

Calculations for $\sin^2 \theta_{\text{eff}}^l$ from ZGRAD2

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Some EW predictions for $pp \rightarrow W \rightarrow \nu l$, $pp \rightarrow Z, \gamma \rightarrow ll$

- Complete EW $\mathcal{O}(\alpha)$ corrections: HORACE, RADY, SANC, WGRAD/ZGRAD2

U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005)

U.Baur, D.W., PRD70 (2004); S.Dittmaier, M.Krämer, PRD65 (2002); A.Andonov *et al*, EPJC46 (2006); Arbuzov *et al*, EPJC54 (2008); S.Dittmaier, M.Huber, JHEP60 (2010).

- Multiple final-state photon radiation: HORACE, RADY, WINHAC, PHOTOS

W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004); S.Brensing *et al*, PRD77 (2008)

- EW Sudakov logarithms up to $N^3 LL$ Jantzen, Kühn, Penin, Smirnov (2005); brief review: J.H.Kühn, Acta Phys.Polon.B39 (2008)

- NLO EW corrections to W production implemented in POWHEG Baraciak, W. (2012); Barze *et al.* (2012) ⇒ Study of mixed QED-QCD effects

- NLO EW corrections to Z production implemented in POWHEG Barze *et al.* (2013) ⇒ Study of mixed QED-QCD effects

- NLO EW corrections to Z production implemented in FEWZ (NNLO QCD) Li, Petriello (2012)

- $W + 1j, Z + 1j, Z + 2j$ (stable Z) at NLO EW, now with leptonic W, Z decays W.Hollik *et al* (2008); S.Dittmaier *et al* (2009); J.H.Kühn *et al* (2008); A.Denner *et al*. (2010); Actis *et al* (2012); weak Sudakov corr. to $Z + \leq 3$ jets in Alpgen Chiesa *et al* (2013)

- Toward W and Z production at $\mathcal{O}(\alpha\alpha_s)$ Kotikov *et al* (2008); Bonciani (2011); Kilgore, Sturm (2011); S.Dittmaier, A.Huss, C.Schwinn (2014)

ZGRAD2 (in WZGRAD): availability and references

- ZGRAD2 as part of WZGRAD can be downloaded from the DY 2016 report repository:
 <https://twiki.cern.ch/twiki/bin/view/Main/DrellYanComparison>
- See the [DY 2016 report](#) for more results obtained with ZGRAD2:
 Precision studies of observables in $pp \rightarrow W \rightarrow l_l$ and $pp \rightarrow \gamma, Z \rightarrow l^+l^-$ processes at
 the LHC [arXiv:1606.02330 \[hep-ph\]](#)

Original references:

- complete QED $\mathcal{O}(\alpha)$ corrections (ZGRAD) [U.Baur, S.Keller, W.Sakumoto, PRD57 \(1998\)](#)
- complete EW $\mathcal{O}(\alpha)$ corrections (ZGRAD2) [U.Baur et al, PRD65 \(2002\)](#).

ZGRAD2 (in WZGRAD): a brief description

- WZGRAD combines the MC programs WGRAD2 and ZGRAD2.
- It is a parton-level MC program that includes the complete $\mathcal{O}(\alpha)$ electroweak radiative corrections to $p\overset{\leftarrow}{p} \rightarrow W^\pm \rightarrow \ell^\pm \nu X$ (WGRAD2) and $p\overset{\leftarrow}{p} \rightarrow \gamma, Z \rightarrow \ell^+ \ell^- X$ ($\ell = e, \mu$) (ZGRAD2) in the on-shell renormalization scheme.
- The phase space slicing method for next-to-leading-order (NLO) calculations is used.
- Final-state charged lepton mass effects are included in the following approximation: The lepton mass regularizes the collinear singularity associated with final-state photon radiation. The associated mass singular logarithms of the form $\ln(\hat{s}/m_\ell^2)$, are included in the calculation, but terms of $\mathcal{O}(m_\ell^2/\hat{s})$ are neglected.
- The absorption of the universal initial-state quark mass singularities by redefined (*renormalized*) PDFs, and the cross sections become dependent on the QED factorization scale μ_{QED} . WZGRAD can be used both in the QED $\overline{\text{MS}}$ and DIS schemes, which are defined analogously to the usual $\overline{\text{MS}}$ and DIS schemes used in QCD calculations.
- It is recommended that WZGRAD is used with a constant width and the G_μ input scheme, which corresponds to the EW input scheme used for producing the benchmark results in the DY 2016 report.
- Radiative corrections beyond $\mathcal{O}(\alpha)$ are partially implemented (see, e.g., DY 2016 report).
- ZGRAD2 (in WZGRAD) provides separate results for QED (FSR, ISR, and interference) and weak corrections.

