Electroweak corrections at hadron colliders

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Significance of EW corrections at hadron colliders

$\frac{\alpha(M_Z)}{\pi} \approx 0.0025$ vs. $\frac{\alpha_s(M_Z)}{\pi} \approx 0.037$

Possible enhancements:

QED: $\frac{\alpha(0)}{\pi} \log(\frac{m_f^2}{Q^2}) \approx -0.024$ for $Q = M_W, f = \mu$

Origin: Soft/collinear FS photon radiation
In sufficiently inclusive observables these mass singularities completely cancel. Kinoshita, Lee, Nauenberg (1962,1964)

Weak at LL: $-\frac{\alpha}{\pi s_w^2} \log^2(\frac{M_V^2}{Q^2}) \approx -0.052$ for Q=2 TeV

Origin: Remnants of UV singularities after renormalization and soft/collinear IS and FS emission of virtual and real W and Z bosons.
In contrast to QED and QCD, also in inclusive observables these corrections do not completely cancel. Ciafaloni, Ciafaloni, Comelli (2000)

NLO EW calculations are available for
$pp, p\bar{p} \to W; Z \to l\nu; l^+l^-; VV; Wj; Zj \to \nu lj; l^+l^-j; t\bar{t}$; single top, and $b\bar{b}, jj$ (weak); and for dominant Higgs production processes ($gg \to H; W/ZH; VBF$, for a review see, e.g., Higgs cross section WG report, arXiv:1101.0593)

Mass singular logarithms of QED origin

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

- Exponentiation of YFS form factor Yennie,Frautschi,Suura (1961):

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

  Implemented in `WINHAC` for W production Placzek *et al* (2003), matched to NLO EW of `SANC` Bardin *et al* (2008).

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

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

  Neglects photon momentum transverse to lepton momentum. Implemented in W production Brensing, Dittmaier, Krämer, Mück (2008) and Z production Dittmaier, Huber (2009), matched to full NLO EW.

- `PHOTOS` Golonka, Was (2005,2006).

Initial-state photon radiation (ISR)

Mass singularities always 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) Baur, Keller, W., Phys. Rev. **D59**, 013002 (1999)

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

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

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

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

- PDFs including QED corrections have been made available by the MSTW collaboration A.D.Roberts *et al.*, EPJC39 (2005).
- Photon PDFs allow for inclusion photon-induced processes.

EW Sudakov logarithms $\alpha_w^l \log^n(Q^2/M^2)$, $n \leq 2l$

In the high-energy limit, $\frac{Q}{M_{W,Z}} \to \infty$, EW Sudakov logarithms have been studied in analogy to soft/collinear logarithms in QED,QCD.

- 1-loop: LL and NLL are universal and factorize Denner, Pozzorini (2001)
- Beyond 1-loop: Resummation techniques based on IR evolution equations (IREE) or SCET yield results up to NNLL ($ln^n(\frac{s}{M_W^2})$, $n = 2, 3, 4$).
  - IREE: EW theory splits into symmetric $SU(2) \times U(1)$ ($M_W = M_Z = M_\gamma = M$ for $\mu > M$) and QED regime and effect of EW symmetry breaking neglected. Fadin, Lipatov, Martin, Melles (2000)
  - SCET: At $\mu = Q$ match full theory to SCET($M = 0$), evolve to $\mu = M$ SCET($M \neq 0$), match to SCET with no gauge bosons.
  - SCET and IREE Sudakov form factors are equivalent. Chiu, Golf, Kelley, Manohar (2008); Chiu, Fuhrer, Hoang, Kelley, Manohar (2009); Chiu, Fuhrer, Kelley, Manohar (2010), Fuhrer et al (2011)

Resummation results at LL and NLL confirmed by explicit diagramatic one-loop and two-loop calculations.

