Standard Candles: DY and Higgs

Massimiliano Grazzini (INFN, Firenze)

QCD at the LHC, Trento, september 29 2010

Outline

- Drell-Yan
  - Inclusive predictions
  - Fully exclusive NNLO calculations
  - Transverse momentum spectrum
- Higgs through gluon fusion
  - Recent updated results
  - Uncertainties
  - Fully exclusive NNLO programs
- Summary

Drell-Yan

The production of vector bosons through the Drell-Yan mechanism was historically the first application of parton model ideas to hadron collisions and is the most “classical” process at hadron colliders

Drell, Yan (1970)

W and Z production is important for physics studies within and beyond the SM

- Large production rates and clean experimental signatures make these processes standard candles for detector calibration
- Background for new physics searches
- Important information on PDFs

→ It is thus essential to have reliable theoretical predictions

Drell-Yan

- QCD corrections:

The total cross section for the DY process is known since long time up to NNLO in QCD perturbation theory (NNLO effect at the percent level)

R.Hamberg, T.Matsuura, W.L. Van Neerven (1991)

NLO corrections at large transverse momentum

K.Ellis, G.Martinelli, R.Petronzio (1983)
P.B.Arnold, M.H. Reno (1989)
R.J.Gonsalves, J.Pawlowski, C.F.Wai (1989)

Rapidity distributions and fully exclusive calculation up to NNLO

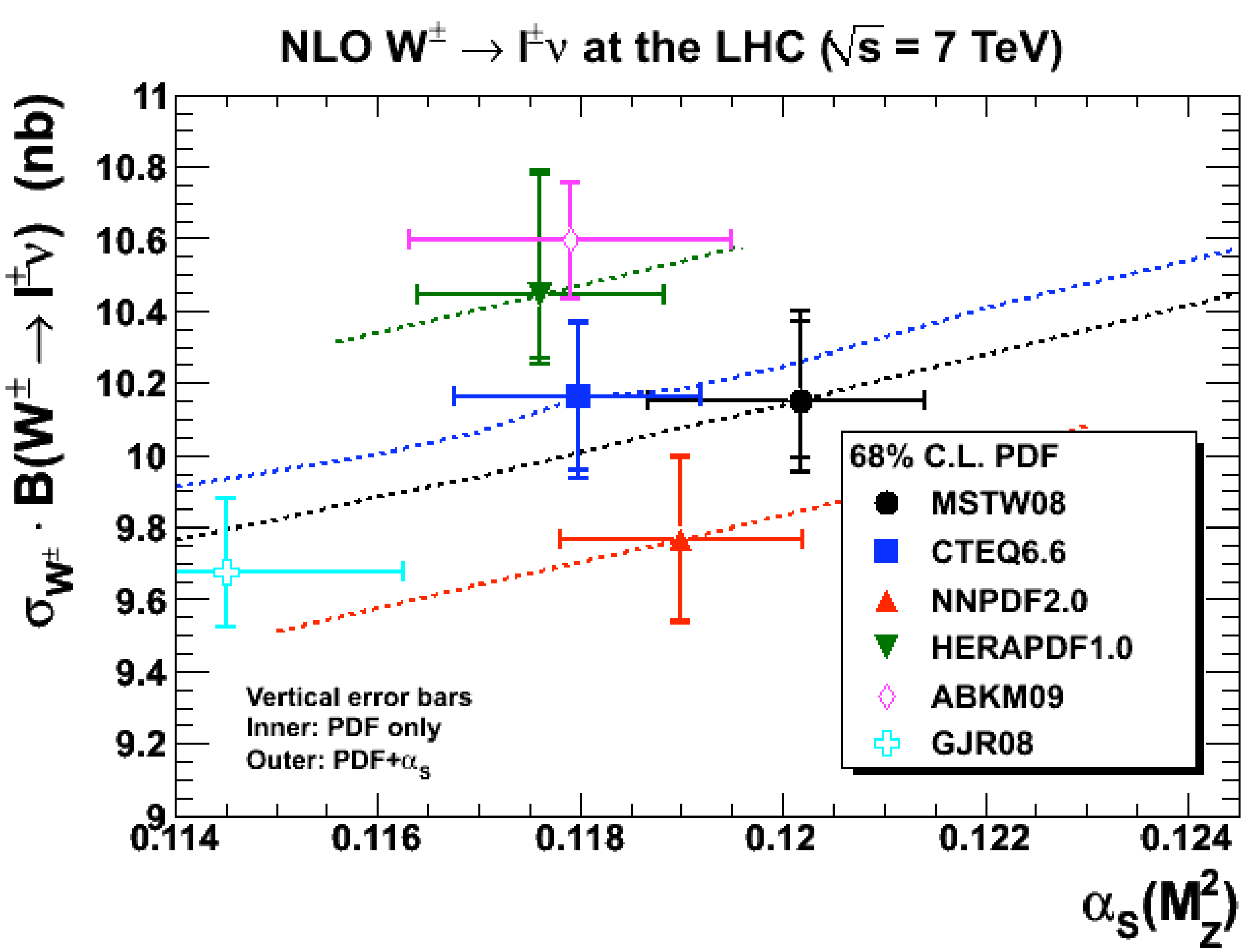
C.Anastasiou, L.Dixon, K.Melnikov, F.Petriello (2003)
K.Melnikov and F.Petriello (2006)
S.Catani, L.Cieri, G.Ferrera, D. de Florian, MG (2009)

- EW corrections:

Known up to $\mathcal{O}(\alpha)$ for both W and Z production

S.Dittmaier,M.Kramer (2002)
U.Baur et al. (2002)
G.Montagna et al. (2006,2007)
A.Arbuzov et al. (2006,2008)
S.Dittmaier, M.Huber (2009)

Drell-Yan



Comparisons of results using different PDFs is typically done at NLO

Comparison of NNLO cross sections at 10 TeV with 1σ PDF errors (thanks to Sergey for providing his numbers !)

σ(nb)	W^+	W^-
MSTW2008	82.2+1.4-1.3	59.9±1.0
ABKM09	85.7±1.5	59.9±1.0
JR09	78.7±2.0	55.8±1.4

A fully exclusive NNLO calculation

Higher order calculations in QCD are complicated by the presence of infrared (soft and collinear) singularities that enter the intermediate stages of the computation and prevent the straightforward implementation of numerical techniques

Life is easier for sufficiently inclusive quantities, when phase space integrations can be carried out analytically

The total cross section for the Drell-Yan process is known since long time up to NNLO in QCD perturbation theory

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The first fully exclusive NNLO calculation was completed 15 years later !

K.Melnikov, F.Petriello (2006)

→ Same Feynman diagrams but IR cancellation achieved at the fully exclusive level

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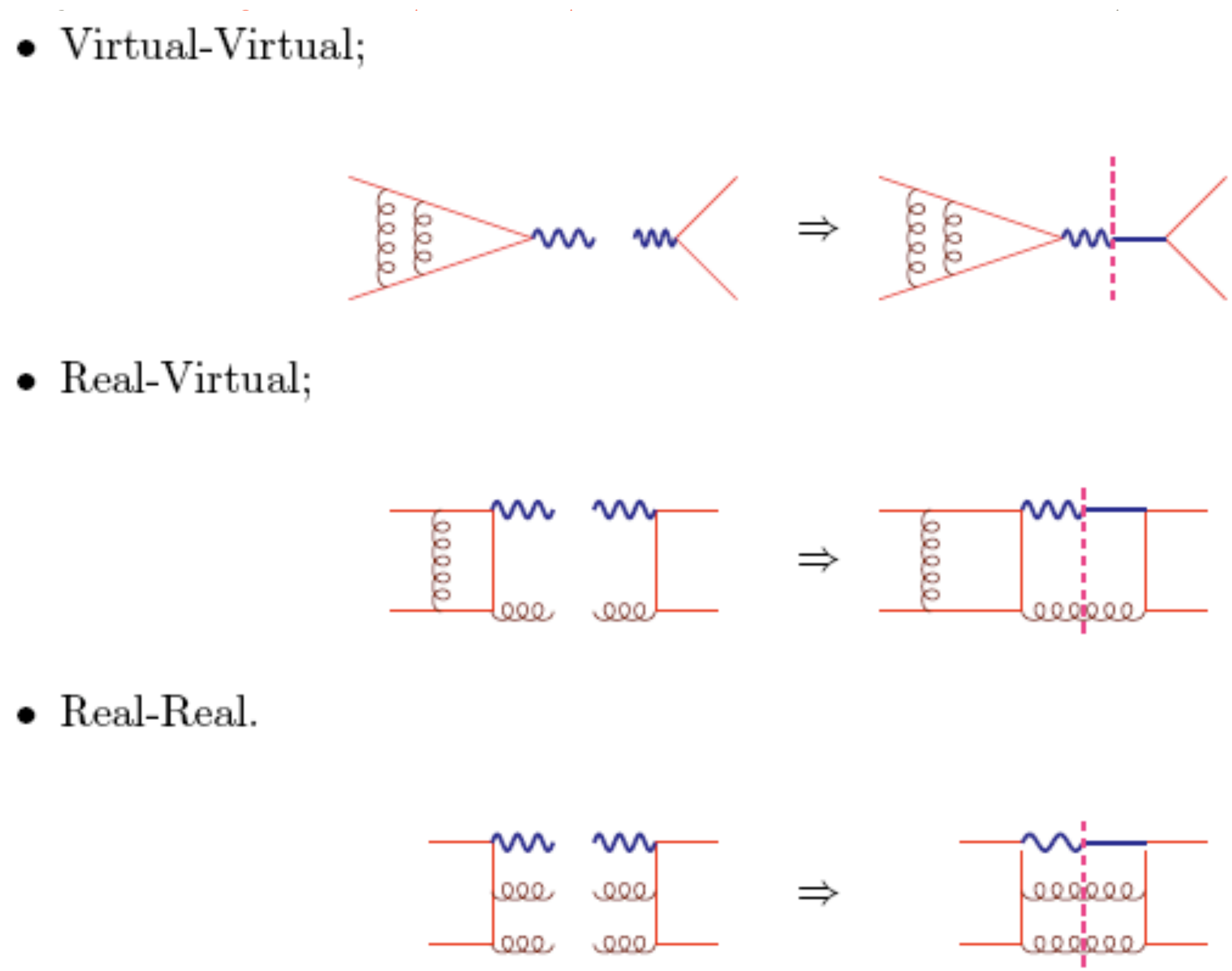

