Theory Challenges in Electroweak Precision Physics

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LHC Run II and the Precision Frontier
&
Experimental Challenges for the LHC Run II

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A new era of Electroweak (EW) precision physics

All Standard Model (SM) parameters are known and SM observables can in principle be precisely predicted after choosing a suitable set of SM input parameters:

$$\alpha(0), \alpha(M_Z), \alpha_s(M_z), G_\mu, \Delta\alpha^{(5)}_{had}, M_Z, M_W, M_H, m_t, m_b, m_{u,d,s,c}, m_e, m_\mu, m_\tau, V_{qq'}$$

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha(0)M_Z^2}{2(M_Z^2 - M_W^2)M_W^2}[1 + \Delta r(\alpha(0), M_Z, M_W, m_t, M_H, \ldots)]$$

$$\alpha(M_Z) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

We can look forward to increasingly stringent tests of the SM and higher sensitity to new physics. But potential for discovery or constraining new physics models also relies on control of all relevant

- higher-order contributions in perturbation theory, e. g., at the LHC: NNLO QCD and NLO EW (both in parton shower MCs), combined QCD/EW, resummation (QCD, QED, EW Sudakovs)
- non-perturbative effects ($\Delta\alpha^{(5)}_{had}$, PDFs, ...),
- parametric uncertainties due to uncertainties in the measurement of the input parameters: $M_W, M_H, m_t, \ldots$.

The role of M_W, M_H, and m_t in precision tests of the SM

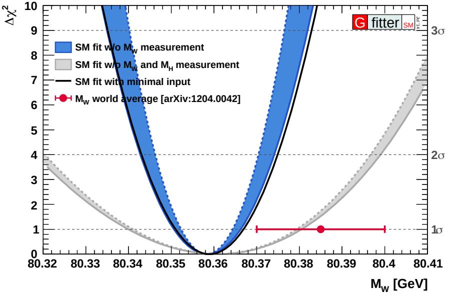
The SM has proven to be very robust and increasingly precise tests of the SM are needed.
M_W, M_H, m_t play important roles both as input parameters and electroweak precision observables (EWPO).
They have been measured with impressive high precision (from PDG and arXiv:1403.4427):

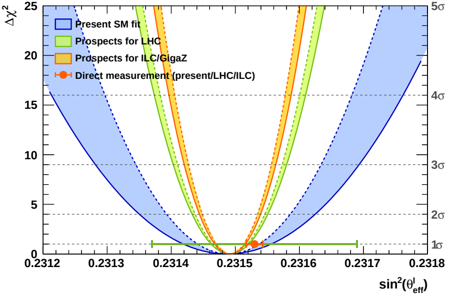
$$M_W = 80385 \pm 15\ MeV;\ m_t = 173.34 \pm 0.76\ GeV;\ M_H = 125.09 \pm 0.24\ GeV$$

Further improved measurements will allow for:

- Decreased parametric uncertainties in precision observables.
- Precise SM predictions for Higgs boson properties, e.g., the Higgs width directly depends on M_H!
- More and more stringent consistency checks of the SM: measurement vs SM prediction of M_W, M_H, m_t.
- Increased sensitivity to loop-induced new physics effects and for discriminating between SM and new physics, or even between different new physics scenarios.
- Precise prediction for the Higgs quartic coupling at high energy scales (EW vacuum stability).

Global SM fit result for M_W and $\sin^2\theta^l_{eff}$





Fit result for M_W

before (gray band) and after (blue)

M_H measurement is included in the fit.

Indirect determination is now more precise than direct measurements!

Fit: $M_W = 80358 \pm 8$ MeV (present)

Exp.: $M_W = 80385 \pm 15$ MeV

Prospect (fit): $\Delta M_W = 5.5$ MeV

Fit: $\sin^2\theta^l_{eff} = 0.23149 \pm 0.00007$

Exp.: $\sin^2\theta^l_{eff} = 0.23153 \pm 0.00016$

GFITTER, arXiv:1407.3792

see also Snowmass EW WG report, arXiv:1310.6708

Theory and parametric uncertainties in predictions for M_W and $\sin^2\theta^l_{\rm eff}$

Parametric uncertainties (Awramik *et al*, hep-ph/0311148; hep-ph/0608099):

$$M_W = M_W^0 - c_1 \ln\left(\frac{M_H}{100\mathrm{GeV}}\right) + c_6 \left(\frac{m_t}{174.3\mathrm{GeV}}\right)^2 + \dots$$

$$\sin^2\theta^f_{eff} = (1 - \frac{M_W^2}{M_Z^2})(1+\Delta\kappa)\ ,\ \Delta\kappa = \Delta\alpha\Delta\kappa^{(\alpha)} + \Delta\kappa^{(\alpha^2)}_{rem}$$

