Diboson and triboson production – theory overview

Marek Schönherr

IPPP, Durham University

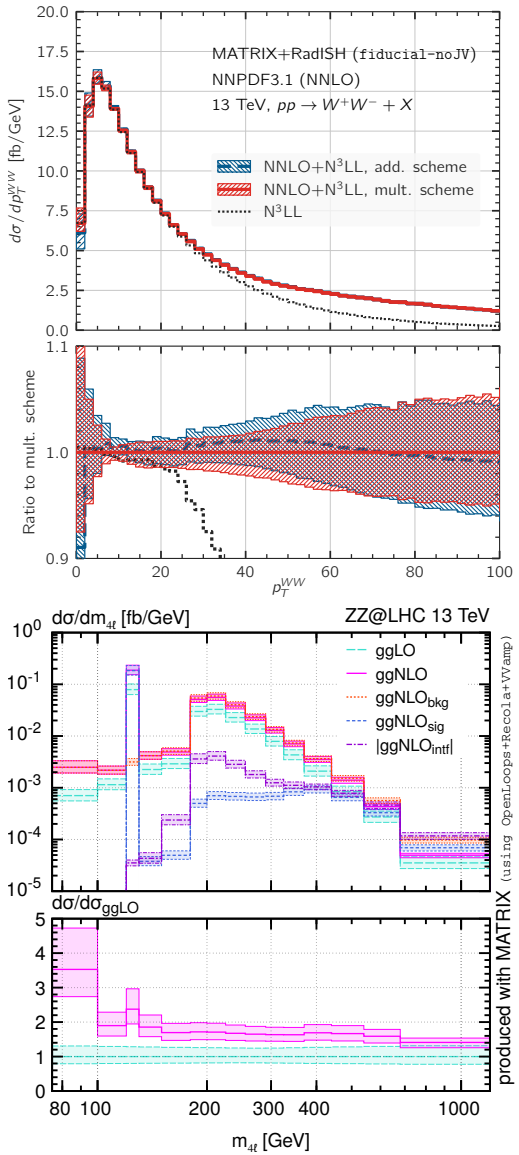
Overview

Diboson production

Current status

inclusive VV production

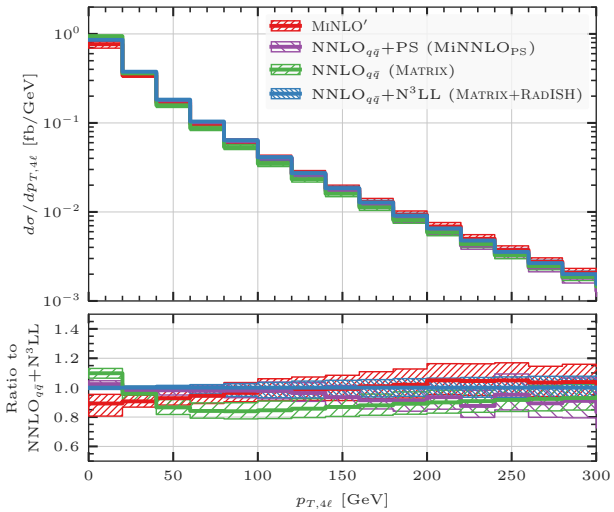
- **NNLO QCD** for all off-shell processes
  e.g. in MATRIX, MCFM, others
- **NLO QCD** for all g-induced processes
  Caola et.al '15,'16
  Grazzini, Kallweit, Wiesemann, Yook '21
- **N^{3}LL+N^{2}LO** small-q_{T} resummation
  Grazzini, Kallweit, Rathlev, Wiesemann '15
  Kallweit, Re, Rottoli, Wiesemann '20
- **NLO EW** for all off-shell processes
  Denner, Dittmaier et.al '14-'16, ..

