Higgs production at the Tevatron and the LHC

Massimiliano Grazzini (INFN, Firenze)

Zurich, january 7, 2009

Outline

- Introduction

- Total cross section:

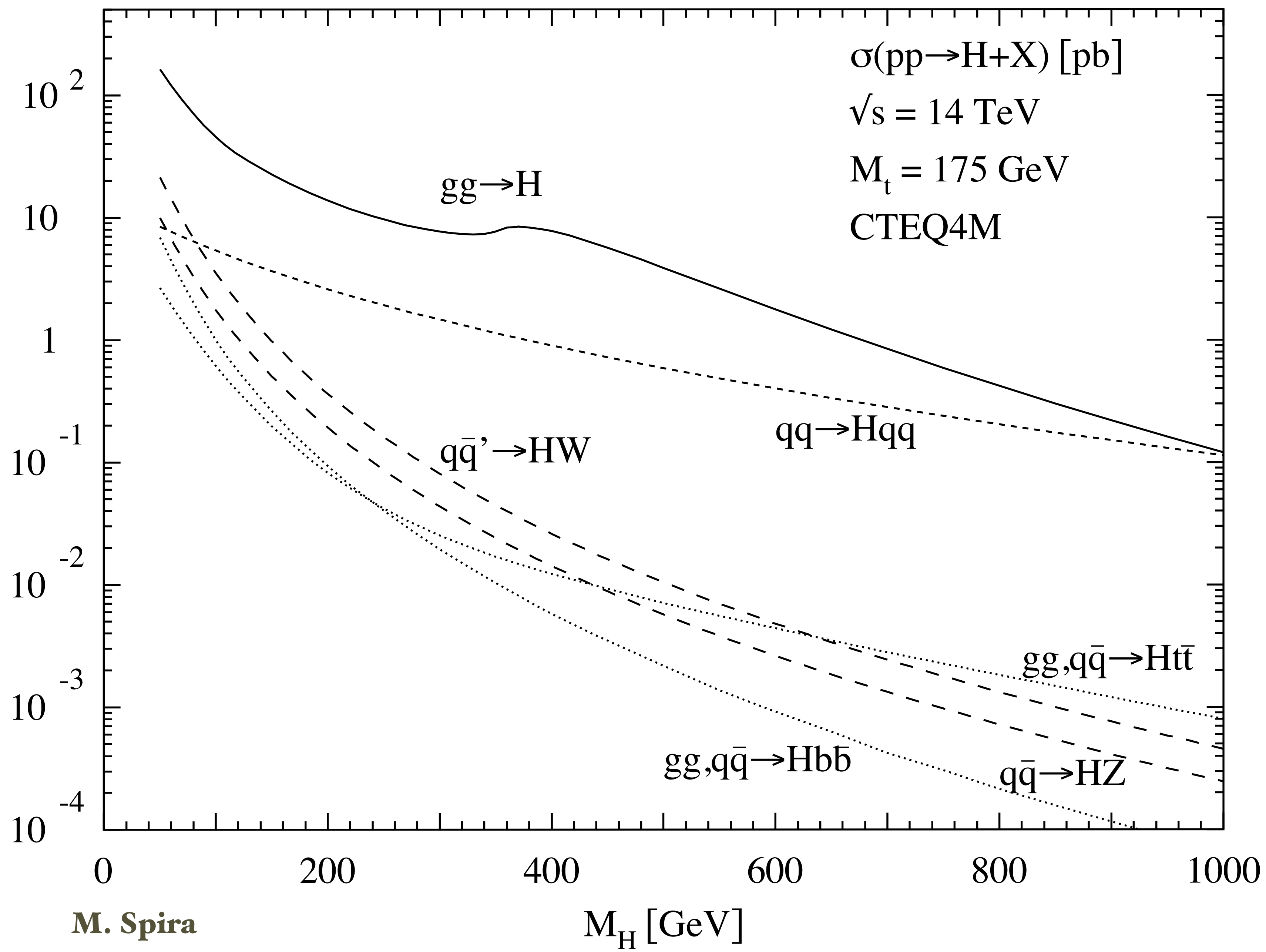
  - The NNLO calculation
  - Soft gluon resummation at NNLL accuracy: an update

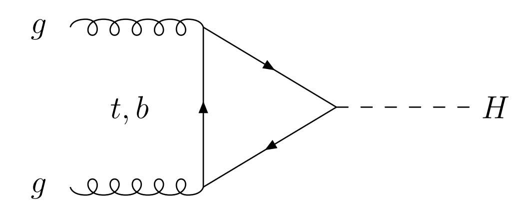
- The fully exclusive NNLO calculation: a study of $gg \to H \to WW \to l\nu l\nu$ at the Tevatron

