Electroweak corrections for triboson production

Marek Schönherr

CERN

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Content

Introduction and current status

Triboson production

- triboson production clean testbed to test EW quartic couplings
- contribs from

signature	process	resonance structure
0 SFOS	$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	WWW
1 SFOS	$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	$WWW + WZZ$
	$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	WZZ
	$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	WZZ
2 SFOS	$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	$WWW + WZZ$
	$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	WZZ

  and $e \leftrightarrow \mu$
- exchange $+ \leftrightarrow -$ for $W^+W^-W^-$ production
- main backgrounds: $t\bar{t}W$, $tWW \Rightarrow$ apply jet veto
  WZ in 1, 2 SFOS $\Rightarrow$ req. large $\not{p}_{\mathrm{T}}$, $m_{\ell\ell}^{\mathrm{SFOS}} \not\approx m_Z$

Current status

NLO QCD

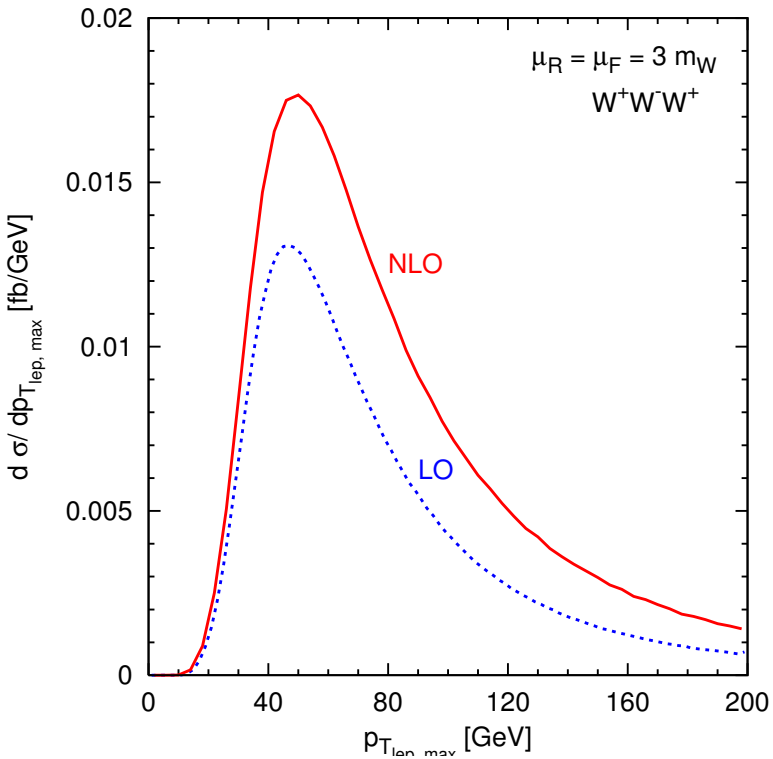
- on-shell fixed-order Binoth et.al. arXiv:0804.0350
  off-shell fixed-order Campanario et.al. arXiv:0809.0790
  → available in aut. tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)
- on-shell matched to parton showers in SHERPA,
  multijet merged $WWW + 0, 1j$ Höche et.al. arXiv:1403.7516
- off-shell matched to parton showers should be available in automated tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)

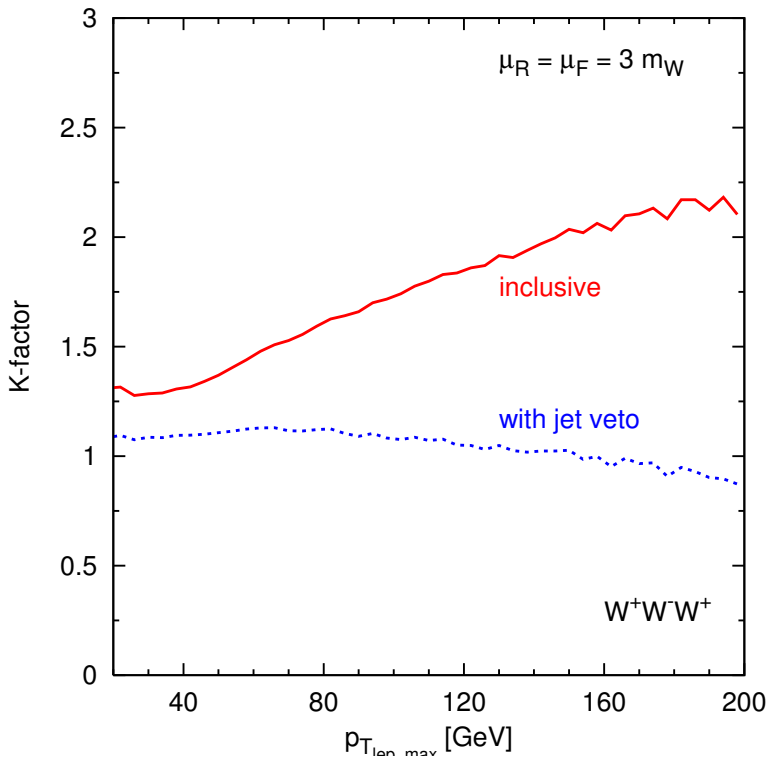
NLO EW

- on-shell known for some time Yong-Bai et.al. arXiv:1605.00554
  Dittmaier, Huss, Knippen arXiv:1705.03722
- off-shell recently computed MS arXiv:1806.00307
- no matching to parton showers available yet

NLO QCD for off-shell production

Campanario et.al. arXiv:0809.0790





- QCD correction driven by additional jet activity
  $\rightarrow$ strong observable dependence
- jet veto ($p_T^{\text{cut}} = 50\,\text{GeV}$) reduces size and phase space dependence

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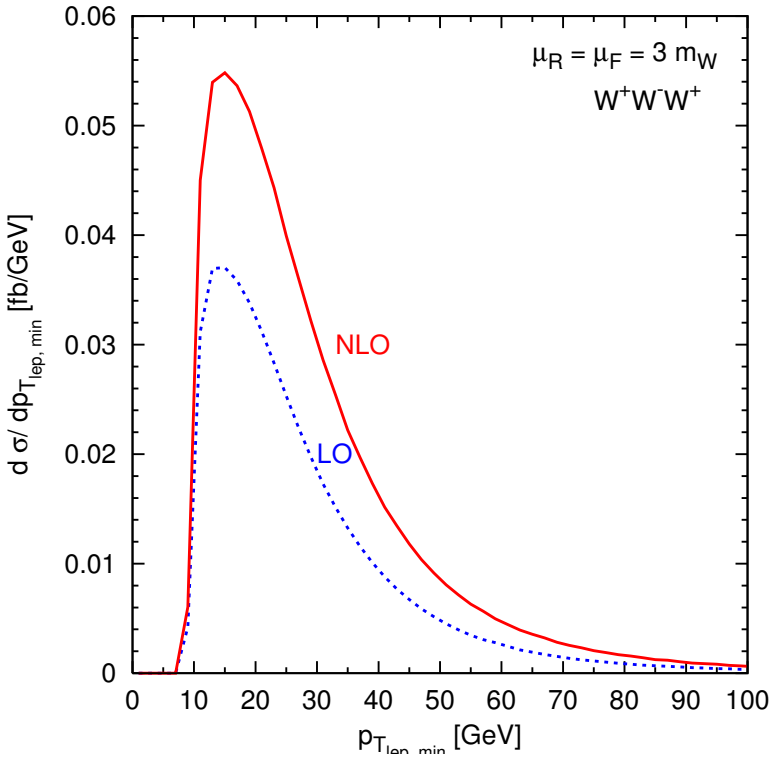

