Higgs production at the LHC : selected results

Massimiliano Grazzini (INFN, Firenze)

Physics at LHC, Split, september 2008

Outline

- Introduction
- Status of Higgs production cross sections at the LHC

  - gg fusion
    - total cross section
    - fully differential results
  - Vector boson fusion
  - Associated production with a heavy quark pair
  - Associated production with a vector boson
- Summary

Introduction

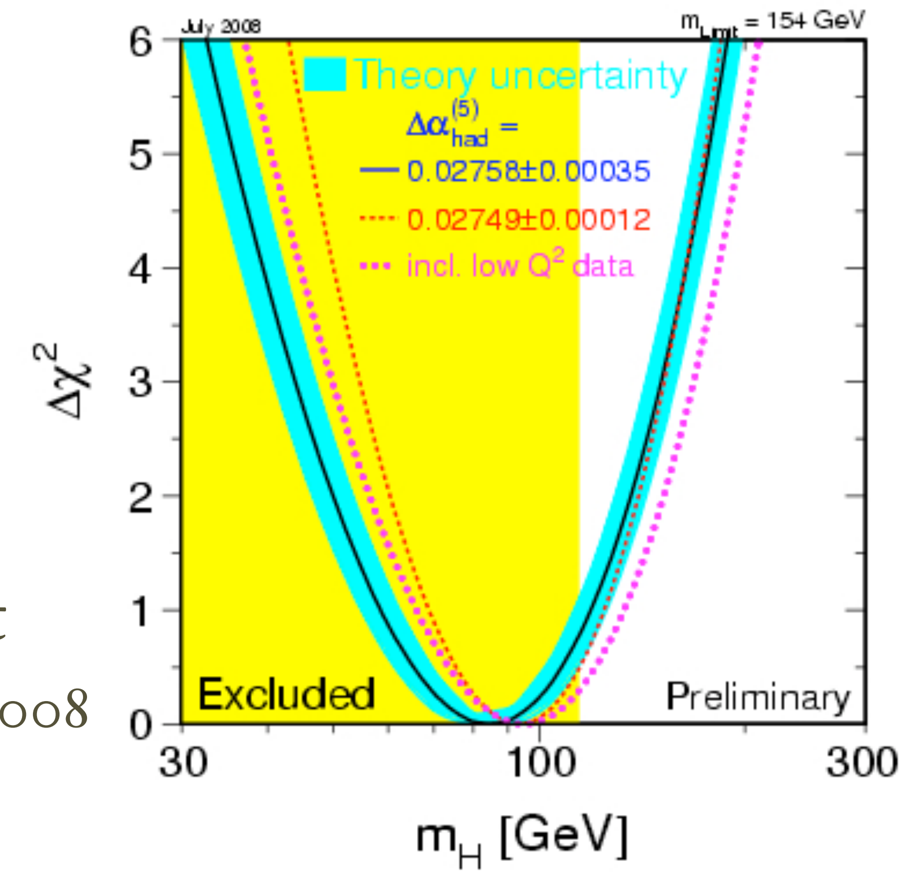
The Higgs boson is a fundamental ingredient in the SM but it has not been observed yet

LEP limit: $M_H \geq 114.4$ GeV at 95% CL

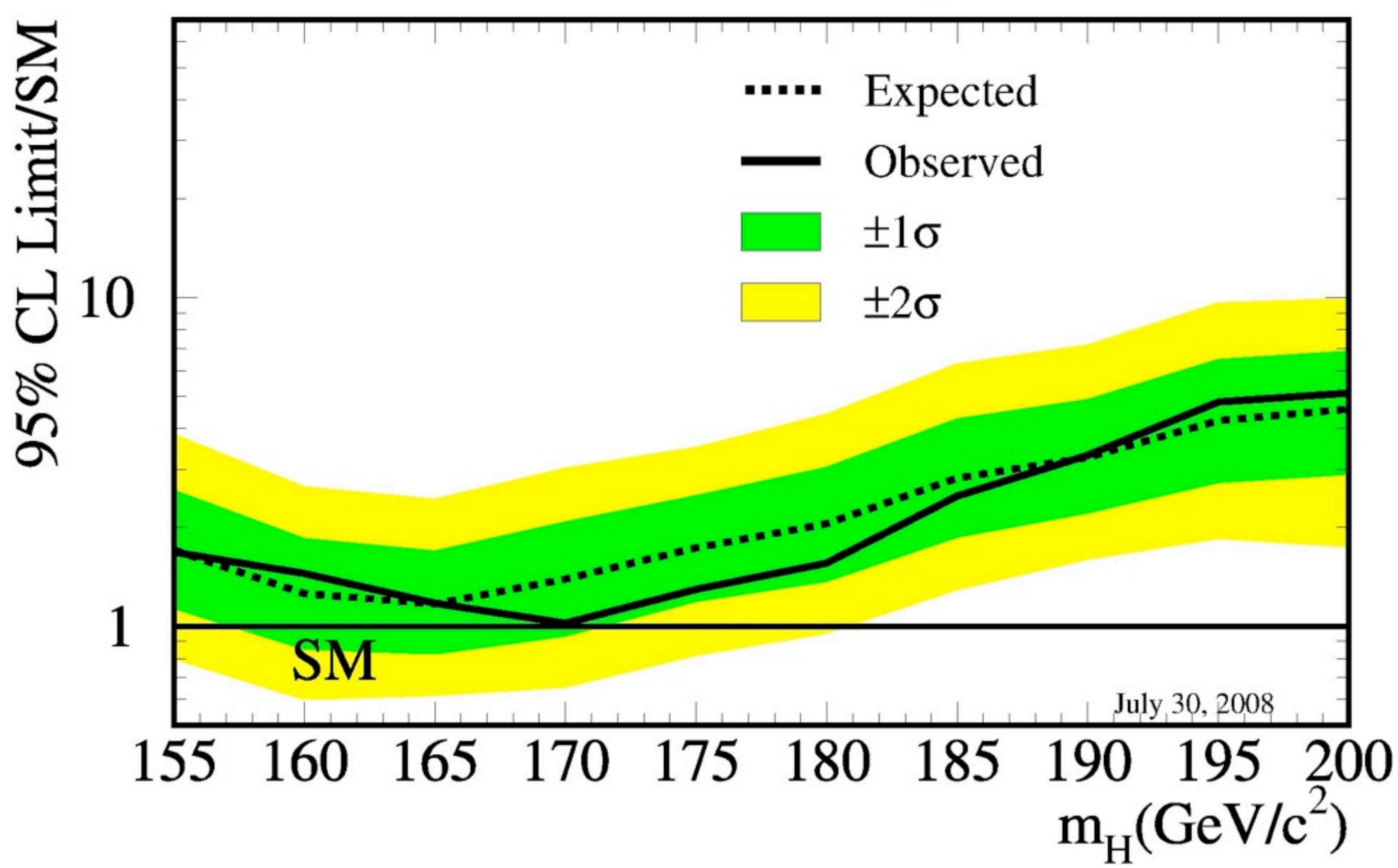
Precision EW data suggest: $M_H = 84^{+34}_{-26}$ GeV

$M_H < 185$ GeV taking into account LEP limit

LEP EWWG, summer 2008



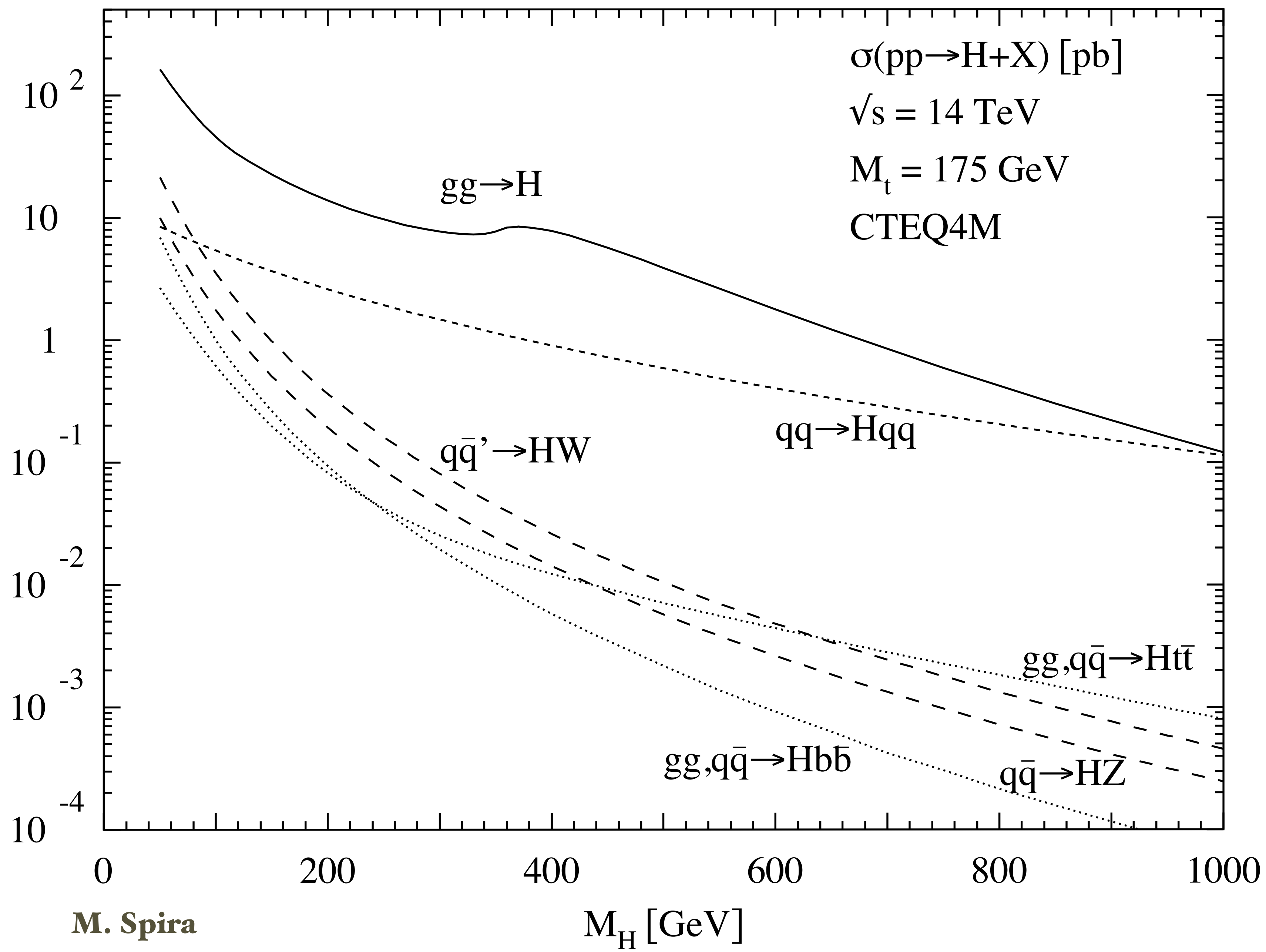
Tevatron Run II Preliminary, L=3 fb^{-1}

