The search for the Higgs boson at the Tevatron and the LHC

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Outline

- Introduction
- Higgs search at the LHC
  - Main production channels
  - Theoretical predictions
- Higgs search at the Tevatron
- Summary

Introduction

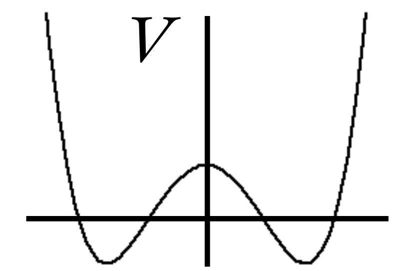
- The Standard Model (SM) of electroweak interactions is an $SU(2)_L \otimes U(1)_Y$ gauge theory
- Explicit mass terms for the gauge bosons are forbidden by gauge invariance
- Left and right-handed fermions couple differently to gauge fields → mass terms are forbidden
- The way out is provided by Spontaneous Symmetry Breaking (SSB): the lagrangian is still invariant but the gauge symmetry is broken by the vacuum

In the minimal version of the SM the SSB is achieved by introducing one complex scalar doublet:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} w_1 + i w_2 \\ H + i w_3 \end{pmatrix}$$ → 4 real degrees of freedom

$$\mathcal{L}_{SB} = D_\mu \Phi^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi)$$

where V has the usual "mexican hat" form



3 go to give mass to W and Z bosons

1 remains in the spectrum → **Higgs boson**

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Extensions of the SM may contain more Higgs doublets

MSSM: two doublets Φ_u, Φ_d each with its own vev v_u, v_d

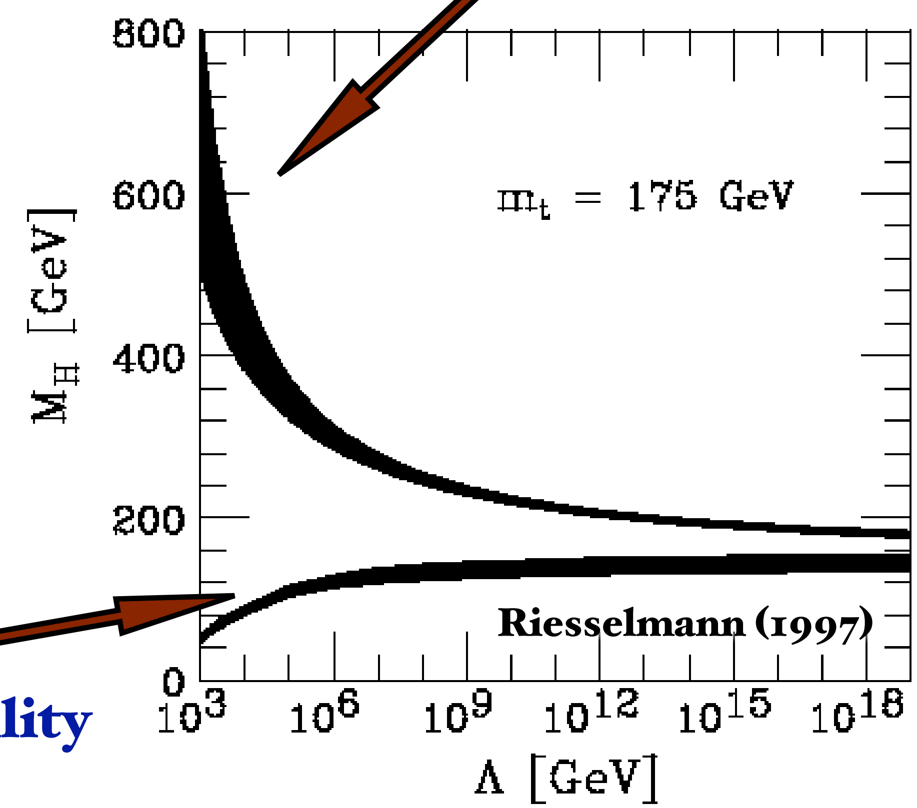
→ $8 - 3 = 5$ degrees of freedom

Two scalars h, H one pseudoscalar, A , one charged $H^\pm$

LEP has put a lower limit on the mass of the SM Higgs boson at $m_H \geq 114.4$ GeV at 95% CL

Other constraints come from:

- **Theoretical arguments (or prejudices...)**



$$\frac{d\lambda}{dt} = \frac{3}{4\pi^2}\left[\lambda^2 + 3\lambda h_t^2 - 9h_t^4 + \text{gauge terms}\right]$$

$$t = \ln \Lambda / v$$

If Higgs too heavy $\lambda(t)$ can hit the Landau pole

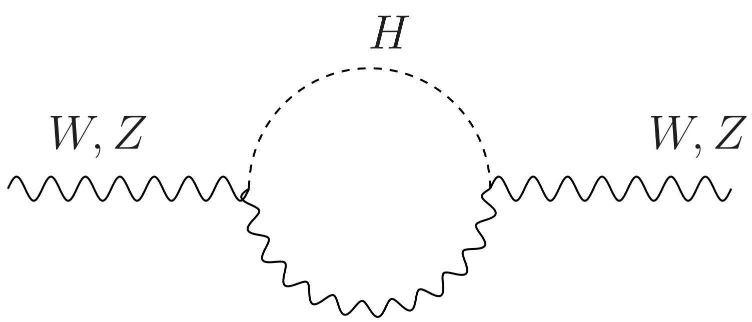
If Higgs too light (and top heavy) h_t wins: vacuum instability but....

....recent lattice simulations do not show the instability !

K. Holland, J. Kuti (2003)

Precision electroweak data: radiative corrections are sensitive to the mass of virtual particles

.... but screening effect: the dependence is only logarithmic at one loop (for top quark the dependence is quadratic → m_{top} predicted before discovery !)

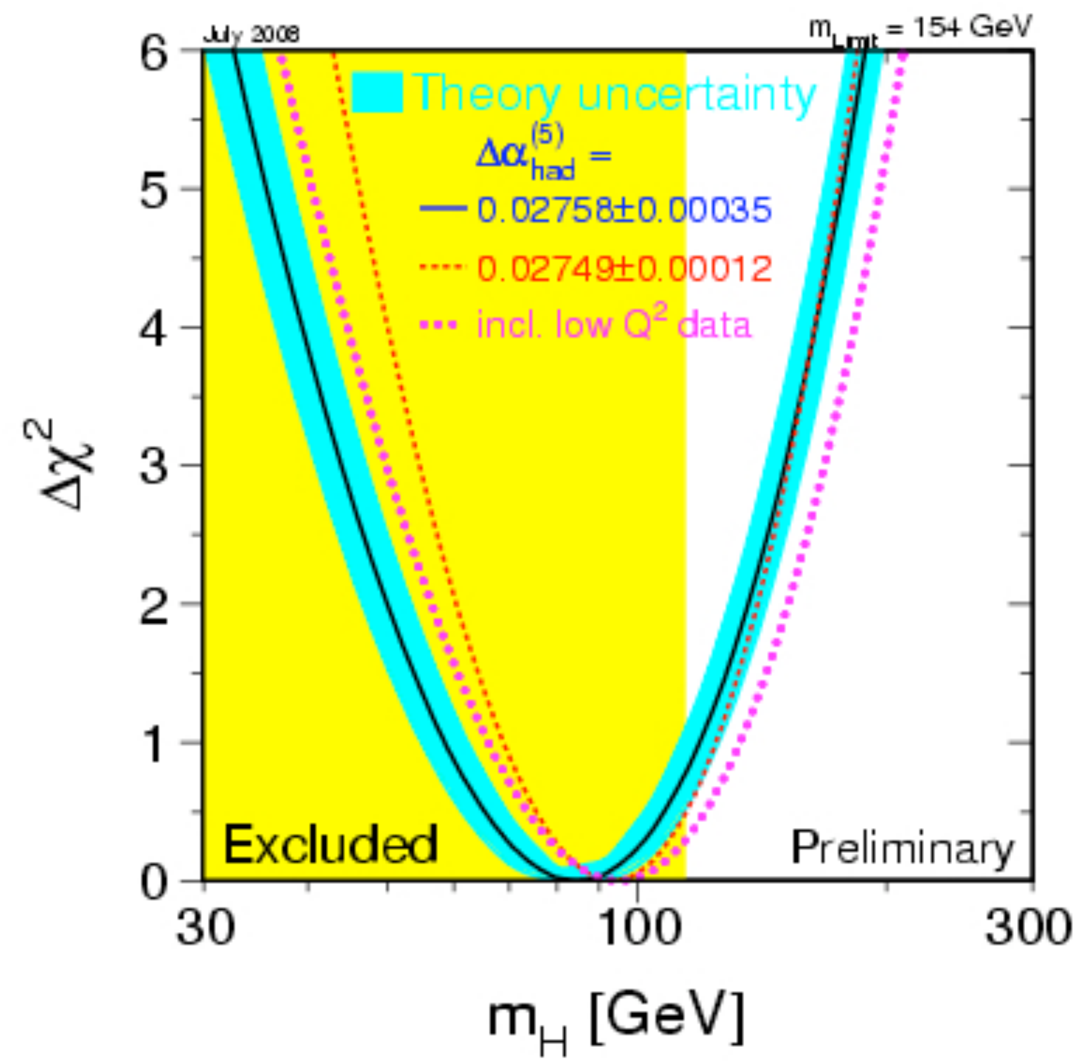


→

$$m_H = 87^{+35}_{-26}\ \text{GeV}$$

$$m_H < 157\ \text{GeV}$$ at 95 % CL

LEP EWWG, summer 2009



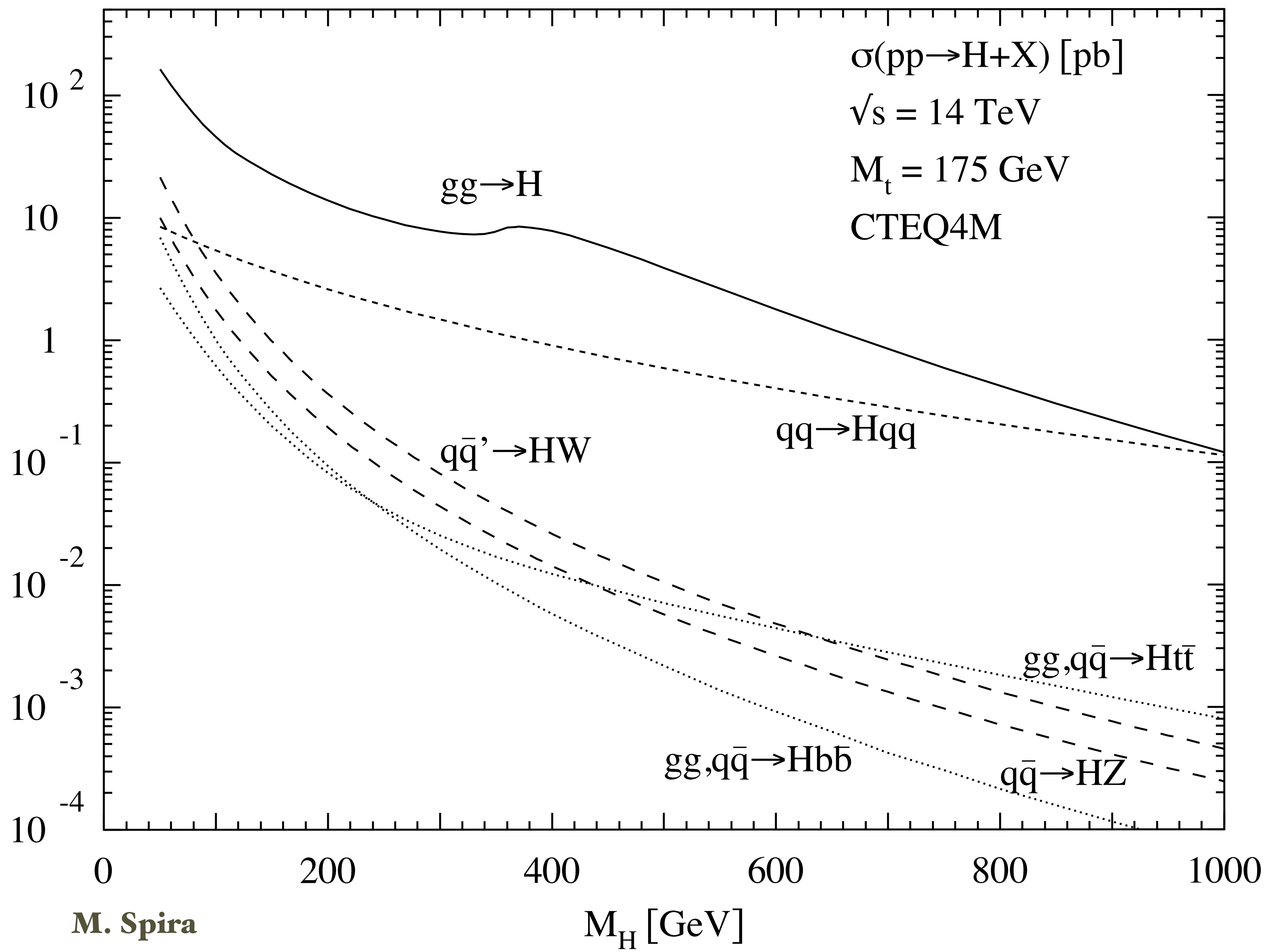
Taking into account LEP limit:

$$m_H < 186\ \text{GeV}$$ at 95 % CL

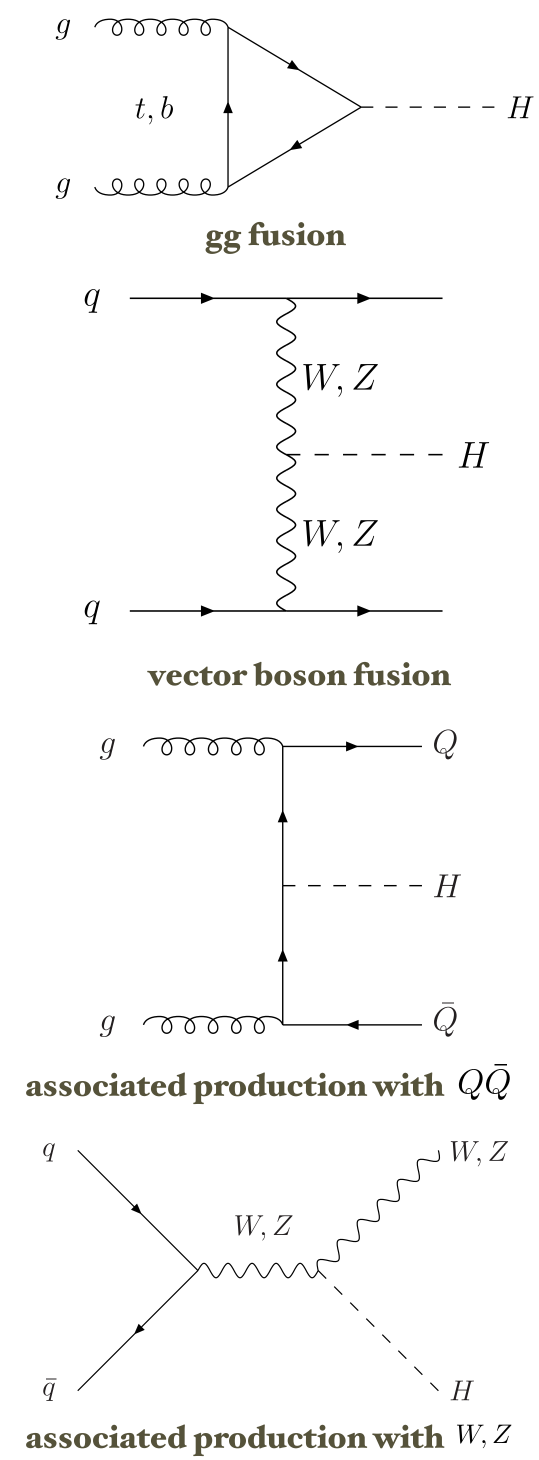
MSSM: at tree level $m_H < m_Z$

Radiative corrections lift up this limit → $M_h \lesssim 135\ \text{GeV}$

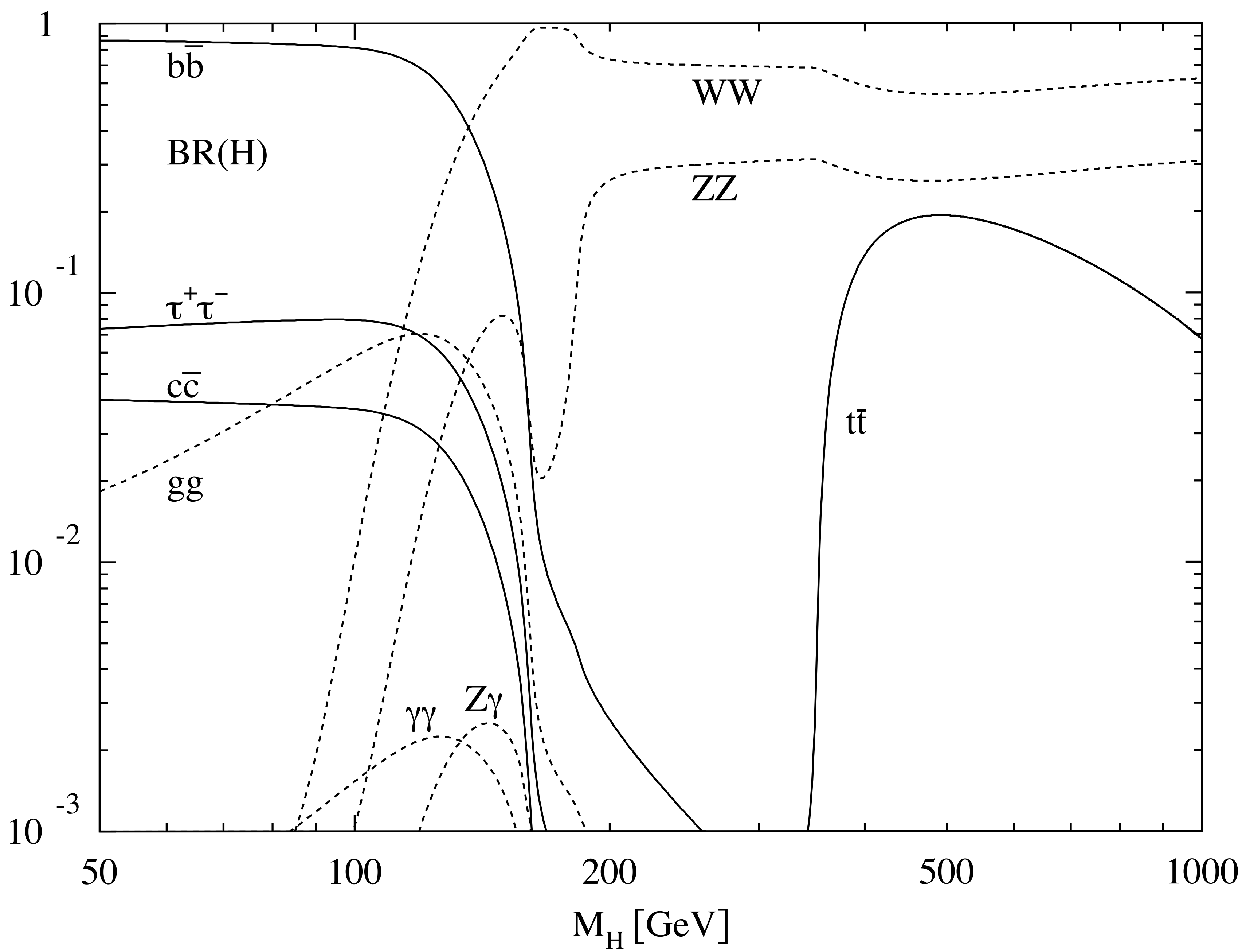
Higgs production at the LHC



M. Spira



Large gluon luminosity ➡ gg fusion is the dominant production channel over the whole range of m_H



