NLO QCD+EW predictions for $2\ell 2\nu$ production

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MC@NNLO

NLO EW corrections

- 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
  - $pp \to t\bar{t}h$ — LH'15 arXiv:1605.04692
  - $pp \to Zj/pp \to \gamma j$ ratio — LH'15 arXiv:1605.04692; Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1505.05704
  - $pp \to Vh$ — FCC report, arXiv:1607.01831
  - $pp \to 2\ell 2\nu$ — Kallweit,Lindert,Pozzorini,MS, arXiv:1705.00598
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2$ jets, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. arXiv:1704.05783
- 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

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

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

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

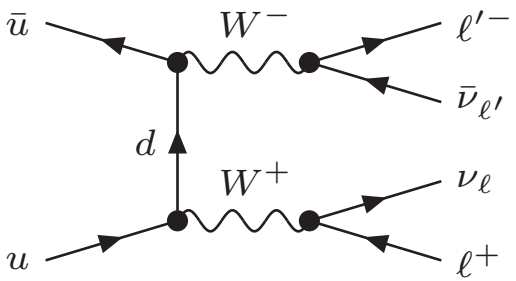
NLO EW for photon initiated processes

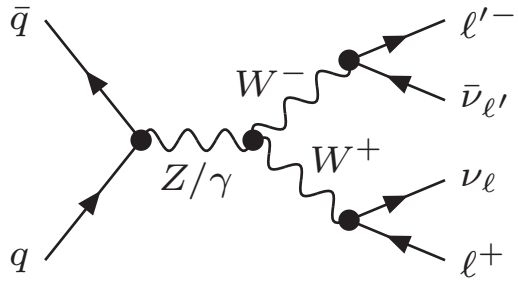
- resolved final state photons should be renormalised on-shell ($\alpha(0)$)
  $\rightarrow$ absorbs IR divergences from $\gamma \rightarrow f\bar{f}$ splittings not included
- initial state (and unresolved final state) photons should be renormalised at the hard scale ($\alpha(m_Z)$, G_μ, $\overline{\mathrm{MS}}$,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

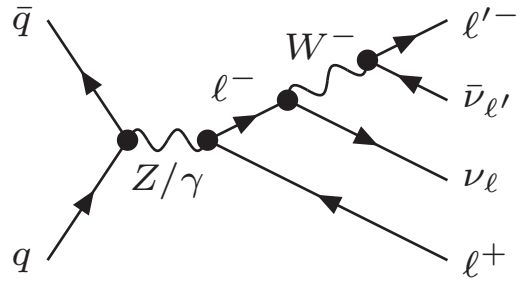
Harland-Lang, Khoze, Ryskin Phys.Lett.B761(2016)20-24
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

Diboson production – $q\bar{q}$ $\mathcal{O}(\alpha^4)$ LO diagrams

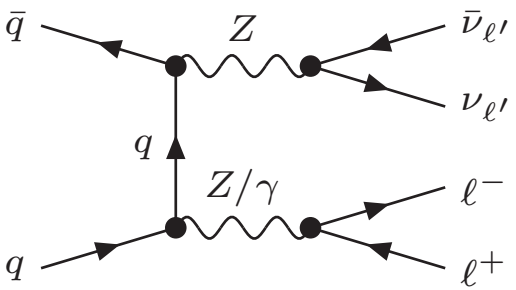
SF and DF

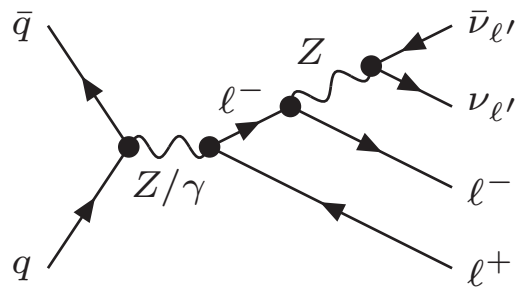






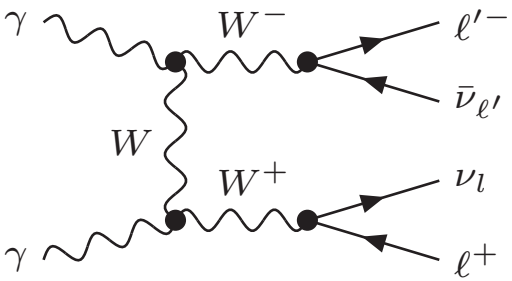
SF only

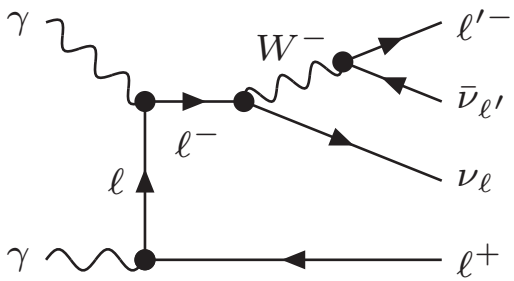


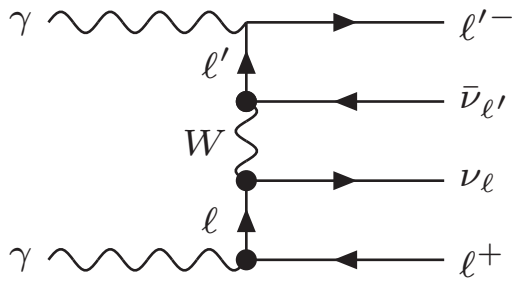


Diboson production – $\gamma\gamma$ $\mathcal{O}(\alpha^4)$ LO diagrams

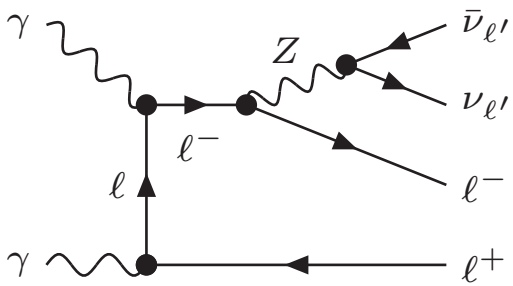
SF and DF





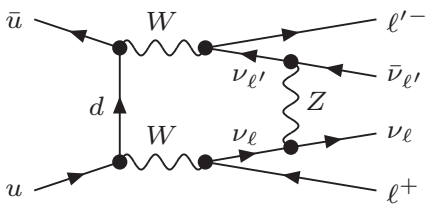


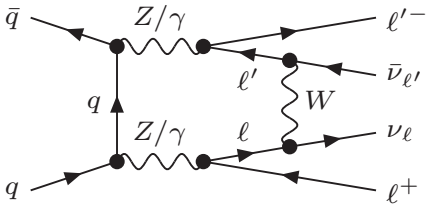
SF only

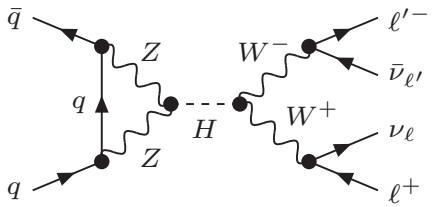


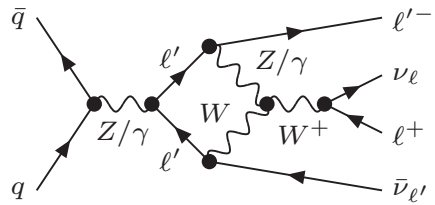
Diboson production – $q\bar{q}$ $\mathcal{O}(\alpha^5)$ 1-loop diagrams

