Precision calculations for Higgs physics

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CERN Theory Colloquium, august 3, 2011

*On leave of absence from INFN, Sezione di Firenze

Outline

- Introduction
- Inclusive cross sections
  - gg fusion
  - Vector boson fusion
  - Associated VH production
  - Associated production with a $t\bar{t}$ pair
- The NNLO revolution
  - WH
  - $\gamma\gamma$
- Theory uncertainties: two issues
  - Scale uncertainties and jet bins
  - Heavy Higgs
- Summary and Outlook

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)

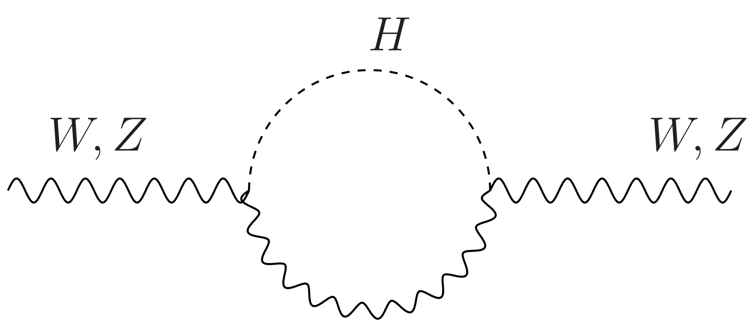
- LEP has put a lower limit on the mass of the SM Higgs boson at $m_H \geq 114.4$ GeV at 95% CL

- 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**

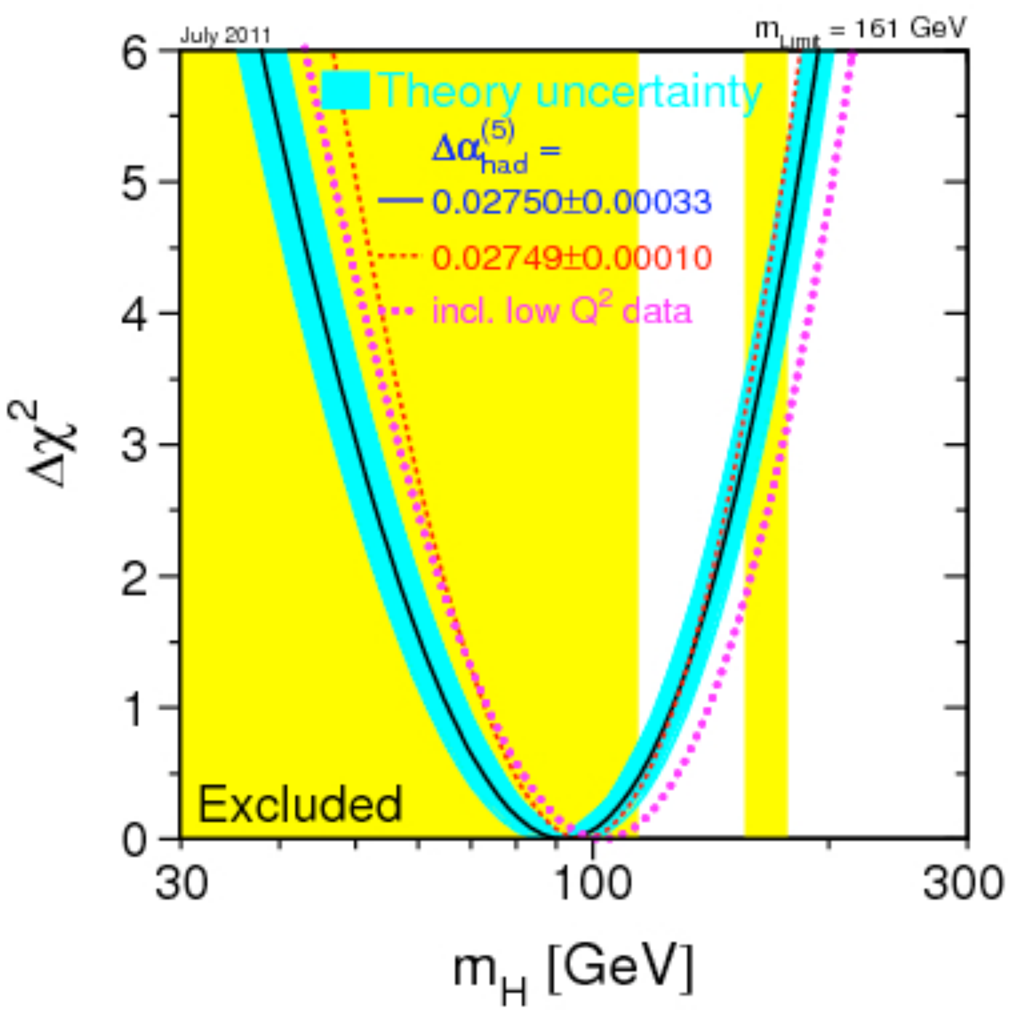
.... but screening effect: the dependence is only logarithmic at one loop (for top quark the dependence is quadratic → m_{top} predicted before discovery !)



→

$$m_H = 92^{+34}_{-26}\ \text{GeV}$$
$$m_H < 157\ \text{GeV}\ \text{ at 95 \% CL}$$

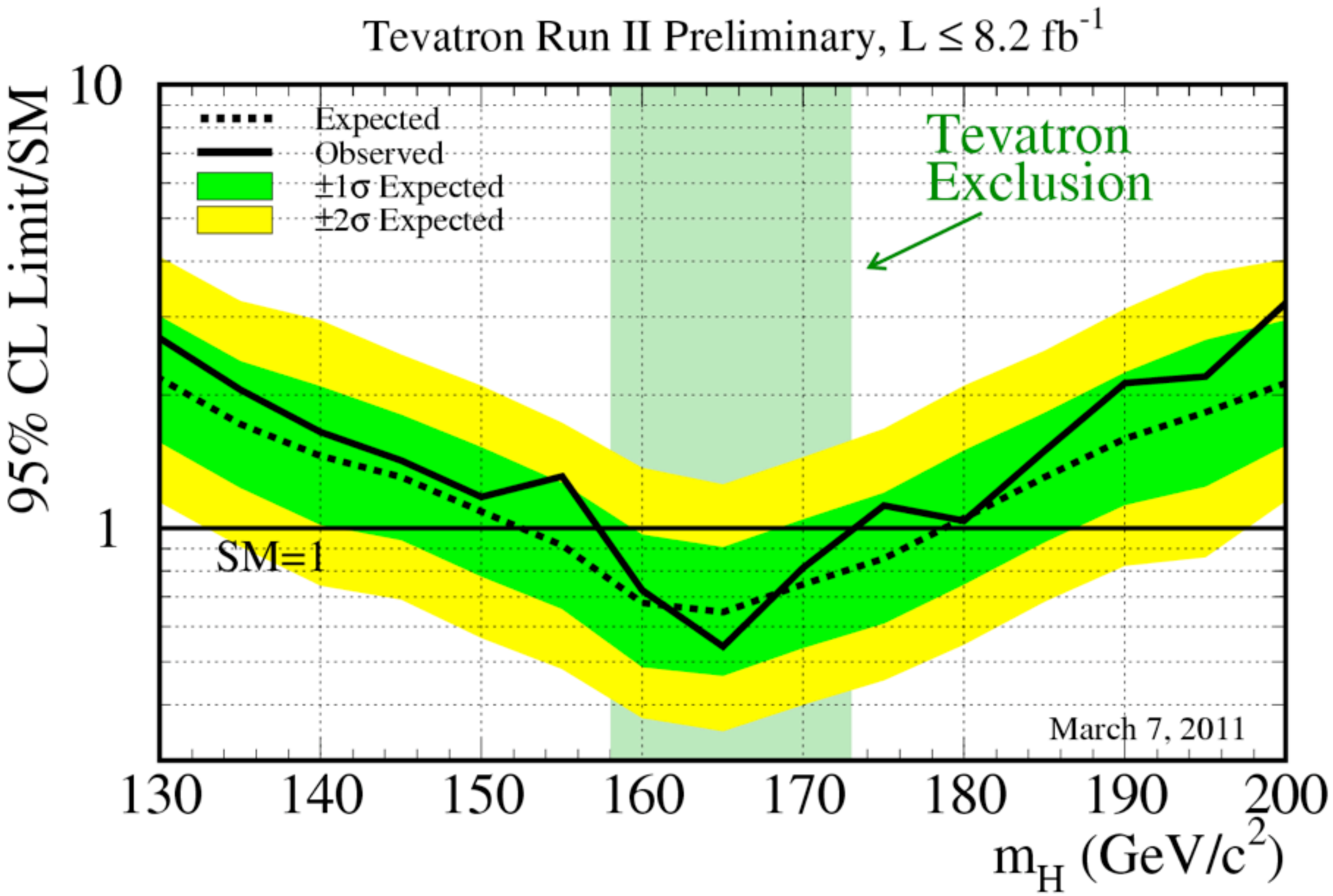
LEP EWWG, july 2011

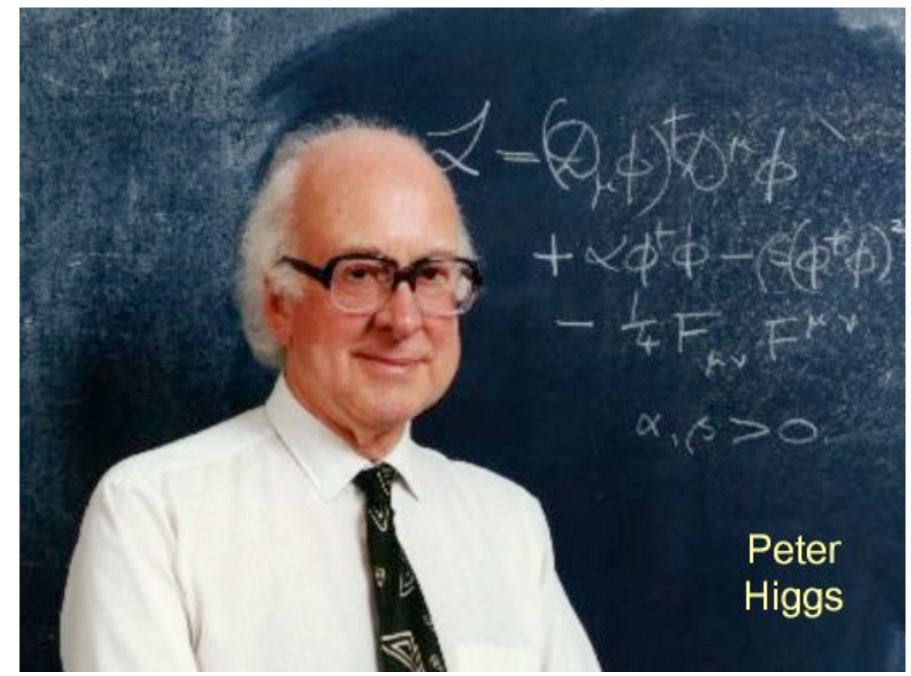


Taking into account LEP limit:

$$m_H < 185\ \text{GeV}\ \text{ at 95 \% CL}$$

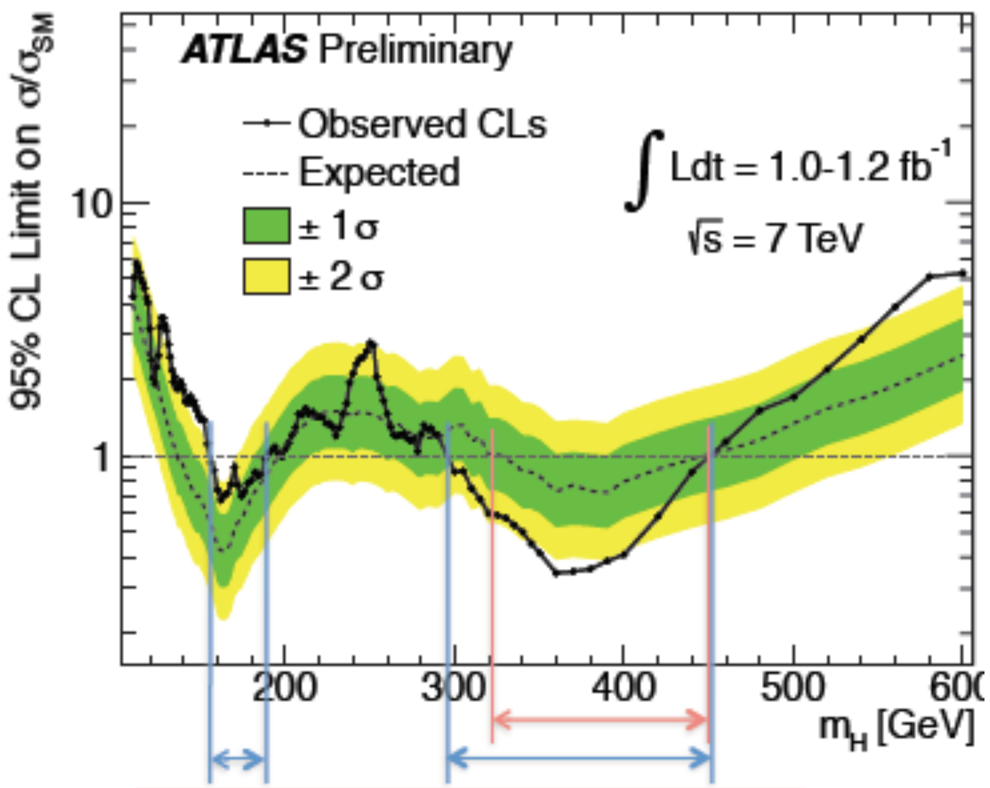
Where we were....



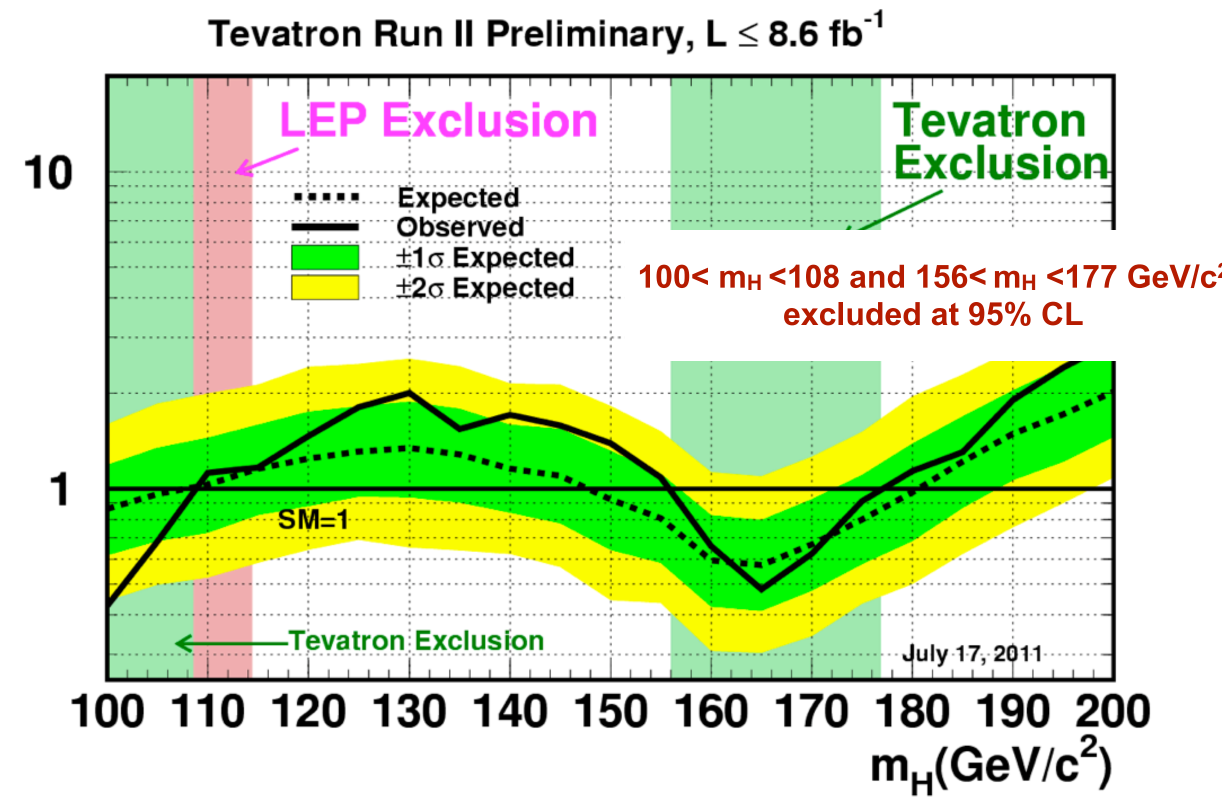


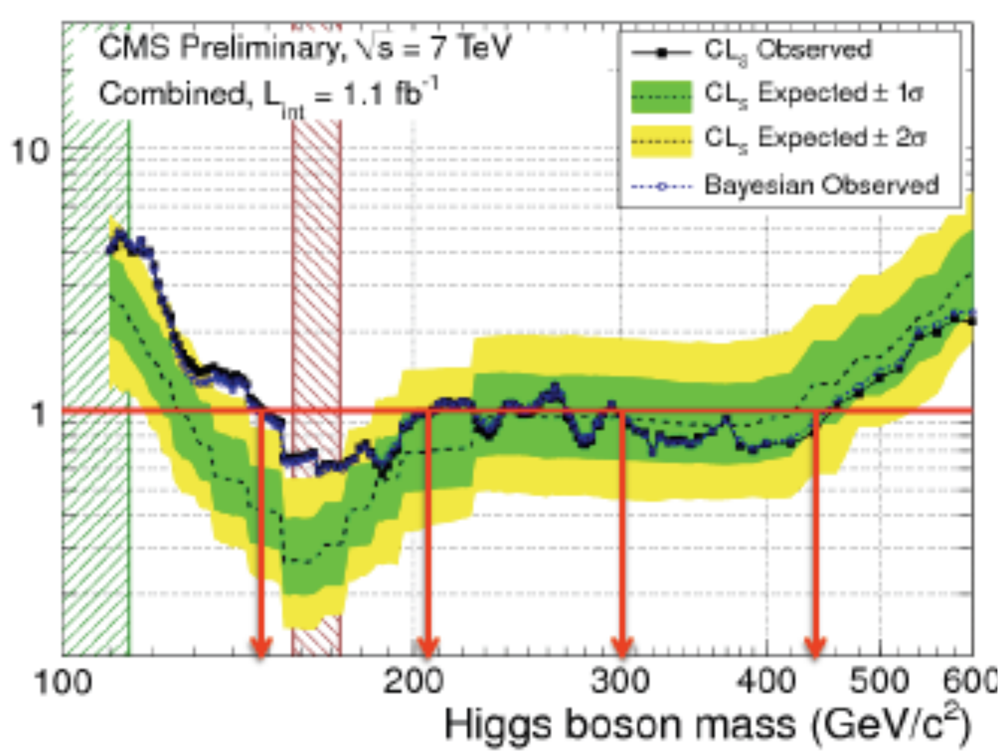
Tevatron combination of Winter 2011:
SM Higgs boson with 158 GeV ≤ m_H ≤ 173 GeV excluded at 95% CL

Where we are now !



155<M_H<190 and 295 <M_H< 450 GeV/c^2
excluded at @ 95% CL

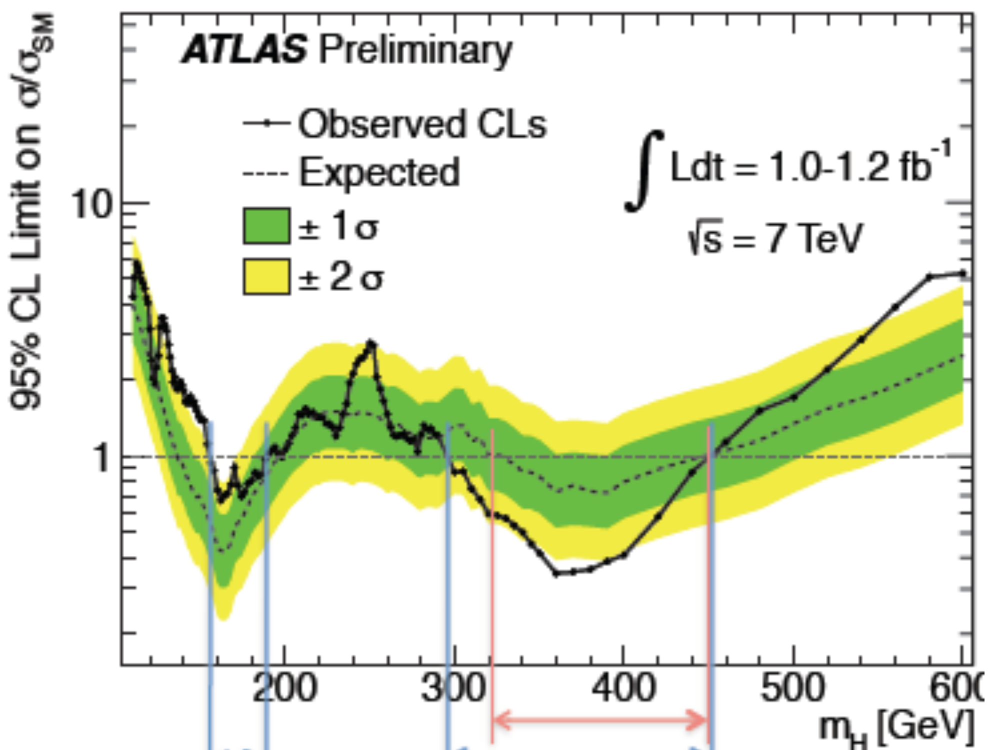




Excluded (GeV)

[149-206] … [300-440] and 3 short segments in between

Where we are now !