Key point: enormous QCD background

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

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

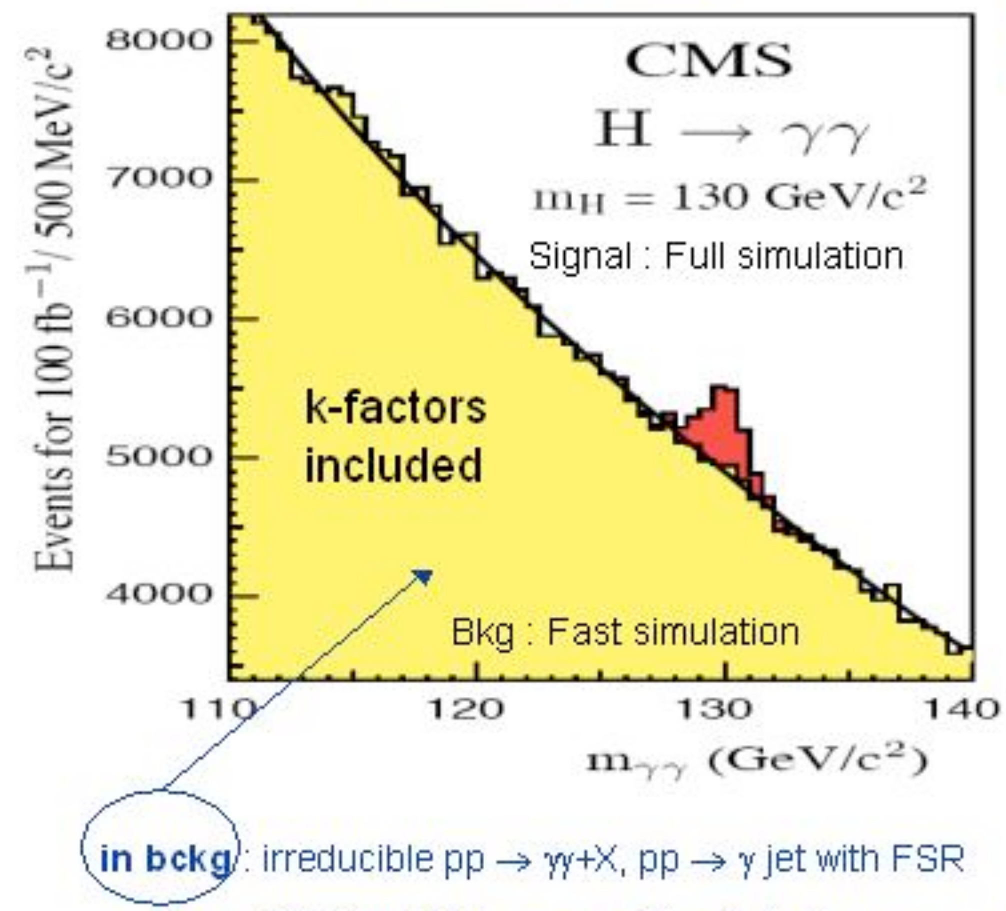
→ No chance to look at fully hadronic final states

- For $m_H \leq 140$ GeV → $H \to \gamma\gamma$ (BR $\sim 10^{-3}$)
- For $140 \leq m_H \leq 180$ GeV → $H \to WW^* \to l\nu l\nu$
- For $m_H \geq 180$ GeV → $H \to ZZ \to 4l$ (gold pleated)

- $H \to \gamma\gamma$

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

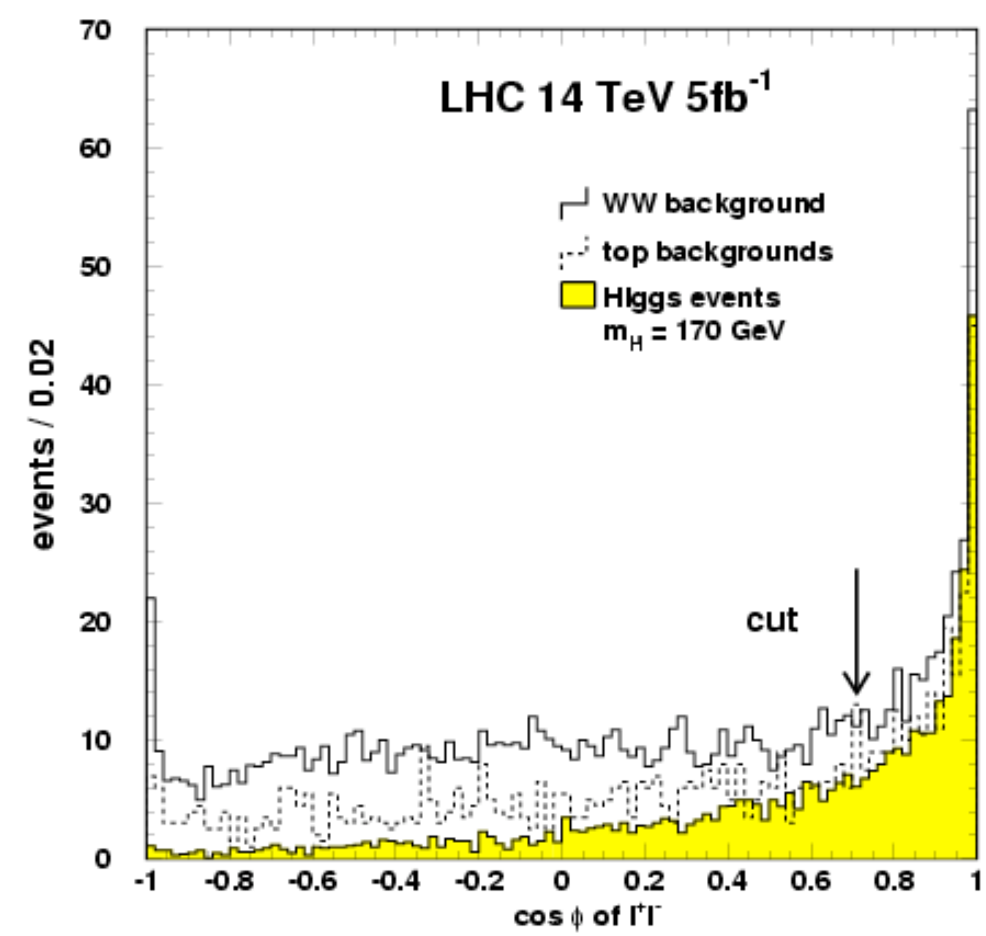
Background measured from sidebands



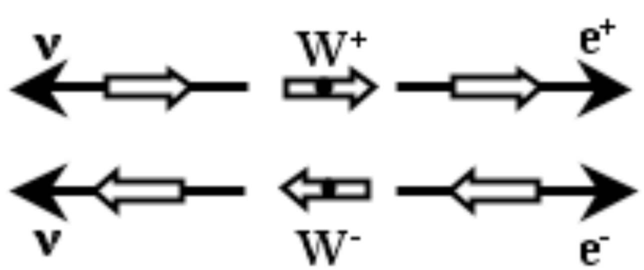
- $H \to WW^* \to l\nu l\nu$

No mass peak but strong angular correlations between the leptons

M.Dittmar, H.Dreiner (1996)



V-A interaction:

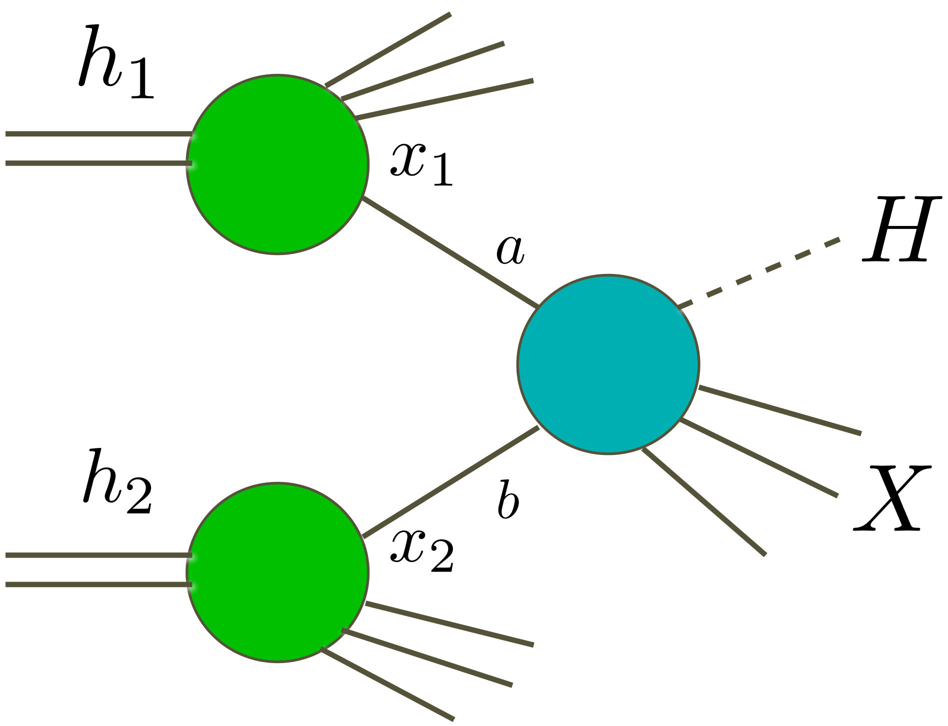


$l^{+(-)}$ (anti-) parallel to $W^{+(-)}$ spin

H scalar → charged leptons tend to be close in angle

Theoretical predictions

The framework: QCD factorization theorem



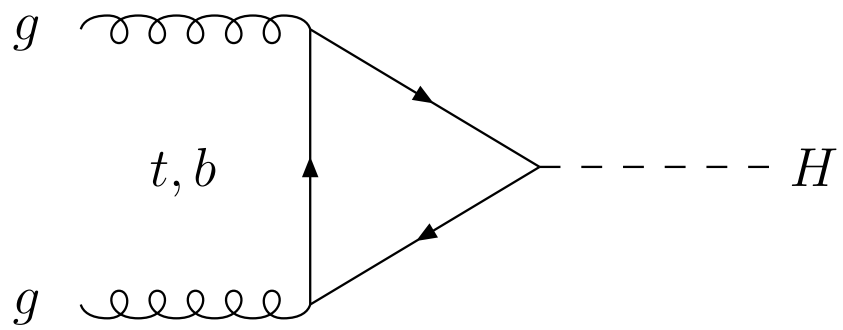
Parton distributions

Partonic cross section

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

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

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 % !

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)

Effect ranges from 15 to 20 % for $m_H < 200$ GeV

Effects of soft-gluon resummation at NNLL included: additional +6 %

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

NLO EW effects also known (effect is +5 % or smaller)

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

The large-m_{top} approximation

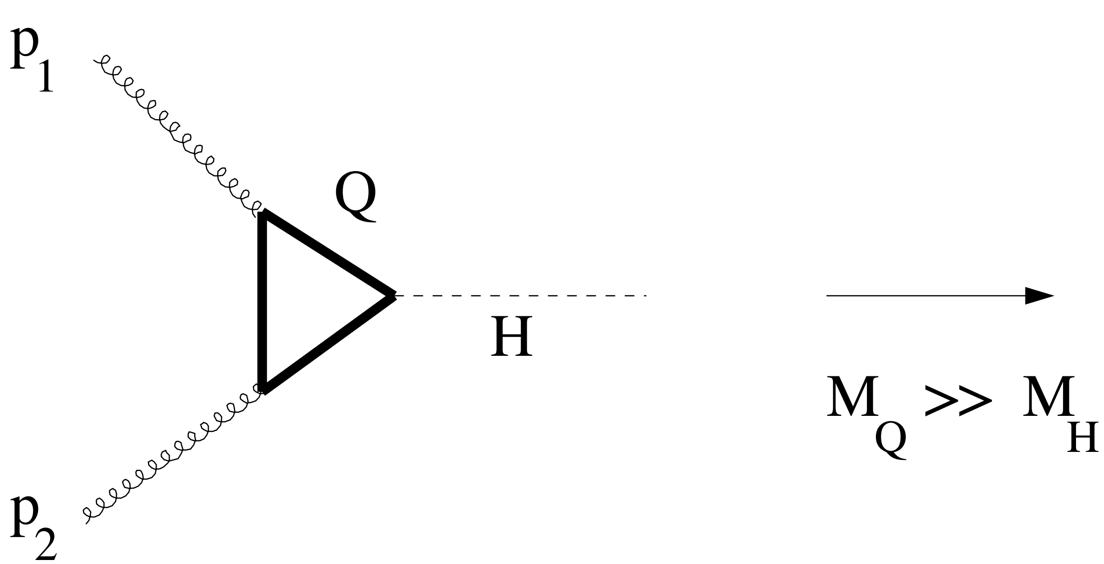
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

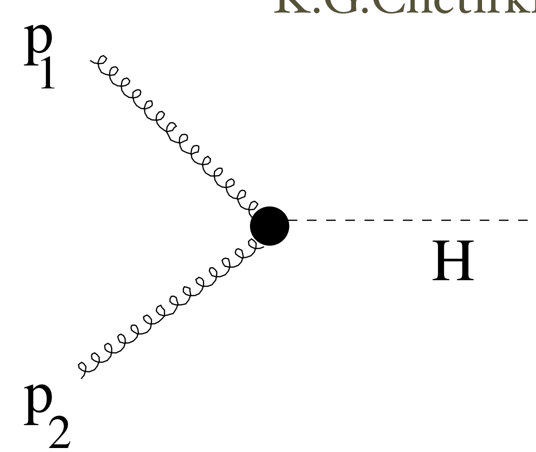
J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1976)
M.Voloshin, V.Zakharov, M.Shifman (1979)

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

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

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





Effective vertex: one loop less !

Recently the subleading terms in large-m_{top} limit at NNLO have been evaluated

R.Harlander, K.Ozeren (2009),
M.Steinhauser et al. (2009)

→ **The approximation works to better than 0.5 % for m_H < 300 GeV**

Updated cross sections

D. De Florian, MG (2009)

- 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 !

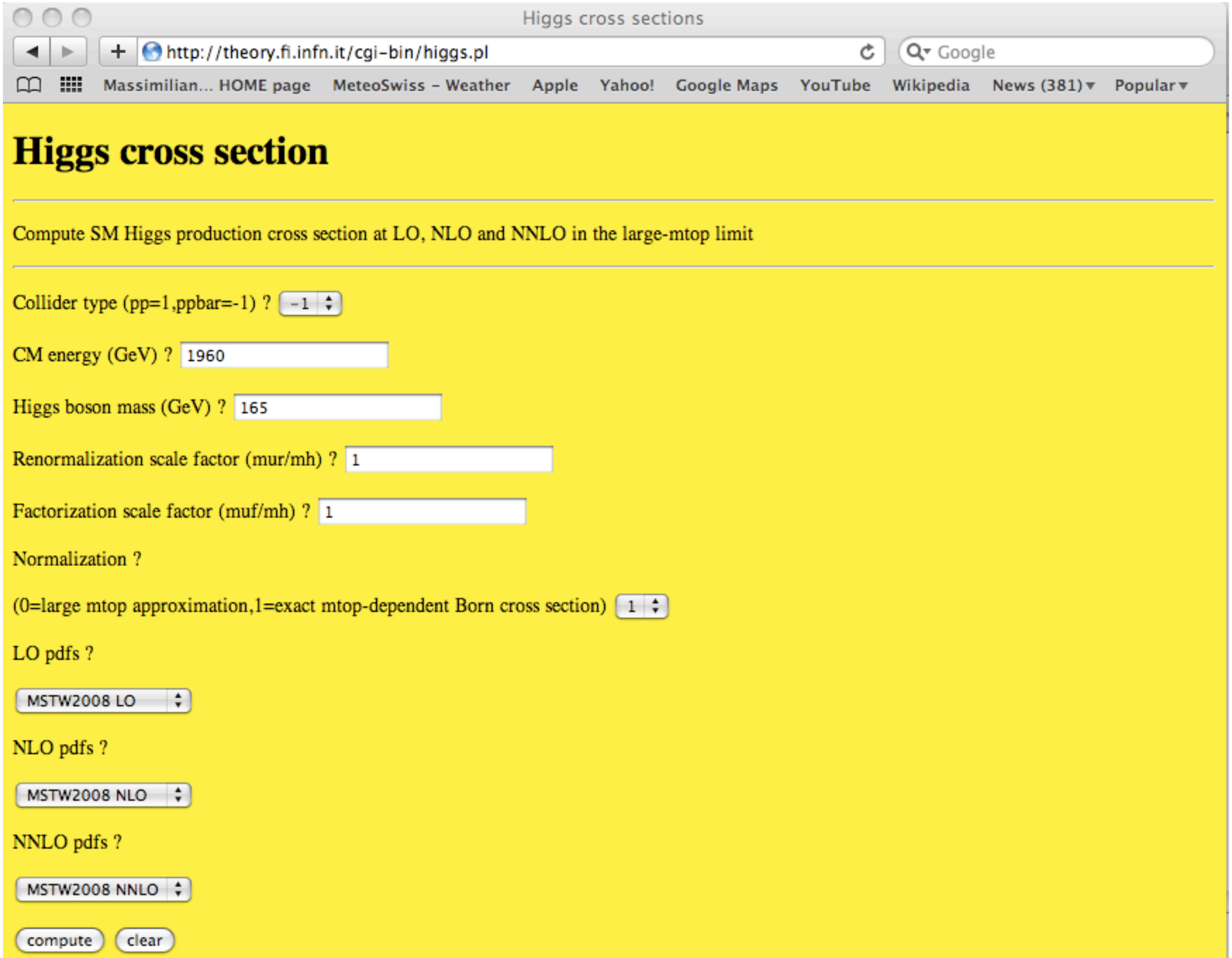
+30 % at m_H=115 GeV   +9 % at m_H=300 GeV

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%)