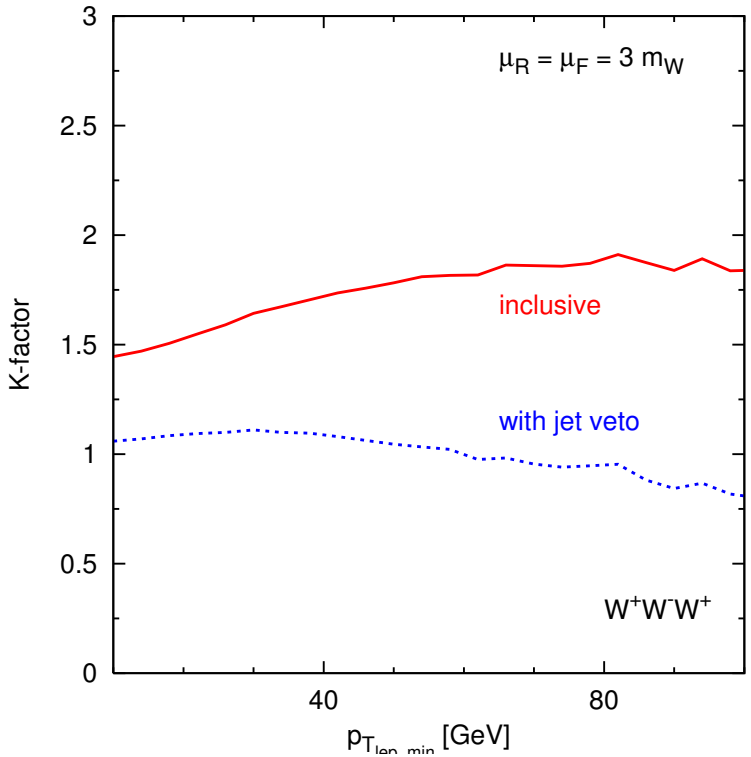

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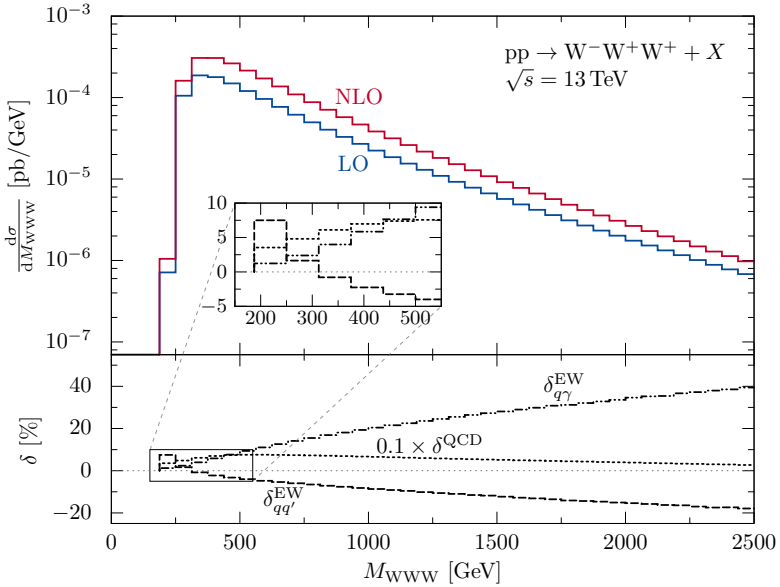
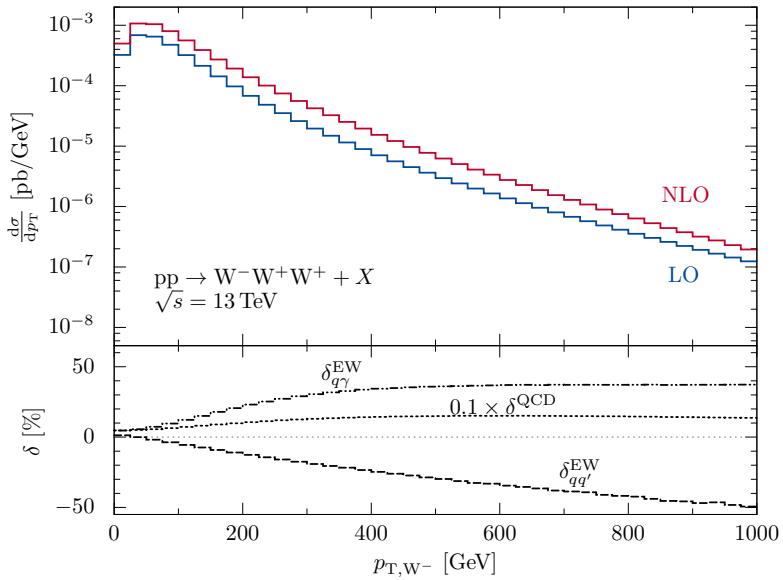
NLO QCD+EW corrections in on-shell production

Dittmaier, Huss, Knippen arXiv:1705.03722

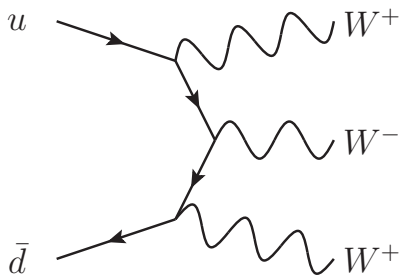


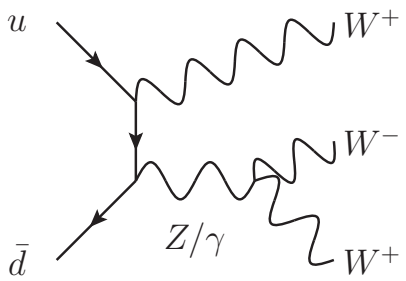


- corrections w/o jet veto
- QCD corrections $\approx 70\%$, slight observable dependence
- γ-induced EW corrections large and observable dependent
  $\rightarrow$ large accidental cancellations with EW corrections in $q\bar{q}$-channel

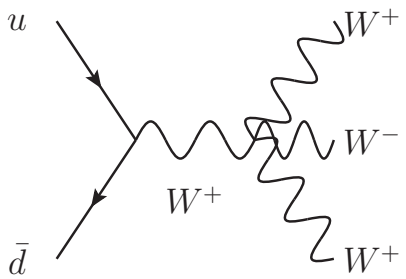
On-shell vs. off-shell triboson production

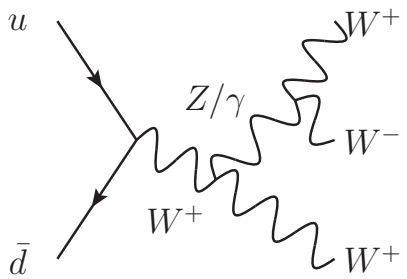
On-shell production

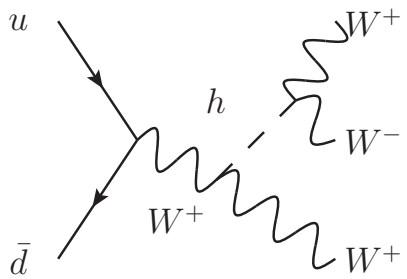




- only triple resonant diagrams
- strong interference between diagrams in which different numbers of gauge bosons couple to quark line
- some kinematic width effects recoverable through BW-shape improved spin-correlated decays
- threshold at $3\,m_W$

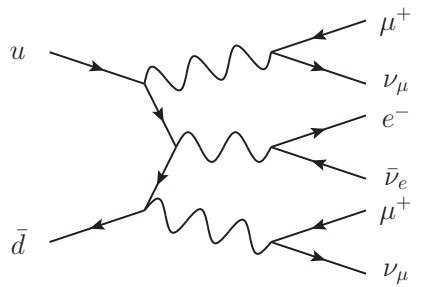


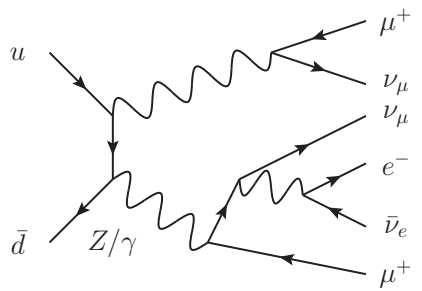


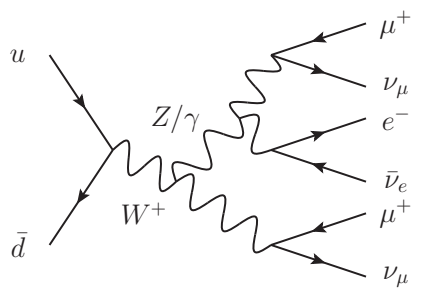


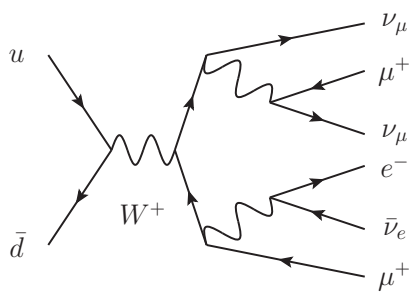
On-shell vs. off-shell triboson production

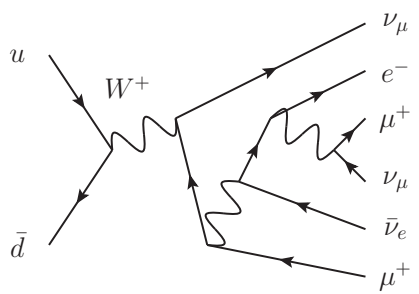
Off-shell production







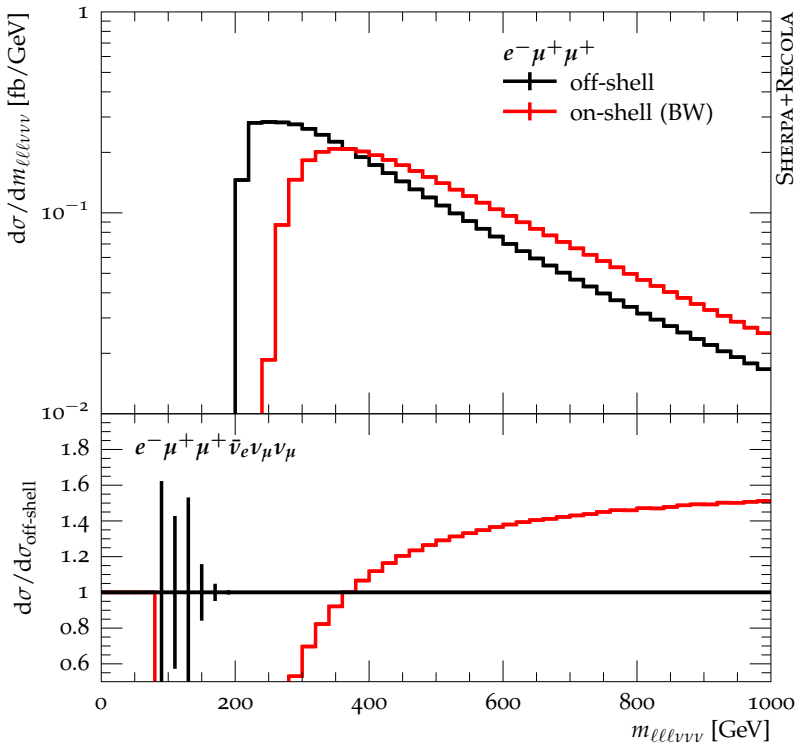




- triple, double and single resonant diagrams
- much richer internal structure, contains on-shell *WWW* as part of triple resonant subset
- includes *WZ* diagrams with $Z \to 2\ell 2\nu$
- thresholds given by acceptance cuts
- importance of single/double resonant topologies already seen in *WW*

