Electroweak Physics - Theoretical Overview

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Hadron Collider Physics Symposium 2006 at Duke University

May 23, 2006

Physics of W and Z bosons

- Introduction
- Status of higher-order QCD and EW calculations
- Work in progress: TeV4LHC Electroweak WG
- Conclusions

Standard Model Higgs physics

- Introduction
- Status of QCD predictions for Higgs production processes
- EW one-loop corrections to $H \to 4f$
- Conclusions

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Resources

- LEPEWWG website at http://lepewwg.web.cern.ch/LEPEWWG (status Winter 2006)
- CDF Physics Results website at http://www-cdf.fnal.gov/physics/physics.html
- D0 Physics Results website at http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

Many Thanks !

Please note: Experimental results have been chosen and are shown for illustration purposes only. For a detailed discussion please see, e.g., Dave Water's talk at this meeting.

Physics of W and Z bosons

- W and Z production processes are one of the best, most precise probes of the Standard Model
- Precision measurement of the W mass and width (direct and indirect):
  $d\sigma/dM_T, d\sigma/dp_T(l)$ and ratio of σ_Z and σ_W
- Detector calibration and luminosity monitoring:
  M_Z, Γ_Z from $d\sigma/dM(ll)$ at the Z peak and $\sigma_{W,Z}$
- Constraints on quark PDFs:
  W charge asymmetry and Z rapidity distributions
- Search for new physics, e.g. heavy new gauge bosons (Z'):
  A_{FB} and $d\sigma/dM(ll)$ at high $M(ll)$

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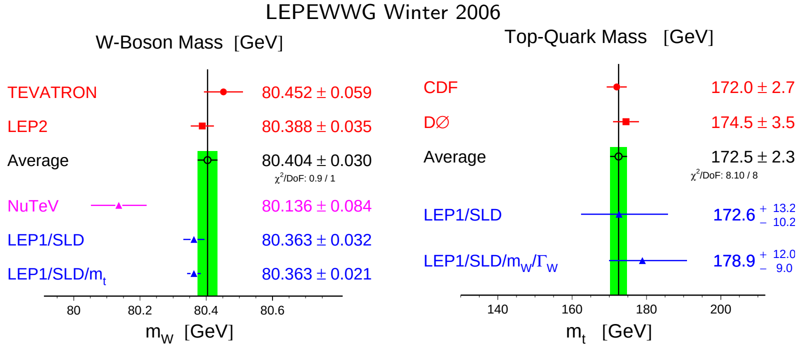
The importance of a precise W mass measurement



uncertainty	now	Tevatron 2 fb^{-1}	LHC
δM_W [MeV]	30	27	15
δm_t [GeV]	2.3	2.7	1.0
$\delta M_H / M_H$ [%] (from all data)	47	35	18

from U.Baur *et al.*, hep-ph/0111314

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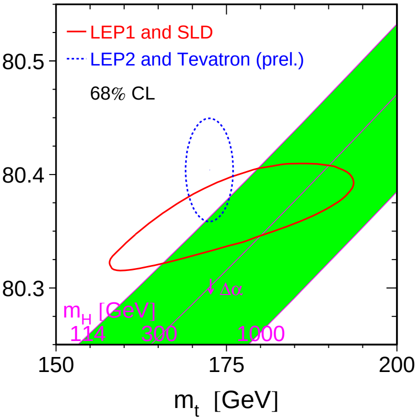

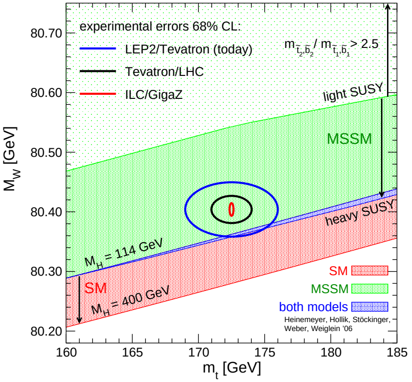

CERN-PH-EP/2005-051 (update: LEPEWWG webpage) S.Heinemeyer *et al.*, hep-ph/0604147

Constraint on SM Higgs mass: $M_H = 89^{+42}_{-30}$ GeV at 68 % C.L.