NEW: Online calculators



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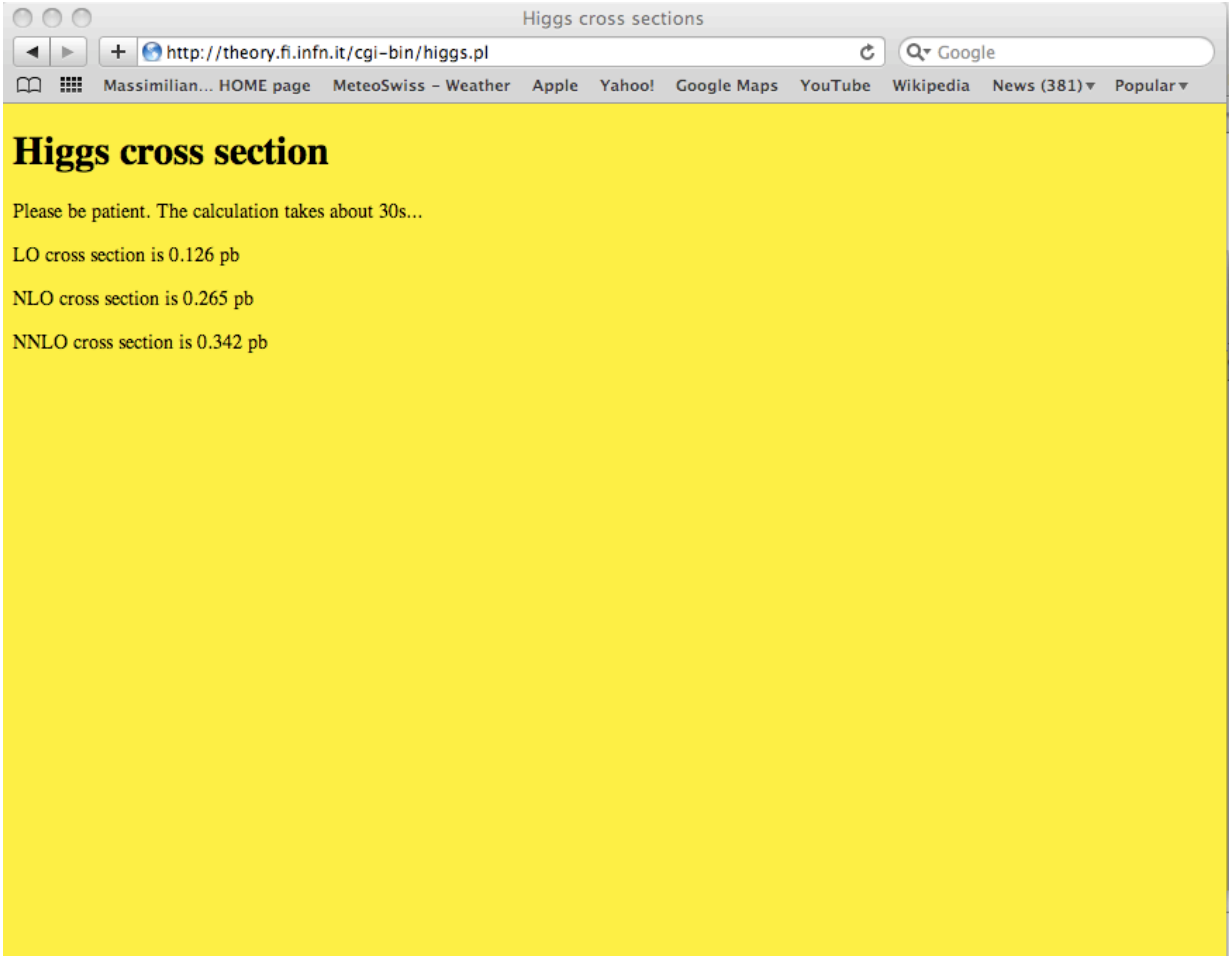

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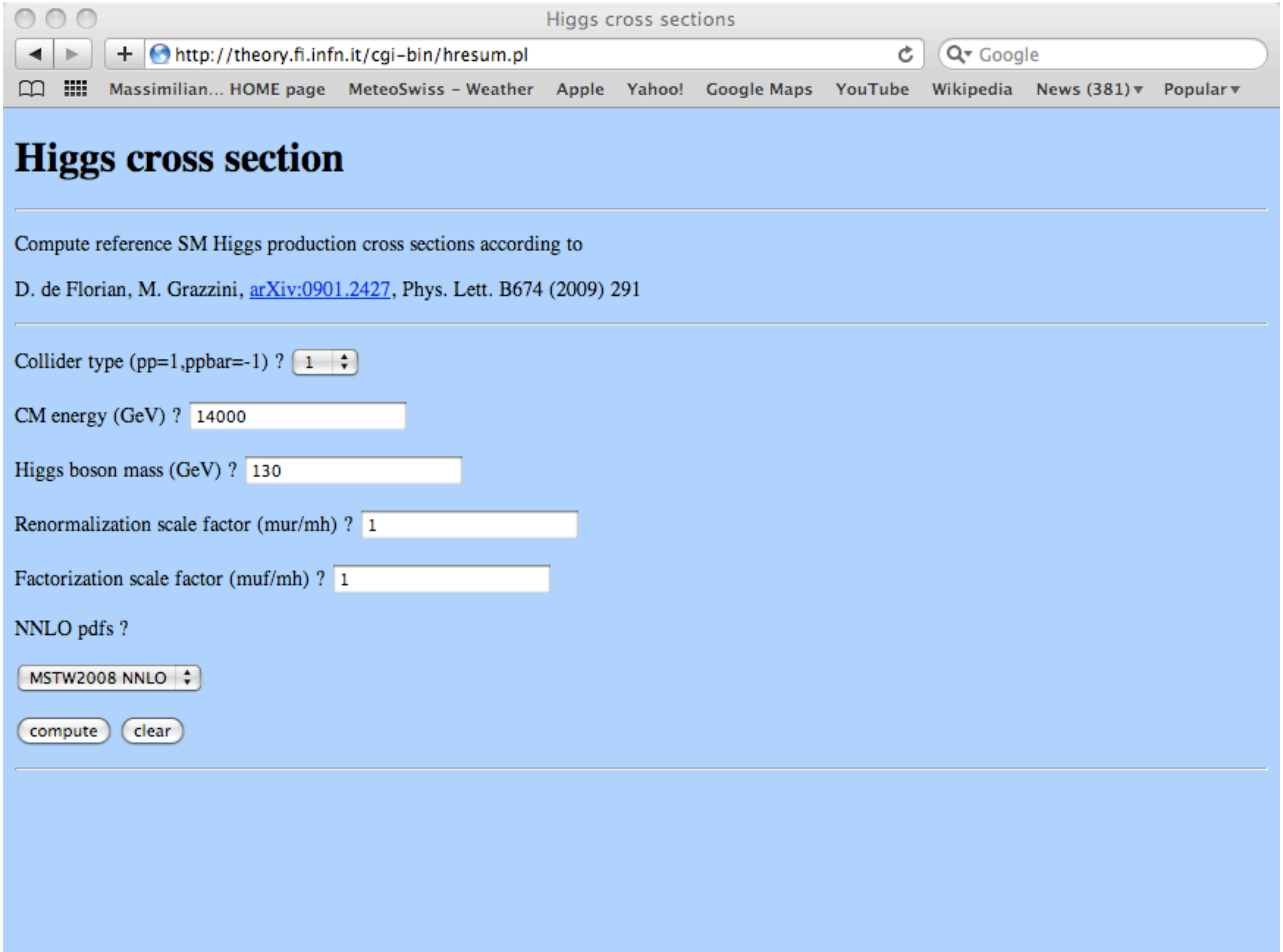
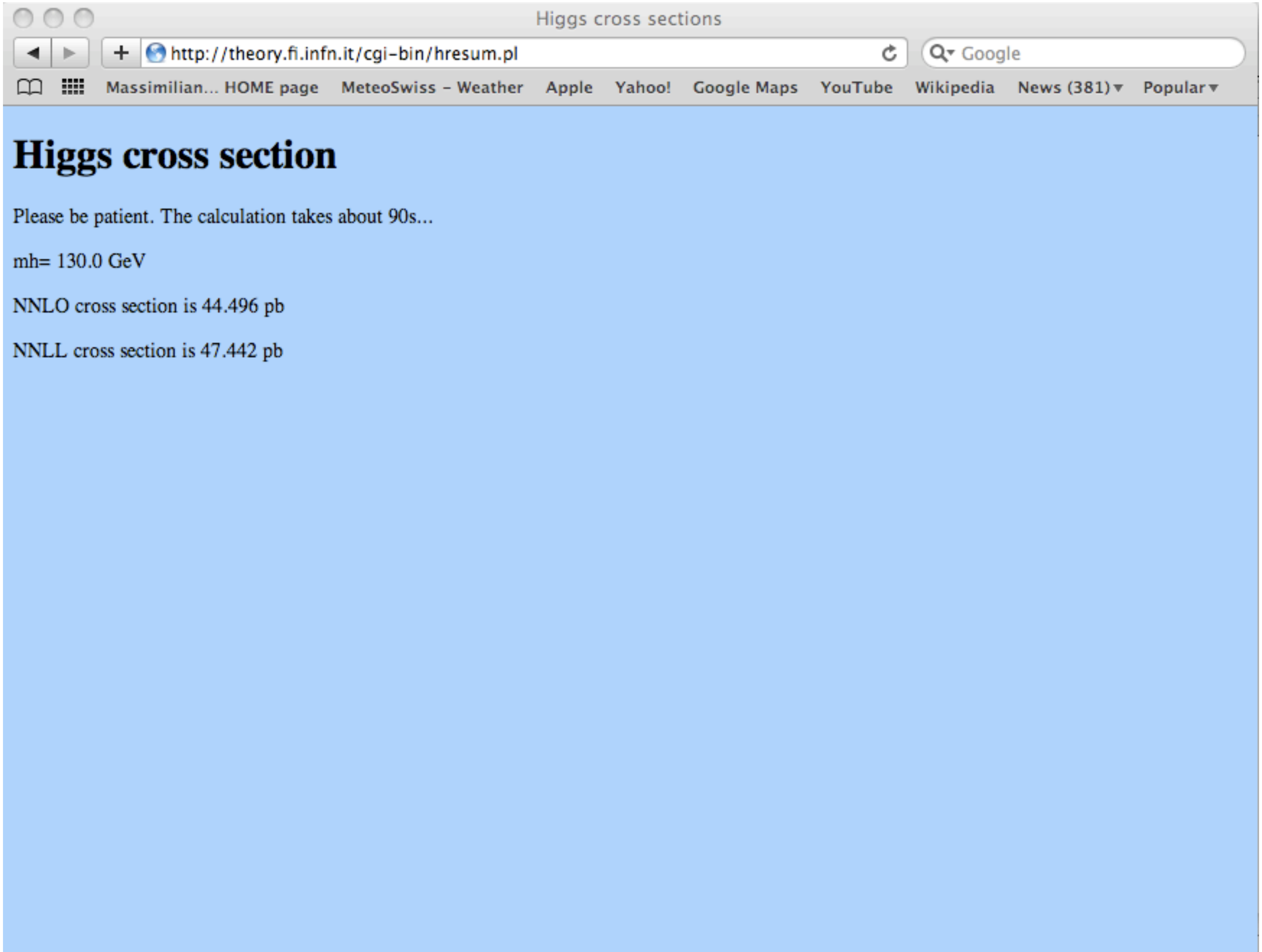


NEW: Online calculators



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

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

$|y| < 2.5$

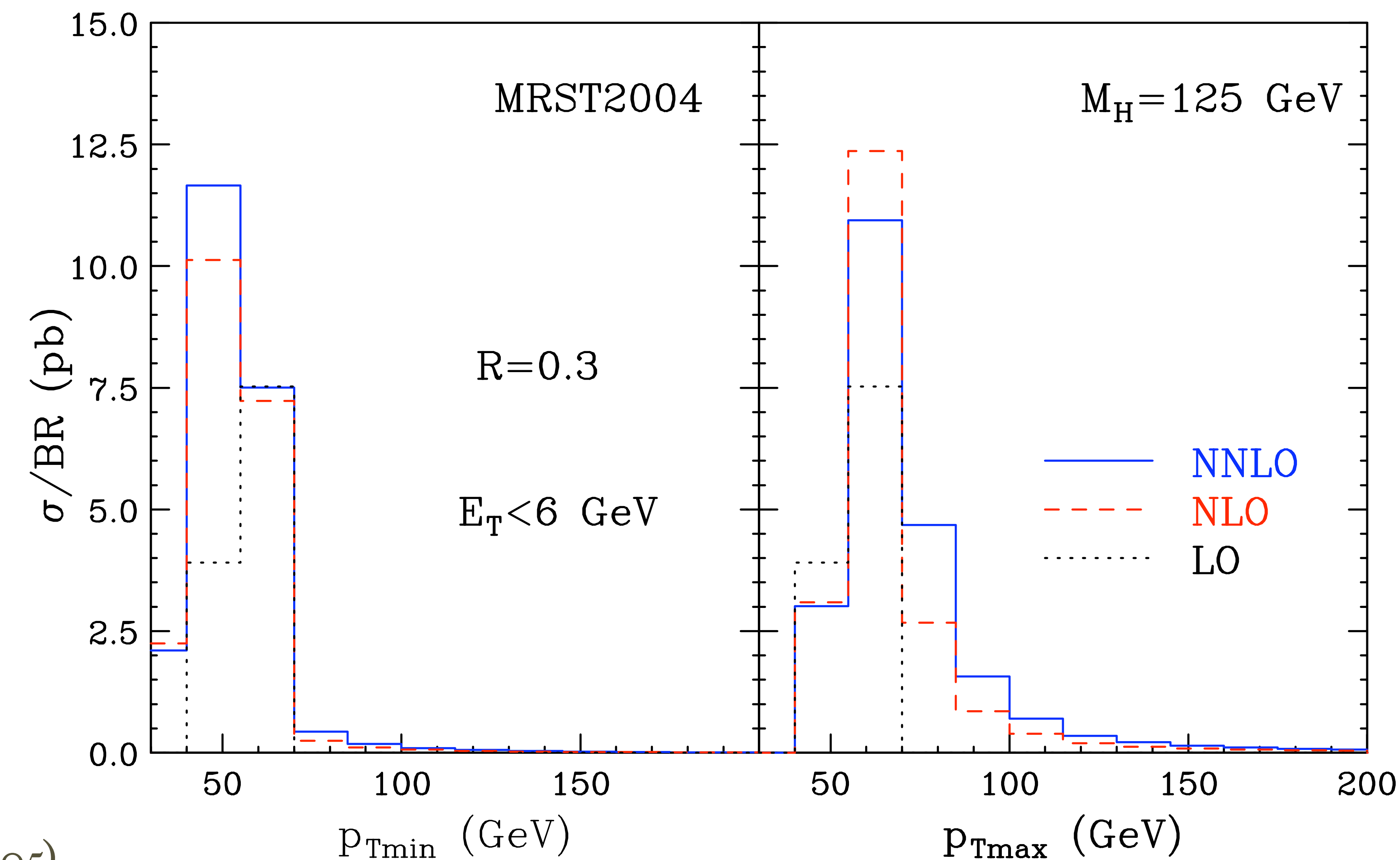
Photons should be isolated: total transverse energy in a cone of radius $R = 0.3$ should be smaller than 6 GeV

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)

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

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

cuts as in Davatz et al. (2003)

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

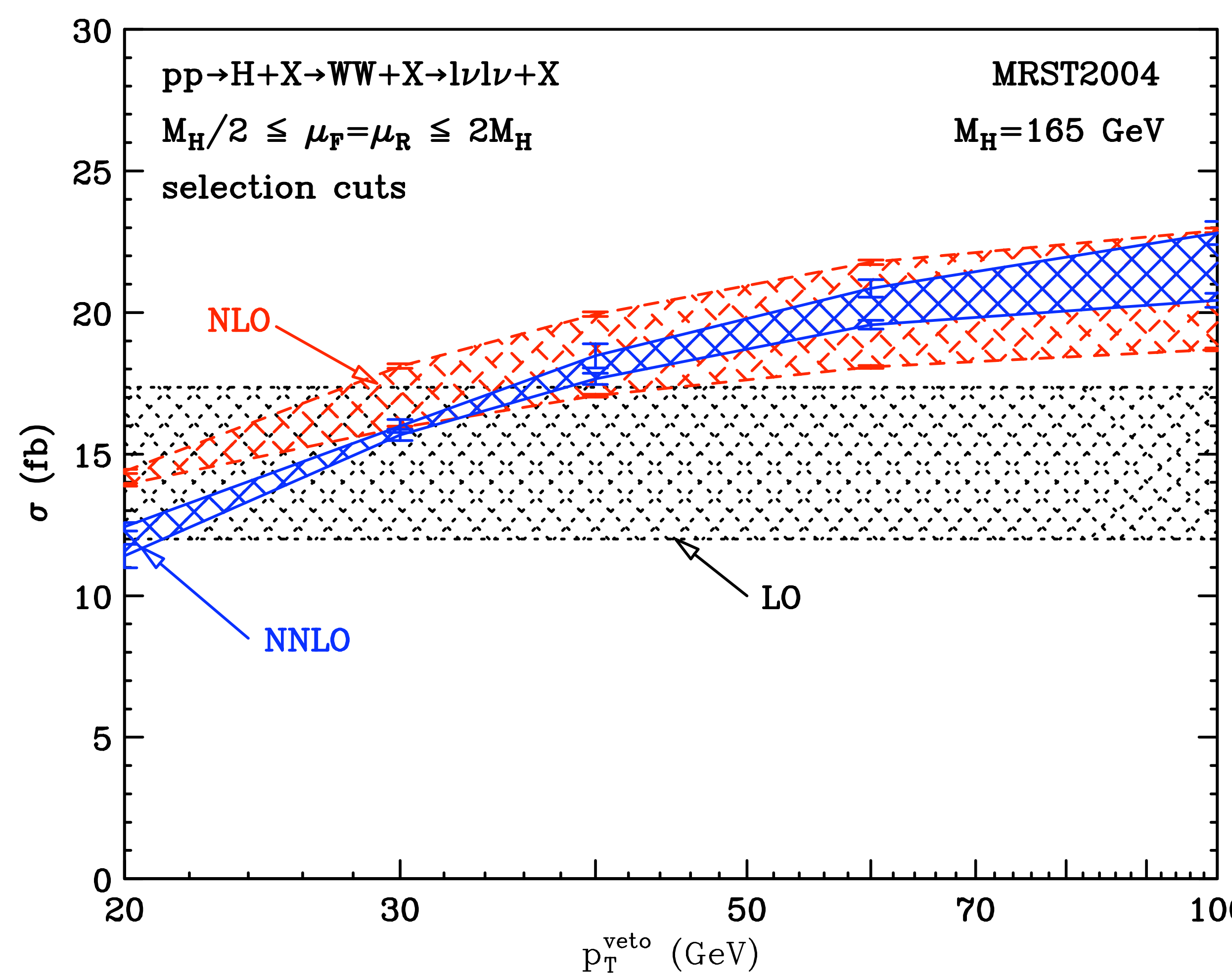
σ (fb)	LO	NLO	NNLO
$\mu_F = \mu_R = M_H/2$	17.36 ± 0.02	18.11 ± 0.08	15.70 ± 0.32
$\mu_F = \mu_R = M_H$	14.39 ± 0.02	17.07 ± 0.06	15.99 ± 0.23
$\mu_F = \mu_R = 2M_H$	12.00 ± 0.02	15.94 ± 0.05	15.68 ± 0.20