Biedermann et.al. arXiv:1605.03419

On-shell vs. off-shell triboson production

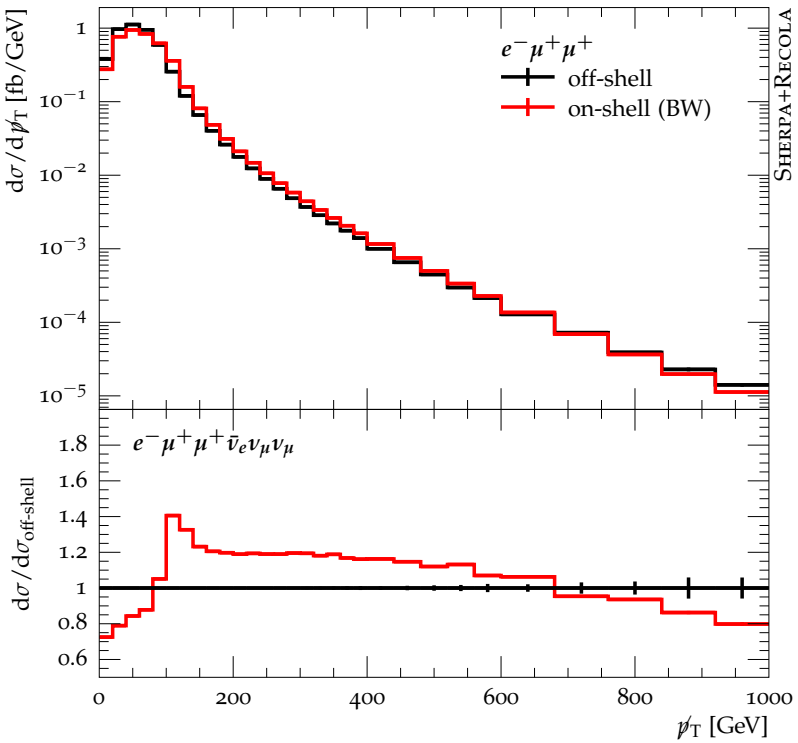


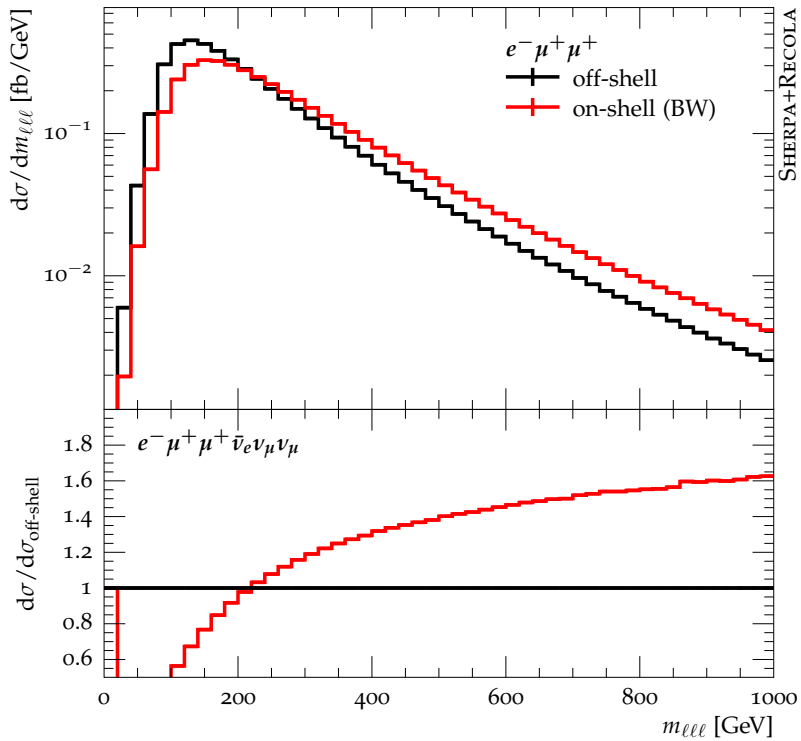
$m_{\ell\ell\ell\nu\nu\nu} = m_{WWW}$

- no unique W identifaction possible in off-shell calculation, even in MC truth, due to occurrence of SF pairs
- no cross section below $3\,m_W$ in on-shell approximation
- at large m_{WWW} masses large interference with other resonance structures

$\rightarrow$ cross checked with off-shell calculation projected on triple W resonant subset of diagrams

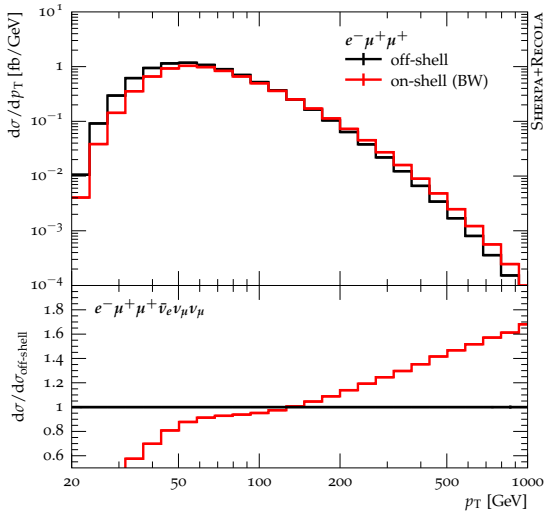
On-shell vs. off-shell triboson production



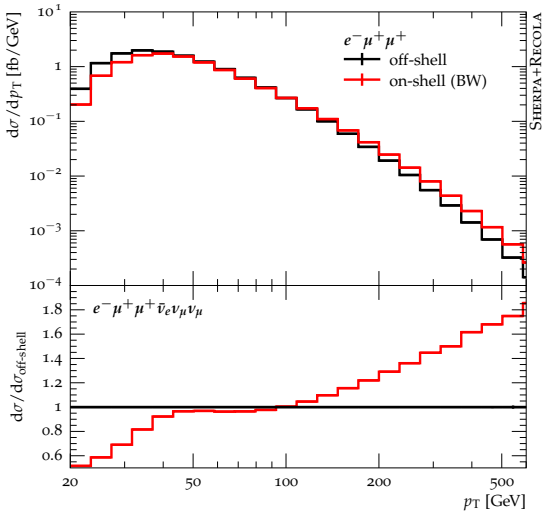


- on-shell approximation reasonable for MET, but fails for $m_{\ell\ell\ell}$ for similar reasons as for $m_{\ell\ell\ell\nu\nu\nu}$

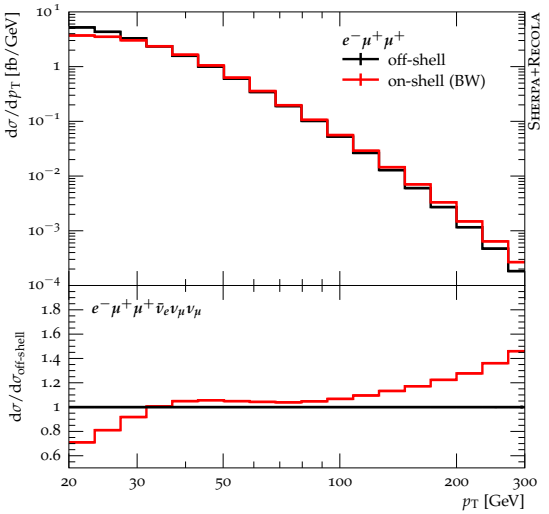
On-shell vs. off-shell triboson production



