Electroweak corrections for LHC processes

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Outline

1. Introduction
2. Automated tools for NLO EW corrections
3. General aspects of EW corrections
4. Recent calculations for specific processes
5. Conclusion and outlook

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Relevance of electroweak (EW) corrections

Generic size $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$ $\Rightarrow$ NLO EW $\sim$ NNLO QCD
typical: few per cent for inclusive observables

systematic enhancements

- by (soft and/or collinear) photon emission:
  kinematic effects, radiative tails
  mass-singular logarithms $\propto \alpha \ln(m_\mu/Q)$ for bare muons
  $\Rightarrow$ huge effects ($> 100\%$) possible (in radiative tails)
- at high energies:
  EW Sudakov logarithms $\propto (\alpha/s_w^2) \ln^2(M_W/Q)$ and subleading logs
  $\Rightarrow$ EW corrections of several 10% in high-energy tails of distributions or cross sections dominated by high scales

$\Rightarrow$ NLO EW corrections can be sizeable
$\Rightarrow$ must be included in theoretical predictions

Good news:
automation of (fixed order) NLO EW corrections basically done

Outline

NLO EW matrix element providers $2 \to (5)6$ processes routinely available

tool	collaboration	
GoSam	Chiesa et al.	1407.0823
MadGraph5_aMC@NLO	Frixione et al.	1804.10017
NLOX	Honeywell et al.	1812.11925
OpenLoops	Pozzorini et al.	1907.13071
Recola	Actis et al.	1211.6316,1605.01090

state-of-the-art applications:

- $2 \to 6$ processes
  - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ $(\mathrm{t}\bar{\mathrm{t}})$ — Denner, Pellen 1607.05571
  - $\mathrm{pp} \to 4\ell\mathrm{jj}$ (VBS) — Denner et al. 1611.02951, 1708.00268, 1904.00882, 2009.00411, 2107.10688, 2202.10844
  - $\mathrm{pp} \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^+\nu_{\ell_3}$ (WWW) — Schönherr 1806.00307, Dittmaier et al. 1912.04117
  - $\mathrm{pp} \to \mathrm{e}^+\mathrm{e}^-\mu^+\nu_\mu\mathrm{jj}_b$ (tZj) — Denner, Pelliccioli, Schwan 2207.11264
- $2 \to 7$ processes
  - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}\mathrm{H}$ $(\mathrm{t}\bar{\mathrm{t}}\mathrm{H})$ — Denner, Lang, Pellen, Uccirati 1612.07138
- $2 \to 8$ processes
  - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ $(\mathrm{t}\bar{\mathrm{t}}\mathrm{W})$ — Denner, Pelliccioli 2102.03246

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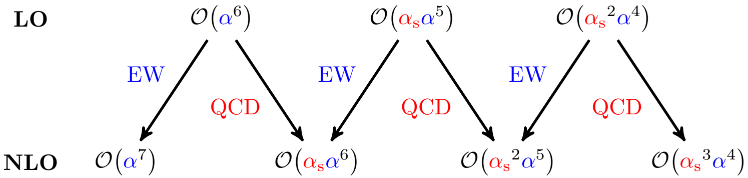
Expansion in multiple couplings

Example: $\mathrm{pp} \to 4\ell\mathrm{jj}$ (vector-boson scattering: $\mathrm{pp} \to \mathrm{VVjj}$)

LO: pure EW diagrams $\mathcal{O}(e^6)$ and diagrams with gluons $\mathcal{O}(e^4 g_\mathrm{s}^2)$

NLO: EW and QCD corrections to both types of diagrams

at level of cross section:



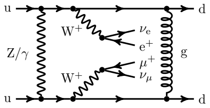
consequences:

- QCD and EW corrections cannot be separated in general
- QCD corrections to leading LO terms well defined
- consider well-defined orders $\mathcal{O}(\alpha_\mathrm{s}^n \alpha^m)$
- automation must deal with expansion in different couplings

Mixing of virtual EW and QCD corrections

Virtual diagrams mix QCD and EW corrections:

- EW correction to LO QCD amplitude
- QCD correction to LO EW amplitude
- QED and QCD IR singularities



$\Rightarrow$ separation into QCD and EW is not well-defined at NLO

real subtraction terms with both gluons and photons needed

For energies $Q \lesssim 300\,\mathrm{GeV}$:

- corrections related to the running of the electromagnetic coupling $\alpha(Q)$ $\propto \alpha \log(m_f/Q)$
  $\Rightarrow$ incorporated by suitable choice of renormalisation of α
  - $\alpha(0)$ for external isolated photons
  - $\alpha(M_\mathrm{Z})$ or α_{G_μ} otherwise

$$\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_\mathrm{W}^2 \left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right)$$

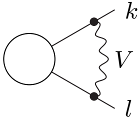
- corrections originating from soft photons or collinear massless fermion–antifermion or (anti)fermion–photon pairs $\propto \alpha \log(m_f/Q)$
  - YFS resummation (Yennie–Frautschi–Suura)
  - electromagnetic parton showers
- top-mass corrections $\propto \alpha m_\mathrm{t}^2/(M_\mathrm{W}^2 s_\mathrm{w}^2)$
  $\Rightarrow$ (partially) incorporated by using α_{G_μ}

For energies $Q \gtrsim 300\,\mathrm{GeV}$ in addition:

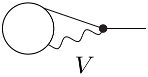
- logarithmic electroweak corrections involving $\alpha \ln(Q/M_\mathrm{W})$ and $\alpha \ln^2(Q/M_\mathrm{W})$

Origin of leading-logarithmic virtual EW corrections

- double logarithms from soft–collinear singular diagrams: $(\alpha/s_{\mathrm{w}}^2)\ln^2(s_{kl}/M_{\mathrm{W}}^2)$
  $\Rightarrow$ angular-dependent logarithms of the form
  $\ln\frac{s_{kl}}{s}\ln\frac{s}{M_{\mathrm{W}}^2}$, $\ln\frac{t}{u}\ln\frac{s}{M_{\mathrm{W}}^2}$



- single logarithms from collinear-singular diagrams and wave-function renormalisation (self-energies): $(\alpha/s_{\mathrm{w}}^2)\ln(Q/M_{\mathrm{W}})$



- single logarithms from coupling renormalisation at scale $M_{\mathrm{W}} \ll \sqrt{s}$
  $\Rightarrow$ running of EW couplings (e, s_{w}, λ, g_{Yukawa}) from M_{W} to $\sqrt{s}$

Leading-logarithmic EW corrections depend only on gauge structure of model, external lines and their polarisations, (and on the running of the couplings).
$\Rightarrow$ Leading-logarithmic EW corrections are universal.

Real emission of EW vector bosons

- separate IR finite contribution, experimentally identifiable
- can be included as extra LO process if needed

General results for EW logarithmic corrections to arbitrary non-mass suppressed processes exist   Denner, Pozzorini '00

EW corrections in logarithmic approximation implemented in

- ALPGEN (specific processes)   Chiesa et al. 1305.6837
- MCFM (specific processes)   Campbell et al. 1608.03356
- Sherpa (general processes)   Bothmann, Napoletano 2006.14635
- MadGraph5_aMC@NLO (general processes)   Pagani, Zaro 2110.03714

optionally including some universal non-logarithmic terms

features

- simple formulas, complexity of tree-level calculation
- non-logarithmic terms neglected ⇒ typical accuracy: few percent
- often not useful for inclusive quantities
  [dominated by small scales, small EW corrections of $\mathcal{O}(\alpha/(s_\mathrm{w}^2\pi)) \sim 1\%$]
- quality needs to be checked case by case

EW Virtual approximation

Implemented in SHERPA
Include only virtual corrections with IR singularities subtracted
e.g. via the I operator of Catani–Seymour subtraction
(and real corrections via a parton shower (PS)):

- definition and application to $\mathrm{pp} \to \mathrm{W} + 1\mathrm{j}, 2\mathrm{j}$ Kallweit et al. 1511.08692
- application to $\mathrm{pp} \to \mathrm{t\bar{t}}(+\mathrm{j})$ Gütschow et al. 1803.00950
- application to $\mathrm{pp} \to \mathrm{WW}(+\mathrm{j})$ Denner et al. 2005.12128
- application to $\mathrm{pp} \to \mathrm{ZZ}(+\mathrm{j})$ Bothmann et al. 2111.13453

features

- Includes all EW logarithms and renormalisation effects
- complexity of one-loop calculation
- neglects subtracted real corrections
  $\Rightarrow$ neglects some non-logarithmic terms
- quality needs to be checked case by case
- bad approximation if real corrections are large
- simplifies PS matching and multi-jet merging