  - Cross sections
  - Distributions

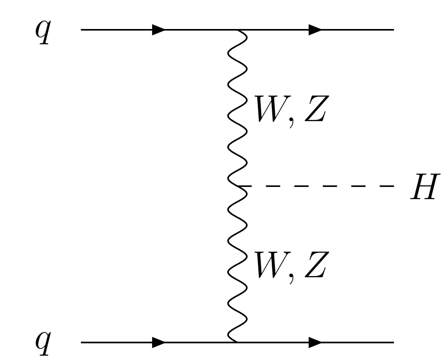
- Summary

Higgs production at the LHC

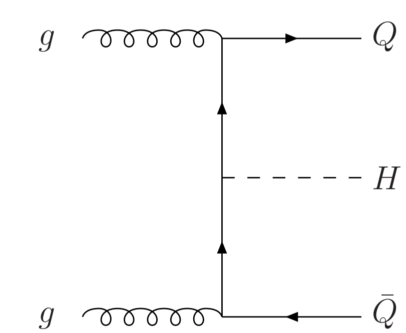




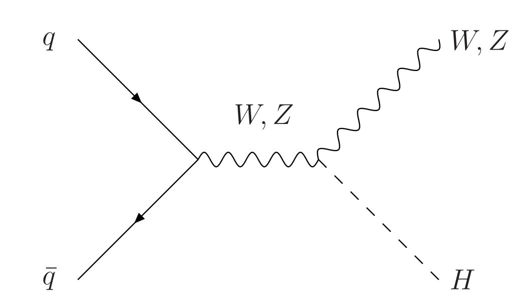
gg fusion



vector boson fusion



associated production with $Q\bar{Q}$

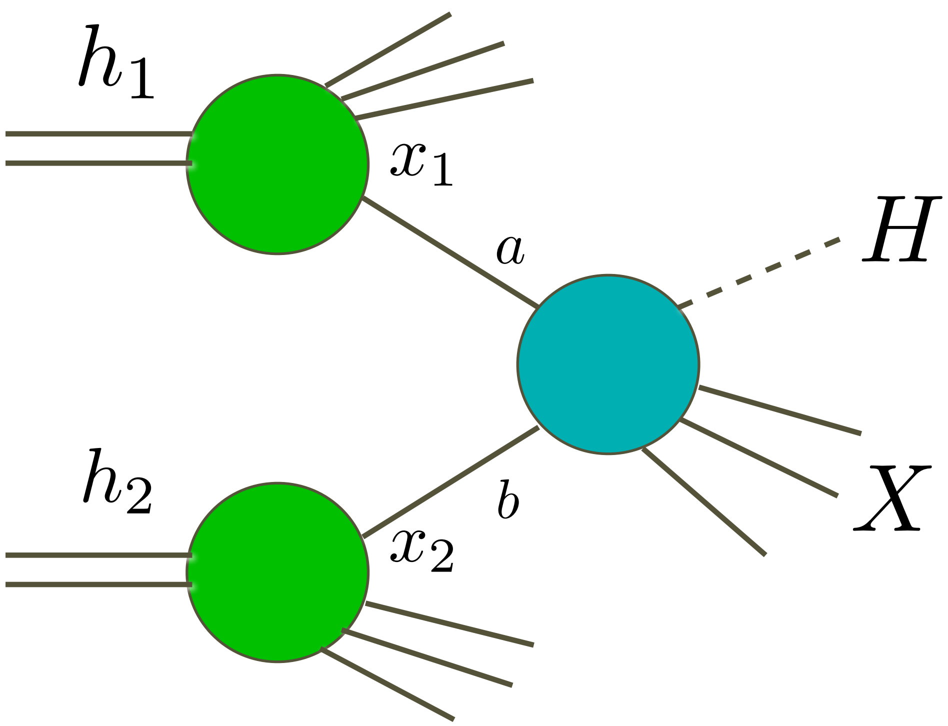


associated production with W, Z

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

Theoretical predictions

The framework: QCD factorization theorem



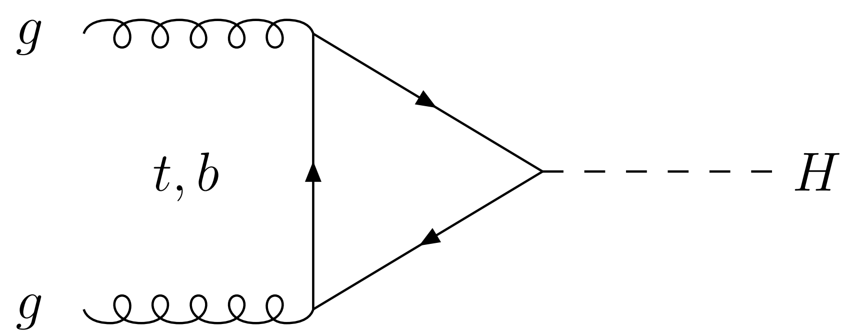
Parton distributions

Partonic cross section

$$\sigma(p_1,p_2;M_H)=\sum_{a,b}\int_0^1 dx_1dx_2\, f_{h_1,a}(x_1,\mu_F^2)\, f_{h_2,b}(x_2,\mu_F^2)\times\hat{\sigma}_{ab}(x_1p_1,x_2p_2,\alpha_S(\mu_R^2);\mu_F^2)$$

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

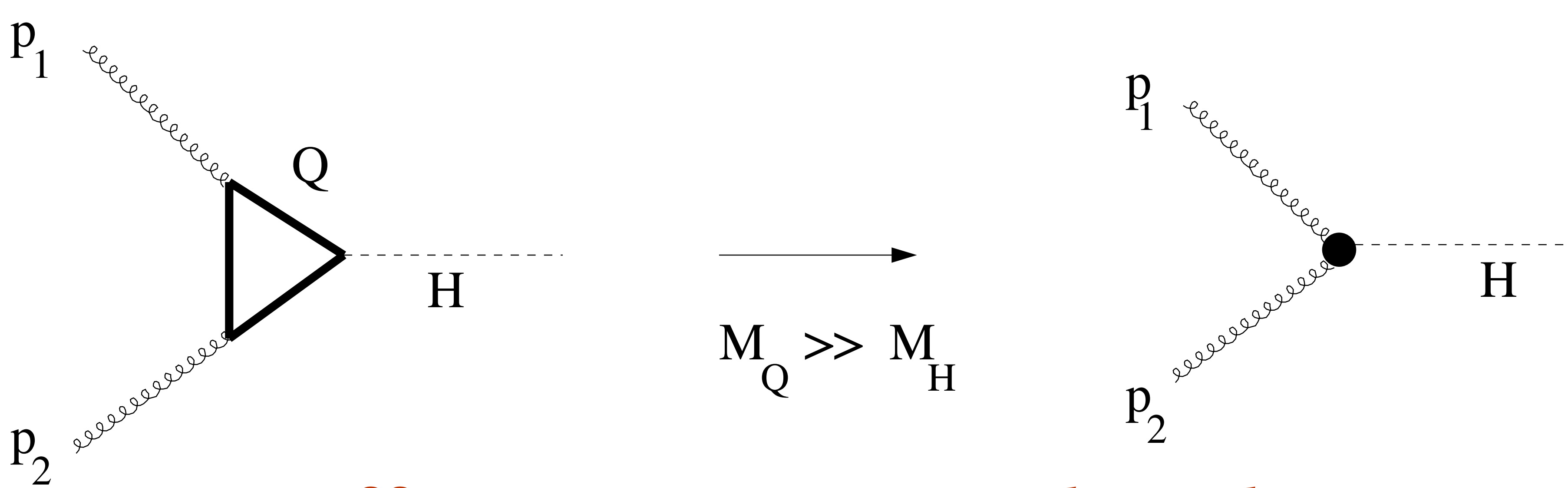
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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**

$gg \to H$ 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**

NNLO corrections computed in the large m_{top} limit

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)

Dominance of soft-virtual effects persists at NNLO

→ This is good because the effects of very hard radiation are precisely those that are not accounted properly by the large m_{top} approximation

Soft-gluon resummation

Soft-virtual effects are important

→ **All-order resummation of soft-gluon effects provides a way to improve our perturbative predictions**

Soft-virtual effects are logarithmically enhanced at $z = M_H^2/\hat{s} \to 1$

The dominant behaviour can be organized in an all order resummed formula

Resummation works in Mellin space $L = \ln N$

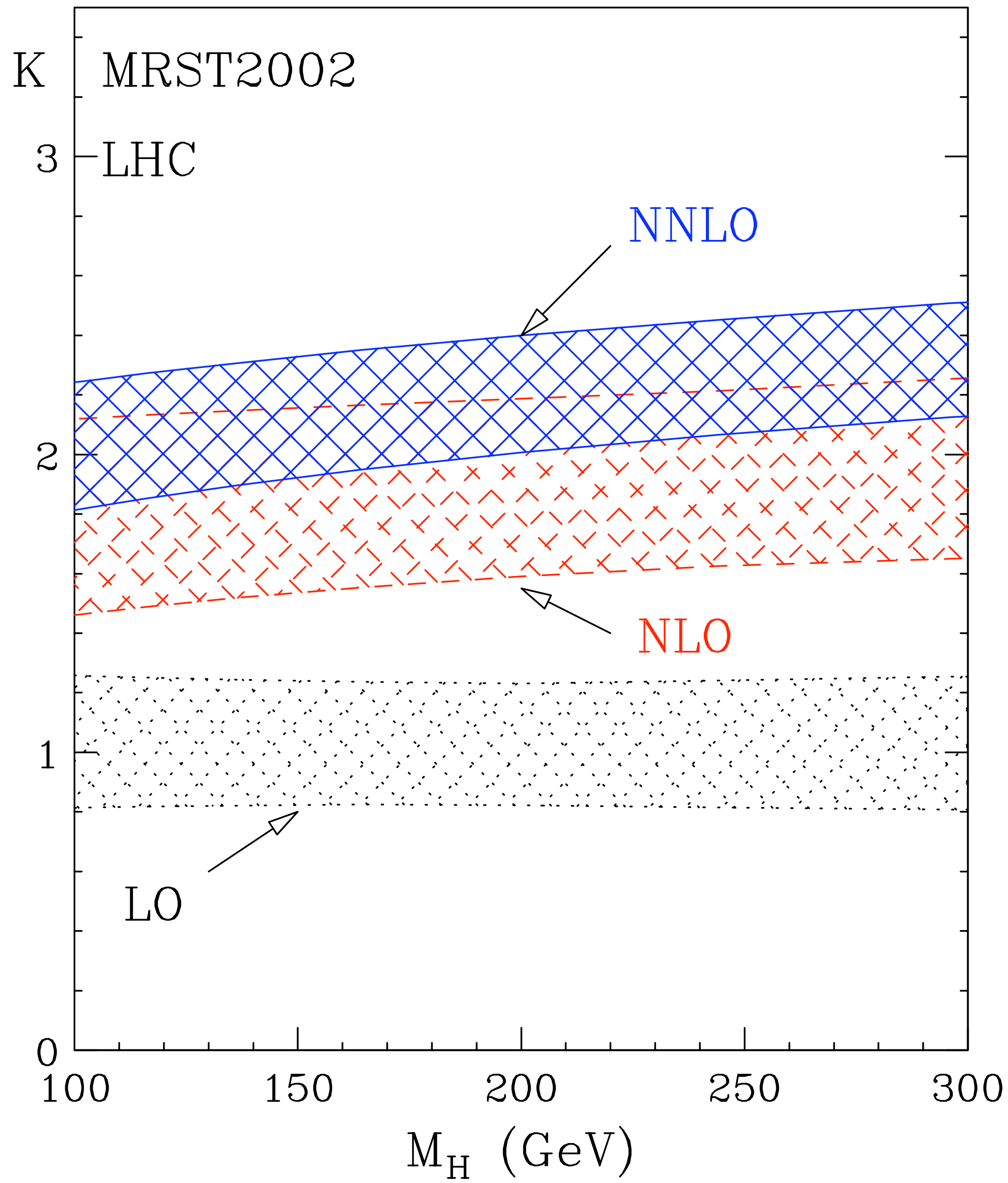
$$\sigma^{\rm res} \sim C(\alpha_{\rm S}) \exp\{L g_1(\alpha_{\rm S} L) + g_2(\alpha_{\rm S} L) + \alpha_{\rm S} g_3(\alpha_{\rm S} L) + ...\}$$