1st lepton



2nd lepton



3rd lepton

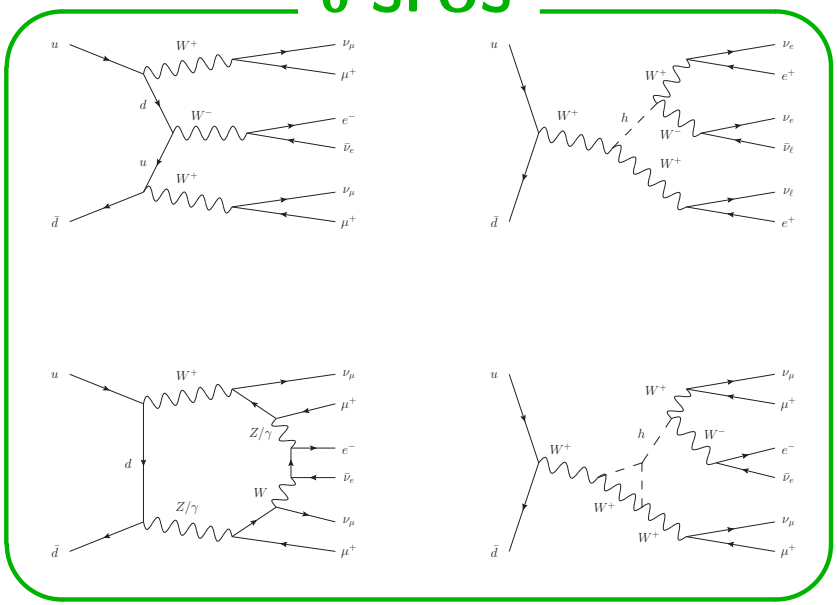
- on-shell approximation reasonable for moderate lepton p_{T}
- fails at low p_{T} due to off-shell effects
- fails at high p_{T} due to importance single and double resonant topologies

NLO EW corrections in off-shell trilepton production

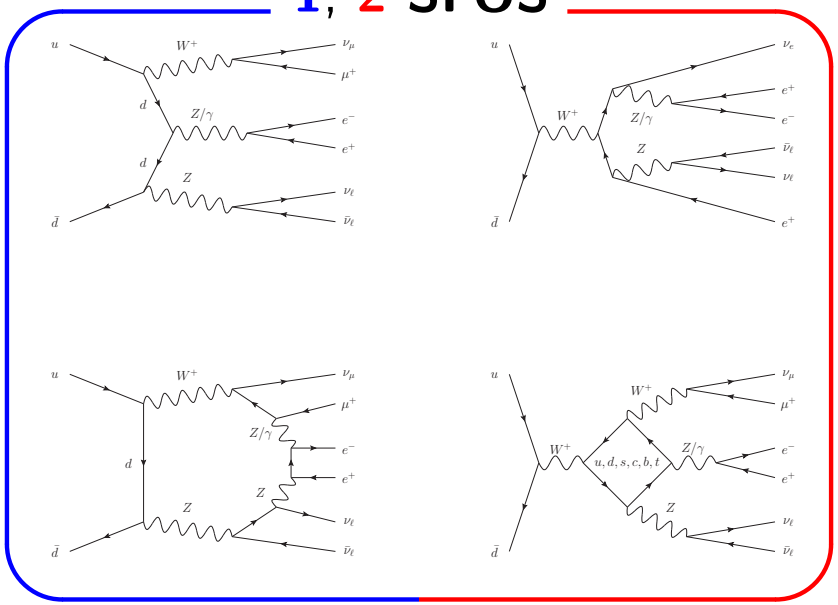
NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307

0 SFOS



1, 2 SFOS



- at LO: triple and quartic gauge boson self-interactions
- at NLO EW: appearance of octagons, closed fermion loops, Higgs self-interactions, Yukawa couplings, etc
- genuine NLO EW $2 \to 6$ calculation with 3 resonances

NLO EW corrections in off-shell trilepton production

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- input parameters for the following calculations

$$
\begin{aligned}
G_\mu &= 1.16637 \times 10^{-5}\ \text{GeV}^2 & & \\
m_W &= 80.385\ \text{GeV} & \Gamma_W &= 2.0897\ \text{GeV} \\
m_Z &= 91.1876\ \text{GeV} & \Gamma_Z &= 2.4955\ \text{GeV} \\
m_h &= 125.0\ \text{GeV} & \Gamma_h &= 0.00407\ \text{GeV} \\
m_t &= 173.2\ \text{GeV} & \Gamma_t &= 1.3394\ \text{GeV}\ .
\end{aligned}
$$

- EW parameter renormalisation in G_μ-scheme
- scale choice: $\mu = \sum m^W_{\mathrm{T},i}$ ambiguous in all channels, also not well motivated scale choice for WZZ channels (or WZZ phase space regions)
- EW corrections largely scale independent: choose $\mu_R = \mu_F = 3\, m_W$
- use `NNPDF31_nlo_as_0118_luxqed` for reliable γPDF

NLO EW corrections in off-shell trilepton production

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- work with dressed leptons with $\Delta R_{\text{dress}} = 0.1$

Selection	Cut	Value	
general	$p_{\text{T}}(\ell)$	$[20\,\text{GeV}, \infty)$	lepton acceptance
	$y(\ell)$	$[-2.5, 2.5]$	
	$\Delta R(\ell, \ell)$	$[0.2, \infty)$	
$\not{p}_{\text{T}} > 20\,\text{GeV}$	$\Delta\phi(\not{p}_{\text{T}}, \ell\ell\ell)$	$[\frac{5}{6}\pi, \pi]$	jet veto
1, 2 SFOS	$\not{p}_{\text{T}}$	$[50\,\text{GeV}, \infty)$	WZ veto
	$m_{\ell\ell}^{\text{SFOS}}$	$[0, 70\,\text{GeV}] \wedge [100\,\text{GeV}, \infty)$	

- minimise $t\bar{t}W$, tWW, WZ backgrounds

Triboson production

MS arXiv:1806.00307

	inclusive			
	LO [fb]	δ_{EW}	$\delta^{\text{EW}}_{q\bar{q}}$	$\delta^{\text{EW}}_{q\gamma/\bar{q}\gamma}$
$\ell^-\ell^+\ell^+$	**0.4209**	**−2.0 %**	**−5.2 %**	**3.2 %**
$e^-e^+e^+$	0.0212	−3.4 %	−7.1 %	3.6 %
$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	0.0206	−3.4 %	−7.0 %	3.6 %
$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	0.0006	−5.4 %	−9.5 %	4.1 %
$e^-e^+\mu^+$	0.0938	−1.4 %	−5.4 %	4.1 %
$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	0.0924	−1.4 %	−5.4 %	4.1 %
$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	0.0007	−2.9 %	−6.1 %	3.2 %
$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	0.0007	−2.7 %	−6.2 %	3.5 %
$e^-\mu^+\mu^+$	0.0955	−2.2 %	−4.6 %	2.4 %
$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	0.0955	−2.2 %	−4.6 %	2.4 %

- large accidental and cut dependent cancellations of Sudadov-type neg. EW corrections and γ-induced pos. contribs w/ extra jet activity
- *WWW* channels receive smaller corrections than pure *WZZ* channels

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$e^-e^+e^+$	0.0031	−10.1 %	−18.3 %	8.2 %
$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	0.0029	−9.9 %	−18.3 %	8.3 %
$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	0.0001	−13.4 %	−19.8 %	6.4 %
$e^-e^+\mu^+$	0.0081	−6.8 %	−16.6 %	9.8 %
$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	0.0079	−6.5 %	−16.5 %	10.0 %
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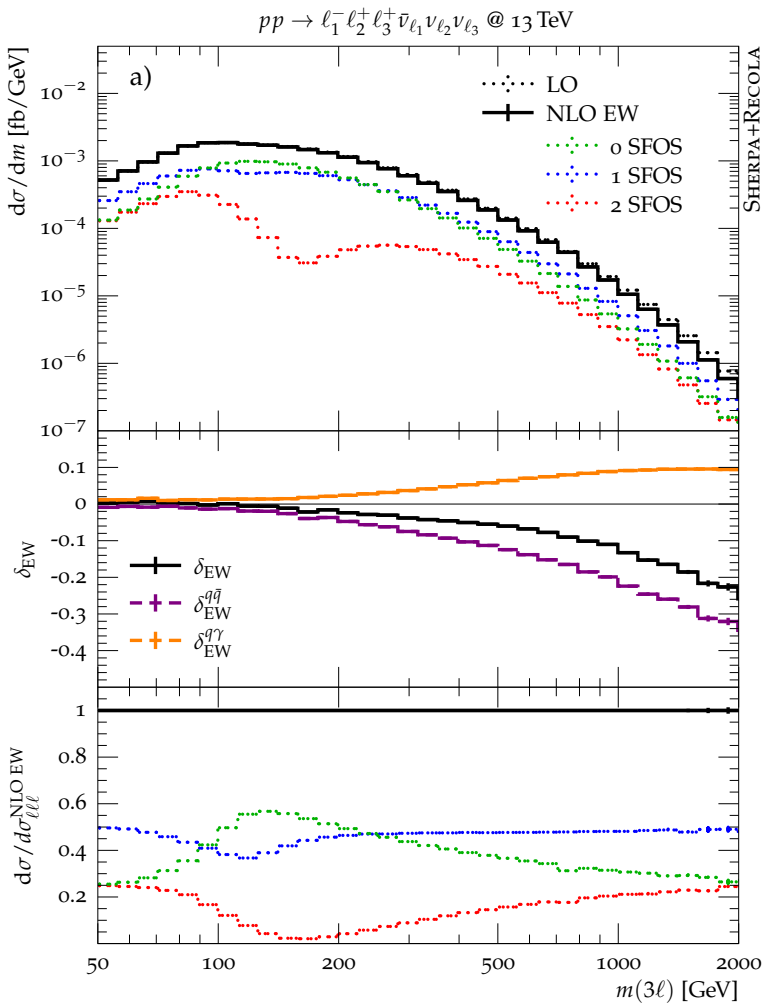
$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	0.0001	−11.2 %	−17.8 %	6.6 %
$e^-\mu^+\mu^+$	0.0057	−7.7 %	−14.8 %	7.0 %
$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	0.0057	−7.7 %	−14.8 %	7.0 %