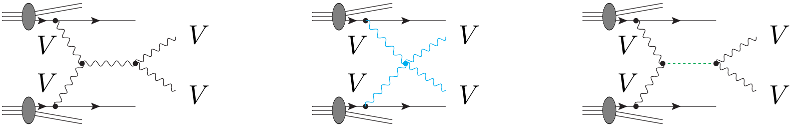
Further ingredients for predictions with full EW effects

- Parton-distribution functions with QED/EW corrections
  Photon PDFs: LUXqed
  Manohar, Nason, Salam, Zanderighi 1607.04266, 1708.01256
  For $\mu_{\mathrm{F}} > M_{\mathrm{Z}}$: all SM particles appear as partons
  $\Rightarrow$ PDFs for massive vector bosons and Higgs boson
  Bauer et al. 1703.0852, 1808.08831; Han et al. 2007.14300, 2103.09844
- EW effects in parton showers
  Chen, Han, Tweedie, 1611.00788 (EW splitting functions);
  Skands, Verheyen 2002.04939; Kleiss, Verheyen 2002.09248;
  Gütschow, Schönherr 2007.15360;
  Masouminia, Richardson 2108.10817; Darvishi, Masouminia 2112.15487
- Isolated photons within higher-order EW corrections
  Pagani, Shao, Tsinikos, Zaro 2106.02059

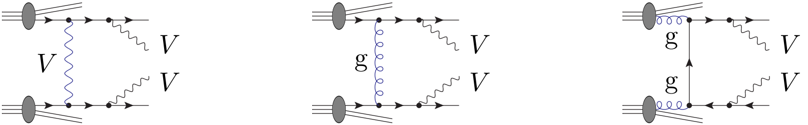
Outline

Processes: $\mathrm{pp} \to VV + 2\mathrm{j} \to 4\ell + 2\mathrm{j}$

Vector-boson scattering (VBS) signal



Irreducible background to VBS



- EW process: $\mathcal{O}(\alpha^4)$ for stable Vs, $\mathcal{O}(\alpha^6)$ with decays
- QCD process $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^2)$ for stable Vs, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^4)$ with decays
- non-vanishing interferences between EW and QCD contributions
  $\mathcal{O}(\alpha_\mathrm{s}\alpha^3)$ for stable Vs, $\mathcal{O}(\alpha_\mathrm{s}\alpha^5)$ with decays
- gluonic channels for neutral final states

Large NLO EW corrections to VBS processes

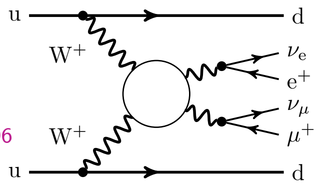
process	$\sigma_{\mathrm{LO}}^{\mathcal{O}(\alpha^6)}$ [fb]	$\Delta\sigma_{\mathrm{NLO,EW}}^{\mathcal{O}(\alpha^7)}$ [fb]	δ_{EW} [%]
Biedermann et al. 1708.00268			
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{W^+W^+}$)	$1.4178(2)$	$-0.2169(3)$	-15.3
Denner et al. 1904.0088			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ ($\mathrm{ZW^+}$)	$0.25511(1)$	$-0.04091(2)$	-16.0
Denner et al. 2009.00411			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ (ZZ)	$0.097681(2)$	$-0.015573(5)$	-15.9
Denner et al. 2202.10844			
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$ ($\mathrm{W^+W^-}$)	$2.6988(3)$	$-0.307(1)$	-11.4

- EW corrections similar for all processes and rather independent of cuts
  $\Rightarrow$ intrinsic feature of VBS process
- smaller corrections to $\mathrm{W^+W^-}$ due to Higgs resonance in fiducial phase space (Higgs contribution about 25%, corresponding EW corrections -6.5%)
- σ^{LO} receives sizeable contributions involving large invariants $s_{ij} \gg M_\mathrm{W}$

Source of large EW corrections

Double-pole approximation (DPA) for outgoing W bosons
effective vector-boson approximation (EVBA) for incoming W bosons

