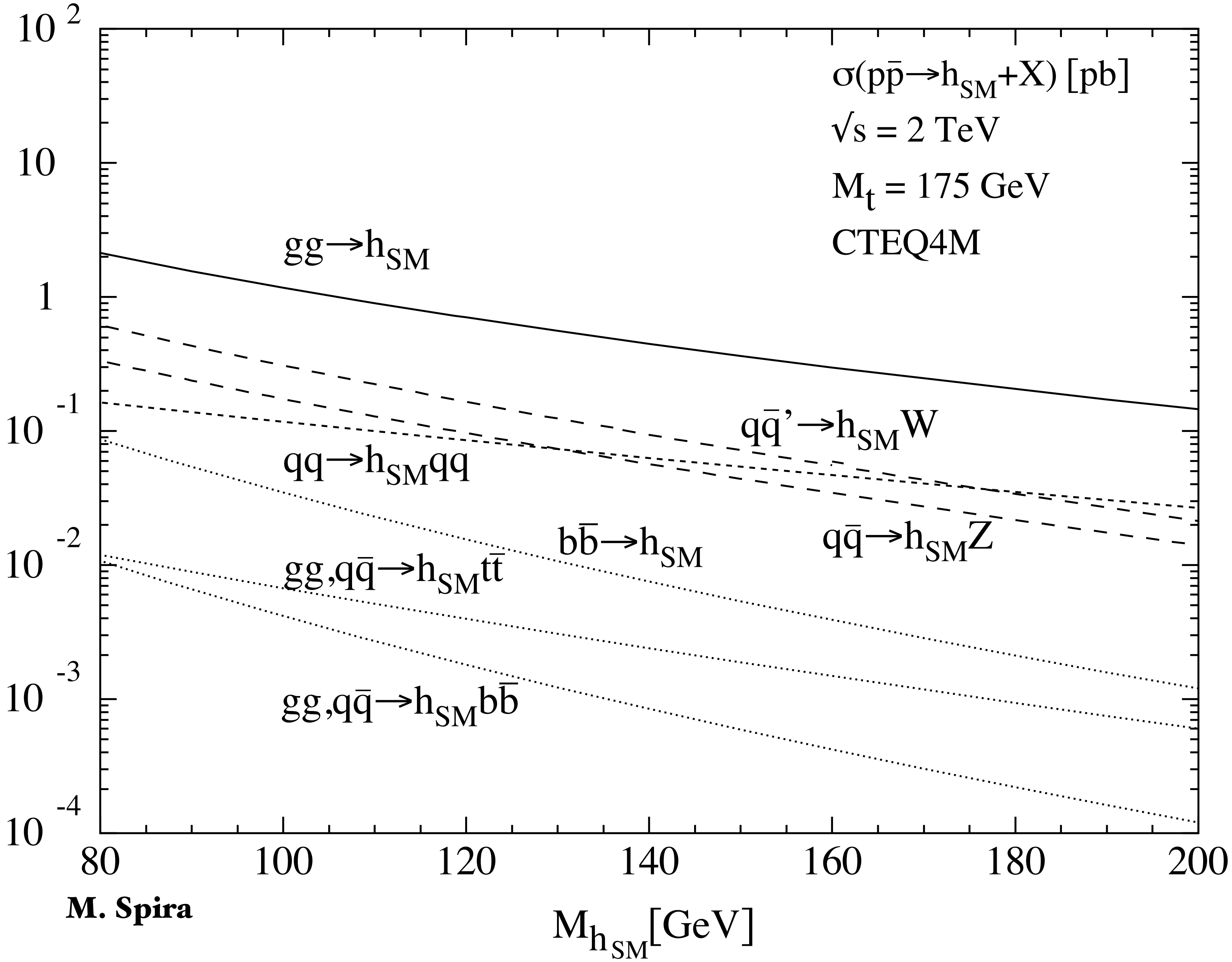
V-A interaction:



$l^{+(-)}$ (anti-) parallel to $W^{+(-)}$ spin

H scalar → charged leptons tend to be close in angle

Higgs production at the Tevatron



As for the LHC

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

is ruled out by the huge background

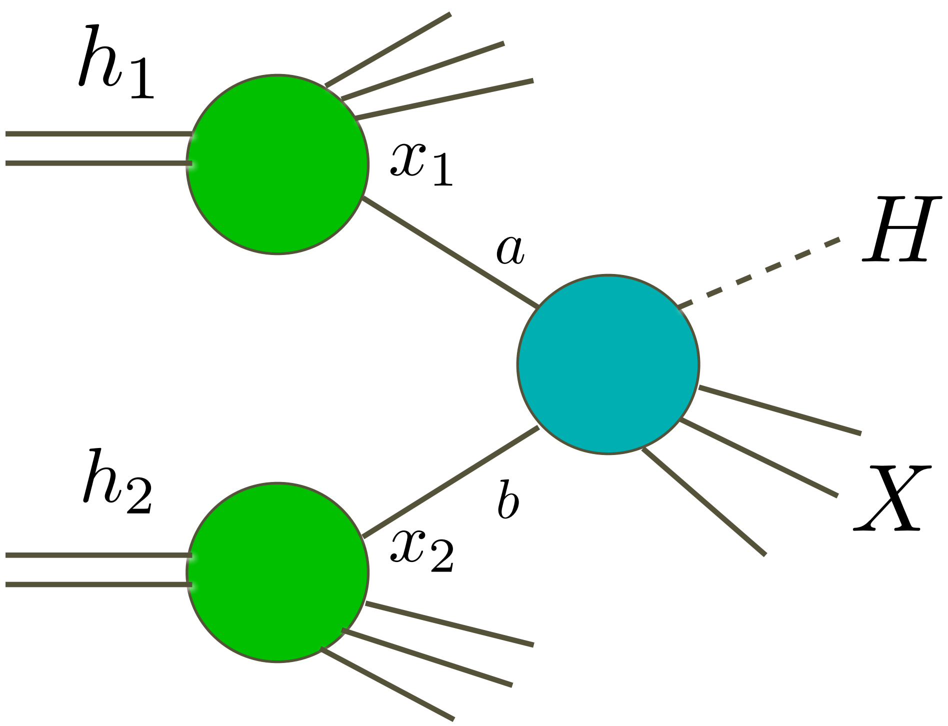
But: $H \to \gamma\gamma$ too small to be observed !

$M_H \lesssim 130$ GeV → $pp \to HW \to b\bar{b}\, l\nu$ → The lepton gives the necessary background rejection

$M_H \gtrsim 130$ GeV → $gg \to WW \to l\nu l\nu$

Theoretical predictions

The framework: QCD factorization theorem



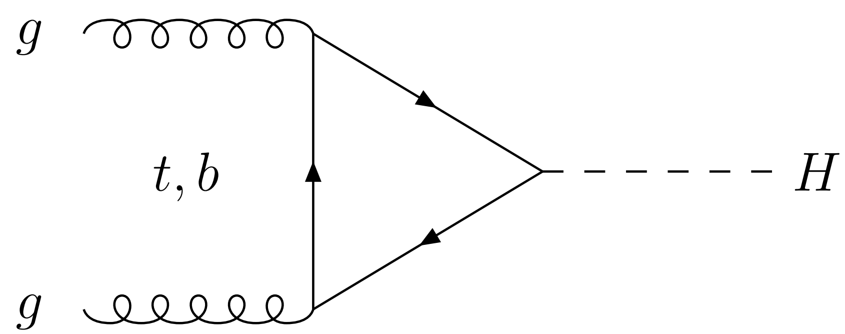
Parton distributions

Partonic cross section

$$\sigma(p_1,p_2;M_H) = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,\mu_F^2)\, f_{h_2,b}(x_2,\mu_F^2) \times \hat{\sigma}_{ab}(x_1p_1, x_2p_2, \alpha_S(\mu_R^2);\mu_F^2)$$

Precise predictions for σ depend on good knowledge of BOTH $\hat{\sigma}_{ab}$ and $f_{h,a}(x,\mu_F^2)$

gg fusion



The Higgs coupling is proportional to the quark mass

→ top-loop dominates

It is a one-loop process already at Born level

→ calculation of higher order corrections is very difficult

NLO QCD corrections to the total rate computed more than 10 years ago and found to be large

They increase the LO result by about 80% !