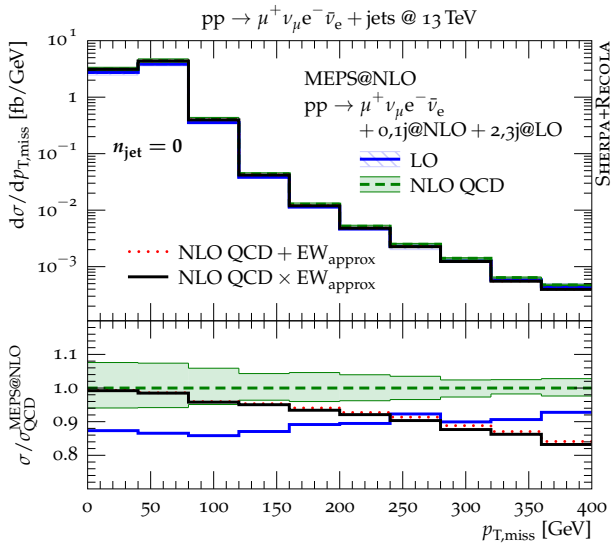


Current status

Event generation of inclusive off-shell *VV* production

- NNLOPS QCD (incl. NLOPS QCD for gluon-fusion)
  Buoncuore et.al '21
- NLOPS EW
  Chiesa, Oleari, Re '20
- MEPS@NLO QCD + EW_{virt}
  Bräuer et.al '20, Bothmann et.al '21





Current status

- VV + jet known **NLO QCD + NLO EW**

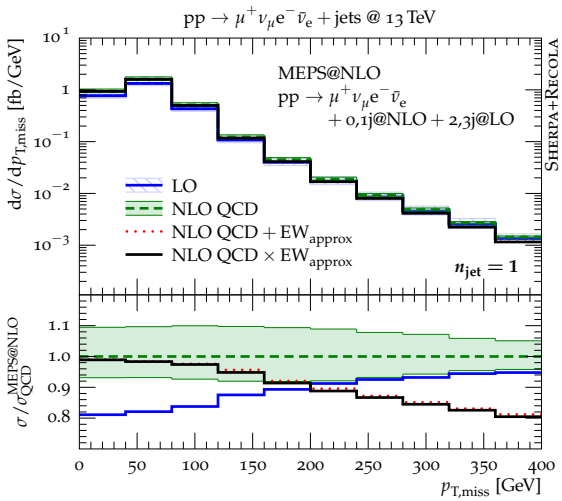
  Bräuer et.al '20, Bothmann et.al '21

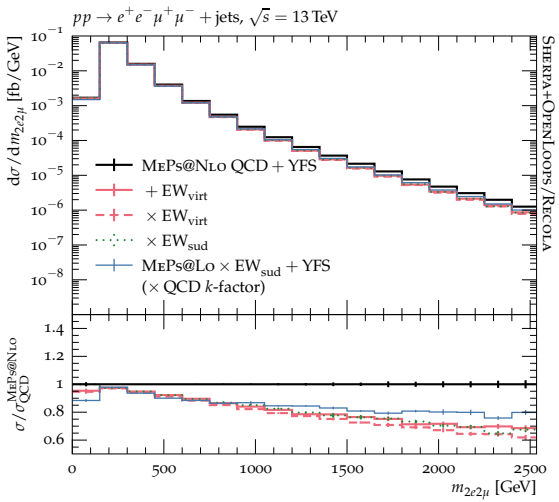
- part of NNLOPS VV, MEPS@NLO + $\mathrm{EW}_{\mathrm{virt}}$

  Bräuer et.al '20, Bothmann et.al '21

- VV + 2 jets is part of VBS

  Denner et.al '17-'21





Resummed corrections in Sudakov limit

NLL Sudakov logarithms (exponentiable) Denner, Pozzorini '01

- universal corrections in limit all invariants $s_{ik} \gg m_W$
- automated implementations Bothmann, Napoletano '20, Pagani, Zaro '21

