Cross sections for SM Higgs boson production

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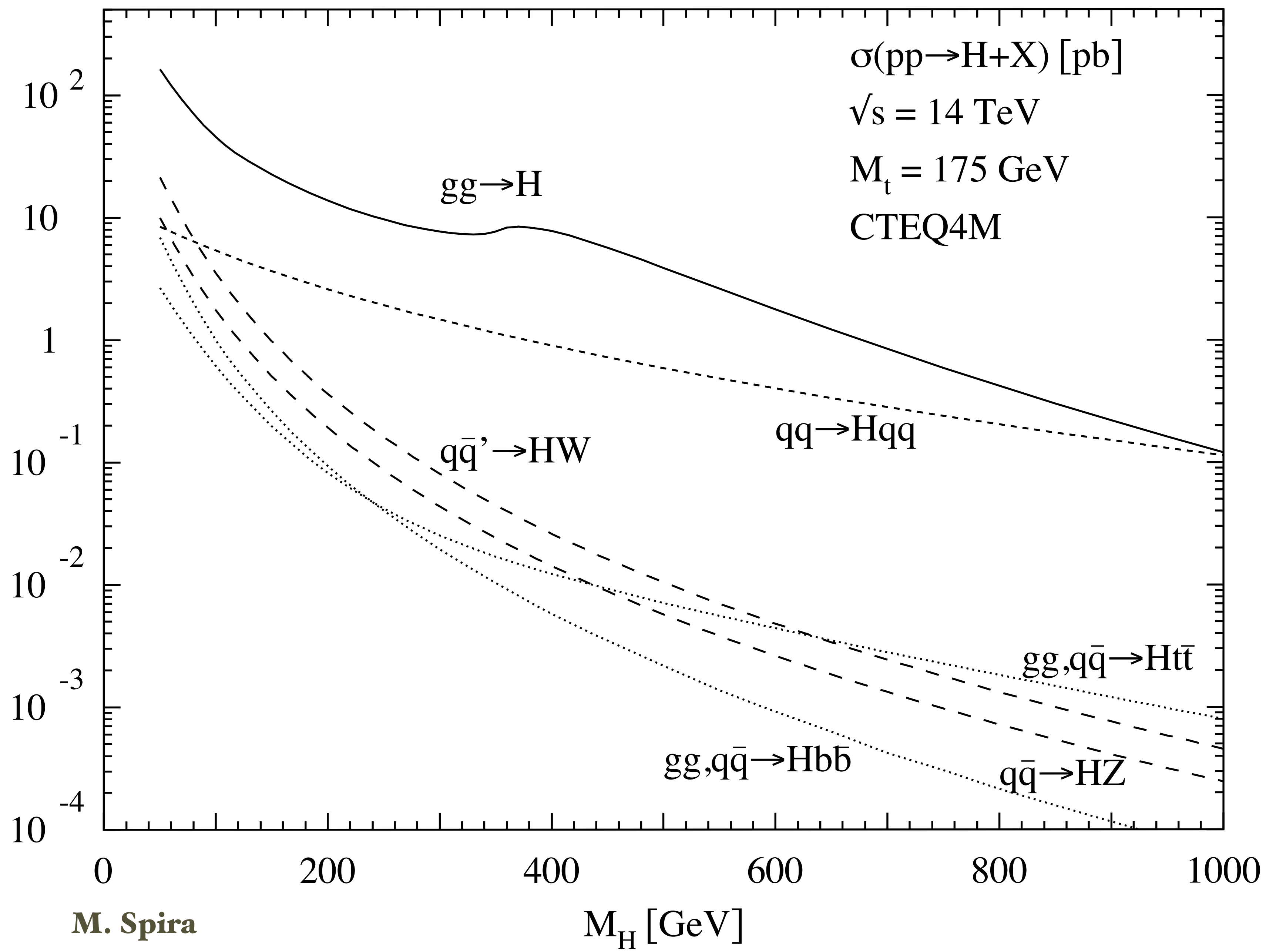
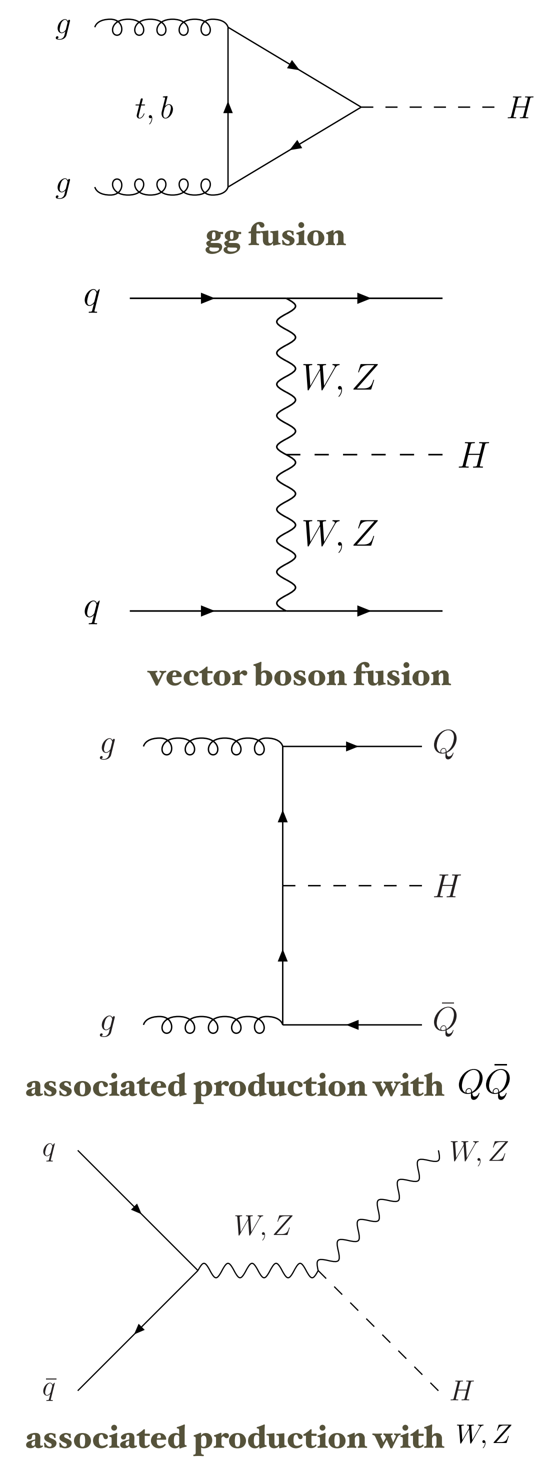
Outline

- Introduction
- Total cross section:
  - The NNLL+NNLO calculation
  - An update
  - The uncertainties
- The fully exclusive NNLO calculation:
  - HNNLO
    - Results at the LHC
    - A study of $gg \to H \to WW \to l\nu l\nu$ at the Tevatron
- Summary

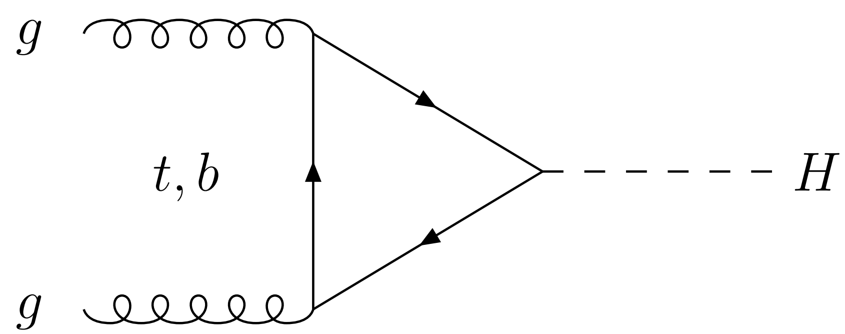
Higgs production at the LHC





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

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 15 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

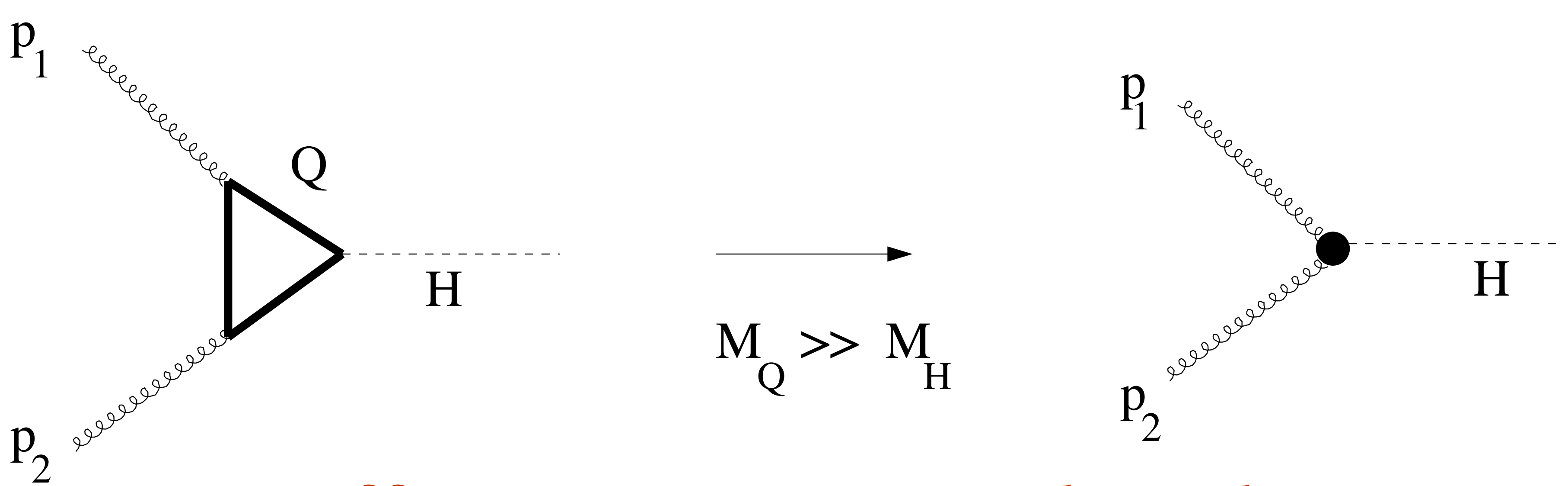
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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**

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

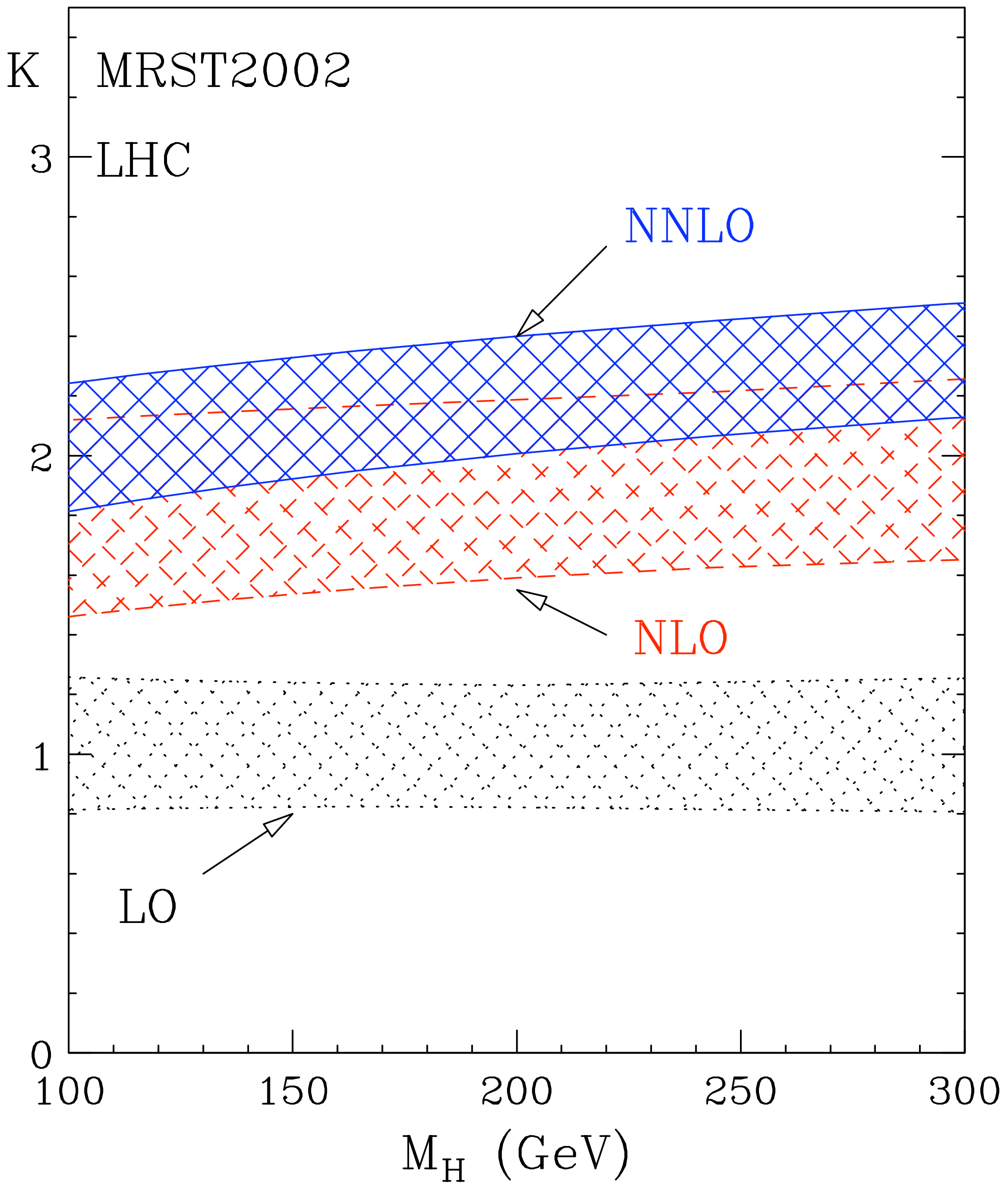
Resummation works in Mellin space L=ln N

