Automation of NLO EW corrections with Sherpa and Recola

Stephan Bräuer

Supervised by: Steffen Schumann

In collaboration with: B. Biedermann, A. Denner, M. Pellen, J. M. Thompson
[Biedermann et al., Eur.Phys.J. C77 (2017) 492, arXiv:1704.05783]

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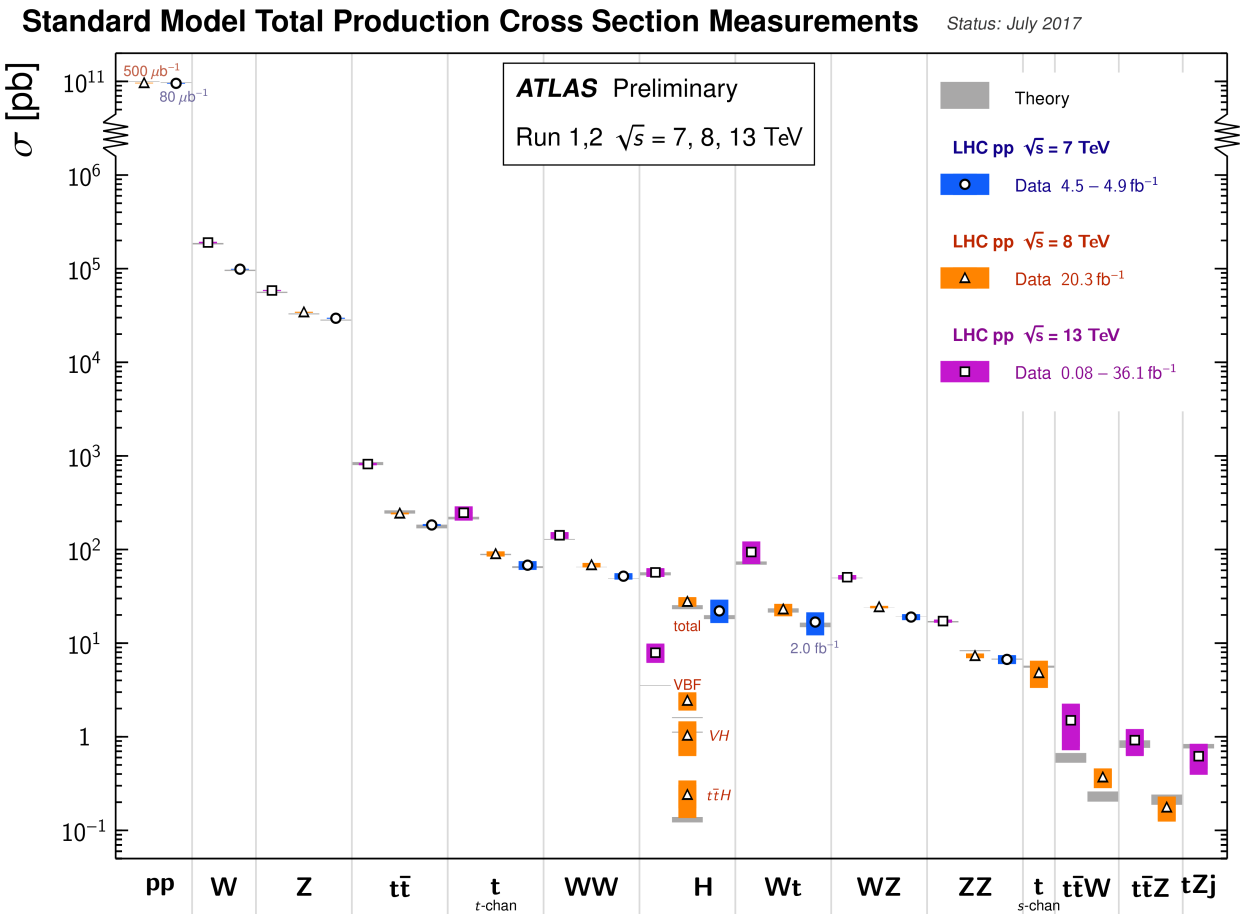
Precision era

- Run II at the LHC
- Comparison experiment and theory



Current status in theory

Many different effects must be taken into account:

- NLO QCD $\mathcal{O}(\alpha_s)$, NNLO QCD $\mathcal{O}(\alpha_s^2)$
- *Resummation* $\mathcal{O}(\alpha_s^n \log^n)$
- *Matching* of parton shower (PS) and matrix element (ME)
- *Merging* of ME with various multiplicities
- NLO EW $\mathcal{O}(\alpha)$, $\alpha \approx \alpha_s^2$

$\Rightarrow$ Automation of EW corrections
$\Rightarrow$ Tools: Monte Carlo (MC) event generators (+ dedicated programs)

NLO EW corrections - an overview

Monte Carlo generators:

- MadGraph5_aMC@NLO [Alwall et al.; 1405.0301]
- MUNICH [Kallweit, in preparation]
- SHERPA [Gleisberg et al.; 0811.4622]
- WHIZARD [Kilian et al.; 0708.4233], [Moretti et al.; hep-ph/0102195]

One-loop generators:

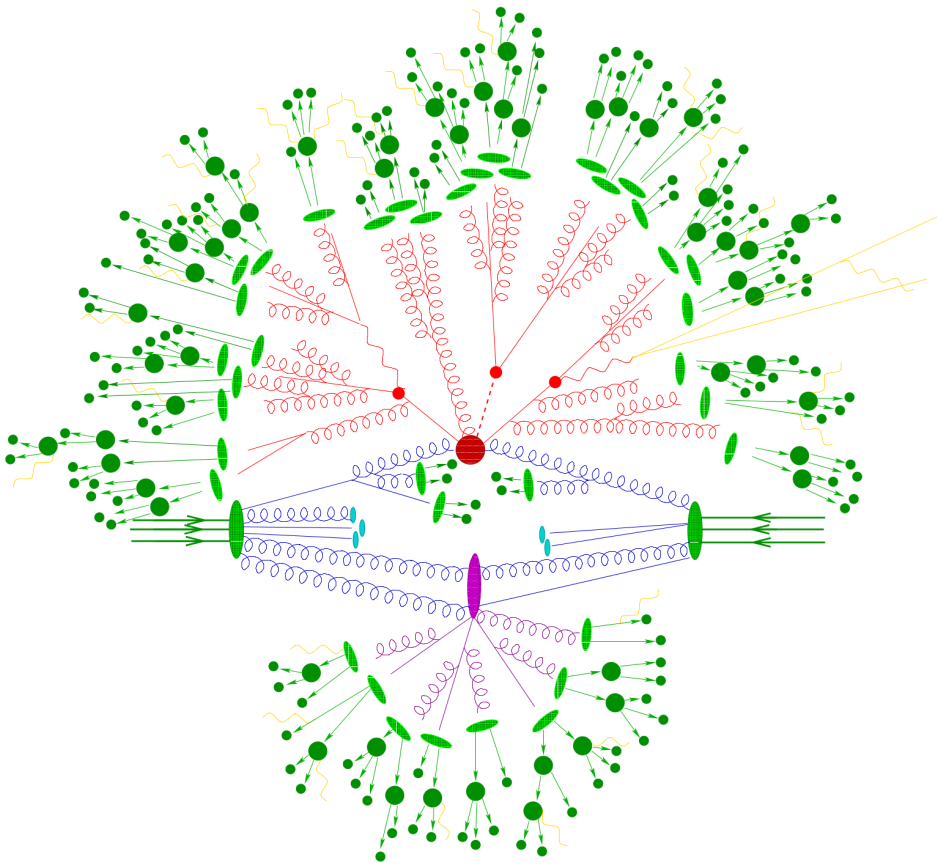
- GoSam-2.0 [Cullen et al.; 1404.7096]
- MadLoop [Hirschi et al.; 1103.0621]
- OpenLoops [Cascioli et al.; 1111.5206]
- RECOLA [Actis et al.; 1605.01090]

$\Rightarrow$ Example: SHERPA+RECOLA

Monte Carlo event generators

[Gleisberg et al., JHEP **02** (2009) 007]

- Factorisation:
  - **Hard process** $|\mathcal{M}|^2$, LO, NLO QCD, NNLO QCD, NLO EW
  - **Parton Shower** soft-collinear evolution of hard process, resummation: LL, NLL
  - **Non-perturbative:** Hadronisation and decay, underlying events
- Combination of matrix elements and parton shower: **Matching and Merging**

