Mixed EW/QCD corrections in MCs

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based on G. Balossini et al., JHEP 1001:013, 2010

Outline

- Introduction
- Factorized prescription: QCD ISR $\otimes$ QED FSR
- Inclusion of exact $\mathcal{O}(\alpha)$ EWK corrections within LL QCD Parton Shower
- Recipes for inclusion of NLO QCD matched with PS $\oplus/\otimes$ NLO EWK matched with QED PS
- Summary of current work in progress

Introduction

- $\mathcal{O}(\alpha_s)$, $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha)$ calculations available and implemented in several codes
- Perturbatively the QCD - EW interference is a two-loop effect

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

- A two loop $\mathcal{O}(\alpha\alpha_s)$ calculation would involve
  - virtual corrections at $\mathcal{O}(\alpha\alpha_s)$
  - EWK corrections to $l\bar{l}^{(\prime)}+$ jet
  - QCD corrections to $l\bar{l}^{(\prime)} + \gamma$
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$

see talk by T. Kasprzik

- However the bulk of the effects are in the soft/collinear regions where factorization holds
  - in the factorized limit, $\mathcal{O}(\alpha\alpha_s)$ terms given by $\mathcal{O}(\alpha) \otimes \mathcal{O}(\alpha_s)$
  - moreover for the specific case of DY at the $V(= W, Z)$ peak the largest part of EW corrections comes from photon emission from external lepton leg(s)

What is available in simulation tools

- the LL factorized approach (with higher order resummation) is available for instance in PS event generators (e.g.)
  - HERWIG +PHOTOS)
  - HERWIG++, PYTHIA and PYTHIA8 have their own QED shower
- Resbos family includes QED final state corrections + pure weak corrections in the form of I(mproved)B(orn)A(pproximation) taking into account leading corrections (running couplings)
- the level of precision of this kind of approach at the W/Z peak (at LHC energies, 7-10-14 TeV) has been tested in

  N. Adam, V. Halyo and S.A. Yost, JHEP bf 11 (2010) 074; JHEP bf 05 (2008) 062; JHEP bf 09 (2008) 133

  by comparing HERWIG + PHOTOS with HERWIG +HORACE which includes QED PS matched to the exact NLO EWK calculation

HERWIG⊕PHOTOS vs. HERWIG⊕HORACE

Z Production

Energy		Born	Born+FSR	Electro-Weak	Difference
7 TeV	$\sigma_{\rm tot}$	906.47 ± 0.40	906.47 ± 0.40	922.14 ± 1.04	$+1.70 \pm 0.12\%$
	$\sigma_{\rm cut}$	356.72 ± 0.46	333.60 ± 0.48	332.82 ± 0.50	$-0.23 \pm 0.21\%$
	A	0.3935 ± 0.0005	0.3680 ± 0.0006	0.3609 ± 0.0007	$+1.96 \pm 0.24\%$
14 TeV	$\sigma_{\rm tot}$	1964.76 ± 1.13	1964.76 ± 1.13	2001.20 ± 1.79	$+1.82 \pm 0.10\%$
	$\sigma_{\rm cut}$	669.09 ± 0.86	625.66 ± 0.89	625.97 ± 0.89	$+0.05 \pm 0.20\%$
	A	0.3405 ± 0.0005	0.3184 ± 0.0005	0.3128 ± 0.0005	$+1.81 \pm 0.23\%$

W^+ Production

Energy		Born	Born+FSR	Electro-Weak	Difference
7 TeV	$\sigma_{\rm tot}$	4993.2 ± 0.4	4993.2 ± 0.4	4948.5 ± 0.3	$-0.904 \pm 0.009\%$
	$\sigma_{\rm cut}$	2065 ± 5	1940 ± 5	1932 ± 5	$-0.41 \pm 0.36\%$
	A	0.4136 ± 0.0010	0.3885 ± 0.0010	0.3904 ± 0.0010	$+0.49 \pm 0.36\%$
14 TeV	$\sigma_{\rm tot}$	10384 ± 1	10384 ± 1	10350 ± 1	$-0.322 \pm 0.014\%$
	$\sigma_{\rm cut}$	3575 ± 10	3372 ± 10	3350 ± 10	$-0.68 \pm 0.41\%$
	A	0.3443 ± 0.0010	0.3248 ± 0.0009	0.3236 ± 0.0009	$-0.36 \pm 0.41\%$

