Higgs production: theory overview

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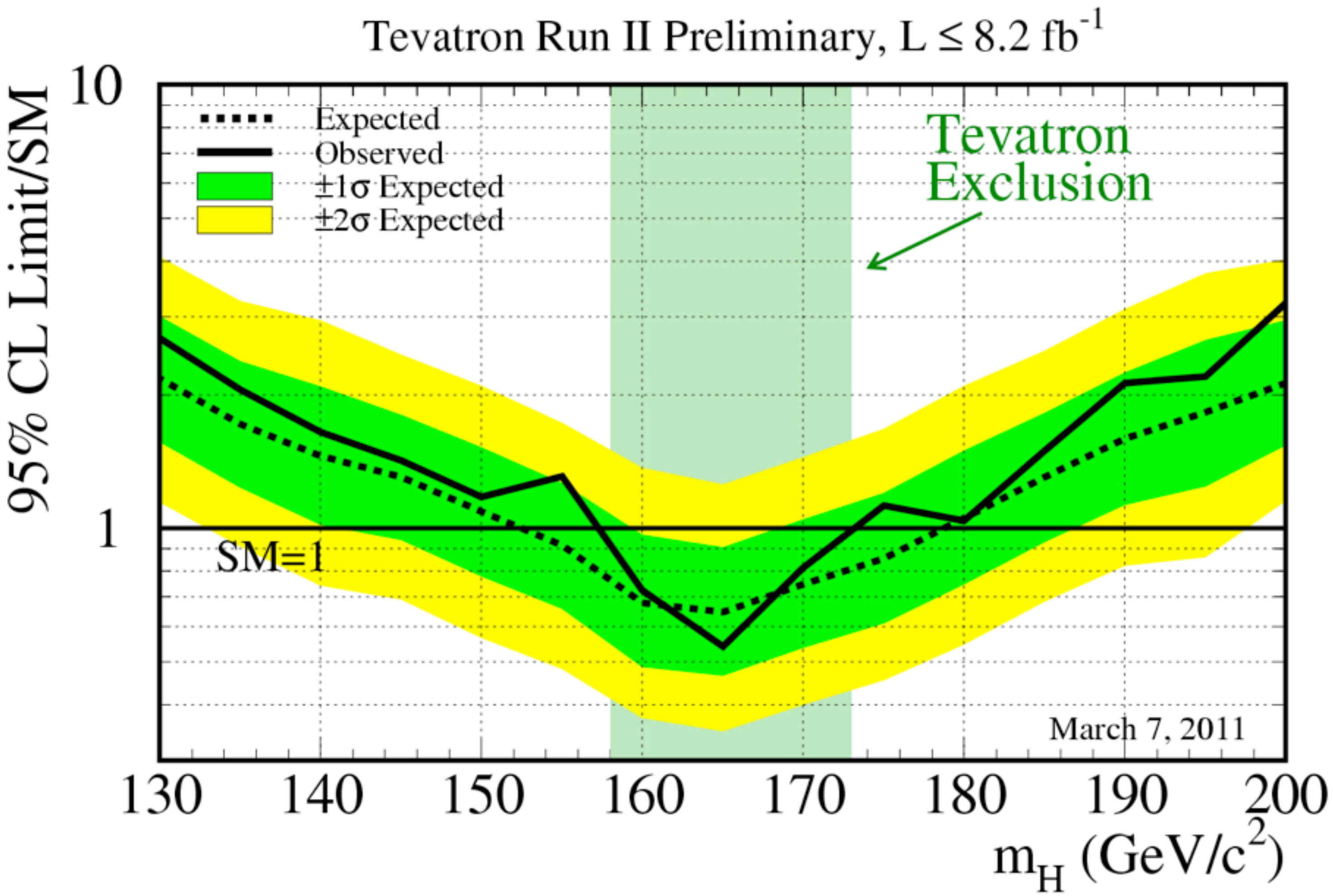
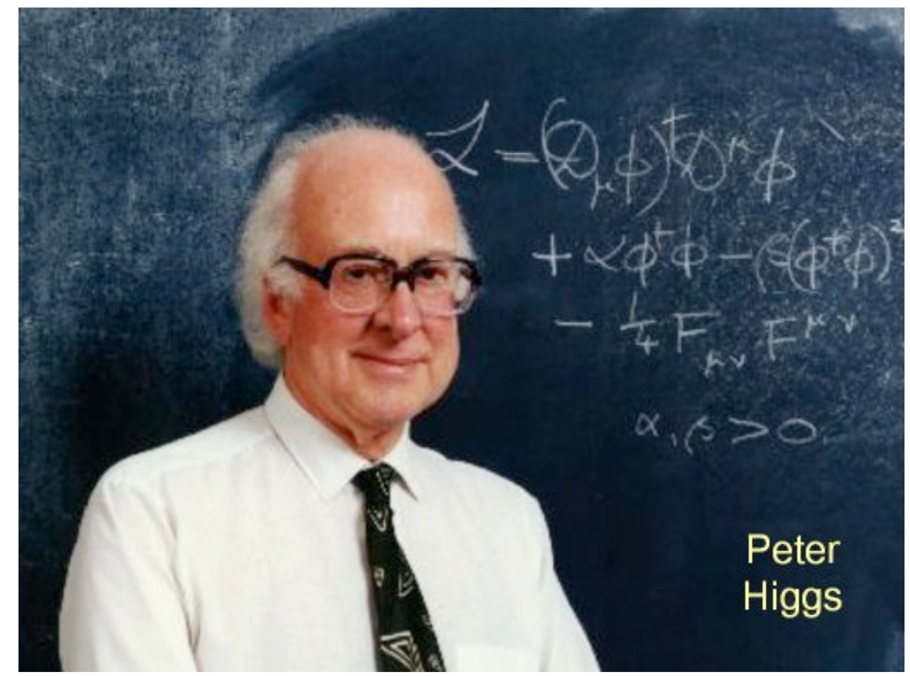
Higgs Hunting 2011, Paris

*On leave of absence from INFN, Sezione di Firenze

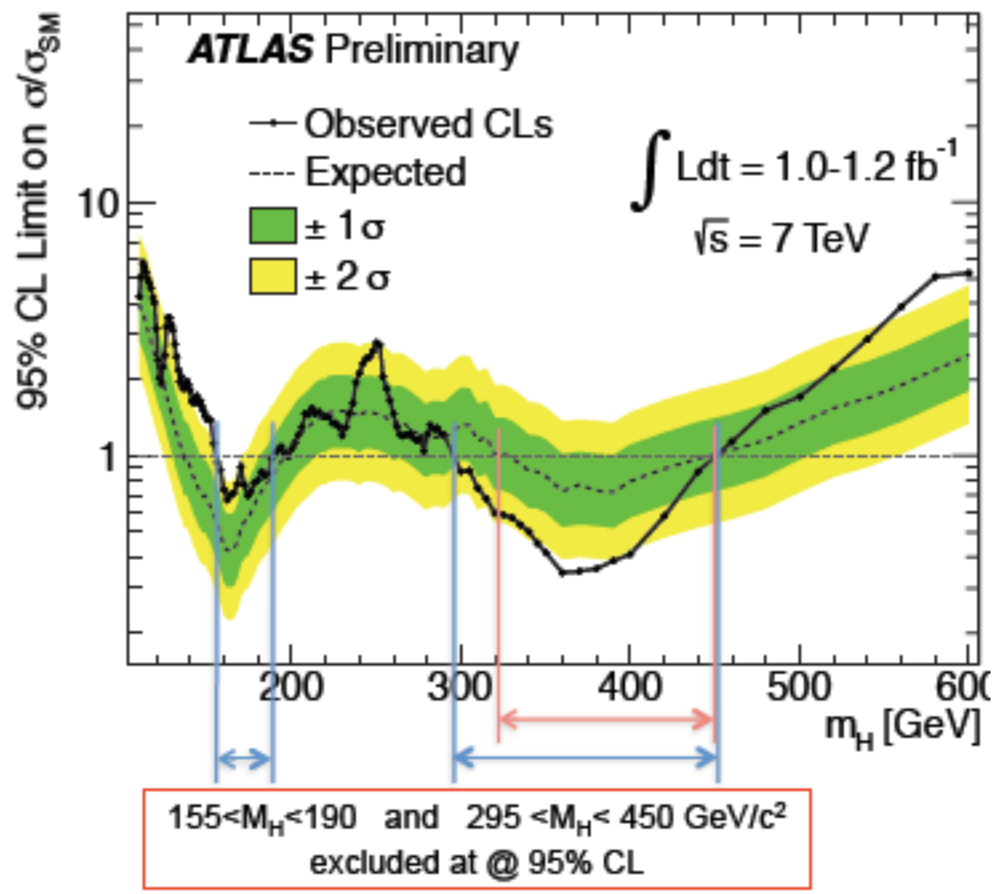
Where we were....