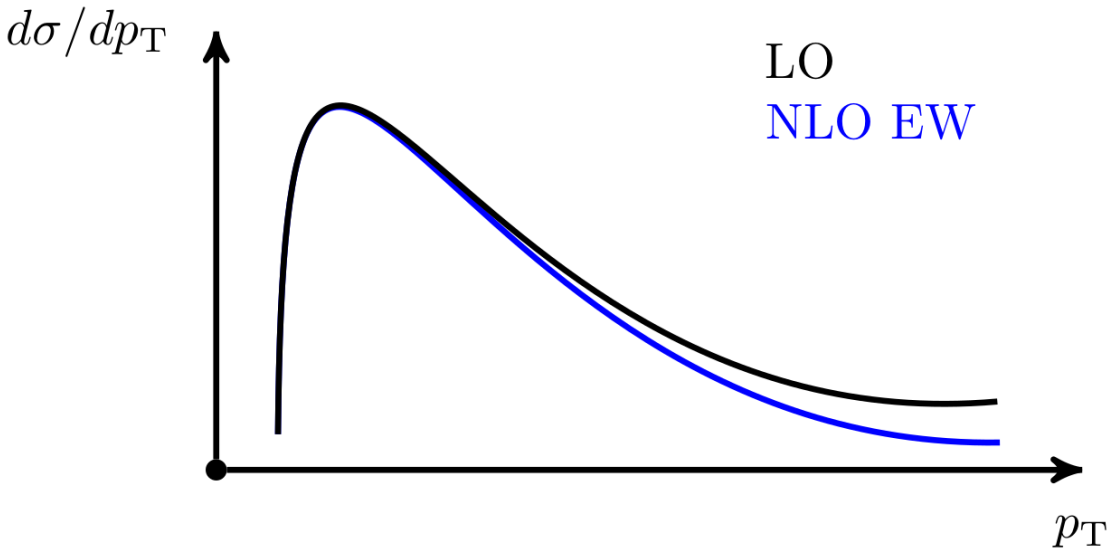


SHERPA+RECOLA

- SHERPA [Gleisberg et al., JHEP **02** (2009) 007]
  - Multi-purpose Monte Carlo event generator
  - From hard process $\rightarrow$ hadronisation
  - Dedicated programs for the loops
  - Publicly available v2.2.4: sherpa.hepforge.org
- RECOLA [Actis et al., Comput. Phys. Commun. **214** (2017) 140]
  - One-loop ME generator for QCD and EW
  - NLO QCD and EW corrections with high multiplicities (up to $2 \rightarrow 7$)
  - Publicly available v2: recola.hepforge.org
- SHERPA+RECOLA [Biedermann et al., Eur.Phys.J. C77 (2017) 492]
  - Any SM processes, NLO QCD and EW accuracy (including loop-induced processes)
  - Interface to RECOLA contained in public version of SHERPA
  - NLO EW dipole subtraction soon publicly available in SHERPA

NLO EW corrections

- Similar order-of-magnitude as NNLO QCD corrections
- Especially relevant at high energies $\sqrt{s}$
- **Sudakov logarithms:** $-\frac{\alpha}{4\pi}\log^2\left(\frac{s}{M_W^2}\right)$



source: M.Pellen

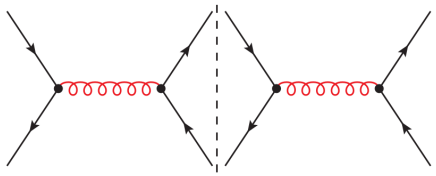
- During Run II: Probing of the tail of the distributions
- Search for new physics

Challenges of NLO EW calculations

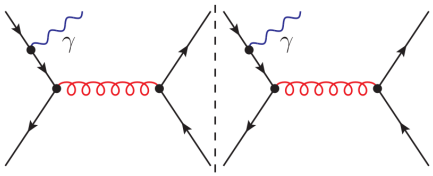
[Kallweit et al., JHEP **04** (2015) 012]

- EW Loops with additional propagators $\rightarrow$ RECOLA
- QED radiation $\rightarrow$ new subtraction terms (SHERPA)
- Photon-induced processes $\rightarrow$ include photon PDF
- NLO QCD+EW calculations lead to interference terms

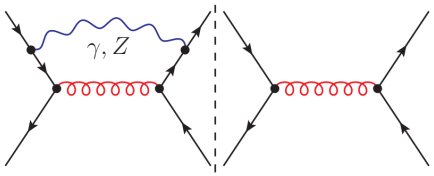
$\Rightarrow$ Implemented in SHERPA+RECOLA