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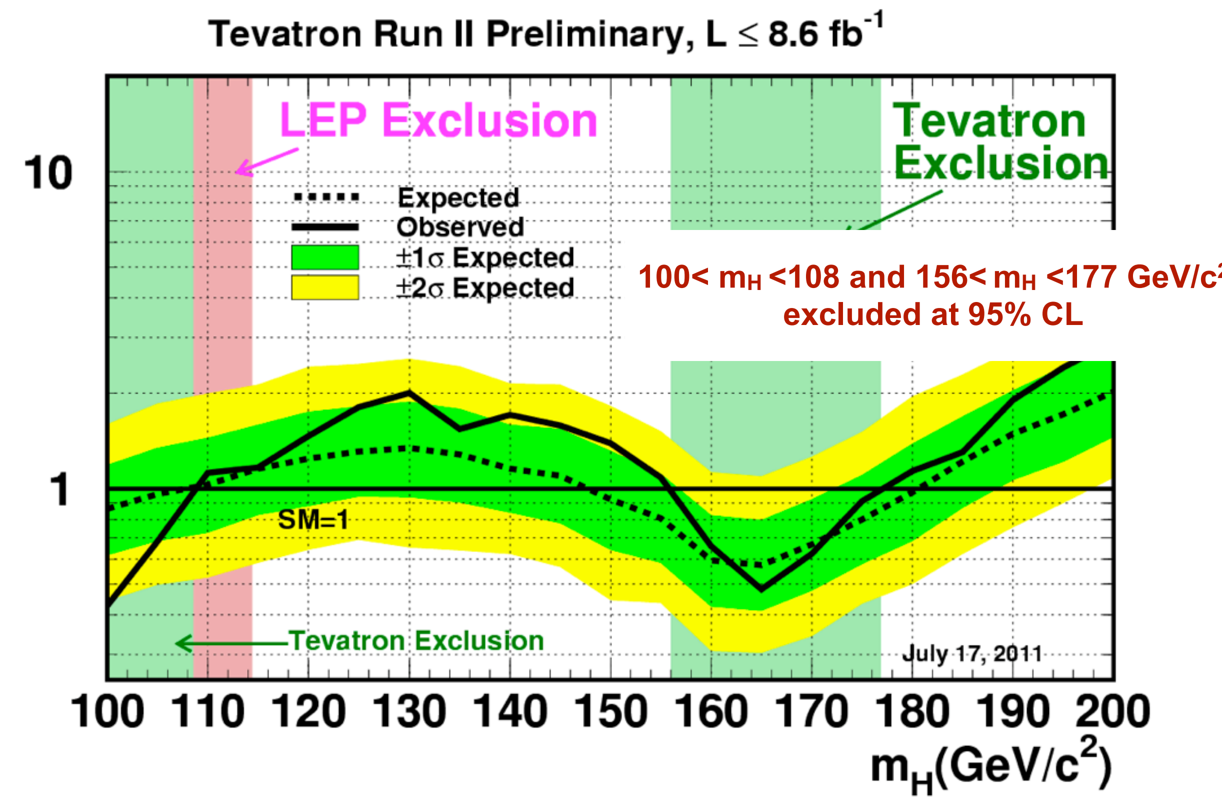

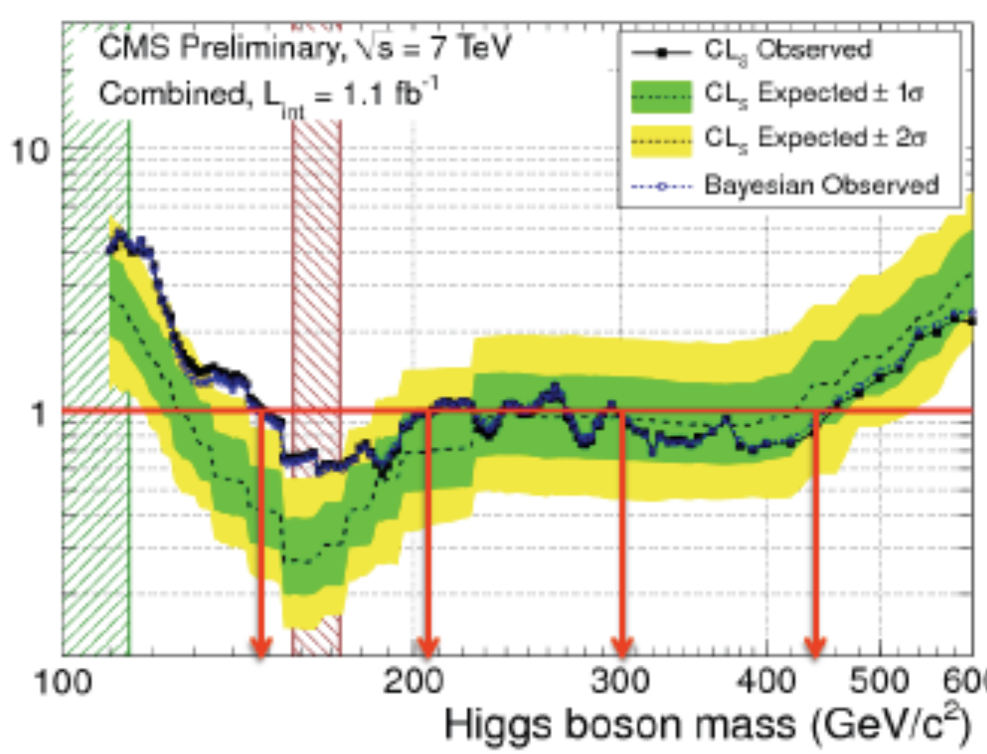

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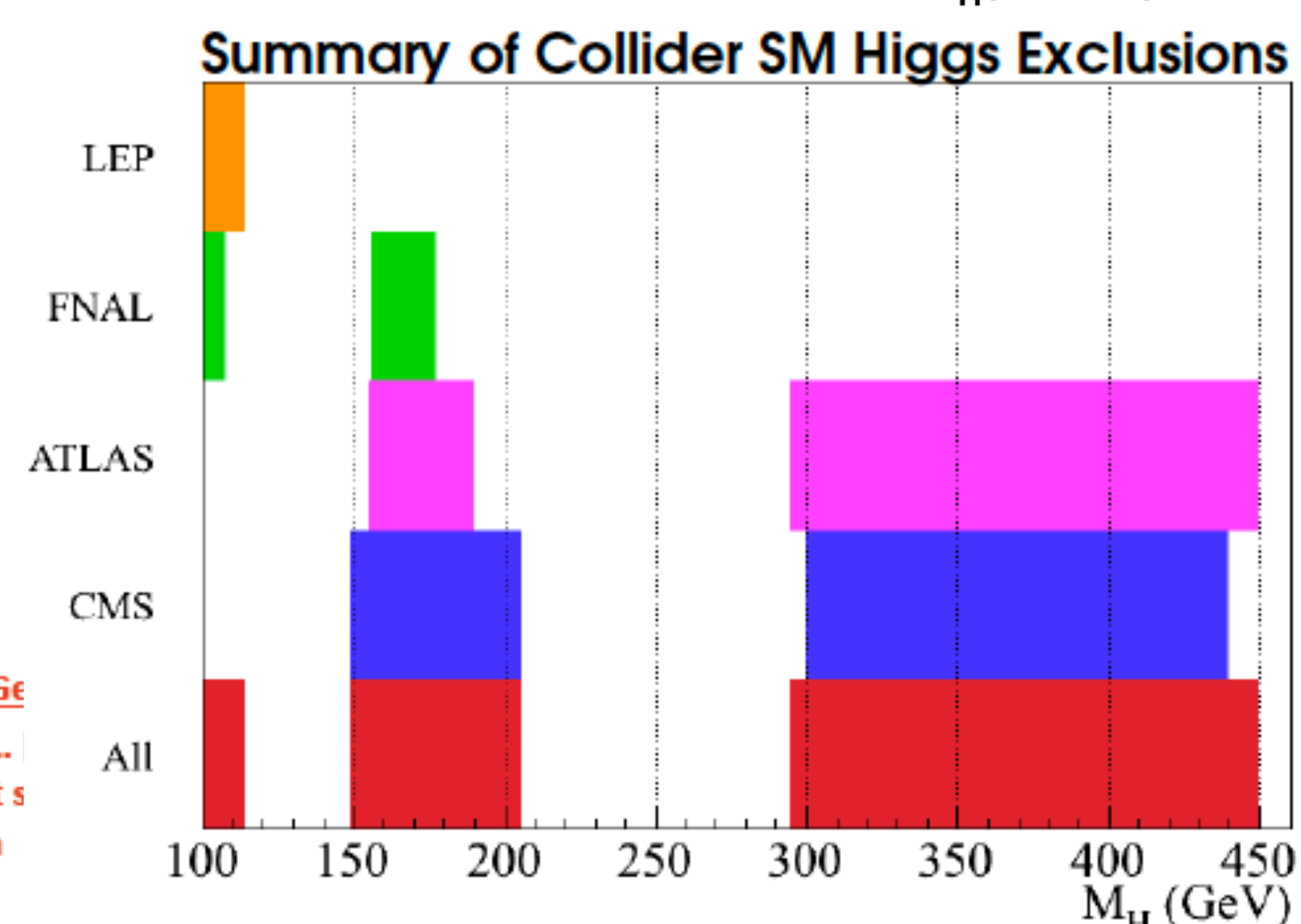
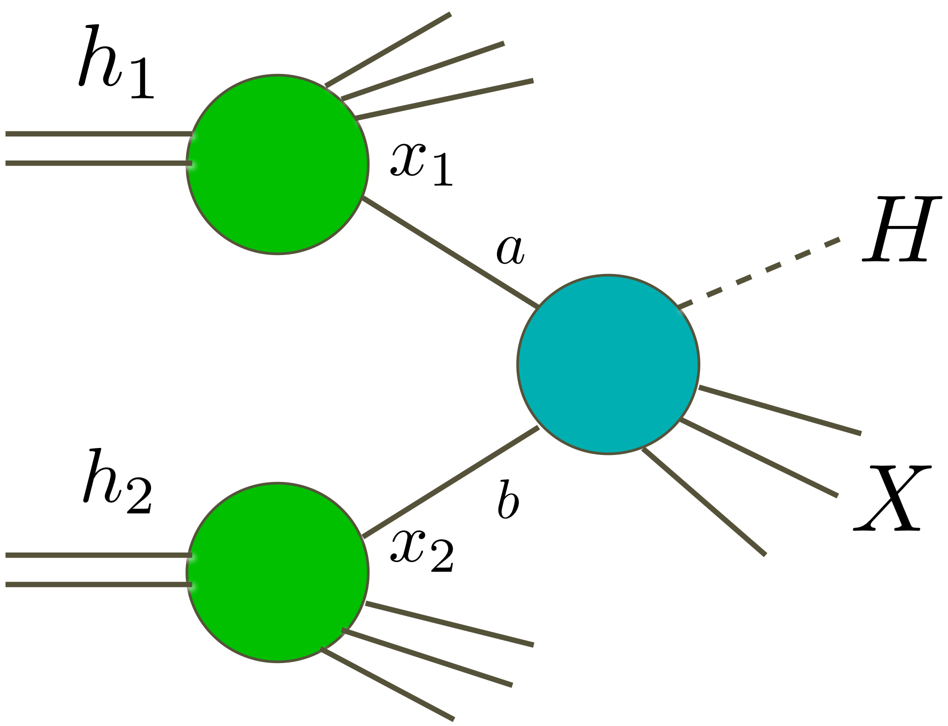


Theoretical predictions

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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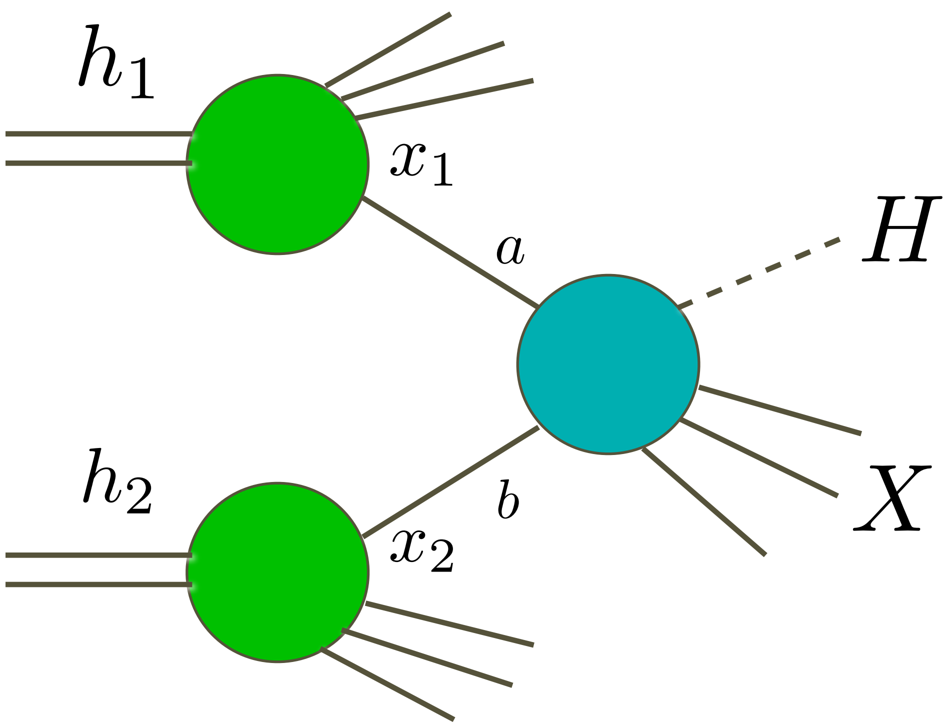

Parton distributions

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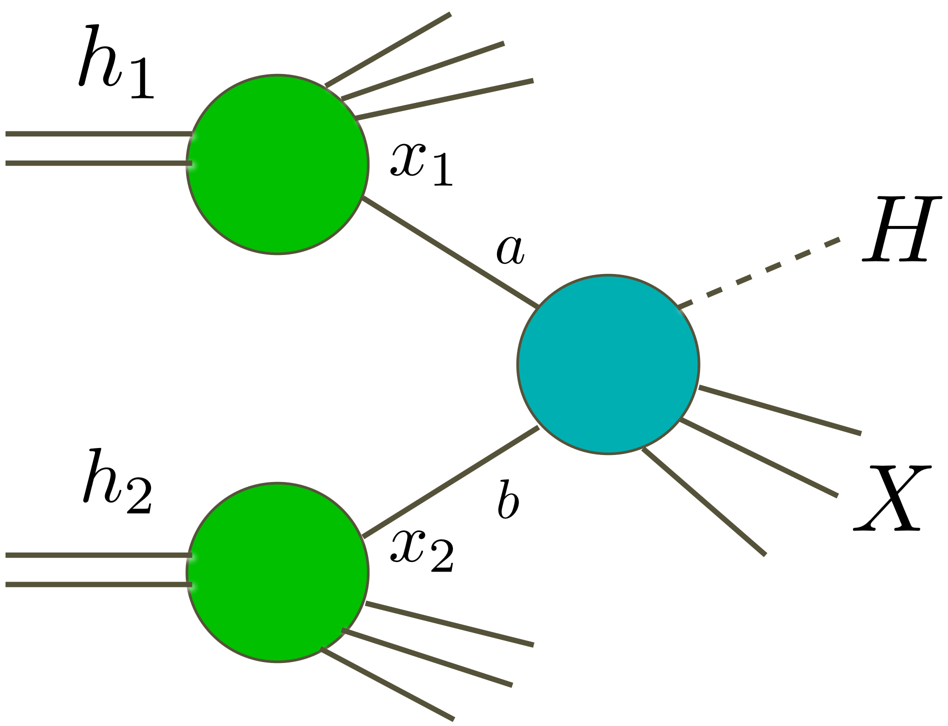

Parton distributions

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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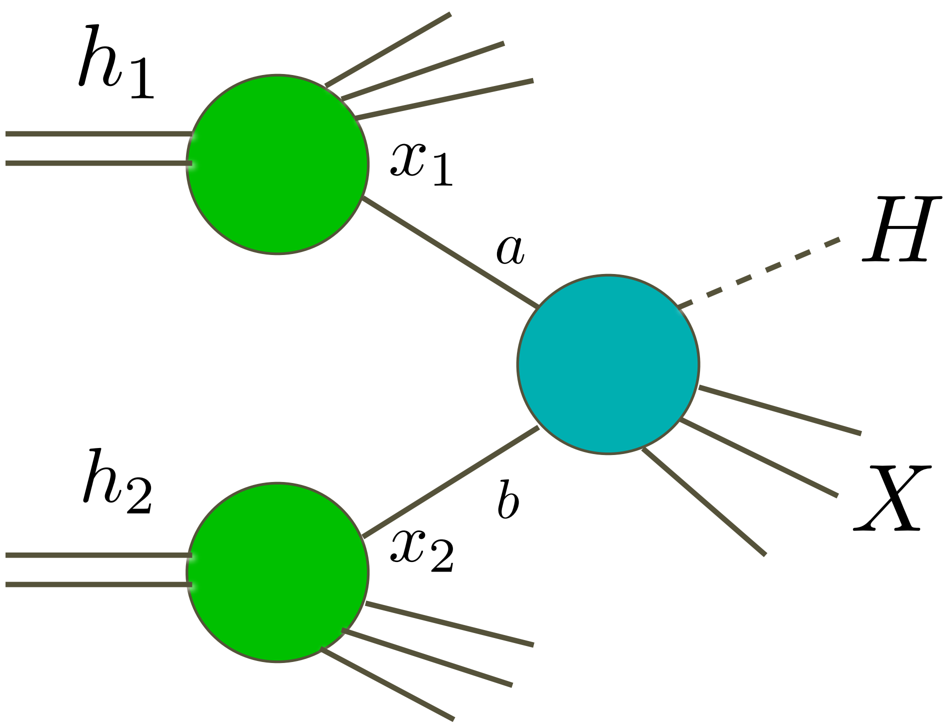

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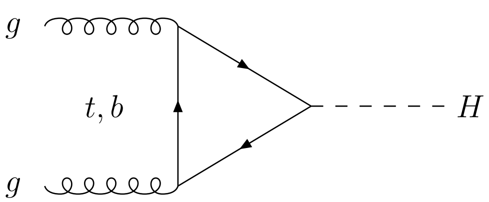
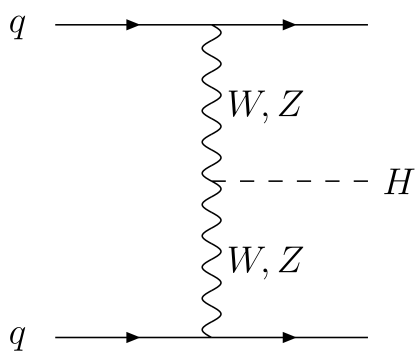
Precise predictions for σ depend on good knowledge of BOTH $\hat{\sigma}_{ab}$ and $f_{h,a}(x, \mu_F^2)$

