Higgs physics and QCD

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IFAE, Roma, 7 aprile 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

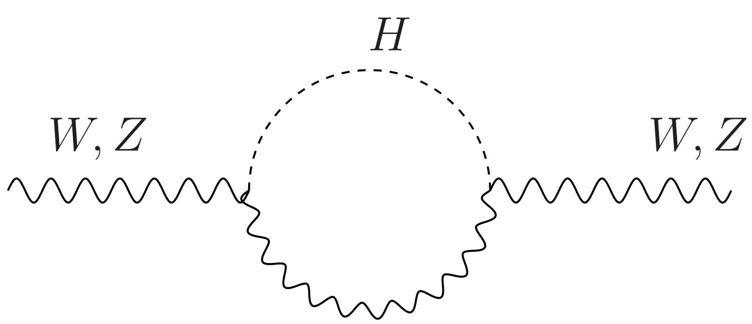
- Theoretical arguments (or prejudices) suggest $50\,\mathrm{GeV} \lesssim m_H \lesssim 800\,\mathrm{GeV}$ (with new physics at the TeV scale)

- 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**



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

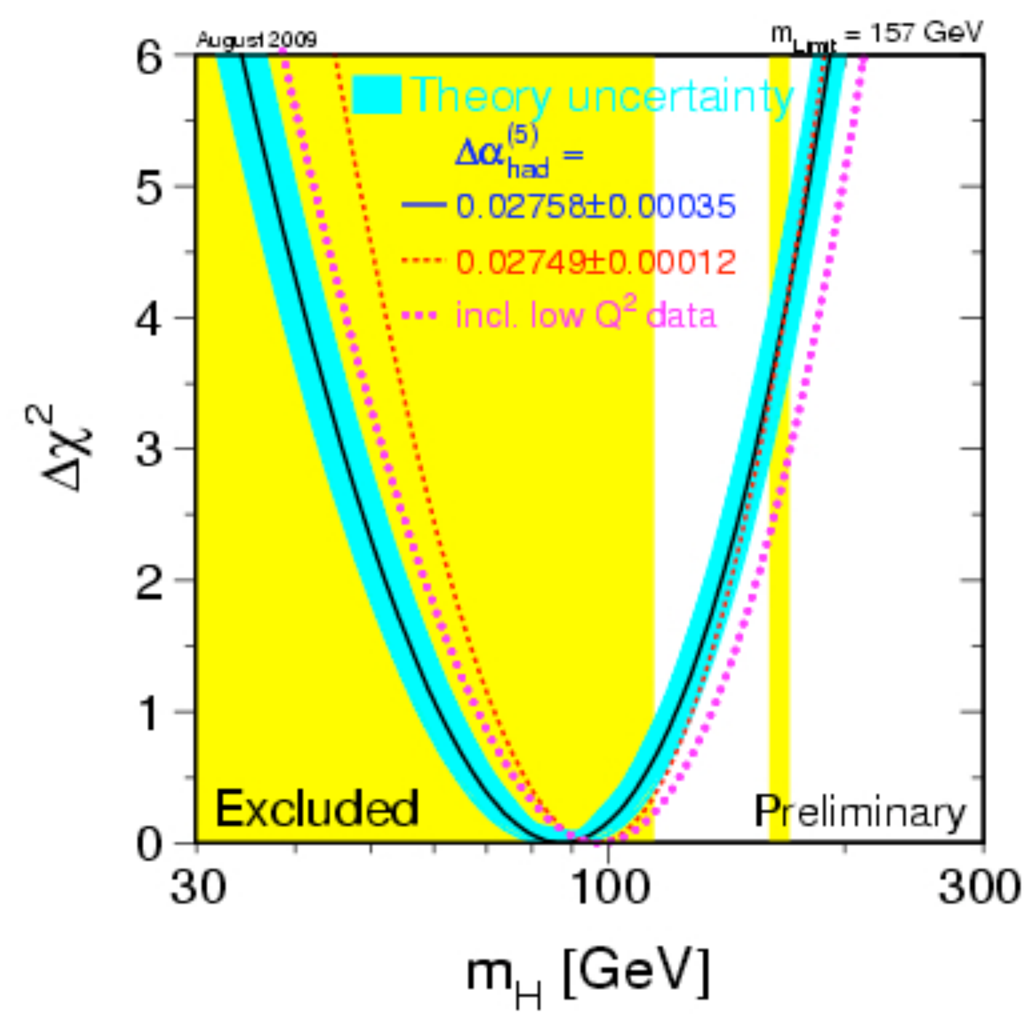
$$m_H < 157\ \text{GeV}$$ at 95 % CL

LEP EWWG, summer 2009

Taking into account LEP limit:

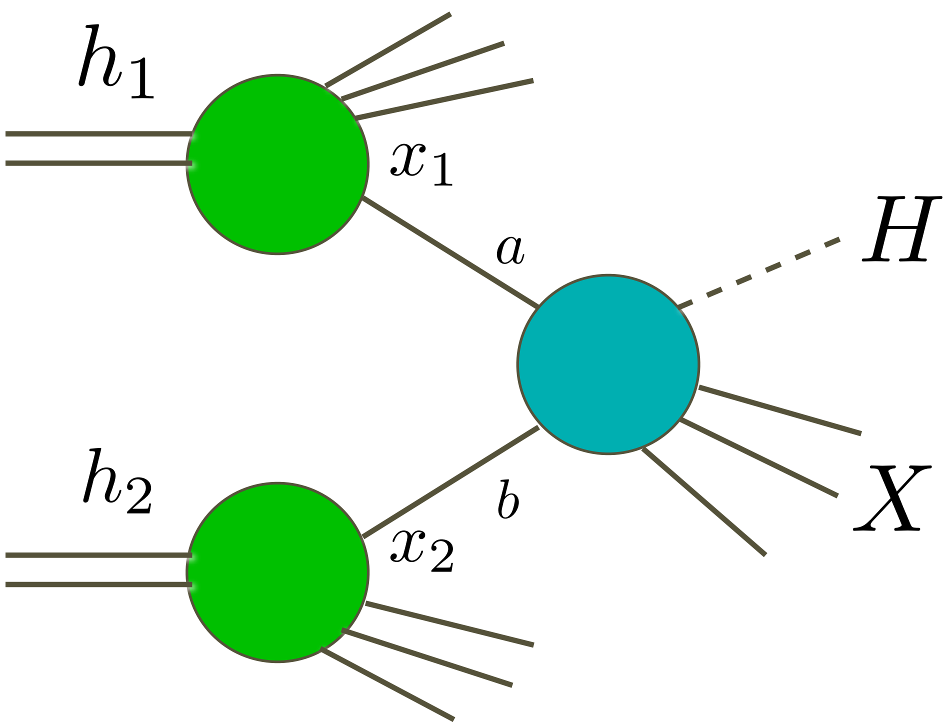
$$m_H < 186\ \text{GeV}$$ at 95 % CL

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



Theoretical predictions at hadron colliders

The framework: QCD factorization theorem



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

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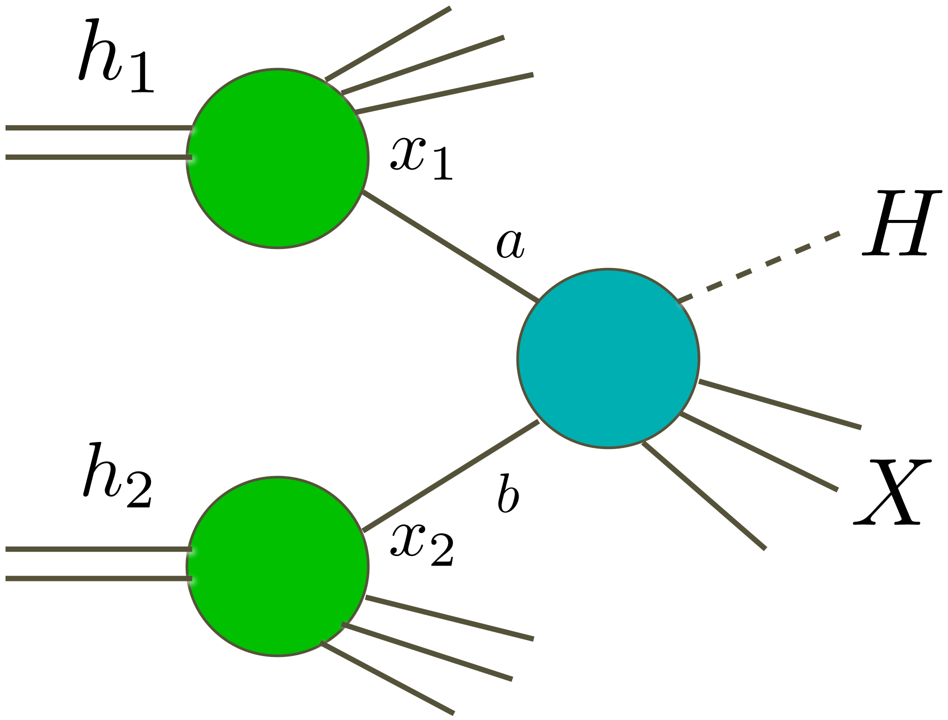

Parton distributions

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

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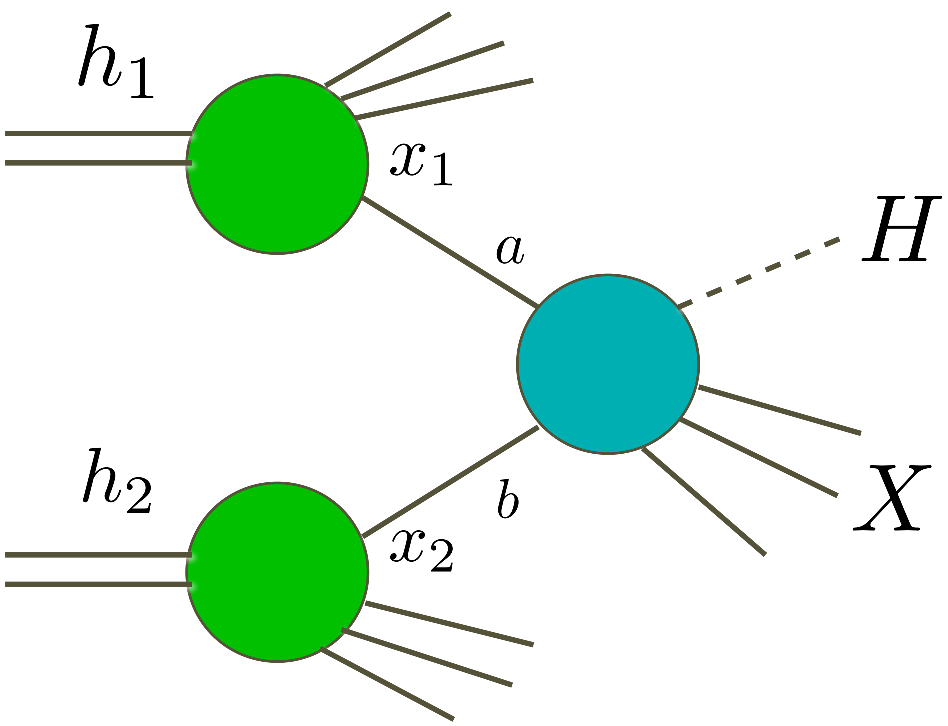


