NNLOPS, parton showers at NLO and NLO EW corrections

Marek Schönherr

Universität Zürich

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Outline

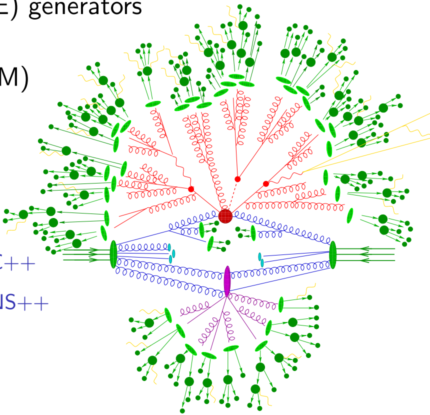
1. Overview
2. NNLOPS
3. Parton showers at NLO
4. NLO EW
5. Conclusions

NNLOPS, parton showers at NLO and NLO EW corrections

The SHERPA event generator framework

JHEP02(2009)007

- Two multi-purpose Matrix Element (ME) generators AMEGIC++, COMIX
- A hard decays module (W, Z, h, t, BSM)
- Two Parton Shower (PS) generators CSSHOWER, DIRE
- A multiple interaction simulation à la PYTHIA AMISIC++
- A cluster fragmentation module AHADIC++
- A hadron and τ decay package HADRONS++
- A higher order QED generator using YFS-resummation PHOTONS++
- A minimum bias simulation SHRiMPS



Sherpa's traditional strength is the perturbative part of the event

LO, NLO, NNLO, LOPS, NLOPS, **NNLOPS**, MEPS, MENLOPS, **MEPS@NLO**

Acronyms and nomenclature

Fixed order calculations

- matrix elements only, implies fixed multiplicities
- no parton shower, no non-perturbative physics, no particle level

⇒ LO, NLO, NNLO

Parton shower matched calculations

- combination of fixed order calculation and parton shower for one multiplicity
- particle level predictions, no multijet observables

⇒ LOPS, NLOPS, **NNLOPS**

Multijet merged calculations

- combination of parton shower matched calculations for increasing final state multiplicities (mostly jets)
- particle level predictions, multijet observables

⇒ MEPS(@LO), **MEPS@NLO** (special case MENLOPS)

NNLOPS, parton showers at NLO and NLO EW corrections

NNLOPS with S-MC@NLO + UN^{2}LOPS + $q_\perp$-slicing

Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773

For $q_\perp > q_{\perp,\text{cut}}$ ($q_{\perp,\text{cut}} < t_c$) a S-MC@NLO calculation in Φ_1 can be used to complement an exclusive NNLO calculation at zero $q_\perp$. Same as in NLO multijet merging, overlap of the Sudakov form factor and the NNLO calculation have to be subtracted.

$$\langle O\rangle^{\text{S-MC@NLO}}_{>q_{\perp,\text{cut}}} = \int\limits_{q_{\perp,\text{cut}}} \mathrm{d}\Phi_1\,\bar{\mathrm{B}}_1(\Phi_1)\,\bar{\mathcal{F}}_1(O) + \int\limits_{q_{\perp,\text{cut}}} \mathrm{d}\Phi_2\,\mathbb{H}_1(\Phi_2)\,\mathcal{F}_2(O)$$

add Δ_0 for resummation wrt. Φ_0, subtract $\mathcal{O}(\alpha_s)$ expansion.

Add explicit NNLO in Φ_0: $\bar{\bar{\mathrm{B}}}_0^{q_{\perp,\text{cut}}}$ for $q_\perp < q_{\perp,\text{cut}} < t_c$. It does not matter whether this term is showered or not since it lives below t_c.