1) Inclusive cross sections

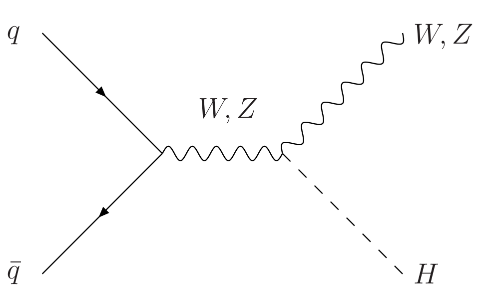
Inclusive cross sections



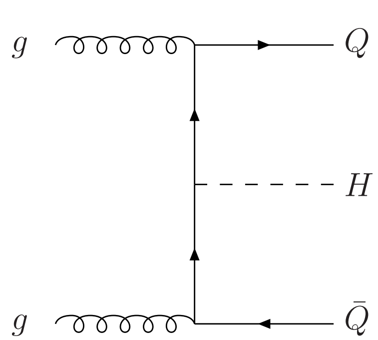
gg fusion



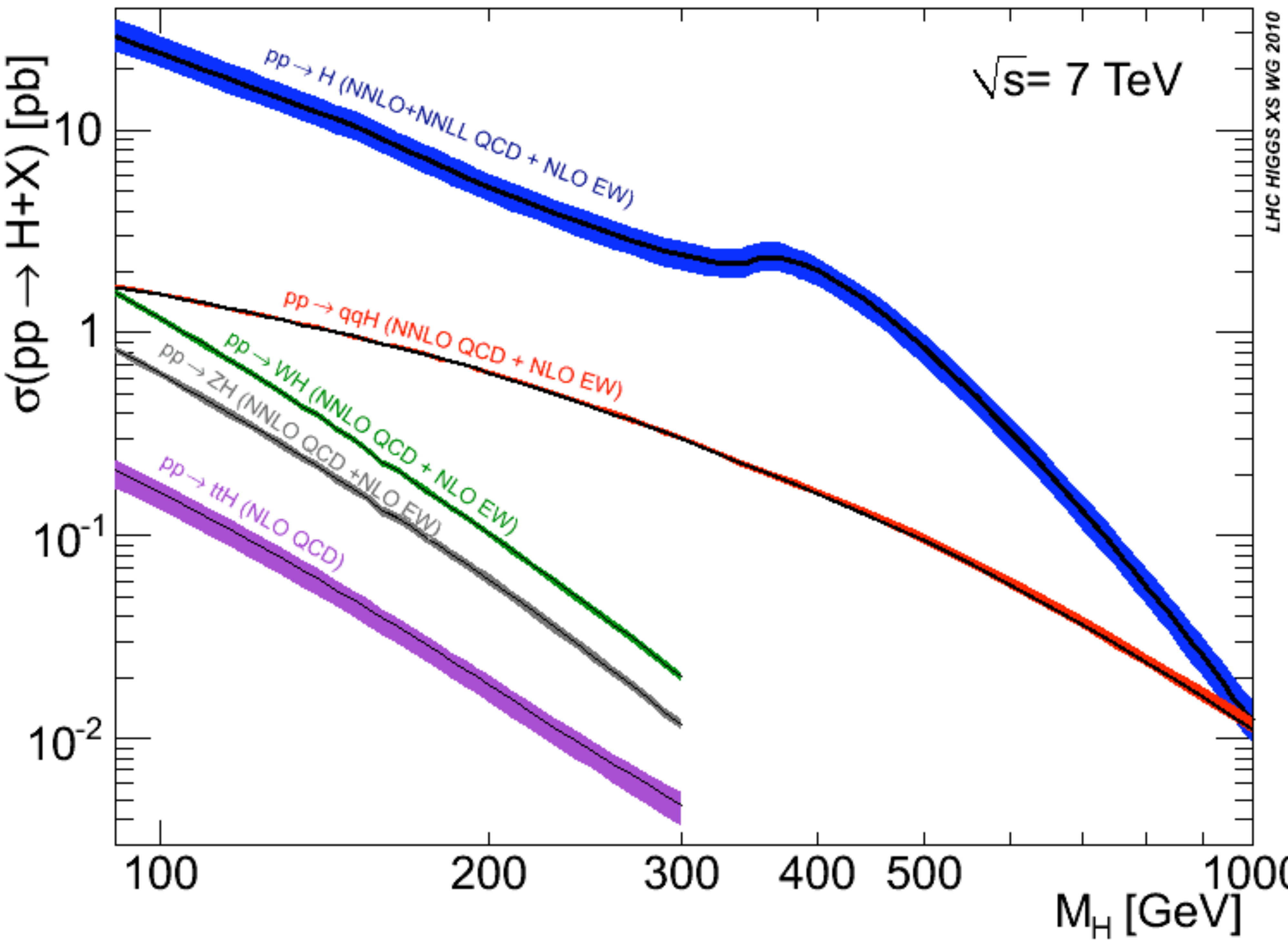
vector boson fusion



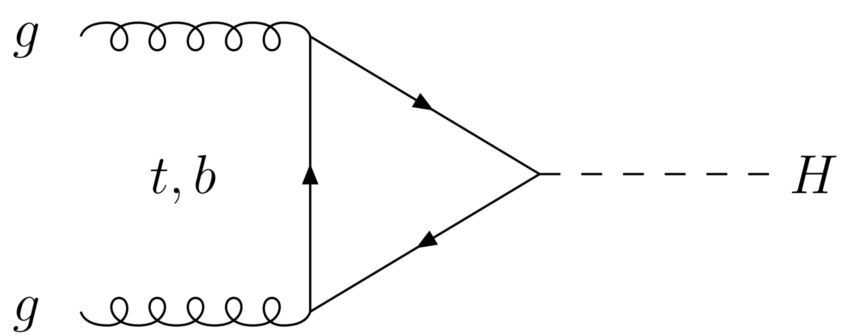
associated production with W, Z



associated production with $Q\bar{Q}$



gg fusion

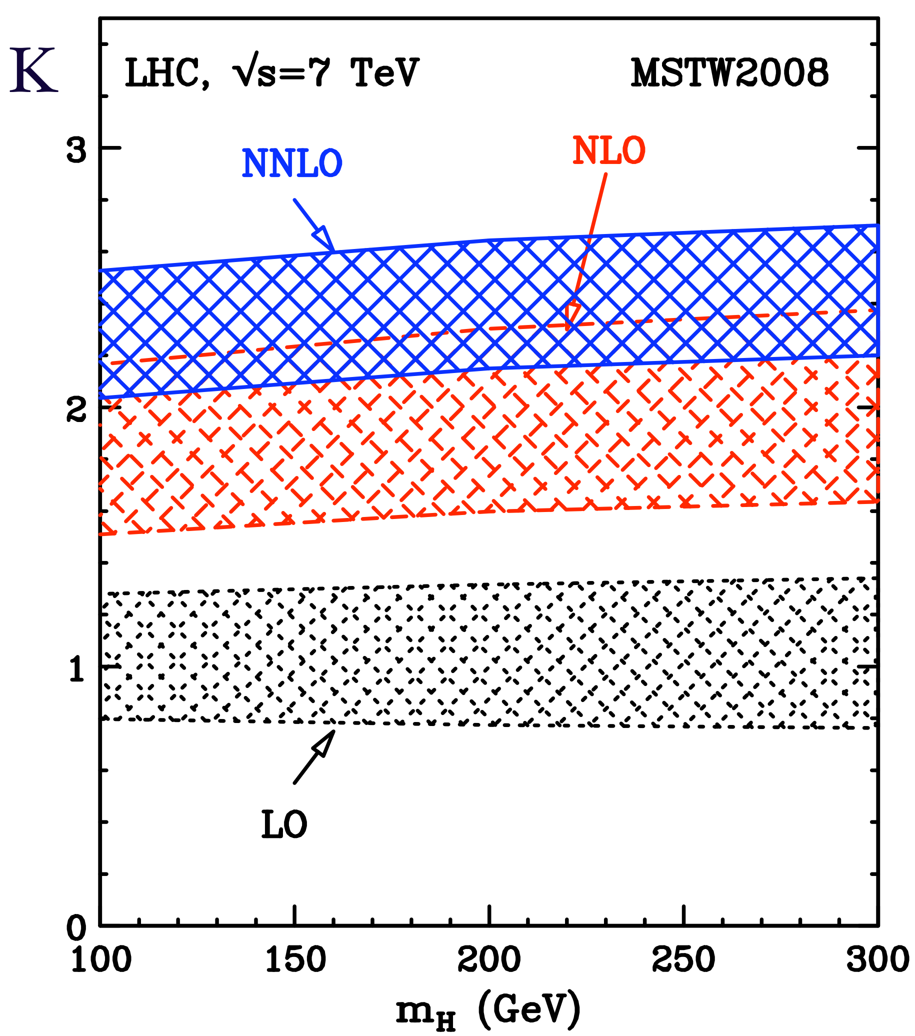


The Higgs coupling is proportional to the quark mass

→ top-loop dominates

QCD corrections to the total rate computed 20 years ago and found to be large → O(100 %) effect !

A. Djouadi, D. Graudenz, M. Spira, P. Zerwas (1991)



Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit (+25 % at the LHC, +30 % at the Tevatron)

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)

scale uncertainty computed with $m_H/2 < \mu_F, \mu_R < 2\, m_H$ and $1/2 < \mu_F/\mu_R < 2$

The large-m_{top} approximation

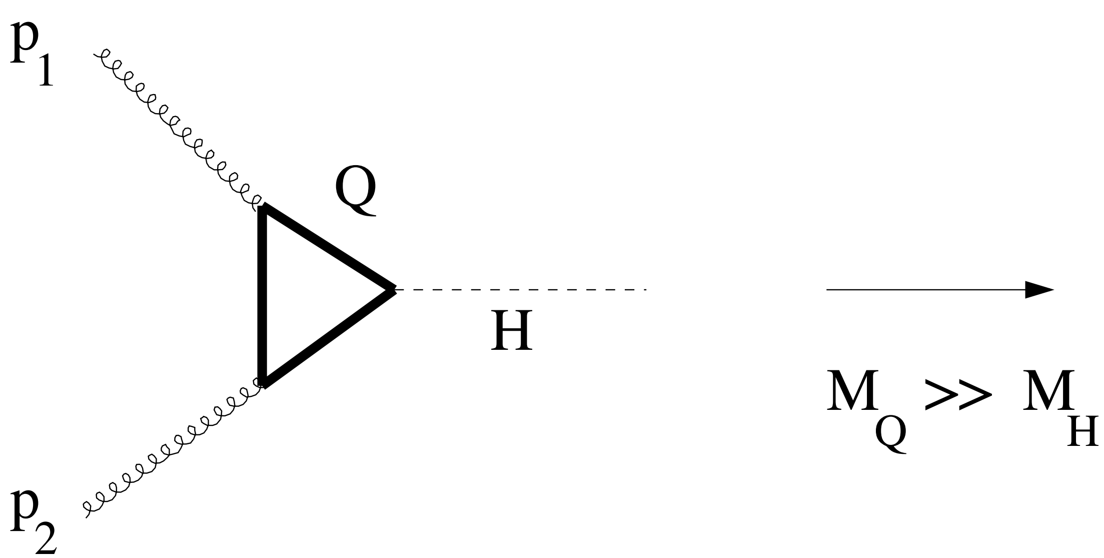
For a light Higgs it is possible to use an effective lagrangian approach obtained when $m_{top} \to \infty$

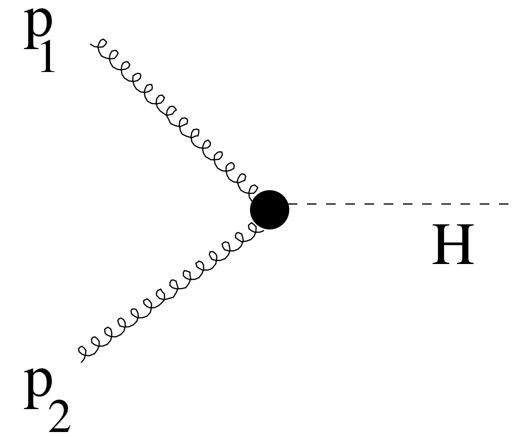
J.Ellis, M.K.Gaillard, D.V.Nanopoulos (1976)
M.Voloshin, V.Zakharov, M.Shifman (1979)

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

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 et al. (2009,2010)
M.Steinhauser et al. (2009)

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

gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about +9-10% at the LHC, +13% at the Tevatron, with slight reduction of scale unc.)

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

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

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

Two-loop EW corrections are also known (effect is about O(5%))

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

Mixed QCD-EW effects evaluated in EFT approach (effect O(1%))

Anastasiou et al. (2008)

→ support "complete factorization": EW correction multiplies the full QCD corrected cross section

EW effects for real radiation (effect O(1%))

W.Keung, F.Petriello, (2009)
O.Brein (2010)
C.Anastasiou et al. (2011)

Results

Quite an amount of work has been done recently to provide updated results that include all the available information → LHC Higgs Cross section WG

- Calculation by Petriello et al.

  - Start from exact NLO and include NNLO in the large-m_{top} limit

  - Effect of resummation is mimicked by choosing $\mu_F = \mu_R = m_H/2$ as central scale (choice motivated by apparent better convergence of the perturbative series)

  - Includes EFT estimate of mixed QCD-EW effects and some effects from EW corrections to real radiation

- Update of NNLL+NNLO calculation of Catani et al. (2003)

  - Perform NNLL+NNLO calculation in the large-m_{top} limit

  - Include exact top and bottom contributions up to NLL+NLO

  - Include EW effects as computed by Passarino et al.

corresponding results for the Tevatron used in CDF+DO combination

Online calculator available at: http://theory.fi.infn.it/grazzini/hcalculators.html

D. De Florian, MG (2009)

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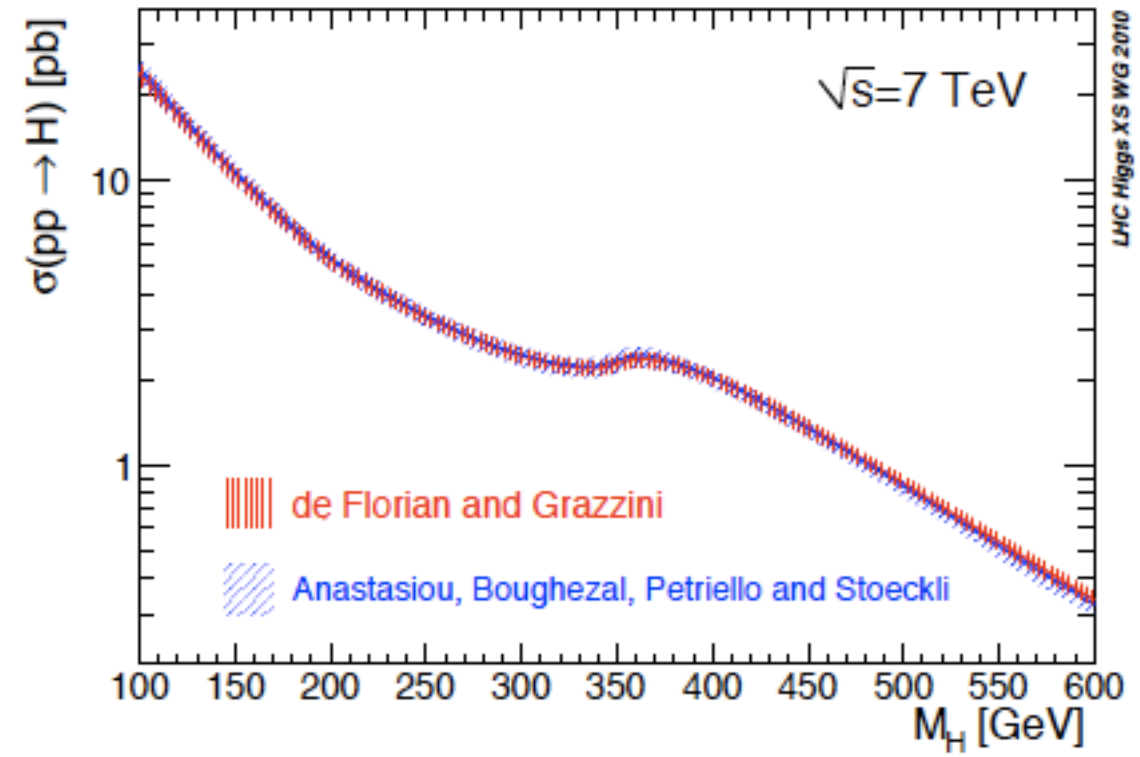

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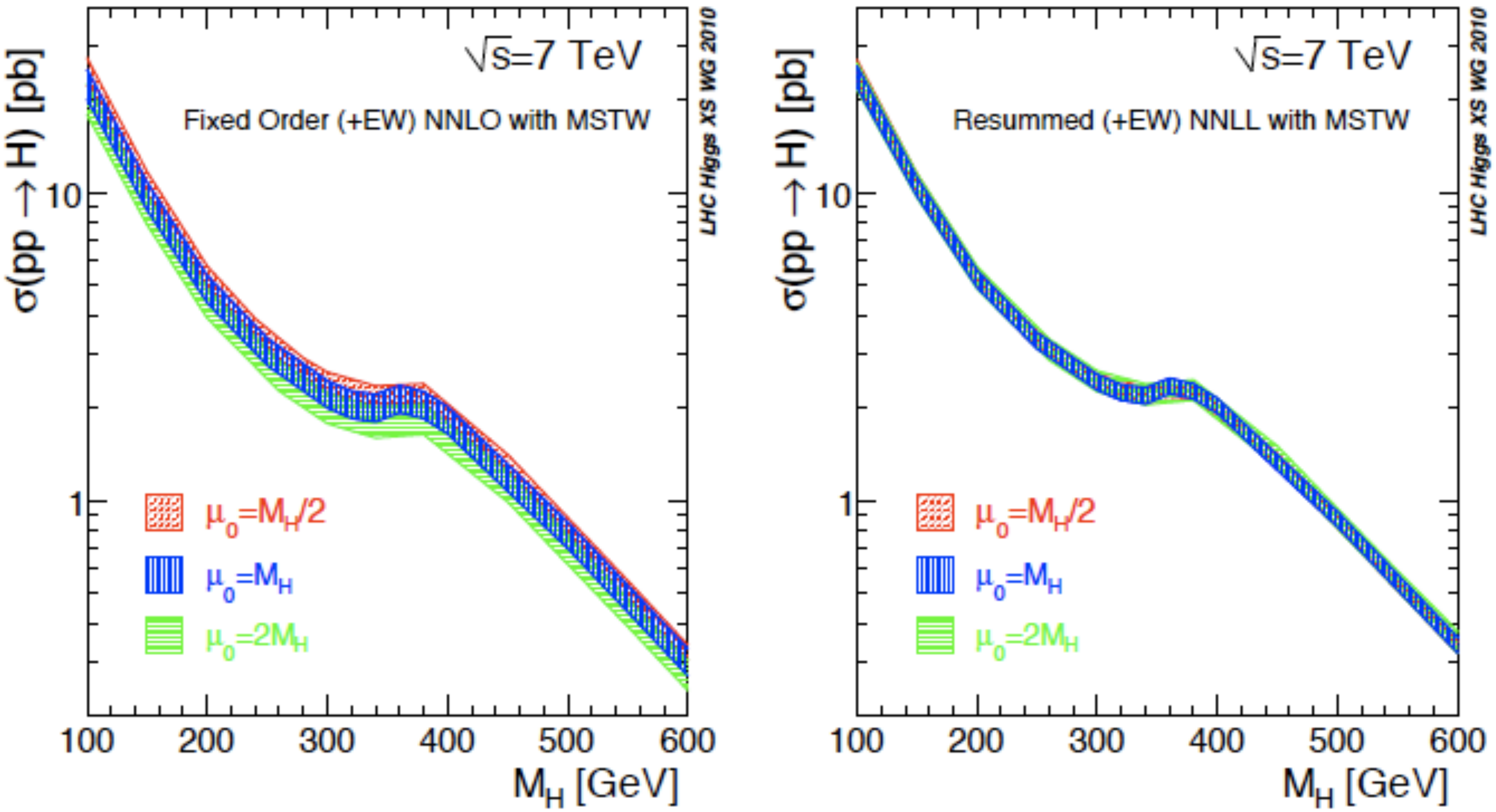


It has been argued that at NNLO the choice $\mu_F=\mu_R=m_H/2$ is the one that should be adopted

It is remarkable that the NNLL resummed calculation is basically insensitive to the central scale choice !

Scale uncertainties of NNLL+NNLO result is ±6-8 % in the range 100-300 GeV

Other Results

- Calculation by Baglio-Djouadi

J.Baglio,A.Djouadi (2010)

- Detailed (and very) conservative study of the various sources of uncertainties → about±25-30 % at 7 TeV
- Further update for the Tevatron uses $\mu_F = \mu_R = m_H/2$ as central scale: agreement with the other calculations

- Calculation by Ahrens et al.

V.Ahrens et al. (2010)

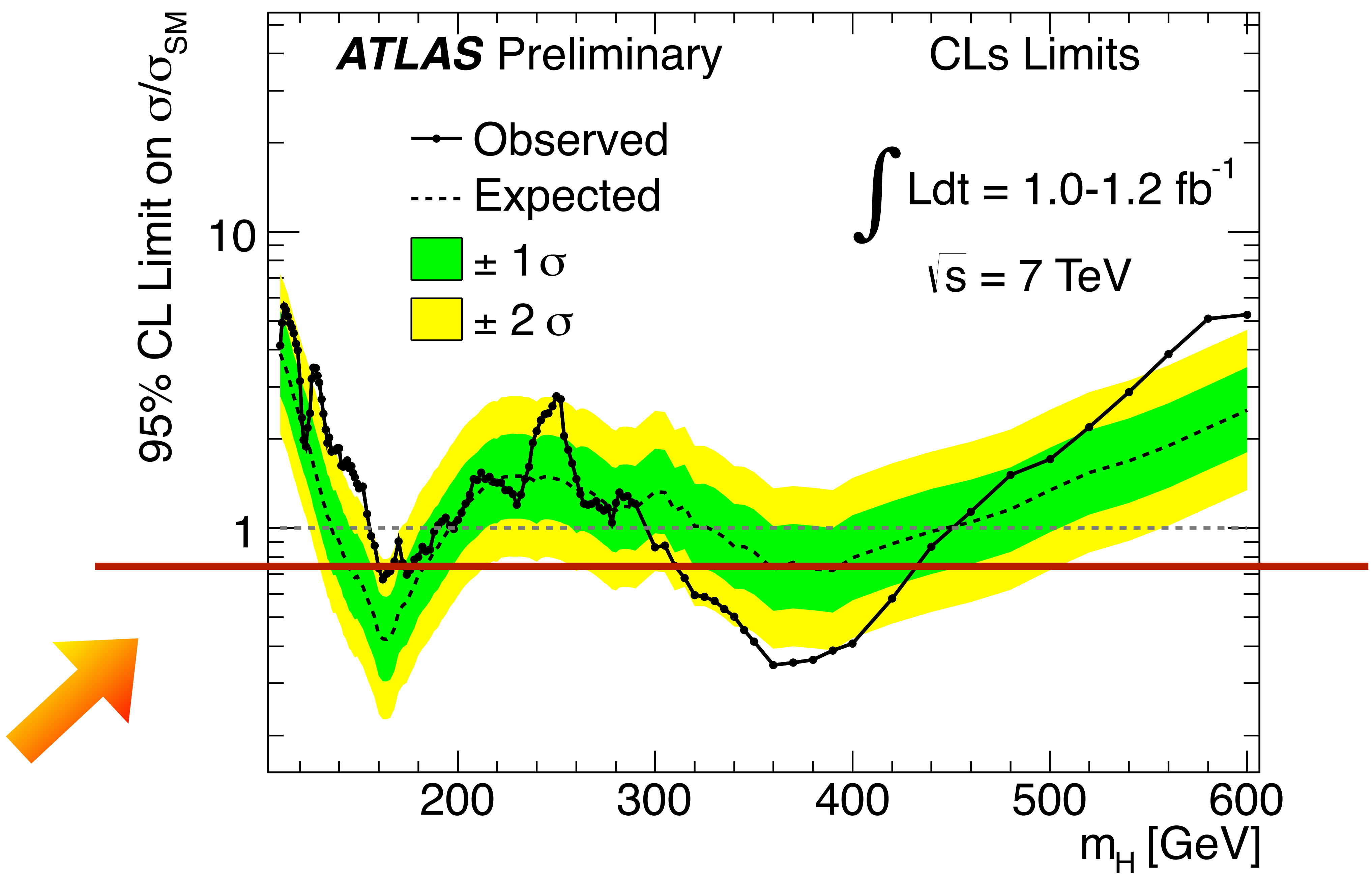
- Based on the so called "π^2-resummation"
- Numerical results agree with the other calculations
- Perturbative uncertainties of about 3% or smaller → largely underestimated !

