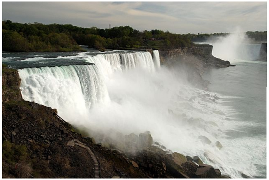
Electroweak precision physics with W and Z bosons

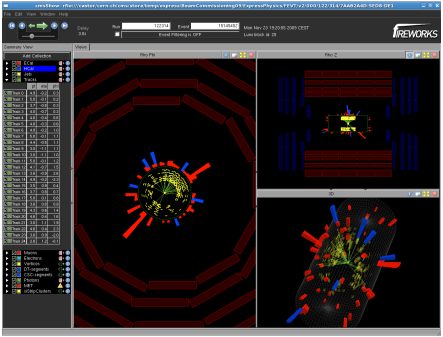
Doreen Wackeroth
Karlsruhe Institute of Technology (KIT)
and
University at Buffalo, SUNY

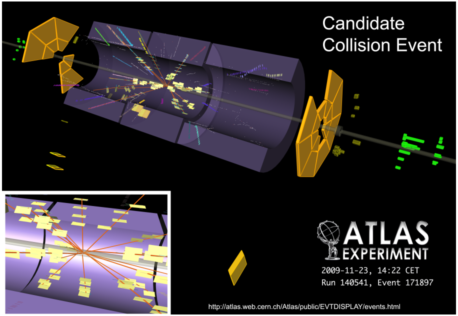


Particle Theory Seminar

Paul Scherrer Institute, Villigen, Switzerland, Dec. 3, 2009

Exciting times ...





www.cern.ch

... and again we are hoping for discoveries: the Higgs boson and signals of *new physics*.

Electroweak precision physics with W and Z bosons

Introduction

Status of predictions for W/Z observables

Studies of theoretical uncertainties

Conclusion and Outlook

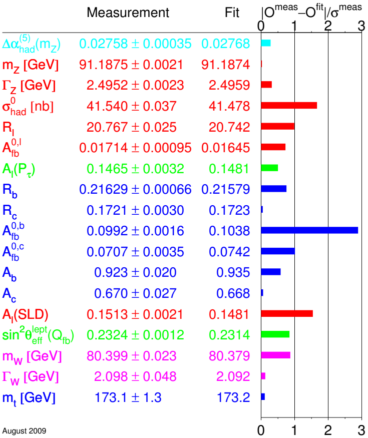
Electroweak precision physics

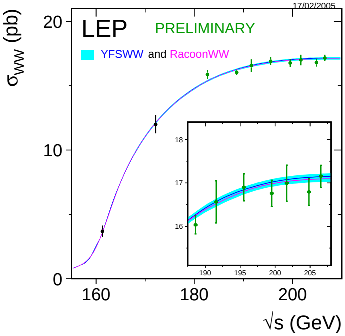
W and Z production processes are one of the theoretically best understood, most precise probes of the Standard Model.

- Test of the Standard Model (SM) of electroweak and strong interactions as a fully-fledged Quantum Field Theory: sensitivity to multi-loop and non-universal corrections.
- Check of the consistency of the SM by comparing direct with indirect measurements of model parameters, e.g., $m_t, M_W, \sin^2\theta_{eff}$.
- Constraint on the SM Higgs boson mass.
- Search for indirect signals of Beyond-the-SM (BSM) physics in form of small deviations from SM predictions.
- Exclusion of or constraints on BSM physics.

EW precision physics at LEP-I/SLC, LEP-II

LEPEWWG Summer 2009





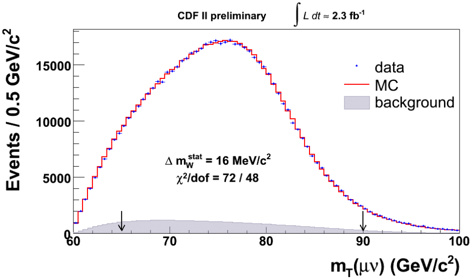
$$\delta\sigma^{theory}_{WW} = 0.4\% \text{ at } \sqrt{s} = 200 \text{ GeV}$$

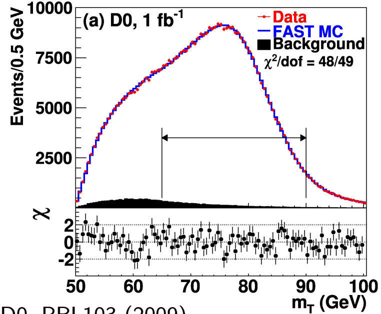
M.Grünewald *et al.*, hep-ph/0005309

$$M_W = 80.376 \pm 0.033 \text{ GeV and } \Gamma_W = 2.196 \pm 0.083 \text{ GeV}$$

