Higher-order EW corrections

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HL–LHC & HE–LHC physics workshop

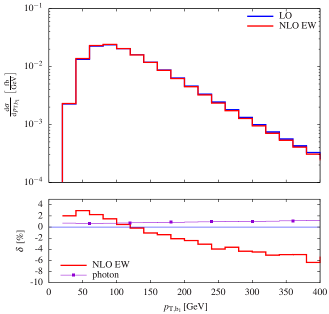
Electroweak corrections at the HL–LHC

HL–LHC: 13 TeV, 3 ab^{-1}

- rare processes and signatures can be observed
- cross sections stay the same, but
  - tails can be measured to much greater accuracy
  - many rare processes become observable
- (multi-)TeV tails strongly affected by EW Sudakov corrections, γ-induced production tends to become more important as relative size of photon PDF is larger at large x
- off-shell tails typically have different corrections (EW and QCD) then on-shell production, full off-shell calculation required
- typical rare SM processes are production of multiple EW bosons within in reach: precise study of $V_1V_2V_3$ production ($V_i = W, Z, \gamma$) EW corrections tend to be larger with more EW bosons around
- more precise prediction $\Rightarrow$ better exclusion limits on NP (AGC, etc.)

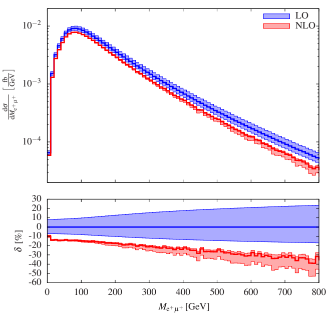
EW corrections at 13 TeV

Denner, Lang, Pellen, Uccirati
arXiv:1612.07138



$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu b\bar{b}h$

Biedermann, Denner, Pellen
arXiv:1708.00268

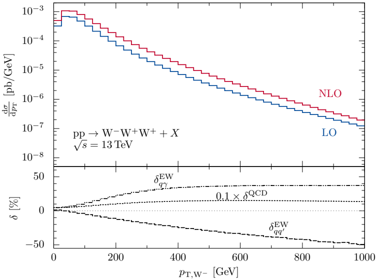


$pp \to e^+\mu^+\nu_e\nu_\mu jj$

- fully off-shell calculations for complex processes
  $\to$ precise predictions for tails (high-p_T, off-shell, ...)

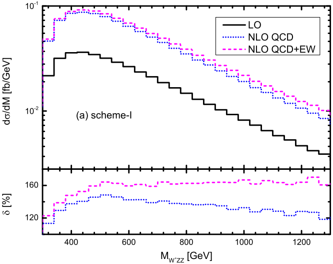
EW corrections at 13 TeV

Dittmaier, Huss, Knippen
arXiv:1705.03722



$pp \to W^+ \, W^+ \, W^-$

Yong-Bai et.al.
arXiv:1507.03693

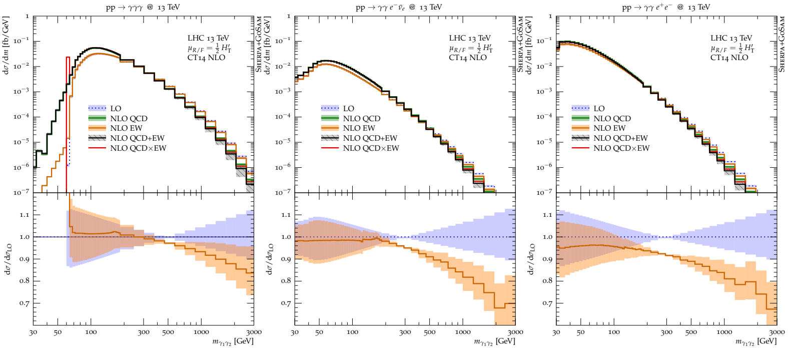


$pp \to W^+ \, Z \, Z$

- precise predictions for rare processes, but on-shell boson only $\to$ can have large off-shell effects

Rare processes – example $\gamma\gamma + V$ production

Greiner, MS arXiv:1711.00xxx



- higher luminosity ⇒ more events in tails
- EW correction more important

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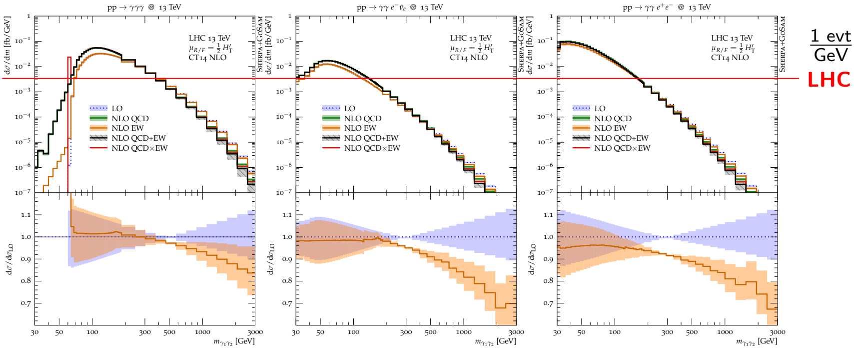