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

They are well approximated by the large-m_{top} limit

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

The large-m_{top} approximation

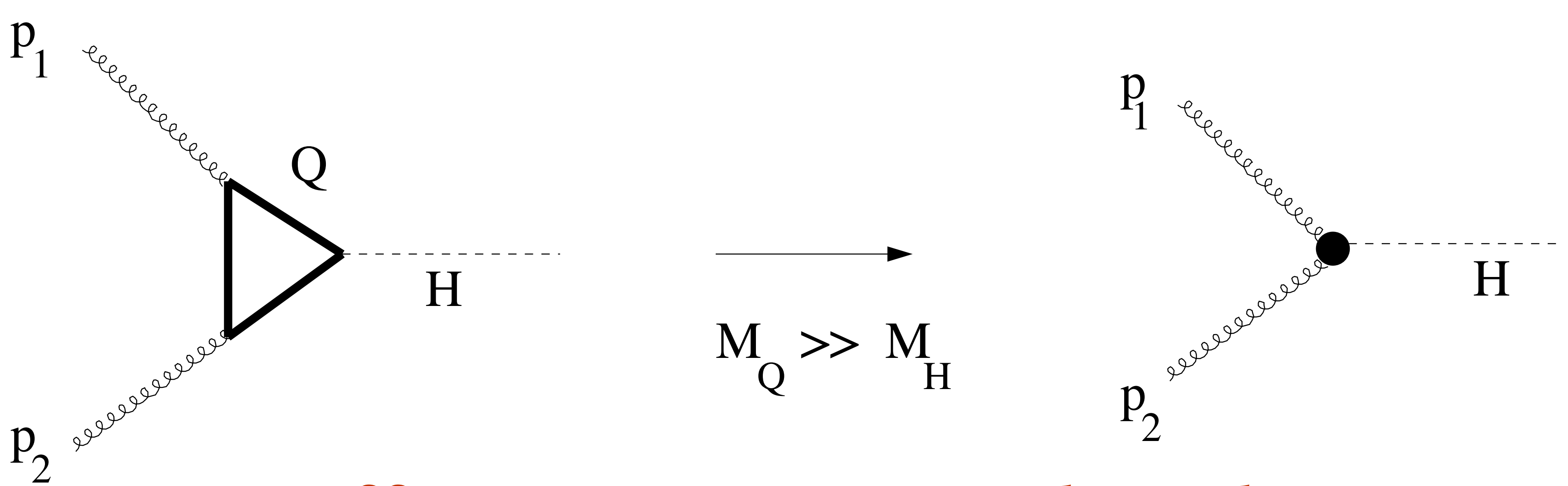
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1976)
M.Voloshin, V.Zakharov, M.Shifman (1979)

$$\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_S}{3\pi}\frac{H}{v}(1+\Delta)\right] \mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu}$$

Known to $\mathcal{O}(\alpha_S^3)$

K.G.Chetirkin, M.Steinhauser, B.A.Kniehl (1997)



Effective vertex: one loop less !

$gg \to H$ at NNLO

NLO corrections are well approximated by the large- m_{top} limit

This is not accidental: the bulk of the effect comes from virtual and real radiation at relatively low transverse momenta: weakly sensitive to the top loop → **reason: steepness of the gluon density at small x**

$$g \sim (1-x)^{\eta}$$
$$\eta \sim 5-7$$

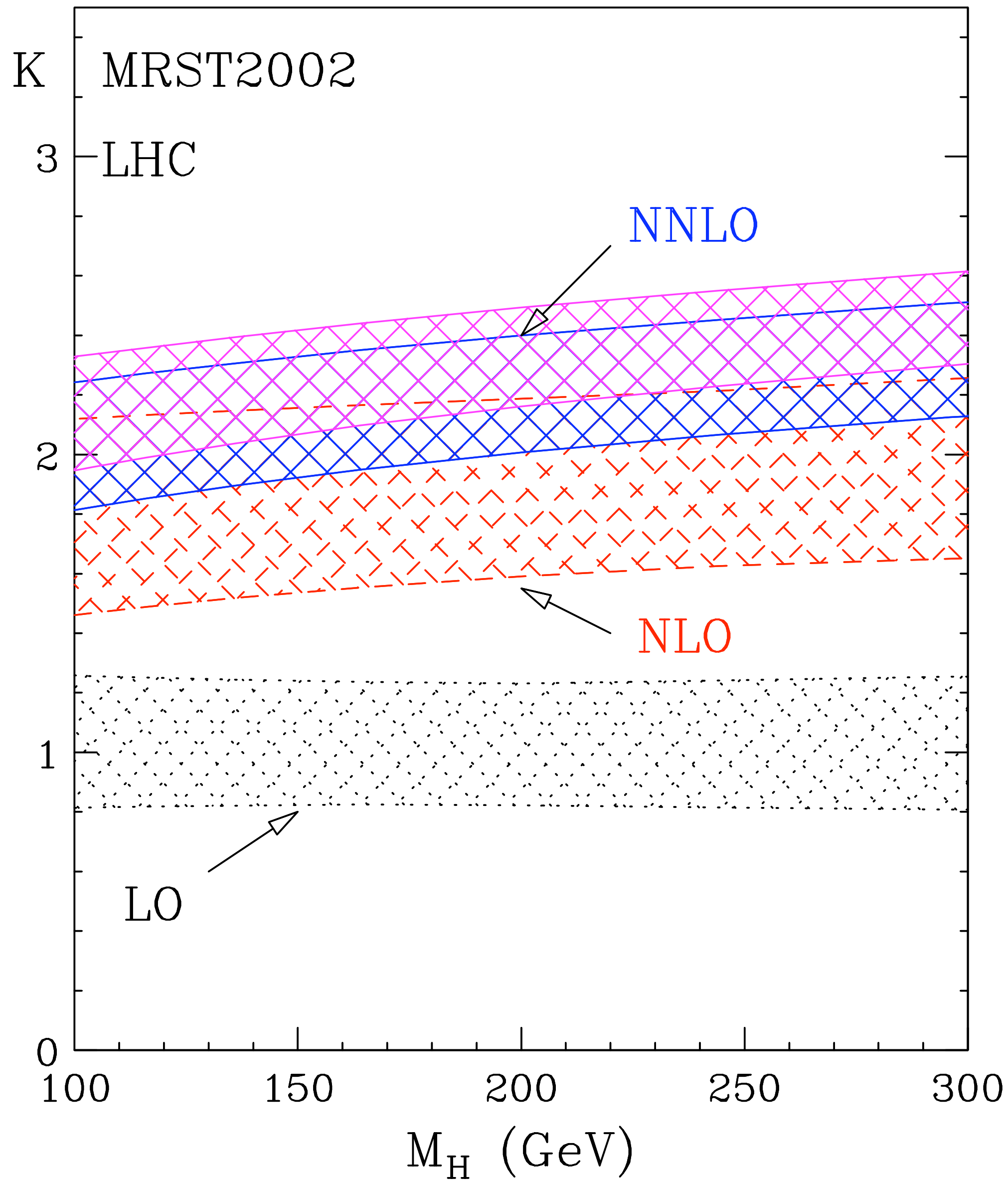
NNLO corrections computed in the large m_{top} limit

Dominance of soft-virtual effects persists at NNLO: hard effects are only about 2% at the LHC

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)

→ This is reassuring because the hard effects are the most sensitive to the heavy quark-loop