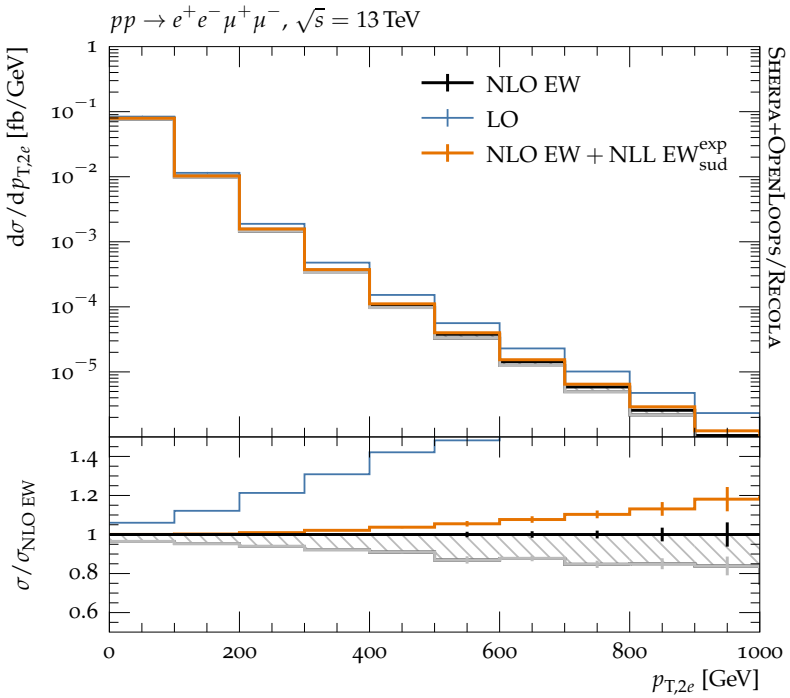
Match to NLO EW

$$\mathrm{d}\sigma^{\mathrm{NLO+NLL}} = \mathrm{d}\sigma_{\mathrm{B}} \left[\exp\left(\delta^{\mathrm{EW}}_{\mathrm{sud}}\right) - \delta^{\mathrm{EW}}_{\mathrm{sud}} + \delta^{\mathrm{EW}} \right]$$

Lindert et.al. '17
Bothmann, Napoletano, MS, Schumann, Villani '21

Can be used to resum dominant EW corrections to all orders in Sudakov region while maintaining the inclusive NLO EW accuracy. Needed when $\mathcal{O}(\alpha)$ corrections are large.

Resummed corrections in Sudakov limit



Bothmann, Napoletano, MS, Schumann, Villani '21

Example: $pp \to e^+e^-\mu^+\mu^-$

- NLO EW corrections reach -50% at 1 TeV
- resum universal Sudakov logs $\Rightarrow -40\%$ corrections

Uncertainties:

- here by varying the EW renormalisation scheme, too conservative?

Triboson production

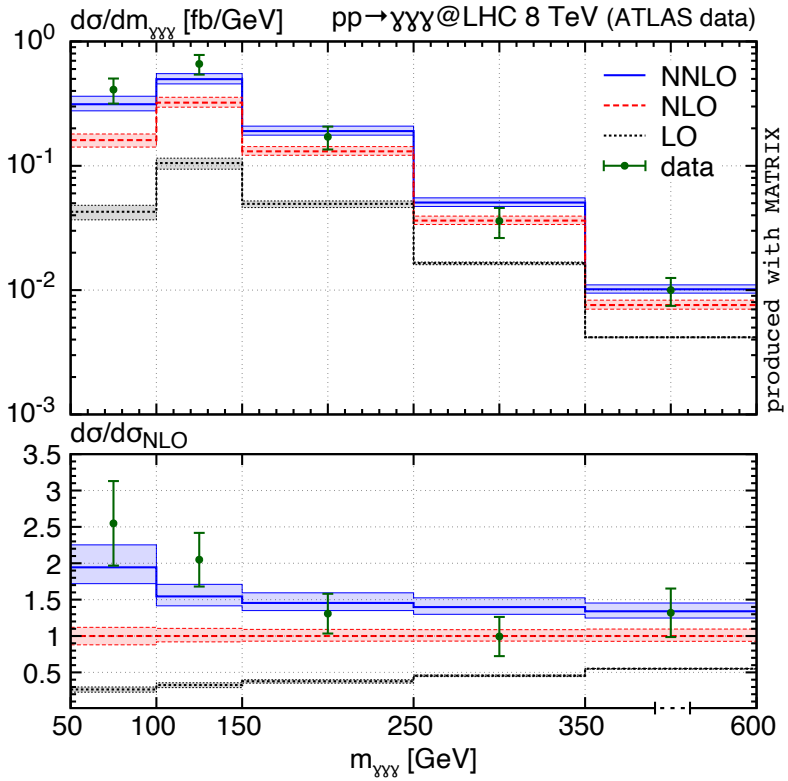
Current status

NLO QCD corrections known for all on-/off-shell processes,

NNLO QCD for $\gamma\gamma\gamma$

Chawdhry, Czakon, Mitov, Poncelet '19
Kallweit, Sotnikov, Wiesemann '20

- corrections are typically large due to gluon-induced channels opening
- beware of single-top topologies in some channels in 5F