SF and DF









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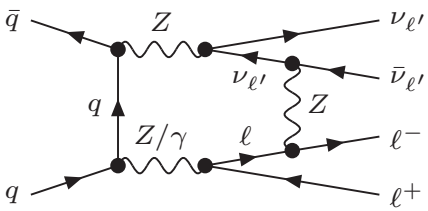
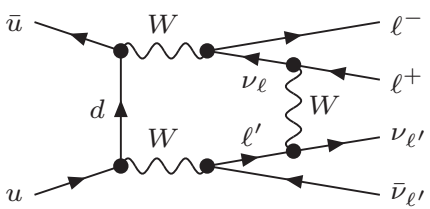
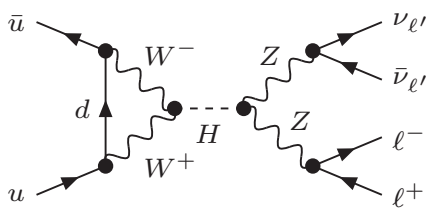
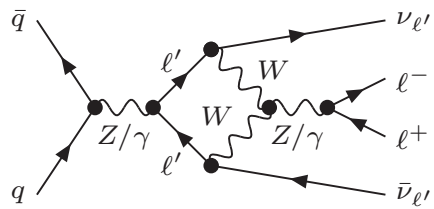


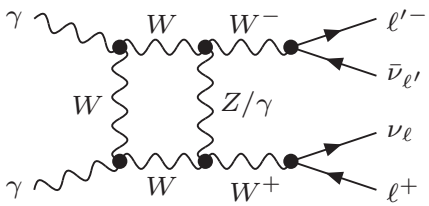


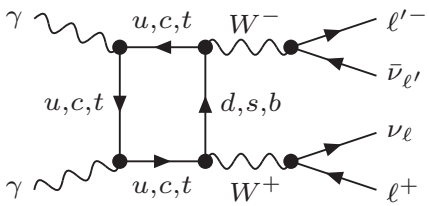


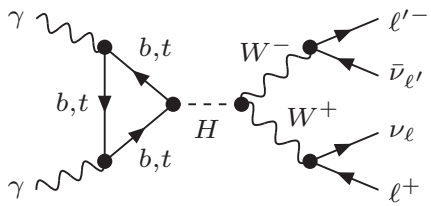


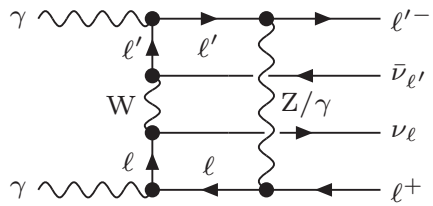
Diboson production – $\gamma\gamma$ $\mathcal{O}(\alpha^5)$ 1-loop diagrams

SF and DF

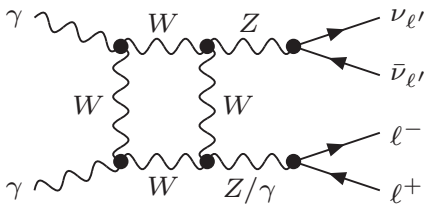


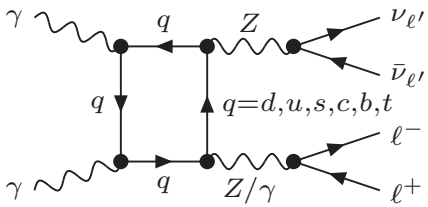


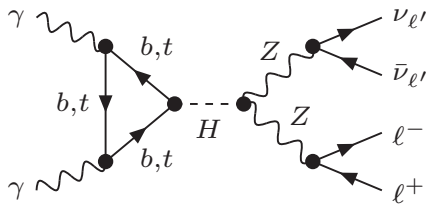


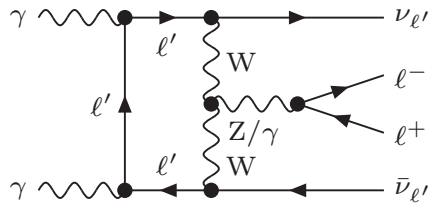


SF only



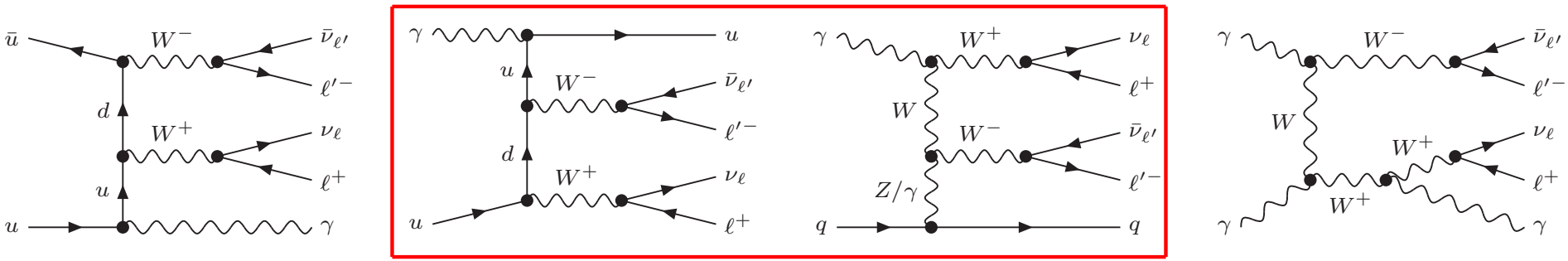






Diboson production – $q\bar{q}$, γq, $\gamma\gamma$ $\mathcal{O}(\alpha^5)$ real em. diagr.

SF and DF, SF only similar

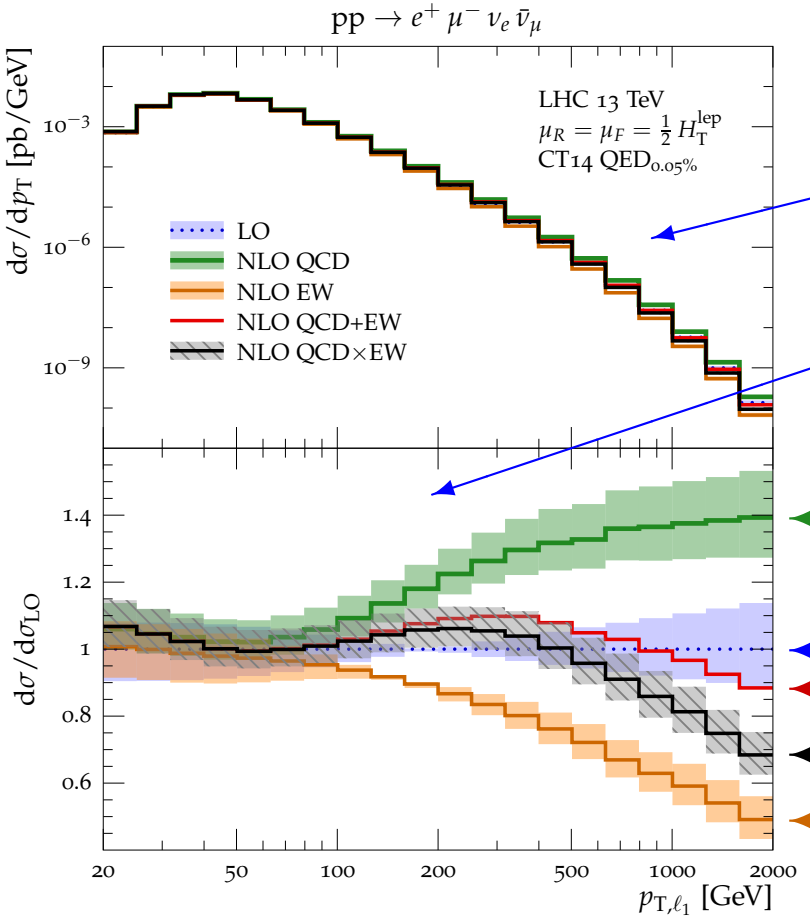


- γq real emission corrections link $q\bar{q}$- and $\gamma\gamma$-induced process
  $\rightarrow$ contain singularities wrt. to both LO configuration