Inclusive results at the LHC



Inclusion of soft-gluon effects at all orders

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

For a light Higgs:
NNLO effect $+15 - 20\,\%$

NNLL effect $+6\%$

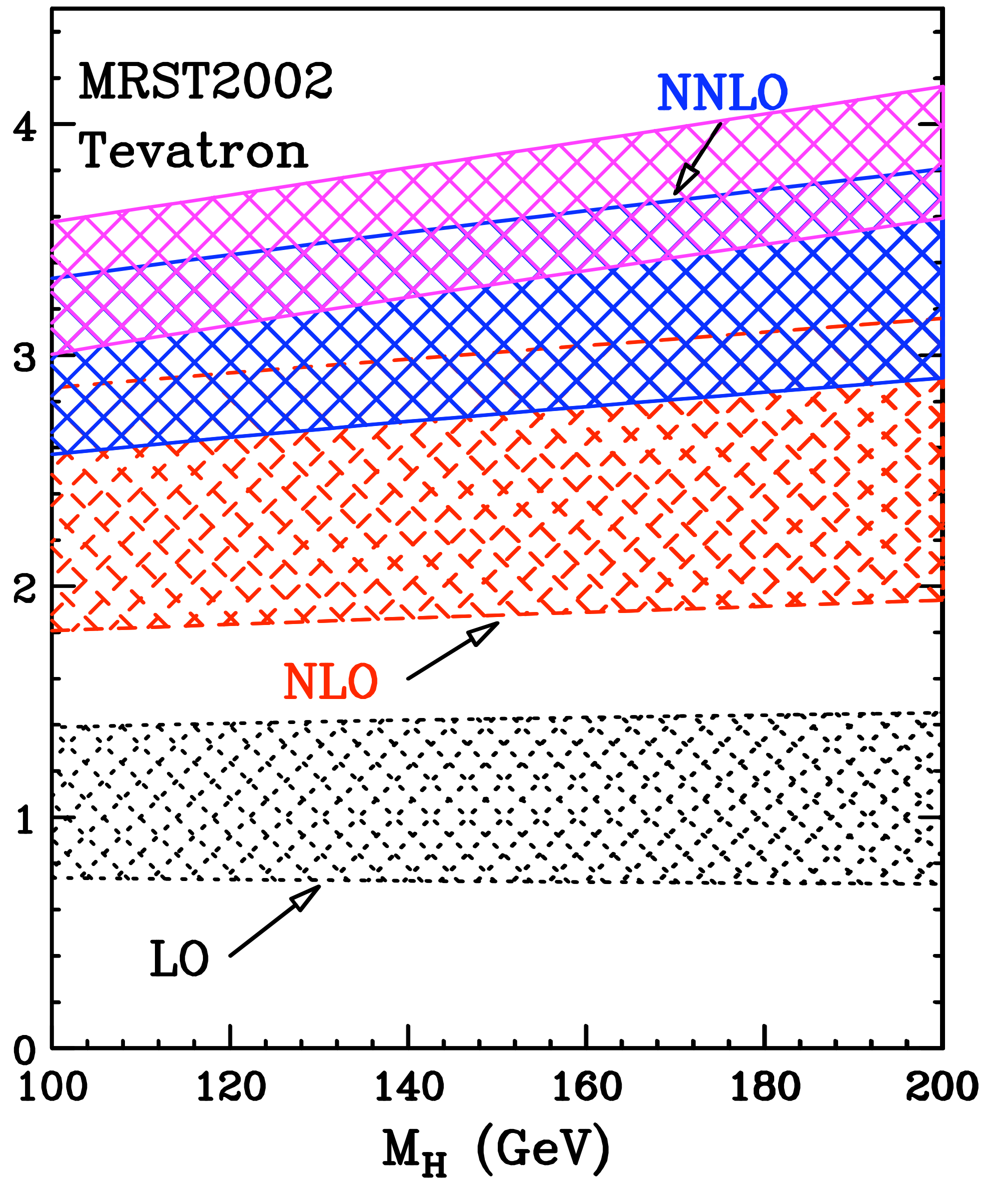
Good stability of perturbative result

Nicely confirmed by computation of soft terms at N^3LO

S. Moch, A. Vogt (2005), E. Laenen, L. Magnea (2005)

- K-factors defined with respect $\sigma_{LO}(\mu_F = \mu_R = M_H)$
- With $\mu_{F(R)} = \chi_{L(R)} M_H$ and $0.5 \leq \chi_{L(R)} \leq 2$ but $0.5 \leq \chi_F/\chi_R \leq 2$

Inclusive results at the Tevatron



Inclusion of soft-gluon effects at all orders

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

For a light Higgs:
NNLO effect $+40\%$

NNLL effect $+12-15\%$

Impact of higher order effects larger than at LHC

- K-factors defined with respect $\sigma_{LO}(\mu_F = \mu_R = M_H)$
- With $\mu_{F(R)} = \chi_{L(R)} M_H$ and $0.5 \leq \chi_{L(R)} \leq 2$ but $0.5 \leq \chi_F/\chi_R \leq 2$

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)

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

C. Anastasiou,
K. Melnikov, F. Petrello(2005)

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

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 $d\sigma^{F+\text{jet(s)}}$ 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 $d\sigma^{F+\text{jet(s)}}$ 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**