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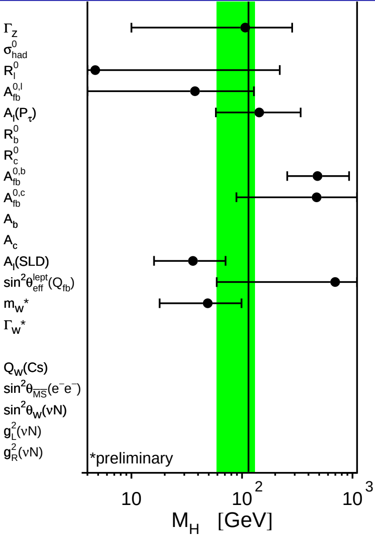
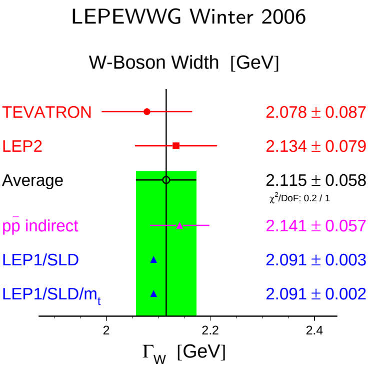
Predictive Power of M_W

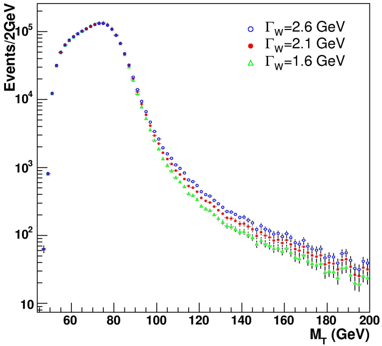


LEPEWWG Winter 2006

Fitted value of M_H strongly depends on m_t and M_W

Direct and Indirect Γ_W measurements





Direct measurement
from D0note 4563-CONF (MC simulation)

Indirect measurement: $R = \frac{\sigma_W}{\sigma_Z}\frac{\Gamma_Z}{\Gamma_{Z\to ll}}\frac{\Gamma_{W\to l\nu}}{\Gamma_W}$

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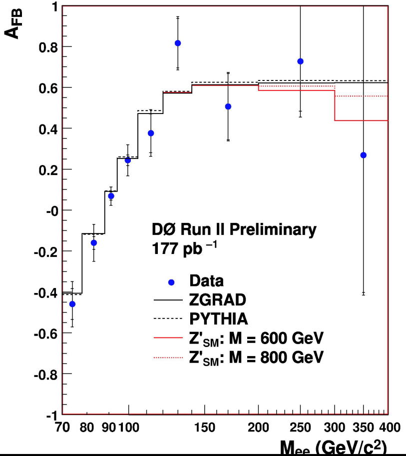
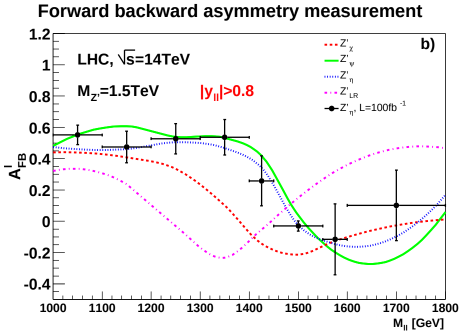
Search for new physics in A_{FB} at high $M(ll)$ at the Tevatron and LHC

from D0note 4757-CONF



from M.Dittmar *et al*, PLB 583 (2004)



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Status of higher-order QCD and EW calculations

