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

Massimiliano Grazzini (INFN, Sezione di Firenze)

QCD@Work, Martina Franca, june 20 2010

Outline

- Introduction
- Higgs production through gluon-gluon fusion
  - Theoretical predictions
  - Tevatron results: the importance of radiative corrections
  - Fully exclusive computations
- Summary

The heritage

Standard Electroweak theory based on $SU(2)_L \otimes U(1)_Y$ gauge theory

A. Salam

S. Weinberg

S. Glashow

Quantum Chromo Dynamics (QCD): $SU(3)_c$ gauge theory

D. Gross

F. Wilczek

D. Politzer

→ Altogether a beautiful theory describing high-energy phenomena at a surprizing level of accuracy

But how do elementary particles acquire their mass ?

The “last” mistery

- The standard solution: masses are generated by the Higgs boson (scalar particle) through Spontaneous Symmetry Breaking

- The mass of the Higgs boson is not predicted by the theory

- Theoretical arguments (or prejudices) suggest $50\,\mathrm{GeV} \lesssim m_H \lesssim 800\,\mathrm{GeV}$ (with new physics at the TeV scale)

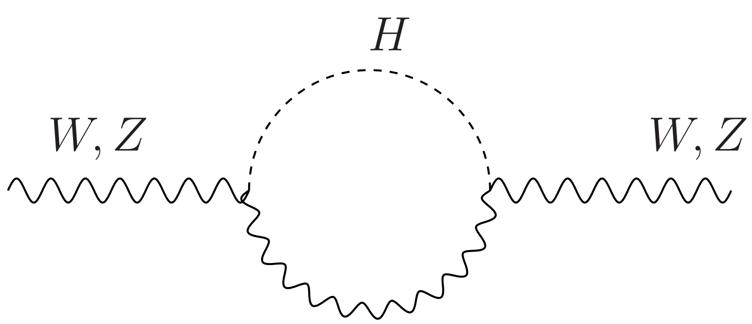
- LEP has put a lower limit on the mass of the SM Higgs boson at $m_H \geq 114.4$ GeV at 95% CL

- The most sought particle in history (LEP, Tevatron, LHC) !

Other constraints come from:

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

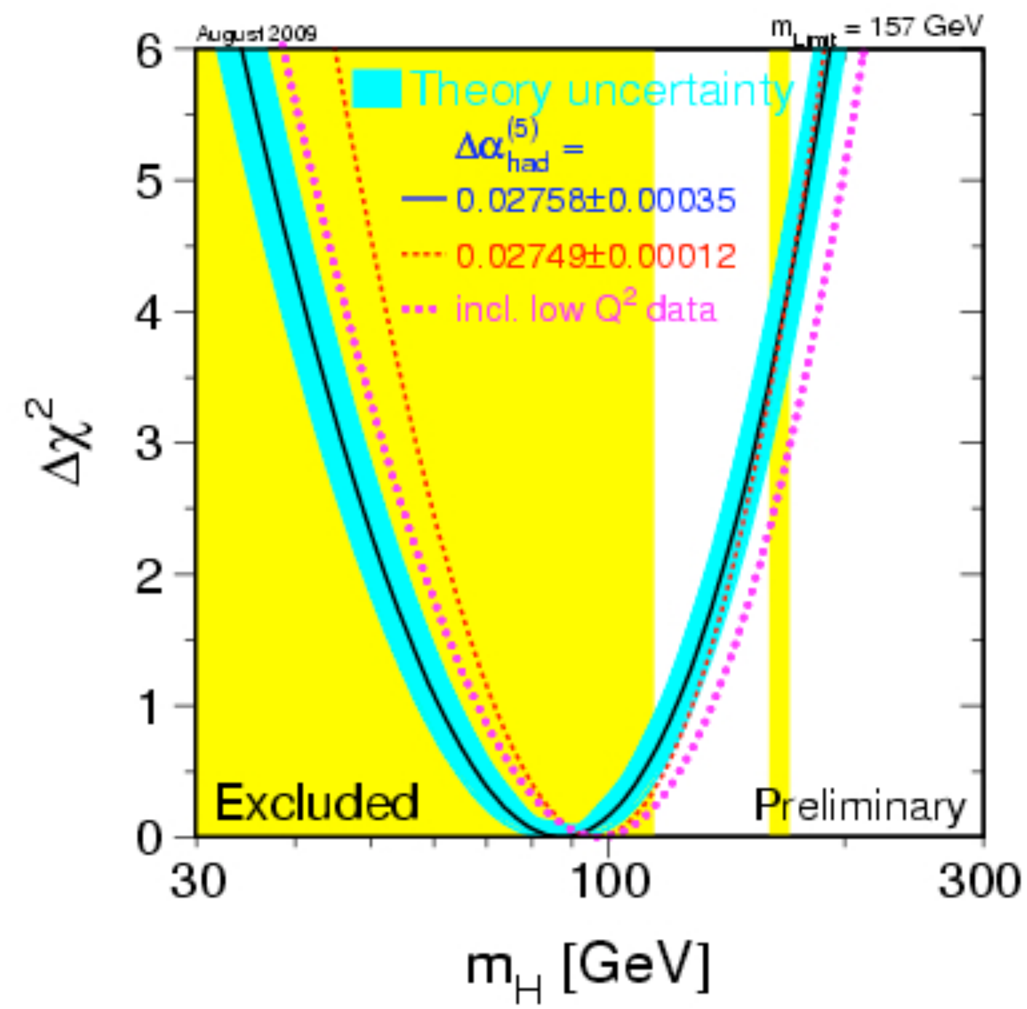
.... but screening effect: the dependence is only logarithmic at one loop (for top quark the dependence is quadratic → m_{top} predicted before discovery !)



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

$m_H < 157$ GeV at 95 % CL

LEP EWWG, summer 2009

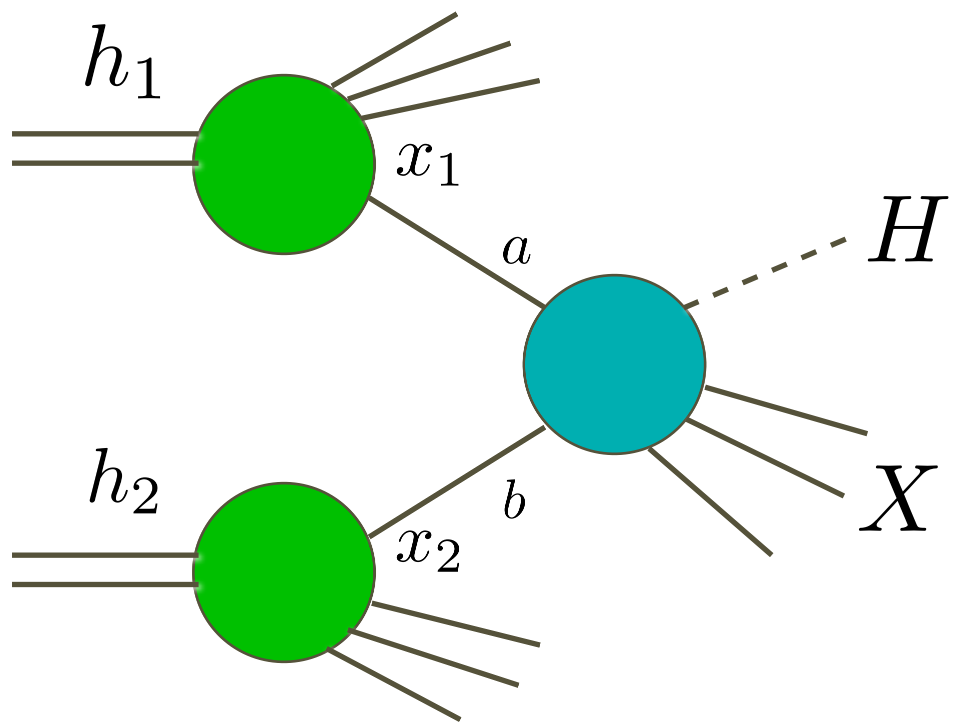


Taking into account LEP limit:

$m_H < 186$ GeV at 95 % CL

Theoretical predictions at hadron colliders

The framework: QCD factorization theorem



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

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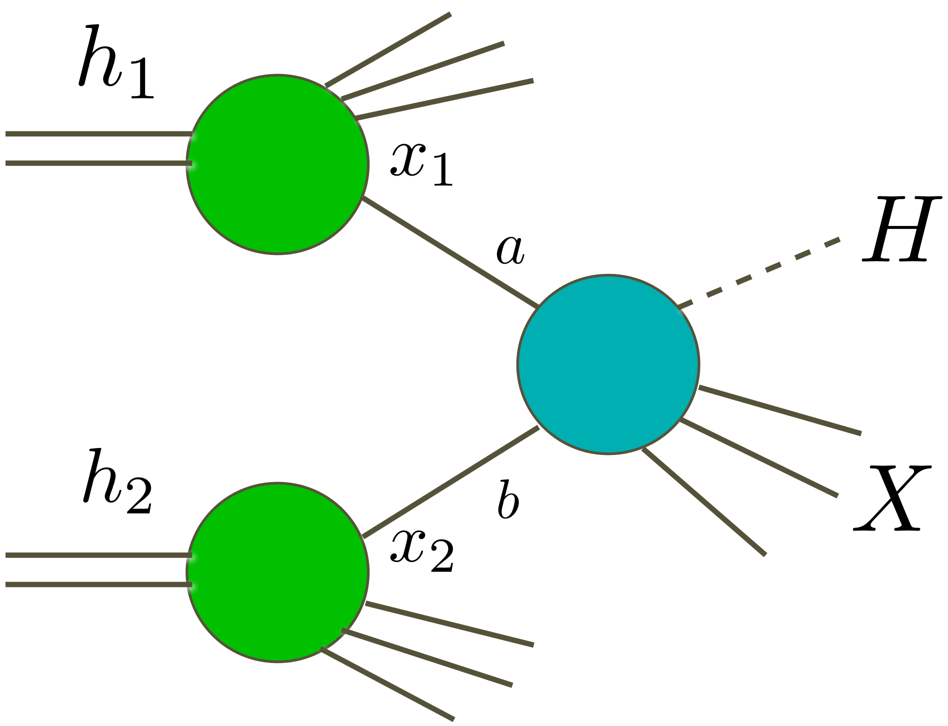