Mass-singular logarithms of QED origin: FSR beyond NLO

Multiple FS photon radiation and exponentiation at LL, $L = \log(\frac{Q^2}{m_f^2})$:

- Exponentiation of YFS form factor [Yennie, Frautschi, Suura \(1961\)](#):

$$Y(m \ll Q) = \frac{\alpha}{\pi} \left\{ 2(L - 1) \ln\left(\frac{2\Delta E_\gamma}{Q}\right) + \frac{1}{2}L - \frac{1}{2} - \frac{\pi^2}{6} \right\}$$

Implemented in **WINHAC** for W production [Placzek et al \(2003\)](#), matched to NLO EW of **SANC** [Bardin et al \(2008\)](#); and in **Sherpa** [M. Schönherr, F. Krauss \(2008\)](#).

- QED parton shower: emission of n photons ($I_+ = \int_0^{1-\epsilon} dz P(z)$)

$$d\sigma = \exp[-\frac{\alpha}{2\pi} I_+ L] \sum_n^\infty |M_n^{LL}|^2 d\Phi_n$$

Implemented in **HORACE** [Carloni-Calame et al \(2003,2004,2006\)](#), matched to full NLO EW.

- QED structure function [Kuraev, Fadin \(1985\)](#):

$$d\sigma = d\sigma_{LO} \int dz \Gamma(z) \theta_{cut}(zp_I); \beta_I = \frac{2\alpha(0)}{\pi} (L - 1)$$

$$\Gamma(z, Q^2) = \frac{\exp[-\beta_I/2\gamma_E + \frac{3}{8}\beta_I]}{\Gamma(1 + \beta_I/2)} \frac{\beta_I}{2} (1 - z)^{\beta_I/2 - 1} + \dots + \mathcal{O}(\beta_I^4)$$

Implemented in W production [Brensing, Dittmaier, Krämer, Mück \(2008\)](#) and Z production [Dittmaier, Huber \(2009\)](#), matched to full NLO EW; **only in private version of ZGRAD2 (WZGRAD)**

- POWHEG(NLO QCD+EW) \otimes (QCD+QED) PS; QED PS with **PHOTOS** ([Golonka, Was \(2005,2006\)](#)) or with **PYTHIA 8** for W production [Carloni Calame et al, 1612.02841](#).

Initial-state photon radiation (ISR)

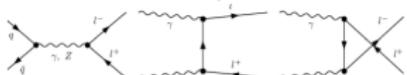
Mass singularities due to collinear radiation survive but are absorbed by universal collinear counterterms to the parton distribution functions; mass factorization done in complete analogy to QCD:

- introduces dependence on QED factorization scheme (in analogy to QCD there is a *DIS* and \overline{MS} scheme) see, e.g. Baur, Keller, D.W., Phys. Rev. D59, 013002 (1999)