We can perform the resummation up to NNLL+NNLO accuracy

This means that we include the full NNLO result plus all-order resummation of the logarithmically enhanced terms

→ No information is lost

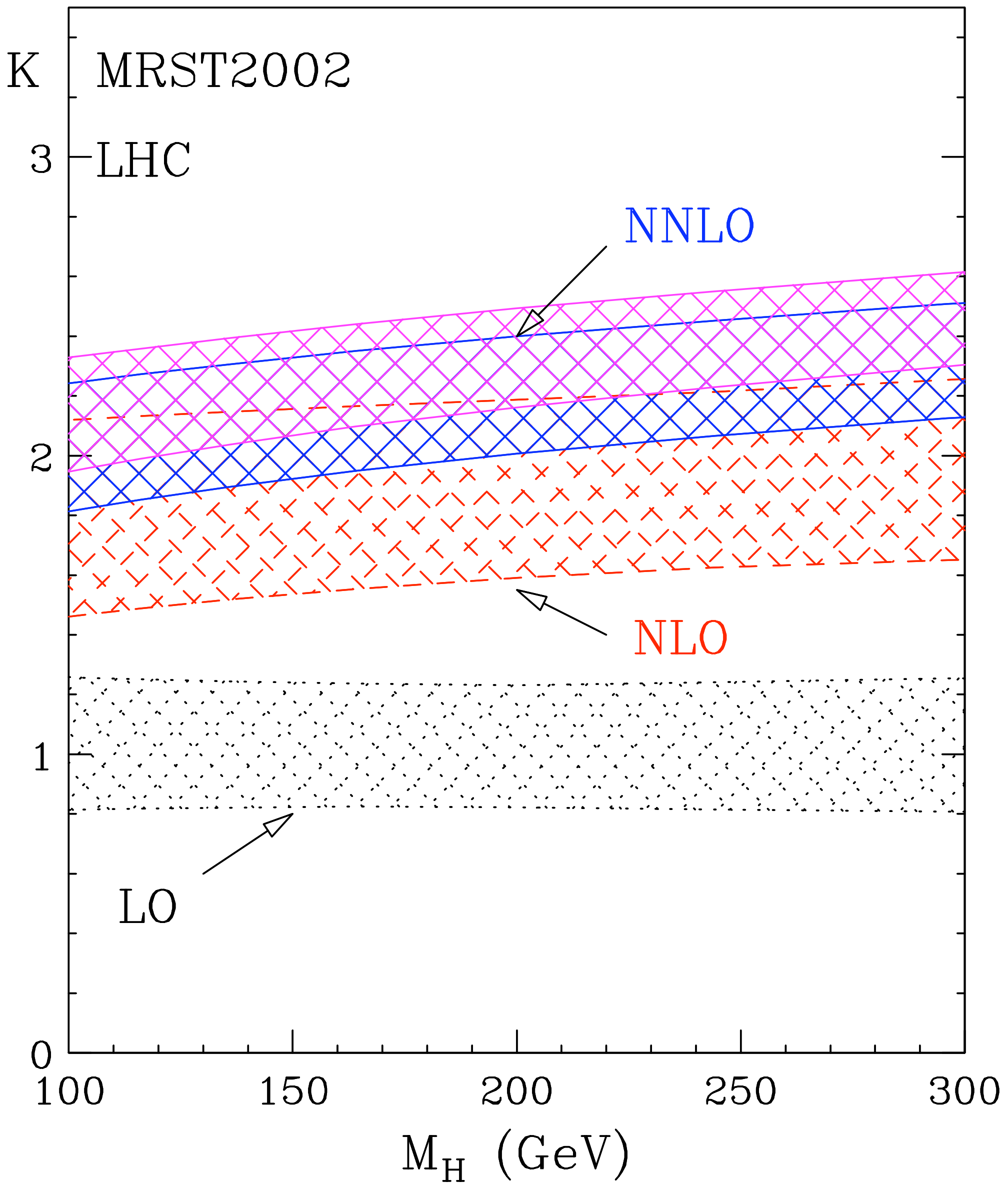
Inclusive results at the LHC



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

- 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 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 $+6\%$