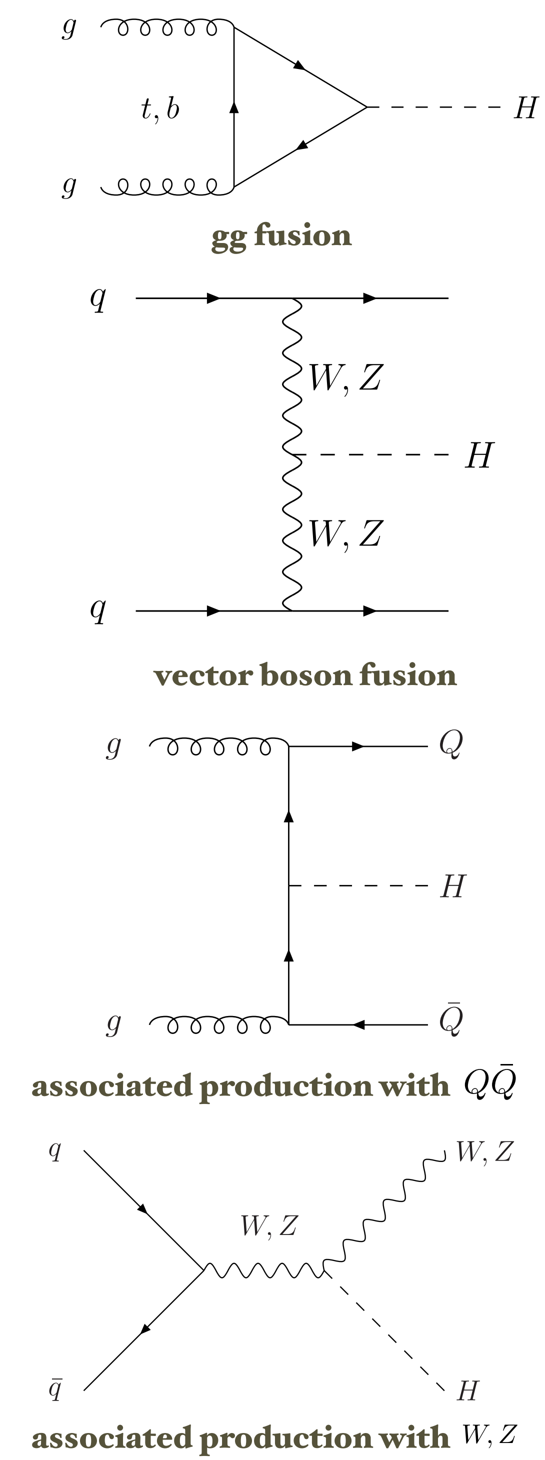


Tevatron experiments may be able to exclude the SM Higgs up to $M_H \sim 200$ GeV or to claim a 3σ evidence

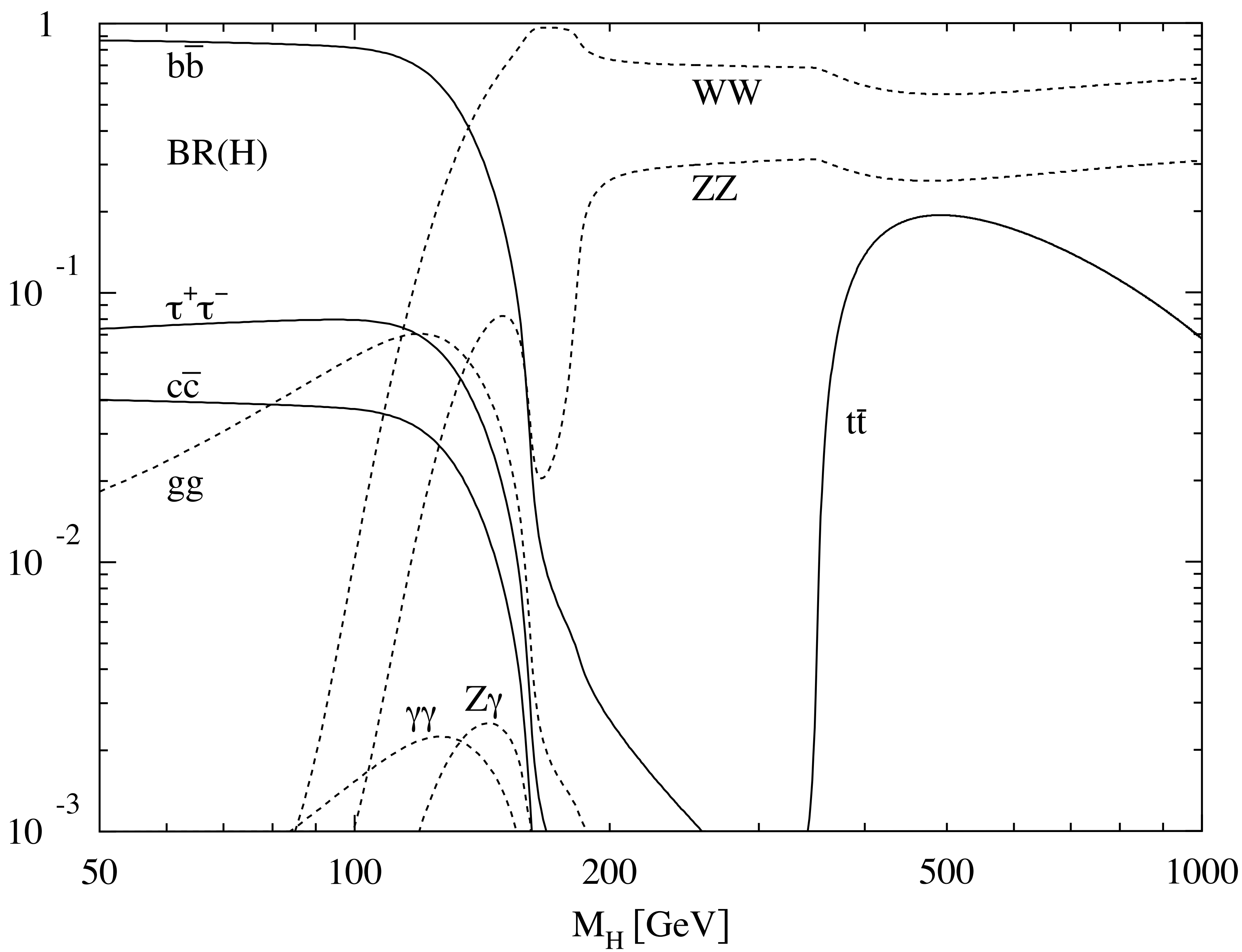
$M_H \sim 170$ GeV already excluded !

Higgs production at the LHC





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



Key point: enormous QCD background

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

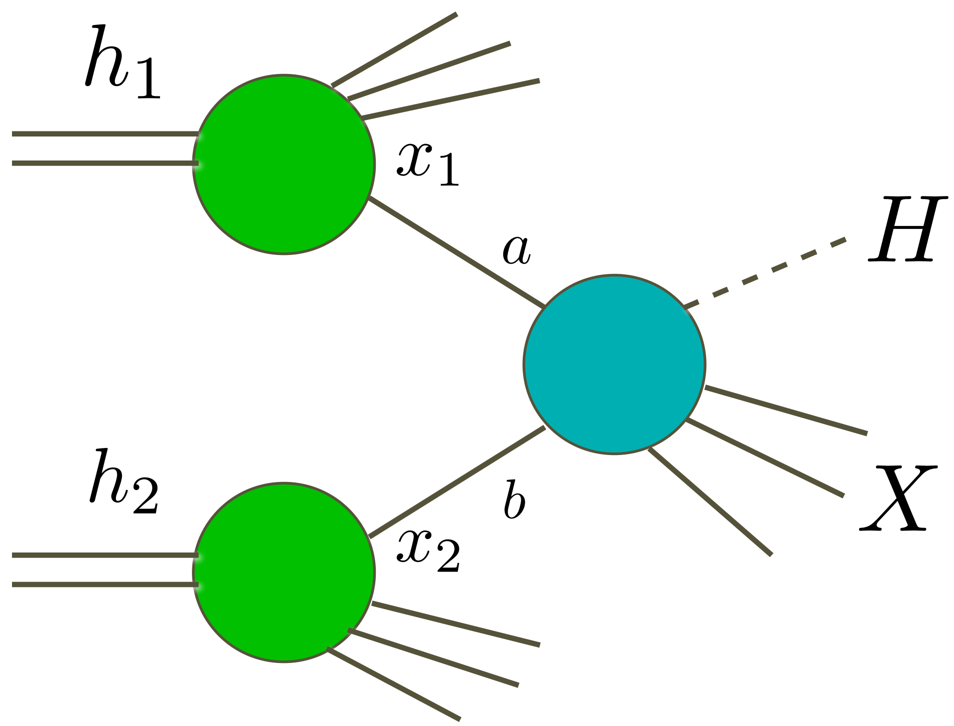
$\sigma(b\bar{b}) \sim 500\ \mu b$

→ No chance to look at fully hadronic final states

- For $M_H \lesssim 140$ GeV → $H \to \gamma\gamma$ (BR $\sim 10^{-3}$)
- For $140 \lesssim M_H \lesssim 180$ GeV → $H \to WW^* \to l\nu l\nu$
- $M_H > 2M_Z$ → $H \to ZZ \to 4l$ (gold pleated)

