Electroweak precision physics with $W$ and $Z$ bosons at hadron colliders

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We live in exciting times ...

the Large Hadron Collider is running ...

... 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
Quarks

\[
\begin{array}{ccc}
\text{up} & \text{charm} & \text{top} \\
\text{down} & \text{strange} & \text{bottom} \\
\end{array}
\]

Forces

\[
\begin{array}{cccc}
\text{Z boson} & \gamma & \text{W boson} & \text{gluon} \\
\end{array}
\]

Leptons

\[
\begin{array}{ccc}
\text{electron} & \text{muon} & \text{tau} \\
\text{electron neutrino} & \text{muon neutrino} & \text{tau neutrino} \\
\end{array}
\]
The SM has been thoroughly scrutinized during the last 30+ years at collider experiments.

CERN LEP $e^+e^-$ collider at energies around 90 GeV (LEP I) and 200 GeV (LEP II) (shutdown in 2000)

Now site of the Large Hadron Collider (LHC)
Goal: $pp$ collisions at 14000 GeV
Status: successfully runs at 7 TeV

Fermilab Tevatron $p\bar{p}$ collider at 1960 GeV, i.e. probes matter down to distances of about $10^{-18}$ meters
Status:
$\sim 8 \text{ fb}^{-1}$ of integrated luminosity on tape
Some ingredients for success

- **Experiment**
  High collision energies and large number of particle collisions (luminosity):
  \[
  \text{number of events} \propto L \sigma
  \]
  Rare processes (higgs production), heavy particles (top), high precision \((M_Z, M_W(m_{t_{op}})\) are known at per-mille (percent) level).

- **Theory**
  Precision calculations of cross sections beyond Born level, i.e. including radiative corrections.

  The SM is successfully tested as a Quantum Field Theory at the per mille level – no deviations found.

Note: We need to extend the SM to incorporate the experimental fact of massive neutrinos.

Moreover: Small discrepancy in the measurement of the anomalous magnetic moment of the muon at BNL.
We rely on perturbation theory, e.g., a Feynman graph expansion in the coupling constant of the scattering amplitude:

**lowest order**: Born approximation, e.g., $Z$ boson production at LEP/SLC

\[ \sigma_{\text{Born}}(q^2, \alpha, m_f, m_e, M_Z) \text{ is of } O(\alpha^2) \]

**1-loop radiative corrections**: in the 'quantum world' the $Z$ boson feels the virtual presence of all particles:

\[ \delta \sigma(q^2, \alpha, m_f, m_e, M_Z, m_{\text{top}}, M_H, \ldots) \text{ is of } O(\alpha^3) \]

\[ \Rightarrow \sigma_{\text{theory}} = \sigma_{\text{Born}} + \delta \sigma(m_{\text{top}}, M_H) + O(\alpha^4) \]
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., $m_t, M_W, \sin^2 \theta_{\text{eff}}$.

- 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

\[ \Delta \alpha^{(S)}_{\text{had}}(m_Z) \approx 0.02758 \pm 0.00035 \quad 0.02768 \]

\[ m_Z \text{ [GeV]} \approx 91.1875 \pm 0.0021 \quad 91.1874 \]

\[ \Gamma_Z \text{ [GeV]} \approx 2.4952 \pm 0.0023 \quad 2.4959 \]

\[ \sigma^0_{\text{had}} \text{ [nb]} \approx 41.540 \pm 0.037 \quad 41.478 \]

\[ R_l \approx 20.767 \pm 0.025 \quad 20.742 \]

\[ A_{tb}^{0,1} \approx 0.01714 \pm 0.00095 \quad 0.01645 \]

\[ A_l(P_T) \approx 0.1465 \pm 0.0032 \quad 0.1481 \]

\[ R_b \approx 0.21629 \pm 0.00066 \quad 0.21579 \]

\[ R_c \approx 0.1721 \pm 0.0030 \quad 0.1723 \]

\[ A_{tb}^0 \approx 0.0992 \pm 0.0016 \quad 0.1038 \]

\[ A_{tb}^0 \approx 0.0707 \pm 0.0035 \quad 0.0742 \]

\[ A_b \approx 0.923 \pm 0.020 \quad 0.935 \]

\[ A_c \approx 0.670 \pm 0.027 \quad 0.668 \]

\[ A_l^{(SLD)} \approx 0.1513 \pm 0.0021 \quad 0.1481 \]

\[ \sin^2\theta_{W}^{\text{lep}}(Q_{fb}) \approx 0.2324 \pm 0.0012 \quad 0.2314 \]

\[ m_W \text{ [GeV]} \approx 80.399 \pm 0.023 \quad 80.379 \]

\[ \Gamma_W \text{ [GeV]} \approx 2.098 \pm 0.048 \quad 2.092 \]

\[ m_t \text{ [GeV]} \approx 173.1 \pm 1.3 \quad 173.2 \]

\[ \delta \sigma_{WW}^{\text{theory}} = 0.4\% \text{ at } \sqrt{s} = 200 \text{ GeV} \]

M.Gr"unewald et al., hep-ph/0005309

\[ M_W = 80.376 \pm 0.033 \text{ GeV and } \Gamma_W = 2.196 \pm 0.083 \text{ GeV} \]
Where is the Higgs boson?