$$\begin{aligned} q_i(x, Q^2) &= q_i(x) \left[1 + \frac{\alpha}{\pi} Q_i^2 \left\{ 1 - \ln \delta_s - \ln^2 \delta_s + \left(\ln \delta_s + \frac{3}{4} \right) \ln \left(\frac{Q^2}{m_i^2} \right) - \frac{1}{4} \lambda_{FC} f_{v+s} \right\} \right] \\ &\quad + \int_x^{1-\delta_s} \frac{dz}{z} q_i \left(\frac{x}{z} \right) \frac{\alpha}{2\pi} Q_i^2 \left\{ \frac{1+z^2}{1-z} \ln \left(\frac{Q^2}{m_i^2} \frac{1}{(1-z)^2} \right) - \frac{1+z^2}{1-z} + \lambda_{FC} f_c \right\} \\ f_{v+s} &= 9 + \frac{2\pi^2}{3} + 3 \ln \delta_s - 2 \ln^2 \delta_s \\ f_c &= \frac{1+z^2}{1-z} \ln \left(\frac{1-z}{z} \right) - \frac{3}{2} \frac{1}{1-z} + 2z + 3 \end{aligned}$$

- PDFs including QED in their evolution have been made available, providing a photon PDF which allow for inclusion of photon-induced processes. See, e.g., combined LO QED \times NNLO QCD DGLAP evolution with APFEL, apfel.mi.infn.it

Photon-induced process at LO (only in private version of ZGRAD2):



A_{FB} and $\sin^2 \theta_{\text{eff}}^I$ in NC DY at the LHC

- Forward-backward asymmetry $A_{FB}(M_{II}, y_{II})$ in NC DY is sensitive to $\sin^2 \theta_I^{\text{eff}}$:

$$A_{FB} = \frac{F - B}{F + B}$$

with

$$F = \int_0^1 \frac{d\sigma}{d \cos \theta^*} d \cos \theta^*, \quad B = \int_{-1}^0 \frac{d\sigma}{d \cos \theta^*} d \cos \theta^*$$

with $\cos \theta^*$ defined in the Collins-Soper frame ($I = \mu, e$):

$$\cos \theta^* = \frac{|p_z(I^+ I^-)|}{p_z(I^+ I^-)} \frac{2[p^+(I^-)p^-(I^+) - p^-(I^-)p^+(I^+)]}{m(I^+ I^-) \sqrt{m^2(I^+ I^-) + p_T^2(I^+ I^-)}}$$

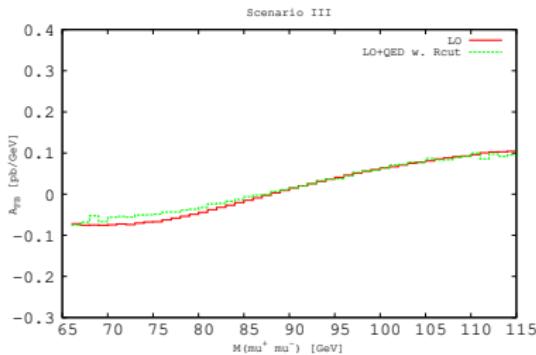
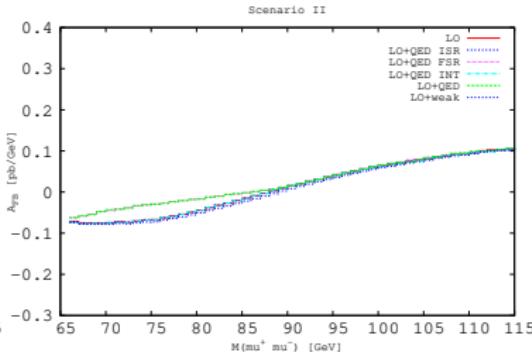
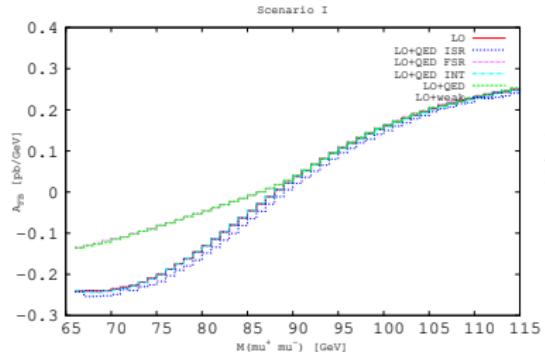
$$(p^\pm = \frac{1}{\sqrt{2}} (E \pm p_z))$$

