W production and decay including EW corrections in the POWHEG BOX

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arXiv:1202.0465[hep-ph]

Outline

- Implementation of NLO EW corrections within POWHEG
  - $\mathcal{O}(\alpha)$ corrections
  - Independent approach of Bernaciak-Wackeroth
  - Comparison with parton-level results provided by HORACE
- Implementation of higher order corrections
  - interface with PHOTOS for QED shower
  - (Not tuned) comparison with recipe based on MC@NLO$\oplus/\otimes$HORACE
  - Example of current uncertainties on higher order QED corrections: comparison HORACE-PHOTOS
- Summary of current work in progress

Master formula and its extension to EW

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \Bigg\{ \Delta^{f_b}\left(\mathbf{\Phi}_n, p_{\mathrm{T}}^{\min}\right) + \sum_{\alpha_{\mathrm{r}} \in \{\alpha_{\mathrm{r}} | f_b\}} \frac{\left[d\Phi_{\mathrm{rad}}\ \theta\left(k_{\mathrm{T}} - p_{\mathrm{T}}^{\min}\right) \Delta^{f_b}(\mathbf{\Phi}_n, k_{\mathrm{T}})\ R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_{\mathrm{r}}}^{\bar{\mathbf{\Phi}}_n^{\alpha_{\mathrm{r}}} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \Bigg\}$$

$$\begin{aligned} \bar{B}^{f_b}(\mathbf{\Phi}_n) &= \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n) \right]_{f_b} \\ &+ \sum_{\alpha_{\mathrm{r}} \in \{\alpha_{\mathrm{r}} | f_b\}} \int \left[d\Phi_{\mathrm{rad}}\ \{ R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1}) \} \right]_{\alpha_{\mathrm{r}}}^{\bar{\mathbf{\Phi}}_n^{\alpha_{\mathrm{r}}} = \mathbf{\Phi}_n} \\ &+ \sum_{\alpha_{\oplus} \in \{\alpha_{\oplus} | f_b\}} \int \frac{dz}{z}\, G_{\oplus}^{\alpha_{\oplus}}(\mathbf{\Phi}_{n,\oplus}) + \sum_{\alpha_{\ominus} \in \{\alpha_{\ominus} | f_b\}} \int \frac{dz}{z}\, G_{\ominus}^{\alpha_{\ominus}}(\mathbf{\Phi}_{n,\ominus}) \end{aligned}$$

$$\Delta^{f_b}(\mathbf{\Phi}_n, p_{\mathrm{T}}) = \exp\left\{ - \sum_{\alpha_{\mathrm{r}} \in \{\alpha_{\mathrm{r}} | f_b\}} \int \frac{\left[d\Phi_{\mathrm{rad}}\ R(\mathbf{\Phi}_{n+1})\ \theta\left(k_{\mathrm{T}}(\mathbf{\Phi}_{n+1}) - p_{\mathrm{T}}\right) \right]_{\alpha_{\mathrm{r}}}^{\bar{\mathbf{\Phi}}_n^{\alpha_{\mathrm{r}}} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

V, R and Counterterms of NLO at $\mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_{em})$

$$
\begin{aligned}
V &= V_{QCD} + V_{EW} \\
R &= R_{QCD} + R_{QED} \\
C &= C_{QCD} + C_{QED} \\
G^{\alpha} &= G^{\alpha}_{QCD} + G^{\alpha}_{QED}
\end{aligned}
$$

- ${\alpha_{\rm r}}^{\rm QCD} \to {\alpha_{\rm r}}^{\rm QCD+QED}$
  - $d\bar{u} \to (W^- \to l\bar{\nu})g$ only singular in ISR region
  - $d\bar{u} \to (W^- \to l\bar{\nu})\gamma$ singular in ISR and FSR region
  - routines that automatically search for singular regions in real contribution extended to recognize also γq and γl pair of external lines as singular
- the automatic calculation of soft, collinear and soft-collinear limit of the real amplitude extended to include in the calculation soft and collinear photon regions
- also the collinear remnant calculation extended to include collinear photons

lepton mass terms and γ induced processes

- the lepton mass is kept finite everywhere because it represents a physical cutoff to the collinear singularity $\Rightarrow$ a new mapping of FSR from massive particles has been introduced (this is relevant also for QCD)
- also the real QCD radiation has been computed with finite lepton mass (necessary for singularity cancellation with massive Born)
- $\gamma q \to (W^- \to l\bar{\nu})q'$ should in principle be considered together with a PDF set containing also the photon among the partons in the proton
- at present we don't include γ induced processes
  - usually PDF sets don't include electromagnetic evolution
  - the photon contribution is usually quite small