EW precision physics at the Tevatron

$$M_T(l\nu_l) = \sqrt{p_T^l p_T^\nu (1 - \cos(\Phi_l - \Phi_\nu))}$$





CDF, www-cdf.fnal.gov D0, PRL103 (2009)

CDF: $\delta M_W = 48$ MeV $(200\ \mathrm{pb}^{-1})$ PRL99 (2007), PRD77 (2008)

D0: $\delta M_W = 43$ MeV $(1\ \mathrm{fb}^{-1})$ PRL103 (2009)

Tevatron combined: TEVEWWG, arXiv:0908.1374[hep-ex]

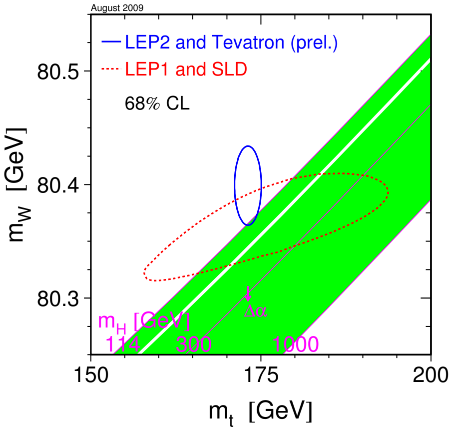
$M_W = 80.420 \pm 0.031$ GeV and $\Gamma_W = 2.050 \pm 0.058$ GeV

Electroweak precision physics at the Tevatron and LHC

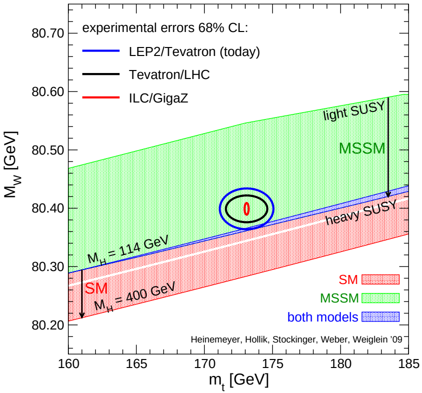
EW precision physics at the Tevatron and the LHC has many facets:

- Precision measurements of the W mass and width and $\sin^2\theta_{eff}$:
  $d\sigma/dM_T, d\sigma/dp_T(l)$ and ratio of σ_Z and σ_W, and A_{FB}
- 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 BSM physics, e.g., heavy new gauge bosons (Z'):
  A_{FB} and $d\sigma/dM(ll)$ at high $M(ll)$
- Limits on anomalous triple and quartic EW gauge boson self couplings (VV and VVV production not discussed here).

Constraint on M_H and sensitivity to BSM physics



LEPEWWG Summer 2009

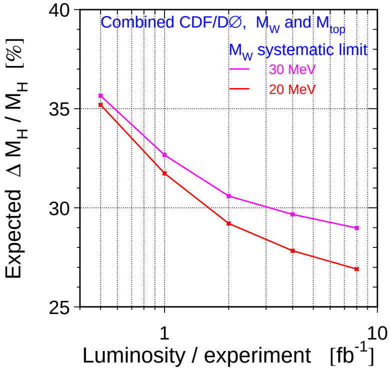


S.Heinemeyer *et al.*, hep-ph/0604147

www.ifca.unican.es/∼heinemey/uni/plots/

Constraint on SM Higgs mass: $M_H = 87^{+35}_{-26}$ GeV at 68% C.L.

Prospects for M_W, m_t measurements and M_H constraints



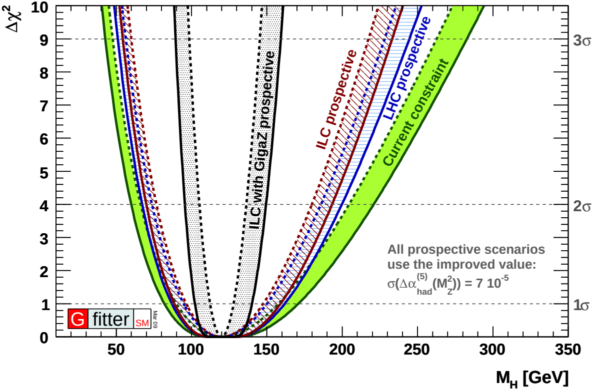
P5 committee (2005)

uncertainty	now	Tevatron $2\ \mathrm{fb}^{-1}$(final)	LHC	ILC/GigaZ
δM_W [MeV]	23	20(15)	15	7
δm_t [GeV]	1.3	1.2	1.0	0.13
$\delta M_H / M_H$ [%] (from all data)	40	~ 28	18	8

U.Baur *et al.*, hep-ph/0202001 (updated); see also A.Hoecker, arXiv:0909.0961[hep-ph]

A.Kotwal, and J.Stark, Annurev.Nucl.58 (2008)

