Precise theoretical predictions for Drell-Yan processes at hadron colliders: lecture 3

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Electroweak radiative corrections

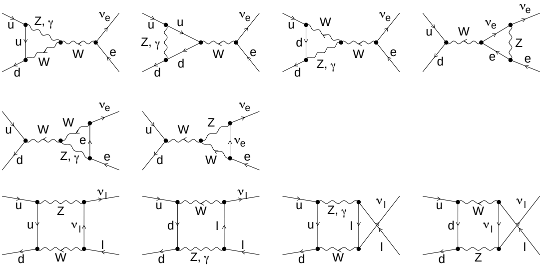
- from the first lecture

$$\sigma = \sigma_0(1 + \alpha_s \delta_1^{\rm QCD} + \alpha_s^2 \delta_2^{\rm QCD} + \alpha \delta_1^{\rm EW} + \ldots)$$

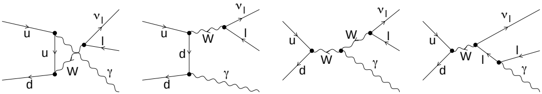
- $\alpha_s^2(M_Z) \simeq \alpha \Longrightarrow$ NLO EW potentially comparable with NNLO QCD corrections
- virtual EW corrections: (in the unitary gauge) all possible insertions of internal bosonic lines (γ, W, Z and H) and virtual fermionic lines on tree-level diagrams
- real corrections: all possible insertions of real photon lines on tree-level diagrams

Examples of EW NLO Feynman diagrams for CC DY

- virtual one-loop corrections



- bremsstrahlung corrections

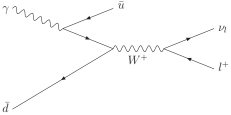


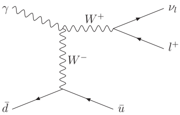
general features of EW radiative corrections (I)

- (in addition to fermion masses and the Higgs mass) three input parameters in the gauge sector in EWRC vs one (coupling const) in QCD
- being the photon massless, QED IR soft singularities as for QCD
- most of the calculations existing in the literature adopt the mass scheme for the regularization IR soft and collinear singularities: photon mass and fermionic masses
  - for IS collinear singularities this entails a redefinition of the PDF's to subtract collinear $\log(\frac{Q^2}{m_q^2})$
  - final state collinear $\log(\frac{Q^2}{m_l^2})$ are "physical" for exclusive observables; different effects for muons or electrons:
    - muons are detected through a magnetic field $\Longrightarrow$ they are well separated from the emitted photons (enhanced QED RC)
    - electrons are detected through a calorimetric measurement, which is sensitive to the sum of momenta of electron and collinear photons ($\log(\frac{Q^2}{m_l^2})$ partially screened, the detector "sees" an electromagnetic jet)

general features of EW radiative corrections (II)

- at the same perturbative order contribute diagrams with γ in the initial state

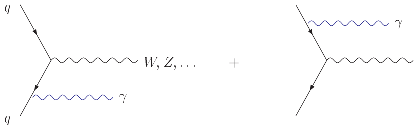




- at present only one set of PDF (MRST2004QED) provides the photon distribution function
- w.r.t. NLO QCD calculations, EWRC involve the presence of unstable particles in the loops, which require some care in order to avoid gauge invariance violation
- at the peak of the W/Z QED corrections by far dominant
- different methods to treat higher order photonic corrections
  - QED parton shower
  - QED structure functions in collinear approximation
  - YFS formalism

QED initial-state collinear singularities

- QED initial-state collinear singularities are universal $\rightarrow$ can be absorbed into PDFs, as in QCD



$$f(x) \rightarrow f(x,\mu_F^2) - \int_x^1 \frac{dz}{z}\, f\left(\frac{x}{z},\mu_F^2\right) \frac{\alpha}{2\pi} Q_q^2 \times \left\{ \ln\left(\frac{\mu_F^2}{m_q^2}\right) \left[P_{ff}(z)\right]_+ - \left[P_{ff}(z)\left(2\ln(1-z)+1\right)\right]_+ + C(z) \right\}$$

$$C(z) = \begin{cases} 0 & \overline{\text{MS}} \\ \left[P_{ff}(z)\left(\ln\left(\frac{1-z}{z}\right) - \frac{3}{4}\right) + \frac{9+5z}{4}\right]_+ & \text{DIS} \end{cases}$$

input parameters (in the gauge sector)

