

EW corrections in POWHEG-EW

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in collaboration with

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Electroweak Precision Measurements
2-6 October 2017, Orsay-LAL

From summary of the talk in Mainz

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

- presented an improved version of POWHEG_{ew} (for CC and NC DY)
- comparison on $\mathcal{O}(\alpha_s \alpha)$ contributions 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 ~ 5 MeV if QED FSR is simulated with PYTHIA (M_\perp) and of ~ 29 MeV (p_\perp^ℓ)
- the differences between PYTHIA and PHOTOS disappear if used on top of EW NLO precision
- leptonic pair corrections at the level of 5 MeV, evaluated with HORACE
- $\mathcal{O}(\alpha^2)$ uncertainties by exploring different input param schemes at the level of 1 – 2 MeV (with the available statistics)
- prospects: include electroweak corrections to Vj in the framework of POWHEG+MiNLO
 - in particular work in progress by M. Chiesa and J. Zhou)

- The POWHEG-BOX-V2 includes NLO QCD & EW corrections interfaced to QCD/QED shower, i.e. **NLOPS EW \oplus QCD** accuracy

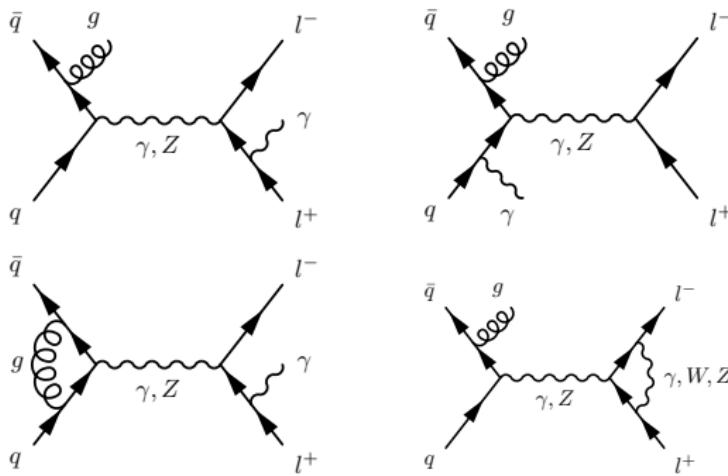
① POWHEG_W_ew_BMNNP, CC DY

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

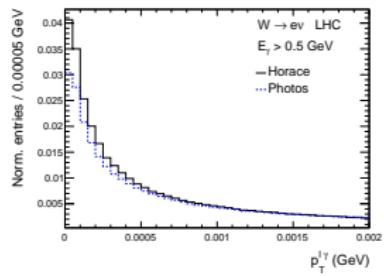
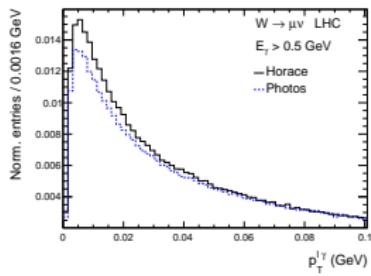
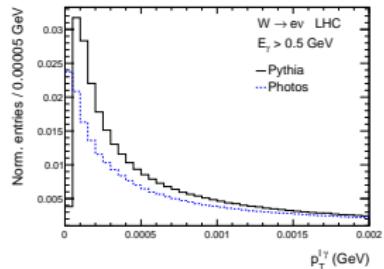
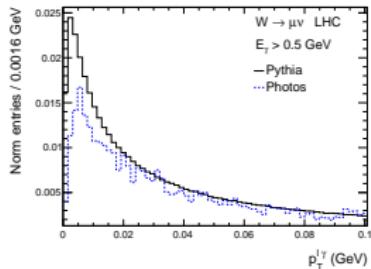