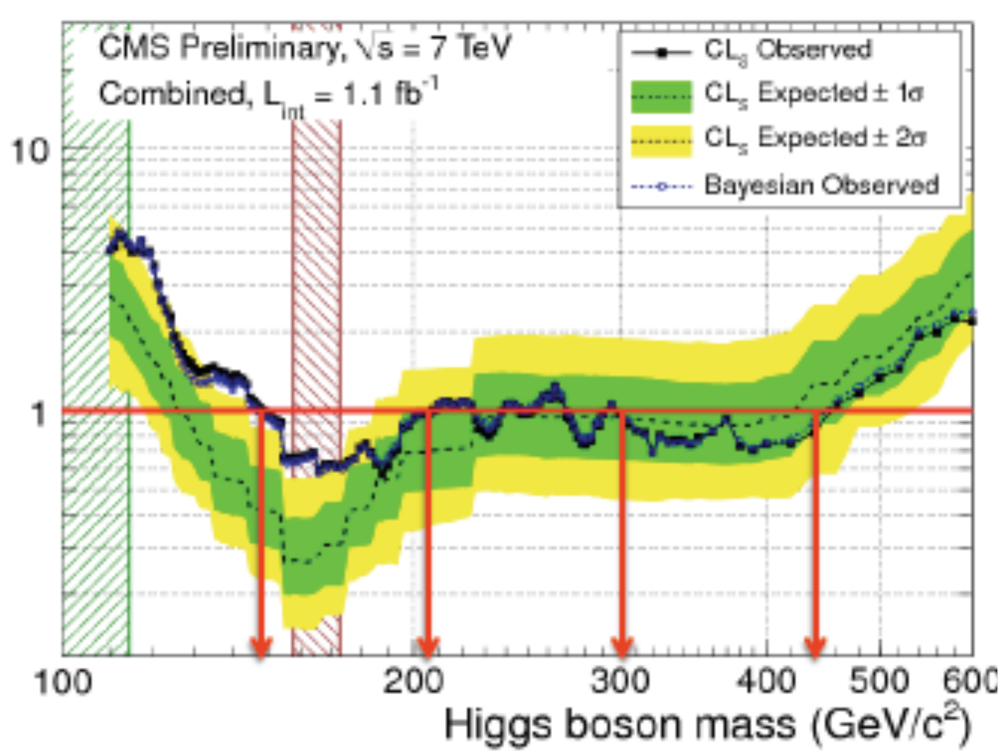
Tevatron combination of Winter 2011:
SM Higgs boson with 158 GeV ≤ m_H ≤ 173 GeV excluded at 95% CL

Where we are now !



How a theorist feels.....

....like having a banquet after years of diet !

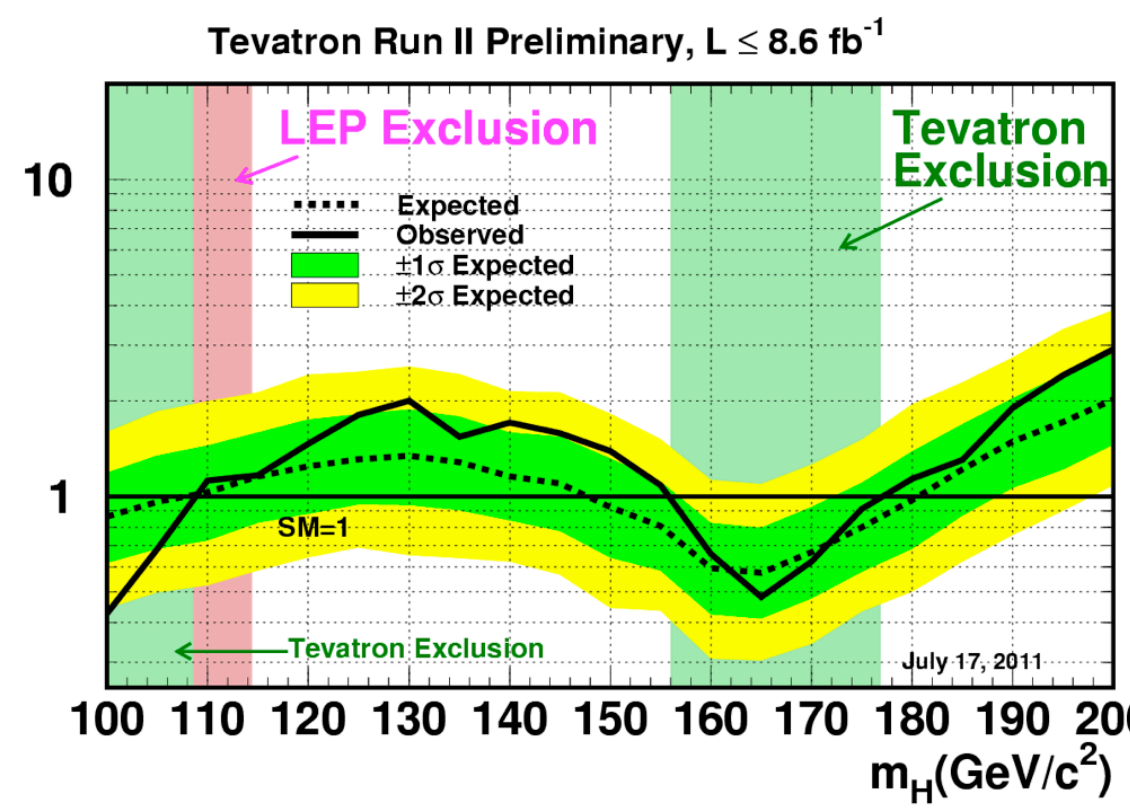


Excluded (GeV)

[149-206] ... [300-440]

and 3 short segments

in between

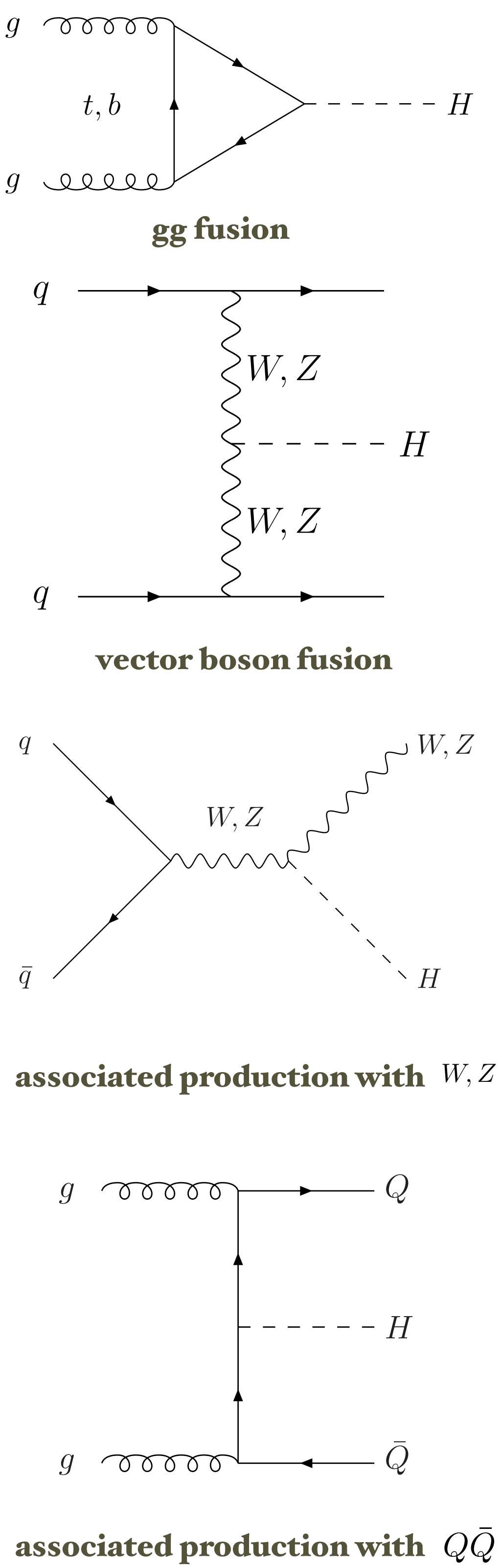


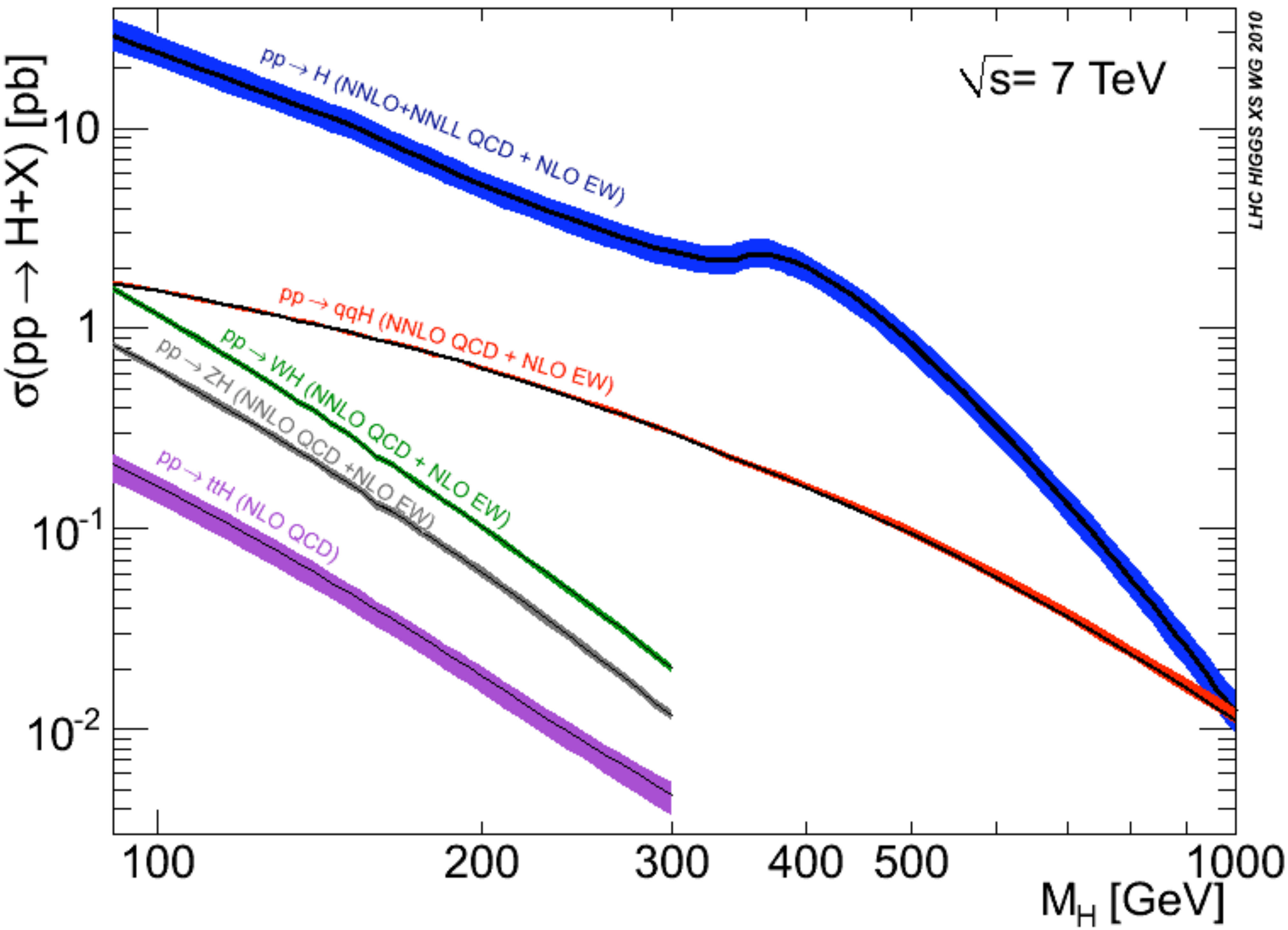
Outline

- Inclusive cross sections
  - gg fusion
  - Vector boson fusion
  - Associated VH production
- The NNLO revolution
  - WH
  - $\gamma\gamma$
- Theory uncertainties: two issues
  - Scale uncertainties and jet bins
  - Heavy Higgs
- Summary and Outlook