	ΔM_W [MeV]		$\Delta\sin^2\theta^l_{\rm eff}[10^{-5}]$	
	present	future	present	future
$\Delta m_t = 0.9; 0.5(0.1)$ GeV	5.4	3.0(0.6)	2.8	1.6(0.3)
$\Delta(\Delta\alpha_{\rm had}) = 1.38(1.0); 0.5\cdot 10^{-4}$	2.5(1.8)	1.0	4.8(3.5)	1.8
$\Delta M_Z = 2.1$ MeV	2.6	2.6	1.5	1.5
missing h.o.	4.0	1.0	4.5	1.0
total	7.6(7.4)	4.2(3.0)	7.3(6.5)	3.0(2.6)

Theory uncertainty is due to missing 3-loop corrections of $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$.
To match or better exceed the experimental accuracy, EWPOs had to be calculated beyond NLO, some up to leading 4-loop corrections, but complete NNLO EW for all EWPOs is not available (yet).

From Snowmass EW WG report arXiv:1310.6708 [hep-ph].

Projected uncertainties for M_W from $M_T(l\nu)$ at the Tevatron and LHC

ΔM_W [MeV]	present	CDF	D0	combined	LHC		
$\mathcal{L}$[fb]	7.6	10	10	20	20 (8 TeV)	300	3000
PDF	10	5	5	5	10	5	3
QED rad.	4	4	3	3	4	3	2
$p_T(W)$ model	2	2	2	2	2	1	1
other systematics	9	4	11	4	10	5	3
W statistics	9	6	8	5	1	0.2	0
Total	16	10	15	9	15	8	5

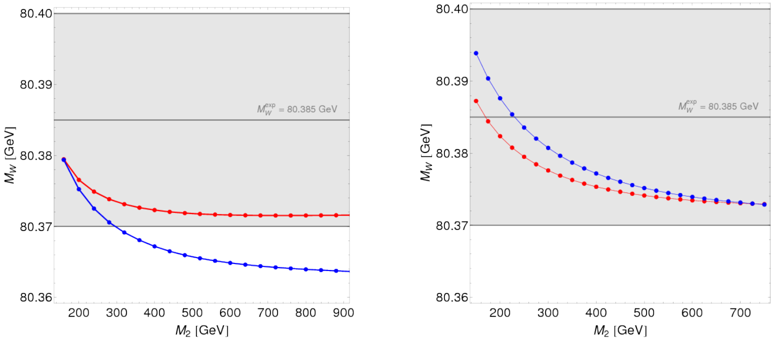
From the Snowmass 2013 EW WG report, arXiv:1310.6708.

- CDF, arXiv:1203.0275: δM_W(QED)=4 MeV
  ResBos+PHOTOS, HORACE used to assess the impact of the not included $\mathcal{O}(\alpha)$ corrections
- D0, arXiv:1203.0293: δM_W(QED)=7 MeV
  ResBos+PHOTOS, WGRAD used to assess the impact of the not included EW $\mathcal{O}(\alpha)$ corrections
- PDF uncertainty is the limiting factor!
  LHCb measurements with forward muons can help, e.g., 30% improvement in M_W when including LHCb $p_T(l)$ measurement compared to only using ATLAS/CMS measurment
  G.Bozzi *et al*, 1508.06954 See also: A.Bodek *et al*, 1507.02470

$M_W(\Delta r)$ in the MSSM and NMSSM

From O.Stal, G.Weiglein, L.Zeune *et al*, arXiv:1506.07465 [hep-ph].

$$\Delta r^{\mathrm{SUSY(h.o.)}} = \Delta r_{\mathrm{red}}^{\mathrm{SUSY}(\alpha^2)} - \frac{c_\mathrm{w}^2}{s_\mathrm{w}^2}\Delta\rho^{\mathrm{SUSY},(\alpha\alpha_s)} - \frac{c_\mathrm{w}^2}{s_\mathrm{w}^2}\Delta\rho^{\mathrm{SUSY},(\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2)}$$



MSSM, NMSSM

$\tan\beta = 3$(*left*); 5.5(*right*), $\mu = 200$ GeV; points allowed by HiggsBounds; $M_{h1} = 125.09 \pm 3.04$ GeV for $M_2 < 725$ GeV from NMSSMTools.

r.h.s. plot: the MSSM and NMSSM Higgs sectors are chosen to be similar.