$\Rightarrow$ once a γPDF present, both channels have to be computed at NLO EW, otherwise dependence on subtraction scheme

- γq contribution sizeable in TeV range without jet veto

Diboson production – DF



absolute prediction

relative correction wrt. LO

NLO QCD

LO

NLO QCD+EW

NLO QCD×EW

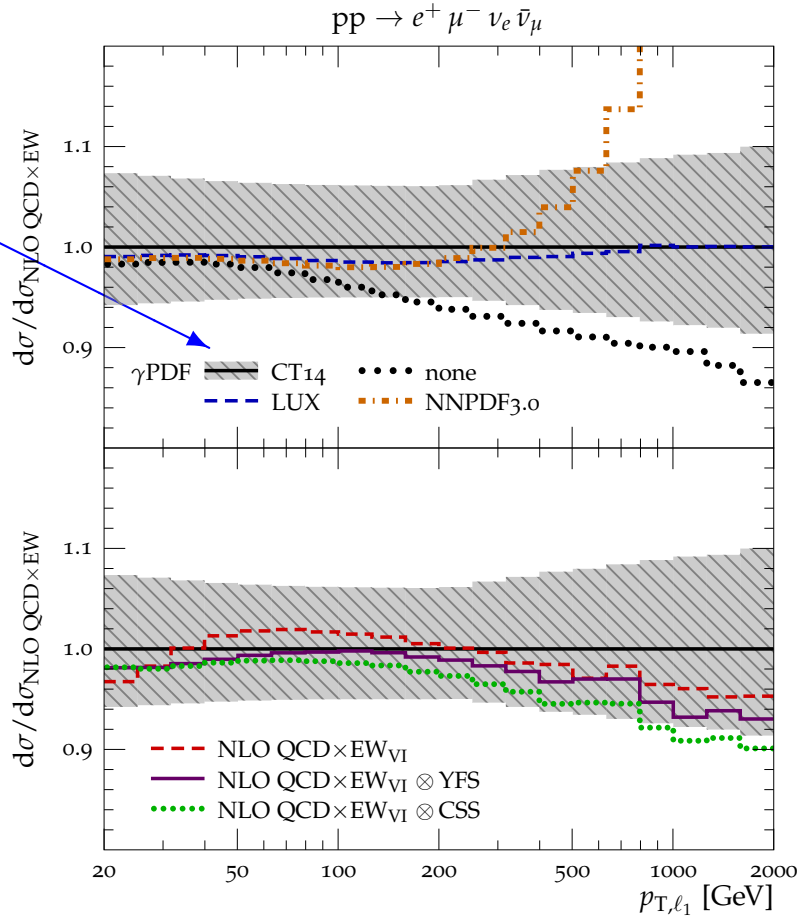
NLO EW

- large pos. NLO QCD, large neg. NLO EW
  → NLO QCD+EW and NLO QCD⊗EW differ significantly

Diboson production – DF

relative importance of γ-induced channels wrt. NLO QCD×EW

CT14qed (baseline) no γPDF
LUXqed NNPDF3.0qed



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

Diboson production – DF

reproduction of full result using publically available tools

EW$_{\text{VI}}$ apprixomation

Kallweit et.al. JHEP04(2016)021

exact virtual correction
appr. integrated real correction

YFS soft photon resummation

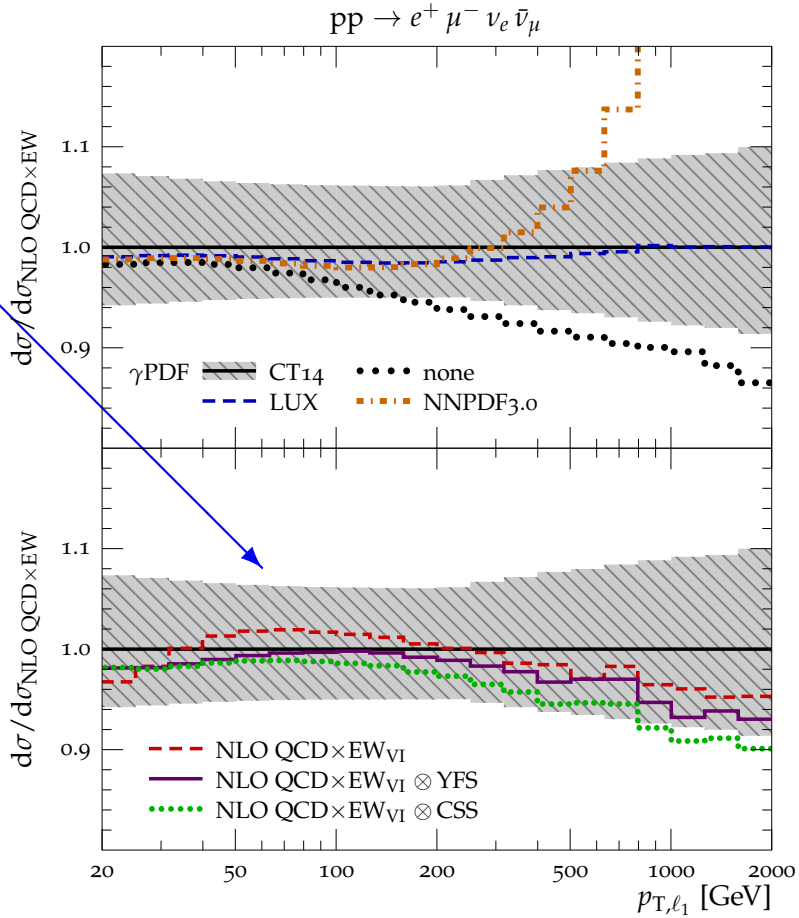
Schönherr, Krauss JHEP12(2008)018

QED corr. to decays
NLO QED for Z/W decays
resonance aware

QED dipole shower (CSS)