- QCD radiative corrections to W/Z production: exact up to $\mathcal{O}(\alpha_s^2)$ (total cross sections) and soft gluon resummation ($p_T(W, Z)$ distributions).
  R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992) ; W.T.Giele *et al*, NPB403 (1993); C.Balazs *et al*, PRD56 (1997) (RESBOS)
  Fully differential distributions to W boson production and Z rapidity distribution up to $\mathcal{O}(\alpha_s^2)$
  K.Melnikov, F.Petriello, hep-ph/0603182; L.Dixon *et al.*, hep-ph/031226
- Electroweak (EW) corrections to Z and W boson production: complete EW $\mathcal{O}(\alpha)$ contribution and multiple final state radiation.
  U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005) and U.Baur, D.W., PRD70 (2004); S.Dittmaier, M.Krämer, PRD65 (2002); A.Andonov *et al*, hep-ph/0506110, L.Akhushevich *et al*(2003); W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004)

Tools for W/Z production at the Tevatron and LHC

Most of these calculations have been implemented in MC programs: (see also talk by S.Jadach at CERN MC4LHC workshop)

HORACE: Multiple photon radiation from final state in W/Z production as solution of QED DGLAP evolution for lepton SF. C.M.Carloni Calame *et al*, PRD69 (2004)

RESBOS: QCD corrections to W/Z production, soft gluon resummation. C.Balazs, C.P.Yuan, PRD56 (1997)
`http://www.pa.msu.edu/ balazs/ResBos/`

WGRAD2: QED $\mathcal{O}(\alpha)$ and weak corrections to W production. U.Baur, D.W., PRD70 (2004)
`http://ubpheno.physics.buffalo.edu/~dow/wgrad.tar.gz`

WINHAC: Multiple photon radiation from final state in W production, YFS exponentiation of soft photons. W.Placzek, S.Jadach, EPJC20 (2003)
`http://placzek.home.cern.ch/placzek/winhac`

ZGRAD2: QED $\mathcal{O}(\alpha)$ and weak corrections to Z boson production with proper treatment of higher-order terms around the Z resonance. U.Baur *et al* PRD65 (2002)
`http://ubhex.physics.buffalo.edu/~baur/zgrad2.tar.gz`

and also DYRAD, MCFM, MC@NLO, PHOTOS, SANC (semi-analytical),...

Next step: Use the available tools for precision studies of W/Z observables to answer the following questions:

- What is their impact and how does it compare to their anticipated experimental precision ?
- What is the residual theoretical uncertainty of the best predictions ?
- Do we need improvements to be able to fully exploit the physics potential at the Tevatron and the LHC ?

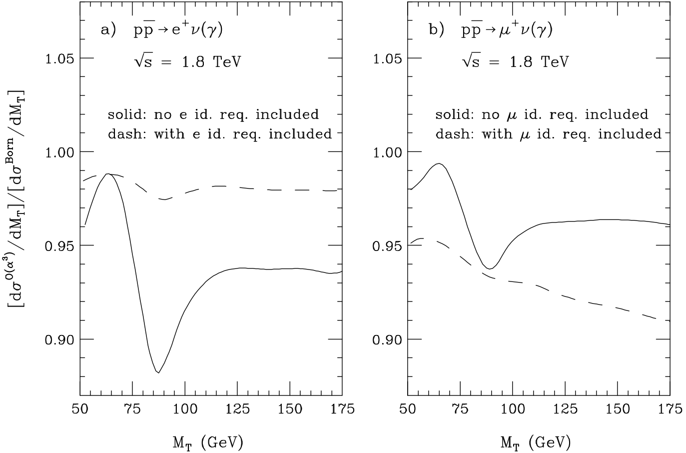
Goal: Experimental precision not to be limited by theory uncertainty !

Characteristics of EW corrections

- Final-state photon radiation (FSR):
  in sufficiently inclusive observables the mass singularities completely cancel (KLN theorem). But, depending on the experimental set up, large contributions of the form $\alpha \log(s/m_l^2)$ can survive.
- Initial-state photon radiation (ISR):
  mass singularities always survive but are absorbed by universal collinear counterterms to the parton distribution functions (mass factorization done in complete analogy to QCD).
  - introduces dependence on QED factorization scheme (in analogy to QCD, a *DIS* and $\overline{MS}$ scheme has been introduced)
  - PDFs including QED corrections have been made available by the MRST collaboration A.D.Roberts *et al.*, EPJC39 (2005).
- Electroweak corrections at large energies, $s \gg M_{W,Z}^2$:
  Sudakov-like contributions of the form $\alpha \log^2 s/M_{Z,W}^2$ can significantly enhance one-loop corrections.