EW corrections are especially needed

- in modeling signal and background processes for new physics searches either directly or through higher-dimensional operators or the virtual presence of new particles in SM observables,
- in precisely measuring parameters of the SM, e.g., M_W, m_{top}, M_H, $y_{b,t}$, ...,
- in reducing systematic errors, e.g., improve studies of effects of selection/analysis of data, use $\sigma_{W,Z}$ as luminosity monitor, constrain PDFs (W charge asymmetry, γ, jet production), ...

Naturally, EW corrections play an especially important role in EW gauge boson production: V, VV, VVV (+jets) gauge boson production.
Even in QCD dominated processes they can be numerically at least as important as NNLO QCD corrections and in certain kinematic regions they may be the dominant corrections.

For a historic review of the role of radiative corrections in EW precision physics see, e. g., A.Ferroglia, A.Sirlin, Reviews of Modern Phsyics 85 (2013).

Characteristics of EW corrections

Naive estimate of relative size of EW and QCD corrections:

$\frac{\alpha(M_Z)}{\pi} \approx 0.0025$ vs. $\frac{\alpha_s(M_Z)}{\pi} \approx 0.037$ and $(\frac{\alpha_s(M_Z)}{\pi})^2 \approx 0.0014$

Possible enhancements:

QED corrections: $\frac{\alpha(0)}{\pi} \log(\frac{m_f^2}{Q^2}) \approx -0.024$ 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)
Depending on the experimental lepton identification cuts they can significantly affect the shape of distributions.
IS mass singularities are factorized into PDFs which introduces a QED factorization scheme; PDFs with QED corrections and photon PDFs provided by NNPDF coll.

Weak Sudakov corrections, e.g., 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. M.Ciafaloni, P.Ciafaloni, D.Comelli (2000,2001) see, e.g., K.Mishra *et al*, 1308.1430; J.H.Kühn, Acta Phys.Polon.B39 (2008) for examples and a brief review

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

- Complete EW $\mathcal{O}(\alpha)$ corrections: `HORACE`, `RADY`, `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`, `RADY`, `WINHAC`, `PHOTOS`
  C.M.Carloni Calame *et al*, PRD69 (2004); S.Brensing *et al*, PRD77 (2008); W.Placzek *et al*, EPJC29 (2003); Golonka, Was (2005,2006)
- EW Sudakov logarithms up to N^3LL Jantzen, Kühn, Penin, Smirnov (2005); brief review: J.H.Kühn, Acta Phys.Polon.B39 (2008); $p_T(V)$ with SCET T.Becher *et al*, 1305.4202
- NLO EW corrections to W production implemented in POWHEG Bernaciak, DW (2012); Barze *et al.* (2012) $\Rightarrow$ Study of mixed QED-QCD effects
- NLO EW corrections to Z production implemented in POWHEG Barze *et al.* (2013) $\Rightarrow$ Study of mixed QED-QCD effects
- NLO EW corrections to Z production implemented in FEWZ (NNLO QCD) Li, Petriello (2012)
- $W + 1j, Z + 1j, Z + 2j$ 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.* (2010,2014); 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 (2014,2015)

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

- NLO and NNLO QCD (up to $\mathcal{O}(\alpha_s^2)$): total cross sections ($\sigma_{W,Z}$) and fully differential distributions (DYNNLO, FEWZ):

  R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992); W.T.Giele *et al*, NPB403 (1993)

  L.Dixon *et al.*, hep-ph/031226; K.Melnikov, F.Petriello, PRL96, PRD74 (2006); S.Catani *et al.*, PRL103 (2009), JHEP1005 (2010); R.Gavin *et al*, 1011.3540

- NLO QCD corrections matched to an all-order resummation of large logarithms $\ln^n(q_T/Q)$ (at NLL and NNLL accuracy) (Q: W/Z virtuality, q_T: W/Z transverse momentum).

  C.Balazs, C.-P.Yuan, PRD56 (1997) (ResBos); G.Bozzi *et al*, NPB815 (2009), arXiv:1007.2351; S.Catani *et al*, 1209.0158; N.Kidonakis, R.Gonsalves, 1404.4302

- NLO QCD corrections matched to a parton shower (HERWIG, PYTHIA): MC@NLO, POWHEG.