- Calculation by Anastasiou et al. → implemented in the public program iHixs

- Start from exact NLO and include NNLO in the large-m_{top} limit
- Includes virtual and some real EW corrections and mixed QCD-EW effects

The relevance of higher orders

The recent ATLAS and CMS exclusion is based on the gg→H improved result



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

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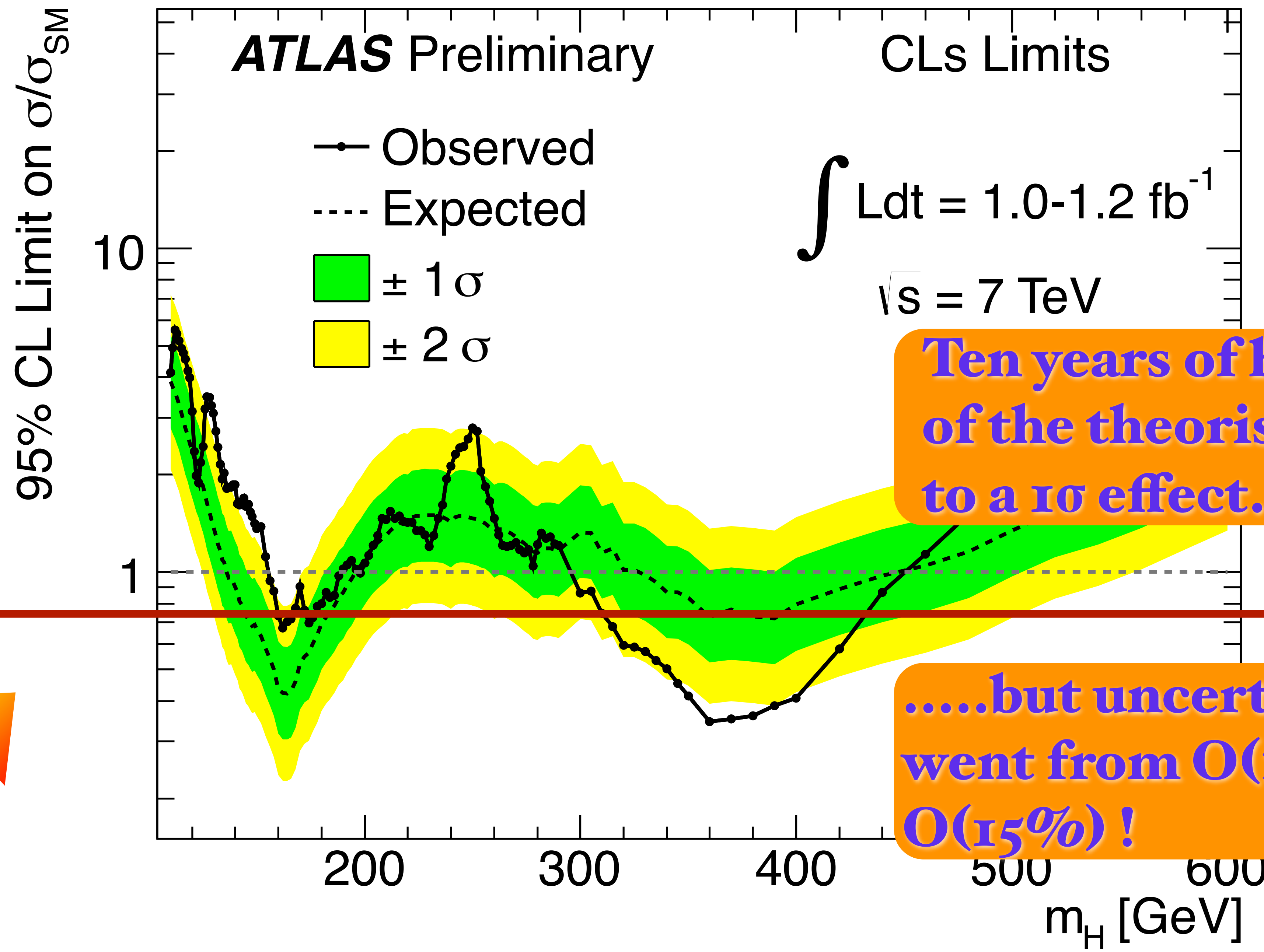
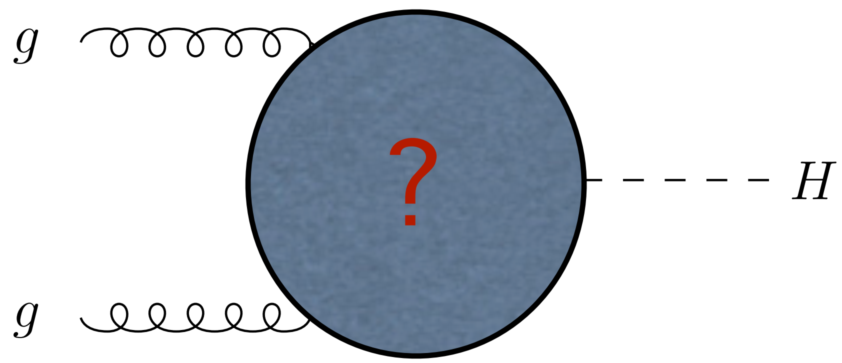


Ten years of hard work of the theorists amount to a 1σ effect......

.....but uncertainties went from O(100%) to O(15%) !

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

gg fusion as BSM portal



gluon-gluon fusion may open a window on new physics scenarios

sensitive to heavy particle spectrum

Models with additional SM-like heavy quarks

C.Anastasiou, R.Boughezal, E.Furlan (2010)
C.Anastasiou et al. (2011)

→ cross section enhanced by roughly a factor 9 with respect to the SM

Colored scalars

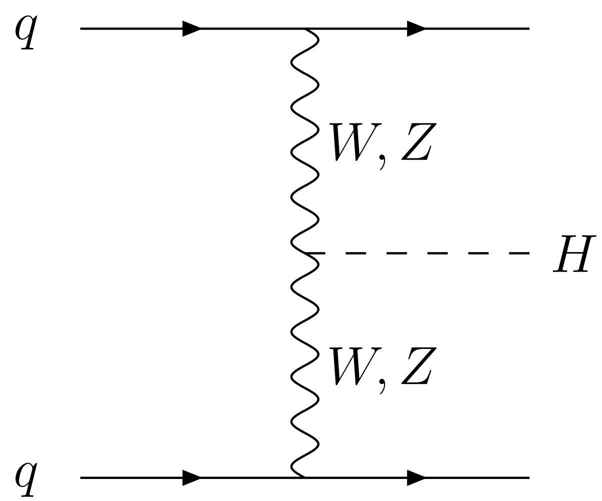
R.Boughezal, F.Petriello (2011)
R.Boughezal (2011)

Models with general Yukawa couplings

E.Furlan (2011)
C.Anastasiou et al. (2011)

→ NNLO calculation implemented in iHixs

Vector boson fusion



VBF is a cornerstone in the Higgs-boson search at the LHC

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

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

T. Han, S. Willenbrock (1991)

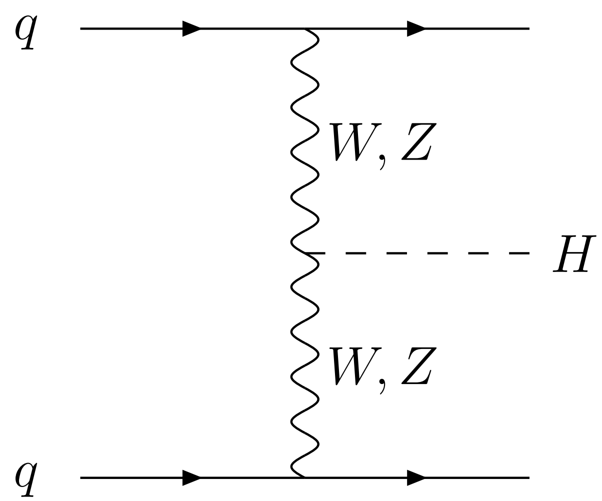
Implemented for distributions in VBFNLO

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

EW+QCD corrections have also been evaluated and implemented in a flexible parton level generator HAWK

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

Vector boson fusion



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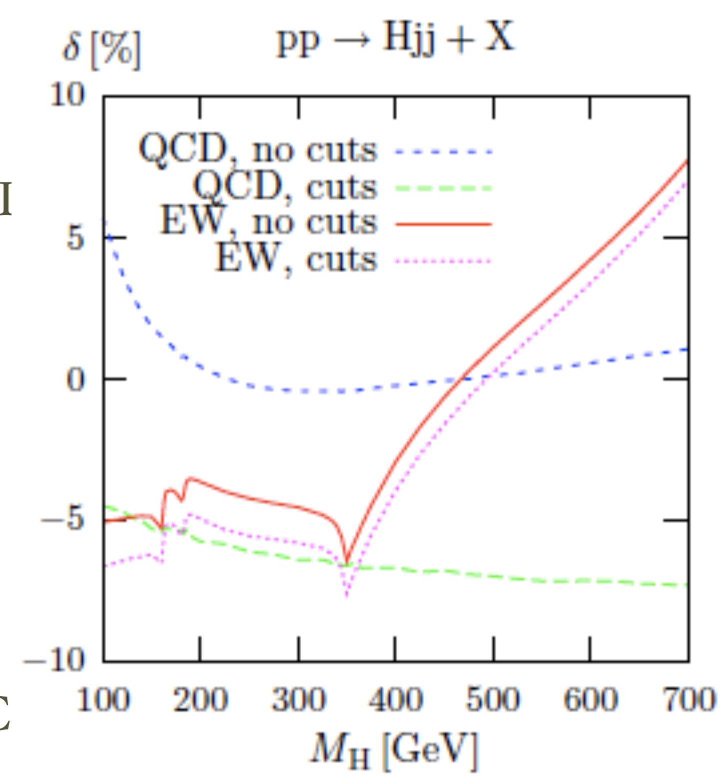


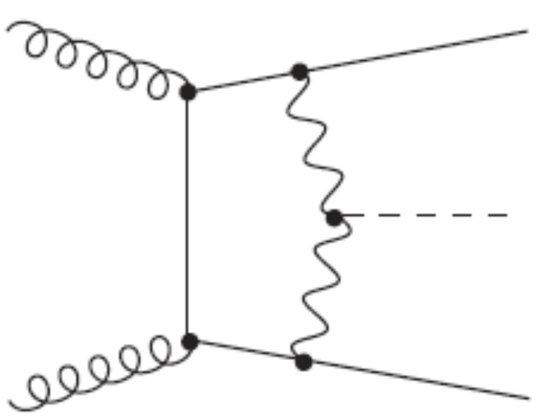
Vector boson fusion

Other radiative contributions:

Interference with gluon fusion

Andersen, Binoth, Heinrich, Smillie (2007)
Andersen, Smillie (2008)
Bredenstein, Hagiwara, Jäger (2008)

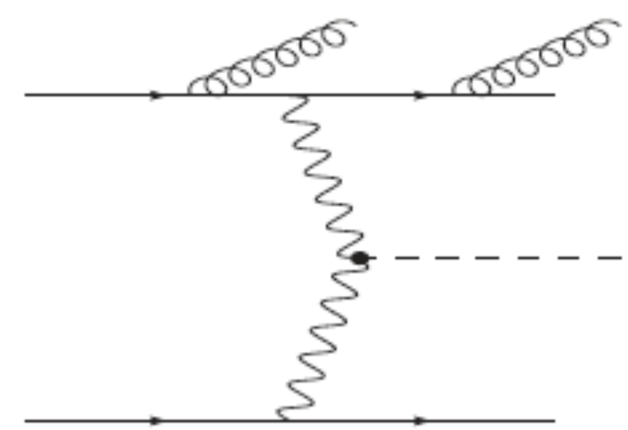
Other refinements include some NNLO contributions like gluon-induced diagrams



well below 1% level

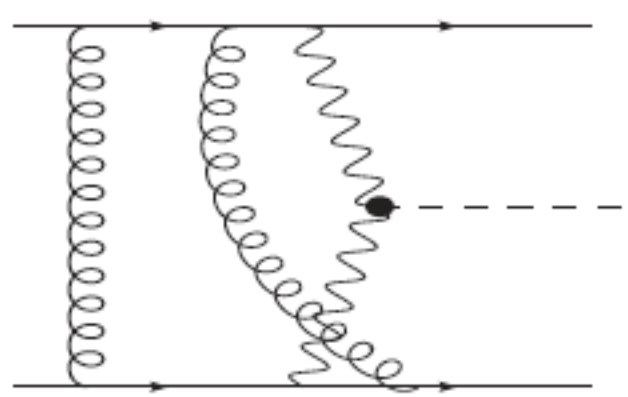
R.Harlander, J.Vollinga,M.Weber (2008)

and the more relevant DIS like NNLO contributions computed within the structure function approach



scale uncertainty reduced to the 2% level

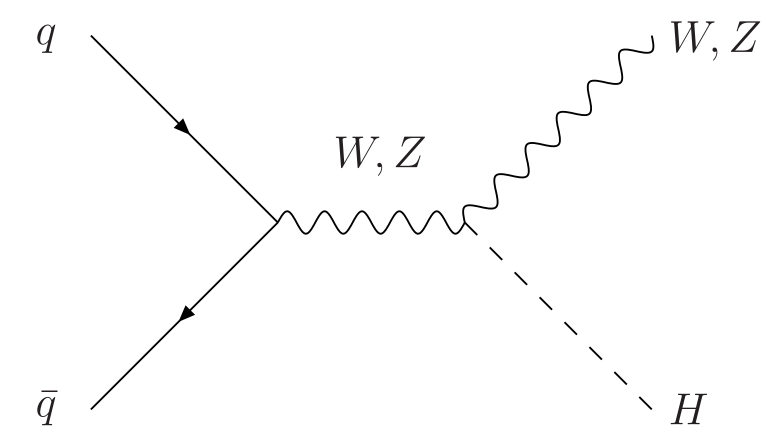
still missing :
(but kinematically and parametrically suppressed)



P.Bolzoni, F.Maltoni, S.Moch, M. Zaro (2010)

Associated VH production

Most important channel for low mass
at the Tevatron



→ lepton(s) provide the necessary background rejection

Would provide unique information on the HWW and HZZ couplings

Considered not promising at the LHC due to the large backgrounds

Resurrected through boosted analysis

J.Butterworth et al. (2008)

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

T. Han, S. Willenbrock (1990)

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

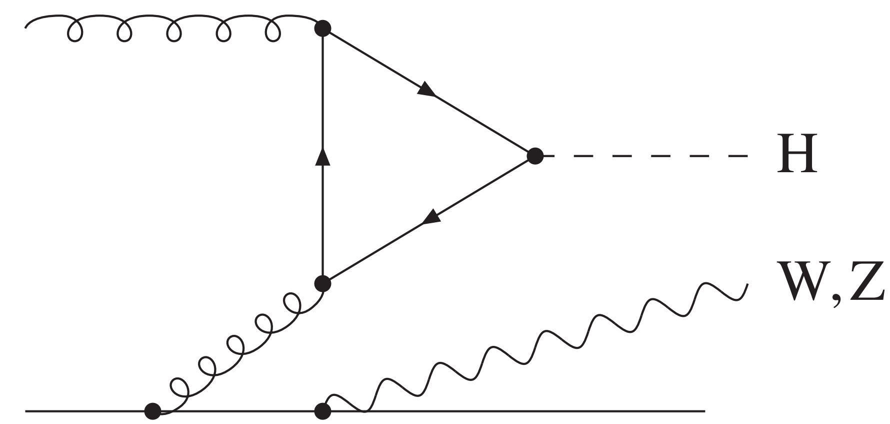
M.L. Ciccolini, S. Dittmaier, M. Kramer (2003)

Associated VH production

NNLO QCD corrections are essentially given by those of Drell-Yan

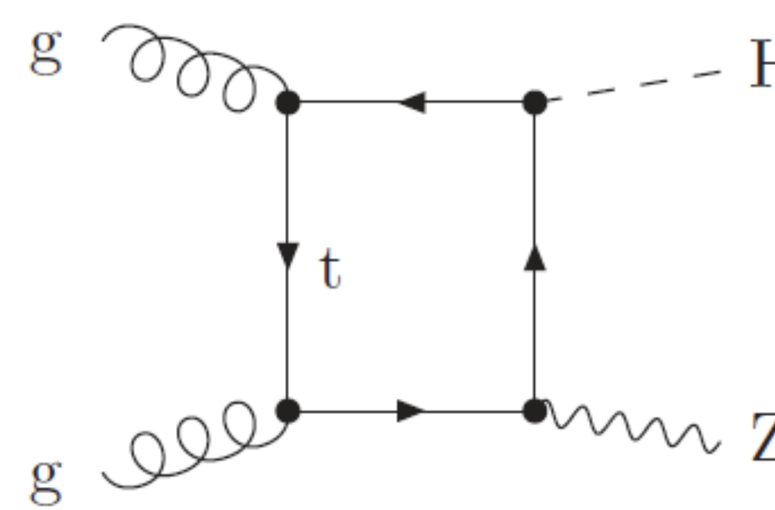
W. Van Neerven e al. (1991)

There are however additional diagrams where the Higgs is produced through a heavy quark loop



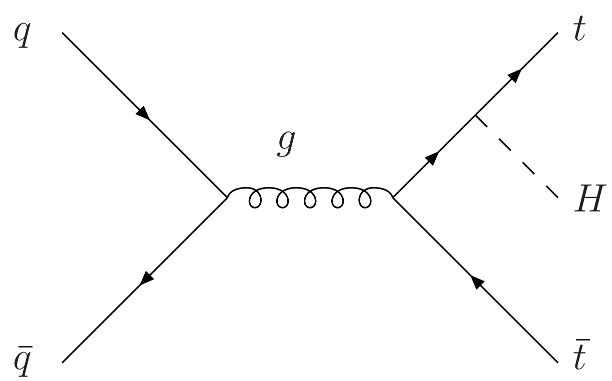
These diagrams are expected to give a small contributions

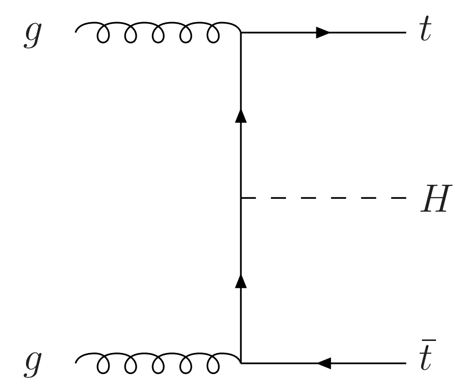
For ZH at NNLO additional diagrams from gg initial state must be considered: important at the LHC (+2-6 % effect)



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

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

→ Resurrected exploiting boosted analysis ?

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

2) The NNLO revolution

The NNLO revolution

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 extreme technical complications

In hadron collisions:

- gg→H FEHIP, HNNLO
- Drell-Yan FEWZ, DYNNLO

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

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

K.Melnikov, Petriello (2006)
R.Gavin et al. (2010)

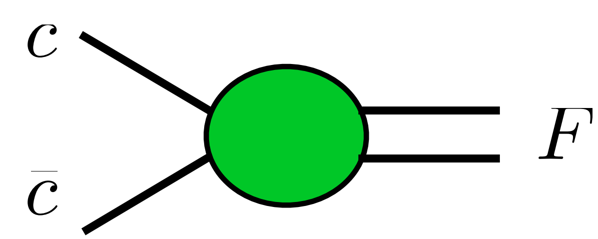
L.Cieri et al. (2009)

Our method

S. Catani, MG (2007)

Let us consider a specific, though important class of processes: the production of colourless high-mass systems F in hadron collisions (F may consist of lepton pairs, vector bosons, Higgs bosons......)

At LO it starts with $c\bar{c} \to F$



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

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

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

But.....
the singular behaviour of $d\sigma^{F+\text{jets}}_{(N)LO}$ 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 $d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$

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

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

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

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

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots.$$

For a generic $pp \to F + X$ process:

- At NLO we need a LO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$
  - the counterterm $d\sigma^{CT}_{LO}$ requires the resummation coefficients $A^{(1)}, B^{(1)}$ and the one loop anomalous dimensions
  - the general form of $\mathcal{H}^{F(1)}$ is known

D. de Florian, MG (2000)
G. Bozzi, S. Catani, D. de Florian, MG (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\mathrm{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$
  - the counterterm $d\sigma^{CT}_{NLO}$ depends also on the resummation coefficients $A^{(2)}, B^{(2)}$ and on the two loop anomalous dimensions
  - we have computed $\mathcal{H}^{F(2)}$ for Higgs and vector boson production !

S. Catani, MG (2007)
S. Catani, L. Cieri, G.Ferrera, D. de Florian, MG (2009)

→ **this is enough to compute NNLO corrections for *any* process in this class provided F+jet is known up NLO and the two loop amplitude for $c\bar{c} \to F$ is known**

HNNLO

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

HNNLO is a numerical program to compute Higgs boson production through gluon fusion in pp or ppbar 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

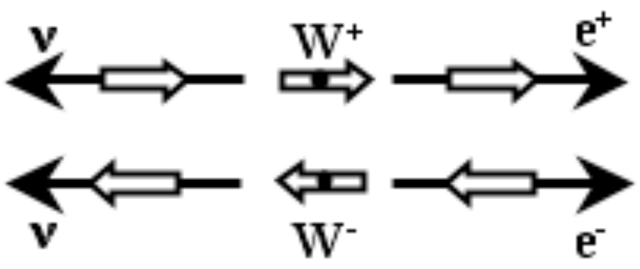
Results: $gg \to H \to WW \to l\nu l\nu$

MG (2007)

No mass peak but strong angular correlations

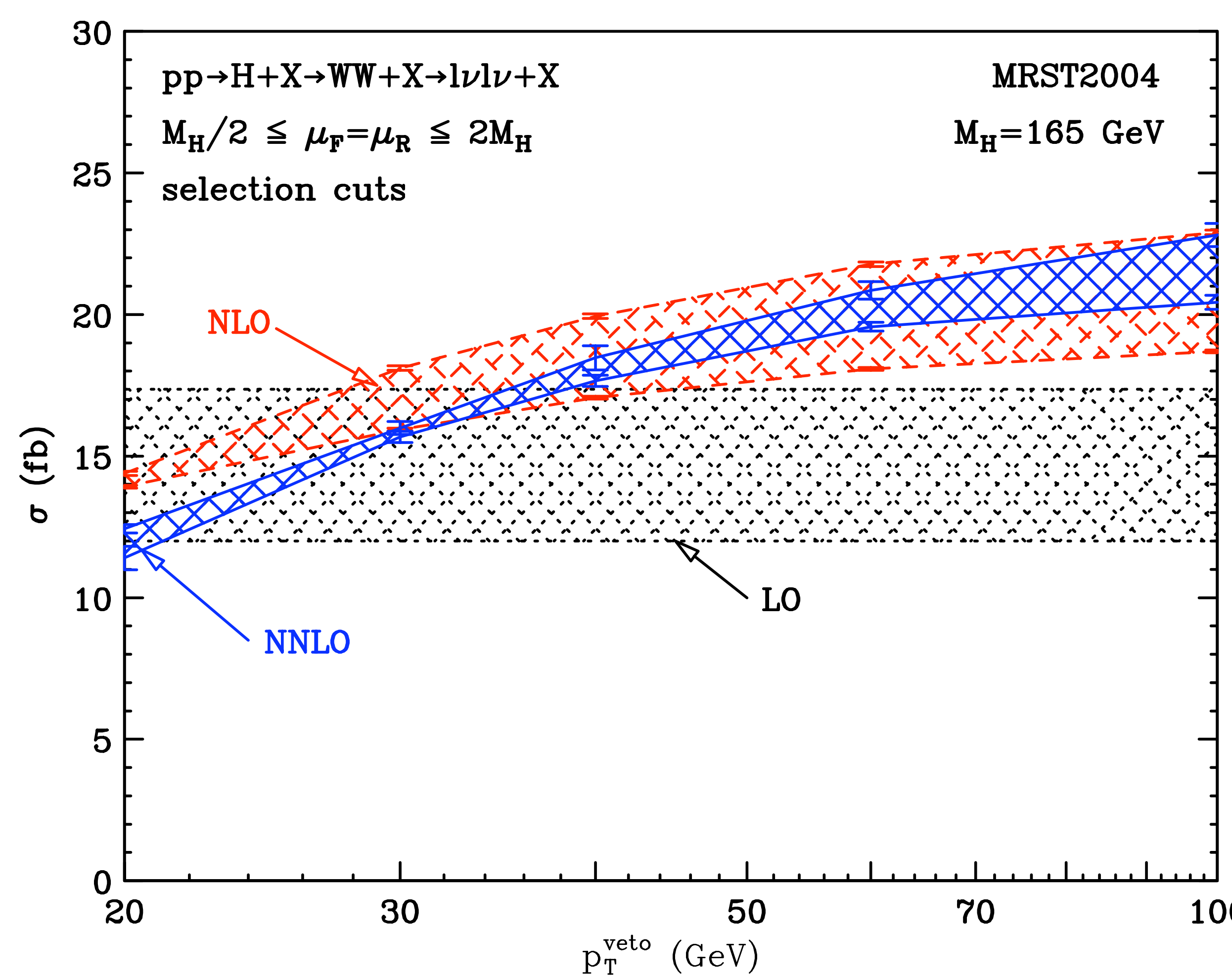
H scalar ➡ charged leptons tend to be close in angle

M.Dittmar, H.Dreiner (1997)



The $t\bar{t}$ background is characterized by high-p_T b-jets and requires the use of a jet veto

Selection cuts in this channel typically imply a strong reduction of the impact of higher order corrections



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

NNLO scale uncertainty becomes suspiciously small at $p_T^{\text{veto}} \sim 30$ GeV

cuts as in Davatz et al. (2003)

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

Further applications

The method successfully applied to gg→H and the Drell-Yan process can be used to perform NNLO computations for other important processes

$$c\bar{c} \longrightarrow F + X \qquad c = q, g$$

S.Catani, L Cieri, G.Ferrera, D. de Florian, MG (to appear)

Arbitrary colourless final state

Examples:

- Higgs-strahlung: F=WH, ZH
- $b\bar{b} \longrightarrow H$ R.Harlander, K.Ozeren, Wiesemann (2010)
- Vector boson pair production: F= $\gamma\gamma$,WW, ZZ, WZ........