Parton distributions

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

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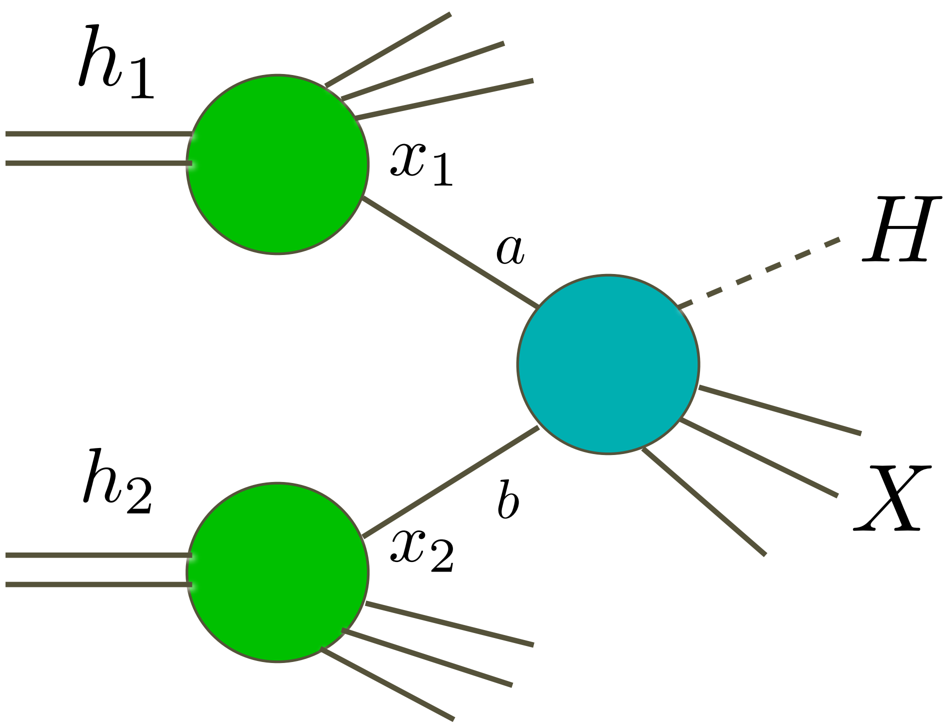

Parton distributions

Partonic cross section

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

Theoretical predictions at hadron colliders

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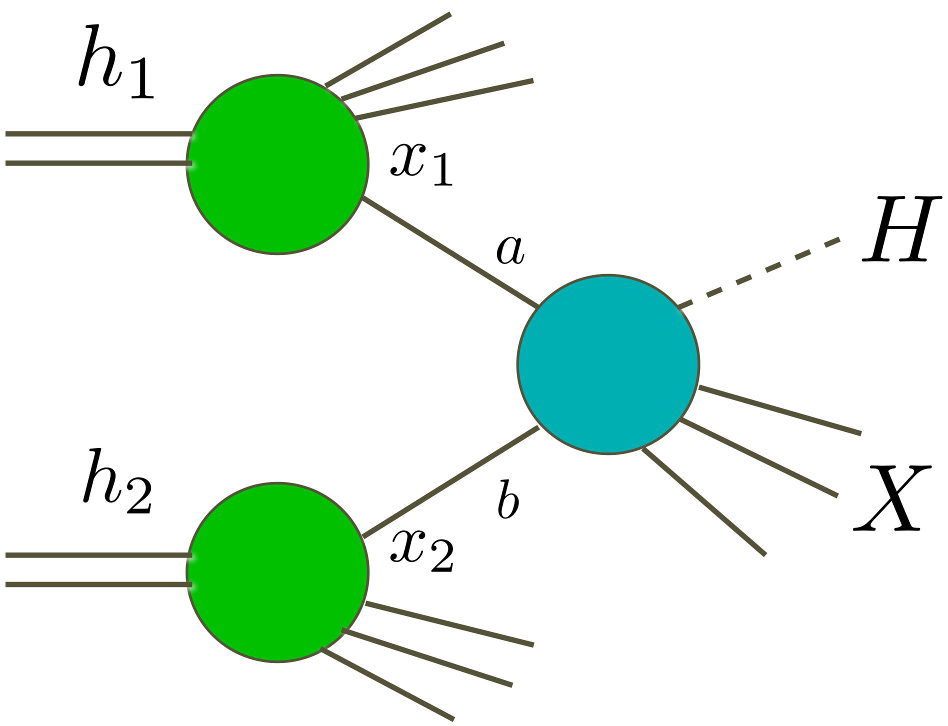


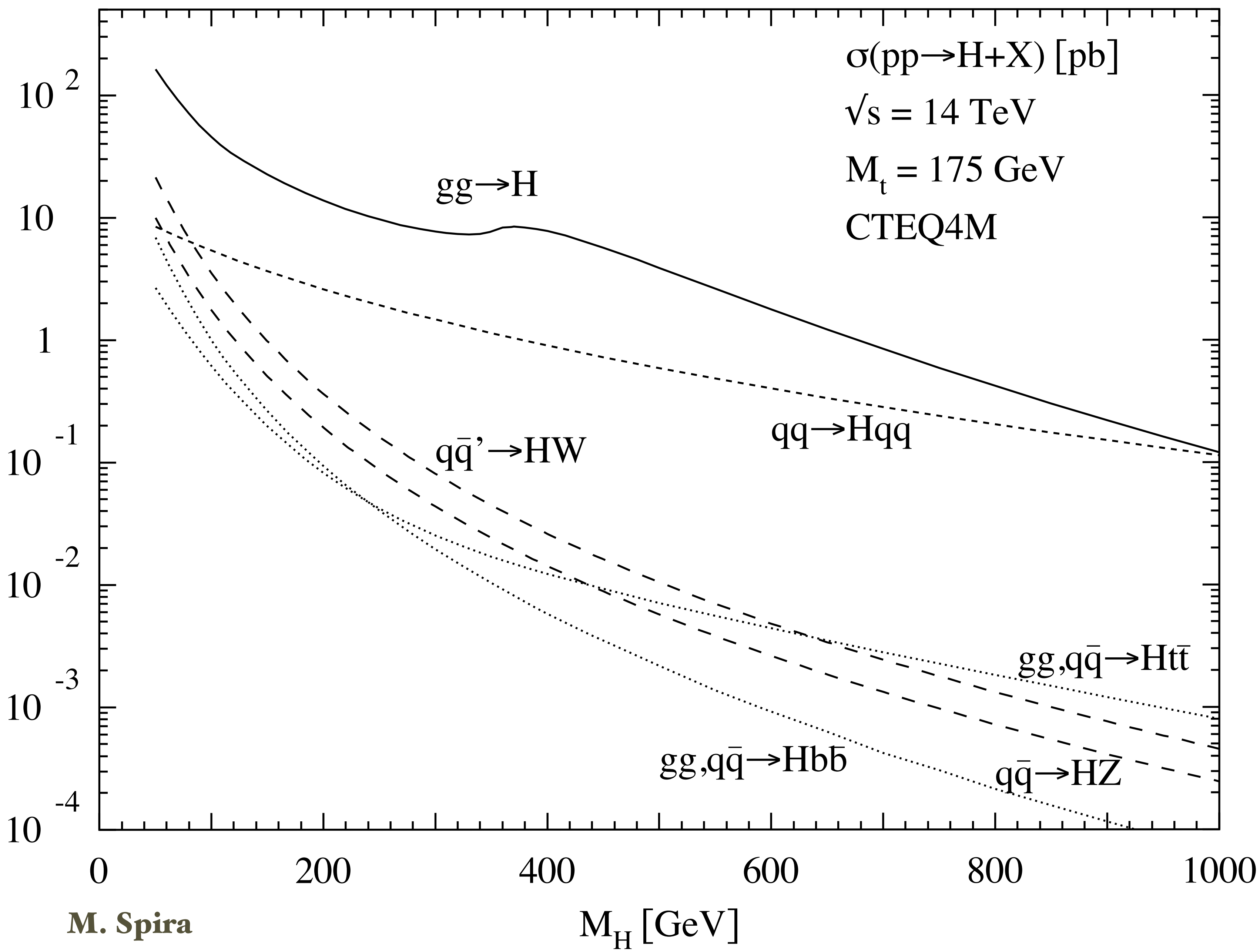
Parton distributions

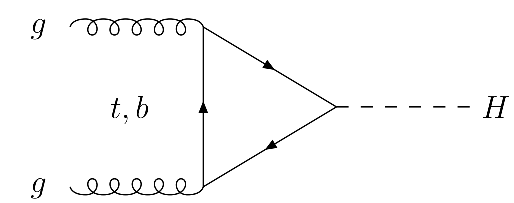
Partonic cross section

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

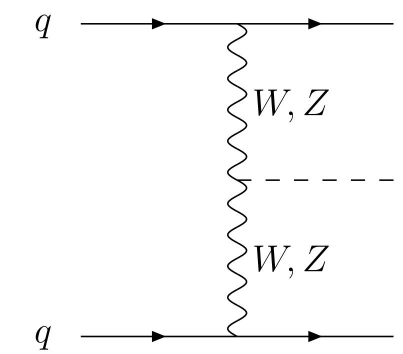
Precise predictions for σ depend on good knowledge of BOTH $\hat{\sigma}_{ab}$ and $f_{h,a}(x, \mu_F^2)$

