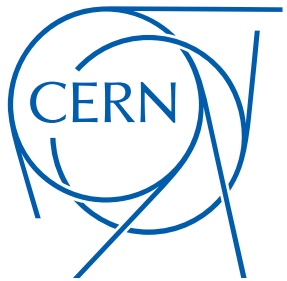
ZZ production

Marek Schönherr

Oxford

11 Apr 2018



4ℓ production – fixed order

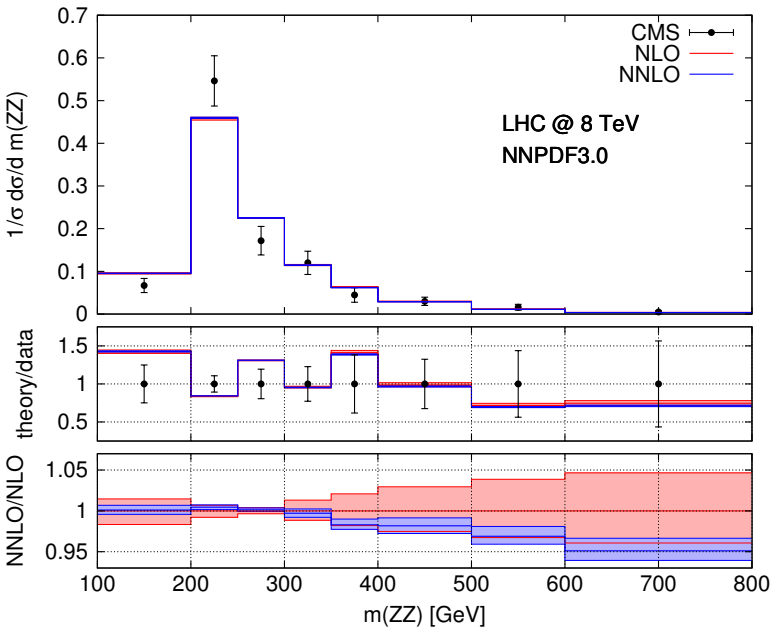
- $pp \to e^+e^-e^+e^-$ and $pp \to e^+e^-\mu^+\mu^-$
  single and double resonant topologies
  (photon induced also non-resonant)
- NNLO QCD arXiv:1405.2219, 1507.06257, arXiv:1710.06294
  MATRIX arXiv:1711.06631
- NLO EW RECOLA arXiv:1601.07787, arXiv:1611.05338
  SHERPA+RECOLA arXiv:1704.05783
- loop induced $gg \to 4\ell$ arXiv:1509.06734
  (only double resonant known at NLO,
  single resonant important in off-shell regions)
- no overlap with $t\bar{t}$ or tV production, no need for jet veto

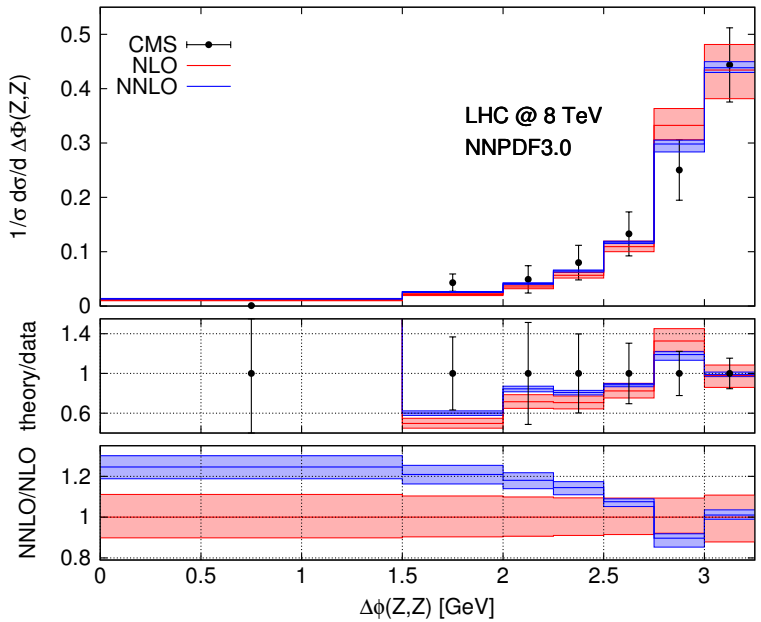
4ℓ production – MC

- $pp \to e^+e^-e^+e^-$ and $pp \to e^+e^-\mu^+\mu^-$
  single and double resonant topologies
  (photon induced also non-resonant)
- SHERPA: MEPS@NLO+MEPS@LOOP^2 arXiv:1309.0500
  $pp \to 4\ell + 0, 1j$@NLO $+ 2j$@LO and
  $gg \to 4\ell + 0, 1j$@LO
  also including single resonannt $gg \to gZ[\to 4\ell]$
  possibility to include approximate EW corrections à la
  arXiv:1705.00598
- POWHEG-BOX: $pp \to 4\ell$@NLO arXiv:1311.1365
  $gg \to 4\ell$@NLO arXiv:1509.06734
  (only double resonant production in gg)

