Higgs cross sections: a brief overview

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HCP 2011, Paris

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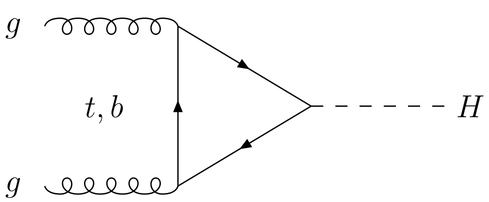
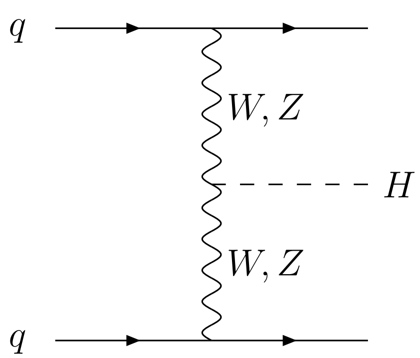
Outline

- Inclusive Higgs boson production
  - gg fusion
  - Vector boson fusion
  - Associated VH production
- Going differential
  - WH
  - $\gamma\gamma$
  - $H \rightarrow b\bar{b}$
- Summary

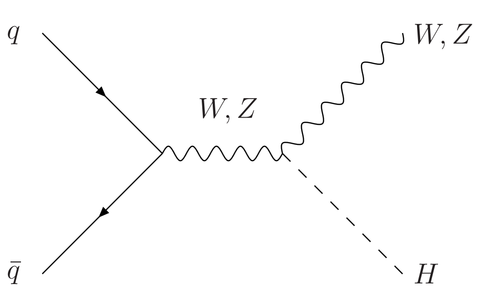
Inclusive cross sections



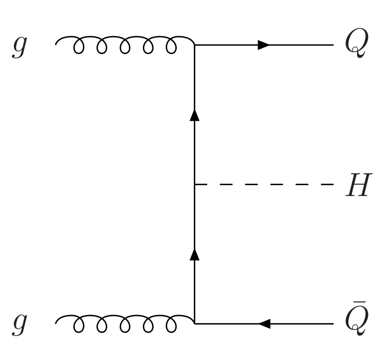
gg fusion



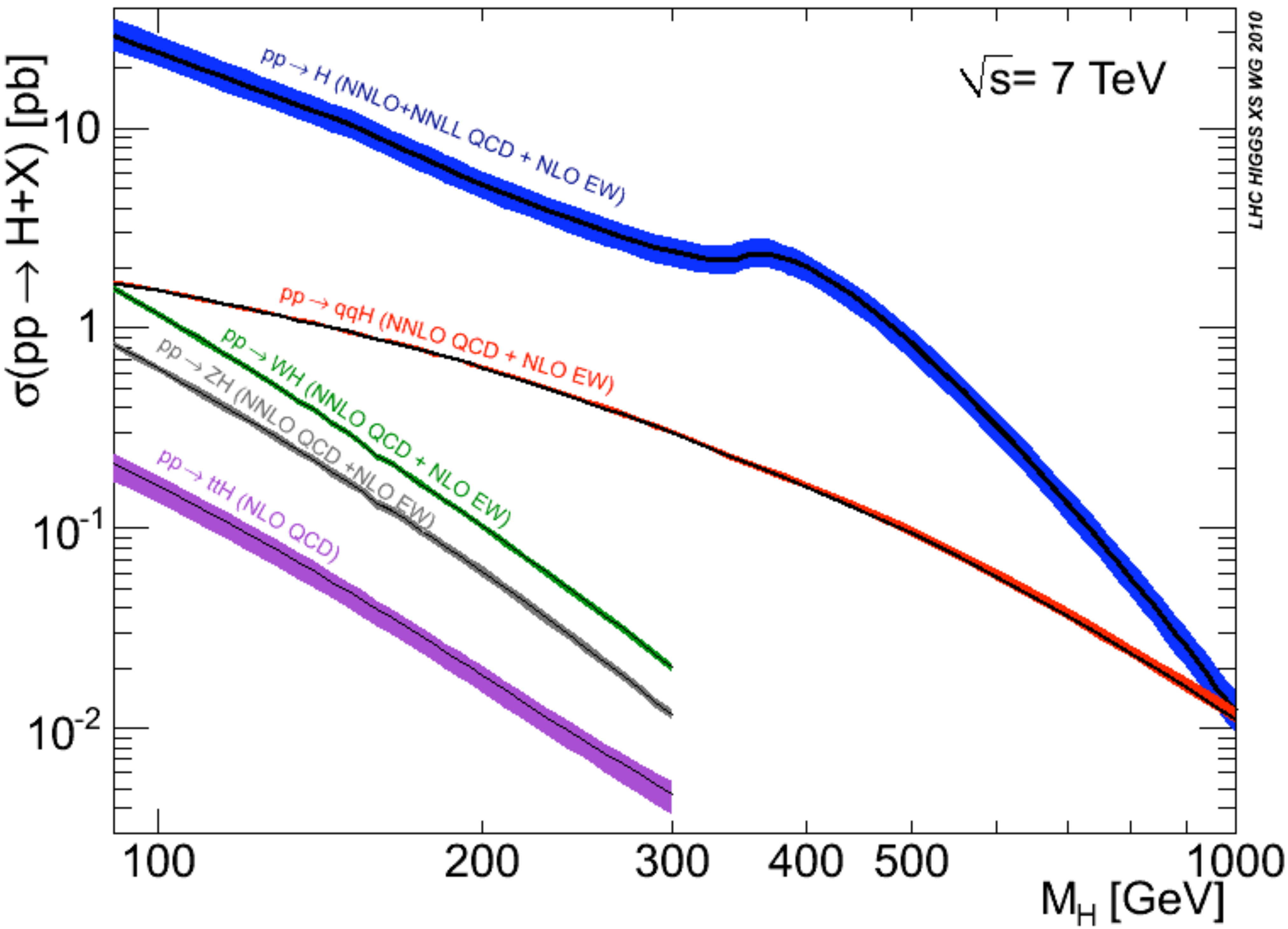
vector boson fusion



associated production with W, Z

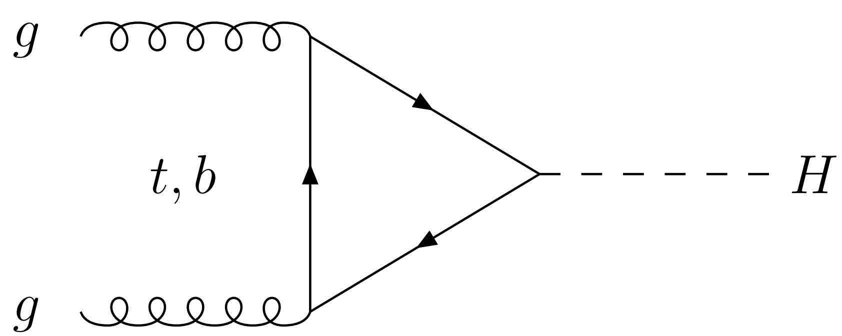


associated production with $Q\bar{Q}$



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

QCD corrections to the total rate computed 20 years ago and found to be large

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

They increase the LO result by O(100 %) !

Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit (+25 % at the LHC, +30 % at the Tevatron)

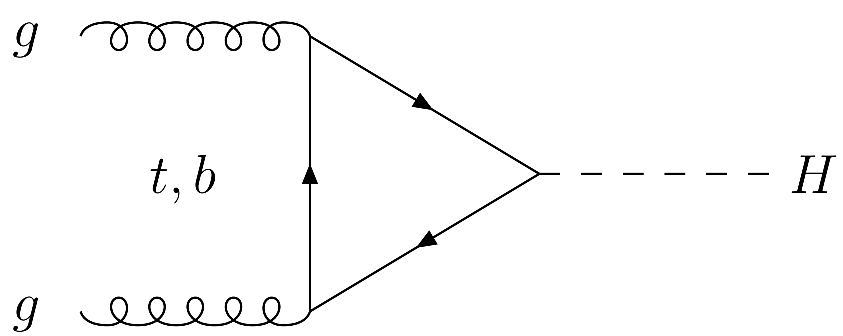
R.Harlander (2000)
S. Catani, D. De Florian, MG (2001)
R.Harlander, W.B. Kilgore (2001,2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

Large-m_{top} approximation works extremely well up to m_H=300 GeV (differences of the order of 0.5 % !)