  S.Frixione, B.R.Webber, hep-ph/0612272; S.Alioli *et al*, JHEP0807 (2008)

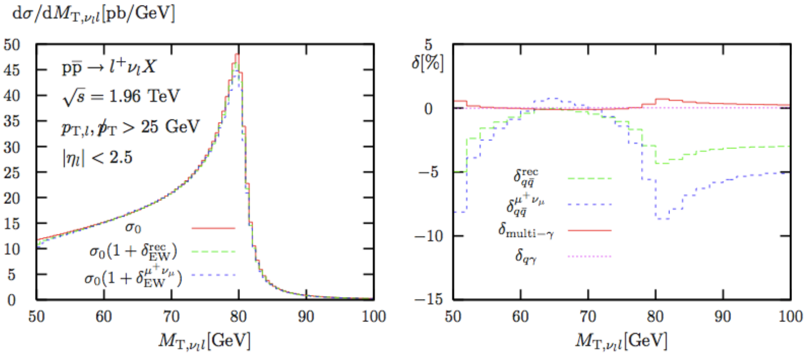
- NNLO+NNLL QCD: DYRes Catani, de Florian, Ferrera, Grazzini, 1507.06937
- NNLO QCD corrections matched to a parton shower: SHERPA Hoeche, Li, Prestel, 1405.3607, 1507.05325; POWHEG+MiNLO+DYNNLO Karlberg, Re, Zanderighi, 1407.2940; GENEVA S.Alioli *et al*, 1508.01475.
- $W + n$-jets ($n \leq 5$) and $Z + n$-jets ($n \leq 4$) at NLO QCD (and matched to PS).

  C.F.Berger *et al.* (2010,2009); Z.Bern *et al.* (2013); H.Ita *et al.* (2011); K.Ellis *et al.* (2009); J.Campbell *et al* (2002, 2013 (POWHEG)); B.Jaeger *et al* (2012) (POWHEG); S.Hoeche *et al* (2012)

- $W + 1$ jet and $Z + 1$ jet at NNLO QCD: Boughezal *et al*, 1504.02131 and Gehrmann *et al*, 1507.02850

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

Brensing, Dittmaier, Krämer, Mück, 0710.3309:



$\delta_{q\gamma}$: relative correction from photon-induced process; PDFs with QED corrections (in evolution) and photon PDFs are provided by the NNPDF collaboration R.D.Ball *et al*, 1308.0598.

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)

Mass-singular logarithms of QED origin

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

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

  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)

$pp \to W \to l\nu X$ at NLO (EW+QCD)+QCD PS with POWHEG

Incorporation of EW $\mathcal{O}(\alpha)$ corrections into $\bar{\mathrm{B}}$ of POWHEG-W[1−2] by C.Bernaciak, D.W., arXiv:1201.4804:

$$d\sigma = \sum_{\text{flavors}} \bar{\mathrm{B}}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \sum_{\alpha_r} \frac{\left[d\Phi_{\text{rad}} \Delta(\Phi_n, k_T > p_T^{\min}) R(\Phi_{n+1}) \right]}{B(\Phi_n)} \right\}$$

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

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

- ⇒ $V_{\text{EW}}(\Phi_2)$ virtual + soft finite EW corrections
- ⇒ $\mathrm{G}_{\text{EW}}(\Phi_2, z)$ IS collinear EW pieces
- ⇒ $\mathrm{R}_{\text{EW}}(\Phi_3)$ finite real piece - IS and FS together

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

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

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

$pp \to W \to l\nu X$ at NLO(EW+QCD)+QCD/QED PS with POWHEG

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 colored parton emission

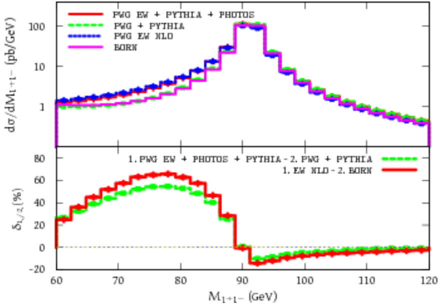
The implementation

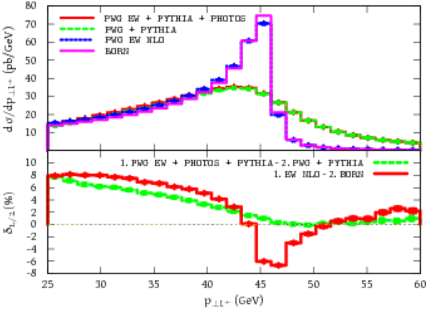
- ensures normalization with NLO QCD + EW accuracy
- combines the complete SM NLO corrections with a mixed QCD$\otimes$QED parton cascade, where the particles present in the shower are coloured particles or photons
- consequently, incorporates mixed $\mathcal{O}(\alpha\alpha_s)$ contributions with a better accuracy w.r.t. existing public codes. In particular, it can allow to study consistently the interplay between QCD and EW radiation, like *e.g.* the link between a photon emitted after QCD radiation and viceversa.

