EW corrections for SM processes

Mathieu PELLEN

University of Freiburg

Physics at TeV Colliders 2021

Les Houches, France

14^{th} of June 2021

Outline:

- What are EW corrections ...
  ... and why you want to compute them

- Brief review on EW corrections since Les Houches 2019
  (*i.e.* arXiv:1906.XXXX)
- Overview of each aspects of EW corrections

Outline:

- What are EW corrections ...
  ... and why you want to compute them

- Brief review on EW corrections since Les Houches 2019 (*i.e.* arXiv:1906.XXXX)
- Overview of each aspects of EW corrections

Aims

- Overview of current progress for EW corrections
- Input for wishlist

Disclaimer

- I might have missed some references (please let me know if so)

Everything You Ever Wanted to Know About **EW corrections** (But Were Afraid to Ask)

→ Electroweak Radiative Corrections for Collider Physics
Denner, Dittmaier; 1912.06823

Everything You Ever Wanted to Know About **EW corrections** (But Were Afraid to Ask)

→ Electroweak Radiative Corrections for Collider Physics
Denner, Dittmaier; 1912.06823

→ reading suggestion for summer... 163 pages with 651 references ...

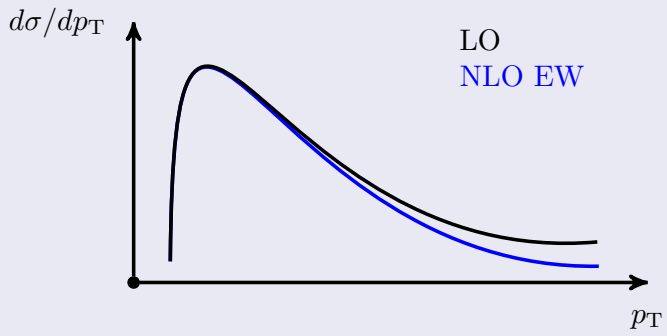
One-slide summary

- $\alpha_s^2 \sim \alpha \rightarrow$ same order of magnitude as NNLO QCD

One-slide summary

- $\alpha_s^2 \sim \alpha \rightarrow$ same order of magnitude as NNLO QCD

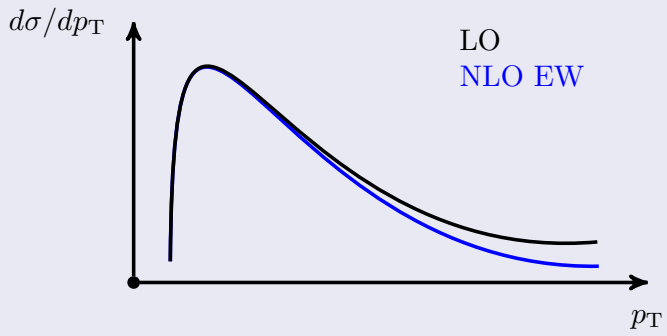
- Sudakov logarithms in high-energy limit



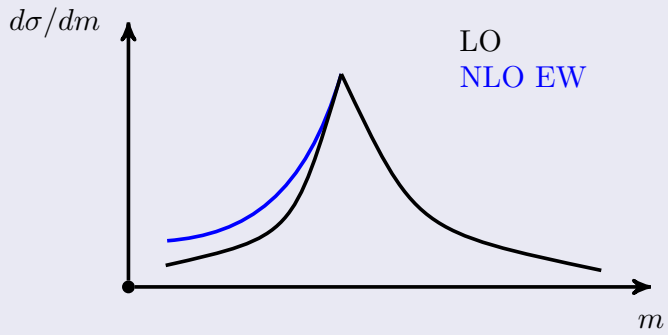
One-slide summary

- $\alpha_s^2 \sim \alpha \rightarrow$ same order of magnitude as NNLO QCD

- Sudakov logarithms in high-energy limit



- Radiative tails near resonances



Overview in classes of processes

Top physics

- Very active (most of the work)

EW physics (DY, diboson, VBS, triboson, ...)

- Mixed QCD/EW corrections for Drell-Yan
- NLO EW corrections for tri-boson / VBS and its backgrounds

Jet physics

- Nothing since EW corrections for di-jet and tri-jet
  [Reyer, Schönherr, Schumann; 1902.01763]