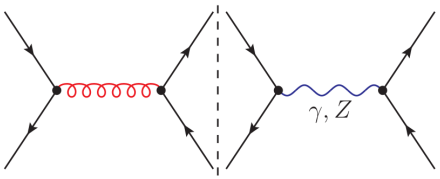
Leading QCD Born



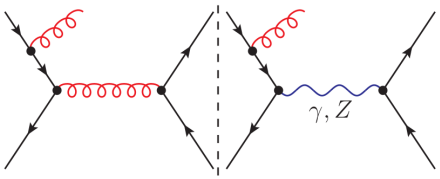
Real $\mathcal{O}(\alpha_S^2\alpha)$ correction



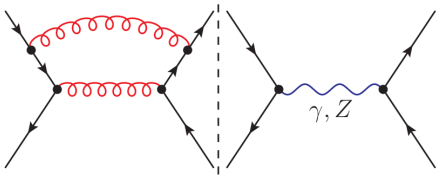
Virtual $\mathcal{O}(\alpha_S^2\alpha)$ correction



QCD-EW Born interference



Real $\mathcal{O}(\alpha_S^2\alpha)$ correction



Virtual $\mathcal{O}(\alpha_S^2\alpha)$ correction

Validation SHERPA+RECOLA

- Phase-space point comparison with OpenLoops for NLO QCD corrections
  VI: **62** processes, loop-induced: **13** processes
- Full support of all Sherpa capabilities (e.g. on-the-fly scale variation)
- Comparison of NLO QCD and EW corrections against literature

Example processes in this talk:

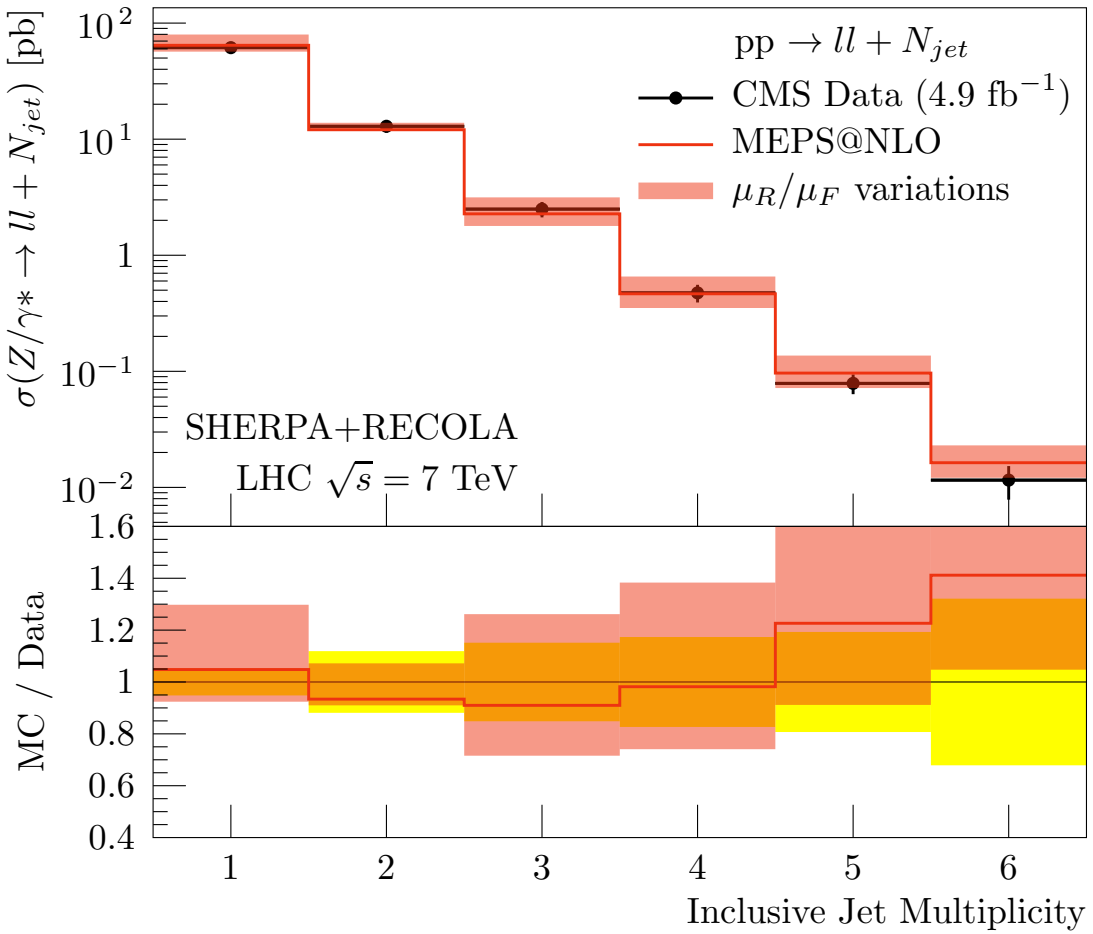
- $pp \to ll + N_{Jet}$ (NLO QCD)
- $pp \to t\bar{t}H$ (NLO QCD+EW)
- $pp \to e^- \mu^+ \bar{\nu}_e \nu_\mu$ (NLO QCD+EW)