- large accidental and cut dependent cancellations of Sudadov-type neg. EW corrections and γ-induced pos. contribs w/ extra jet activity
- *WWW* channels receive smaller corrections than pure *WZZ* channels

Triboson production

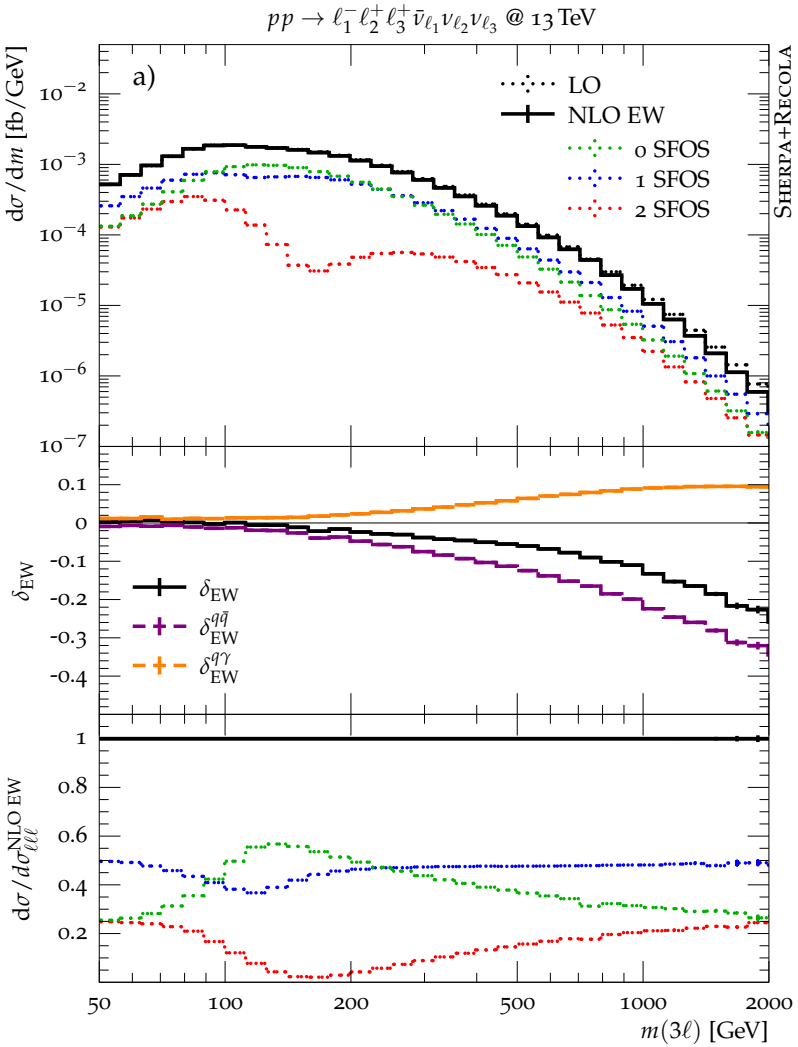
MS arXiv:1806.00307

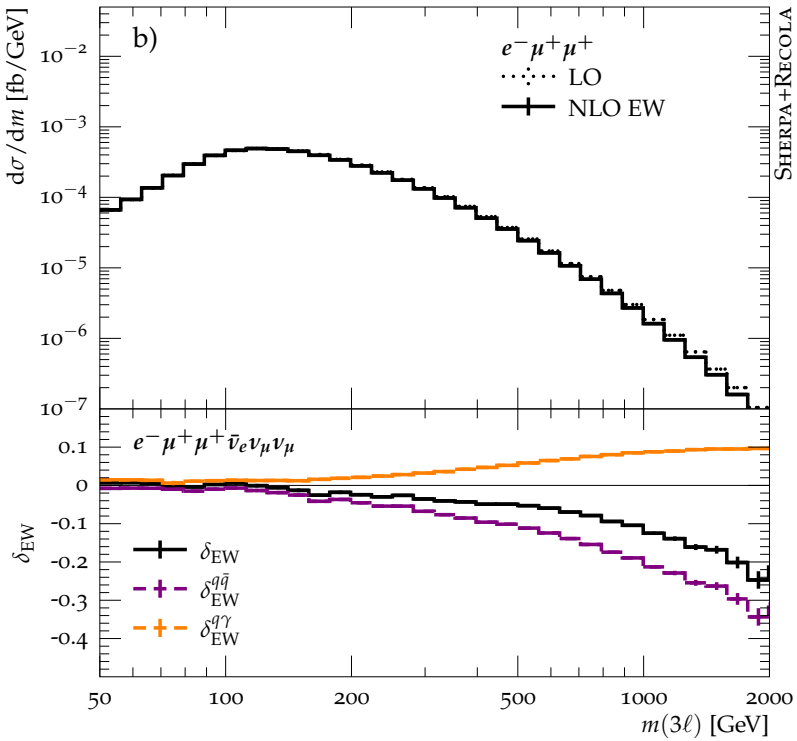
- off-shell $W^+W^+W^-$ production
- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ-induced) important
- cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels highly observable dependent