Important backgrounds for new physics searches

For each of these processes the ingredients that we need are:

- Two loop amplitude for $c\bar{c} \longrightarrow F$
- NLO cross section for F+jet(s)

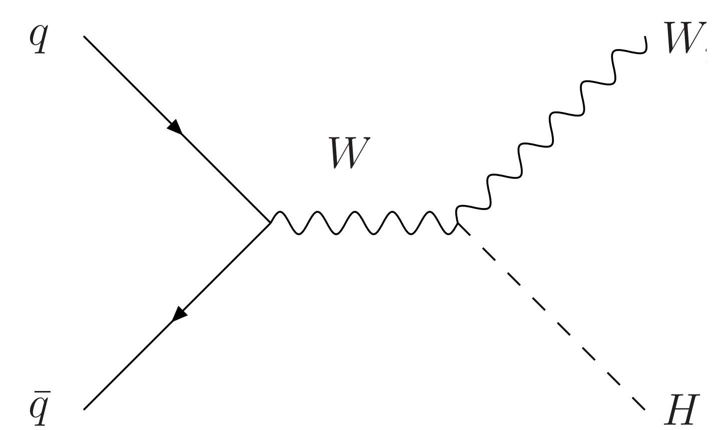
NEW: WH at NNLO

G.Ferrera, F.Tramontano, MG (2011)

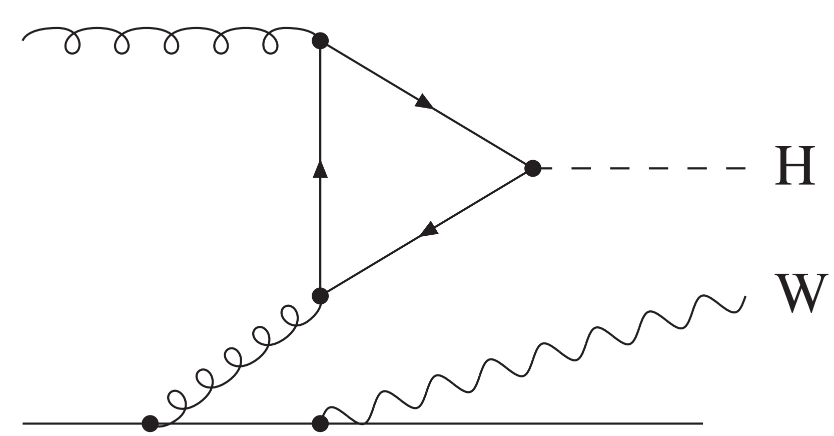
A fully differential NNLO calculation:
extension of NNLO calculation for Drell-Yan to Higgs-strahlung

Fully realistic: we include $H \to b\bar{b}$ decay and $W \to l\nu$ with spin correlations

Only Drell-Yan like diagrams are accounted for



We neglect the additional diagrams where the Higgs is produced through a heavy quark loop



Comparing with NLO results for WH+jet we estimate these contributions to be at the 1% level

Hirschi et al. (2011)

NEW: WH at NNLO

Results at the Tevatron

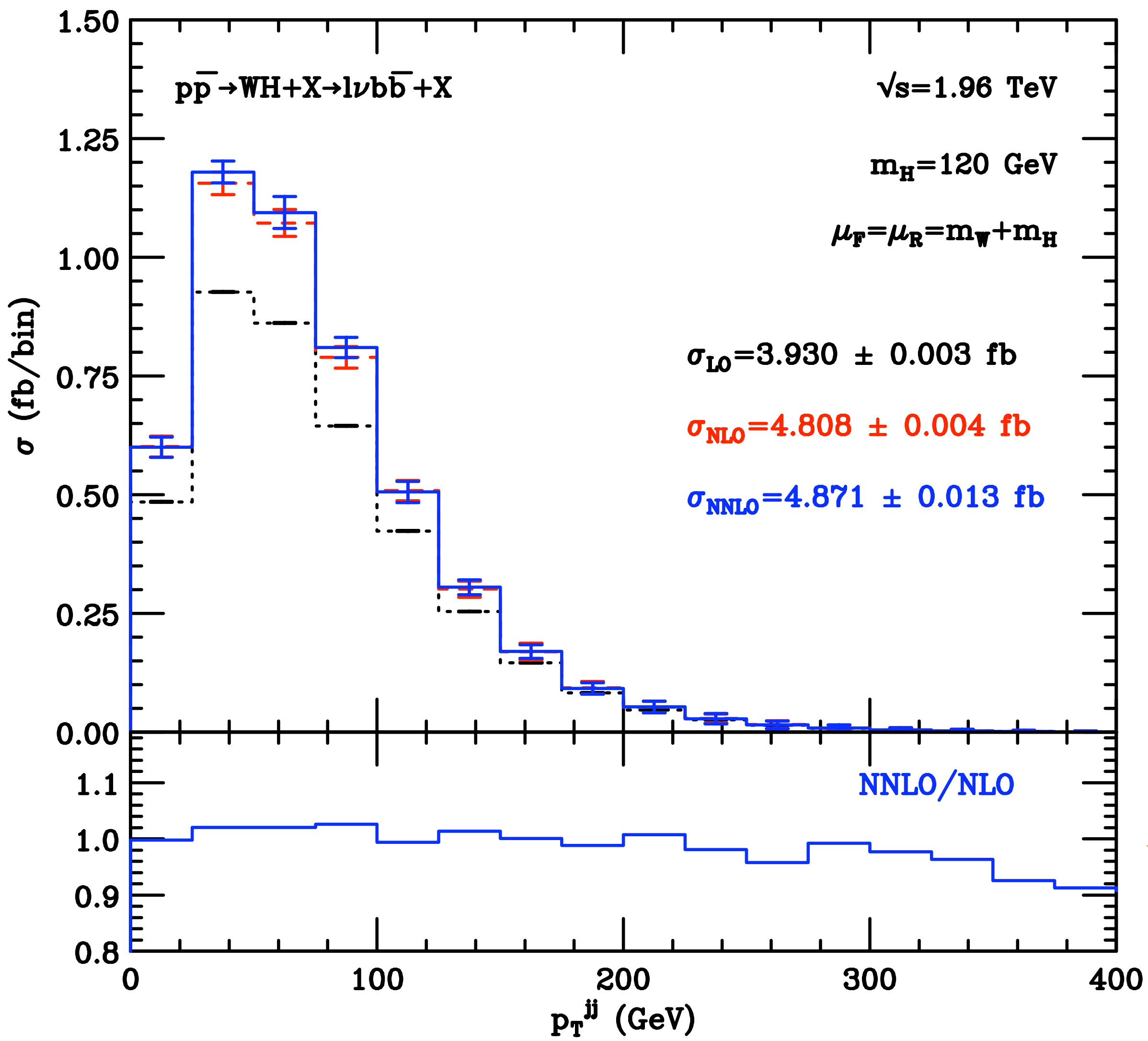
G.Ferrera, F.Tramontano, MG (2011)

Cuts:
lepton: p_T > 20 GeV and |η|<2
p_T^{miss} > 20 GeV

Jets: k_T algorithm with R=0.4

We require exactly 2 jets with p_T > 20 GeV and |η|<2

One of the jets has to be a b-jet with |η|<1



σ (fb)	LO	NLO	NNLO
$\mu_F=\mu_R=(m_W+m_H)/2$	4.266 ± 0.003	4.840 ± 0.005	4.788 ± 0.013
$\mu_F=\mu_R=m_W+m_H$	3.930 ± 0.003	4.808 ± 0.004	4.871 ± 0.013
$\mu_F=\mu_R=2(m_W+m_H)$	3.639 ± 0.002	4.738 ± 0.004	4.908 ± 0.010

Fixed-order results appear to be under good control

Scale dependence at the 1% level both at NLO and NNLO

Shape of p_T spectrum of dijet system is stable

NEW: WH at NNLO

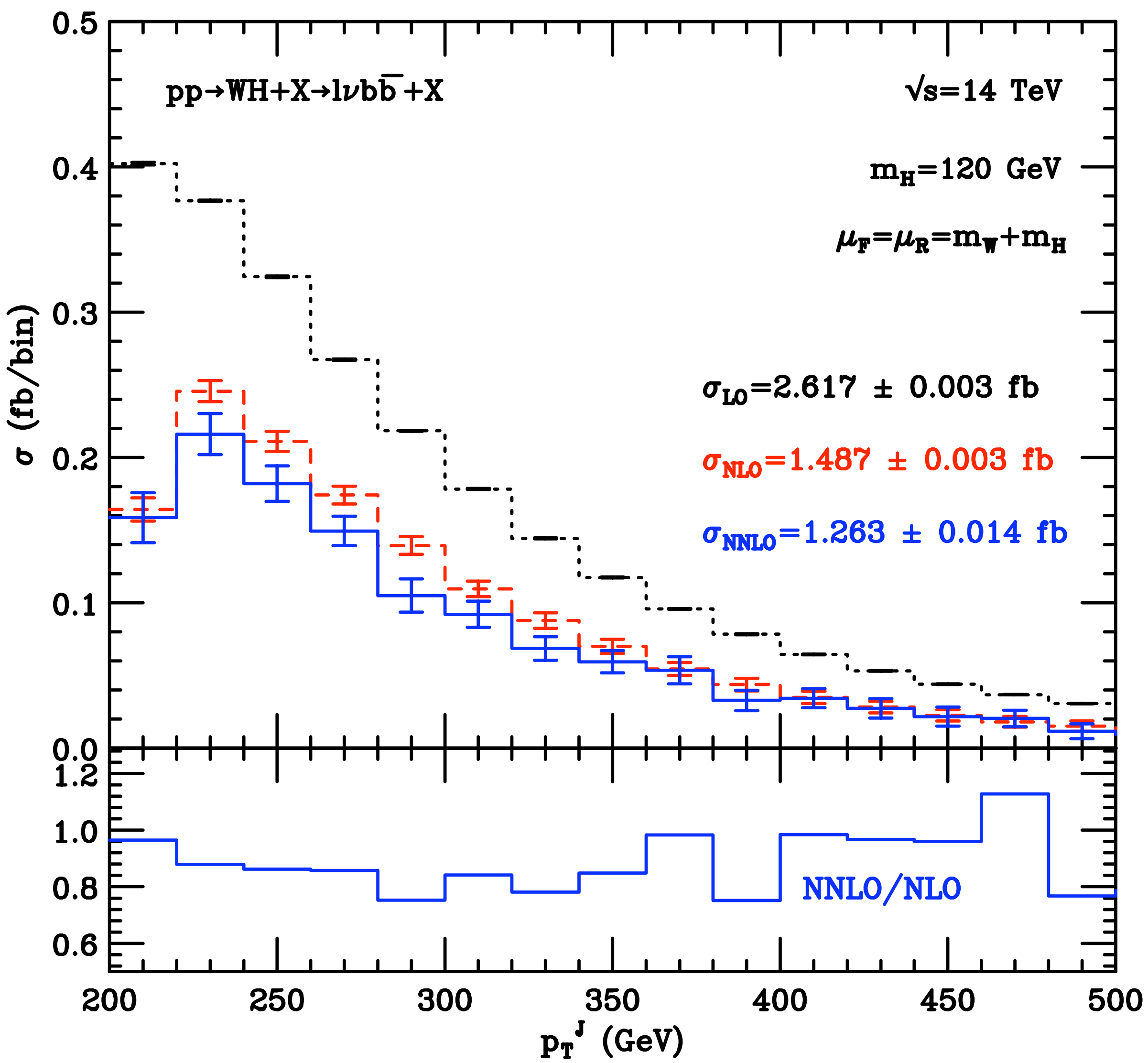
Results at the LHC (√s=14 TeV)

G.Ferrera, F.Tramontano, MG (2011)

Cuts:
lepton: $p_T > 30$ GeV and $|\eta|<2.5$
$p_T^{miss} > 30$ GeV

$p_T^W>200$ GeV

Jets: CA algorithm with R=1.2
One of the jets (fat jet) must have $p_T^J>200$ GeV and $|\eta_J|<2.5$ and must contain the $b\bar{b}$ pair; no other jet with $p_T > 20$ GeV and $|\eta|<5$



σ (fb)	LO	NLO	NNLO
$\mu_F=\mu_R=(m_W+m_H)/2$	2.640 ± 0.002	1.275 ± 0.003	1.193 ± 0.017
$\mu_F=\mu_R=m_W+m_H$	2.617 ± 0.003	1.487 ± 0.003	1.263 ± 0.014
$\mu_F=\mu_R=2(m_W+m_H)$	2.584 ± 0.003	1.663 ± 0.002	1.346 ± 0.013

Impact of radiative corrections strongly reduced by the jet veto ➡

Stability of fixed-order expansion is challenged

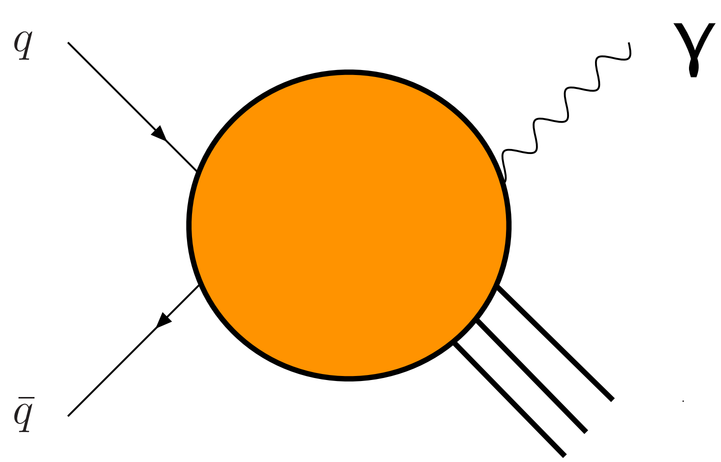
Plan:

- combined effort with HAWK group for 2nd Higgs XS YR
- Extension to ZH and comparison with MC tools

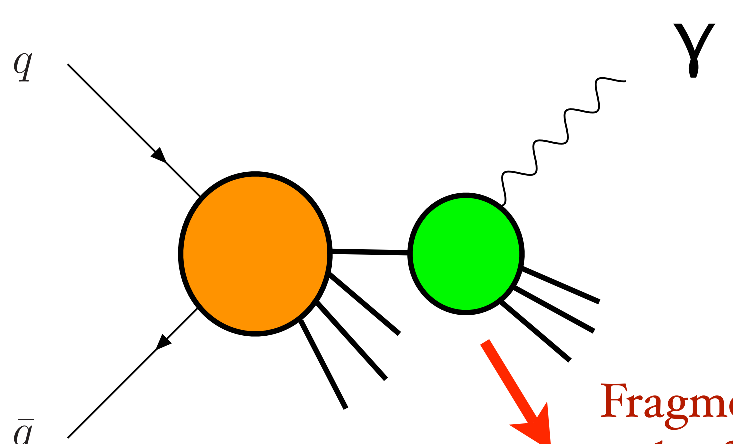
NEW: $pp \to \gamma\gamma$ at NNLO

S. Catani, L. Cieri, D. de Florian, G.Ferrera,
MG (to appear)

When dealing with the production of photons we have to consider two production mechanisms:



Direct component: photon directly produced through the hard interaction

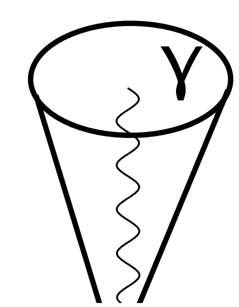


Fragmentation component: photon produced from non-perturbative fragmentation of a hard parton (like a hadron)

Fragmentation function: to be fitted from data

Experimentally photons must be isolated:

Transverse hadronic energy in a cone of fixed radius R smaller than few GeV



NEW: $pp \to \gamma\gamma$ at NNLO

S. Catani, L. Cieri, D. de Florian, G.Ferrera, MG (to appear)

Two loop amplitude available

C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans (2002)

$\gamma\gamma$ +jet at NLO available

Z.Nagy et al. (2003)

➜ We can perform the NNLO calculation using hard-collinear coefficients obtained for Drell-Yan

Use Frixione smooth cone isolation

$E_T^{had}(\delta) \leq \chi(\delta)$ ➜ kills collinear emissions within the cone

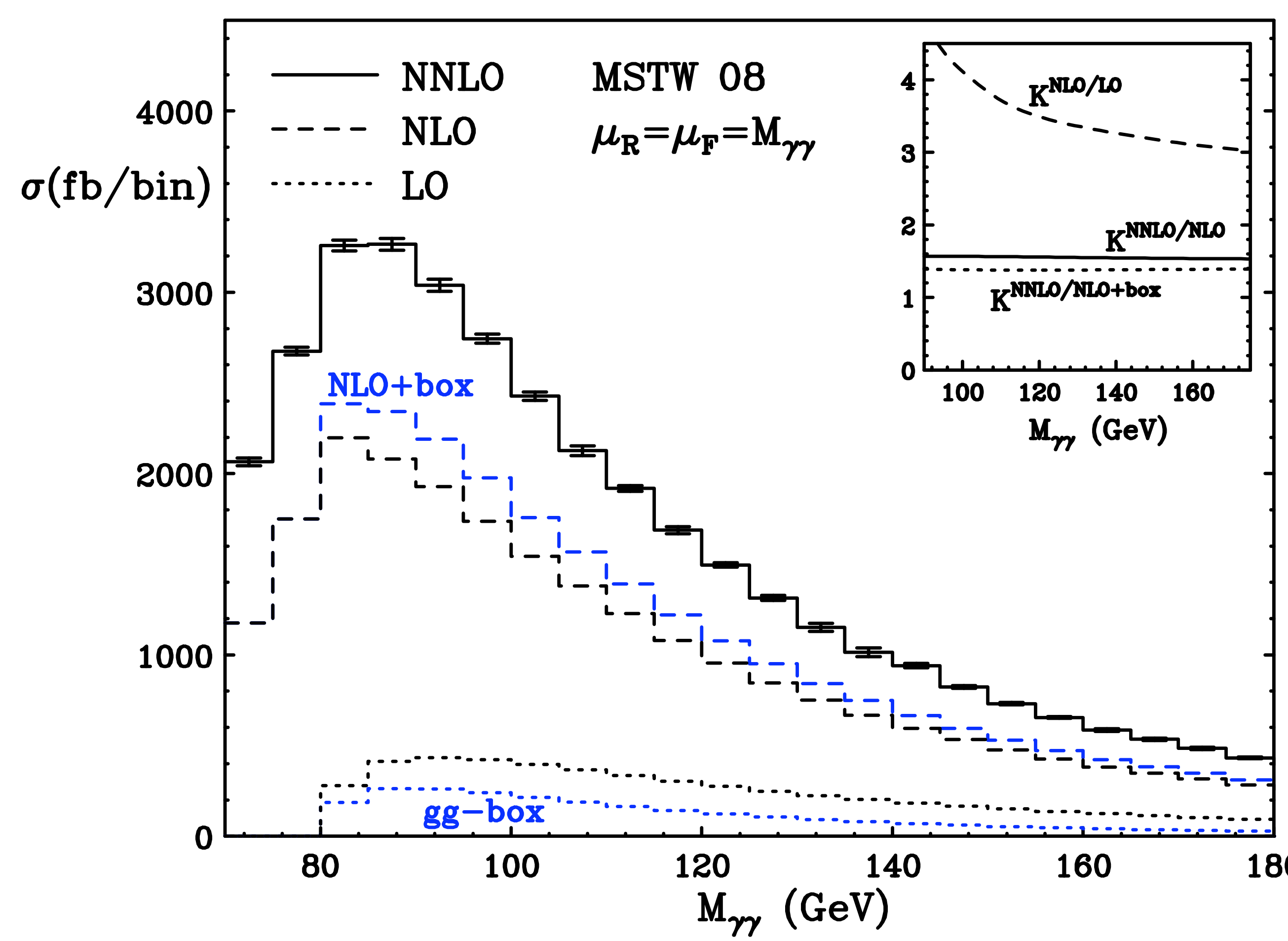
$$\chi(\delta) = \epsilon_\gamma E_T^\gamma \left(\frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n \qquad n=1, \quad \epsilon_\gamma = 0.5, \quad R_0 = 0.4$$

➜ no fragmentation contribution

$p^\gamma_{T1} \geq 40$ GeV $\quad p^\gamma_{T2} \geq 25$ GeV $\quad |\eta^\gamma| \leq 2.5$

$20 \text{ GeV} \leq M_{\gamma\gamma} \leq 250$ GeV

PRELIMINARY RESULTS: LHC, $\sqrt{s}$=14 TeV



3) Theory uncertainties

Scale uncertainties and jet bins

In the Higgs search at the Tevatron and the LHC data are divided into jet bins

This allows to optimize the analysis for H+one, two or more jets

Scale dependence in the 0-jet bin tends to be rather small

How to estimate the corresponding QCD uncertainty ?