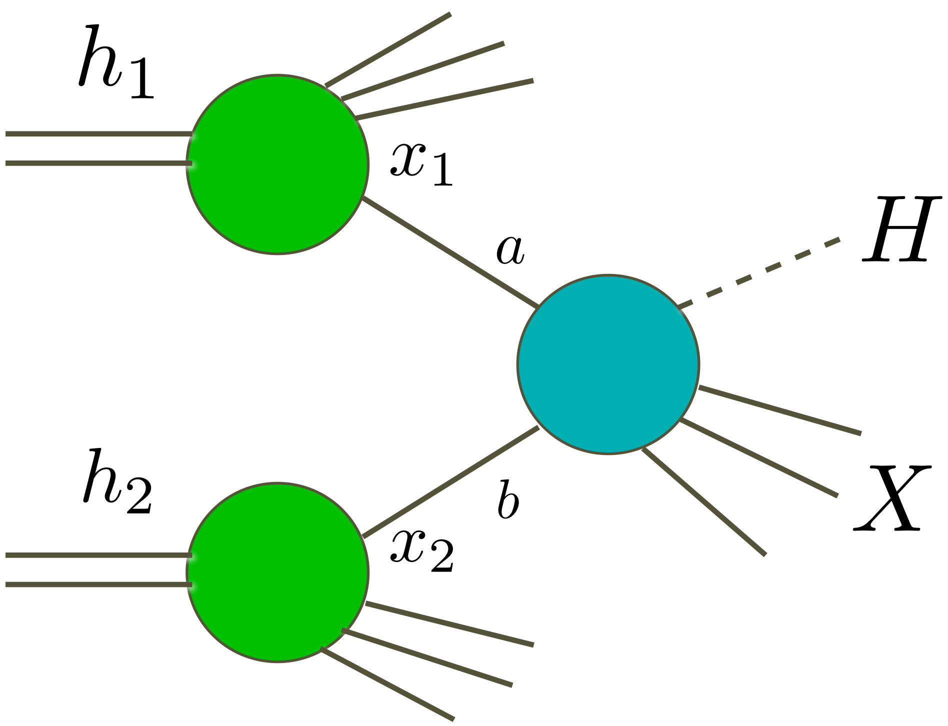
Parton distributions

Partonic cross section

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

Theoretical predictions at hadron colliders

The framework: QCD factorization theorem



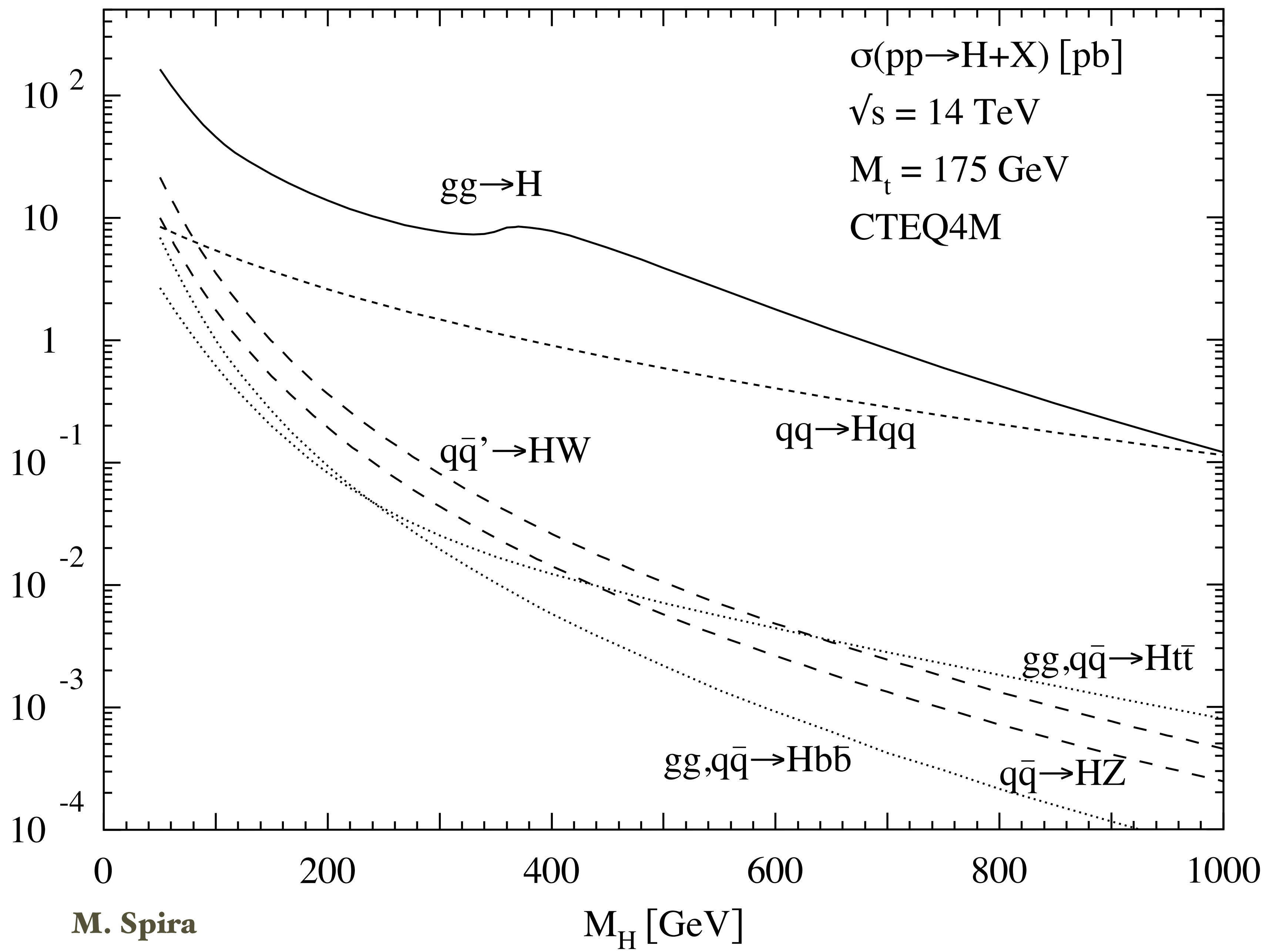
Parton distributions

Partonic cross section

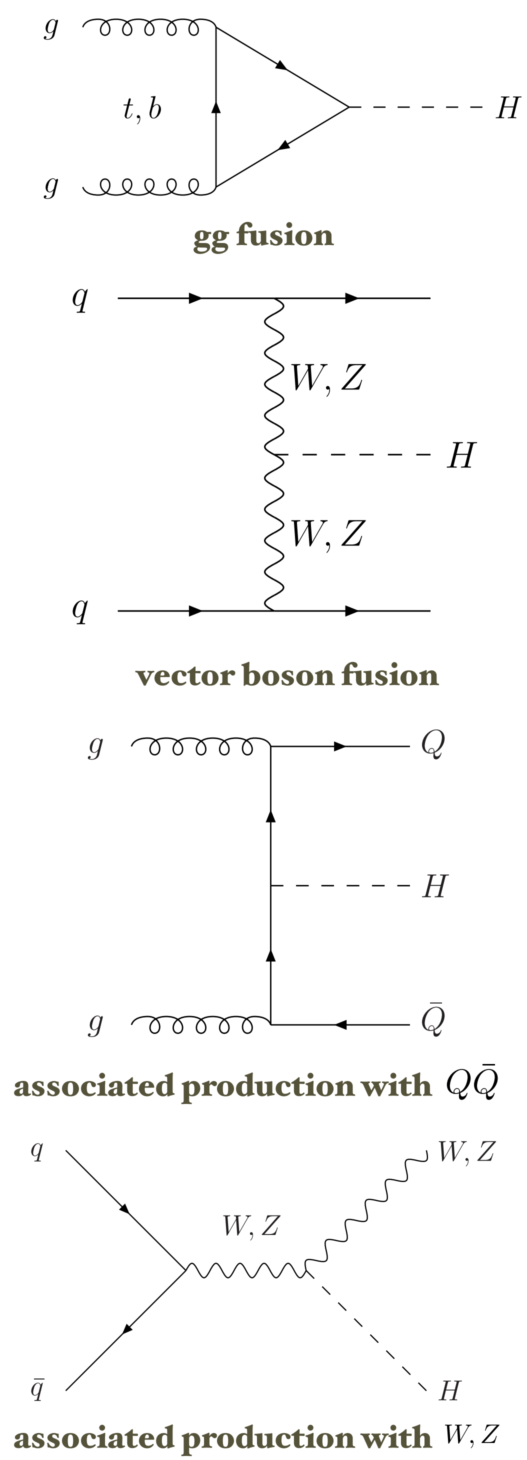
$$\sigma(p_1, p_2; M_H) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1, \mu_F^2)\, f_{h_2,b}(x_2, \mu_F^2) \times \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_S(\mu_R^2); \mu_F^2)$$