- the more precise parameters would be $\alpha(0)$, G_μ and M_Z, as done for instance for LEP calculations
- but in this scheme M_W is a derived quantity
- since we need to measure M_W it is better to have it as an input parameter
- the original on shell scheme could be ideal: $\alpha(0)$, M_W, M_Z
- but...
  - it maximizes the corrections because it contains terms proportional to $\Delta\alpha \sim 1\%$ (the running of the electromagnetic coupling from zero to the M_Z scale) and $\Delta\rho$ $(\sim G_\mu m_t^2 \sim 1\%)$
  - the scheme that minimizes the RC (i.e. the bulk of them is absorbed in the LO prediction) is the G_μ scheme:

$$\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2 (1 - M_W^2/M_Z^2)}{\pi} \simeq \alpha(0)(1 + \Delta r)$$

  - the coupling of the real photon should however be keep $\alpha(0)$

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

Matching NLO electroweak with QED Parton Shower

C.M. Carloni Calame *et al.*, JHEP 12 (2006) 016: HORACE

- NLO ($\mathcal{O}(\alpha)$) electroweak cross section

$$d\sigma^{\alpha}_{\rm ew} \equiv d\sigma^{\alpha,ex} \equiv d\sigma^{\alpha,ex}_{SV} + d\sigma^{\alpha,ex}_{H}$$

- $\mathcal{O}(\alpha)$ Parton Shower (PS) cross section

$$d\sigma^{\alpha,PS} = [\Pi_S(Q^2)]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P_{ff}(x) I(k) dx\; dc\; d\hat{\sigma}_0 = \equiv d\sigma^{\alpha,PS}_{SV} + d\sigma^{\alpha,PS}_{H}$$

- Resummed PS

$$d\sigma^{\infty}_{PS} = \Pi_S(Q^2)\; F_{sv}\; \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left[\frac{\alpha}{2\pi} P_{ff}(x_i) I(k_i) dx_i dc_i\; F_{H,i} \right]$$

where $F_{SV} = 1 + \frac{d\sigma^{\alpha,ex}_{SV} - d\sigma^{\alpha,PS}_{SV}}{d\sigma_0}$ and $F_{H,i} = 1 + \frac{d\sigma^{\alpha,ex}_{H,i} - d\sigma^{\alpha,PS}_{H,i}}{d\sigma^{\alpha,PS}_{H,i}}$

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- Resummed PS + NLO electroweak

$$d\sigma^{\infty}_{\rm matched} = \Pi_S(Q^2)\; F_{sv}\; \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left[\frac{\alpha}{2\pi} P_{ff}(x_i) I(k_i) dx_i dc_i\; F_{H,i} \right]$$

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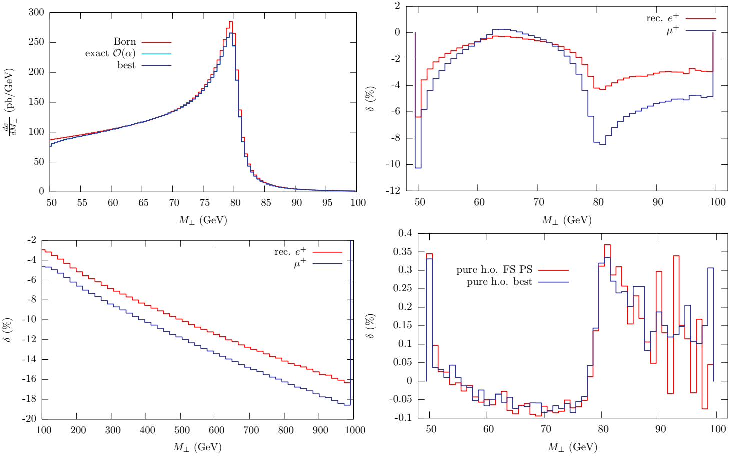
EW effects for W