$pp \to ll + N_{Jet}$ (NLO QCD)

[V. Khachatryan et al. (CMS), Phys. Rev. **D91(5)** (2015)]

- Standard process for QCD validation
- High cross section, easy to trigger, clear experimental signature
- MEPS@NLO set-up

  Up to 2 Jets @ NLO, 3 Jets @ LO
- Phenomenology @ NLO QCD



$pp \to t\bar{t}H$ @ NLO QCD + EW

Status in theory and experiment:

- Evidence with Run I data [ATLAS+CMS; 1606.02266]
- Yukawa coupling, new physics contributions
- State-of-the-art NLO EW corrections:

  [Zhang et al.; 1407.1110], [Frixione et al.; 1504.03446], [Denner, Lang, Pellen, Uccirati; 1612.07138]

Technical challenges:

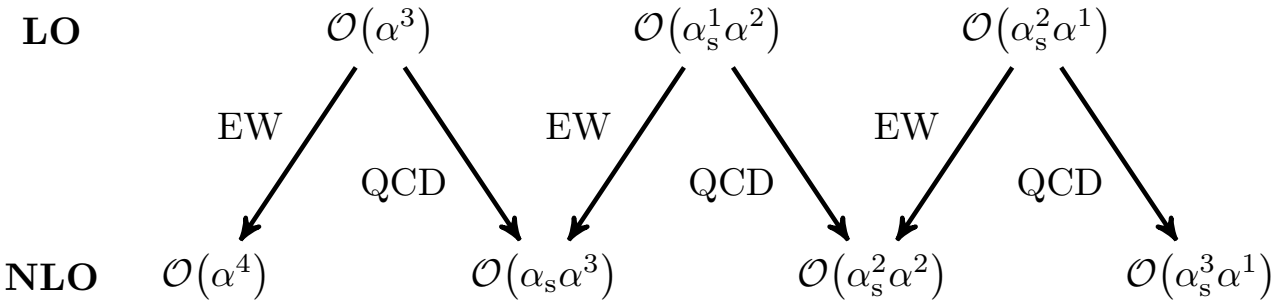
- Massive and coloured final state particles
- Interferences of EW and QCD processes

Validation against Les Houches report:
[J. R. Andersen et al., Les Houches Workshop **9** (2016)], comparison of OpenLoops and MG5

$pp \to t\bar{t}H$ @ NLO QCD + EW (II)