The total … n since long
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A fully exclusive NNLO calculation

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

We have now completed an independent NNLO calculation by using a recently proposed version of the subtraction method

S.Catani, MG (2007)

Our calculation includes γ-Z interference, finite-width effects, the leptonic decay of the vector boson and the corresponding spin correlations

The calculation is implemented in a parton level event generator with which we can apply arbitrary cuts on the final state leptons and the associated jet activity

- **Possible to compute acceptances....**
- **....but also all the kinematical distributions you want !**

→ DYNNLO

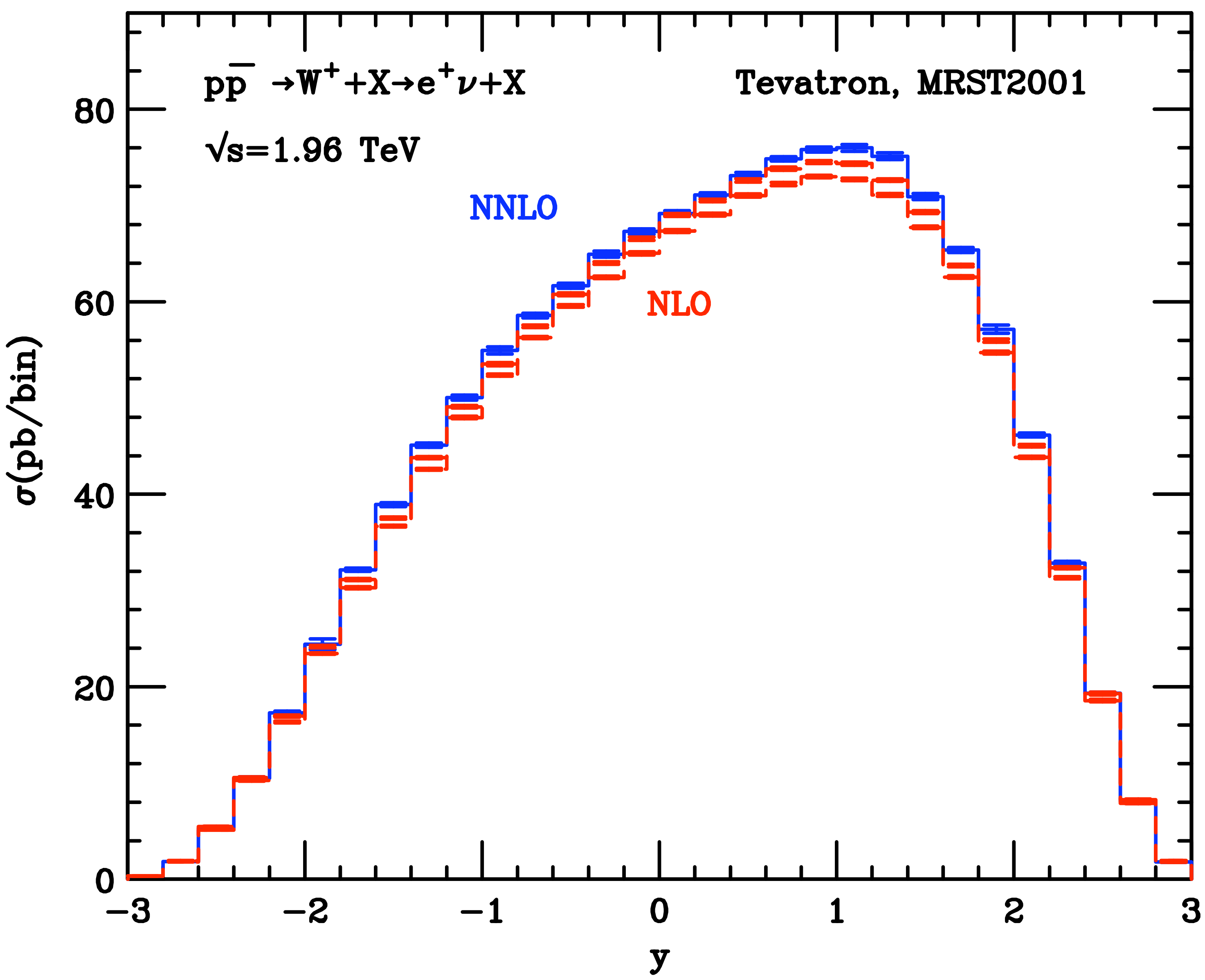
http://theory.fi.infn.it/grazzini/dy.html

Rapidity distribution of the vector boson

When no cuts are applied our numerical program provides the first independent check of the vector boson rapidity distribution up to NNLO

C.Anastasiou et al. (2003)

Tuned comparison for on shell W production at the Tevatron:



In this plot I compare the NNLO result with the NLO band (obtained by varying $\mu_F = \mu_R$ between 0.5 m_W and $2m_W$) and with the result by Anastasiou et al.

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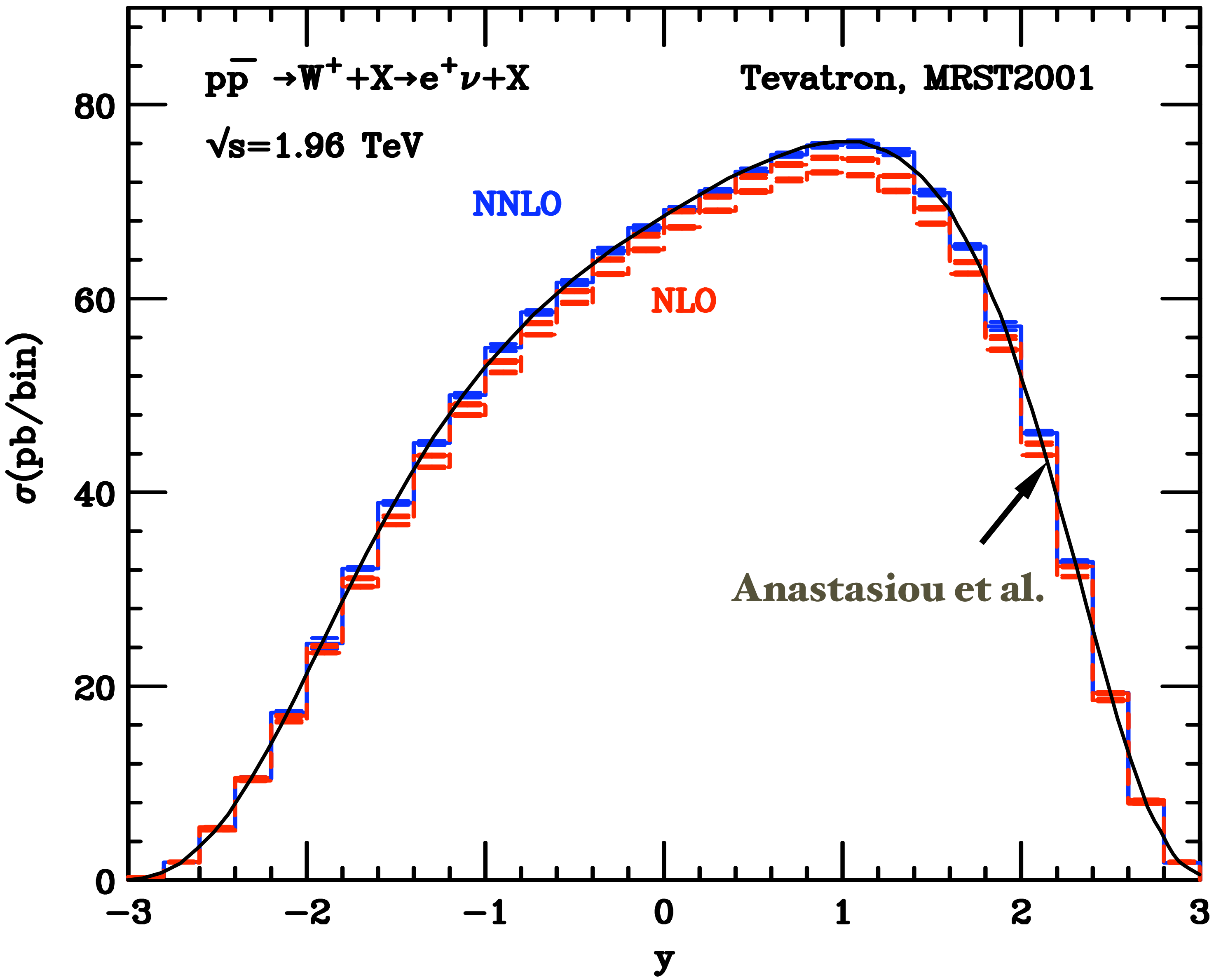