C.M. Carloni Calame *et al.*, JHEP 12 (2006) 016

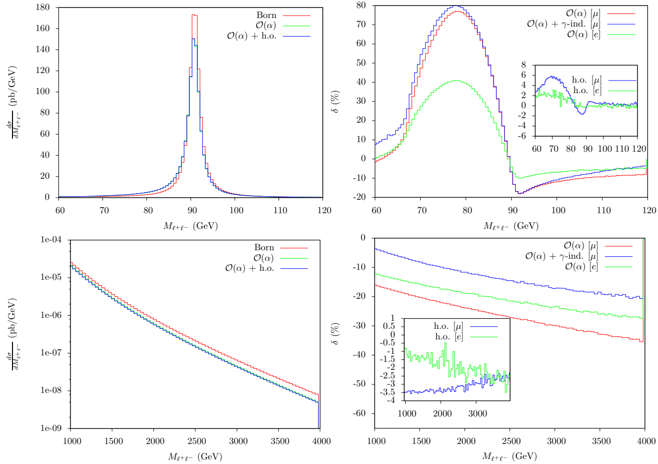
- M_T^W distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, h.o. QED effects at peak



EW effects for Z

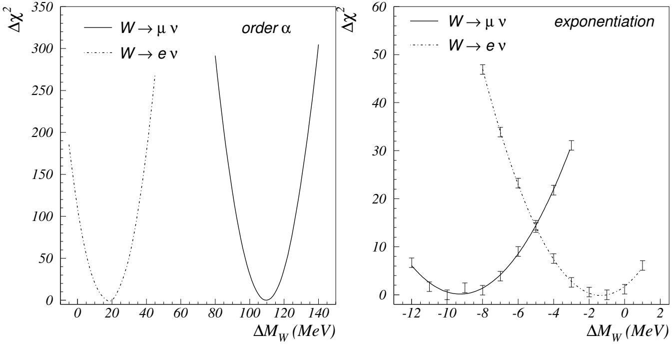
C.M. Carloni Calame *et al.*, JHEP **10** (2007) 190

- $M_{\ell^+\ell^-}$ distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, h.o. QED effects at peak



Why higher-order QED is important: W mass

C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301



$$\Delta M_W^{\alpha,e} \sim 20 \text{ MeV}$$
$$\Delta M_W^{\alpha,\mu} \sim 110 \text{ MeV}$$

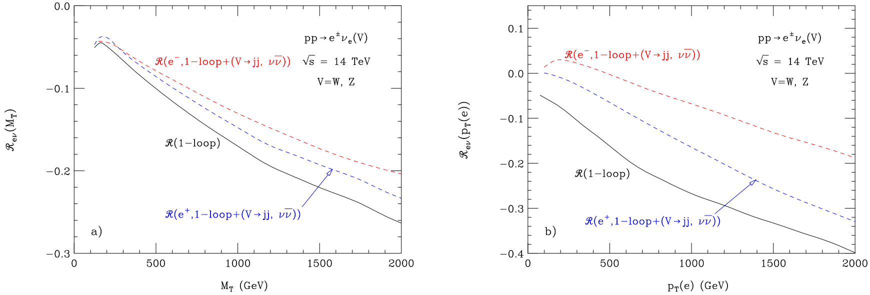
$$\Delta M_W^{\infty,e} \sim 2 \text{ MeV}$$
$$\Delta M_W^{\infty,\mu} \sim 10 \text{ MeV}$$

- W-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission $\rightarrow$ non-negligible for W mass!

Emission of real weak bosons

U. Baur, Phys. Rev. **D** 75:013005, 2007

- ⋆ virtual weak corrections induce large negative effects due to Sudakov (logs)^2 in the high Q^2 region
- real radiation of (undetected) real vector bosons (partially) cancels the Sudakov effect
- e.g., $pp \to e^+\nu_e V + X \quad V \equiv W, Z \quad V \to jj, \nu\bar{\nu}, \dots$