S.Marzani et al. (2008)
R.Harlander et al. (2009,2010)
M.Steinhauser et al. (2009)

Probably the most important recent result on this channel

gg fusion



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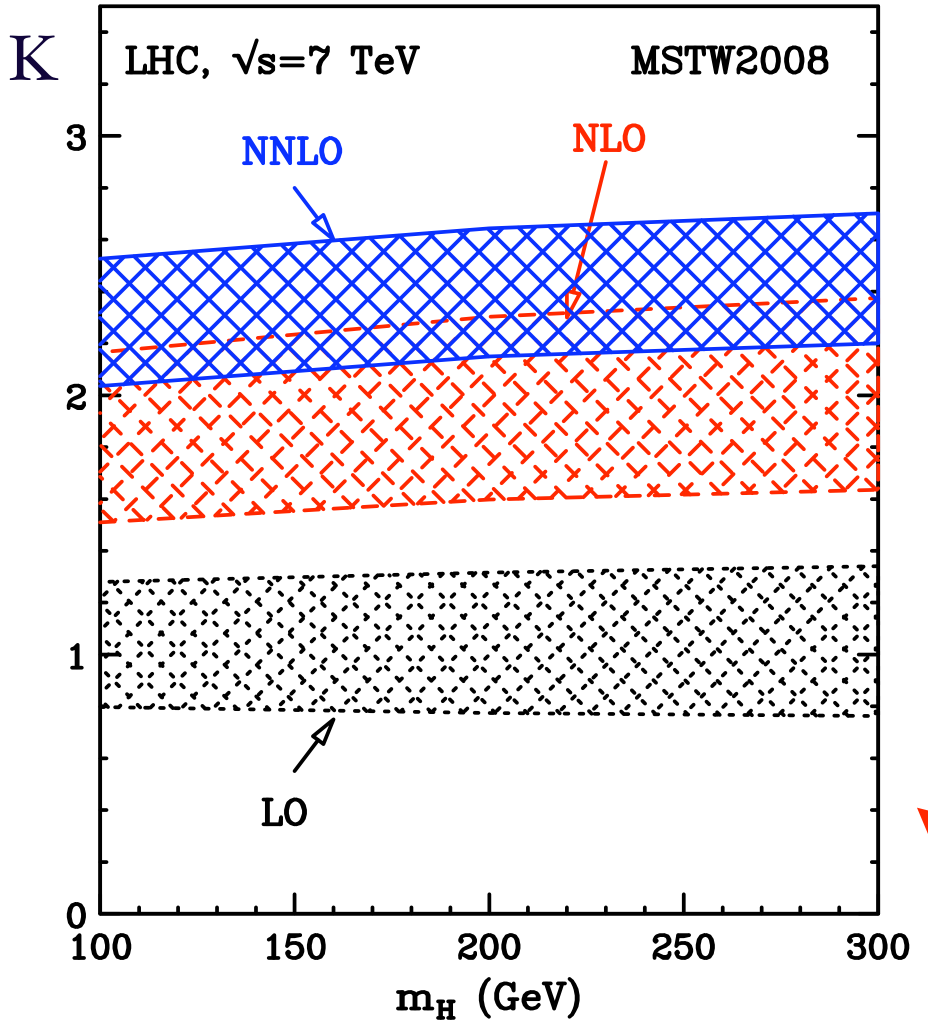

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scale uncertainty computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about +9-10% at the LHC, +13% at the Tevatron, with slight reduction of scale unc.)

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

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

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

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach (effect O(1%))

Anastasiou et al. (2008)

→ support "complete factorization": EW correction multiplies the full QCD corrected cross section

EW effects for real radiation (effect O(1%))

W.Keung, F.Petriello, (2009)
O.Brein (2010)
C.Anastasiou et al. (2011)

Results

Quite an amount of work has been done recently to provide updated results that include all the available information → LHC Higgs Cross section WG

- Calculation by Petriello et al.

  - Start from exact NLO and include NNLO in the large-m_{top} limit

  - Effect of resummation is mimicked by choosing $\mu_F = \mu_R = m_H/2$ as central scale (choice motivated by apparent better convergence of the perturbative series)

  - Includes EFT estimate of mixed QCD-EW effects and some effects from EW corrections to real radiation

- Update of NNLL+NNLO calculation of Catani et al. (2003)

  - Perform NNLL+NNLO calculation in the large-m_{top} limit

  - Include exact top and bottom contributions up to NLL+NLO

  - Include EW effects as computed by Passarino et al.

corresponding results for the Tevatron used in CDF+DO combination

Online calculator available at: http://theory.fi.infn.it/grazzini/hcalculators.html

D. De Florian, MG (2009)

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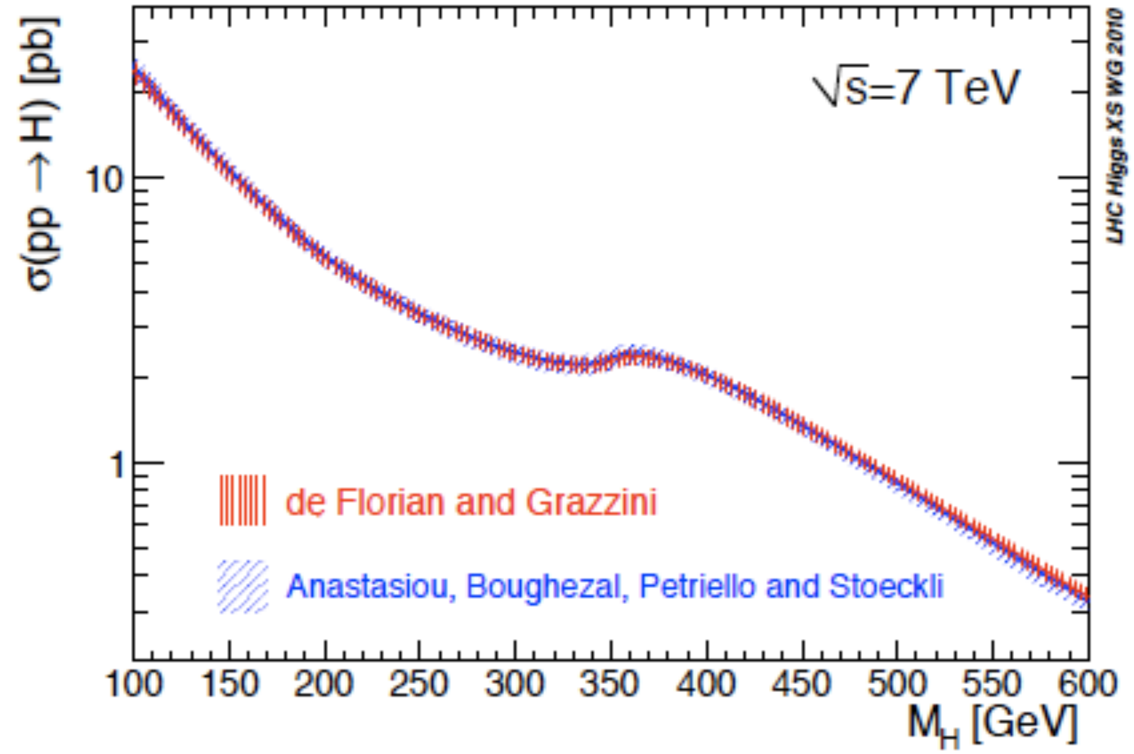

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D. De Florian, MG (2009)

Other Results

- Calculation by Baglio-Djouadi

J.Baglio,A.Djouadi (2010)

- Detailed (and very) conservative study of the various sources of uncertainties → about±25-30 % at 7 TeV

- Further update for the Tevatron uses $\mu_F = \mu_F = m_H/2$ as central scale: agreement with the other calculations

- Calculation by Ahrens et al.

V.Ahrens et al. (2010)

- Based on the so called "π^2-resummation"

- Numerical results agree with the other calculations

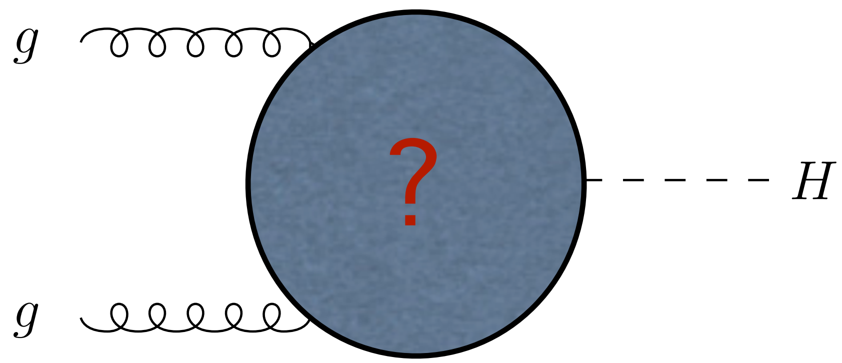
- Perturbative uncertainties of about 3% or smaller → largely underestimated !