Triboson production – 0, 1, 2 SFOS decomposition

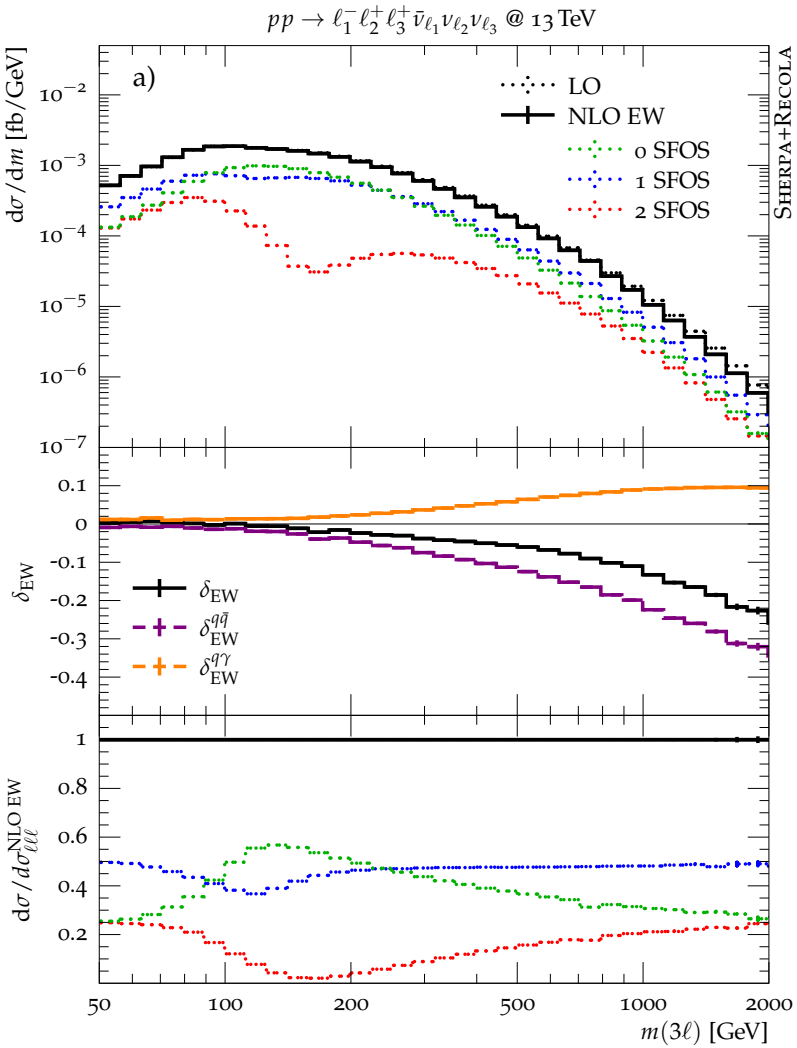
MS arXiv:1806.00307

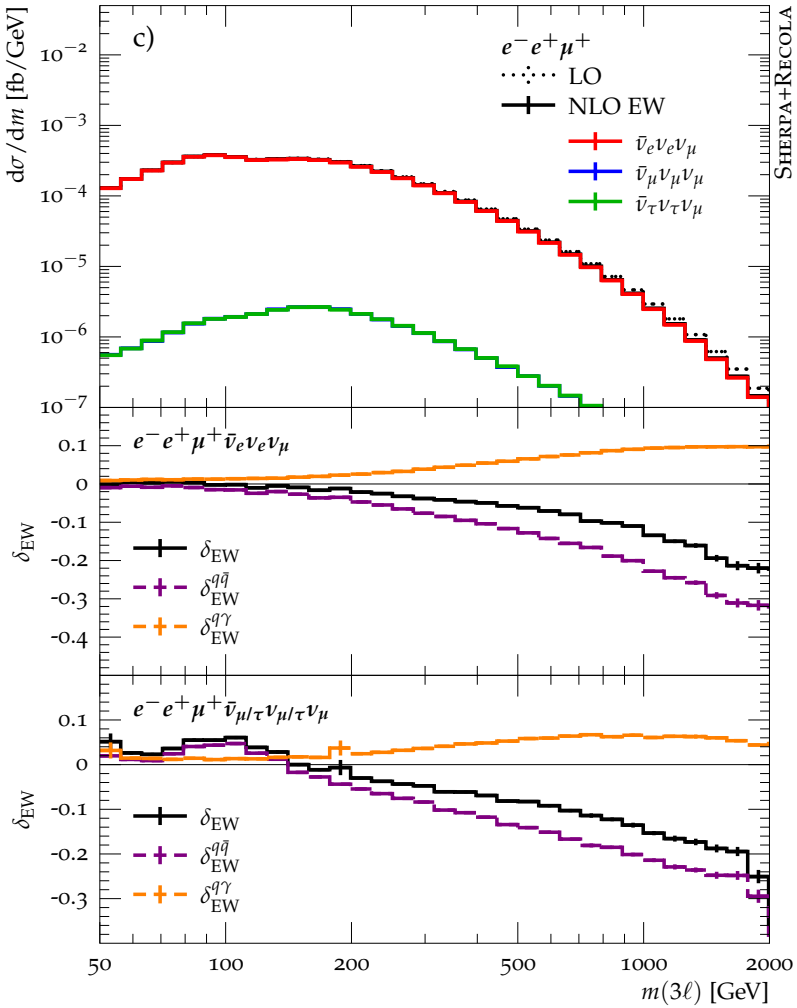




Triboson production – 0, 1, 2 SFOS decomposition

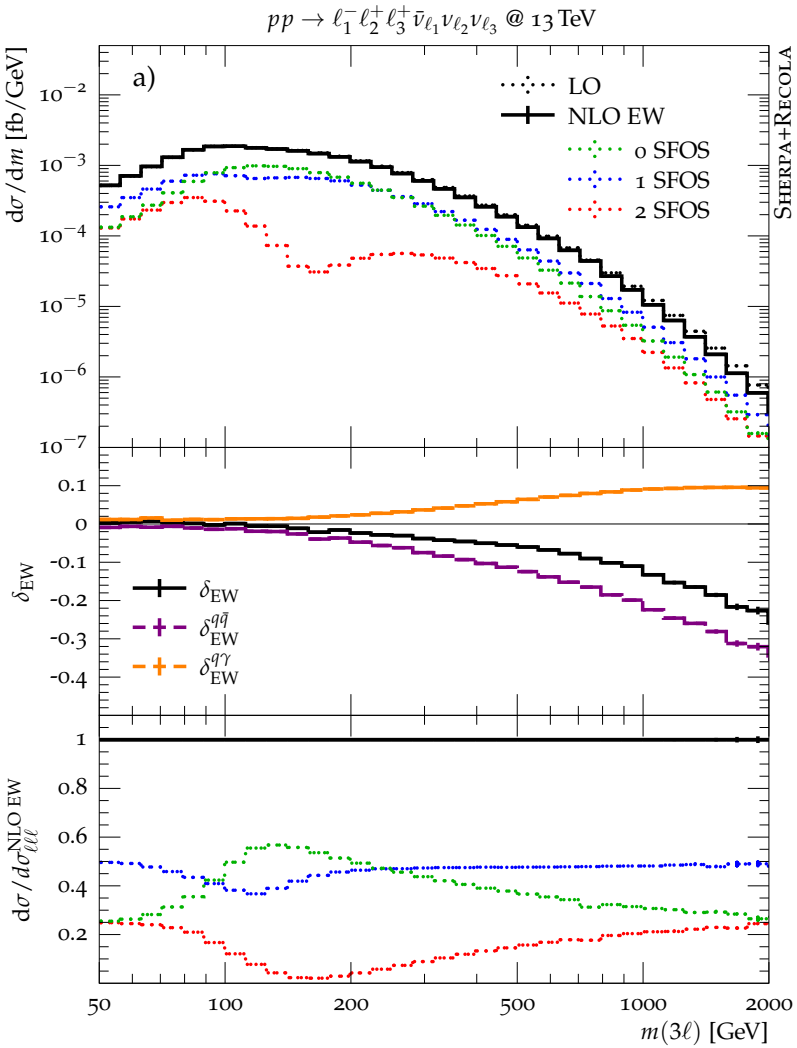
MS arXiv:1806.00307

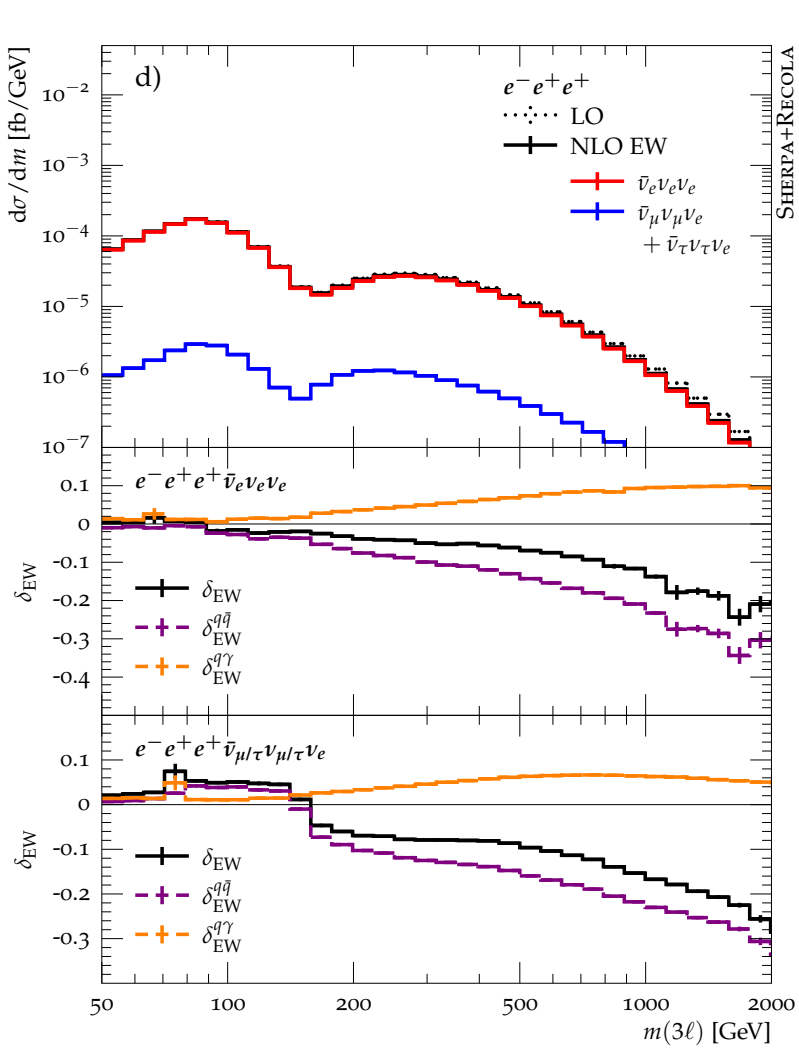




Triboson production – 0, 1, 2 SFOS decomposition

MS arXiv:1806.00307

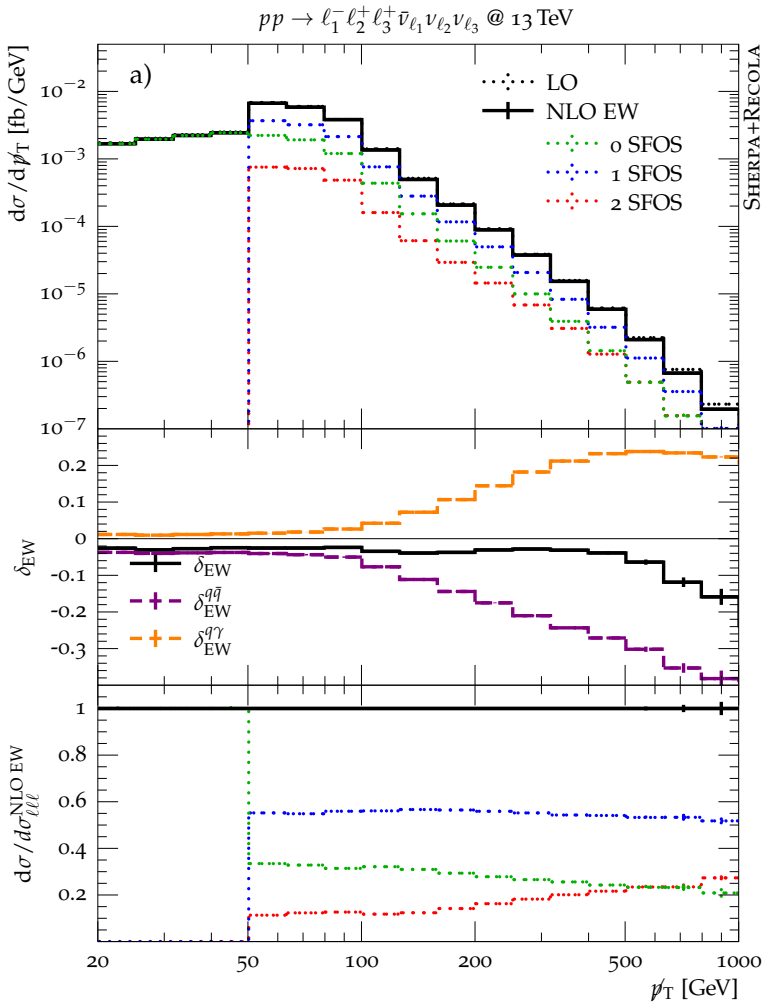




Triboson production

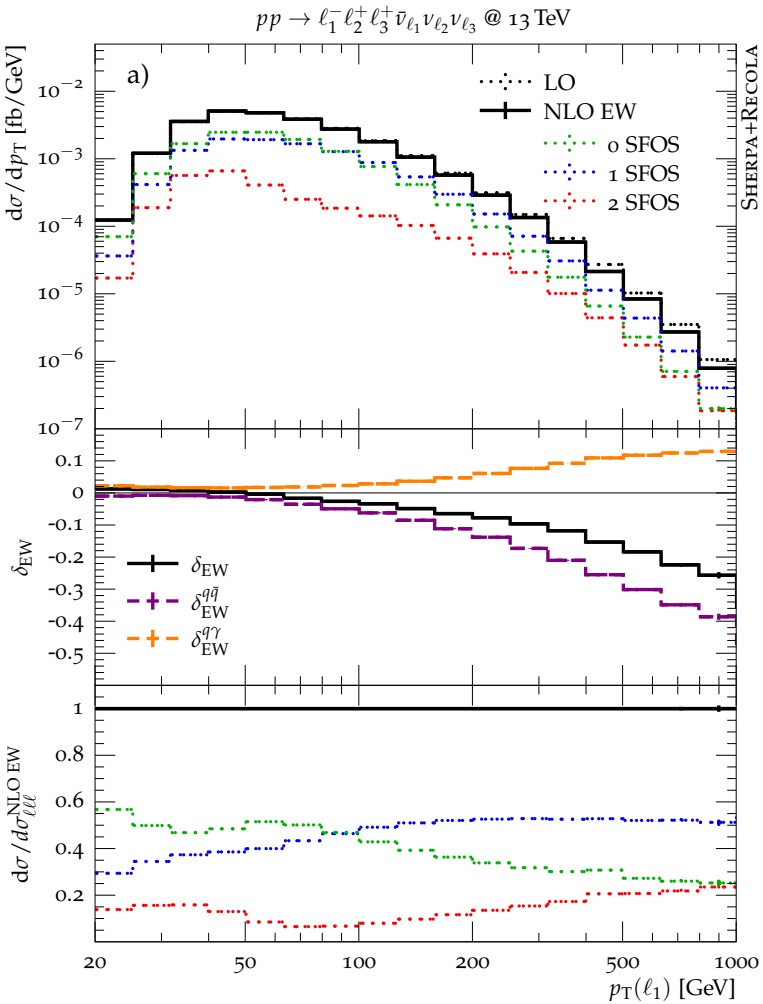
MS arXiv:1806.00307

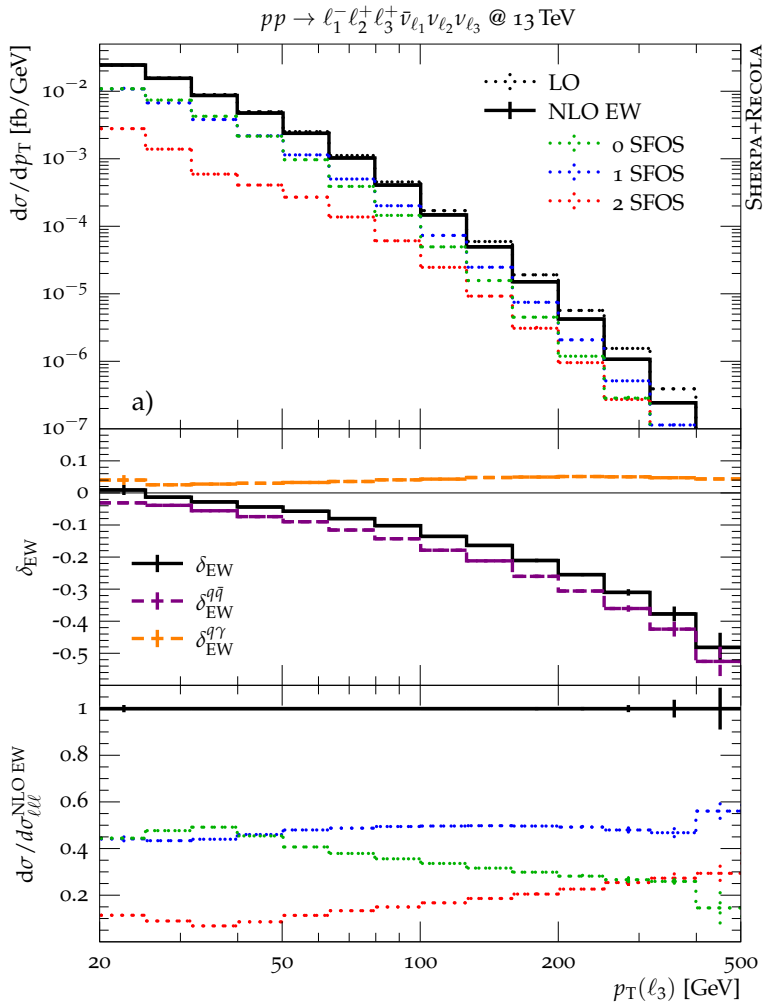
- 1, 2 SFOS: req. $\not{p}_{\mathrm{T}} > 50\,\mathrm{GeV}$ to suppress WZ background
- substantial γ-induced contributions
- accidental cancellations



Triboson production

MS arXiv:1806.00307



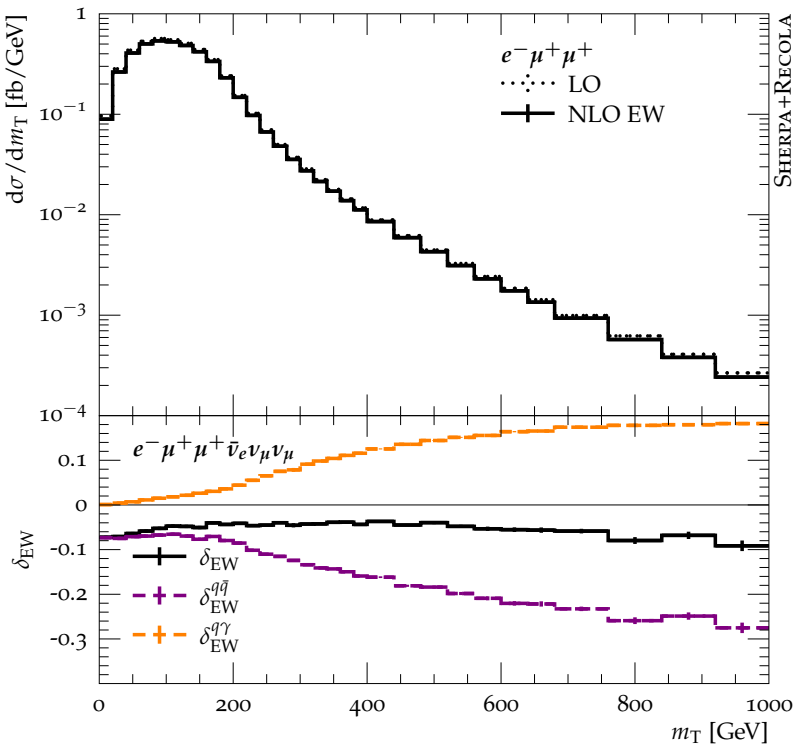


Results for LHC EW WG

Selection	Cut	Value