Virtual part: $V_{QCD} + V_{EW}$

$$|\mathcal{M}_{QCD+EW}^{\text{one loop}}|^2 = (1 + 2\,\Re\{\delta_{QCD}\} + 2\,\Re\{\delta_{EW}\})|\mathcal{M}_0|^2$$

- δ_{QCD} already available in the POWHEG-BOX
- δ_{EW} from DK (well tested vs HORACE, WGRAD, SANC)

  Dittmaier and Krämer, PRD65 (2002) 073007

  with $m_q = m_\gamma = 0 \Rightarrow$ mixed scheme for IR singularities: soft and ISR collinear in dim. reg. and FSR collinear in mass reg.
- B_0, B_{0p}, C_0 and D_0 scalar integrals with mixed scheme

  Denner and Dittmaier, NPB844 (2011) 199242

  Dittmaier, NPB565 (2000) 69122
- factor $\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu^2}{Q^2}\right)^\epsilon$ extracted from the scalar form factors to comply with FKS subtraction implemented in POWHEG
- quark masses $\neq 0$ in fermionic loops, to ensure the correct running of $\Delta\alpha_{\text{had}}$ in the $\alpha(0)$ scheme
- default: G_μ scheme, G_μ, M_W and M_Z as input

Unstable particle mass treatment

- diagrams involving a virtual photon attached to a W line develop terms $\sim \log(1 - \frac{M_W^2}{\hat{s}} + i\epsilon)$
- divergence at the W peak
- two possible developed solutions
  - CLA: $M_W^2 \to M_W^2 - i\Gamma_W M_W$ in the arguments of the logarithms (the coefficient of this log is gauge invariant in the full $\mathcal{O}(\alpha)$) calculation

    Dittmaier and Krämer, PRD65 (2002) 073007
  - Complex Mass Scheme

    Denner, Dittmaier, Roth and Wieders, NPB724 (2005) 247294

    $M_W^2 \to M_W^2 - i\Gamma_W M_W$, $M_Z^2 \to M_Z^2 - i\Gamma_Z M_Z$ everywhere, also in scalar integrals and couplings
- the two schemes start to differ at NNLO
- a flag has been introduced to switch from one scheme to the other

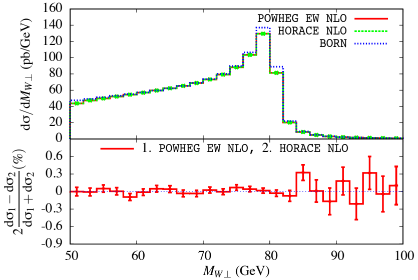
An independent implementation of NLO EW

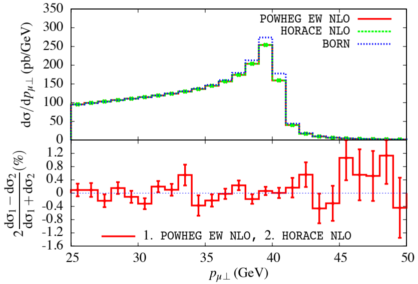
C. Bernaciak and D. Wackeroth, arXiv:1201.4804

