# Subtleties in NLO EW corrections

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# NLO EW calculations

- fixed-order next-to-leading order electroweak corrections
- MUNICH/SHERPA+OPENLOOPS for a range of processes:
  - $pp \to V + 0, 1, 2(, 3)$ jets — Lindert et.al. arXiv:1705.04664, FCC report, arXiv:1607.01831, EW report arXiv:1606.02330, LH'15 arXiv:1605.04692, Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2015)012, JHEP04(2016)021
  - $pp \to Zj/pp \to \gamma j$ ratio — LH'15 arXiv:1605.04692, Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1505.05704
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + j$ — Lindert et.al arXiv:1705.04664
  - $pp \to Vh$ — FCC report, arXiv:1607.01831
  - $pp \to 2\ell 2\nu$ — Kallweit,Lindert,Pozzorini,MS, arXiv:1705.00598
  - $pp \to t\bar{t}h$ — LH'15 arXiv:1605.04692
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2$ j, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. arXiv:1704.05783
- SHERPA+GOSAM
  - $pp \to \gamma\gamma + 0, 1, 2$ jets — Chiesa et.al. arXiv:1706.xxxxx
- dedicated comparisons in LH'15 against RECOLA $(Z + 2j)$ and MADGRAPH $(t\bar{t}h)$ showed agreement

# Diboson production

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

NLO QCD+EW calculation of DF and SF $pp \to 2\ell 2\nu$ production

1) $pp \to e^+\mu^-\nu\bar{\nu}$ Biedermann, et.al. JHEP06(2016)065
DPA: Billoni, Dittmaier, Jäger, Speckner JHEP12(2013)043

$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$ at LO through $WW$
photon induced processes contribute twice as much as $c\bar{c}$-channel at LO to inclusive xs, more in TeV range, incl. at NLO EW new

2) $pp \to e^+e^-\nu\bar{\nu}$ new

$pp \to e^+e^-\nu_e\bar{\nu}_e$ at LO through $WW$ and $ZZ$
$pp \to e^+e^-\nu_{\mu/\tau}\bar{\nu}_{\mu/\tau}$ at LO through $ZZ$
contribution of ind. procs. depends very much on observable
photon induced process included at NLO EW

- all double-, single- and non-resonant diagrams included
- 4F to suppress single-top contribs at NLO QCD,
  jet veto to control large NLO QCD
- explore how NLO QCD⊗EW can be reproduced with current tools

# NLO EW corrections

**Combination of QCD and EW correction**

- additive – strict fixed order expansion

$$\mathrm{d}\sigma^{\text{NLO}}_{\text{QCD+EW}} = \mathrm{d}\sigma^{\text{LO}}\left(1+\delta_{\text{QCD}}+\delta_{\text{EW}}\right)$$

- multiplicative – contains terms of $\mathcal{O}(\alpha_s\alpha)$

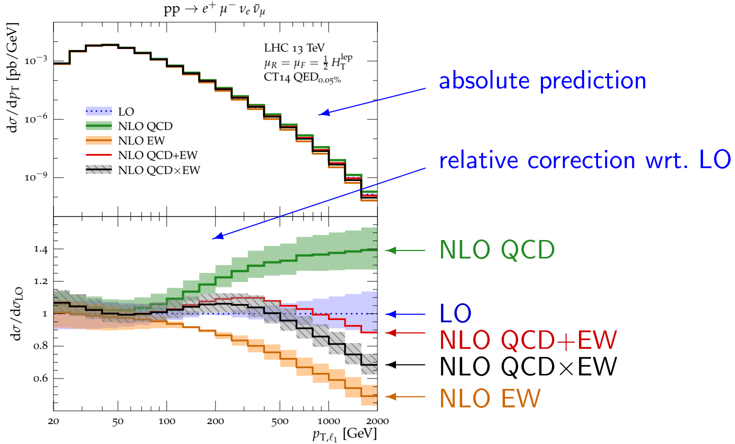
$$\mathrm{d}\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}} = \mathrm{d}\sigma^{\text{LO}}\left(1+\delta_{\text{QCD}}\right)\left(1+\delta_{\text{EW}}\right)$$

**NLO EW for photon initiated processes**

- resolved final state photons should be renormalised on-shell ($\alpha(0)$)
  $\to$ absorbs IR divergences from $\gamma \to f\bar{f}$ splittings not included
- initial state (and unresolved final state) photons should be renormalised at the hard scale ($\alpha(m_Z)$, $G_\mu$, $\overline{\text{MS}}$, etc.)
  $\to$ match IR divergences in PDF evolution and collinear counter term

Harland-Lang, Khoze, Ryskin Phys.Lett.B761(2016)20-24
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

# Diboson production – DF

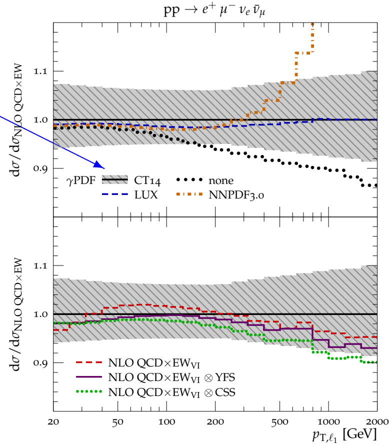



- large pos. NLO QCD, large neg. NLO EW
  $\rightarrow$ NLO QCD+EW and NLO QCD$\otimes$EW differ significantly