Higgs production at hadron colliders

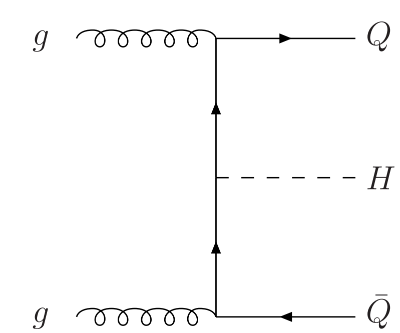




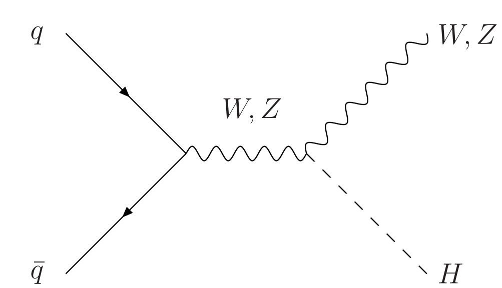
gg fusion



vector boson fusion



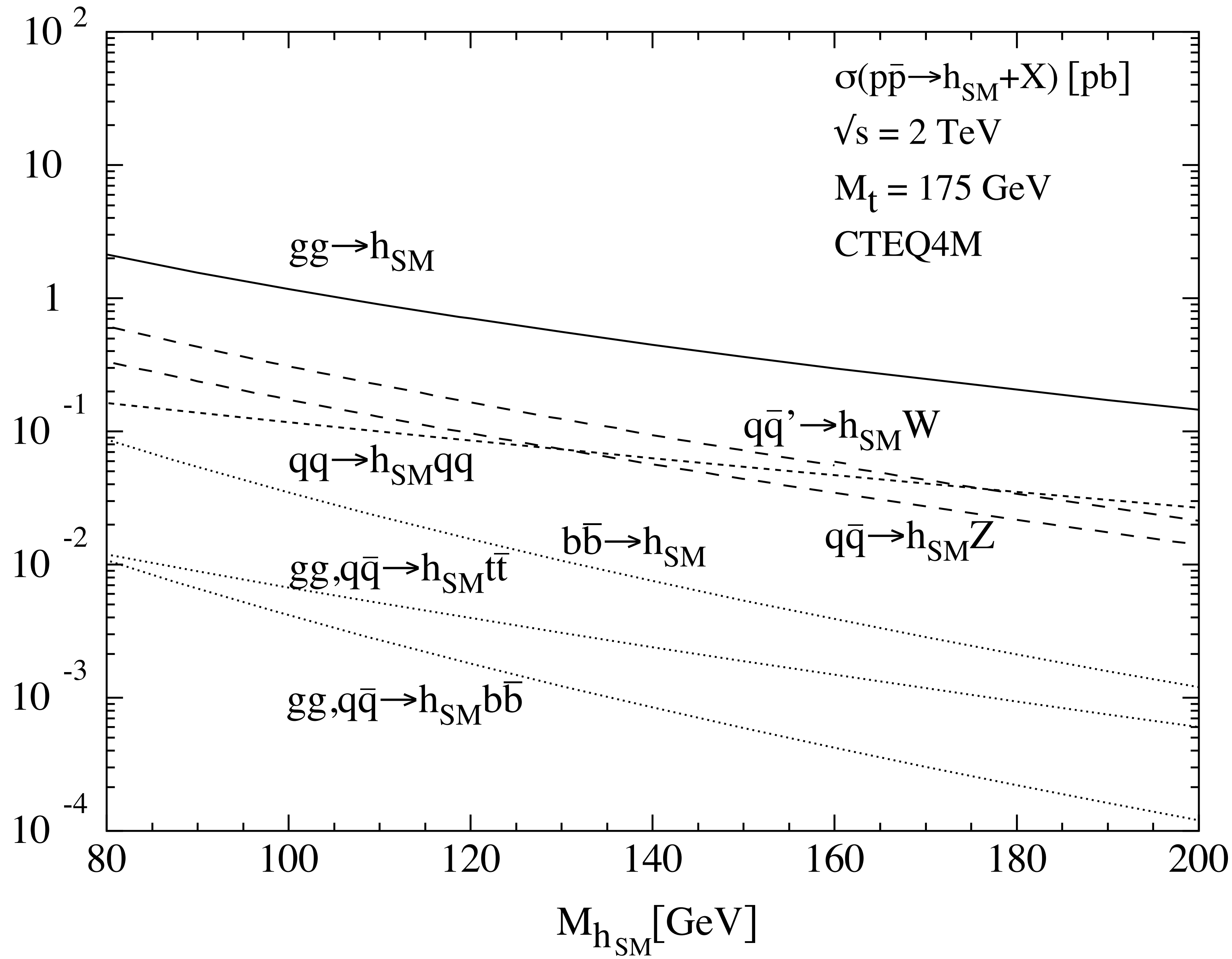
associated production with $Q\bar{Q}$



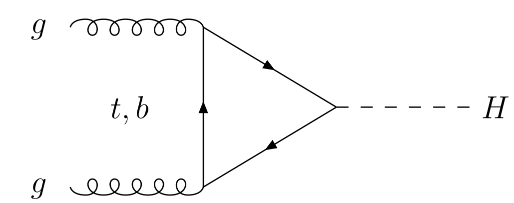
associated production with W, Z

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

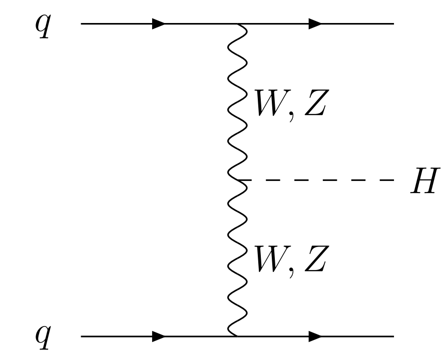
Higgs production at hadron colliders



M. Spira



gg fusion



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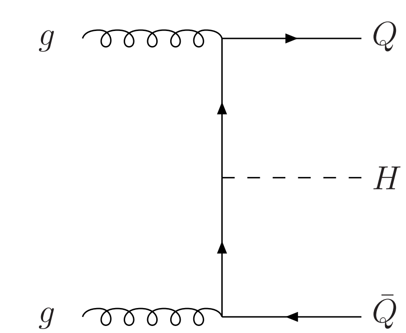

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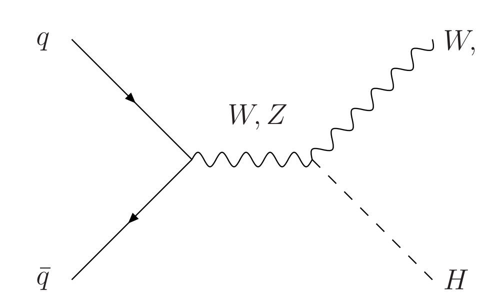
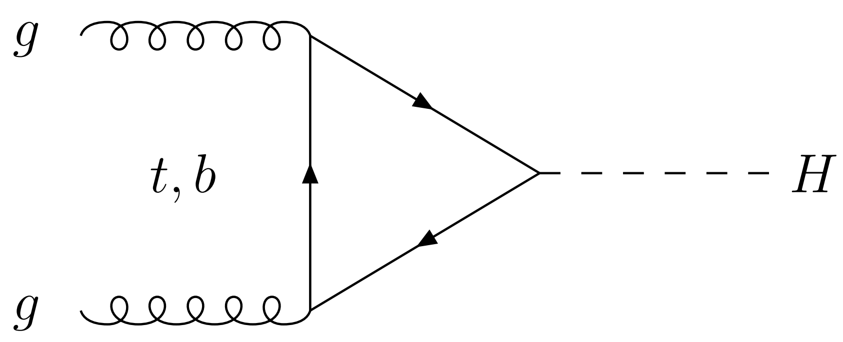


associated production with W, Z

Similar situation at the Tevatron
(although gg dominance less pronounced)

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 already 20 years ago and found to be large

They increase the LO result by about 80-100 % !

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)

$gg \to H$ 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

The large-m_{top} approximation

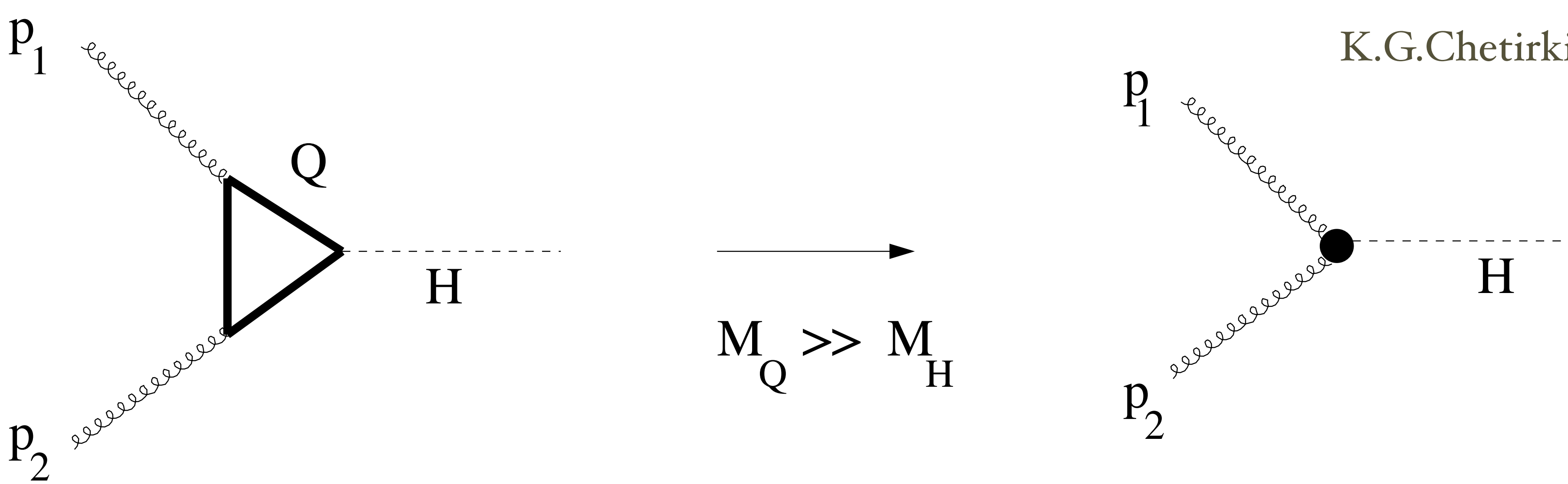
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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

Soft-gluon resummation

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

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 $z = m_H^2/\hat{s} \to 1$

Partonic CM energy

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

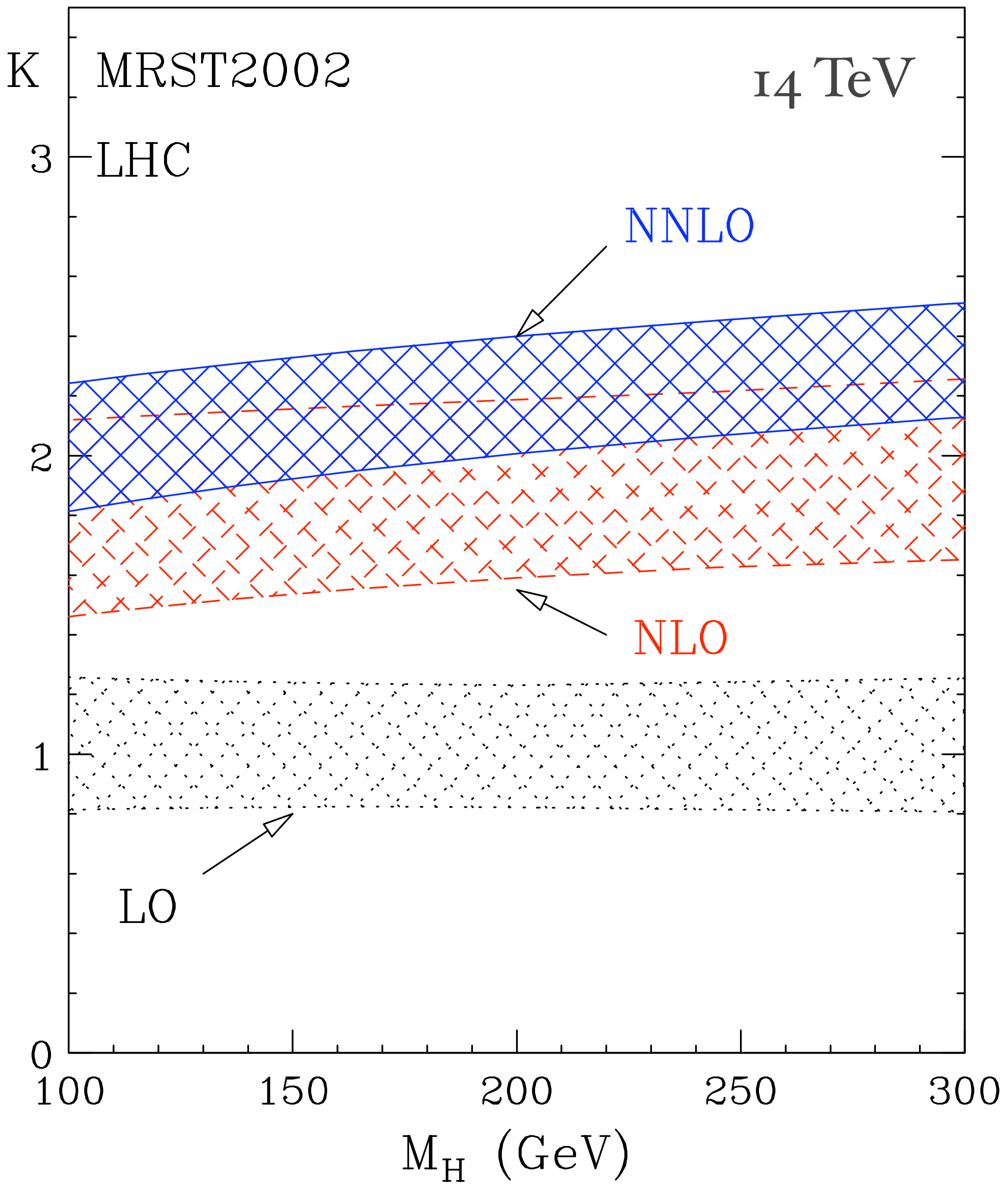
Resummation works in Mellin space L=ln N