4ℓ production – NNLO QCD $q\bar{q}$

arXiv:1405.2219, 1507.06257, arXiv:1710.06294

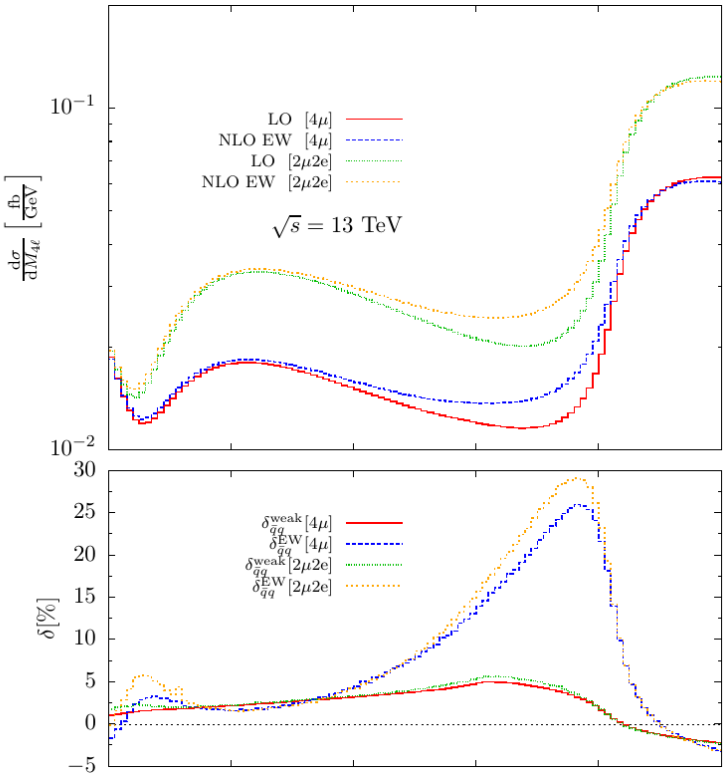


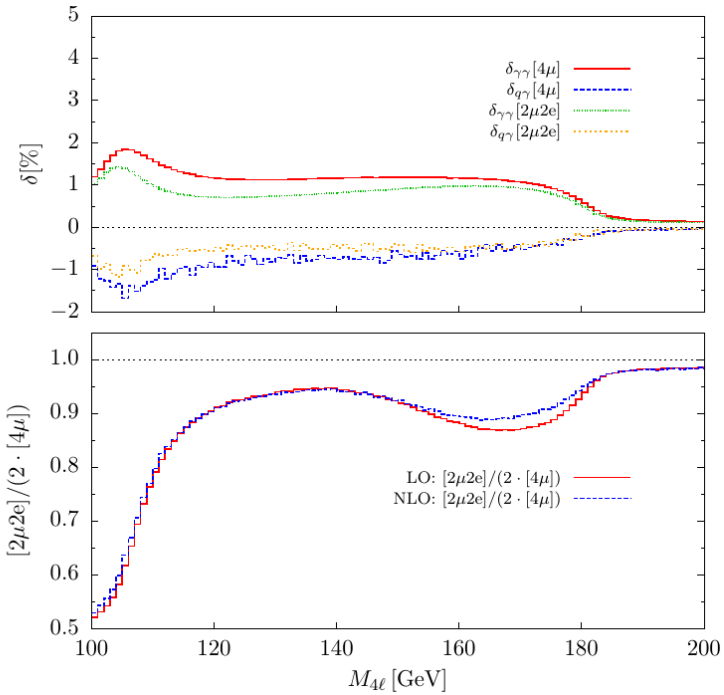


- corrections very moderate, but phase space dependent
- $\Delta\Phi(Z,Z) = 0$ at LO

4ℓ production – NLO EW $q\bar{q}$

arXiv:1601.07787, arXiv:1611.05338, arXiv:1704.05783

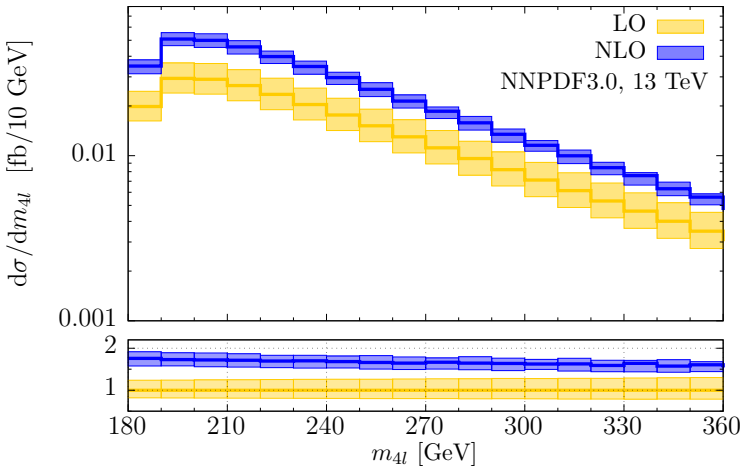


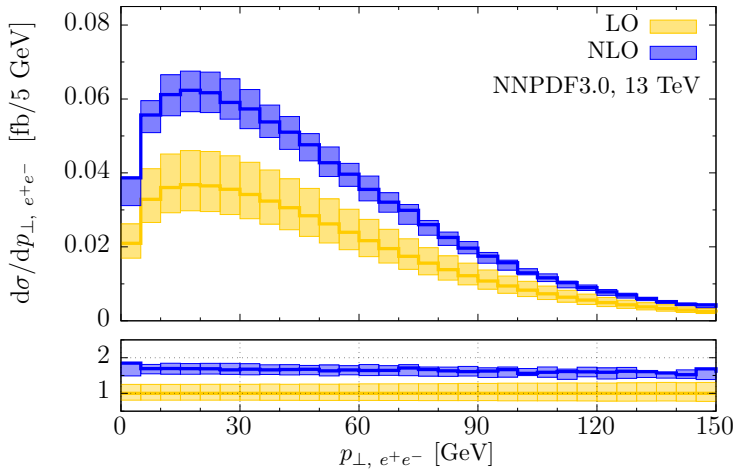


- EW corrections small in $m_{4\ell} \approx m_h$
- slightly different between $4e$ and $2e2\mu$