Theoretical predictions

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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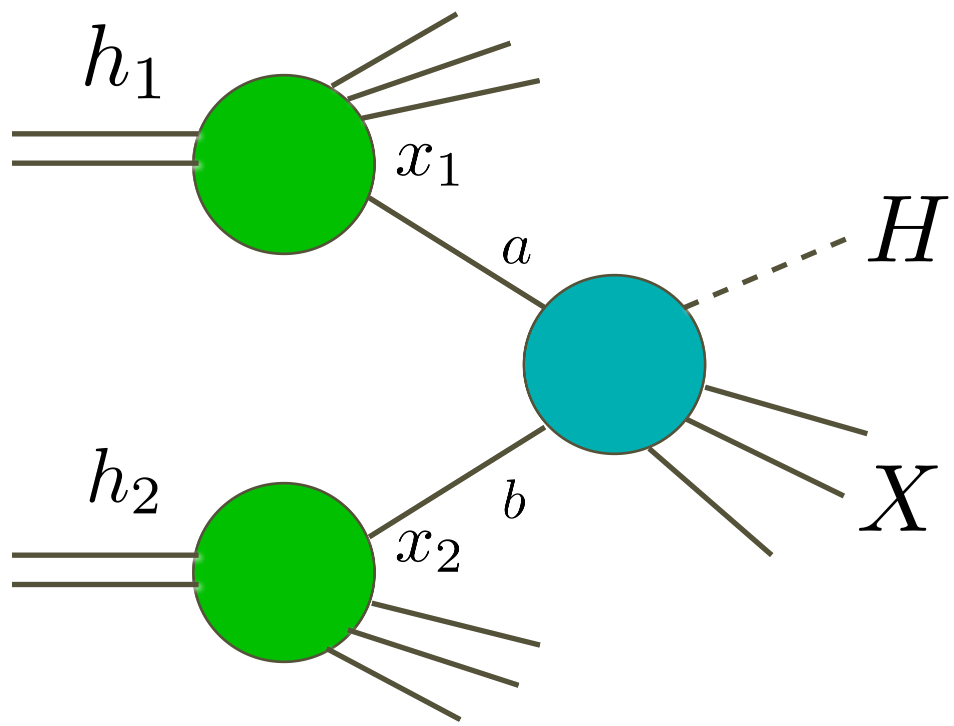

Parton distributions

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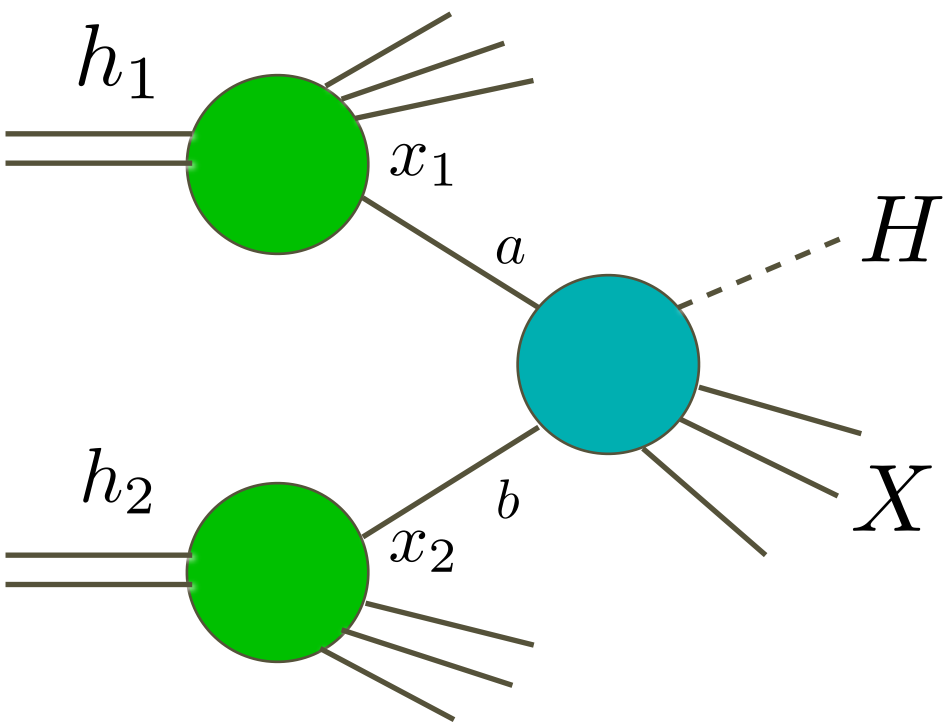

Parton distributions

Partonic cross section

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

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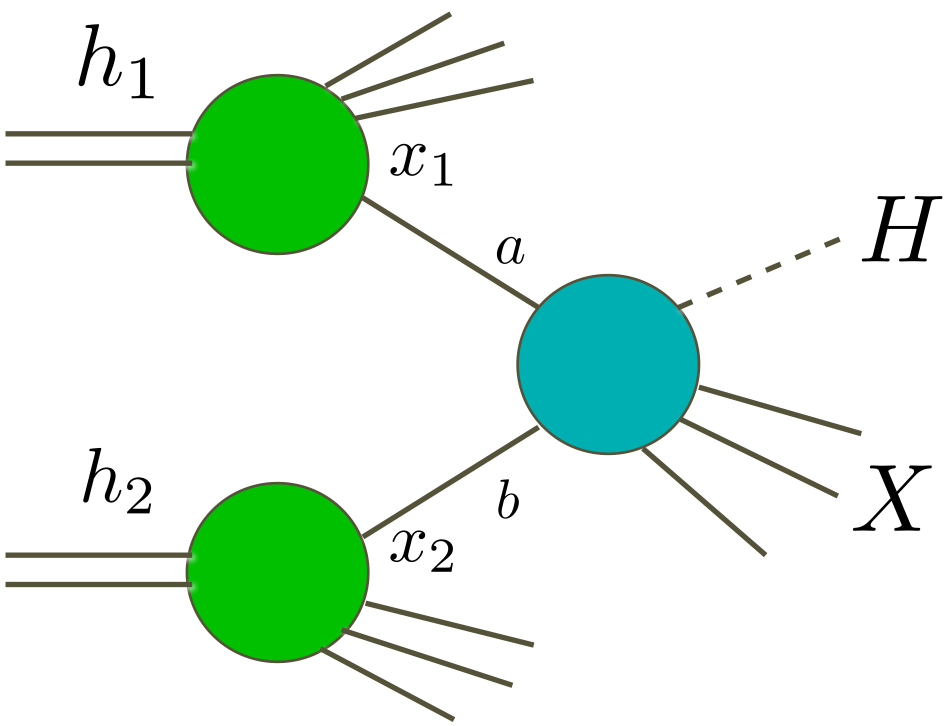

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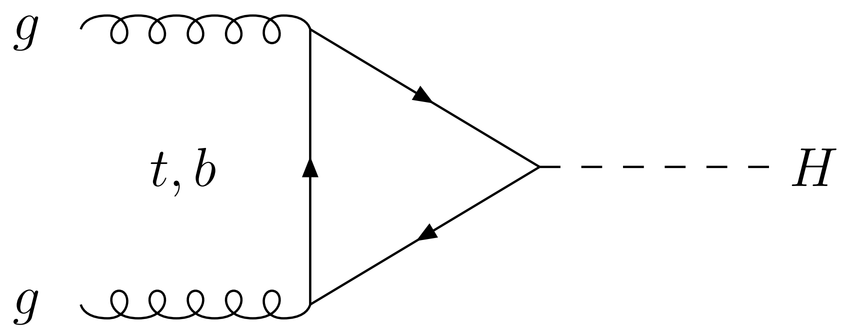
Precise predictions for σ depend on good knowledge of BOTH $\hat{\sigma}_{ab}$ and $f_{h,a}(x, \mu_F^2)$

gg fusion



SM: 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 % !