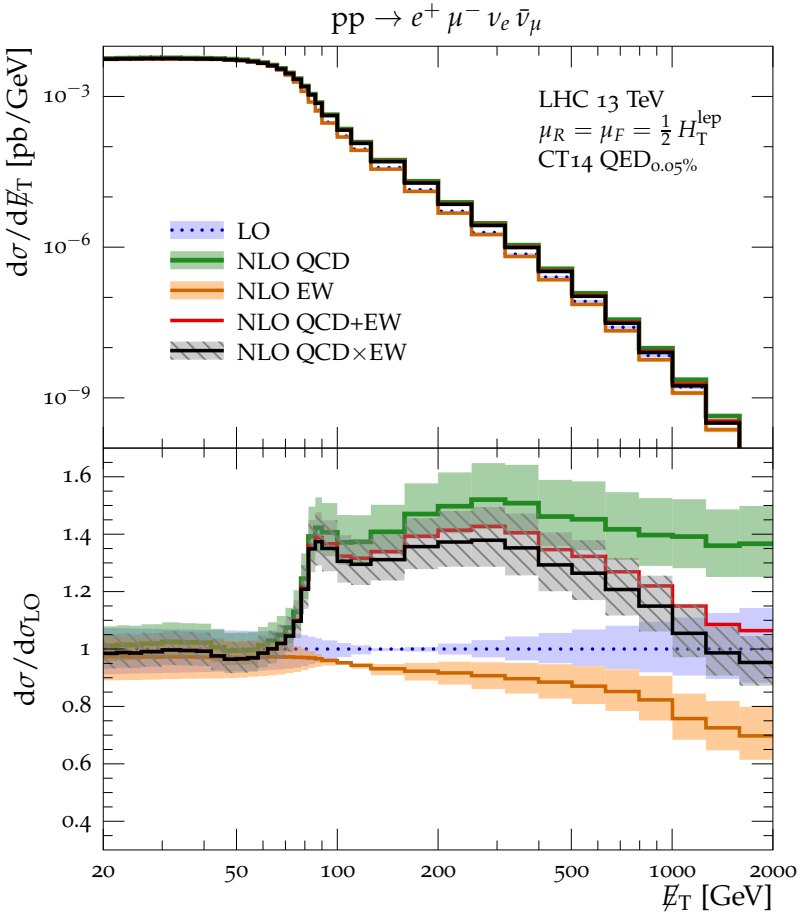
Höche et.al. Phys.Rev.D81(2010)034026

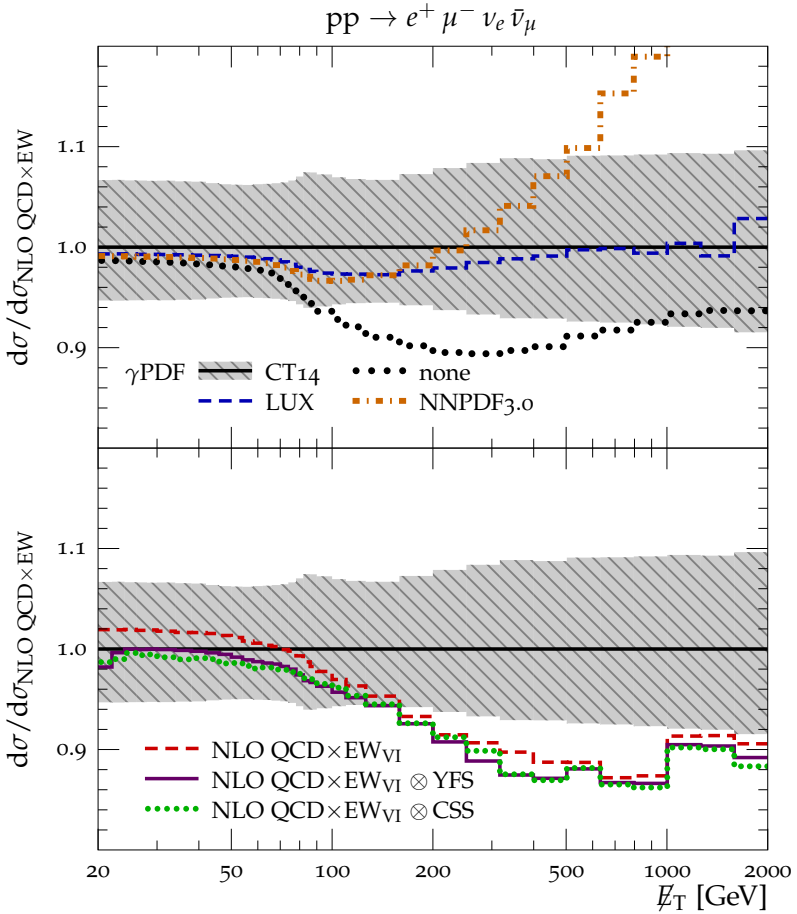
QED ISR & FSR
not resonance aware



- both YFS-based and QED-PS approx. reproduce exact result well
  → possibility of practical approximation with current tools

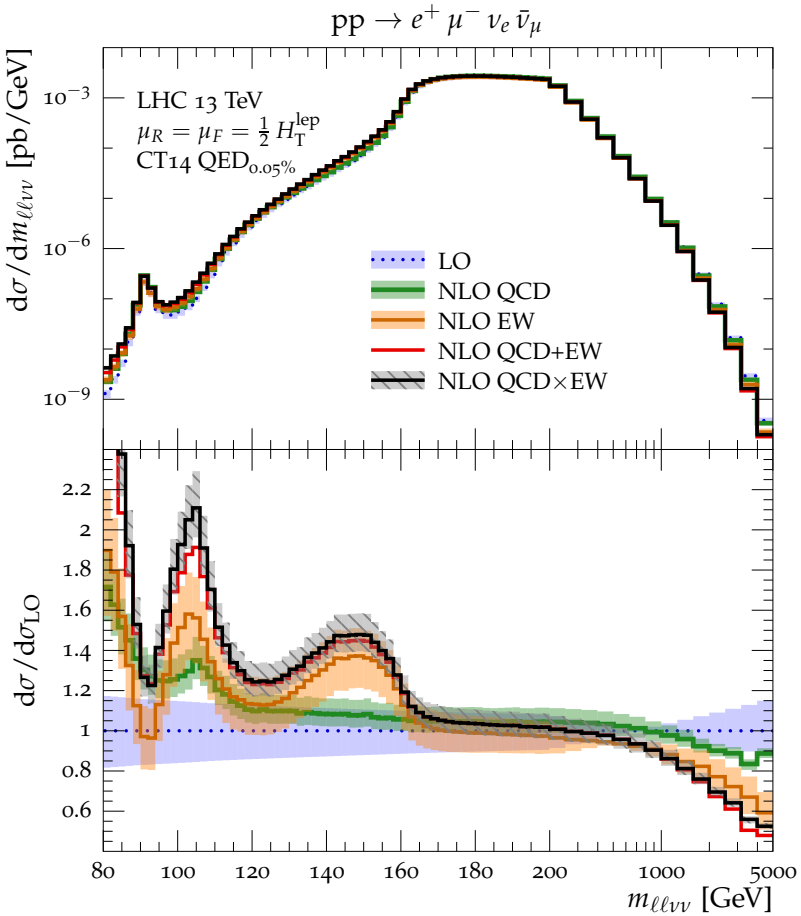
Diboson production – DF

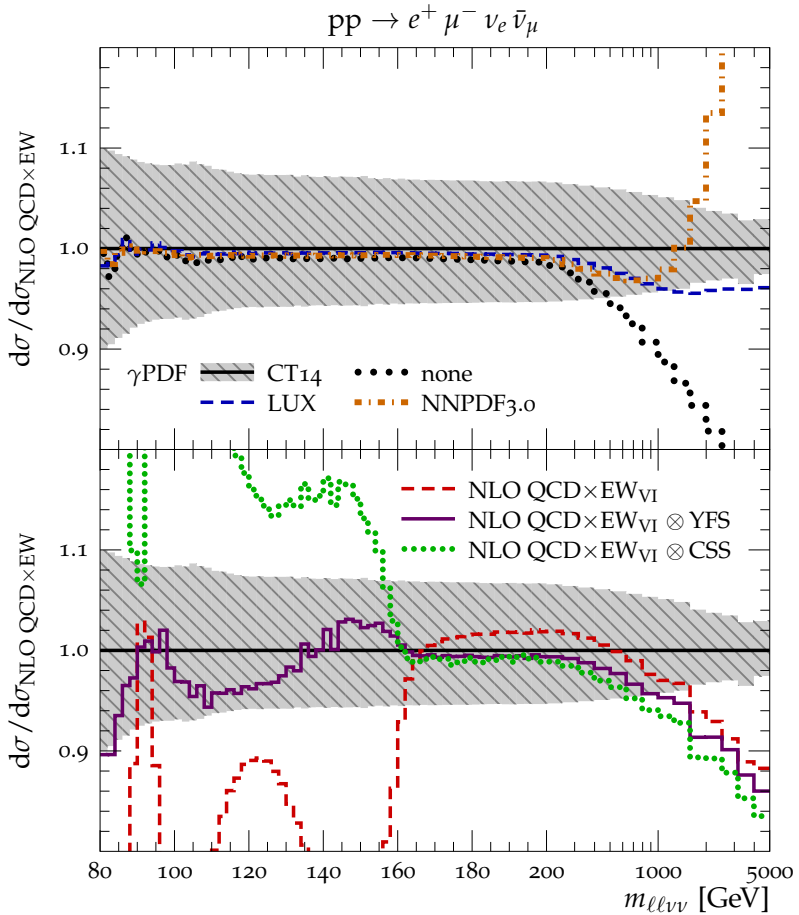




- kinematic suppression for $p_{\mathrm{T}}^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced $\Rightarrow$ large contrib