Improvement: refined treatment of QED radiation from the resonance

- the treatment of radiation from resonances at NLO level has been addressed within POWHEG (with QCD interaction) for processes involving top quarks
- keep track of the hardest QED radiation tried from the resonance and use this as starting scale for the QED FS shower
- ⇒ four kinds of events written on disk
 - elastic $2 \rightarrow 2$ events ($q\bar{q} \rightarrow l\bar{l}^{(\prime)}$)
 - QCD radiative events $2 \rightarrow 3$ ($q\bar{q} \rightarrow l\bar{l}^{(\prime)}g$), ($gq \rightarrow l\bar{l}^{(\prime)}q$)
 - QED radiative events $2 \rightarrow 3$ ($q\bar{q} \rightarrow l\bar{l}^{(\prime)}\gamma$)
 - radiative $2 \rightarrow 4$ events
 - ($q\bar{q} \rightarrow l\bar{l}^{(\prime)}g\gamma$), ($gq \rightarrow l\bar{l}^{(\prime)}q\gamma$), where the γ is emitted by the W/Z boson decay products
 - ($q\bar{q} \rightarrow l\bar{l}^{(\prime)}\gamma\gamma$)
 - contribution from events of the kind $\gamma q \rightarrow l\bar{l}^{(\prime)}q$ not yet available
⇒ included in the near future

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

difference between codes in exclusive QED radiation



comparison QCD \oplus EW_{NLOPS} vs QCD_{NLOPS} \otimes QEDPS

pp $\rightarrow W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD _{PS}			$W^+ \rightarrow \mu^+ \nu$		$W^+ \rightarrow e^+ \nu$ (dres)	
Pseudodata accuracy		QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED) _{PS}	PYTHIA	-95.2 \pm 0.6	-400 \pm 3	-38.0 \pm 0.6	-149 \pm 2
2	NLO-QCD+(QCD+QED) _{PS}	PHOTOS	-88.0 \pm 0.6	-368 \pm 2	-38.4 \pm 0.6	-150 \pm 3
3	NLO-(QCD+EW)+(QCD+QED) _{PS two-rad}	PYTHIA	-89.0 \pm 0.6	-371 \pm 3	-38.8 \pm 0.6	-157 \pm 3
4	NLO-(QCD+EW)+(QCD+QED) _{PS two-rad}	PHOTOS	-88.6 \pm 0.6	-370 \pm 3	-39.2 \pm 0.6	-159 \pm 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).

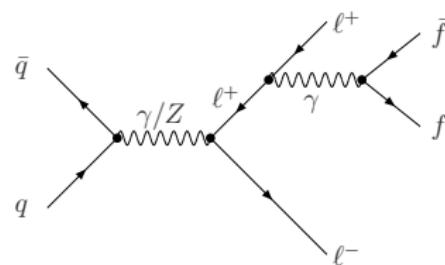
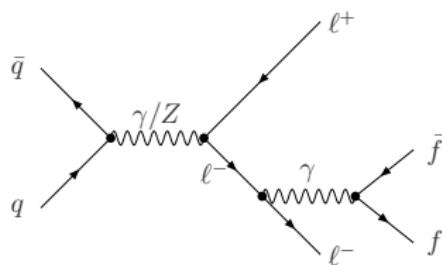
Summary of effects present in $(\text{QCD} \oplus \text{EW})_{\text{NLOPS}}$ but missing in $\text{QCD}_{\text{NLOPS}} \otimes \text{QEDPS}$

		$\Delta M_W (\text{MeV})$	
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

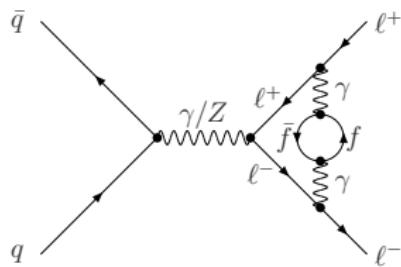
Lepton pair corrections: virtual and real contributions

- 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

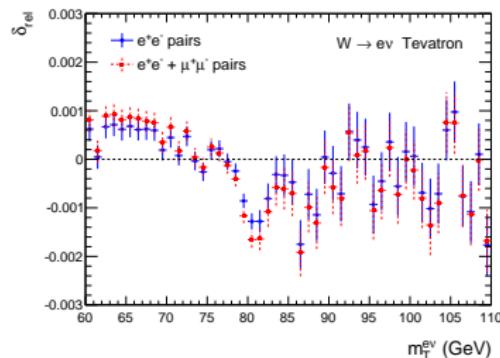
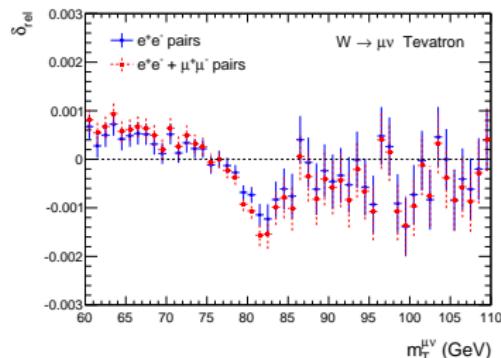