Tevatron winter 2011 combination:

jet bin	0	1	2
unc.	±7%	±23.5%	±33.3%

Based on NNLO scale uncertainties from HNNLO
given in our 2008 study plus update for 2 jet bin from H+2j at NLO

C.Anastasiou et al. (2009)
J.Campbell, K.Ellis,C.Williams (2010)

Tevatron combination uses $gg \to H$ cross section from de Florian, MG

For comparison: our inclusive scale uncertainty is ±7 %

Note: inclusive uncertainty not used at all in this analysis ! (the discussion on how to evaluate scale uncertainties in inclusive cross section becomes irrelevant......)

Scale uncertainties and jet bins

Using HNNLO to naively compute scale uncertainty can be dangerous

Example: use anti-kt jets with: $p_{T\text{jet}}^{\text{min}} > 25$ GeV $\eta_{\text{jet}}^{\text{max}} > 4.5$ GeV

Choose $m_H/2$ as central scale choice

Scale uncertainty in the 0-jet bin: $\Delta\sigma_0/\sigma_0$ turns out to be only about ±2 % !

Alternative procedure:

F.Tackmann, I.Stewart (2011)

consider instead inclusive H+jet(s) cross sections

σ_{total} , $\sigma_{\geq 1}$, $\sigma_{\geq 2}$ ....

Treat them as uncorrelated and propagate the uncertainty on $\sigma_0 = \sigma_{\text{total}} - \sigma_{\geq 1}$

➡ leads to uncertainties on σ_0 that are about ±20% at the Tevatron and ±17% at the LHC

Propagating the uncertainties on the acceptance $\sigma_0/\sigma_{\text{total}}$ I find about ±19% at the Tevatron and ±15 % at the LHC

Scale uncertainties and jet bins

Scale Uncertainty Prescription

- **Theory gives cross section uncertainties**
  - Higgs + >= 0 jets: 7.05% (Grazzini, de Florian)
  - Higgs + >= 1 jets: 25.5% (MCFM)
  - Higgs + >= 2 jets: 33% (Campbell, Ellis, Williams)
- **We use: 0 jet, 1 jet, >=2 jets**

Jet bin	s0	s1	s2
0 jet	13.4%	-23.0%	0
1 jet	0	35%	-12.7%
>= 2 jets	0	0	33%

+27 % !!

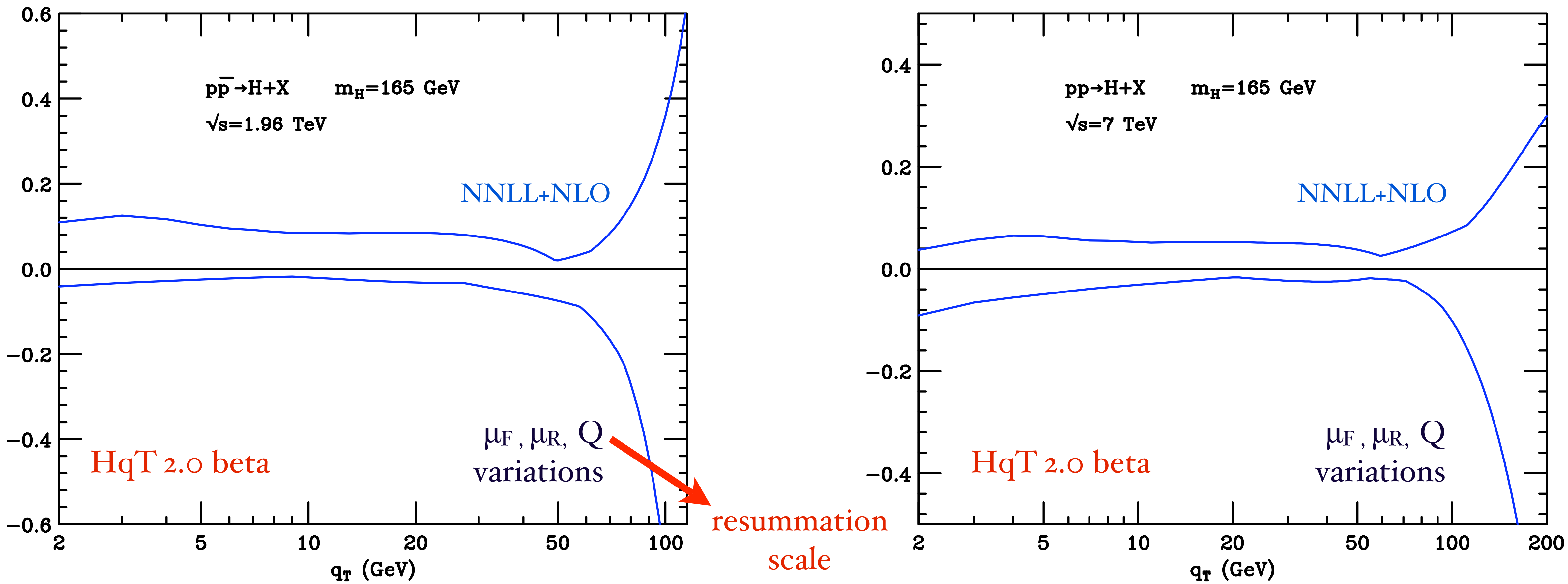
Scale uncertainties and jet bins

My opinion: definitely better than using naive scale uncertainty but.....

Aren't we risking to overestimate perturbative uncertainties ?

For comparison:

- Uncertainty in the shape of NNLL+NLO p_T spectrum for p_T between 20 and 30 GeV is about ±7% at the Tevatron and ±5 % at the LHC

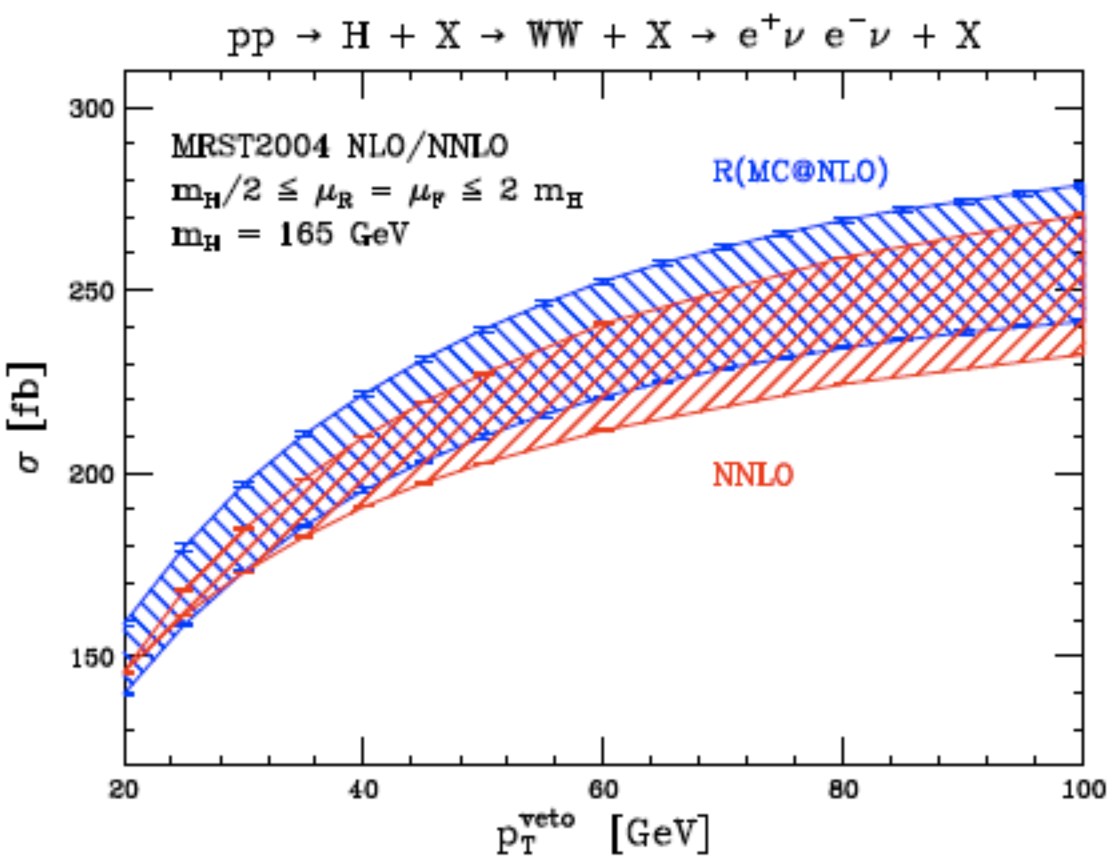


G.Ferrera, D. de Florian, D.Tommasini, MG (to appear)

Scale uncertainties and jet bins

- Uncertainties in the acceptance in the zero-jet bin estimated by comparing the NNLO result with various MC event generators are of the order of about ±10% or smaller

C.Anastasiou, G.Dissertori, F.Stoeckli, B.Webber (2008)
C. Anastasiou, G.Dissertori, F.Stoeckli, B.Webber, MG (2009)

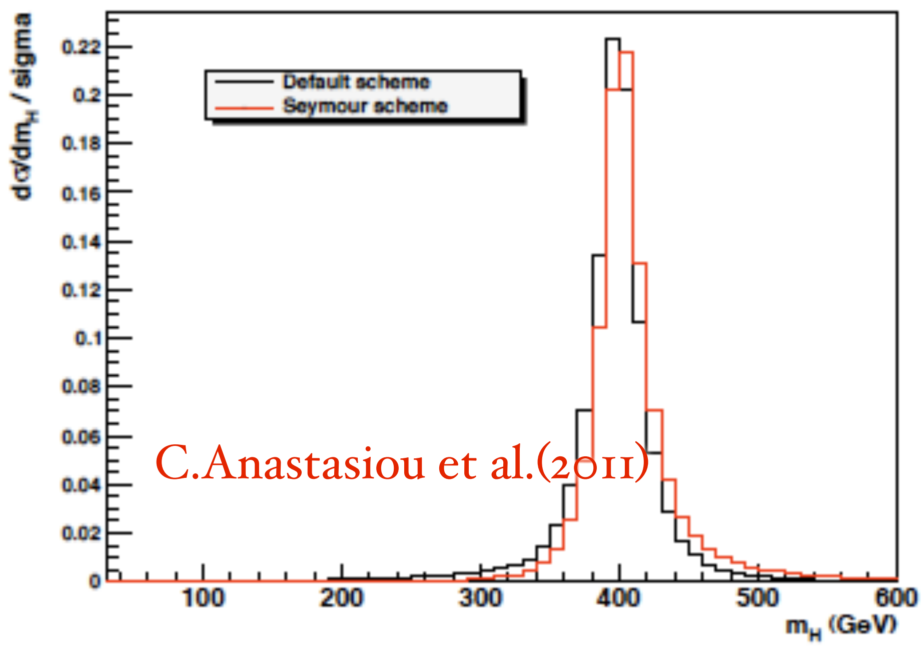


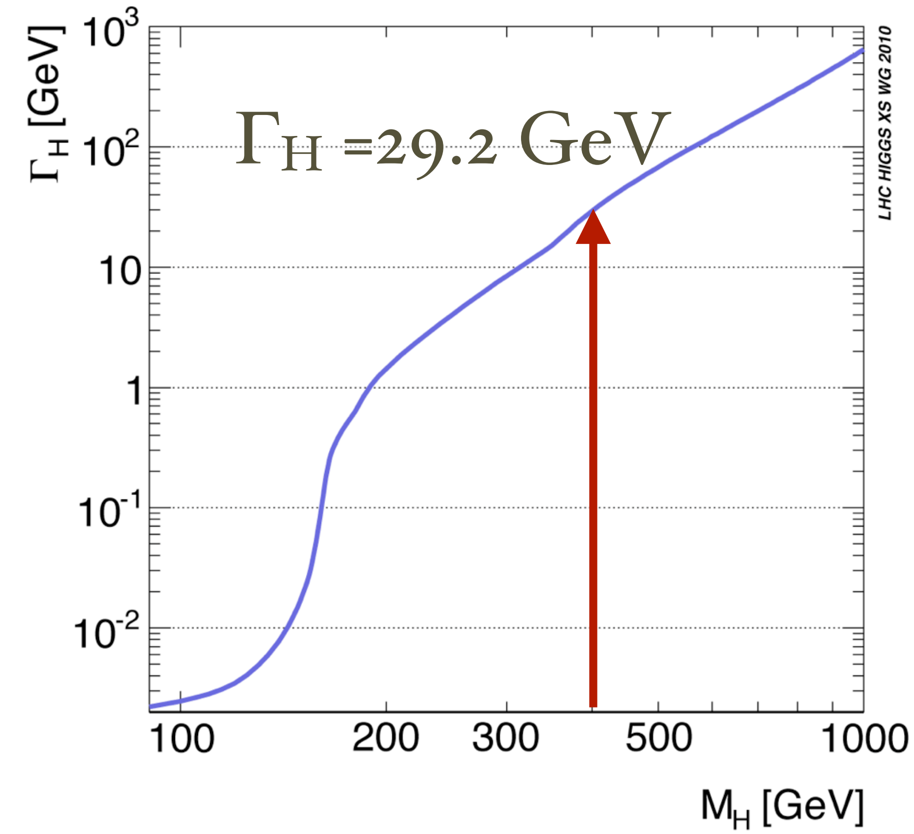
$\sigma_{acc}/\sigma_{incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_H/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\, m_H$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_H/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\, m_H$)	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%)

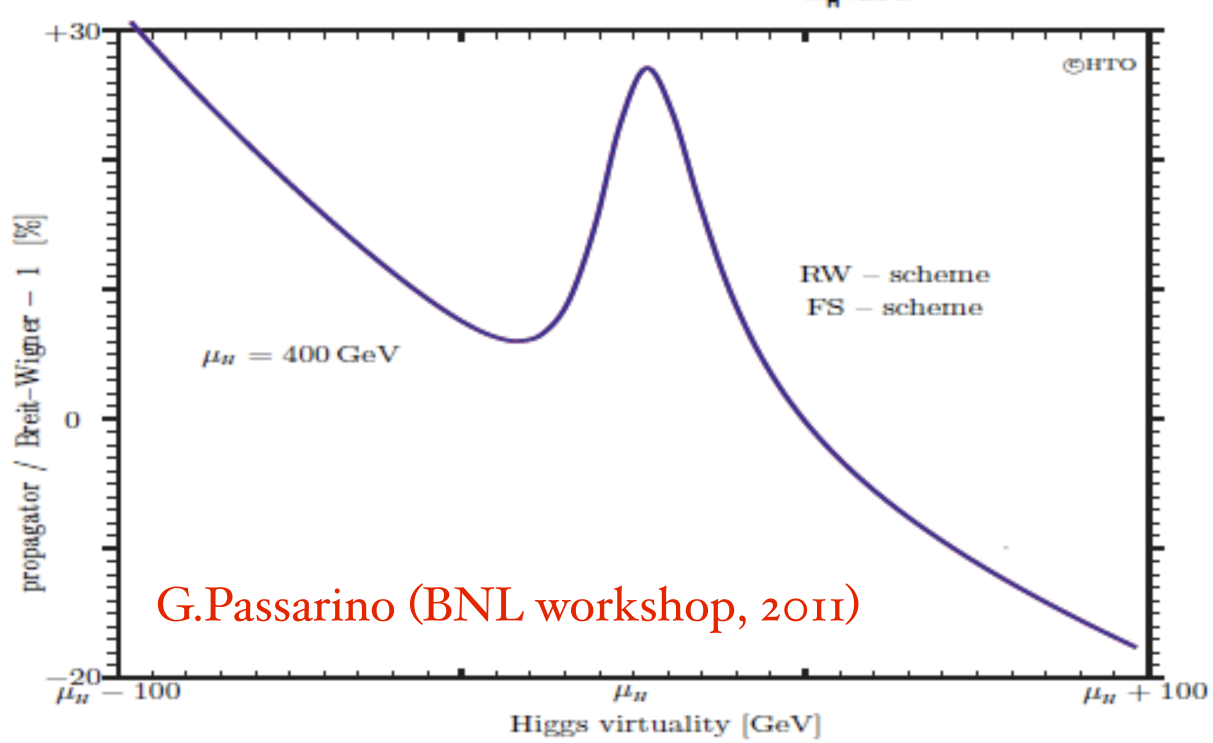
Table 5: Comparison of the predicted selection efficiency after successive application of cuts, as obtained by fixed order calculations and event generators. Between parentheses we give the efficiency due to a single cut, after all previous cuts have been applied. The event generator predictions correspond to the parton level only, i.e., no hadronization and underlying event effects are included. The first column lists the lepton selection ("trigger") efficiencies, the second (third) columns give the results when also the jet-veto (isolation) cuts are applied in sequence and the last column lists the results after applying all remaining cuts.

Heavy Higgs

When m_H=400 GeV life is not so easy: effects beyond naive BW and signal-background interference become relevant







Can we include these effects in the analysis ?

If not, the corresponding uncertainties should be taken into account !
(and not forget the large-m_{top} approx.)

Summary & Outlook

- The Higgs boson is an essential ingredient of the SM but it has not been observed yet
- The results presented at the EPS 2011 conference challenge the theory community to provide the best possible predictions for signal and background processes relevant for Higgs physics
- In the last few years theory has done an enormous effort to achieve this goal and to be prepared to this exciting moment
- Inclusive cross sections at high accuracy have been computed for the most important signal processes
- New fully differential NNLO QCD calculations are being performed to provide flexible tools for the analyses

→ important to assess theoretical uncertainties in the experimental search

Summary & Outlook

- Precision is now such that we should try to join efforts from different communities:

  - (N)NLO QCD, EW corrections

  - Production and decay.......

- The issue of quantifying theory uncertainties is crucial when exclusion is concerned: I have discussed just two examples

  - Jet bin uncertainties
  - Heavy Higgs

- A solid assessment of theory uncertainties can come only through a careful and critical comparison of different tools

  ➡ **Planned within the LHC Higgs XS Working Group**

BACKUP SLIDES

More on inclusive gg→H

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 N3LO would lead to a reduction of scale uncertainty to about *5%*

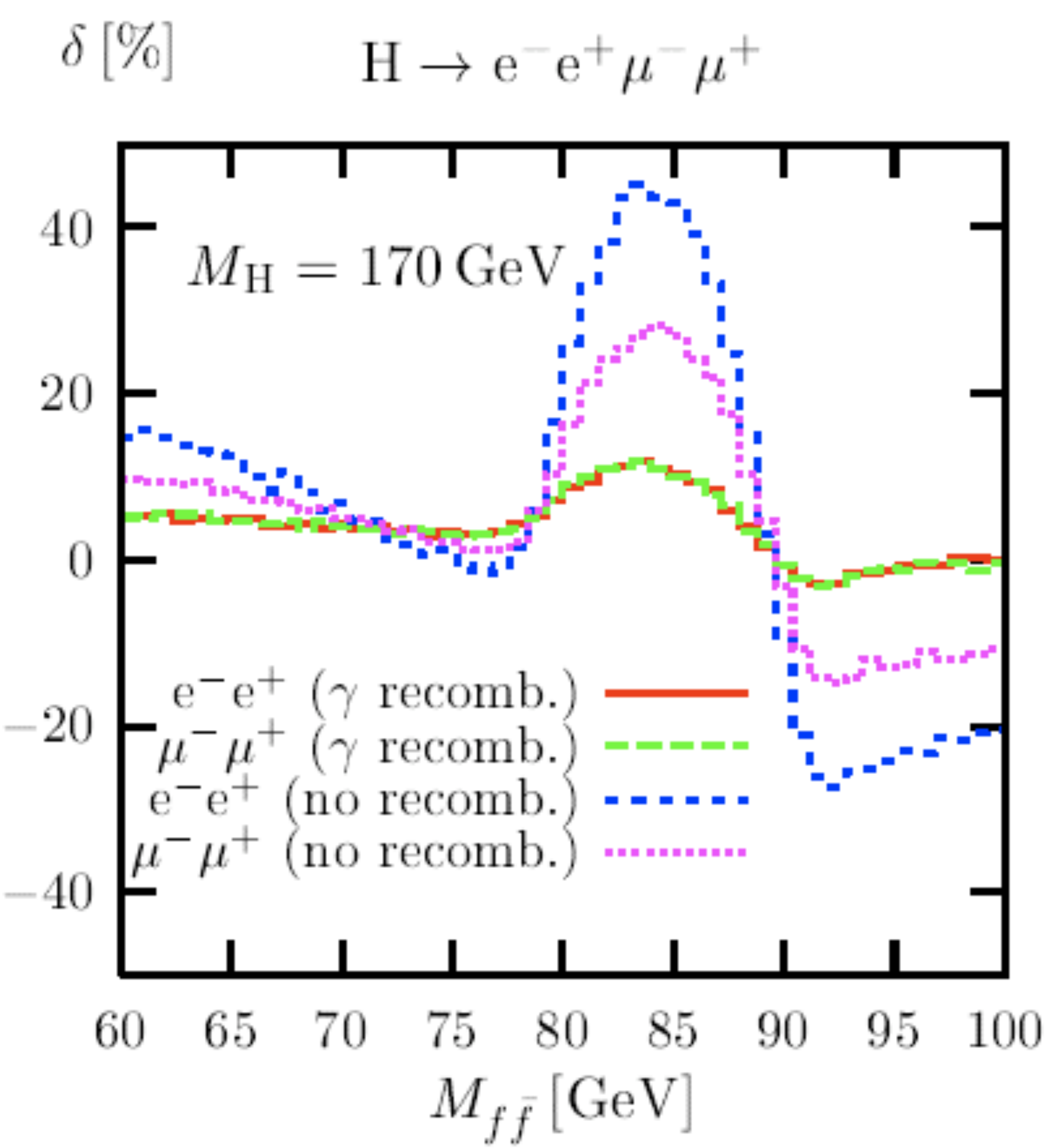
  S.Moch, A. Vogt (2005)

- Computation of soft-virtual effects at N3LO now possible !

  P. Baikov, K. Chetyrkin, A.V. Smirnov, V.A. Smirnov, M. Steinhauser (2009)
  E.W.N. Glover, T. Huber, N. Ikizlerli, C. Studerus, T.Gehrmann (2010)

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

The α_S riddle

What is the value of α_S ?