LHC

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

Use cuts as in CMS TDR

$p_T^{\min} > 35$ GeV

$p_T^{\max} > 40$ GeV

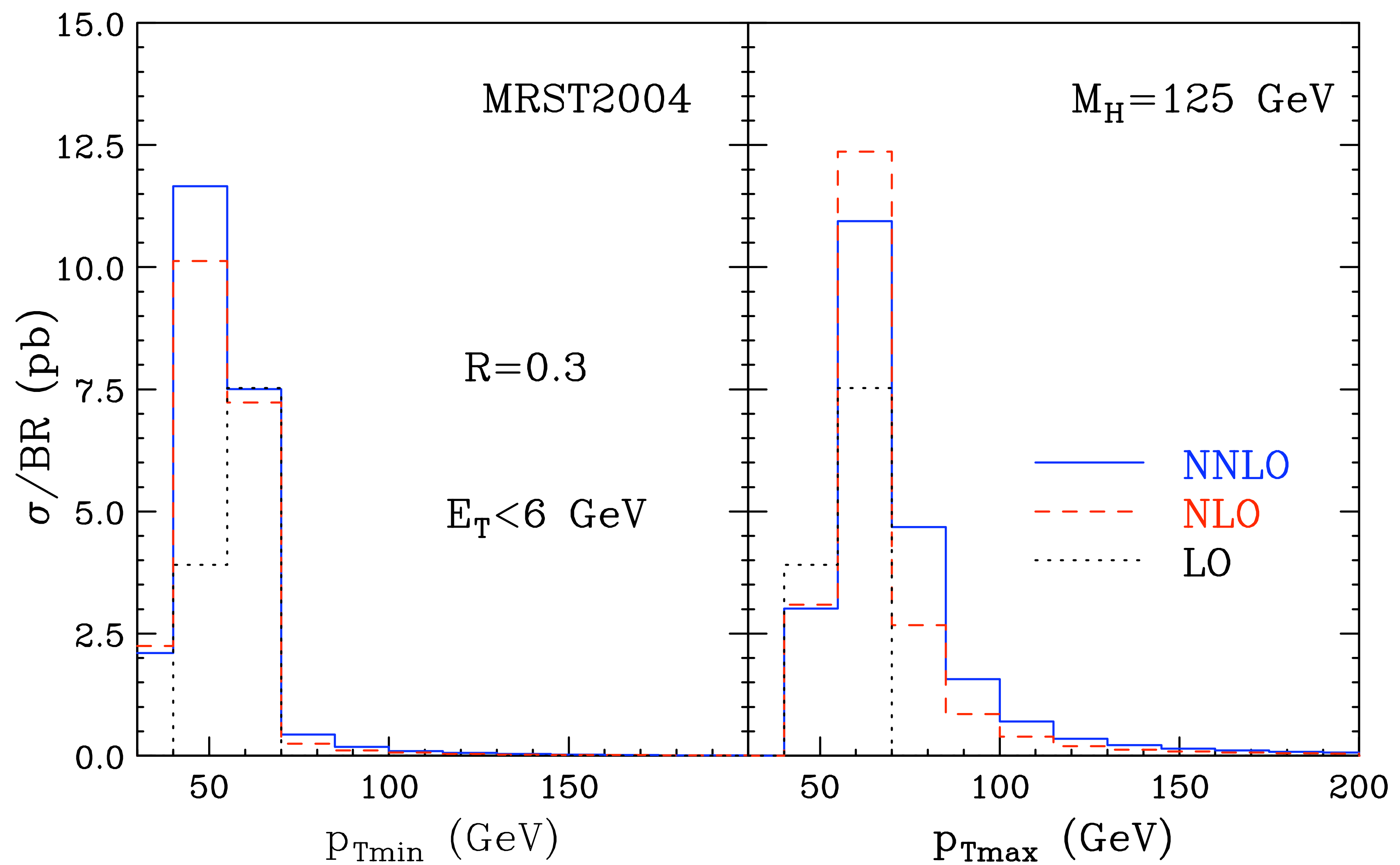
$|y| < 2.5$

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



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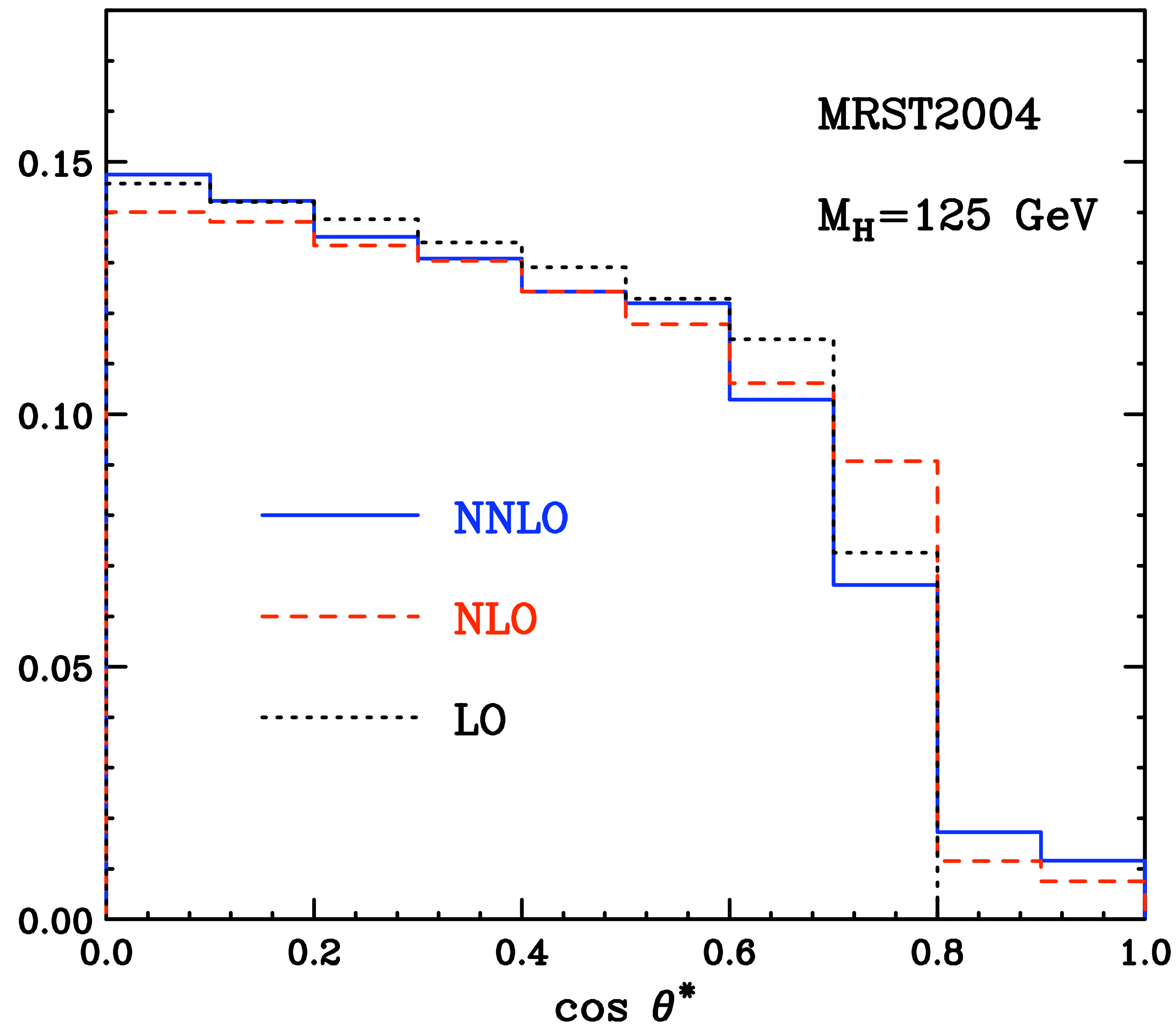
define $\cos\theta^*$ **distribution**

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

MG (2007)