They are well approximated by the large- m_{top} limit (differences range from 1 to 4 % for $M_H < 200$ GeV)

S.Dawson (1991)
M.Kramer, E. Laenen, M.Spira(1998)

NNLO corrections to σ_H^{tot} computed in the large m_{top} limit

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: 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)

MSSM: 2 Higgs doublets → 5 physical Higgs bosons $h, H, A, H^{\pm}$

SM results can be extrapolated only for small tgβ

NLO corrections to squark loops known for large squark masses

S. Dawson, A. Djouadi, M. Spira (1991)

Full SUSY-QCD corrections in limit of the heavy SUSY masses

→ `evalcsusy`

R. Harlander, M. Steihauser (2003)

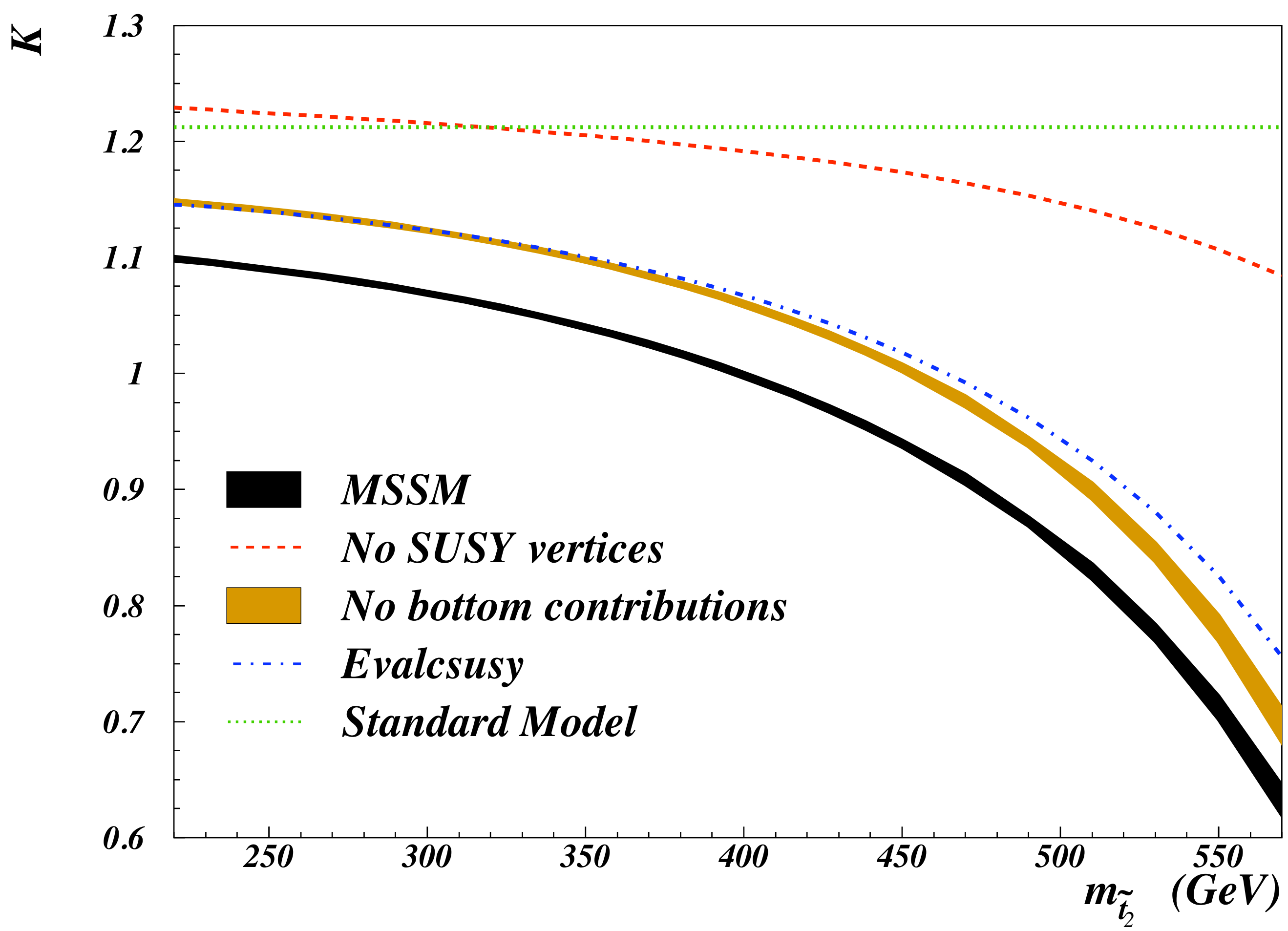
G.Degrassi, P.Slavich (2008)

Full NLO calculation of squarks contribution completed

M. Muhlleitner, M. Spira (2006)

Recently the calculation of the full two-loop amplitude in the MSSM was completed

C. Anastasiou, S. Beerli, A. Daleo (2008)



Relative effect with respect to the $\mathcal{O}(\alpha_S^2)$ result

$$\tan\beta = 20 \quad m_{\tilde{t}_1} = 150 \text{ GeV}$$

$$\mu = 300 \text{ GeV} \quad m_{\tilde{b}_1} = 350 \text{ GeV}$$

$$m_h = 115 \text{ GeV} \quad m_{\tilde{b}_2} = 370 \text{ GeV}$$

Effective field theory provides a very good approximation

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

Back to the SM:

NNLO corrections computed for arbitrary cuts

→ FEHIP, HNNLO

C. Anastasiou, K. Melnikov, F. Petrello(2005)
S.Catani, MG (2007)

- H+ 1 jet: NLO corrections known

D. de Florian, Z. Kunszt, MG (1999)
J. Campbell, K.Ellis (MCFM)

- H+ 2 jet: NLO corrections recently computed

J. Campbell, K.Ellis, G. Zanderighi (2006)

→ background for VBF

All these predictions are obtained in the large-m_{top} limit

→ (it is a good approximation for small transverse momenta of the accompanying jets)

Del Duca et al. (2001)

MSSM:

O. Brein, W. Hollik (2003)

h+ 1 jet known at LO only

HNNLO

S. Catani, MG (2007)

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 $q_T \to 0$

$$d\sigma^{F}_{(N)NLO} = \mathcal{H}^{F}_{(N)NLO} \otimes d\sigma^{F}_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right]$$