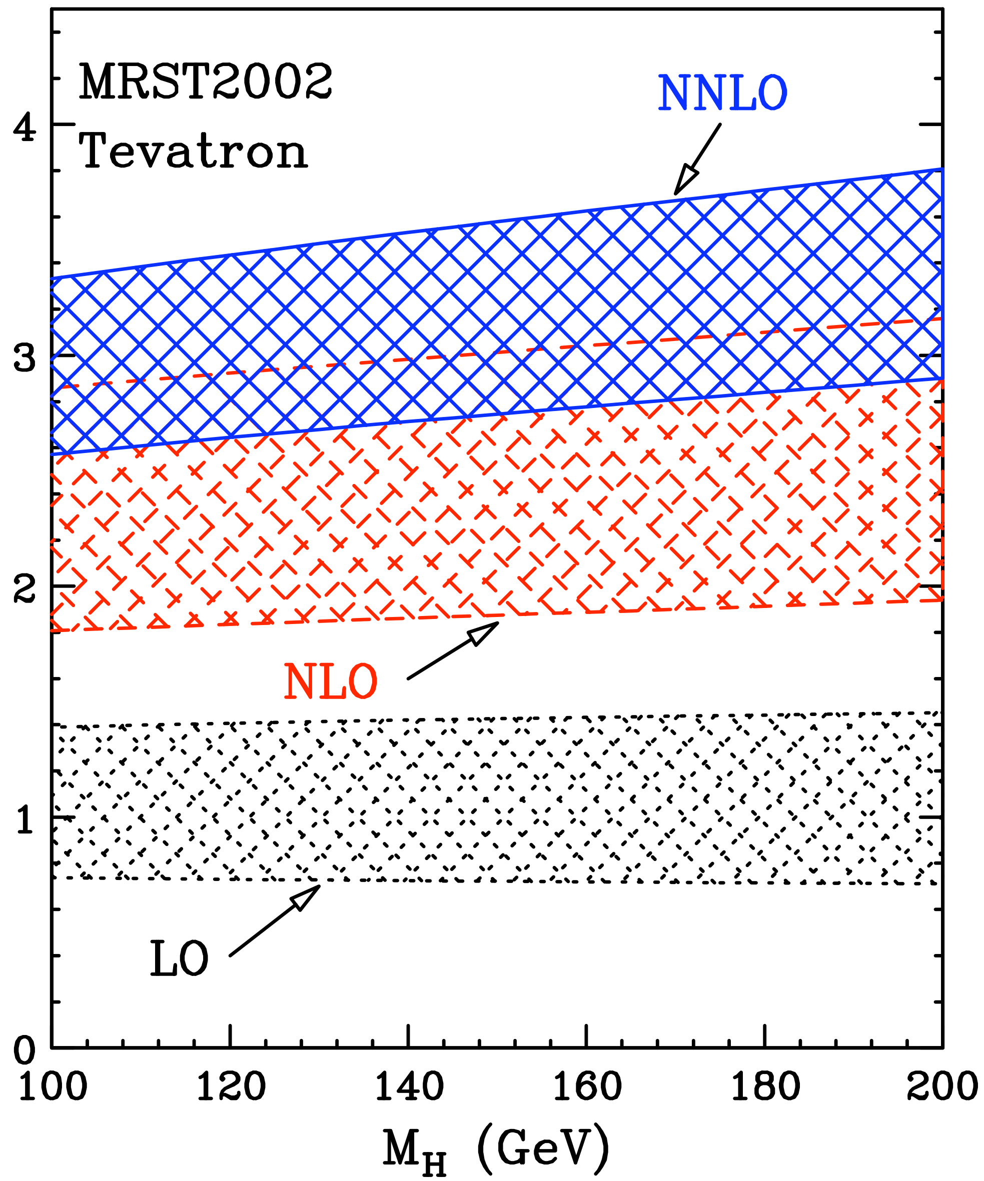
Good stability of perturbative result

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

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 $0.5 \leq \chi_F/\chi_R \leq 2$

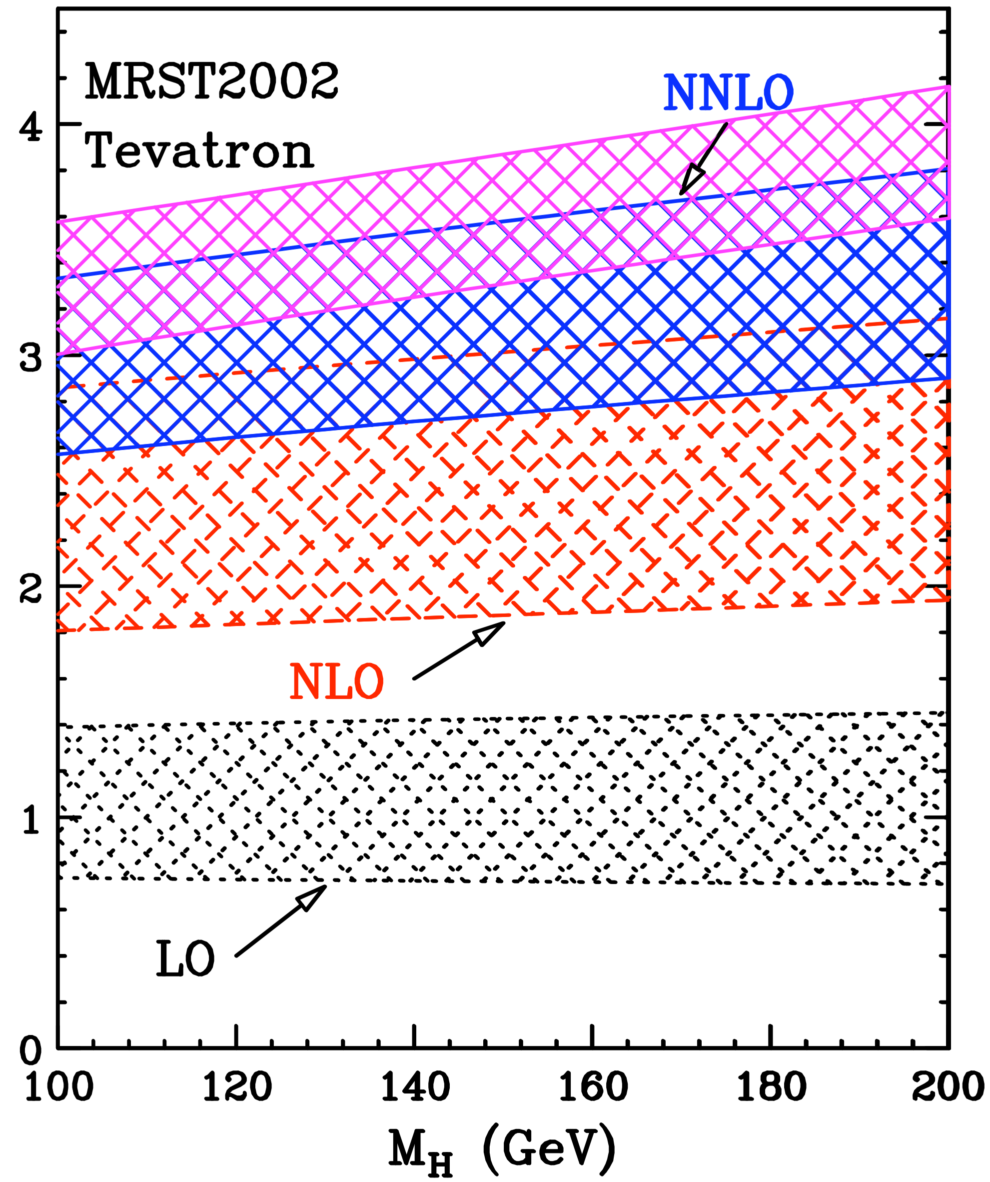
Inclusive results at the Tevatron



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

- 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 $0.5 \le \chi_{L(R)} \le 2$ but $0.5 \le \chi_F/\chi_R \le 2$

An update

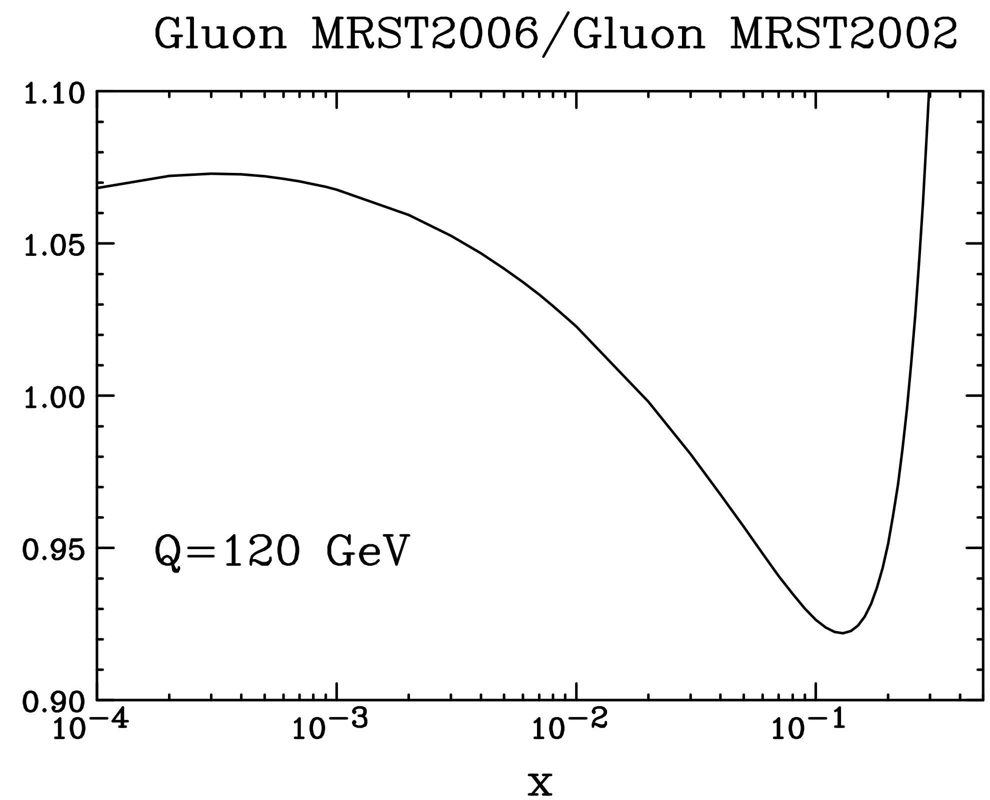
D. De Florian, MG (in progress)