Prospective SM Higgs mass constraints from Gfitter



A.Hoecker, arXiv:0909.0961[hep-ph]

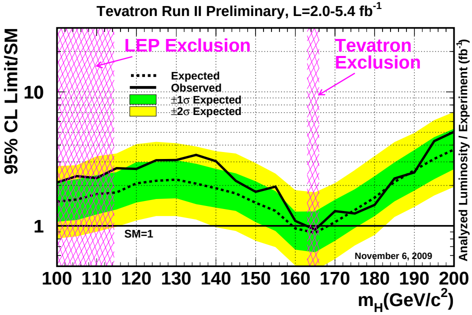
Now (for a hypothetical central value): $M_H = 120^{+50}_{-40}$ GeV
LHC ($\delta M_W = 15$ MeV): $M_H = 120^{+45}_{-35}$ GeV
ILC/GigaZ ($\delta M_W = 6$ MeV,$\delta m_t = 0.1$ GeV): $M_H = 120 \pm 19$ GeV

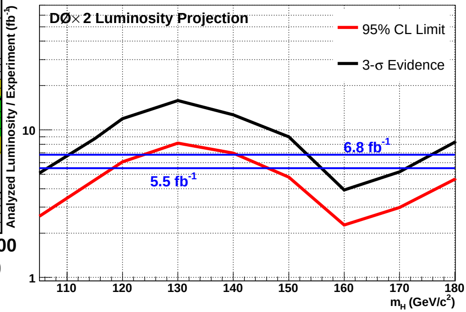
A.Hoecker, arXiv:0909.0961[hep-ph]

SM Higgs searches at the Tevatron

LEP-II & electroweak precision data: LEPEWWG Summer 2009

$$114\,\mathrm{GeV} < M_H < 186\,\mathrm{GeV}(95\%\mathrm{C.L.})$$



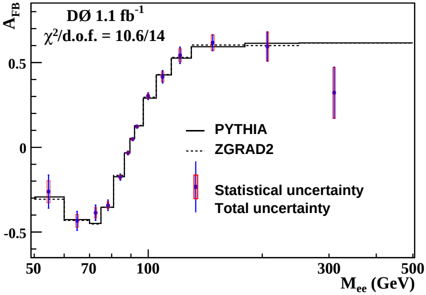


Tevatron New Phenomena & Higgs WG, arXiv:0911.3930[hep-ex] G.Bernardi, arXiv:0809.5265

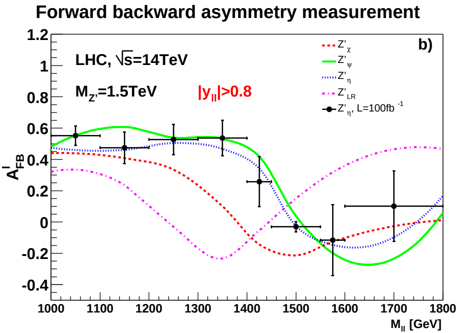
The Tevatron has the potential to exclude a large part of the M_H range preferred by EWPOs at 95 % C.L. (now: $\approx 7\ \mathrm{fb}^{-1}$, by 2010: $8 - 8.5\ \mathrm{fb}^{-1}$).

Search for new physics in Z production: A_{FB} at high $M(ll)$

D0, arXiv:0804.3220 [hep-ex]



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



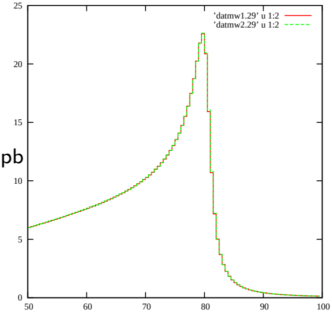
Sensitivity to $\sin^2\theta_{eff}$:

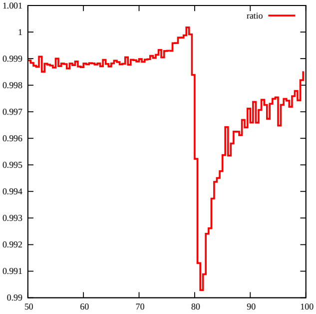
$\delta\sin^2\theta_{eff} = 19\times10^{-4}$ (Tevatron) and $\delta\sin^2\theta_{eff} = 14-20\times10^{-5}$ (LHC)

An illustration: how well do we need to control the relevant observables for $\delta M_W \approx 15$ MeV?