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

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

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

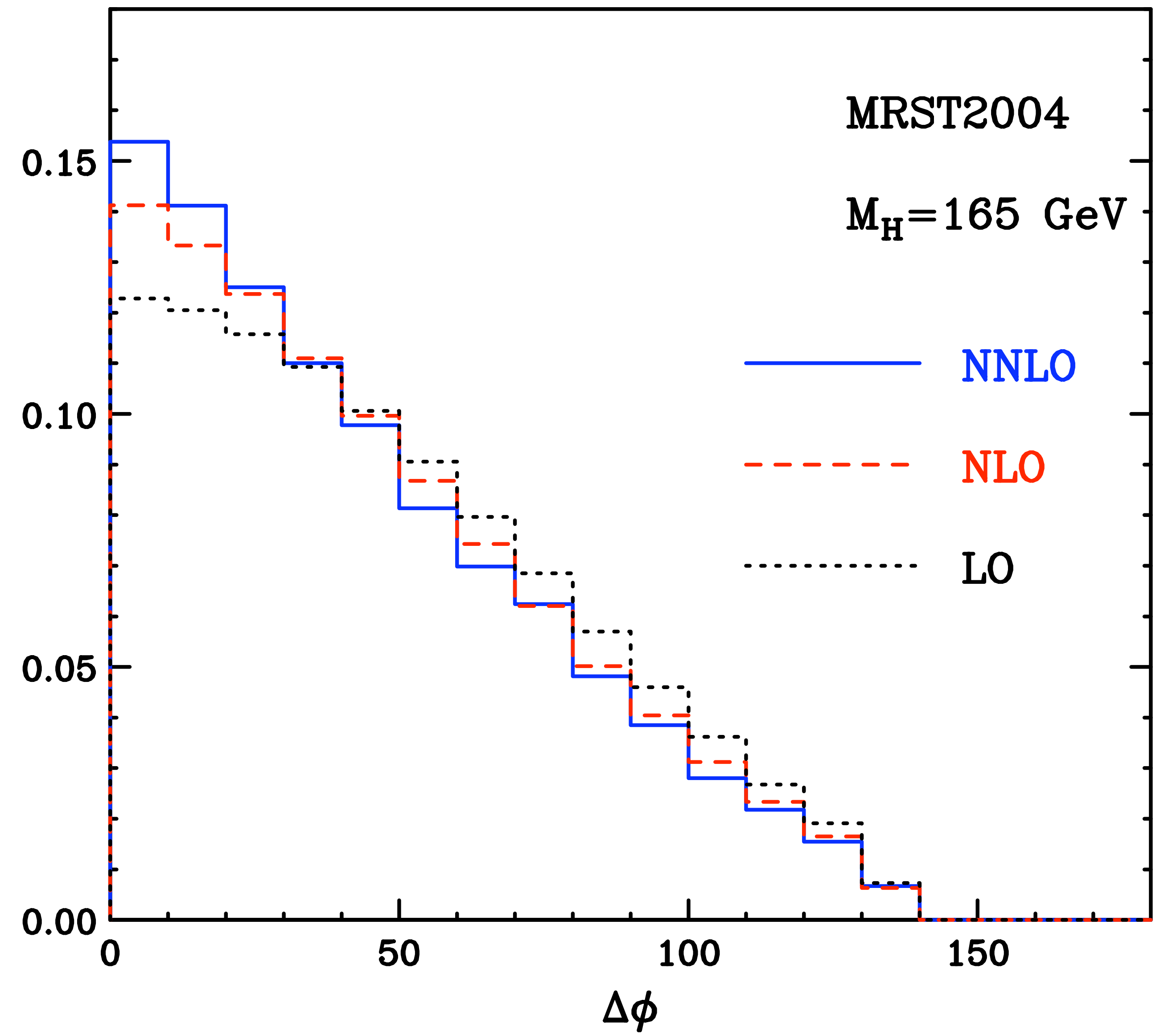
$|y_l| < 2$

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

$\Delta\phi < 135^o$

$m_{ll} < 80\ \text{GeV}$

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



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

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

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

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

Results for

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

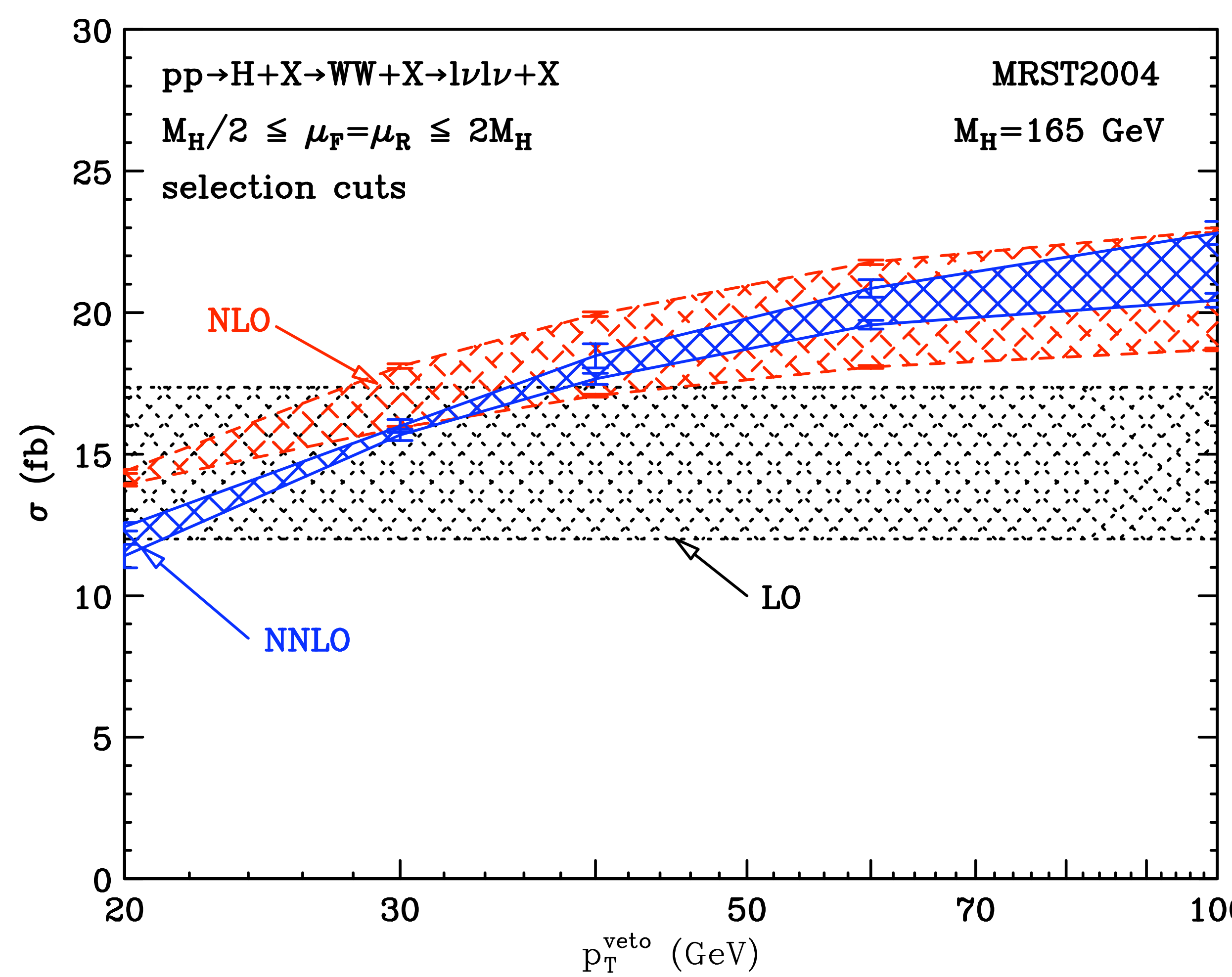
σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_H/2$	17.36 ± 0.02	18.11 ± 0.08	15.70 ± 0.32
$\mu_F = \mu_R = M_H$	14.39 ± 0.02	17.07 ± 0.06	15.99 ± 0.23
$\mu_F = \mu_R = 2M_H$	12.00 ± 0.02	15.94 ± 0.05	15.68 ± 0.20

➡ **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

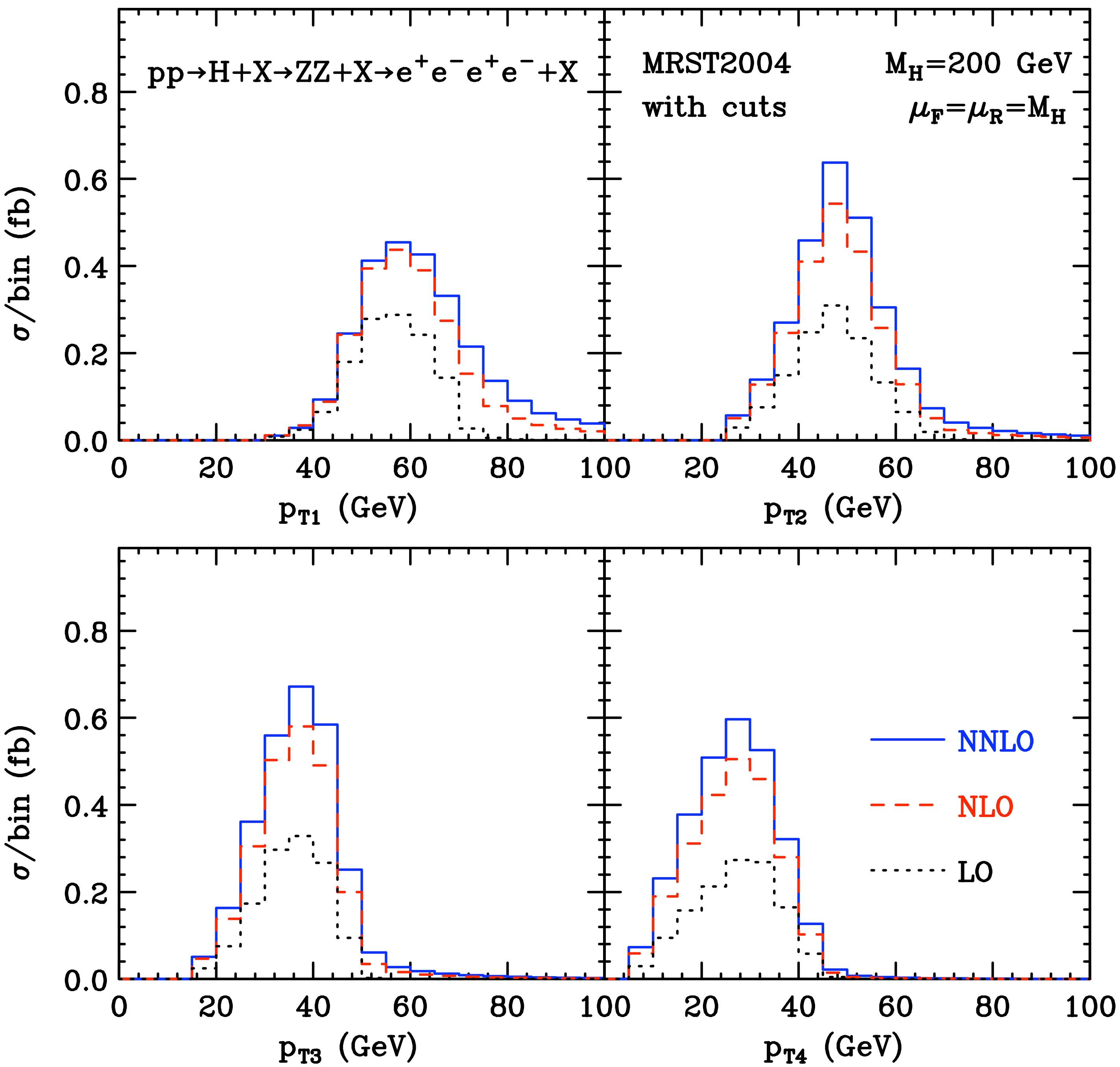
➡ 81 GeV $< m_1 < 101$ GeV and 40 GeV $< m_2 < 110$ GeV

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
- $16\ \text{GeV} < m_{ll} < 75\ \text{GeV}$
- Count jets with $E_T > 15$ GeV and $|\eta| < 2.5$