4ℓ production – NLO QCD *gg*

arXiv:1509.06734

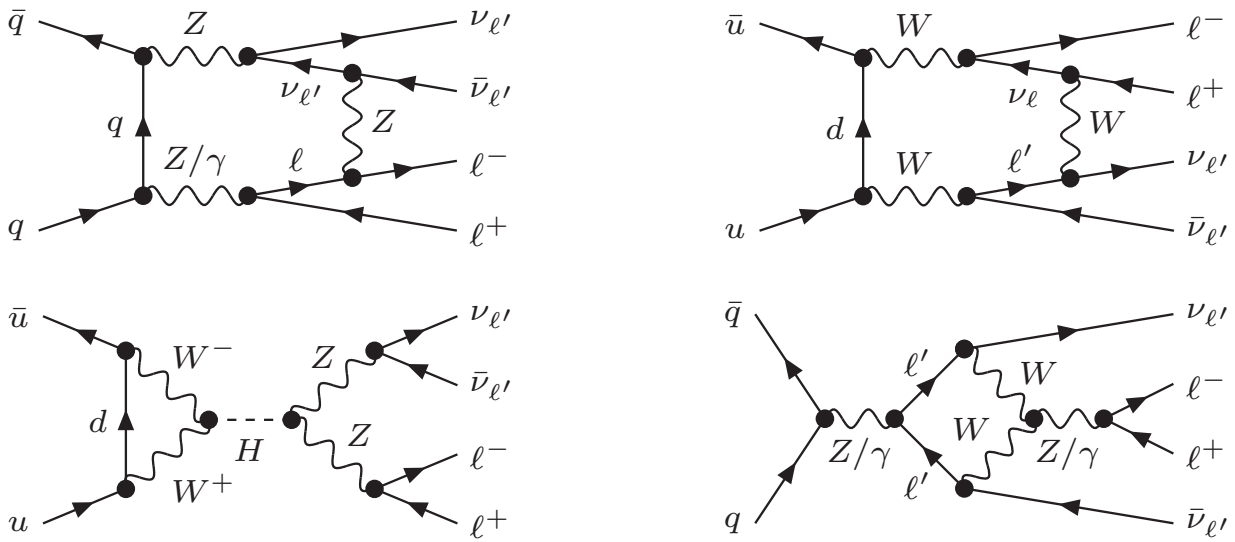




- NLO QCD corrections large, as in many gluon induced processes
- only in double resonant approximation

$2\ell 2\nu$ production

- $pp \to e^+e^-\nu\bar{\nu}$ has three subprocesses:
  $pp \to e^+e^-\nu_e\bar{\nu}_e$ coherent sum of WW and ZZ diagrams
  $pp \to e^+e^-\nu_{\mu/\tau}\bar{\nu}_{\mu/\tau}$ only ZZ
- single and double resonant topologies
  (photon induced also non-resonant)
- rich phenomenology



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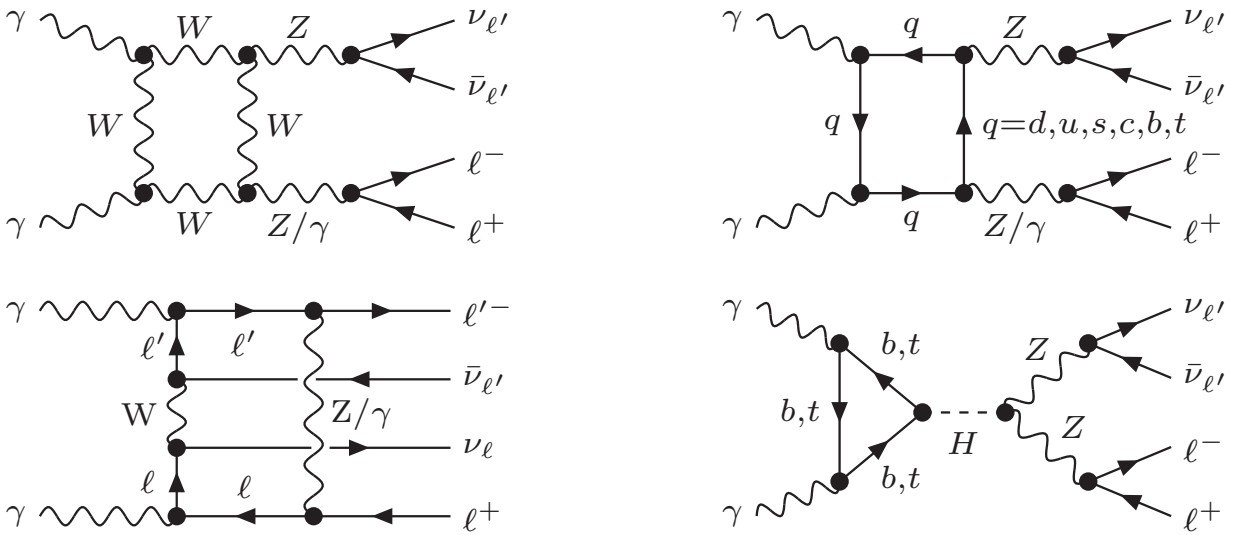

$2\ell 2\nu$ production

- received little attention so far
- NNLO QCD — MATRIX arXiv:1711.06631
- NLO EW — SHERPA+OPENLOOPS arXiv:1704.05783
- loop induced only known at LO
- in general overlap with $t\bar{t}$ and tV production, but should be small in $m_{ee} \approx m_Z$

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- SHERPA: MEPS@NLO+MEPS@LOOP^2 à la arXiv:1309.0500
  $pp \to 2\ell 2\nu + 0, 1j$@NLO $+ 2j$@LO and
  $gg \to 2\ell 2\nu + 0, 1j$@LO
  also including single resonannt $gg \to gZ[\to 2\ell 2\nu]$
  possibility to include approximate EW corrections à la arXiv:1705.00598
- POWHEG-BOX: $pp \to 2\ell 2\nu$@NLO (?) arXiv:1311.1365

$2\ell 2\nu$ production – DF and SF

Combination of QCD and EW correction

- additive – strict fixed order expansion

$$\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \mathrm{d}\sigma^{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}\right)$$

