W boson properties and EW and QCD corrections to Drell Yan in the POWHEG BOX

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based on

L. Barzè, G. Montagna, P. Nason and O. Nicrosini JHEP 1204 (2012) 037 [arXiv:1202.0465[hep-ph]]

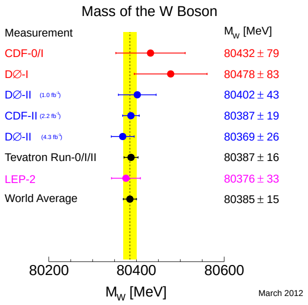
and

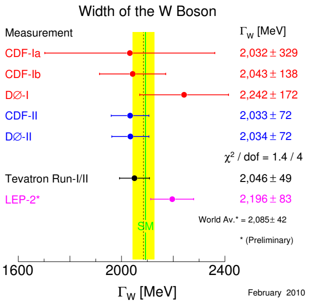
G. Balossini et al., JHEP 1001 (2010) 013 [arXiv:0907.0276]

Outline

- Introduction
- present status of QCD and EW corrections and their interplay in DY processes
- Two different implementations of NLO EW corrections within POWHEG
  - Approach of Bernaciak-Wackeroth: POWHEG BOX subprocess W_ew-BW
  - Our approach: POWHEG BOX subprocess W_ew-BMNNP
  - Comparison with parton-level results provided by HORACE
- Implementation of QED higher order corrections in W_ew-BMNNP
  - interface with PHOTOS for QED shower
  - (Not tuned) comparison with recipe based on MC@NLO$\oplus/\otimes$HORACE
- Summary of current work in progress

Summary of direct measurements

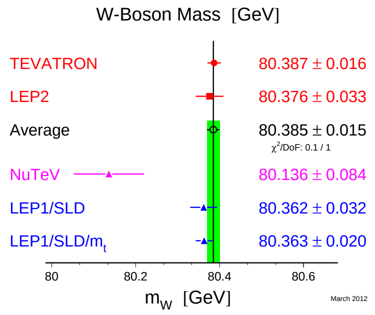




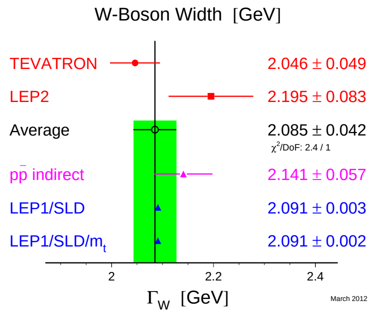
TEVEWWG: arXiv:1204.0042[hep-ex]

TEVEWWG: arXiv:1003.2826[hep-ex]

SM consistency checks (I)



LEPEWWG homepage



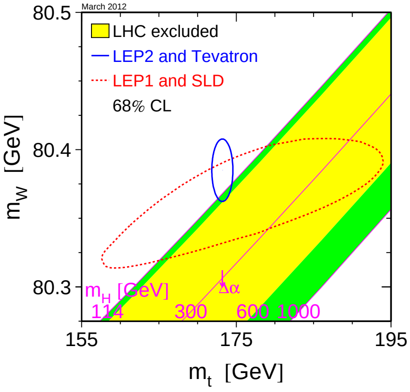
LEPEWWG homepage

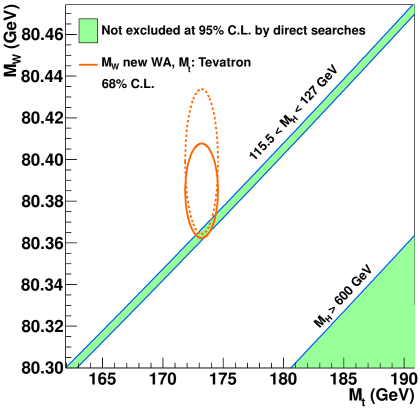
LEP1/SLD values results from theory: highly non trivial test!

$$M_W^2 = \frac{4\sqrt{2}\pi\alpha}{8G_\mu \sin^2\vartheta}\,(1+\Delta r)$$

input parameters: α, G_μ, M_Z, $m_{\rm top}$, m_H, $\alpha_s(M_Z^2)$

SM consistency checks (II)





