

# Electroweak corrections to vector boson pair production at the LHC

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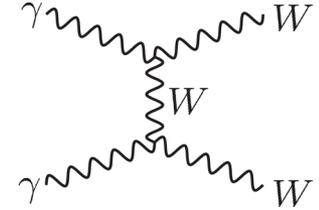
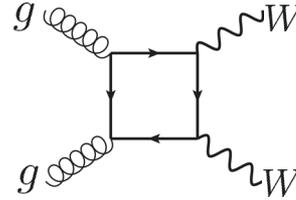
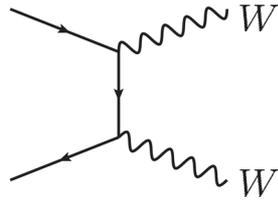
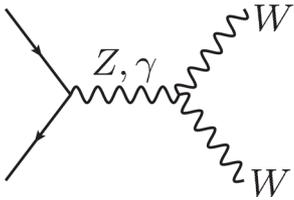
In collaboration with  
Ansgar Denner, Stefan Dittmaier,  
Barbara Jäger, Lars Hofer

DIS 2017, Birmingham

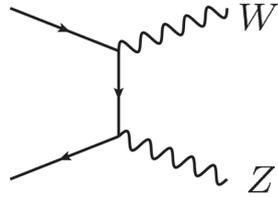
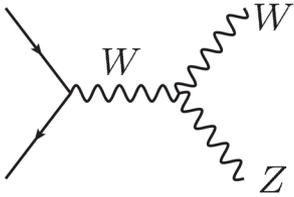
Talk partially based on [arXiv:1611.05338](https://arxiv.org/abs/1611.05338), [arXiv:1605.03419](https://arxiv.org/abs/1605.03419), [arXiv:1601.07787](https://arxiv.org/abs/1601.07787)

# Complementarity in WW/WZ/ZZ production

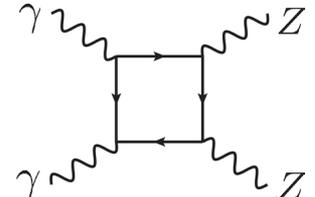
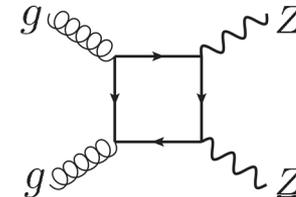
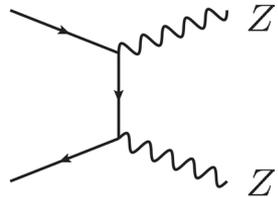
**WW:**



**WZ:**

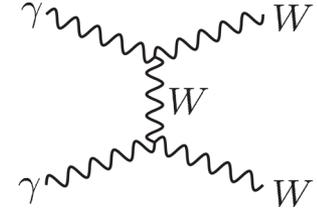
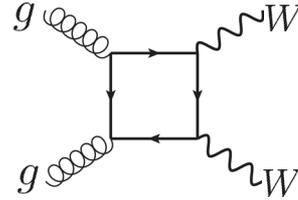
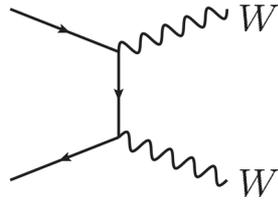
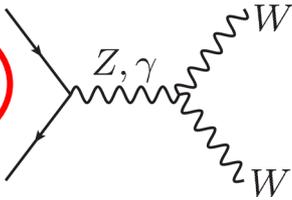


**ZZ:**

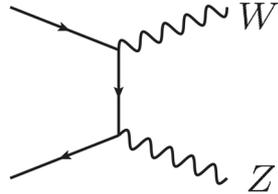
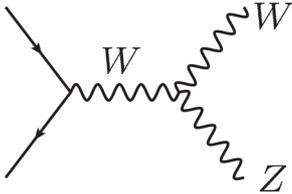