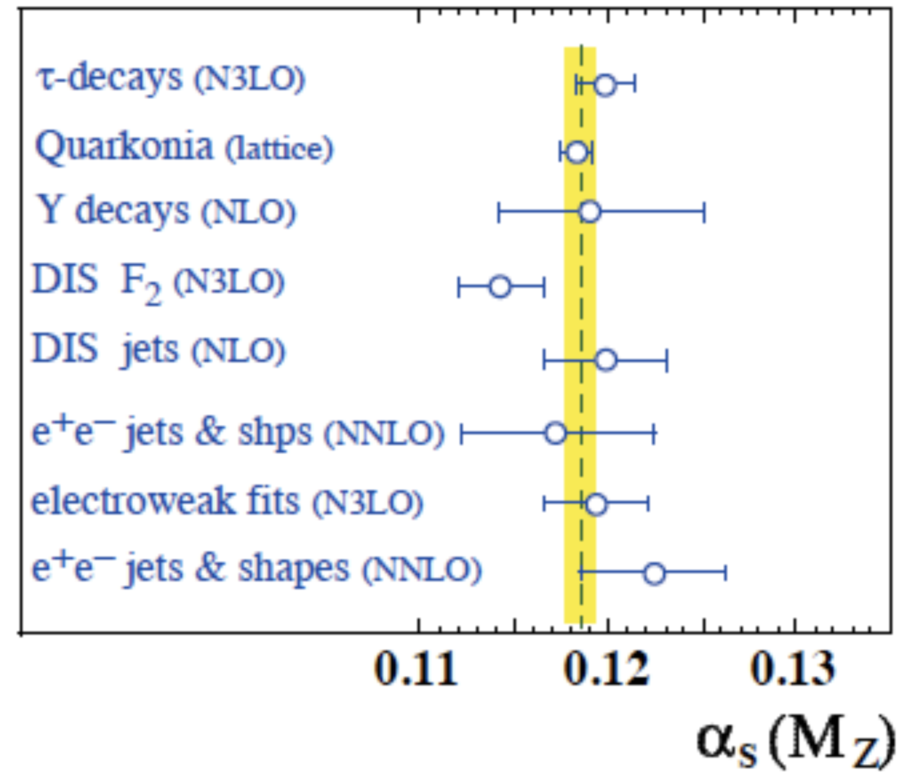
World average $\alpha_S = 0.1184 \pm 0.0007$

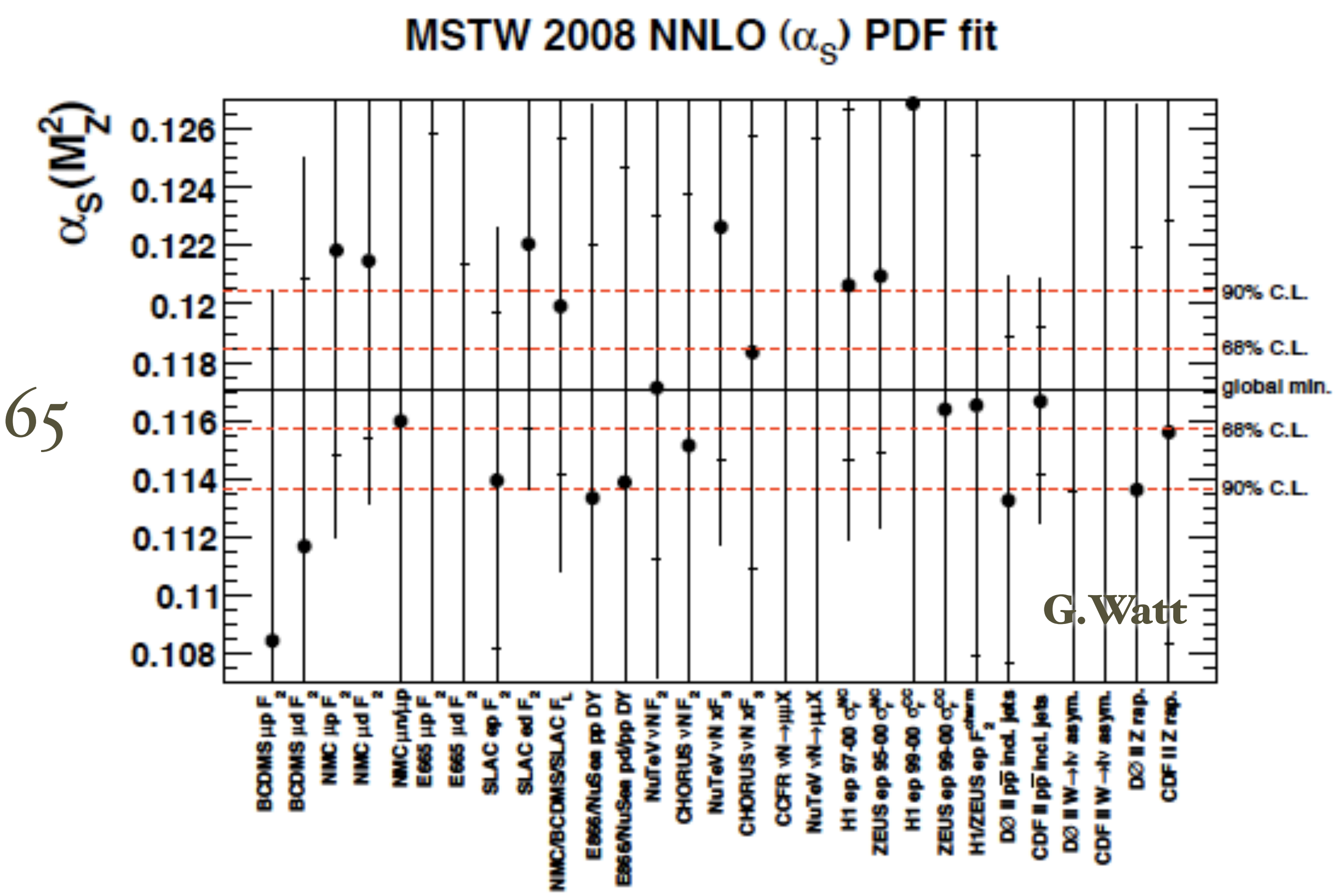
S. Bethke (2009)

Exclude older and less precise measurements → The α_S scandal ! (S. Forte, DIS2010)

Should we trust this result ?
Common lore: DIS data prefer lower α_S

Apparently true only for BCDMS, E665 and SLAC ep data





The α_S riddle

MSTW2008 result $\alpha_S(m_Z) = 0.11707$ at NNLO

Recent claim: this high α_S could be due to mistreatment of NMC data

S. Alekhin et al. (2011)

No such effect seen by MSTW
Similar stability found by NNPDF at NLO and at NNLO

MSTW: impact of Tevatron jet data crucial to get high-x gluon right and thus higher α_S

It is a fact that all NNLO fits (except MSTW) have lower $\alpha_S(m_Z)$

	$\alpha_s(M_Z^2)$	
BBG	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO [1]
GRS	0.112	valence analysis, NNLO [2]
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$ [3]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [3]
JR	0.1124 ± 0.0020	dynamical approach [4]
JR	0.1158 ± 0.0035	standard fit [4]
MSTW	0.1171 ± 0.0014	[5]
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data [6]
Gehrmann et al.	$0.1153 \pm 0.0017 \pm 0.0023$	e^+e^- thrust [7]
Abbate et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust [8]
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^3LO [1]
world average	0.1184 ± 0.0007	[9]

S. Alekhin, J.Blumlein, H. Bottcher, S.Moch (2011)

You think this is boring ?
Let's see implications for Higgs search

Consequences for Higgs cross section

Computation using ABKM or HERAPDFs leads to a cross section smaller by 20-50 % !

Djouadi et al. have used this to challenge the Tevatron exclusion

Thorne-Watt: check the PDFs description of Tevatron jet data

Only global analyses provide good description of jet data

CDF Run II inclusive jet data using k_T

NLO PDF (with NLO $\hat{\sigma}$)	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MRST04	1.06 (0.59)	0.94 (0.31)	0.84 (0.31)
MSTW08	**0.75** (0.30)	**0.68** (0.28)	0.91 (0.84)
CTEQ6.6	1.25 (0.14)	1.66 (0.20)	2.38 (0.84)
CT10	1.03 (0.13)	1.20 (0.19)	1.81 (0.84)
NNPDF2.1	**0.74** (0.29)	**0.82** (0.25)	1.23 (0.69)
HERAPDF1.0	2.43 (0.39)	3.26 (0.66)	4.03 (1.67)
HERAPDF1.5	2.26 (0.40)	3.05 (0.66)	3.80 (1.66)
ABKM09	1.62 (0.52)	2.21 (0.85)	3.26 (2.10)
GJR08	1.36 (0.23)	0.94 (0.13)	**0.79** (0.36)

no jet data

Transverse-momentum spectrum

Among the various distributions an important role is played by the transverse momentum spectrum of the Higgs boson

Its accurate knowledge could help to find strategies to improve statistical significance

Transverse momentum (q_T) and rapidity (y) identify the Higgs kinematics

The shape of rapidity distribution mainly determined by PDFs

→ Effect of QCD radiation mainly encoded in the q_T spectrum

Moreover: the Higgs is a scalar → production and decay processes essentially factorized

When considering the transverse momentum spectrum it is important to distinguish two regions of transverse momenta

$q_T \sim M$

To have $q_T \neq 0$ the Higgs boson has to recoil against at least one parton → the LO is of relative order α_S

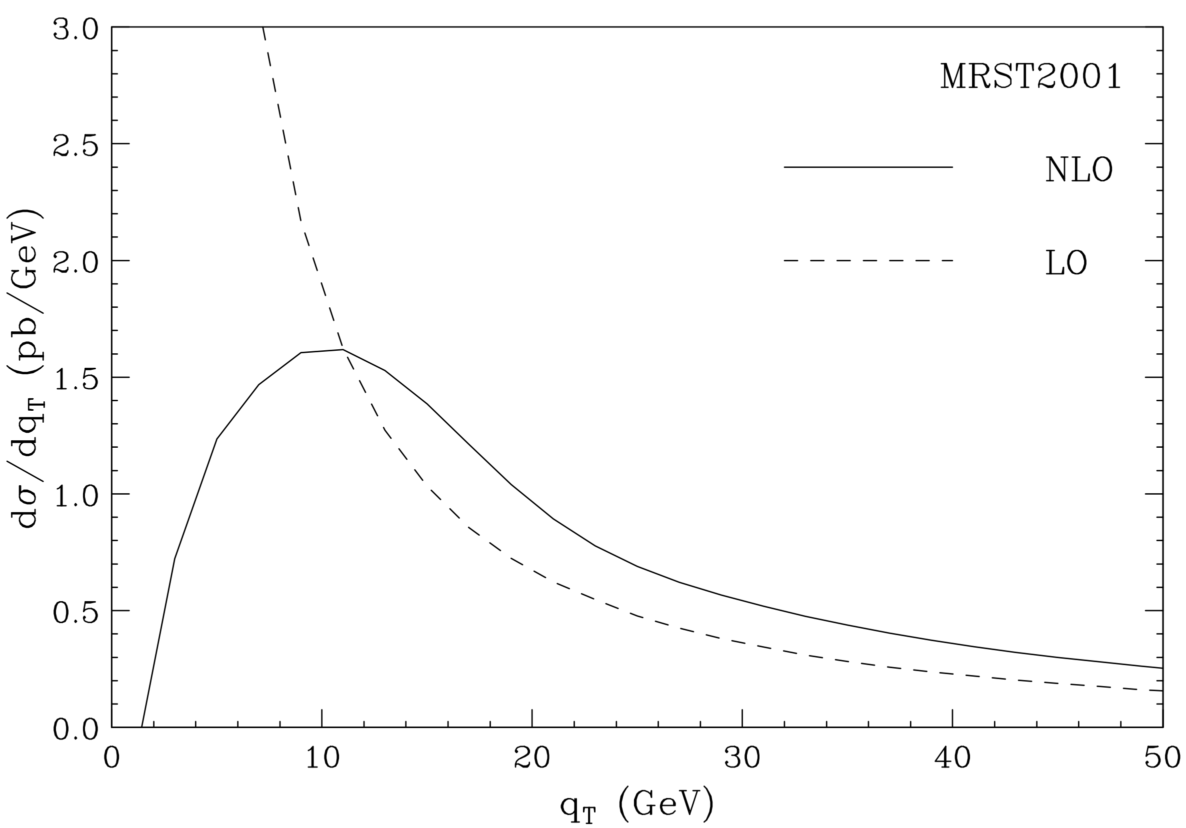
D. de Florian, Z.Kunszt, MG (1999)
V.Ravindran, J.Smith, V.Van Neerven (2002)
C.Glosser, C.Schmidt (2002)

NLO corrections are known → **Part of inclusive NNLO corrections**

$q_T << M$

Large logarithmic corrections of the form $\alpha_S^n \ln^{2n} M^2/q_T^2$ appear that originate from soft and collinear emission

→ the perturbative expansion becomes not reliable



LO: $\frac{d\sigma}{dq_T} \to +\infty$ as $q_T \to 0$

NLO: $\frac{d\sigma}{dq_T} \to -\infty$ as $q_T \to 0$

→ RESUMMATION NEEDED (effectively perfomed by standard MC generators)

The resummation formalism has been developed in the eighties

Y.Dokshitzer, D.Diakonov, S.I.Troian (1978)
G. Parisi, R. Petronzio (1979)
G. Curci, M.Greco, Y.Srivastava(1979)
J. Collins, D.E. Soper, G. Sterman (1985)

As it is customary in QCD resummations one has to work in a conjugate space in order to allow the kinematics of multiple gluon emission to factorize

In this case, to exactly implement momentum conservation, the resummation has to be performed in impact parameter b-space

Many phenomenological studies performed at different levels of theoretical accuracy

I.Hinchliffe, S.F.Novaes (1988)
R.P. Kauffmann (1991)
C.P.Yuan (1992)
C.Balazs, C.P.Yuan (2000)
E. Berger, J. Qiu (2003)
A.Kulezsa, J.Stirling (2003)
....

Recent studies also in the context of SCET

S.Mantry, F.Petriello (2009,2010)
T. Becher, M.Neubert (2010)
....

Our formalism

We proposed a version of the b-space formalism with some novel features

S.Catani, D. de Florian, MG (2000)
G. Bozzi, S.Catani, D. de Florian, MG(2005)

Parton distributions factorized at $\mu_F \sim M = m_H$ → **avoids PDF extrapolation to small scales**

$$\frac{d\hat{\sigma}_{ac}^{(\mathrm{res.})}}{dq_T^2} = \frac{1}{2}\int_0^\infty db\, b J_0(bq_T)\mathcal{W}_{ac}(b, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)$$

$$\mathcal{W}_N^F(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \mathcal{H}_N^F\left(M, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2\right) \times \exp\{\mathcal{G}_N(\alpha_S(\mu_R^2), L; M^2/\mu_R^2, M^2/Q^2)\}$$

process dependent (→ $\mathcal{H}_N^F$)

universal (→ $\mathcal{G}_N$)

where the large logs are organized as:

$$\mathcal{G}_N(\alpha_S, L; M^2/\mu_R^2, M^2/Q^2) = L\, g^{(1)}(\alpha_S L) + g_N^{(2)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2) + \alpha_S\, g_N^{(3)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2) + \dots$$

with $L = \ln M^2 b^2/b_0^2$ → $\tilde{L} = \ln\left(1 + Q^2 b^2/b_0^2\right)$ and $\alpha_S = \alpha_S(\mu_R)$

resummation scale (→ Q^2)

- **The form factor takes the same form as in threshold resummation**
- **Unitarity constraint enforces correct total cross section**
- **Allows a consistent study of perturbative uncertainties**

The resummed and fixed order calculations can then be combined to achieve uniform theoretical accuracy over the entire range of q_T

$$\frac{d\hat{\sigma}}{dq_T^2} = \frac{d\hat{\sigma}^{(\mathrm{res.})}}{dq_T^2} + \frac{d\hat{\sigma}^{(\mathrm{fin.})}}{dq_T^2}$$

→ **standard fixed order result minus expansion of resummed formula at the *same* order**

The calculation can be done at:

- NLL+LO*: we need the functions $g^{(1)}$, $g_N^{(2)}$ and the coefficient $\mathcal{H}_N^{(1)}$ plus the matching at relative order α_S
- NNLL+NLO*: we also need the function $g_N^{(3)}$ and the coefficient $\mathcal{H}_N^{(2)}$ plus the matching at relative order α_S^2

* **Note that here LO and NLO refer to the spectrum: they contribute to NLO and NNLO normalization !**

NNLL+NLO represents the highest accuracy available to date

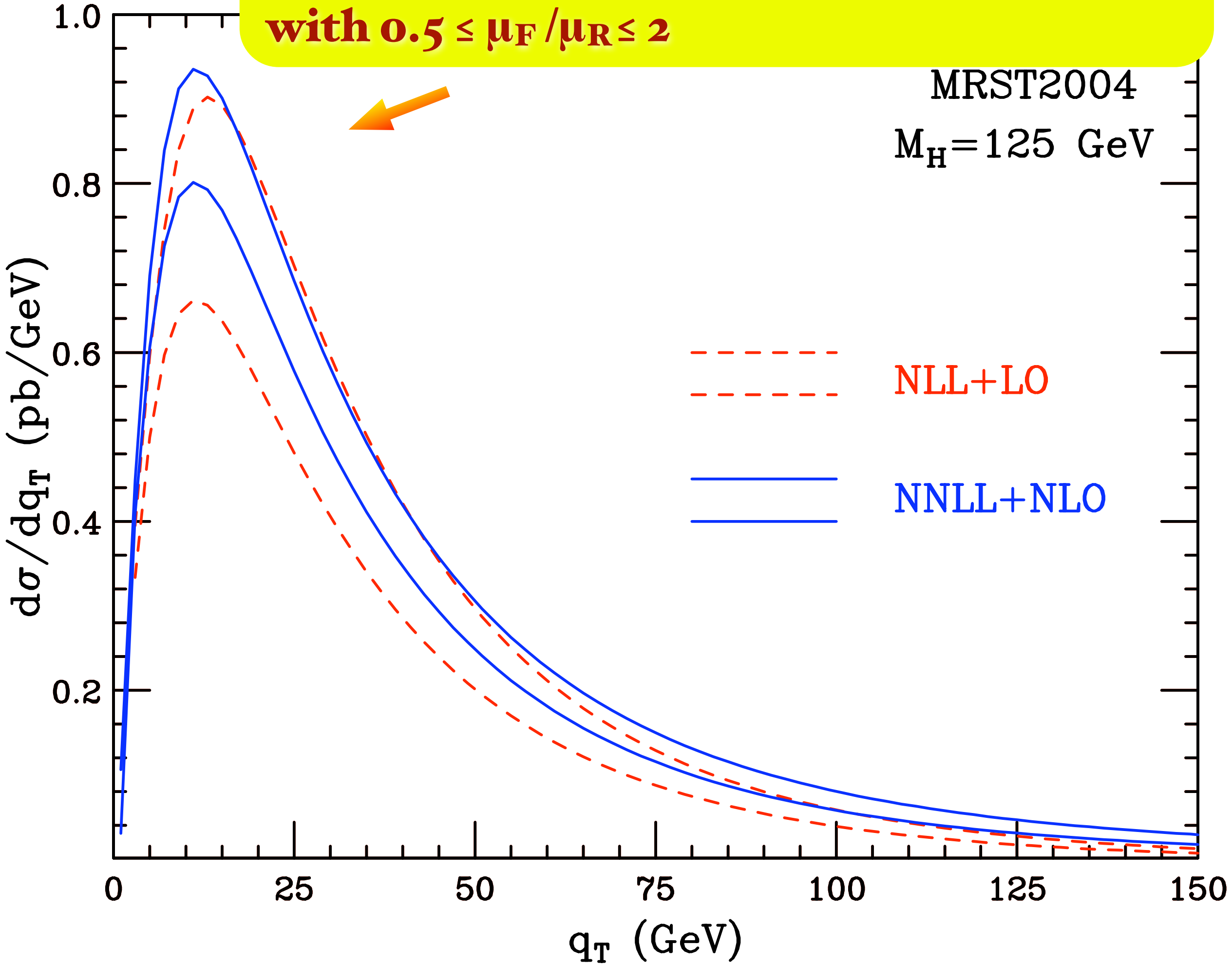
→ Implemented in HqT

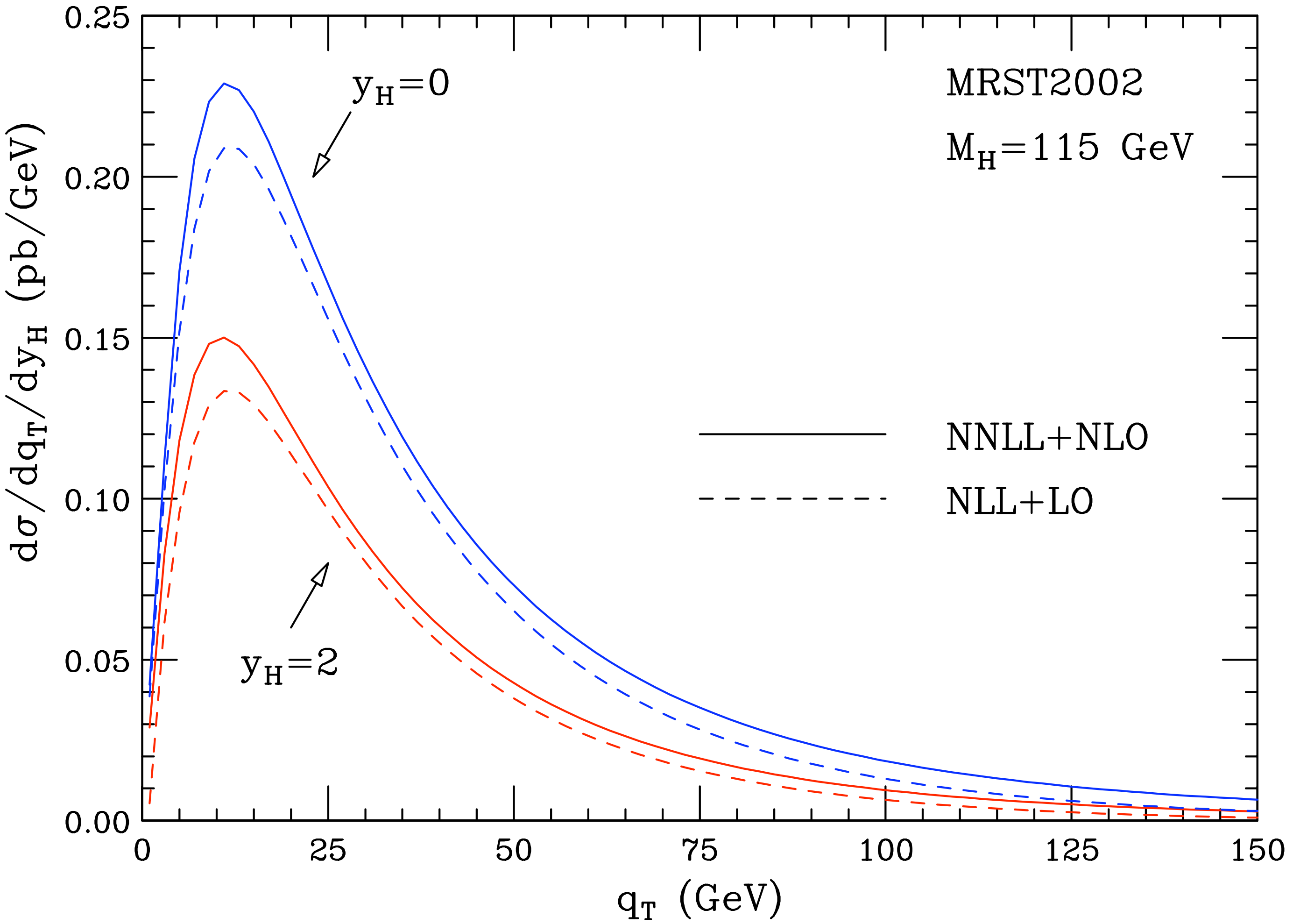
At NLL+LO the accuracy is essentially the same as in MC@NLO/POWEG