UN^{2}LOPS: subtract anything beyond $\mathcal{O}(\alpha_s^2)$ such that incl. cross section is exact NNLO

NNLOPS with S-MC@NLO + UNLOPS + $q_\perp$-slicing

Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773

schematically:

$$\langle O\rangle^{\text{UN}^2\text{LOPS}}$$

$$= \int \mathrm{d}\Phi_0\; \bar{\bar{\mathrm{B}}}_0^{q_\perp,\text{cut}}(\Phi_0)\;\mathrm{O}(\Phi_0)$$

$$+ \int\limits_{q_{\perp,\text{cut}}} \mathrm{d}\Phi_1\;\Delta_0(1+\Delta_0^{(1)})\,\bar{\mathrm{B}}_1(\Phi_1)\;\bar{\mathcal{F}}_1(O) + \int\limits_{q_{\perp,\text{cut}}} \mathrm{d}\Phi_1\left[1-\Delta_0(1+\Delta_0^{(1)})\right]\bar{\mathrm{B}}_1(\Phi_1)\;O(\Phi_1)$$

$$+ \int\limits_{q_{\perp,\text{cut}}} \mathrm{d}\Phi_2\;\Delta_0\,\mathbb{H}_1(\Phi_2)\;\mathcal{F}_2(O) + \int\limits_{q_{\perp,\text{cut}}} \mathrm{d}\Phi_2\,[1-\Delta_0]\,\mathbb{H}_1(\Phi_2)\;O(\Phi_2)$$

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excl. NNLO contribution

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S-MC@NLO in Φ_1, with Δ_0 resummation

NNLOPS with S-MC@NLO + UNLOPS + $q_\perp$-slicing

Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773

schematically:

$$\langle O\rangle^{\text{UN}^2\text{LOPS}}$$
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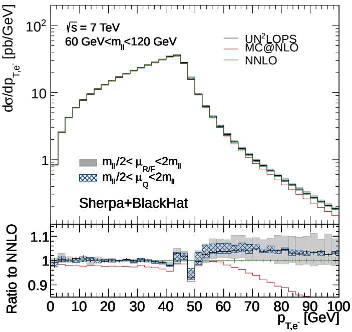
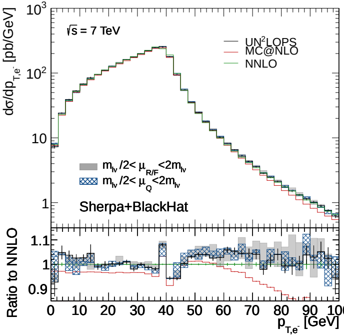
UNLOPS subtraction

NNLOPS for $pp \to h/W/Z$

Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773



$pp \to \ell\ell$



$pp \to \ell\nu$

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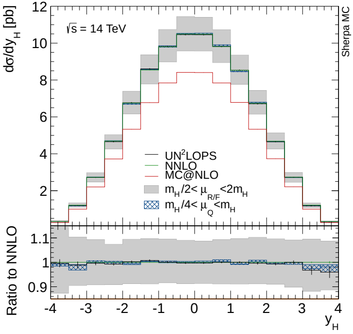
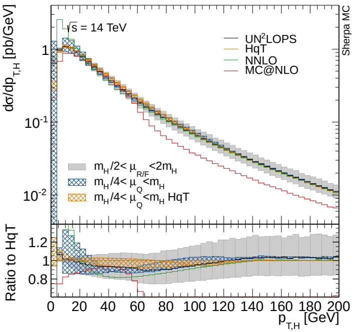
Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773



$pp \to H$



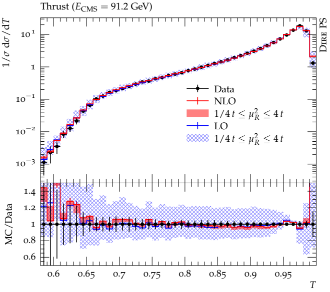
$pp \to H$

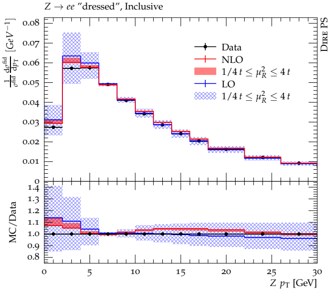
NNLOPS, parton showers at NLO and NLO EW corrections

Parton showers at NLO

Höche, Prestel arXiv:1705.00742
Höche, Krauss, Prestel arXiv:1705.00982

- DIRE developed with the idea of full analytic control over resummation
- recently been extended to NLO correction to splitting functions
  $\rightarrow$ virtual corrections to $1 \rightarrow 2$ splittings
  $\rightarrow$ triple-collinear $1 \rightarrow 3$ splittings