- multiplicative – contains terms of $\mathcal{O}(\alpha_s\alpha)$

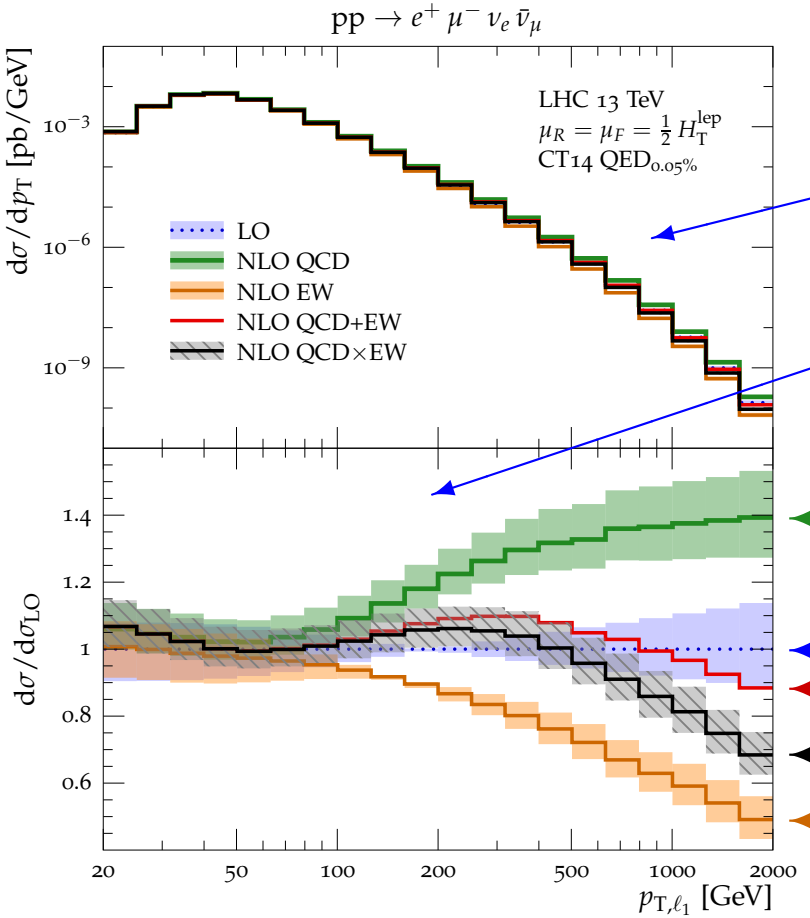
$$\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{QCD}\times\mathrm{EW}} = \mathrm{d}\sigma^{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}}\right)\left(1 + \delta_{\mathrm{EW}}\right)$$

NLO EW for photon initiated processes

- resolved final state photons should be renormalised on-shell ($\alpha(0)$)
  $\rightarrow$ absorbs IR divergences from $\gamma \rightarrow f\bar{f}$ splittings not included
- initial state (and unresolved final state) photons should be renormalised at the hard scale ($\alpha(m_Z)$, G_μ, $\overline{\mathrm{MS}}$, etc.)
  $\rightarrow$ match IR divergences in PDF evolution and collinear counter term

Harland-Lang, Khoze, Ryskin Phys.Lett.B761(2016)20-24
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

2ℓ2ν production – DF



Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

NLO QCD+EW

NLO QCD×EW

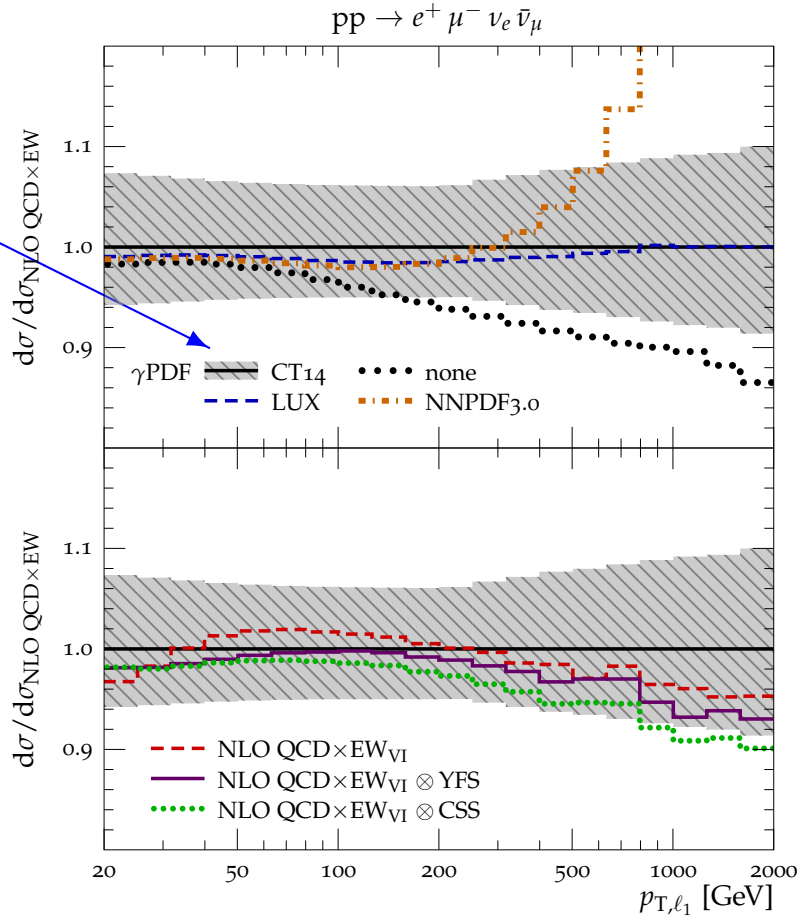
NLO EW

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

2ℓ2ν production – DF

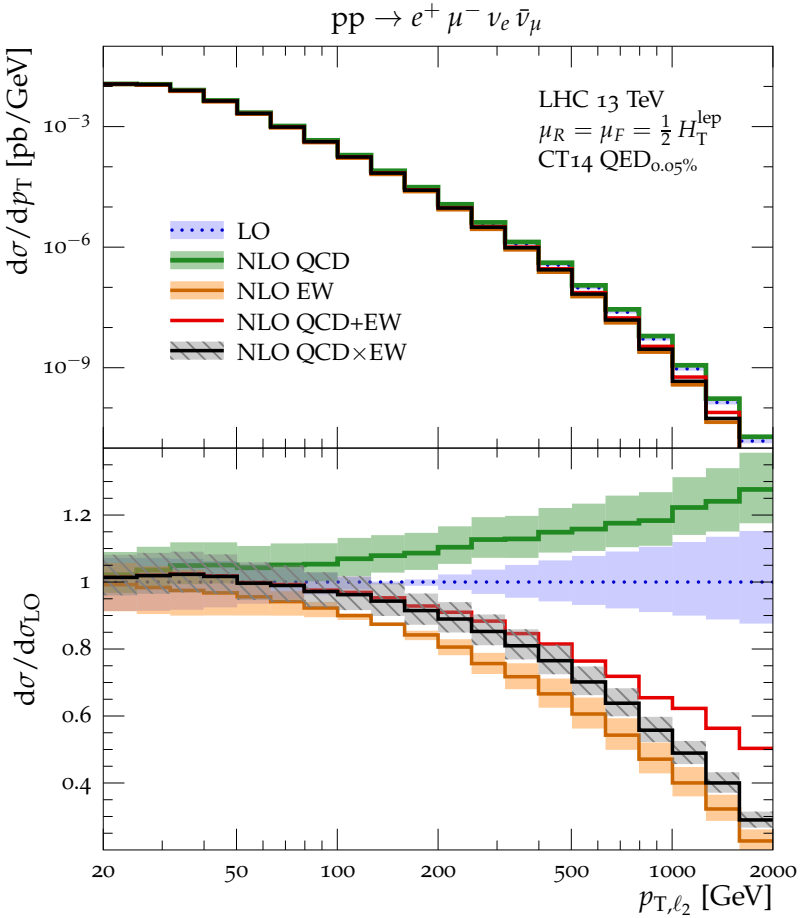
relative importance of γ-induced channels wrt. NLO QCD×EW