- DPA and EVBA reduce discussion to $V_1V_2 \to V_3V_4$
- DPA accurate for cross section within 1%
- EVBA crude approximation Kuss, Spiesberger '96 sufficient to understand dominant effects



high-energy, logarithmic approximation for $V_1V_2 \to V_3V_4$ Denner, Pozzorini '00

$$\mathrm{d}\sigma_{\mathrm{LL}} = \mathrm{d}\sigma_{\mathrm{LO}}\left[1 - \frac{\alpha}{4\pi}4C_{\mathrm{W}}^{\mathrm{EW}}\log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) + \frac{\alpha}{4\pi}2b_{\mathrm{W}}^{\mathrm{EW}}\log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)\right]$$

$$C_{\mathrm{W}}^{\mathrm{EW}} = \frac{2}{s_{\mathrm{w}}^2}, \quad b_{\mathrm{W}}^{\mathrm{EW}} = \frac{19}{6s_{\mathrm{w}}^2} \qquad \text{for transverse W bosons}, \qquad Q \to M_{4\ell}$$

(double EW logs, collinear single EW logs, and single logs from parameter renormalisation included) (angular-dependent logarithms omitted, $\log\frac{t}{u}\log\frac{Q}{M_{\mathrm{W}}}$)

large NLO EW corrections intrinsic feature of VBS

Simple formula for total cross section

$$\mathrm{d}\sigma_{\mathrm{LL}} = \mathrm{d}\sigma_{\mathrm{LO}}\left[1 - \frac{\alpha}{4\pi} 4C_{\mathrm{W}}^{\mathrm{EW}} \log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) + \frac{\alpha}{4\pi} 2b_{\mathrm{W}}^{\mathrm{EW}} \log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)\right]$$

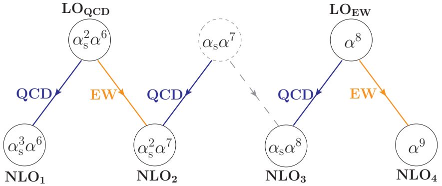
process	δ_{EW} [%]	$\delta_{\mathrm{EW}}^{\mathrm{log,int}}$ [%]	$\delta_{\mathrm{EW}}^{\mathrm{log,diff}}$ [%]	$\langle M_{4\ell}\rangle$ [GeV]
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	-16.0	-16.1	-15.0	390
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$	-16.0	-17.5	-16.4	413
$\mathrm{pp} \to \mu^+\mu^- \mathrm{e}^+\mathrm{e}^-\mathrm{jj}$	-15.9	-15.8	-14.8	385

- surprisingly good agreement with complete calculation ($\delta_{\mathrm{EW}} = -16.0\%$)
- large EW corrections are due to large gauge couplings of vector bosons (C^{EW}) and large scale $Q \sim \langle M_{4\ell}\rangle \sim 400\,\mathrm{GeV}$
- angular-dependent logarithms different for different processes ~ 1–2% owing to cancellations

large NLO EW corrections intrinsic feature of VBS

Process:
$\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}$
$(\mathrm{pp} \to \mathrm{t\bar{t}W^+})$ $(2 \to 8)$
Denner, Pellicciol 2102.03246

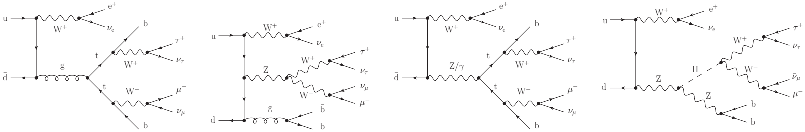
contributions to cross section



LO:

- QCD and EW contributions
- interference of order $\mathcal{O}(\alpha_s\alpha^7)$ vanish for unit quark-mixing matrix

Sample diagrams for $\mathrm{LO_{QCD}}$ (left) and to $\mathrm{LO_{EW}}$ (right)



$\mathrm{NLO_1}$: QCD corrections to LO QCD

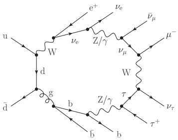
Bevilaqua et al. 2005.9427; Denner, Pellicciol 2007.12089

NLO_2: EW corrections to $\mathrm{LO}_{\mathrm{QCD}}$ and QCD corrections to LO interference

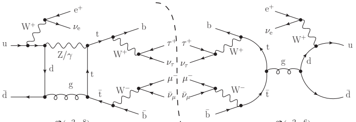
Denner, Pellicciolli 2102.03246

Virtual corrections

- up 10-point functions



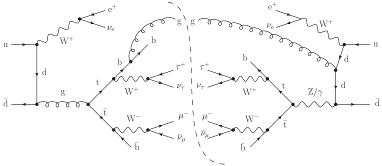
- Classification as QCD or EW corrections ambiguous