Lepton pair corrections: implementation in HORACE v3.1

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

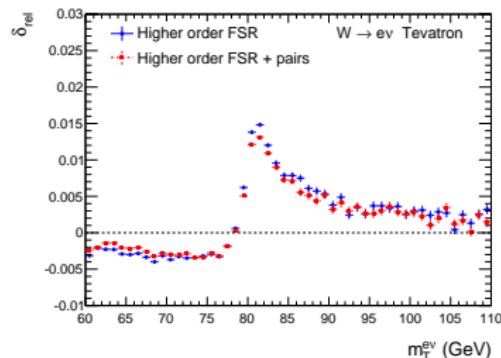
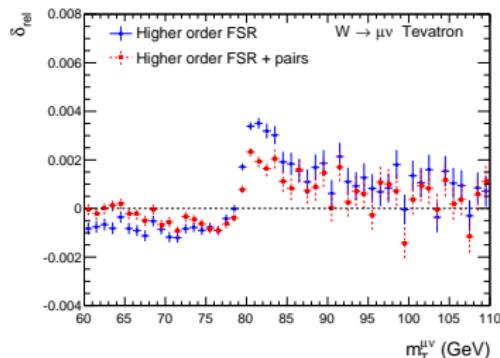
$$\alpha \implies \alpha(s) = \begin{cases} \alpha / \left(1 - \frac{\alpha}{3\pi} \ln \frac{s}{m_e^2} \right) & \text{electrons only} \\ \alpha / \left(1 - \frac{\alpha}{3\pi} \ln \frac{s}{m_e^2} - \theta(s - m_\mu^2) \frac{\alpha}{3\pi} \ln \frac{s}{m_\mu^2} \right) & \text{electrons + muons} \end{cases}$$

- running of α included in the Sudakov form factor



- Normalization: multiphoton radiation

- Normalization: one-photon radiation from HORACE

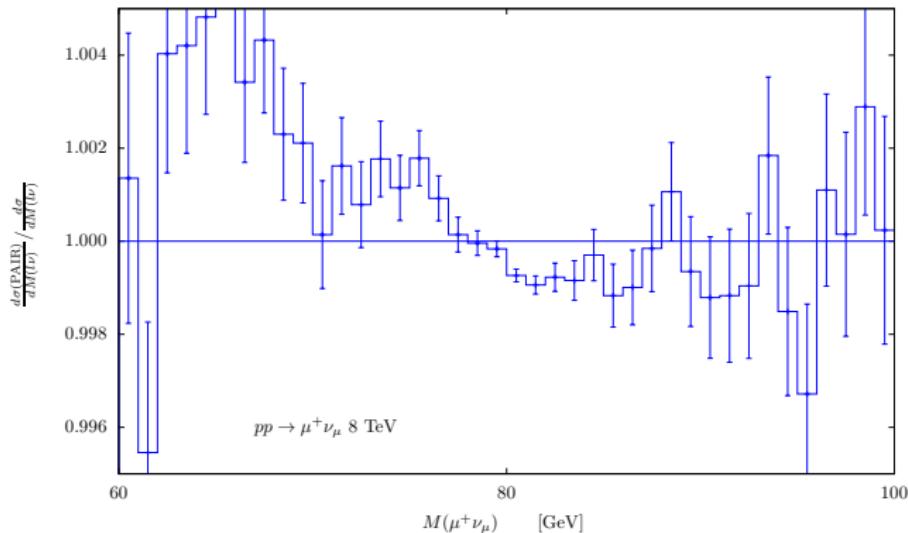


$pp \rightarrow W^+, \sqrt{s} = 14 \text{ TeV}$		M_W shifts (MeV)			
		M_T	p_T^ℓ	M_T	p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94 ± 1	-104 ± 1	-204 ± 1	-230 ± 2
2	HORACE FSR-LL	-89 ± 1	-97 ± 1	-179 ± 1	-195 ± 1
3	HORACE NLO-EW with QED shower	-90 ± 1	-94 ± 1	-177 ± 1	-190 ± 2
4	HORACE FSR-LL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