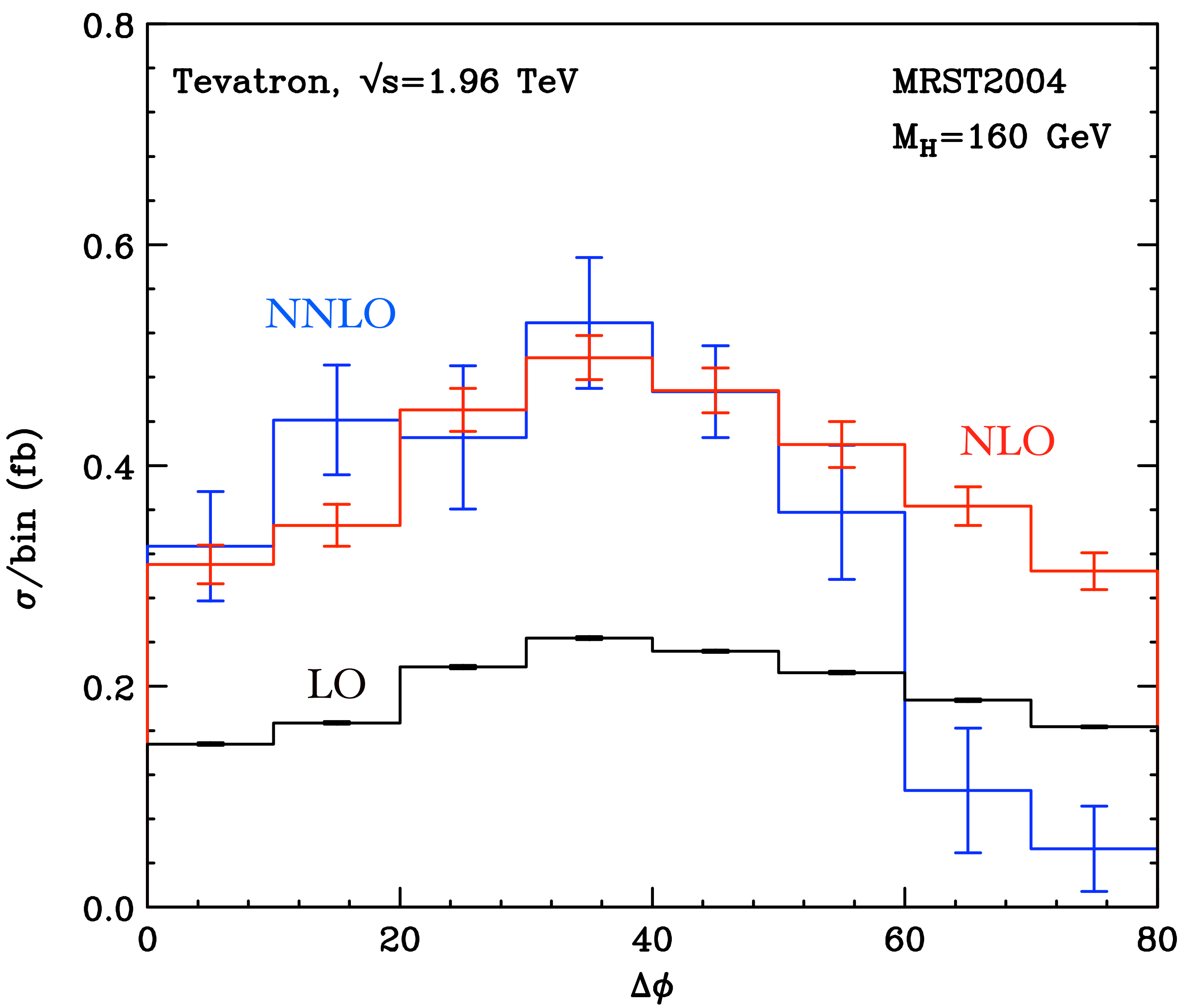
  ➡ Require either no such jet, or one of such jets and $E_T < 55$ GeV or two with $E_T < 40$ GeV (reduces $t\bar{t}$ background)
- Scalar sum of the p_T of the two leptons and $\not{E}_T$ should be smaller than M_H
- Concentrate on small $\Delta\phi$ region: $\Delta\phi < 80^o$

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

.....when fixed order calculations fail....

The transverse momentum (q_T) spectrum

A precise knowledge of the q_T spectrum may help to find strategies to improve statistical significance

The region $q_T \ll M_H$ where most of the events are expected is affected by large logarithmic contributions of the form $\alpha_S^n \ln^{2n} M_H^2/q_T^2$ that must be resummed to all orders

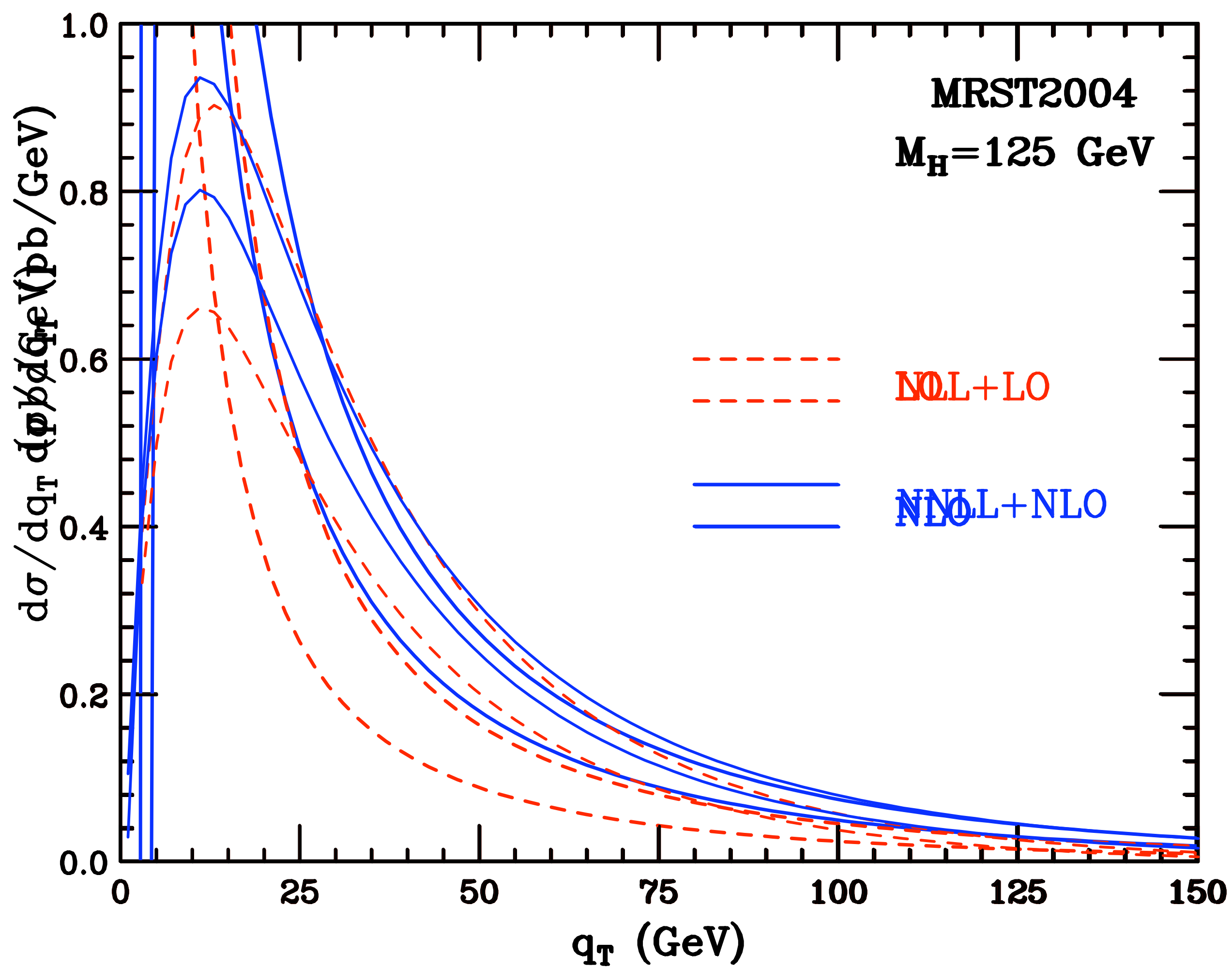
Resummed calculation at low q_T matched to fixed order at large q_T with the correct normalization