LO $M_T(l\nu)$ distributions at the Tevatron for $M_W = 80.398$ GeV and $M_W = 80.408$ GeV:

$\frac{d\sigma}{dM_T(l\nu)}$, pb





$M_T(l\nu)$, GeV

inspired by A.Vicini, talk at RADCOR 2009

Status of predictions for W/Z observables

QCD corrections:

- NLO and NNLO QCD (up to $\mathcal{O}(\alpha_s^2)$): total cross sections ($\sigma_{W,Z}$) and fully differential distributions

  R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992); W.T.Giele *et al*, NPB403 (1993)

  L.Dixon *et al.*, hep-ph/031226; K.Melnikov, F.Petriello, hep-ph/0603182; S.Catani *et al.*, PRL103 (2009)

- NLO QCD corrections matched to an all-order resummation of large logarithms $\ln^n(q_T/Q)$ (at NLL) (Q: W/Z virtuality, q_T: W/Z transverse momentum).

  C.Balazs, C.-P.Yuan, PRD56 (1997) (ResBos); G.Bozzi *et al*, NPB815 (2009)

- NLO QCD corrections matched to a parton shower such as HERWIG (MC@NLO) or POWEG.

  S.Frixione, B.R.Webber, hep-ph/0612272; S.Alioli *et al*, JHEP0807 (2008)

Status of predictions for W/Z observables

Electroweak corrections:

- EW $\mathcal{O}(\alpha)$ corrections
  U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005) U.Baur, D.W., PRD70 (2004); S.Dittmaier, M.Krämer, PRD65 (2002); A.Andonov *et al*, hep-ph/0506110, L.Akhushevich *et al*(2003)
- Multiple final-state photon radiation
  W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004);S.Brensing *et al*, PRD77 (2008)
- Logarithmic enhanced EW corrections at high energies (EW-like Sudakov logarithms)
  J.H.Kühn, Acta Phys.Polon.B39 (2008) (brief review); S.Brensing *et al*, PRD77 (2008).
- Electroweak corrections to $W + 1 - jet$ production S.Dittmaier *et al*, JHEP0908 (2009); J.H.Kühn, *et al*, NPB797 (2008).

Public MC programs for W/Z precision physics

HORACE: Electroweak $\mathcal{O}(\alpha)$ corrections and multiple photon radiation from initial and final-state leptons as solution of QED DGLAP evolution for lepton SF. EW-like Sudakov logarithms. Interface to MC@NLO.
C.M.Carloni Calame *et al*, PRD69 (2004); JHEP0612 (2006)

`http://www.pv.infn.it/~hepcomplex/horace.html`

RESBOS: NLO QCD corrections and all-order soft-gluon resummation. Final-state QED $\mathcal{O}(\alpha)$ corrections. C.Balazs, C.P.Yuan, PRD56 (1997)

`http://www.pa.msu.edu/~balazs/ResBos/`

WGRAD2/ZGRAD2: Electroweak $\mathcal{O}(\alpha)$ corrections. Z production with proper treatment of higher-order terms around the Z resonance. EW-like Sudakov logarithms (Z boson production). U.Baur *et al* PRD65 (2002), U.Baur, D.W., PRD70 (2004)

`http://ubhex.physics.buffalo.edu/~baur/zgrad2.tar.gz`

`http://ubpheno.physics.buffalo.edu/~dow/wgrad.tar.gz`

SANC: Electroweak $\mathcal{O}(\alpha)$ and NLO QCD corrections.
A. Arbuzov *et al*, EPJ.C54 (2008); EPJ.C46 (2006); arXiv:0901.2785 `http://sanc.jinr.ru`

FEWZ: NNLO QCD corrections (fully exclusive).
K.Melnikov, F.Petriello, hep-ph/0603182; L.Dixon *et al.*, hep-ph/031226

`http://www.phys.hawaii.edu/ kirill/FEHiP.htm`

and also DYRAD, MCFM, MC@NLO, WINHAC, PHOTOS

Gerneral structure of EW corr. to W/Z production

As usual, the structure is determined by phase space generation ($d\Phi^{(n)}$) and computation of matrix elements squared ($|\mathcal{M}|^2$):

$$d\sigma = d\Phi^{(n)} dx_1 dx_2 f_i(x_1) f_j(x_2) |\mathcal{M}(b_1, b_2, p_1, ..., p_n)|^2$$

with

$$|\mathcal{M}|^2 = |\mathcal{M}^{(0)}|^2 \left[1 + 2\mathcal{R}e(\tilde{F}^{initial}_{weak} + \tilde{F}^{final}_{weak})(M_W^2)\right]$$
$$+ \sum_{\substack{a=initial, final,\\ interf.}} |\mathcal{M}^{(0)}|^2 \; F^a_{QED}(\hat{s}, \hat{t}, \delta_{s,c}) + |\mathcal{M}_{non-res.}|^2(\hat{s}, \hat{t}) +$$
$$+ \sum_{\substack{a=initial, final,\\ interf.}} |\mathcal{M}_{2\to 3}|^2_a(\delta_{s,c})$$

$2 \to 3$ weight in blue and $2 \to 4$ weight in red.