W^- Production

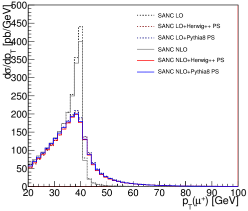
Energy		Born	Born+FSR	Electro-Weak	Difference
7 TeV	$\sigma_{\rm tot}$	3535.2 ± 0.2	3535.2 ± 0.2	3504.0 ± 0.2	$-0.890 \pm 0.008\%$
	$\sigma_{\rm cut}$	1489 ± 4	1412 ± 3	1397 ± 3	$-1.03 \pm 0.35\%$
	A	0.4213 ± 0.0010	0.3993 ± 0.0010	0.3987 ± 0.0010	$-0.14 \pm 0.35\%$
14 TeV	$\sigma_{\rm tot}$	7899.2 ± 0.8	7899.2 ± 0.8	7875.7 ± 0.6	$-0.297 \pm 0.013\%$
	$\sigma_{\rm cut}$	2919 ± 8	2747 ± 8	2748 ± 8	$+0.03 \pm 0.39\%$
	A	0.3695 ± 0.0010	0.3477 ± 0.0010	0.3489 ± 0.0010	$+0.32 \pm 0.39\%$

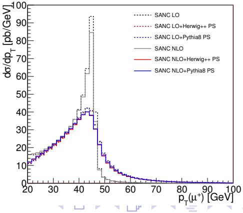
N. Adam, V. Halyo and S.A. Yost, JHEP bf 11 (2010) 074

SANC interfaced to HERWIG++ and PYTHIA8

P. Richardson, R.R. Sadykov and A.A. Sapronov, M.H. Seymour, P.Z. Skands, arXiv:1011.5444[hep-ph]

- The EW NLO calculation of SANC has been implemented in the LO PS HERWIG++ and PYTHIA8
- The shower algorithms have been modified to handle photon-induced hard processes
- PS multiphoton emission switched off to avoid double counting with NLO EWK calculation
- main differences due to shower model expected to become smaller once matrix element corrections are switched on





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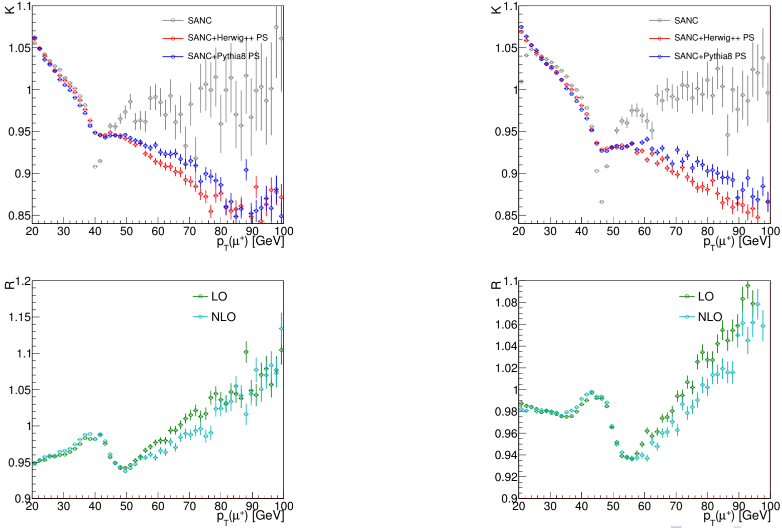


Towards matching QCD NLO and EWK NLO with PS

- at present not yet available in a single complete generator
- using different generators, a recipe to combine QCD and electroweak corrections has been proposed according to the following recipes (additive/factorized form):