Depends on a single hard function $\mathcal{H}^H$

Finite as $q_T \to 0$

An example: $gg \to H \to \gamma\gamma$

Use cuts as in CMS TDR

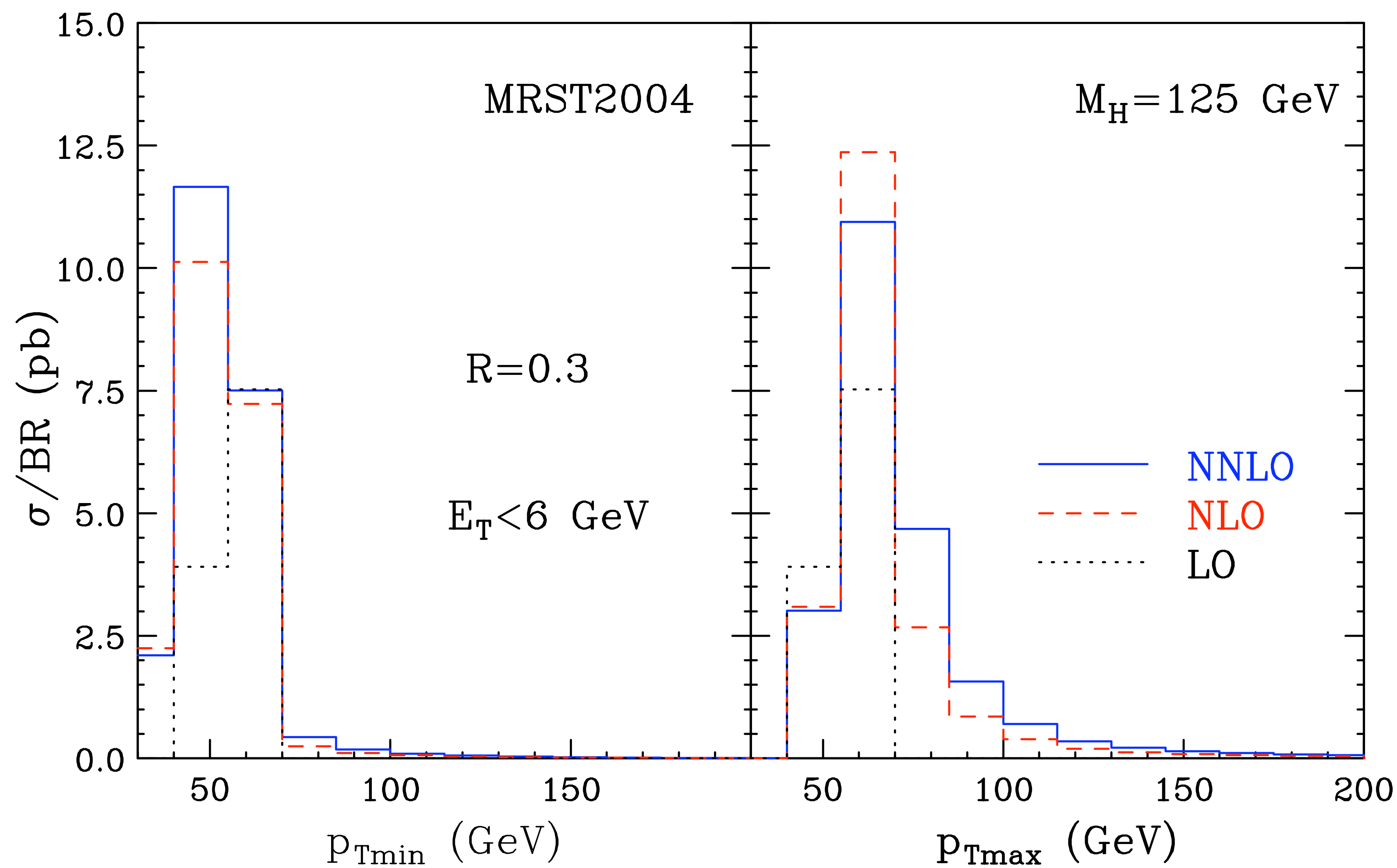
$p_T^{\min} > 35$ GeV

$p_T^{\max} > 40$ 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

An example: $gg \to H \to \gamma\gamma$

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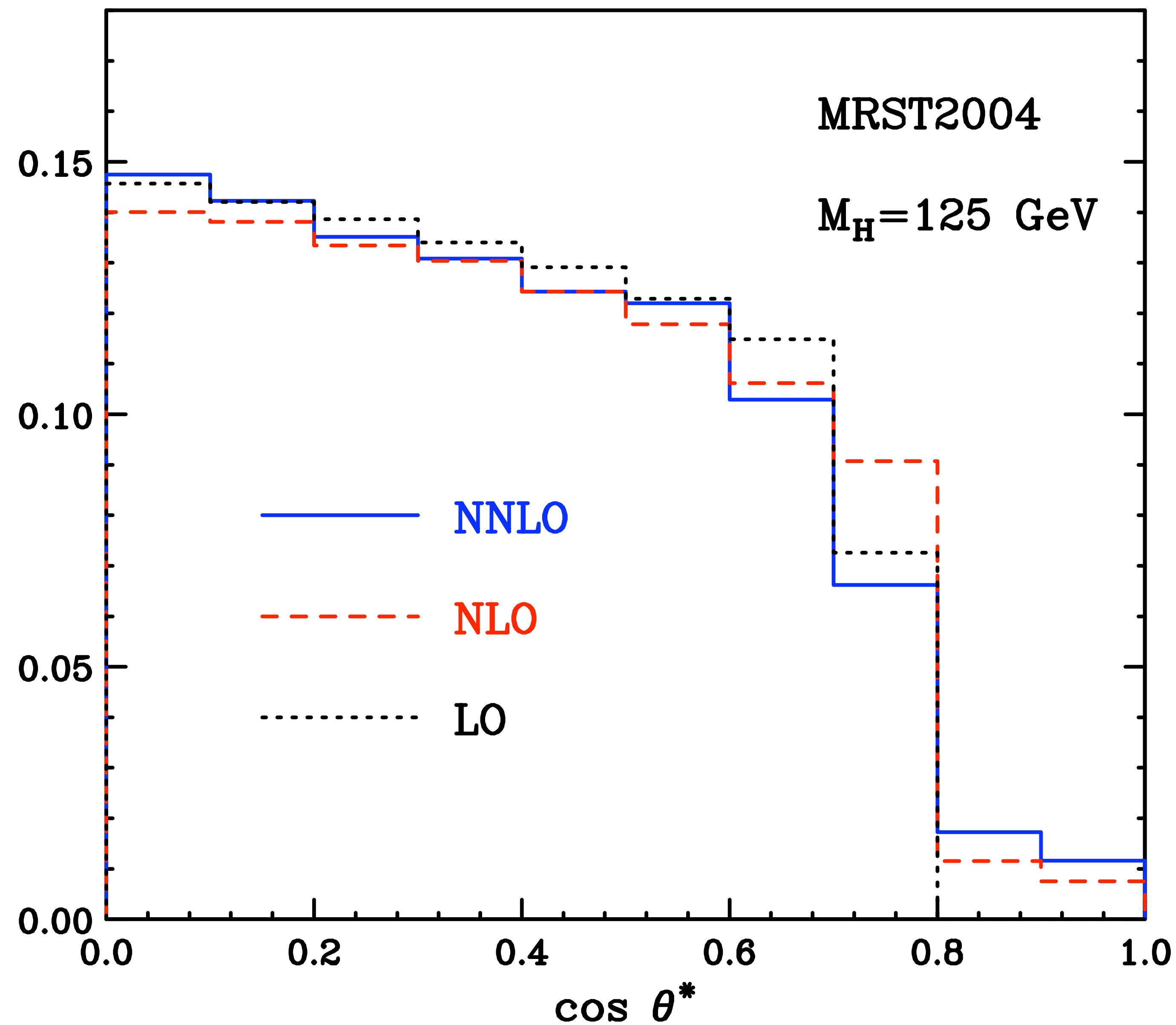
define $\cos\theta^*$ **distribution**

θ^* **polar angle of one of the photons in the Higgs rest frame (used by ATLAS)**

note upper bound on $\cos\theta^*$ at LO

➡ again perturbative instability beyond LO !



An example: $gg \to H \to WW \to l\nu l\nu$

MG (2007)

Use preselection cuts as in Davatz. et al (2003)

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

$p_T^l > 20$ GeV

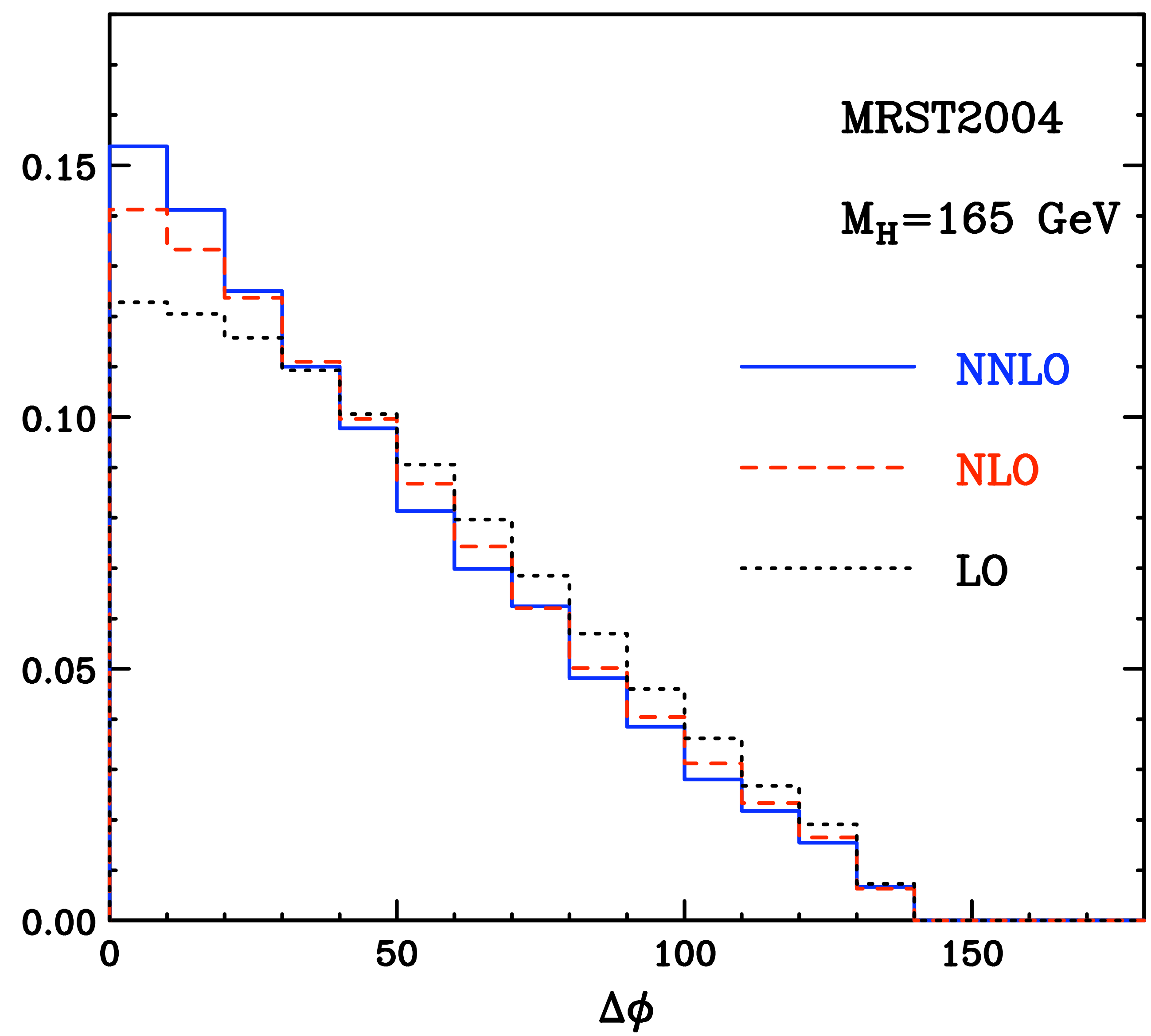
$|y_l| < 2$

$p_T^{\rm miss} > 20$ GeV

$\Delta\phi < 135^o$

$m_{ll} < 80$ GeV

normalized $\Delta\phi$ **distribution**



The distributions appears to be steeper when going from LO to NLO and from NLO to NNLO

Use now *selection cuts* as in Davatz. et al (2003)

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

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

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

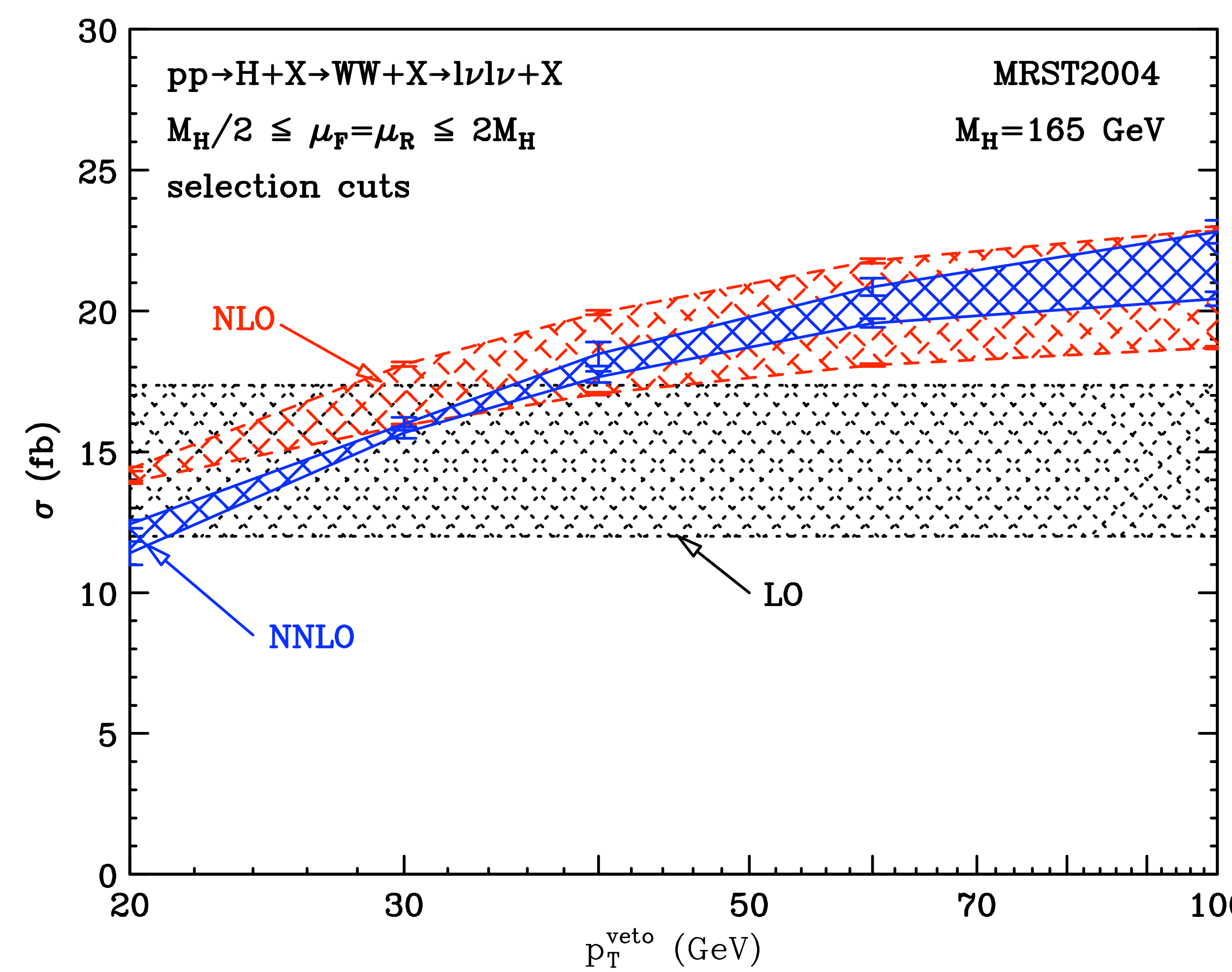
Impact of higher order corrections strongly reduced by selection cuts