Melles (2000), Hori et al (2000), Beenakker, Werthenbach (2000,2002), Pozzorini (2004); Feucht et al (2003,2004); Jantzen et al (2005,2006); Denner et al (2003,2008)

EW Sudakov logarithms $\alpha_w^l \log^n(Q^2/M^2), n \leq 2l$

- Results available for hadronic cross sections for W, Z production, VV, $t\bar{t}$, bb, cc, jj, VBF.
- Best studied so far: $f\bar{f} \to f\bar{f}$
  - up to N^3LL for massless fermions ($a = \frac{\alpha}{4\pi s_w^2}, L = \log(s/M_W^2)$):

$$\frac{\delta\sigma(e^+e^- \to q\bar{q})(s)}{\sigma_{LO}} = a(-2.18L^2 + 20.94L - 35.07) +$$
$$+a^2(2.79L^4 - 51.98L^3 + 321.20L^2 - 757.35L)$$
$$\approx 2.4\% - 0.4\% \text{ at } 2\,\mathrm{TeV}$$

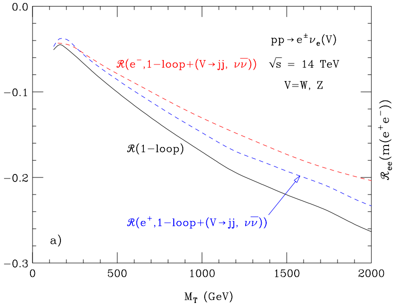
    Note: only LL at 2-loop: $+3\%$

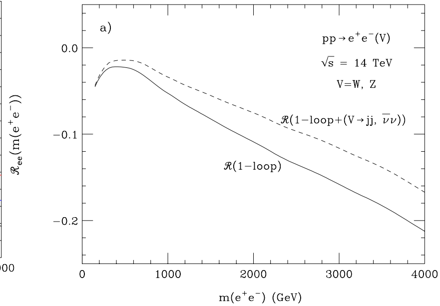
    Jantzen, Kühn, Penin, Smirnov, hep-ph/0509157
  - up to NNLL for massive fermions Denner, Jantzen, Pozzorini (2008).
  - See also SCET results by Chiu et al, (2008).

Enhanced EW corrections at high energies: impact of real W/Z radiation

Large virtual corrections may be partially canceled by real W/Z radiation, which strongly depends on the experimental setup. see, e.g., G.Bell *et al.*, 1004.4117

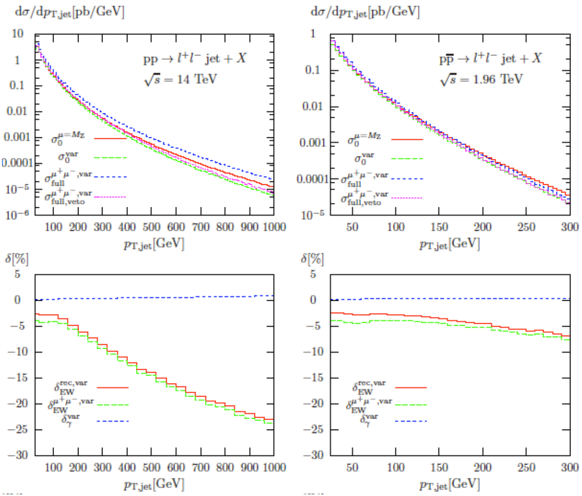
An example: Impact of real weak gauge boson radiation on $M_T(l\nu)$ and M_{ee} distributions at the LHC





U.Baur, PRD75 (2007)

$pp, p\bar{p} \to l^+l^- j$ at NLO EW



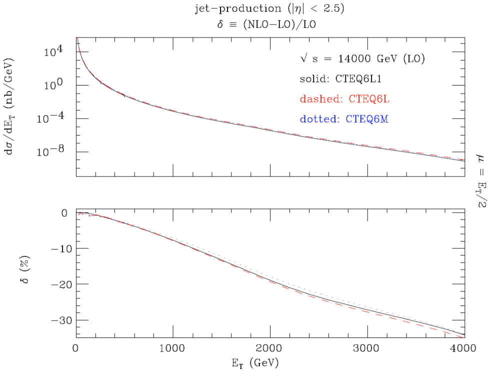
$pp \to l^+l^-$ jet $+ X$ at $\sqrt{s} = 14$ TeV