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

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

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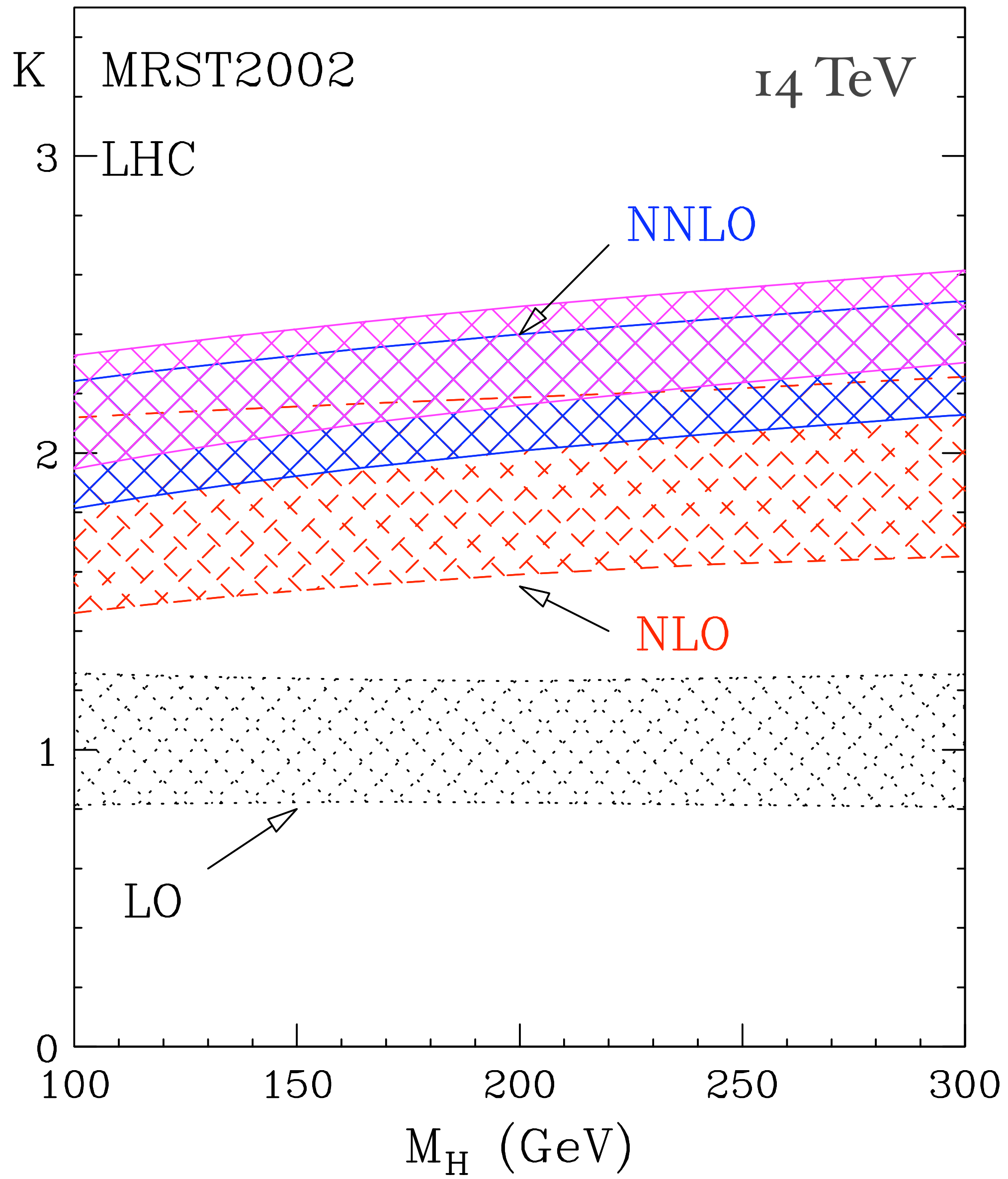


