Higher-order EWK corrections for W mass determination at hadron colliders

Fulvio Piccinini

INFN Sezione di Pavia

in collaboration with

Carlo Carloni Calame, Mauro Chiesa, Homero Martinez, Guido Montagna, Oreste Nicrosini, Alessandro Vicini

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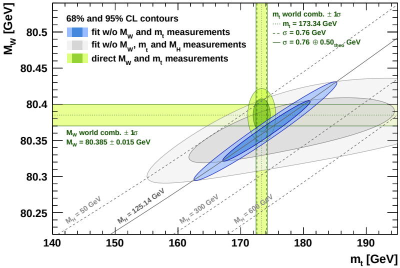
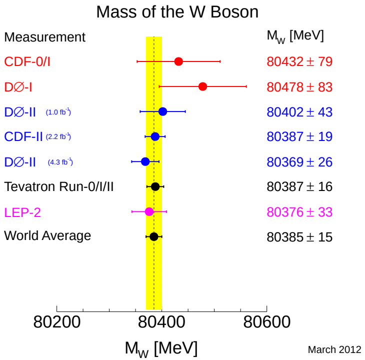
M_W direct measurement: crucial for a SM stress-test



Gfitter, EPJC 74 (2014) 3046

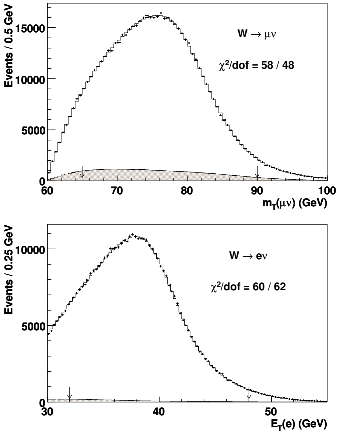


TeVatron EWWG, arXiv:1204.0042

- A precise ($\delta M_W < 10$ MeV) M_W measurement at LHC Run2 and beyond will be an important goal of the LHC precision physics pogramme
- CMS delivered recently the first W-like M_Z mass measurement @$\sqrt{s}$ =7 TeV (CMS-PAS-SMP-14-007)

M_W measurement: relevant observables

- M_W from the $p_\perp^\ell$ distribution, showing a (Jacobian) peak at $M_W/2$
- more reliable is $M_T^W = \sqrt{2p_\perp^\ell p_\perp^\nu(1-\cos\phi_{\ell\nu})}$ (**mildly sensitive to QCD RC**)



2.2/fb, CDF, PRL 108 (2012) 151803

- M_W is extracted with a template fit technique to M_T and/or $p_\perp^\ell$ distributions

⋆ EW corrections (mainly QED FSR) can distort the shape → the extracted M_W is affected

⋆ with high lumi the lepton $p_\perp^\ell$ can be experimentally convenient (smaller uncertainties in E_{miss}^T from pile up)

Uncertainty sources breakdown

p_T^ℓ fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

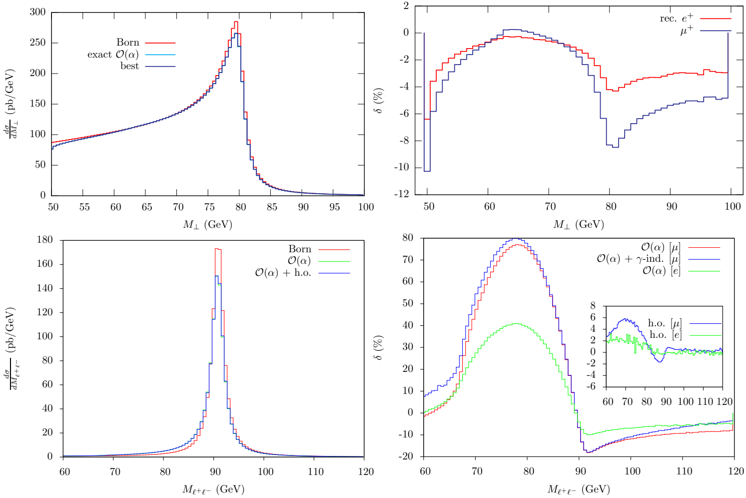
Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

CDF, arXiv:1311.0894

D0, arXiv:1310.8628

ongoing studies for LHC future M_W measurement
within the CERN LPCC EWWG activities