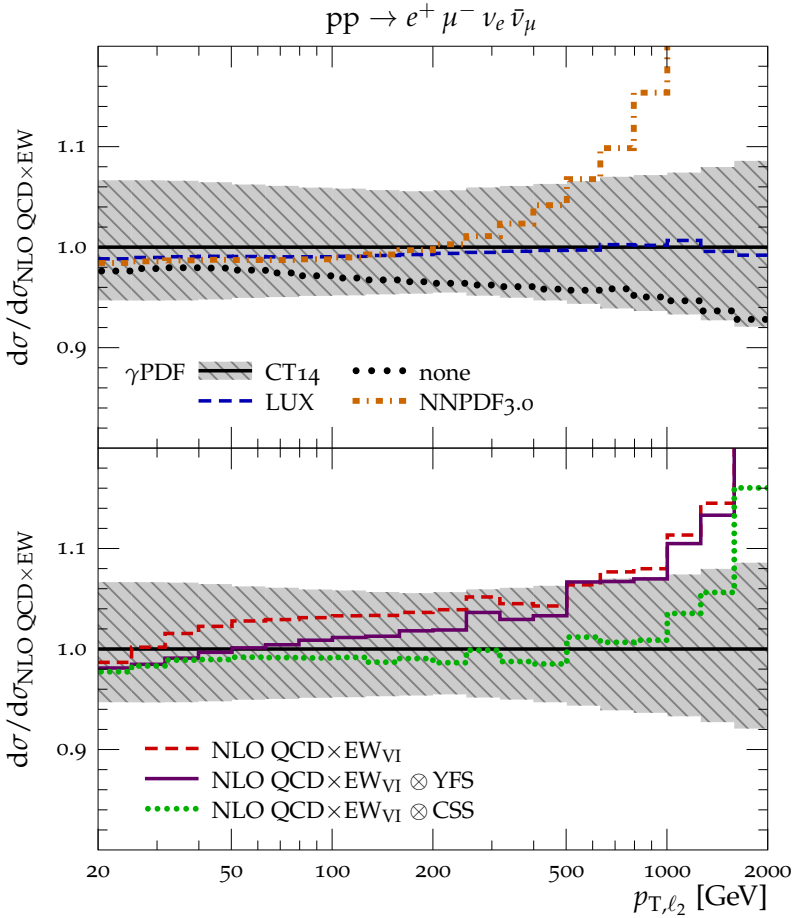
CT14qed (baseline) no γPDF
LUXqed NNPDF3.0qed