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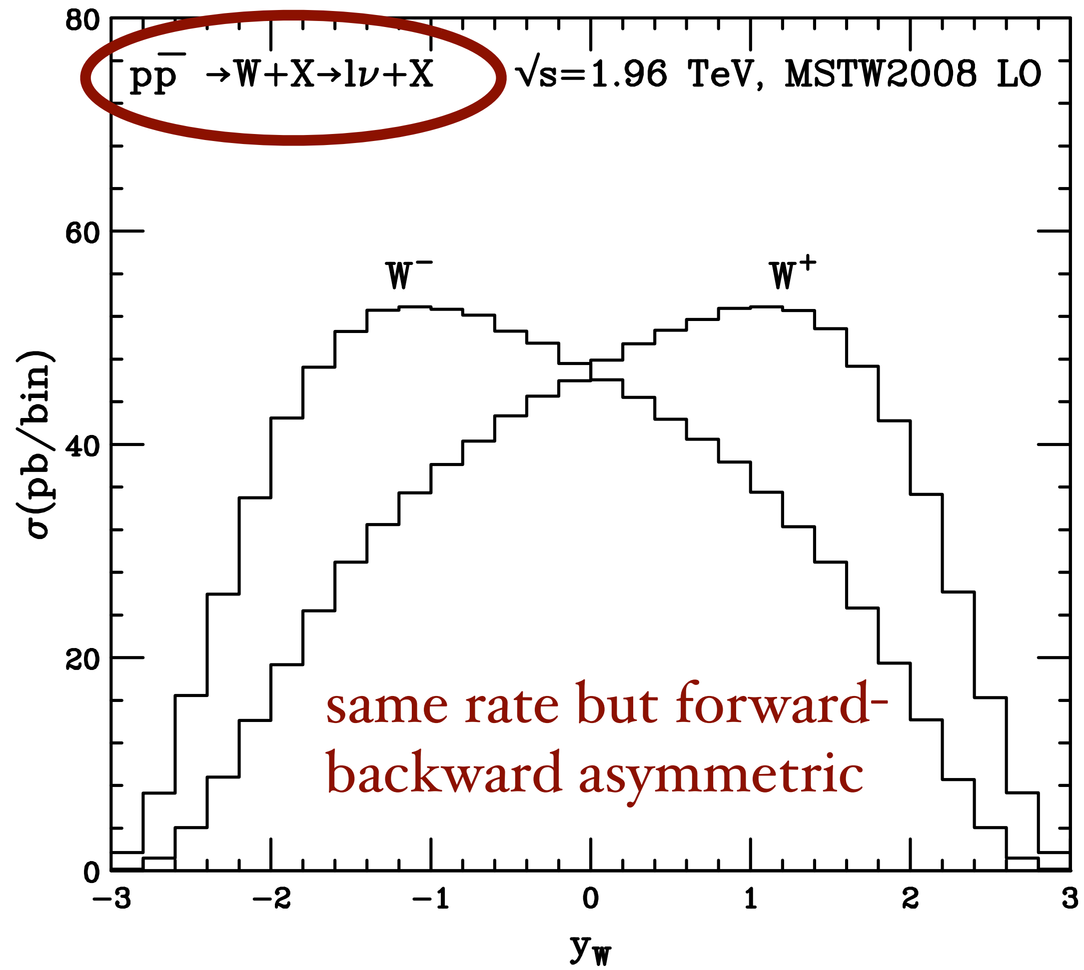
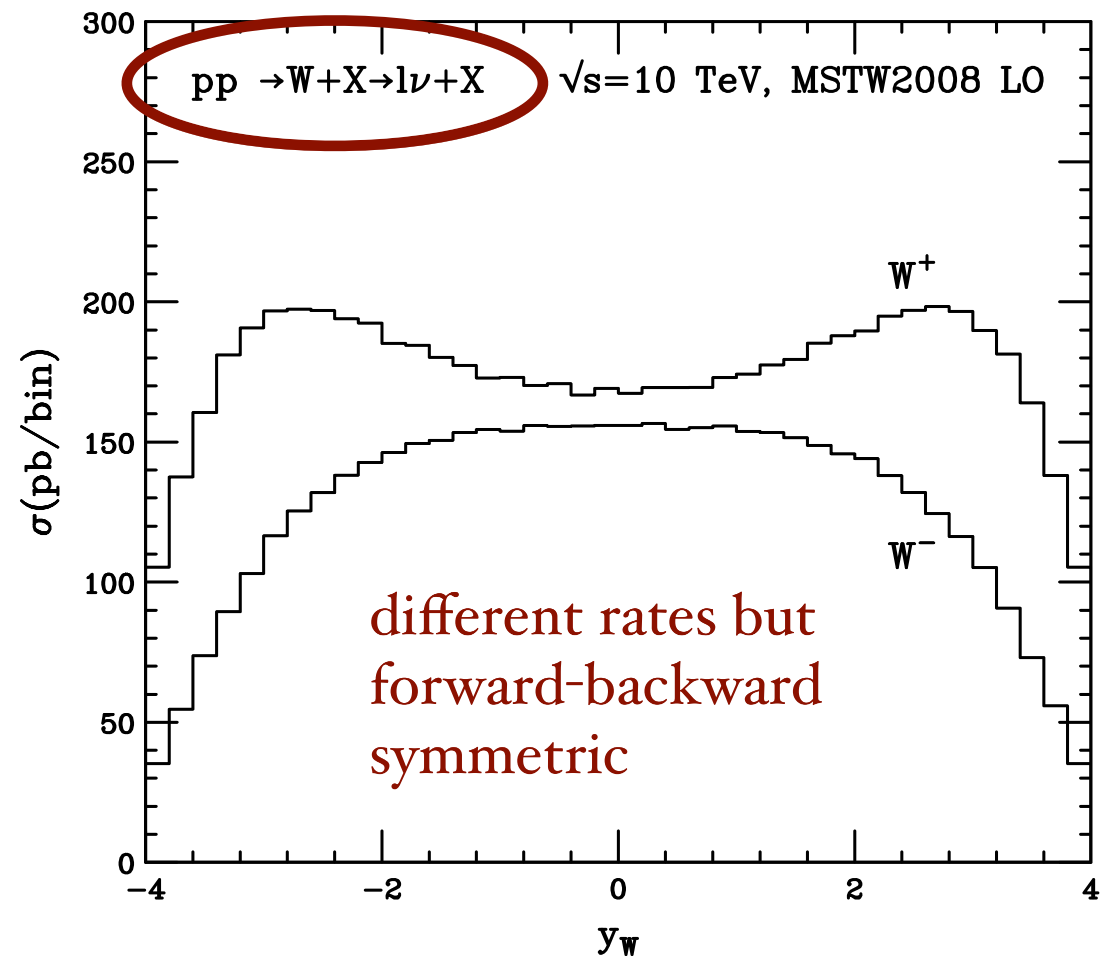
The agreement is good

W asymmetry

An important observable is the asymmetry in the rapidity distributions of the W





These asymmetries are mainly due to the fact that, on average, the u quark carries more proton momentum fraction than the d quark