Effects of EW corrections: W and Z production



- EW $\mathcal{O}(\alpha)$ change the shape $\rightarrow \delta M_W \simeq 100$ MeV
- effects dominated by QED FSR (strongly dependent on event selection)

Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0710 (2007) 1

Higher-order corrections

$$
\begin{aligned}
d\sigma &= d\sigma_0 \\
&+ d\sigma_{\alpha_s} + d\sigma_{\alpha} \\
&+ d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \ldots
\end{aligned}
$$

- multi-photon emission from the final state $\rightarrow \delta M_W \simeq 10$ MeV for $\mu\nu_\mu$ final state

  Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0710 (2007) 1

- mixed QCD-EWK corrections   main focus of this talk
- NNLO EWK effects
  - EWK input scheme
  - lepton pair emission

QCD-EWK interference

- the $\mathcal{O}(\alpha\alpha_s)$ calculation involves as building blocks
  - NNLO virtual corrections at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
    - ⋆ necessary two-loop master integrals (with $m = 0$ external particles and $M_W = M_Z$) just appeared

      R. Bonciani et al., arXiv:1604.08581
  - NLO EW corrections to $l\bar{l}^{(\prime)}+$ jet
  - NLO QCD corrections to $l\bar{l}^{(\prime)} + \gamma$
  - double real contributions $l\bar{l}^{(\prime)} + \gamma+$ jet
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
    - ⋆ very recent calculation of NLO mixed QCD-QED corrections to the Altarelli-Parisi evolution kernels

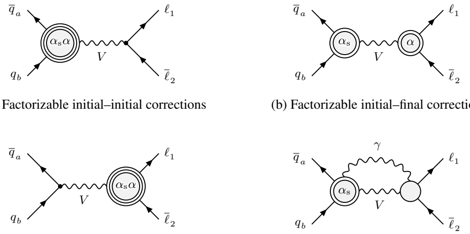
      De Florian, Sborlini and Rodrigo, arXiv:1512.00612
- what is available:
  - fixed order dominant $\mathcal{O}(\alpha_s\alpha)$ corrections to DY in pole approximation

    Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216
  - Monte Carlo estimates through NLO QCD $\otimes$ NLO EW (with higher orders)

    L. Barzè et al., JHEP 1204 (2012) 037, Eur. Phys. J. C73 (2013) 2474

fixed order $\mathcal{O}(\alpha_s\alpha)$ in pole approximation

- two main classes of contributions:
  - factorizable
  - non-factorizable



(a) Factorizable initial–initial corrections

(b) Factorizable initial–final corrections

(c) Factorizable final–final corrections

(d) Non-factorizable corrections

S. Dittmaier, A. Huss and C. Schwinn, arXiv:1601.02027

a) not known but expected to be very small
($\mathcal{O}(\alpha)$ corrections in PA $\Longrightarrow$ $M_\perp$ and $M(l^+l^-)$ insensitive to QED ISR
in addition $M_\perp$ and $M(l^+l^-)$ mildly affected by NLO QCD corrections)

b) this gives the bulk of the contribution

c) no real contributions $\Longrightarrow$ no impact on shape of $M_\perp$ and $M(l^+l^-)$

d) numerical impact below 0.1%

effects on M_W

	bare muons		dressed leptons	
	$M_{\mathrm{W}}^{\mathrm{fit}}$ [GeV]	ΔM_{W}	$M_{\mathrm{W}}^{\mathrm{fit}}$ [GeV]	ΔM_{W}
LO	80.385	$-$ 90 MeV	80.385	$-$ 40 MeV
$\mathrm{NLO}_{\mathrm{ew}}$	80.295		80.345	
$\mathrm{NLO}_{\mathrm{s}\oplus\mathrm{ew}}$	80.374	$-$ 14 MeV	80.417	$-$ 4 MeV
NNLO	80.360		80.413	

Dittmaier, Huss, Schwinn, NPB 904 (2016) 216

twofold aim of the present study

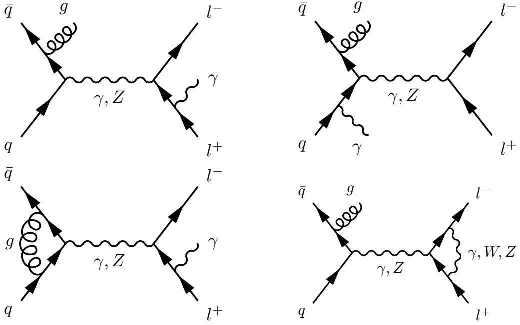
- comparison of the shifts induced by $\mathcal{O}(\alpha_s\alpha)$ terms of the pole approximation with the ones induced by the factorized prescription through Monte Carlo (POWHEG with PYTHIA/PHOTOS)
  - using PHOTOS with only one emissions on top of NLO QCD, the difference with the complete $\mathcal{O}(\alpha_s\alpha)$ in pole approximation is of 3 MeV out of 14 MeV
  - above result obtained without a cut on p_T^W, which is used in the experimental analysis