Inclusion of soft-gluon effects at all orders

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

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

NNLL effect $+6\%$

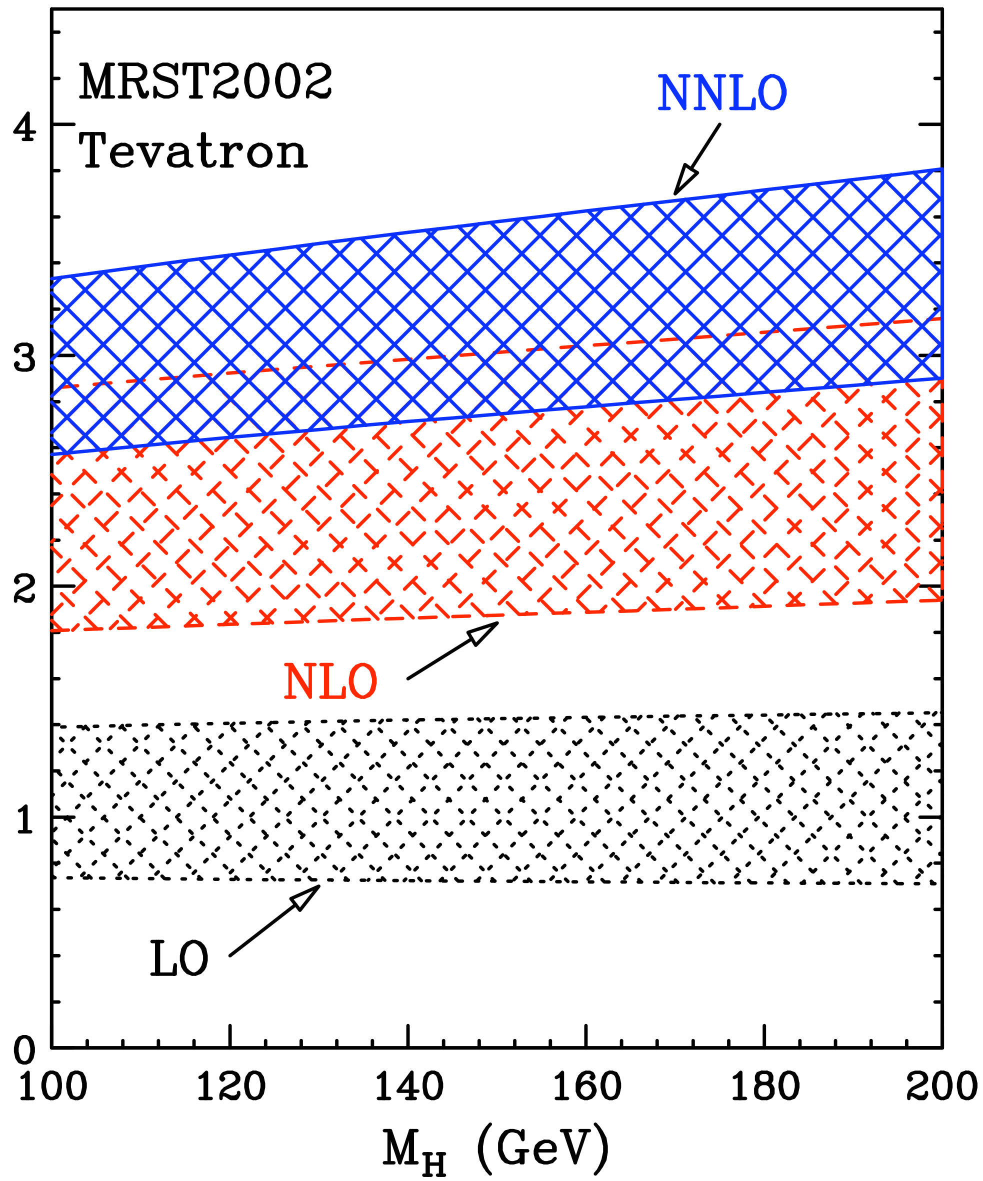
Good stability of perturbative result

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

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

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

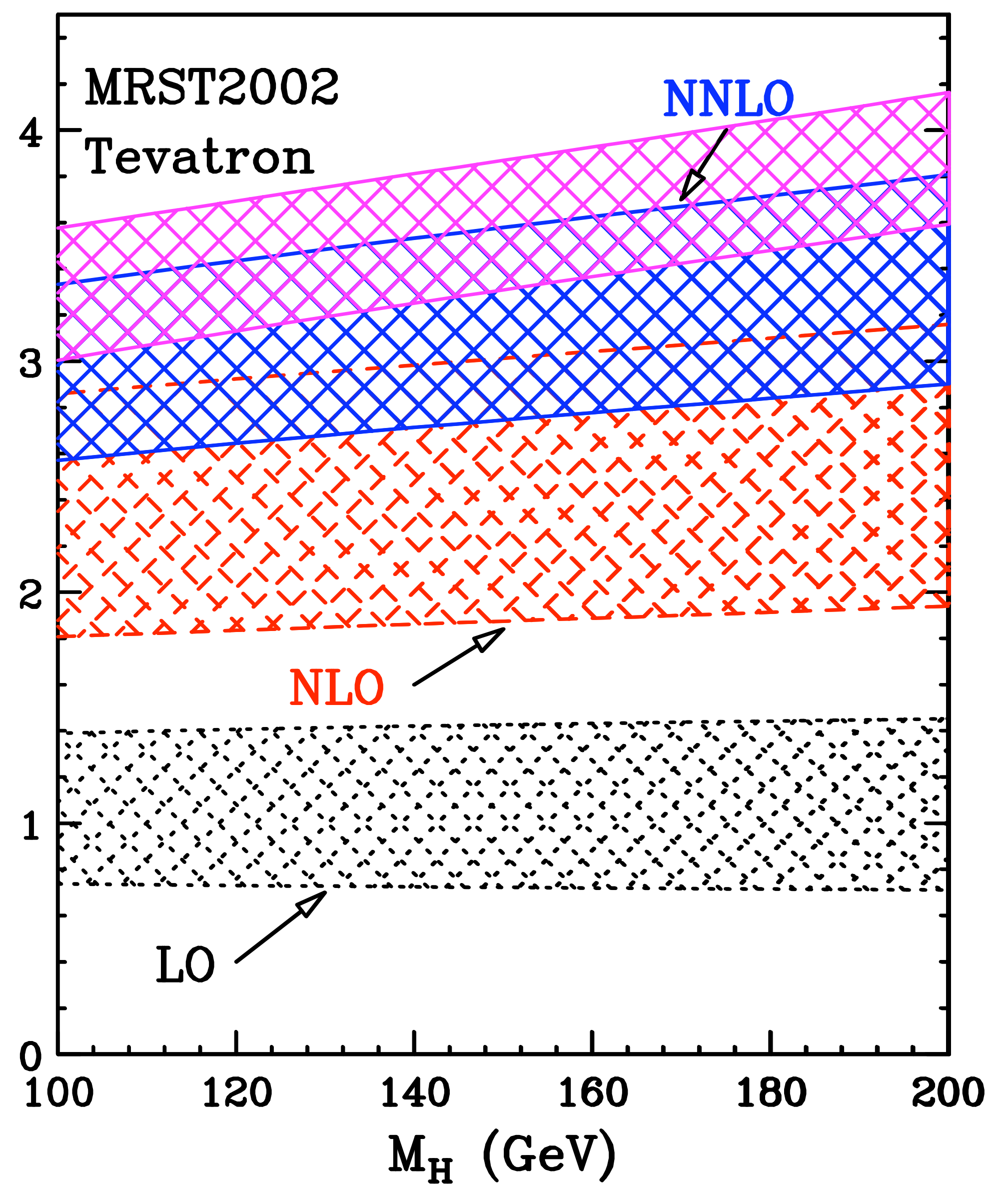
Inclusive results at the Tevatron



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

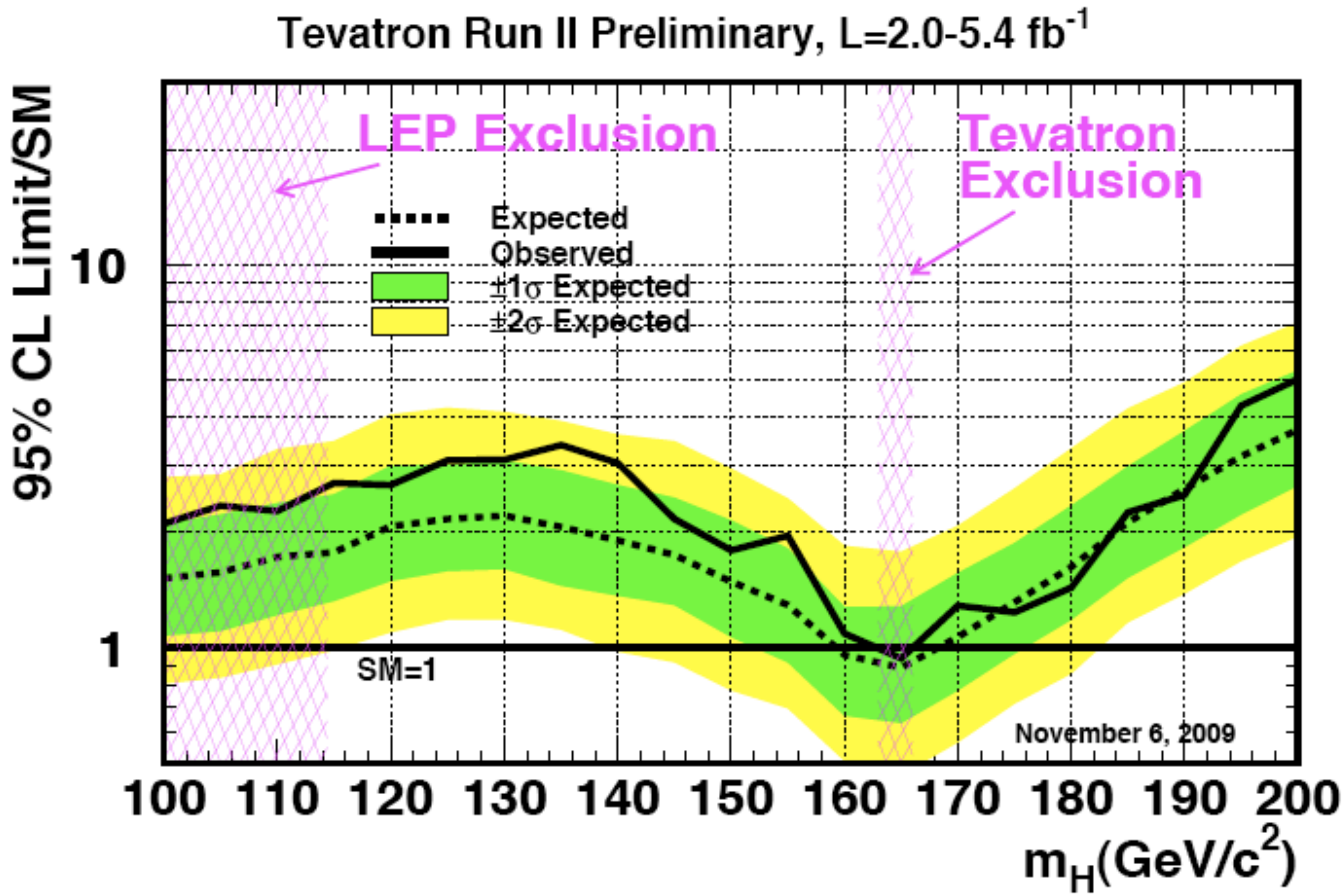
- K-factors defined with respect $\sigma_{LO}(\mu_F=\mu_R=M_H)$
- With $\mu_{F(R)}=\chi_{L(R)}M_H$ and $0.5\leq\chi_{L(R)}\leq 2$ but $0.5\leq\chi_F/\chi_R\leq 2$

Tevatron Higgs search

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

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

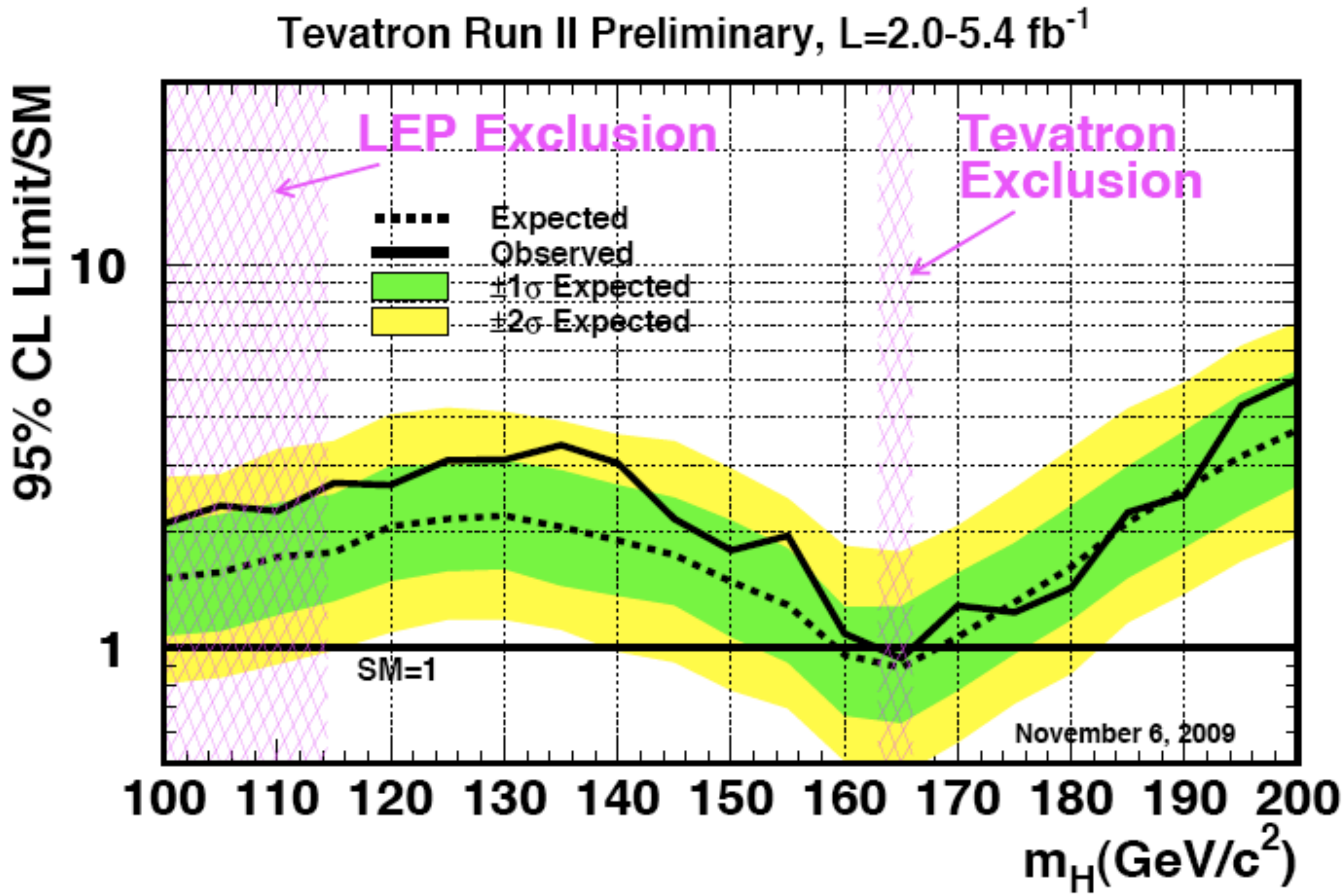
→ Now sensitive to the region m_H≈160-170 GeV



