Impact of QED/EW corrections on M_W measurement: POWHEG EW

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based on

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arXiv:1612.02841

LHC EW Precision

22-25 May 2018, LAL, Orsay

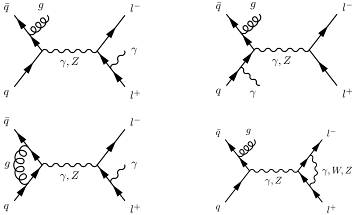
Higher-order contributions to M_W

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

- multi-photon emission
  from the final state $\rightarrow \delta M_W \simeq 10$ MeV for $\mu\nu_\mu$ final state (with bare μ)
  Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0710 (2007) 1
- mixed QCD-EW corrections
- NNLO EW effects
  - lepton pair emission
  - EW input scheme
- estimate of uncertainties through available NLOPS (POWHEG and HORACE) MC's and perturbative calculations

$\mathcal{O}(\alpha_s\alpha)$ corrections through MC POWHEG-BOX-V2

- 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_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



- refined treatment of QED radiation from the resonance
  - keep track of the hardest QED radiation tried from the resonance and use this as starting scale for the QED FS shower

comparison POWHEG-BOX-V2 vs NNLO in pole approx

$$d\sigma_{\rm POWHEG} = d\sigma_0 \left[1 \; + \; \delta_{\alpha_s} + \delta_{\alpha} + \sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n} \right],$$

	Templates	Pseudodata	M_W shifts (MeV)
1	LO	POWHEG(QCD NLO)	56.0 ± 1.0
2	LO	POWHEG(QCD NLO) +PYTHIA(QCD)	74.4 ± 2.0
3	LO	HORACE(EW NLO)	-94.0 ± 1.0
4	LO	HORACE(EW NLO) + QEDPS	-88.0 ± 1.0
5	LO	POWHEG(QCD,EW) NLO	-14.0 ± 1.0
6	LO	POWHEG(QCD,EW) `two-rad`+PYTHIA(QCD)+PHOTOS	-5.6 ± 1.0

correction factor	samples in table	M_W shift (MeV)
$\sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n}$	[6]-[5]	8.4 ± 1.4 MeV
$\sum_{m=2}^{\infty} \delta'_{\alpha_s^m}$	[2]-[1]	18.4 ± 2.2 MeV
$\sum_{n=2}^{\infty} \delta'_{\alpha^n}$	[4]-[3]	6.0 ± 1.4 MeV

$\Delta M_W{}^{\alpha_s \alpha}(\mu^+ \nu_\mu) = -16.0 \pm 3.0$ MeV vs $\delta_{\rm NNLO} = -14$ MeV

Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216

comparison QCD⊕EW$_{\mathrm{NLOPS}}$ vs QCD$_{\mathrm{NLOPS}}$ ⊗ QEDPS

$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{\mathrm{PS}}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Photos	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$`two-rad`	Pythia	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$`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.
- 1 vs 3 and 2 vs 4: 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.
- 3 vs 4: 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).

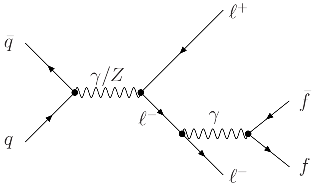
Summary of effects present in $(\mathrm{QCD}\oplus\mathrm{EW})_{\mathrm{NLOPS}}$ but missing in $\mathrm{QCD}_{\mathrm{NLOPS}} \otimes$ QEDPS

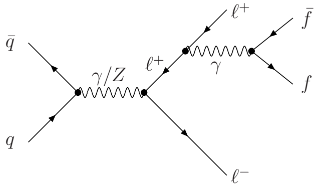
		$\Delta M_W(\mathrm{MeV})$	
	QED FSR model	M_T	p_T^ℓ
Tevatron	PYTHIA	$+5 \pm 2$	$+17 \pm 5$
	PHOTOS	-2 ± 1	-8 ± 5
LHC	PYTHIA	$+6.2 \pm 0.8$	$+29 \pm 4$
	PHOTOS	-0.6 ± 0.8	-2 ± 4

Lepton pair corrections: virtual and real contributions

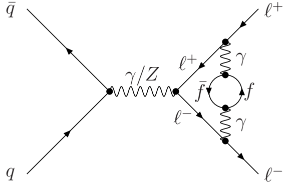
- emission of a photon converting to a lepton pair
  $\sim \mathcal{O}(\alpha^2 L^2) \sim$ two-photon contribution