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

Higgs production at hadron colliders

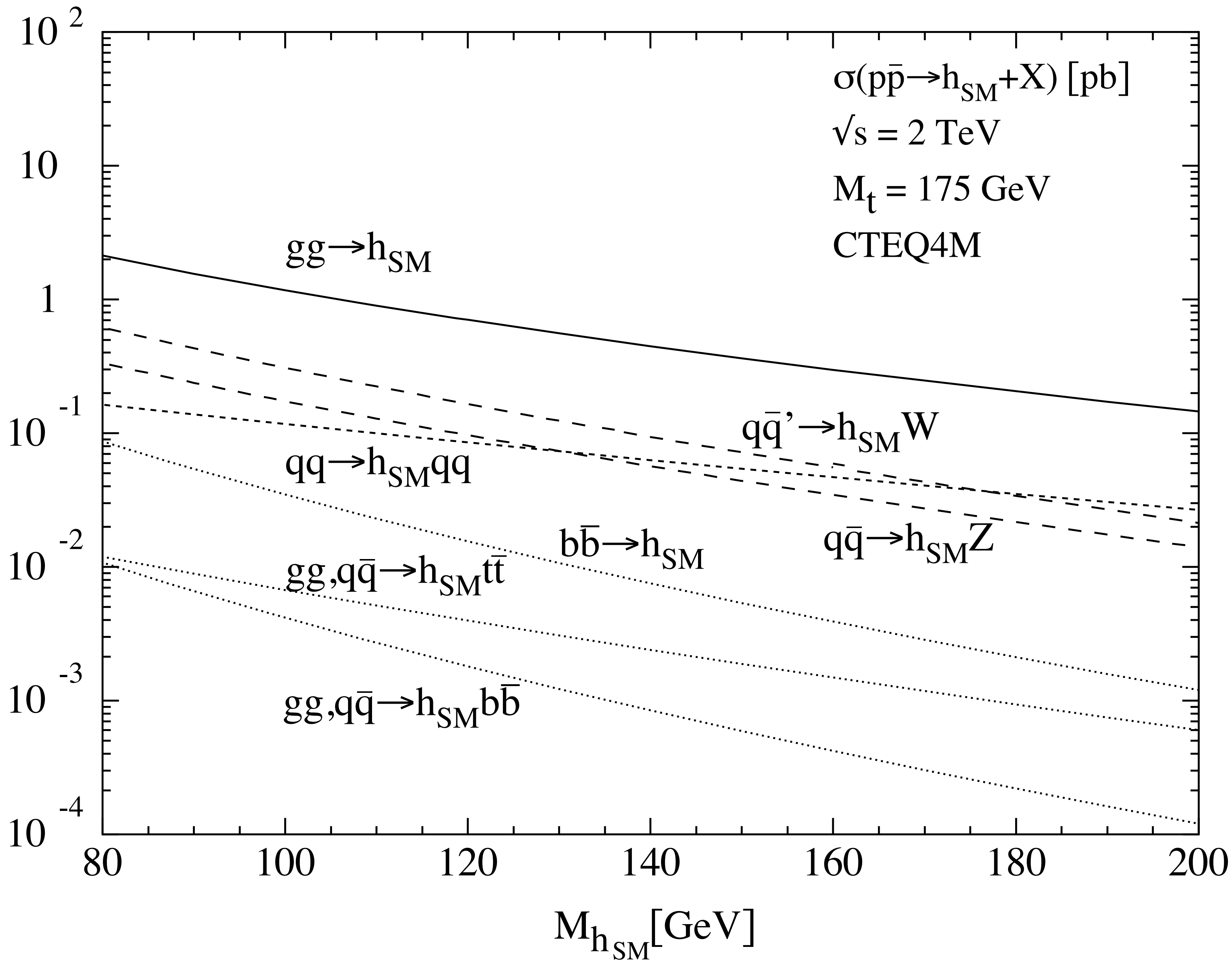


M. Spira



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

Higgs production at hadron colliders



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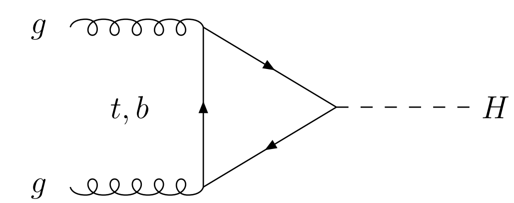
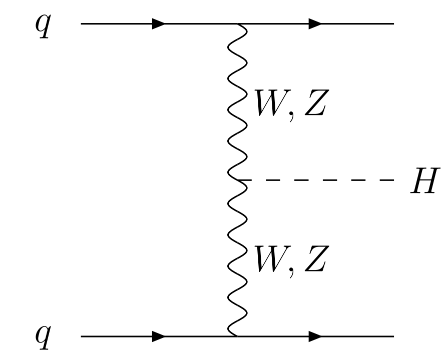
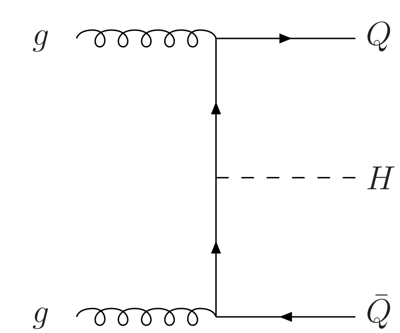


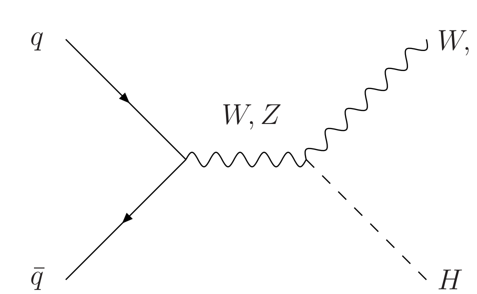
gg fusion



vector boson fusion



associated production with $Q\bar{Q}$



associated production with W, Z

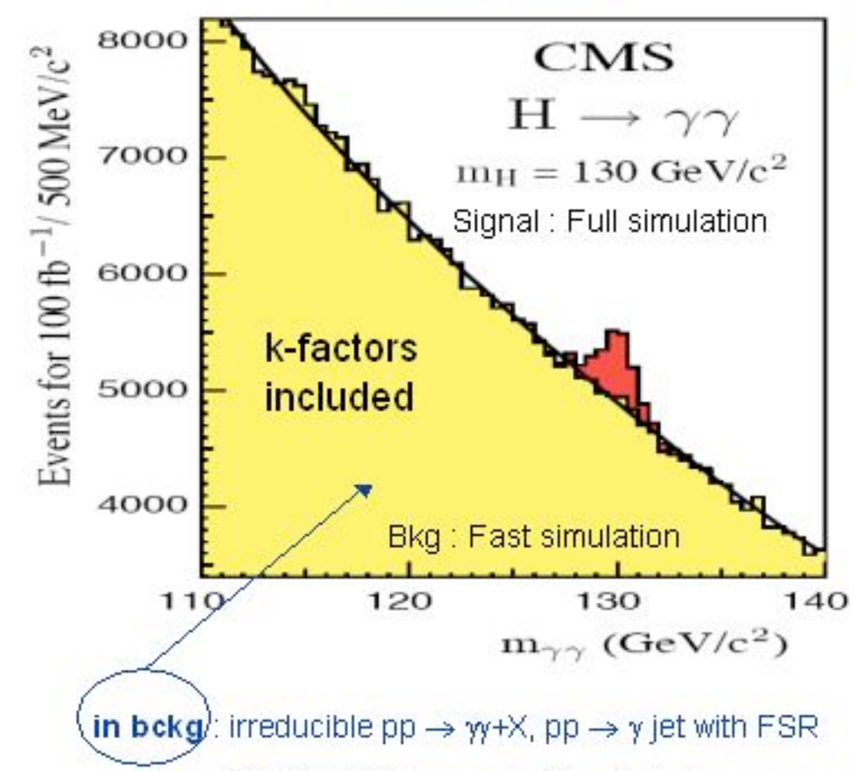
Similar situation at the Tevatron
(although gg dominance less pronounced)

Higgs decays

- $H \rightarrow \gamma\gamma$

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

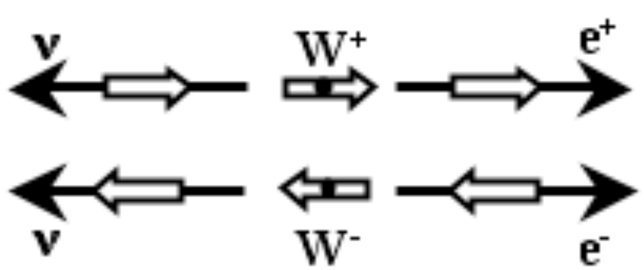


- $H \rightarrow WW^* \rightarrow l\nu l\nu$

No mass peak but strong angular correlations between the leptons

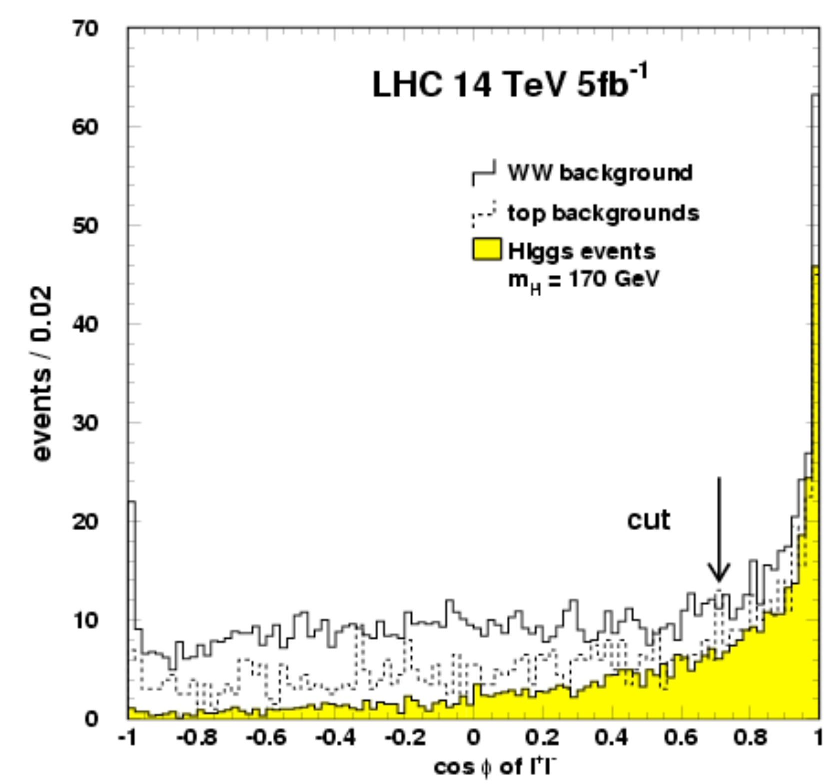
M.Dittmar, H.Dreiner (1996)

V-A interaction:



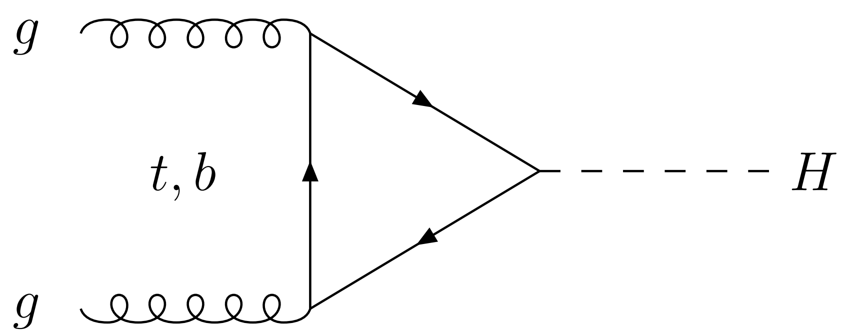
$l^{+(-)}$ (anti-) parallel to $W^{+(-)}$spin

H scalar → charged leptons tend to be close in angle



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

gg fusion



The Higgs coupling is proportional to the quark mass

→ top-loop dominates

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 % !

Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit (excellent approx. for a light Higgs)

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)

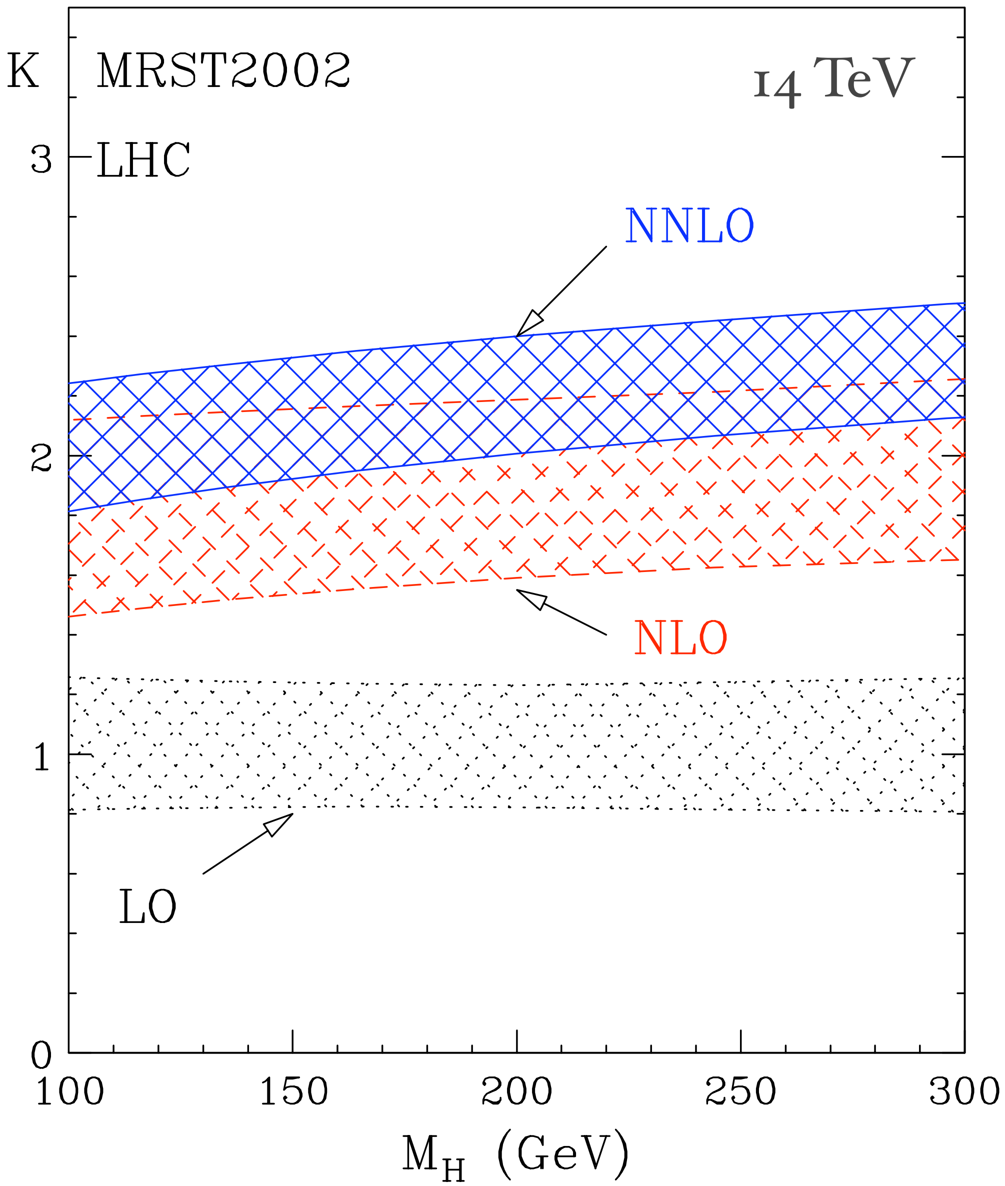
Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy

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

EW corrections are also known (effect is about 5%)