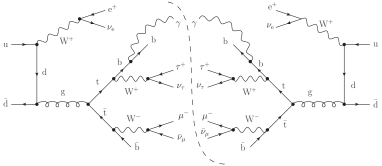


$\mathcal{O}(g_s^2 g^8)$ $\mathcal{O}(g_s^2 g^6)$

Real corrections

- $2 \to 9$ process
- large number of IR singular regions
- real QCD correction to LO interference non-zero



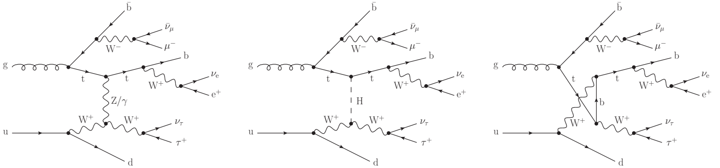


Virtual IR-singularities in $\mathcal{O}(g_s^2 g^8) \times \mathcal{O}(g_s^2 g^6)$ cancelled by both classes of real corr.

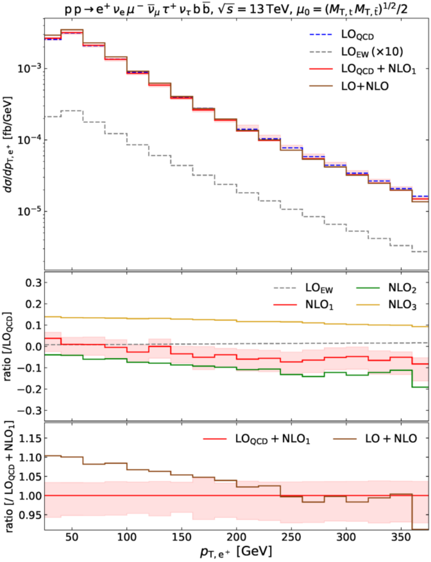
NLO_3: Pure QCD corrections to $\mathrm{LO}_{\mathrm{EW}}$
EW corrections do not change colour structure of LO interference

Naively expected to be subleading but larger than NLO_2
Frederix et al. 1711.02116, 1804.10017

Dominated by gq channel contribution involving $\mathrm{tW} \to \mathrm{tW}$ scattering



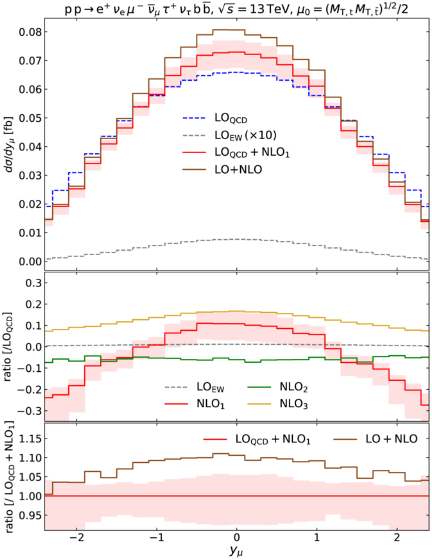
NLO_4: EW corrections to $\mathrm{LO}_{\mathrm{EW}}$
0.04% of $\mathrm{LO}_{\mathrm{QCD}} \Rightarrow$ negligible
Frederix et al. 1711.02116



Denner, Pelliccioli 2102.03246

- $p_{\mathrm{T,e}}$ proxy for $p_{\mathrm{T,t}}$
- NLO_1 = NLO QCD corrections vary by 10%
- NLO_2 = NLO EW corrections vary between -3% and -15%
- NLO_3 = $\mathcal{O}(\alpha^2/\alpha_s)$ corrections vary between 14% and 10%
- corrections beyond NLO_1 exceed QCD scale uncertainty