Higgs physics

- Few (in quantity) because of two-loop amplitudes needed

State of the art (fixed order) - NLO EW corrections

- Precise predictions for single-top production: the impact of EW corrections and QCD shower on the t-channel signature Frederix, Pagani, Tsinikos; 1907.12586
- Top-quark pair hadroproduction in association with a heavy boson at NLO+NNLL including EW corrections Broggio et al.; 1907.04343
- NNLO QCD + NLO EW with Matrix+OpenLoops: precise predictions for vector-boson pair production Grazzini et al.; 1912.00068
- Next-to-leading-order QCD and electroweak corrections to triple-W production with leptonic decays at the LHC Dittmaier, Knippen, Schwan; 1912.04117 ★
- Subleading EW corrections and spin-correlation effects in $t\bar{t}W$ multi-lepton signatures Frederix, Tsinikos; 2004.09552
- Precise predictions for double-Higgs production via vector-boson fusion Dreyer, MP et al.; 2005.13341
- RIP Hbb: how other Higgs production modes conspire to kill a rare signal at the LHC Pagani, Shao, Zaro; 2005.10277
- NLO QCD+EW predictions for tHj and tZj production at the LHC Pagani, Tsinikos, Vryonidou; 2006.10086
- Electroweak corrections to the angular coefficients in finite-p_{T} Z-boson production and dilepton decay Frederix, Vitos; 2007.08867
- NLO QCD and EW corrections to vector-boson scattering into ZZ at the LHC Denner, MP et al.; 2009.00411 ★
- Probing the spin correlations of $t\bar{t}$ production at NLO QCD+EW Frederix, Tsinikos, Vitos; 2105.11478
- Combined NLO EW and QCD corrections to off-shell tt-W production at the LHC Denner, Pelliccioli; 2102.03246 ★
- Automated EW corrections with isolated photons: $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$ and $t\gamma j$ as case studies Pagani et al.; 2106.02059

★ In the Les Houches wishlist 2019

State of the art (fixed order)

Two-loop mixed corrections

- Mixed QCD×QED corrections to on-shell boson production at the LHC Delto et al.; 1909.08428 ★
- NNLO QCD×EW corrections to Z production in the $q\bar{q}$ channel Bonciani et al.; 1911.06200 ★
- Mixed QCD-electroweak corrections to on-shell Z production at the LHC Buccioni et al.; 2005.10221 ★
- Mixed QCD×QED corrections to exclusive Drell Yan production using the q_T-subtraction method Cieri et al.; 2005.01315 ★
- Next-to-leading order corrections to light-quark mixed QCD-EW contributions to Higgs boson production Becchetti et al.; 2010.09451
- Two-loop mixed QCD-EW corrections to $gg \to Hg$ Bonetti et al.; 2007.09813
- Next-to-next-to-leading order mixed QCD-electroweak corrections to on-shell Z production Bonciani et al.; 2007.06518 ★
- Mixed NNLO QCD×electroweak corrections of $\mathcal{O}(N_f \alpha_s \alpha)$ to single-W/Z production at the LHC Dittmaier, Schmidt, Schwarz; 2009.02229 ★
- Mixed QCD-electroweak corrections to W-boson production in hadron collisions Behring et al.; 2009.10386 ★
- Mixed QCD-EW corrections to $pp \to \ell\nu_\ell + X$ at the LHC Buonocore et al.; 2102.12539 ★
- Estimating the impact of mixed QCD-electroweak corrections on the W-mass determination at the LHC Behring et al.; 2103.02671 ★
- Mixed EW-QCD two-loop amplitudes for $q\bar{q} \to \ell^+\ell^-$ and γ_5 scheme independence of multi-loop corrections Heller et al.; 2012.05918 ★

State of the art (beyond fixed order)

Combination with QCD/QED shower

- An event generator for same-sign W-boson scattering at the LHC including electroweak corrections Chiesa, MP et al.; 1906.01863
- Fixed-order and merged parton-shower predictions for WW and WWj production at the LHC including NLO QCD and EW corrections Bräuer, MP et al.; 2005.12128 ★
- NLO QCD+NLO EW corrections to diboson production matched to parton shower Chiesa, Oleari, Re; 2005.12146
- WWγ production at hadron colliders with NLO QCD+EW corrections and parton shower effects Zhu et al.; 2005.10707

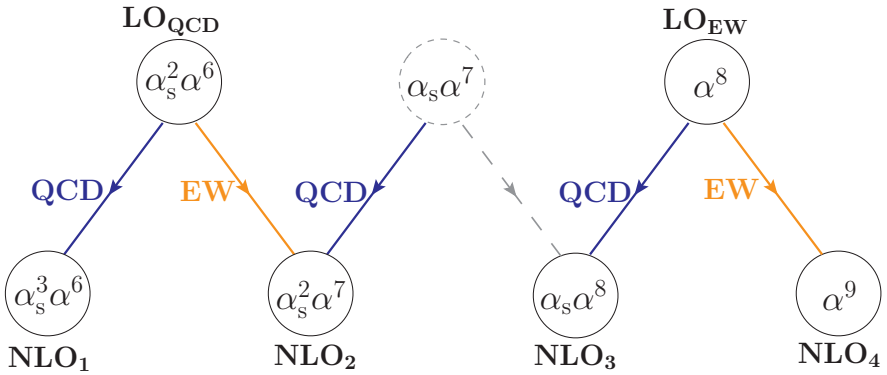
EW shower

- Multipole photon radiation in the Vincia parton shower Skands, Verheyen; 2002.04939
- Collinear electroweak radiation in antenna parton showers Kleiss, Verheyen; 2002.09248
- Automated evaluation of electroweak Sudakov logarithms in Sherpa Bothmann, Napoletano; 2006.14635
- Four lepton production and the accuracy of QED FSR Gütschow, Schönherr; 2007.15360