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

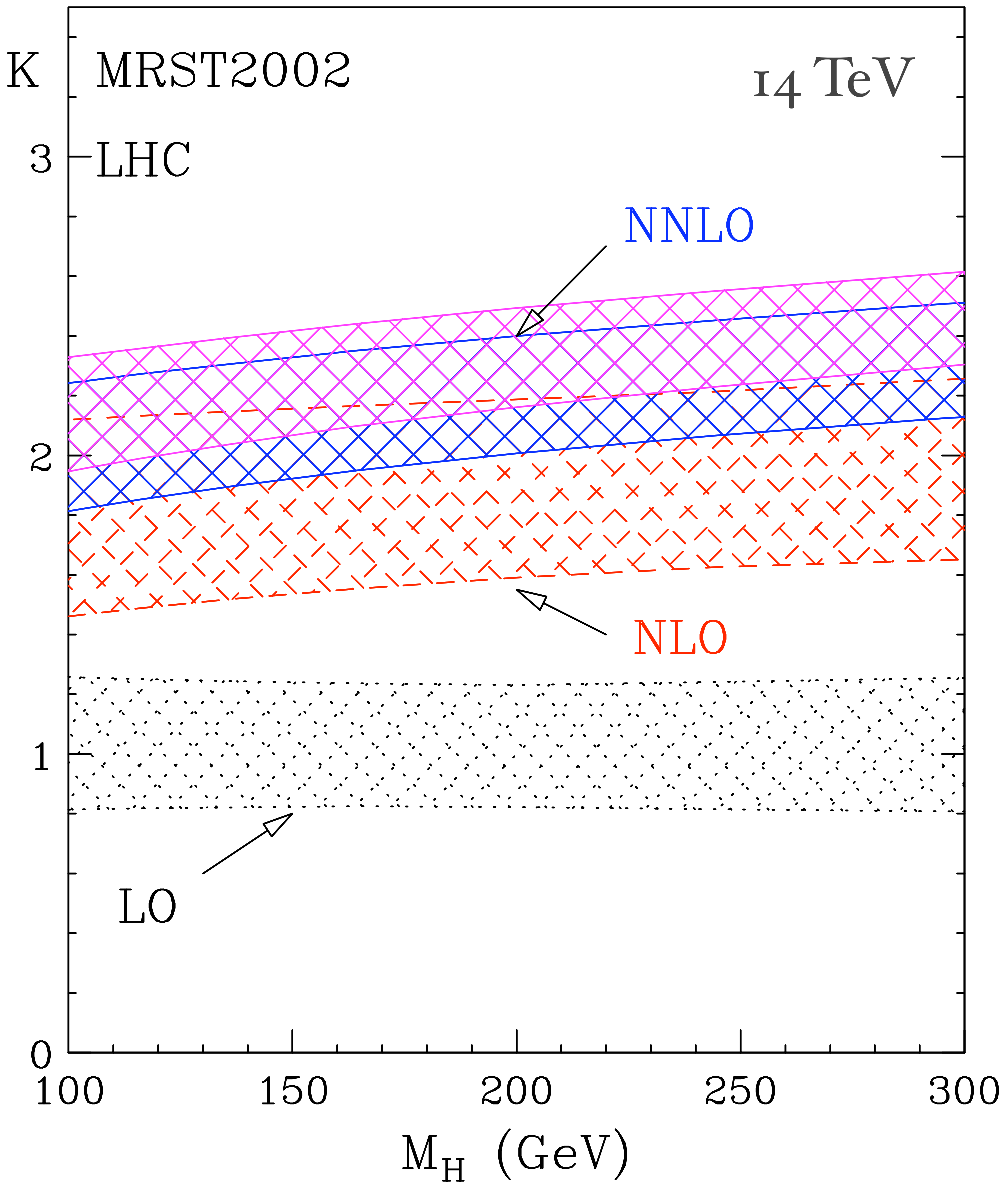
Inclusive results at the LHC



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 $+6\%$

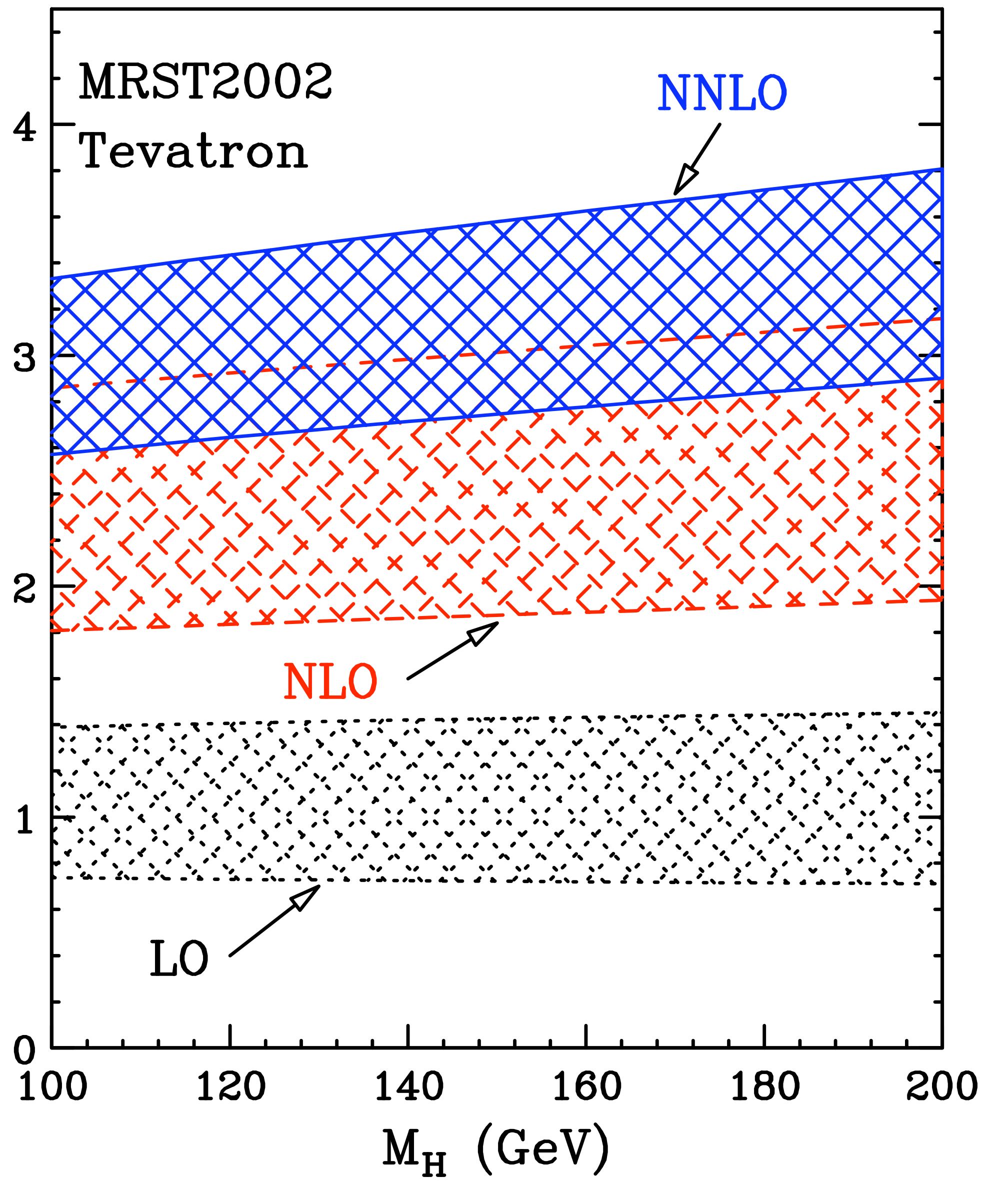
Good stability of perturbative result

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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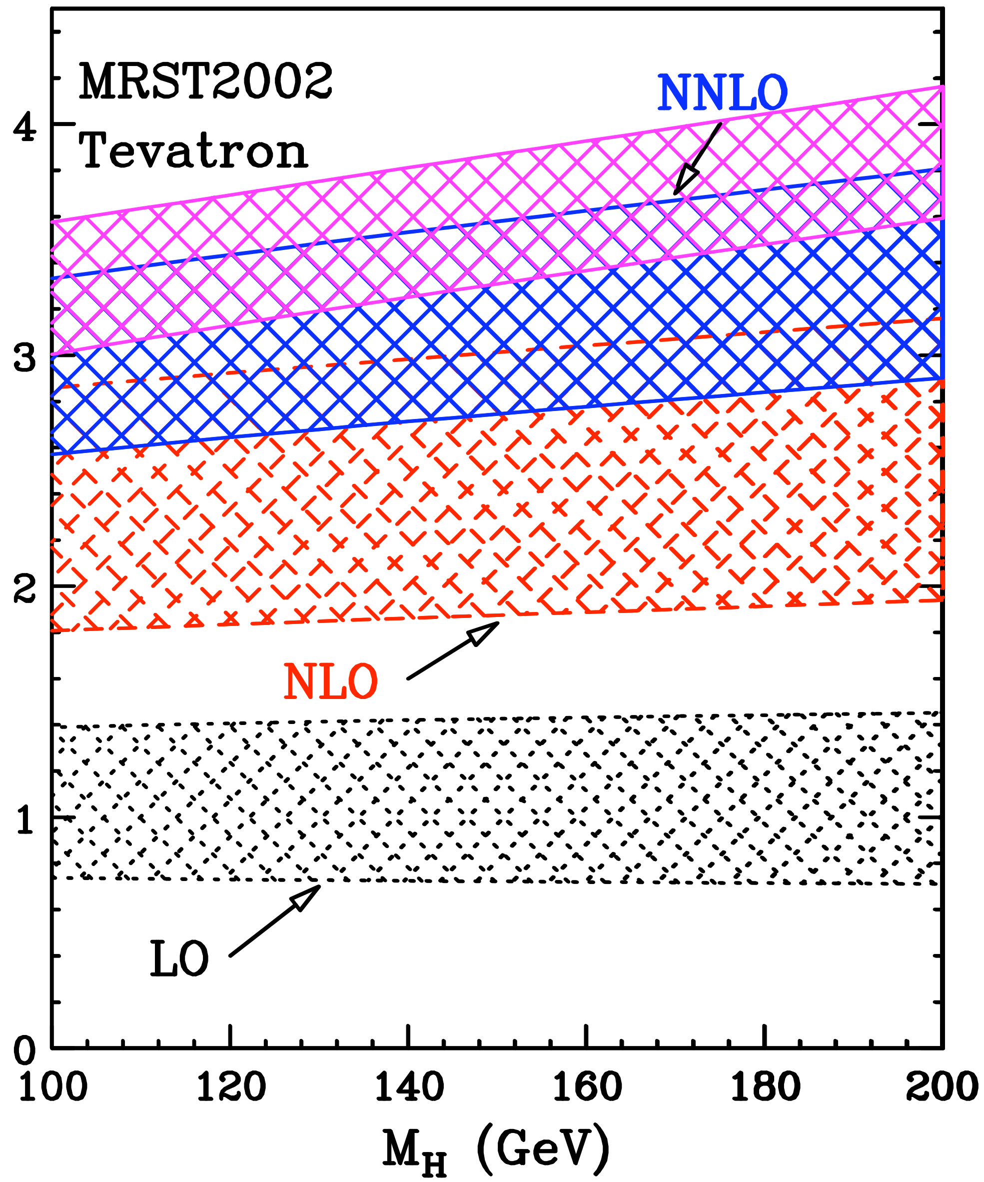


Inclusion of soft-gluon effects at all orders

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

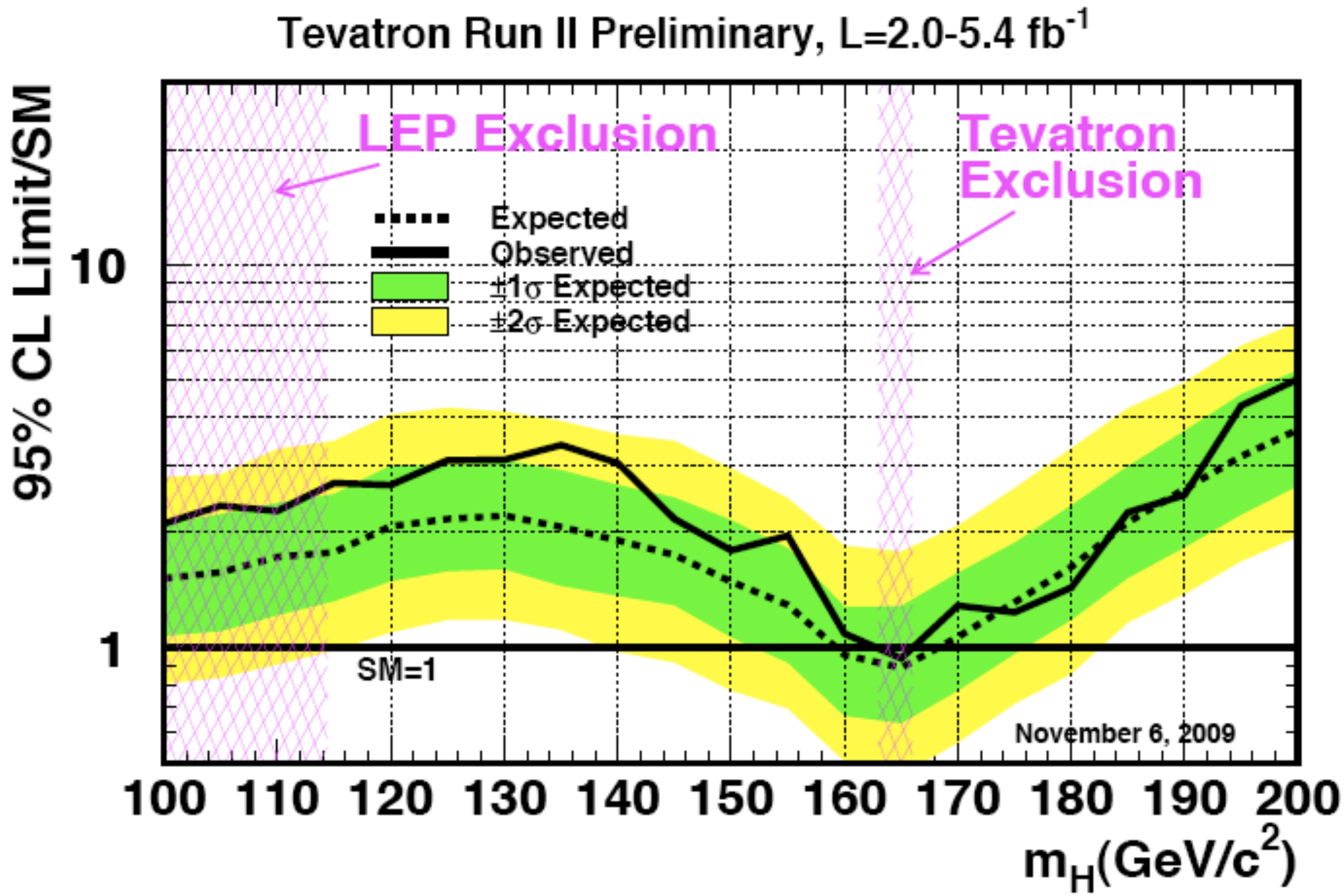
- With $\mu_{F(R)} = \chi_{L(R)} M_H$ and $0.5 \leq \chi_{L(R)} \leq 2$ but $0.5 \leq \chi_F/\chi_R \leq 2$