LEPEWWG homepage

Sources of systematic uncertainties @ Tevatron

Source	Uncertainty (MeV) [CDF]	Uncertainty (MeV) [D0]
Subtotal exp	10	18
PDFs	10	11
QED radiation	4	7
$p_\perp^W$ model	5	2
Subtotal	12	13
Total	19	26

T. Aaltonen et al. (CDF), Phys. Rev. Lett. 108 (2012) 151803, [aXiv:1203.0275[hep-ex]]

V.M. Abazov et al. (D0), Phys. Rev. Lett. 108 (2012) 151804, [aXiv:1203.0293[hep-ex]]

- The estimate of EW uncertainties relies on comparisons between ResBos⊕PHOTOS with HORACE and W(Z)GRAD for $M_\perp(l\nu)$, $p_\perp^l$ and $\not{E}_T$
- at the LHC an even more thourough comparison between different calculations/codes for both higher order QCD and electroweak corrections will be crucial

Higher-order QCD & generators: state of the art

- Multi-parton matrix elements Monte Carlos (ALPGEN, HELAC, MADEVENT, SHERPA...) matched with vetoed Parton Showers

  (not treated in these lectures)

- NLO calculations for $W, Z \to l\bar{l}'$ (DYRAD, MCFM)

  W.T. Giele, E.W.N. Glover and D.A. Kosower, Nucl. Phys. **B403** (1993) 633

  J.M. Campbell and R.K. Ellis, Phys. Rev. **D65** (2002) 113007

- soft-gluon resummation of leading/NLL $(p_\perp^V / M_V)$ (ResBos)

  C. Balazs and C.P. Yuan, Phys. Rev. **D56** (1997) 5558

- fully differential NNLO corrections to W/Z production (FEWZ, DYNNLO)

  K. Melnikov and F. Petriello, Phys. Rev. Lett. **96** (2006) 231803, Phys. Rev. **D74** (2006) 114017

  S. Catani, L. Cieri, G. Ferrera, D. de Florian, M. Grazzini, Phys. Rev. Lett. **103** (2009) 082001

  S. Catani, G. Ferrera, M. Grazzini, JHEP **1005** (2010) 006

- NNLL resummation of W/Z transverse momentum

  G. Bozzi, S. Catani, G. Ferrera, D. de Florian, M. Grazzini, Phys. Lett. **B696** (2011) 207

- NLO merged with Parton Showers (MC@NLO, POWHEG, SHERPA)

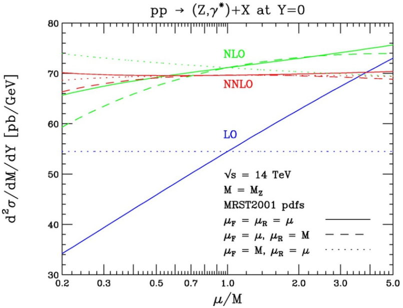
  S. Frixione and B.R. Webber, JHEP **0206** (2002) 029

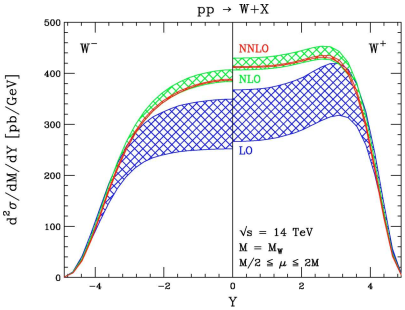
  P. Nason, JHEP 0411 (2004) 040; S. Alioli et al., JHEP 0807 (2008) 060, JHEP 1006 (2010) 043

  S. Höche, F. Krauss, M. Schönherr, F. Siegert, arXiv:1207.5030

typical effects of (N)NLO QCD corrections

- stabilize the prediction w.r.t. scale variations



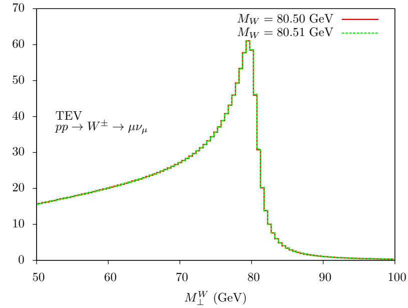


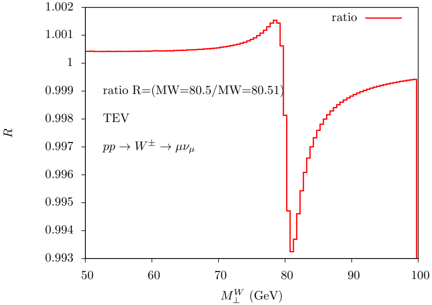
Anastasiou, Dixon, Melnikov, Petriello, Phys. Rev. **D69** (2004) 094008