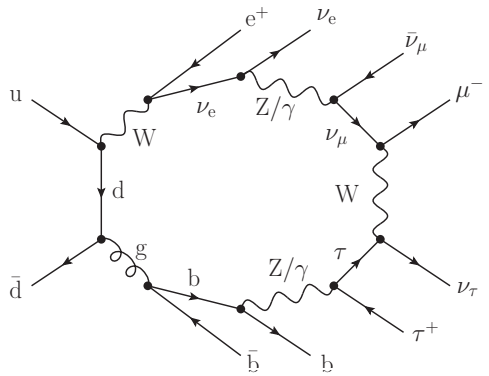
EW corrections and PDF/Fragmentation functions

- PineAPPL: combining EW and QCD corrections for fast evaluation of LHC processes Carrazza et al.; 2008.12789
- Quark and Gluon Contents of a Lepton at High Energies; Han, Ma, Xie; 2103.09844
- On factorisation schemes for the electron parton distribution functions in QED; Frixione; 2105.06688
- Initial conditions for electron and photon structure and fragmentation functions; Frixione; 1909.03886
- Low-virtuality photon transitions $\gamma^* \to f\bar{f}$ and the photon-to-jet conversion function; Denner, MP et al.; 1907.02366

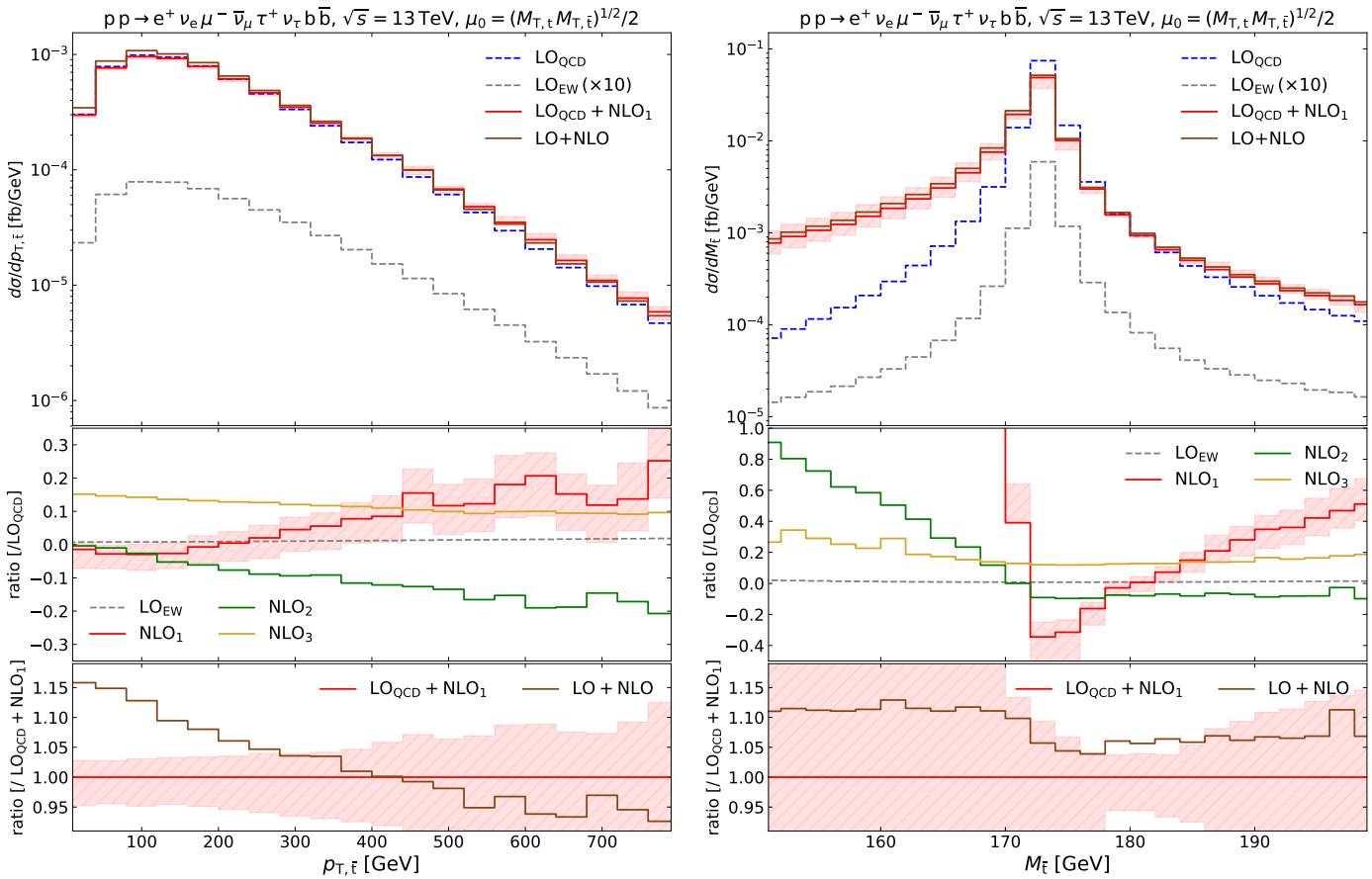
Few examples



- Computation of full off-shell NLO1, NLO2, and NLO3 for ...
  ... $pp \to e^+\nu_e\tau^+\nu_\tau\mu^-\bar{\nu}_\mu\, b\,\bar{b}$
- First NLO EW $2 \to 8$ computation
  $\to$ First time virtual with 10-point functions for phenomenology applications



