Electroweak corrections for LHC physics

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Introduction

Electroweak correction come in two variants: virtual corrections and real emission correction.

Virtual electroweak corrections often studied in the context of gauge boson and jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and increasing with $p_\perp$.

Real electroweak corrections usually constitute a separate process. However, largest BR of W/Z bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

When large scale differences occur resummation is needed in either case. Practically at LHC13/14 these scale differences are moderate.

Beware of subleading orders.

Outline

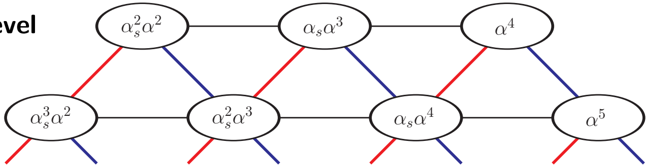
Electroweak corrections for LHC physics

Higher order corrections

Example: *Vjj* production

tree-level

NLO



- strictly defined only through order counting
- in principle must differentiate between short-distance objects (partons) and long distance objects (observable objects):
  - well known in QCD (quarks, gluons $\leftrightarrow$ jets)
  - introduce similar concepts in EW sector for photons and leptons

Higher order corrections

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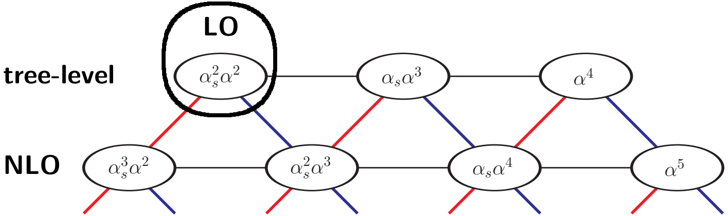

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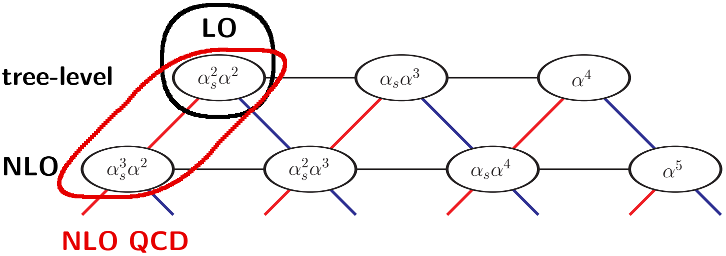

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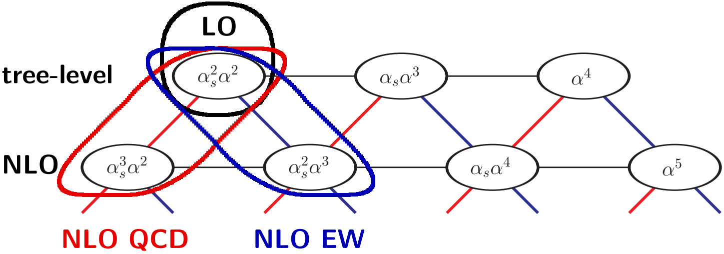

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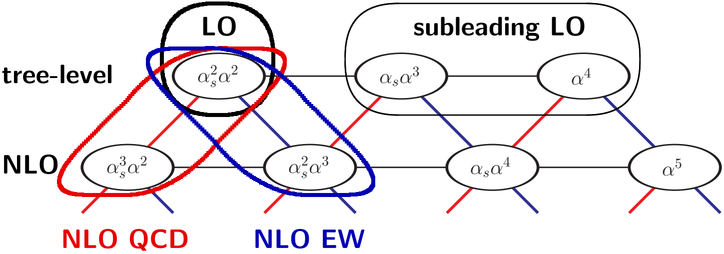

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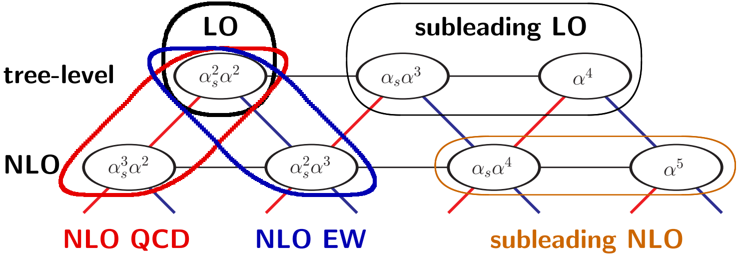

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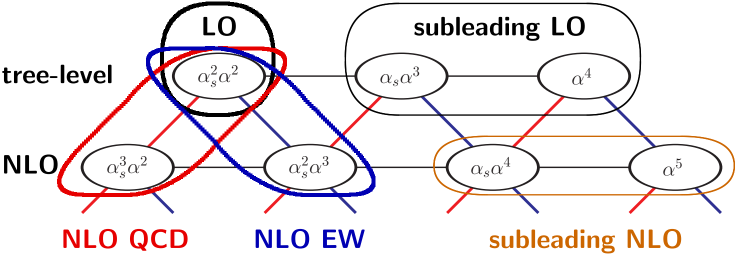

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Definition of physical objects

What is a jet?