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

$K_{NLO} = 1.87$ $\qquad$ $K_{NNLO} = 2.26$

Consider the *selection cuts* as in the CMS TDR: $|y| < 2.5$

$p_{T1} > 30$ GeV $\quad p_{T2} > 25$ GeV $\quad p_{T3} > 15$ GeV $\quad p_{T4} > 7$ 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

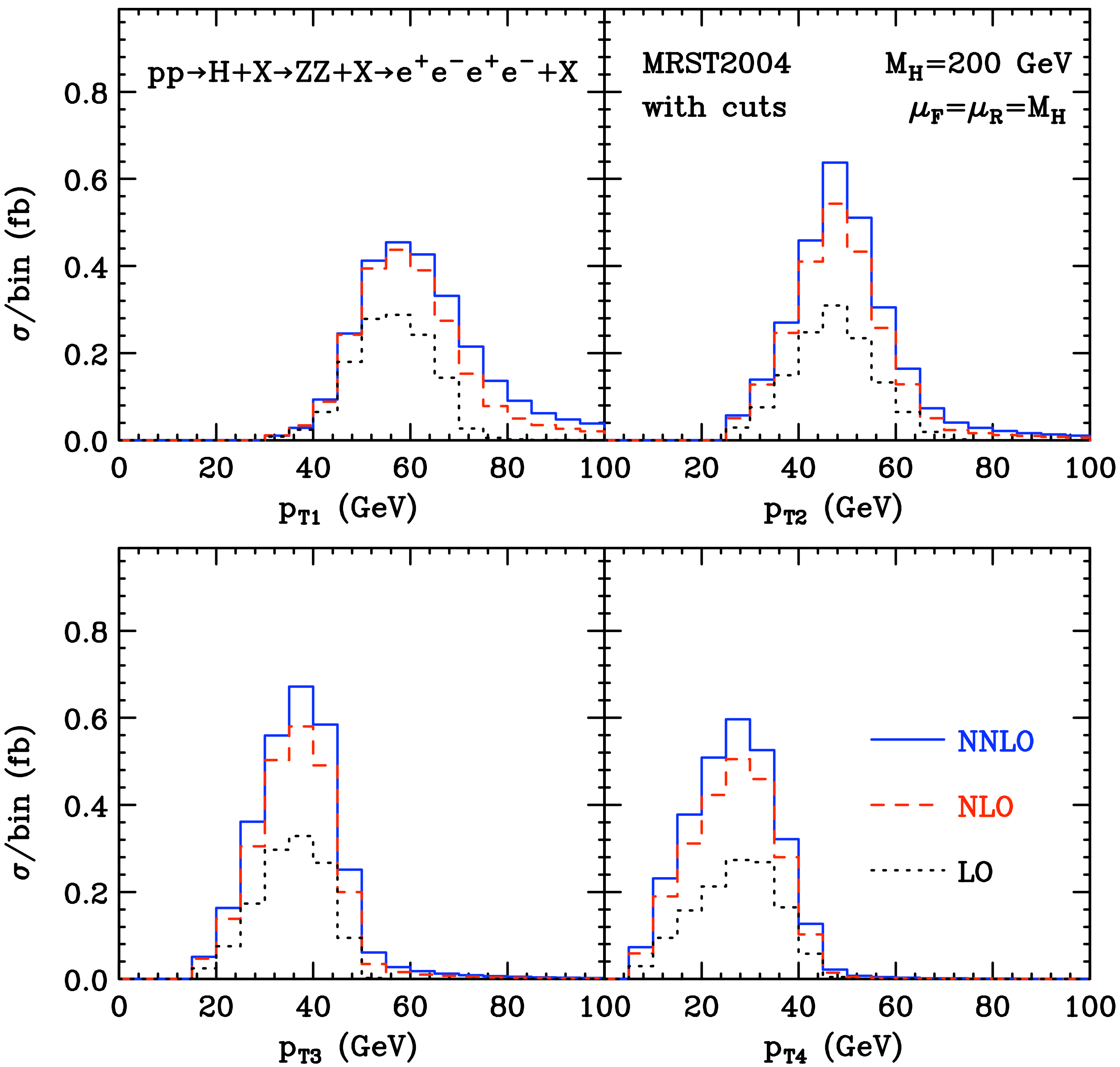
➡ $81\text{ GeV} < m_1 < 101\text{ GeV}$ and $40\text{ GeV} < m_2 < 110\text{ GeV}$

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

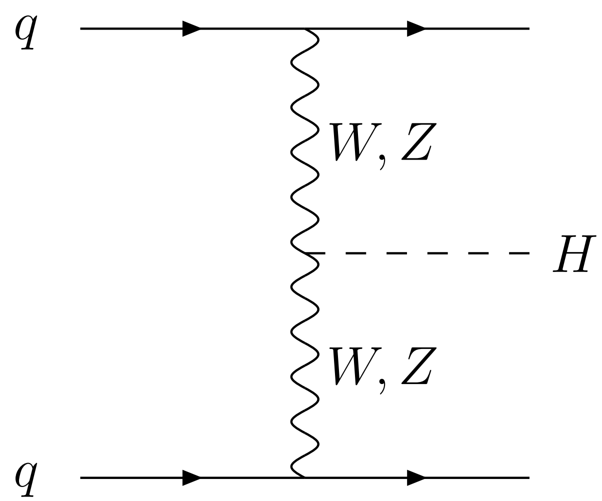
$$p_{T1}, p_{T2} < M_H/2$$

$$p_{T3} < M_H/3 \quad p_{T4} < M_H/4$$

Behaviour at the kinematical boundary is smooth

→ No instabilities beyond LO

Vector boson fusion



Valence quarks pdf peaked around $x \sim 0.1 - 0.2$

Transverse momentum of final state quarks of order of a fraction of the W(Z) mass

→ Tends to produce two highly energetic jets with a large rapidity interval between them

Since the exchanged boson is colourless, there is no hadronic activity between the quark jets

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

Implemented for distributions in VBFNLO

T. Han, S. Willenbrock (1991)
T. Figy, C. Oleari, D. Zeppenfeld (2003)
J. Campbell, K. Ellis (2003)

EW+QCD corrections have also been evaluated

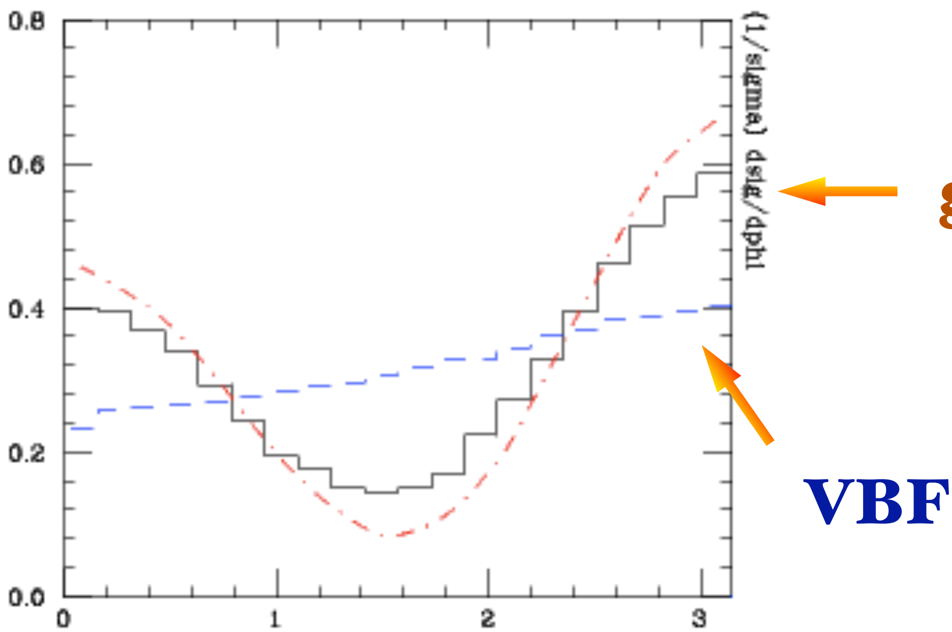
M.Ciccolini, A.Denner, S.Dittmaier (2007)

→ 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

Gluon fusion as well gives rise to events with two jets in the final state

how to separate it from VBF ?

- Azimuthal correlations between tagging jets



correlation is more pronounced in gg fusion
only mildly affected by parton shower effects

V. Del Duca, W. Kilgore, C. Oleari, C. Schmidt, D. Zeppenfeld (2001)
V. Del Duca, G. Klamke, D. Zeppenfeld, M.L.Mangano, M. Moretti, F. Piccinini, R. Pittau, A. Polosa (2006)

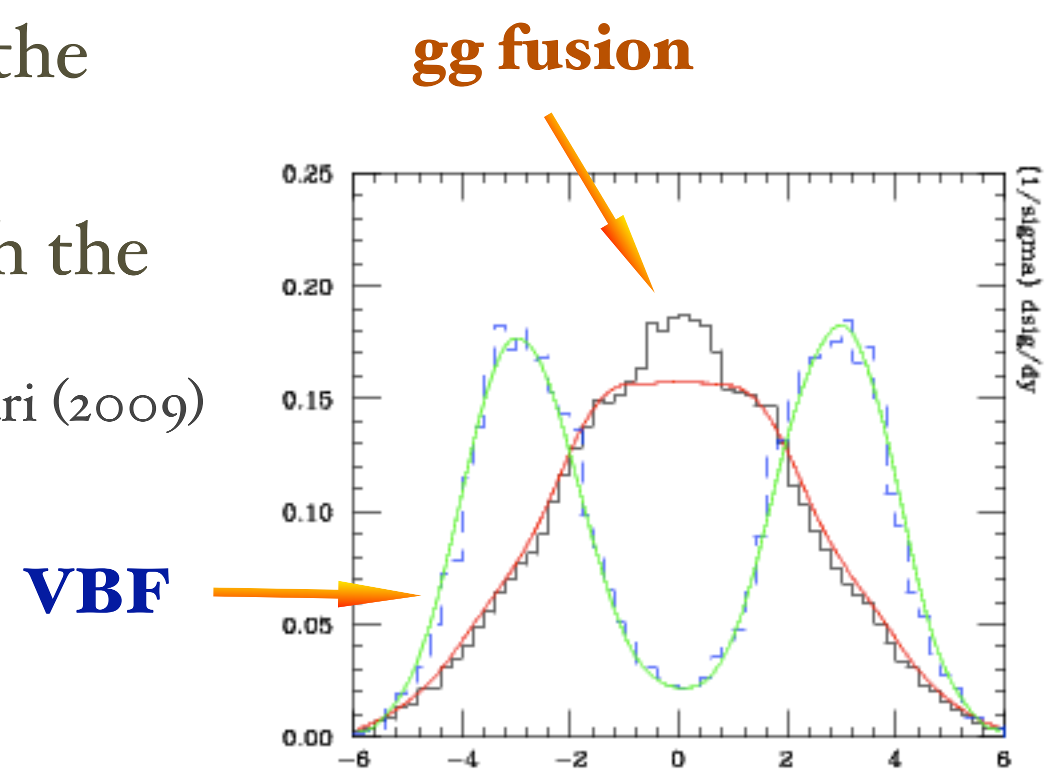
Rapidity of third hardest jet with respect to the average of the first two

Shape of VBF results recently confirmed with the POWEG method

P.Nason, C.Oleari (2009)

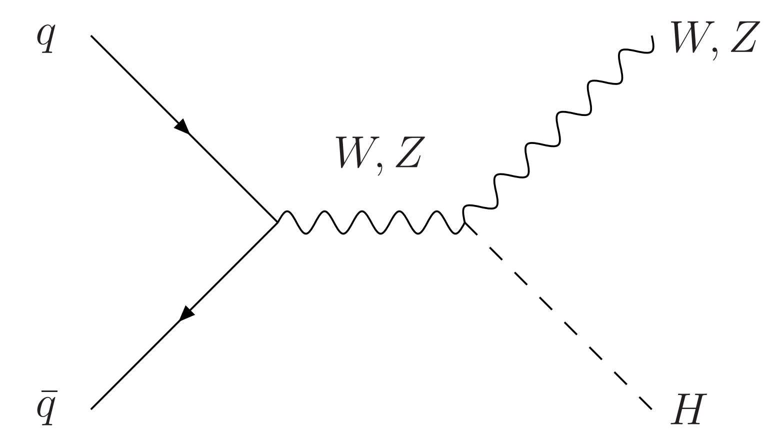
Apply central jet veto

- Effect of UE ?
- Impact of ln m_H/p_{Tveto} ?



Associated production with a W or Z

Most important channel for low mass at the Tevatron



→ lepton(s) provide the necessary background rejection

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

T. Han, S. Willenbrock (1990)

W. Van Neerven e al. (1991)

For ZH at NNLO additional diagrams from gg initial state must be considered: important at the LHC

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

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

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

Would provide unique information on the HWW and HZZ couplings

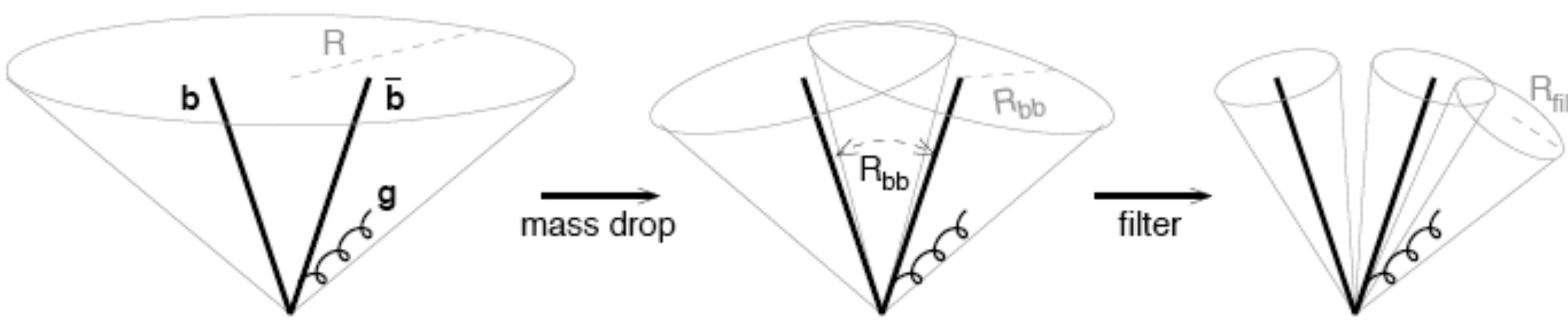
Associated production with a W or a Z

Not promising at the LHC:

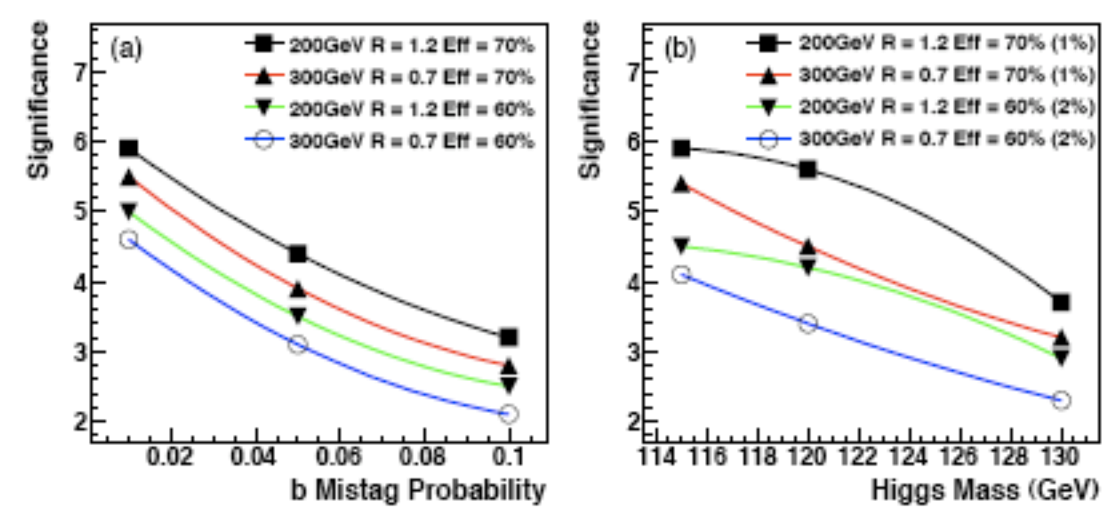
- HV produced at rapidities often beyond the detector acceptance
- presence of large background with scales close to the Higgs mass (eg b from top decays has energy about 65 GeV)

Recently a new analysis strategy has been proposed

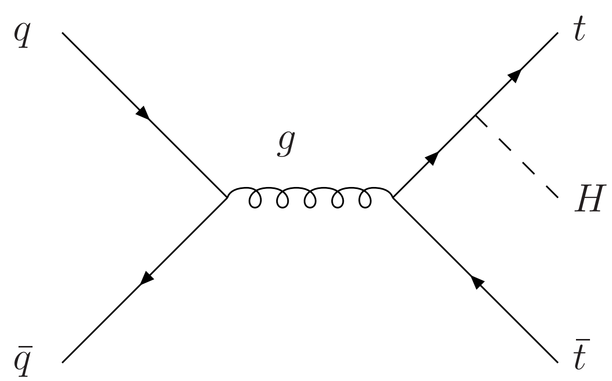
J.Butterworth, A.Davison, M.Rubin, G.Salam, (2008)

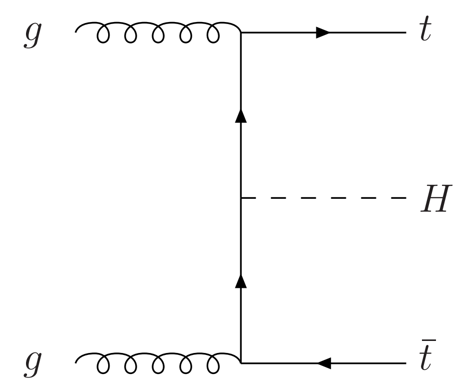


- Look for events where the Higgs and the vector are back to back
- Cluster into "fat jets" and then undo the last clustering
- Look for two b-tagged smaller jets and filter UE with a smaller jet parameter



Associated production with a $t\bar{t}$ pair





LO result known since long time

Z. Kunszt (1984)

It was considered as an important discovery channel in low mass region:

$H \to b\bar{b}$ triggering on the leptonic decay of one of the top

→ Requires good b-tagging efficiency

relevant also to measure $t\bar{t}H$ Yukawa coupling

NLO corrections computed by two groups

They increase the cross section by about 20 %

W.Beenakker, S. Dittmaier, B.Plumper, M. Spira, P. Zerwas (2002)
S.Dawson, L.Reina (2003)

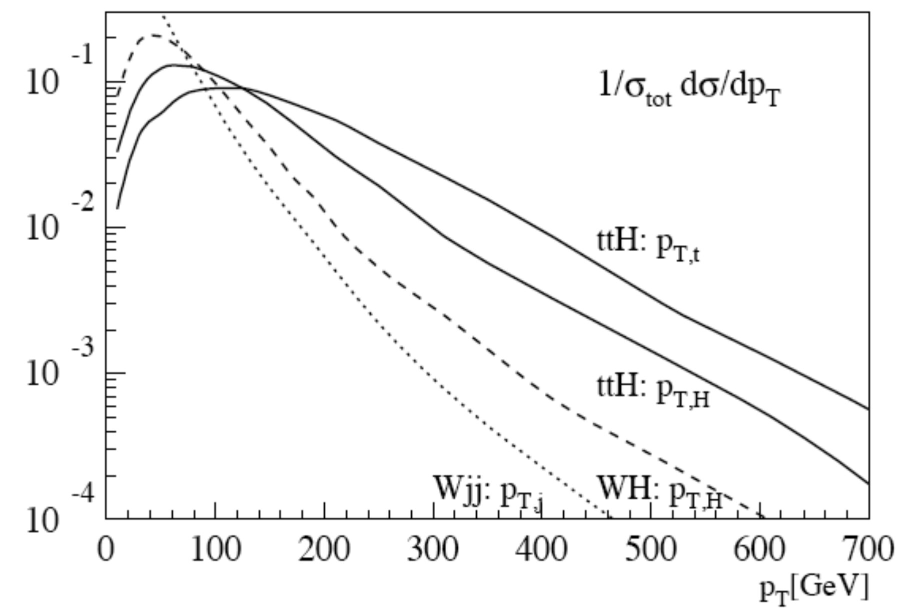
BUT.... full detector simulation and better background evaluation lead to more pessimistic view → Abandoned in the recent ATLAS and CMS discovery plots

Associated production with a $t\bar{t}$ pair

Can we resurrect it with "jet tomography" ?