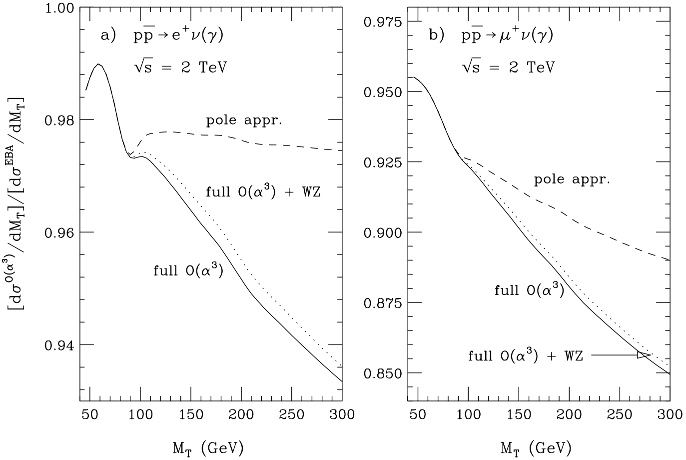
Impact of EW corrections on $M_T(l\nu)$ at the Tevatron

$$M_T = \sqrt{2 p_T(l) p_T(\nu)(1 - \cos \Phi^{l\nu})}$$



from U.Baur *et al*, PRD59 (1999)

Pole approximation vs. complete calculation at the Tevatron - above the W peak

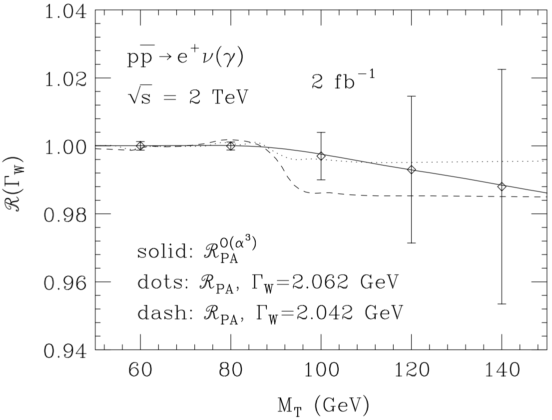


from U.Baur, D.W., PRD70 (2004)

Impact of electroweak corrections on the W mass

M_W extracted from $M_T(l\nu)$ at RUN I: $\delta M_W^{exp} = 59$ MeV	
final state QED (approximation) F.A.Berends *et al*, Z.Phys.C27 (1985)	Shift due to FSR (RUN I): -65$\pm$ 20 (-168$\pm$ 20) MeV in the electron (muon) case. $\delta M_W^{theory} = 10 - 20$ MeV
M_W extracted from $M_T(l\nu)$ at RUN II: $\delta M_W^{exp} = 27$ MeV	
full $\mathcal{O}(\alpha)$ contribution to resonant W production in a pole approx. W.Hollik, D.W, PRD55 (1997)	shift in M_W: $\delta M_W = 10$ MeV
full $\mathcal{O}(\alpha)$ electroweak corrections U.Baur, D.W., PRD70 (2004)	high Q^2, Γ_W
real two-photon radiation in W, Z production U.Baur *et al*, PRD61 (2000)	significantly changes shape of M_T
multiple final state photon radiation C.M.Carloni Calame *et al*, PRD69 (2004)	$\delta M_W = 2(10)$ MeV in the $e(\mu)$ case

Impact of EW corrections on Γ_W at the Tevatron



$$\frac{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W^{SM}}}{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W}} \propto \frac{\Gamma_W}{\Gamma_W^{SM}}$$