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

$\oplus$ **Additive prescription:**

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\oplus\text{EW}} = \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{LO}}\right\}_{\texttt{HERWIG}\ \text{PS}}$$

$\otimes$ **Factorized prescription:**

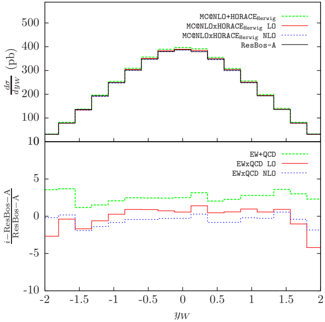
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\texttt{HERWIG}\ \text{PS}}}{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{(N)LO}}}\right) \times \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}}\right\}_{\texttt{HERWIG}\ \text{PS}}$$

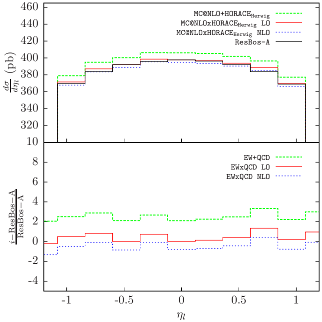
Combining EWK and QCD corrections

- QCD $\Rightarrow$ ResBos, MCFM, MC@NLO, POWHEG, ...
- EW $\Rightarrow$ Electroweak + multiphoton corrections from HORACE convoluted with HERWIG QCD Parton Shower
  - ⋆ NLO electroweak corrections are interfaced to QCD Parton Shower evolution $\Rightarrow \mathcal{O}(\alpha\alpha_s)$ corrections reliable only at LL level
  - not reliable when hard non collinear QCD radiation is important (e.g. p_T^W and p_T^l for nearly on shell W)
- Additive and factorized prescription have Same $O(\alpha)$, $O(\alpha_s)$ and leading $O(\alpha_s^2)$ content
- Differences at $O(\alpha\alpha_s)$ and $O(\alpha_s^2)$ non-leading-log
  - MCFM $\oplus$ HORACE no $\mathcal{O}(\alpha\alpha_s)$ and no $\mathcal{O}(\alpha_s^2)$ terms
  - MC@NLO $\oplus$ HORACE no $\mathcal{O}(\alpha\alpha_s)$ terms
- (N)LO normalization of factorized prescription is an issue for observables starting from $\mathcal{O}(\alpha_s)$ (e.g. p_T^W)
- difference between additive and factorized prescription gives an estimate of the impact of $\mathcal{O}(\alpha\alpha_s)$ contributions

Comparison with Resbos−A at Tevatron: y_W and η_l

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





- the comparison between the factorized (NLO) prescription and RESBOS−A is at the per cent level

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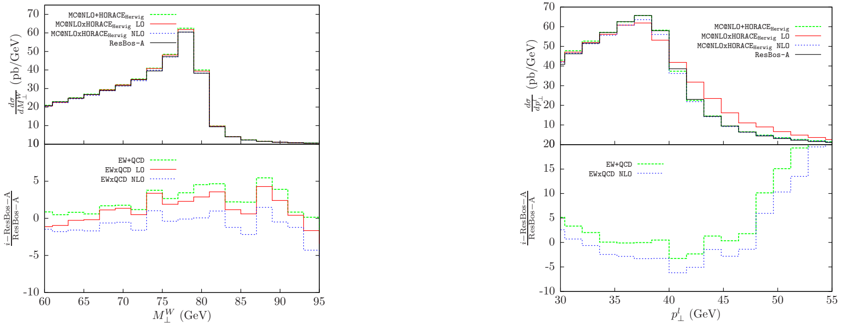