- photons and leptons must be part of a jet, but to what extent?
- **democratic:**
  - $+$ straight forward, always well defined
  - $-$ many contributions
  - $\rightarrow$ single photons constitute a jet
  - $\rightarrow$ single leptons constitute a jet
- **anti-tagging jets with certain flavour content:**
  - $+$ fewer contributions
  - $-$ needs a lot of care to be well-defined at all contributing orders
  - $\rightarrow$ anti-tag jets with too large photon content
  - $\rightarrow$ anti-tag jets with net lepton content
- which approach is closer to experiment depends on analysis, general anti-tagging must proceed through fragmentation functions

Definition of physical objects

What is a photon?

- differentiate: short-distance photon (photon as parton),
  long-distance photon (identified, measurable photon)

a) treat as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \to f\bar{f}$
$\to$ renormalisation contains IR poles
$\to$ problematic if both identified and unresolved photons in Born

b) treat democratically (just another parton), renormalise in short distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \to f\bar{f}$ splittings
$\to$ pure UV renormalisation
$\to$ identify photon through frag. function $D^p_\gamma(z,\mu)$

$$\text{i.e. } D^\gamma_\gamma(z,\mu) = \frac{\alpha(0)}{\alpha_{\text{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha^2)$$

and $D^q_\gamma(z,\mu) = \mathcal{O}(\alpha)$, $D^g_\gamma(z,\mu) = \mathcal{O}(\alpha_s\alpha)$

- identical at NLO EW, if fragmentation D^q_γ on Born is negligible

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Definition of physical objects

What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus

  $D_\ell^\ell(z,\mu) = \delta(1-z)+$QED bremsstrahlung

  $D_\ell^\gamma(z,\mu) = \mathcal{O}(\alpha)$ problematic in processes with ℓ and unresolved photons in Born

  all other $D_\ell^q(z,\mu) = \mathcal{O}(\alpha^2)$, $D_\ell^g(z,\mu) = \mathcal{O}(\alpha_s\alpha^2)$
- dressed lepton: masseless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept

Automation

⇒ emergence of automated frameworks for NLO EW computations along the principles of NLO QCD automation

- Monte-Carlo frameworks (Born and real emission matrix elements, infrared subtraction, phase space generation, process coordination)
  - Sherpa — MS arXiv:1712.07975
  - MadGraph — Frederix et.al. arXiv:1804.10017
- virtual corrections (EW one-loop matrix elements, renormalisation)
  - GoSam — Chiesa et.al. arXiv:1507.08579
  - MadLoop — Frixione et.al. arXiv:1407.0823
  - OpenLoops — Kallweit et.al. arXiv:1412.5157
  - Recola — Actis et.al. arXiv:1211.6316
- currently generally limited to fixed-order
- a number of dedicated calculations and private codes

NLO EW calculations with SHERPA

- SHERPA+OPENLOOPS:
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2(, 3)$ jets — FCC report, EW report, LH'15
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1412.5157, arXiv:1511.08692
    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
  - $pp \to t\bar{t}/t\bar{t}j$ — Gütschow, Lindert, MS arXiv:1803.00950
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- SHERPA+GOSAM
  - $pp \to \gamma\gamma + 0, 1, 2$ jets — Chiesa et.al. arXiv:1706.09022
  - $pp \to \gamma\gamma\gamma \,/\, \gamma\gamma\ell\nu \,/\, \gamma\gamma\ell\ell$ — Greiner, MS arXiv:1710.11514
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  - $pp \to V + 0, 1, 2$ j, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. arXiv:1704.05783
  - $pp \to 3\ell 3\nu$ — MS arXiv:1806.00307
  - $pp \to jj/jjj$ — Reyer, MS, Schumann arXiv:1902.01763