- Calculation by Anastasiou et al. → implemented in the public program iHixs

- Start from exact NLO and include NNLO in the large-m_{top} limit

- Includes virtual and some real EW corrections and mixed QCD-EW effects

gg fusion as BSM portal



gluon-gluon fusion may open a window on new physics scenarios

sensitive to heavy particle spectrum

Models with additional SM-like heavy quarks

C.Anastasiou, R.Boughezal, E.Furlan (2010)
C.Anastasiou et al. (2011)

→ cross section enhanced by roughly a factor 9 with respect to the SM

Colored scalars

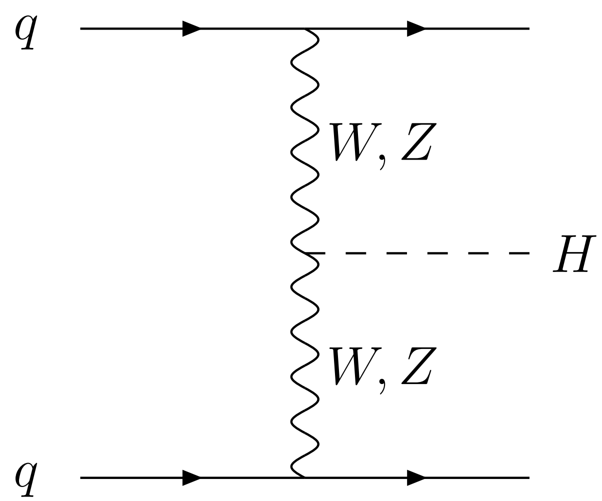
R.Boughezal, F.Petriello (2011)
R.Boughezal (2011)

Models with general Yukawa couplings

E.Furlan (2011)
C.Anastasiou et al. (2011)

→ NNLO calculation implemented in iHixs

Vector boson fusion



VBF is a cornerstone in the Higgs-boson search at the LHC

Even if the cross section is almost one order of magnitude smaller than for gg fusion this channel is very attractive both for discovery and for precision measurements of the Higgs couplings

QCD corrections to the total rate increase the LO result by +5-10%

T. Han, S. Willenbrock (1991)

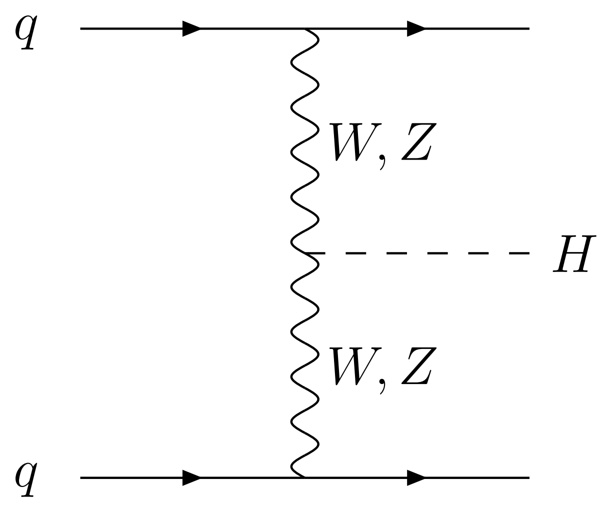
Implemented for distributions in VBFNLO

T. Figy, C. Oleari, D. Zeppenfeld (2003)
J. Campbell, K. Ellis (2003)

EW+QCD corrections have also been evaluated and implemented in a flexible parton level generator HAWK

M.Ciccolini, A.Denner, S.Dittmaier (2007)

Vector boson fusion



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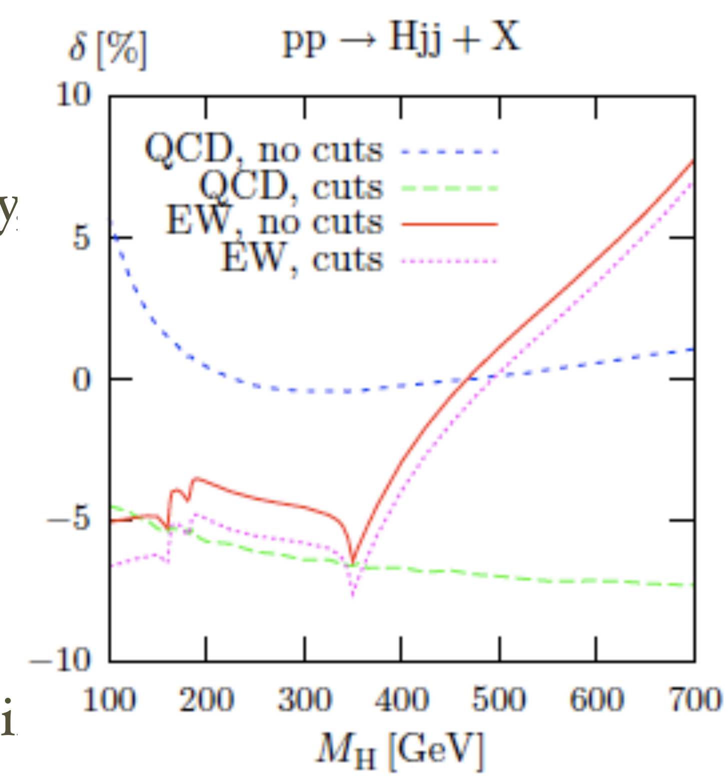

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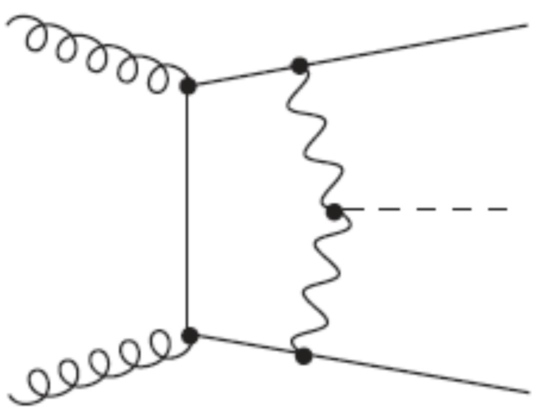
Vector boson fusion

Other radiative contributions:

Interference with gluon fusion

Andersen, Binoth, Heinrich, Smillie (2007)
Andersen, Smillie (2008)
Bredenstein, Hagiwara, Jäger (2008)

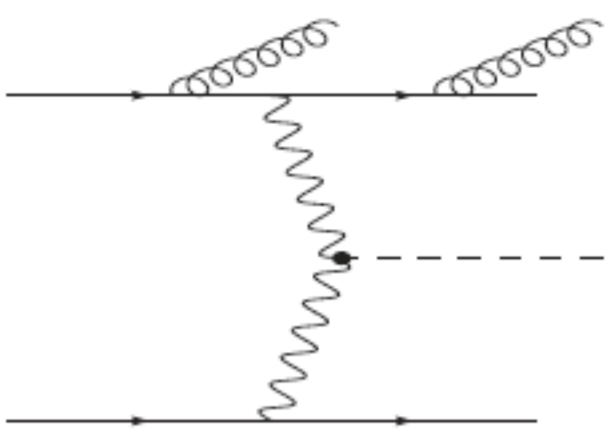
Other refinements include some NNLO contributions like gluon-induced diagrams



well below 1% level

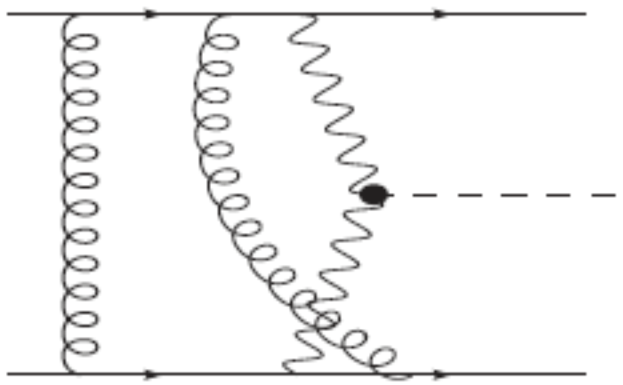
R.Harlander, J.Vollinga,M.Weber (2008)

and the more relevant DIS like NNLO contributions computed within the structure function approach