- with the partonic cross section: $d\hat{\sigma}_{NLO\,EW} = d\hat{\sigma}_{QED} + d\hat{\sigma}_{weak}$ with
 $d\hat{\sigma}_{weak} = dP_{2f}[|A_\gamma^{(0+1)} + A_Z^{(0+1)}|^2(s, t, u)] + d\sigma_{box}(s, t, u)$
- A_{FB} (measured) $\leftrightarrow A_{FB}(\sin^2 \theta_{\text{eff}}^I)$ (MC)?
 Requires a parametrization of MC prediction for A_{FB} in terms of $\sin^2 \theta_{\text{eff}}^I$ around the Z resonance in the presence of higher-order corrections and quark-couplings to the Z boson (work in progress).
- Estimate of theoretical/parametric uncertainty (work in progress).

Input and cuts:

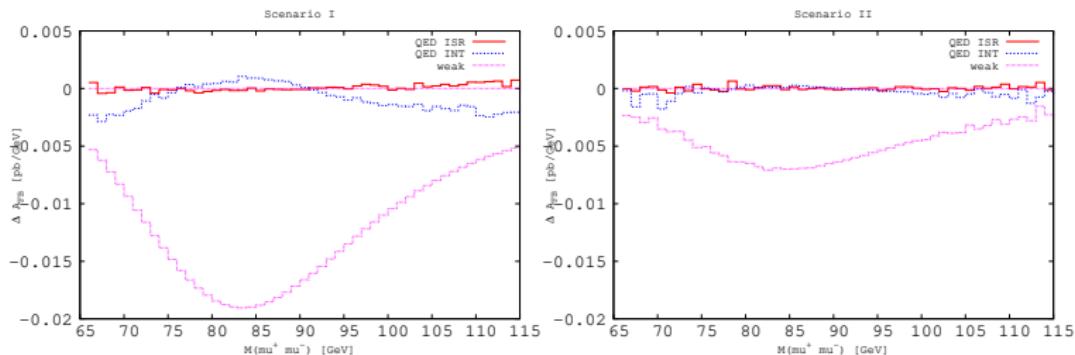
- Input as described in the DY 2016 report: $\alpha(0), M_W, M_Z, m_f, \Gamma_Z \dots$
- $66 \text{ GeV} < M_{\mu^+\mu^-} < 116 \text{ GeV}$
- 3 scenarios:
 - I: no lepton id cuts
 - II: $p_T(\mu^\pm) > 25 \text{ GeV}, |\eta(\mu^\pm)| < 2.4$
 - III: $p_T(\mu^\pm) > 25 \text{ GeV}, |\eta(\mu^\pm)| < 2.4$ and event is cut if $E_\gamma > 2 \text{ GeV}$ for $\Delta R(\mu\gamma) < 0.1$ or if $0.1 < \Delta R(\mu\gamma) < 0.4$ for $E_\gamma > 0.1E_\mu$

Preliminary studies for $A_{FB}(M(\mu^+\mu^-))$ with WZGRAD (ZGRAD2)