The Higgs particle is predicted as a necessary consequence of our understanding of the origin of mass in the SM.

The Higgs particle so far eluded direct observation.

We know from direct (LEP II) and indirect searches (fits to electroweak data) that the SM Higgs boson mass lies in the range

$$114.4 \text{ GeV} < M_H \lesssim 186 \text{ GeV} \ (95 \% \ C.L.)$$

⇒ the Higgs boson might be “just around the corner” …
Searches for the Higgs boson are extremely challenging

LEP-II and the Tevatron mainly look for the Higgs boson produced in association with a electroweak gauge boson, e.g., $e^+e^- \rightarrow Z \rightarrow HZ$:

Signature in the detector: 2 b-quark jets (identified via b-tagging) and two light quark jets.

These events are extremely rare:

- **LEP-II**: the background (same signature in the detector but contains no Higgs) is up to two orders of magnitude larger than the Higgs signal.

- **Tevatron**: $\sigma(p\bar{p})/\sigma(p\bar{p} \rightarrow H) \approx 10^{10}$.

- **LHC**: the background for the light Higgs search ($H \rightarrow b\bar{b}$) is of the order $10^7$ times larger than the Higgs signal.
Direct SM Higgs searches at the Tevatron

LEP-II & electroweak precision data: LEPEWWG Summer 2009

$114.4 \text{ GeV} < M_H < 186 \text{ GeV} (95\% \text{ C.L.})$

The Tevatron has the potential to exclude a large part of the $M_H$ range preferred by EWPOs at 95 % C.L.
Indirect searches via presence in loops

$M_W - M_Z$ correlation:

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

$\Delta r$: radiative corrections to $\mu$ decay

Direct and indirect measurements of $M_W$ are in good agreement:

$M_W(\text{LEP}, p\bar{p}) = 80.399 \pm 0.025$ GeV

$M_W(\text{LEP/SLD}) = 80.363 \pm 0.032$ GeV

August 2009
Sensitivity to BSM physics

experimental errors 68% CL:
- LEP2/Tevatron (today)
- Tevatron/LHC
- ILC/GigaZ

Heinemeyer, Hollik, Stockinger, Weber, Weiglein ’09

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

www.ifca.unican.es/~heinemey/uni_plots/
Prospects for $M_W$, $m_t$ measurements and $M_H$ constraints

\begin{center}
\begin{tabular}{|c|c|c|c|c|}
\hline
uncertainty & now & Tevatron 2 fb$^{-1}$ (final) & LHC & ILC/GigaZ \\
\hline
$\delta M_W$ [MeV] & 23 & 20(15) & 15 & 7 \\
$\delta m_t$ [GeV] & 1.3 & 1.2 & 1.0 & 0.13 \\
$\delta M_H / M_H$ [%] (from all data) & 40 & $\sim$ 28 & 18 & 8 \\
\hline
\end{tabular}
\end{center}

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

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 $\sin^2 \theta_{\text{eff}}$: $d\sigma/dM_T, d\sigma/dp_T(l)$ and ratio of $\sigma_Z$ and $\sigma_W$, and $A_{FB}$

- Detector calibration and luminosity monitoring: $M_Z, \Gamma_Z$ from $d\sigma/dM(\ell\ell)$ 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 $d\sigma/dM(\ell\ell)$ at high $M(\ell\ell)$

- Limits on anomalous triple and quartic EW gauge boson self couplings ($VV$ and $VVV$ production not discussed here).
Search for new physics in $Z$ production: $A_{FB}$ at high $M(\ell\ell)$

D0, arXiv:0804.3220 [hep-ex]

\[ \chi^2/d.o.f. = 10.6/14 \]

Forward backward asymmetry measurement

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

$M_Z=1.5$ TeV, $|y_\| > 0.8$

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

$\delta \sin^2 \theta_{eff} = 19 \times 10^{-4}$ (Tevatron) and $\delta \sin^2 \theta_{eff} = 14 - 20 \times 10^{-5}$ (LHC)
$M_T(l\nu_l) = \sqrt{p_T^l p_T^{\nu}(1 - \cos(\Phi_l - \Phi_{\nu}))}$

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


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

$M_T(l\nu)$, 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

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

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

- 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)

- Electroweak corrections to $W + 1 - jet$ production S.Dittmaier et al,
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/


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.