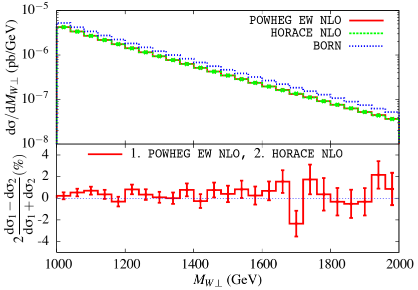
$$
\begin{aligned}
\bar{B}^{f_b}(\Phi_2) \quad = \quad & \left[B(\Phi_2) + V_{\mathsf{QCD}}(\Phi_2) + \boxed{V_{\mathsf{EW}}(\Phi_2)} \right]_{f_b} \\
+ \quad & \sum_{\alpha_r=0}^{2} \int \left\{ d\Phi_{\mathsf{rad}} \left[R_{\mathsf{QCD}}(\Phi_3) - C(\Phi_3) \right] \right\}_{\alpha_r, f_b}^{\bar{\Phi}_2^{\alpha_r}=\Phi_2} \\
+ \quad & \boxed{\int d\Phi_{\mathsf{rad}}^{\alpha_r=0} R_{\mathsf{EW}}^{f_b}(\Phi_3) \theta(E_\gamma - \delta_s \frac{\sqrt{\hat{s}}}{2}) \theta(\hat{s}_{q\gamma} - \delta_c E_\gamma \sqrt{\hat{s}}) \theta(\hat{s}_{\bar{q}\gamma} - \delta_c E_\gamma \sqrt{\hat{s}})} \\
+ \quad & \int \frac{dz}{z} \left[\sum_{\alpha_\oplus=1}^{2} G_{\mathsf{QCD},\oplus}^{\alpha}(\Phi_{2,\oplus}) + \boxed{G_{\mathsf{EW},\oplus}^{1}(\Phi_{2,\oplus}) \theta(1 - \delta_s - z)} \right]_{f_b} \\
+ \quad & \int \frac{dz}{z} \left[\sum_{\alpha_\ominus=1}^{2} G_{\mathsf{QCD},\ominus}^{\alpha}(\Phi_{2,\ominus}) + \boxed{G_{\mathsf{EW},\ominus}^{1}(\Phi_{2,\ominus}) \theta(1 - \delta_s - z)} \right]_{f_b}
\end{aligned}
$$

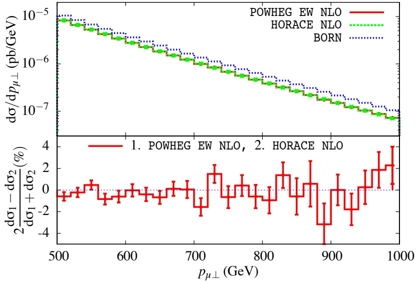
- $\mathcal{O}(\alpha)$ EW corrections as in WGRAD
- IR singularities with slicing scheme $\Rightarrow$ parameters δ_s and δ_c

parton level comparison HORACE-POWHEG($\alpha_s \to 0$)







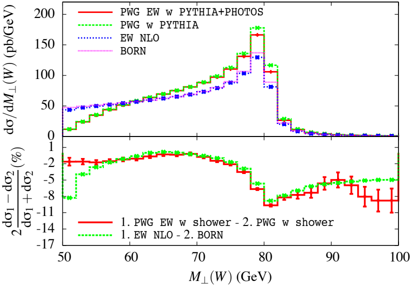


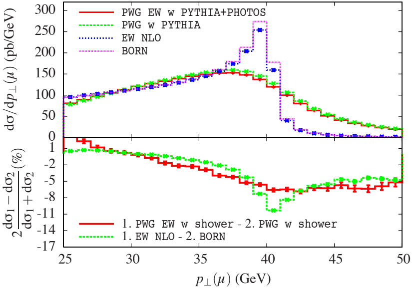
Higher Orders

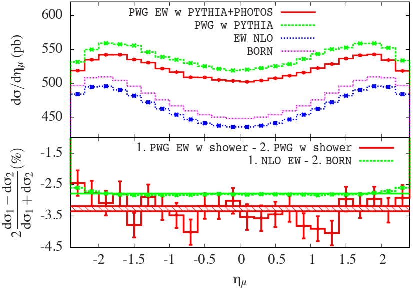
$$\Delta \equiv \Delta_{QCD} \times \Delta_{EW}$$

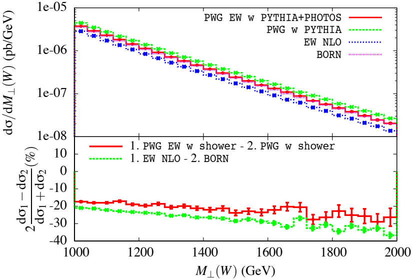
- generation of a radiation $p_\perp$ for each Sudakov form factor and choice of the largest one as maximum scale for gluon and γ radiation
- different lower radiation $p_\perp$ cutoff
  - Λ_{QCD} for g or γ radiation from quarks
  - m_l for γ radiation off leptons
- QED radiation handled with PHOTOS
  - PHOTOS generation of a QED shower ordered in energy between $E^{\max}$ and $E^{\min}$
  - veto photons with $p_\perp \geq p_\perp^{\max}$