The relevance of higher orders

The recent Tevatron exclusion is based on our recent (updated) result

D. De Florian, MG (2009)



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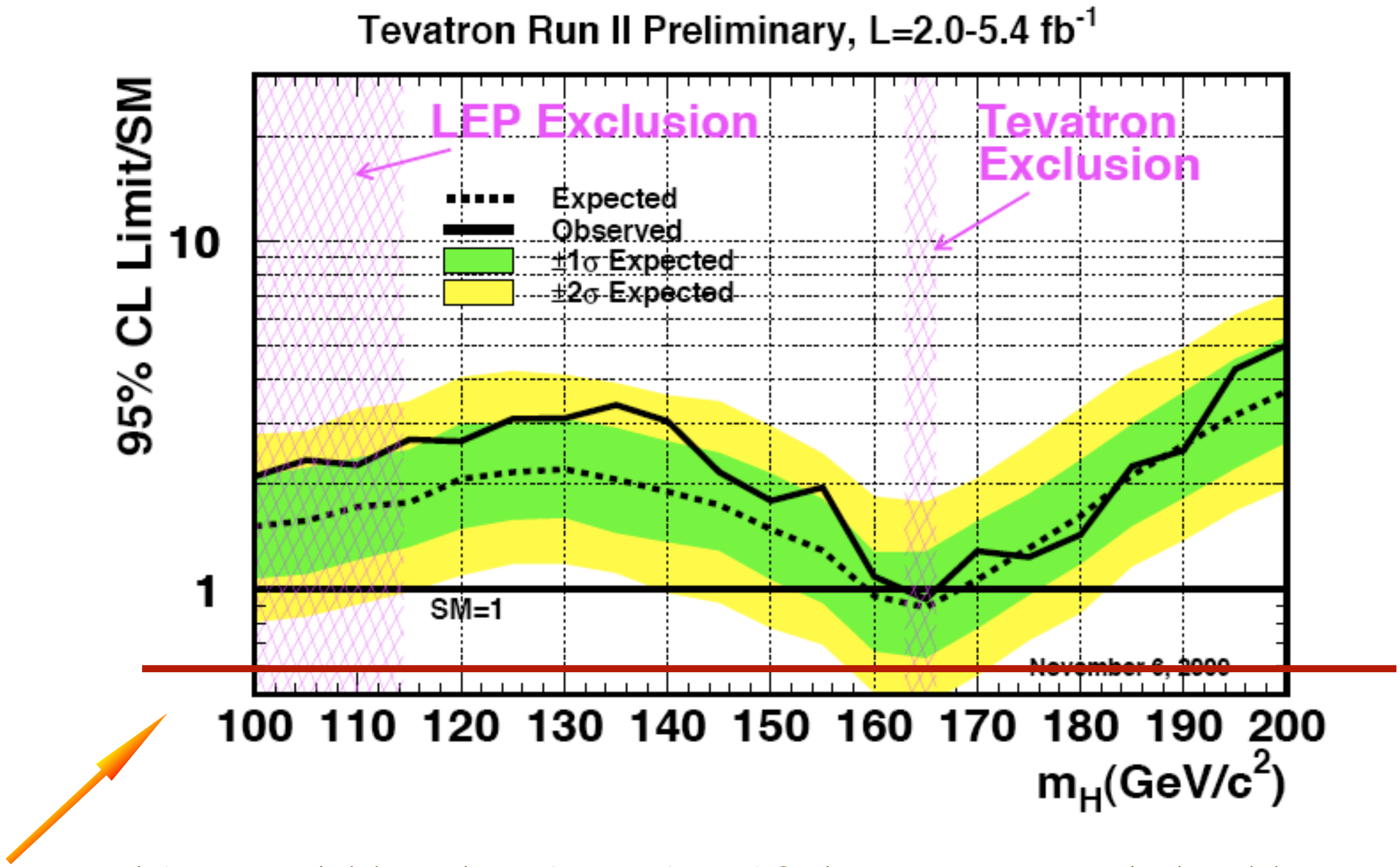
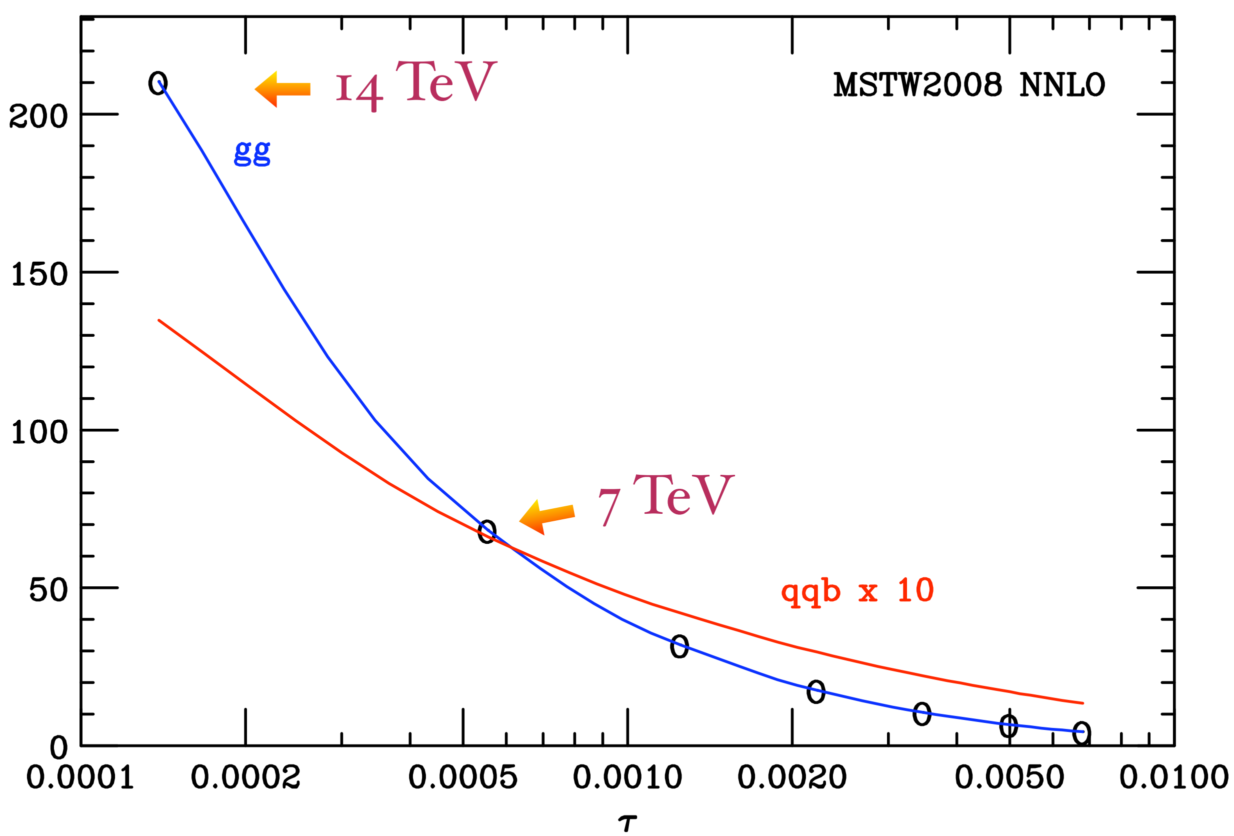


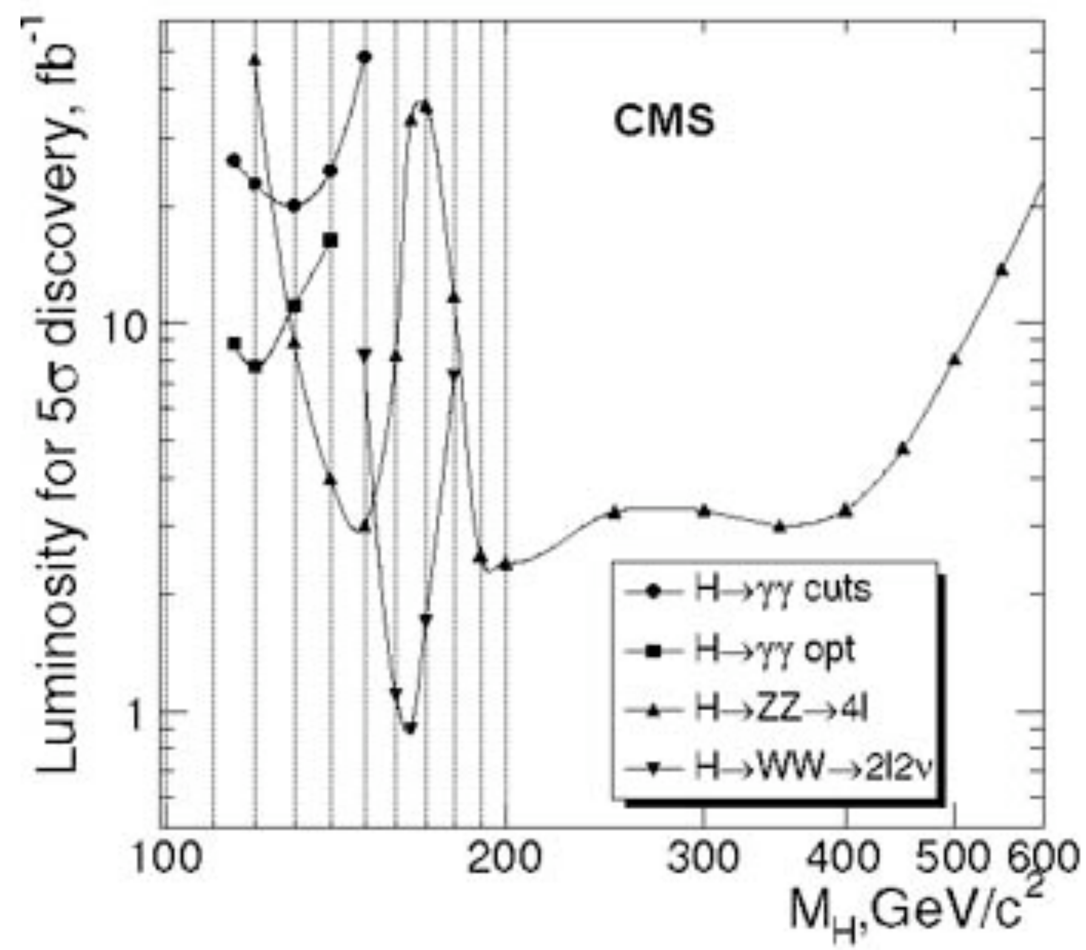
This would be the situation if the NLO result had been used !

LHC @ 7 TeV

At 14 TeV a SM Higgs boson with m_H ~ 160 GeV can be discovered with about 1 fb^{-1}

From 14 to 7 TeV both signal and background cross sections decrease





But gg parton luminosity drops faster

$$\mathcal{L}_{c\bar{c}}(\tau,\mu_F^2) = \int_\tau^1 \frac{dx}{x} f_c(x,\mu_F^2) f_{\bar{c}}(\tau/x,\mu_F^2)$$

Recent NLO study shows that luminosity needed for discovery may be a factor 6-7 larger

E.Berger et al. (2010)

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

At NLO the problem is solved: general methods exist that allow to handle and cancel infrared singularities

W.Giele, N.Glover (1992)
W.Giele, N.Glover, D.Kosower (1993)
S. Frixione. Z.Kunszt, A.Signer (1996)
S.Catani, M.Seymour (1997)

At NNLO, only few fully exclusive computations exist, due to their substantial technical complications

C.Anastasiou et al. (2004,2005)
K.Melnikov, F.Petriello (2006)
S.Catani, MG (2007)
L.Cieri et al . (2009)

Fortunately the NNLO computation 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

Important to assess theoretical uncertainties in the experimental search

The program: HNNLO implements three decay channels

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

→ includes appropriate interference contribution

The user can choose the cuts and plot the required distributions by modifying the appropriate user subroutines

Now being used by Tevatron and LHC collaborations

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 $m_{ll} < 35$ GeV $\Delta\phi < 45^o$

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

cuts as in Davatz et al. (2003)

Results for $p_T^{\text{veto}} = 30$ 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