source: B. Biedermann

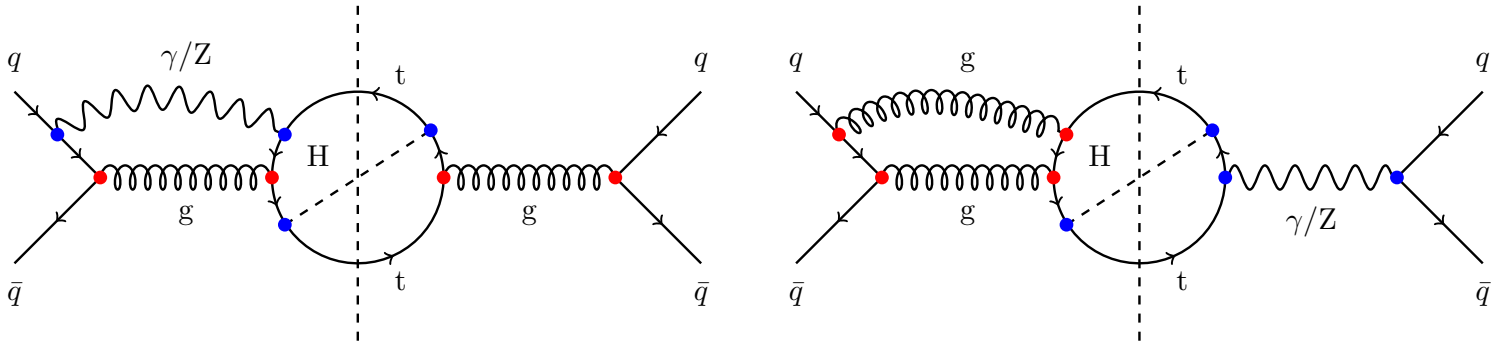
Contributions to $t\bar{t}H$ from different orders in α_s and α:



In the following:

$$\text{LO} = \mathcal{O}\left(\alpha_s^2\alpha^1\right) \qquad \text{NLO QCD} = \mathcal{O}\left(\alpha_s^3\alpha^1\right) \qquad \text{NLO EW} = \mathcal{O}\left(\alpha_s^2\alpha^2\right)$$

Interference effects at $\mathcal{O}\left(\alpha_s^2\alpha^2\right)$:

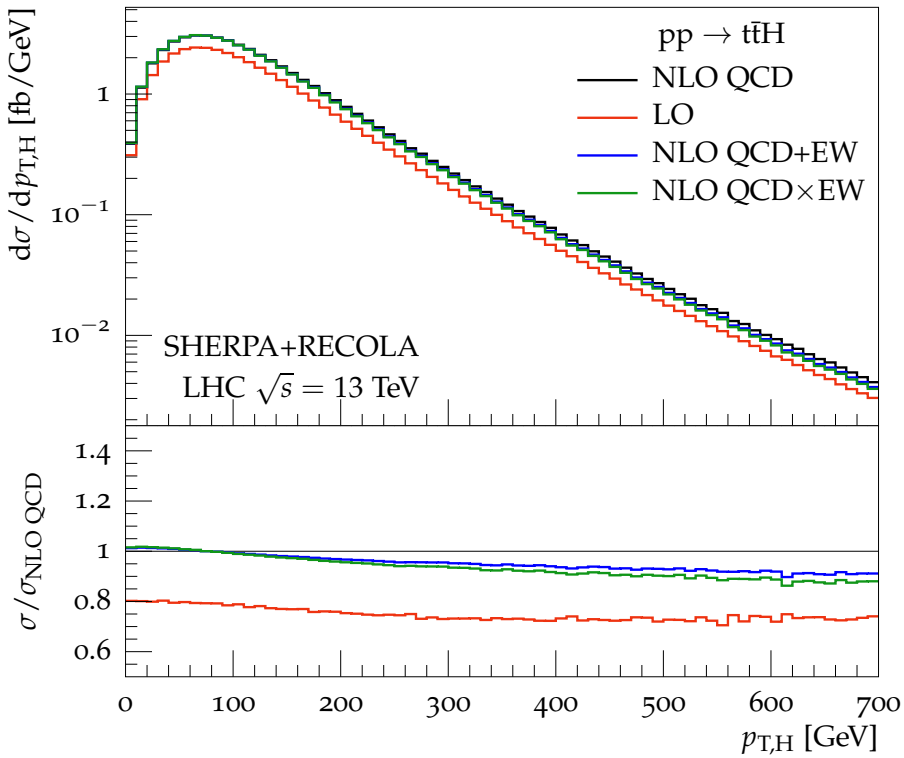


$pp \to t\bar{t}H$ @ NLO QCD + EW (III)

- Sizeable NLO EW corrections at high transverse momentum
- Compare NLO QCD+EW and NLO QCD×EW:

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

[J. R. Andersen et al., Les Houches Workshop **9** (2016)]
[S. Frixione et al., JHEP **06** (2015) 184]