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

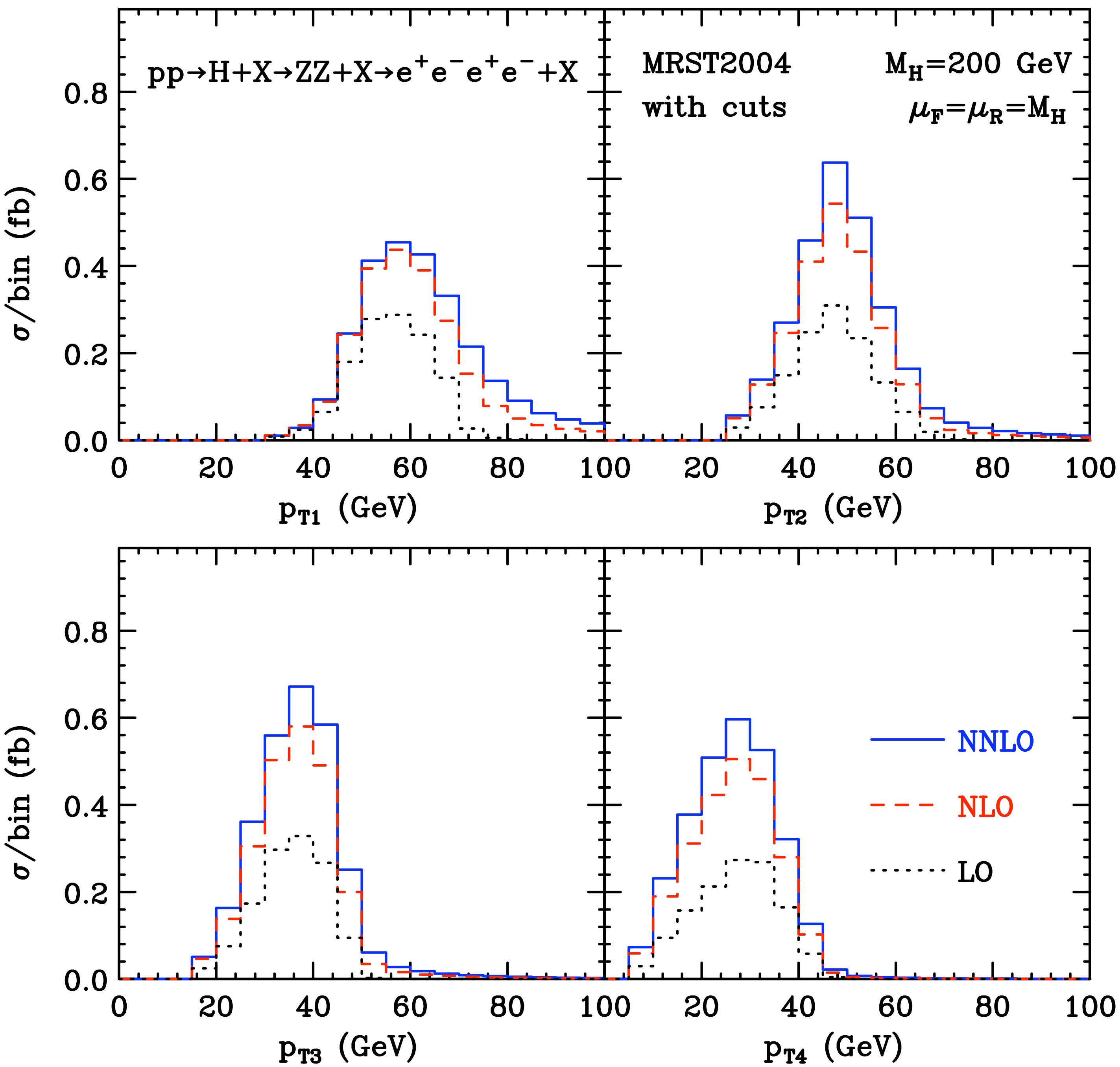
➡ $81 \text{ GeV} < m_1 < 101 \text{ GeV}$ and $40 \text{ GeV} < m_2 < 110 \text{ GeV}$

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

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

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

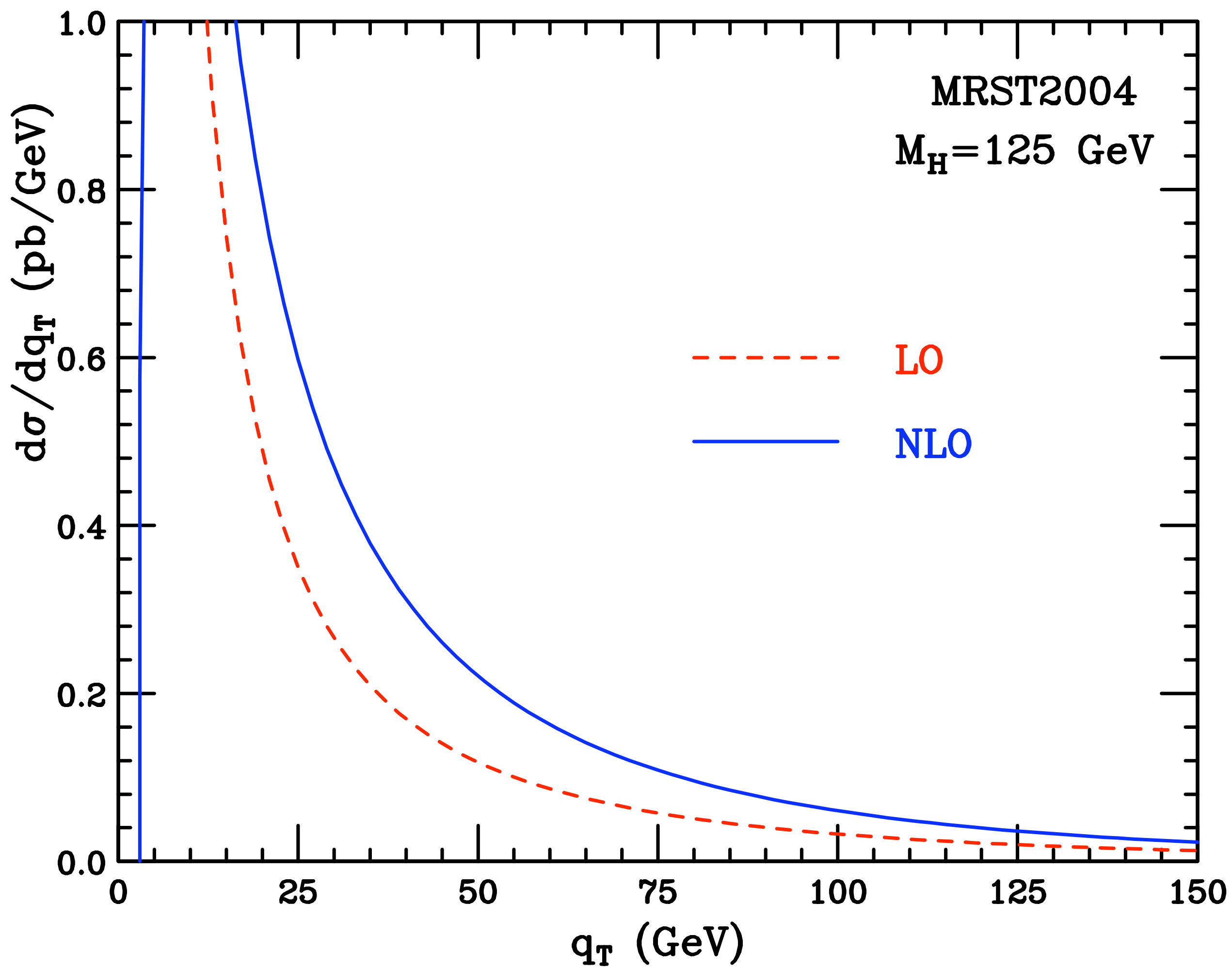
Behaviour at the kinematical boundary is smooth