T.Plehn, G.Salam, M.Spannowsky (2009)

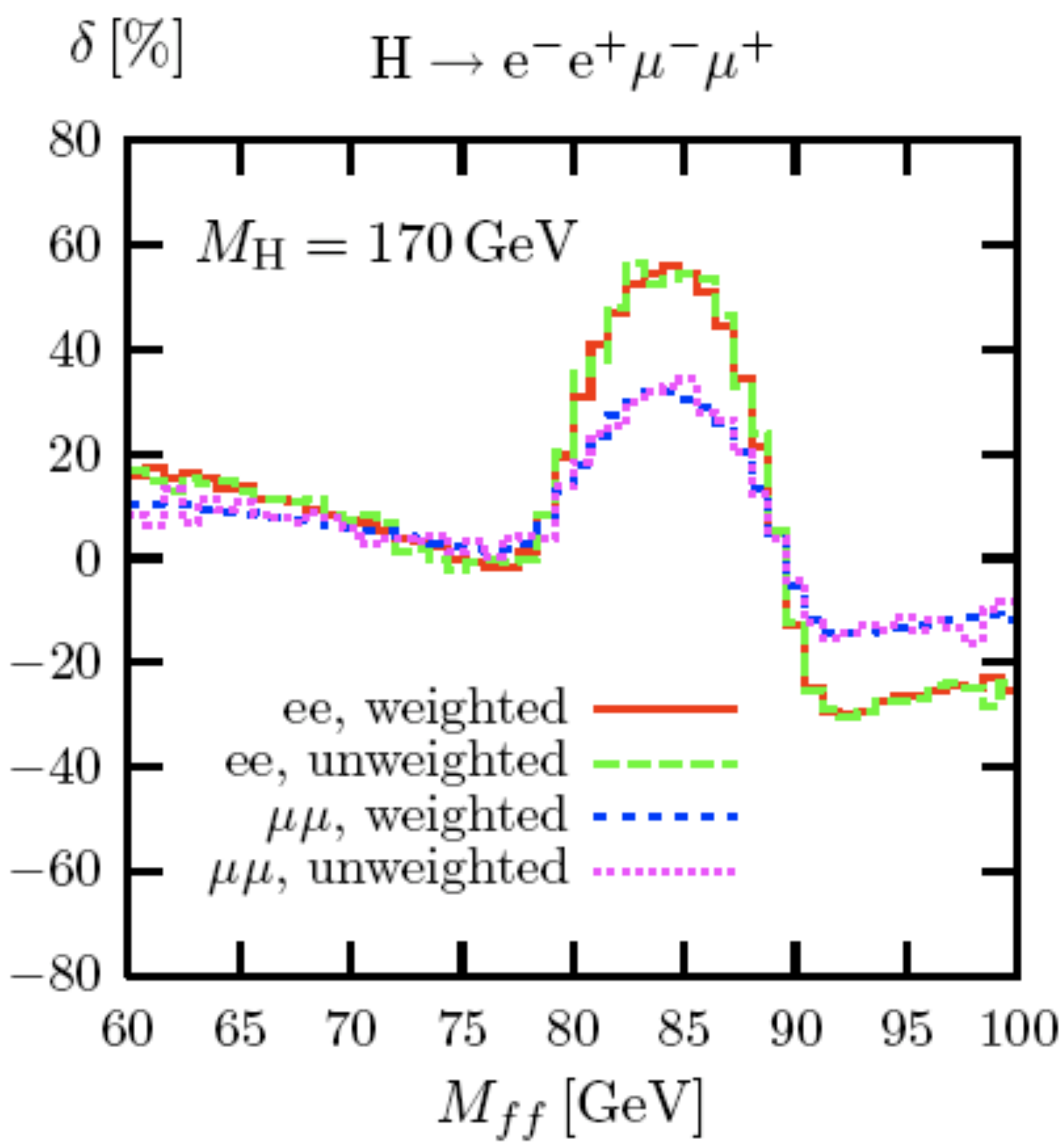
- Exploit boosted heavy states
- Find two "fat" jets with large pt (one from one top, the other from the Higgs)
- Top and Higgs taggers work by undoing the last clustering
- Promising results but requires high integrated luminosity and more detailed studies with full detector simulation



	$S[\text{fb}^{-1}]$	$B[\text{fb}^{-1}]$	S/B	$S/\sqrt{B}$
m_H = 115 GeV	1.2	4.5	1/3.8	5.7
120 GeV	1.0	4.5	1/4.5	4.7
130 GeV	0.51	3.9	1/4.7	3.3

Higgs decays

Precise predictions for Higgs production must be followed by comparable precision in the Higgs decay



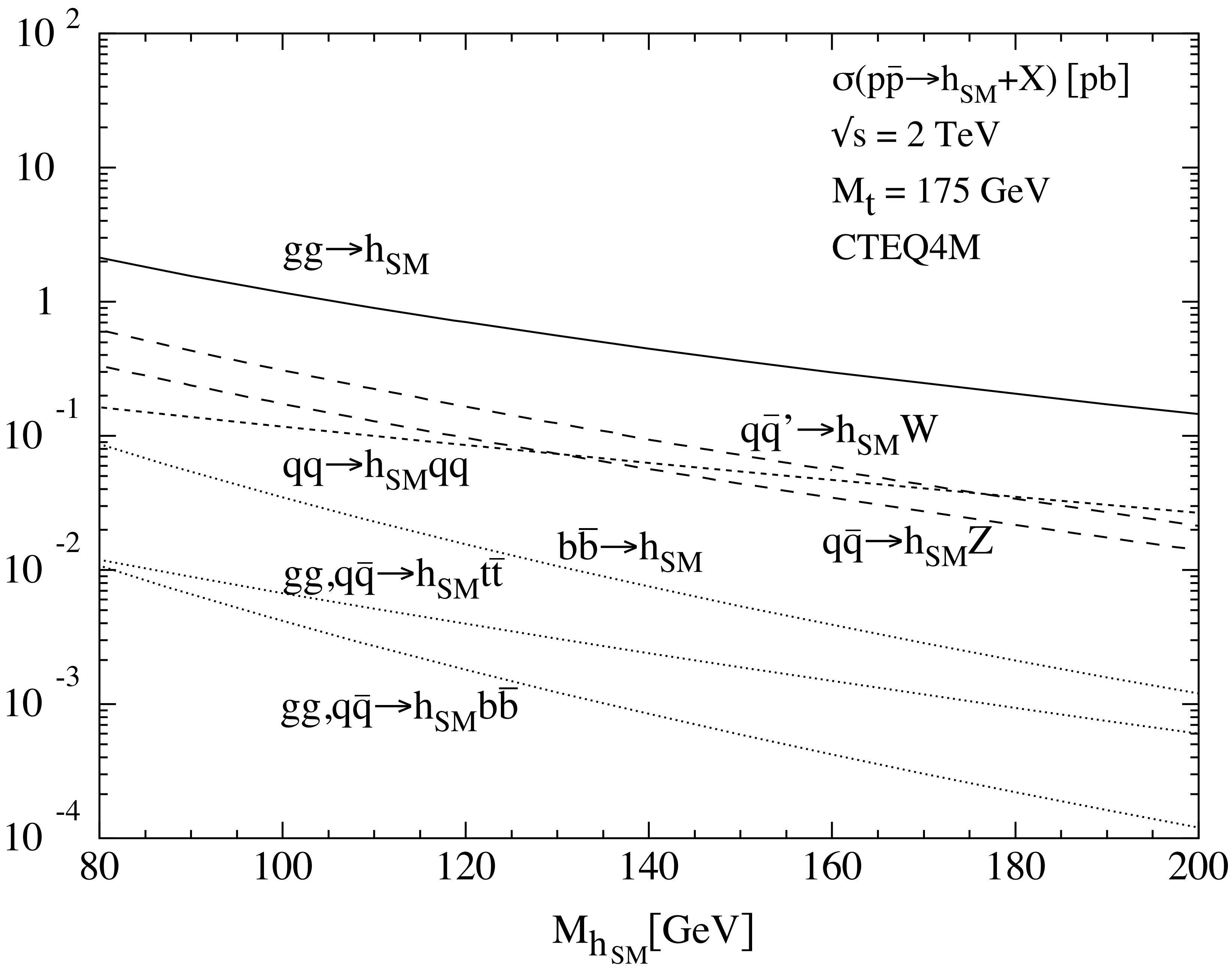
One-loop EW and QCD effects for the H→WW(ZZ)→4fermions decay channels are known

A.Bredenstein, A.Denner, S.Dittmaier, M.Weber (2007)

Important effects in the peak region but not taken into account at present

Implemented in PROPHECY4F

Higgs production at the Tevatron



As for the LHC

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

is ruled out by the huge background

But: $H \longrightarrow \gamma\gamma$

too small to be observed !

For $m_H \leq 130$ GeV → $pp \longrightarrow HW \longrightarrow b\bar{b}\, l\nu$ → The lepton gives the necessary background rejection

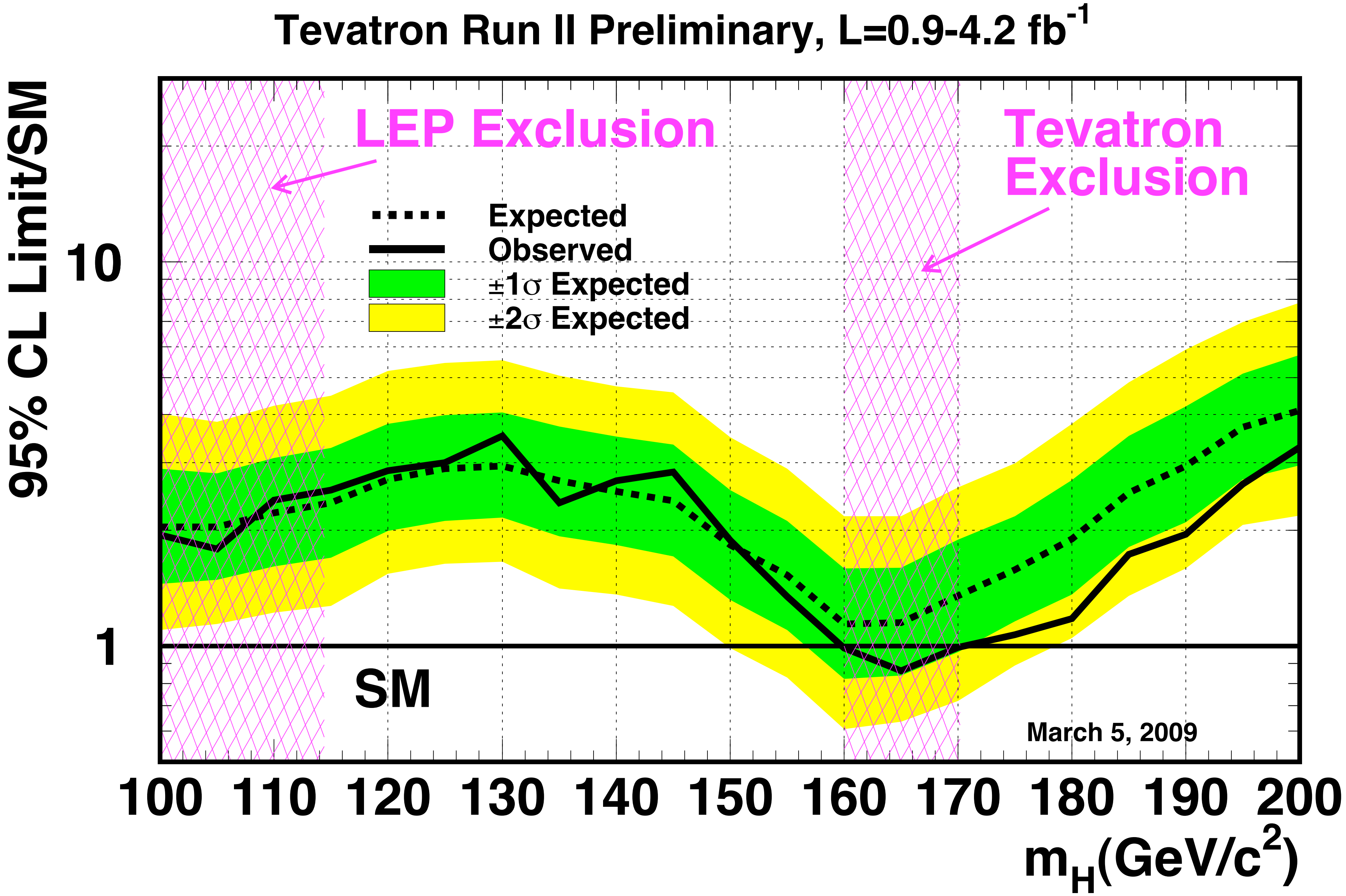
For $m_H \geq 130$ GeV → $gg \longrightarrow WW \longrightarrow l\nu l\nu$

Results

Latest results presented up to L=5.4 fb^{-1}

Expressed in terms of R=95 % CL limits/SM

Now sensitive to the region m_H≈160-170 GeV



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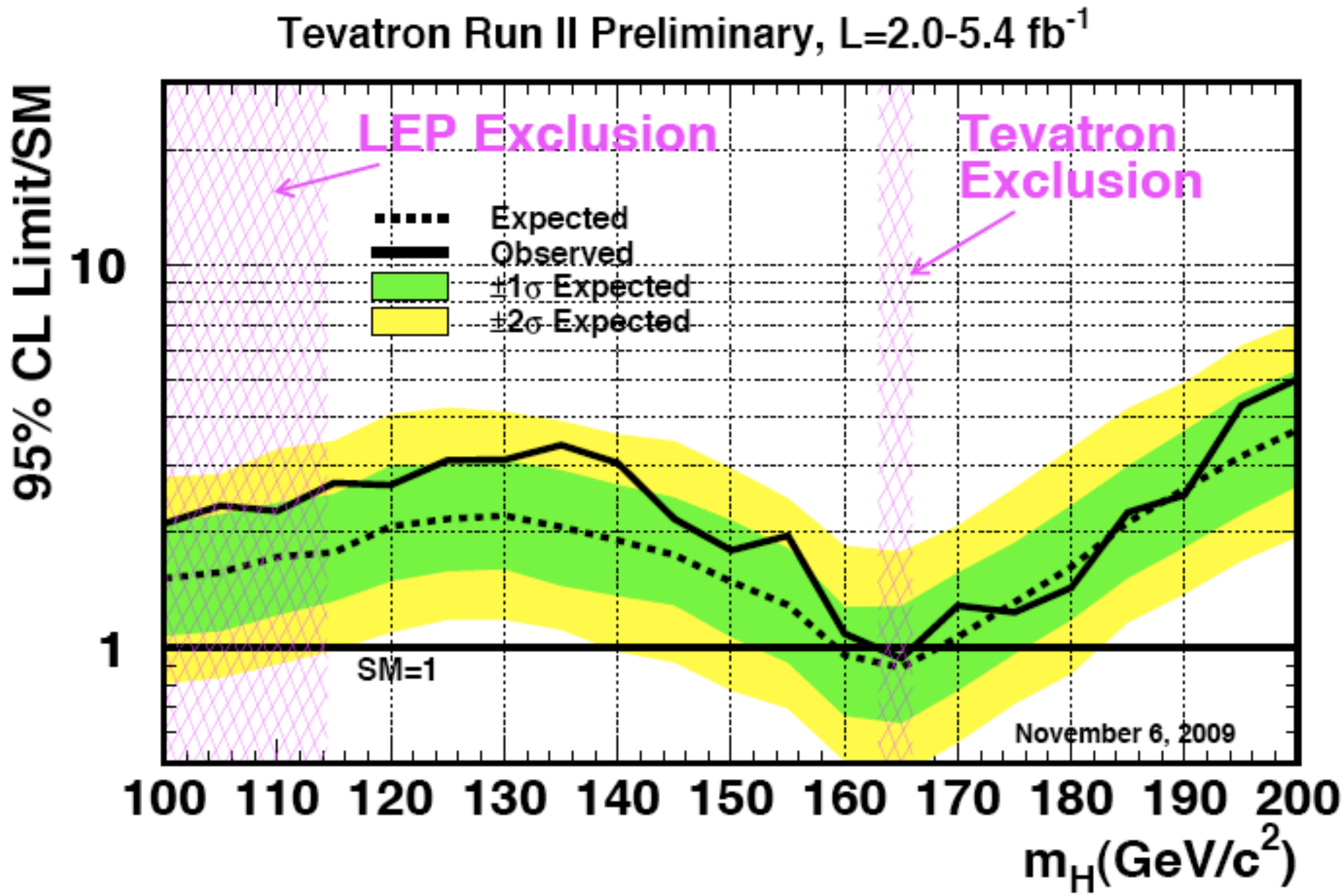
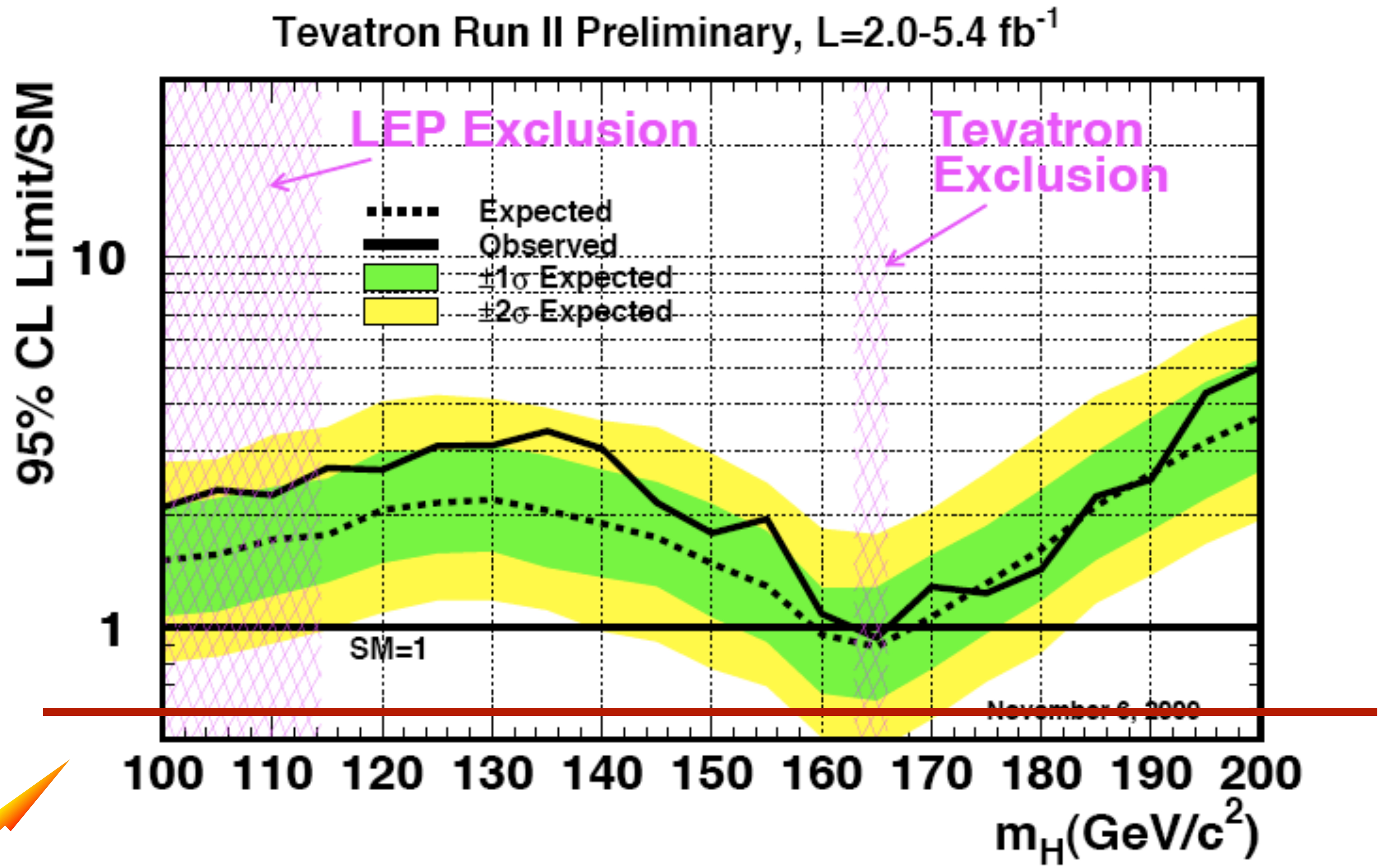