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

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

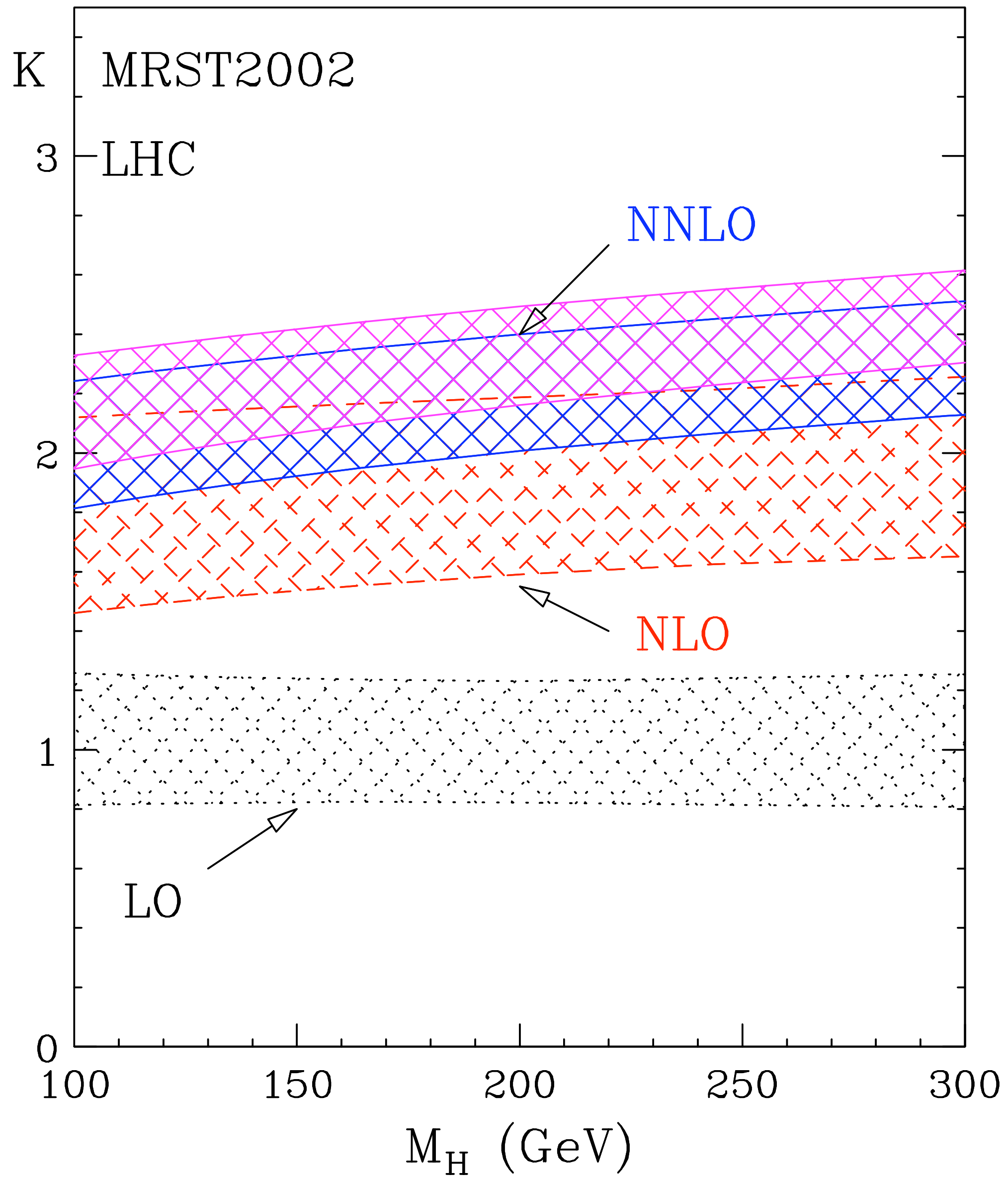
Inclusive results at the LHC



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 $+6\%$

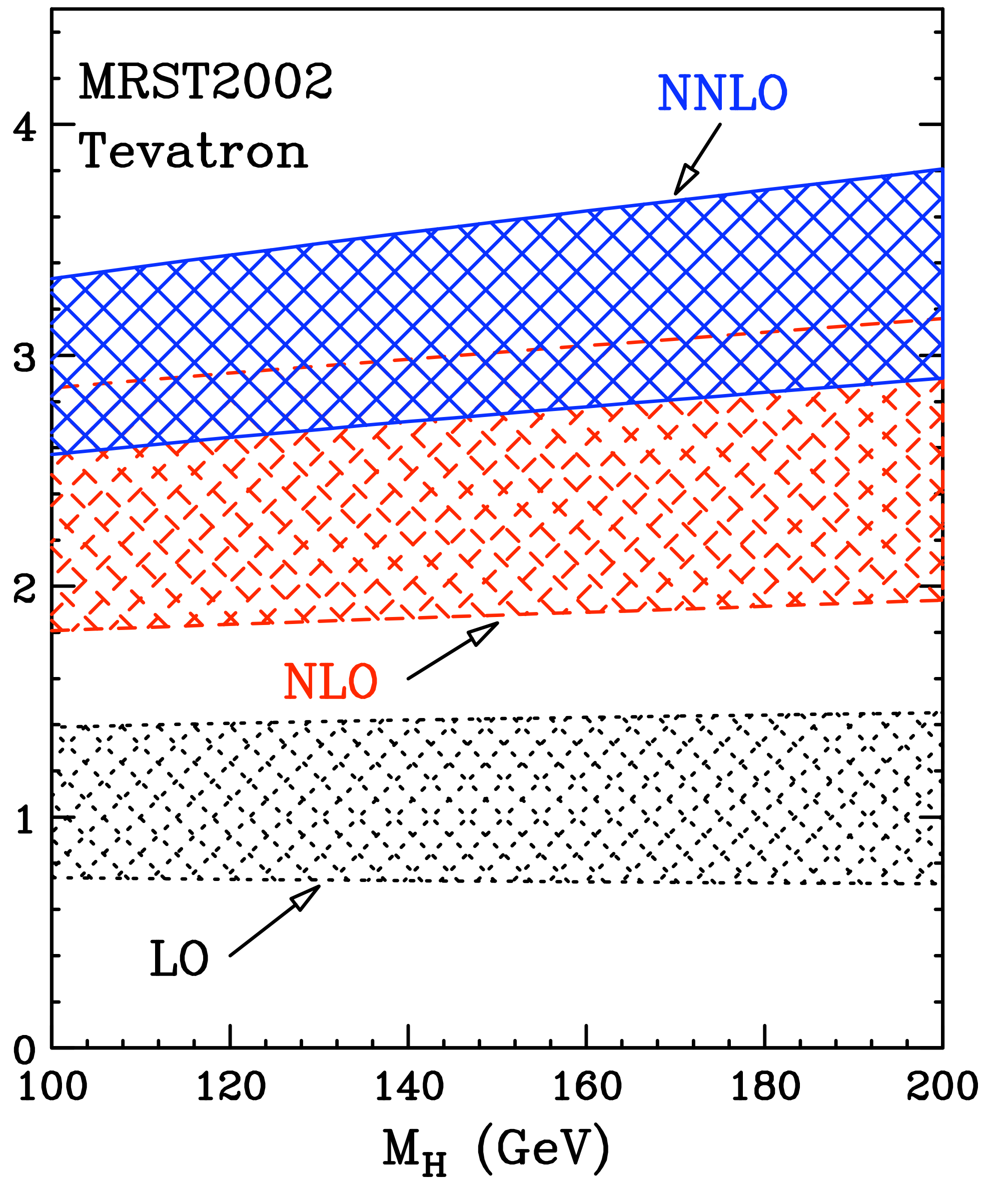
Good stability of perturbative result

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 $\sigma_{LO}(\mu_F = \mu_R = M_H)$
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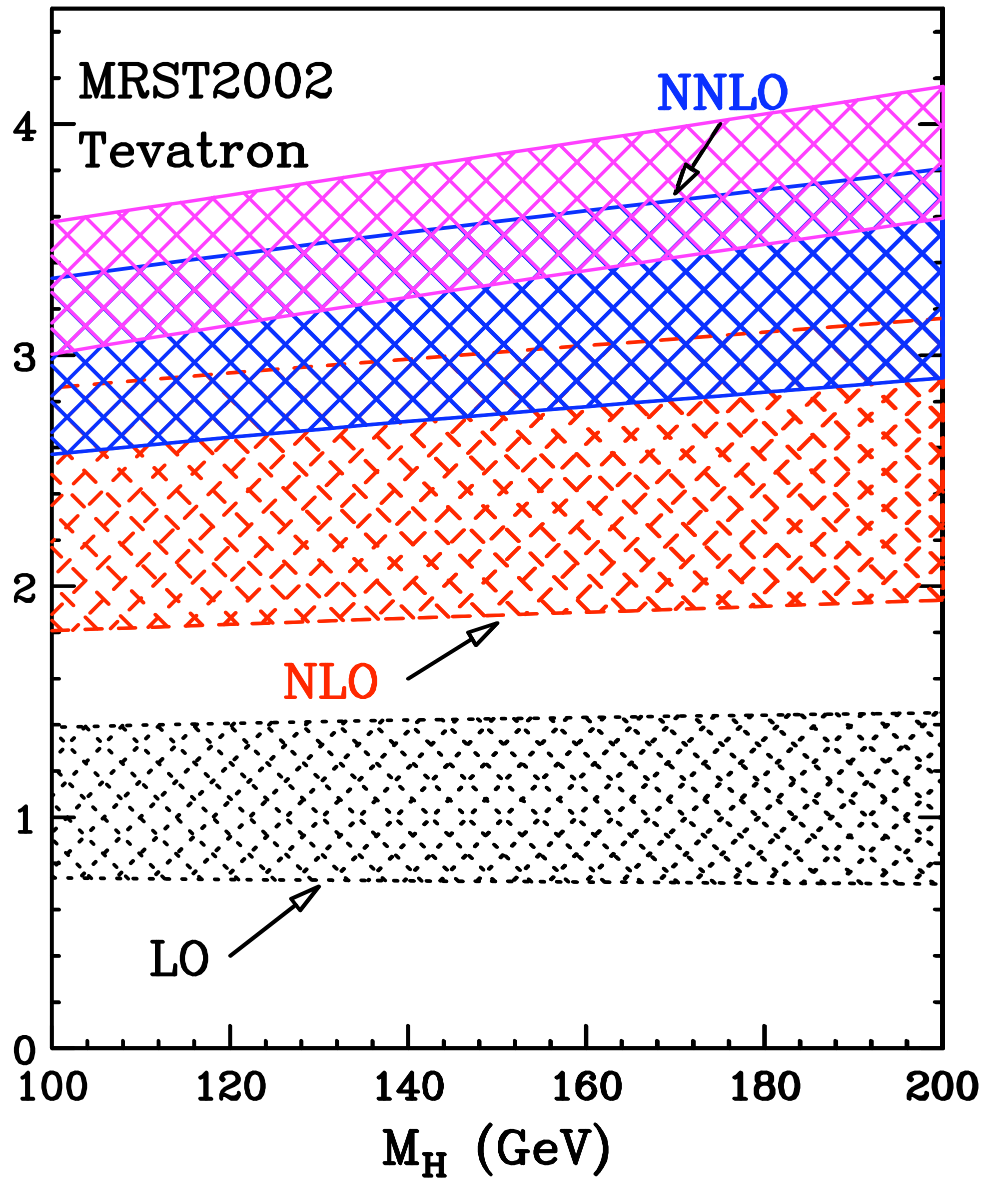


Inclusion of soft-gluon effects at all orders

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

An update

D. De Florian, MG (2009)

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

- New NNLO partons: MSTW2008

  Important differences with respect to MRST2002:

  - more appropriate treatment of heavy quark thresholds
  - sizeable changes in the gluon → E.g.: at x~0.01 (relevant for m_H=120 GeV at the LHC) the gluon increases by *6%* with respect to MRST2002 !
  - $\alpha_S(m_Z)$ from 0.1154 to 0.1171

- 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 MSTW2008 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
- Include EW effects according to the calculation by Passarino et al. assuming "complete factorization" (EW correction multiplies the full QCD corrected cross section: supported by the calculation of Anastasiou et al.)
- Use $m_t = 170.9\,\mathrm{GeV}$ and $m_b = 4.75\,\mathrm{GeV}$ pole masses

The results: LHC@14 TeV

With respect to our 2003 results the effect is huge !