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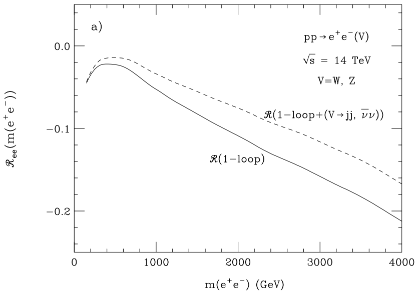
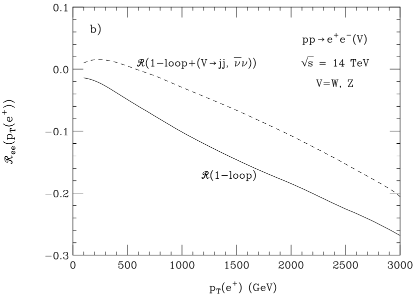




- partial cancellation of Sudakov $(\text{logs})^2$ by real vector boson radiation

EWRC for DY processes: dedicated generators

$pp \to W^{\pm} \to l\nu$

- ⋆ **Pole approximation**
  Wackeroth, Hollik, Phys. Rev. D55 (1997) 6788;
  Baur, Keller, Wackeroth, PRD59 (1999) 013002;

  WGRAD

- ⋆ **Complete $\mathcal{O}(\alpha)$ corrections**

  V.A. Zykunov, Eur. P. J. **C3** (2001) 9,
  Phys. Atom. Nucl. 69 (2006) 1522;
  Dittmaier, Krämer, Phys. Rev. D65 (2002) 073007;
  Brensing et al., Phys. Rev. D77 (2008) 073006;
  Baur, Wackeroth, Phys. Rev. D70 (2004) 073015;

  WGRAD2

  A. Arbuzov *et al.*, Eur. Phys. J. C46 (2006) 407;
  D. Bardin et al., arXiv:1207.4400

  SANC

  C.M. Carloni Calame *et al.*, JHEP 12 (2006) 016;

  HORACE

$pp \to \gamma^* Z \to l^+ l^-$

- ⋆ **$\mathcal{O}(\alpha)$ photonic corrections**
  Baur, Keller, Sakumoto, PRD57 (1998) 199;

  ZGRAD

- ⋆ **Complete $\mathcal{O}(\alpha)$ corrections**
  U. Baur *et al.*, Phys. Rev. **D65** (2002) 033007;

  ZGRAD2

  C.M. Carloni Calame *et al.*, JHEP **10** (2007) 190;

  HORACE

  V.A. Zykunov, Phys. Rev. **D75** (2007) 073019;
  A. Arbuzov *et al.*, Eur. Phys. J **C54**:451-460, 2008;
  D. Bardin et al., arXiv:1207.4400

  SANC

  S. Dittmaier and M. Huber, JHEP 01 (2010) 060.

Higher order electroweak corrections

- Multi-photon radiation
  - Higher-order (real+virtual) QED corrections to $W/Z/\gamma^*$ production
    - $\rightarrow$ HORACE: QED PS + NLO EWRC to $W/Z/\gamma^*$ production

      C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301;
      C.M. Carloni Calame *et al.*, JHEP **05** (2005) 019; JHEP **12** (2006) 016; JHEP **10** (2007) 190;
    - $\rightarrow$ WINHAC: YFS exponentiation + $\mathcal{O}(\alpha)$ EWRC to W decay

      S. Jadach and W. Płaczek, Eur. Phys. J. **C29** (2003) 325
    - $\rightarrow$ WINHAC⊕SANC: YFS exponentiation + $\mathcal{O}(\alpha)$ EWRC to W

      Bardin, Bondarenko, Jadach, Kalinowskaya, Placzek, Acta Phys. Pol. B40 (2009) 75
  - Improved treatment of multiphoton radiation in HERWIG(++) (with SOPHTY via YFS) and PHOTOS (via QED Parton Shower)

    K. Hamilton and P. Richardson, JHEP **0607** (2006) 010
    P. Golonka and Z. Was, Eur. Phys. J. **C45** (2006) 97
  - Higher order QED FSR with collinear structure funcions

    S. Dittmaier and M. Huber, JHEP 01 (2010) 060; Dittmaier, Krämer, Phys. Rev. D65 (2002) 073007
- Higher order effects from couplings ($\Delta\alpha(M_Z)^n$, $\Delta\rho^2$, $\Delta\alpha(M_Z)\Delta\rho$)
- Higher orders from two-loop leading Sudakov logs $(\alpha_W \log^2 \frac{s}{M_W^2})$