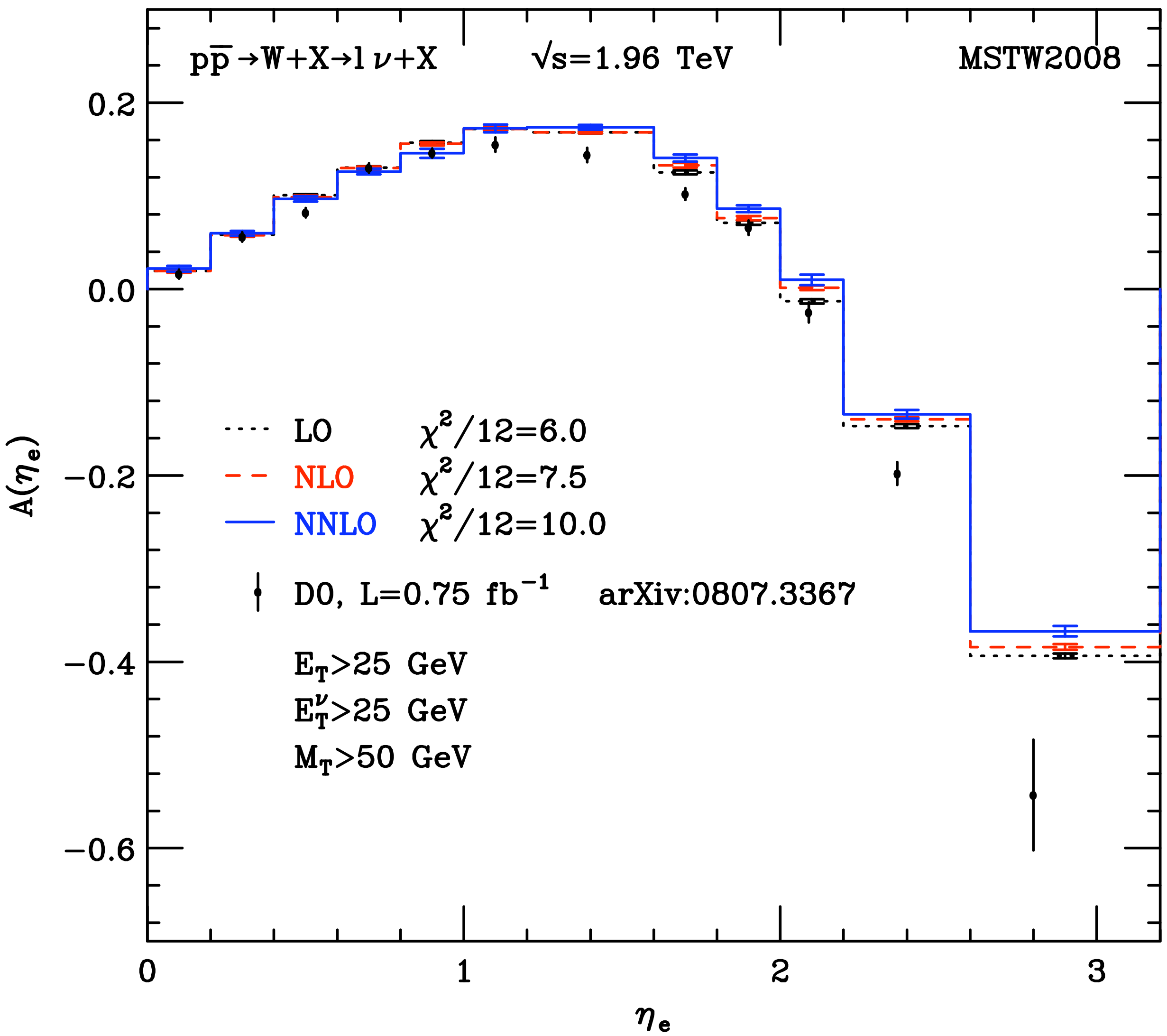
But W bosons are identified through their leptonic decay $W \rightarrow l\nu$

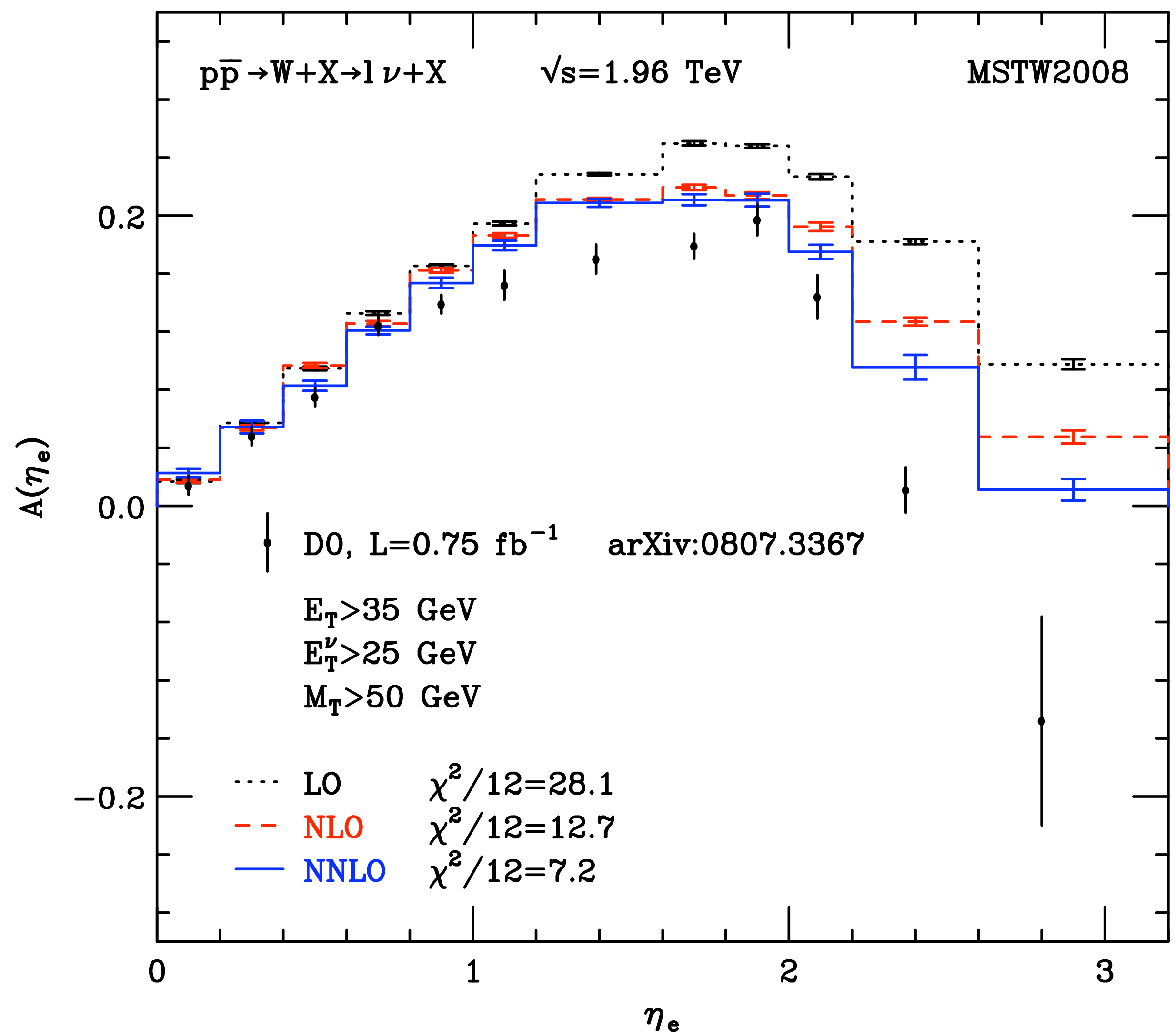
The longitudinal component of the neutrino momentum is not measured → What is typically measured is the lepton asymmetry

W asymmetry

An application of DYNNLO: first NNLO computation of the lepton asymmetry

S. Catani, G.Ferrera, MG (2010)





The calculation takes into account all cuts used in the analysis

Recent DØ data difficult to fit ➡ NNLO effect goes in the right direction

Transverse momentum spectrum

Among the various distributions an important role is played by the transverse momentum (q_T) spectrum

In the case of Z boson production the spectrum is precisely measured

→ Uncertainties on the W spectrum directly affect W mass

When considering the transverse momentum spectrum of the vector boson it is important to distinguish two region of transverse momenta

- **$q_T \sim m_V$**

  In this region the fixed order $O(\alpha_S^2)$ calculation is reliable

- **$q_T << m_V$**

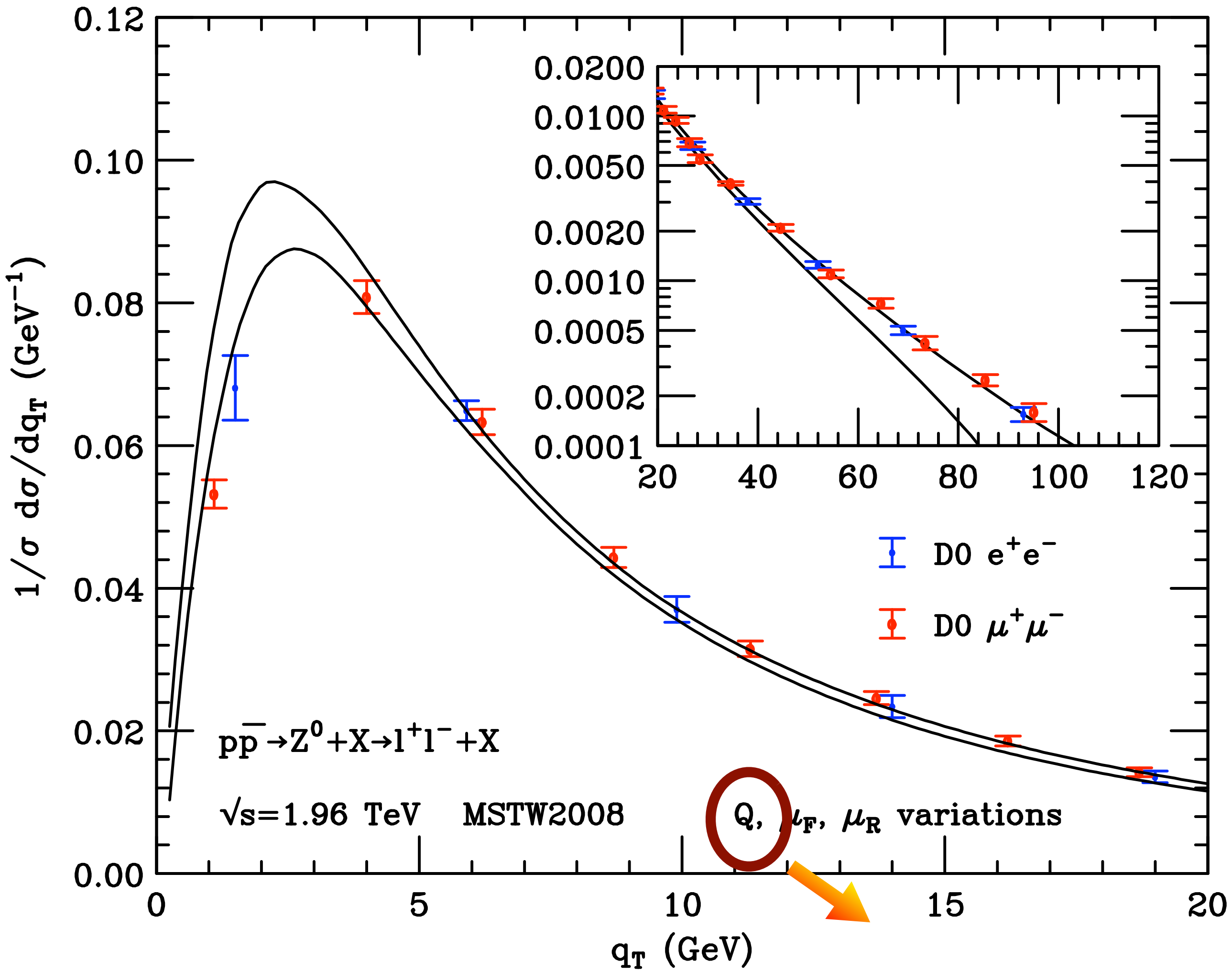
  Here large logarithmic contributions of the form $\alpha_S^n \ln^{2n} m_V/q_T$ that must be resummed to all orders