+30 % at m_H=115 GeV +9 % at m_H=300 GeV

m_H (GeV)	σ_{best}(pb)	Scale (%)
100	74.58	+9.6 -10.1
110	63.29	+9.3 -9.8
120	54.48	+9.0 -9.5
130	47.44	+8.7 -9.2
140	41.70	+8.3 -9.0
150	36.95	+8.2 -8.8
160	32.59	+8.0 -8.6
170	28.46	+7.8 -8.4
180	25.32	+7.6 -8.2
190	22.63	+7.4 -8.1
200	20.52	+7.3 -7.9
220	17.38	+7.0 -7.7
240	15.10	+6.8 -7.4
260	13.41	+6.6 -7.3
280	12.17	+6.4 -7.1
300	11.34	+6.3 -6.9

Scale uncertainties computed with independent variations of renormalization and factorization scales (with $0.5m_H < \mu_F, \mu_R < 2m_H$ and $0.5 < \mu_F/\mu_R < 2$)

The uncertainty ranges from 10 to 7% (note that at NNLO it ranges from 12 to 9%)

The results: Tevatron

With respect to our 2003 results the effect ranges from +9% to -9%

m_H (GeV)	σ_{best}(pb)	Scale (%)
110	1.413	+10.0 -9.0
115	1.240	+9.9 -8.9
120	1.093	+9.8 -8.7
125	0.967	+9.7 -8.6
130	0.858	+9.6 -8.4
135	0.764	+9.5 -8.3
140	0.682	+9.5 -8.2
145	0.611	+9.4 -8.1
150	0.548	+9.3 -8.0
155	0.492	+9.2 -7.9
160	0.439	+9.2 -7.8
165	0.389	+9.2 -7.7
170	0.349	+9.1 -7.6
175	0.314	+9.1 -7.5
180	0.283	+9.1 -7.4
185	0.255	+9.0 -7.4
190	0.231	+9.0 -7.3
195	0.210	+9.0 -7.3
200	0.192	+9.0 -7.2

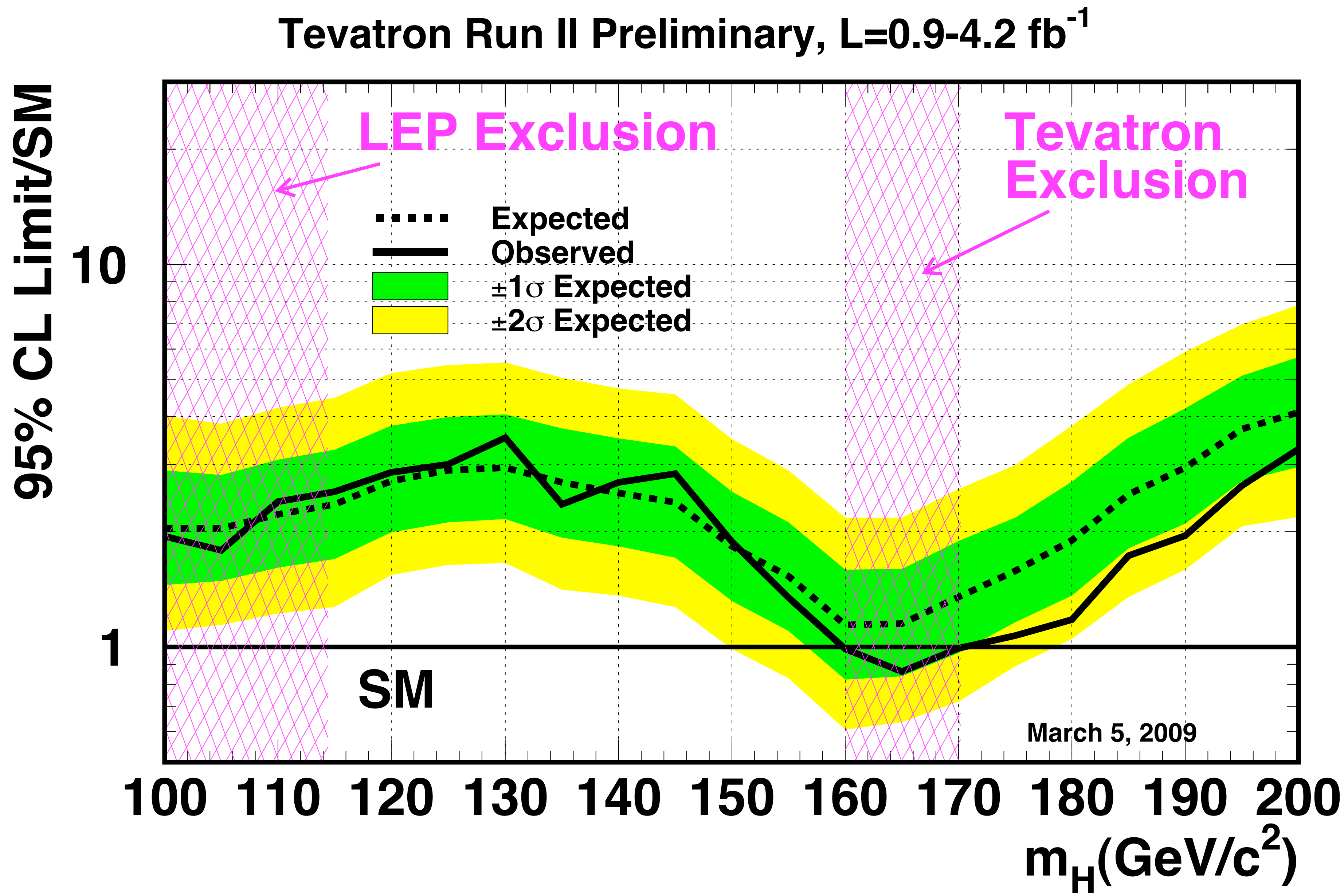
Uncertainty from scale variations is about 9-10 % (note sizeable reduction with respect to the 14% that we get at NNLO !)

Used in the recent Tevatron analysis

Consistent with result from Anastasiou et al. (obtained with a different approach)
differences are of about 1%

The relevance of higher orders

The recent Tevatron exclusion is based on this updated result



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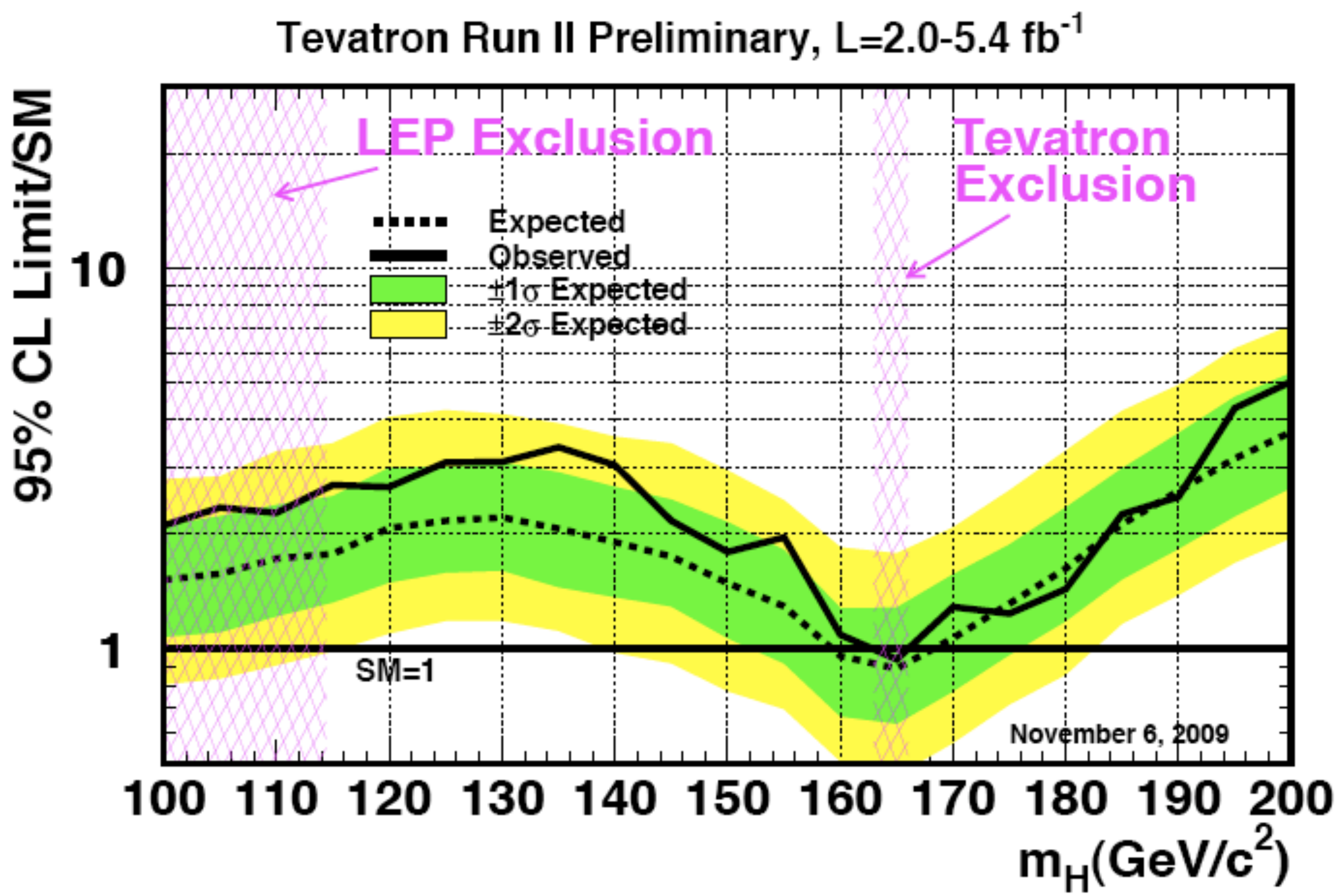

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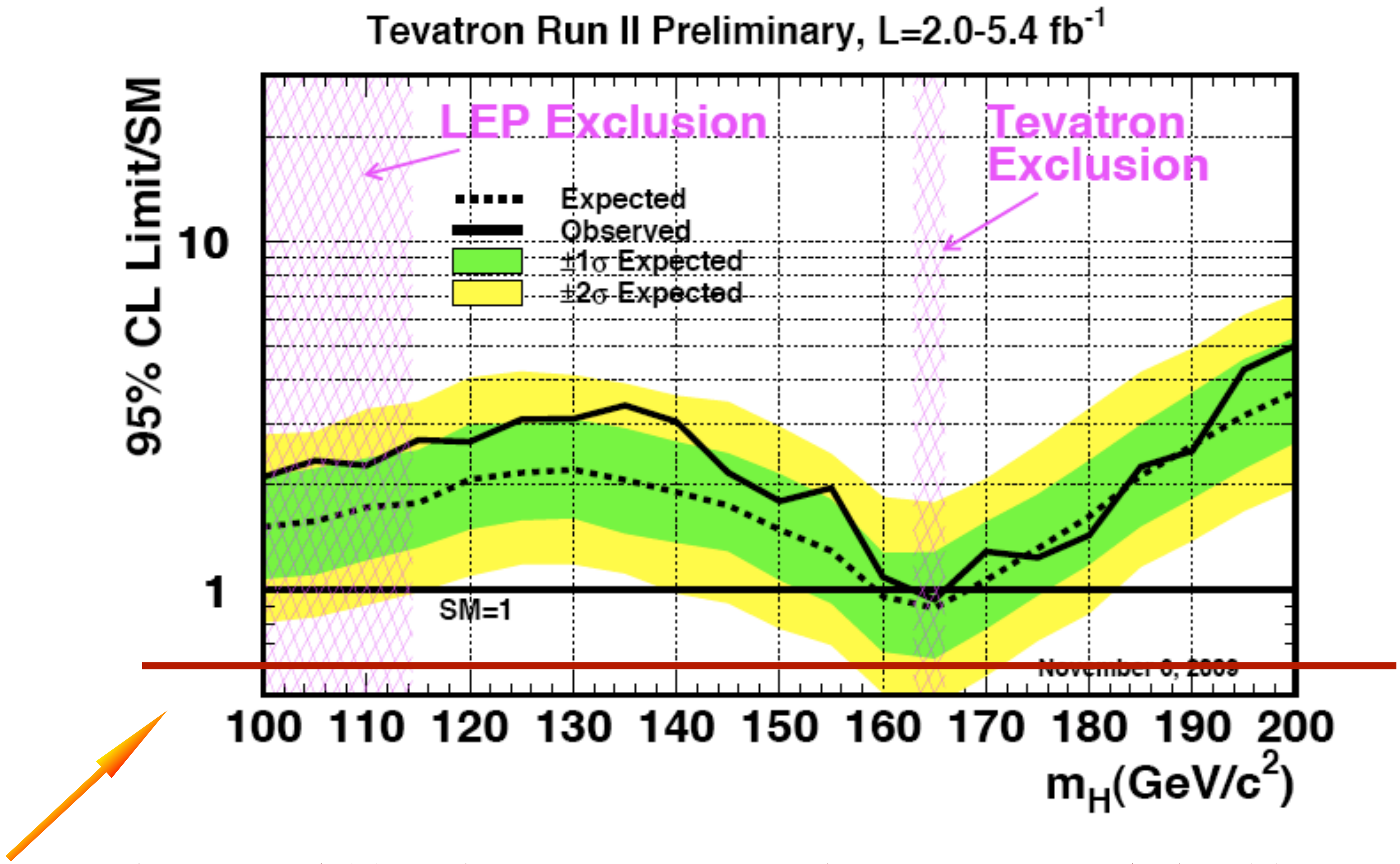

This would be the situation if the NLO result had been used !

What else ?

Further improvements are possible:

- Correct small-x behavior evaluated and included through a matching procedure

  S.Forte et al. (2008)

  → Effect smaller than 1% for a light Higgs

- Additional soft terms in soft-gluon resummation (the g_4 function)

  S.Moch, A. Vogt (2005)
  E. Laenen, L.Magnea (2005)
  V. Ravindran (2006)

Together with full N^3LO would lead to a reduction of scale uncertainty to about 5%

S.Moch, A. Vogt (2005)

but.......

What are the uncertainties ?

- Implementation of EW corrections:
  changing to the "partial" factorization scheme would lead to an effect going from -3 % (m_H=115 GeV) to +2 % (m_H=200 GeV) at the Tevatron and similarly at the LHC

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  a recent paper by Harlander and Ozeren shows that it works to better than **0.5 %** for $m_H \leq 300$ GeV

  → important confirmation of the accuracy of this approximation

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- **PDF uncertainty:** computed by using the 40 grids provided by MSTW:
  - at the LHC it is about 3% at 90% CL ($m_H \leq 300$ GeV)
  - at the Tevatron it ranges from 6 to 10% at 90% CL ($m_H \leq 200$ GeV)

What are the uncertainties ?