→ scale uncertainty reduced to the 2% level

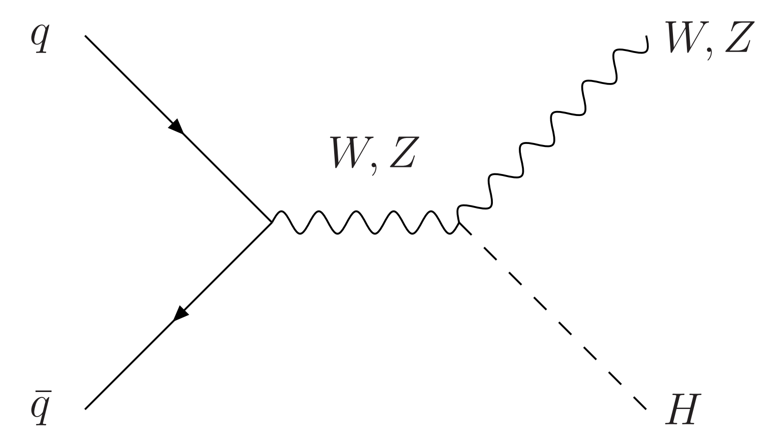
still missing :
(but kinematically and parametrically suppressed)



P.Bolzoni, F.Maltoni, S.Moch, M. Zaro (2010)

Associated VH production

Most important channel for low mass at the Tevatron



→ lepton(s) provide the necessary background rejection

Would provide unique information on the HWW and HZZ couplings

Considered not promising at the LHC due to the large backgrounds

Resurrected through boosted analysis

J.Butterworth et al. (2008)

NLO QCD corrections can be obtained from those to Drell-Yan: +30%

T. Han, S. Willenbrock (1990)

Full EW corrections known: they decrease the cross section by 5-10%

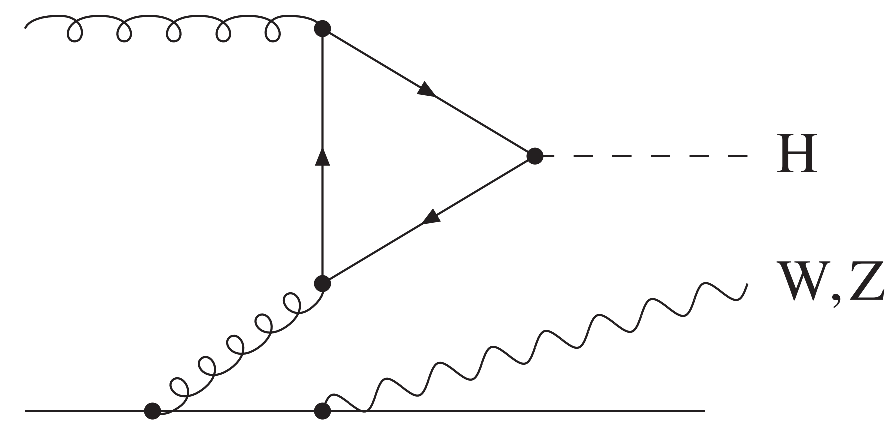
M.L. Ciccolini, S. Dittmaier, M. Kramer (2003)

Associated VH production

NNLO QCD corrections are essentially given by those of Drell-Yan

W. Van Neerven e al. (1991)

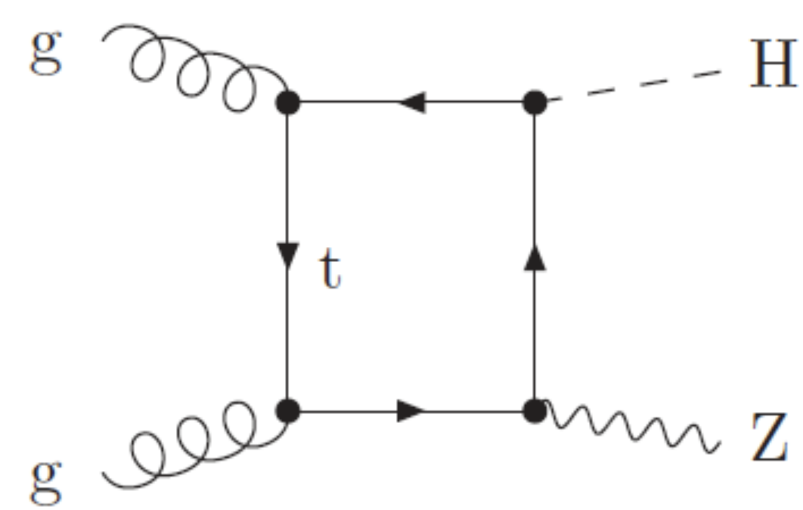
There are however additional diagrams where the Higgs is produced through a heavy quark loop



The effect is in the 1-3 % range

O. Brein, R. Harlander, M. Wiesemann, T. Zirke (2011)

For ZH at NNLO further diagrams from gg initial state must be considered: important at the LHC (+2-6 % effect)



O. Brein, R. Harlander, A. Djouadi (2000)

Going differential

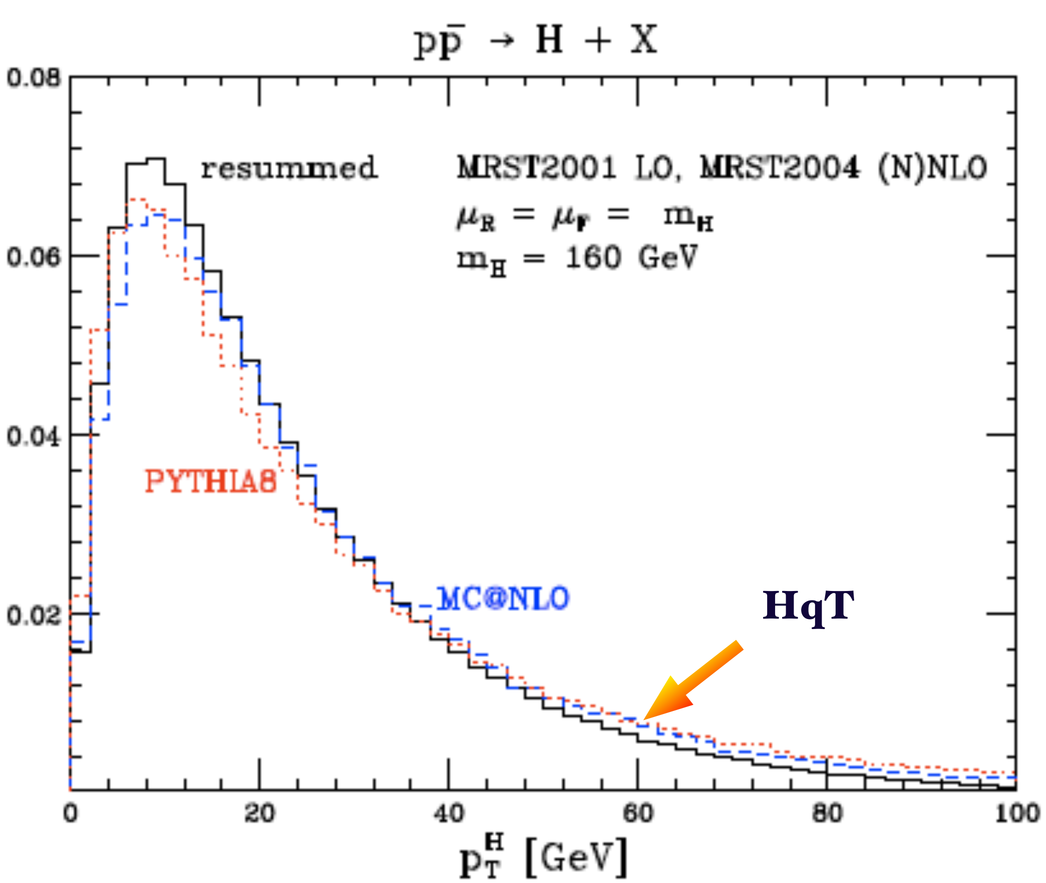
Total cross sections are ideal quantities:
real experiments have always a finite acceptance

→ How are theoretical predictions exploited in practice ?

Tevatron experience: experimental search based on Monte Carlo (mainly Pythia)

Use "best" total cross section as over all normalization

→ Works only if the Monte Carlo correctly predicts relevant kinematical distributions



Needs careful MC validation against higher-order (and resummed) computations

See e.g. Higgs p_T spectrum: MC@NLO vs PYTHIA vs NNLL resummed result from HqT

→ reweighting techniques

What about other distributions ?