results for QCD⊗EW with POWHEG



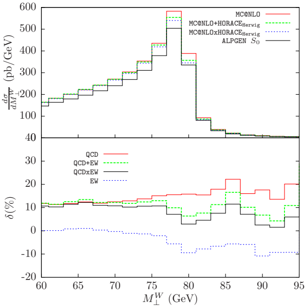


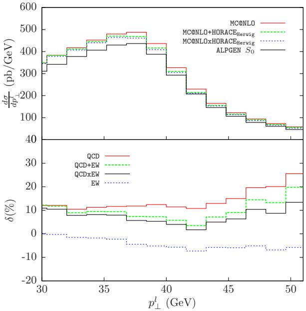




Not tuned comparison with MC@NLO$\oplus/\otimes$HORACE

G. Balossini *et al.*, JHEP 1001:013, 2010

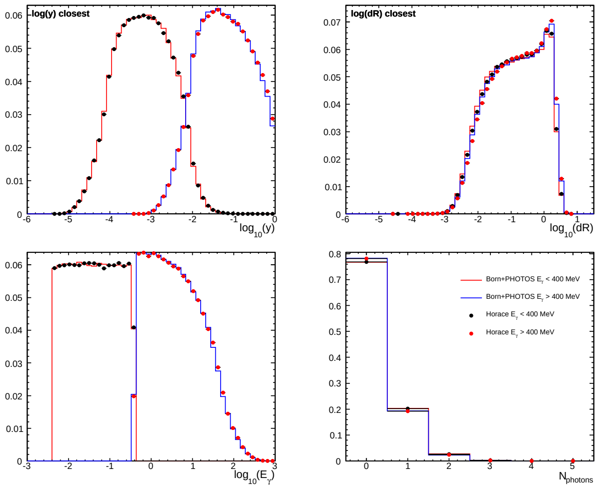




$\delta(\%)$	NLO QCD	NLL QCD	NLO EW	Shower QCD	$O(\alpha\alpha_s)$
Tevatron	8	16.8	-2.6	-1.3	~ 0.5
LHC a	-2	12.4	-2.6	1.4	~ 0.5
LHC b	21.8	20.9	-21.9	-0.6	~ 5

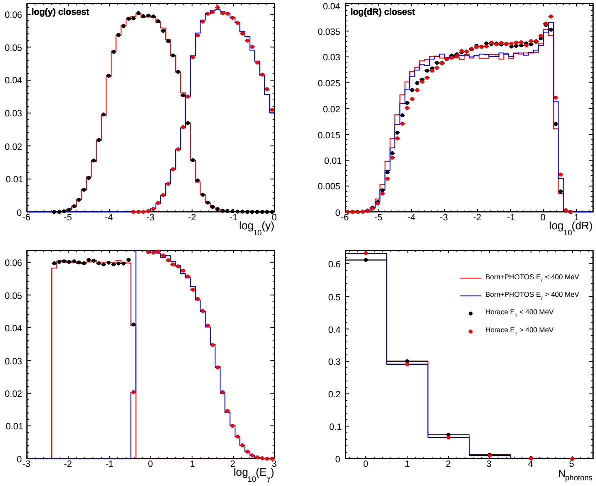
Effects very similar to POWHEG+PYTHIA+PHOTOS

comparison HORACE QED PS vs PHOTOS: $\mu^+\mu^-$



courtesy of A. Kotwal, CDF/DOC/ELECTROWEAK/CDFR/10482

comparison HORACE QED PS vs PHOTOS: e^+e^-



courtesy of A. Kotwal, CDF/DOC/ELECTROWEAK/CDFR/10482

Summary

New version of POWHEG for c.c. Drell-Yan with QCD&EW corrections

- normalization with NLO QCD $\oplus$ EW accuracy
- NLO predictions with mixed QCD$\otimes$QED parton cascade
- part of mixed $\mathcal{O}(\alpha\alpha_s)$ corrections included

To do list

- Extension to neutral DY in progress
- Detailed comparison with other approaches

Bernaciak and Wackeroth, arXiv:1201.4804[hep-ph]

MC@NLO$\oplus/\otimes$HORACE, G. Balossini et al., JHEP1001 (2010) 013

HERWIRI Yost, Halyo, Hejna and Ward, arXiv:1201.5906[hep-ph]

SANC$\oplus$HERWIG++/PYTHIA8, arXiv:1011.5444[hep-ph]

- Validation with existing data