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

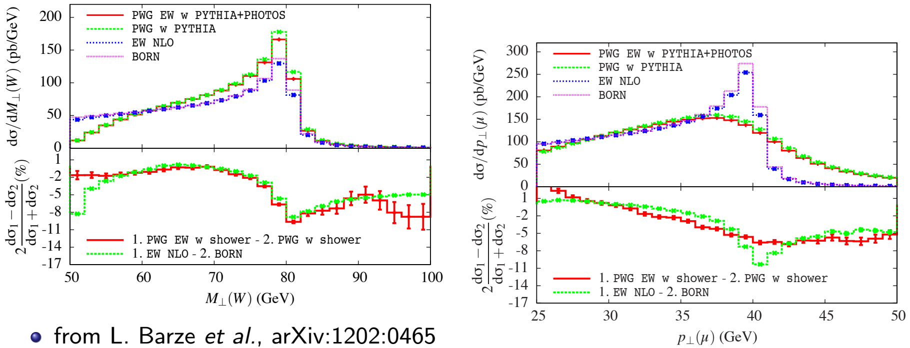
$pp \to \gamma, Z \to l^+ l^- X$ at NLO(EW+QCD)+QCD/QED PS with POWHEG

Implementation of EW corrections to $pp \to Z, \gamma \to l^+ l^-$ in POWHEG by L. Barze et al., arXiv:1302.2716:





$M_T(l\nu)$ and $p_T(\mu)$ distributions at the LHC



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

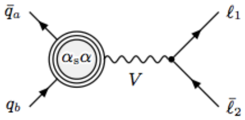
See also earlier studies of mixed QED-QCD effects using HORACE+MC@NLO and ResBos+QED FSR G. Balossini *et al*, arXiv:0907.0276; Cao, Yuan, hep-ph/0401026; and B.F.L. Ward *et al* (2008) (HERWIRI)

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

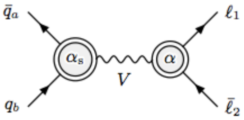
S.Dittmaier, A.Huss, C.Schwinn, arXiv:1405.6897; 1403.3216; 1511.08016

Gauge-invariant separation in factorizable, non-factorizable resonant and non-resonant contributions:

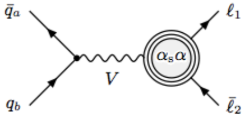
$$\mathcal{M} = \frac{W(\mu_V^2)}{p_V^2 - \mu_V^2} \frac{1}{1 + \Sigma'(\mu_V^2)} + \frac{W(p_V^2)}{p_V^2 - \mu_V^2 + \Sigma(p_V^2)} - \frac{W(\mu_V^2)}{p_V^2 - \mu_V^2} \frac{1}{1 + \Sigma'(\mu_V^2)} + N(p_V^2)$$



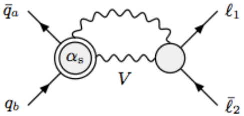
(a) Factorizable initial×initial corrections



(b) Factorizable initial×final corrections



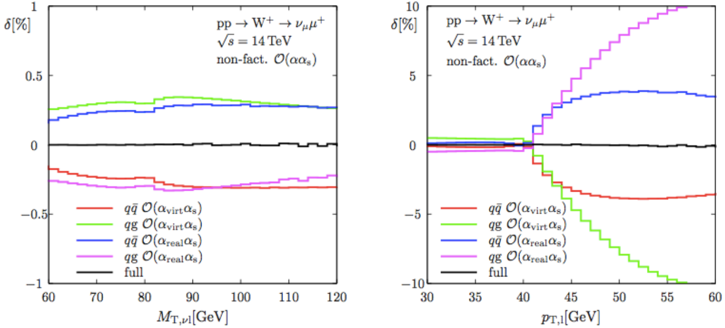
(c) Factorizable final×final corrections



(d) Non-factorizable corrections

Non-factorizable corrections to $pp \to \nu l X$ at $\mathcal{O}(\alpha\alpha_s)$ in pole approximation