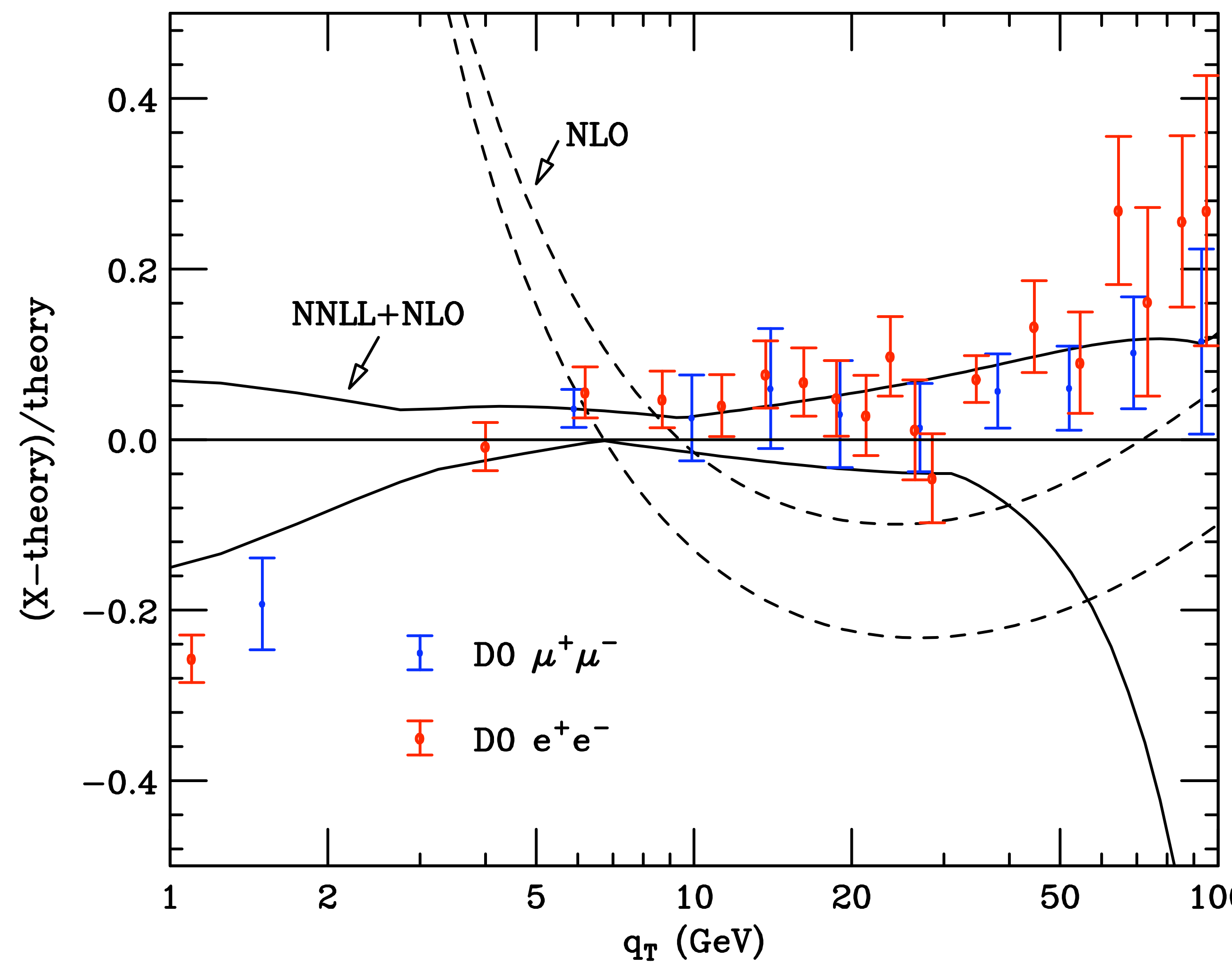
→ Resummation is accomplished by working in b-space

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)
S.Catani et al. (2000,2005)

First complete NNLL+NLO results

G. Bozzi, S.Catani,
G. Ferrera, D. de Florian, MG(2010)





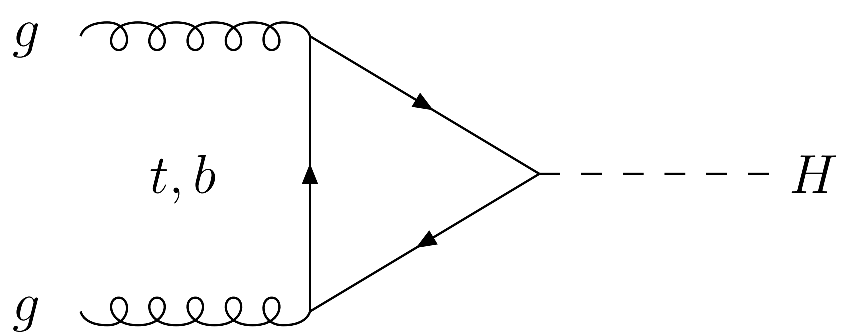
Resummation scale Q

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

Perturbative uncertainty at NNLL+NLO ranges from about ±6% at the peak to about ±12% at q_T=50 GeV
At large values of q_T the resummed result looses predictivity: better to use NLO

Nice description of the data even without non-perturbative effects

Higgs production through gg fusion



The Higgs coupling is proportional to the quark mass

top-loop dominates

QCD corrections to the total rate computed almost 20 years ago and found to be large

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

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

Next-to-next-to leading order (NNLO) corrections computed in the large-m_{top} limit

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)

Higgs production through gg fusion

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 9-10% at 7 TeV)

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

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)

Soft-gluon resummation

Soft-virtual effects are important

→ **All-order resummation of soft-gluon effects provides a way to improve our perturbative predictions**

Soft-virtual effects are logarithmically enhanced at $z = M_H^2/\hat{s} \to 1$

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

Resummation works in Mellin space L=ln N

$$\sigma^{\rm res} \sim C(\alpha_S) \exp\{L g_1(\alpha_S L) + g_2(\alpha_S L) + \alpha_S g_3(\alpha_S L) + \dots\}$$

We can perform the resummation up to NNLL+NNLO accuracy

This means that we include the full NNLO result plus all-order resummation of the logarithmically enhanced terms → No information is lost

→ Quantitative results nicely confirmed by computation of soft terms at N^3LO

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

Results

Quite an amount of work has been done recently to present updated results that include all the available information $\rightarrow$ LHC Higgs Cross section WG

- Calculation by Anastasiou et al.

C.Anastasiou, R.Boughezal, F.Petriello (2008) + F.Stoeckli

  - 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)

D. De Florian, MG (2009)

  - 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.

Results

- Calculation by Baglio-Djouadi

J.Baglio,A.Djouadi (2010)

- Does not include resummation

- Detailed (and very) conservative study of the various sources of uncertainties → about±25-30 % at 7 TeV

- Recent 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.