1) Inclusive cross sections

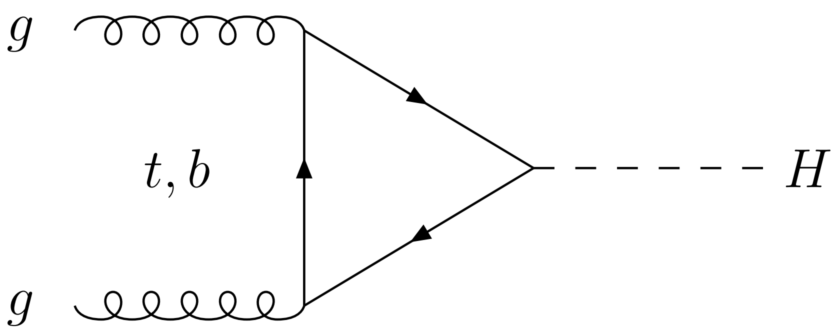
Inclusive cross sections





Focus here on the three main channels

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

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

They increase the LO result by O(100 %) !

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)

Large-m_{top} approximation works extremely well up to m_H=300 GeV (differences of the order of 0.5 % !)

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

Probably the most important recent result on this channel

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)

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 $\mu_F = \mu_F = m_H/2$ 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

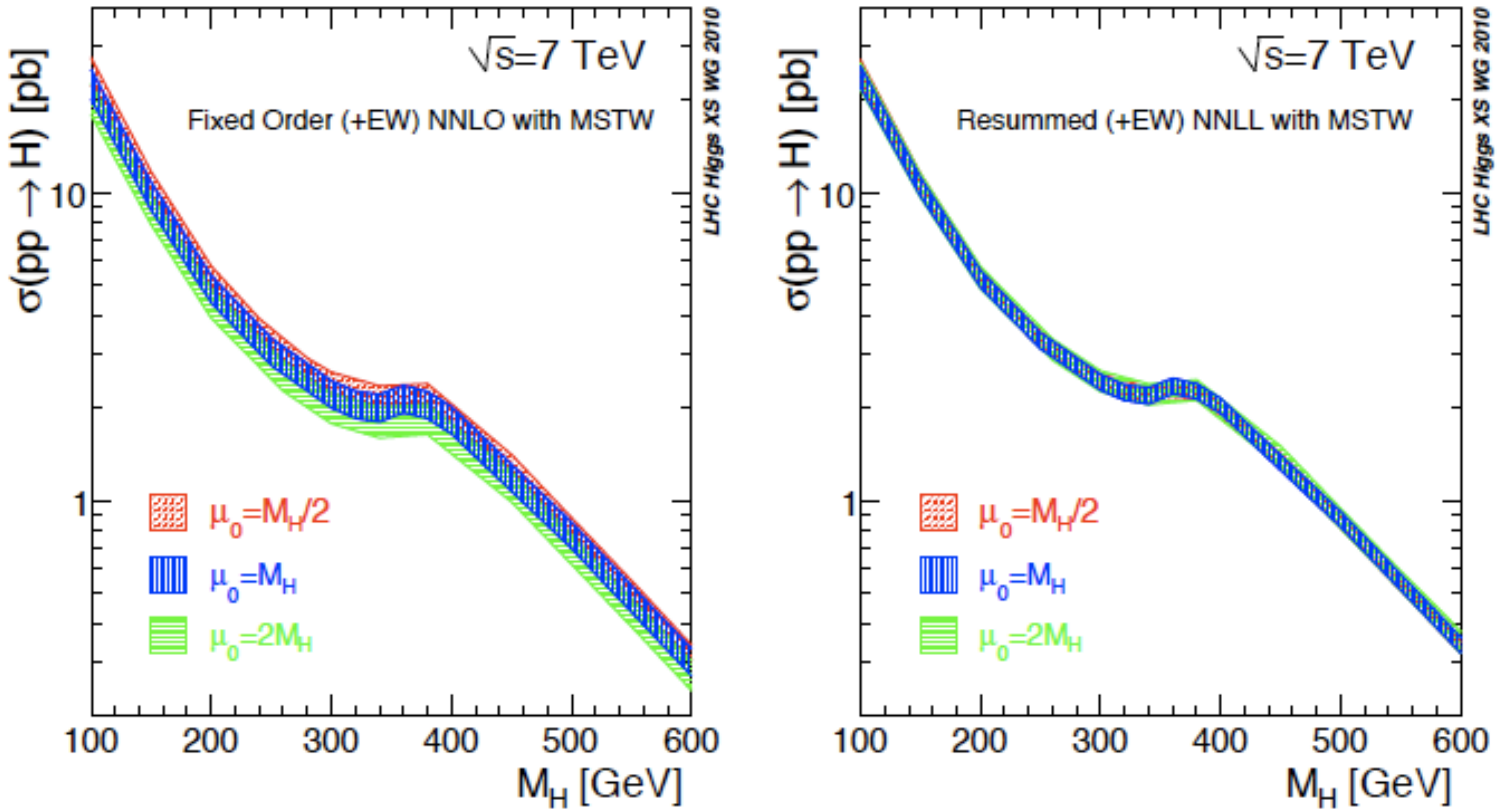
  - Include EW effects as computed by Passarino et al.

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)

Results



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 !

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 $\mu_F = \mu_F = m_H/2$ 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

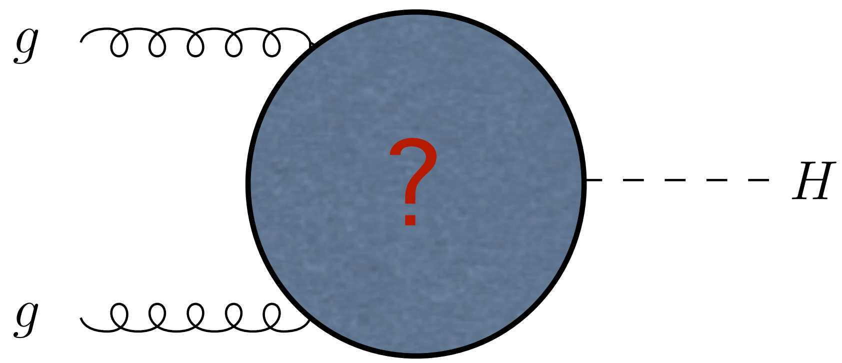
- Perturbative uncertainties of about 3% or smaller → largely underestimated !

- 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

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

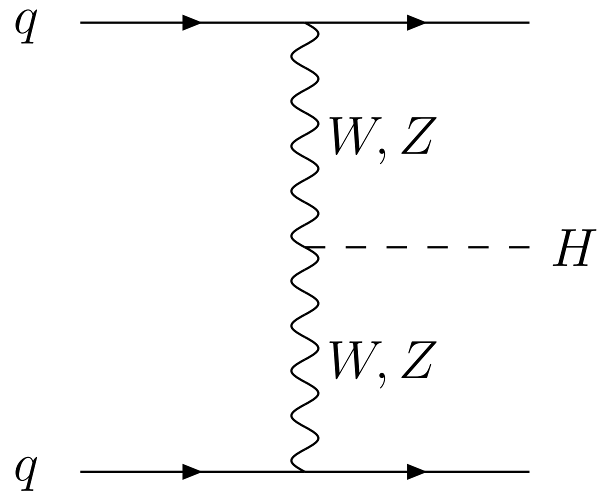
R.Boughezal, F.Petriello (2011)
R.Boughezal (2011)

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)