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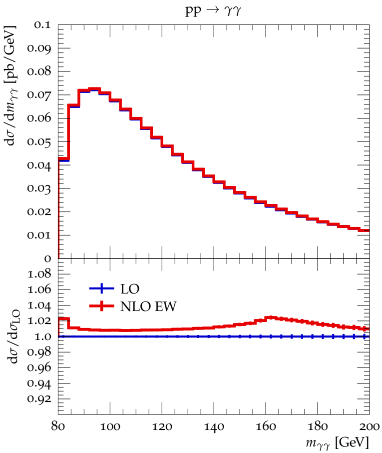
General setup

- work with dressed leptons with $\Delta R_{\text{dress}} = 0.1$
- 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
- photon induced processes considered throughout

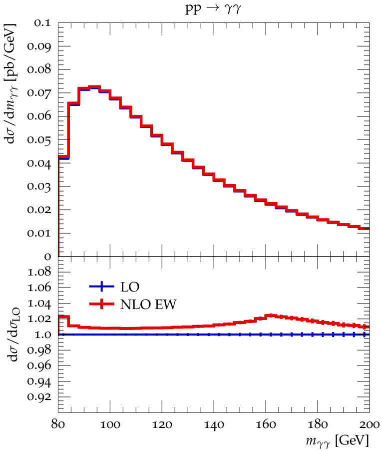
Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

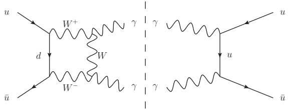
- peak-like enhancement around $m_{\gamma\gamma} \approx 160\,\mathrm{GeV}$
- induced by W-box creating pseudo-resonant structures

Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

- peak-like enhancement around $m_{\gamma\gamma} = 2\,m_W$
- induced by W-box creating pseudo-resonant structures



Diboson production – $2\ell 2\nu$ – DF and SF

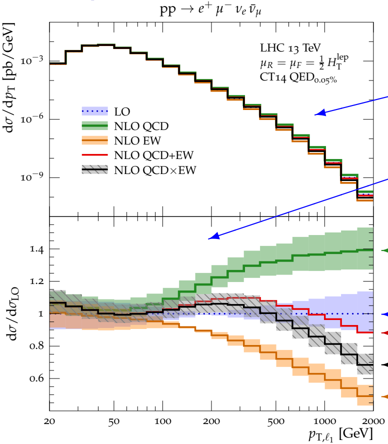
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

- study $e^+\mu^-\nu\bar{\nu}$ (DF) and $e^+e^-\nu\bar{\nu}$ (SF) production, and $e \leftrightarrow \mu$

DF	$e^+\mu^-\nu_e\bar{\nu}_\mu$	WW
SF	$e^+e^-\nu_e\bar{\nu}_e$	$WW + ZZ$
	$e^+e^-\nu_{\mu/\tau}\bar{\nu}_{\mu/\tau}$	ZZ

- incl. event selection w/ standard lepton acceptance cuts, ($p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$), $|\eta_\ell| < 2.5$), $n_f = 4$ and mild jet veto to suppress large NLO QCD corr.

Diboson production – $2\ell 2\nu$ – DF



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absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