- There is a remaining uncertanty that should be considered: the one from the QCD coupling α_S
  Higgs production through gluon fusion starts at second order in α_S

→ We expect this uncertainty to be particularly important

Recently MSTW have studied the combined effect of PDF+ α_S uncertainties

A.Martin,J.Stirling,R.Thorne,G.Watt (2009)

We find that:

- at the LHC PDF+ α_S uncertainty is about **7%** at 90% CL ($m_H \leq 300$ GeV)

- at the Tevatron PDF+ α_S uncertainty ranges from **7 to 18%** ! ($m_H \leq 200$ GeV)

For m_H=165 GeV

$$\sigma_{\rm best} = 0.389\ {\rm fb}\ ^{+9.2\%}_{-7.7\%}({\rm scale})\ ^{+13.2\%}_{-10.1\%}(\alpha_S + {\rm PDFs}\ @\ 90\%\ {\rm CL})$$

What are the uncertainties ?

Note also that at present, besides MSTW, we have only two other NNLO global parton analyses: A09 and JR09

S.Alekhin et al. (2009)
P.Jimenez-Delgado, E.Reya (2009)

A quick comparison of the central results shows that:

- at the LHC A09 (JR09) result is smaller than MSTW2008 by 7% (11%) fo m_H=115 GeV and by 11% (8%) for m_H=300 GeV

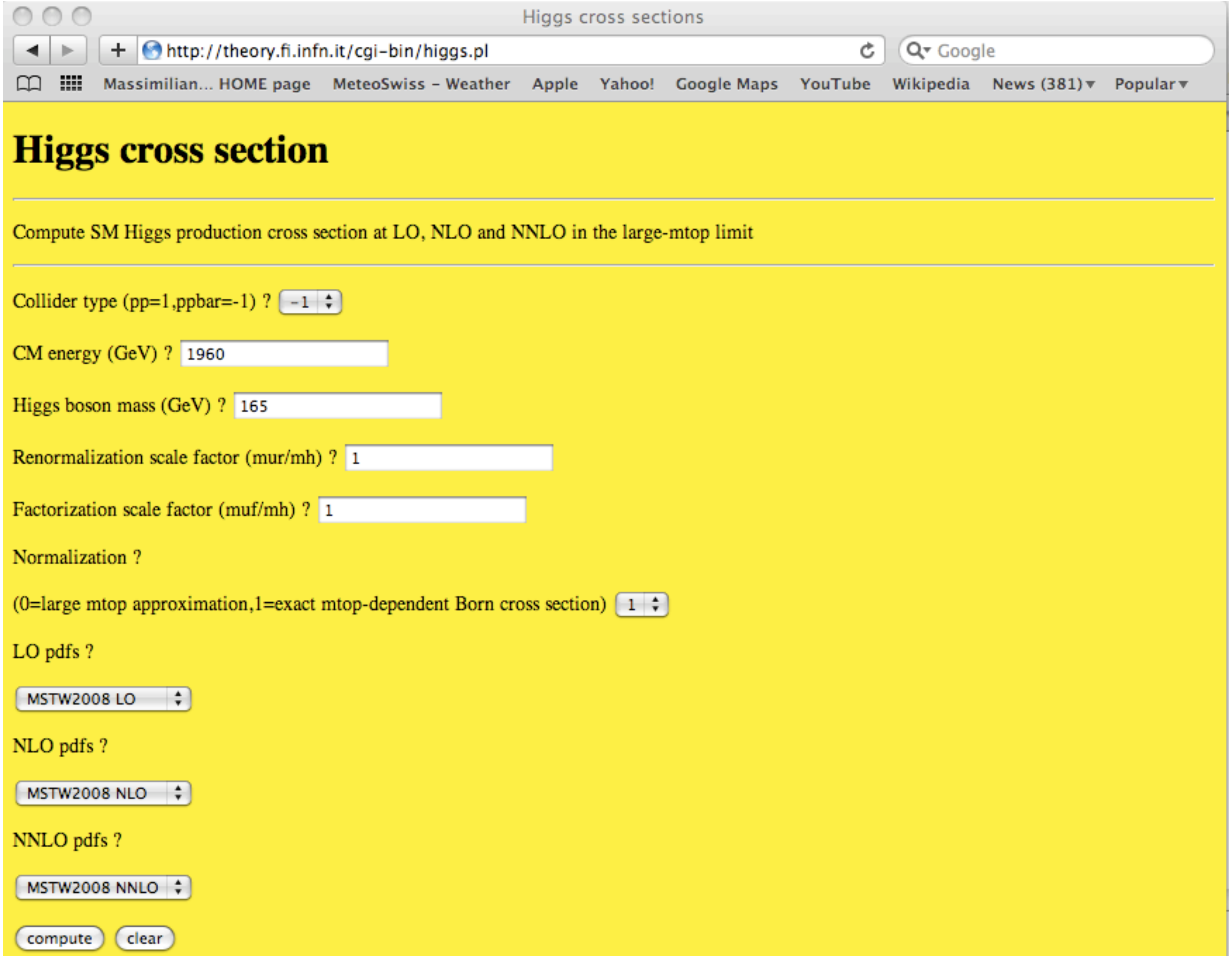
- at the Tevatron for m_H=165 GeV the effect is -26 % (-2%)

(reason: smaller α_S , Tevatron jet data not included........)

BOTTOM LINE:

The uncertainty on the inclusive gg→H cross section is still relatively large and, at least at the Tevatron, it is dominated by the PDFs (and α_S)

NEW: Online calculators



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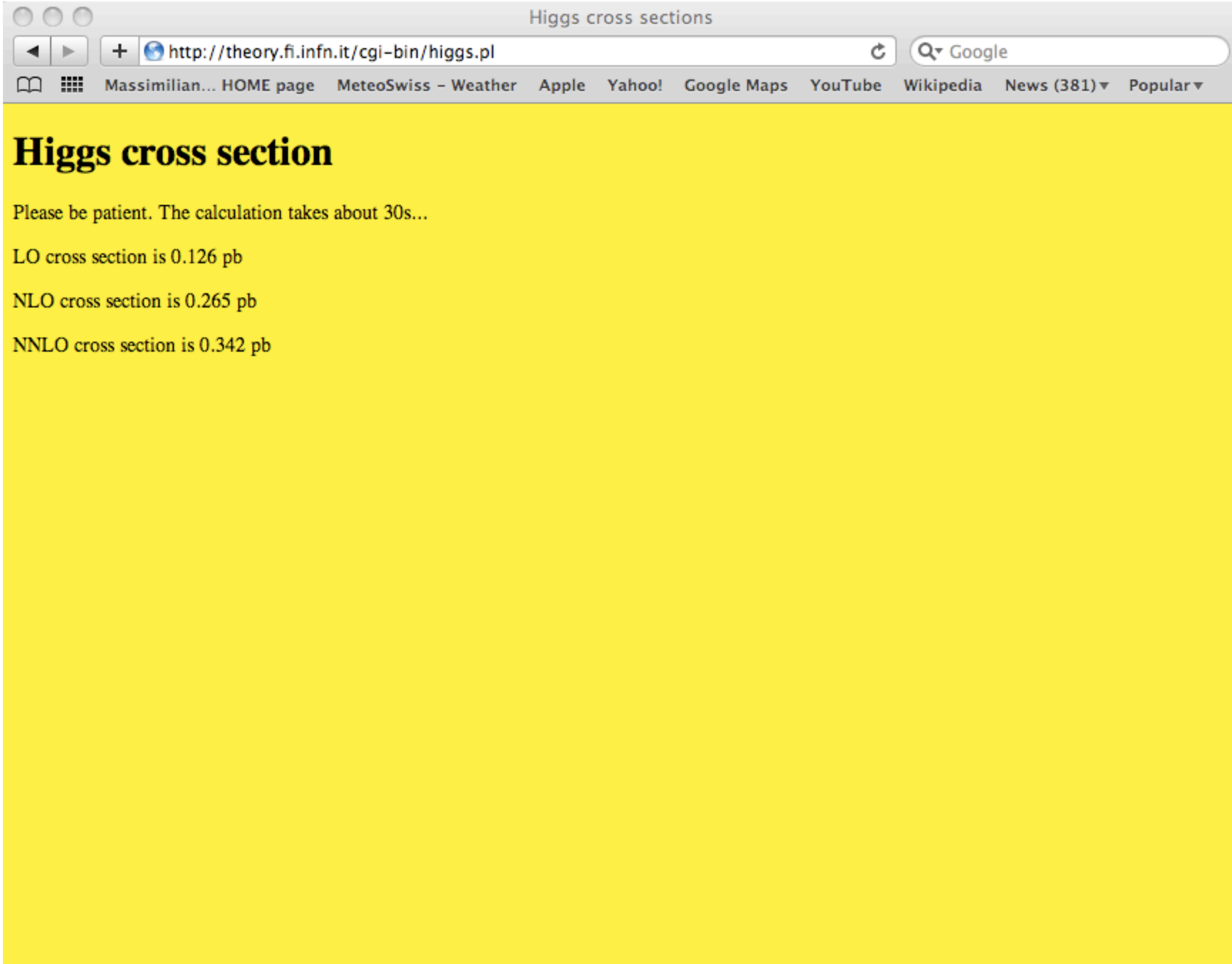

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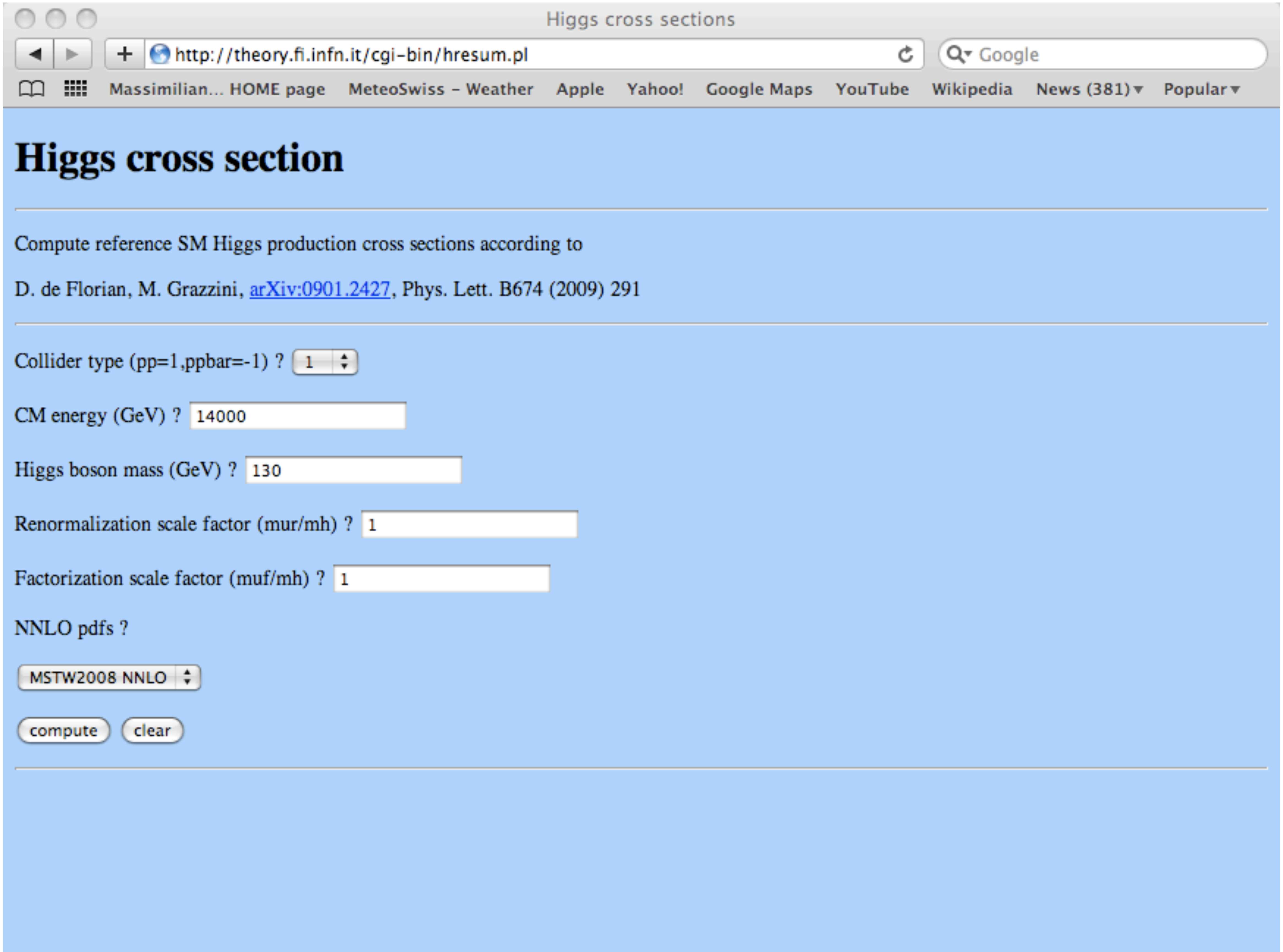