- W mass determination very sensitive to the shape of distributions, induced by both QCD and EW corrections

Example of sensitivity of $M_\perp(l\nu)$ and σ to M_W

Bozzi, Rojo and Vicini, arXiv:1104.2056[hep-ph]





M_W (GeV)	80.368	80.378	80.388	80.398	80.408	80.418
$\sigma_{tot}(M_W)$ (pb)	368.72	368.87	369.03	369.17	369.32	369.46
$\left(\sigma_{tot}^{i+1} - \sigma_{tot}^{i}\right)/\sigma_{tot}^{i}$		0.04%	0.04%	0.04%	0.04%	0.04%

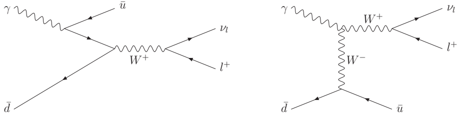
- in order to determine M_W with 10 MeV precision, control of corrections at few 0.1% level needed

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

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 kept $\alpha(0)$

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
  - DK: $M_W^2 \to M_W^2 - i\Gamma_W M_W$ in the arguments of the logarithms (the coefficient of this log is gauge invariant in the full $\mathcal{O}(\alpha)$ calculation)

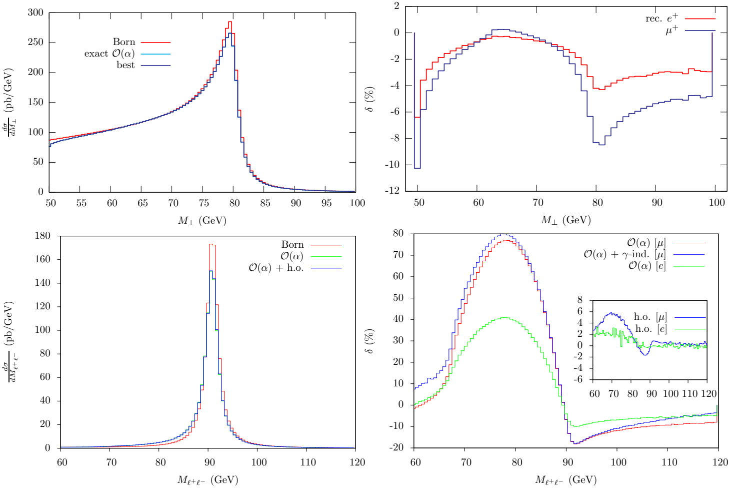
    Dittmaier and Krämer, PRD65 (2002) 073007
  - Complex Mass Scheme

    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

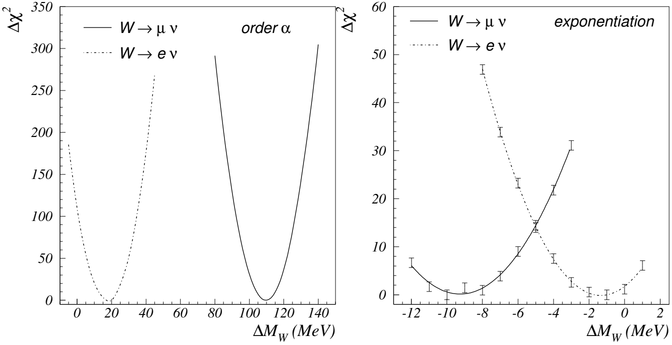
EW effects for $M_\perp(l\nu)$ and $M(l^+l^-)$ (with HORACE)

C.M. Carloni Calame *et al.*, JHEP 12 (2006) 016
C.M. Carloni Calame *et al.*, JHEP **10** (2007) 190