Very stable results

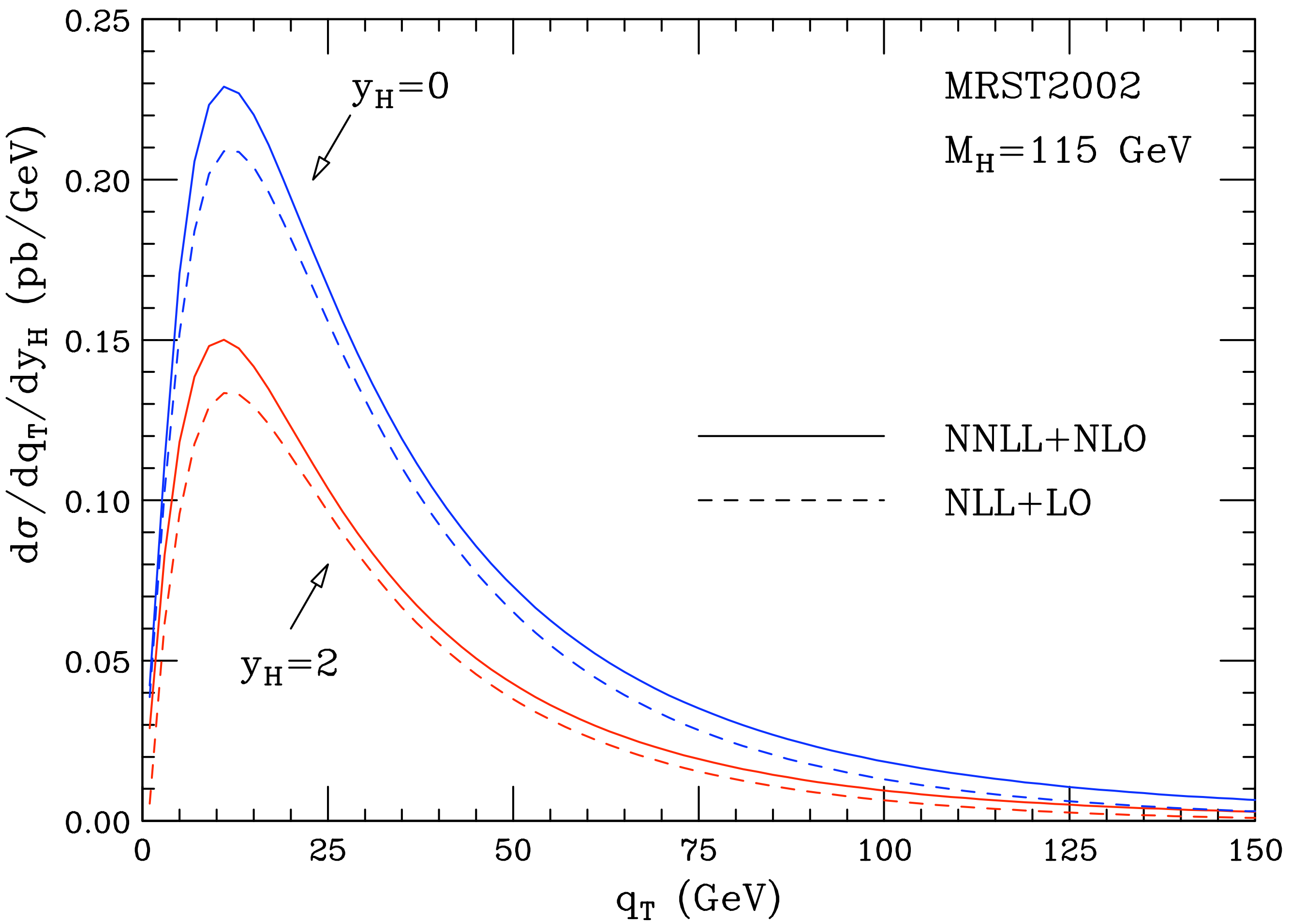
G. Bozzi, S. Catani,
D. de Florian, MG (2003, 2005)