No instabilities beyond LO

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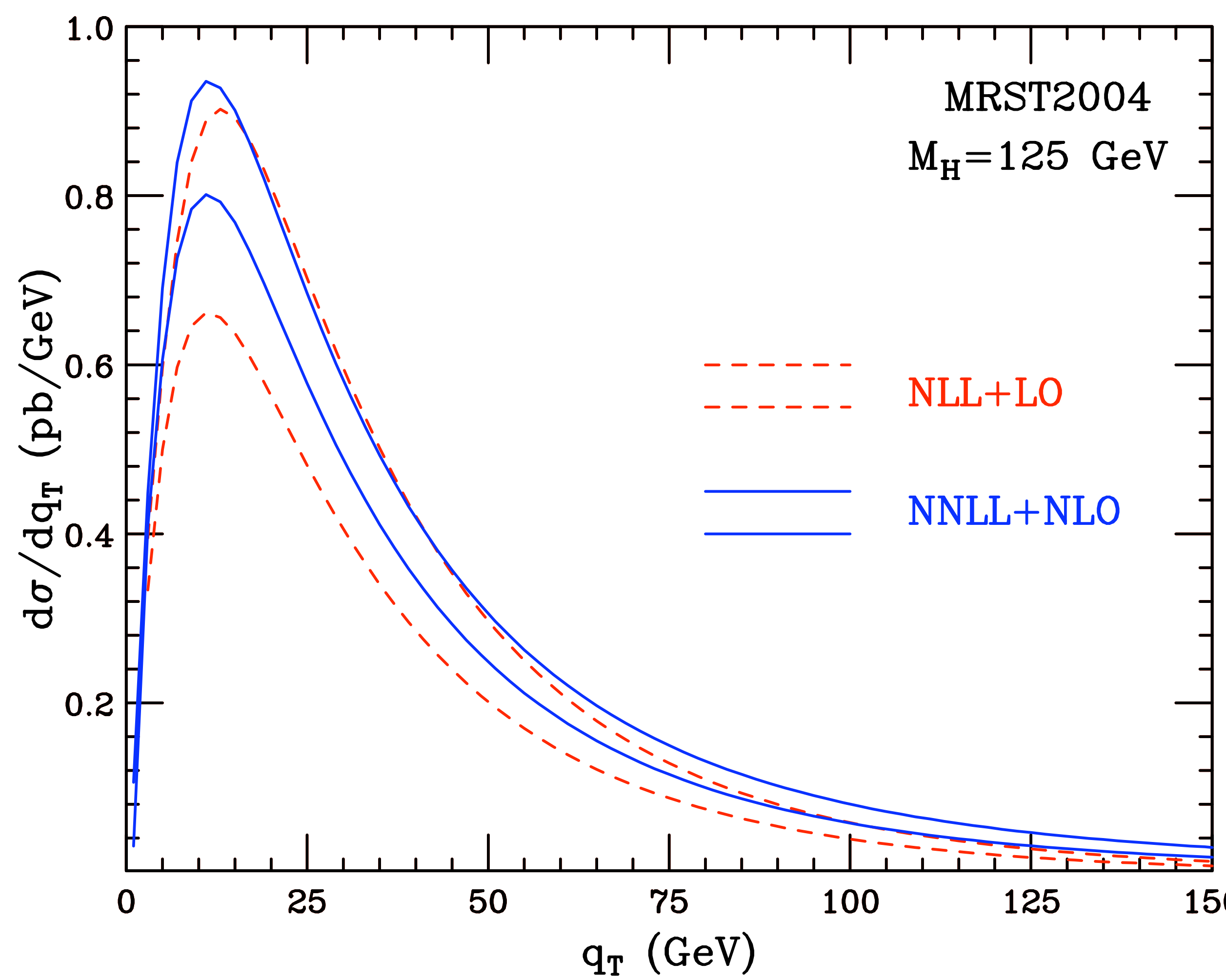
G. Bozzi, S. Catani, D. de Florian, MG (2003, 2005)

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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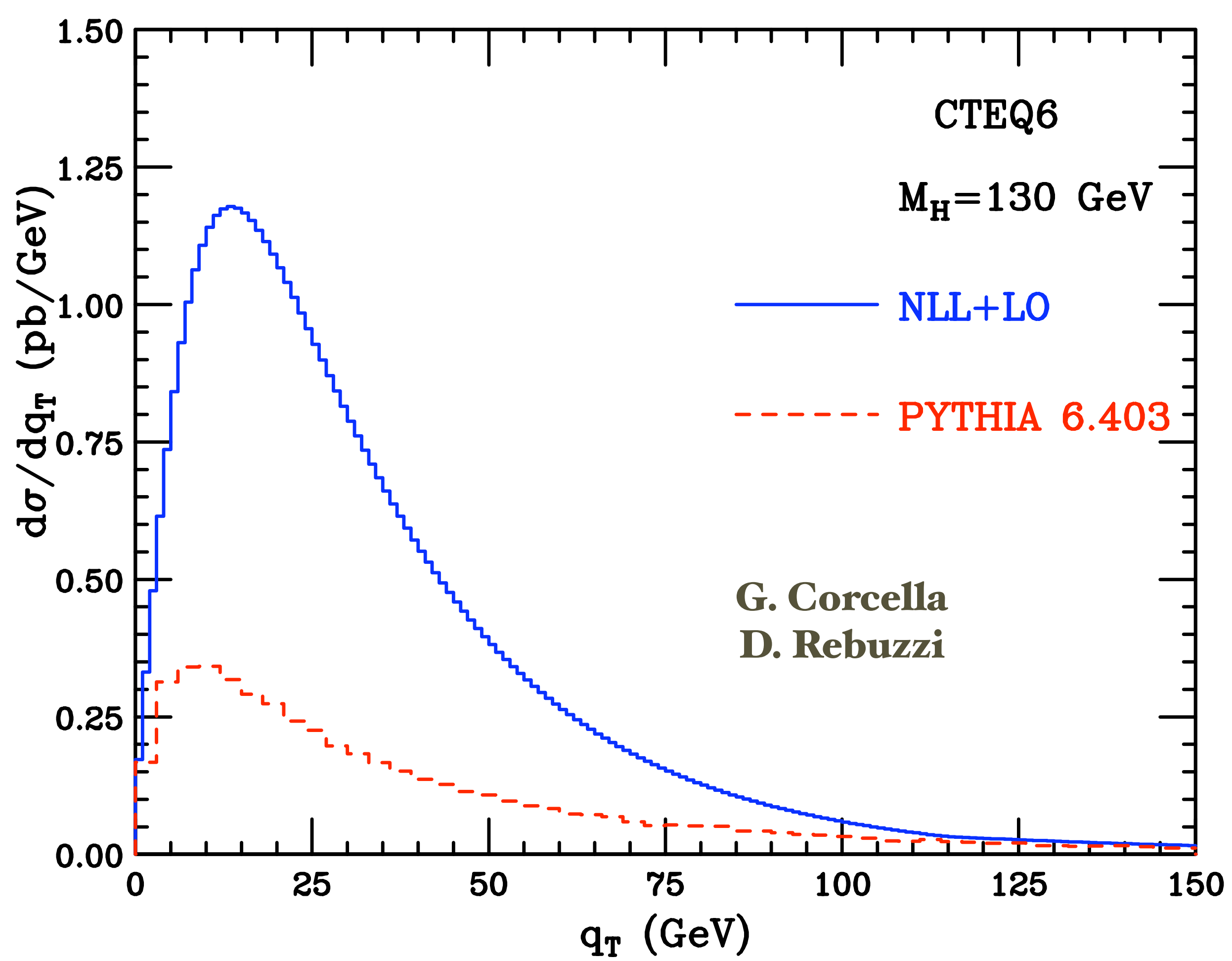
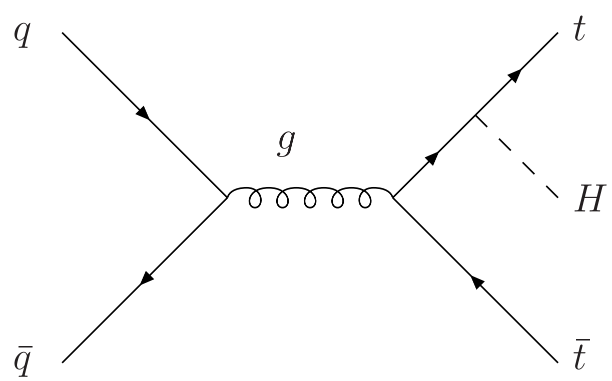
Highly stable results → HqT

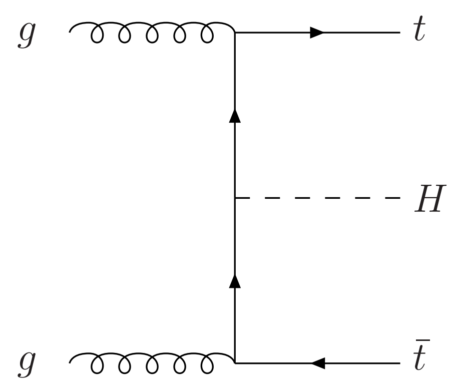
The resummation is effectively performed through standard MC event generators.....

PYTHIA PEAK STILL SOFTER !