NLO QCD+EW

NLO QCD×EW

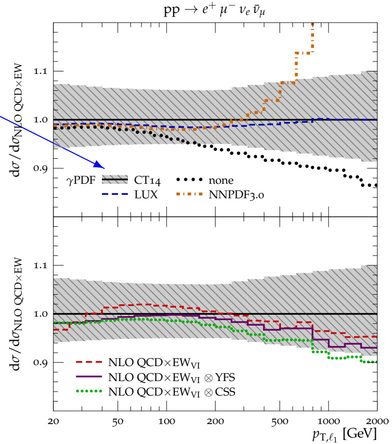
NLO EW

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

Diboson production – $2\ell 2\nu$ – DF

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

CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed



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

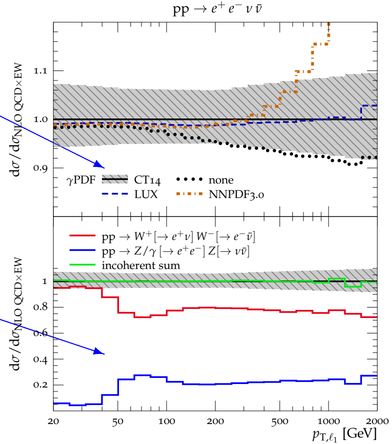
Diboson production – $2\ell 2\nu$ – SF

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

CT14qed (baseline) no γPDF
LUXqed NNPDF3.0qed

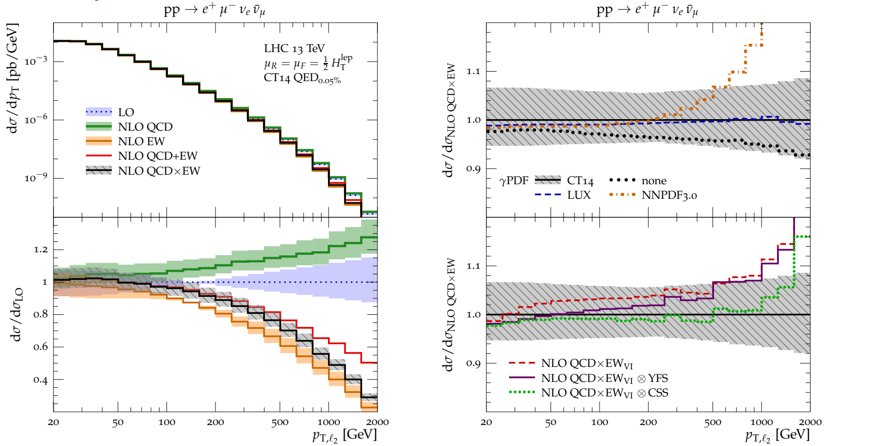
rel. contribs of *WW* and *ZZ* subtops

coherent $|WW + ZZ|^2$
incoherent $|WW|^2 + |ZZ|^2$
only $|WW|^2$
only $|ZZ|^2$



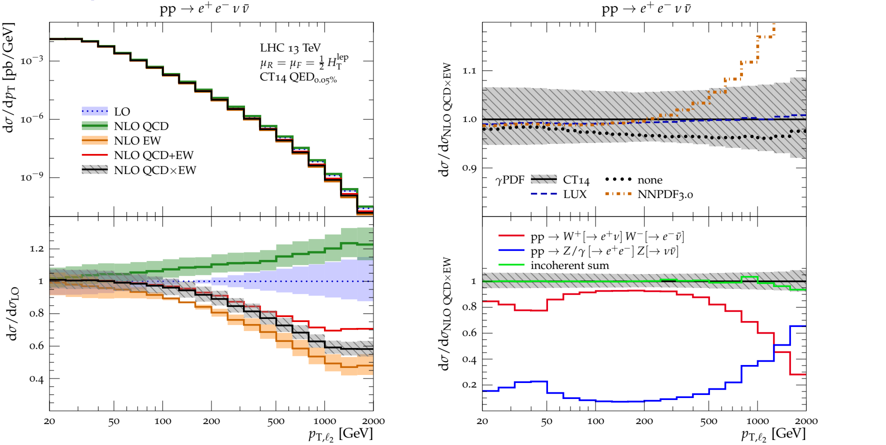
- *WW* dominant throughout, *ZZ* only contribs 10-20%
  → overall very similar to DF case

Diboson production – $2\ell 2\nu$ – DF



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

Diboson production – $2\ell 2\nu$ – SF



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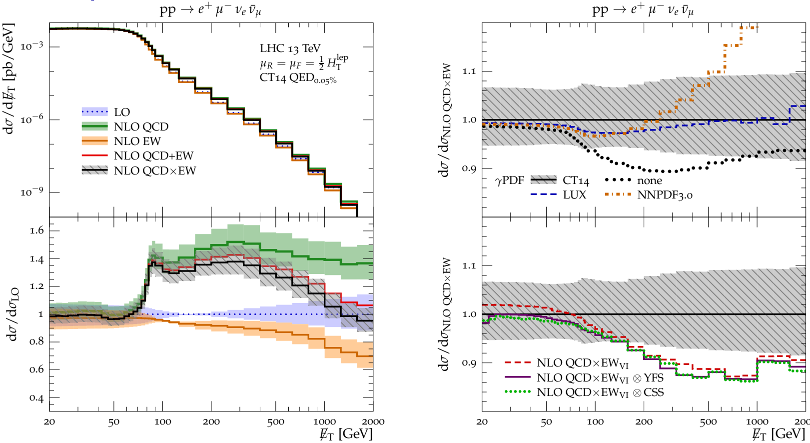
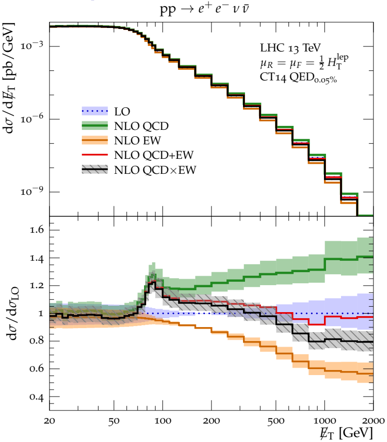
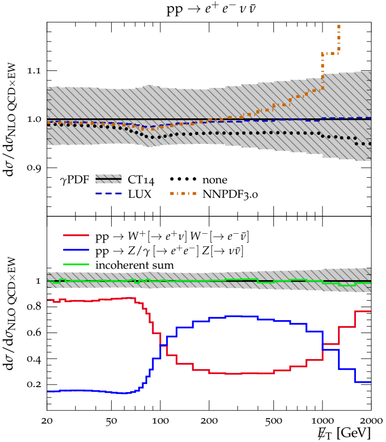