Differential distributions



- Non-trivial cancellation between different orders
  [Frederix, Pagani, Zaro; 1711.02116]

  → Importance of full NLO predictions in realistic final state

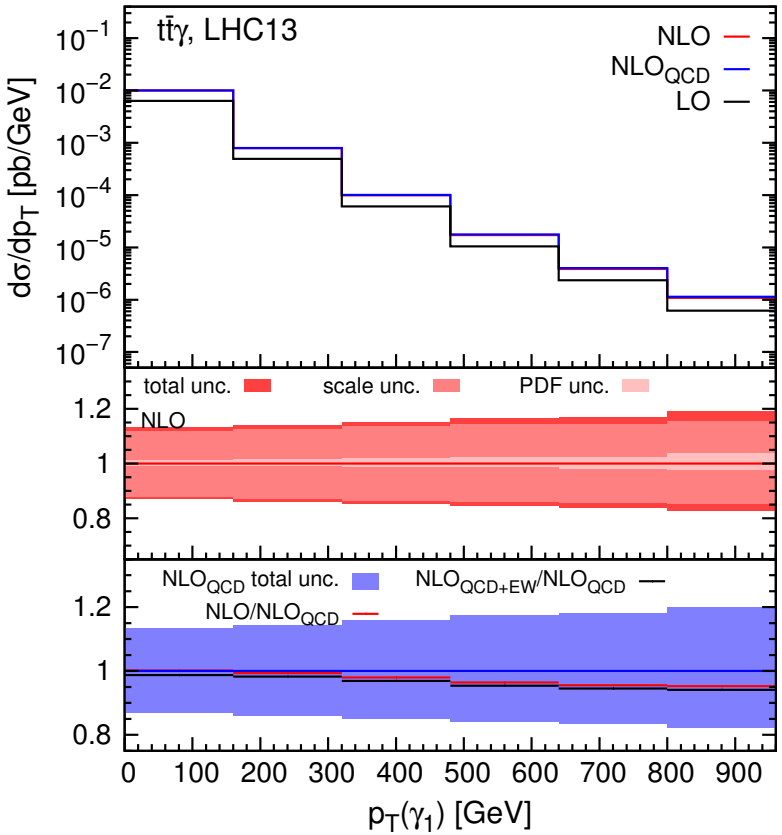
- NLO EW corrections for processes with final state photon ...
  ... not yet fully automatised
  $\rightarrow$ Solution: modified renormalisation, adapted FKS counterterms, photon isolation with democratic jets
  (no fragmentation function)
  $\rightarrow$ Automation of full NLO corrections in MadGraph5_aMC@NLO