  A. Denner, B. Jantzen and S. Pozzorini, Nucl. Phys. **D761** (2007) 1
  B. Jantzen *et al.*, Nucl. Phys. **D731** (2005) 188

QCD - EW corrections interference

- Perturbatively the QCD - EW interference is a two-loop effect

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

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

Related existing approaches

- the LL factorized approach (with higher order resummation) is available for instance in PS event generators (e.g.)
  - HERWIG +PHOTOS
  - HERWIG++, SHERPA, PYTHIA and PYTHIA8 have their own QED shower
  - HERWIG++ and SHERPA use YFS formalism for QED radiation from W and Z decays
- 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 preliminarily tested in

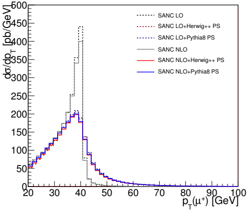
  N. Adam, V. Halyo and S.A. Yost, JHEP bf 11 (2010) 074; JHEP bf 05 (2008) 062; JHEP bf 09 (2008) 133

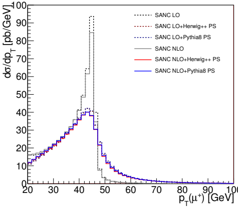
  by comparing HERWIG + PHOTOS with HERWIG +HORACE which includes QED PS matched to the exact NLO EW calculation
  $\Rightarrow$ differences found at the level of 1-2% on cross sections

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 EW calculation
- main differences due to shower model expected to become smaller once matrix element corrections are switched on





Towards matching QCD NLO and EW NLO with PS

- 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:**

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

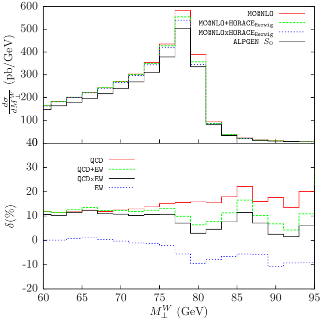
$\otimes$ **Factorized prescription:**

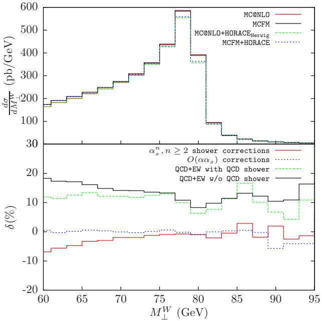
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{QCD}} - \left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\texttt{HERWIG}\ \text{PS}}}{\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{(N)LO}}}\right)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

Combining EW 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
- (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

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

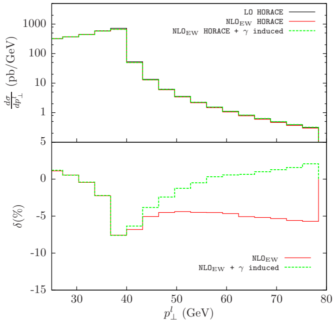


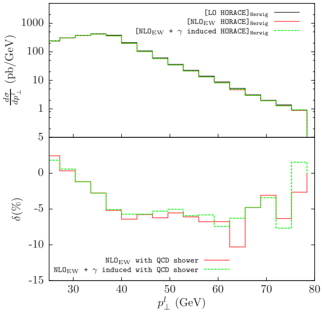


- QCD shower evolution very important below peak
- $\mathcal{O}(\alpha\alpha_s)$ corrections play a role above peak

$p_\perp^l$ @ 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

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

LHC a): LHC@ 14 TeV; LHC b): LHC @ 14 TeV with $M_T > 1$ TeV

$\delta(\%)$	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.