Current status

NLO EW on-shell corrections known for all process,
but unfortunately often not very useful, *see* slide 13

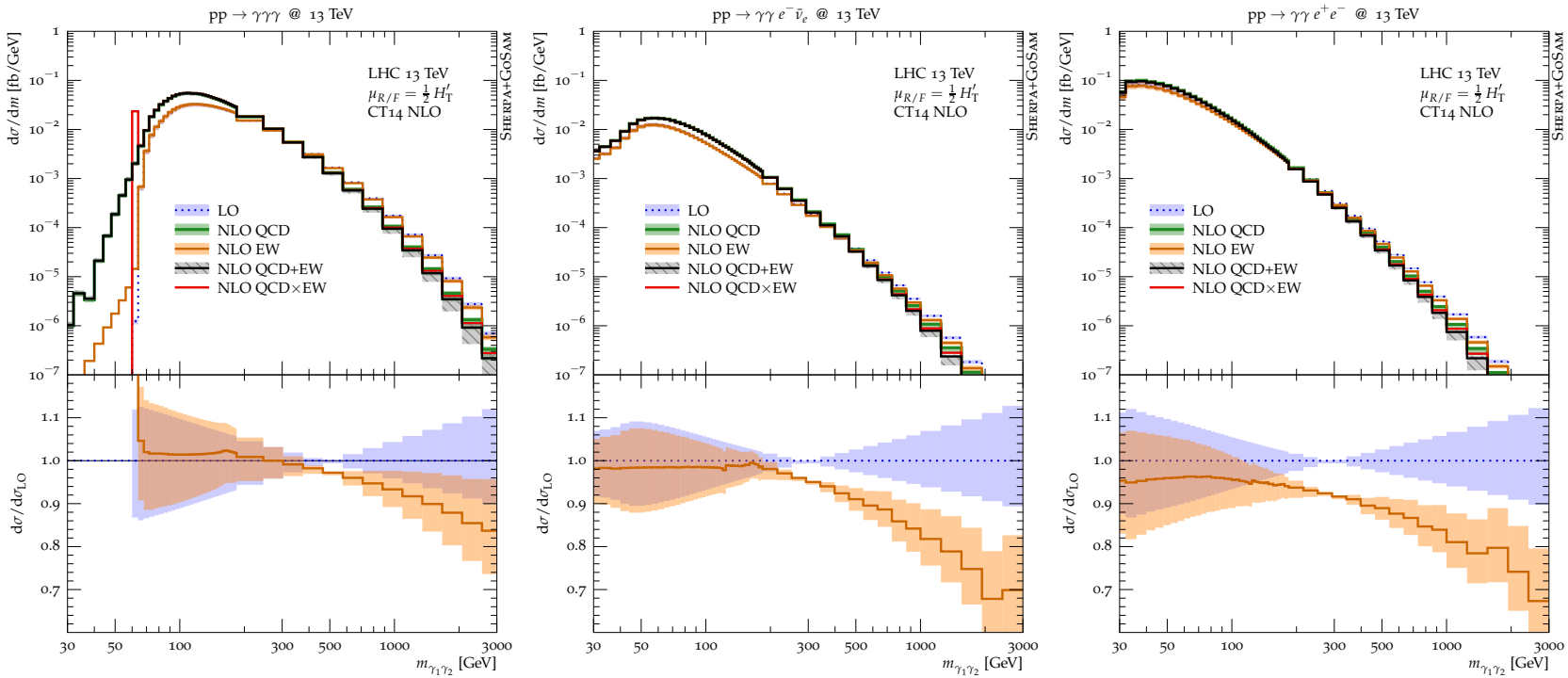
NLO EW off-shell corrections among the most involved involved,
up to $2 \to 6$ (typically w/ competing resonance structures)