Associated top-pair and W-boson production



Denner, Pelliccioli 2102.03246

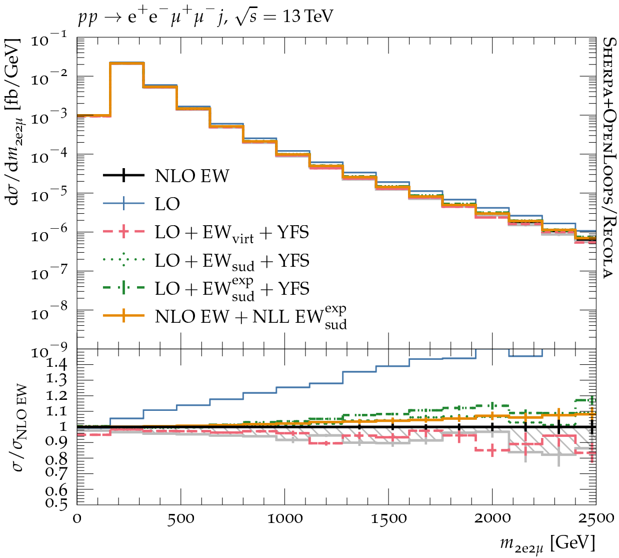
- y_μ proxy for $y_{\bar{t}}$
- NLO_1 = NLO QCD corrections vary by 35%
- NLO_2 = NLO EW corrections vary between -4% and -8%
- NLO_3 = $\mathcal{O}(\alpha^2/\alpha_s)$ corrections vary between 8% and 16%
- corrections beyond NLO_1 up 11% exceed QCD scale uncertainty

Process $\mathrm{pp} \to \mathrm{e^+e^-}\mu^+\mu^-,\ \mathrm{e^+e^-}\mu^+\mu^-\mathrm{j}$

Bothmann, Napoletano, Schönherr, Schumann, Villani 2111.13453 (SHERPA)

- Comparison of exact NLO EW results
  with EW virtual and NLL Sudakov approximation:
  - NLO EW: full virtual EW corrections V_{EW} and full real corrections
  - $\mathrm{EW}_{\mathrm{virt}}$: $V_{\mathrm{EW}} + I_{\mathrm{EW}}$, full virtual EW + integrated real corrections in soft-collinear limit (Catani–Seymour I-operator)
  - $\mathrm{EW}_{\mathrm{sud}}$: NLL part of V_{EW}: $\delta^{\mathrm{EW}}_{\mathrm{sud}}$, also exponentiated $\exp(\delta^{\mathrm{EW}}_{\mathrm{sud}})$
  - NLO EW + NLL $\mathrm{EW}^{\mathrm{exp}}_{\mathrm{sud}}$:
    NLL part beyond NLO included via exponentiation
    relative correction: $\delta^{\mathrm{EW}}_{\mathrm{virt}} + \exp(\delta^{\mathrm{EW}}_{\mathrm{sud}}) - \delta^{\mathrm{EW}}_{\mathrm{sud}}$
    $\Rightarrow$ matching of NLO EW to resummed Sudakov logarithms
  - + YFS: soft photon resummation in the YFS scheme
- $\mathrm{EW}_{\mathrm{virt}}$ works well in phase-space regions not dominated by real photon radiation
- resummation of NLL $\Rightarrow$ reduction of Sudakov suppression of 5–10%
- inclusion of leading EW corrections in MEPS@NLO in SHERPA

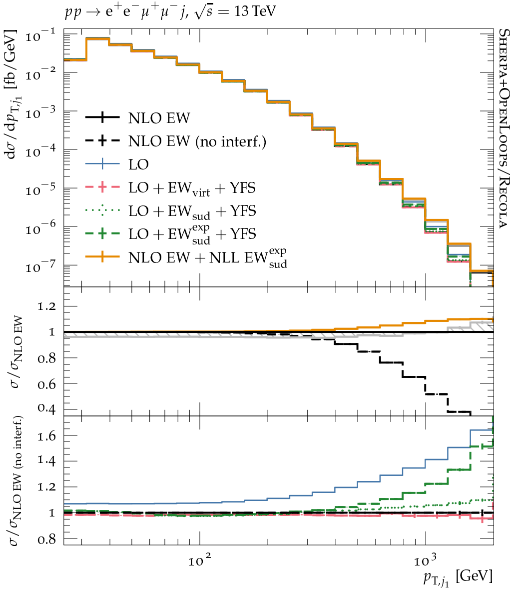
Z-pair production plus 1 jet



Bothmann et al. 2111.13453

- Sudakov suppression up to 50%
- approximations work within 5–10%
- grey band: difference between G_μ and $\alpha(M_Z)$ schemes