The recent combination shows more signal like events that shrink the excluded region

The relevance of higher orders

The recent Tevatron exclusion is based on our updated NNLL result

D. De Florian, MG (2009)



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

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 $p_T > 15\,\text{GeV}$ and $|\eta| < 3$

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

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)
- $\text{MET}^* > 25\,\text{GeV}$

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

$K_{NLO} = 2.15$

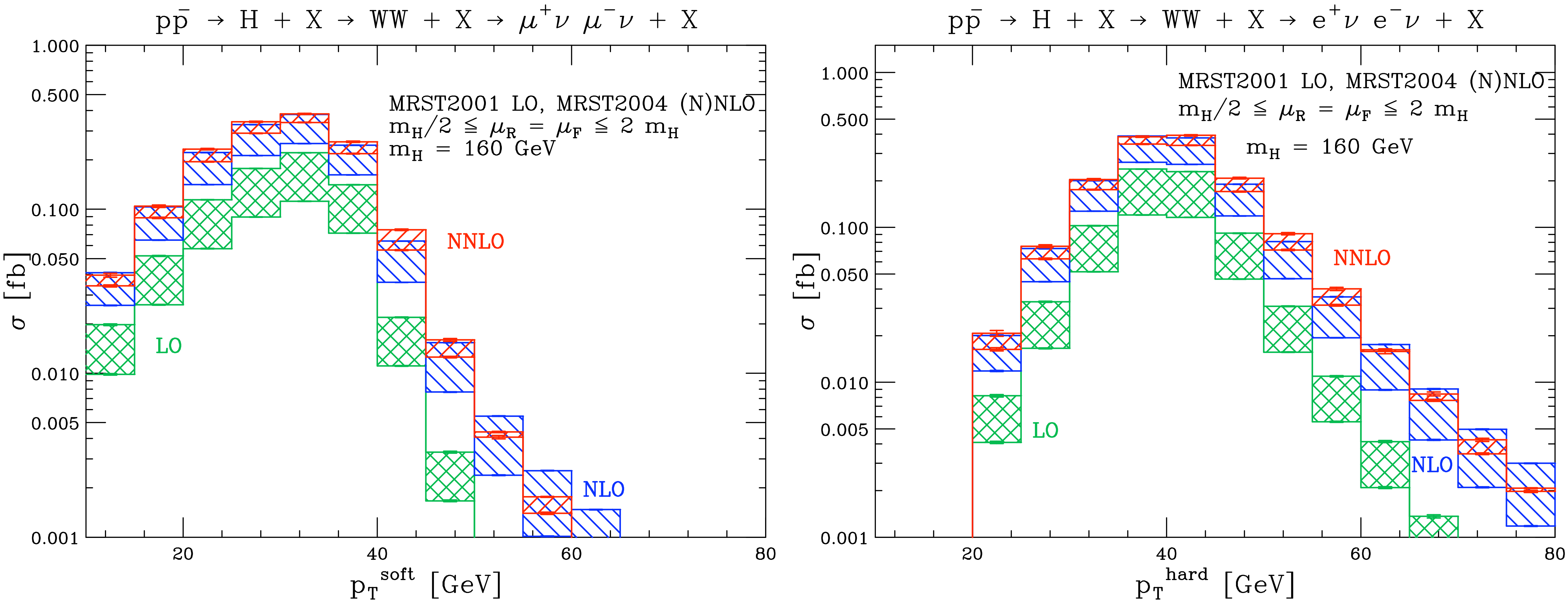
$K_{NNLO} = 2.63$

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

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

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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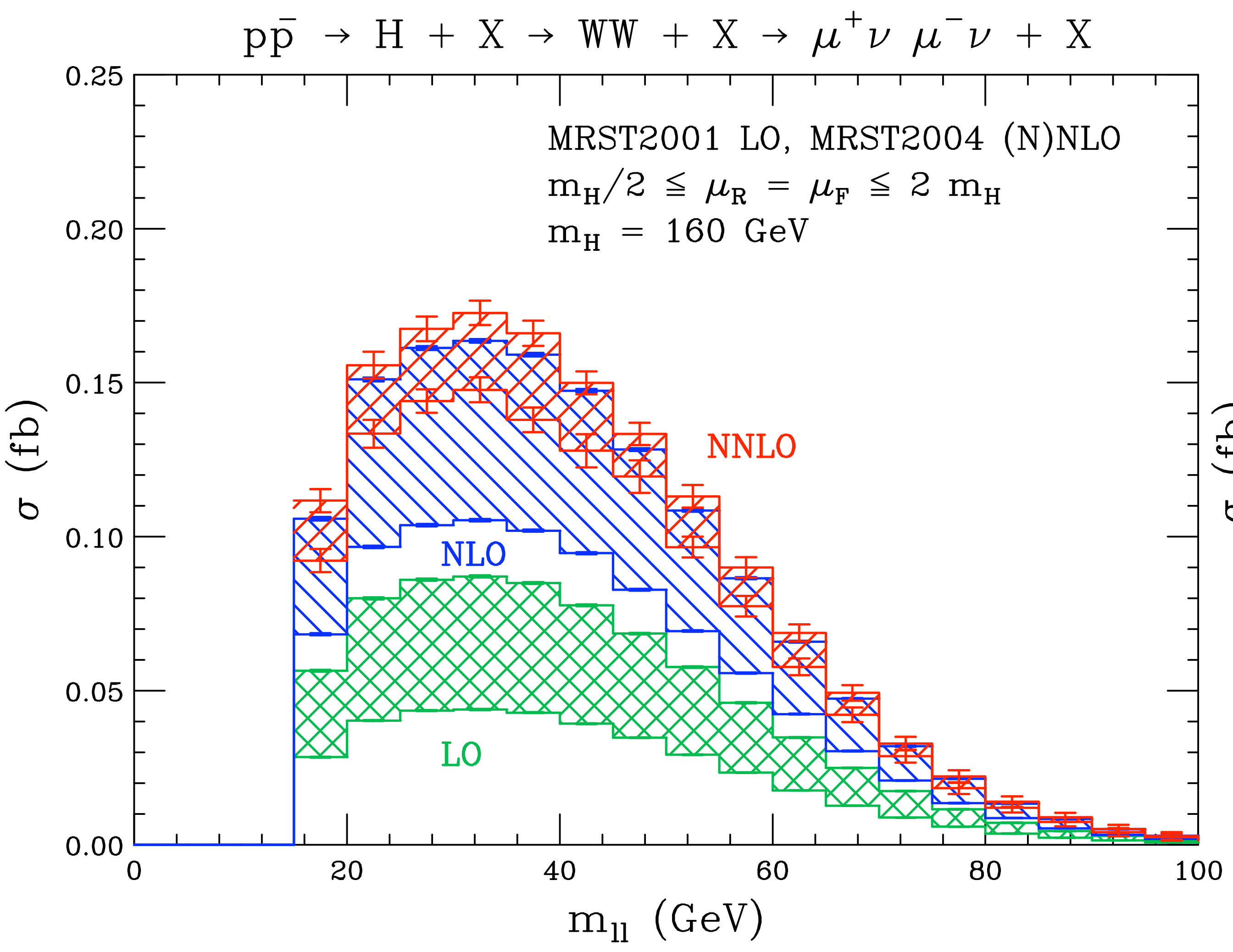

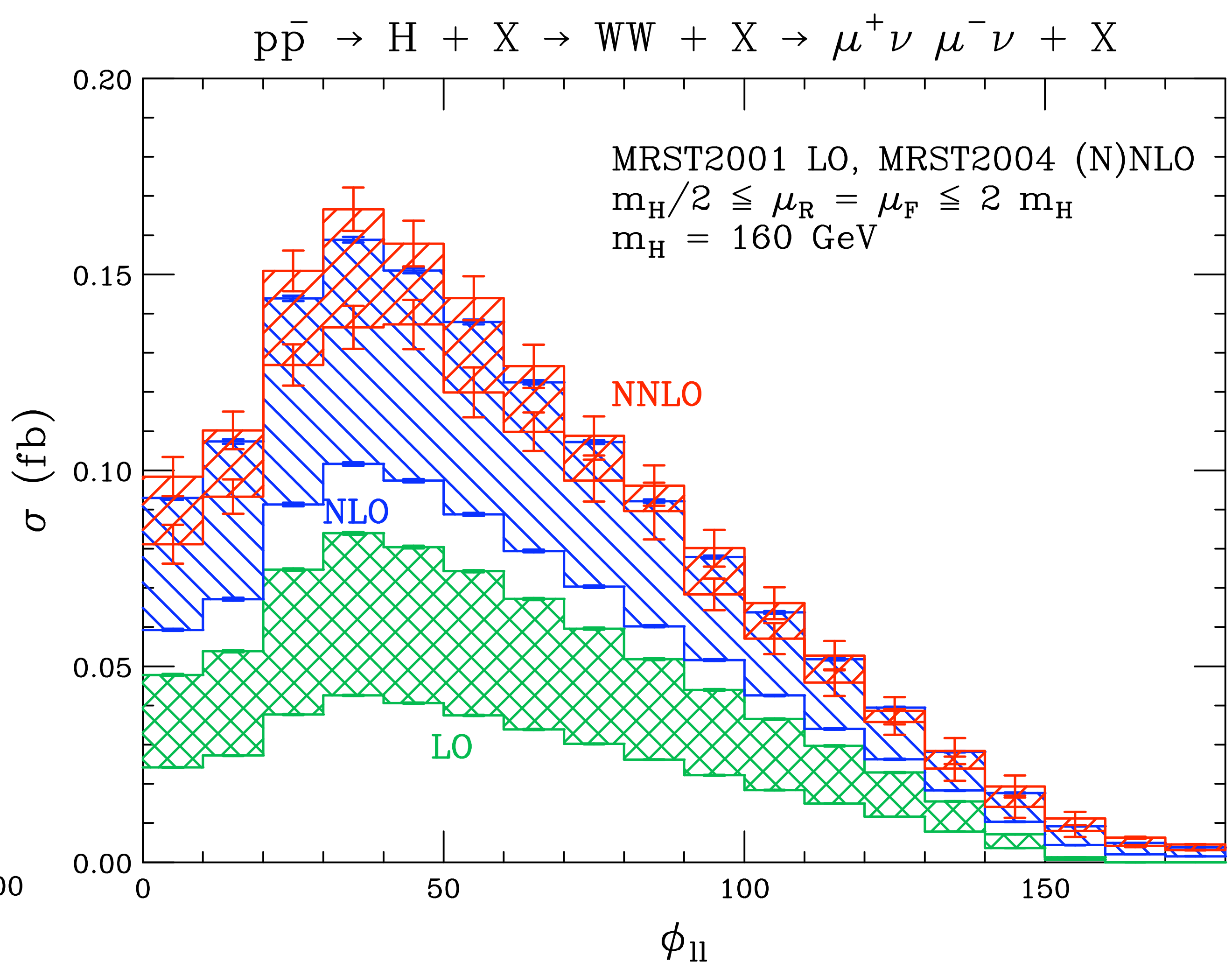

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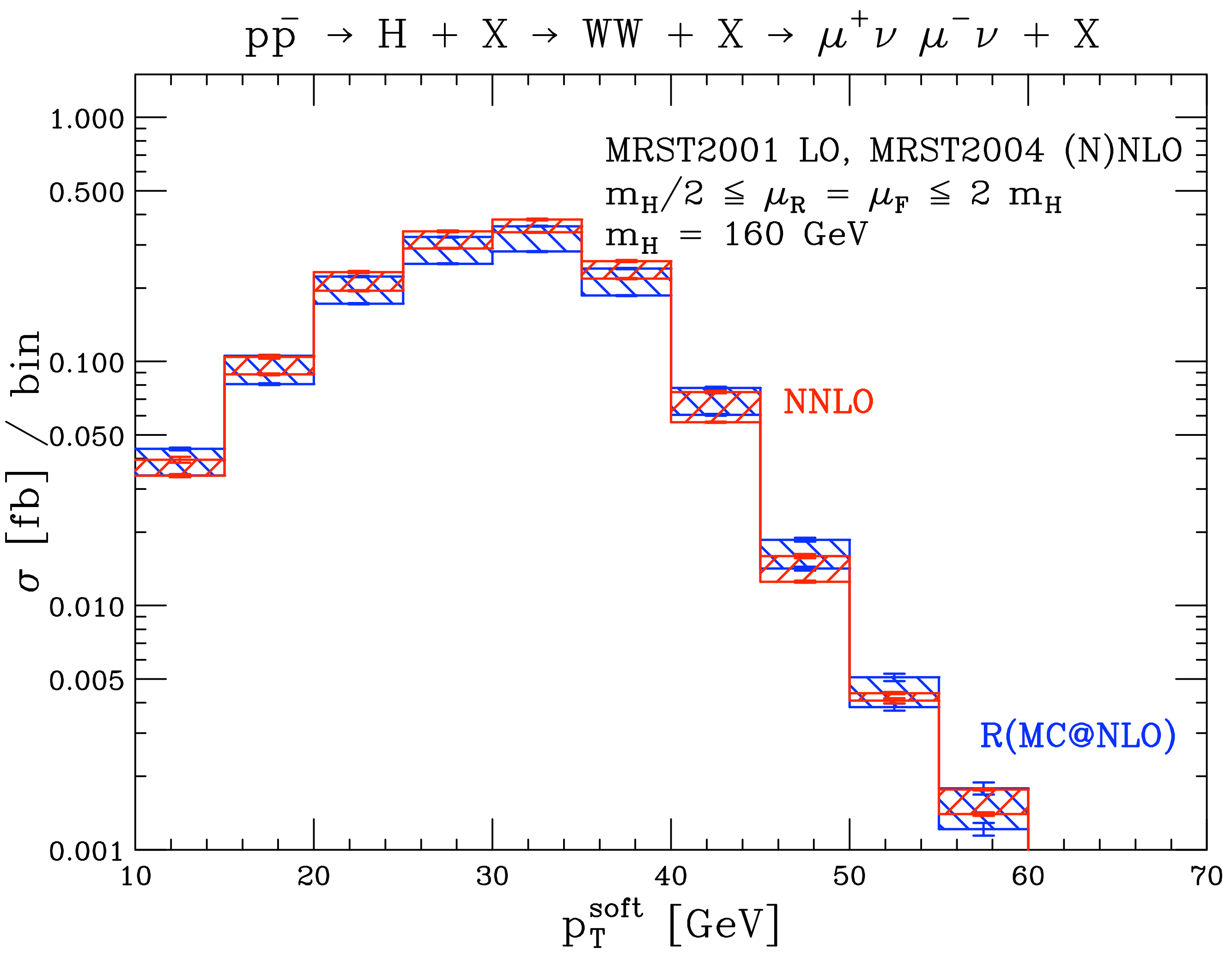