In the last 5 years quite an amount of work has been done: an update is desirable

- New NNLO partons: MRST2006

  Important differences with respect to MRST2002

  - sizeable changes in the gluon
  - $\alpha_S(m_Z)$ from 0.1154 to 0.1191



- Two-loop electroweak corrections have been computed

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

Effect up to 5 % whose sign depends on the Higgs mass

The recipe

- Update to MRST2006 NNLO partons
- Consider top-quark contribution to the cross section and compute it at NNLL+NNLO
- Normalize top-quark contribution with exact Born cross section
- Add bottom contribution and top-bottom interference up to NLO computed with HIGLU
- Include EW effects assuming complete factorization
Supported by recent computation by Anastasiou et al.
- Use $m_t = 170.9\,\mathrm{GeV}$ and $m_b = 4.8\,\mathrm{GeV}$ pole masses

The results: Tevatron

m_H	σ^{best}	Scale	PDF
100	1.979	$^{+0.212}_{-0.193}$	$^{+0.033}_{-0.033}$
105	1.728	$^{+0.183}_{-0.165}$	$^{+0.032}_{-0.031}$
110	1.516	$^{+0.158}_{-0.142}$	$^{+0.030}_{-0.029}$
115	1.336	$^{+0.137}_{-0.123}$	$^{+0.029}_{-0.027}$
120	1.182	$^{+0.120}_{-0.107}$	$^{+0.028}_{-0.026}$
125	1.050	$^{+0.105}_{-0.094}$	$^{+0.027}_{-0.024}$
130	0.936	$^{+0.093}_{-0.082}$	$^{+0.025}_{-0.023}$
135	0.837	$^{+0.082}_{-0.072}$	$^{+0.024}_{-0.022}$
140	0.751	$^{+0.073}_{-0.064}$	$^{+0.023}_{-0.021}$
145	0.675	$^{+0.065}_{-0.057}$	$^{+0.022}_{-0.020}$
150	0.608	$^{+0.058}_{-0.051}$	$^{+0.021}_{-0.019}$
155	0.548	$^{+0.052}_{-0.045}$	$^{+0.020}_{-0.018}$
160	0.492	$^{+0.046}_{-0.040}$	$^{+0.019}_{-0.017}$
165	0.438	$^{+0.041}_{-0.035}$	$^{+0.018}_{-0.016}$
170	0.395	$^{+0.036}_{-0.031}$	$^{+0.017}_{-0.015}$
175	0.357	$^{+0.033}_{-0.028}$	$^{+0.016}_{-0.014}$
180	0.323	$^{+0.029}_{-0.025}$	$^{+0.015}_{-0.013}$
185	0.293	$^{+0.027}_{-0.023}$	$^{+0.014}_{-0.012}$
190	0.266	$^{+0.024}_{-0.020}$	$^{+0.013}_{-0.011}$
195	0.243	$^{+0.022}_{-0.018}$	$^{+0.012}_{-0.011}$
200	0.223	$^{+0.020}_{-0.017}$	$^{+0.012}_{-0.010}$

PDF uncertainties computed using the 30 grids provided by MRST

Scale uncertainties computed with independent variations of renormalization and factorization scales

$$0.5\, m_H \leq \mu_F, \mu_R \leq 2 m_H \qquad 0.5 \leq \mu_F/\mu_R \leq 2$$

With respect to our 2003 results the effect is an increase of the cross section ranging from 17% to 5 %

Uncertainty from scale variations is about 9-10 % (at NNLO it is 14%)

PDF uncertainty goes from 2 to 5%

We find a good agreement with result from Anastasiou et al. (obtained with a different approach) differences are of about 1%

The results: LHC

m_H	σ^{best}	Scale	PDF
100	74.45	${}^{+7.51}_{-7.77}$	${}^{+1.40}_{-1.45}$
110	63.26	${}^{+6.15}_{-6.40}$	${}^{+1.12}_{-1.17}$
120	54.52	${}^{+5.13}_{-5.35}$	${}^{+0.91}_{-0.96}$
130	47.53	${}^{+4.33}_{-4.53}$	${}^{+0.76}_{-0.81}$
140	41.83	${}^{+3.69}_{-3.89}$	${}^{+0.63}_{-0.68}$
150	37.11	${}^{+3.18}_{-3.36}$	${}^{+0.53}_{-0.58}$
160	32.77	${}^{+2.74}_{-2.90}$	${}^{+0.45}_{-0.49}$

m_H	σ^{best}	Scale	PDF
170	28.64	${}^{+2.35}_{-2.48}$	${}^{+0.39}_{-0.41}$
180	25.52	${}^{+2.03}_{-2.17}$	${}^{+0.32}_{-0.35}$
190	22.83	${}^{+1.78}_{-1.90}$	${}^{+0.28}_{-0.30}$
200	20.73	${}^{+1.58}_{-1.70}$	${}^{+0.24}_{-0.27}$
210	19.03	${}^{+1.42}_{-1.53}$	${}^{+0.21}_{-0.23}$
220	17.60	${}^{+1.30}_{-1.39}$	${}^{+0.19}_{-0.21}$
230	16.37	${}^{+1.18}_{-1.28}$	${}^{+0.17}_{-0.19}$

m_H	σ^{best}	Scale	PDF
240	15.32	${}^{+1.09}_{-1.18}$	${}^{+0.16}_{-0.17}$
250	14.42	${}^{+1.01}_{-1.09}$	${}^{+0.14}_{-0.15}$
260	13.65	${}^{+0.94}_{-1.02}$	${}^{+0.13}_{-0.14}$
270	12.98	${}^{+0.88}_{-0.96}$	${}^{+0.12}_{-0.13}$
280	12.42	${}^{+0.84}_{-0.91}$	${}^{+0.12}_{-0.12}$
290	11.95	${}^{+0.79}_{-0.86}$	${}^{+0.11}_{-0.12}$
300	11.59	${}^{+0.76}_{-0.83}$	${}^{+0.11}_{-0.11}$

With respect to our 2003 results the effect is huge !

+30 % at $m_H = 115\,\mathrm{GeV}$
+6 % at $m_H = 300\,\mathrm{GeV}$

Scale uncertainty ranges from 10 to 7 % (at NNLO it ranges from 12 to 9 %)

PDF uncertainty is very small: 1-2 %

....but...

On january 5 2009 (two days ago !) MSTW released the new pdf set

How are the above results affected ?

PRELIMINARY:

- At the LHC the results do not change very much: differences are at most -2% ($m_H = 300\,\mathrm{GeV}$)
- At the Tevatron there seem to be big differences ! From -6% to -15 % for $m_H = 100 - 200\,\mathrm{GeV}$

....but...

On january 5 2009 (two days ago !) MSTW released the new pdf set

How are the above results affected ?