$\Rightarrow$ now not only accurate, but also precise

NNLOPS, parton showers at NLO and NLO EW corrections

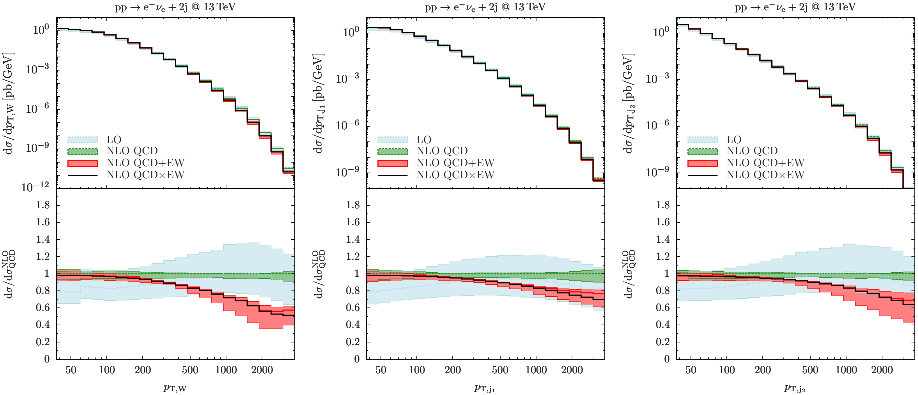
NLO EW corrections

Kallweit,Lindert,Maierhöfer,Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021

- fixed-order next-to-leading order electroweak corrections
- use one-loop matrix element from OPENLOOPS
- already studied a range of processes:
  - $pp \to V + 0, 1, 2(, 3)$ jets
    Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2015)012, JHEP04(2016)021
    EW report arXiv:1606.02330
  - $pp \to t\bar{t}h$
    LH'15 arXiv:1605.04692
  - $pp \to Zj/pp \to \gamma j$ ratio
    Kallweit,Lindert,Maierhöfer,Pozzorini,MS arXiv:1505.05704
    LH'15 arXiv:1605.04692
  - $pp \to Vh$
    FCC report, arXiv:1607.01831
  - $pp \to 2\ell 2\nu$
    Kallweit,Lindert,Pozzorini,MS, arXiv:1705.00598
- dedicated comparisons in LH'15 against RECOLA ($Z + 2j$) and MADGRAPH (tth) showed agreement

$pp \to Wjj$ @ 13 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021



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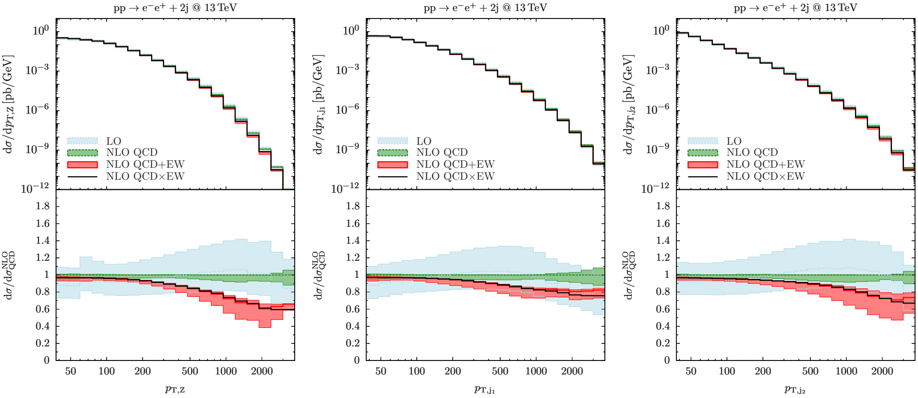
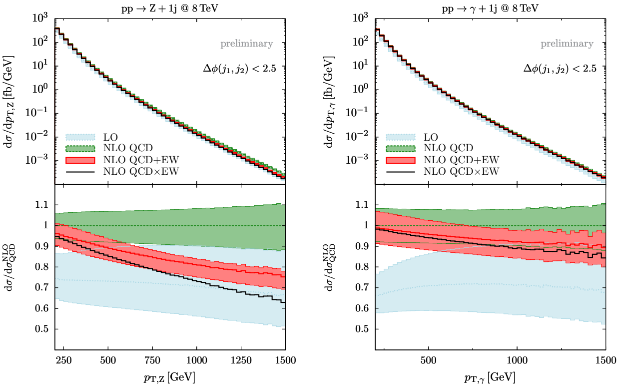