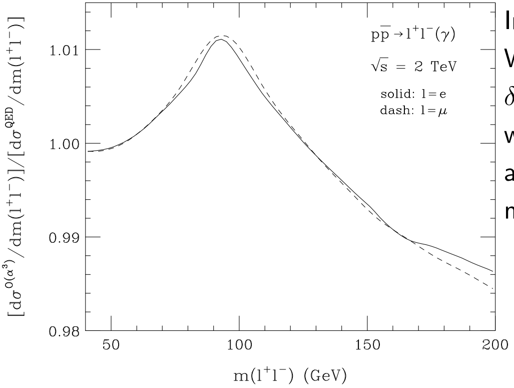
input: $\Gamma_W^{SM} = 2.072$ GeV

size of non-res. corr. is of same order as effects due to non-SM values of Γ_W

χ^2 fit: ignoring these corrections shifts Γ_W by -7.2 MeV ($\delta\Gamma_W^{exp} = 87$ MeV)

from U.Baur, D.W., PRD70 (2004)

Impact of EW corrections on $M(ll)$ at the Tevatron - at the Z resonance



Impact on extraction of M_Z:

With approximation by Berends,Kleiss:

δM_Z=-100 (-300) MeV ($e(\mu)$ case)

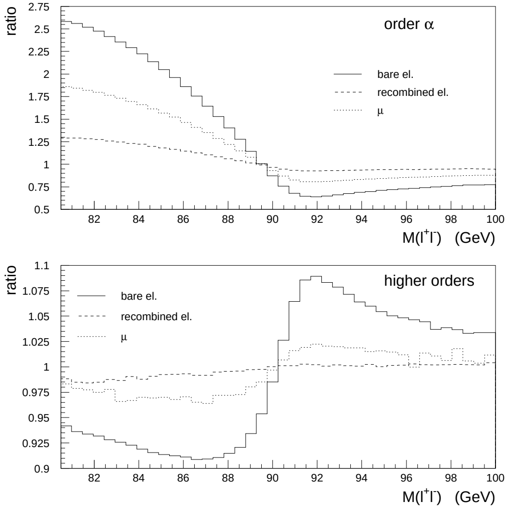
with full O(alpha):

additional shift of -10 MeV

mainly due to FSR

from U.Baur *et al*, PRD65 (2002)

Impact of multiple photon radiation on $M(ll)$ at the Tevatron

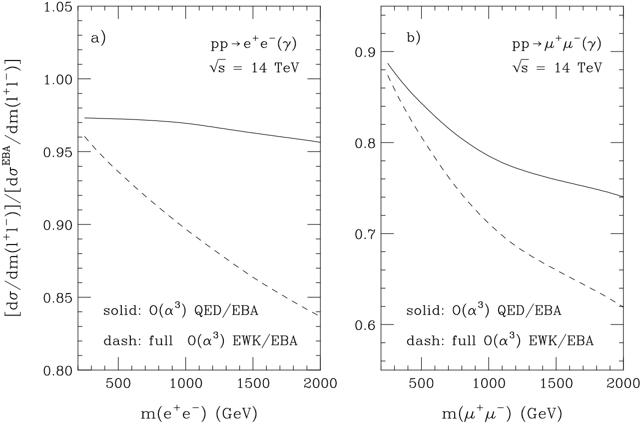


Effect on M_Z:

10% of NLO shift.

from C.M. Carloni Calame *et al.*, hep-ph/0502218 (HORACE)

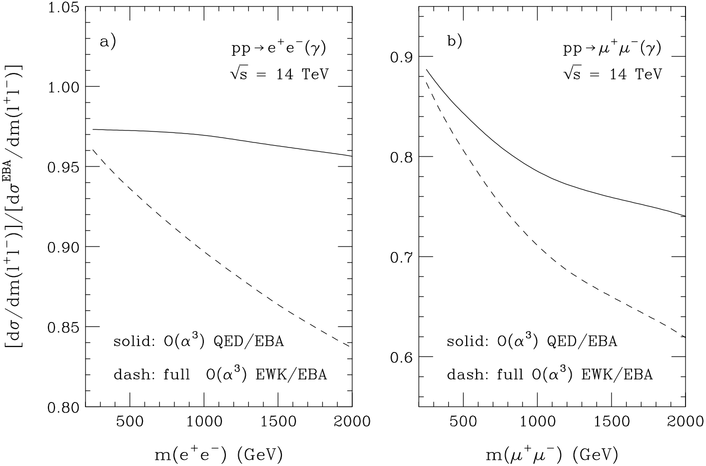
Impact of EW corrections on $M(ll)$ at the LHC - above the Z peak



from U.Baur *et al*, PRD65 (2002)