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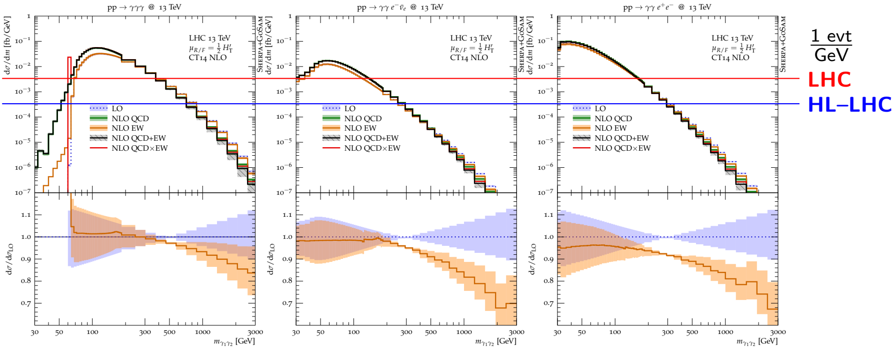


- higher luminosity ⇒ more events in tails
- EW correction more important

Electroweak corrections at the HE–LHC

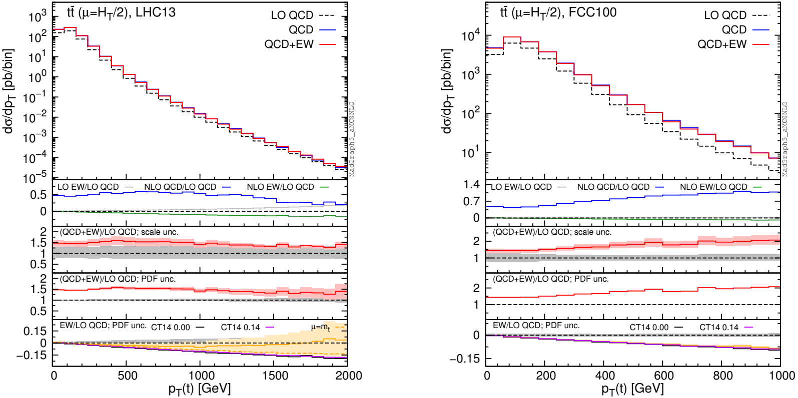
HE–LHC: 27 TeV, 12 ab^{-1}

- rare processes and signatures can be observed
- cross sections change, most importantly relative to one another
- simultaneous increase in luminosity
  - tails can be measured to greater accuracy
  - rare processes become observable
- (multi-)TeV tails strongly affected by EW Sudakov corrections, γ-induced production tends to become more important
  $\rightarrow$ remains to be seen whether change in QCD corrections not much larger, especially for real radiation dominated ones
- everything moves to smaller x, large increase of g flux for fixed m
  $\rightarrow$ EW corrections more important to q-induced processes
- off-shell tails typically have different corrections (EW and QCD) then on-shell production, full off-shell calculation required
- typical rare SM processes are production of multiple EW bosons, within in reach: precise study of $V_1V_2V_3$ production ($V_i = W, Z, \gamma$) EW corrections tend to be larger with more EW bosons around

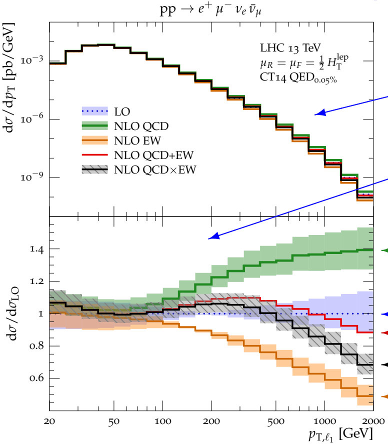
EW corrections at higher collider energies

- multiple studies so far, mostly for FCC 100 TeV
  → benefits mostly from reach into TeV scale observables