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:

$H \rightarrow b\bar{b}$ 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)

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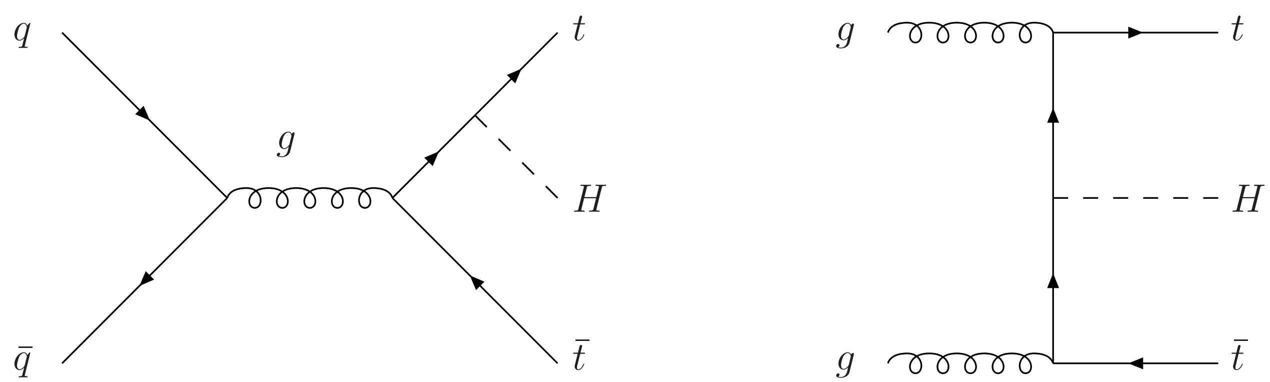

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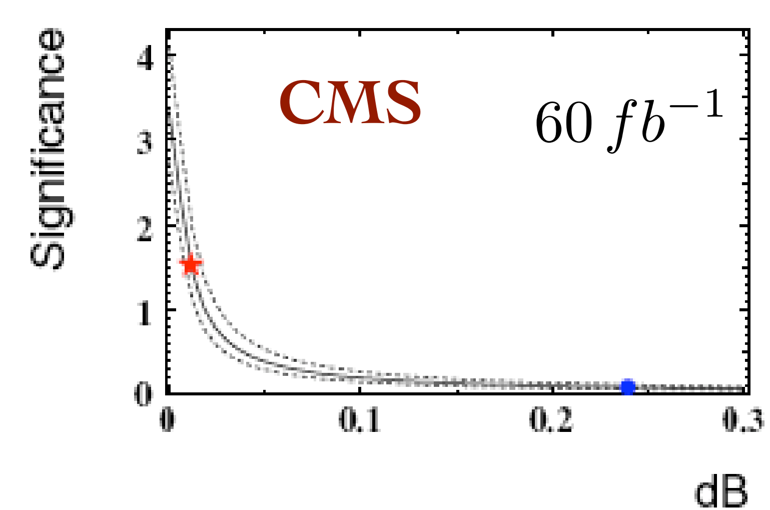
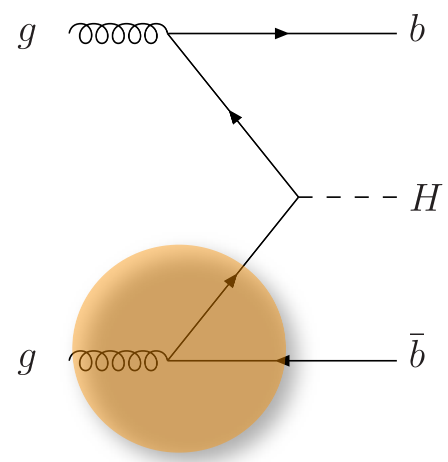
BUT....

full detector simulation and better background evaluation lead to more pessimistic view



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

In the SM the cross section is very small but it becomes dominant in the MSSM at large $\tan\beta = v_u/v_d$



Already at LO there are large contributions of the form $\alpha_S \log M_H/m_b$ originating from the collinear splitting $g \to b\bar{b}$

two computational schemes:

- four-flavour scheme (begins with $gg \to b\bar{b}H$ at LO)
- five-flavour scheme: introduces bottom pdf (begins with $b\bar{b} \to H$ at LO)

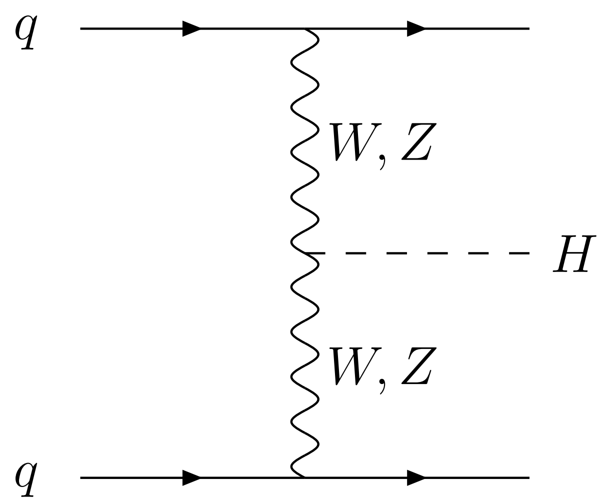
Higher order corrections computed in the two schemes

R.Harlander, W.Kilgore (2003)
S. Dittmaier, M. Kramer, M. Spira(2003)
S.Dawson, C. Jackson, L.Reina, D. Wackeroth (2003)
J.Campbell, K. Ellis, F.Maltoni, S. Willenbrock (2003)

Careful comparison performed in recent years

Initial differences reduced if more consistent comparison is performed

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 $5 - 10\%$

T. Han, S. Willenbrock (1991)

Now implemented for distributions

T. Figy, C. Oleari, D. Zeppenfeld (2003)
J. Campbell, K. Ellis (2003)

EW corrections also known and of the same order

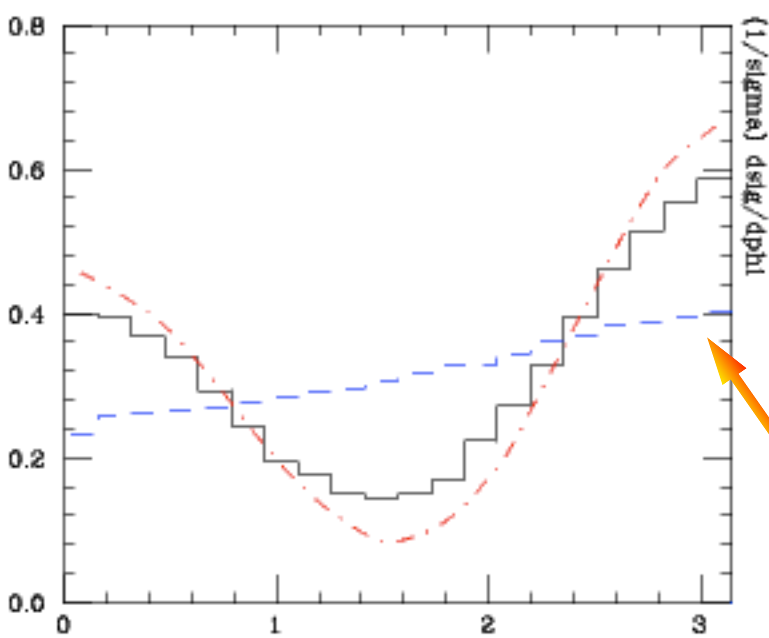
M.Ciccolini, A.Denner, S.Dittmaier (2007)

→ 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



gg fusion

VBF

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)

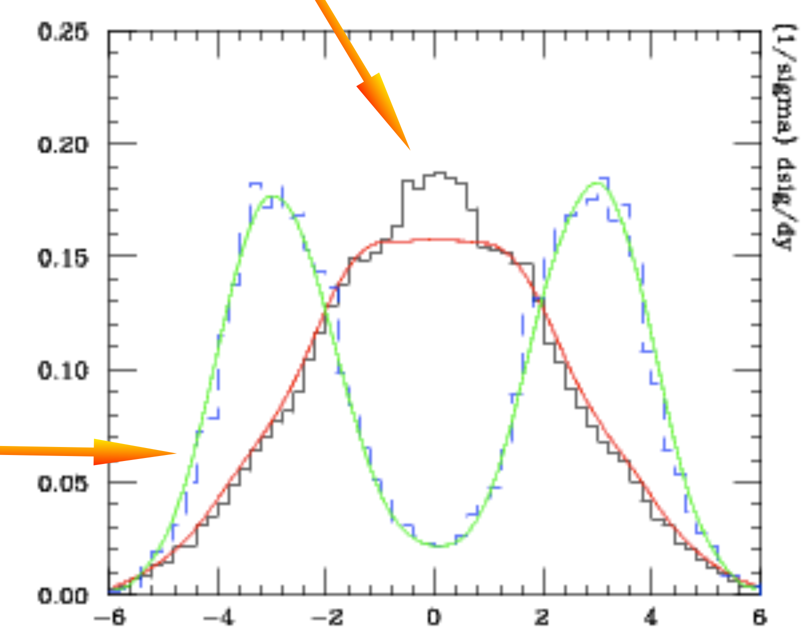
gg fusion

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

→ Apply central jet veto

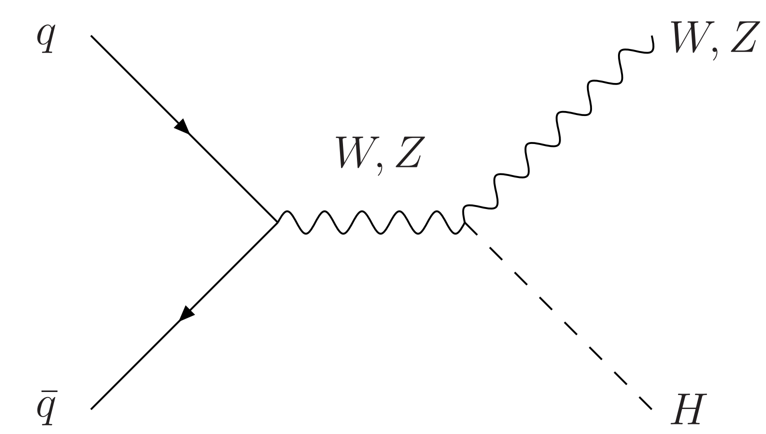
Impact of $\ln M_H/p_T^{\text{veto}}$?

VBF



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)

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 $M_H \geq 114.4$ at 95% CL
- The Tevatron may exclude a light Higgs or could see a Higgs signal if enough integrated luminosity will be accumulated
- The SM Higgs can be discovered at the LHC over the full mass range in about one year of run at low luminosity
- 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