Note: At the LHC at $M(ll) = 1$ TeV, QCD NLO corrections enhance $\frac{d\sigma}{dM(ll)}$ by about 15-20 % (from U.Baur, private communications).

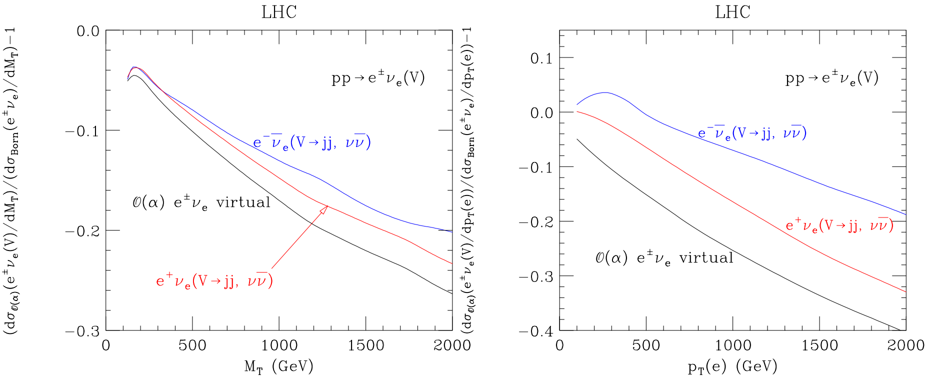
Impact of EW corrections on A_{FB} at the LHC



from U.Baur *et al*, PRD65 (2002)

How numerically important are EW Sudakov logarithms ?

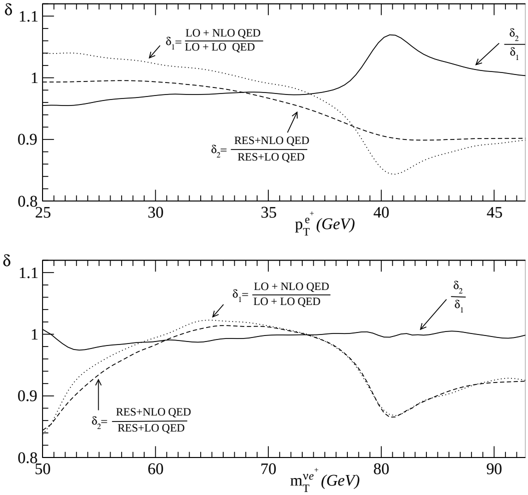
Depends on the observable, i.e. the more inclusive the observable in the treatment of the weak gauge boson, the less numerical important are these EW contributions:



Talk given by U.Baur at Pheno 2006:
`http://www.pheno.info/symposia/pheno06`

Impact of combined EW and QCD corrections

From C.-P.Yuan, Q.-H.Cao, PRL93 (2004)



Work in progress: TeVLHC Electroweak WG

see `http://conferences.fnal.gov/tev4lhc`

- Tuned comparison of available Monte Carlo programs that provide precise predictions for W/Z observables a la LEPI/II CERN yellow books (RESBOS, W/ZGRAD, HORACE, WINHAC, SANC, PHOTOS,...): first studies in LesHouches proceedings, hep-ph/0406152
  - Provide an estimate of remaining theoretical uncertainties due to missing higher order corrections, PDF uncertainties, ...
  - Identify necessary improvements to match experimental precision.
  - Provide a recommendation of how to implement (dominant) electroweak corrections in multi-purpose event generators.