- $pp \to \gamma\gamma\gamma$ Greiner, MS '17
- $pp \to \gamma\gamma\ell\nu \,/\, \gamma\gamma\ell\ell$ Greiner, MS '17
- $pp \to \gamma 2\ell 2\nu$ ($\ell = e^{\pm}, \mu^{\pm}$, 0,1 SFOS channels, incl. γWW and γZZ topologies) Ju, Lindert, MS in prep.
- $pp \to 3\ell 3\nu$ ($\ell = e^{\pm}, \mu^{\pm}$, 0/1/2 SFOS channels, incl. WWW and WZZ topologies) MS '18

  $pp \to e^{\mp}\nu_e\, \mu^{\pm}\nu_\mu\, \tau^{\pm}\nu_\tau$ (WWW only) Dittmaier, Knippen, Schwan '19

Example: $\gamma\gamma\gamma$, $\gamma\gamma\ell\nu$, $\gamma\gamma\ell\ell$

Greiner, MS '17

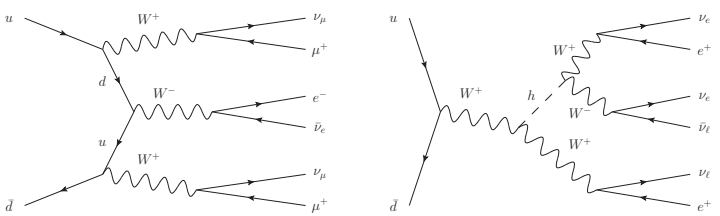


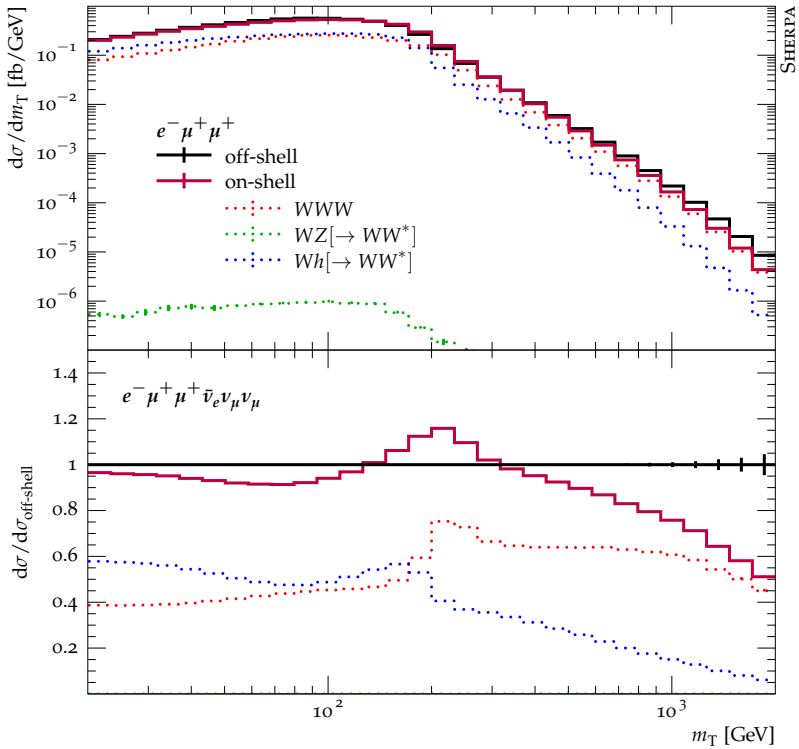
$\gamma\gamma\gamma$ $\gamma\gamma\ell\nu$ $\gamma\gamma\ell\ell$

Necessity of off-shell calculations

Example *WWW*:
Typically $3\ell + \text{MET}$ with $\ell = e, \mu$, thus 0/1/2 SFOS lepton pairs.

This means that 0 SFOS channel contains interference of *WWW*, $Wh[\to WW^*]$, $WZ[\to WW^*]$ at Born level, more at NLO EW.