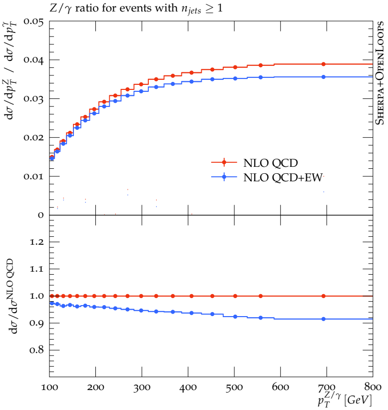
Z/γ ratio @ 8 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704



→ EW corrections different for Z and γ

Z/γ ratio @ 8 TeV

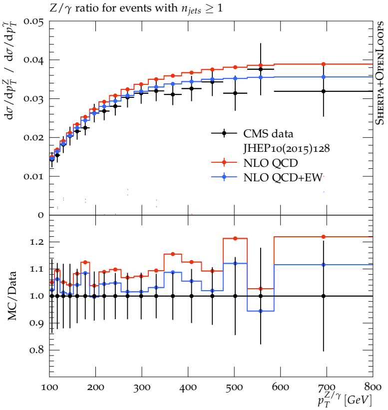


Kallweit, Lindert, Pozzorini, MS for LH'15

- use this ratio to get handle on $p_\perp^Z$ in $Z \to \nu\bar{\nu}$ for NP searches
- test how well data is described in $Z \to \ell\ell$

$\Rightarrow$ NLO EW improves data description

Z/γ ratio @ 8 TeV



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Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- 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)
- simple stand-in for proper QCD+EW matching and merging
  → validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ for observables not driven by real radiation

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optionally include subleading Born

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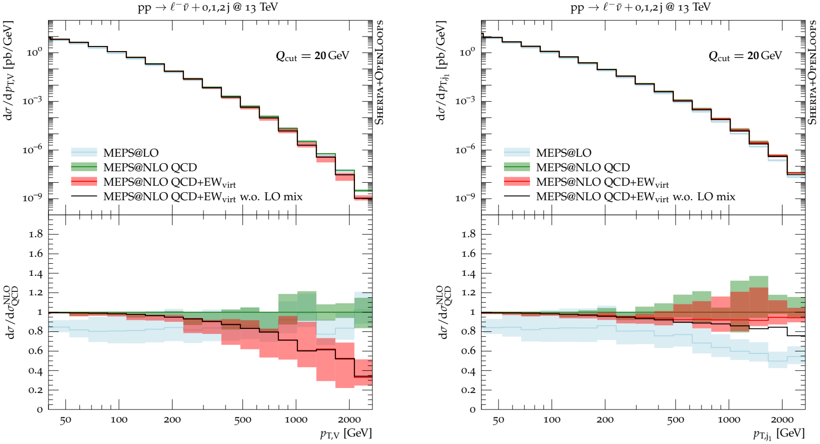
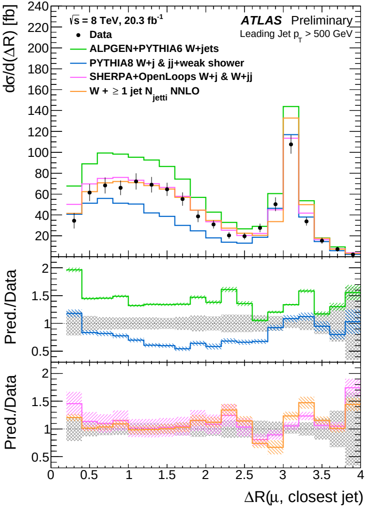
Results: $pp \to \ell^- \bar{\nu} + \text{jets}$

Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2016)021



$\Rightarrow$ particle level events including dominant EW corrections

NLO EW predictions for $\Delta R(\mu, j_1)$



Data comparison

M. Wu ICHEP'16, ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
  $pp \to W +$ jets MLM merged
  Mangano et.al. JHEP07(2003)001
- PYTHIA 8
  $pp \to Wj$ + QCD shower
  $pp \to jj$ + QCD+EW shower
  Christiansen, Prestel EPJC76(2016)39
- SHERPA+OPENLOOPS
  NLO QCD+EW+subLO
  $pp \to Wj/Wjj$ excl. sum
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- NNLO QCD $pp \to Wj$
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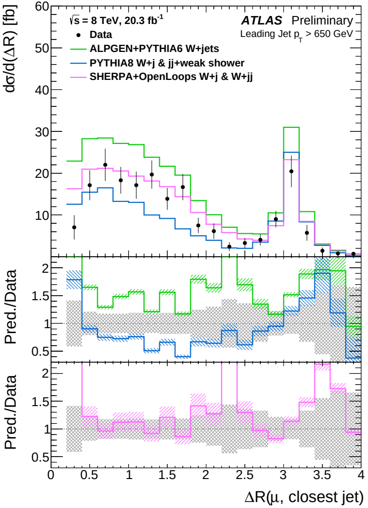

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Diboson production

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

NLO QCD+EW calculation of DF and SF $pp \to 2\ell 2\nu$ production

1) $pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$ Biedermann, et.al. JHEP06(2016)065
DPA: Billoni, Dittmaier, Jäger, Speckner JHEP12(2013)043

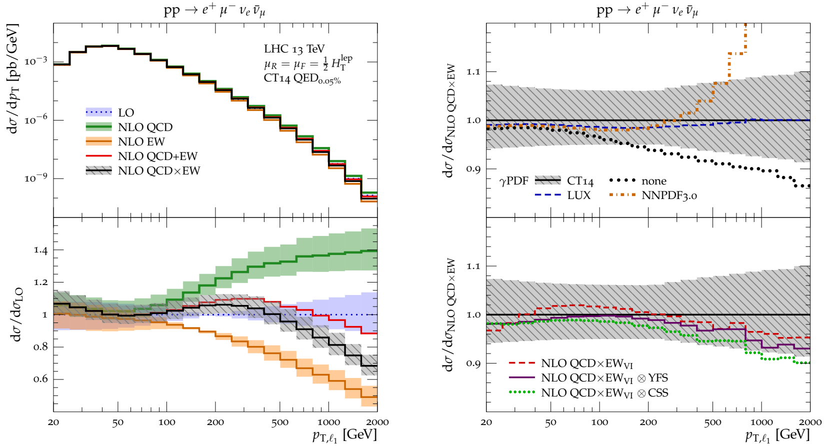
at LO through WW
photon induced processes contribute twice as much as $c\bar{c}$-channel at LO to inclusive xs, more in TeV range, incl. at NLO EW new

2) $pp \to e^+e^-\nu_e\bar{\nu}_e$ 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

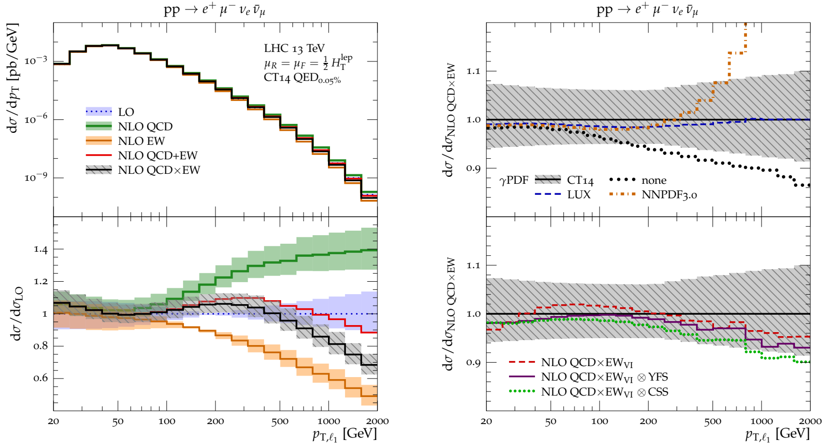
- all double-, single- and non-resonant diagrams included
- 4F to suppress single-top contribs at NLO QCD, jet veto to control large NLO QCD
- explore how NLO QCD⊗EW can be reproduced with current tools