Pagani, Tsinikos, Zaro arXiv:1606.01915



EW corrections in diboson production at 13 and 27 TeV



Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

absolute prediction

relative correction wrt. LO

NLO QCD

LO

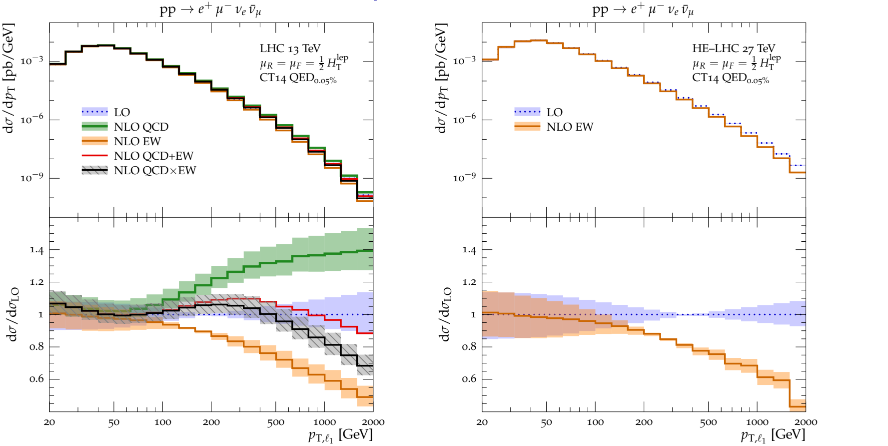
NLO QCD+EW

NLO QCD×EW

NLO EW

- xs increase in identical fiducial region: inclusive ~ 2, with $p_T > 500$ GeV ~ 5.5
- EW corrections very similar (at least in Sudakov regime where large)

EW corrections in diboson production at 13 and 27 TeV



- xs increase in identical fiducial region: inclusive ~ 2, with $p_T > 500\,\text{GeV} \sim 5.5$, or with $m_{\ell\ell} > 1\,\text{TeV} \sim 4.5$
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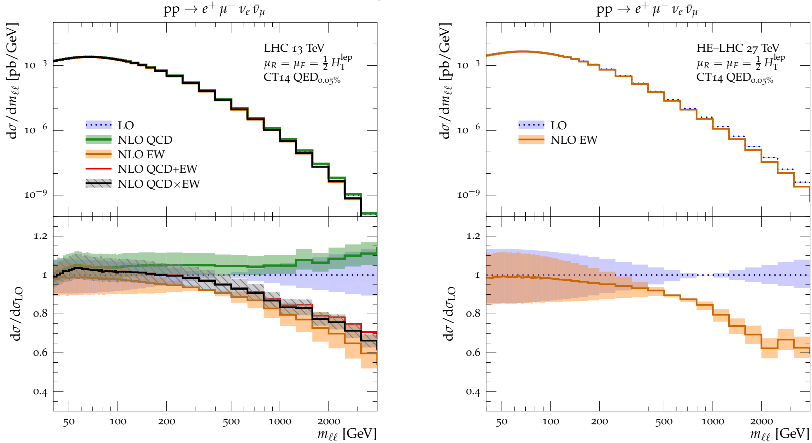
EW corrections in diboson production at 13 and 27 TeV



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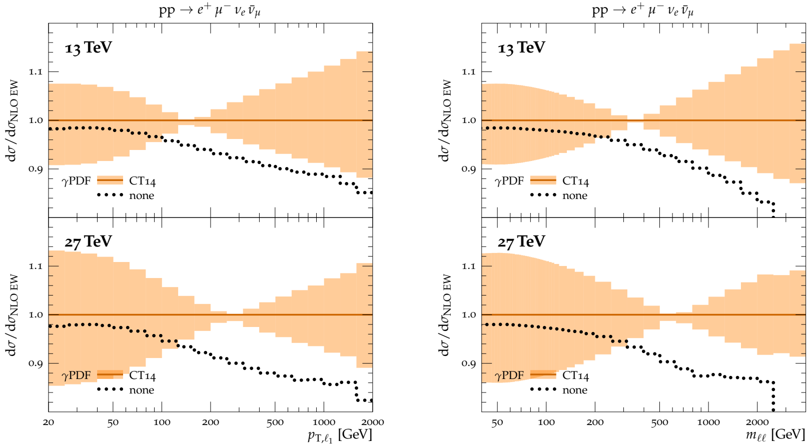
γ-PDF importance at 13 and 27 TeV



- importance of γ-PDF in same order of magnitude, but somewhat larger at 27 TeV

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 $\rightarrow$ splittings $\gamma \rightarrow \gamma$, $\gamma \rightarrow q\bar{q}$, $q \rightarrow q\gamma$
- 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_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...)

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_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), 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_γ^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

- EW correction have a rich phenomenology, especially in complex processes
- both at HL–LHC and HE–LHC more complex processes can be measured to higher accuracy
- need to include EW corrections the further into tails or rare processes one looks
- photon-initiated processes become somewhat more important, both for HL–LHC and HE–LHC, and should be accounted for consistently at NLO EW
- some systematic issues to be resolved (e.g. jet definition)
- many calculations exists (automatition of NLO EW)
  $\rightarrow$ evaluate in light of HL–LHC and HE–LHC

Thank you for your attention!