- kinematic suppression for $p_T^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced $\Rightarrow$ large contrib

Diboson production – $2\ell 2\nu$ – SF





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

Electroweak corrections for LHC physics

Triboson production – $3\ell 3\nu$ – 0, 1, 2 SFOS

MS arXiv:1806.00307

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW	$WZ[\to 2\ell 2\nu]$	Wh
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh

- standard lepton acceptance cuts, idealised from ATLAS arXiv:1610.05088

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0 SFOS	$e^-\mu^+\mu^+\bar\nu_e\nu_\mu\nu_\mu$	WWW	$WZ[\to 2\ell 2\nu]$	Wh
1 SFOS	$e^-e^+\mu^+\bar\nu_e\nu_e\nu_\mu$	$WWW+WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar\nu_\mu\nu_\mu\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar\nu_\tau\nu_\tau\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
2 SFOS	$e^-e^+e^+\bar\nu_e\nu_e\nu_e$	$WWW+WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
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	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	$WZ[\to 2\ell 2\nu]$	Wh
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ	$WZ[\to 2\ell 2\nu]$	Wh

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NLO EW corrections in off-shell trilepton production

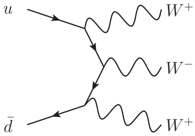
MS arXiv:1806.00307

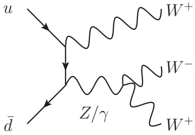
Selection	Cut	Value	
general	$p_{\mathrm{T}}(\ell)$	$[20\,\text{GeV}, \infty)$	lepton acceptance
	$y(\ell)$	$[-2.5, 2.5]$	
	$\Delta R(\ell,\ell)$	$[0.2, \infty)$	
$\not{p}_{\mathrm{T}} > 20\,\text{GeV}$	$\Delta\phi(\not{p}_{\mathrm{T}}, \ell\ell\ell)$	$[\frac{5}{6}\pi, \pi]$	jet veto
1, 2 SFOS	$\not{p}_{\mathrm{T}}$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

- minimise $t\bar{t}W$, tWW, WZ backgrounds
- scale choice: $\mu = \sum m_{\mathrm{T},i}^{W}$ ambiguous in all channels,
  EW corrections largely scale independent: choose $\mu_R = \mu_F = 3\,m_W$
- use `NNPDF31_nlo_as_0118_luxqed` for reliable γPDF

On-shell vs. off-shell triboson production

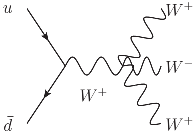
On-shell production

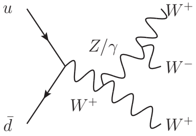


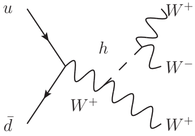


- only triple res. dgrms, threshold at $3\,m_W$
- strong interference between diagrams in which different numbers of gauge bosons couple to quark line
- some kinematic width effects recoverable through BW-shape improved spin-correlated decays
- NLO QCD+EW

Dittmaier, Huss, Knippen arXiv:1705.03722

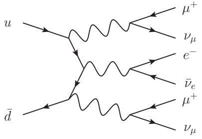






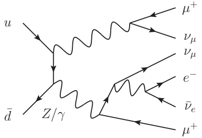
On-shell vs. off-shell triboson production

Off-shell production



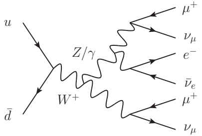
- triple, double and single res. diagrams, importance of single/double resonant topologiess as in WW