$pp \to e^- \mu^+ \bar{\nu}_e \nu_\mu$ @ NLO QCD + EW

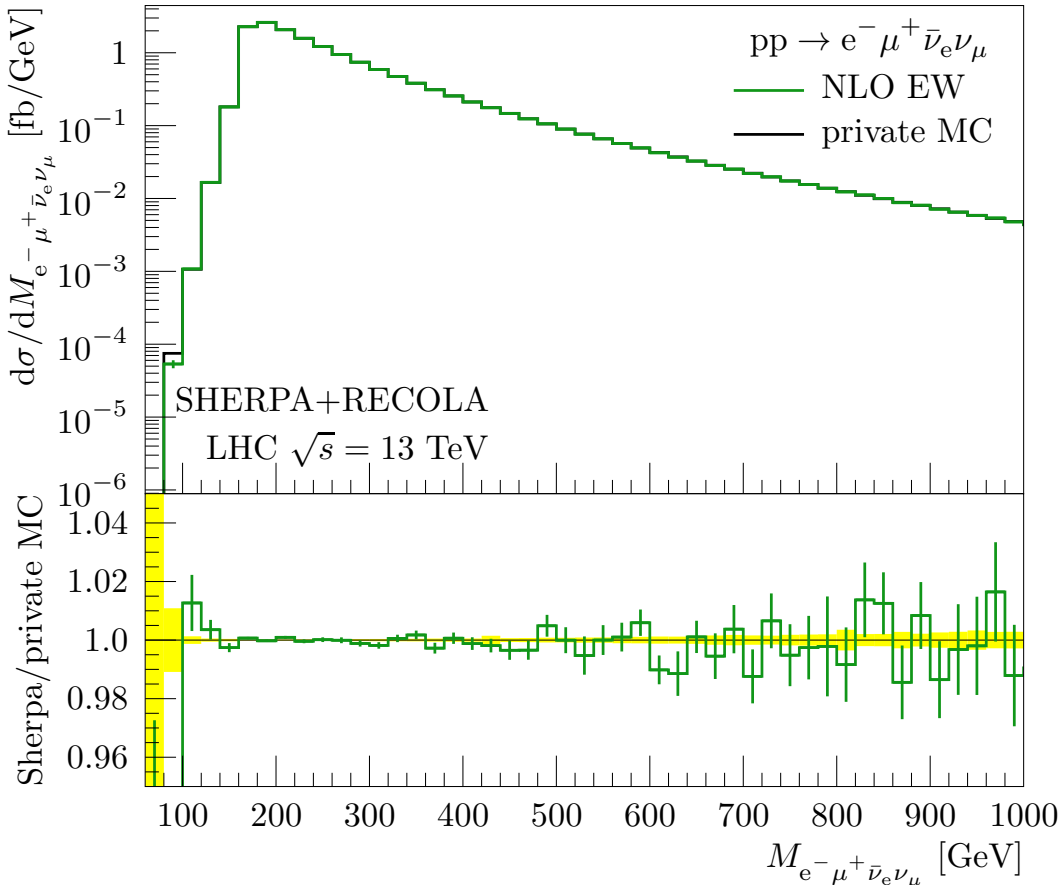
- **Off-shell** production of W^+W^- $\Rightarrow$ Complex final state
- Study EW physics, new physics contributions (i.e. neutral resonances $X \to WW$)
- LO: Pure, complicated EW process
- NLO: Single-top resonances (vetoed), QCD and EW contributions
- State-of-the-art NLO EW corrections:
  On-shell: [Bierweiler et al.; 1208.3147], [Baglio et al.; 1307.4331]
  Off-shell: [Billoni et al., 1310.1564] (DPA), [Biedermann et al.; 1605.03419]

Simplified set-up:

- 4 active flavours $\Rightarrow$ no top resonance
- PDF: LUXqed [Manohar et al., 1607.04266], here: without $\gamma\gamma$ initial states
- Veto event if $p_{T,\text{jet}} > 25$ GeV
- **Validation:** SHERPA+RECOLA vs. private MC