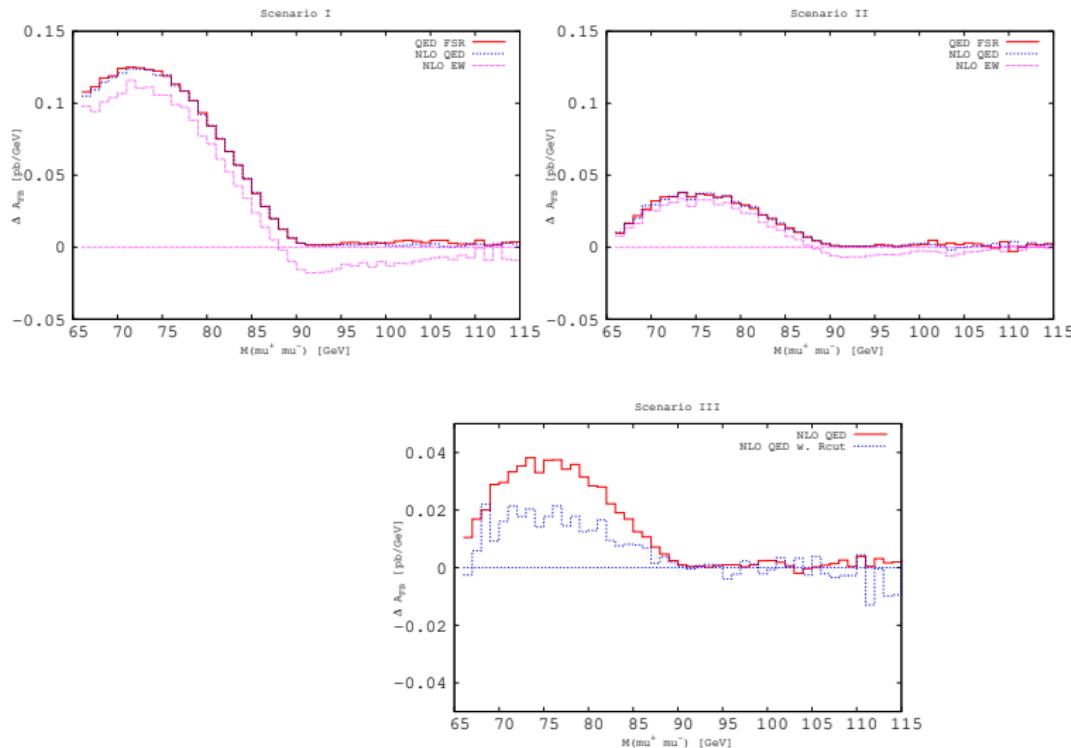
Preliminary studies for $A_{FB}(M(\mu^+\mu^-))$ with WZGRAD (ZGRAD2)

$$\Delta A_{FB} = A_{FB}(\text{LO} + \mathcal{O}(\alpha) \text{ corrections}) - A_{FB}(\text{LO})$$



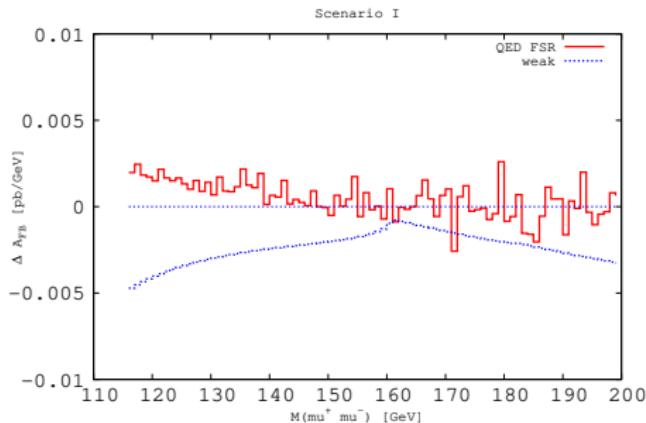
Preliminary studies for $A_{FB}(M(\mu^+\mu^-))$ with WZGRAD (ZGRAD2)

$$\Delta A_{FB} = A_{FB}(\text{LO} + \mathcal{O}(\alpha) \text{ corrections}) - A_{FB}(\text{LO})$$



Preliminary studies for $A_{FB}(M(\mu^+\mu^-))$ with WZGRAD (ZGRAD2)

$$\Delta A_{FB} = A_{FB}(\text{LO} + \mathcal{O}(\alpha) \text{ corrections}) - A_{FB}(\text{LO}) \text{ at high } M(\mu^+\mu^-)$$



Next steps

- Participate in the tuned comparison/benchmarking, e.g., with HORACE, SANC, RADY.
- Implement possible “new” parametrization of A_{FB} in terms of $\sin^2 \theta_{\text{eff}}^l$.