At LO we don't find problems: compute the corresponding matrix element and integrate it numerically over the multiparton phase-space

Beyond LO the computation is affected by **infrared singularities**

Although these singularities cancel between real and virtual contributions, they prevent a straightforward implementation of numerical techniques

Fortunately gg→H is now implemented at fully exclusive level

FEHIP: Based on sector decomposition: computes NNLO corrections for $H \to \gamma\gamma$ and $H \to WW \to l\nu l\nu$

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

HNNLO: Parton level Monte Carlo program that computes NNLO corrections for $H \to \gamma\gamma$ $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$

S. Catani, MG (2007)
MG (2008)

With these programs it is possible to study the impact of higher order corrections with the cuts used in the experimental analysis

Further applications

The method successfully applied to gg→H and the Drell-Yan process can be used to perform NNLO computations for other important processes

S.Catani, L Cieri, G.Ferrera, D. de Florian, MG (to appear)

$$c\bar{c} \to F + X \qquad c = q, g$$

Arbitrary colourless final state

Examples:

- Higgs-strahlung: F=WH, ZH
- $b\bar{b} \to H$

R.Harlander, K.Ozeren, M.Wiesemann (2010)
R.Harlander, M.Wiesemann (2011)

- Vector boson pair production: F= $\gamma\gamma$, WW, ZZ....

Important backgrounds for new physics searches

For each of these processes the ingredients that we need are:

- Two loop amplitude for $c\bar{c} \to F$
- NLO cross section for F+jet(s)

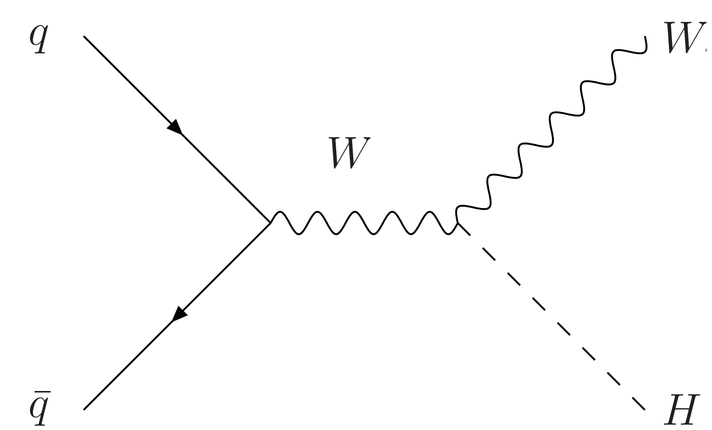
NEW: WH at NNLO

G.Ferrera, F.Tramontano, MG (2011)

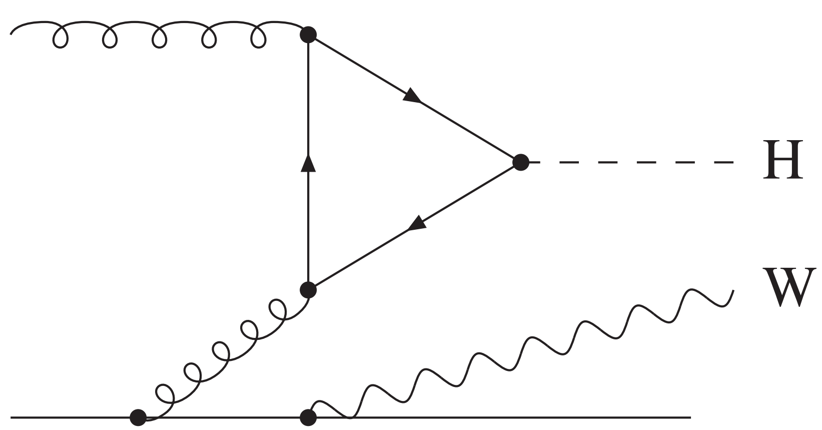
A fully differential NNLO calculation:
extension of NNLO calculation for Drell-Yan to Higgs-strahlung

Fully realistic: we include $H \to b\bar{b}$ decay and $W \to l\nu$ with spin correlations

Only Drell-Yan like diagrams are accounted for



We neglect the additional diagrams where the Higgs is produced through a heavy quark loop



Comparing with NLO results for WH+jet we estimate these contributions to be at the 1% level

Hirschi et al. (2011)

NEW: WH at NNLO

Results at the Tevatron

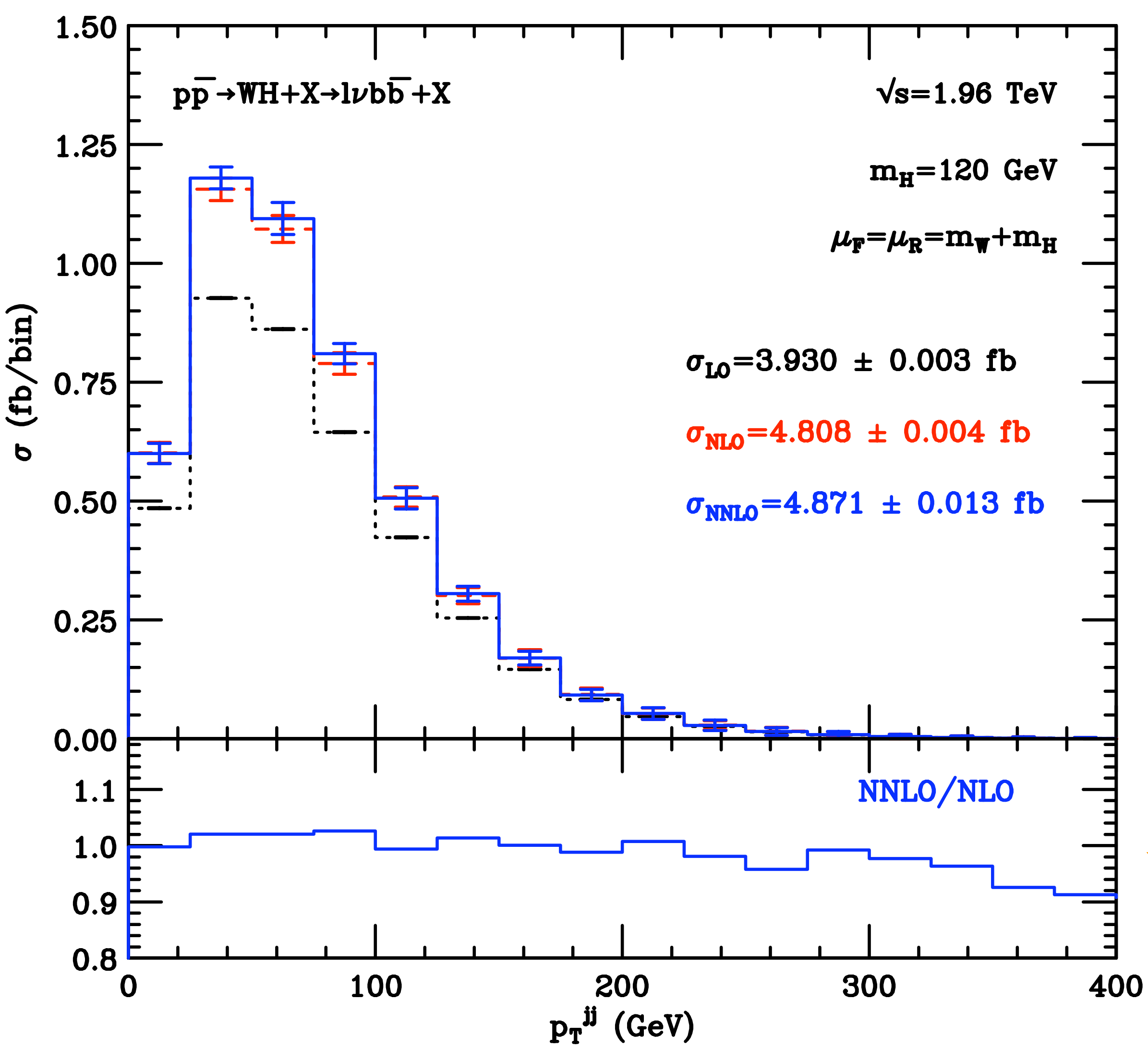
G.Ferrera, F.Tramontano, MG (2011)

Cuts:
lepton: p_T > 20 GeV and |η|<2
p_T^{miss} > 20 GeV

Jets: k_T algorithm with R=0.4

We require exactly 2 jets with p_T > 20 GeV and |η|<2

One of the jets has to be a b-jet with |η|<1



σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = (m_W + m_H)/2$	4.266 ± 0.003	4.840 ± 0.005	4.788 ± 0.013
$\mu_F = \mu_R = m_W + m_H$	3.930 ± 0.003	4.808 ± 0.004	4.871 ± 0.013
$\mu_F = \mu_R = 2(m_W + m_H)$	3.639 ± 0.002	4.738 ± 0.004	4.908 ± 0.010