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

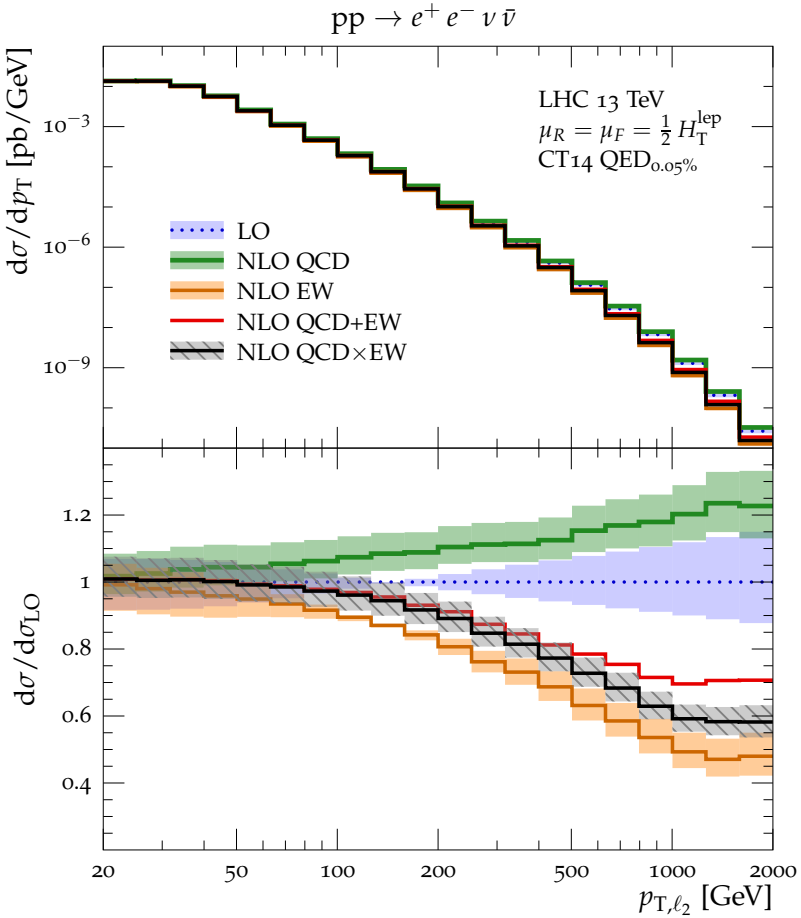
2ℓ2ν production – DF

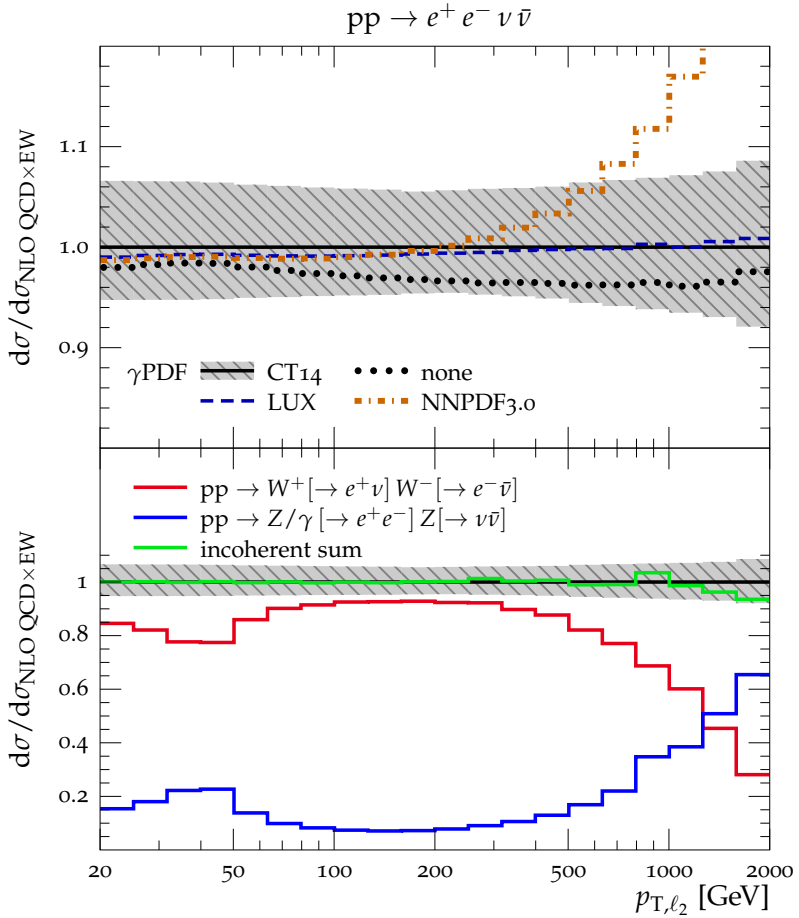




- ZZ dominant at very large p_T
  $\rightarrow$ different EW corrections, take care when extrapolating