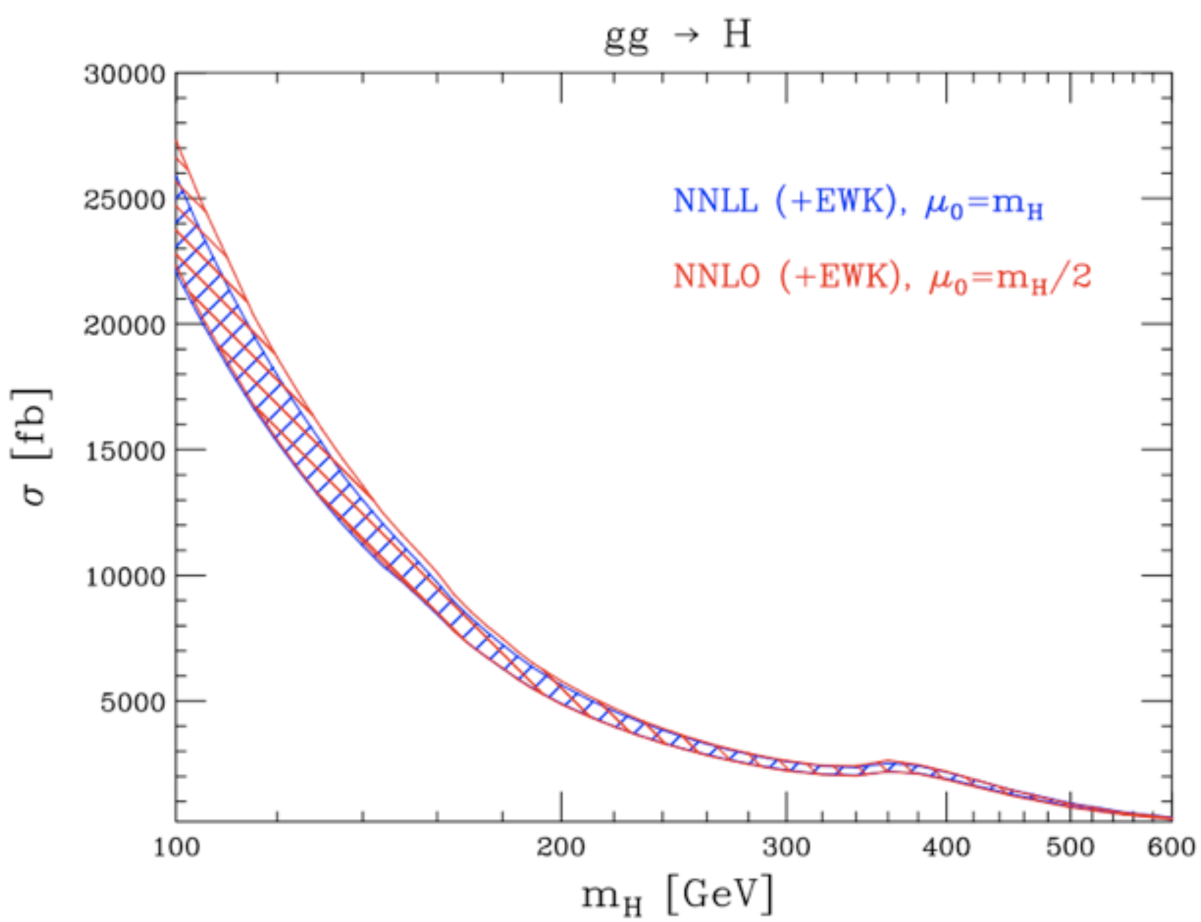
V.Ahrens et al. (2010)

- Based on the so called "π^2-resummation"

- Numerical results agree with the other calculations

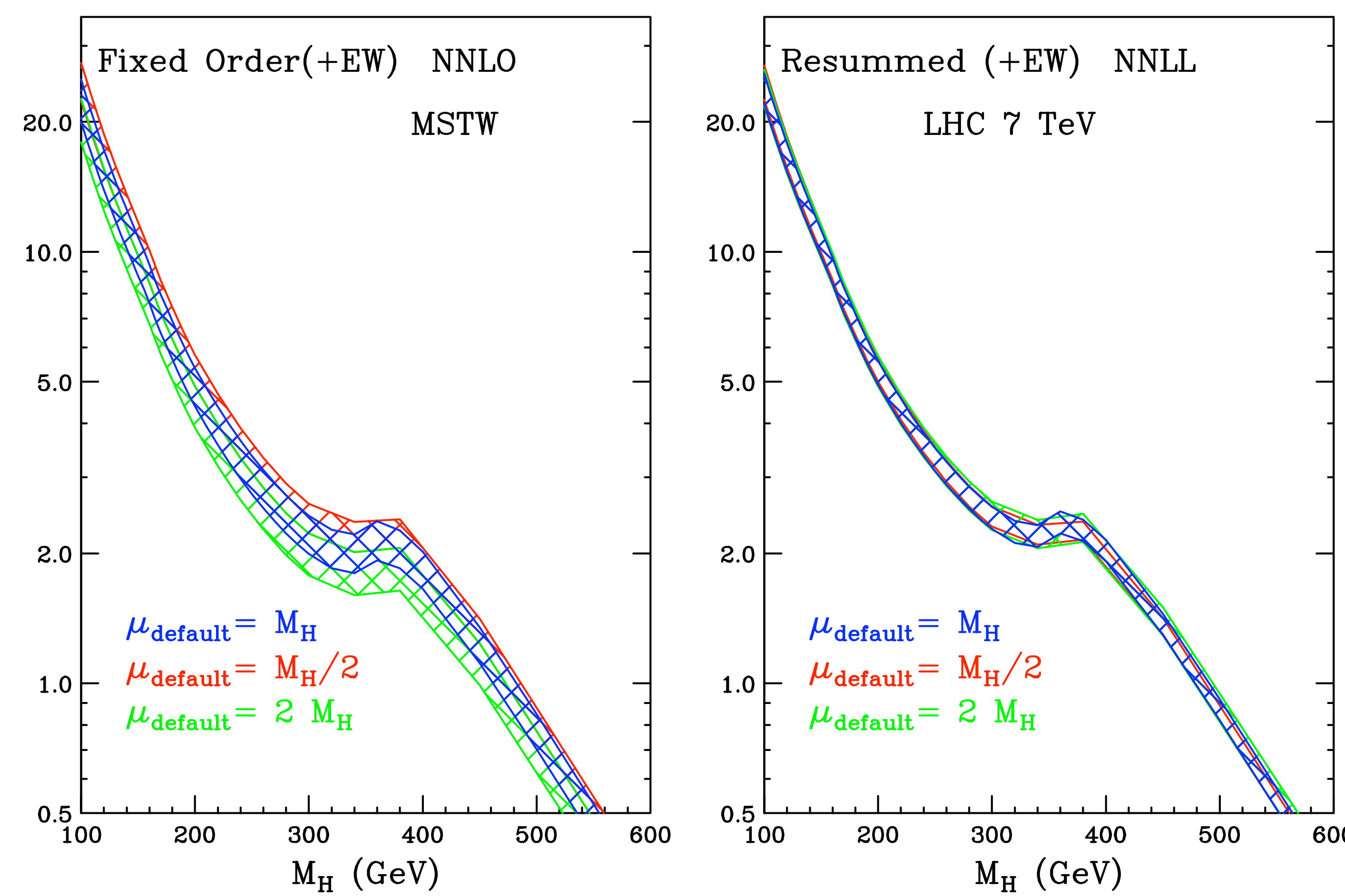
- Scale uncertainties of about 3% or smaller → largely underestimated !

Results



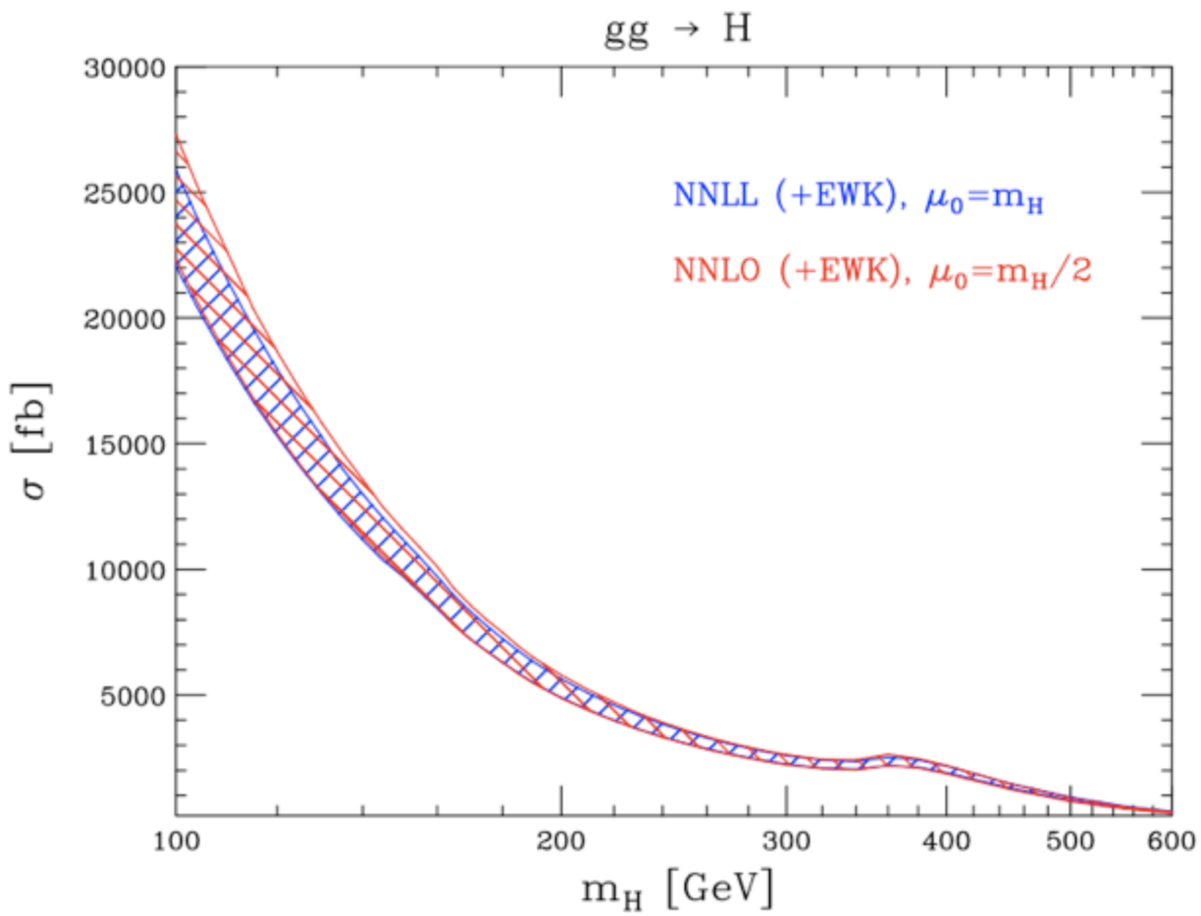
Scale uncertainties computed with independent variations of renormalization and factorization scales (with $0.5 m_H < \mu_F, \mu_R < 2 m_H$ and $0.5 < \mu_F/\mu_R < 2$)