$p_{T,jet}$/ GeV	$25-\infty$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$
$\sigma_0^{\mu=M_Z}$ / fb	123491(7)	44603(2)	11364.4(5)	1813.26(8)	64.120(2)	2.11859(6)
σ_0^{var} / fb	122024(7)	43254(2)	10445.0(4)	1475.76(6)	38.648(1)	0.90847(3)
$\delta_{EW}^{\mu^+\mu^-,var}$/%	-4.2	-4.5	-5.1	-8.5	$-17.4(1)$	$-27.0(1)$
$\delta_{EW}^{rec,var}$/%	-2.8	-3.2	-4.2	-7.8	$-16.7(1)$	$-26.3(1)$

Denner, Dittmaier, Kasprzk, Mück, arXiv:1103.0914

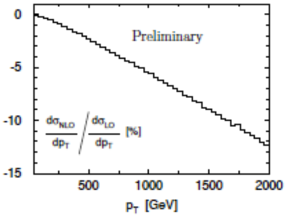
- $p_T^l > 25$ GeV, $p_T^j > 25$ GeV, $M_{ll} > 50$ GeV
- $|y| < 2.5$ for leptons and at least one jet
- $R_{lj} > 0.5$

Weak 1-loop corrections to di-jet production



Weak $\mathcal{O}(\alpha)$ corrections to the E_T^j distribution at the 14 TeV LHC

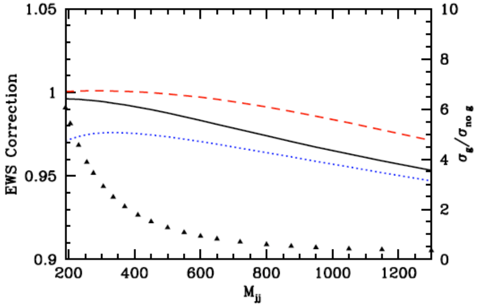
Moretti, Nolten, Ross, hep-ph/0606201



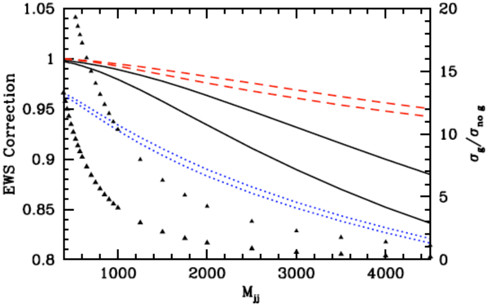
Scharf, arXiv:0910.0223

Similar effects in $b\bar{b}$ production at NLO EW Kühn, Scharf, Uwer (2009)

EW corrections to di-jet production using SCET



Weak Sudakov corrections to the M_{jj} distribution at the Tevatron



and the 7 TeV (lower curves) and 14 TeV LHC (upper curves)

Manohar and Trott, arXiv:1201.3926

Significance of EW corrections: W mass measurement

Most precise M_W measurement to date from the Tevatron: $M_W = 16$ MeV arXiv:1204.0042, see talk by A.Kotwal

Present QED uncertainty:

- CDF, arXiv:1203.0275: $\delta M_W(\text{QED}){=}4$ MeV
  ResBos[1]+PHOTOS[2], HORACE[3] used to assess impact of full EW $\mathcal{O}(\alpha)$ corrections
- D0, arXiv:1203.0293: $\delta M_W(\text{QED}){=}7$ MeV
  ResBos+PHOTOS, WGRAD[4] used to assess impact of full EW $\mathcal{O}(\alpha)$ corrections

