Calculations for $\sin^2\theta^l_{\rm eff}$ from ZGRAD2

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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 $pp \to W \to l_l$ and $pp \to \gamma, Z \to l^+ l$ 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 $p^{(-)}p \to W^{\pm} \to \ell^{\pm}\nu X$ (WGRAD2) and $p^{(-)}p \to \gamma,\, Z \to \ell^{+}\ell^{-} X$ ($\ell = e,\, \mu$) (ZGRAD2) in the on-shell renormalization scheme.
- The phase space slicing method for next-to-leading-order (NLO) calculation 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 $\mu_{\rm QED}$. WZGRAD can be used both in the QED $\overline{\rm MS}$ and DIS schemes, which are defined analogously to the usual $\overline{\rm MS}$ 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) in form of leading two-loop EW and QCD corrections to the ρ parameter.
- ZGRAD2 (in WZGRAD) provides separate results for QED (FSR, ISR, and interference (IFI)) and weak corrections.

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)

$$q_i(x,Q^2) = q_i(x)\left[1+\frac{\alpha}{\pi}Q_i^2\left\{1-\ln\delta_s-\ln^2\delta_s+\left(\ln\delta_s+\frac{3}{4}\right)\ln\left(\frac{Q^2}{m_i^2}\right)-\frac{1}{4}\lambda_{FC}f_{v+s}\right\}\right]$$

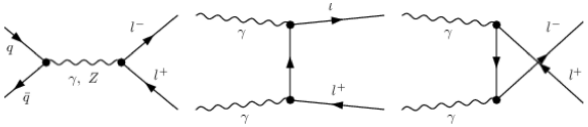
$$+\int_x^{1-\delta_s}\frac{dz}{z}\,q_i\left(\frac{x}{z}\right)\,\frac{\alpha}{2\pi}Q_i^2\left\{\frac{1+z^2}{1-z}\ln\left(\frac{Q^2}{m_i^2}\frac{1}{(1-z)^2}\right)-\frac{1+z^2}{1-z}+\lambda_{FC}f_c\right\}$$

$$f_{v+s} = 9+\frac{2\pi^2}{3}+3\ln\delta_s-2\ln^2\delta_s$$

$$f_c = \frac{1+z^2}{1-z}\ln\left(\frac{1-z}{z}\right)-\frac{3}{2}\frac{1}{1-z}+2z+3$$

- 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} in NC DY at the LHC

- Forward-backward asymmetry A_{FB} in NC DY at the LHC:

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

with

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

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

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

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

- with the partonic cross section: $d\hat{\sigma}_{NLO\,EW} = d\hat{\sigma}_{QED} + d\hat{\sigma}_{weak}$ with $d\hat{\sigma}_{weak} = dP_{2f}[|A_\gamma^{(0+1)} + A_Z^{(0+1)}|^2(s,t,u)] + d\sigma_{box}(s,t,u)$

Preliminary studies with ZGRAD2 and comparison with MCSANC

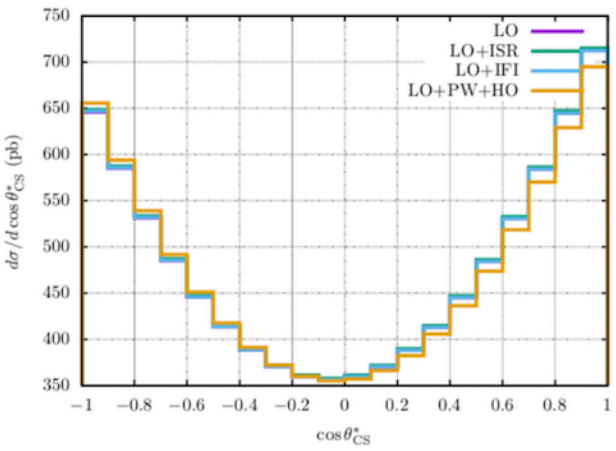
$p\,p \to \gamma,\, Z \to \mu^+\mu^- X$ at 8 TeV
Input and cuts as described by MCSANC at the January 29 meeting:

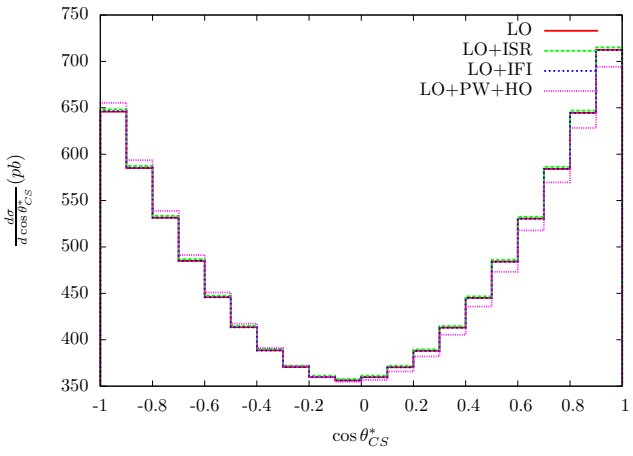
- LO QCD – no QCD corrections
- Fixed-width scheme: $\mathrm{prop}(s, M_Z) = 1/(s - [M_Z^2 - iM_Z w_Z])$
- MSTW2008nlo68cl PDF-function (dynamical scale)
- Physical parameters:
  α_0=1/137.0360, $\alpha(\mathrm{G}_\mu)$=132.3560, g_{Fermi}=1.166389 $\cdot$ 10^{-5},
  M_W=80.35797 GeV, M_Z=91.15348 GeV, Γ_Z=2.494266 GeV
- Pure weak (PW) virtual corrections (self-energies, vertices, ZA and ZZ-boxes) and high-order (HO) corrections (α^2_{fer} and $\alpha\alpha_s(s)$ terms to $\Delta\rho$ parameter)
- Initial-State-Radiation (ISR) and Initial-Final-Interference (IFI) QED corrections: virtual (vertices, AA-boxes), soft and hard real photon radiation
- G_μ EW-scheme is considered
- No p_T and η cuts, only m_{ll}=[60-120] GeV

$$m_t = 173\,\mathrm{GeV}, \mathrm{m_u} = 0.06984\,\mathrm{GeV}, \mathrm{m_d} = 0.06983\,\mathrm{GeV}$$

Preliminary studies with ZGRAD2 and comparison with MCSANC

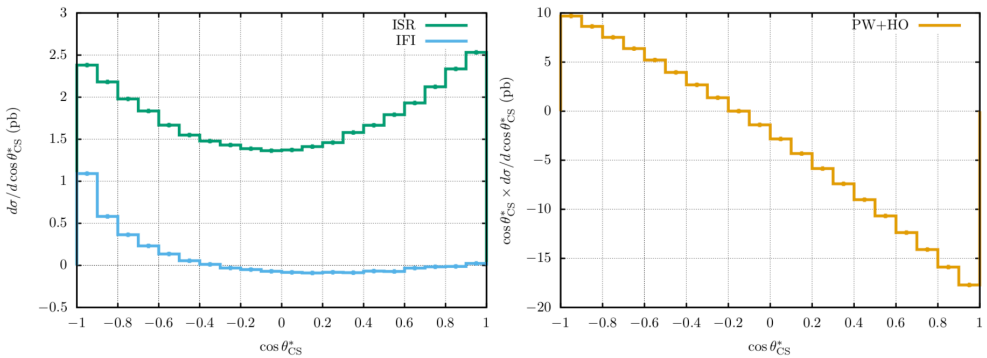
Distributions on $\cos\theta^*_{\rm cs}$