Real pair emission





Virtual pair correction



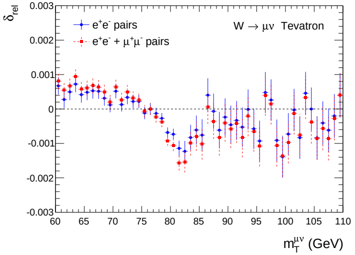
S. Antropov, A. Arbuzov, R. Sadykov, Z. Was, arXiv:1706.0557

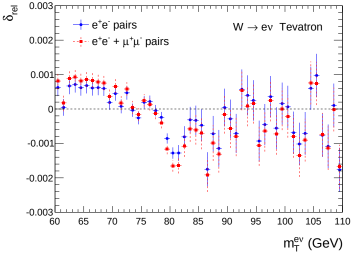
Lepton pair corrections: implementation in HORACE v3.1

C.M. Carloni Calame et al., arXiv:1612.02841

$$\alpha \Longrightarrow \alpha(s) = \begin{cases} \alpha / \left(1 - \frac{\alpha}{3\pi} \ln \frac{s}{m_e^2}\right) & \text{electrons only} \\ \alpha / \left(1 - \frac{\alpha}{3\pi} \ln \frac{s}{m_e^2} - \theta(s - m_\mu^2) \frac{\alpha}{3\pi} \ln \frac{s}{m_\mu^2}\right) & \text{electrons + muons} \end{cases}$$

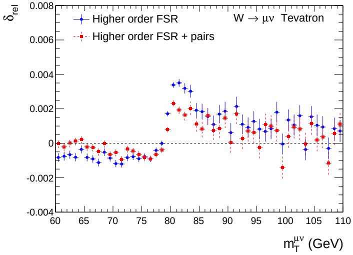
- running of α included in the Sudakov form factor

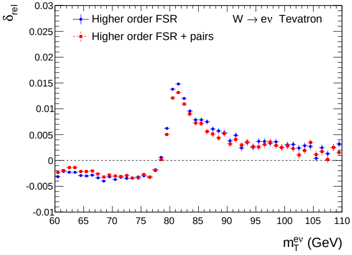




- Normalization: multiphoton radiation

- Normalization: one-photon radiation from HORACE



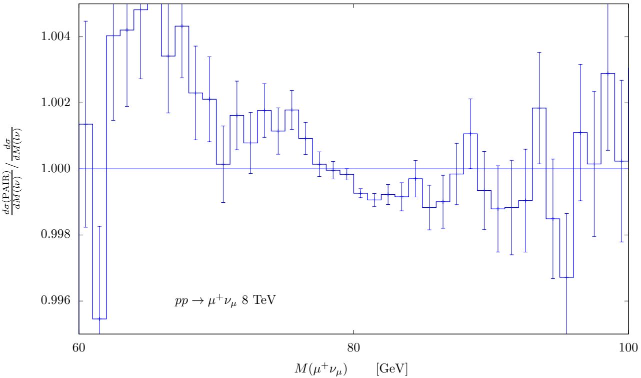


$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy		M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$ M_T	 p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

$\Delta M_W(\mu^+\nu) \sim 5 \pm 1$ MeV (from $M_\perp$) and $\sim 3 \pm 2$ MeV (from $p_\perp^\ell$)

switching on pair contribution in POWHEG

- Sudakov form factor modified to consider the running of α_{QED} (e^+e^- and $\mu^+\mu^-$ contribution)
- input: `emalpharunning 1`



- av. in POWHEG V2 svn revision $\geq$ 3453 (W_ew) and $\geq$ 3452 (Z_ew)

issues with real pair radiation

- pair effects estimated at LHE level are reliable if the event selection is completely inclusive on additional pairs from photon conversion

- otherwise we have to switch on real pair emission in the QED shower
  - e.g. the emission of a soft e^+e^- pair will not reach the detector, changing the momentum of the emitting particle

- the QED shower must handle the conversion of the hardest photon into fermion pairs, e.g. PYTHIA8
- for a simulation of pair corrections with PHOTOS (from v. 3.57), ew corrections in POWHEG should be switched off (`noew = 1`)

NNLO uncertainty: input parameter scheme

- pert. EW calculations require a coherent set of input param. in the gauge sector, e.g.
  - $\alpha(0)$, M_W and M_Z
  - G_μ, M_W and M_Z to be preferred in the CC DY
  - we can define

$$\begin{aligned} \alpha_\mu^{tree} &\equiv \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2\vartheta \\ \alpha_\mu^{1l} &\equiv \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2\vartheta \, (1 - \Delta r) \end{aligned}$$