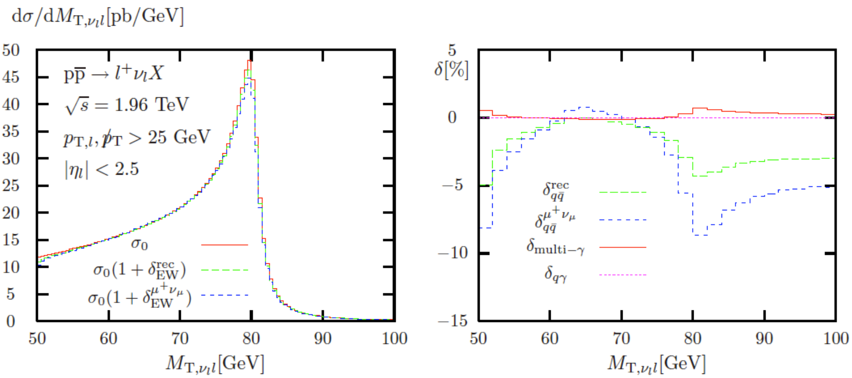
How about mixed QED-QCD effects, missing higher-order corrections ?

[1] C.Balazs and C.-P. Yuan, Pys. Rev. **D56**, 5558 (1997)
[2] P.Golonka and Z.Was, EPJC 45 (2006)
[3] C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP 0612 (2006) 016
[4] U.Baur,S.Keller and D.W., Phys. Rev. **D59**, 013002 (1999)

Status of EW predictions for $pp \to W \to \nu l, pp \to Z, \gamma \to ll$

- EW $\mathcal{O}(\alpha)$ corrections: `HORACE, SANC, W/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, WINHAC, PHOTOS`
  W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004); S.Brensing *et al*, PRD77 (2008)
- EW-like Sudakov logarithms up to N^3LL Jantzen, Kühn, Penin, Smirnov (2005); brief review: J.H.Kühn, Acta Phys.Polon.B39 (2008)
- NLO EW corrections to W production implemented in POWHEG Bernaciak, W. (2012); Barze et al. (2012) $\Rightarrow$ Study of mixed QED-QCD effects
- $W + j, Z + j$ 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).
- Two-loop virtual $\mathcal{O}(\alpha\alpha_s)$ correction to DY Kilgore, Sturm (2011)

Impact of EW corrections on $M_T(l\nu)$



Brensing, Dittmaier, Krämer, Mück (2008)

Shifts in M_W: δM_W(QED FSR) $\approx \mathcal{O}(100)$ MeV

$\delta M_W(mFS) \approx 2, 10$ MeV for e, μ Carloni-Calame et al (2003)

WGRAD2+POWHEG-W

Incorporation of EW $\mathcal{O}(\alpha)$ corrections into $\bar{\mathrm{B}}$ of POWHEG-W[1−4] by Bernaciak, W., arXiv:1201.4804:

$$\bar{\mathrm{B}}(\Phi_2) = \mathrm{B}(\Phi_2) + V_{\mathrm{QCD}}(\Phi_2) + V_{\mathrm{EW}}(\Phi_2) + \int_{\oplus} \frac{dz}{z}\left[\mathrm{G}_{\oplus,\mathrm{QCD}}(\Phi_{2,\oplus}) + \mathrm{G}_{\oplus,\mathrm{EW}}(\Phi_{2,\oplus})\right]$$

$$+ \int_{\ominus} \frac{dz}{z}\left[\mathrm{G}_{\ominus,\mathrm{QCD}}(\Phi_{2,\ominus}) + \mathrm{G}_{\ominus,\mathrm{EW}}(\Phi_{2,\ominus})\right] + \sum_{\alpha_r \in \mathrm{IS}} \int d\Phi_{\mathrm{rad},IS}\left[\hat{\mathrm{R}}(\Phi_3) + \mathrm{R}_{\mathrm{EW}}(\Phi_3)\right]$$