general	$p_{\mathrm{T}}(\ell)$	$[20\,\mathrm{GeV}, \infty)$
	$y(\ell)$	$[-2.5, 2.5]$
	$\Delta R(\ell, \ell)$	$[\mathbf{0.1}, \infty)$
	$\Delta\phi(\not{p}_{\mathrm{T}}, \ell\ell\ell)$	$[\mathbf{2.5}, \pi]$
0 SFOS	$\mathbf{m}_{\ell\ell}^{\mathrm{SF}}$	$[\mathbf{20}\,\mathrm{GeV}, \infty)$
	$\mathbf{m}_{\ell\ell}^{\mathrm{eeSS}}$	$[\mathbf{0}, \mathbf{m_Z} - \mathbf{15}\,\mathrm{GeV}] \wedge [\mathbf{m_Z} + \mathbf{15}\,\mathrm{GeV}, \infty)$
1 SFOS	$\not{p}_{\mathrm{T}}$	$[\mathbf{45}\,\mathrm{GeV}, \infty)$
	$m_{\ell\ell}^{\mathrm{SFOS}}$	$[\mathbf{0}, \mathbf{m_Z} - \mathbf{35}\,\mathrm{GeV}] \wedge [\mathbf{m_Z} + \mathbf{20}\,\mathrm{GeV}, \infty)$
2 SFOS	$\not{p}_{\mathrm{T}}$	$[\mathbf{55}\,\mathrm{GeV}, \infty)$
	$m_{\ell\ell}^{\mathrm{SFOS}}$	$[\mathbf{0}, \mathbf{m_Z} - \mathbf{20}\,\mathrm{GeV}] \wedge [\mathbf{m_Z} + \mathbf{20}\,\mathrm{GeV}, \infty)$