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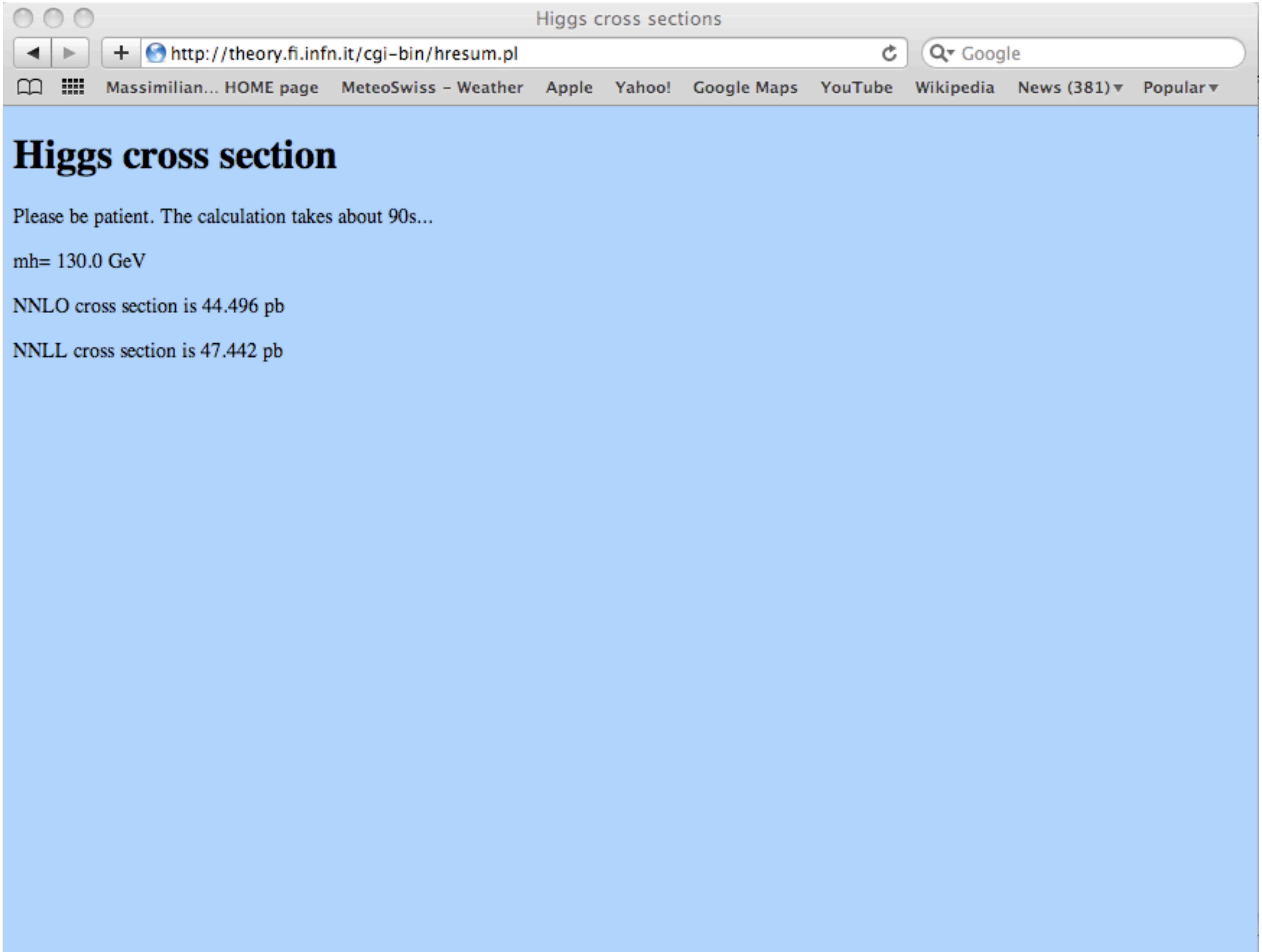


Total cross section is thus OK but....more exclusive observables are needed !

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

In particular, at NNLO, only few fully exclusive computations exist, due to their substantial technical complications

For Higgs boson production through gluon fusion two independent computations are available and are implemented in two numerical codes:

- FEHIP

  Based on sector decomposition

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

- HNNLO

  Based on an extension of the subtraction method

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

HNNLO

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

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

- $H \to \gamma\gamma \quad (\texttt{higgsdec} = 1)$
- $H \to WW \to l\nu l\nu \quad (\texttt{higgsdec} = 2)$
- $H \to ZZ \to 4l$
  - $H \to e^+e^-\mu^+\mu^- \quad (\texttt{higgsdec} = 31)$
  - $H \to e^+e^-e^+e^- \quad (\texttt{higgsdec} = 32)$

→ includes appropriate interference contribution

The user can choose the cuts and plot the required distributions by modifying the `cuts.f` and `plotter.f` subroutines

LHC

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

S. Catani, MG (2007)

Use cuts as in CMS TDR

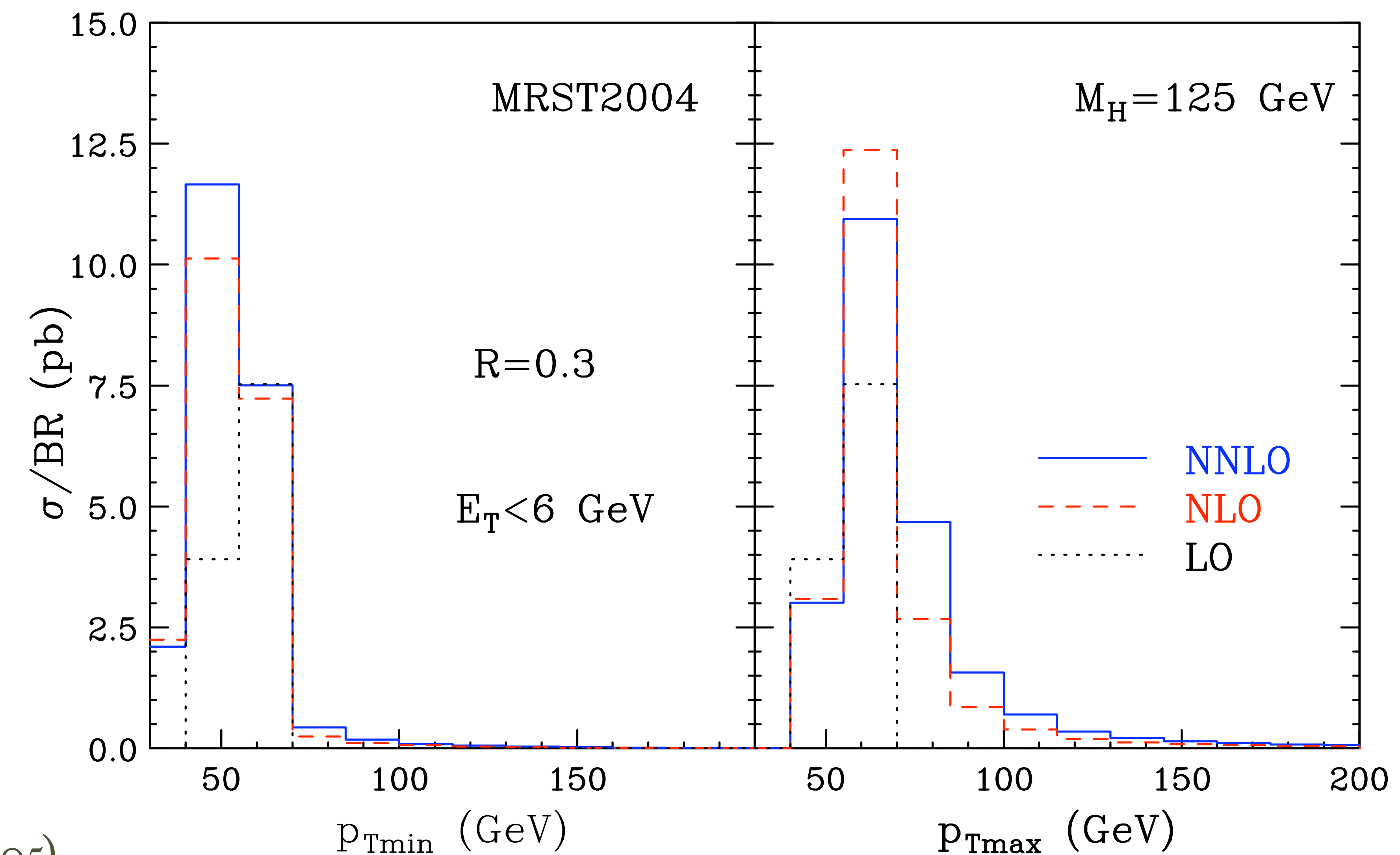
$p_T^{\min} > 35$ GeV

$p_T^{\max} > 40$ 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)

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

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

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

cuts as in Davatz et al. (2003)

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

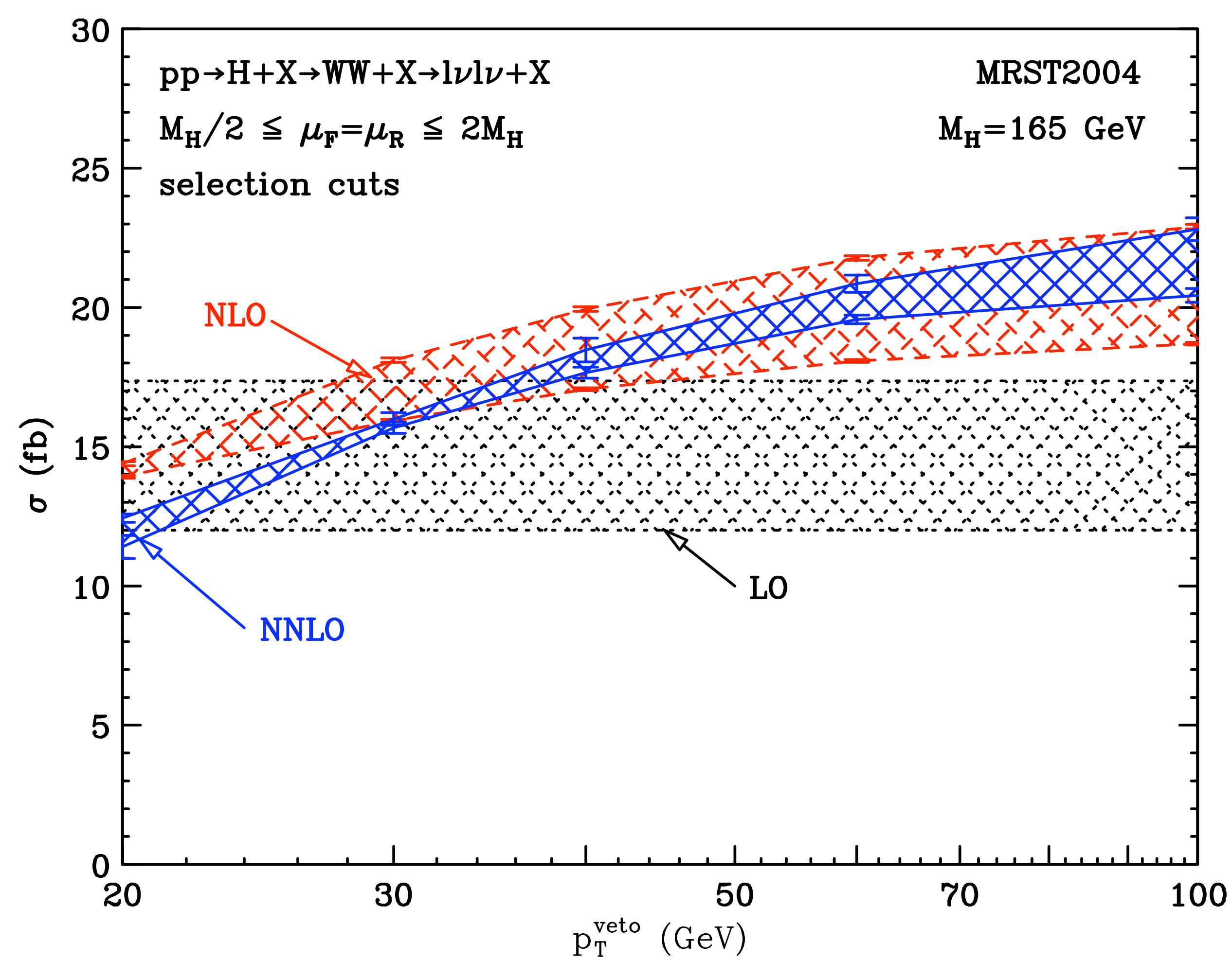
σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_H/2$	17.36 ± 0.02	18.11 ± 0.08	15.70 ± 0.32
$\mu_F = \mu_R = M_H$	14.39 ± 0.02	17.07 ± 0.06	15.99 ± 0.23
$\mu_F = \mu_R = 2M_H$	12.00 ± 0.02	15.94 ± 0.05	15.68 ± 0.20

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

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

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

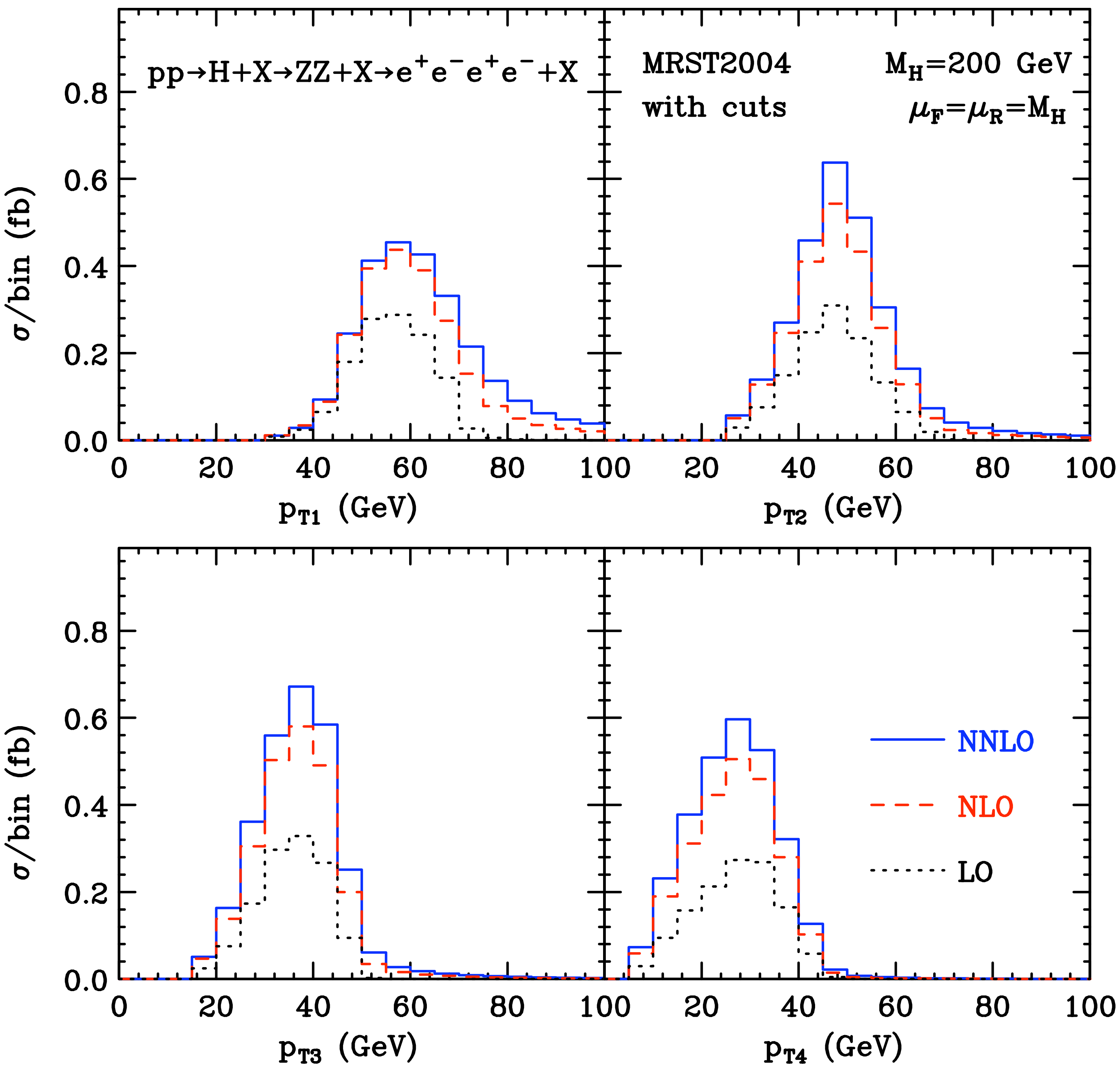
➡ $81 \text{ GeV} < m_1 < 101 \text{ GeV}$ and $40 \text{ GeV} < m_2 < 110 \text{ GeV}$