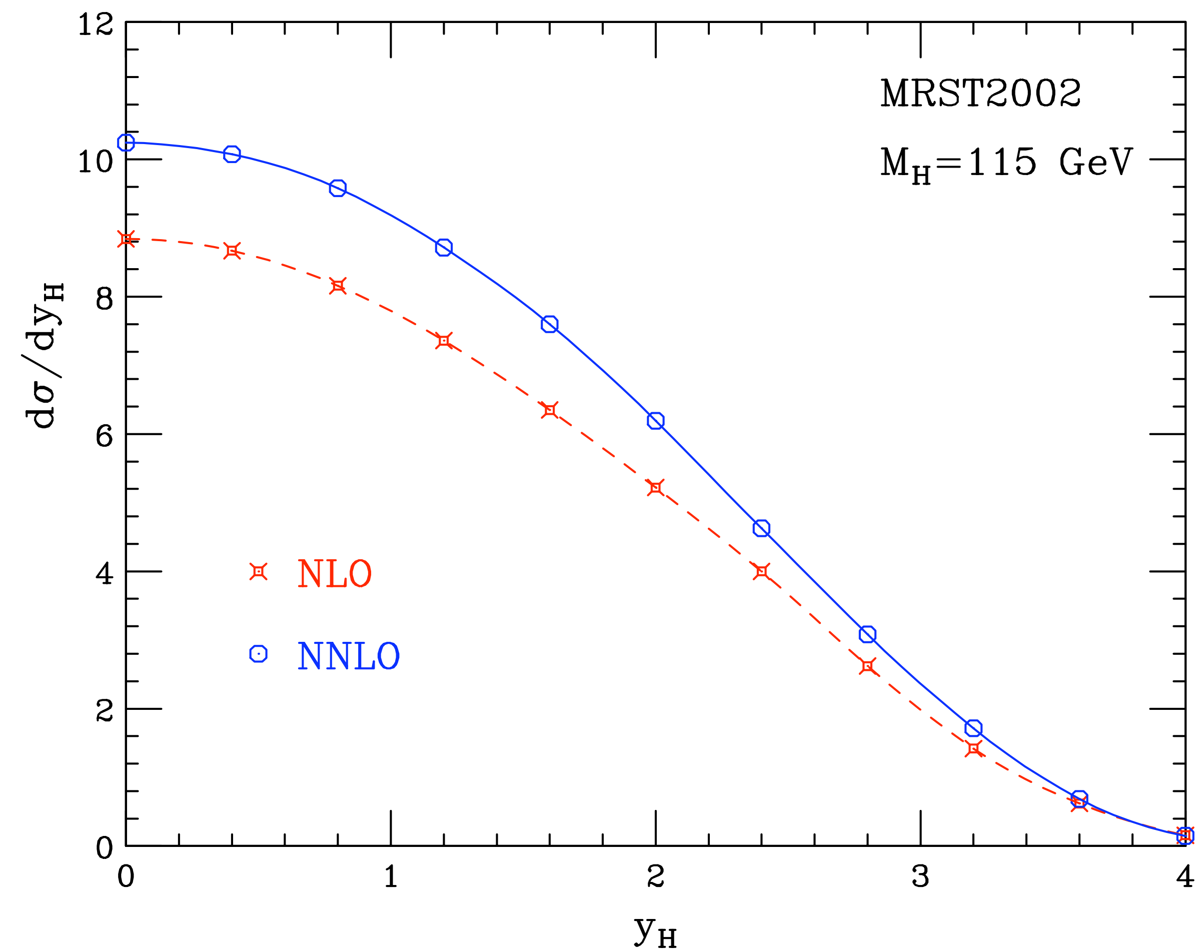
Public program available: HqT

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

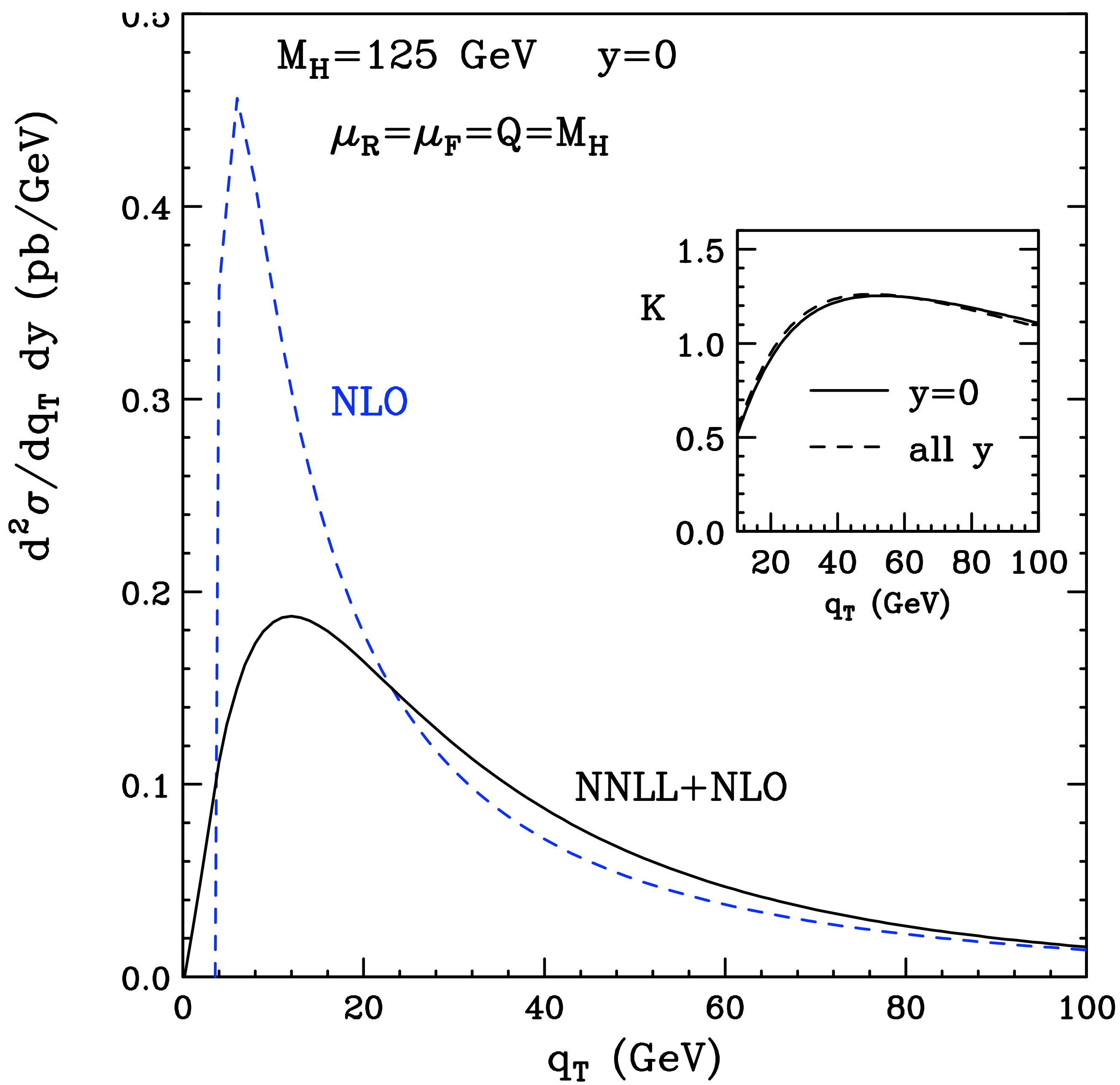


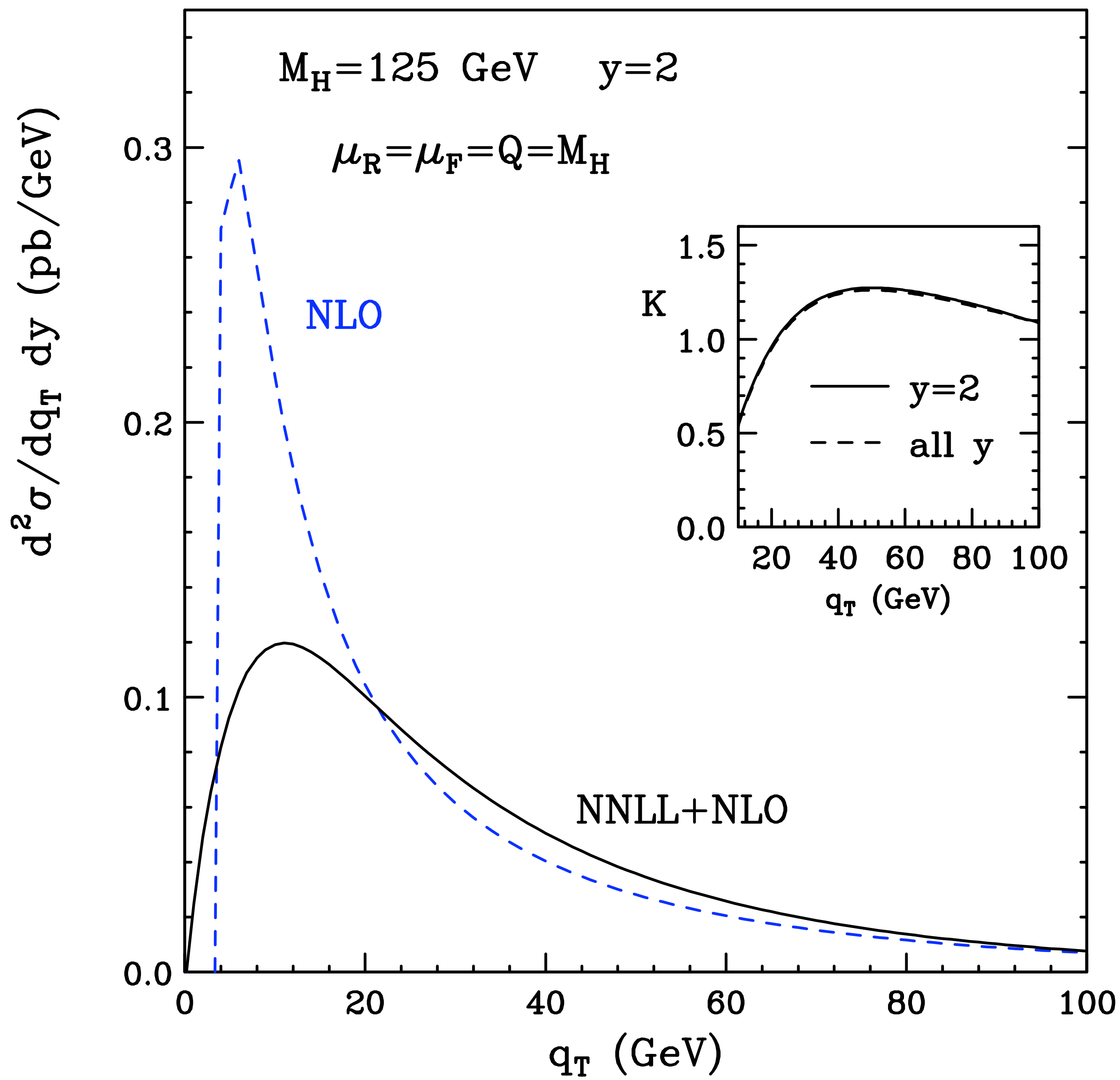
NEW: inclusion of rapidity dependence





- Quality of the matching and perturbative stability are confirmed
- Upon integration over q_T we obtain an independent calculation of the NLO and NNLO rapidity distribution





- Define $K(q_T, y) = \dfrac{d\sigma_{NNLL+NLO}/(dq_T\,dy)}{d\sigma_{NLO}/(dq_T\,dy)}$

➡ Impact of resummation mildly dependent on rapidity

Summary (I)

- Gluon-gluon fusion is the dominant production channel for the SM Higgs boson at hadron colliders for a wide range of M_H

- QCD corrections are important and are now known up to NNLO

- HNNLO is a parton level MC program that computes Higgs production through gluon fusion in pp or $p\bar{p}$ collisions in the large- m_{top} limit at LO, NLO and NNLO

- It implements $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$ decay modes and allows the user to apply *arbitrary cuts* on the momenta of the partons and of the leptons (photons) produced in the final state

- The corresponding distributions can be obtained as usual in the form of bin histograms

Summary (II)

- At small transverse momenta or, more generally, when we deal with observables sensitive to the Higgs q_T

  → transverse momentum resummation is needed

- HqT implements transverse momentum resummation at NLL+LO and NNLL+NLO accuracy

- Resummed calculation at low q_T matched to fixed order at large q_T with the correct NLO and NNLO normalization

- Recently we have included the effect of rapidity dependence: resummation effects turn out to be mildly dependent on rapidity

- Both HNNLO and HqT can be downloaded from

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