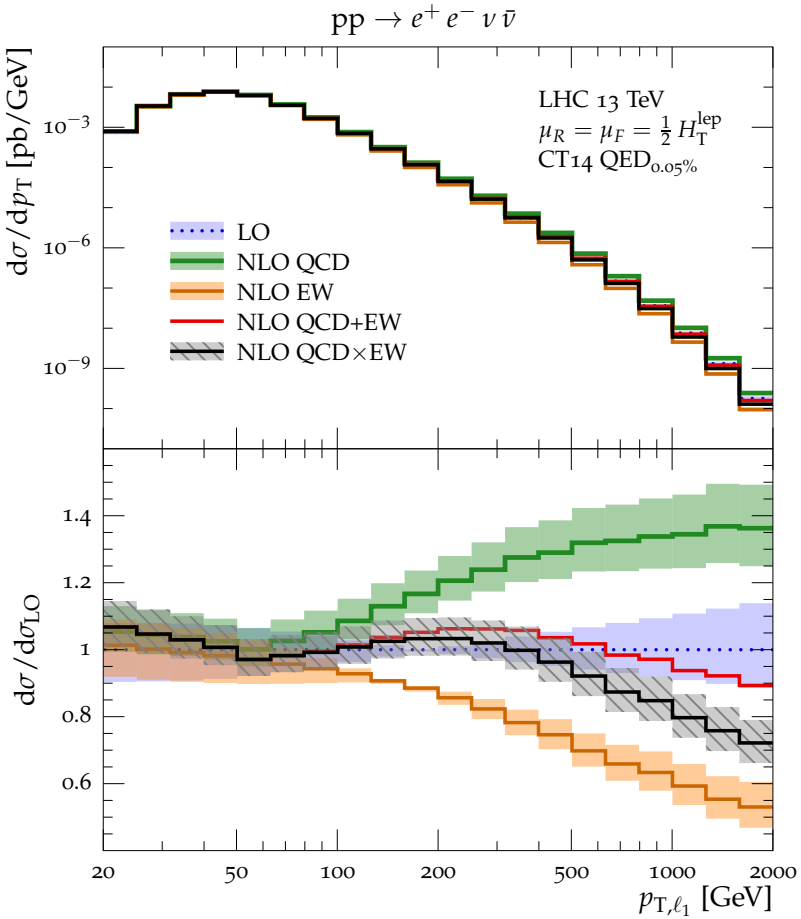
Diboson production – DF

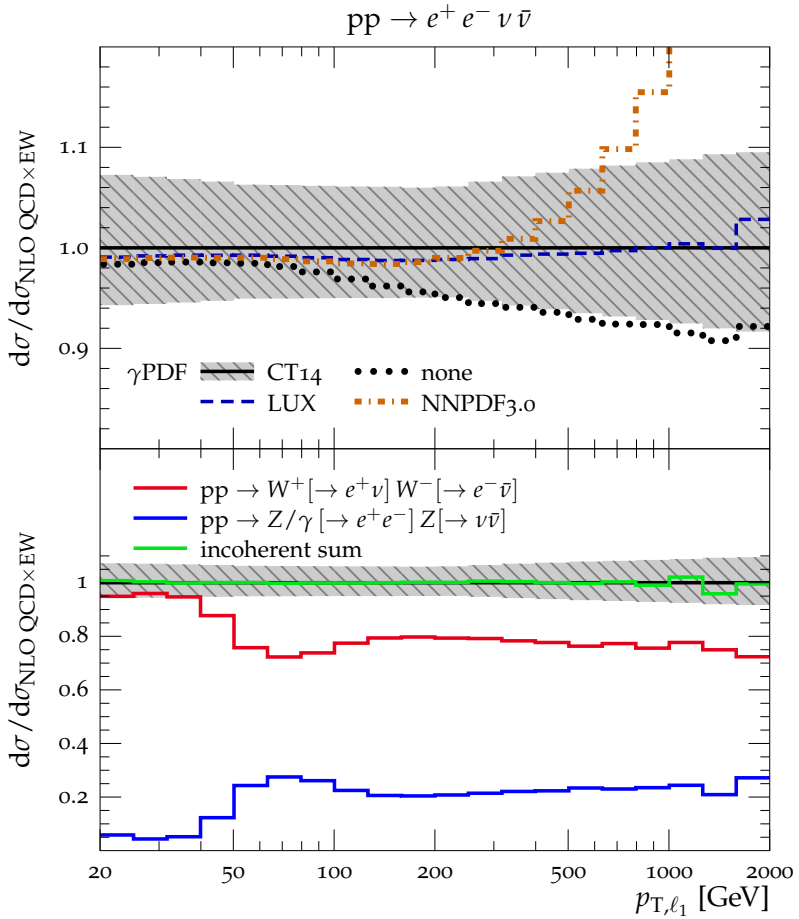




- resonance preservation crucial, otherwise δ_{EW} off by factor ≈ 2
- at high p_{T} hard non-resummable radiation dominates