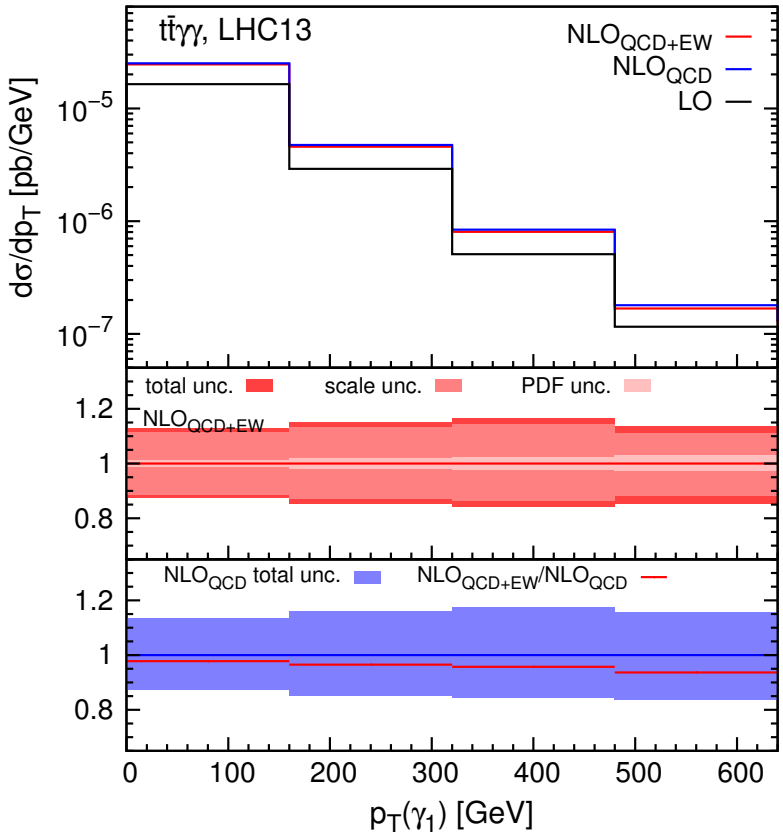
Application

Full NLO predictions for

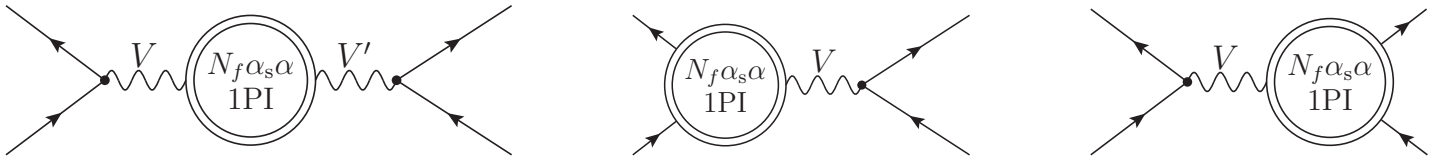
- $t\bar{t}\gamma$
- $t\bar{t}\gamma\gamma$
- $t\gamma j$

Differential distributions





- In this case, expected hierarchy of EW corrections
  ⚠ Fully automatised computation / publicly available

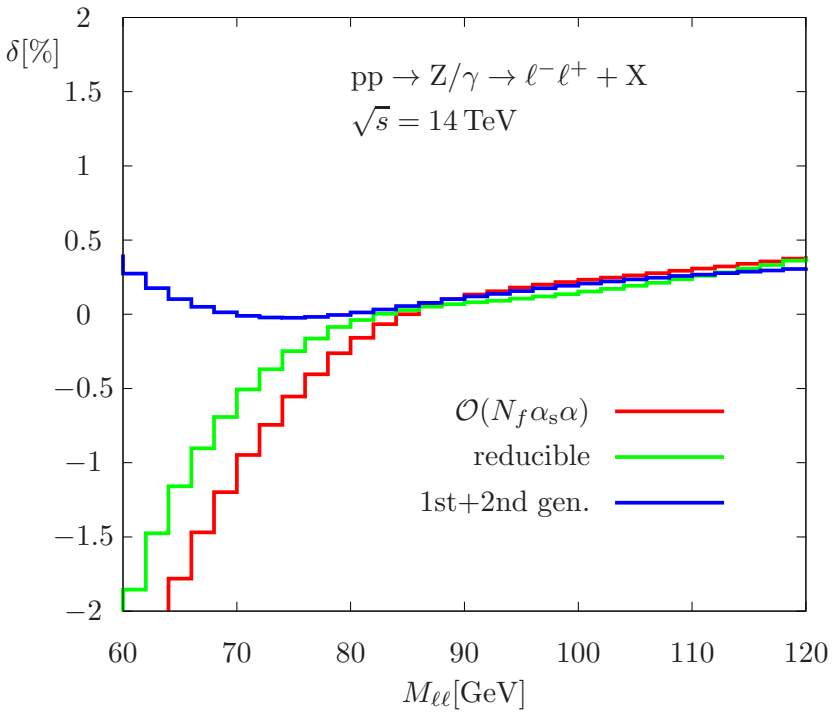


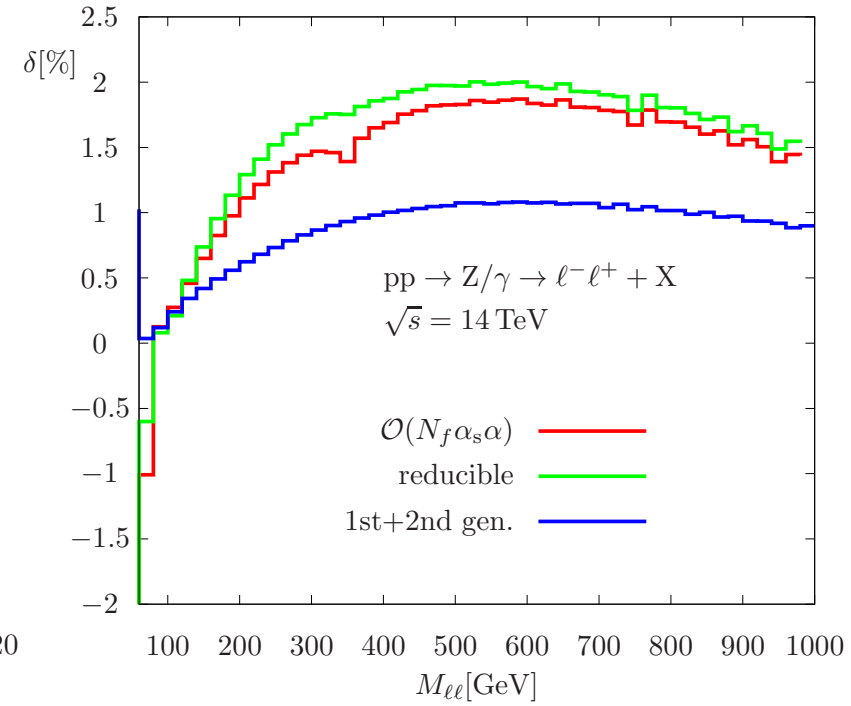
Drell-Yan: best measured process at the LHC