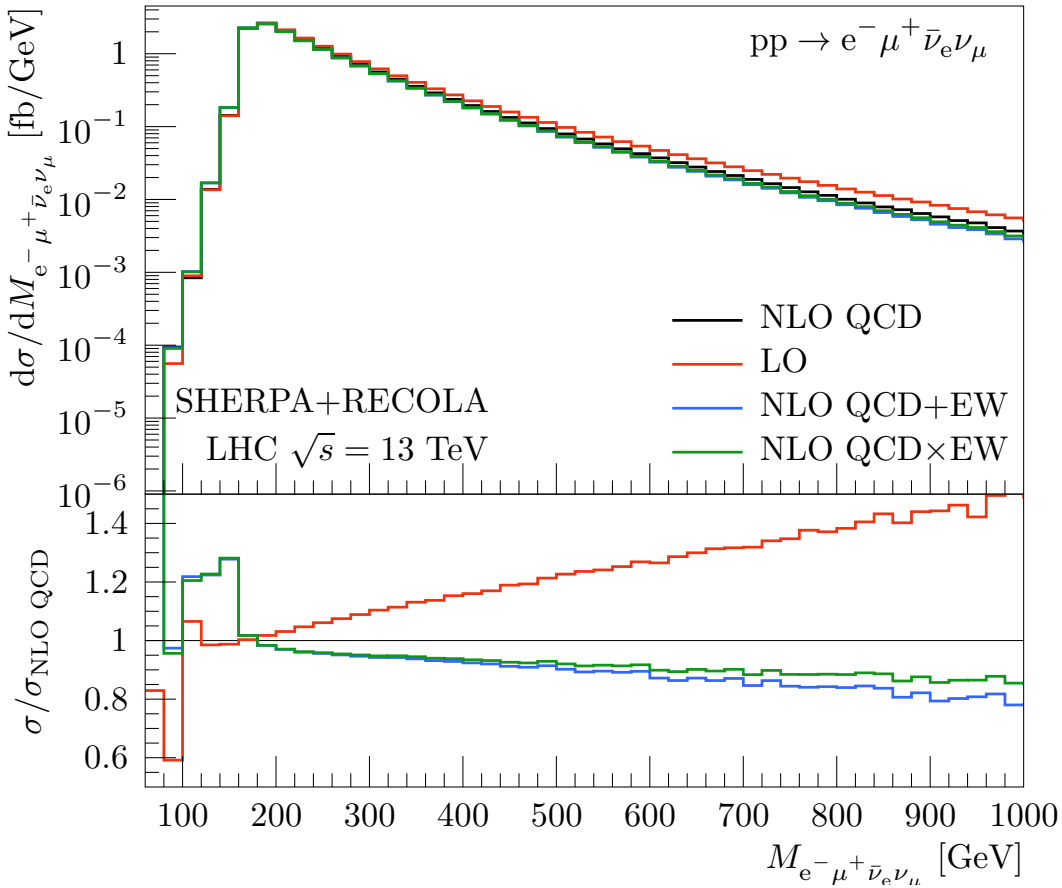
$pp \to e^- \mu^+ \bar{\nu}_e \nu_\mu$ @ NLO QCD + EW (II)

- $p_{T,l^\pm} > 20$ GeV
- $p_{T,miss} > 20$ GeV
- Pure NLO EW comparison
- **(Sub-)Percent level agreement** over the whole phase space
  $\Rightarrow$ On-shell and off-shell regions
- Experimentally unobservable invariant mass $M_{e^- \mu^+ \bar{\nu}_e \nu_\mu}$



$pp \to e^- \mu^+ \bar{\nu}_e \nu_\mu$ @ NLO QCD + EW (III)

- Full combination NLO QCD and NLO EW
- Highly non-trivial corrections below $2M_W$
- **Large negative corrections in the tail**



Next: Full off-shell W^+W^-j (possible double top resonances, first step towards QED parton shower)

Summary & Outlook

- Automation of NLO QCD+EW correction with SHERPA+RECOLA
- Technical details & installation:
  [Biedermann et al., Eur.Phys.J. C77 (2017) 492, arXiv:1704.05783]
- **Fully automated NLO EW corrections, soon public**
- Example processes: $\mathrm{pp} \to \mathrm{ll} + \mathrm{N_{Jet}}$, $\mathrm{pp} \to \mathrm{t\bar{t}H}$, $\mathrm{pp} \to \mathrm{e^- \mu^+ \bar{\nu}_e \nu_\mu}$

$\Rightarrow$ Towards precision EW phenomenology studies at the LHC

- Outlook:
  - Include EW parton shower
    (currently working on (off-shell) $\mathrm{pp} \to \mathrm{W^+W^-j}$)
  - Combine different multiplicities and include QCD corrections
    (full MEPS@NLO set-up)