Negative weights, re-weighting: see discussion in proc. of *QCD and Weak Boson Physics in Run2* (hep-ex/0011009).

Characteristics of EW corrections to W/Z production

- 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.

Enhanced EW corrections at high energies

- At energies $\sqrt{s} \gg M_{W,Z}$ EW corrections are enhanced by

$$\alpha^L \log^N(\frac{s}{M_V^2}) \;\; ; \;\; 1 \leq N \leq 2L \; (L = 1(1 - loop), \ldots)$$

  Origin: Remnants of UV singularities after renormalization + soft/collinear ISR and FSR emission of virtual and real W/Z bosons.

  In contrast to QED and QCD, also in inclusive observable these corrections do not completely cancel.

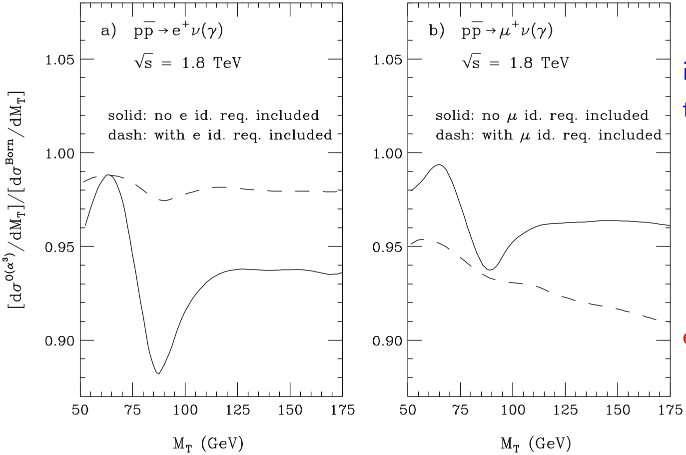
  W/Z mass is physical cut-off: real W/Z radiation is usually not included, since it leads to a different initial/final state.

- EW logarithmic corrections to 4-fermion processes are known up to 2-loop N^3LL order and are available in form of compact analytical formula.

  for a brief review, see, e.g.,J.H. Kühn, Acta Phys.Polon.B39 (2008)

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

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

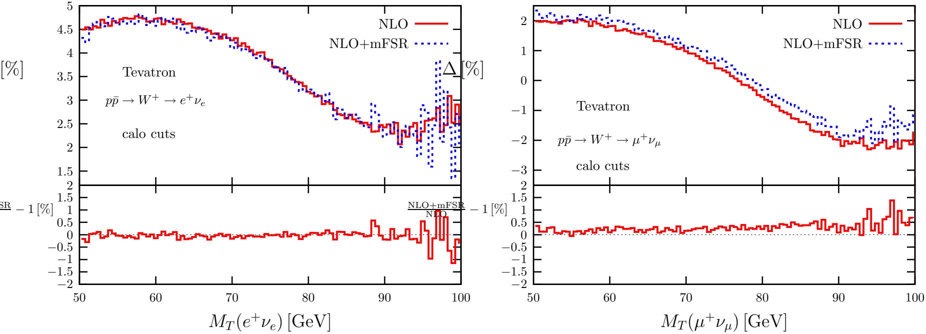


inclusive vs.exclusive treatment of photon

effect of $\log(s/m_\mu^2)$

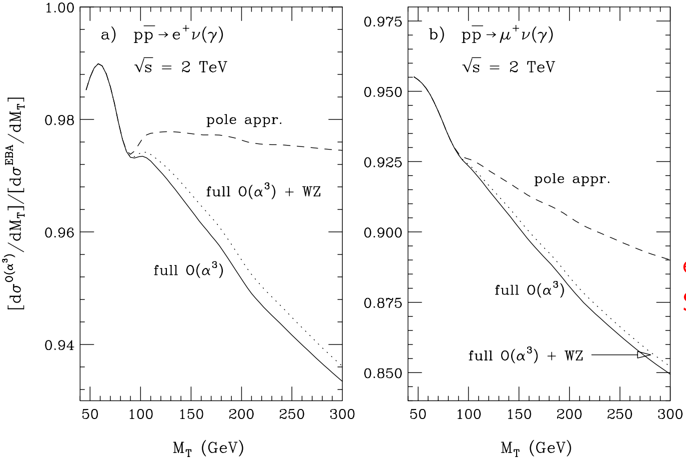
U.Baur.D.W. *et al*, PRD59 (1999)

Impact of multiple photon radiation on $M_T(l\nu)$ at the Tevatron



C.Gerber, T.Tait, D.W. *et al*, TEV4LHC TopEW WG report, arXiv:0705.3251 [hep-ph] (with HORACE)