- Highest theoretical precision required
- In addition to QCD and EW corrections
  $\rightarrow$ mixed corrections of $\mathcal{O}(\alpha\alpha_s)$ for pp $\rightarrow 2\ell$ are needed
- First step in this direction: $\mathcal{O}(n_F \alpha\alpha_s)$ corrections

NB: Very recently, complete two-loop amplitude for the neutral current dilepton process obtained [Heller et al.; 2012.05918]

Differential distributions





- Size of corrections: phenomenologicaly relevant
  → relevant for W/Z mass determination

Inclusion of EW corrections in (QCD) merged predictions
$\rightarrow$ Merged PS effects with approximate EW corrections
(included via virtual EW approximation)

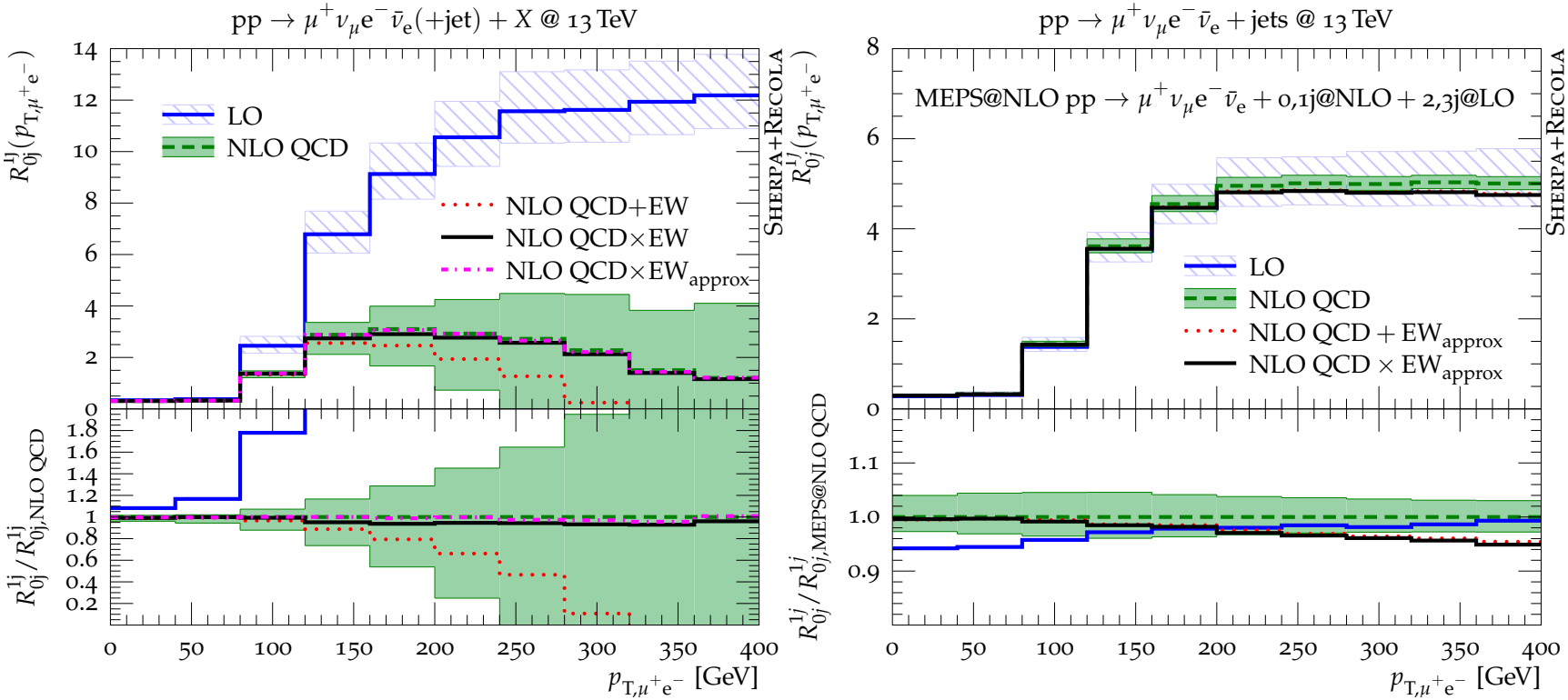
- Fixed-order analysis at NLO QCD+EW
  $\rightarrow$ for off-shell pp $\rightarrow \mu^+\nu_\mu e^-\bar{\nu}_e$
  $\rightarrow$ for off-shell pp $\rightarrow \mu^+\nu_\mu e^-\bar{\nu}_e j$

- Inclusive sample with:
  - Merged predictions + PS + approximate EW corrections
    $\rightarrow$ pp $\rightarrow \mu^+\nu_\mu e^-\bar{\nu}_e + 0, 1j@\mathrm{NLO} + 2, 3j@\mathrm{LO}$