- similar selection as before (differences marked in **red**)
- otherwise same setup as above

Results for LHC EW WG – 0 SFOS channel ($e^-\mu^+\mu^+$)

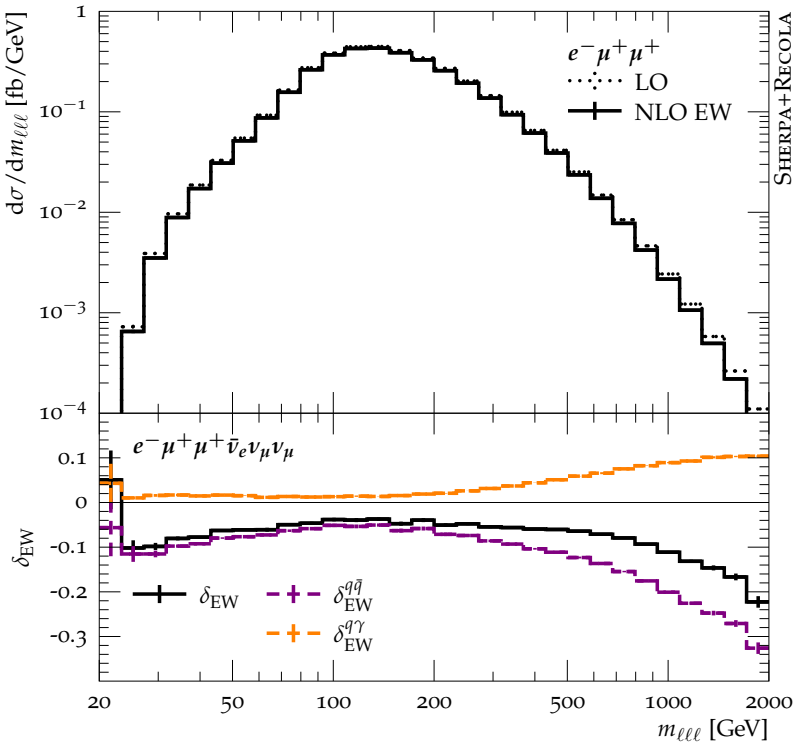


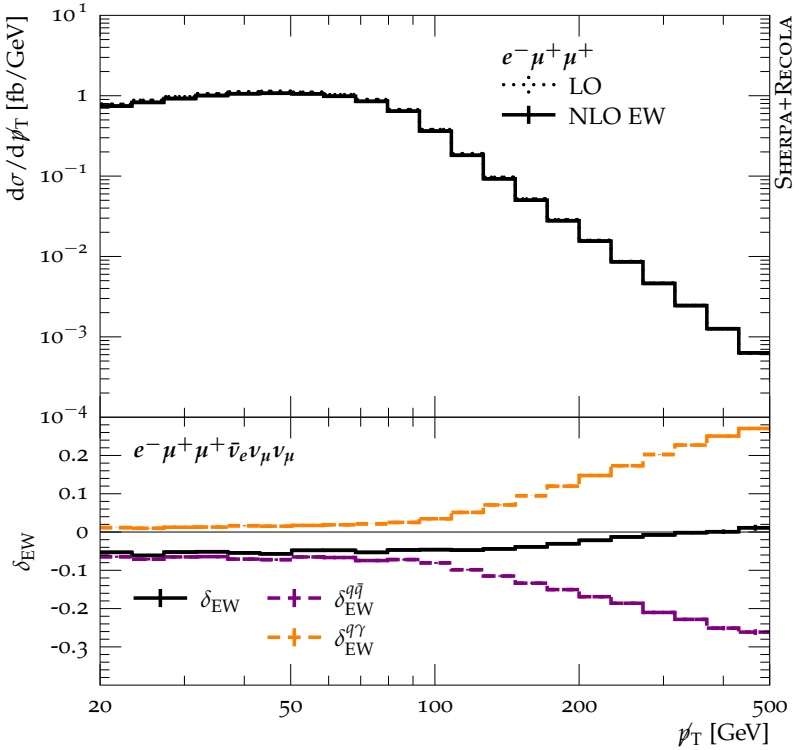
- similar findings as before
  - modest EW corrections in $q\bar{q}$ channel
  - rel. large corrections from γ-induced jet production

  $\rightarrow$ large accidental cancellations

  $\rightarrow$ net NLO EW correction small
- large dependence on fiducial phase space definition and observable

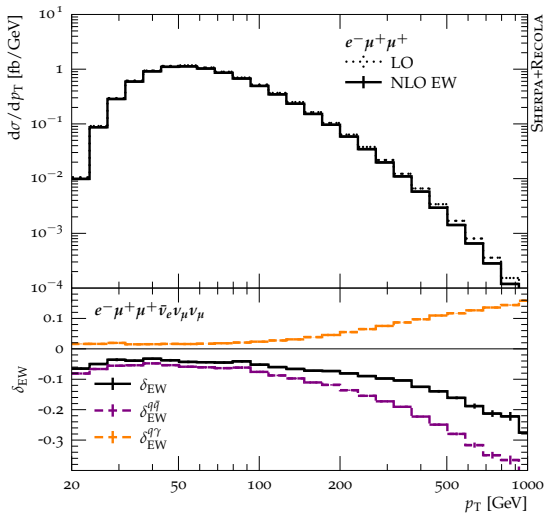
Results for LHC EW WG – 0 SFOS channel ($e^-\mu^+\mu^+$)



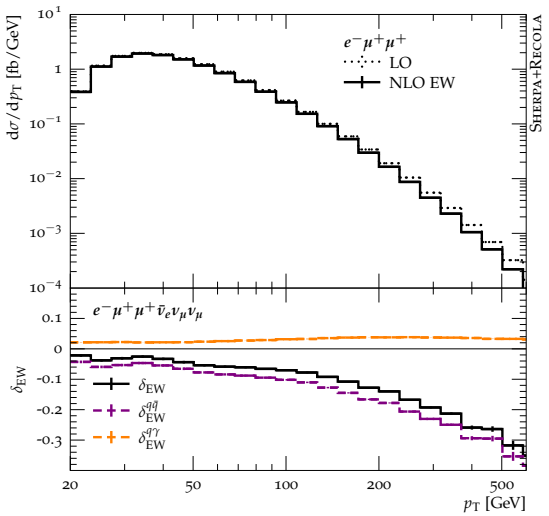


- similar findings as before
  $\rightarrow$ large accidental cancellations between $q\bar{q}$- and $q\gamma/\bar{q}\gamma$-channels

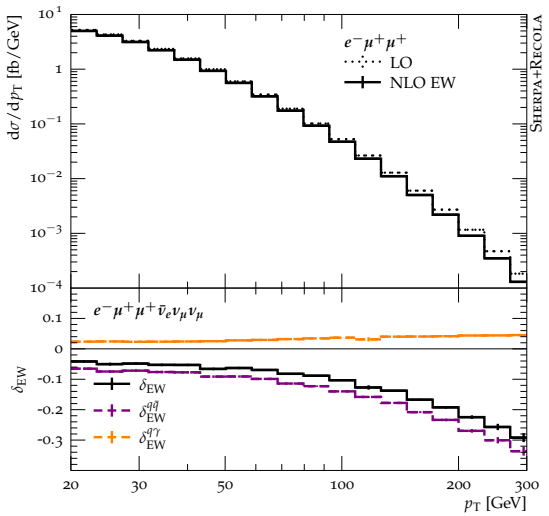
Results for LHC EW WG – 0 SFOS channel ($e^-\mu^+\mu^+$)



1st lepton



2nd lepton



3rd lepton

- similar findings as before
  $\rightarrow$ size of accidental cancellations between $q\bar{q}$- and $q\gamma/\bar{q}\gamma$-channels very observable dependent

Conclusion

- fully off-shell triboson processes known at NLO QCD+EW

$3\ell 3\nu$	Campanario et.al. arXiv:0809.0790, MS arXiv:1806.00307
$\ell^{\pm}\nu\gamma\gamma$	Bozzi et.al. arXiv:1103.4613, Greiner, MS arXiv:1710.11514
$\ell^{+}\ell^{-}\gamma\gamma$	Bozzi et.al. arXiv:1107.3149, Greiner, MS arXiv:1710.11514
$\gamma\gamma\gamma$	Greiner, MS arXiv:1710.11514

- on-shell production poor approximation of full off-shell production in the given fiducial phase space
- for $3\ell 3\nu$ production sizeable Sudakov-type EW corrections, but also large γ-induced real emission corrections
  $\rightarrow$ large accidental and observable dependent cancellations