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

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 $p_T > 20\,\text{GeV}$ and $|\eta| < 0.8$

Preselection:

- Other lepton must have $p_T > 10\,\text{GeV}$ and $|\eta| < 1.1$
- Invariant mass of the charged leptons $m_{ll} > 16\,\text{GeV}$
- 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 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

Accepted cross sections at fixed order

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

→ $K_{NLO} = 2.15$

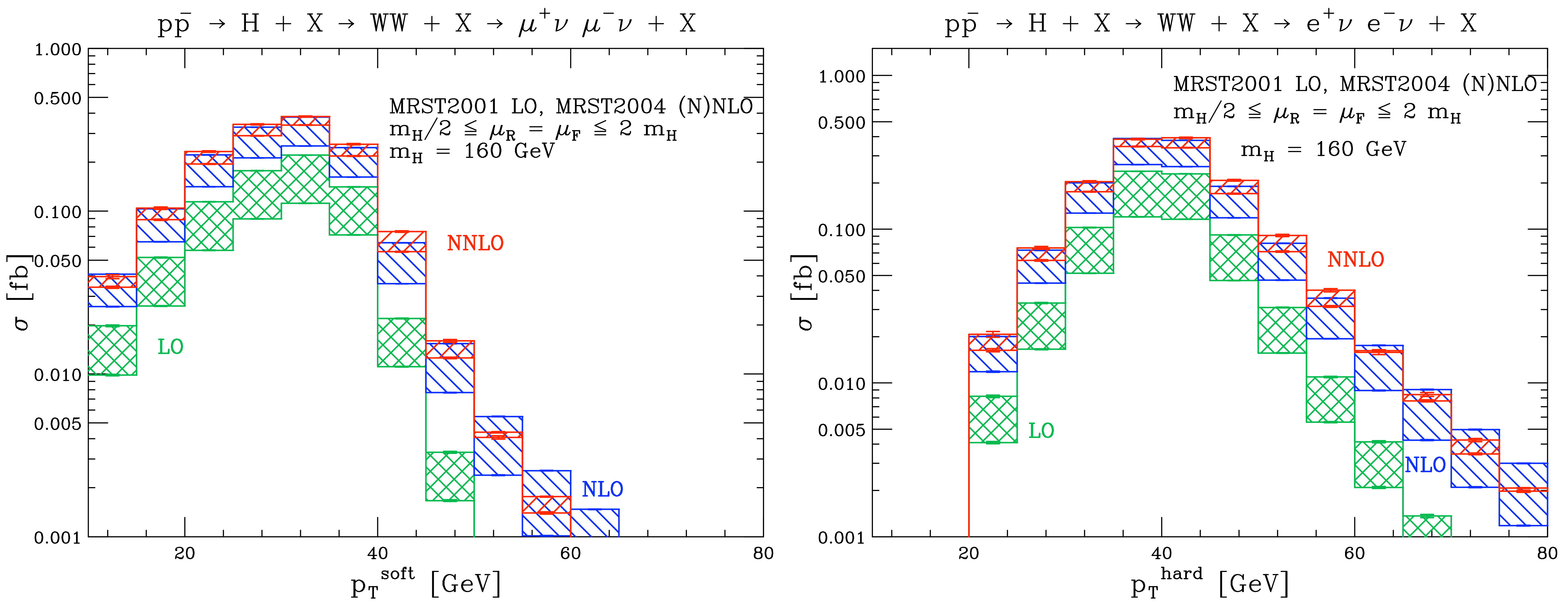
$K_{NNLO} = 2.63$

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

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

Distributions

We study a few kinematical distributions: p_{Tmin}, p_{Tmax}, m_{ll}, ϕ_{ll}, MET



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

The distributions do not show significant instabilities when going from LO to NLO to NNLO

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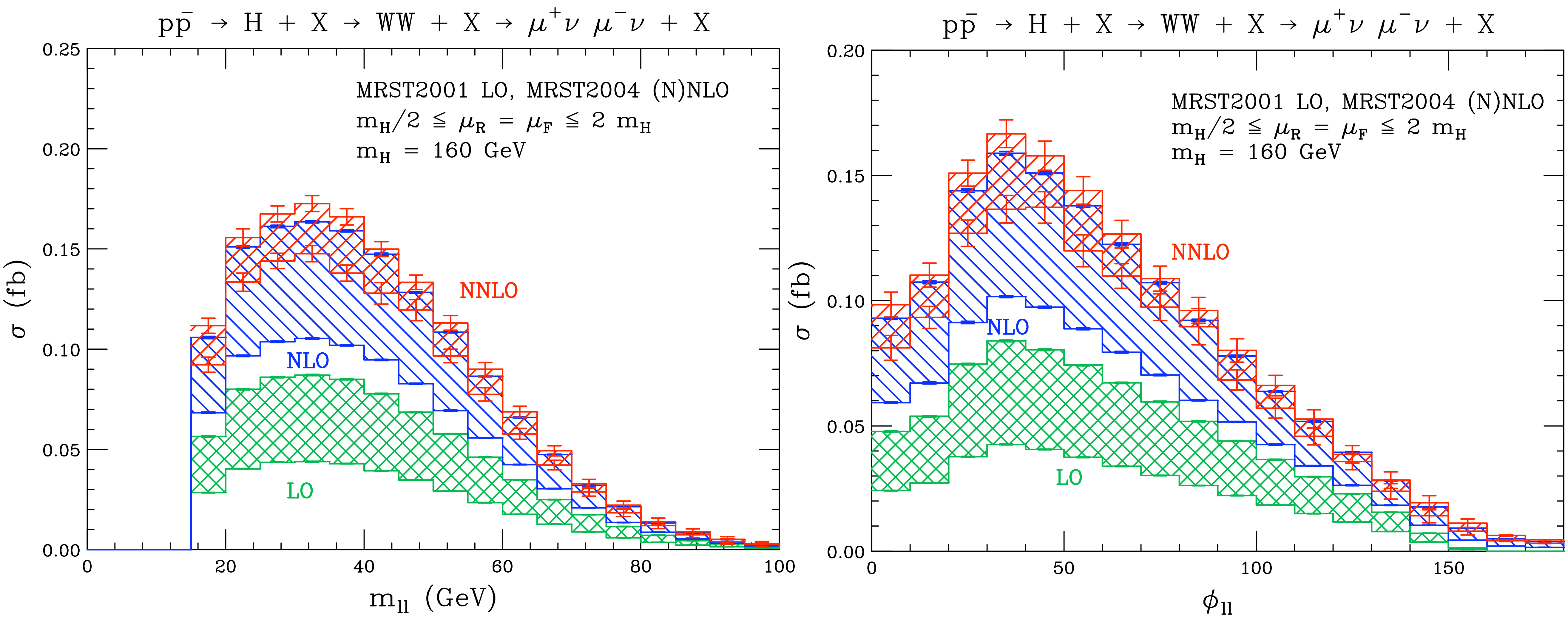

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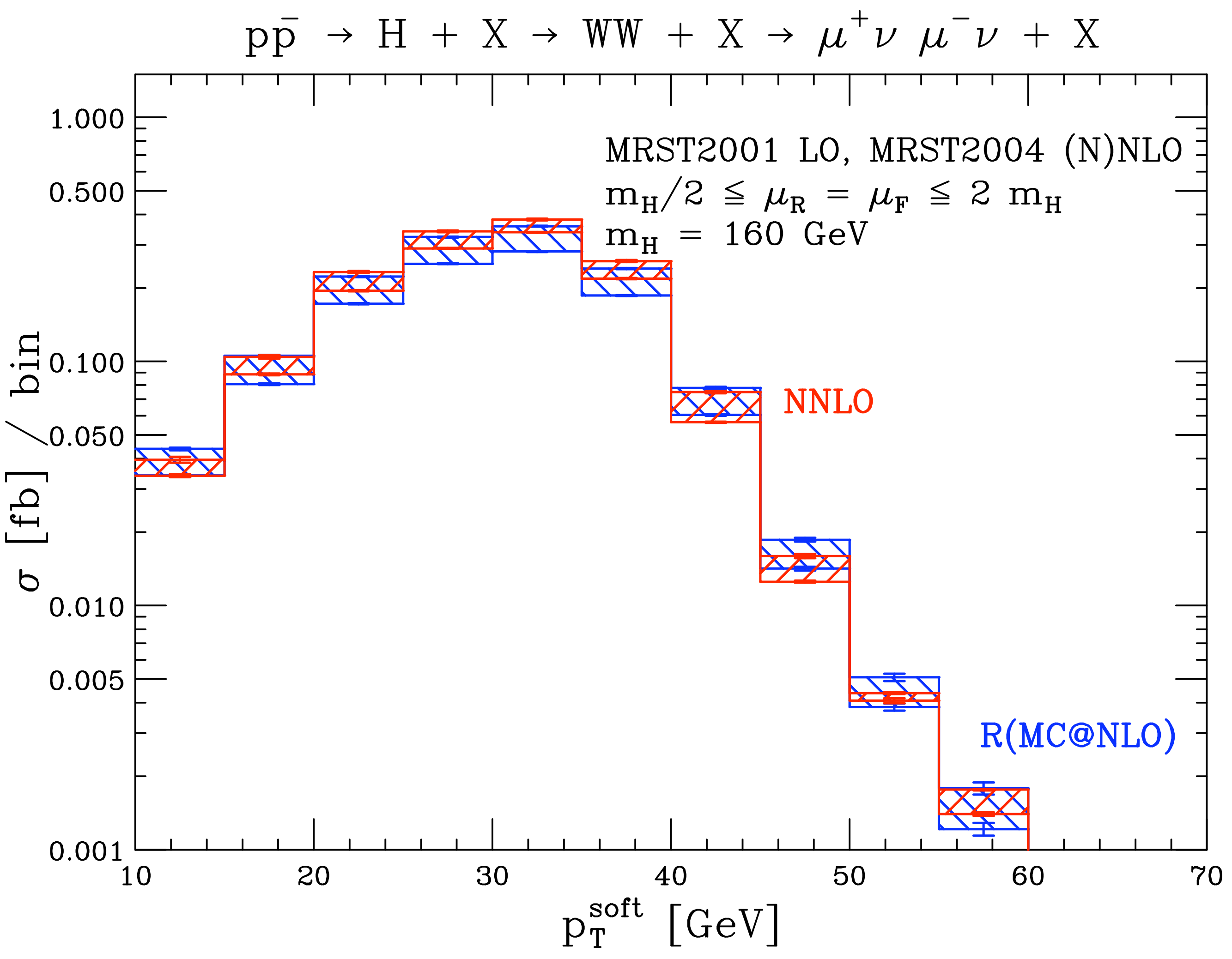