  $\rightarrow$ Can be studied with $n_j = 0$ (WW) or $n_j = 1$ (WWj)

NB: [Chiesa, Oleari, Re; 2005.12146]
$\rightarrow$ no approximation but restricted to WW

Ratio W^+W^-j/W^+W^-: fixed order vs. beyond fixed order

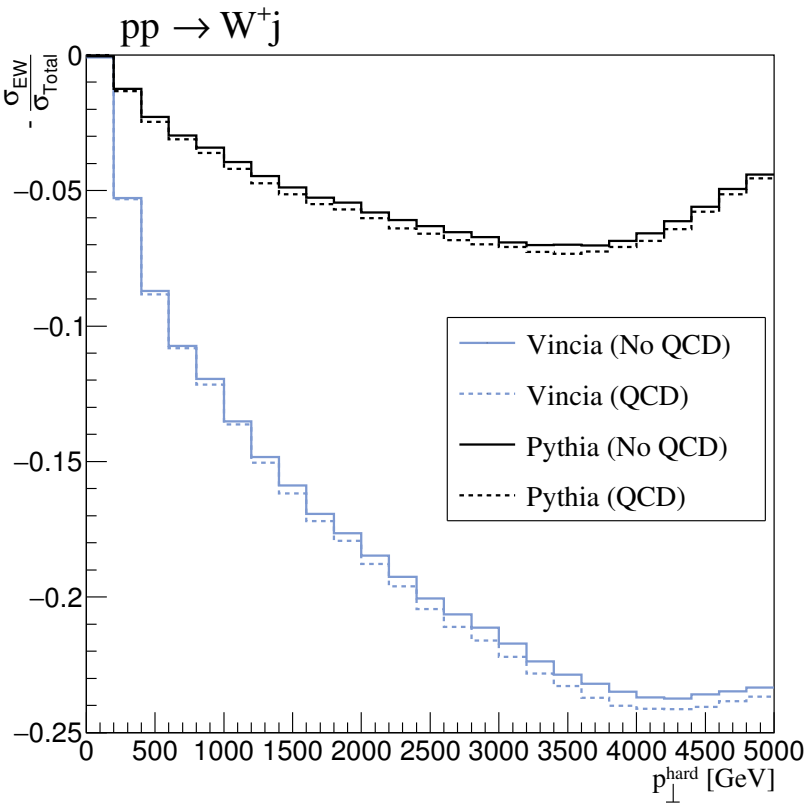


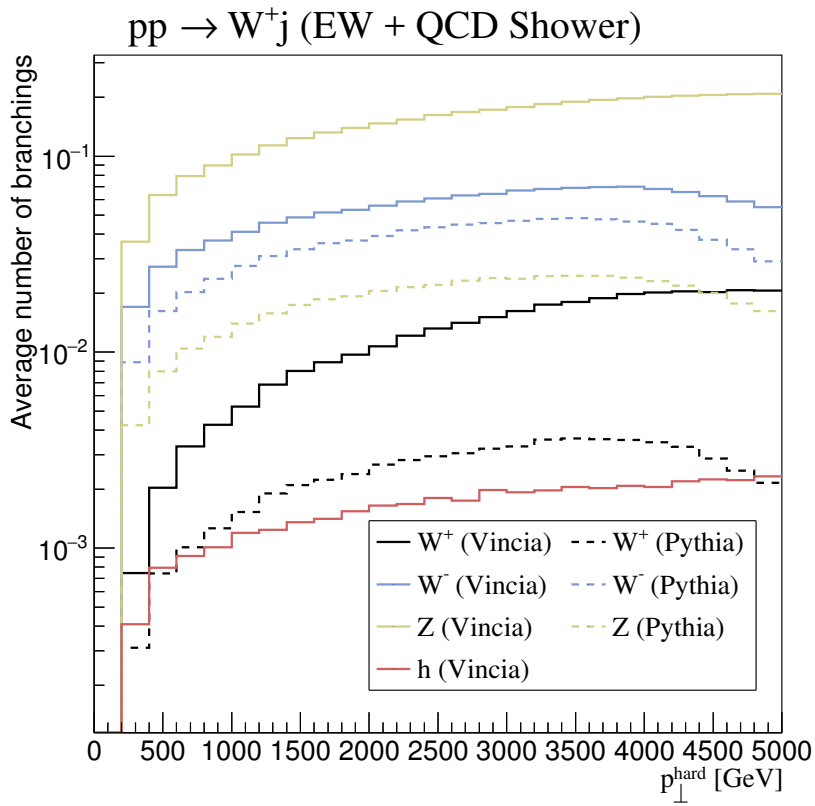
- Very large ratios between WWj and WW (sensitive to jet veto)
  → Ratio motivated by ATLAS measurement [1608.03086]
- For multi-jet merged parton-shower: much more stable ratios

EW parton shower: received less attention

- ⚠ Phenomenologically relevant
- ⚠ Complications due to EW theory (chiral, massive particles, resonances ...)
  - First implementation of collinear electroweak radiation VINCIA
    → include all possible final-state collinear EW branchings
    → collinear vector boson emissions off the initial state included