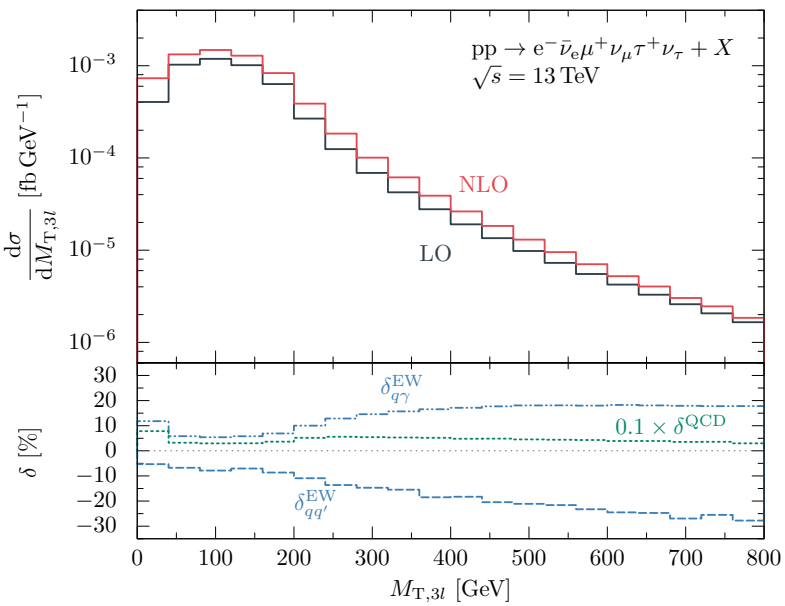


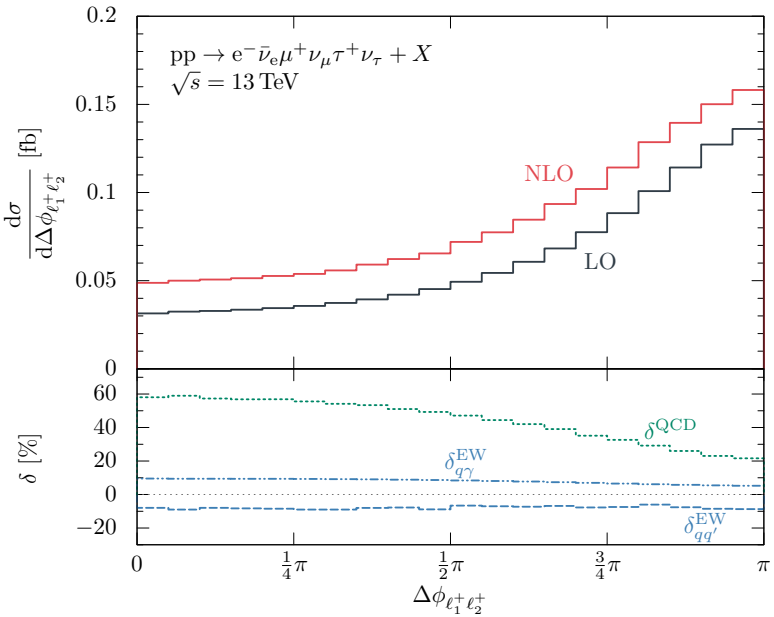
1/2 SFOS additionally contain *WZZ*, $Wh[\to ZZ^*]$, etc.

off-shell effects of $\mathcal{O}(20\%)$ or larger

Differential distributions

Example distributions for $3\ell + \text{MET}$: Dittmaier, Knippen, Schwan '19





- large photon-induced corrections, can be controlled through jet veto, or $\Delta\phi(\ell\ell\ell, \not{E}_{\mathrm{T}})$ veto (no jet-related uncertainties, better for theory)

Conclusions

Diboson production

- VV (off-shell) at
  - NNLO QCD + NLO EW throughout, NLO QCD for gluon-fusion channels
  - MiNNLOPS QCD available for most processes, NLOPS EW in POWHEG
- VVj at NLO QCD + NLO EW, MEPS@NLO+EW_{virt} in ev.gen
- $VVjj$ overlap with VBS

Triboson production

- Off-shell calculations a necessity due to large contributions from
  - different resonant subchannels (Wh vs WWW)
  - interferences
  - non-resonant topologies

  in the typical analysis phase spaces
- NLO QCD matched event generation available

Thank you!