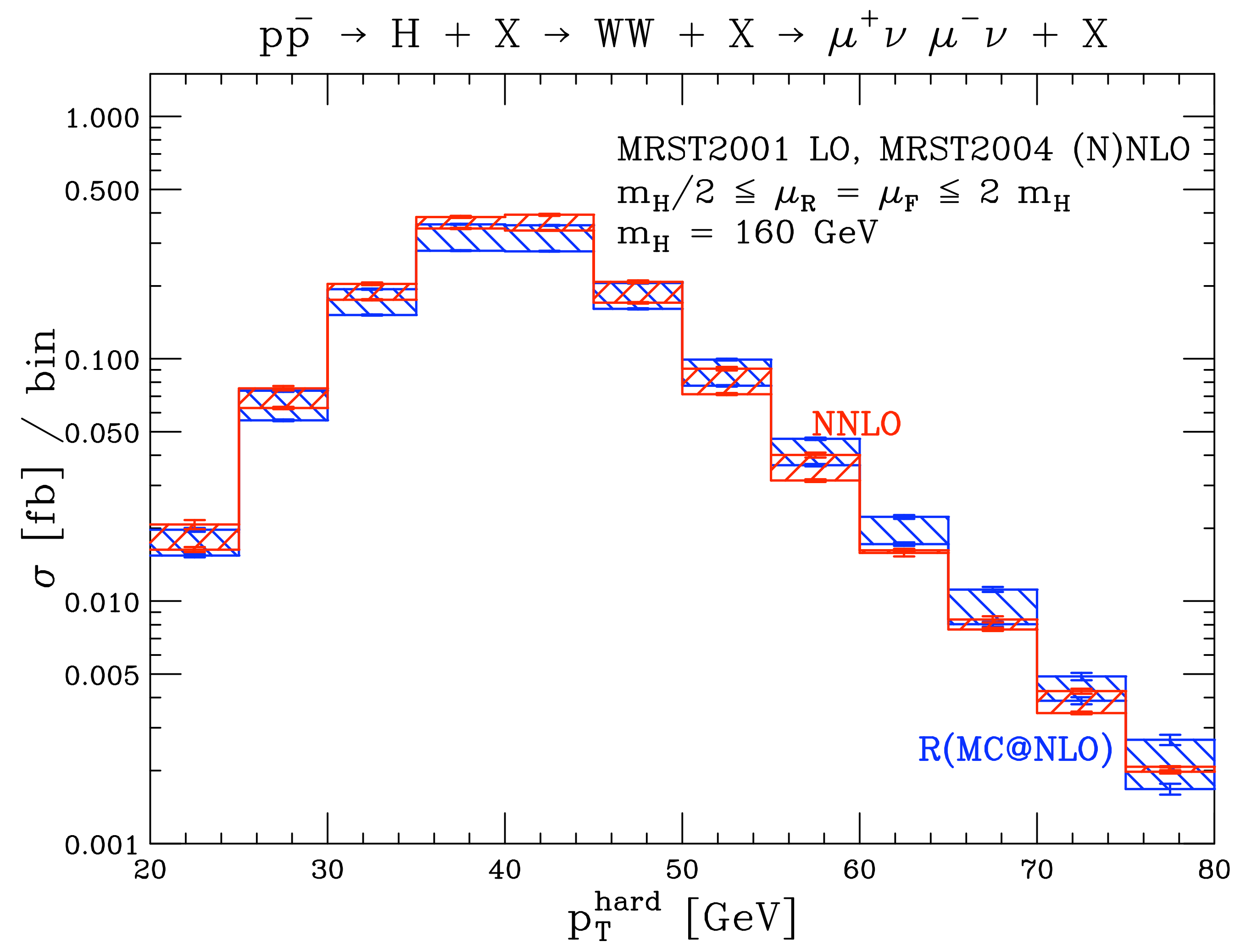

MC results are rescaled so as to match the inclusive NNLO cross section

They appear to be in reasonably good agreement with NNLO

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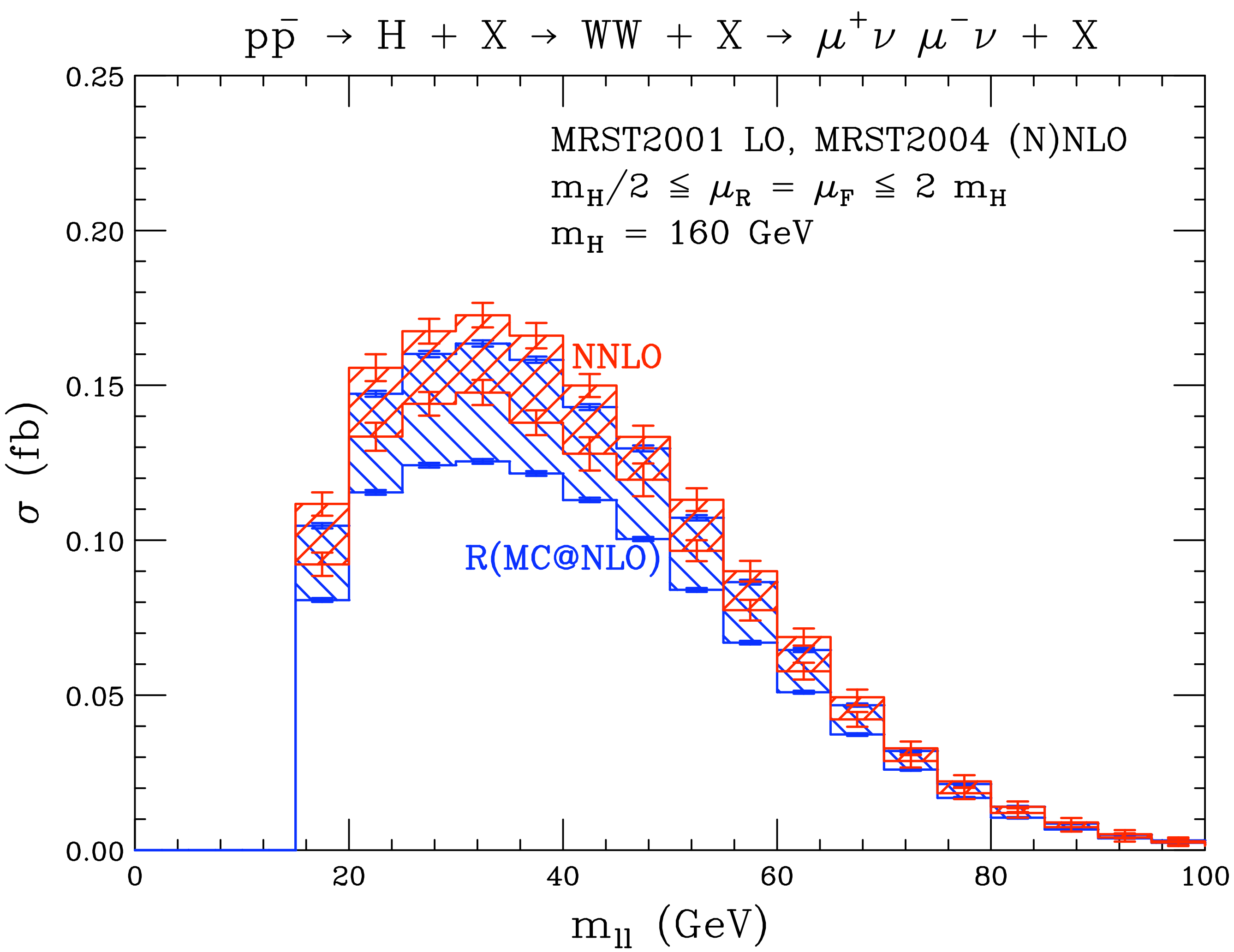

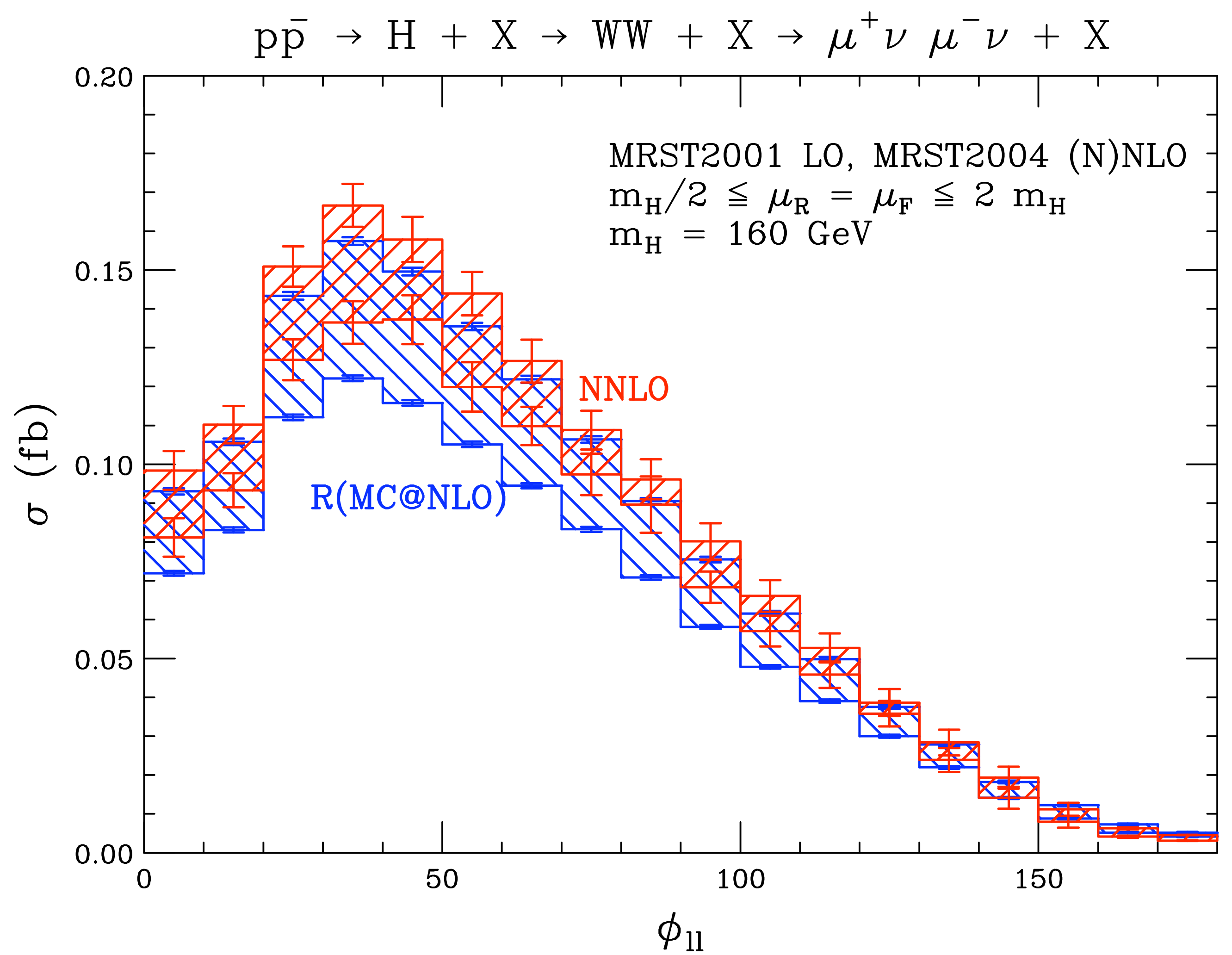

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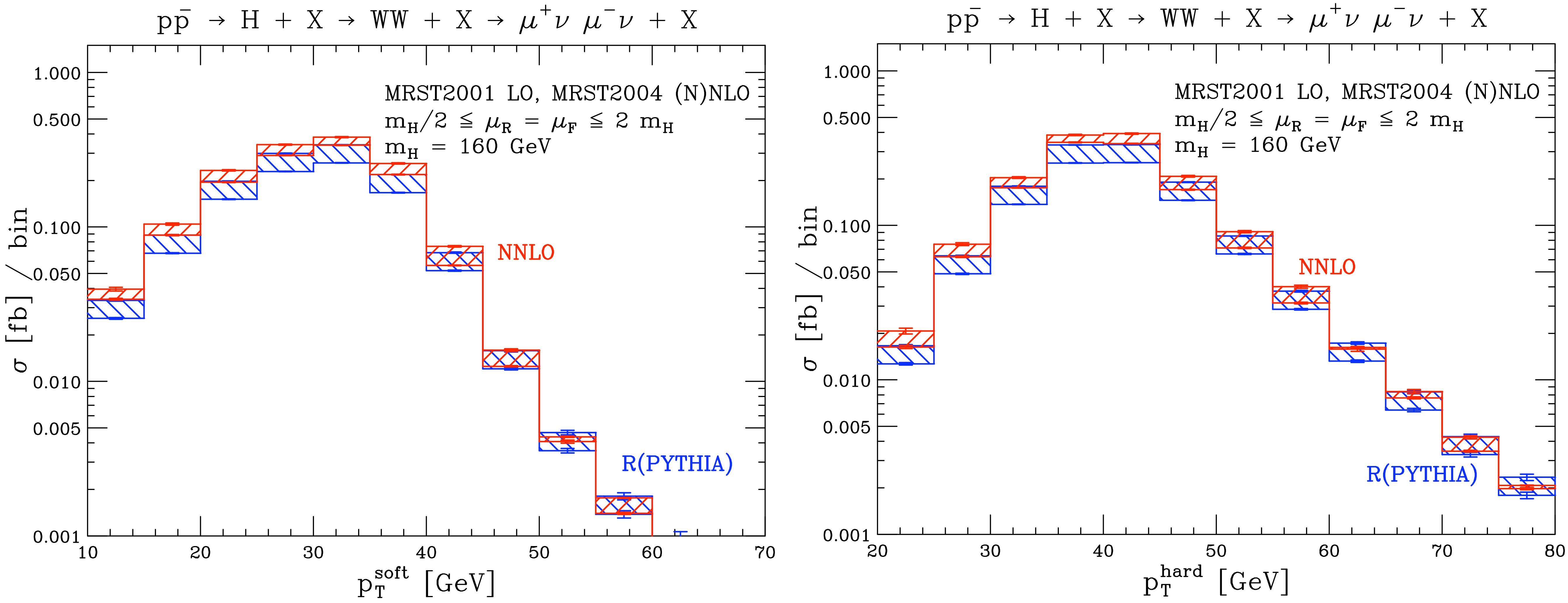