Higher-order QED effect on W mass

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

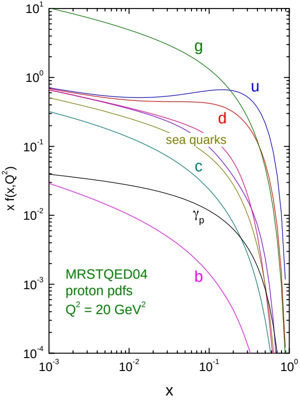


$$\Delta M_W^{\alpha,e} \sim 20 \text{ MeV}$$
$$\Delta M_W^{\alpha,\mu} \sim 110 \text{ MeV}$$

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

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

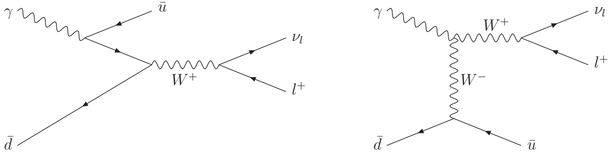
QED-improved PDFs



- effect of QED evolution on PDFs through DGLAP equation is small ($\sim$ 0.1% for $x < 1$)

H. Spiesberger, Phys. Rev. **D52** (1995) 4936
M. Roth and S. Weinzierl, Phys. Lett. **B590** (2004) 190
A.D. Martin *et al.*, Eur. Phys. J. **C39** (2005) 155

- dynamic generation of photon parton distribution $\rightarrow$ photon induced processes enter the game



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 matched to 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
    Brensing, Dittmaier, Krämer, Mück, PRD77 (2008) 073006
    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

Adding up QCD and EW corrections

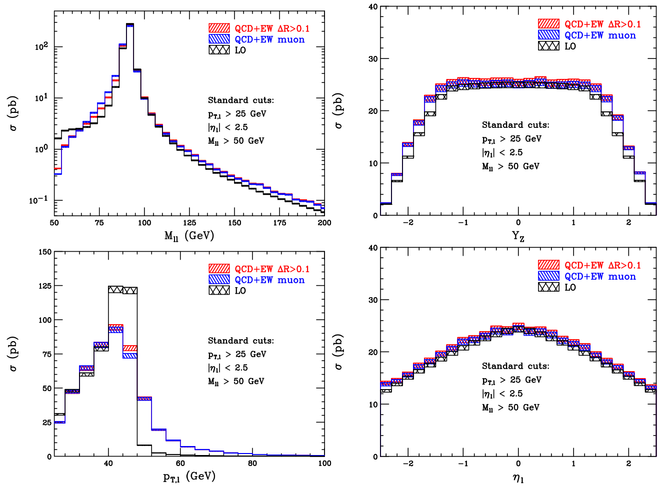
$$d\sigma = d\sigma_0 + d\sigma_{\alpha_s} + d\sigma_{\alpha} + d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \ldots$$

- Fixed order MC tools
  - `SANC`: QCD NLO $\oplus$ EW NLO for NC and CC DY
    Bardin, Bondarenko, Christova, Kalinowskaya, Rumyantsev, Sapronov, von Schlippe, arXiv:1207.4400[hep-ph]
  - `FEWZ`: QCD NNLO $\oplus$ EW NLO for NC DY
    Li and Petriello, arXiv:1208.5967[hep-ph]
- PS Event Generators interfaced to NLO QCD $\oplus$ NLO EW: complementary approach which allows to keep under control also (partially) $\mathcal{O}(\alpha\alpha_s)$ corrections, in addition to higher order QCD and QED corrections

see the following slides

NC DY with FEWZ (NNLO QCD $\oplus$ NLO EW)

Li and Petriello, arXiv:1208.5967[hep-ph]



Shaded regions give the PDF (68%) uncertainty band (MSTW2008NNLO) (no α_s error included)

QCD - EW corrections interference

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

$$d\sigma = d\sigma_0 + d\sigma_{\alpha_s} + d\sigma_\alpha + d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \dots$$

- 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

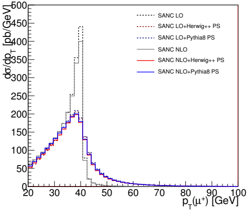
  N. Adam, V. Halyo and S.A. Yost, JHEP bf 11 (2010) 074; JHEP bf 05 (2008) 062; JHEP bf 09 (2008) 133