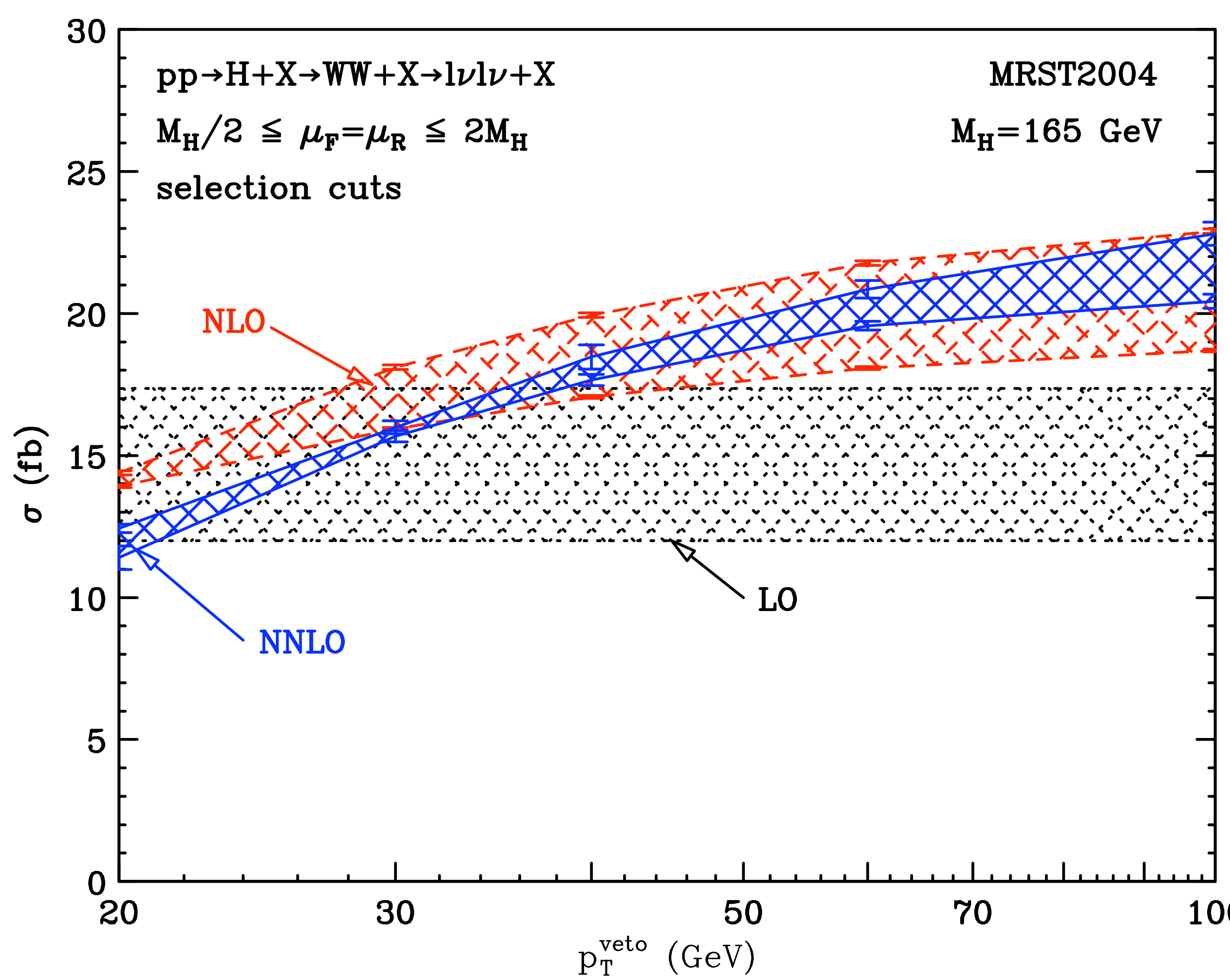
➡ **Impact of higher order corrections strongly reduced by selection cuts**

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

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

NNLO efficiencies found in good agreement with MC@NLO

Anastasiou et al. (2008)



Summary

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

- It is probably also the channel that provides the only possibility to observe or exclude the Higgs in the near future

- A great work has been done to improve the accuracy of the theoretical prediction that is now known at NNLO with all-order resummation of soft-gluon contributions (plus EW corrections)

  → crucial effect on overall normalization

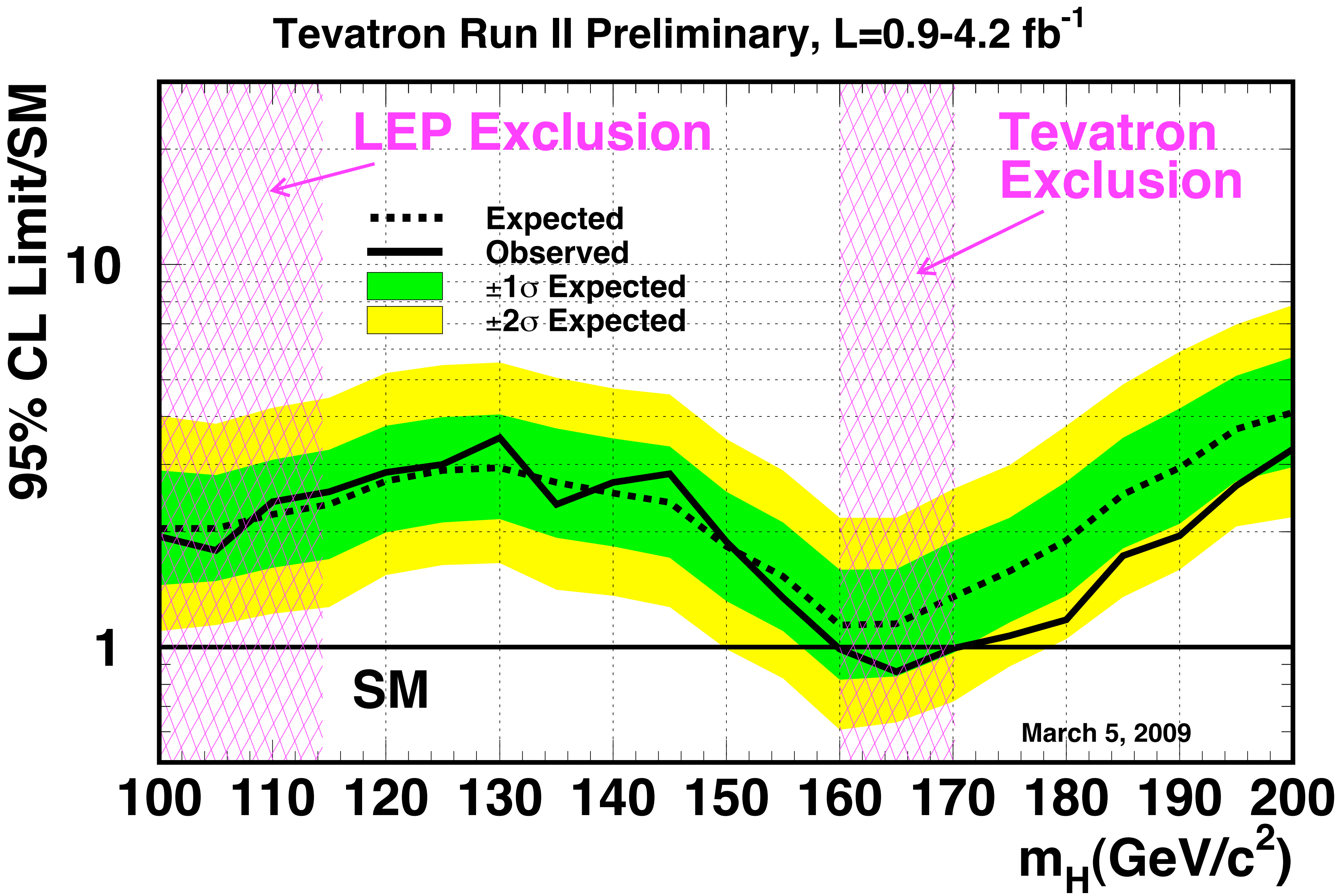
- NNLO computation now implemented at fully exclusive level

  → important to assess theoretical uncertainties in the experimental search

BACKUP SLIDES

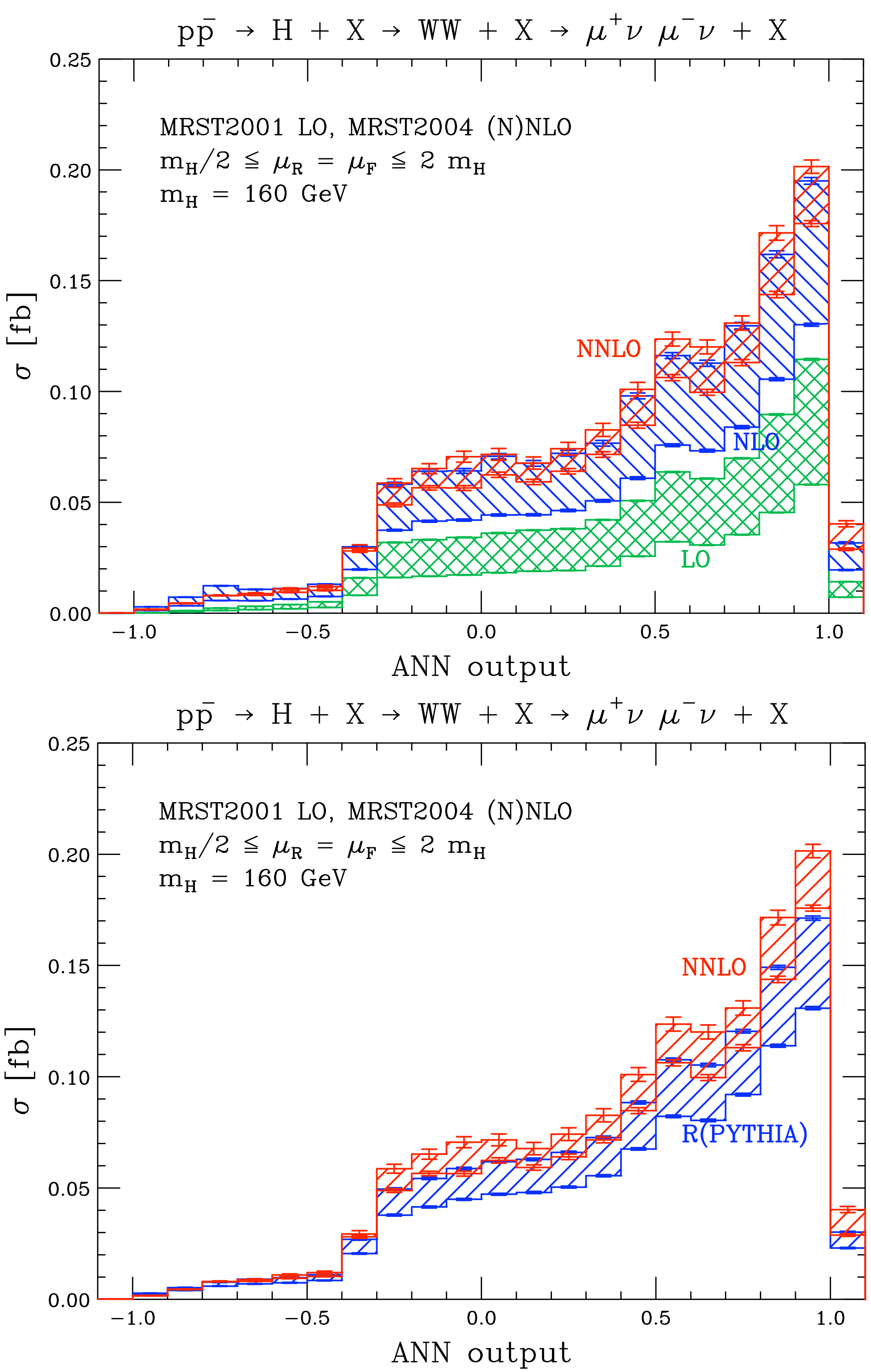
Tevatron results

Results with up to L=4.2 fb^{-1}



Deficit of events at m_H ~ 160-170 GeV gave wider excluded region

When theorists play.....