PRELIMINARY:

- At the LHC the results do not change very much: differences are at most -2% ($m_H = 300\,\mathrm{GeV}$)
- At the Tevatron there seem to be big differences ! From -6% to -15 % for $m_H = 100 - 200\,\mathrm{GeV}$

BOTTOM LINE:

PDF uncertainties on Higgs boson production are still pretty large

Experimental uncertainties that come with the MRST2006 and MSTW2008 sets give only a lower limit on the true uncertainty

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

NNLO computation is now implemented in two fully exclusive programs

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: Based on the subtraction method: computes NNLO corrections for $H \to \gamma\gamma$ $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$ can be downloaded from **http://theory.fi.infn.it/grazzini/codes.html**

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

A study of $gg \to H \to WW \to l\nu l\nu$ at the Tevatron

C. Anastasiou, G.Dissertori,
F. Stoeckli, B.Webber, MG (2009)

We consider $M_H = 160$ GeV → The inclusive K-factors are:
$K_{NLO} = 2.42 \quad K_{NNLO} = 3.31$

Consider dimuon final state $WW \to \mu^+\mu^-\nu\bar{\nu}$

We use the following cuts (CDF note 9500 (2008)):

Trigger: at least one lepton with $p_T > 20\,\mathrm{GeV}$ and $|\eta| < 0.8$

Preselection:

- Other lepton must have $p_T > 10\,\mathrm{GeV}$ and $|\eta| < 1.1$
- Invariant mass of the charged leptons $m_{ll} > 16\,\mathrm{GeV}$
- Leptons should be isolated: total transverse energy in a cone of radius $R = 0.4$ should be smaller than 10% of lepton p_T

Selection cuts for $M_H = 160\ \mathrm{GeV}$*:*

Define jets according to the kt algorithm with $D = 0.4$:
a jet must have $p_T > 15\,\mathrm{GeV}$ and $|\eta| < 3$

Define: $$\mathrm{MET}^* = \begin{cases} \mathrm{MET} & , \phi \geq \pi/2 \\ \mathrm{MET} \times \sin\phi\,, & \phi < \pi/2 \end{cases}$$

where ϕ is the angle in the transverse plane between MET and the nearest charged lepton or jet

We require:

- At most one jet (effective only beyond NLO)
- $\mathrm{MET}^* > 25\,\mathrm{GeV}$

This defines the neural net input stage

→ Being a NN based analysis it is important to check that the distributions used are stable against radiative corrections and that they are correctly described by the MC generators

Preliminary: cross sections

Inclusive cross sections:

$\sigma(fb)$	LO	NLO	NNLO
$\mu = m_H/2$	1.998 ± 0.003	4.288 ± 0.004	5.252 ± 0.016
$\mu = m_H$	1.398 ± 0.001	3.366 ± 0.003	4.630 ± 0.010
$\mu = 2m_H$	1.004 ± 0.001	2.661 ± 0.002	4.012 ± 0.007

$K_{NLO} = 2.42$

$K_{NNLO} = 3.31$

Cross sections after cuts:

$\sigma(fb)$	LO	NLO	NNLO
$\mu = m_H/2$	0.750 ± 0.001	1.410 ± 0.003	1.454 ± 0.006
$\mu = m_H$	0.525 ± 0.001	1.129 ± 0.003	1.383 ± 0.003
$\mu = 2m_H$	0.379 ± 0.001	0.903 ± 0.002	1.243 ± 0.003