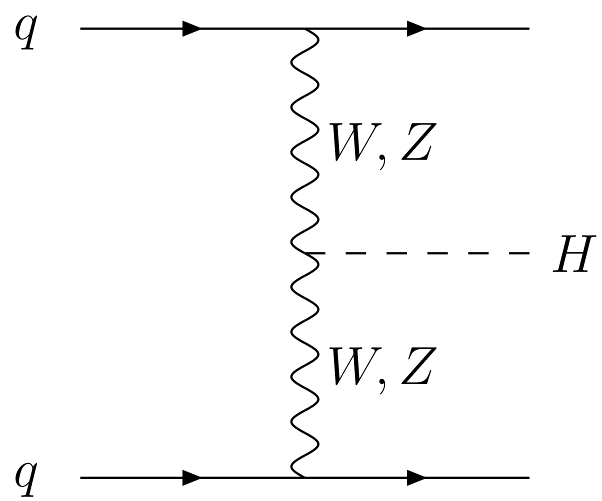
Implemented for distributions in VBFNLO

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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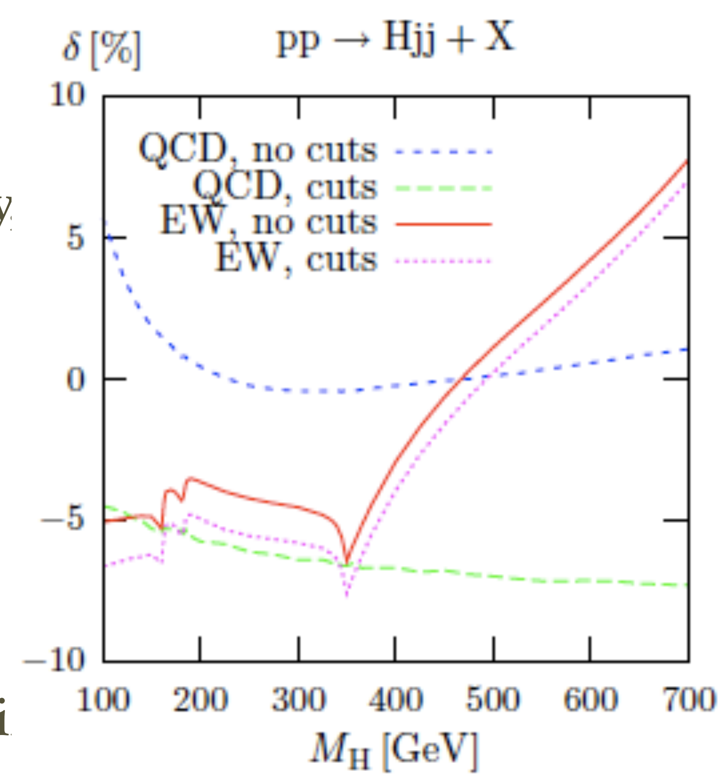
M.Ciccoli



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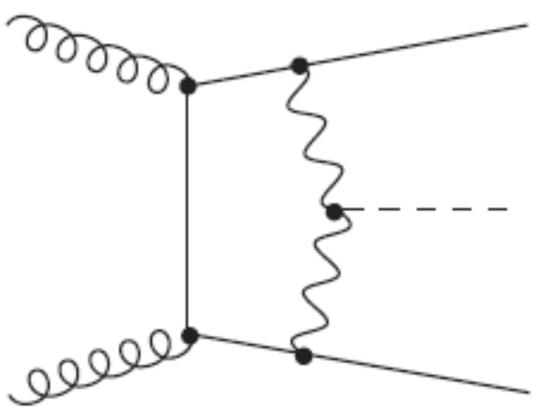
Vector boson fusion

Other radiative contributions:

Interference with gluon fusion

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

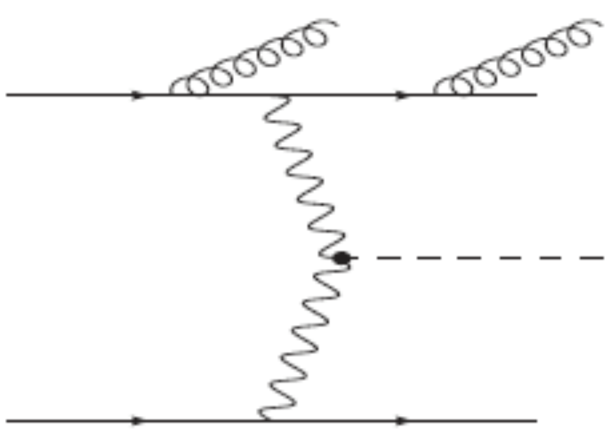
Other refinements include some NNLO contributions like gluon-induced diagrams



well below 1% level

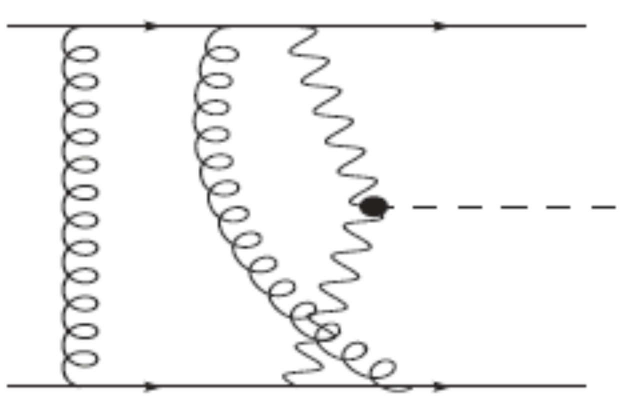
R.Harlander, J.Vollinga,M.Weber (2008)

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



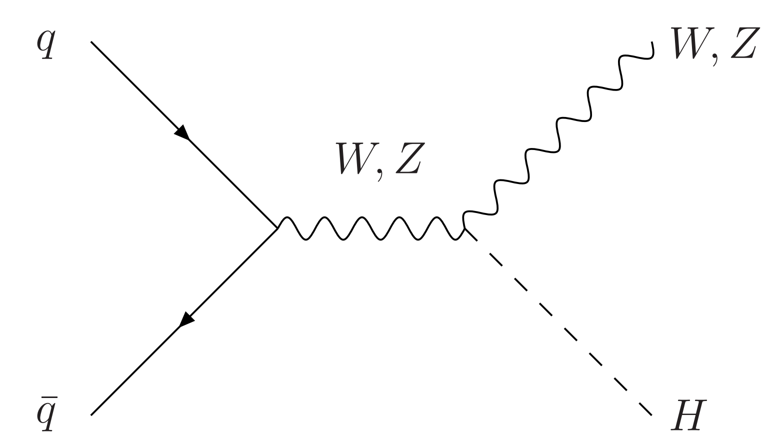
scale uncertainty reduced to the 2% level

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%

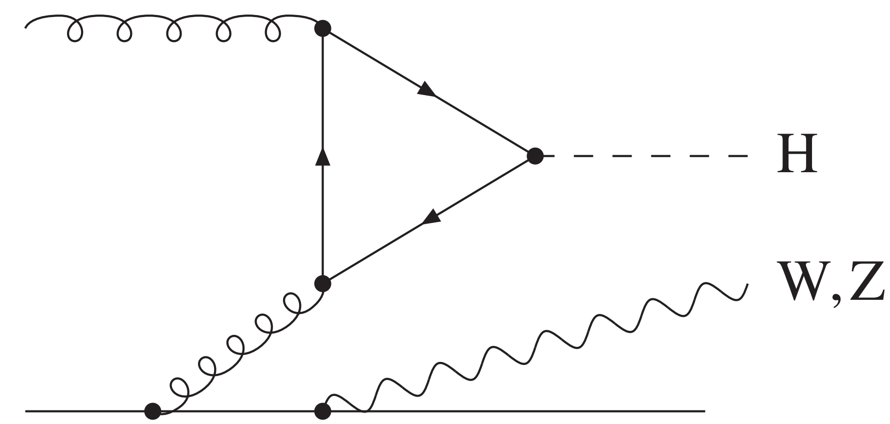
M.L. Ciccolini, S. Dittmaier, M. Kramer (2003)

Associated VH production

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

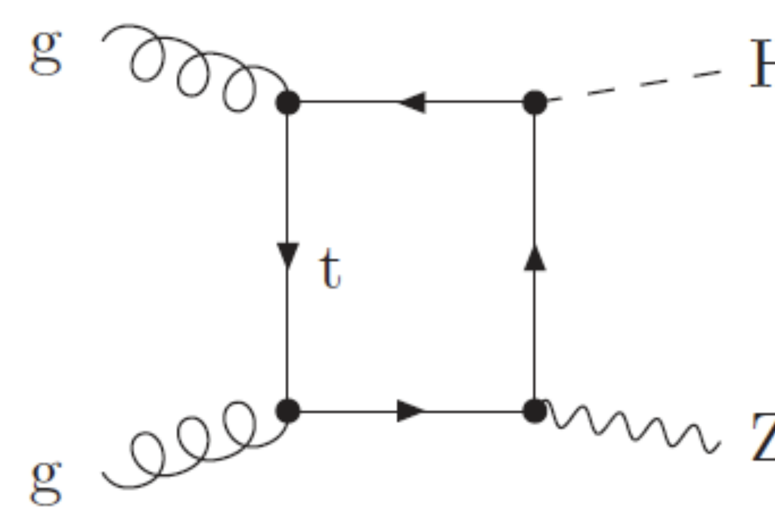
W. Van Neerven e al. (1991)

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)

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

- $gg \to H$ 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)

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

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

→ 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)