Recent Improvements:

QCD New in ResBos:

- Improved fit for nonperturbative part to q_T distribution (*Konychev,Nadolsky*)
- Final state QED contribution included (*Cao,Yuan*)

Fully differential W distributions known at NNLO QCD (*Melnikov,Petriello*).

EW Multiple photon radiation in W and Z production implemented in MC program HORACE (*Carloni Calame,Montagna,Nicrosini,Treccani*) and WINHAC (*Jadach,Placzek*).

QED corrections included in extraction of PDFs (*MRST collaboration*)

Conclusions

- W and Z boson physics at hadron colliders offers plentiful and unique opportunities to test the SM and search for signals of physics beyond the SM.
- Impressive progress has been made in providing precise predictions at NLO, NNLO and higher (leading logarithms).
- We are now in the process to determine if the tools provided are sufficient in view of the anticipated experimental capabilities for EW precision physics at the Tevatron and the LHC.
  This involves a careful study of the residual theoretical uncertainties (TeV4LHC workshop).

Conclusions: Work in Progress

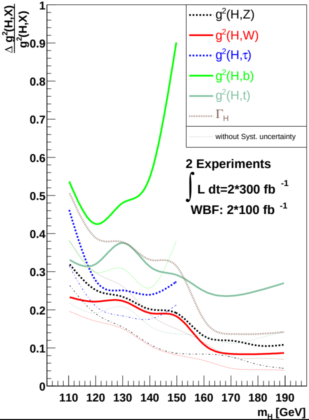
Ongoing work by the authors of WINHAC,RESBOS,HORACE,WGRAD/ZGRAD:

- Combination of EW and QCD corrections in one MC generator
- Interface of higher-order EW calculations, i.e. multiple photon radiation from final state leptons and EW Sudakov logarithms, with fixed $\mathcal{O}(\alpha)$ calculations.

Moreover:
Inclusion of mixed QED/QCD $\mathcal{O}(\alpha\alpha_s)$ corrections.

Standard Model Higgs physics

Once a Higgs boson is discovered, to fully exploit the potential of the LHC to determine its properties it is crucial to provide higher-order QCD and EW calculations of signal and background processes.



Example:

Extraction of SM Higgs couplings at the LHC:

LHC can measure Higgs couplings to t, τ, W, Z with 10-20 % accuracy in multi-Higgs-doublet models (300 fb^{-1})

from M.Duhrssen *et al.*, hep-ph/0407190

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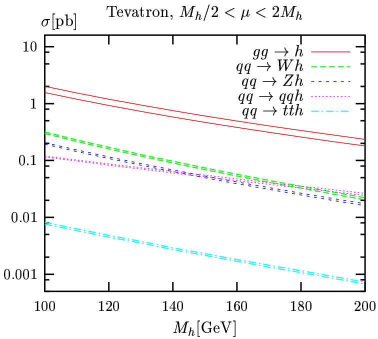
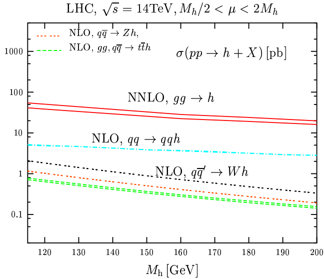
State-of-the-art of QCD predictions for Higgs production at hadron colliders:

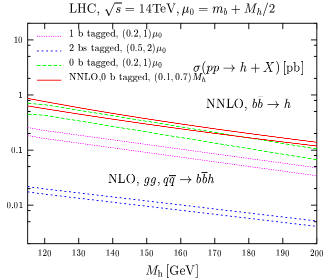
Dominant production modes: $gg \to H$ (background very large);
$q\bar{q} \to WH, ZH$ (most promising for leptonic decay of W/Z)