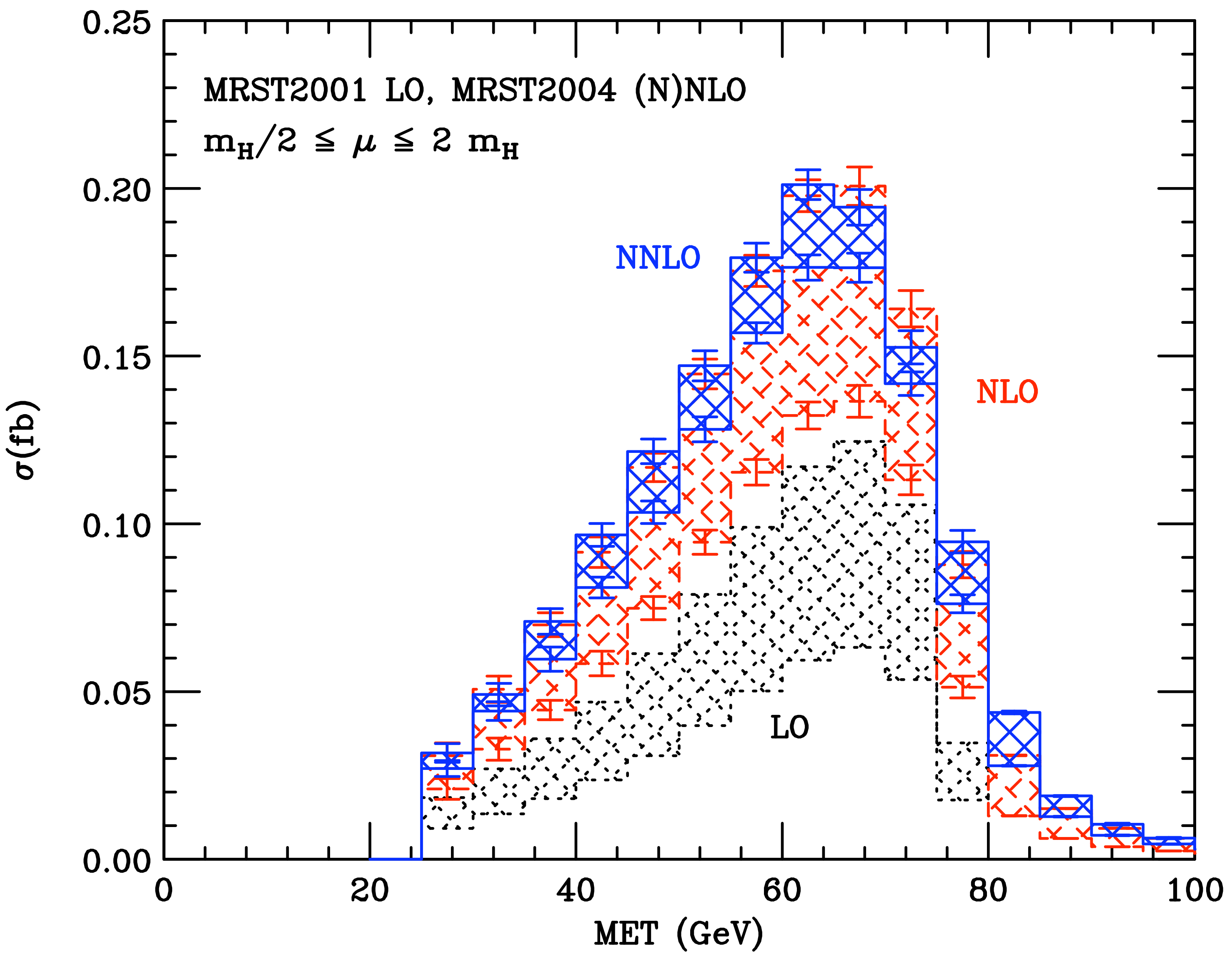
$K_{NLO} = 2.15$

$K_{NNLO} = 2.63$

$\epsilon_{LO} = 38\%$ $\epsilon_{NLO} = 34\%$ $\epsilon_{NNLO} = 30\%$

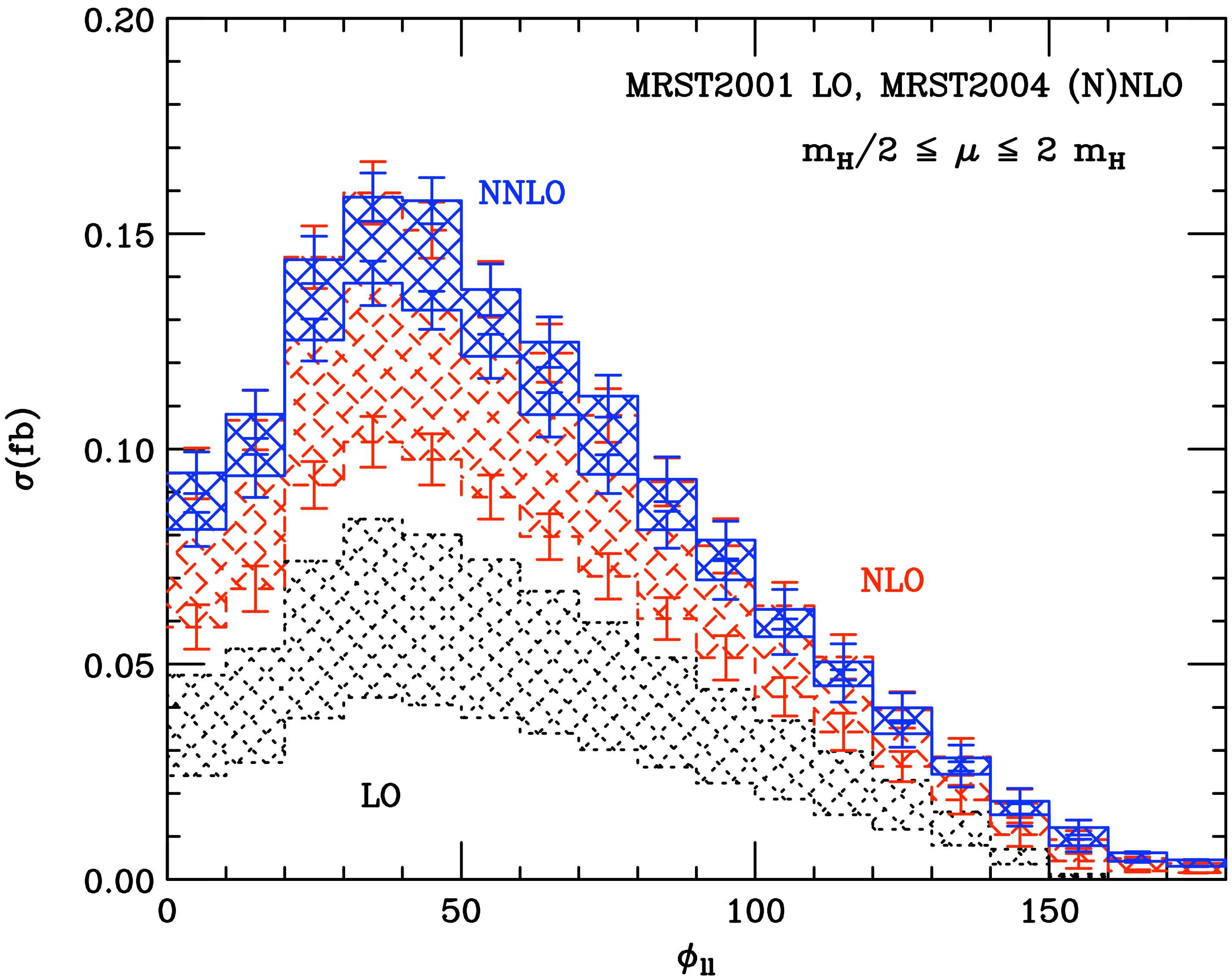
Effect of radiative corrections significantly reduced when cuts are applied
Efficiency of the cuts decreases when going from LO to NLO and NNLO

Preliminary: distributions



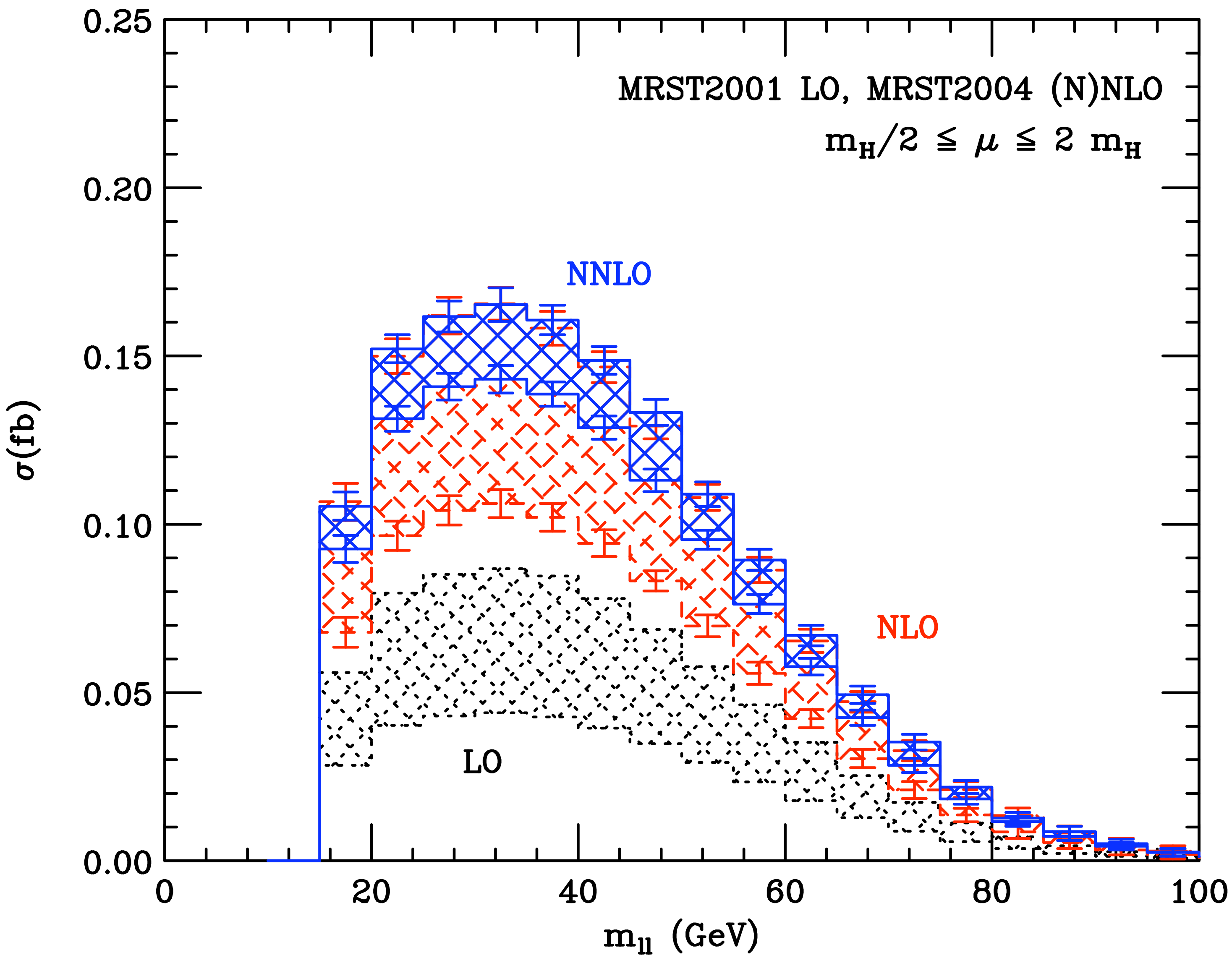
Bands obtained by varying $\mu \equiv \mu_F = \mu_R$ between $1/2\, m_H$ and $2\, m_H$