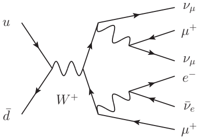
Biedermann et.al. arXiv:1605.03419

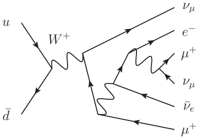


- includes on-shell WWW production, WZ production with $Z \to 2\ell 2\nu$, Wh production with $h \to WW^*/ZZ^*$
- thresholds given by acceptance cuts
- NLO QCD

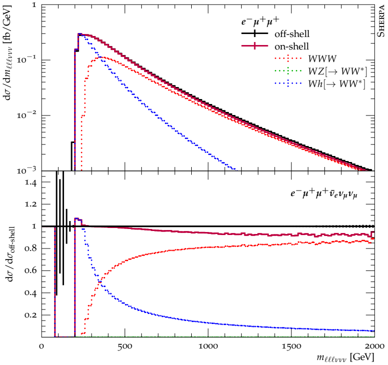
Campanario et.al. arXiv:0809.0790







On-shell vs. off-shell triboson production

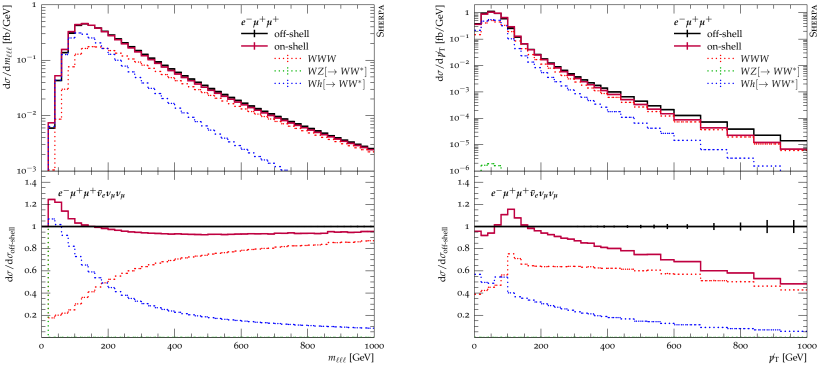


$$m_{\ell\ell\ell\nu\nu\nu} = m_{WWW}$$

- no unique W identifaction possible in off-shell calculation, even in MC truth, due to occurrence of SF pairs
- on-shell WWW not dominating for incl. xsec
- large cross section from Wh, WZ negligible
- at larger m_{WWW} contribs from double (single) resonant

→ cross checked with off-shell calculation projected on triple W resonant subset of diagrams

On-shell vs. off-shell triboson production

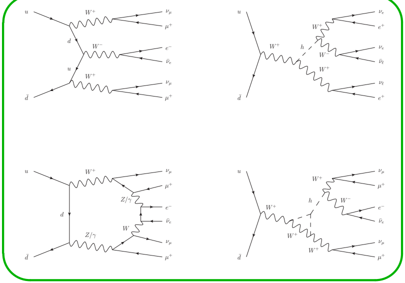


- on-shell approximation reasonable for $m_{\ell\ell\ell}$
- large single and double resonant contribs for MET

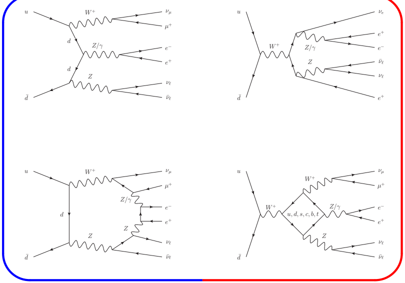
NLO EW corrections in off-shell trilepton production

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

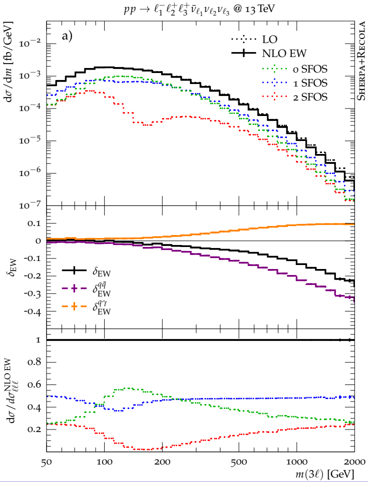
Triboson production

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
- accidental cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels

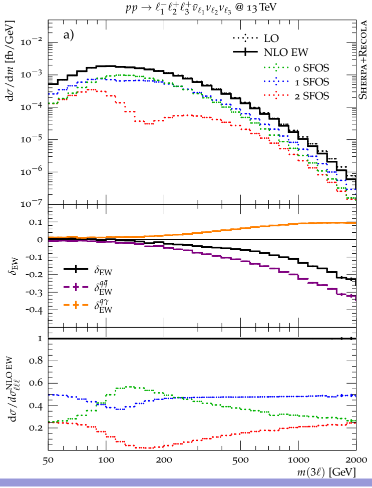
Dittmaier, Huss, Knippen arXiv:1705.03722