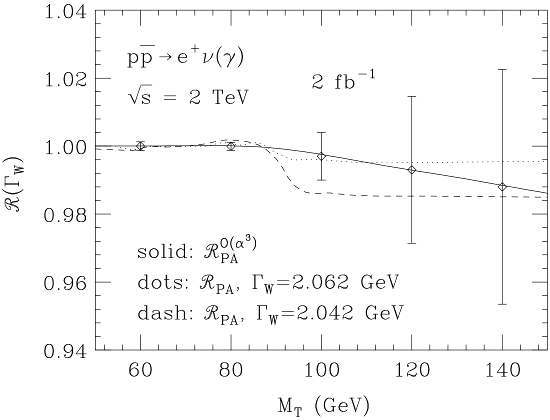
Pole approximation vs. full $\mathcal{O}(\alpha)$ calculation of $p\bar{p} \longrightarrow W^+ \longrightarrow l^+\nu$ at the Tevatron



effect of EW Sudakov-like logs

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

Impact of non-resonant 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

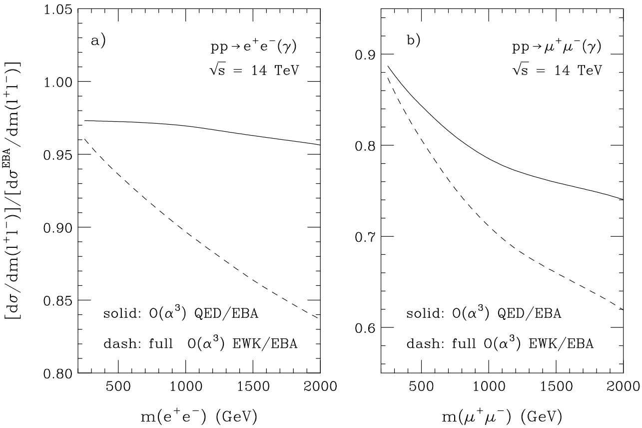
χ^2 fit: ignoring these corrections shifts Γ_W by -7.2 MeV ($\delta\Gamma_W^{exp} = 58$ MeV)

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

Impact of electroweak corrections on the W mass

Exp. Precision	Extra rad. corr.	Shift in M_W
TRI: 59 MeV	final-state QED $\mathcal{O}(\alpha)$ $W \to e\nu$ $W \to \mu\nu$	 -65 ± 20 MeV -168 ± 20 MeV
TRII(now): 31 MeV TRII(goal): 15 MeV	full QED and weak $\mathcal{O}(\alpha)$ corr. in pole approx.	~ 10 MeV
LHC: 15 MeV	full EW $\mathcal{O}(\alpha)$ corr. (no approx.): shifts W width by ≈ 7 MeV; affects distributions at high Q^2	?
	real two-photon radiation changes shape of $M_T(l\nu_l)$ distr.	?
	multiple final-state photon radiation in $W \to e(\mu)\nu$	2(10) MeV

Impact of EW corrections on $M(ll)$ at the LHC at high $M(ll)$

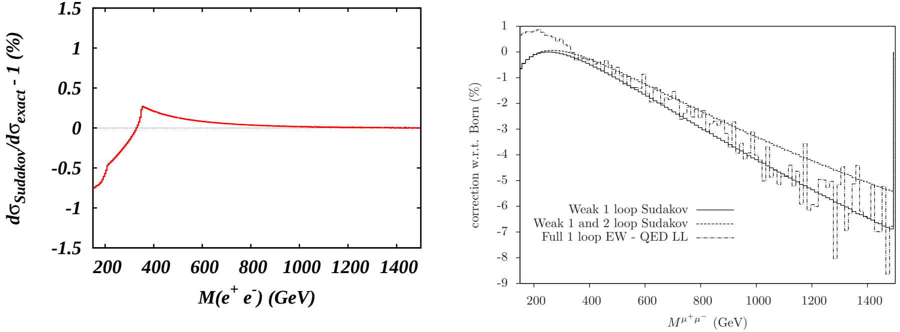


effect of EW Sudakov-like logs

U.Baur,D.W. *et al*, PRD65 (2002)

see also U.Baur, PRD75 (2007)

Complete EW $\mathcal{O}(\alpha)$ vs 1-loop and 2-loop Sudakov approximation

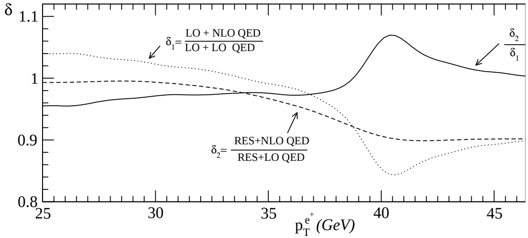


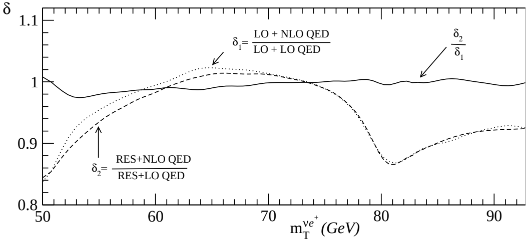
Buttar *et al*, LesHouches WG report, arXiv:0803.0678 [hep-ph] (with `ZGRAD2` and `HORACE`)