A QCD⊗EW generator: the case of POWHEG

L. Barzè, G. Montagna, O. Nicrosini, P. Nason and F.P., arXiv:1202.0465[hep-ph]

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

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

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

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

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

- ${\alpha_{\mathrm{r}}}^{\mathrm{QCD}} \rightarrow {\alpha_{\mathrm{r}}}^{\mathrm{QCD+QED}}$
  - $d\bar{u} \rightarrow (W^- \rightarrow l\bar{\nu})g$ only singular in ISR region
  - $d\bar{u} \rightarrow (W^- \rightarrow l\bar{\nu})\gamma$ 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: $V_{QCD} + V_{EW}$

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

- 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

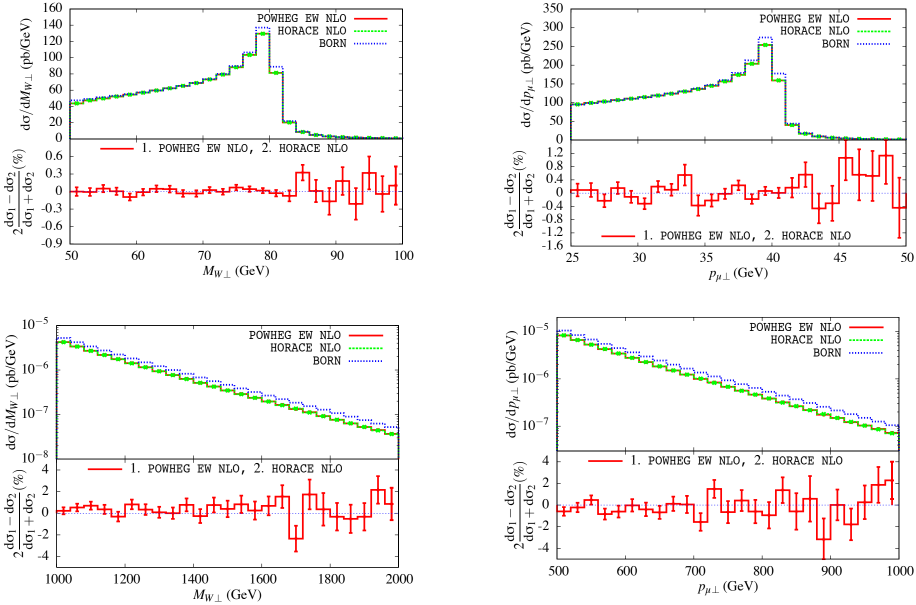
An independent implementation of NLO EW

C. Bernaciak and D. Wackeroth, arXiv:1201.4804

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

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

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

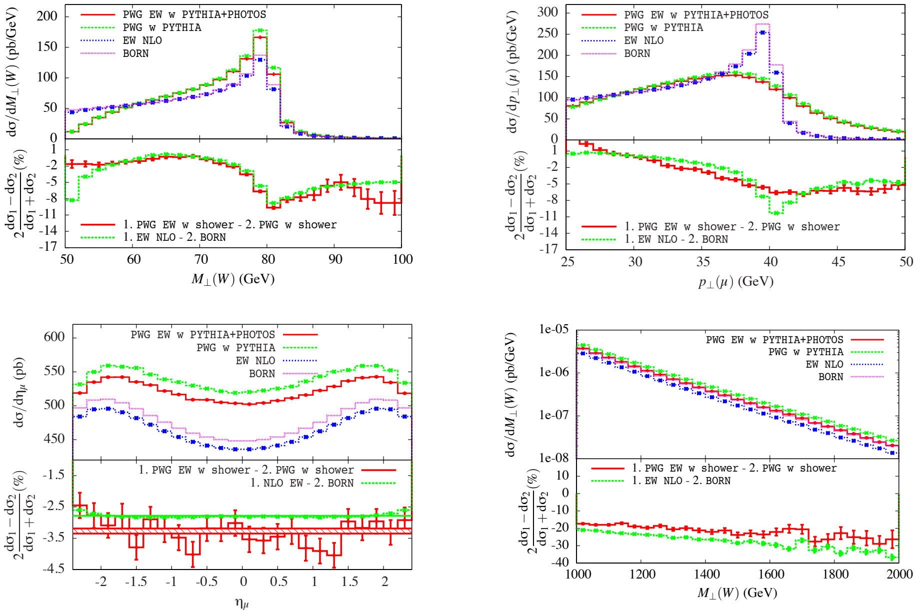


Higher Orders

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

- 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



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

- development of `HERWIRI` S. Joseph, S. Majhi, B.F.L. Ward, S.A. Yost, PRD81 (2010) 076008
- Extension to neutral DY in progress
- Comparison with other approaches and validation with LHC data

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]

THANK YOU FOR YOUR ATTENTION!