# Complementarity in WW/WZ/ZZ: Background to Higgs decay

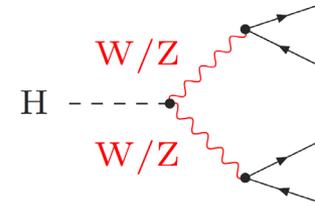
**WW:**



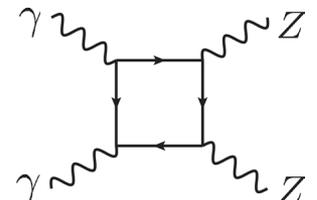
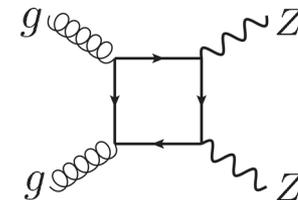
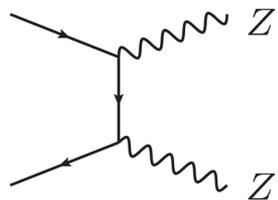
~~**WZ:**~~



irreducible background in channel  
 $H \rightarrow WW^*/ZZ^* \rightarrow 4$  fermions

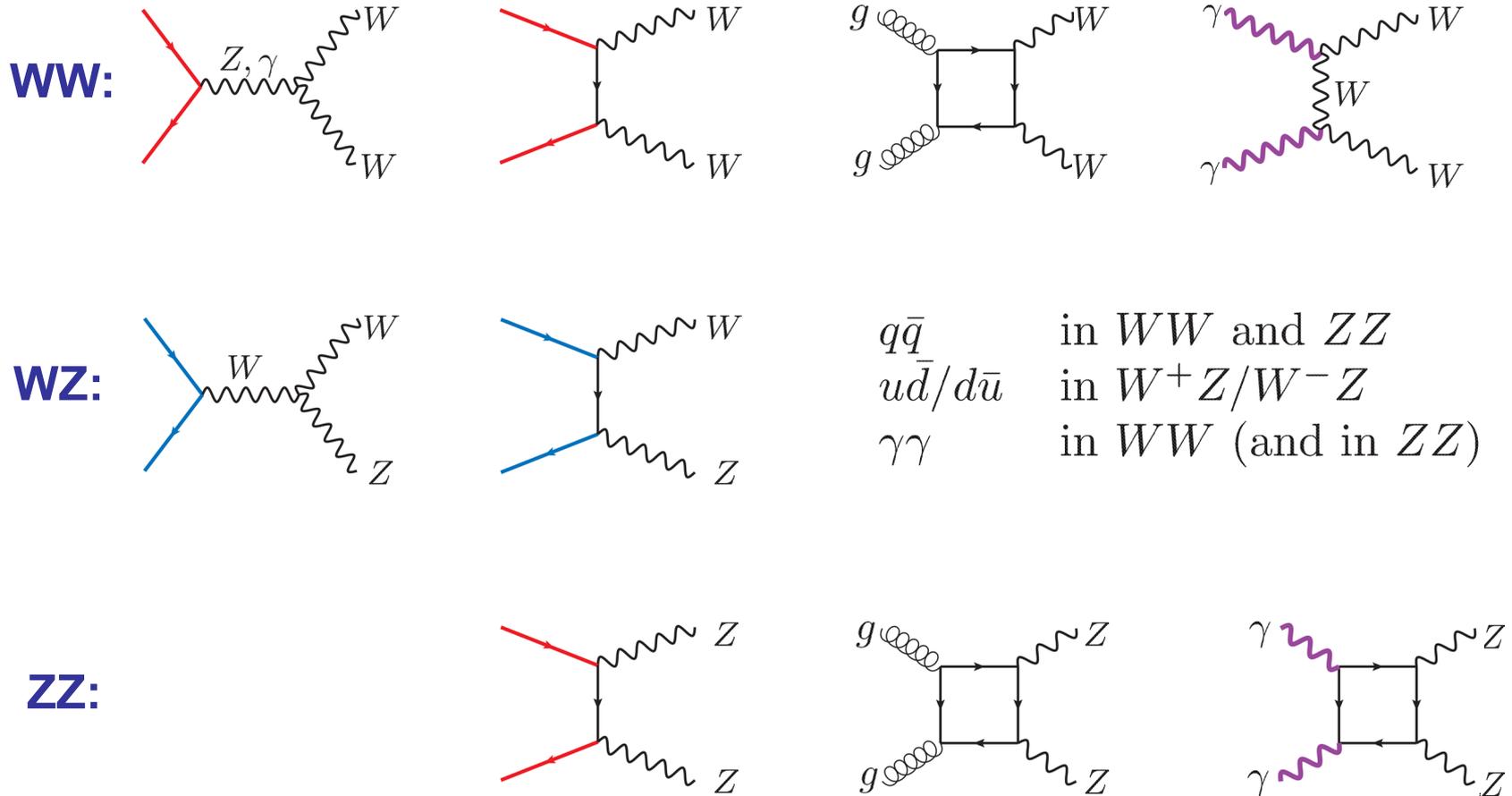


**ZZ:**

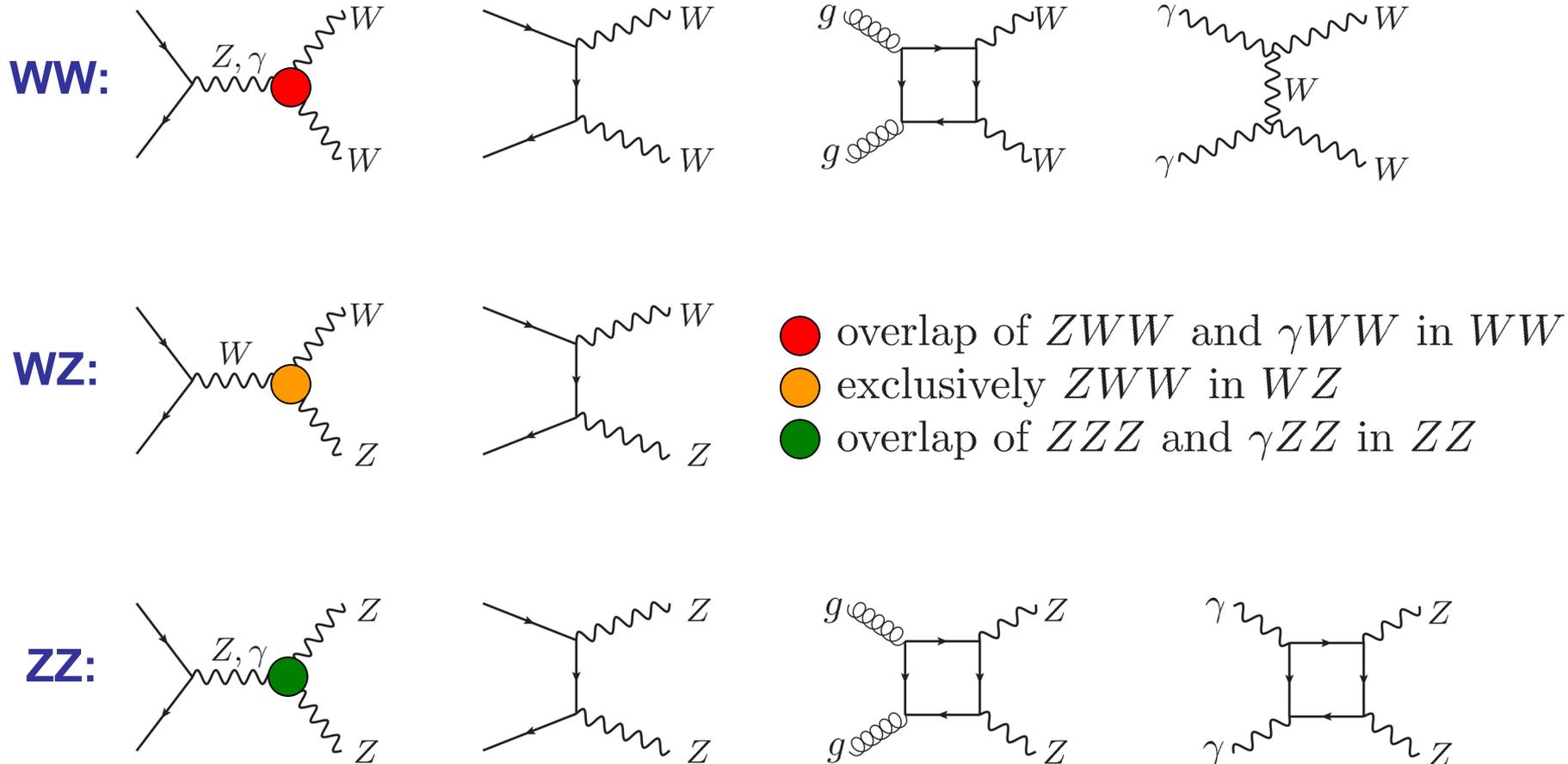


Higgs Background particularly sensitive to off-shell effects!