Fixed-order results appear to be under good control

Scale dependence at the 1% level both at NLO and NNLO

Shape of p_T spectrum of dijet system is stable

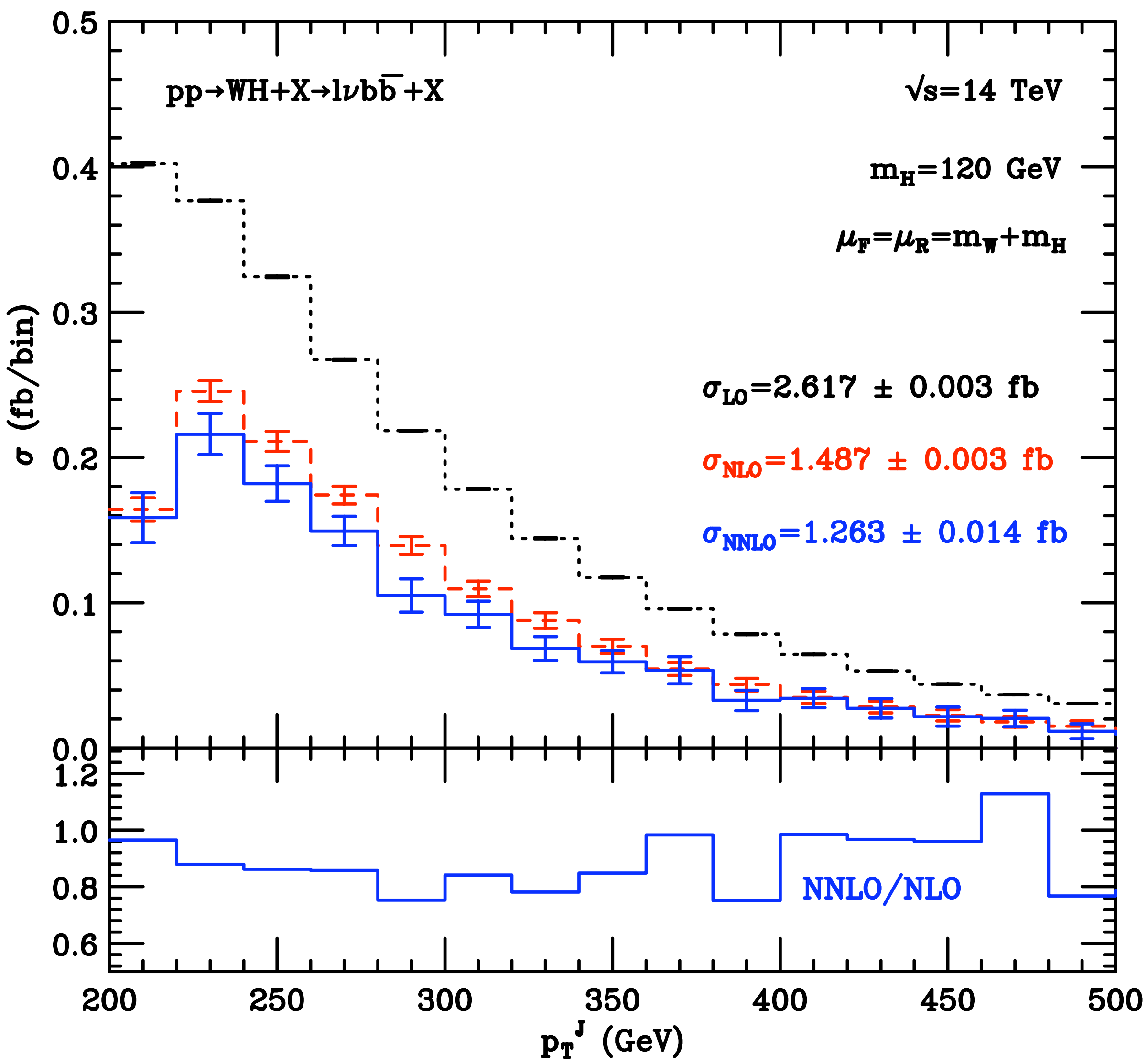
NEW: WH at NNLO

G.Ferrera, F.Tramontano, MG (2011)

Results at the LHC (√s=14 TeV)

Cuts:
lepton: p_T > 30 GeV and |η|<2.5
p_T^{miss} > 30 GeV
p_T^W>200 GeV

Jets: CA algorithm with R=1.2
One of the jets (fat jet) must have p_T^J>200 GeV and $|\eta_J|$<2.5 and must contain the $b\bar{b}$ pair; no other jet with p_T > 20 GeV and |η|<5



σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = (m_W + m_H)/2$	2.640 ± 0.002	1.275 ± 0.003	1.193 ± 0.017
$\mu_F = \mu_R = m_W + m_H$	2.617 ± 0.003	1.487 ± 0.003	1.263 ± 0.014
$\mu_F = \mu_R = 2(m_W + m_H)$	2.584 ± 0.003	1.663 ± 0.002	1.346 ± 0.013

Impact of radiative corrections strongly reduced by the jet veto ➡

Stability of fixed-order expansion is challenged

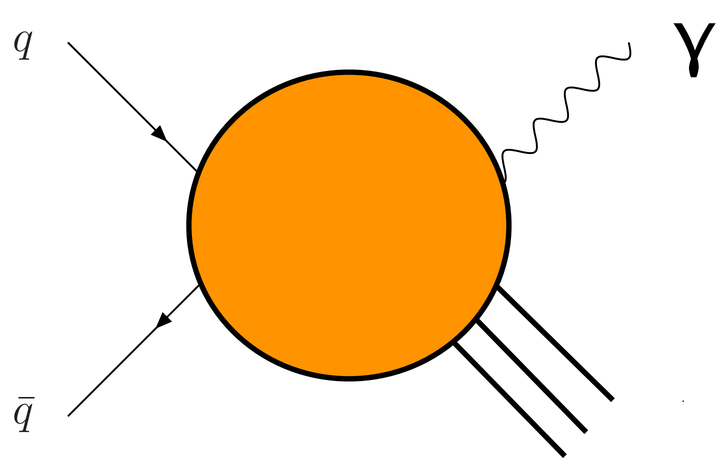
Plan:

- combined effort with HAWK group for 2nd Higgs XS YR
- Extension to ZH and comparison with MC tools

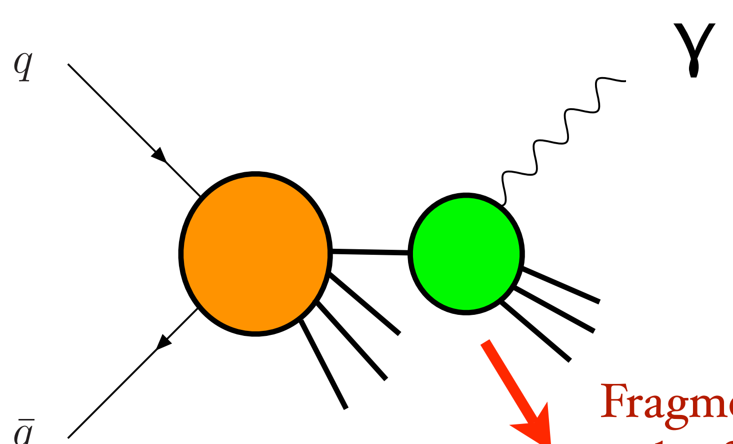
NEW: $pp \rightarrow \gamma\gamma$ at NNLO

S. Catani, L. Cieri, D. de Florian, G.Ferrera, MG (2011)

When dealing with the production of photons we have to consider two production mechanisms:



Direct component: photon directly produced through the hard interaction

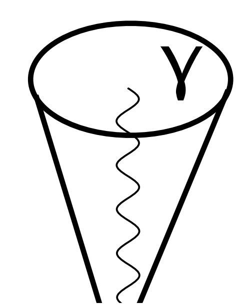


Fragmentation component: photon produced from non-perturbative fragmentation of a hard parton (like a hadron)

Fragmentation function: to be fitted from data

Experimentally photons must be isolated:

Transverse hadronic energy in a cone of fixed radius R smaller than few GeV



NEW: $pp \to \gamma\gamma$ at NNLO

S. Catani, L. Cieri, D. de Florian, G.Ferrera, MG (2011)

Two loop amplitude available

C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans (2002)

$\gamma\gamma$ +jet at NLO available

Z.Nagy et al. (2003)

➡ We can perform the NNLO calculation using hard-collinear coefficients obtained for Drell-Yan