Z-pair production plus 1 jet



Bothmann et al. 2111.13453

NLO EW (no interf.):
real corrections from interference of orders $\mathcal{O}(g_s^2 g^4)$ and $\mathcal{O}(g^6)$ for $pp \to e^+e^-\mu^+\mu^- jj$ neglected
(not included in approximations)
$\Rightarrow$ strong discrepancy between approximations and full NLO EW for $p_{T,j_1} > 300\,\text{GeV}$

approximations reproduce NLO EW (no interf.) well

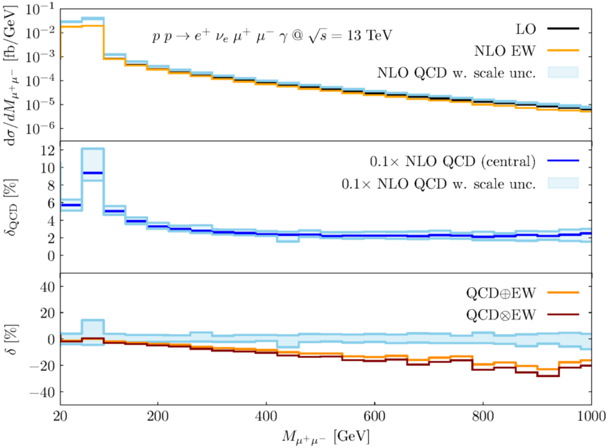
$pp \to e^+\nu_e\mu^+\mu^-\gamma$ ($W^+Z\gamma$)

Cheng, Wackeroth 2112.12052

- tools
  - RECOLA for virtual corrections Actis et al.
  - MadDipole for real corrections Frederix, Gehrmann, Greiner '08 –'10
- isolated photons
  - mixed renormalisation scheme with $\alpha(0)$ for on-shell photons
  - Frixione isolation Frixione hep-ph/9801442
- results for EW corrections
  - small ($\sim 1\%$) for total cross section
  - up to 20%–40% for differential distributions
  - larger than QCD scale uncertainty for some distributions
  - cancellations between EW corrections from quark-induced and photon-induced processes

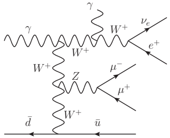
Cheng, Wackeroth 2112.12052

Distribution in invariant mass of $\mu^+\mu^-$ pair (Z boson)



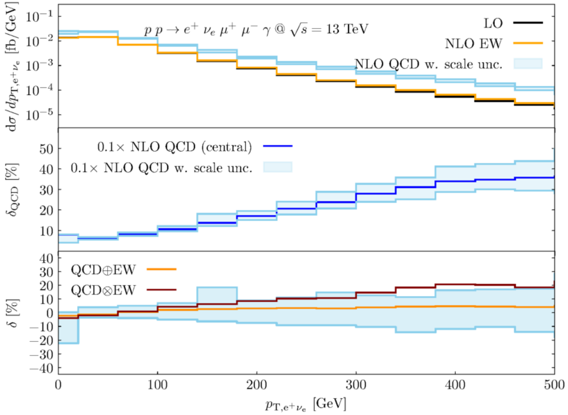
- EW corrections reach $\approx -25\%$ at $1\,\mathrm{TeV}$ (Sudakov logarithms)
- photon-induced corrections at most 5%
- EW corrections larger than QCD scale uncertainty

NLO EW and QCD corrections to $e^+\nu_e\mu^+\mu^-\gamma$



Cheng, Wackeroth 2112.12052

Distribution in transverse momentum of $e^+\nu_e$ pair (W boson)



- (photon-induced) EW corrections $\approx +20\%$ at $500\,\mathrm{GeV}$, opening of new γq channels with hard jets, similar to $\mathrm{pp}\to\mathrm{e}^+\nu_e\gamma$ Denner et al. 1412.7421
- differences between multiplicative and additive combinations of QCD and EW corrections

Status of fixed-order EW corrections

- EW corrections automated in several codes
  - EW corrections to $2 \to 5(6)$ processes easily available
  - present frontier $2 \to 7(8)$ processes
- EW corrections typically $\lesssim 5$–10% for inclusive observables
- large EW corrections possible
  - in radiative tails ($> 100\%$)
  - in high-energy tails of distributions ($\mathcal{O}(40\%)$)
  - in fiducial cross sections for specific processes ($\mathcal{O}(20\%)$ for VBS)
- naively suppressed coupling orders may be important due to opening of new kinematic channels

Ongoing work

- matching of EW corrections with parton showers
- PDFs and parton showers including EW effects
- automation for processes with polarized vector bosons and/or top quarks
  Pelliccioli et al., Baglio et al., Buarque Franzosi et al. (Madgraph)