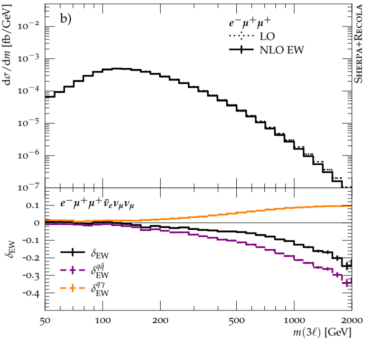
but highly obs. dependent



Triboson production – 0, 1, 2 SFOS decomposition

MS arXiv:1806.00307





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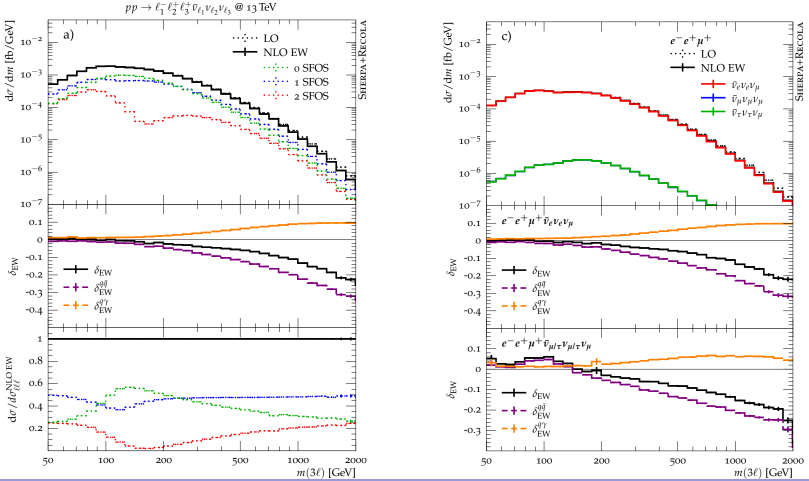

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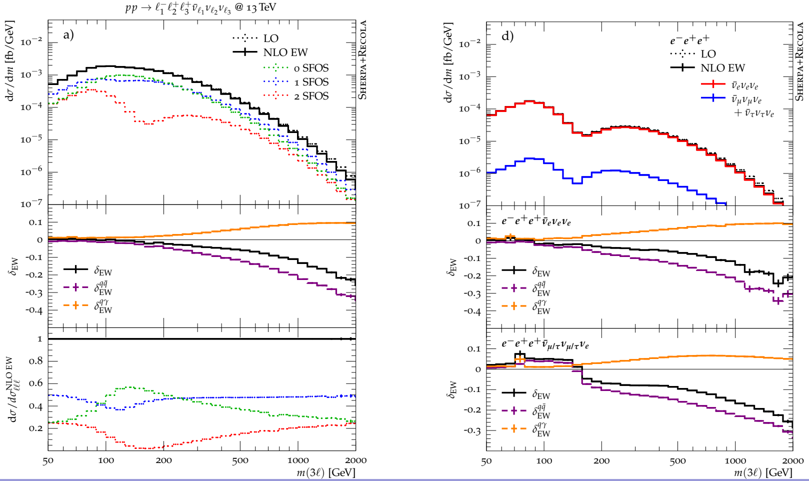
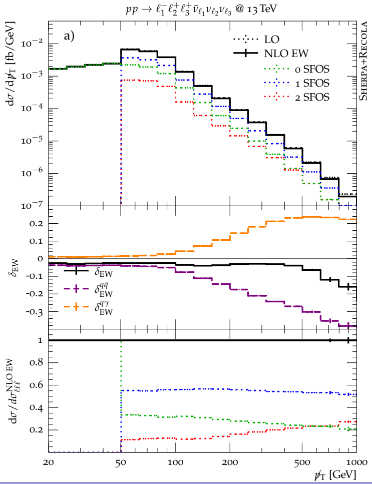