Results

G. Bozzi, S.Catani, D. de Florian, MG (2005,2007)

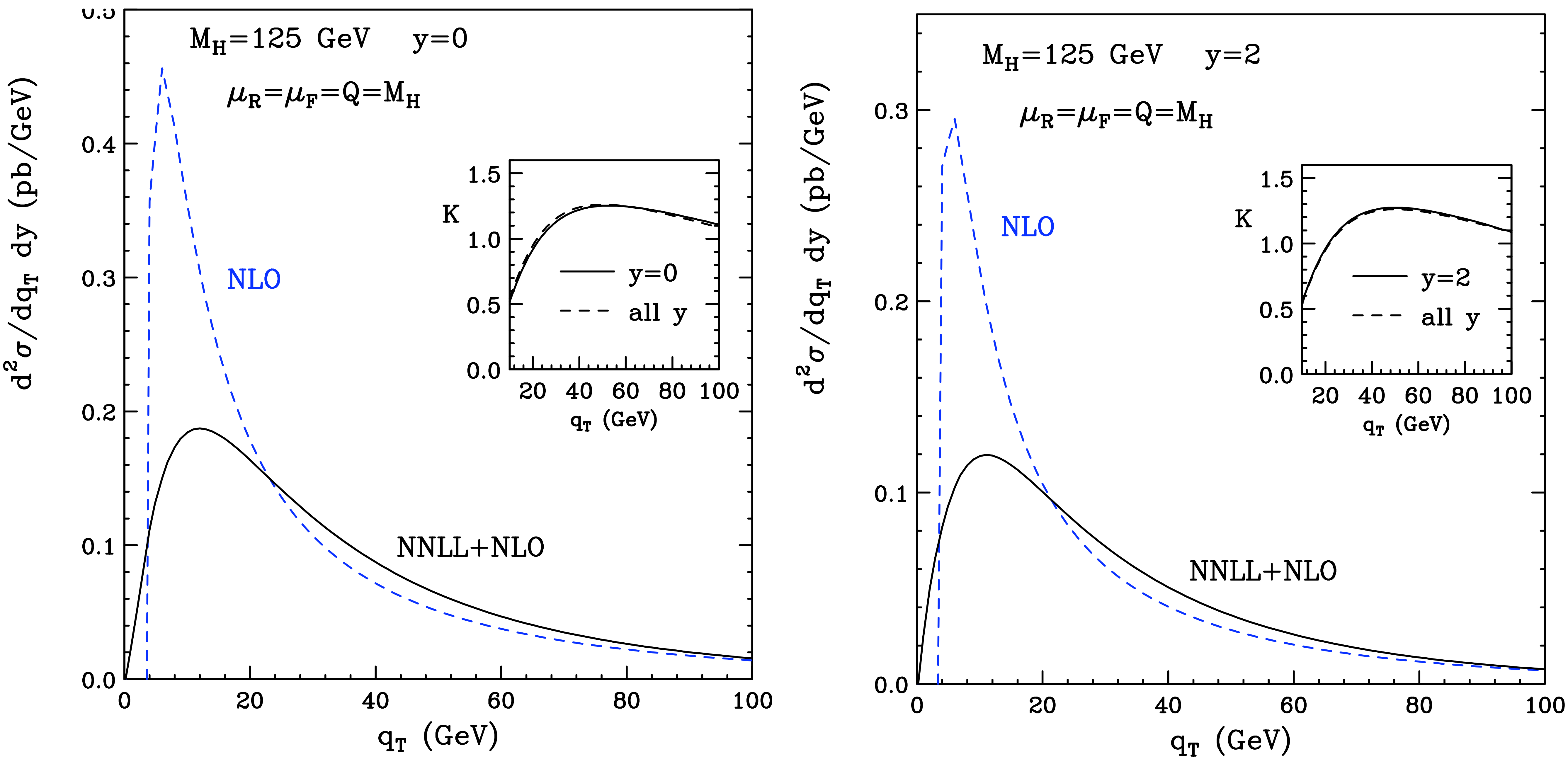
scale uncertainty computed by varying μ_F and μ_R in the range $0.5\, m_H \leq \mu_F, \mu_R \leq 2\, m_H$ with $0.5 \leq \mu_F/\mu_R \leq 2$





NNLL+NLO and NLL+LO bands overlap: nice convergence of the perturbative resummed result

Shape of resummed spectrum mildly dependent on rapidity



- Define $K(q_T, y) = \dfrac{d\sigma_{NNLL+NLO}/(dq_T dy)}{d\sigma_{NLO}/(dq_T dy)}$

→ Impact of resummation mildly dependent on rapidity

NEW: Preliminary: HqT2.0

D. de Florian, G.Ferrera,
D. Tommasini, MG (2011)

Few improvements:

- The present version of HqT is based on a crude estimate of $\mathcal{H}_N^{(2)}$

$$\mathcal{H}^{(2)}_{gg\leftarrow ab}(z) \sim \delta_{ga}\delta_{gb}\delta(1-z)\left(\left(\frac{19}{8}+\frac{2}{3}n_F\right)\ln m_H^2/m_{top}^2 + c\right)$$

Consider only δ(1-z) term and fix its normalization using knowledge of total cross section ➡ works reasonably well both at the Tevatron and the LHC but now exact result is known and can be implemented

S.Catani, MG (2011)

- Exact treatment of resummation scale Q

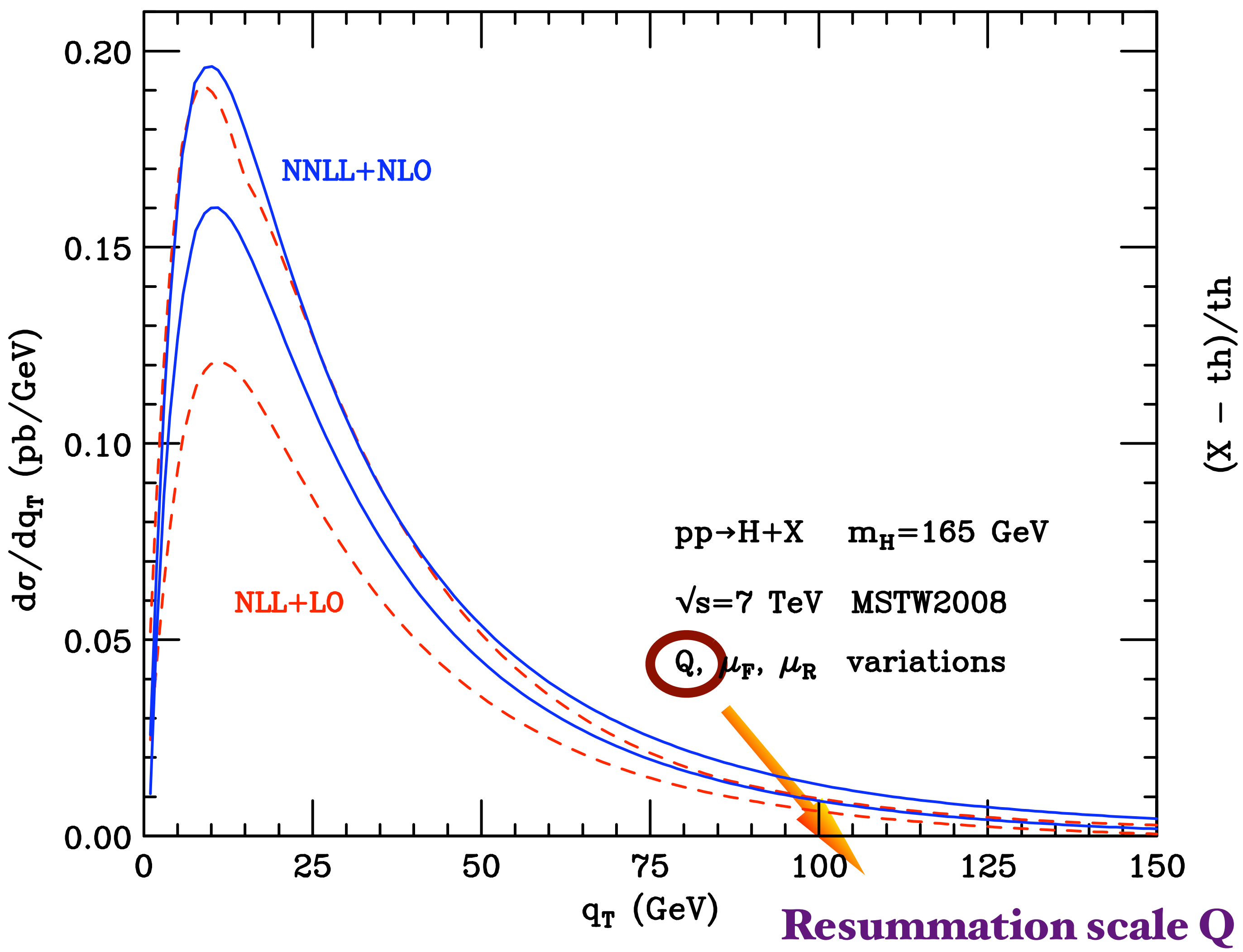
- Value of $A^{(3)}$ for q_T resummation implemented

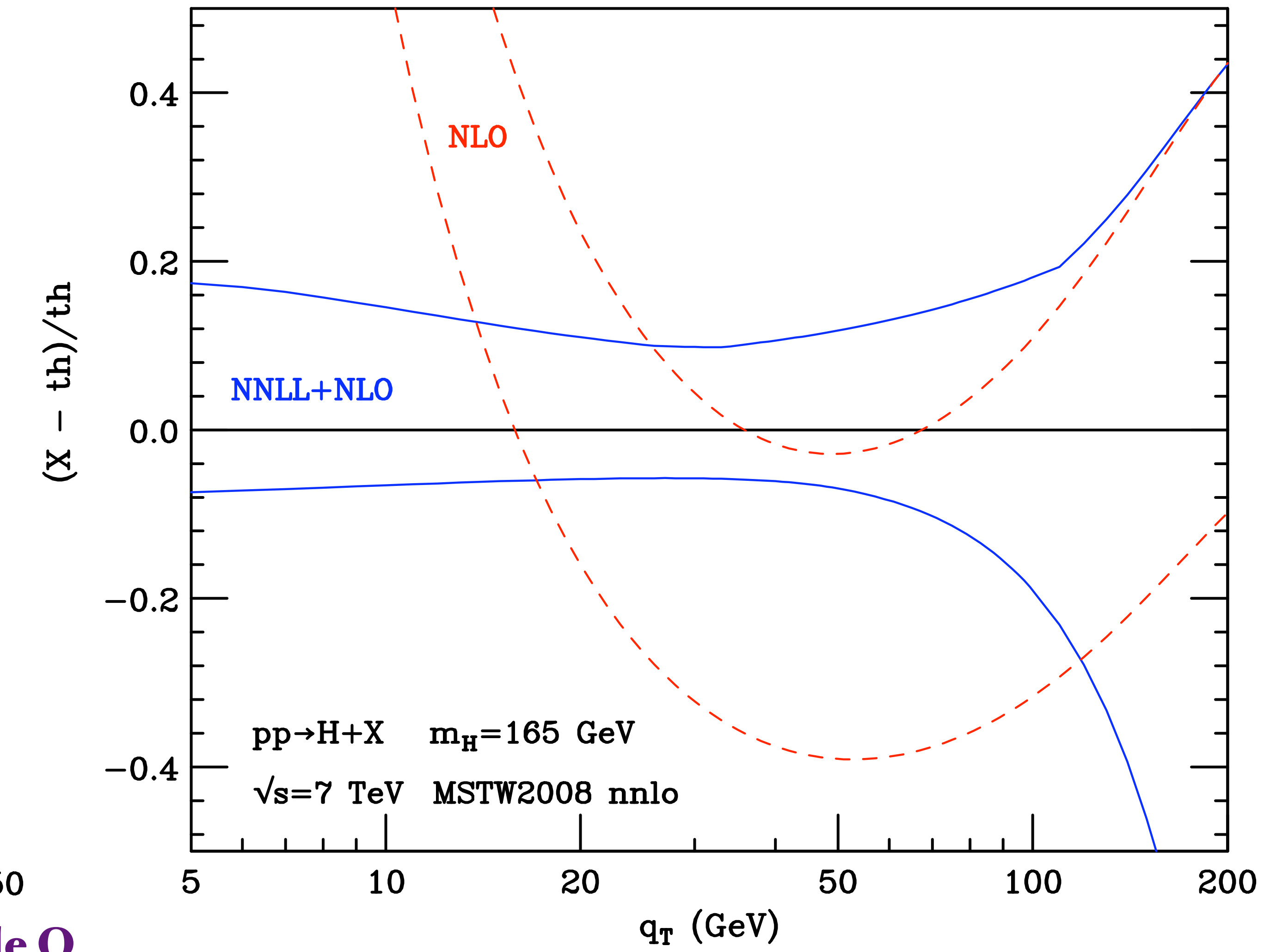
T.Becher, M.Neubert (2010)

- Interface with LHAPDF

Differences with current version at the percent level

NEW: Preliminary: HqT2.0





Scale uncertainty computed by independent variations of μ_F,μ_R and Q in the ranges $1/2\ m_H < \{\mu_F,\mu_R\} < 2m_H$ and $1/4\ m_H < Q < m_H$ with the constraints $1/2 < \mu_F/\mu_R < 2$ and $1/2 < Q/\mu_R < 2$

Perturbative uncertainty at NNLL+NLO ranges from about ±10% at the peak to about ±13% at q_T=75 GeV

At large values of q_T the resummed result looses predictivity: better to use NLO

Shape uncertainty

One of the main issues that is being discussed is how to evaluate the uncertainty on the cross section after cuts

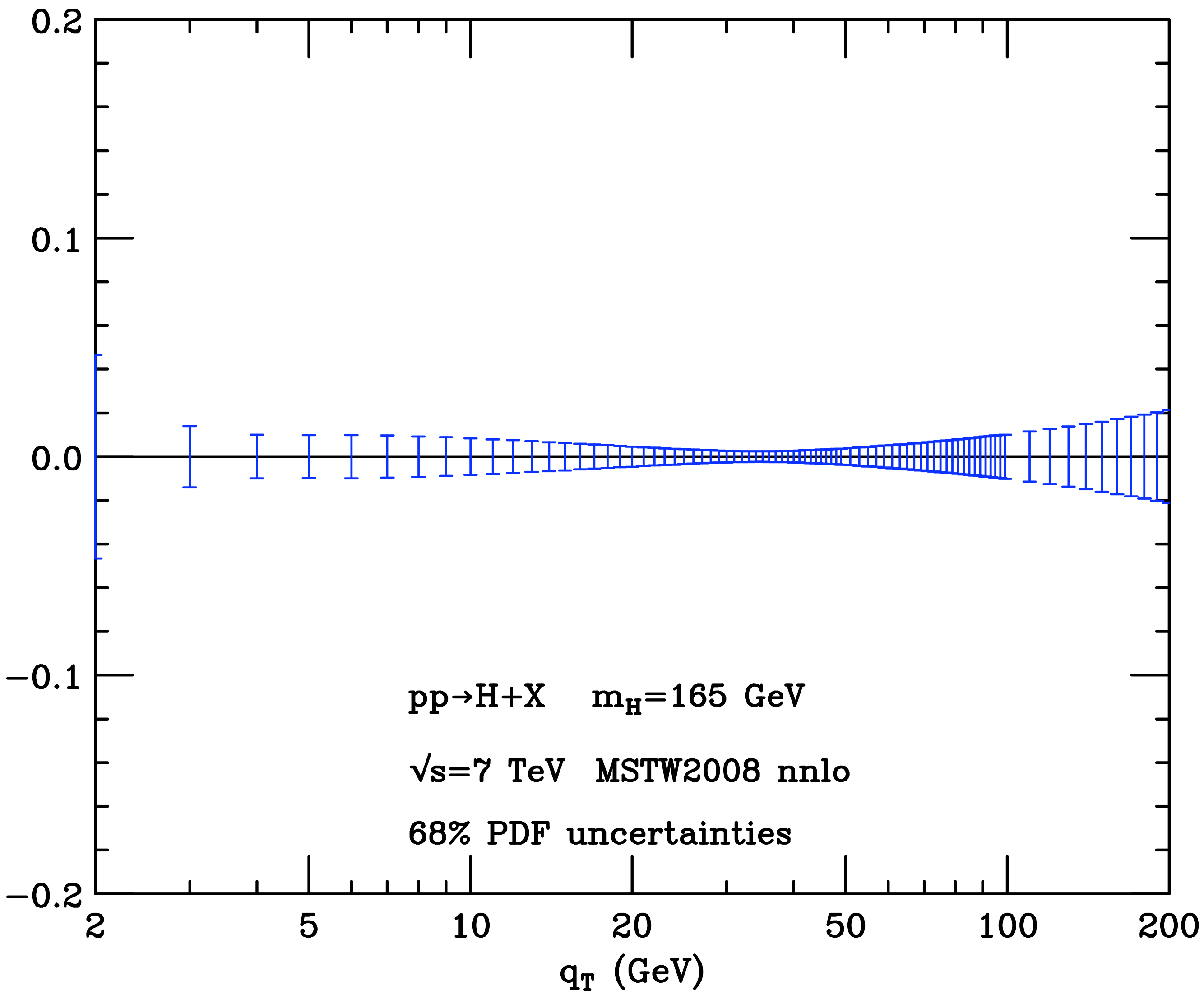
If HqT is used to reweight the spectrum of MC event generators

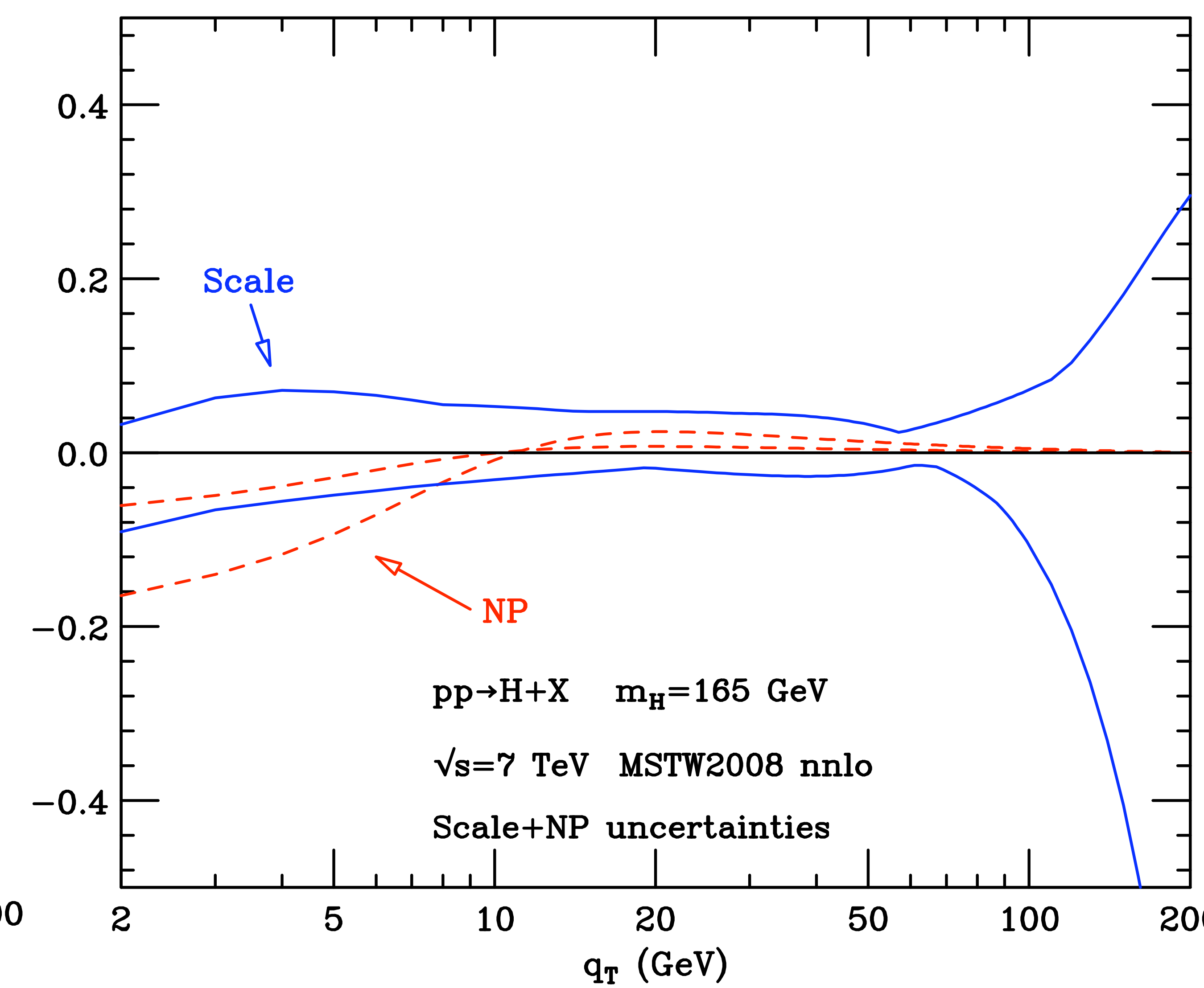
→ What matters is actually the uncertainty on the SHAPE of the q_T distribution provided by HqT

Sources of uncertainties:

- Scale dependence
- PDFs
- Non-perturbative effects
- Large m_{top} approximation ?

Shape uncertainty





PDF uncertainties apparently have a small impact on the shape of the spectrum

As q_T increases different x ranges are probed

➡ Other PDFs could lead to more sizable effects

Scale uncertainties at the level of about ±5%

NP effects estimated as in Bozzi et al. (2005)

They become important at small q_T