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

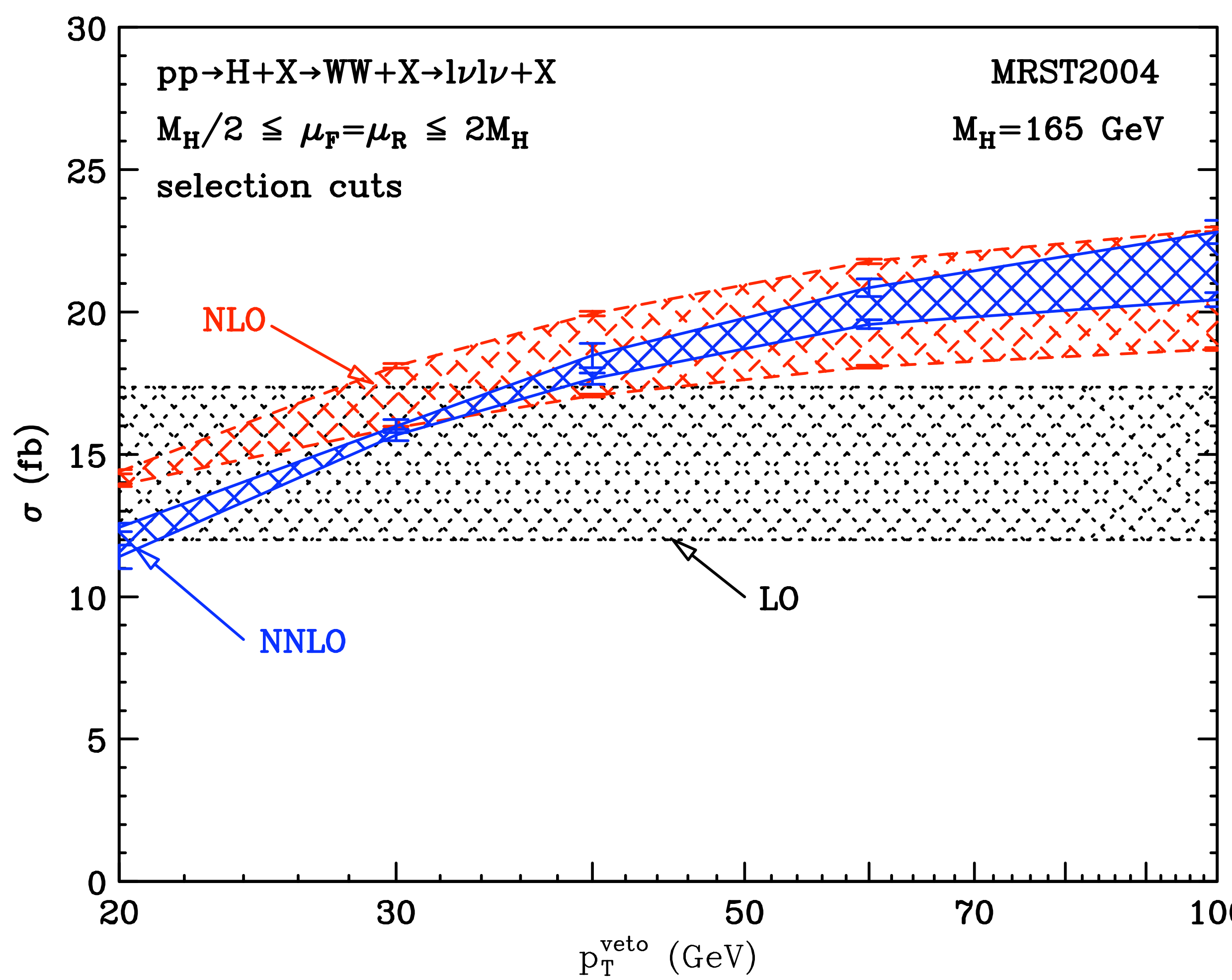
The $t\bar{t}$ background is characterized by high-p_T b-jets and requires the use of a jet veto

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 $p_T^{veto} \gtrsim 30$ GeV

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

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



cuts as in Davatz et al. (2003)

The NNLO revolution

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= γγ,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)

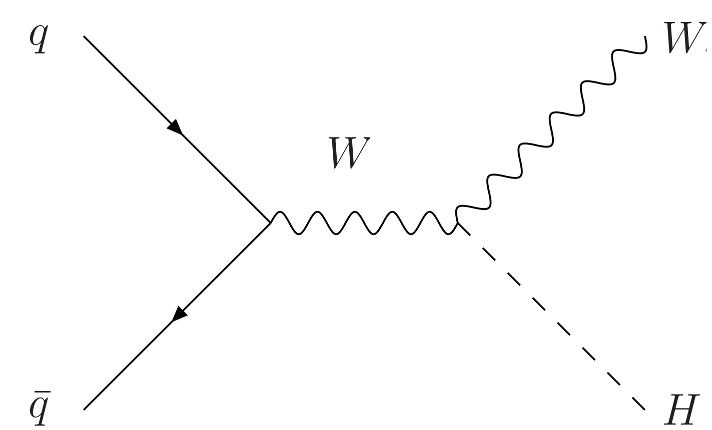
NEW: WH at NNLO

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

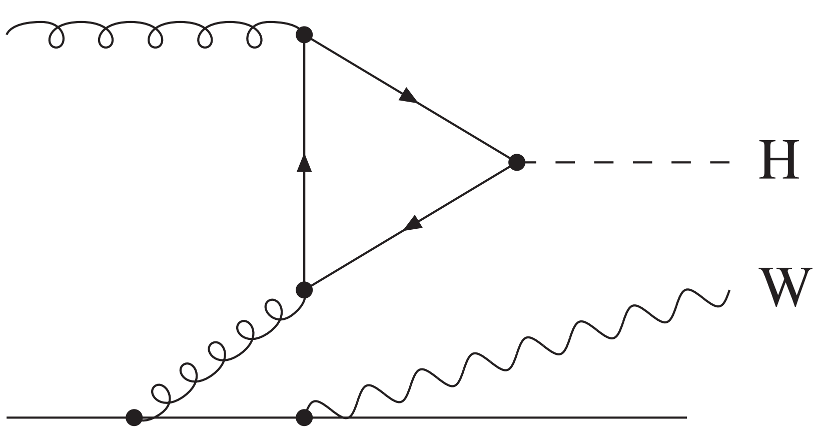
A fully differential NNLO calculation:
extension of NNLO calculation for Drell-Yan to Higgs-strahlung

Fully realistic: we include $H \to b\bar{b}$ decay and $W \to l\upsilon$ 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