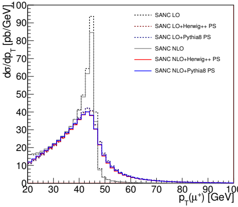
  by comparing HERWIG + PHOTOS with HERWIG +HORACE which includes QED PS matched to the exact NLO EW calculation
  $\Rightarrow$ differences found at the level of 1-2% on cross sections

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





A recipe to match 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

⊕ **Additive prescription:**

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

⊗ **Factorized prescription:**

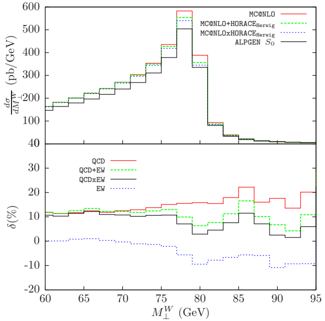
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\texttt{HERWIG}\ \text{PS}}}{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{(N)LO}}}\right) \times \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}}\right\}_{\t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

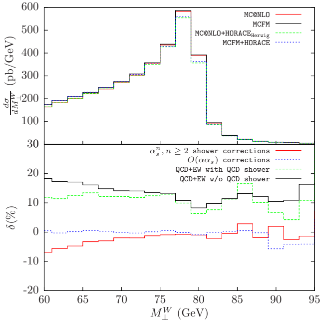
Combining EW and QCD corrections

- QCD ⇒ ResBos, MCFM, MC@NLO, POWHEG, ...
- EW ⇒ Electroweak + multiphoton corrections from HORACE convoluted with HERWIG QCD Parton Shower
  - ⋆ NLO electroweak corrections are interfaced to QCD Parton Shower evolution ⇒ $\mathcal{O}(\alpha\alpha_s)$ 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

$M_{\perp}^{W}$ @ LHC

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

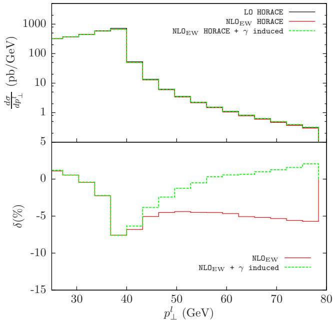


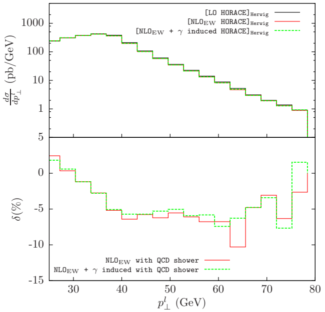


- QCD shower evolution very important below peak
- $\mathcal{O}(\alpha\alpha_s)$ corrections play a role above peak

$p_\perp^l$ @ 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).

Towards a unified QCD⊗EW generator: POWHEG

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

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

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

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

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

- ${\alpha_{\rm r}}^{\rm QCD} \rightarrow {\alpha_{\rm r}}^{\rm QCD+QED}$
    - $d\bar{u} \rightarrow (W^- \rightarrow l\bar{\nu})g$ 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: $V_{QCD} + V_{EW}$

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

- 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 $\Delta\alpha_{\rm had}$ in the $\alpha(0)$ scheme
- default: G_μ scheme, G_μ, M_W and M_Z as input