# Diboson production – DF

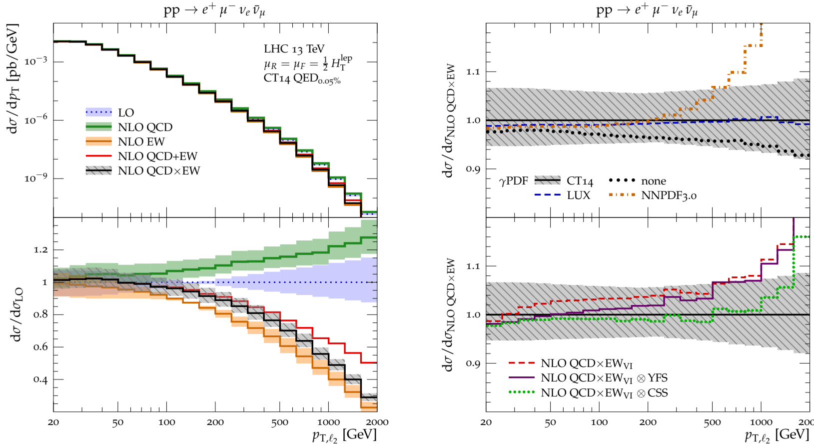
relative importance of $\gamma$-induced channels wrt. NLO QCD$\times$EW

| | |
|---|---|
| CT14qed (baseline) | no $\gamma$PDF |
| LUXqed | NNPDF3.0qed |



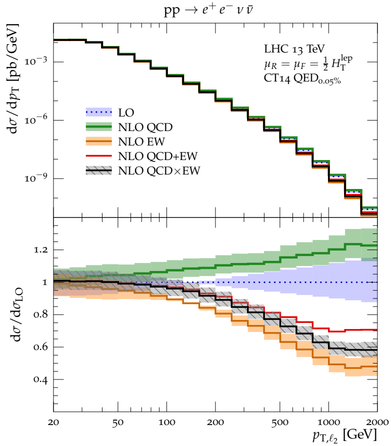

- all $\gamma$PDF agree that $\gamma$-ind. $> 10\%$ for $p_T > 500\,\text{GeV}$
  very good agreement between CT14qed and LUXqed

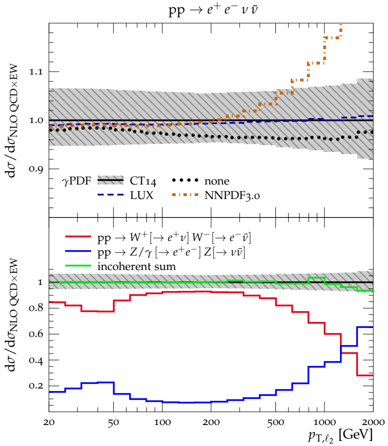
# Diboson production – DF




- *ZZ* dominant at very large $p_T$
  → different EW corrections, take care when extrapolating

# Diboson production – SF

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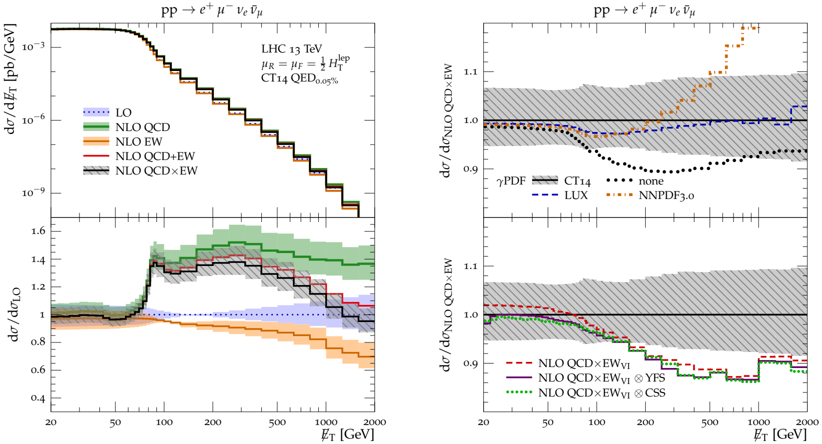
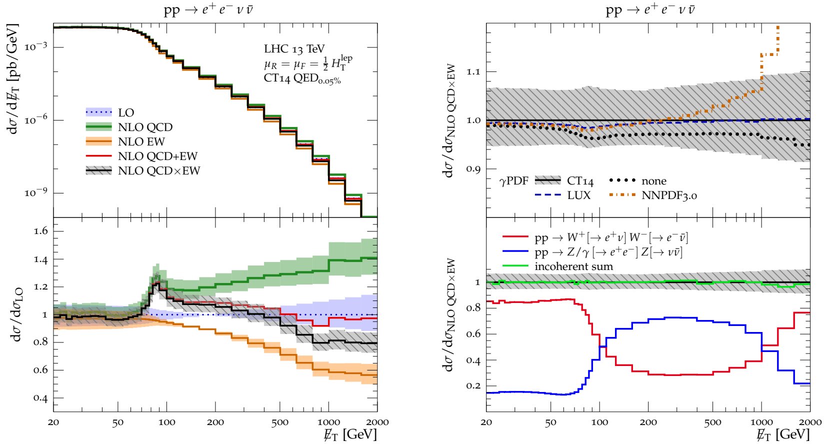
# Diboson production – DF