- main differences due to the QCD program (for RESBOS-A no NLO correction (Y term) was available
- for $p_\perp^l$ distribution pathological behaviour of the LO normalized factorized prescription

y_W @ LHC

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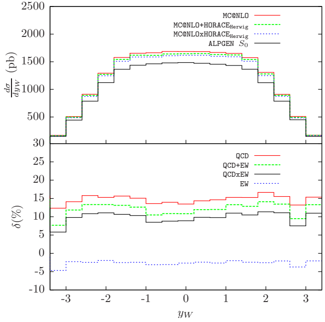

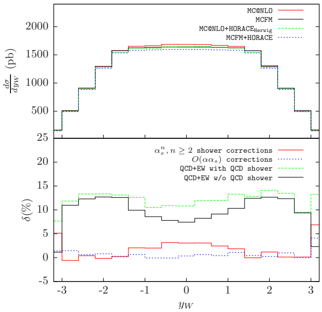

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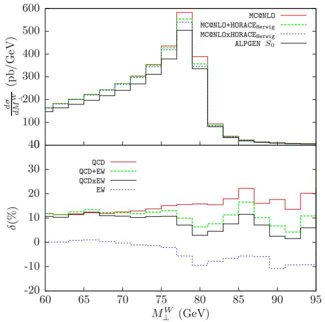
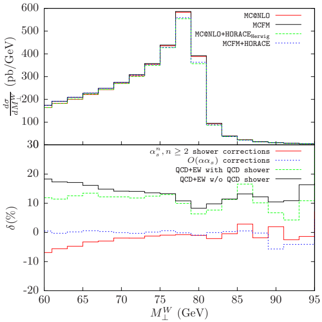
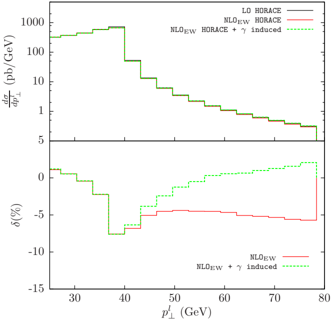


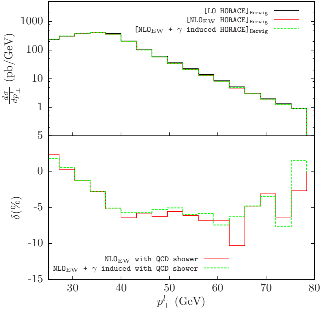


- QCD shower evolution very important below peak
- $\mathcal{O}(\alpha\alpha_s)$ corrections play a role above peak

$p_\perp^l$ @ LHC: γ-induced processes

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





- Large difference on $p_\perp^l$ before and after parton-showering of γ-induced processes

Some summary numbers

$\delta(\%)$	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

Table: Relative effect of the main sources of QCD, EW and mixed radiative corrections to the integrated cross sections for the Tevatron, LHC a and LHC b.

$\delta(\%)$	$\delta\sigma/\sigma$ (scale)	$\delta\sigma/\sigma$ (FA)	$\delta\sigma/\sigma$
Tevatron	~ 1	~ 2	2
LHC a	~ 2.5	~ 2	2.5
LHC b	~ 1.5	~ 5	5

Table: Estimate of the present theoretical accuracy for the calculation of the integrated cross section at the Tevatron, LHC a and LHC b.

Summary and Outlook

- $\mathcal{O}(\alpha\alpha_s)$ corrections will become important soon for precision study of DY@LHC both at the peak and in the large mass tail
- recent activity to combine QCD generators with complete NLO EWK corrections
- it would be important to have a quantitative estimate (even though very CPU demanding) of the impact of different implementations of $\mathcal{O}(\alpha\alpha_s)$ contributions on M_W determination
- it will be very useful to have a single MC generator incorporating both QCD and EWK corrections
- current work in progress on matching QCD and EWK higher order effects
    - interface of HORACE with POWHEG — L. Barzè, F.P., HORACE and POWHEG teams
    - interface of W/ZGRAD with POWHEG — C. Bernaciak, D. Wackeroth
    - development of HERWIRI — S. Joseph, S. Majhi, B.F.L. Ward, S.A. Yost, PRD81 (2010) 076008