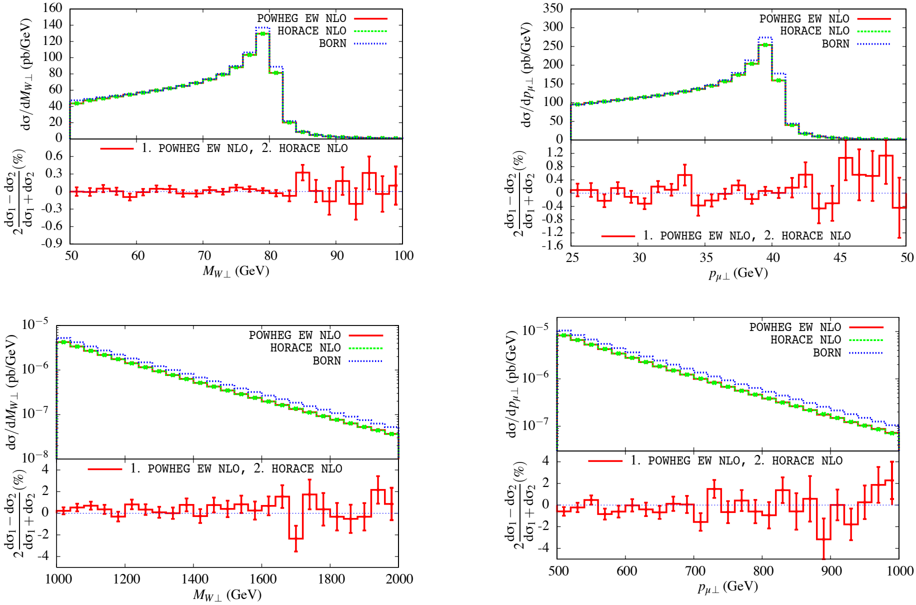
An independent implementation of NLO EW

C. Bernaciak and D. Wackeroth, arXiv:1201.4804

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

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

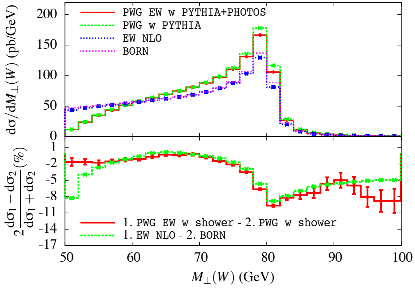
parton level comparison HORACE-POWHEG($\alpha_s \to 0$)

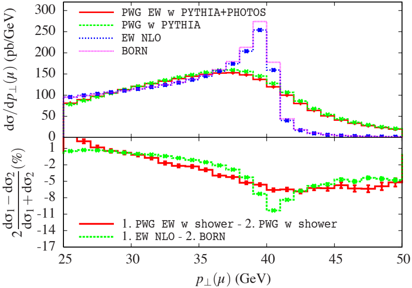


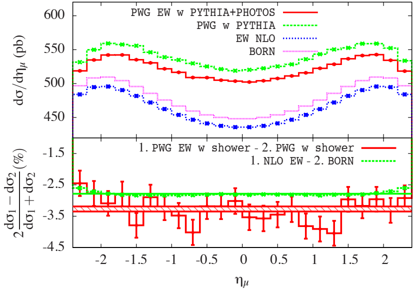
$$\Delta \equiv \Delta_{QCD} \times \Delta_{EW}$$

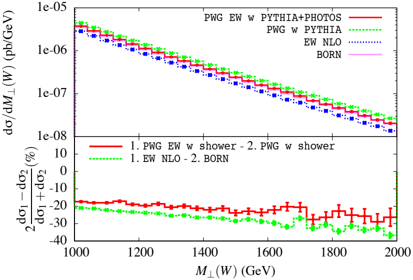
- generation of a radiation $p_\perp$ for each Sudakov form factor and choice of the largest one as maximum scale for gluon and γ radiation
- different lower radiation $p_\perp$ cutoff
  - Λ_{QCD} for g or γ radiation from quarks
  - m_l for γ radiation off leptons
- QED radiation handled with PHOTOS
  - 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



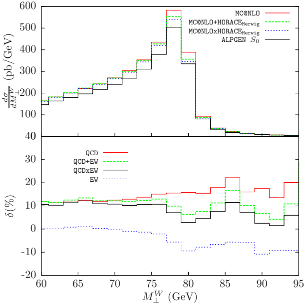


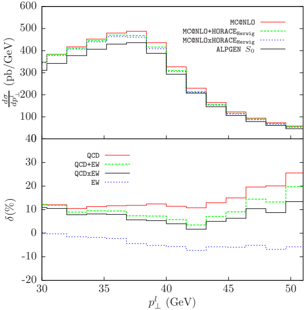




Not tuned comparison with MC@NLO$\oplus/\otimes$HORACE

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

Summary

Two new versions of POWHEG for c.c. Drell-Yan with QCD&EW RC

- 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

Work in progress

- Extension to neutral DY in progress
- Detailed comparison between the two approaches
- More in general, within the CERN LPCC EWWG, critical comparison of predictions from several codes used in the LHC experimental analysis, with the aim of assess the present systematic uncertainty of theoretical predictions
- Validation with existing data