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

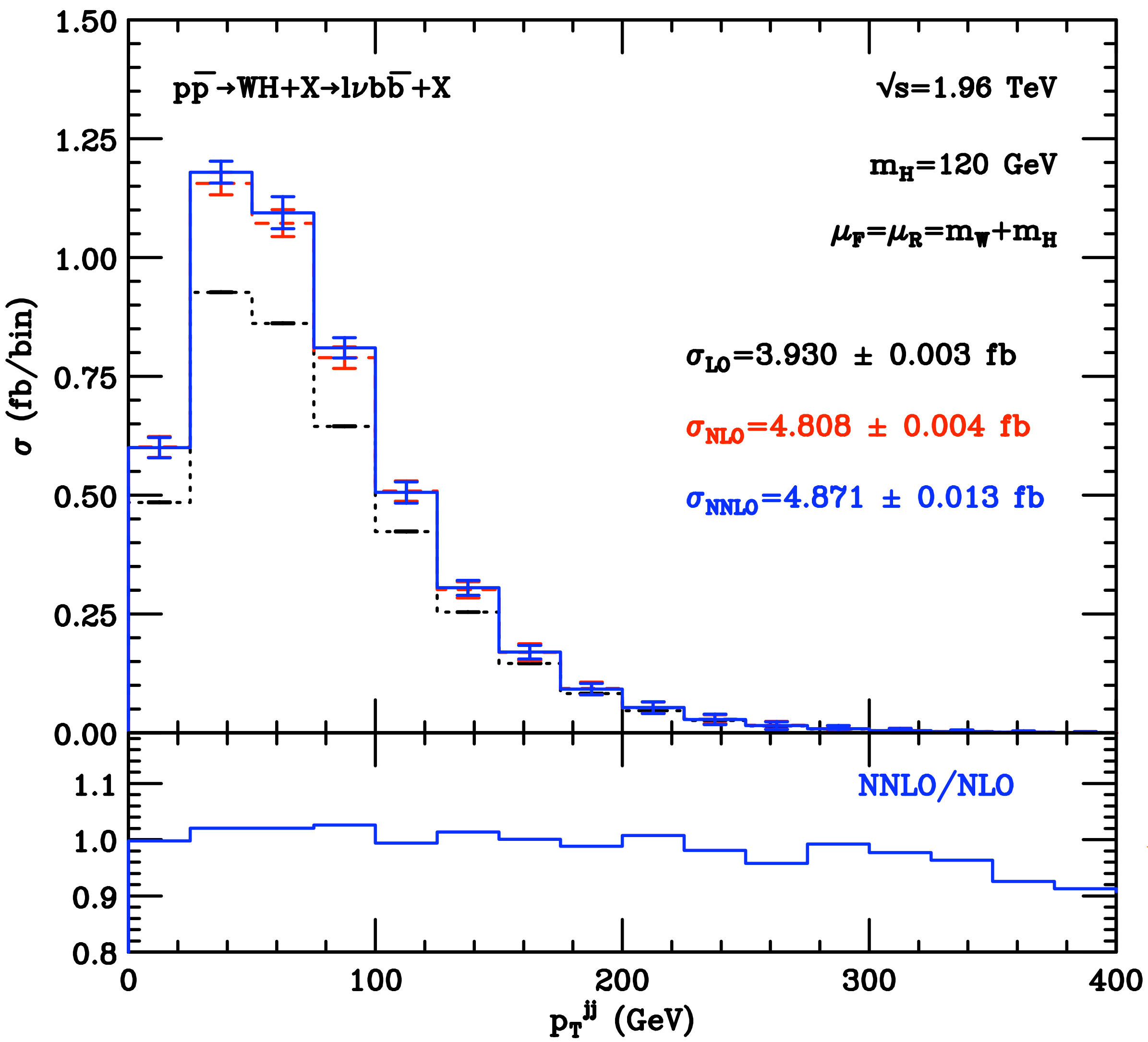
Results at the Tevatron

Cuts:
lepton: p_T > 20 GeV and $|\eta|<2$
p_T^{miss} > 20 GeV

Jets: k_T algorithm with R=0.4

We require exactly 2 jets with p_T > 20 GeV and $|\eta|<2$

One of the jets has to be a b-jet with $|\eta|<1$



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

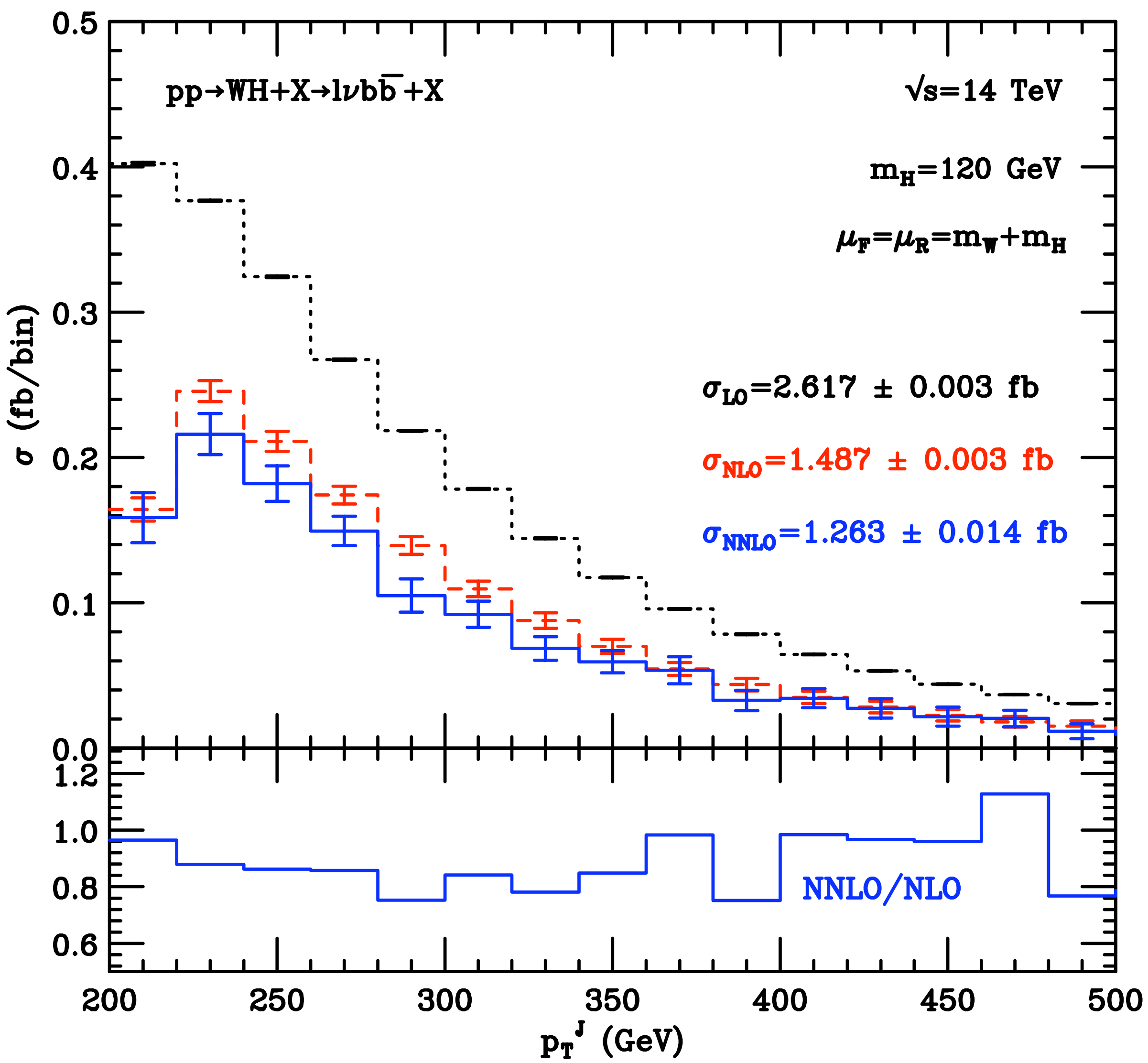
NEW: WH at NNLO

Results at the LHC ($\sqrt{s}$=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 (in progress)

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 coefficients obtained for Drell-Yan

Use Frixione isolation ➡ no fragmentation contribution

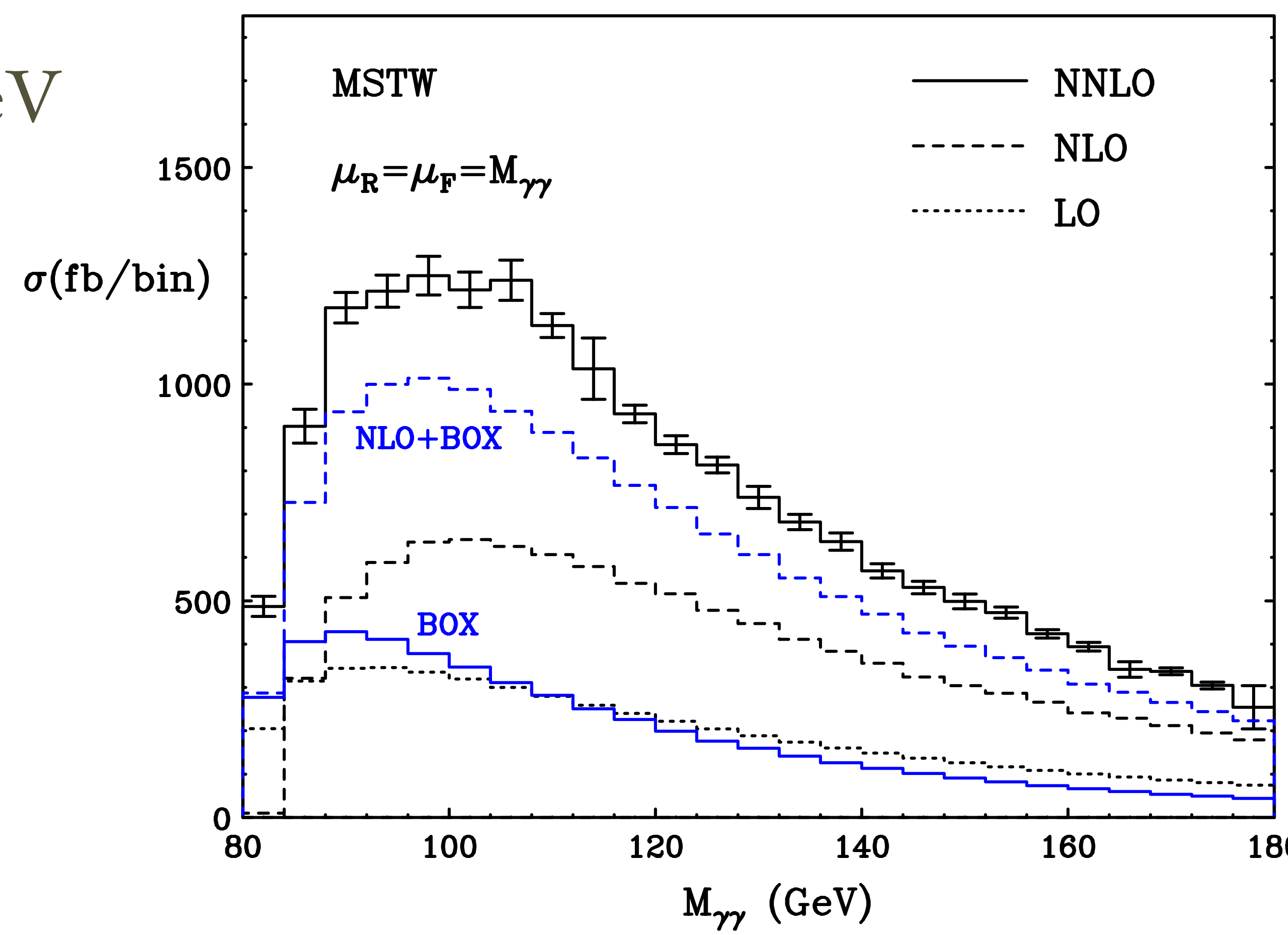
PRELIMINARY RESULTS LHC, $\sqrt{s}$=14 TeV

$p^{\gamma}_T \geq 40$ GeV $|\eta^{\gamma}| \leq 2.5$

60 GeV $\leq M_{\gamma\gamma} \leq$ 180 GeV

$$E_T^{had}(\delta) \leq \chi(\delta)$$

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



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: CMS cuts with anti-kt jets: $p_{T\mathrm{jet}}^{\mathrm{min}} > 25$ GeV $\eta_{\mathrm{jet}}^{\mathrm{max}} > 4.5$ 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:

consider instead inclusive H+jet(s) cross sections

F.Tackmann, I.Stewart (2011)

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

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

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

Propagating the uncertainties on the acceptance $\sigma_0/\sigma_{\mathrm{total}}$ 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 % !!