Tevatron Higgs search

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

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

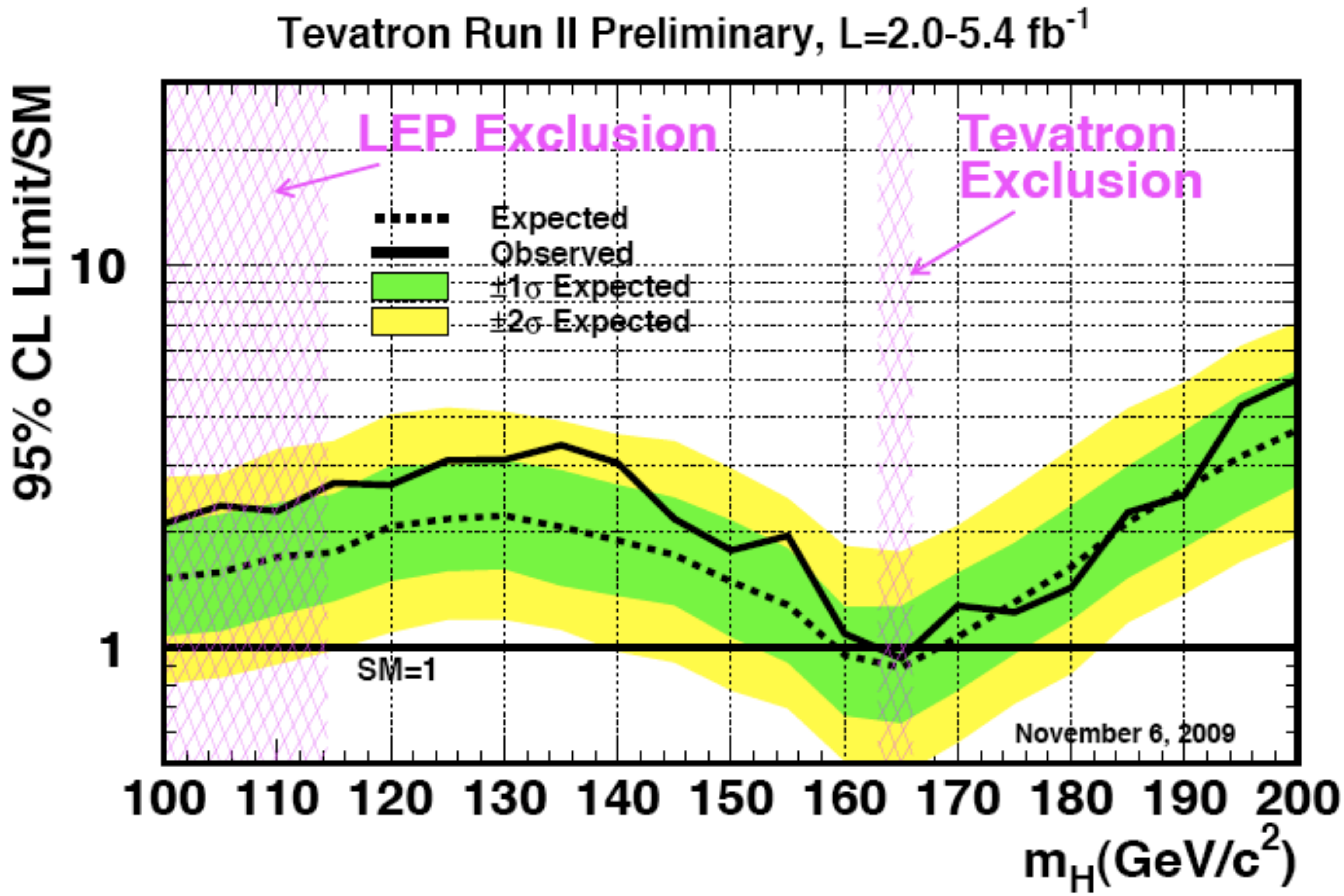
→ Now sensitive to the region $m_H \approx 160\text{-}170$ GeV



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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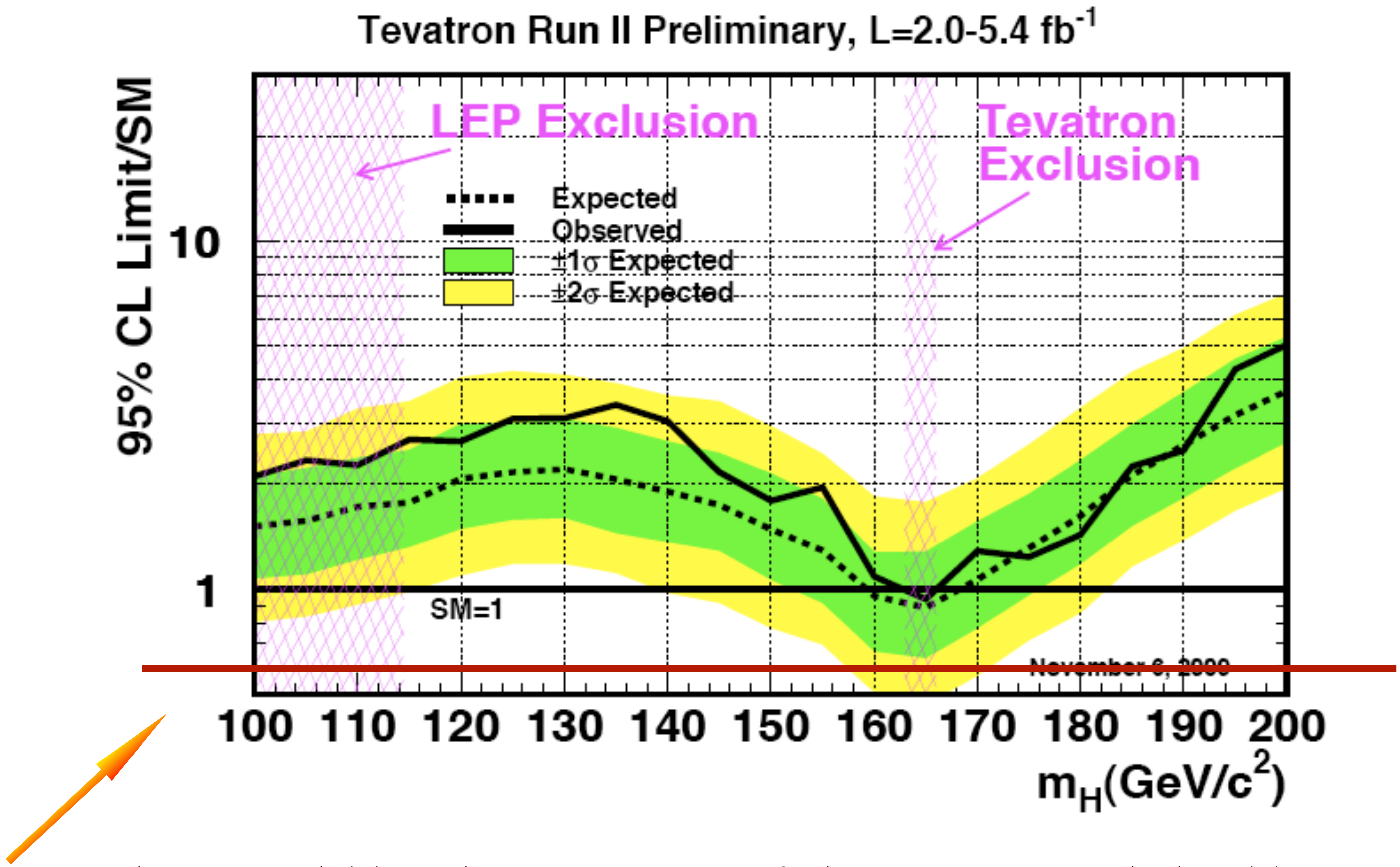
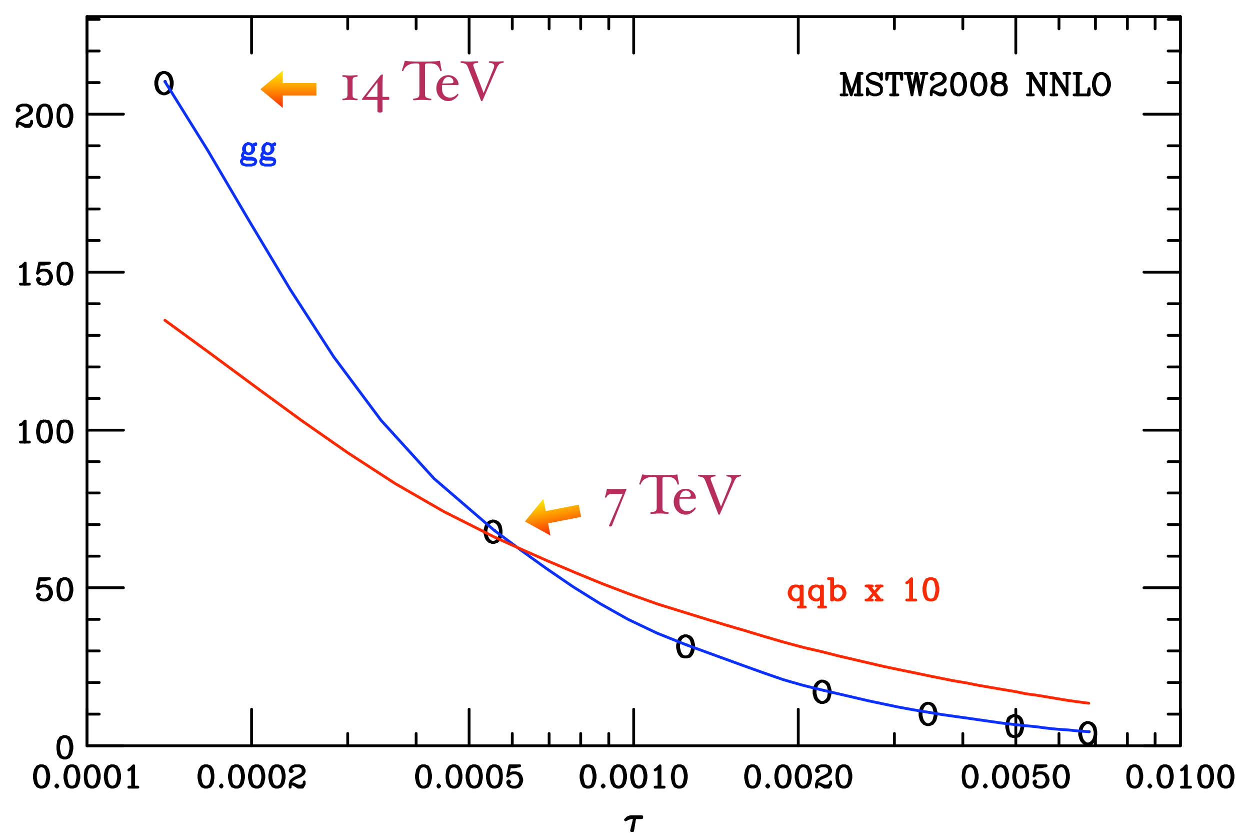