- ⇒ $V_{\mathrm{EW}}(\Phi_2)$ virtual + soft finite EW corrections
  - ⇒ switch for resonant/non-resonant (box diagrams) effects
- ⇒ $\mathrm{G}_{\mathrm{EW}}(\Phi_2, z)$ IS and FS collinear EW pieces
- ⇒ $\mathrm{R}_{\mathrm{EW}}(\Phi_3)$ finite real piece - IS and FS together
  - ⇒ switch for IS, FS, interference QED radiation
- ⇒ finite charged lepton mass effects included

Resulting public code available within POWHEG-BOX as subprocess W_ew-BW

[1] P.Nason, *JHEP* **0411** (2004) 040, hep-ph/0409146

[2] S.Frixione,P.Nason and C. Oleari, *JHEP* **0711** (2007) 070, arXiv:0709.2092

[3] S.Alioli,P.Nason,C. Oleari and E.Re, *JHEP* **1006** (2010) 043, arXiv:1002.2581

[4] S.Alioli,P.Nason,C. Oleari and E.Re, *JHEP* **0807** (2008) 060, arXiv:0805.4802

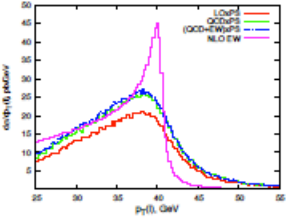
EW+POWHEG-W+QED PS

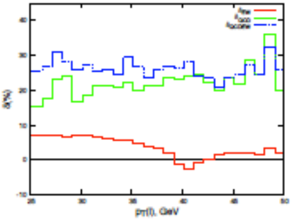
Implementation of EW corrections in POWHEG by L. Barze et al., arXiv:1202.0465:

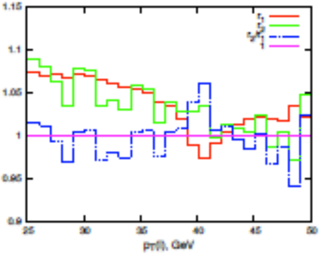
- Virtual $\mathcal{O}(\alpha)$ corrections from S.Dittmaier and M.Krämer, PRD 65 (2002), and checked against HORACE
- soft and collinear photon radiation is treated in the same way as light partons
- NLO EW and QCD are both interfaced to QCD and QED shower MCs
- Multiple photon radiation included (PHOTOS)

Resulting public code available within POWHEG-BOX as subprocess W_ew-BMNNP

- Tuned comparison of these two implementations and implementation of EW corrections in POWHEG for Z production is work in progress.







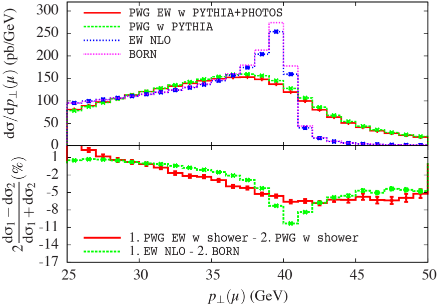
Bernaciak, W., arXiv:1201.4804

Sensitive to QED FSR effects around Jacobian peak due to collinear logs $\alpha \, log(m_l^2/\hat{s})$

$\delta_a = \left[\left(\frac{d\sigma_a}{d\mathcal{O}} - \frac{d\sigma_{LO}}{d\mathcal{O}} \right) / \frac{d\sigma_{LO}}{d\mathcal{O}} \right] \times 100$

$r_1 = \frac{d\sigma_{EW}}{d\mathcal{O}} \, / \, \frac{d\sigma_{LO}}{d\mathcal{O}}$

$r_2 = \frac{d\sigma_{(QCD+EW)xPS}}{d\mathcal{O}} \, / \, \frac{d\sigma_{QCDxPS}}{d\mathcal{O}}$



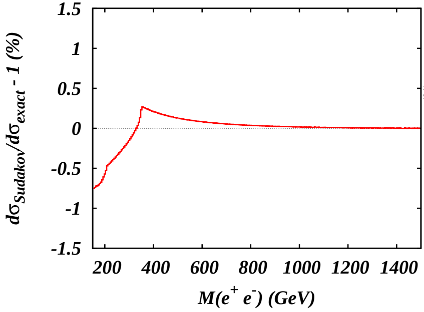
- similar behavior: *EW in presence of QCD is 'washed out'*