# Complementarity in WW/WZ/ZZ: Sensitivity to different PDF combinations



# Complementarity in WW/WZ/ZZ: Sensitivity to anomalous gauge couplings



$$p p \rightarrow Z Z \rightarrow 4 \ell$$

$$p p \rightarrow W Z \rightarrow 3 \ell + \nu$$

**ZZ:**

$$pp \rightarrow e^+ e^- e^+ e^-$$
$$pp \rightarrow \mu^+ \mu^- e^+ e^-$$
$$pp \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

**WZ:**

$$pp \rightarrow \mu^+ \mu^- e^{+/-} \nu_e / \bar{\nu}_e$$
$$pp \rightarrow \mu^+ \mu^- \mu^{+/-} \nu_\mu / \bar{\nu}_\mu$$

**Very clean signal:**

- no jets
- no missing transverse energy

**Relatively clean signal:**

- no jets
- missing transverse energy

Leading order (LO) process for ZZ, WZ (and WW)  
pure electro-weak  $O(\alpha^4)$

NLO EW and QCD corrections can be computed separately  
→ Mixing only at higher orders

**WW:** Not discussed in this talk, look at arXiv:1605.03914

# Vector boson pair production beyond leading order

## QCD corrections:

**NLO QCD:** dominant corrections, scale dependence still an issue, very well automated, parton shower matching

**NNLO QCD:** enormous progress recently, reduction of scale uncertainty, results even with spin-correlation and off-shell effects available

[Grazzini et al., Cascioli et al., Caola et al., Gehrmann et al., 14-17]

## Electroweak corrections (NLO EW):

naïve expectation:  $\alpha_s^2 \approx \alpha \leftrightarrow \text{NNLO QCD} \approx \text{NLO EW}$

In reality more complicated because

- In high energy regime (TeV scale) enhancement of Sudakov logarithms can give rise to corrections of several 10%

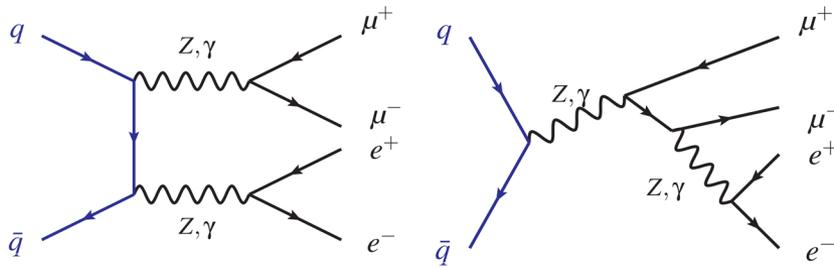
[M. Ciafaloni, P. Ciafaloni, Comelli; Beccaria, Renard, Verzegnassi; Beenakker, Werthenbach; Denner, Pozzorini; Melles; Fadin, Lipatov, Martin; Hori, Kawamura, Kodaira; Jantzen, Kühn, Penin, Smirnov; Chiu, Fuhrer, Golf, Kelley, Manohar, . . .]

- EW corrections near resonances can be large due to kinematic effects

# Born contribution

Quark induced contributions:

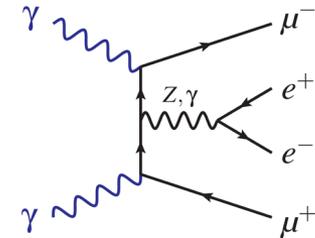
**ZZ:**  $q\bar{q} \rightarrow \mu^+\mu^-e^+e^-$



Two or one possibly resonant Z-propagator(s)

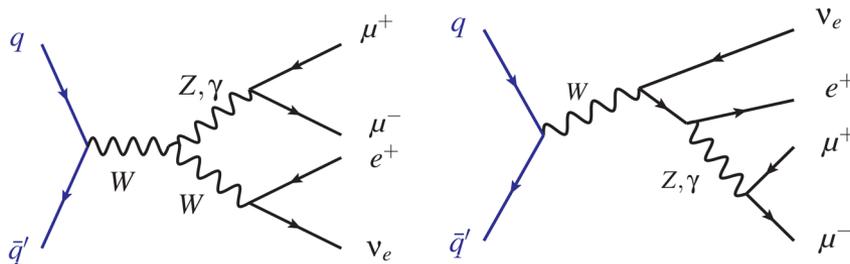
Photon induced contributions:

$\gamma\gamma \rightarrow \mu^+\mu^-e^+e^-$



One possibly resonant Z-propagator

**WZ:**  $q\bar{q}' \rightarrow \mu^+\mu^-e^+\nu_e$



Two or one possibly resonant propagator(s) (W and Z)

No photon induced Born contribution

# $p p \rightarrow \mu^+ \mu^- e^+ e^-$ at NLO EW

virtual electro-weak corrections:

$$q \bar{q} \rightarrow \mu^+ \mu^- e^+ e^-$$

~~$$\gamma \gamma \rightarrow \mu^+ \mu^- e^+ e^-$$~~

real photonic corrections:

$$q \bar{q} \rightarrow \mu^+ \mu^- e^+ e^- + \gamma$$

$$q \gamma \rightarrow \mu^+ \mu^- e^+ e^- + q$$

$$\bar{q} \gamma \rightarrow \mu^+ \mu^- e^+ e^- + \bar{q}$$

~~$$\gamma \gamma \rightarrow \mu^+ \mu^- e^+ e^- + \gamma$$~~

# $p p \rightarrow \mu^+ \mu^- e^+ \nu_e$ at NLO EW

virtual electro-weak corrections:

$$q \bar{q}' \rightarrow \mu^+ \mu^- e^+ \nu_e$$

real photonic corrections:

$$q \bar{q}' \rightarrow \mu^+ \mu^- e^+ \nu_e + \gamma$$

$$q \gamma \rightarrow \mu^+ \mu^- e^+ \nu_e + q'$$

$$\bar{q}' \gamma \rightarrow \mu^+ \mu^- e^+ \nu_e + \bar{q}'$$

Use dipole subtraction for real radiation

# Computational and physical setup

RECOLA as matrixelement generator [Actis, Denner, Hofer, Scharf, Uccirati 12]  
[Actis, Denner, Hofer, Lang, Scharf, Uccirati 16]

COLLIER for the evaluation of the occurring tensor integrals  
[Denner, Dittmaier, Hofer 16]

Phase space integration: inhouse multi-channel Monte Carlos

Checks: two independent calculations of all contributions

$G_\mu$ -scheme for electromagnetic coupling

Complex-mass scheme for vector boson resonances  
[Denner, Dittmaier, Roth, Wackerroth, Wieders '99, '05]

Massless light fermions:  $u, d, c, s, b; e, \mu, \tau;$

DIS-scheme for factorisation of initial-state singularities

# Numerical setup for ZZ/WZ

Center of mass energy:  $\sqrt{s} = 13 \text{ TeV}$

Photon recombination:

Collinear real photons recombined with charged leptons according to a Cambridge/Aachen type jet algorithm with  $R = 0.2$ [ZZ],  $R = 0.1$ [WZ]

Fixed renormalisation and factorisation scale:

$$\mu_r = \mu_f = M_Z[\text{ZZ}], \quad \mu_r = \mu_f = (M_Z + M_W)/2[\text{WZ}]$$

PDF set (includes a photon density):

NNPDF23\_nlo\_as\_0118\_qed [ZZ] [Ball et al. 2013]

LUXqed\_plus\_PDF4LHC\_nnlo\_100 [WZ] [Manohar et al. 2016]  
[Butterworth et al. 2016]

# Fiducial volume and observable definitions for $ZZ$ production

Inclusive scenario:

$$p_T(\ell^\pm) > 15 \text{ GeV}, \quad |y(\ell^\pm)| < 2.5, \quad \Delta R(\ell_i, \ell_j) = 0.2.$$

Higgs-search specific:

$$p_T(\ell^\pm) > 6 \text{ GeV}, \quad |y(\ell^\pm)| < 2.5, \quad \Delta R(\ell_i, \ell_j) = 0.2.$$