2ℓ2ν production – SF





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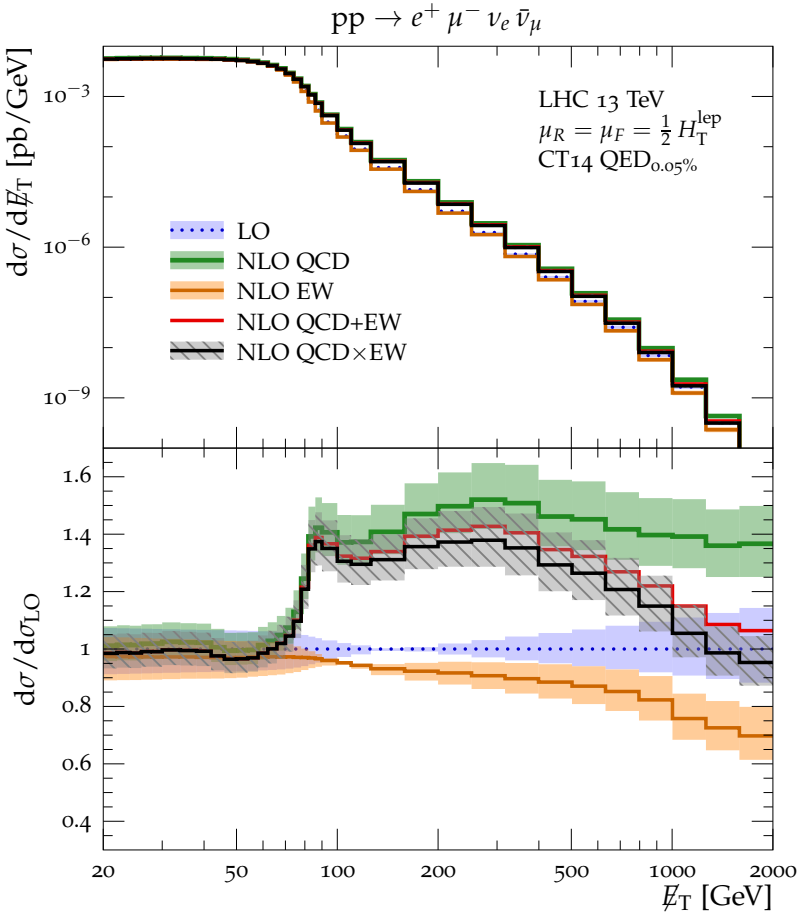
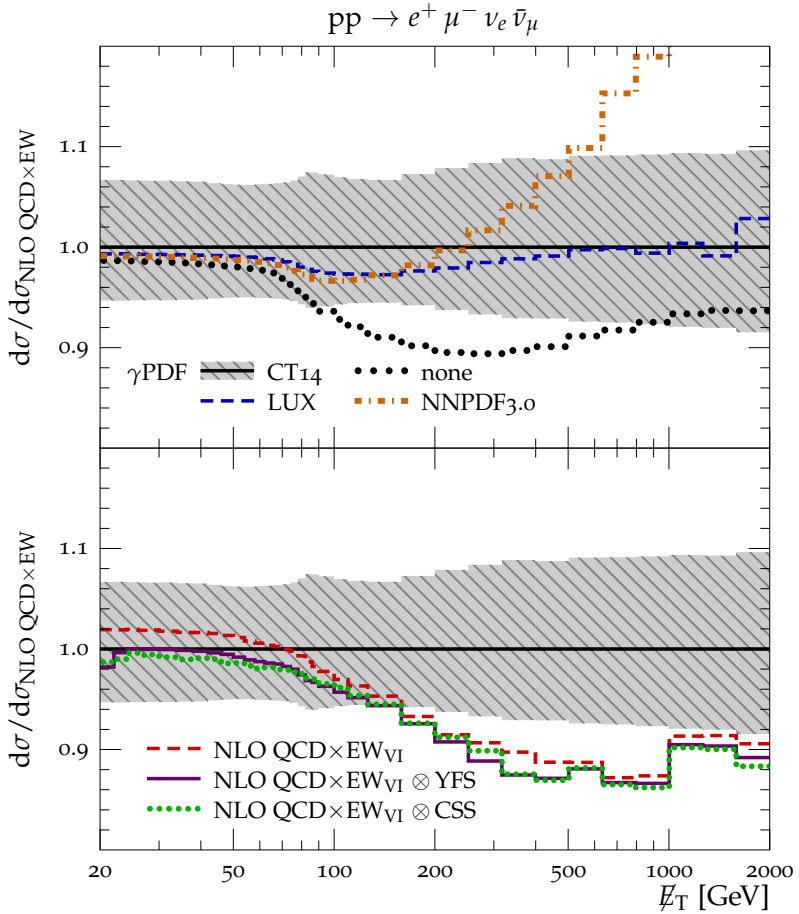
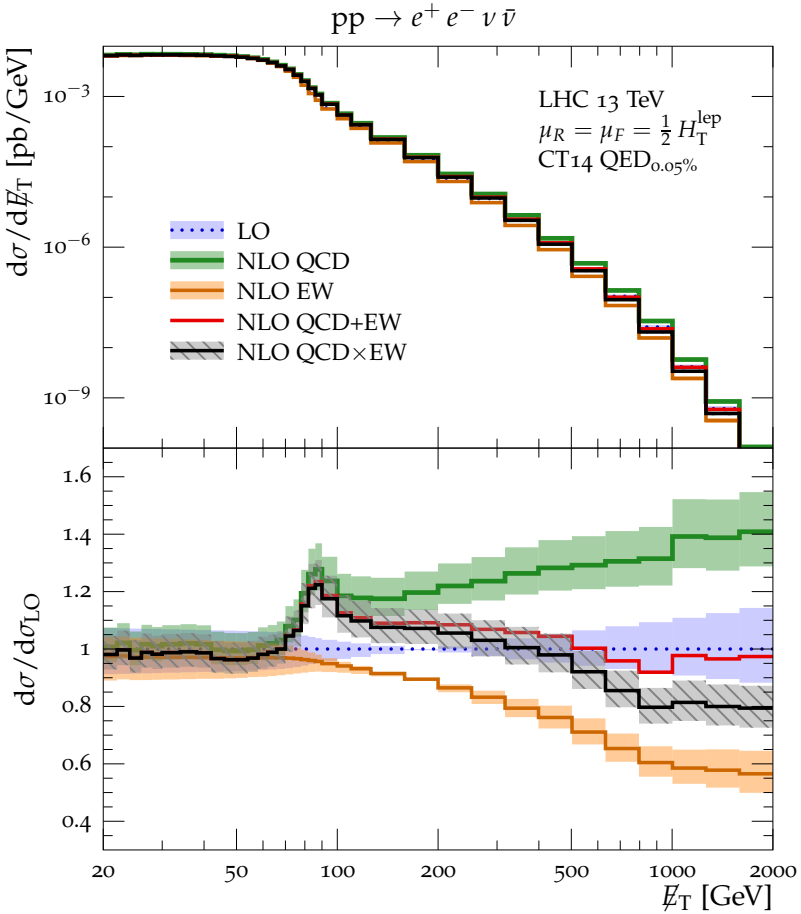
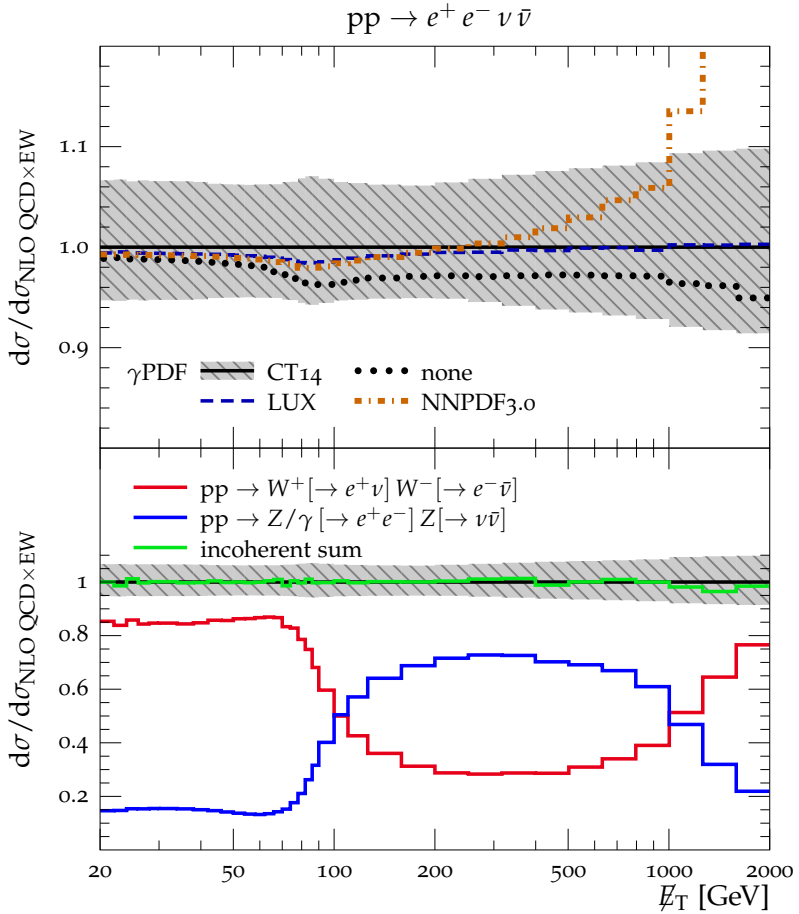




- kinematic suppression for $p_{\mathrm{T}}^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced $\Rightarrow$ large contrib