Good agreement of the two predictions



Including NNLL resummation leads to a remarkable stability with respect to the central scale choice

Results



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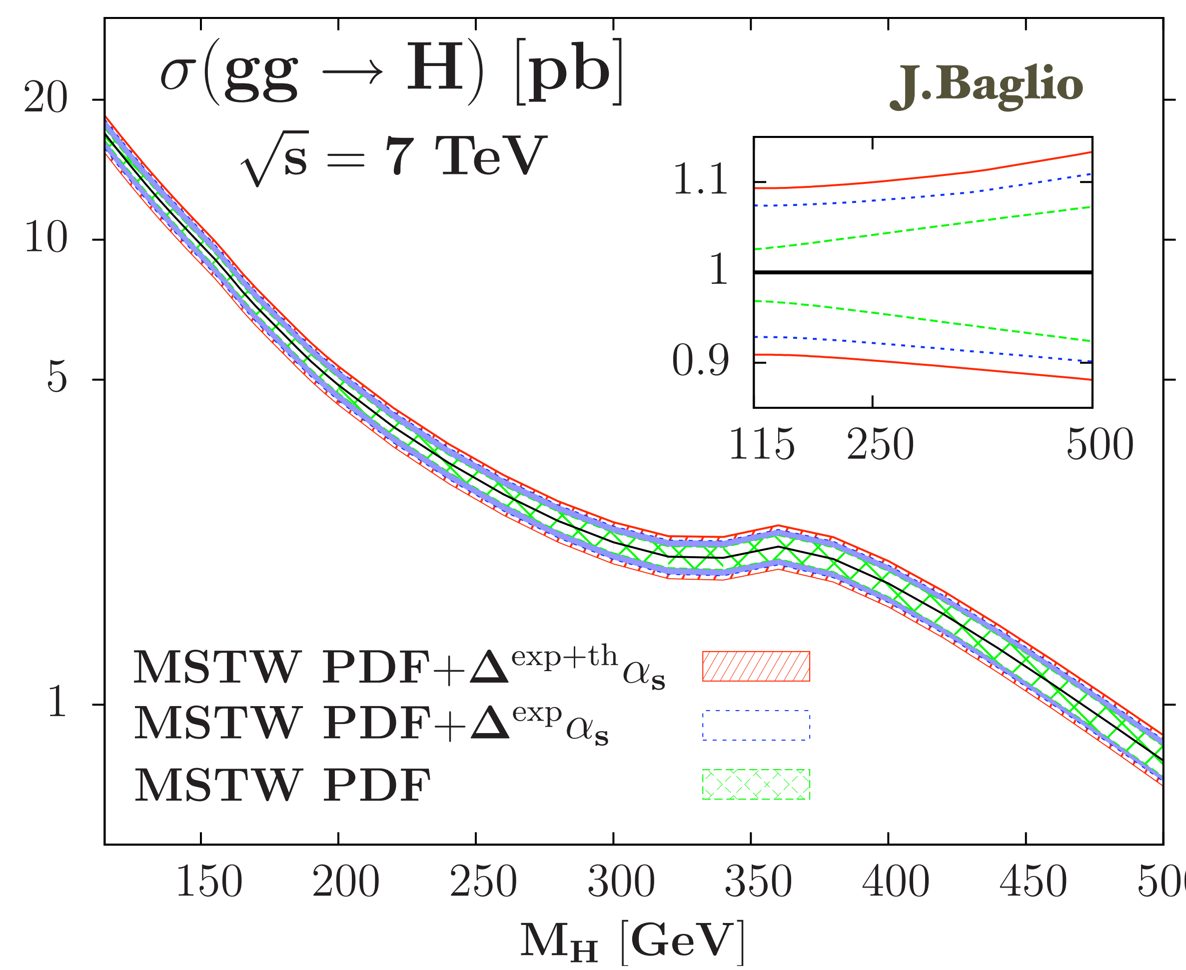
Results by Baglio-Djouadi are lower (resummation neglected)*

*Further recent Tevatron update uses $\mu_F = \mu_R = m_H/2$ as central scale



Uncertainties (LHC@7 TeV)

- Uncertainty from missing higher orders: ± 8% from scale dependence
- PDF+α_S : ±4% at 68% CL using MSTW

Note also that at present, besides MSTW, we have only three other NNLO analyses: ABKM09 and JR09 and HERAPDF1.0

→ Take m_H=165 GeV and compare the corresponding NNLO cross sections at the LHC at 7 TeV

ABKM09 (JR09VF) result is smaller than MSTW2008 by 12% (8%)

HERANNLO α_S=0.1176 (α_S=0.1145) result is smaller than MSTW2008 by 5% (10%)

PDF4LHC recommendation:

"For NNLO, multiply the MSTW uncertainty at NNLO by the factor obtained by dividing the full PDF+α_s uncertainty obtained from the envelope of MSTW, CTEQ and NNPDF results at NLO by the MSTW PDF+α_s uncertainty at NLO (~ factor 2 at 7 TeV)."

→ End up with ±8%

What else ?

How are theoretical predictions exploited in practice ?

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

Use "best" total cross section as over all normalization

→ Works only if the MC correctly predicts relevant distributions: needs careful MC validation against higher-order (and resummed) computations

Luckly the NNLO computation is now implemented at fully exclusive level:

FEHIP: Based on sector decomposition: computes NNLO corrections for $H \to \gamma\gamma$ and $H \to WW \to l\nu l\nu$

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

HNNLO: Parton level Monte Carlo program that computes NNLO corrections for $H \to \gamma\gamma$ $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$

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

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

Summary & Outlook

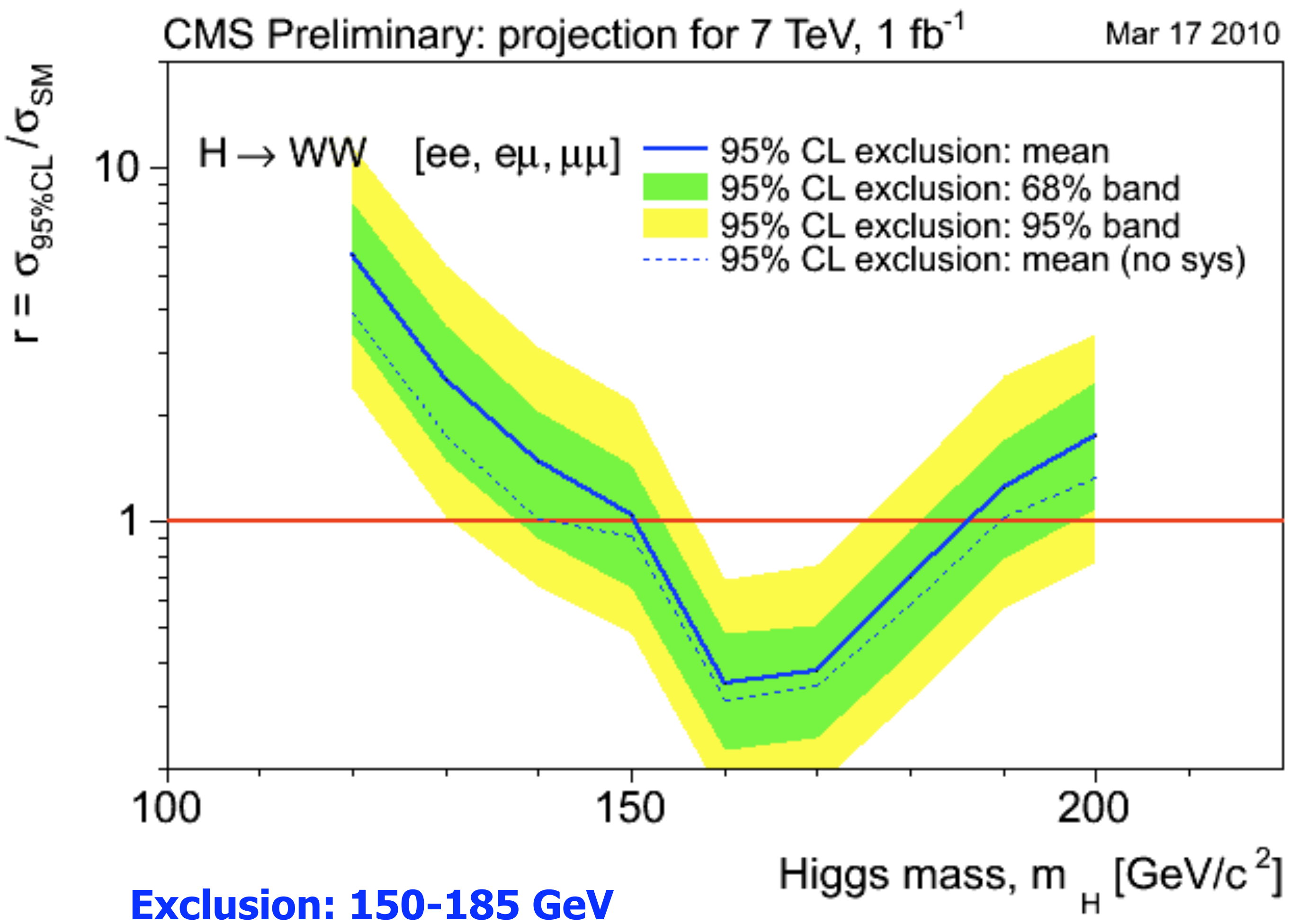
- DY and Higgs production are benchmark processes at the LHC
- In the case of DY QCD corrections are well under control and even full EW corrections have been computed
    - NNLO corrections known at inclusive and fully exclusive level
    - Now complete NNLL+NLO results also for the q_T spectrum (next step: inclusion of leptonic decay)
- In the case of $gg \to H$ QCD corrections are large but the impressive work done in recent years put things under much better control now
    - Not enough ? If you are brave all the ingredients for a N^{3}LO calculation (at least in the soft approximation) are now available ! (three loop form factors recently computed)