Use Frixione smooth cone isolation

$E_T^{had}(\delta) \le \chi(\delta)$ ➡ kills collinear emissions within the cone

$$\chi(\delta) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n \qquad n = 1, \quad \epsilon_\gamma = 0.5, \quad R_0 = 0.4$$

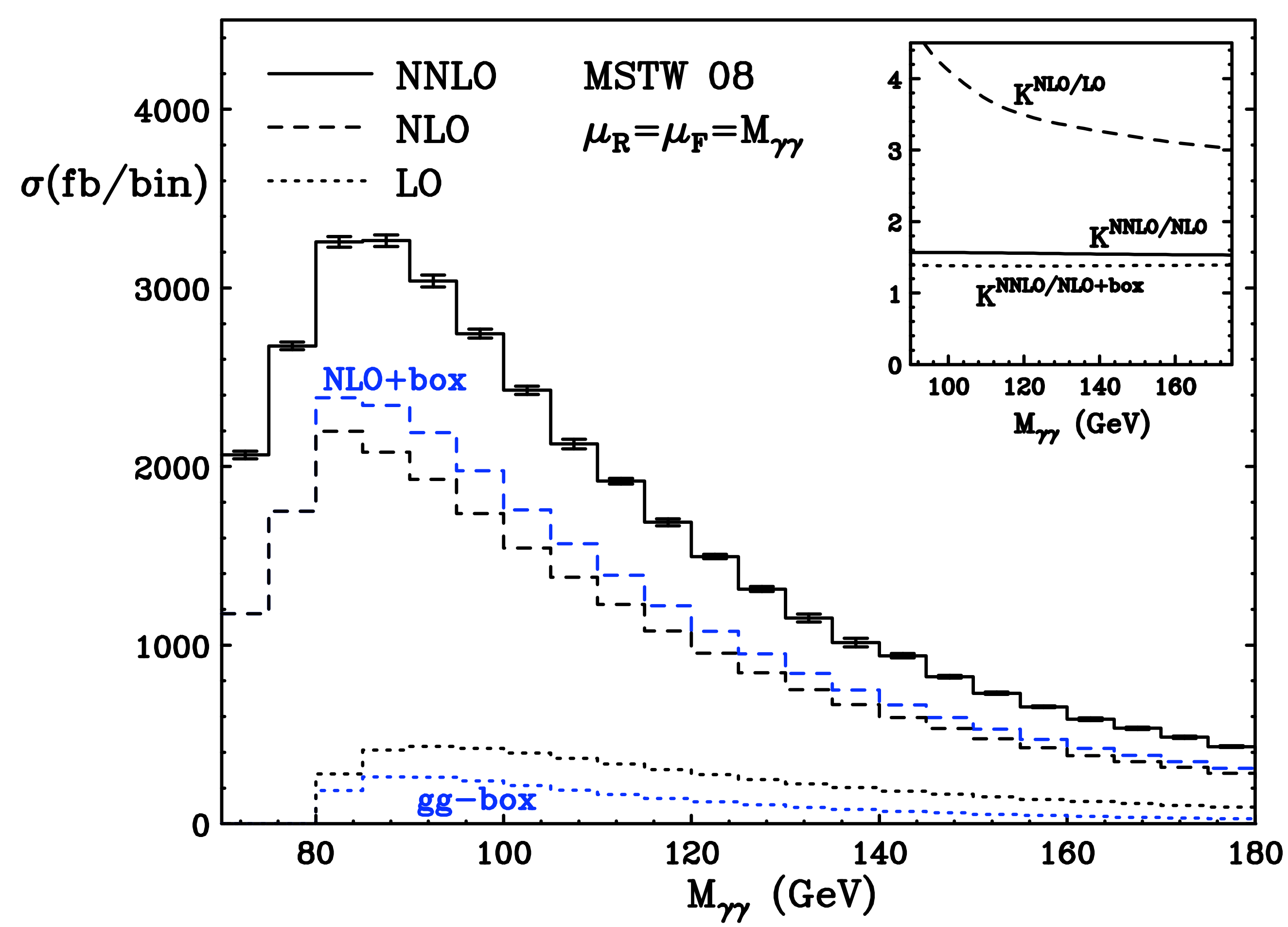
➡ no fragmentation contribution

$p^\gamma_{T1} \geq 40$ GeV $\quad p^\gamma_{T2} \geq 25$ GeV $\quad |\eta^\gamma| \leq 2.5$