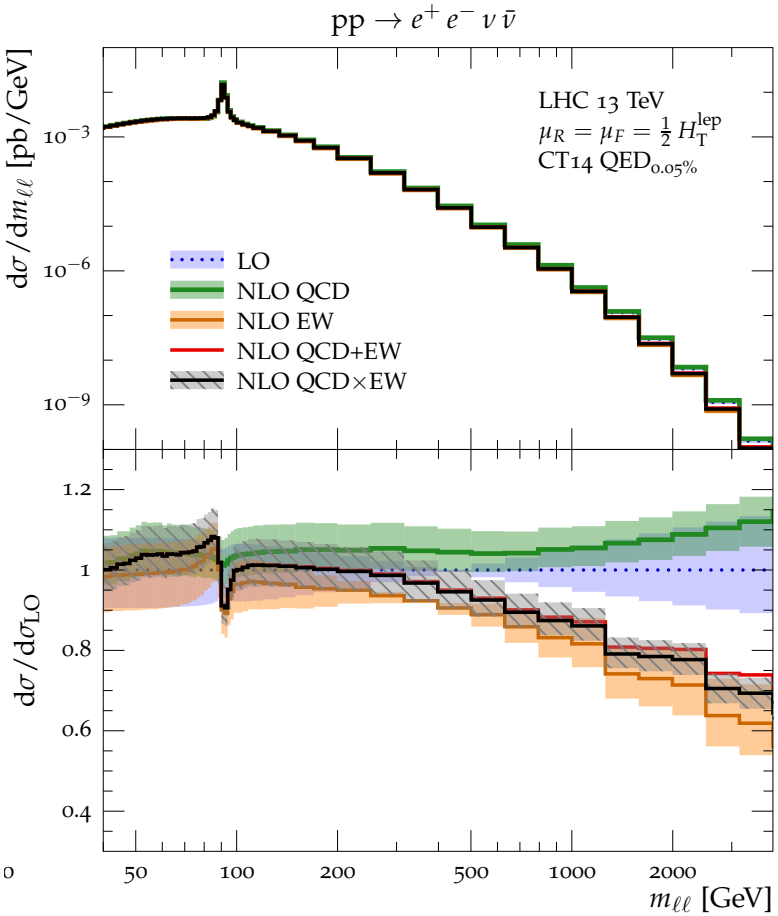
2ℓ2ν production – SF

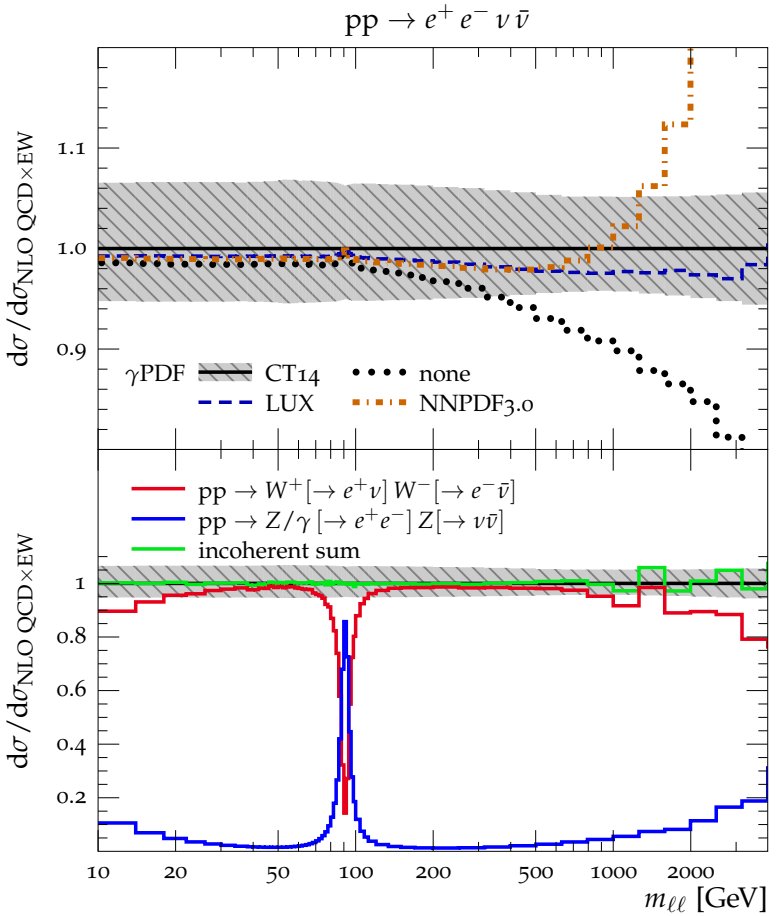




- kinematic suppression for $p_{\mathrm{T}}^{\nu\nu}$ for WW, but not ZZ
  ZZ dominates for MET $> 100\,\mathrm{GeV}$ with large EW corr.

2ℓ2ν production – SF





- ZZ dominates on $m_{\ell\ell} \approx m_Z$, but WW still non-neglible

Conclusions

4ℓ

- fixed order:
  $pp \to 4\ell$ in good shape, NNLO QCD + NLO EW known
  $gg \to 4\ell$ known to NLO QCD in double resonant approximation
- MC:
  $pp \to 4\ell$ available at MEPS@NLO + MEPS@LOOP^2 + approx. EW
  $gg \to 4\ell$ known to NLO QCD in double resonant approximation

$2\ell 2\nu$

- fixed order:
  $pp \to 4\ell$ in good shape, NNLO QCD + NLO EW known
  $gg \to 4\ell$ known to LO QCD
- MC:
  $pp \to 4\ell$ available at MEPS@NLO + MEPS@LOOP^2 + approx. EW
  $gg \to 4\ell$ known to LO QCD

Conclusions

SHERPA

- MEPS@NLO + MEPS@LOOP^2 + approx. EW available
- access to LO ME available to simple Python interface
- there will be a bugfix release soon (SHERPA-2.2.5)
- next major release SHERPA-2.3.0 in validation
  - will include fixed order NLO EW
  - improved and extended loop induced production
    e.g. $pp \to HH$ (full m_t arXiv:1711.03319)
  - NNLO QED + NLO EW in Z and W decays
  - DIRE with full NLO DGLAP splitting kernels and fit for NLO QCD multijet merging

http://sherpa.hepforge.org

Thank you for your attention!

Backup