Preliminary: distributions



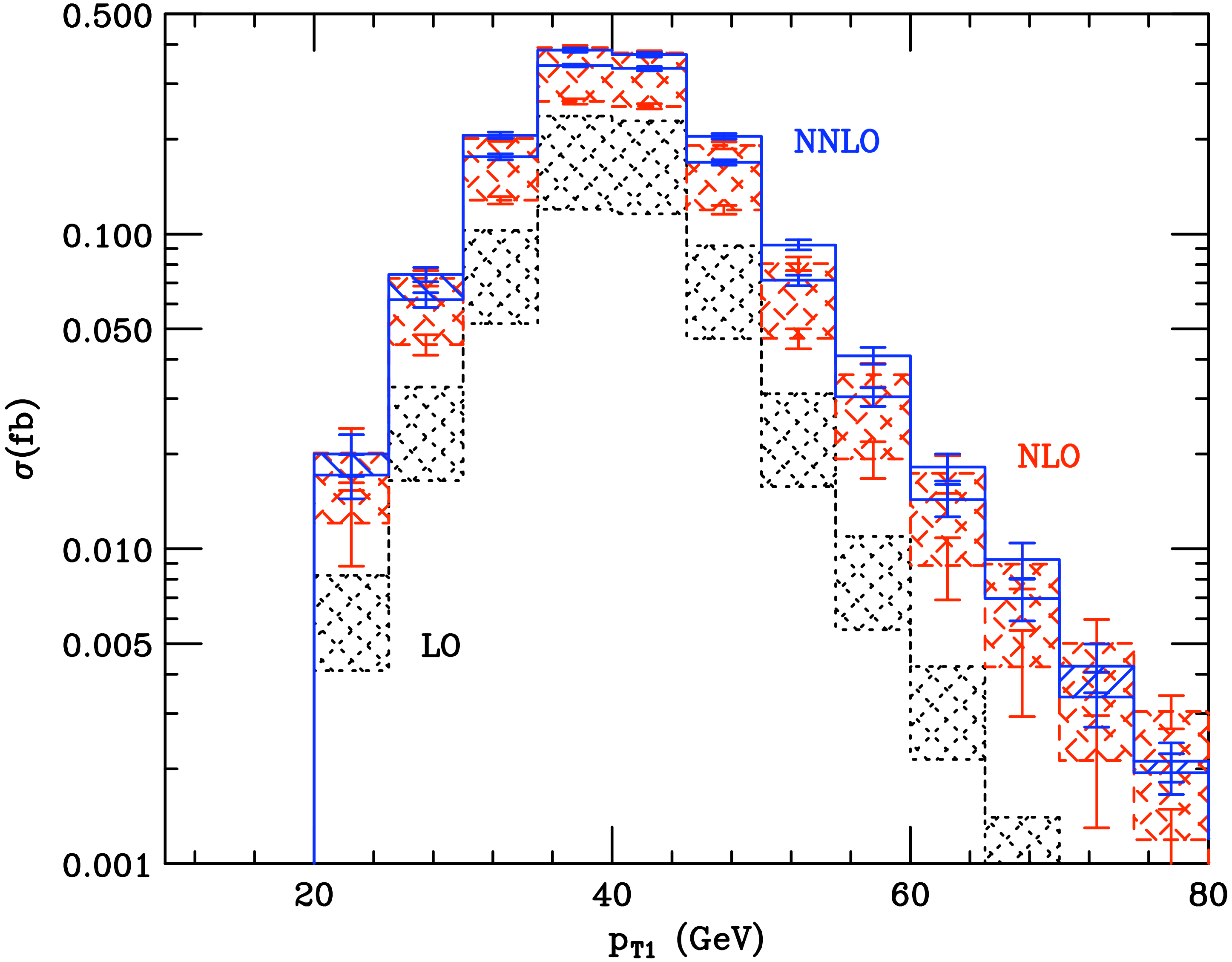
Bands obtained by varying $\mu \equiv \mu_F = \mu_R$ between $1/2\, m_H$ and $2\, m_H$

Preliminary: distributions



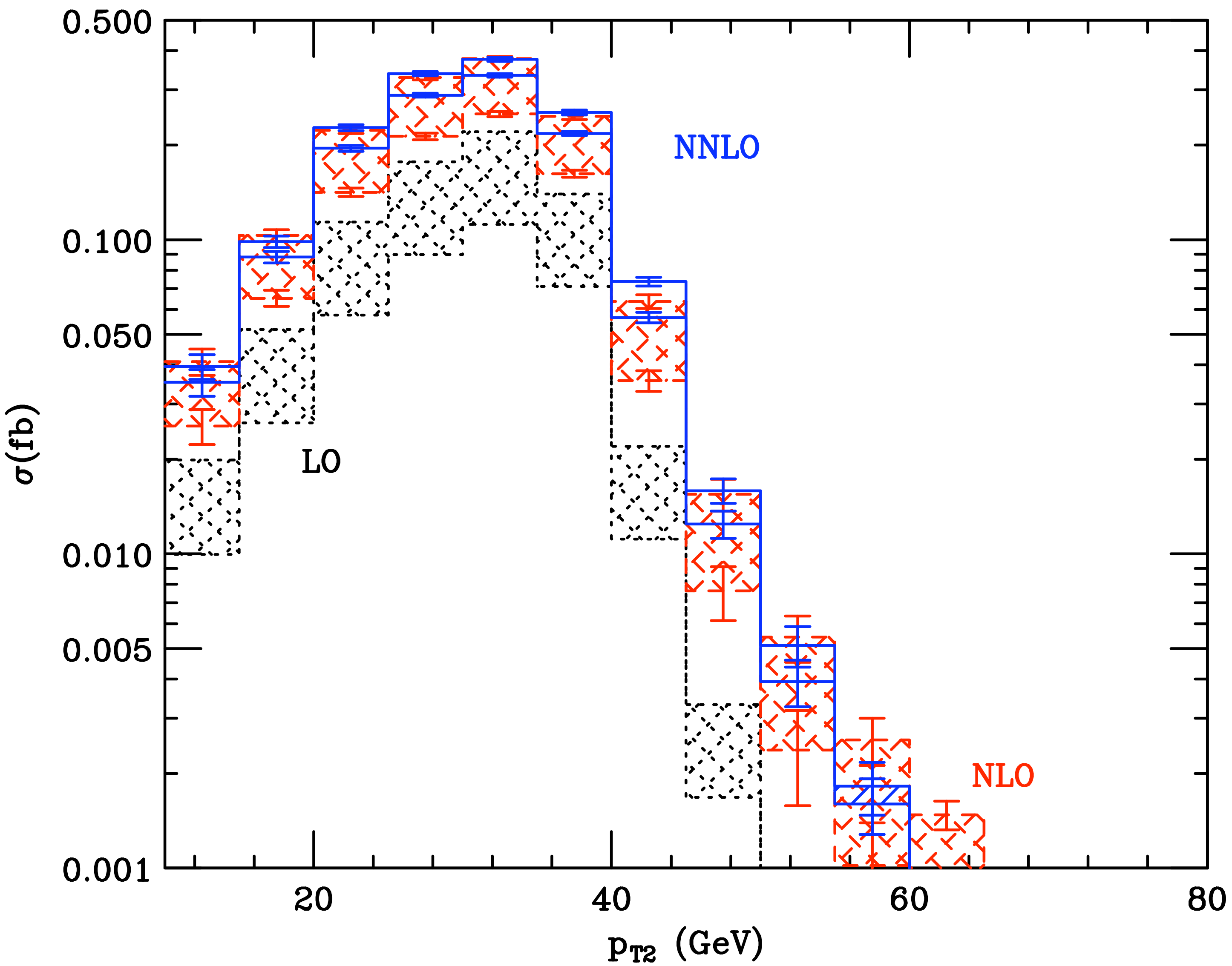
Bands obtained by varying $\mu \equiv \mu_F = \mu_R$ between $1/2\, m_H$ and $2\, m_H$

Preliminary: distributions



Bands obtained by varying $\mu \equiv \mu_F = \mu_R$ between $1/2\, m_H$ and $2\, m_H$

Preliminary: distributions



Bands obtained by varying $\mu \equiv \mu_F = \mu_R$ between $1/2\, m_H$ and $2\, m_H$

How well do the distributions agree with those coming in the analysis ? To check it we train our own NN !
See talk by Fabian Stoeckli this afternoon

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
- Resummation provides a way to improve the fixed order NNLO predictions by adding the all-order resummation of soft-gluon contributions
- I have presented updated predictions at the Tevatron and the LHC
- Compared to our 2003 results the cross sections are significantly increased
- The recent MSTW2008 set appears to wash out the increase at the Tevatron

Summary (II)

- Total cross sections are ideal quantities: real experiments have finite acceptances !

- NNLO QCD computation is now implemented in two independent fully exclusive programs: FEHIP and HNNLO

- I have presented preliminary results of a study of $gg \to H \to WW \to l\nu l\nu$ at the Tevatron

- As expected, the impact of QCD corrections is reduced when the selection cuts are applied

- The distributions used in the NN experimental analysis do not show significant instabilities when going from LO to NLO to NNLO

BACKUP SLIDES

Soft-gluon resummation

Knowledge of the function g_4 is not enough get N^{3}LL accuracy

Example: effect of g_4 $\qquad$ $\alpha_S^2(\alpha_S L)^n$

Combined effect of $C^{(3)}$ and g_1 $\qquad$ $\alpha_S^3 L(\alpha_S L)^n$

→ They are of the same logarithmic order !

The sole inclusion of the function g_4 does not lead to a consistent improvement of the logarithmic accuracy

Dominance of SV terms