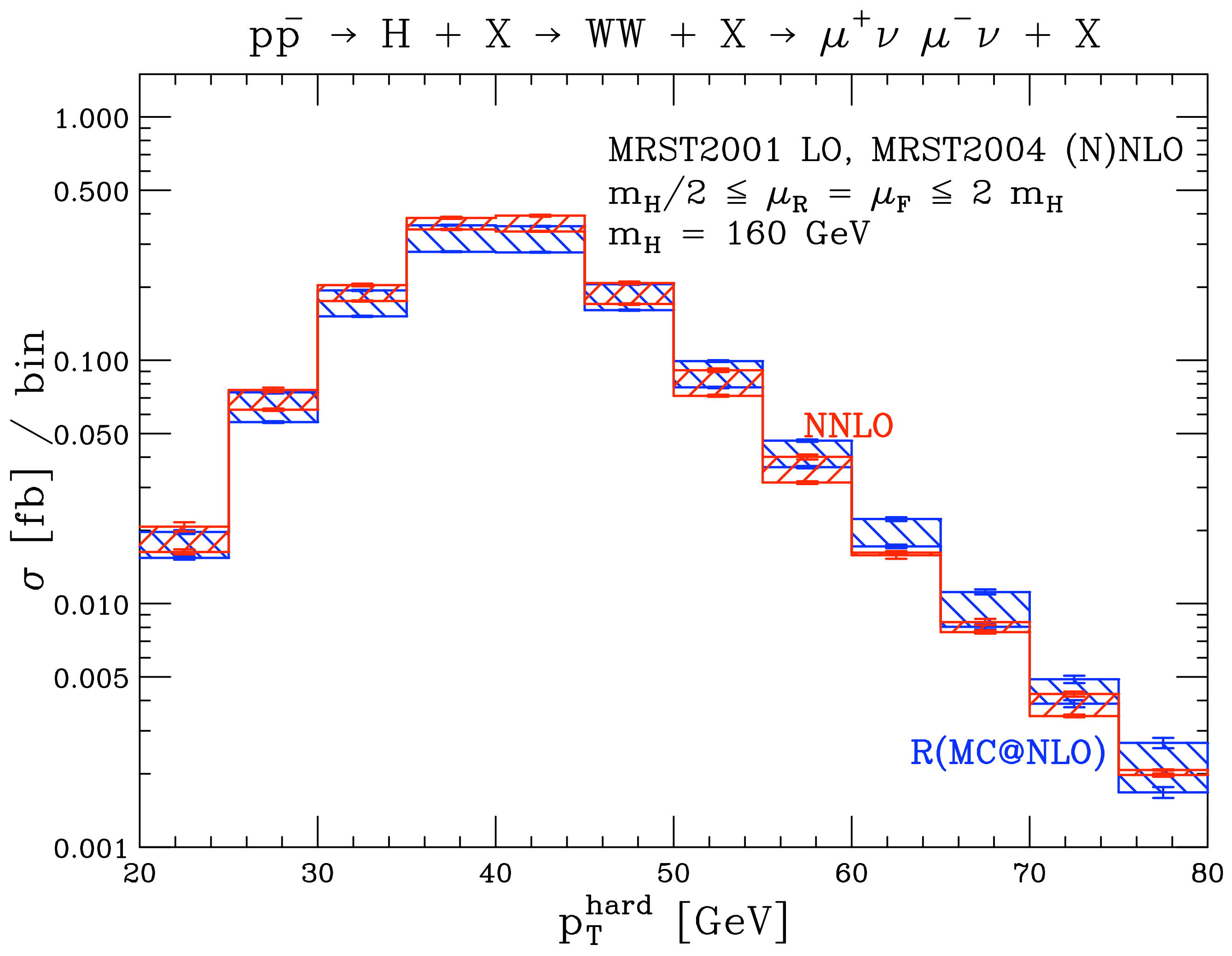

MC results are rescaled so as to match the inclusive NNLO cross section

They appear to be in reasonably good agreement with NNLO

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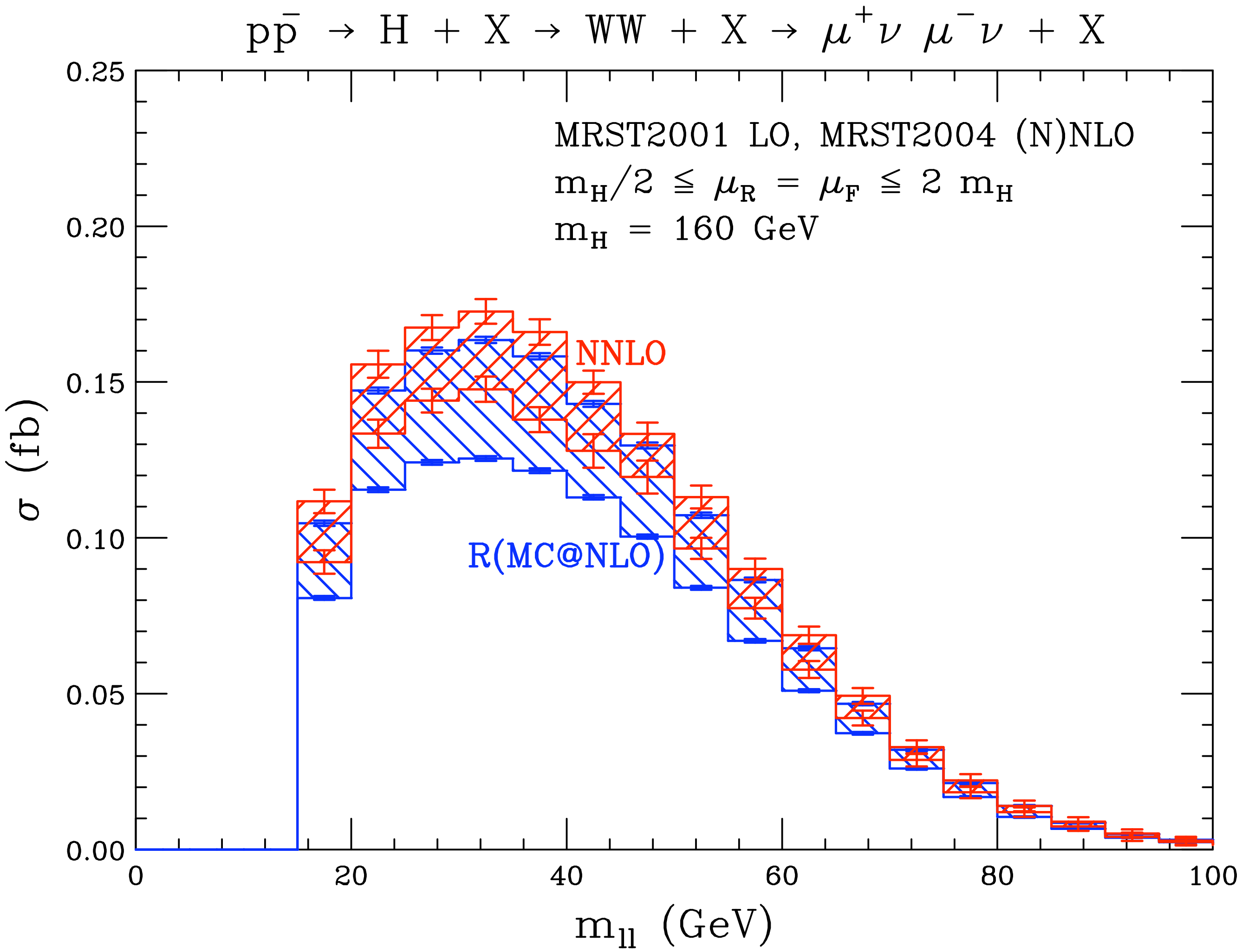

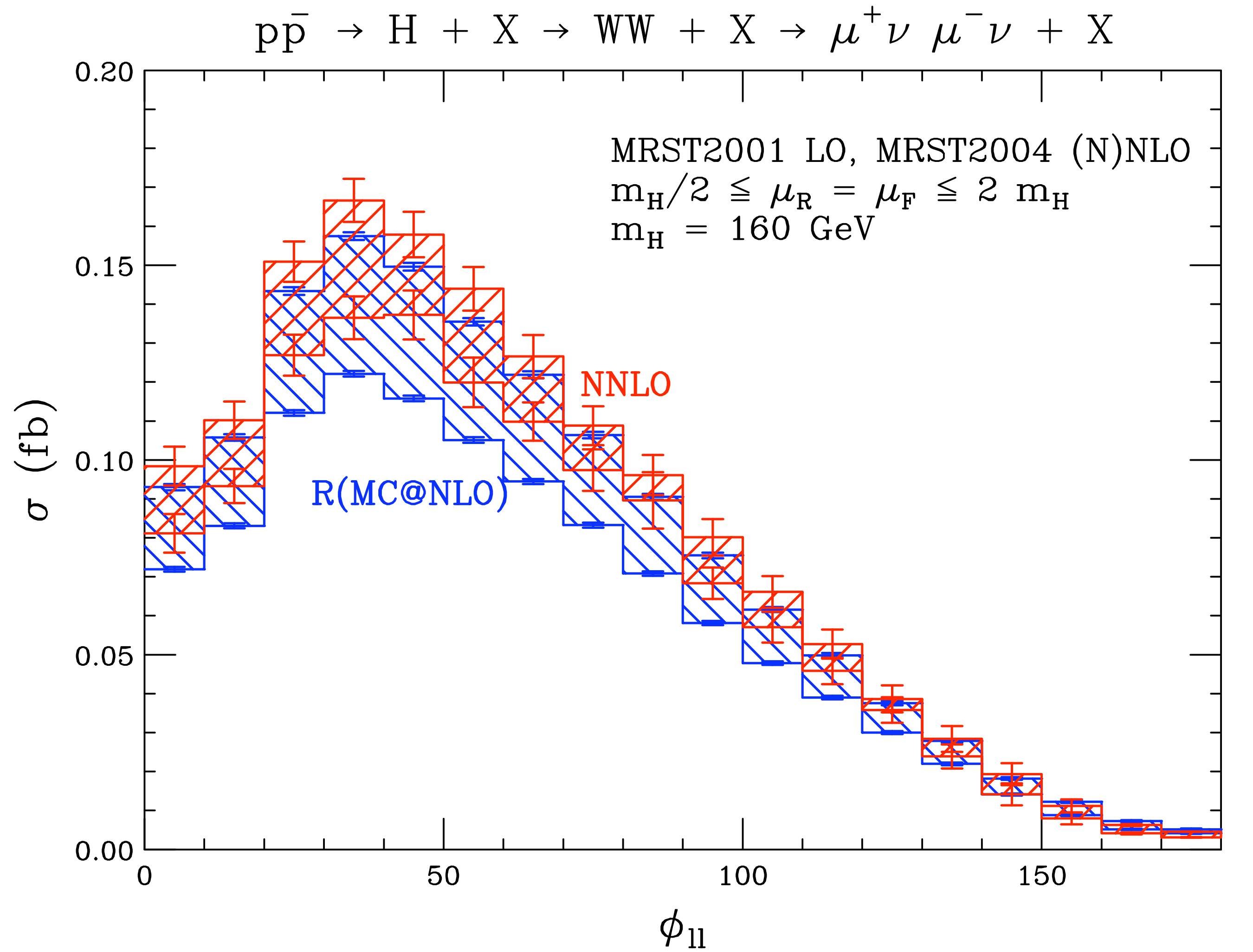

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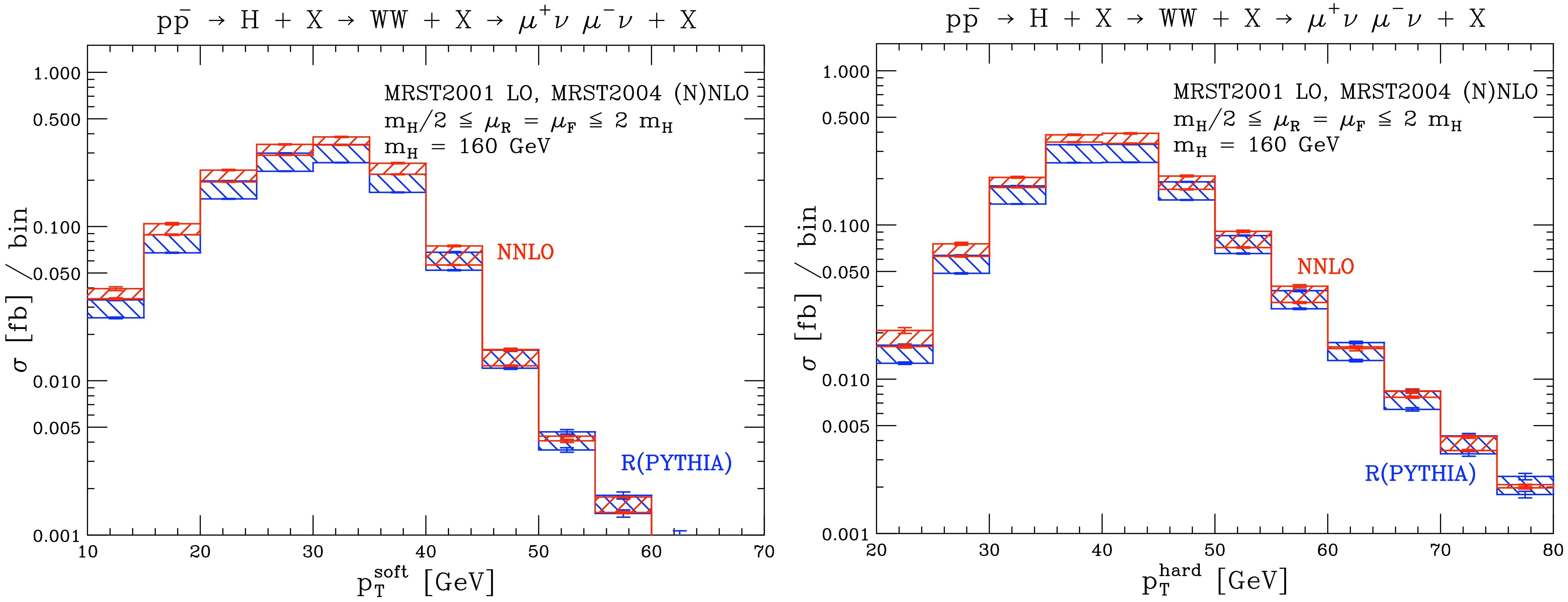

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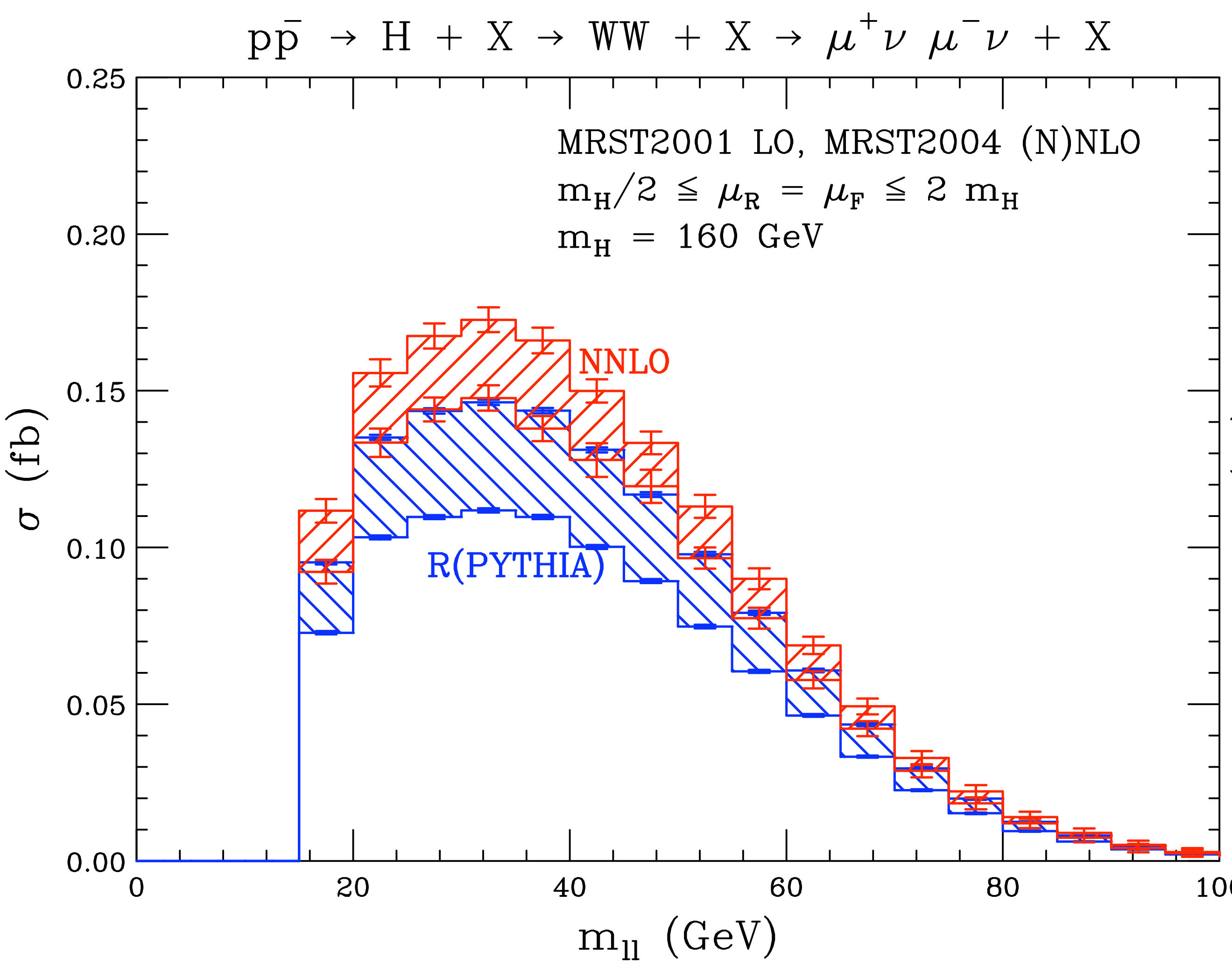
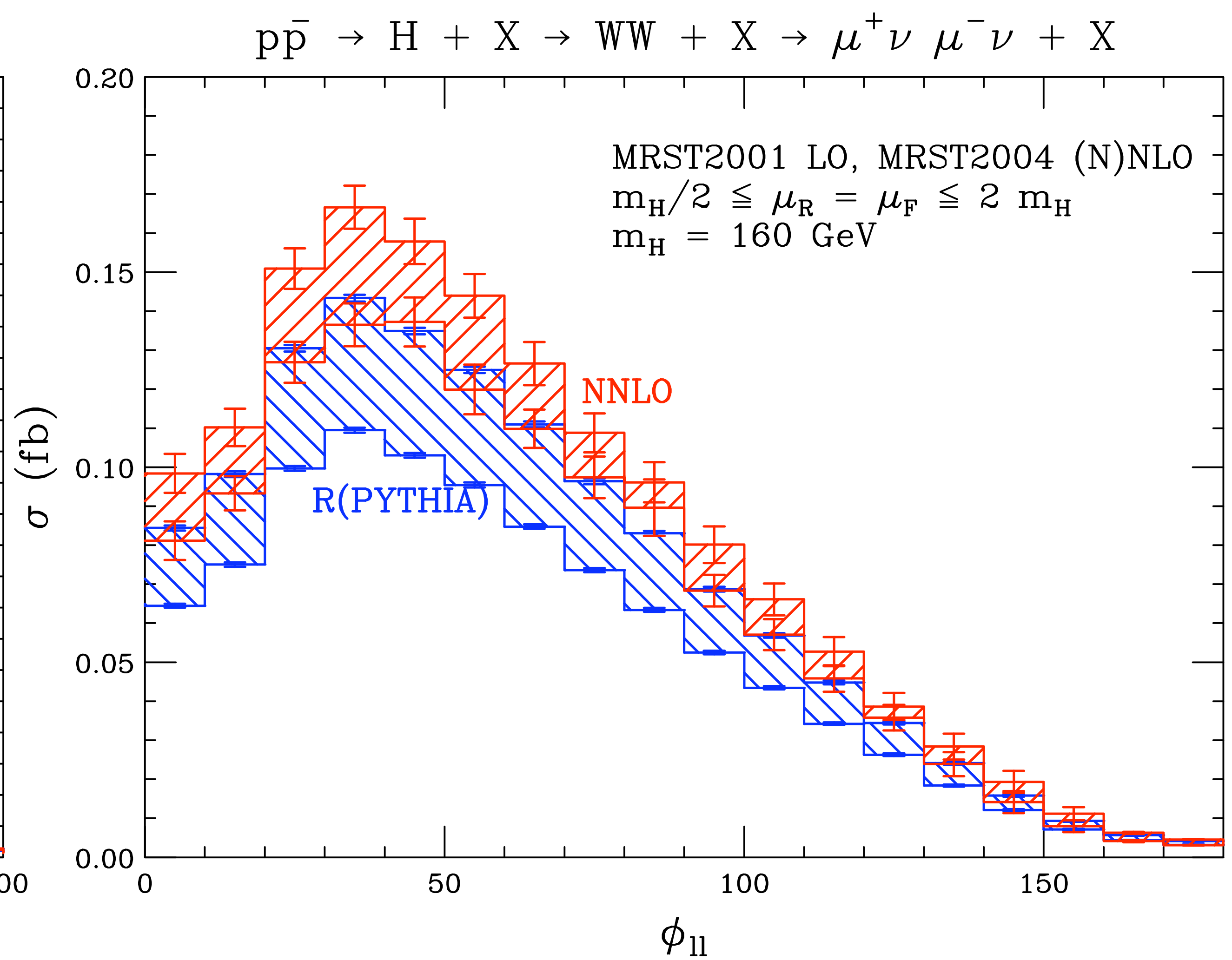