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

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



- available in POWHEG V2 svn revision 3453 (W_ew) and 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`)

- definition:

$$\sin^2 \vartheta_{eff}^l = \frac{1}{4} \left(1 - \text{Re} \frac{g_v}{g_a} \right), \quad Z\bar{l}l \text{ vertex} \sim \bar{l} \gamma^\mu (g_v - g_a \gamma_5) l Z_\mu$$

- it is calculated within the Standard Model: 0.23147 ± 0.00017
- with the input parameters: $\alpha, G_\mu, M_Z, m_{\text{top}}, m_{\text{Higgs}} \alpha_s(M_Z)$
 - ▶ at one loop $\mathcal{O}(\alpha)$
 A. Sirlin, PRD22, (1980) 971; W.J. Marciano, A. Sirlin, PRD22 (1980) 2695
 G. Degrassi, A. Sirlin, NPB352 (1991) 352; P. Gambino and A. Sirlin, PRD49 (1994) 1160
 - ▶ at higher orders:
 - ★ $\mathcal{O}(\alpha \alpha_s)$
 A. Djouadi, C. Verzegnassi, PLB195 (1987) 265
 B. Kiehl, NPB353 (1991) 567; B. Kniehl, A. Sirlin, NPB371 (1992) 141, PRD47 (1993) 883
 A. Djouadi, P. Gambino, PRD49 (1994) 3499
 - ★ $\mathcal{O}(\alpha \alpha_s^2)$
 L. Avdeev et al., PLB336 (1994) 560;
 K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394; NPB482 (1996) 213
 - ★ $\mathcal{O}(\alpha \alpha_s^3)$
 Y. Schröder, M. Steinhauser, PLB622 (2005) 124;
 K.G. Chetyrkin et al., hep-ph/0605201; R. Boughezal, M. Czakon, hep-ph/0606232
 - ★ $\mathcal{O}(\alpha^2)$ for large Higgs / top mass
 G. Degrassi, P. Gambino, A. Sirlin, PLB394 (1997) 188
 - ★ exact $\mathcal{O}(\alpha^2)$
 M. Awramik, M. Czakon, A. Freitas, JHEP0611 (2006) 048

M_W calculated in the Standard Model

$$\begin{aligned} M_W^2 &= \frac{M_Z^2}{2} \left\{ 1 + \left[1 - \frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2} (1 + \Delta r) \right]^{1/2} \right\} \\ M_W^2 &= 80.357 \pm 0.009 \pm 0.003 \text{ GeV} \end{aligned}$$

- one loop $\mathcal{O}(\alpha)$ calculation

A. Sirlin, PRD22 (1980) 971

- two loop $\mathcal{O}(\alpha\alpha_s)$

A. Djouadi, C. Verzegnassi, PLB195 (1987) 265

- three loop $\mathcal{O}(\alpha\alpha_s^2)$

L. Avdeev et al., PLB336 (1994) 560;

K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394

- $\mathcal{O}(\alpha^2)$ for large top / Higgs mass

R. Barbieri et al., PLB288 (1992) 95; NPB409 (1993) 105

G. Degrassi, P. Gambino, A. Vicini, PLB383 (1996) 219

- exact $\mathcal{O}(\alpha^2)$

A. Freitas et al., PLB495 (2000) 338; NPB632 (2002) 189
M. Awramik, M. Czakon, PLB568 (2003) 48; PRL89 (2002) 241801

A. Onishchenko, O. Veretin, PLB551 (2003) 111; M. Awramik et al., PRD68 (2003) 053004

- precise fitting formulae have been derived both for M_W and $\sin^2 \vartheta_{eff}^l$ as functions of the input parameters

G. Degrassi, P. Gambino, M. Passera, A. Sirlin, hep-ph/9708311
A. Ferroglia, G. Ossola, M. Passera, A. Sirlin, PRD65 (2002) 113002