Differential distributions





- Noticeable impact at high energy
  (in Pythia, only radiation of electroweak gauge bosons and no spin information kept)

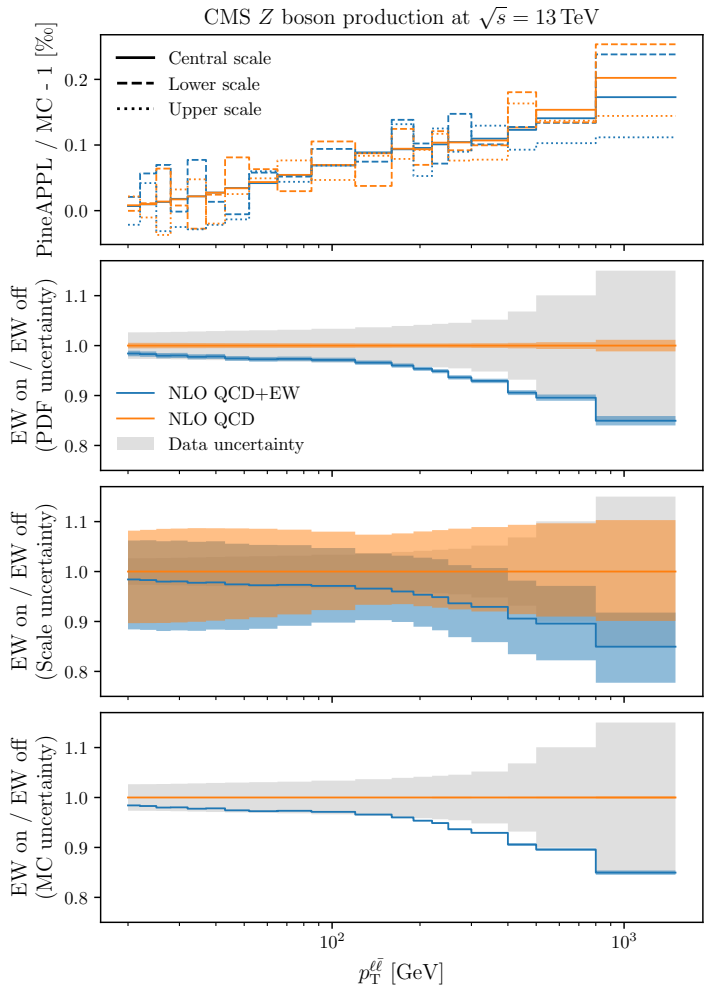
  → particularly relevant for future colliders

PineAPPL:

- library producing fast-interpolation grids of cross sections
- to be interfaced with *any* Monte Carlo generator
  → Application to MadGraph5_aMC@NLO
- Applicable for all higher order (QCD, EW, mixed)
  ⚠ Crucial for global PDF fits to include EW corrections

→ `https://n3pdf.github.io/pineappl`

Validation plot



- MC reproduced extremely precisely (sub-permille)
- Next step: inclusion of EW corrections in global PDF fits!

Summary of each sections

State of the art (fixed order)

NLO EW corrections

- Up to $2 \to 8$ processes
  - ⚠ Tools not always public
  - ⚠ Computations can be extremely CPU intensive
  - ⚠ Processes with photon in the final state
  - ⚠ Loop-induced processes (*e.g.* $gg \to H$) requires two-loop EW amplitudes

Mixed QCD/EW or NNLO EW corrections

- Up to $2 \to 2$
  - ⚠ Main bottleneck: two-loop EW amplitudes

State of the art (beyond fixed order)

Combination with QCD/QED shower

- Up to $2 \to 6$ processes
  - ⚠ Treatment of mixed corrections not yet accounted

EW shower

- First steps in direction of a full treatment
  - ⚠ No matching of weak corrections to EW shower

EW corrections and PDF/Fragmentation functions

- Great progresses
  - ⚠ More studies in this directions to be expected

Summary

Significant progress on EW corrections in the Standard Model

- Any process @ NLO EW can be computed
- Challenges:
  - Two-loop amplitudes with massive EW particles
  - Combination of EW corrections with QCD/QED/EW PS
  - ... and make all this publicly available/usable

Summary

Significant progress on EW corrections in the Standard Model

- Any process @ NLO EW can be computed
- Challenges:
  - Two-loop amplitudes with massive EW particles
  - Combination of EW corrections with QCD/QED/EW PS
  - ... and make all this publicly available/usable

Remarks:

- The wishlist may not be restricted to fixed order
- Processes on wishlist are strong motivations for theorists

Summary

Significant progress on EW corrections in the Standard Model

- Any process @ NLO EW can be computed
- Challenges:
  - Two-loop amplitudes with massive EW particles
  - Combination of EW corrections with QCD/QED/EW PS
  - ... and make all this publicly available/usable

Remarks:

- The wishlist may not be restricted to fixed order
- Processes on wishlist are strong motivations for theorists

→ If you want EW corrections for your favourite process:

Put it on the wishlist!