20 GeV $\leq M_{\gamma\gamma} \leq$ 250 GeV

NNLO effect about +40 % in the peak region

RESULTS: LHC, $\sqrt{s}$=14 TeV

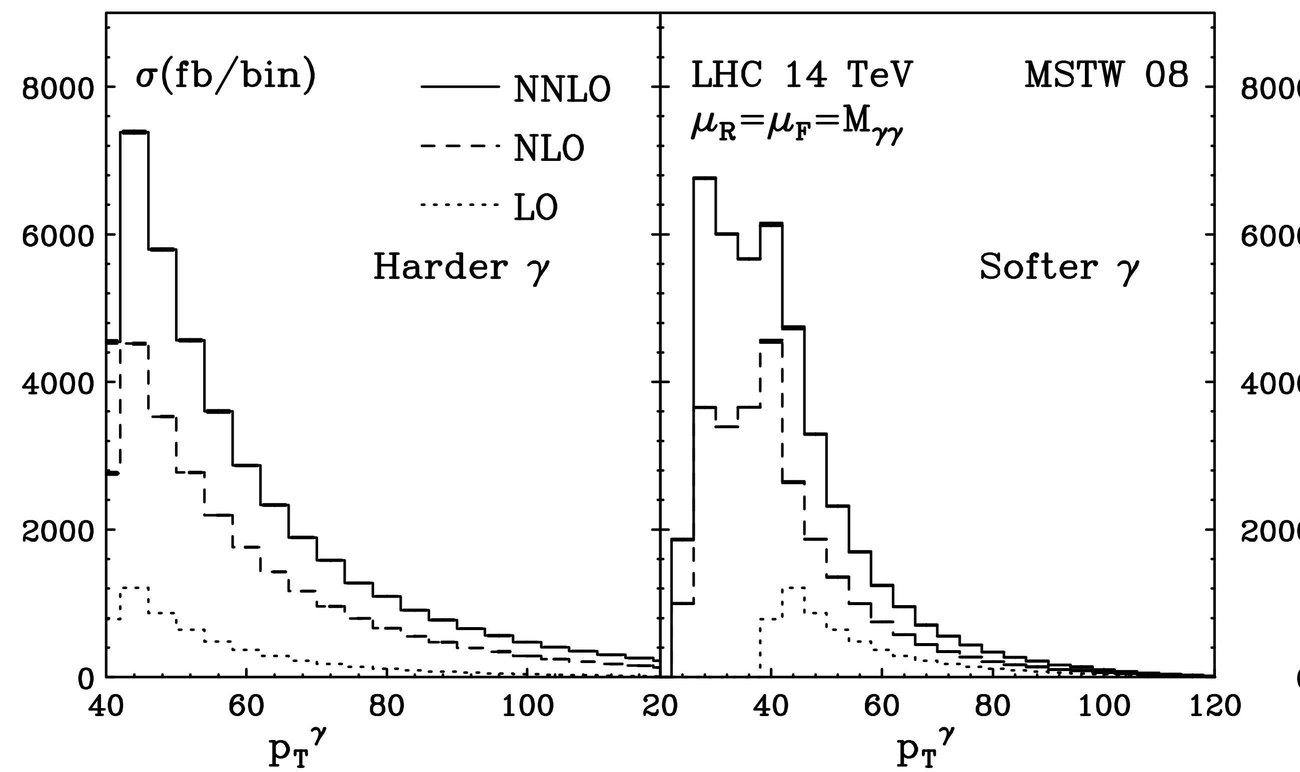


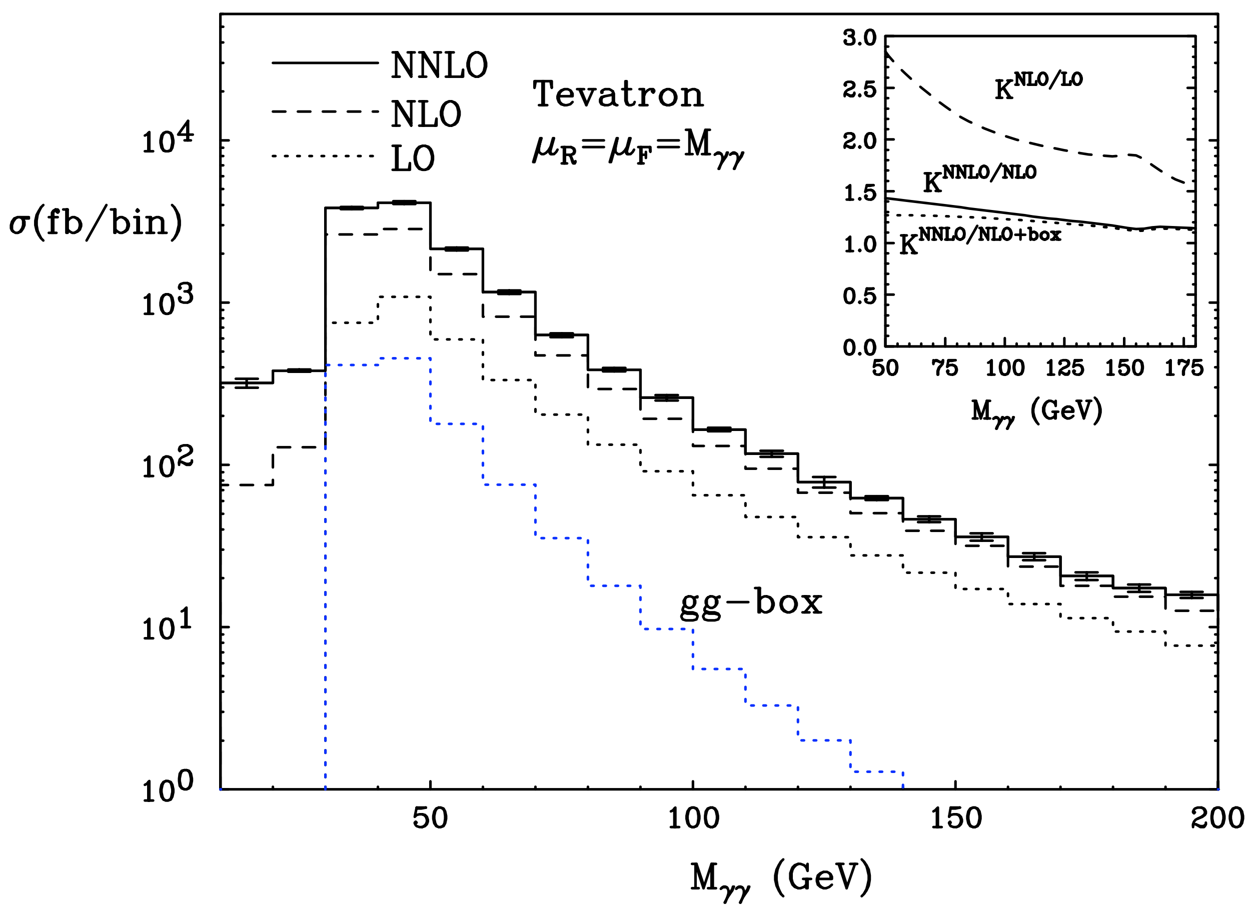
NEW: pp → γγ at NNLO

S. Catani, L. Cieri, D. de Florian, G.Ferrera, MG (2011)

The requirement $p^{\gamma}_{T1} \geq 40$ GeV implies that at LO also the softer photon must have $p^{\gamma}_{T} \geq 40$ GeV

- Substantial contribution from radiation in the region 25 GeV < p_T < 40 GeV
- Unphysical peak in p^{γ}_{T2} at p_T=40 GeV





RESULTS: Tevatron

Only slightly asymmetric p_T cuts

$p^{\gamma}_{T1} \geq 17$ GeV $p^{\gamma}_{T2} \geq 15$ GeV $|\eta^{\gamma}| \leq 1$

Impact of NLO corrections a bit smaller than at the LHC but still important

NNLO effect about +30 %

NEW: $H \to b\bar{b}$ at NNLO

C. Anastasiou, F.Herzog, A.Lazopoulos (2011)

First computation of fully exclusive $H \to bb$ decay at NNLO

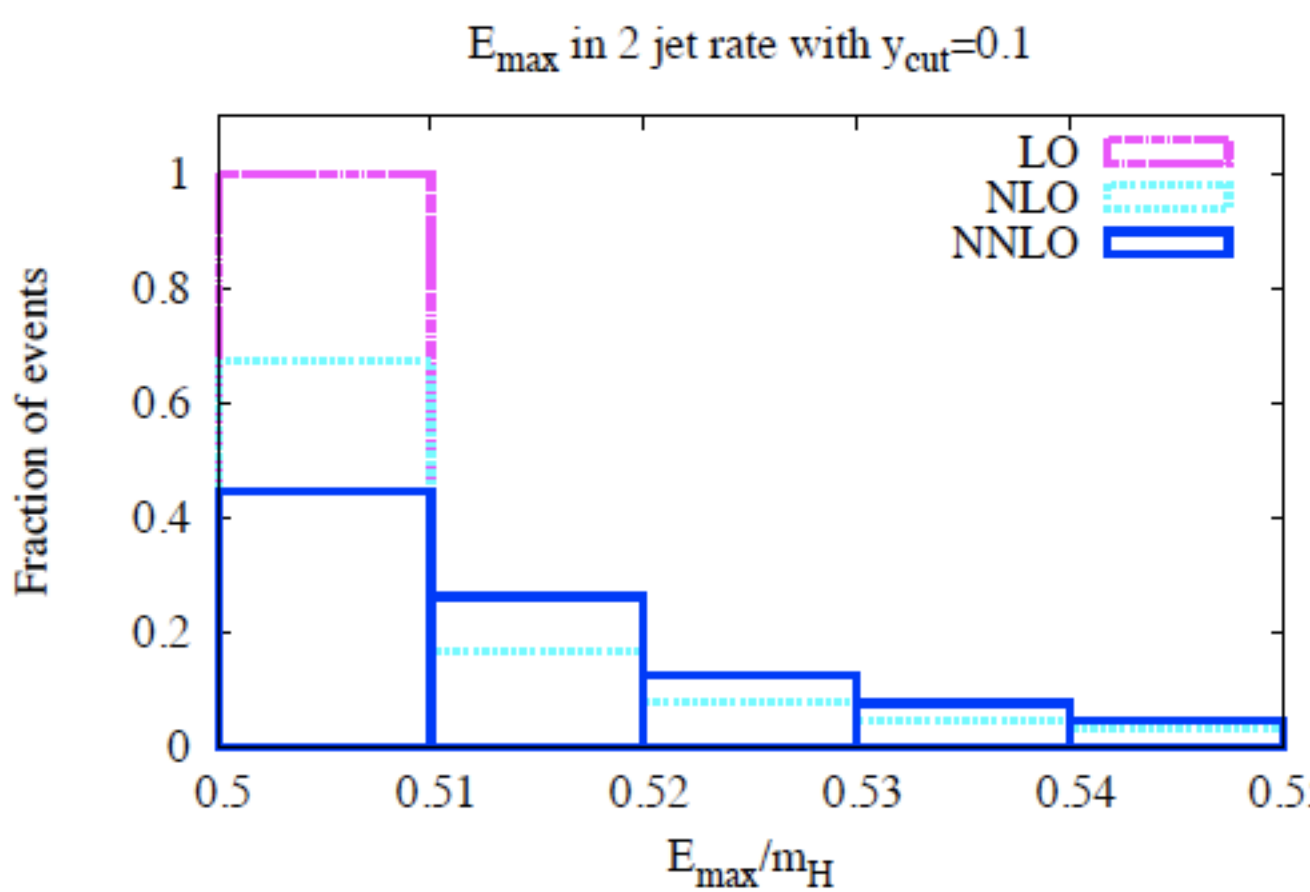
First application of new method based on non-linear mappings

Aims at reducing large number of terms obtained in sector decomposition

Promising results

EXAMPLE:

Spectrum of leading jet in dijet events with y_{cut}=0.1



Summary & Outlook

- The Higgs boson is an essential ingredient of the SM but it has not been observed yet

- The LHC has already excluded a wide range of Higgs boson masses

  → the attention is now on the low mass region, where the Higgs search is more difficult

- With the about 5 fb^{-1} integrated in 2011 ATLAS and CMS should become sensitive also to the low mass region: stay tuned !

- The performances of the LHC challenge the theory community to provide the best possible predictions for signal and background processes relevant for Higgs physics

Summary & Outlook

- In the last few years theory has done an enormous effort to achieve this goal and to be prepared to this exciting moment

- Inclusive cross sections at high accuracy have been computed for the most important signal processes

- Accurate resummed calculation for the Higgs spectrum used to correct the shape of the spectrum from MC event generators

- New fully differential NNLO QCD calculations are being performed to provide flexible tools for the analyses

  → important to assess theoretical uncertainties in the experimental search