  - three possible different expression for the cross section, starting to differ at $\mathcal{O}(\alpha^2)$

$$\begin{aligned} \alpha_0 \quad &: \quad \sigma = \alpha_0^2 \sigma_0 + \alpha_0^3 (\sigma_{SV} + \sigma_H)\,, \\ G_\mu\ I \quad &: \quad \sigma = (\alpha_\mu^{tree})^2 \sigma_0 + (\alpha_\mu^{tree})^2 \alpha_0 (\sigma_{SV} + \sigma_H) - 2\Delta r (\alpha_\mu^{tree})^2 \sigma_0\,, \\ G_\mu\ II \quad &: \quad \sigma = (\alpha_\mu^{1l})^2 \sigma_0 + (\alpha_\mu^{1l})^2 \alpha_0 (\sigma_{SV} + \sigma_H) \end{aligned}$$

- potentially effects on M_W because of the different sharing among different photon multiplicities

	$p\bar{p} \to W^+$, $\sqrt{s} = 1.96$ TeV Templates accuracy: LO Pseudodata accuracy	Input scheme	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	p_T^ℓ
1	HORACE NLO-EW	α_0	-101±1	-117±2
2		$G_\mu - I$	-112±1	-130±1
3		$G_\mu - II$	-101±1	-117±1
4	HORACE NLO-EW+QED-PS	α_0	-70±1	-81±1
5		$G_\mu - I$	-72±2	-83±1
6		$G_\mu - II$	-72±1	-82±2

- differences present at NLO, after matching with higher orders, become much smaller

$$\Delta M_W \sim 2 \text{ MeV} \pm 1 - 2 \text{ MeV}$$

work in progress on NC DY

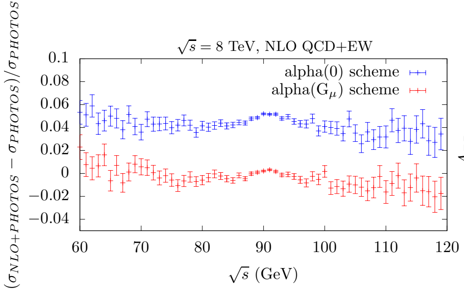
M. Chiesa, C.M. Carloni Calame, G. Montagna, O. Nicrosini, F.P., A. Vicini, J. Zhou

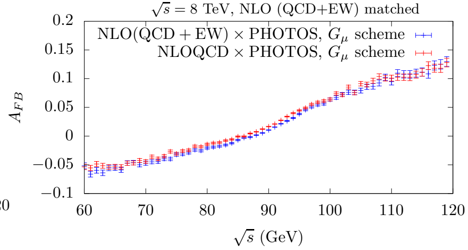
- splitting of EW NLO corrections into separate (gauge invariant) contributions with proper flags (QCD and full EW separation already available)
  - pure QED $\surd$
    - ⋆ (ISR+FSR) from IFS interference
  - pure weak $\surd$
- addition of pheno subleading contributions
  - photon induced contributions $\surd$ (for NLO)
    - ⋆ LO $\gamma\gamma \to \mu^+\mu^-$
    - ⋆ NLO $\gamma q \to \mu^+\mu^- q$
  - higher-order weak effects (dominated by $\Delta\alpha$ and $\Delta\rho$) with NNLO accuracy $\surd$

    S. Dittmaier, M. Huber, JHEP01(2010)060
- analysis of separate NLO classes for $d\sigma/dM_{\mu^+\mu^-}$ and $dA_{FB}/dM_{\mu^+\mu^-}$

  available for $d\sigma/dM_{\mu^+\mu^-}$ in S. Dittmaier, M. Huber, JHEP01(2010)060
  - their uncertainties estimated by varying the input parameter scheme
    - ⋆ $\alpha(M_Z)$, $\alpha(0)$, G_μ

NLO EWQCD×PHOTOS vs NLO QCD×PHOTOS





Summary

- aiming at a precision $\delta M_W \leq 10$ MeV, the details of simulating radiation in MC's become relevant
- comparison with fixed order in pole approximation nicely compatible, at the MeV scale
- differences in the simulation of QED FSR with PYTHIA or PHOTOS
- the pragmatic recipe QCD NLOPS$\otimes$ QEDLL (with PHOTOS) agrees at the MeV level with the factorized prescription QCD NLOPS$\otimes$ EWNLOPS
  - the above prescription inherits an uncertainty of $\sim$ 5 MeV if QED FSR is simulated with PYTHIA ($M_\perp$) and of ~ 29 MeV ($p_\perp^\ell$)
- the differences between PYTHIA and PHOTOS disappear if used on top of EW NLO precision
- leptonic pair corrections at the level of 5 MeV
- $\mathcal{O}(\alpha^2)$ uncertainties by exploring different input param schemes at the level of $1-2$ MeV (with the available statistics)