Diboson production



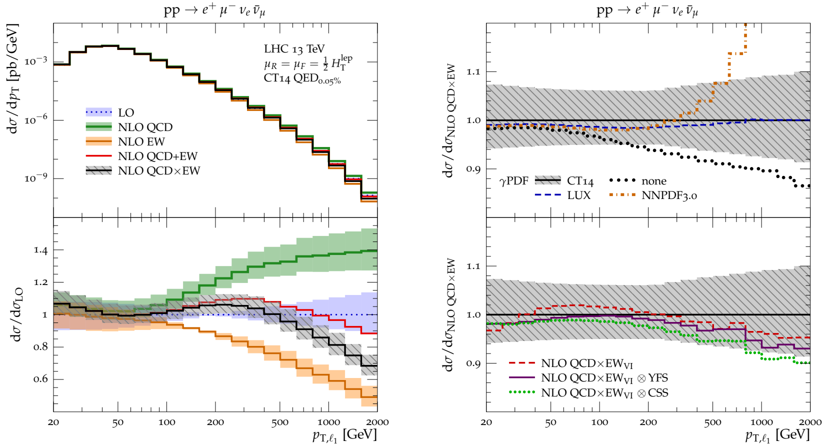
- large pos. NLO QCD, large neg. NLO EW
  → NLO QCD+EW and NLO QCD⊗EW differ significantly

Diboson production



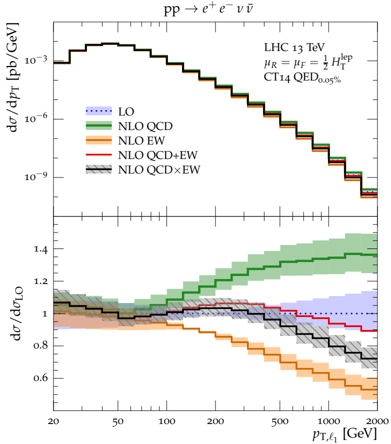
- all γPDF agree that γ-ind. $> 10\%$ for $p_T > 500$ GeV
  very good agreement between CT14qed and LUXqed