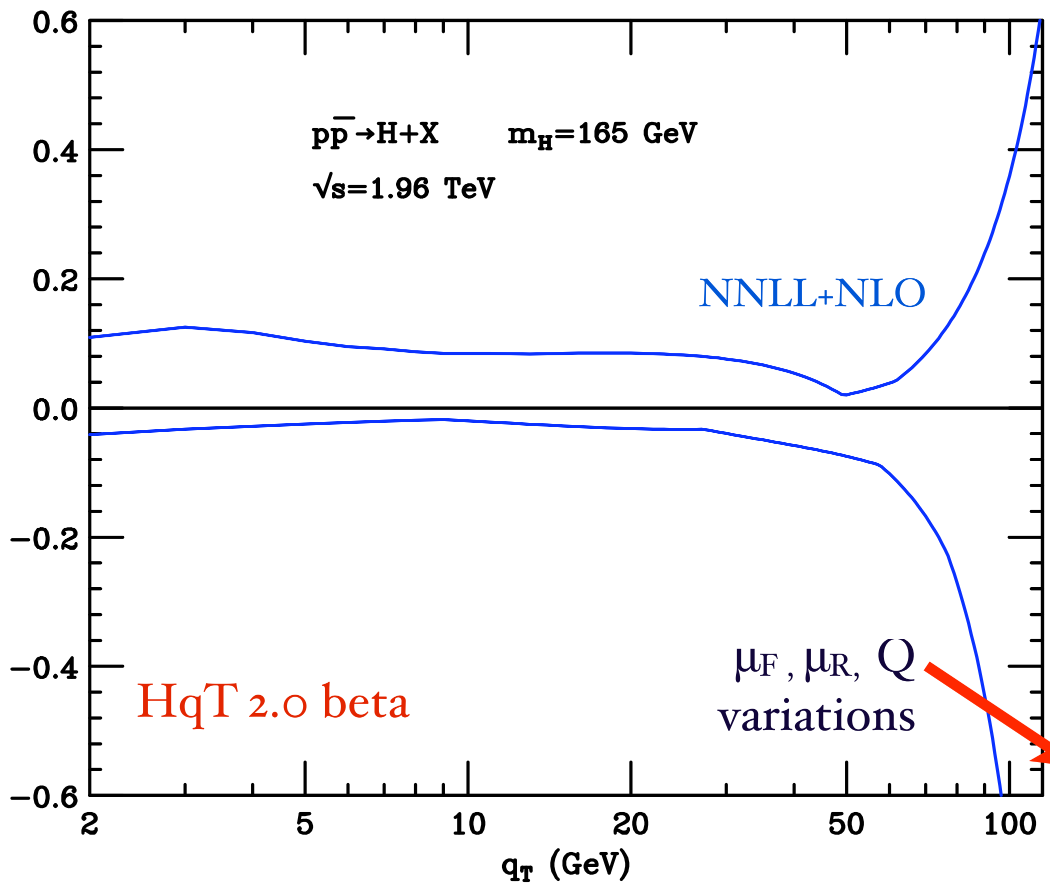
Scale uncertainties and jet bins

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

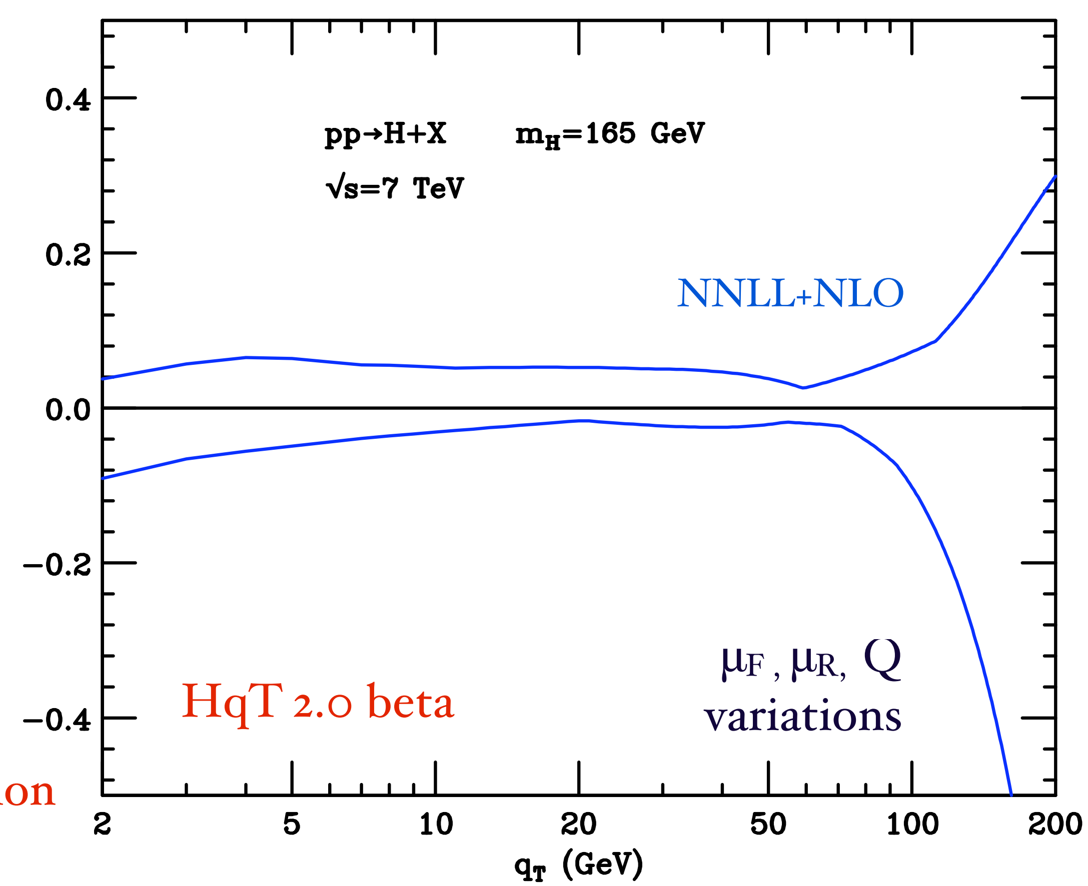
Aren't we risking to overestimate perturbative uncertainties ?

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



resummation
scale

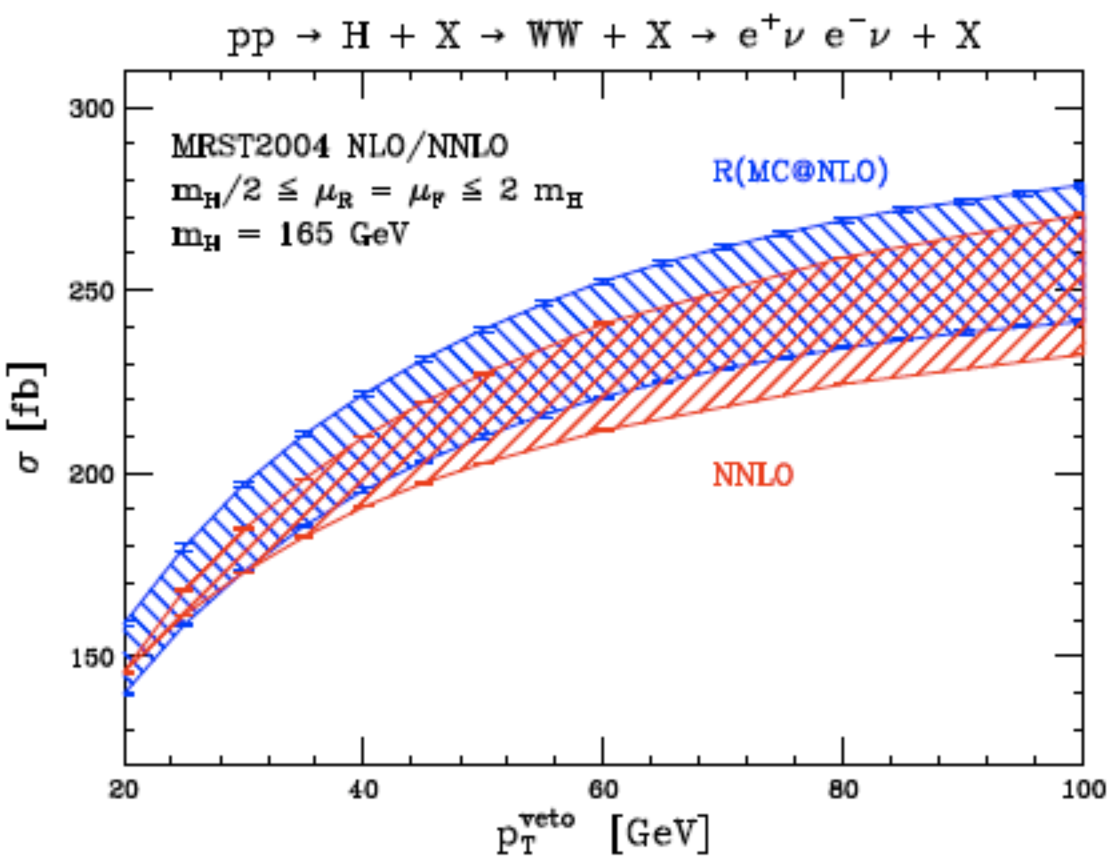


G.Ferrera, D. de Florian, D.Tommasini, MG (to appear)

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)