Dittmaier, Huss, Schwinn, NPB 904 (2016) 216

- quantify the uncertainty of the practical solution used in the experimental analysis of QCD NLOPS$\otimes$QEDLL
  - at Tevatron: ResBos+PHOTOS
  - at LHC, in present preliminary investigations:
    - ATLAS: POWHEG+PYTHIA&PHOTOS
    - CMS: POWHEG+PYHTIA

$\mathcal{O}(\alpha_s\alpha)$ corrections through Monte Carlo

- The POWHEG-BOX includes NLO QCD & EW corrections interfaced to QCD/QED shower, i.e. NLOPS EW $\oplus$ QCD accuracy
  1. `POWHEG_W_ew_BMNNP`, CC DY
     Barzè et al, JHEP 1204 (2012) 037
  2. `POWHEG_W_ew_BW`, CC DY
     Bernaciak and Wackeroth, PRD 85 (2012) 093003
  3. `POWHEG_Z_ew_BMNNPV`, NC DY
     Barzè et al, EPJC 73 (2013) 6, 2474
- correctly taken into account the NLO contribution with one additional radiation in the soft/collinear limit



improvement of QED radiation at generation level in POWHEG

- <u>three kinds</u> of events in the **file.lhe**:
  - elastic $2 \to 2$ events $(q\bar{q} \to l\bar{l}^{(\prime)})$
  - QCD radiative events $2 \to 3$ $(q\bar{q} \to l\bar{l}^{(\prime)}g)$, $(gq \to l\bar{l}^{(\prime)}q)$
  - QED radiative events $2 \to 3$ $(q\bar{q} \to l\bar{l}^{(\prime)}\gamma)$
- QCD and QED emissions in competition
- QCD emission scale typically larger than QED one
- in POWHEG-V2 only hardest (in $p_\perp$) parton written on disk
  - $\Longrightarrow$ events with one QCD parton largely dominate the sample
  - ambiguity in the QED shower starting scale (overestimated)
  - effects emphasized when the observable displays enhanced sensitivity to EW/QED w.r.t. QCD corrections, as in the case of $M(l\nu)$ and $M_\perp(l\nu)$
- keep track of the hardest QED radiation tried from the resonance and use this as starting scale for the QED FS shower
- the treatment of radiation from resonances at NLO level has been addressed within POWHEG (with QCD interaction) for top quark decays

T. Jezo and P. Nason, JHEP 1512 (2015) 065

Methodology

- Selection of events:

LHC	Tevatron
$\sqrt{s} = 14$ TeV, pp	$\sqrt{s} = 1.96$ TeV, p$\bar{p}$
400 M events	100 M events
$\|\eta^l\| < 2.5$	$\|\eta^l\| < 1.05$
$p_T^l > 20$ GeV	$p_T^l > 25$ GeV
$p_T^\nu > 20$ GeV	$p_T^\nu > 25$ GeV
$p_T^W < 15$ GeV	$p_T^W < 30$ GeV

- The analysis in the muon channel is done using "bare" definition, and in the electron channel using the "dressed one" (recombining photons with the emmiter electron when they have a $\Delta R < 0.1$ (R defined in the η, ϕ space).
- All the samples were generated with $m_W^{nom} = 80.398$ GeV and $\Gamma_W = 2.141$ GeV. The reweighting is done for m_W values spanning ≈ 1 GeV around m_W^{nom}.
- We perform the fits using the lepton pair transverse mass distribution: $m_T^W = \sqrt{2|p_T^\mu||p_T^{\nu_\mu}|(1 - \cos\Delta\phi)}$, and the charged lepton p_T.