production process	$\sigma_{\mathrm{NLO,NNLO}}$ by
$gg \to H$	S.Dawson, NPB 359 (1991); A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser, C.R.Schmidt, JHEP (2002); V.Ravindran *et al*,NPB 634 (2002); D.de Florian *et al.*, PRL 82 (1999) (distrib.) V.Ravindran *et al*, NPB 665 (2003) (NNLO) R.Harlander, W.Kilgore, PRL 88 (2002) (NNL0) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNL0)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) (distrib.)
$gg, q\bar{q} \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 68 (2003)
$gg, q\bar{q} \to b\bar{b}H$	S.Dittmaier, M.Krämer, M.Spira, PRD 70 (2004) S.Dawson *et al.*, PRD 69 (2004)
$gb(\bar{b}) \to b(\bar{b})H$	for a review see, e.g.,S.Dawson *et al.*, MPLA 21 (2006)
$b\bar{b} \to H$	for a review see, e.g., S.Dawson *et al.*, MPLA 21 (2006); R.Harlander, W.Kilgore, PRD 68 (2003) (NNL0)

$\sigma_{NLO,NNLO}$ for Higgs production processes at hadron colliders:







from S.Dawson *et al.*, hep-ph/0210109

$t\bar{t}h$7: μ varied between $\mu_0 = m_t + M_h/2$ and $2\mu_0$.

from S.Dawson *et al.*, in prep. (prelim.)

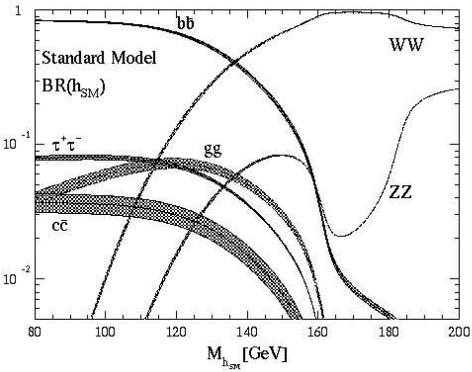
Many thanks to W.Kilgore and R.Harlander for providing their NNLO results.

Dominant decay modes:

M_H <135 GeV: $H \to b\bar{b}$ with $BR = 43\%$,

M_H >135 GeV: $H \to W^+W^-$ with $BR = 40\%$

Branching ratios of the dominant SM Higgs decay modes (including QCD corrections):



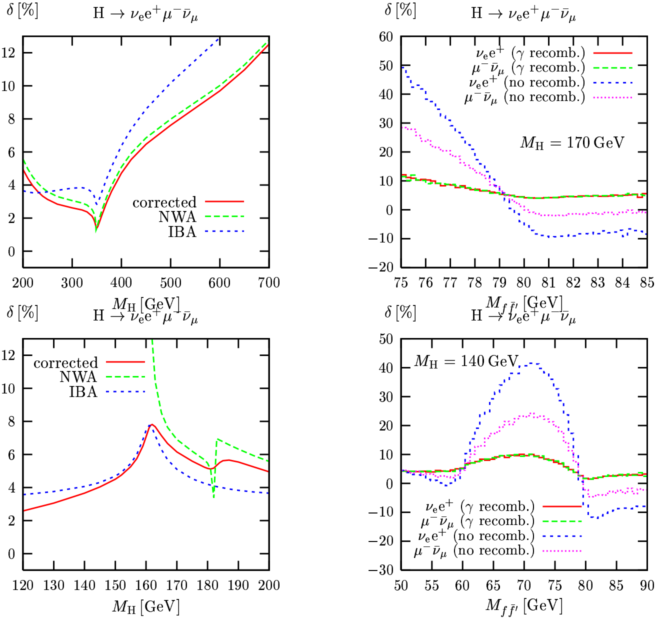
from M.Carena and H.Haber,

hep-ph/0208209

HDECAY (A.Djouadi *et al.*)

M.Spira, hep-ph/9810289

EW one-loop corrections to $H \longrightarrow 4f$



from A.Bredenstein *et al.*, hep-ph/0604011

Conclusions

- Predictions for SM Higgs production and decay processes are under good theoretical control.
  Possible improvements: Interface of resummed QCD calculations with fixed order calculations (e.g., threshold logarithms in Higgs production in association with heavy quarks).
- Predictions for background processes also need to include higher order QCD corrections.