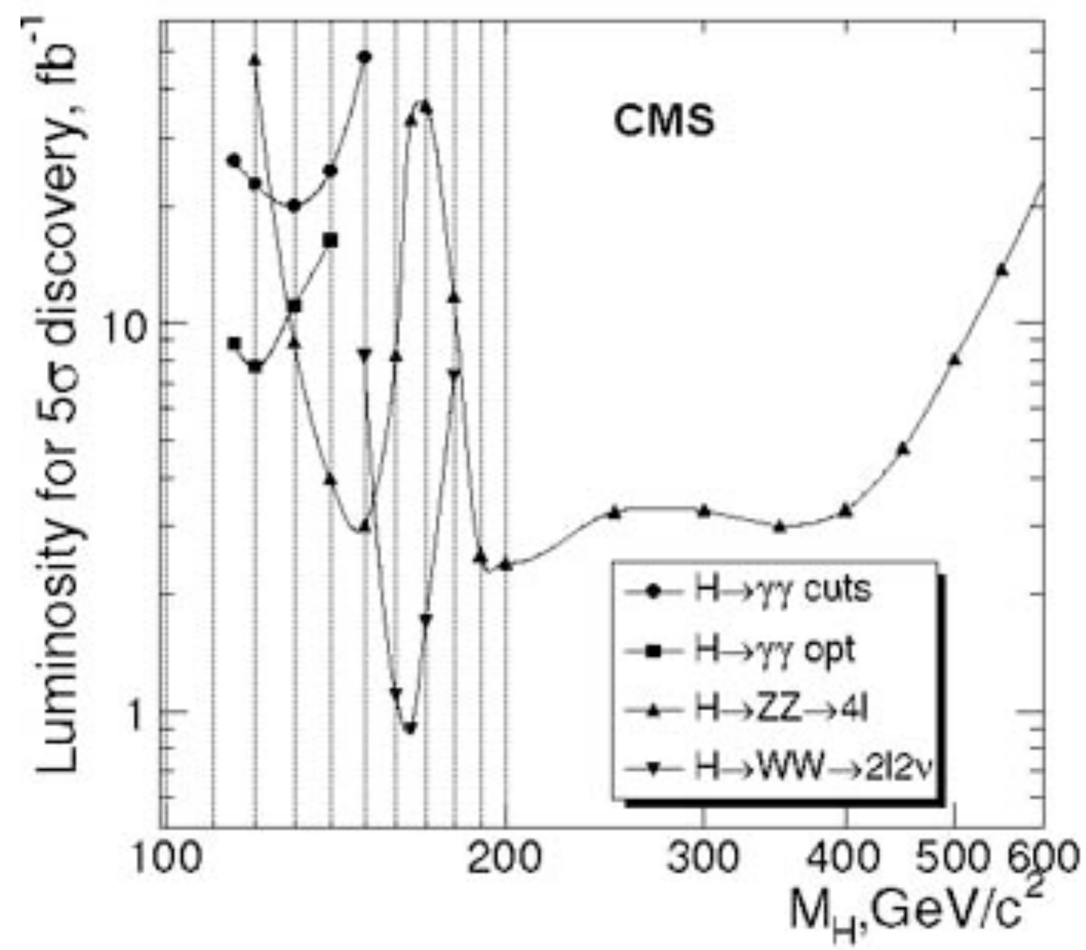
This would be the situation if the NLO result had been used !

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)

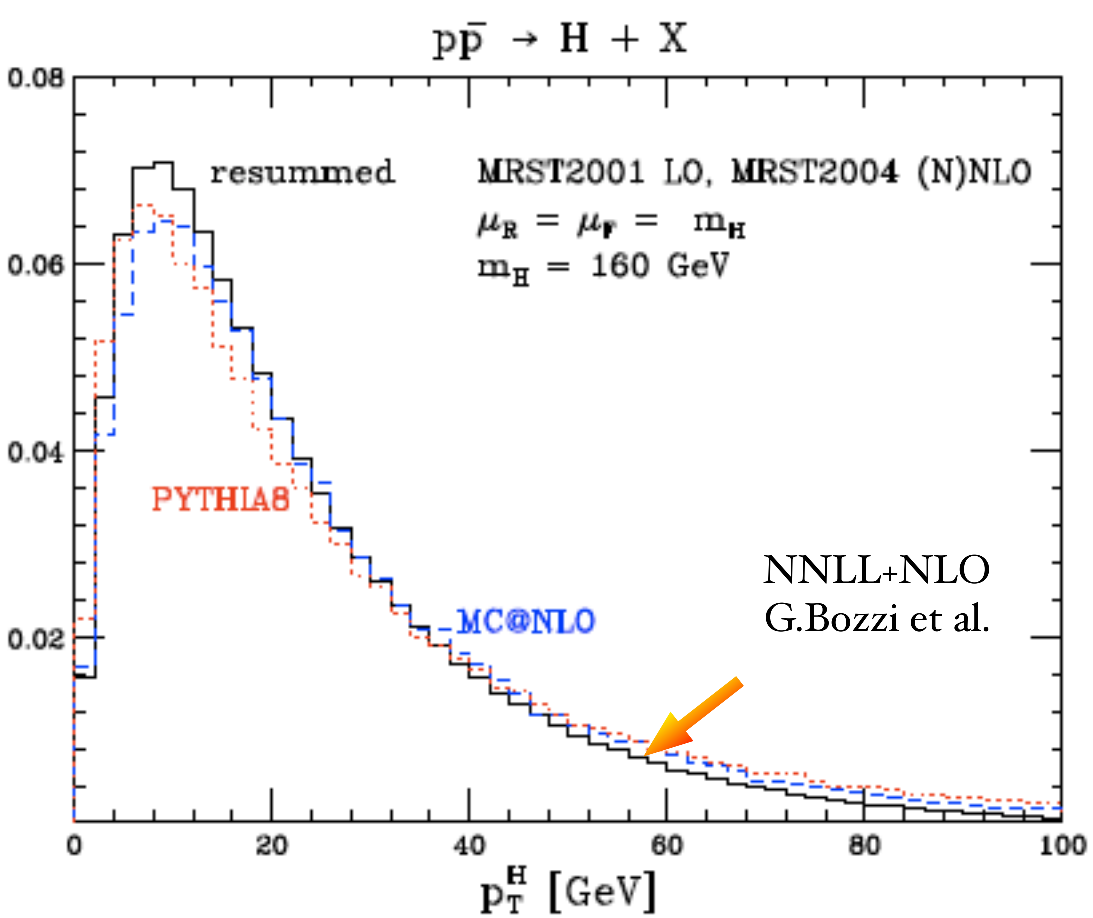
What else ?

How are theoretical predictions exploited in practice ?

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

Use “best” total cross section as over all normalization

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



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

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

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 $H \to ZZ \to 4l$

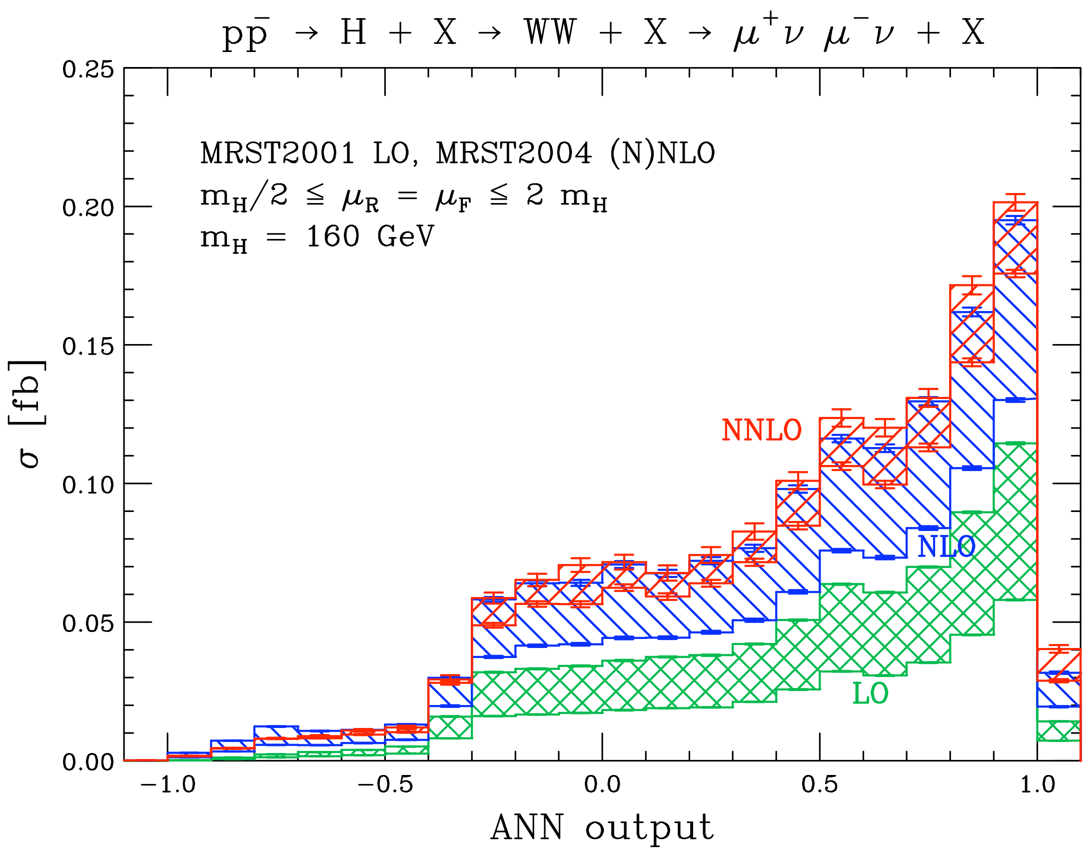
S. Catani, MG (2007)
MG (2008)