Baikov et al. (2009)
Gehrmann et al. (2010)

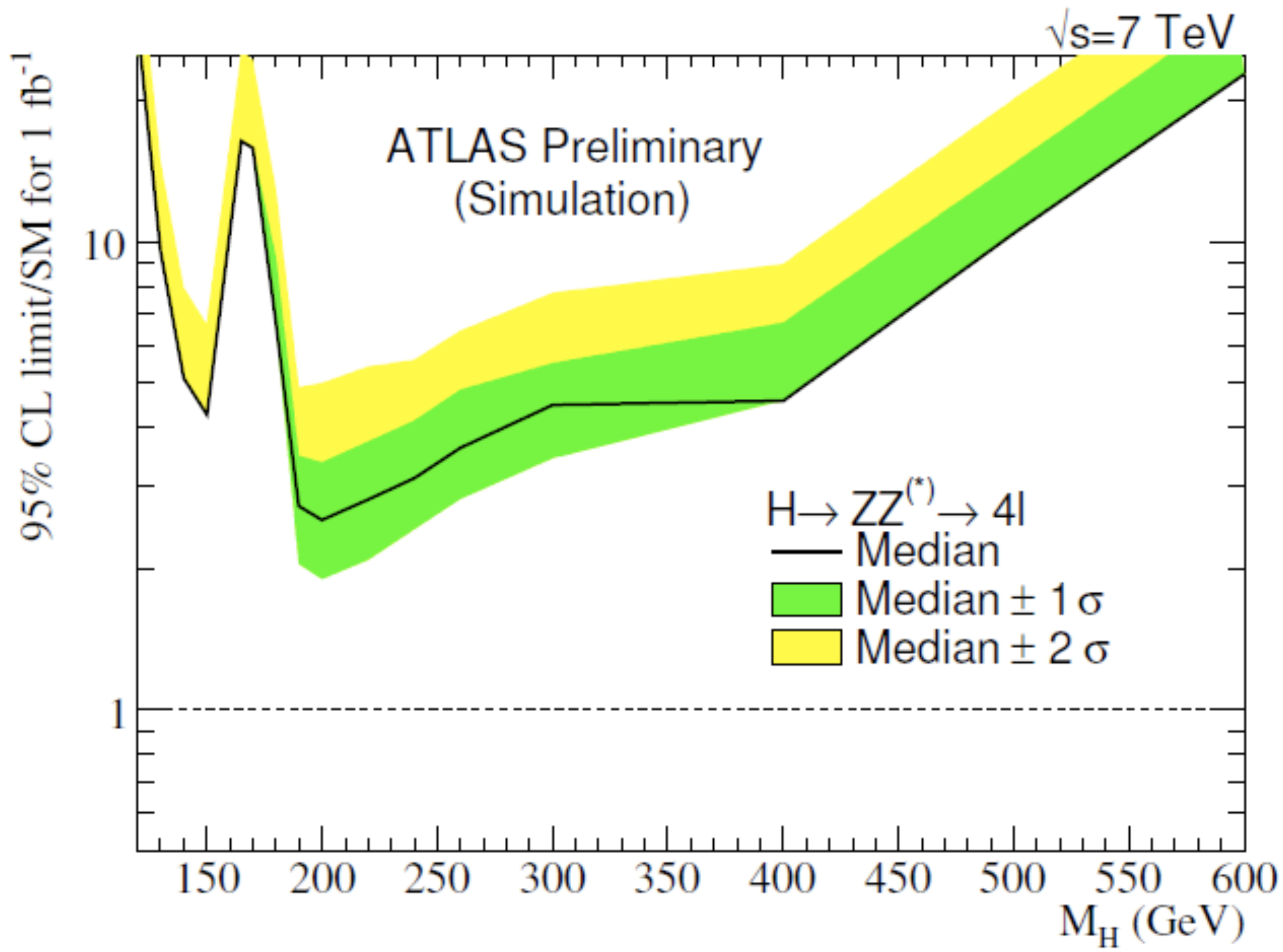
- PDF uncertainties still crucial and difficult to quantify precisely

Extra slides

SM Higgs@7 TeV



Exclusion: 150-185 GeV
Discovery: 160-170 GeV



gg fusion with H→WW

Further improvements

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

S.Moch, A. Vogt (2005)

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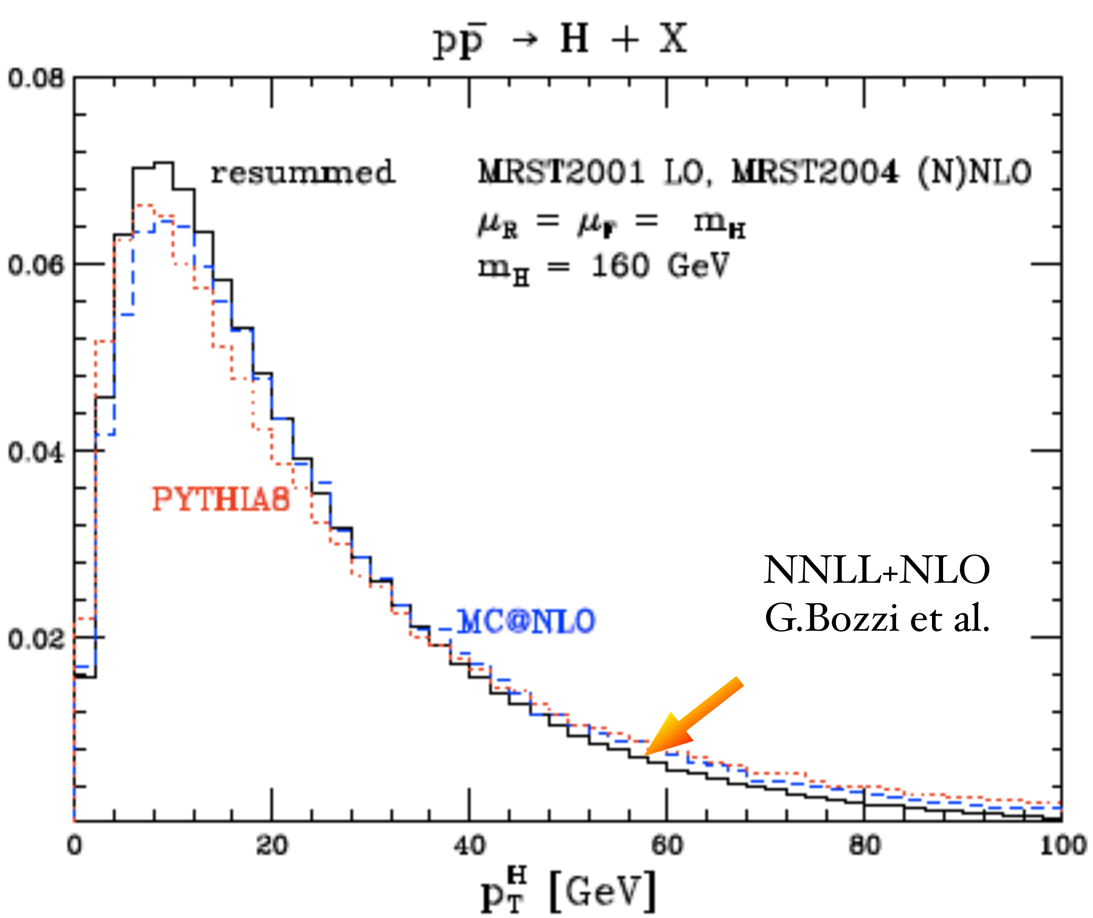

Needs careful MC validation against higher-order (and resummed) computations

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