B.Jantzen *et al*, NPB731 (2005)

Impact of combined EW and QCD corrections using ResBos

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

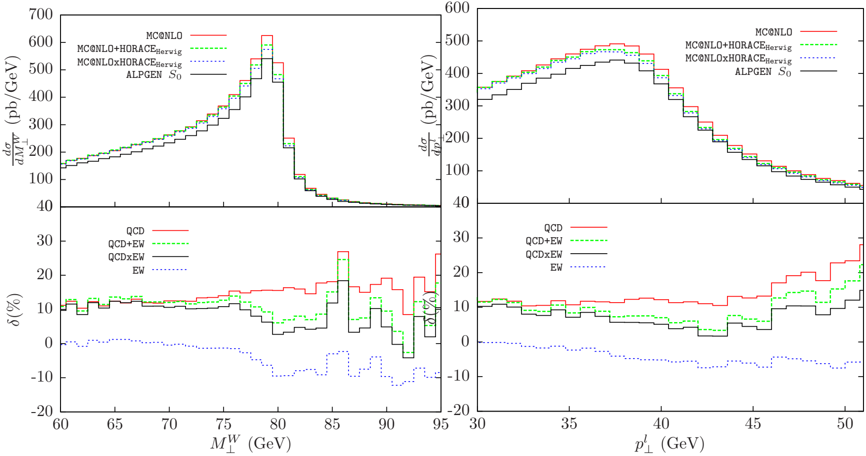




ResBos combines QCD ISR and QED FSR.

Effects of QED when combined with QCD differ from the only QED case !

Impact of combined EW and QCD corrections using MC@NLO/HORACE



G. Balossini *et al*, arXiv:0907.0276 [hep-ph]

Combined QED/QCD resummation

Simultaneous QCD and QED resummation of large IR effects based on YFS exponentiation (B.F.L. Ward and S.Jadach) suitable for implementation in parton shower MCs (e.g., `HERWIG`):

$$d\hat{\sigma}_{\rm exp} = e^{\rm SUM_{IR}(QCED)} \sum_{n,m=0}^{\infty} \frac{1}{n!m!} \int \prod_{j_1=1}^{n} \frac{d^3 k_{j_1}}{k_{j_1}} \prod_{j_2=1}^{m} \frac{d^3 {k'}_{j_2}}{{k'}_{j_2}}$$

$$\int \frac{d^4 y}{(2\pi)^4} e^{iy\cdot(p_1+q_1-p_2-q_2-\sum k_{j_1}-\sum {k'}_{j_2})+D_{\rm QCED}}$$

$$\tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)\frac{d^3 p_2}{p_2^0}\frac{d^3 q_2}{q_2^0}$$

B.F.L. Ward *et al*, arXiv:0810.0723 [hep-ph]

Studies of theoretical uncertainties

Are W/Z observables under theoretical control ?

Theoretical uncertainty due to *missing* higher-order corrections:

- Tevatron: D0, PRL103 (2009)
  $\delta M_W^{theory} \approx 7(7)$ MeV $(M_T(p_T^l))$ due to missing higher-order photon radiation
- LHC: N.Adam *et al.*, arXiv:0808.0758 [hep-ph]
  $\delta\sigma_W/\sigma_W = 4.00 \pm 0.61\%$ due to missing O(α) EW corrections
  $\delta\sigma_W/\sigma_W = 1.66 \pm 0.69\%$ due to missing NNLO QCD corrections

Theoretical uncertainty due to *unknown* higher-order corrections

A MC program providing the *best* prediction by including all known higher-order corrections (EW and QCD) is not yet available.

Tev4LHC (arXiv:0705.3251 [hep-ph]) and Les Houches (arXiv:0803.0678 [hep-ph]) workshop reports

Assessment of QCD uncertainties:

- QCD factorization/renormalization scale dependence
- Different treatments of non-perturbative QCD contributions and different implementation of subleading logarithms for $q_T \lesssim 20$ GeV) in soft-gluon resummation (mainly effects M_W from p_T^l)

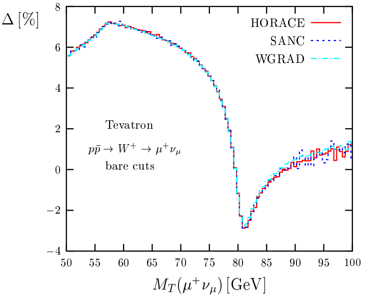
Assessment of EW uncertainties:

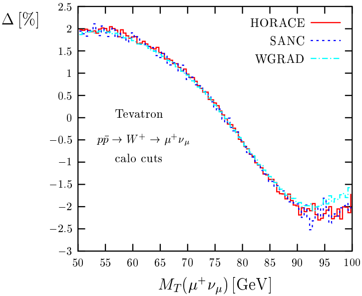
- Tuned comparisons of EW $\mathcal{O}(\alpha)$ calculations
- EW input scheme dependence and different implementations of higher-order corrections
- QED scale dependence of PDFs

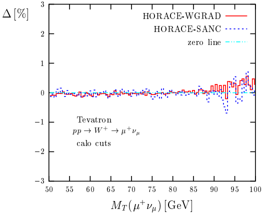
PDF uncertainty: $\delta M_W^{PDF} = 9(11)$ MeV and $\delta\sigma_W/\sigma_W(PDF) = 4\%$

D0, PRL103 (2009), and N.Adam *et al.*, arXiv:0808.0758 [hep-ph]

Results of a tuned comparison







C.Gerber, T.Tait, D.W. *et al*, TEV4LHC TopEW WG report, arXiv:0705.3251 [hep-ph]

- 'NLO at $\mathcal{O}(\alpha^3)$ incl. h.o.': EW input of tuned comparison with

$$\delta M_Z^2 = \mathcal{R}e\left(\Sigma^Z(M_Z^2) - \frac{(\hat{\Sigma}^{\gamma Z}(M_Z^2))^2}{M_Z^2 + \hat{\Sigma}^{\gamma}(M_Z^2)}\right)$$

higher-order (irreducible) corrections connected to the ρ parameter, $\Delta\rho^{HO}$

$$\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2} \to \frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2} - \Delta\rho^{HO}$$

- 'NLO at $\mathcal{O}(\alpha G_\mu^2)$ incl. h.o.': In addition, change the EW input parameter scheme ($\alpha(0)$ scheme $\to$ G_μ scheme)

$$\alpha(0) \to \alpha(G_\mu) = \frac{\sqrt{2} G_\mu M_W^2}{\pi}\left(1 - \frac{M_W^2}{M_Z^2}\right)(1 - \Delta r),$$

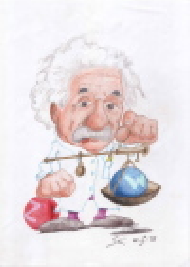
	Tevatron, σ_W [pb]	LHC, σ_W [pb]
	$p\bar{p} \to W^+ \to \mu^+\nu_\mu$	$pp \to W^+ \to \mu^+\nu_\mu$
NLO at $\mathcal{O}(\alpha^3)$	738.00(1)	4943.0(1)
NLO at $\mathcal{O}(\alpha^3)$ incl. h.o.	745.80(1)	4995.5(1)
NLO at $\mathcal{O}(\alpha G_\mu^2)$ incl. h.o.	747.62(1)	5006.5(1)

Conclusion and Outlook

- 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 (resummation of 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.

Milano W mass workshop



Organizers: Alessandro Vicini, D.W.

http://wwwteor.mi.infn.it/∼vicini/wmass.html

sponsored by the University of Milano

The aim of this meeting was to have extensive discussion sessions where

- the authors of the NLO event generators (HORACE, RESBOS, W/ZGRAD, SANC, MC@NLO, ...) can discuss theoretical uncertainties, limitations of their codes, possible improvements, plans/recipes for combining with or interfacing to different codes;
- the experimentalists involved in the W-mass and W-width measurements can present and discuss the challenges in the analysis with emphasis on the theory input, and communicate the necessary improvements in the available codes.

Milano W mass workshop

The following studies are under way:

- Tuned comparisons of EW NLO, multiple photon, QCD NLO+resummed (Resbos and parton shower MCs) and QCD NNLO predictions.
- Comparisons of 'best' predictions under *realistic* conditions and differences expressed in terms of δM_W.
- Impact of multiple photon radiation beyond LL, QCD+EW interplay (also in showers and PDFs), PDF uncertainties, and QCD resummation prescriptions on W/Z cross sections and their ratios.

Outlook: Work in progress in WZGRAD

- Combination of EW NLO and QCD NLO corrections in one MC generator and interface to parton shower (using POWHEG or Sherpa).
- 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.
- Calculation of mixed QED/QCD $\mathcal{O}(\alpha\alpha_s)$ corrections.
- Root ntuples (CTEQ4LHC working group).

Resources

- LEPEWWG website at http://lepewwg.web.cern.ch/LEPEWWG (status Summer 2009)
- 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 !

See also E.Laenen, D.W., *Radiative Corections for the LHC and Linear Collider Era*, Annu.Rev.Nucl.Part.Sci 2009.59:367-96.