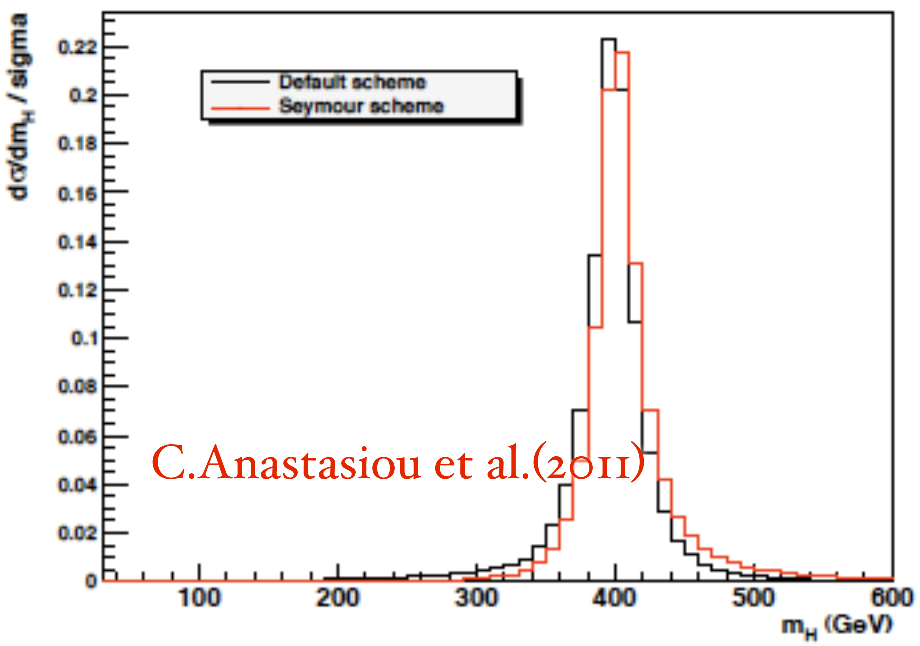


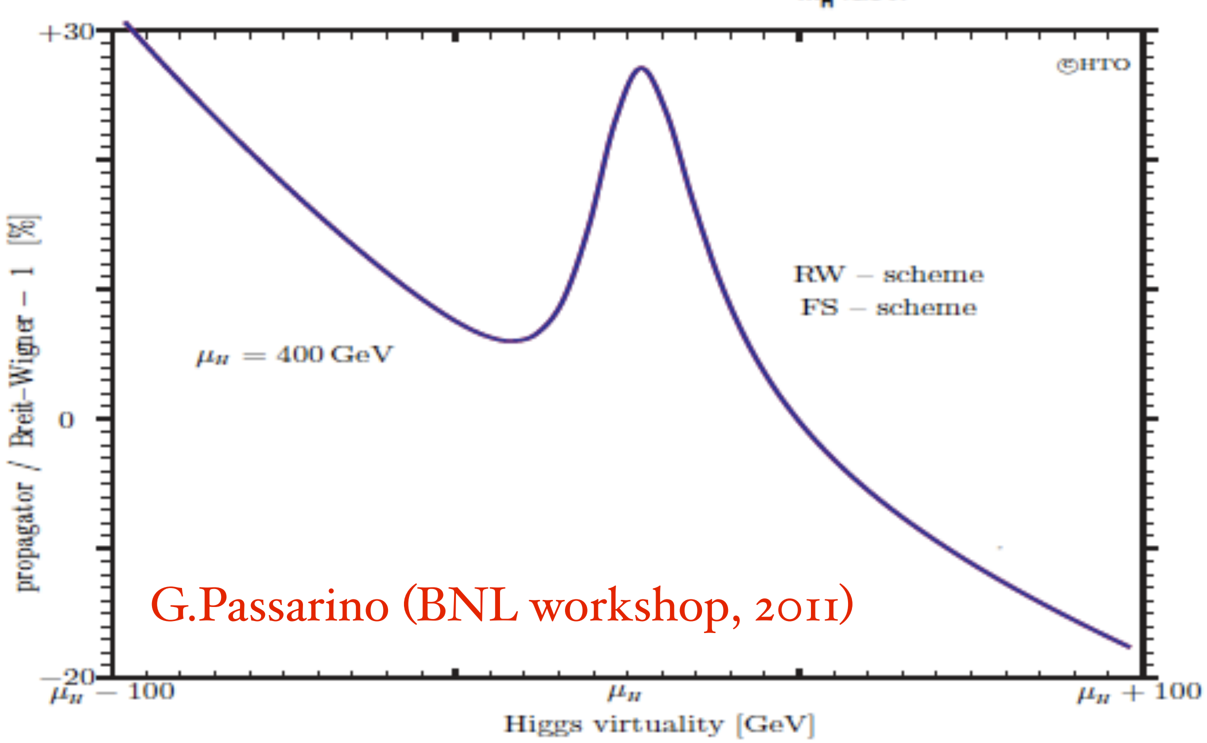
$\sigma_{acc}/\sigma_{incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_H/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\, m_H$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_H/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\, m_H$)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

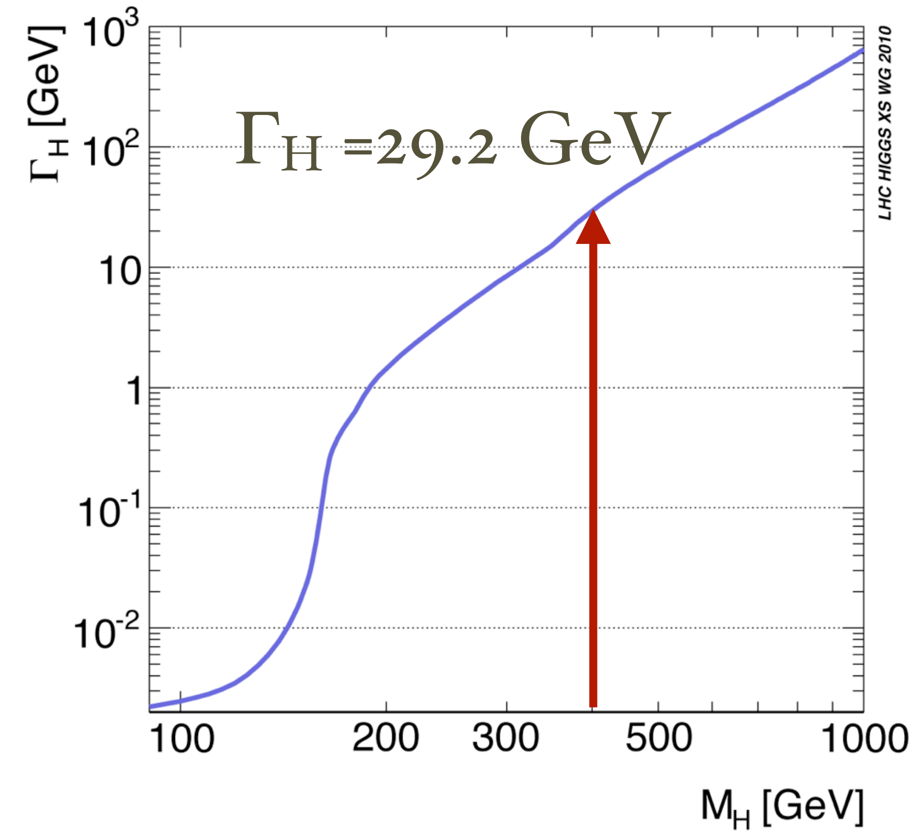
Table 5: Comparison of the predicted selection efficiency after successive application of cuts, as obtained by fixed order calculations and event generators. Between parentheses we give the efficiency due to a single cut, after all previous cuts have been applied. The event generator predictions correspond 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 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

  ➡ **Hopefully carried out within the LHC Higgs XS Working Group to which you are all very much welcome to contribute !**

Thanks for your attention !

Many thanks to:

Babis Anastasiou, Stefano Catani , Daniel de Florian, Tom Junk, Frank Krauss, Craig Group, Achilleas Lazopoulos, Giampiero Passarino, Frank Petriello, Frank Tackmann

for various useful discussions on the topics presented here

BACKUP SLIDES

Uncertainties on ggF

- Scale uncertainty: ±6-8 % at the LHC (7 TeV) and ±7 % at the Tevatron

- Implementation of EW corrections:
  changing to the "partial" factorization scheme would lead to an effect going from -3 % (m_H=115 GeV) to +1 % (m_H=300 GeV)

- Large-m_{top} approximation:
  recent work by Harlander, Steinhauser and collaborators shows that it works to better than 0.5 % for $m_H \leq 300$ GeV
  → important confirmation of the accuracy of this approximation

  For a heavier Higgs the uncertainty increases and should not be neglected

- PDF uncertainties → see talk by Daniel de Florian !

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 N^3LO would lead to a reduction of scale uncertainty to about 5%

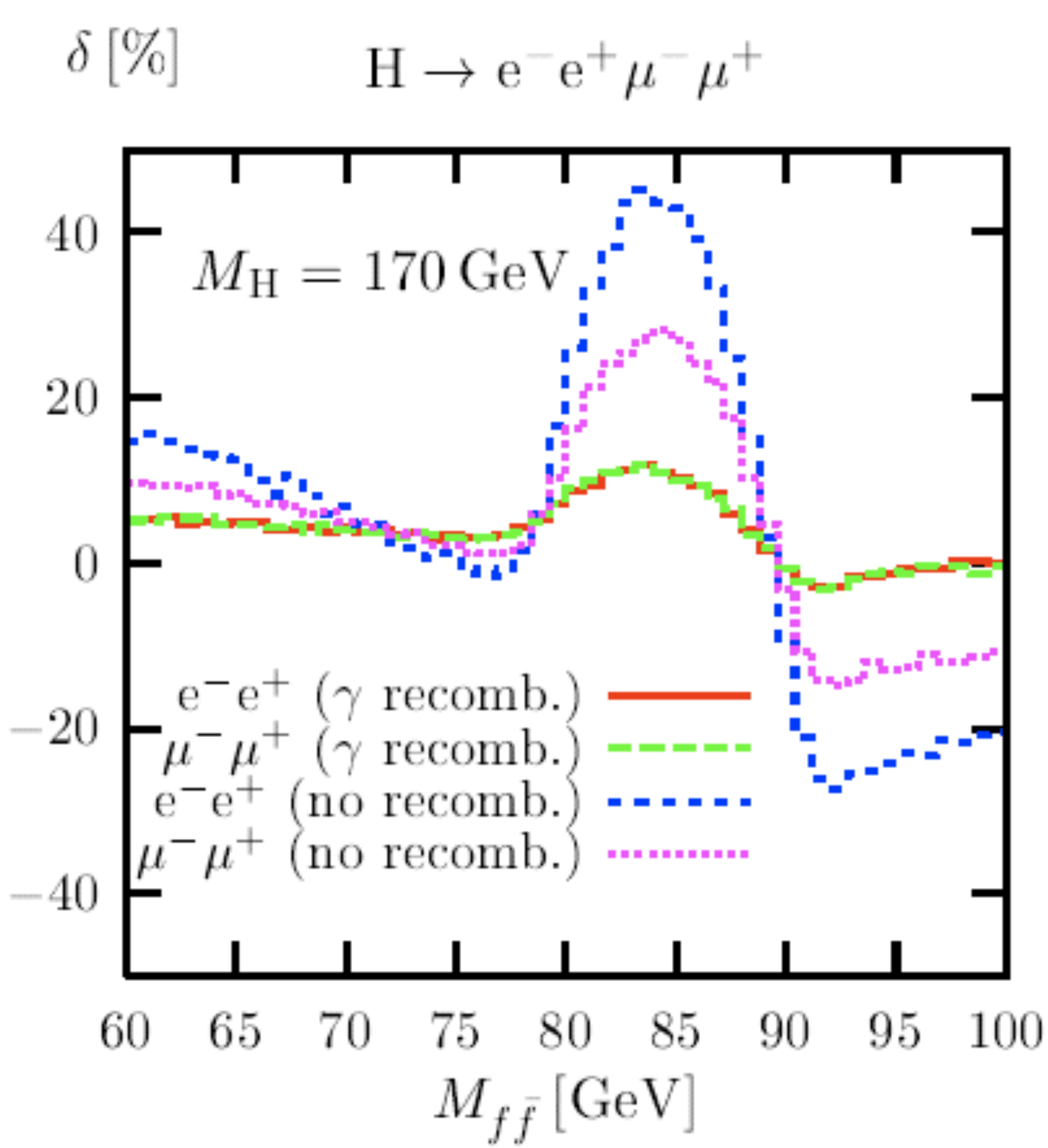
  S.Moch, A. Vogt (2005)

- Computation of soft-virtual effects at N^3LO 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