MC results are rescaled so as to match the inclusive NNLO cross section

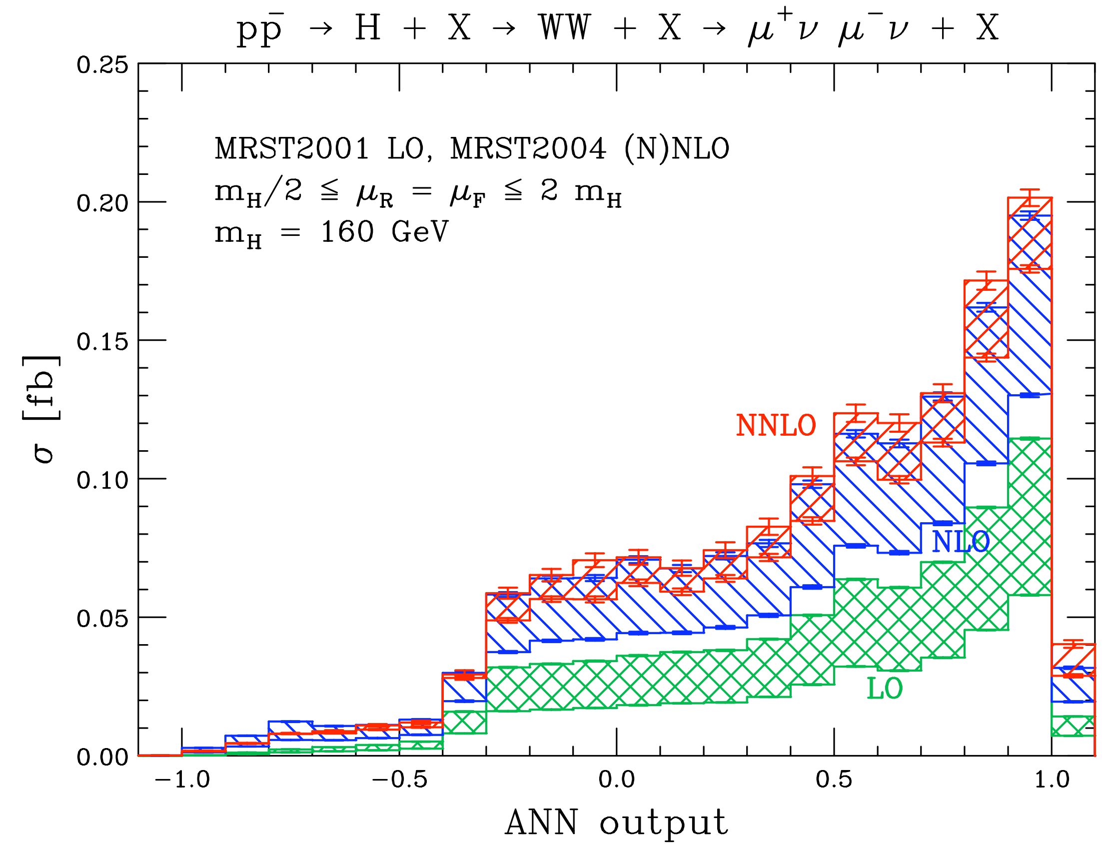
Is there a way to quantify the agreement ?

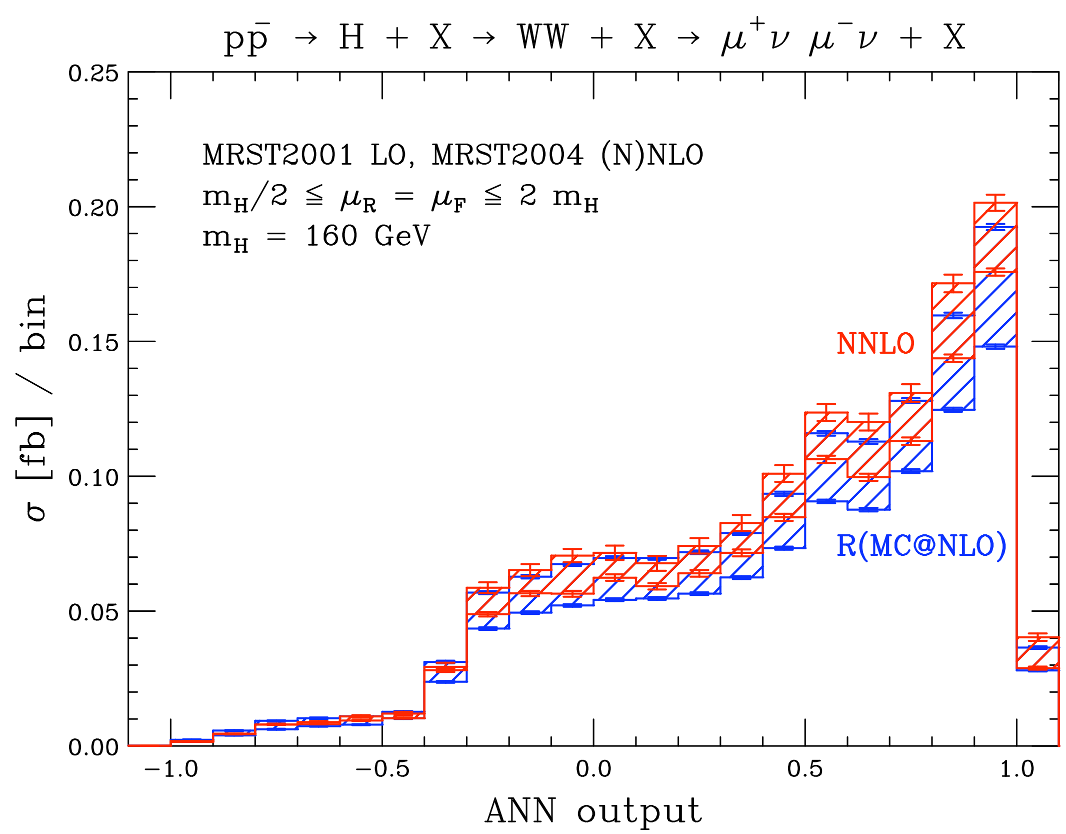
Neural Network

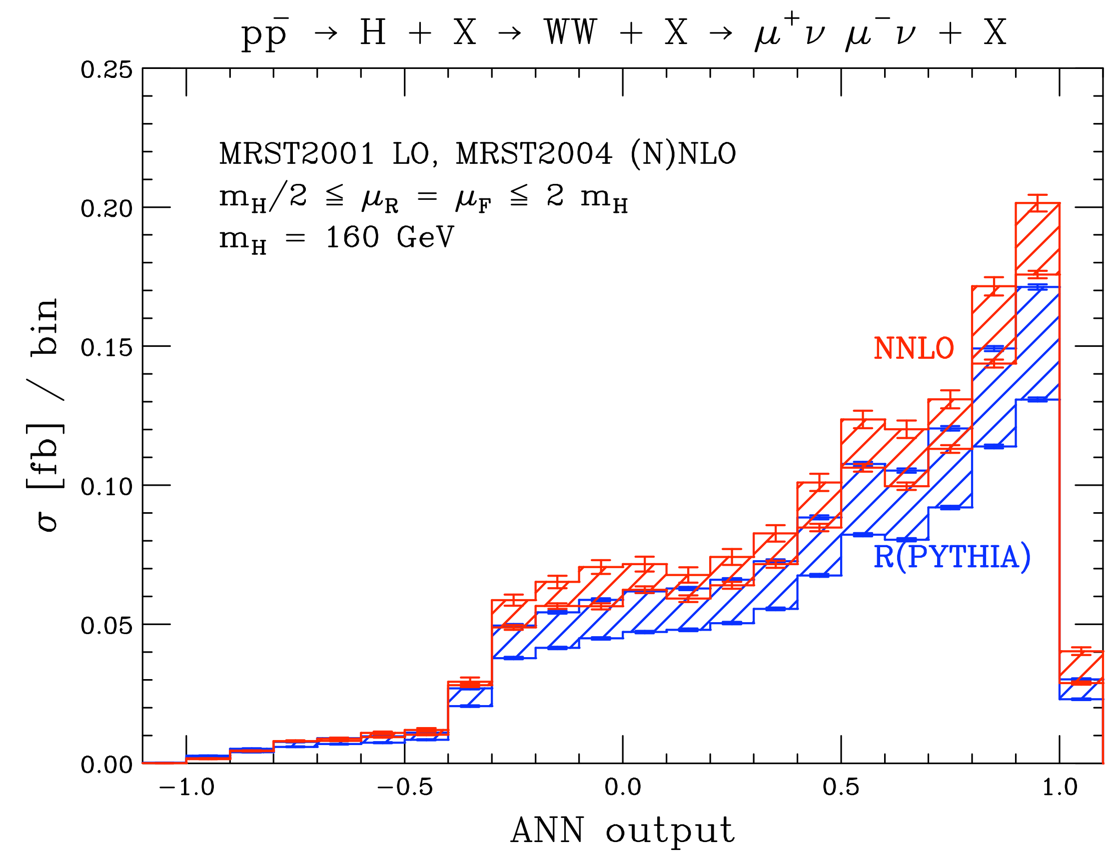
To check it we train a Neural Network

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

- After 35 years of SM the Higgs boson has not been found yet
- LEP has put a lower limit on the mass of the SM Higgs boson at at $m_H \geq 114.4$ GeV at 95% CL
- The Tevatron is now sensitive to SM Higgs masses around $m_H \approx 160\text{-}170$ GeV
- A great effort has been devoted in recent years to improve theoretical predictions for the various production cross sections and also for the corresponding backgrounds
- This knowledge will be essential to improve search strategies, to fully exploit the various channels in the delicate low mass region and to measure the Higgs couplings

Summary

- For gluon fusion: new results for total cross sections available through online calculators
- NNLO calculation implemented at the fully exclusive level: HNNLO is parton level 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 but 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

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

- **Large-m_{top} approximation:**
  recent studies show that it works to better than 0.5 % for $m_H \leq 300$ GeV

  R.Harlander, K.Ozeren (2009)
  M.Steinhauser et al. (2009)

  → important confirmation of the accuracy of this approximation

- **Scale uncertainty:** ranges from 7 to 10 %

- **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

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

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........)

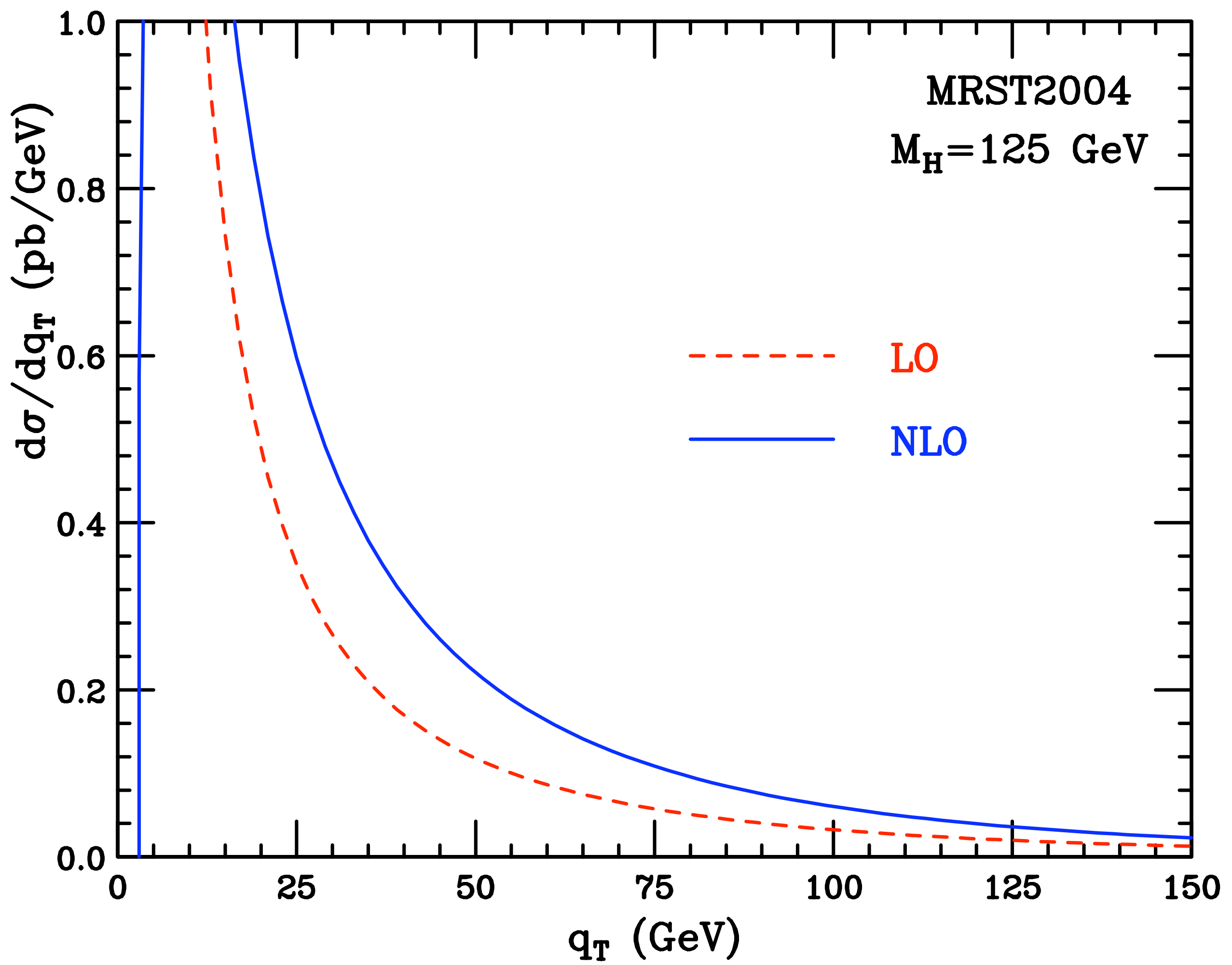
BOTTOM LINE:

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)

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



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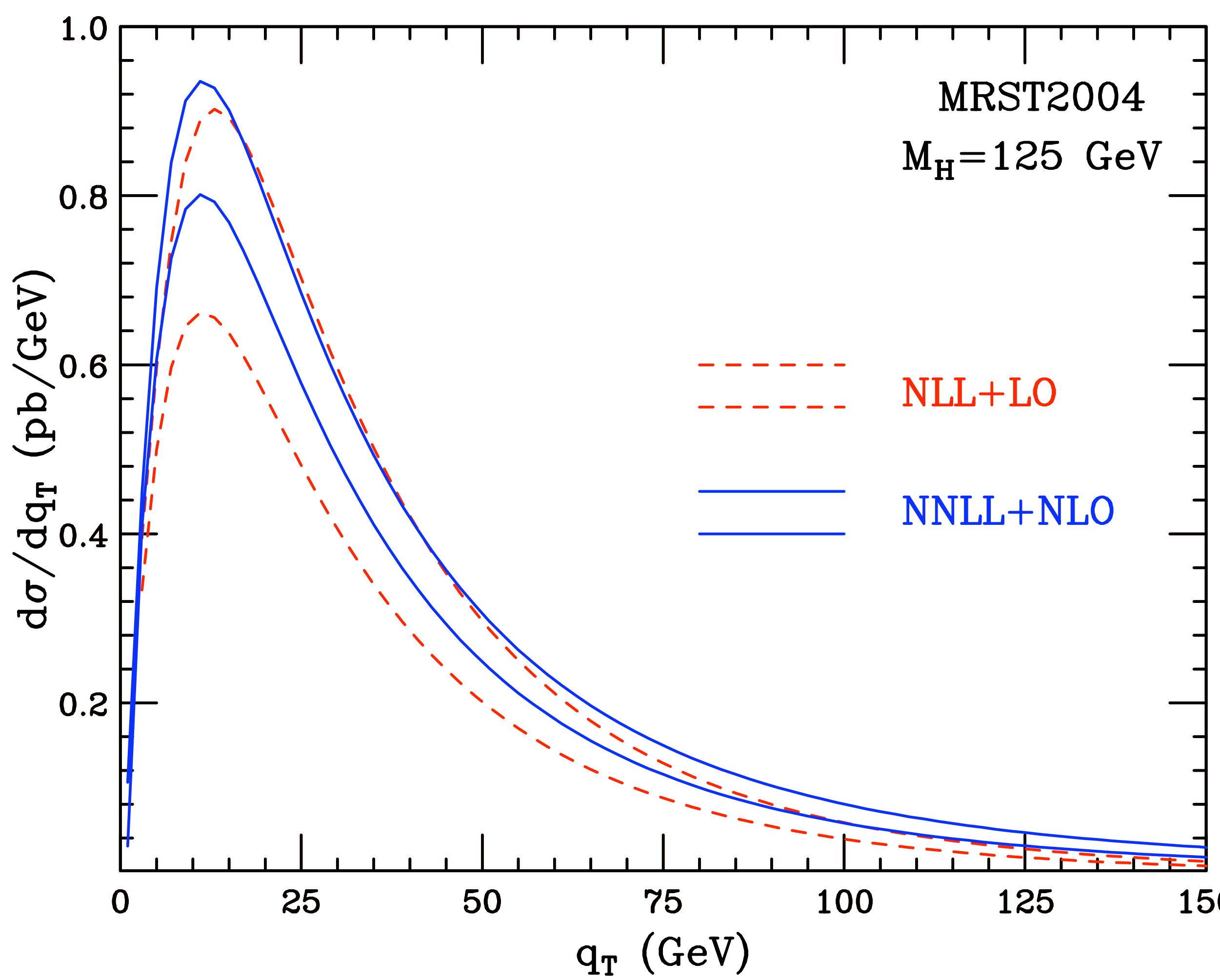
G. Bozzi, S. Catani, D. de Florian, MG (2003, 2005)

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



Highly stable results → HqT

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

Recently extended to include rapidity dependence

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Highly stable results → HqT

The resummation is effectively performed through standard MC event generators.....

PYTHIA PEAK STILL SOFTER !