- kinematic suppression for $p_{\mathrm{T}}^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in $\gamma$-induced $\Rightarrow$ large contrib

# Diboson production – SF




- kinematic suppression for $p_T^{\nu\nu}$ for $WW$, but not $ZZ$
  $ZZ$ dominates for MET $> 100\,$GeV with large EW corr.

# Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
  → validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ for observables not driven by real radiation

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# External photons – initial state

Harland-Lang et.al. arXiv:1605.04935, Kallweit et.al. arxiv:1705.00598

- **initial state photons** are not resolved, treat them identically to any other parton
- both elastic and inelastic photons evolve according to DGLAP $\to$ splittings $\gamma \to \gamma$, $\gamma \to q\bar{q}$, $q \to q\gamma$
- the photon PDF (at NLO QED) contains renormalisation factors that must be cancelled by the partonic cross section

$\Rightarrow$ renormalisation in short-distance scheme ($G_\mu$, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...)

# External photons – final state

- **final state photons** may be resolved or not
  strictly speaking: differentiate between short-distance photon and indentified, measurable photon

⇒ if treated as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \to ff$ splittings
$\to$ renormalisation contains IR poles

⇒ if treated democratically (just another parton), renormalise in short distance scheme ($G_\mu$, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \to ff$ splittings
$\to$ pure UV renormalisation
$\to$ identify photon through fragmentation function $D_\gamma^p(z,\mu)$

i.e. $D_\gamma^\gamma(z,\mu) = \dfrac{\alpha(0)}{\alpha_{\text{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha)$

all others $D_\gamma^q(z,\mu) = \mathcal{O}(\alpha)$, $D_\gamma^g(z,\mu) = \mathcal{O}(\alpha^2)$

- identical at NLO EW, if fragmentation $D_\gamma^q$ on Born is negligible

# External photons – final state

- **jet definition:** completely democratic vs. anti-tagging jets with too large photon content
- **democratic:**
  - \+ straight forward, close to experiment for many procs
  - – more subtractions (Born configs with FS photons)
- **anti-tagging jets with too large photon content:**
  dress quarks for collinear safety,
  discard jets if $E_\gamma > z_{\text{thr}}\, E_{\text{jet}}$ (e.g. $z_{\text{thr}} = 0.5$)
  - \+ fewer contributions
  - – difference to experimental jet definition (usually subpercent)

# $n_f$ schemes and limited PDF availability

- all available QED PDFs are either 5F (CT14, LUX, NNPDF3.0) or 6F (NNPDF2.3)
- will need to scheme conversion terms Cacciari, Greco, Nason hep-ph/9803400

$$
\begin{aligned}
&\sigma^{(n_{lf})}_{\text{NLO}}(\mu_R^2,\mu_R^2)\\
&\quad=\sigma^{(n_f)}_{\text{NLO}}(\mu_R^2,\mu_R^2)\\
&\qquad+\frac{\alpha_s}{3\pi}\sum_{i=n_{lf}}^{n_f}\sum_{\{j_1j_2\}}T_R\left[p\,\log\frac{m_i^2}{\mu_R^2}\,\Theta\left(\mu_R^2-m_i^2\right)-\Delta^{gg}_{j_1j_2}\log\frac{m_i^2}{\mu_F^2}\,\Theta\left(\mu_F^2-m_i^2\right)\right]\sigma^{(n_f)}_{\text{LO};j_1j_2}(\mu_R^2,\mu_F^2)\\
&\qquad-\frac{\alpha}{3\pi}\sum_{i=n_{lf}}^{n_f}\sum_{\{j_1j_2\}}N_{C,i}\,Q_i^2\,\Delta^{\gamma\gamma}_{j_1j_2}\log\frac{m_i^2}{\mu_F^2}\,\Theta\left(\mu_F^2-m_i^2\right)\;\sigma^{(n_f)}_{\text{LO};j_1j_2}(\mu_R^2,\mu_F^2)\,.
\end{aligned}
$$

- all PDFs are LO in QED, will need NLO QED PDFs
- is there a point of still having QCD only PDFs?

# Conclusions

- rich phenomenology, especially in complex processes
- many ambiguities and scheme dependences
- differences usually small
  - unimportant if looking at high-$p_\perp$ observables
  - important for precision observables
- long list of processes calculated by now
- approximate NLO EW corrections can be incorporated in current event generators

http://sherpa.hepforge.org

Thank you for your attention!