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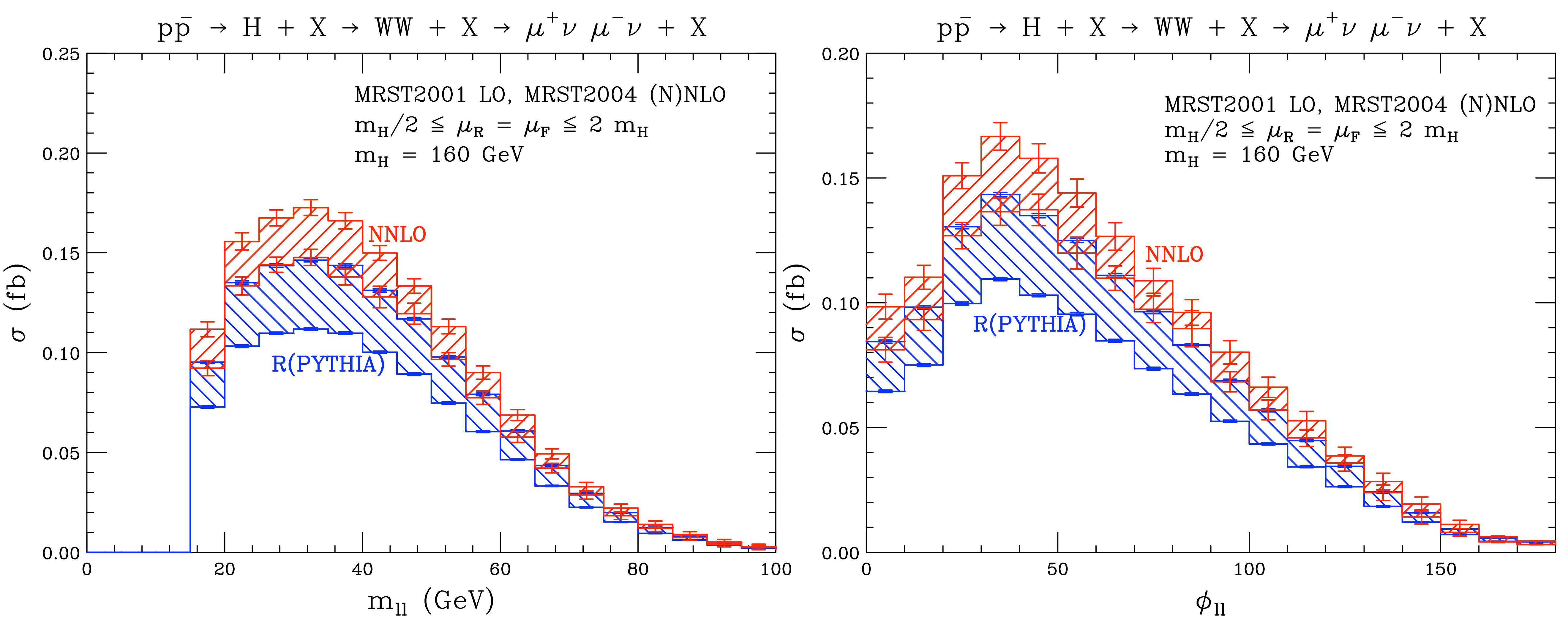

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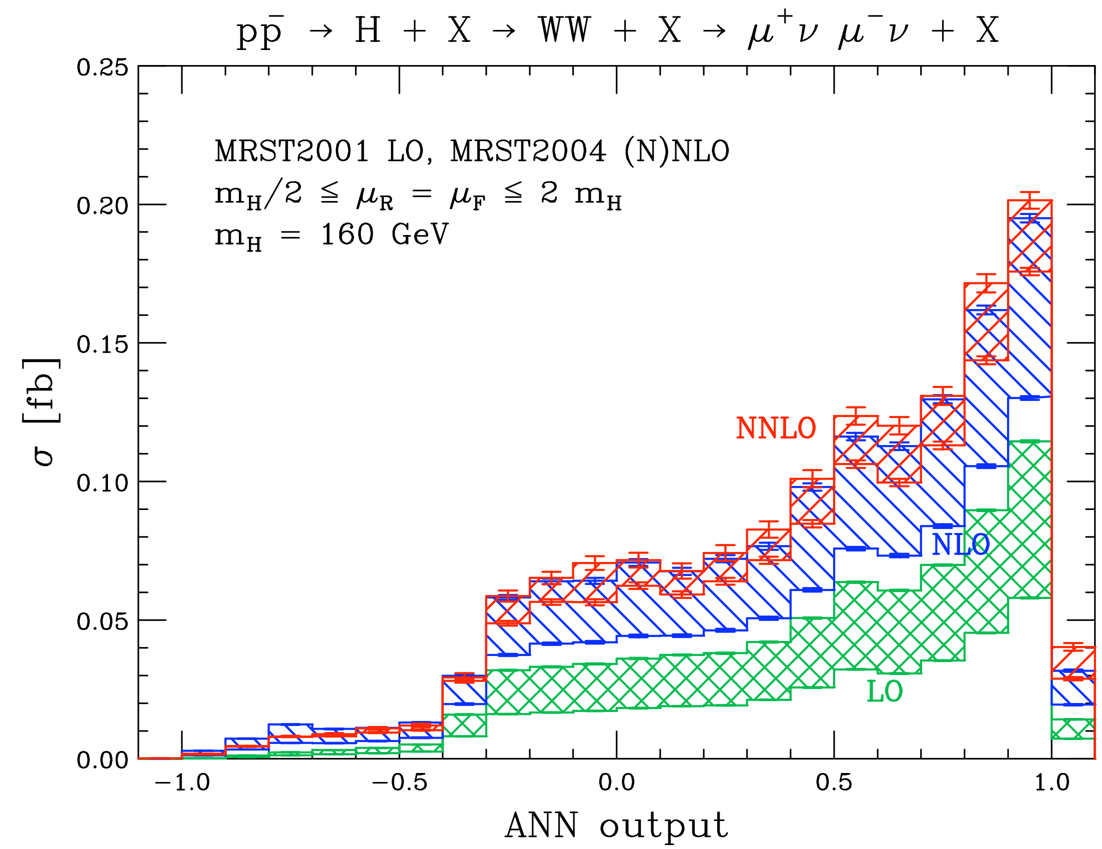
Is there a way to quantify the agreement ?

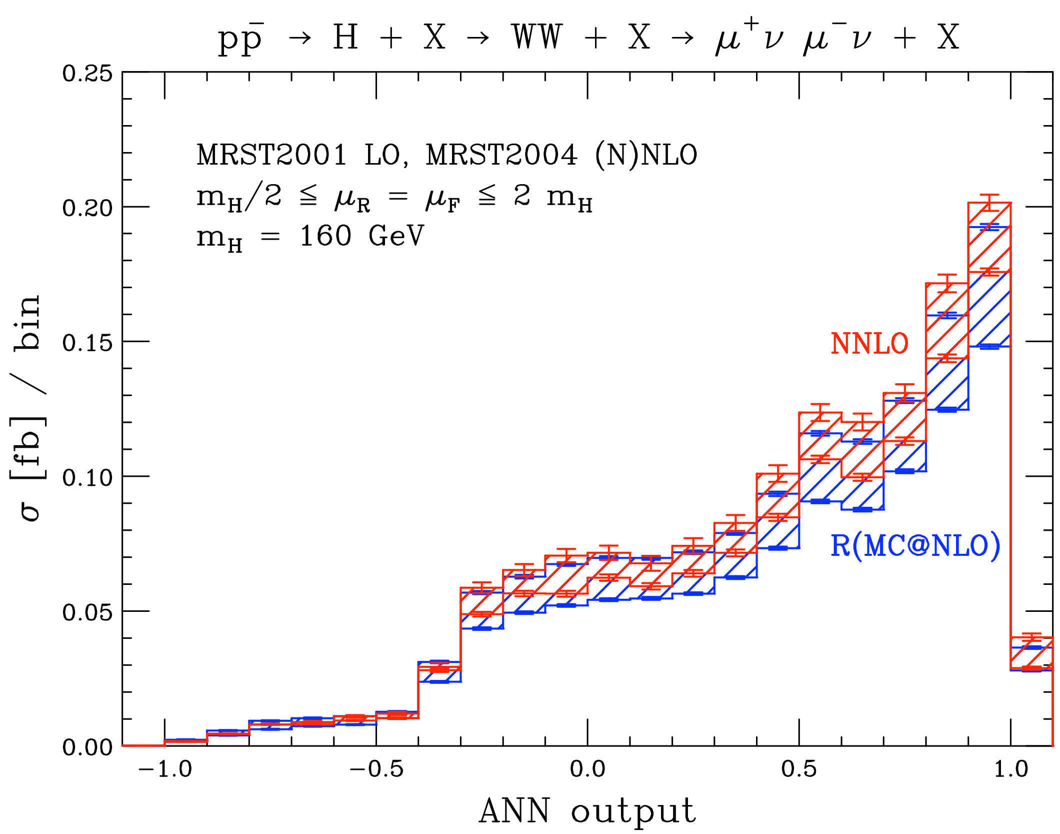
Neural Network

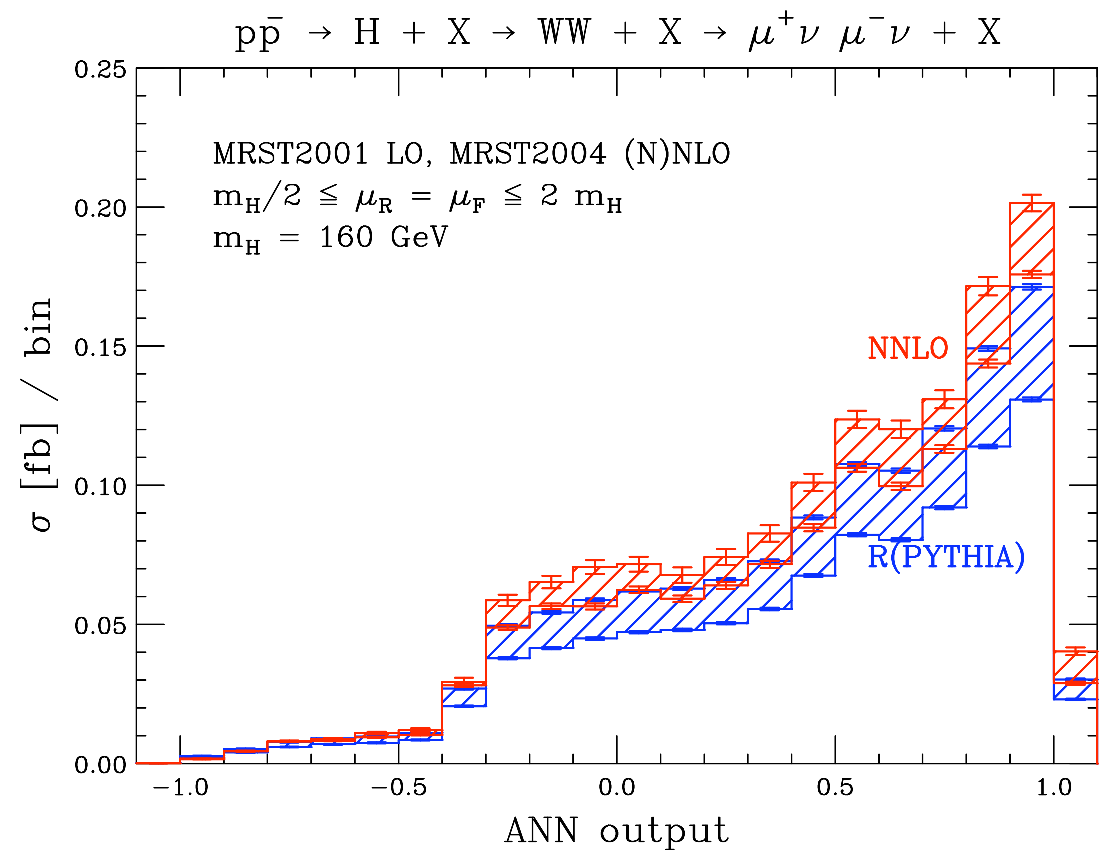
To check it we train a Neural Network

We use the TMVA root package and train the network with samples for Higgs, WW and ttbar processes generated with PYTHIA 8

All the predictions are peaked at ANN~1







Acceptances

Despite this agreement the final acceptances do show some discrepancies

- MC@NLO result smaller than NNLO by 4-14 % depending on the scale choice
- HERWIG results agrees with the NNLO calculation within uncertainties
- PYTHIA result is smaller than NNLO by 12-21 %

$\sigma_{acc}/\sigma_{incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_H/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\ m_H$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_H/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\ m_H$)	44.8%	38.8% (86.7%)	35.9% (92.5%)	27.0% (75.2%)
HERWIG	46.7%	40.8% (87.4%)	37.8% (92.7%)	28.6% (75.7%)
PYTHIA	46.6%	37.9% (81.3%)	32.2% (85.0%)	24.4% (75.8%)

Differences in final acceptance are mainly due to jet veto and isolation

The results do not change significantly if hadronization or UE are taken into account

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 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 cross sections change significantly
- The uncertainties are still relatively large, especially at the Tevatron
- Online calculators are now available

Summary (II)

- Total cross sections are ideal quantities: real experiments have finite acceptances !
- HNNLO is a fully exclusive NNLO MC program for $gg \to H$ that includes all the relevant decay modes of the SM Higgs boson
- I have presented 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 experimental analysis do not show significant instabilities: this is confirmed by using our own NN
- The acceptance obtained with PYTHIA turns out to be smaller than that found at NNLO and with MC@NLO

BACKUP SLIDES

Uncertainties

CDF and DO divide event sample in 0,1 and 2 or more jets

The uncertainty increases when going from 0 to 1 to 2 jets

$$\frac{\Delta N_{\mathrm{inc}}(\mathrm{scale})}{N_{\mathrm{inc}}} = 66.5\% \cdot \begin{pmatrix} +5\% \\ -9\% \end{pmatrix} + 28.6\% \cdot \begin{pmatrix} +24\% \\ -22\% \end{pmatrix} + 4.9\% \cdot \begin{pmatrix} +78\% \\ -41\% \end{pmatrix} = \begin{pmatrix} +14.0\% \\ -14.3\% \end{pmatrix}$$

If different selection cuts are applied in the three jet bins the final uncertainty does not coincide with the uncertainty of the inclusive cross section

$$\frac{\Delta N_{\mathrm{signal}}(\mathrm{scale})}{N_{\mathrm{signal}}} = 60\% \cdot \begin{pmatrix} +5\% \\ -9\% \end{pmatrix} + 29\% \cdot \begin{pmatrix} +24\% \\ -22\% \end{pmatrix} + 11\% \cdot \begin{pmatrix} +78\% \\ -41\% \end{pmatrix} = \begin{pmatrix} +18.5\% \\ -16.3\% \end{pmatrix}$$

In particular, if the events with one or more jets are preferred after the selection cuts the uncertainty will be larger