M. Awramik, M. Czakon, A. Freitas, JHEP 0611 (2006) 048; M. Awramik et al., PRD69 (2004) 053006
A. Freitas, W. Hollik, W. Walter, G. Weiglein, PLB495 (2000) 338; NPB632 (2002) 189
G. Degrassi, P. Gambino, P.P. Giardino, JHEP05 (2015) 154

$$\begin{aligned} M_W &= M_W^0 - c_1 \left(\log \frac{M_H}{100 \text{ GeV}} \right) - c_2 \left(\log \frac{M_H}{100 \text{ GeV}} \right)^2 + c_3 \left(\log \frac{M_H}{100 \text{ GeV}} \right)^4 \\ &\quad - c_4 \left(\frac{\Delta\alpha}{0.05924} - 1 \right) + c_5 \left[\left(\frac{m_t}{174.3 \text{ GeV}} \right)^2 - 1 \right] - c_6 \left[\left(\frac{m_t}{174.3 \text{ GeV}} \right)^2 - 1 \right]^2 \\ &\quad - c_7 \left(\log \frac{M_H}{100 \text{ GeV}} \right) \left[\left(\frac{m_t}{174.3 \text{ GeV}} \right)^2 - 1 \right] \\ &\quad - c_8 \left(\frac{\alpha_s(M_Z)}{0.119} - 1 \right) + c_9 \left(\frac{M_Z}{91.1875 \text{ GeV}} - 1 \right) \\ \sin^2 \vartheta_{eff}^l &= \sin^2 \vartheta_0^l + d_1 \left(\log \frac{M_H}{100 \text{ GeV}} \right) + d_2 \left(\log \frac{M_H}{100 \text{ GeV}} \right)^2 + d_3 \left(\log \frac{M_H}{100 \text{ GeV}} \right)^4 \\ &\quad + d_4 \left[\left(\frac{M_H}{100 \text{ GeV}} \right)^2 - 1 \right] + d_5 \left(\frac{\Delta\alpha}{0.05907} - 1 \right) + d_6 \left[\left(\frac{m_t}{178.0 \text{ GeV}} \right)^2 - 1 \right] \\ &\quad + d_7 \left[\left(\frac{m_t}{178.0 \text{ GeV}} \right)^2 - 1 \right]^2 + d_8 \left[\left(\frac{m_t}{178.0 \text{ GeV}} \right)^2 - 1 \right] \left[\left(\frac{M_H}{100 \text{ GeV}} \right)^2 - 1 \right] \\ &\quad + d_9 \left(\frac{\alpha_s(M_Z)}{0.117} - 1 \right) + d_{10} \left(\frac{M_Z}{91.1876 \text{ GeV}} - 1 \right) \end{aligned}$$

- the above eqs. reproduce M_W within 0.4 MeV and $\sin^2 \vartheta_{eff}^l$ within $4.5 \cdot 10^{-6}$ when the parameters move within their 2σ errors

- we can solve the second equation for one parameter, e.g. $\Delta\alpha$, and introduce its expression in the first giving

$$\sin^2 \vartheta_{eff}^l = f(M_W)$$

- given an input value for $\sin^2 \vartheta_{eff}^l$, we can convert it to a M_W value and use as input for the POWHEG matrix element calculations in the G_μ scheme where everywhere $M_W = M_W(\sin^2 \vartheta_{eff}^l)$
- caveat
 - ▶ the M_W parameterization is given in terms of the “on-shell” W and Z masses (running width scheme), while POWHEG uses the position of the complex pole (fixed width)

$$M_V = \frac{M_V^{OS}}{\sqrt{1 + \left(\frac{\Gamma_V^{OS}}{M_W^{OS}}\right)^2}}$$

$$\Gamma_V = \frac{\Gamma^{OS}}{\sqrt{1 + \left(\frac{\Gamma_V^{OS}}{M_W^{OS}}\right)^2}}$$

- All this is implemented in `Z_ew` svn review 3452 (mass conversion also in `W_ew` 3453)

Work in progress for $pp \rightarrow l\nu j$

preliminary results by M. Chiesa and J. Zhou

- comparison with NLO results of A. Denner et al., arXiv:0906.1656