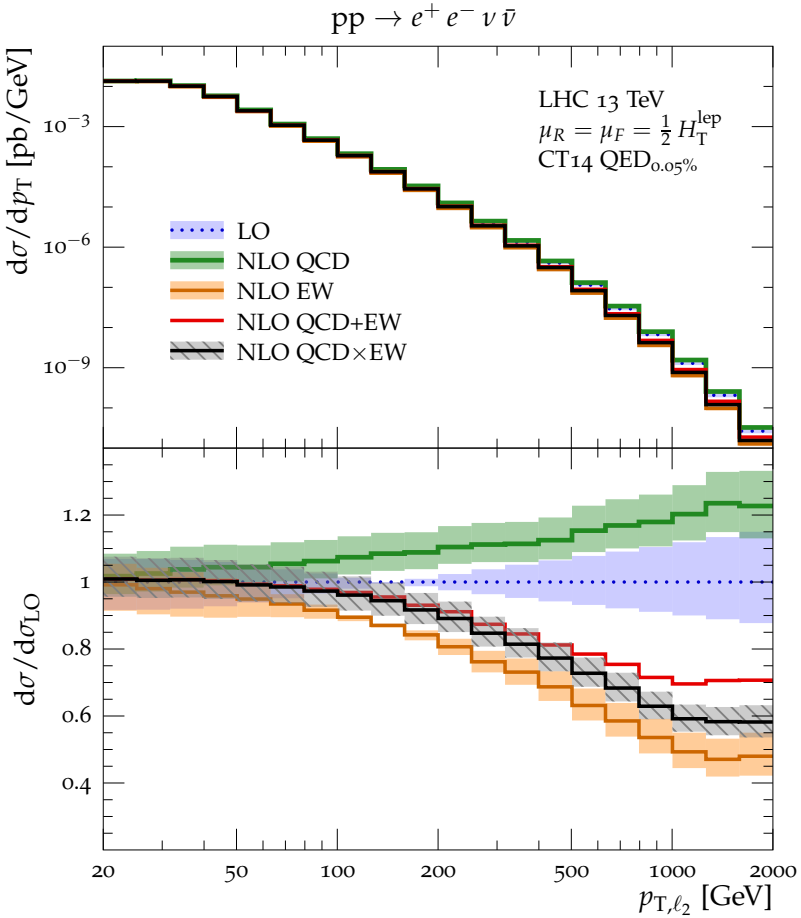
Diboson production – SF

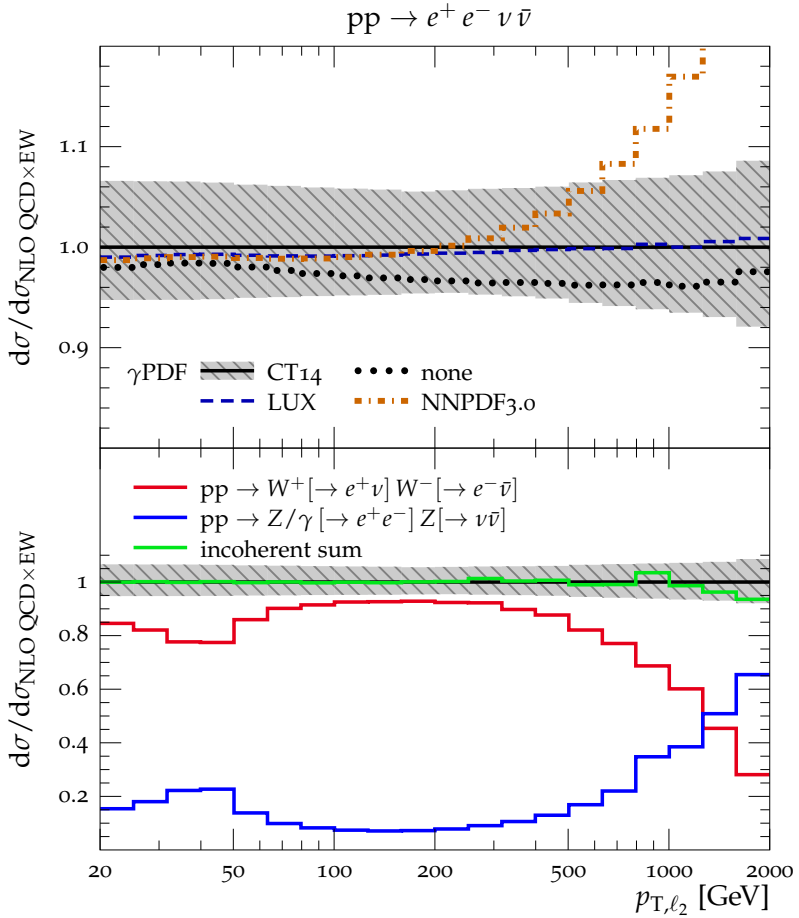




- very similar to DF due to small ZZ contrib
- no interference effects as bosons not forced off-shell

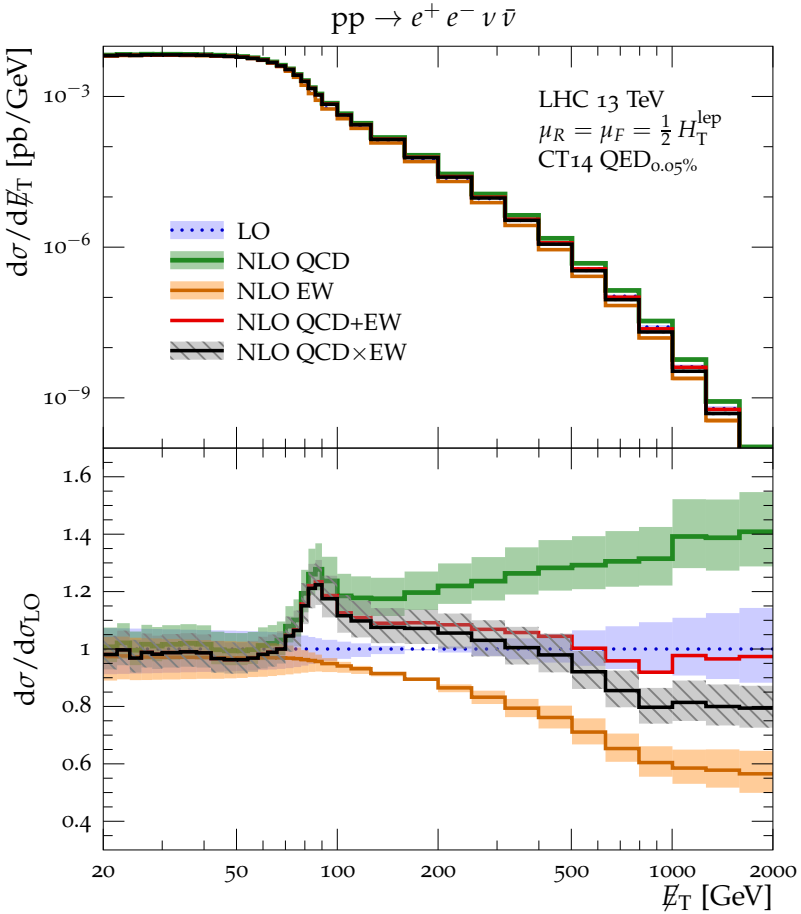
Diboson production – SF

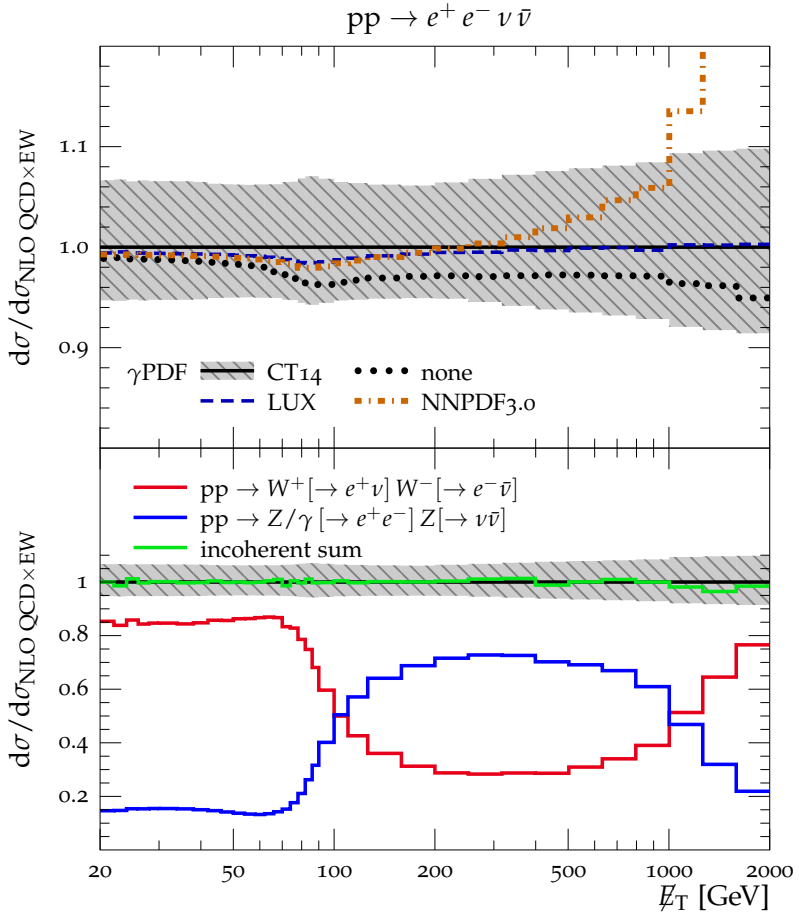




- ZZ dominant at very large p_T
  $\rightarrow$ different EW corrections, take care when extrapolating