**FEWZ**: NNLO QCD corrections (fully exclusive).


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

and also **DYRAD, MCFM, MC@NLO, WINHAC, PHOTOS**
General structure of EW corr. to $W/Z$ production

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

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

with

$$|M|^2 = |M^{(0)}|^2 \left[ 1 + 2\Re(\tilde{F}^{\text{initial}}_{\text{weak}} + \tilde{F}^{\text{final}}_{\text{weak}})(M_W^2) \right]$$

$$+ \sum_{a=\text{initial, final, interf.}} |M^{(0)}|^2 F_{QED}^a(\hat{s}, \hat{t}, \delta_s, c) + |M_{\text{non-res.}}|^2(\hat{s}, \hat{t}) +$$

$$+ \sum_{a=\text{initial, final, interf.}} |M_{2\to3}|^2_a(\delta_s, c)$$

$2 \to 3$ 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 $\alpha \log(s/m_i^2)$ 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
  \[ \alpha^L \log^N \left( \frac{s}{M_W^2} \right) ; \ 1 \leq N \leq 2L \ (L = 1(1 - \text{loop}), \ldots) \]

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.

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

\[ M_T = \sqrt{2p_T(l)p_T(\nu)(1 - \cos \Phi_{l\nu})} \]

**Figure:**

- **a)** $p\bar{p} \rightarrow e^+\nu(\gamma)$
  - \( \sqrt{s} = 1.8 \text{ TeV} \)
  - Solid: no e id. req. included
  - Dash: with e id. req. included

- **b)** $p\bar{p} \rightarrow \mu^+\nu(\gamma)$
  - \( \sqrt{s} = 1.8 \text{ TeV} \)
  - Solid: no \( \mu \) id. req. included
  - Dash: with \( \mu \) id. req. included

**Inclusive vs. exclusive treatment of photon**

**Effect of** \( \log(s/m_{\mu}^2) \)

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

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


effect of EW
Sudakov-like logs
Impact of non-resonant EW corrections on $\Gamma_W$ at the Tevatron

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

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

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

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

### Impact of electroweak corrections on the $W$ mass

<table>
<thead>
<tr>
<th>Exp. Precision</th>
<th>Extra rad. corr.</th>
<th>Shift in $M_W$</th>
</tr>
</thead>
</table>
| TRI: 59 MeV    | final-state QED $O(\alpha)$  
$W \rightarrow e\nu$
$W \rightarrow \mu\nu$   | $-65 \pm 20$ MeV
$-168 \pm 20$ MeV |
| TRII(now): 31 MeV TRII(goal): 15 MeV | full QED and weak $O(\alpha)$
corr. in pole approx. | $\sim 10$ MeV |
| LHC: 15 MeV | full EW $O(\alpha)$ corr.  
(no approx.):
shifts $W$ width by $\approx 7$ 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 $W \rightarrow e(\mu)\nu$ | $? \quad ? \quad 2(10)$ MeV |
Impact of EW corrections on $M(\ell\ell)$ at the LHC at high $M(\ell\ell)$


see also U.Baur, PRD75 (2007)
Complete EW $\mathcal{O}(\alpha)$ vs 1-loop and 2-loop Sudakov approximation

Impact of combined EW and QCD corrections using ResBos


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

Studies of theoretical uncertainties

Are $W/Z$ observables under theoretical control?

Theoretical uncertainty due to \textit{missing} higher-order corrections:

- **Tevatron:** D0, PRL103 (2009)
  \[ \delta M_W^{\text{theory}} \approx 7(7) \text{MeV} \ (M_T(p_T^l)) \] due to missing higher-order photon radiation

- **LHC:** N.Adam \textit{et al}., arXiv:0808.0758 [hep-ph]
  \[ \frac{\delta \sigma_W}{\sigma_W} = 4.00 \pm 0.61\% \] due to missing $O(\alpha)$ EW corrections
  \[ \frac{\delta \sigma_W}{\sigma_W} = 1.66 \pm 0.69\% \] 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.
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: $\delta M^{PDF}_W = 9(11)$ 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

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

$$
\delta M_Z^2 = \Re \left( \Sigma^Z (M_Z^2) - \frac{(\hat{\Sigma}^Z (M_Z^2))^2}{M_Z^2 + \hat{\Sigma} (M_Z^2)} \right)
$$

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

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

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

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

<table>
<thead>
<tr>
<th></th>
<th>Tevatron, $\sigma_W$ [pb]</th>
<th>LHC, $\sigma_W$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p\bar{p} \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$</td>
<td>$pp \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$</td>
</tr>
<tr>
<td>NLO at $\mathcal{O}(\alpha^3)$</td>
<td>738.00(1)</td>
<td>4943.0(1)</td>
</tr>
<tr>
<td>NLO at $\mathcal{O}(\alpha^3)$ incl. h.o.</td>
<td>745.80(1)</td>
<td>4995.5(1)</td>
</tr>
<tr>
<td>NLO at $\mathcal{O}(\alpha G^2_{\mu})$ incl. h.o.</td>
<td>747.62(1)</td>
<td>5006.5(1)</td>
</tr>
</tbody>
</table>
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.
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 $\delta M_W$.

- 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

with Catherine Bernaciak and Andreas Scharf

- 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).
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!