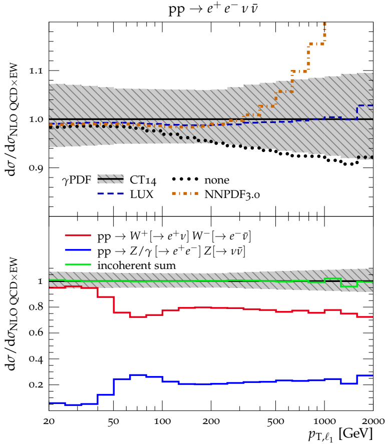
Diboson production



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

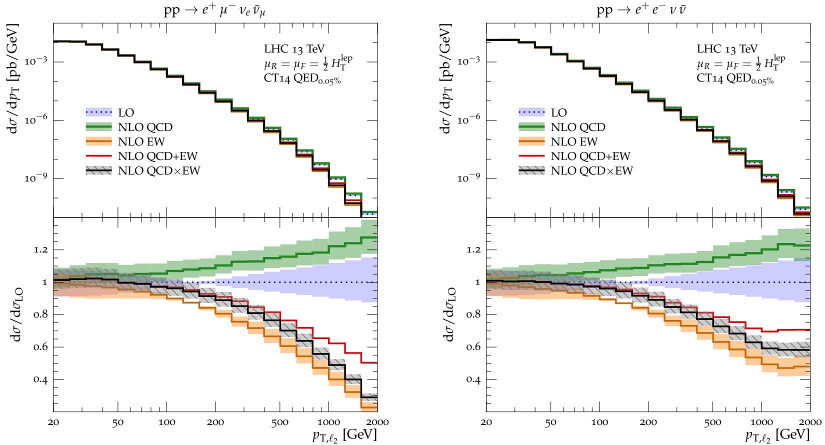
Diboson production





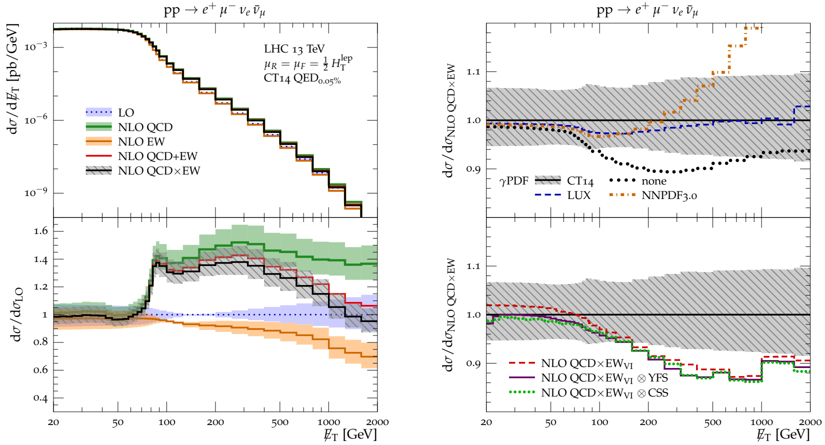
- very similar to DF due to small ZZ contrib
- no interference effects as bosons not forced off-shell

Diboson production



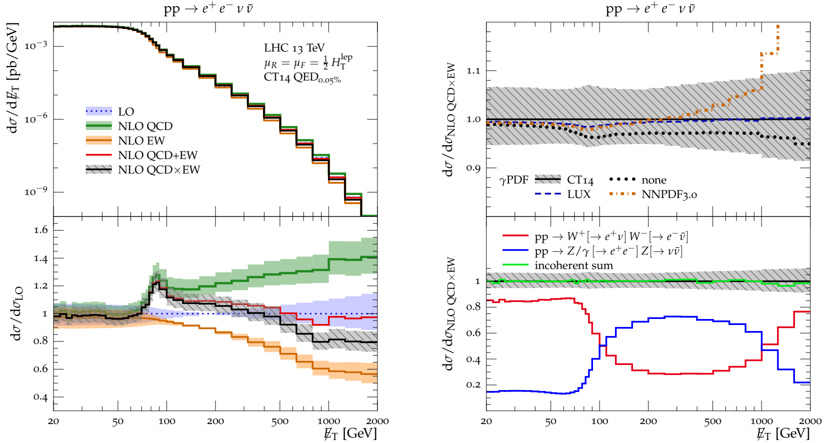
- ZZ dominant at very large p_T
  → different EW corrections, take care when extrapolating

Diboson production



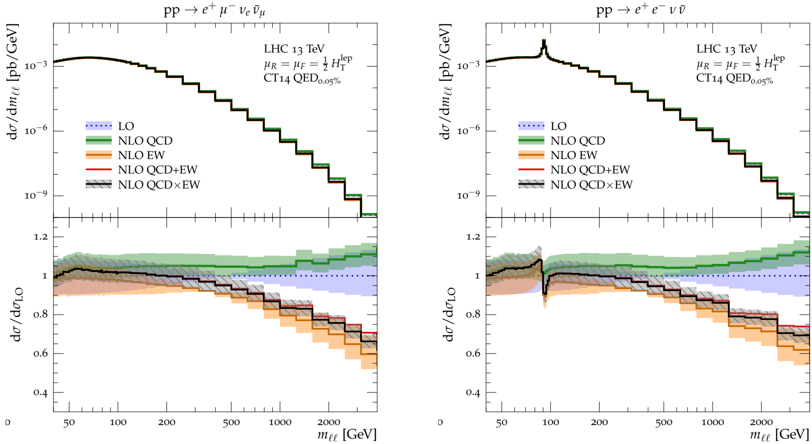
- kinematic suppression for $p_T^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced ⇒ large contrib

Diboson production



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

Diboson production



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

Conclusions

- NNLOPS for $pp \to H, W, Z$ available since SHERPA-2.1 through public plugins
  fully integrated in the code in SHERPA-2.3
- approximate NLO EW corrections can be incorporated in NLO QCD multijet merging since SHERPA-2.2
- fixed-order NLO EW will become available in SHERPA-2.3
- higher order QCD parton showers in the first stages

http://sherpa.hepforge.org

Thank you for your attention!