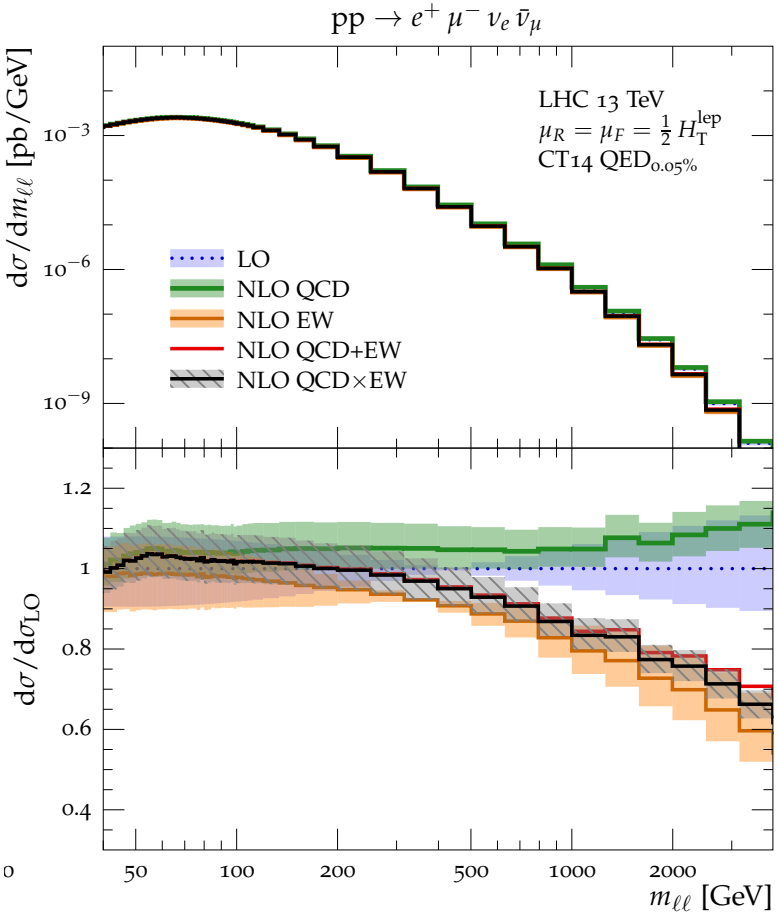
Diboson production – SF

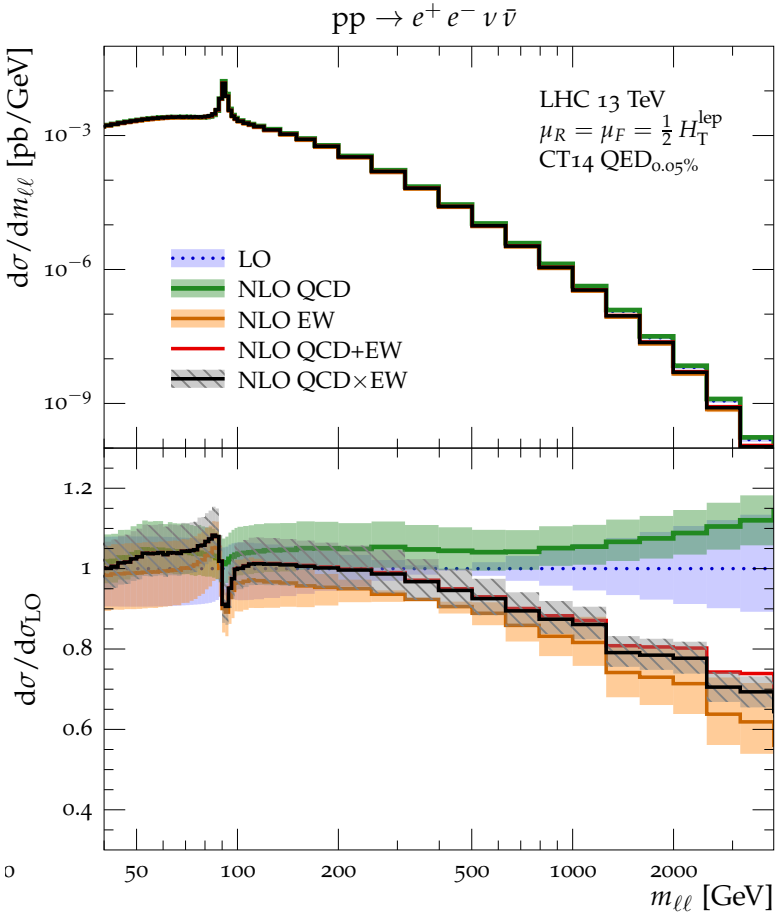




- kinematic suppression for $p_{\mathrm{T}}^{\nu\nu}$ for WW, but not ZZ
  ZZ dominates for MET $> 100\,\mathrm{GeV}$ with large EW corr.

Diboson production – DF vs. SF





- *ZZ* dominant at *Z*-peak otherwise *WW* dominated
  $\rightarrow$ very similar high-$m_{\ell\ell}$ behaviour

Conclusions

- full automation of NLO QCD and NLO EW in SHERPA
- fixed-order NLO EW will become available in SHERPA-2.3
- approximate NLO EW particle level predictions recovarable through public tools
- approximate NLO EW corrections can be incorporated in NLO QCD multijet merging since SHERPA-2.2

http://sherpa.hepforge.org

Thank you for your attention!