S.Dittmaier, A.Huss, C.Schwinn, arXiv:1403.3216

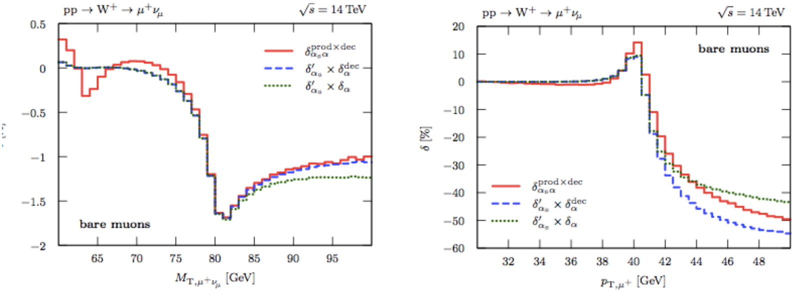


Factorizable corrections to $pp \to \nu l$ at $\mathcal{O}(\alpha\alpha_s)$ in pole approximation

Comparison of initial QCD-final EW factorizable $\mathcal{O}(\alpha\alpha_s)$ correction in pole approximation and a naive factorization defined as

$$d\sigma_{QCD}^{NLO}(1+\delta_\alpha)$$

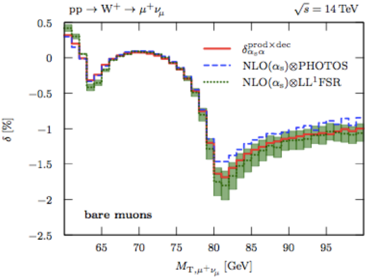
S.Dittmaier, A.Huss, C.Schwinn, arXiv:1511.08016

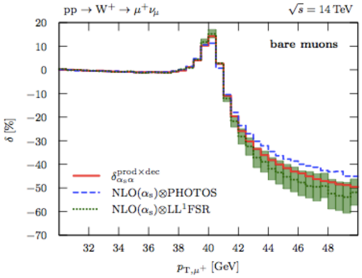


Comparison of initial QCD-final EW factorizable $\mathcal{O}(\alpha\alpha_s)$ correction in pole approximation and NLO QCD convoluted with PHOTOS or structure function approach for FSR QED:

$$d\sigma^{NLO}_{QCD} \frac{\alpha}{2\pi} Q_l^2 (\ln(Q^2/m_l^2) - 1) \int dz \frac{1+z^2}{(1-z)_+}$$

S.Dittmaier, A.Huss, C.Schwinn, arXiv:1511.08016





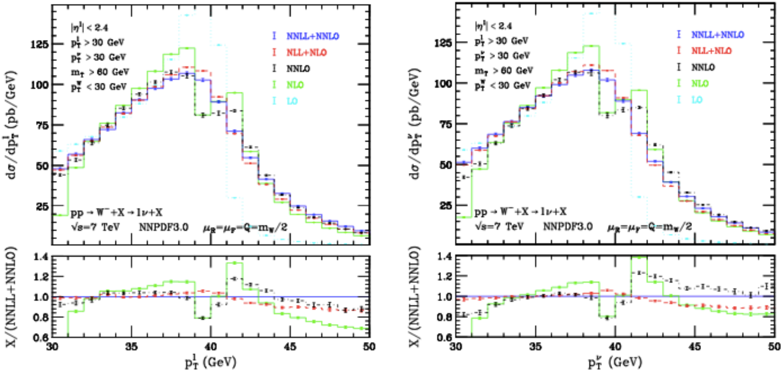
Estimate of additional shift in M_W due to initial-final $\mathcal{O}(\alpha\alpha_s)$ corrections with respect to full NLO QCD+EW result when extracted from $M_T(l\nu)$:
bare muons: -14 MeV; dressed leptons: -4 MeV

Recent advances in automated tools for NLO EW+QCD calculations

Some new results for multi-particle processes which consistently include higher-order QCD and EW corrections for a given order in perturbation theory:

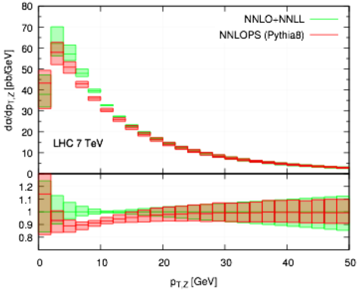
- `Recola+Collier`; S.Actis *et al*, 1211.6316
  Example: $pp \to l^+ l^- jj$ at $\mathcal{O}(\alpha_s^2 \alpha^3)$, A.Denner *et al*, 1411.00916
- `OpenLoops+Sherpa` (+Collier)
  Examples: $pp \to W + 1, 2, 3$ jets, S.Kallweit *et al*, 1412.5157, and $V + 1, 2$ jets with $V \to ll'$ and MEPS@NLO jet merging, S.Kallweit *et al*, 1511.08692
  LO (n jets): $\mathcal{O}(\alpha_s^n \alpha^2)$, NLO: $\mathcal{O}(\alpha_s^{n+1} \alpha^2)$ and $\mathcal{O}(\alpha_s^n \alpha^3)$
- `Madgraph5_AMC@NLO`
  Example: $pp \to t\bar{t} + (H, Z, W)$, S.Frixione *et al*, 1504.03446
  Dominant LO: $\mathcal{O}(\alpha_s^2 \alpha)$, $\mathcal{O}(\alpha_s \alpha^2)$, NLO: $\mathcal{O}(\alpha_s^3 \alpha)$, $\mathcal{O}(\alpha_s^2 \alpha^2)$
- `GOSAM`, G.Cullen *et al*, 1404.7096
  Example: $pp \to W + 2$ jets, M.Chiesa *et al*, `GOSAM+MadDipole`, 1507.08579

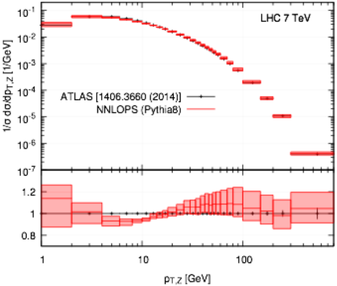
Resummation of $\alpha_s^n(m_V^2/q_T^2)\ln^m(m_V^2/q_T^2)$ at NNLL accuary at small q_T combined with fixed order NNLO at large q_T Catani, de Florian, Ferrera, Grazzini, arXiv:1507.06937:



$pp \to V \to llX, l\nu X$ production at QCD NNLO+PS with DYNNLOPS

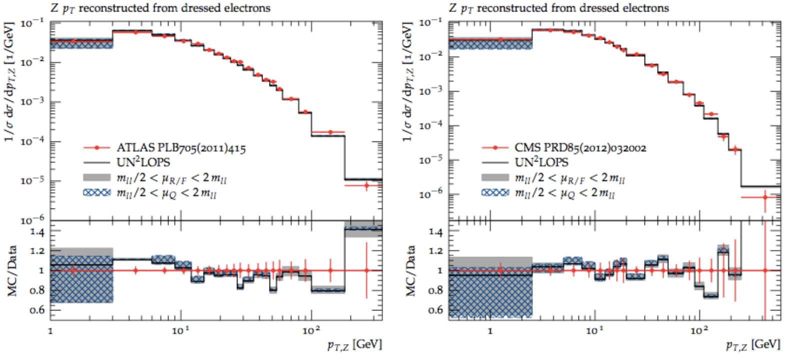
POWHEG+MiNLO for Vj at NLOPS and reweighted with DYNNLO Karlberg, Re, Zanderighi, arXiv:1407.2940:



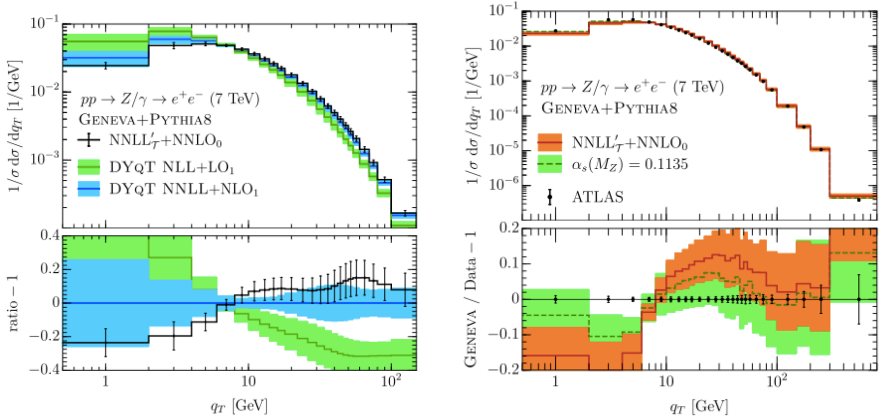


$pp \to V \to llX, l\nu X$ QCD NNLO+PS with SHERPA NNLO+PS

q_T prediction of the UN2LOPS merging scheme in SHERPA compared to LHC data (zero-jet bin at NNLO and NLO Vj matched to shower at large q_T) Hoeche, Li, Prestel, arXiv:1405.3607:



Fixed order NNLO combined with NNLL' resummation of beam thrust matched to Pythia 8 Alioli *et al*, arXiv:1508.01475:



Final remarks

- LHC Run I has already provided a wealth of EW measurements at very high precision (per mil/percent level) and is probing new kinematic regimes, and we can look forward to much more at Run 2.
- Electroweak precision physics, in particular the W mass measurement, requires excellent control of predictions for W and Z boson observables, in some cases at the per mil level.
- Predictions including EW and/or QCD higher-order corrections are provided by a number of publicly available Monte Carlo programs. The usage of these tools and their combination is not trivial and has to be done with care.
- A careful assessment of theory uncertainties using the most advanced predictions is needed.
- PDF uncertainties need to be under control and considerably reduced.
- How about resummation and EW corrections in predictions for PDF fits?

Final remarks

- Estimates of theoretical uncertainties may also rely on comparisons of tools that differ in the implementation of higher-order corrections.
- Before one can interpret differences in predictions of different implementations of higher orders as a measure of the theoretical uncertainty, one has to make sure that two codes that have the same perturbative approximation, the same input parameters (couplings, masses, PDFs), the same setup (choice of scales, acceptance cuts), yield the same results, within the accuracy of the numerical integration.
- Since 2012 we are working on such a tuned comparison and a systematic study of higher-order effects beyond NLO accuracy in DY W and Z production at the LHC.

Report on Precisions Studies of Observables in $pp \to W^\pm \to l\nu_l$ and $pp \to \gamma, Z \to l^+l^-$ processes at the LHC

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This study will provide a tuned comparsion of EW and QCD predictions and a collection of benchmark results for total cross sections and kinematic distributions obtained with the most used publicly available codes for W/Z boson production at hadron colliders.

These results will serve

1) to verify that a given code works properly according to what its authors have foreseen,
2) to demonstrate explicitly the level of agreement of different codes that include identical subsets of radiative corrections, and
3) to expose the impact of different subsets of higher-order corrections and of differences in their implementations.

See also earlier studies:

Tevatron-for-LHC Report, arXiv:0705.3251 (2007); Les Houches report, hep-ph/0604120 (2006)

Participating codes

- NNLO QCD: DYNNLO, FEWZ, SHERPA M.Grazzini, D.de Florian, G.Ferrera; F.Petriello, Y.Li; S.Hoeche, Y.Li, S.Prestel
- NLO QCD⊗Parton Shower: POWHEG, SHERPA S.Alioli, P.Nason, E.Re; S.Hoeche, Y.Li, S.Prestel
- NNLO QCD⊗Parton Shower: DYNNLOPS, SHERPA NNLO+PS A.Karlberg, E.Re, G.Zanderighi; S.Hoeche, Y.Li, S.Prestel
- QED PS/SF: HORACE, PHOTOS, RADY, SHERPA G.Montagna, O.Nicrosini, A.Vicini; Z.Was; S.Dittmaier, M.Krämer, A.Mück; M.Schönherr, F.Krauss
- NLO EW: HORACE, RADY, SANC, WZGRAD G.Montagna, O.Nicrosini, A.Vicini; A.Arbuzov, D.Bardin, S.Bondarenko, L.Kalinowskaya; S.Dittmaier, M.Krämer, A.Mück; D.Wackeroth
- NLO EW⊗QED PS/YFS/SF: HORACE, RADY, WINHAC G.Montagna, O.Nicrosini, A.Vicini; W.Plazek; S.Dittmaier, M.Krämer, A.Mück
- NLO QCD+NLO EW: RADY, SANC, POWHEG_BMNNP(V), POWHEG_BW S.Dittmaier, M.Krämer, A.Mück; A.Arbuzov, D.Bardin, S.Bondarenko, L.Kalinowskaya; L.Barze, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini, A.Vicini; C.Bernaciak, D.Wackeroth
- NNLO QCD+NLO EW: FEWZ F.Petriello, Y.Li
- (NLO QCD+NLO EW)⊗Pythia: POWHEG_BMNNP(V), POWHEG_BW L.Barze, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini, A.Vicini; C.Bernaciak, D.Wackeroth
- (NLO QCD+NLO EW)⊗Pythia⊗PHOTOS: POWHEG_BMNNP(V) L.Barze, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini, A.Vicini