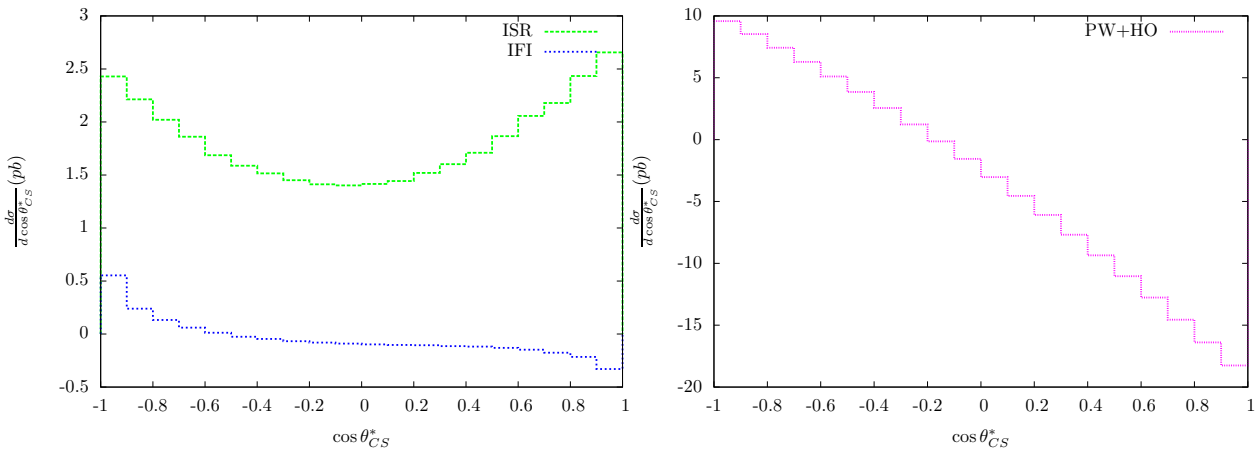




Preliminary studies with ZGRAD2 and comparison with MCSANC

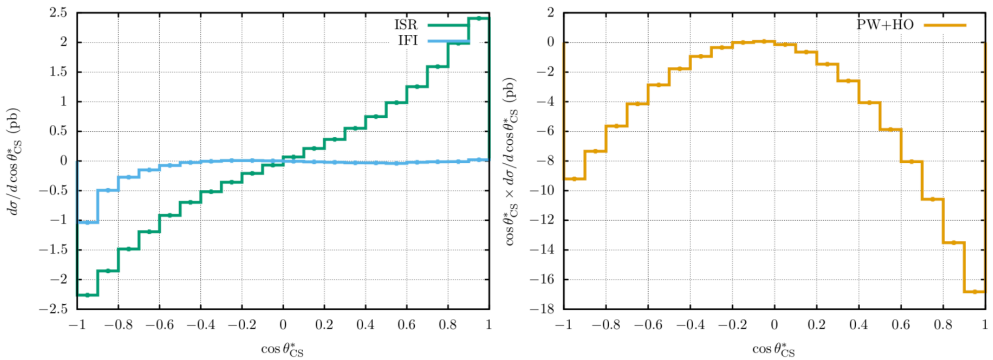
Distributions on $\cos\theta^*_{\rm cs}$: $\sigma - \sigma_{\rm LO}$

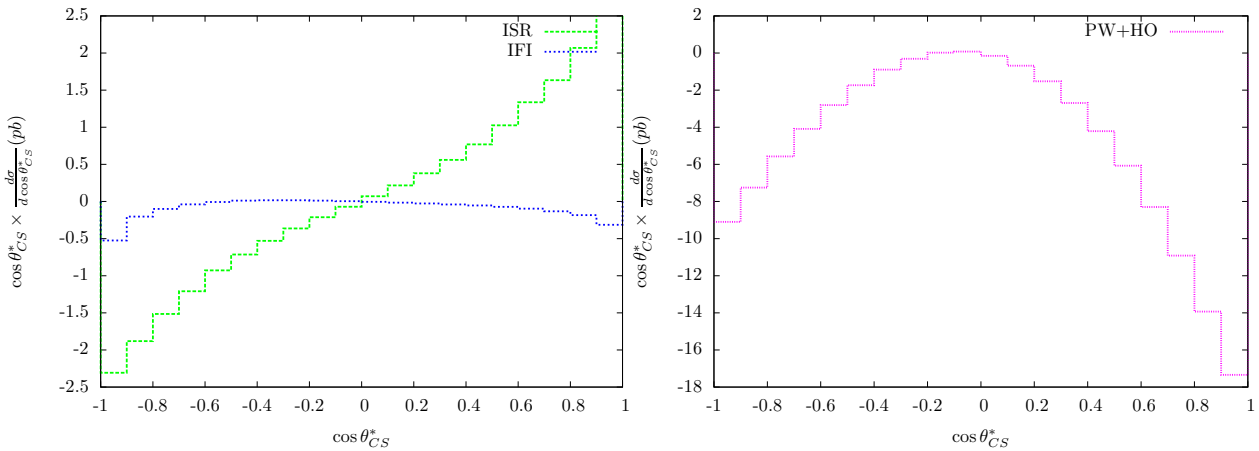




Preliminary studies with ZGRAD2 and comparison with MCSANC

Distributions on $\cos\theta^*_{\rm cs}$: $\cos\theta^*_{\rm cs} \times (\sigma - \sigma_{\rm LO})$





Preliminary studies with ZGRAD2 and comparison with MCSANC

code	σ [pb]	A_{FB}
MCSANC	[LO] 951.76(1)	0.03683(1)
ZGRAD2	[LO] 951.47(1)	0.03683(1)
MCSANC	[LO+ISR] 955.23(1)	0.03678(1)
ZGRAD2	[LO+ISR] 955.12(1)	0.03683(2)
MCSANC	[LO+IFI] 951.93(1)	0.03652(1)
ZGRAD2	[LO+IFI] 951.39(1)	0.03660(2)
MCSANC	[LO+PW] 945.81(1)	0.01997(1)
ZGRAD2	[LO+PW] 945.85(1)	0.01973(2)
MCSANC	[LO+PW+HO] 945.39(1)	0.02180(1)
ZGRAD2	[LO+PW+HO] 946.14(1)	0.02156(2)

Next steps

- Participate in the tuned comparison/benchmarking, e.g., with `HORACE`, `MCSANC`, `RADY` and `DIZET`.
- Implement "new" parametrization of A_{FB} in terms of $\sin^2\theta^l_{eff}$ of
  arXiv:1906.11569 [hep-ph]