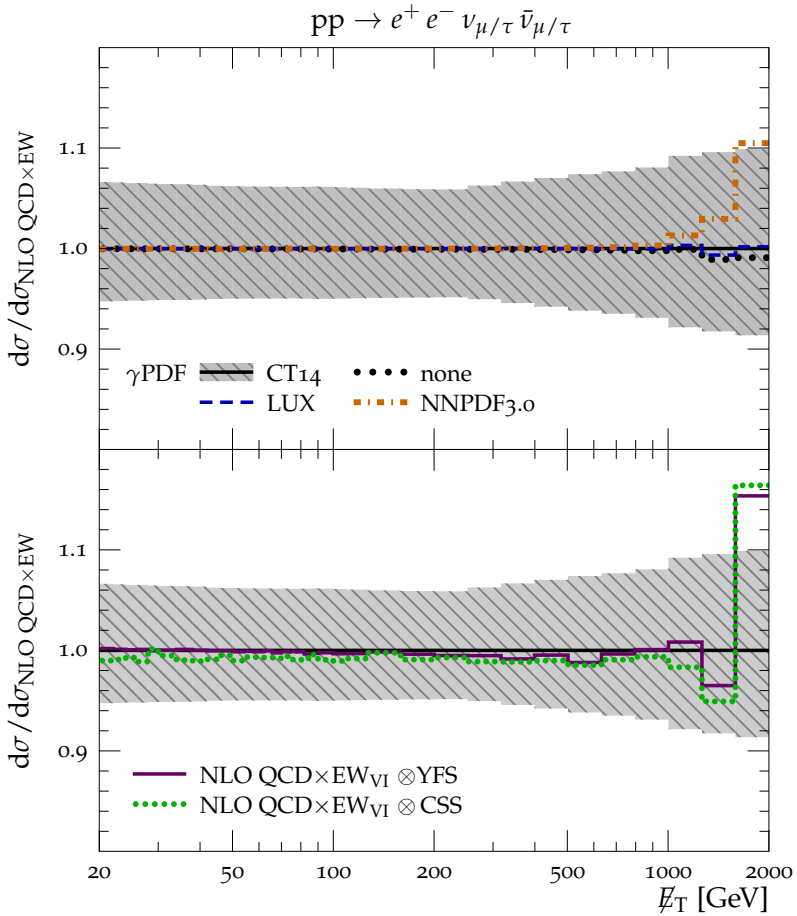
Backup

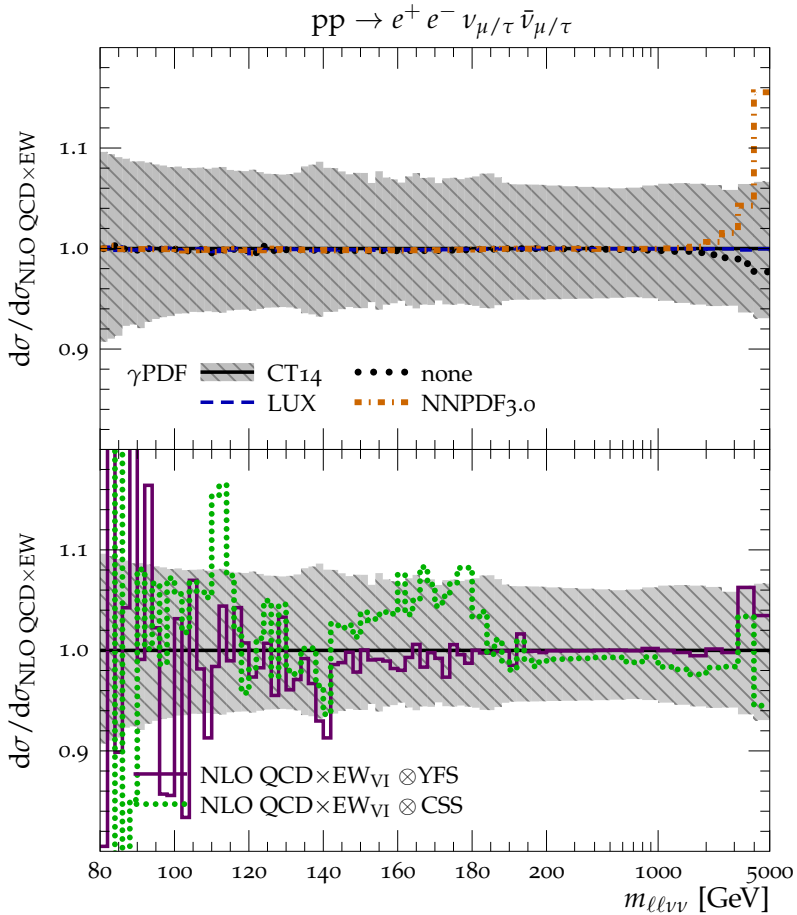
Acceptance cuts and input parameters

$$
\begin{aligned}
\not{E}_{\mathrm{T}} &> 20\,\mathrm{GeV} \\
p_{\mathrm{T},\ell^\pm} &> 20\,\mathrm{GeV} \\
|\eta_{\ell^\pm}| &< 2.5 \\
\Delta R_{\ell^+\ell^-} &> 0.2 \\
H_{\mathrm{T}}^{\mathrm{jet}} &< 0.2\, H_{\mathrm{T}}^{\ell}
\end{aligned}
$$

$$
\begin{aligned}
G_F &= 1.1663787 \cdot 10^{-5}\ \mathrm{GeV}^2 \\
M_W &= 80.385\ \mathrm{GeV} \qquad \Gamma_W = 2.0897\ \mathrm{GeV} \\
M_Z &= 91.1876\ \mathrm{GeV} \qquad \Gamma_Z = 2.4955\ \mathrm{GeV} \\
M_H &= 125\ \mathrm{GeV} \qquad \Gamma_H = 4.07\ \mathrm{MeV} \\
m_b &= 4.75\ \mathrm{GeV} \qquad \Gamma_b = 0 \\
m_t &= 173.2\ \mathrm{GeV} \qquad \Gamma_t = 1.339\ \mathrm{GeV}
\end{aligned}
$$

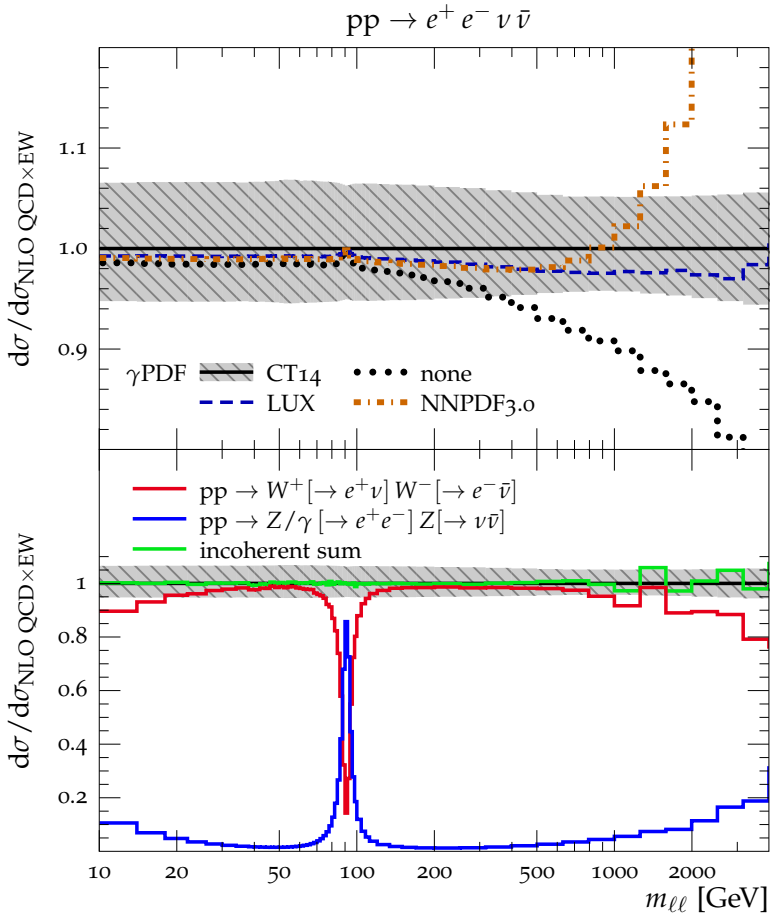
Diboson production – SF ZZ

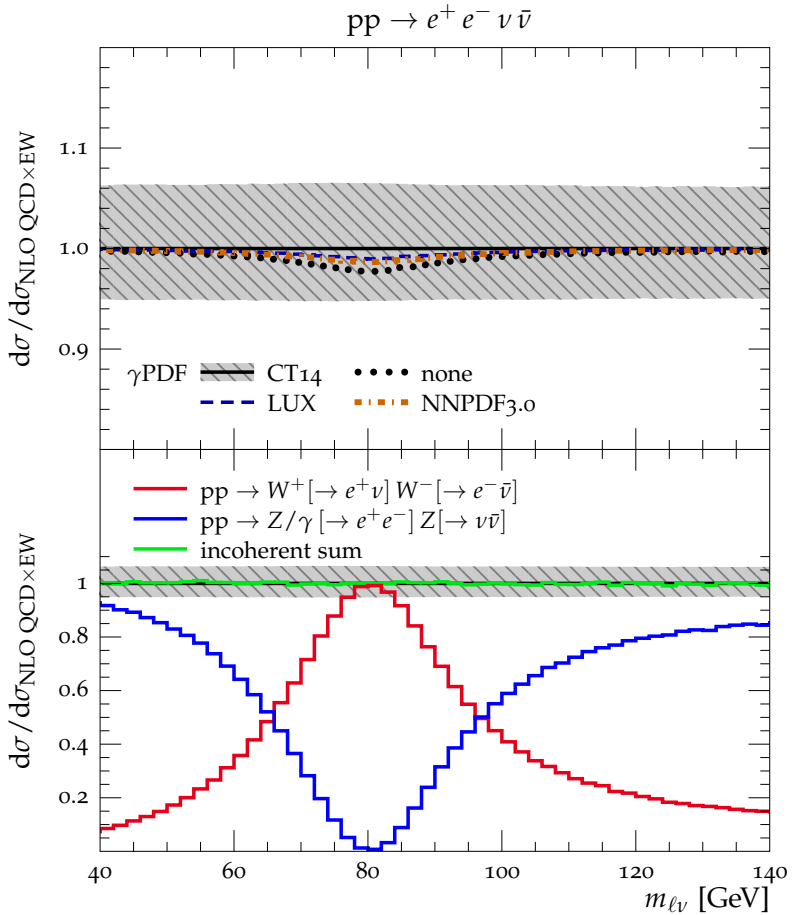




- ZZ-only channels very well recovered through YFS and CSS

Diboson production – SF ZZ





- WW and ZZ topologies dominant in their resonance region