Triboson production

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

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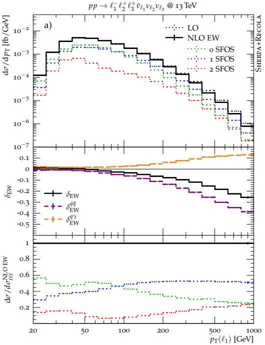
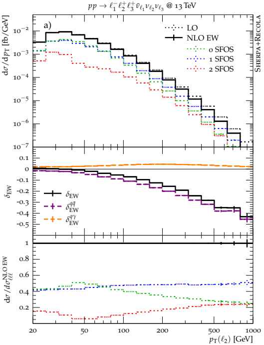
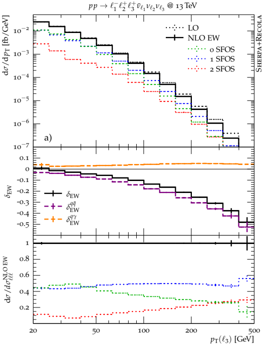


1st lepton



2nd lepton



3rd lepton

Electroweak corrections for LHC physics

Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- taylored to large-p_T regions where EW corrections dominated by virtual W/Z exchange and RG running
- 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)
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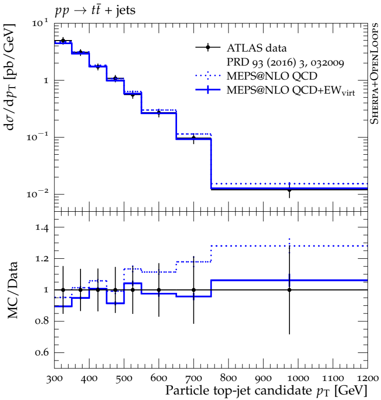
Results: $pp \to t\bar{t} + \text{jets}$



Gütschow, Lindert, MS in arXiv:1803.00950

- $pp \to t\bar{t} + 0, 1j$@NLO $+ 2, 3, 4j$@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential K-factor

  Höche, Krauss, MS, Siegert arXiv:1009.1127
- improved description of data

Conclusions

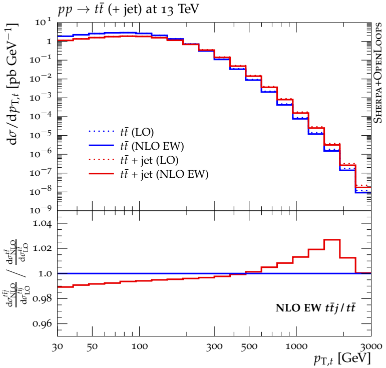
- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- precise definition of physics objects needed
  $\Rightarrow$ differentiate short-distance parton and long-distance measurable object
- can be incorporated in multijet-merged particle-level calculations to improve description in those regions
  $\rightarrow$ currently tailored to TeV-scale physics
- automation of NLO EW follows on the heels of NLO QCD
  $\rightarrow$ much more care with consistent schemes and order counting
  $\rightarrow$ very rich phenomenology
  $\rightarrow$ can induce peaks, edges or kinks in distributions
  $\rightarrow$ includes many more pitfalls than NLO QCD

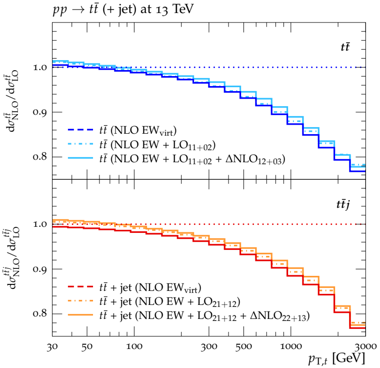
Thank you for your attention!

Backup

Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950

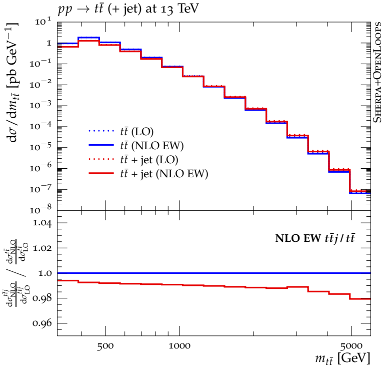


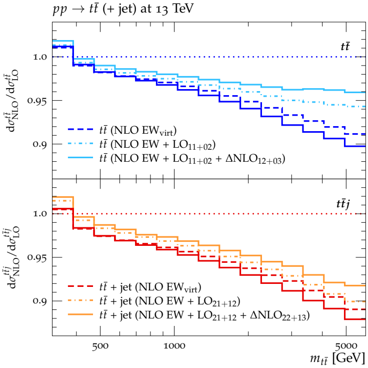


Observation: NLO EW factorises from additional jet activity
when rather inclusive on jet definition

Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950





Observation: subleading orders important