Methodology: Fits

In order to propagate the effects under study up to the extraction of M_W we use a procedure similar to the experimental one:

- Generate 2 different MC samples, using the same value of m_W as input (m_W^{nom}). The samples have different level of EW accuracy.
- Generate templates distribution, using a reweighting procedure of sample 1. (using the Breit-Wigner dependence of the cross section). This way we obtain distributions as if produced with different input values of m_W. This is called the "template sample".
- Compare the templates with the distribution in the other sample ("pseudodata"). Each comparison gives a χ^2 value. We then find the minimum of the χ^2 vs. m_W plot (using a parabolic fit), and obtain m_W^{meas}. The error on the fit is extracted using $\Delta\chi^2 = 1$.
- The shift $m_W^{meas} - m_W^{nom}$ is a measure of the impact on the measurement of m_W, of the different EW accuracy used in sample 2 with respect to that of sample 1.

Results

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+$(QCD+QED)_{PS}$	Pythia	-95.2 ±0.6	-400 ±3	-38.0 ±0.6	-149 ±2
2	NLO-QCD+$(QCD+QED)_{PS}$	Photos	-88.0 ±0.6	-368 ±2	-38.4 ±0.6	-150 ±3
3	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Pythia	-101.8 ±0.4	-423 ±2	-45.0 ±0.6	-179 ±2
4	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	Photos	-94.2 ±0.6	-392 ±2	-45.2 ±0.6	-181 ±2
5	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Pythia	-89.0 ±0.6	-371 ±3	-38.8 ±0.6	-157 ±3
6	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	Photos	-88.6 ±0.6	-370 ±3	-39.2 ±0.6	-159 ±2

- 1 vs 2: Genuine difference between the predictions of Pythia and Photos QED models.

Results

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- 1 vs 5 and 2 vs 6: gives an estimation of the effect of the missing mixed EW-QCD correction in the pure shower approach. Notice that this effect depends on the QED shower model used. The PHOTOS model provides a closer model to the full precision one.

Results

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- 5 vs 6: The description with EW NLO accuracy of the photon radiation makes the prediction independent of the QED shower model used (the difference between the models becomes a higher order effect).

Results

- Tevatron setup, POWHEG events, same observations apply.

	Templates: NLO-QCD+QCD$_{\mathrm{PS}}$		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-91 ±1	-308 ±4	-37 ±1	-116 ±4
2	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Photos	-83 ±1	-282 ±4	-36 ±1	-114 ±3
3	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-96 ±1	-323 ±3	-45 ±1	-129 ±3
4	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$	Photos	-89 ±1	-300 ±3	-44 ±2	-134 ±3
5	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$(two-rad)	Pythia	-86 ±1	-291 ±3	-38 ±1	-115 ±3
6	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$(two-rad)	Photos	-85 ±1	-290 ±4	-37 ±2	-113 ±3

Results

- When using the pure shower approach i.e. (POWHEG(NLO QCD)+PYTHIA(QCD)+QED model), the uncertainty due to the missing mixed QCD-EW corrections, is estimated to be (in MeV)

	LHC				Tevatron			
	$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
	M_T	p_T^ℓ	M_T	p_T^ℓ	M_T	p_T^ℓ	M_T	p_T^ℓ
PYTHIA QED	$\approx 6 \pm 1$	$\approx 29 \pm 4$	$\approx 1 \pm 1$	$\approx 8 \pm 4$	$\approx 5 \pm 1$	$\approx 17 \pm 5$	$\approx 1 \pm 1$	$\approx 1 \pm 5$
PHOTOS	$\approx 1 \pm 1$	$\approx 2 \pm 4$	$\approx 1 \pm 1$	$\approx 9 \pm 4$	$\approx 2 \pm 1$	$\approx 8 \pm 6$	$\approx 1 \pm 2$	$\approx 1 \pm 4$

- If ones uses the version with full EW corrections (POWHEG(NLO QCD NLO EW)+PYTHIA(QCD)+QED model), the remaining mixed EW-QCD is reduced.

Summary and outlook

- aiming at a precision $\delta M_W \leq 10$ MeV, the details of simulating radiation in MC's become relevant
- differences in the simulation of QED FSR with PYTHIA or PHOTOS
- for $M_\perp$ the recipe QCD NLOPS$\otimes$ QEDLL (with PHOTOS) agrees at the MeV level with the factorized prescription QCD NLOPS$\otimes$ EWKNLOPS
- the above prescription inherits an uncertainty of $\sim$5 MeV if QED FSR is simulated with PYTHIA
- the differences between PYTHIA and PHOTOS disappear if used on top of EWK NLO precision
- comparison with fixed order in pole approximation: results still in progress