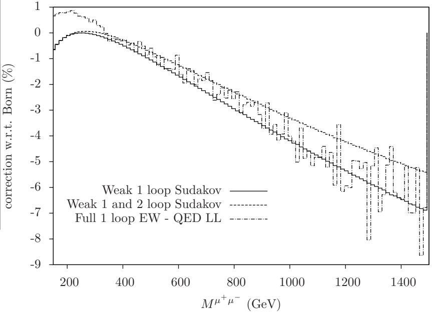
- from L. Barze et al., arXiv:1202:0465
- LHC, $\sqrt{S} = 7$ TeV

See also earlier studies of mixed QED-QCD effects using HORACE+MC@NLO and ResBos+QED FSR G. Balossini *et al*, arXiv:0907.0276; Cao, Yuan; and B.F.L. Ward *et al* (2008) (HERWIRI

Impact in M_W ? Complete $\mathcal{O}(\alpha\alpha_s)$ corrections needed ?

Complete EW $\mathcal{O}(\alpha)$ vs 1-loop and 2-loop Sudakov approx. in Z prod.



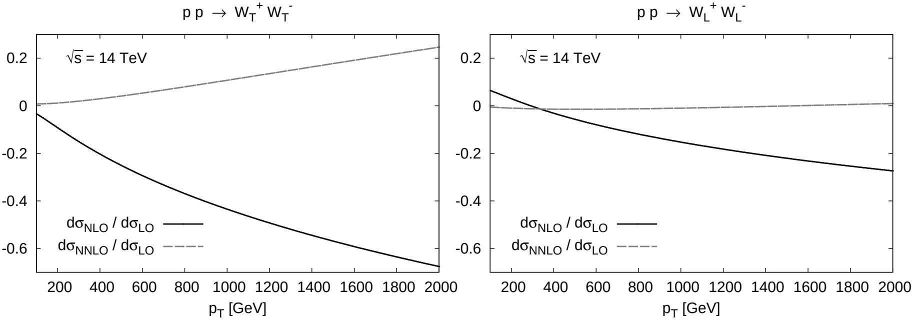


Buttar *et al*, LesHouches WG report, arXiv:0803.0678 (with ZGRAD2 and HORACE)

B.Jantzen *et al*, NPB731 (2005)

WW production at NLL+NNLL EW at the LHC

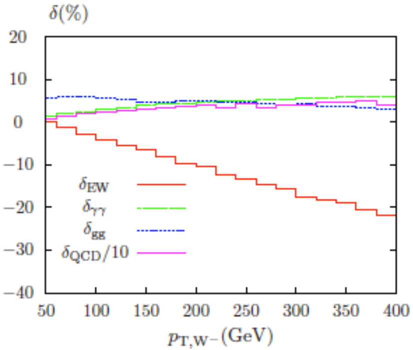
Impact of NLL and NLL+NNLL EW corrections on p_T distributions of W pairs :



J.H. Kühn *et al*, 1101.2563

WW production at NLO EW at the LHC

p_T and y_w (with $M_{WW} > 500$ GeV) distributions of W^- at NLO EW at the 8 TeV LHC:



Bierweiler *et al*, 1208.3147

Interesting feature not seen in single-W production: photon-induced processes contribute considerably.

Final remarks

- Tremendous effort and a lot of progress in calculating higher order EW corrections and in understanding the enhanced logarithmic corrections of ratios of different scales.
- Their significance strongly depends on details of experimental definition of observable, specifically which kinematic regime is probed.
- Implementation of EW corrections in publicly available MCs in progress, enabling studies of higher-order mixed QED-QCD effects.
- Important and difficult task: reliable estimates of theoretical uncertainties due to missing higher-order corrections (work in progress for W/Z observables)