C.Anastasiou,
G.Dissertori,F.Stoeckli,B.Webber, MG

Train a Neural Network with samples for Higgs, WW and ttbar processes generated with PYTHIA 8

Study the NN output up to NNLO is as simple as any other kinematical distribution !

All the predictions are peaked at ANN~1

A way out: HNNLO

S. Catani, MG (2007)

We propose a new version of the subtraction method to compute higher order QCD corrections to a specific class of processes in hadron collisions (vector boson, Higgs boson production, vector boson pairs......)

We compute the NNLO corrections to $gg \to H$ implementing them in a fully exclusive parton level generator including all the relevant decay modes

→ ecompasses previous calculations in a single stand-alone numerical code

it makes possible to apply arbitrary cuts

Strategy: start from NLO calculation of H+jet(s) and observe that as soon as the transverse momentum of the Higgs $q_T \neq 0$ one can write:

$$d\sigma^{H}_{(N)NLO}|_{q_T \neq 0} = d\sigma^{H+\text{jets}}_{(N)LO}$$

Define a counterterm to deal with singular behaviour at $q_T \to 0$

But.....

the singular behaviour of $d\sigma^{H+\mathrm{jet(s)}}_{(N)LO}$ is well known from the resummation program of large logarithmic contributions at small transverse momenta

G. Parisi, R. Petronzio (1979)
J. Collins, D.E. Soper, G. Sterman (1985)
S. Catani, D. de Florian, MG (2000)

→ choose $d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^{H}(q_T/Q)$

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

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Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^H_{(N)NLO} = \mathcal{H}^H_{(N)NLO} \otimes d\sigma^H_{LO} + [d\sigma^{H+\mathrm{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

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

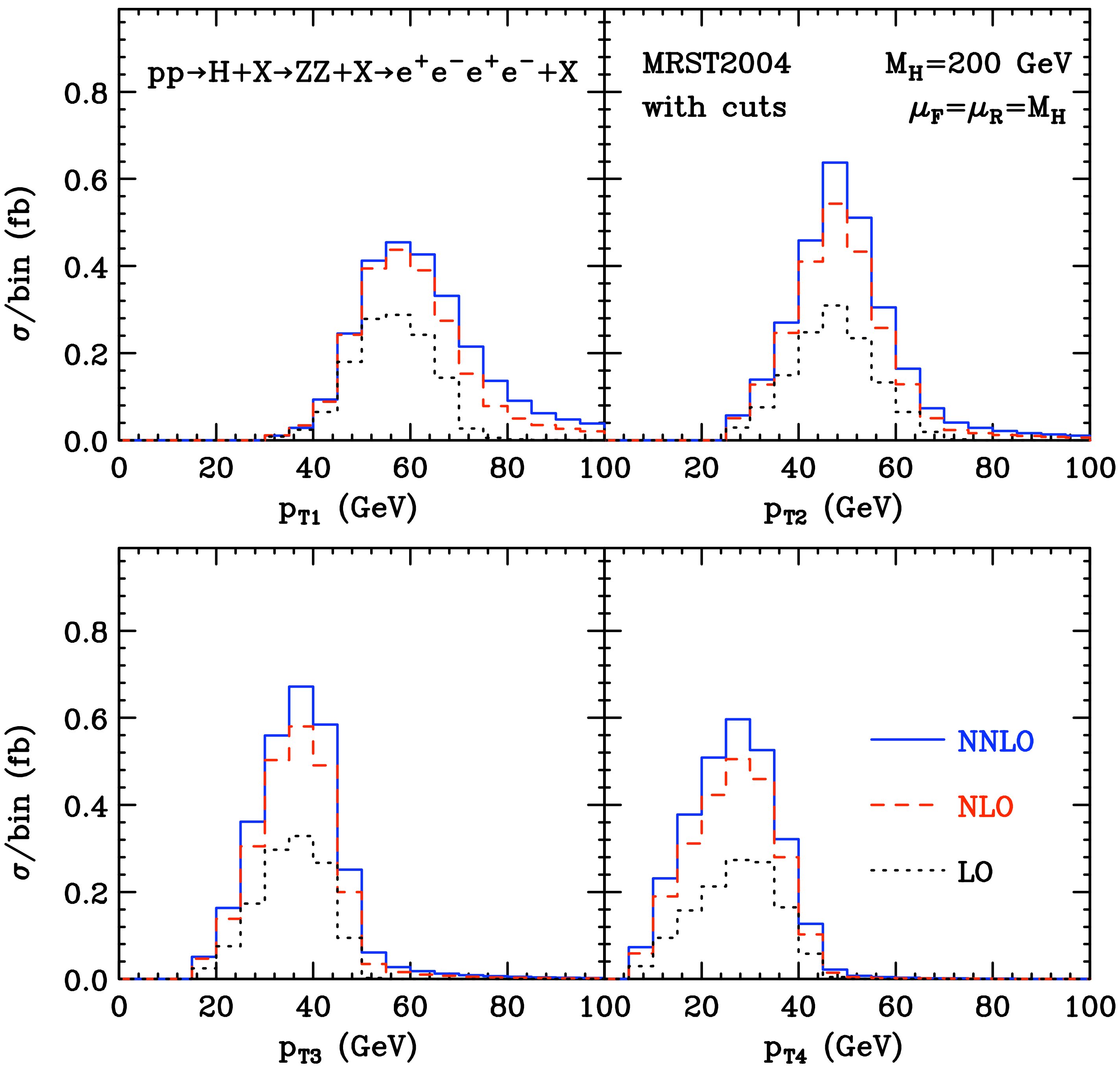
→ $81 \text{ GeV} < m_1 < 101 \text{ GeV}$ and $40 \text{ GeV} < m_2 < 110 \text{ GeV}$

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

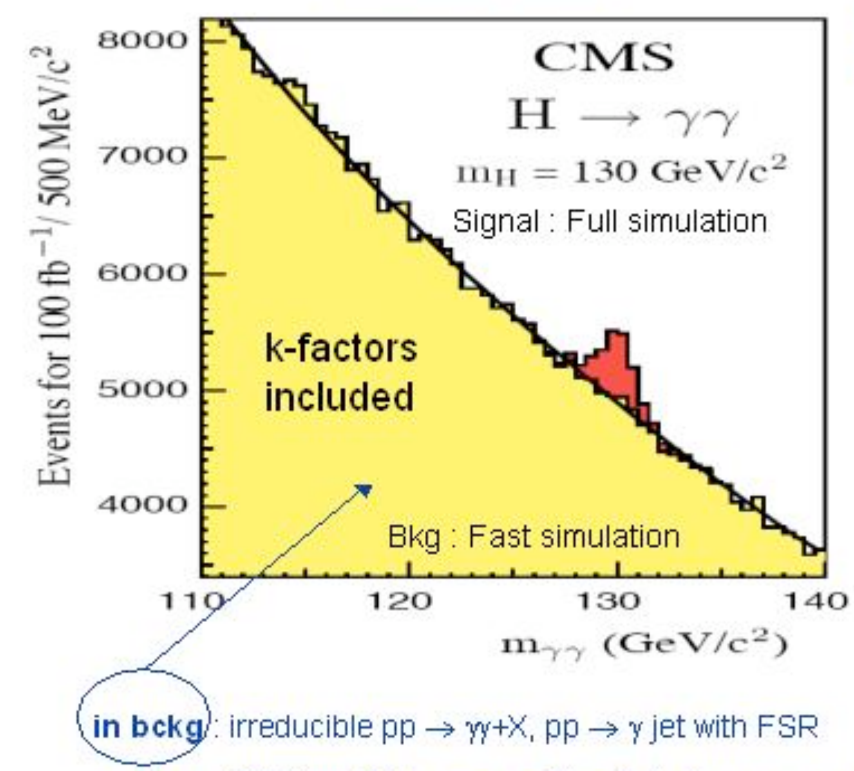
No instabilities beyond LO

Higgs decays

- $H \to \gamma\gamma$

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

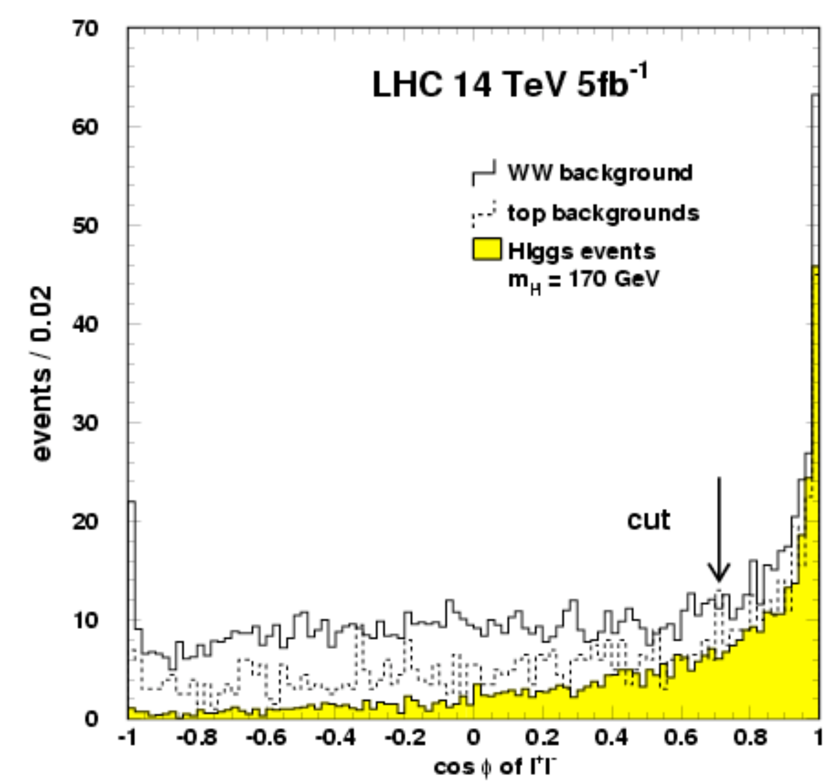
Background measured from sidebands



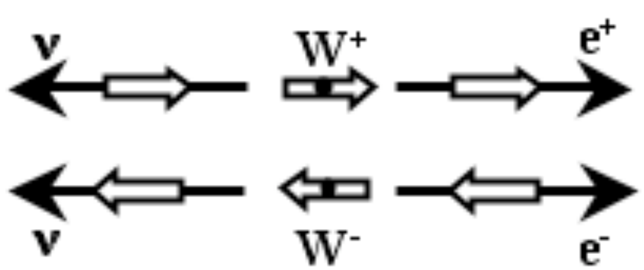
- $H \to WW^* \to l\nu l\nu$

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

- $H \to ZZ \to 4l$ gold pleated → clean four lepton signature