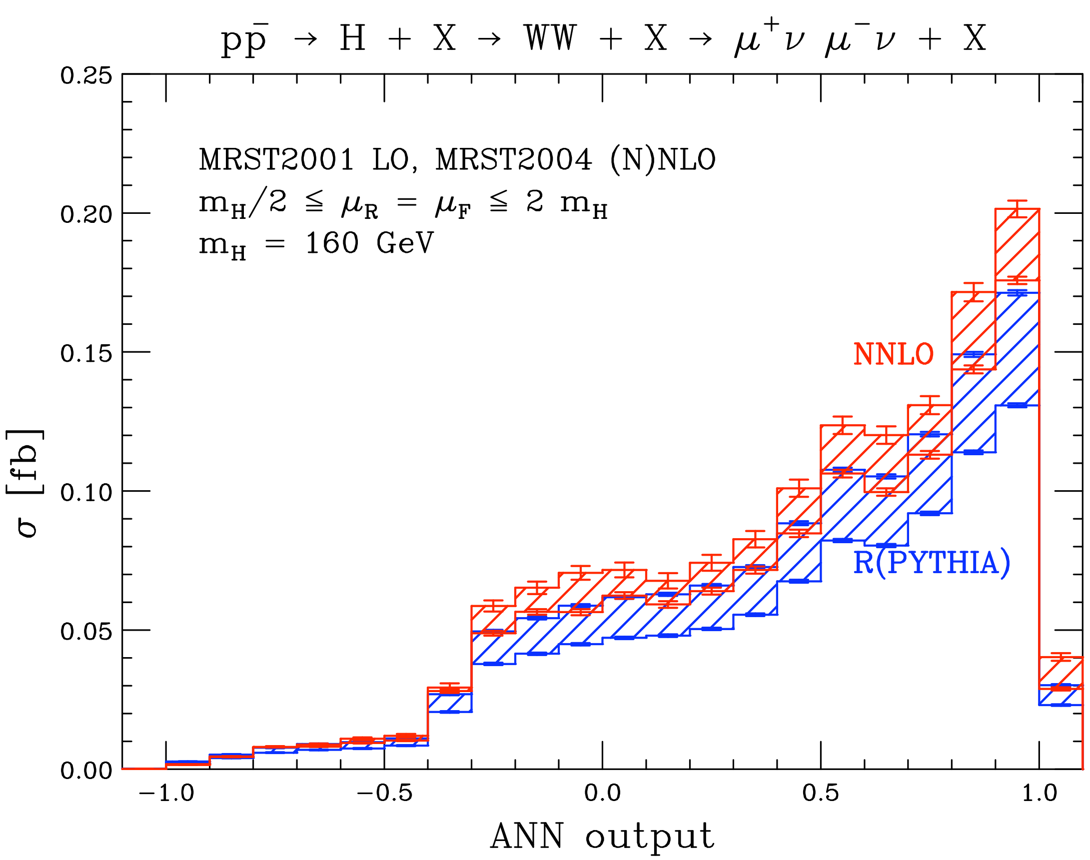
With these programs it is possible to study the impact of higher order corrections with the cuts used in the experimental analysis

Now being used at the Tevatron !

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

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

The large-m_{top} approximation

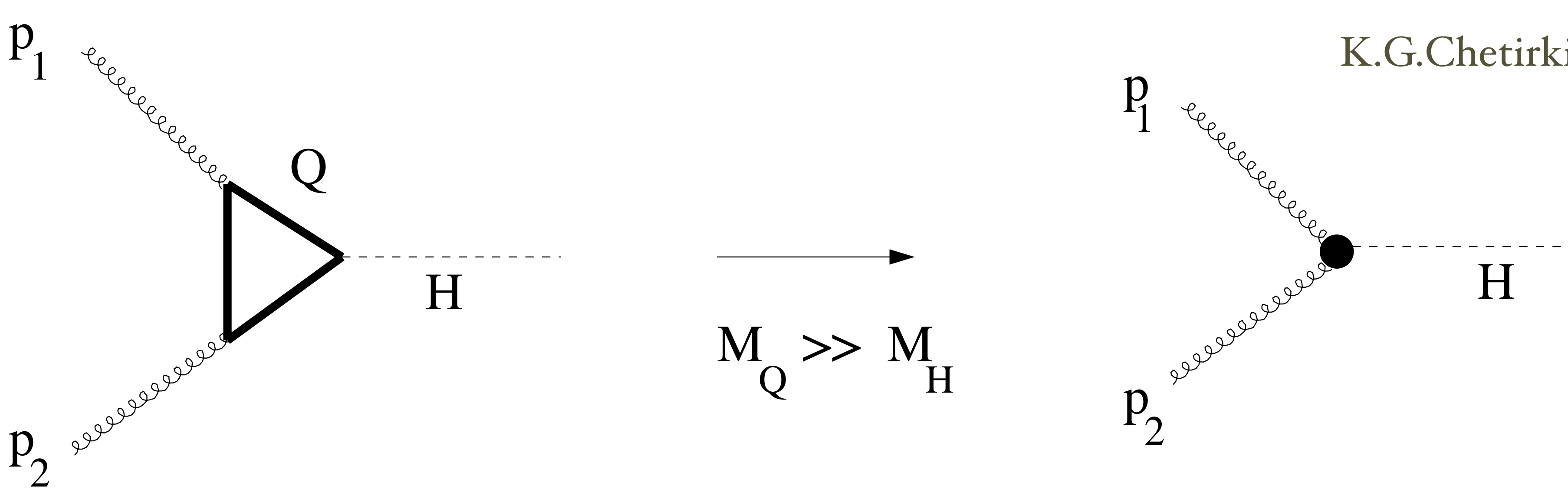
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

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 !

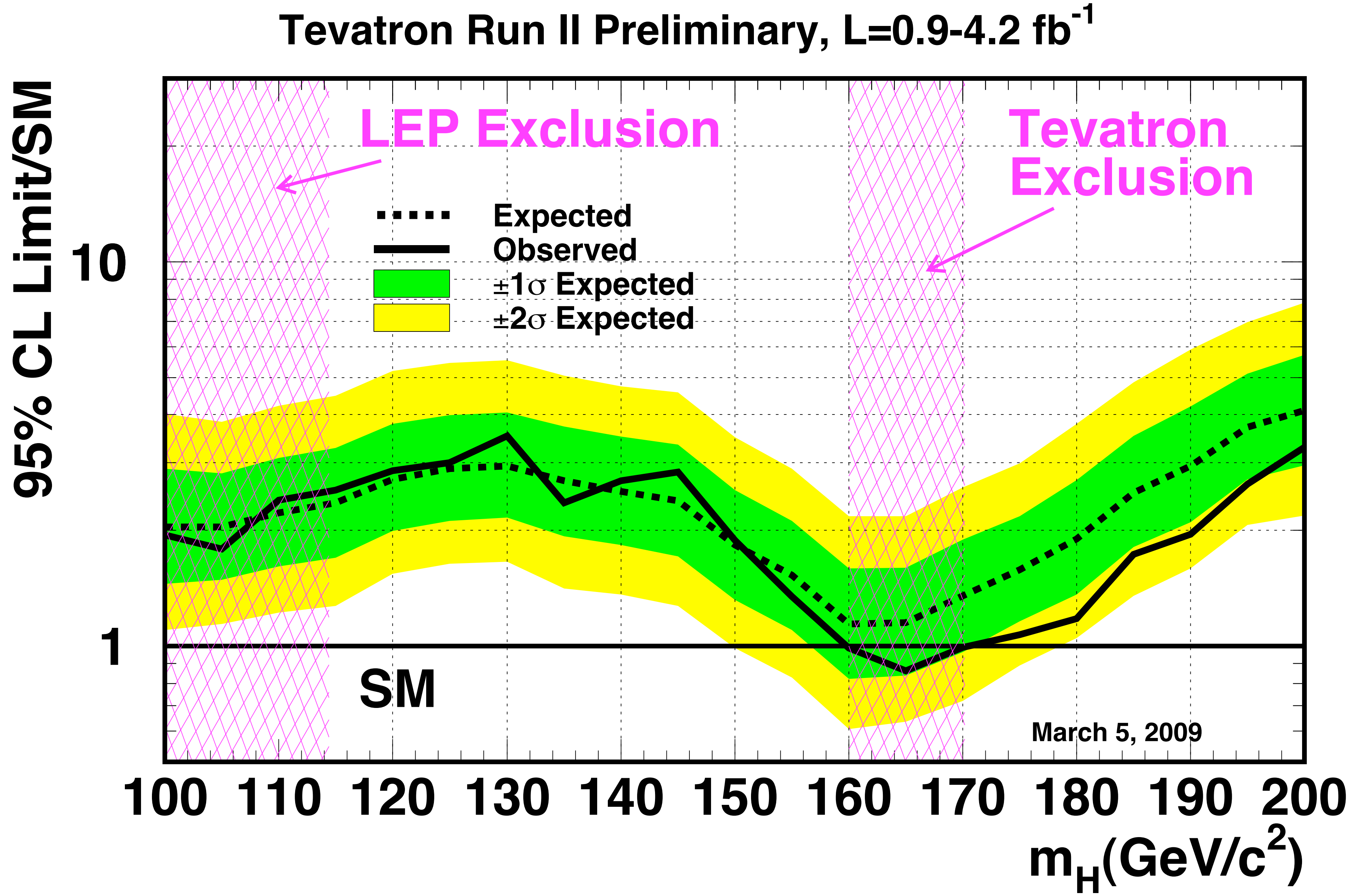
Recently the subleading terms in large-m_{top} limit at NNLO have been evaluated

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

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

Tevatron results

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



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

Tevatron results

Latest combination in the WW decay mode

arXiv:1001.4162