$$40 \text{ GeV} < M(\ell_1^+, \ell_1^-) < 120 \text{ GeV}$$

$$12 \text{ GeV} < M(\ell_2^+, \ell_2^-) < 120 \text{ GeV}$$

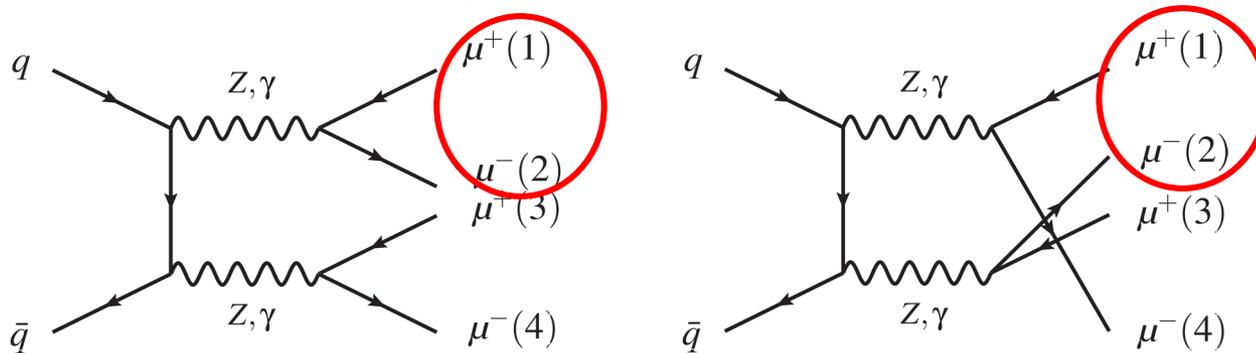
$$M_{4\ell} > 100 \text{ GeV}$$

Leading (subleading) lepton pair: Pair that is closer to (further away from) the nominal value of the Z-boson mass.

# Total Cross sections for ZZ production

	$\sigma_{\bar{q}q}^{\text{LO}}$ [fb]	$\delta_{\bar{q}q}^{\text{weak}}(\%)$	$\delta_{\bar{q}q}^{\text{phot}}(\%)$	$\delta_{\gamma\gamma}(\%)$	$\delta_{q\gamma}(\%)$
incl. $[2\mu 2e]$	11.4962(4)	-4.32	-0.93	+0.1284	+0.017
incl. $[4\mu]$	5.7308(3)	-4.32	-0.94	+0.1145	+0.019
Higgs $[2\mu 2e]$	13.8598(3)	-3.59	-0.04	+0.229	-0.09
Higgs $[4\mu]$	7.1229(2)	-3.42	-0.09	+0.3042	-0.14

## Interference effects in equal-flavour final state:



inclusive:  $\sigma_{\text{LO}}[2\mu 2e]/(2\sigma_{\text{LO}}[4\mu]) \approx 1.003 \rightarrow 0.3\%$

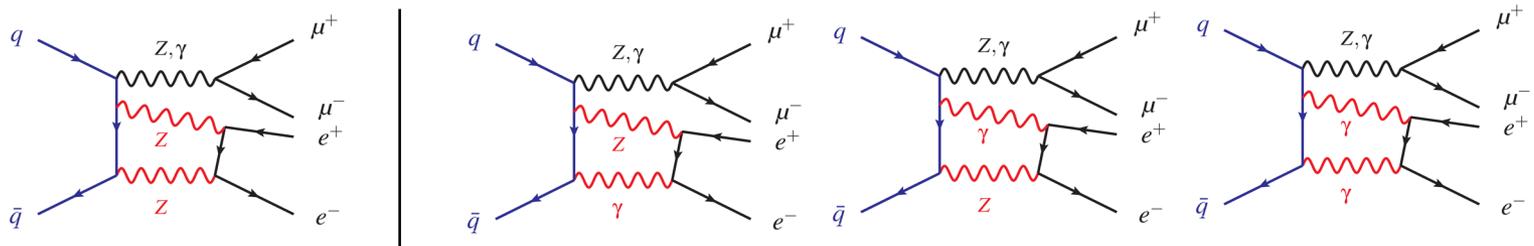
Higgs BG:  $\sigma_{\text{LO}}[2\mu 2e]/(2\sigma_{\text{LO}}[4\mu]) \approx 0.973 \rightarrow 2.5\%$

LO effect, suppressed with respect to resonances.

# Total Cross sections for ZZ production

	$\sigma_{\bar{q}q}^{\text{LO}}$ [fb]	$\delta_{\bar{q}q}^{\text{weak}}$ (%)	$\delta_{\bar{q}q}^{\text{phot}}$ (%)	$\delta_{\gamma\gamma}$ (%)	$\delta_{q\gamma}$ (%)
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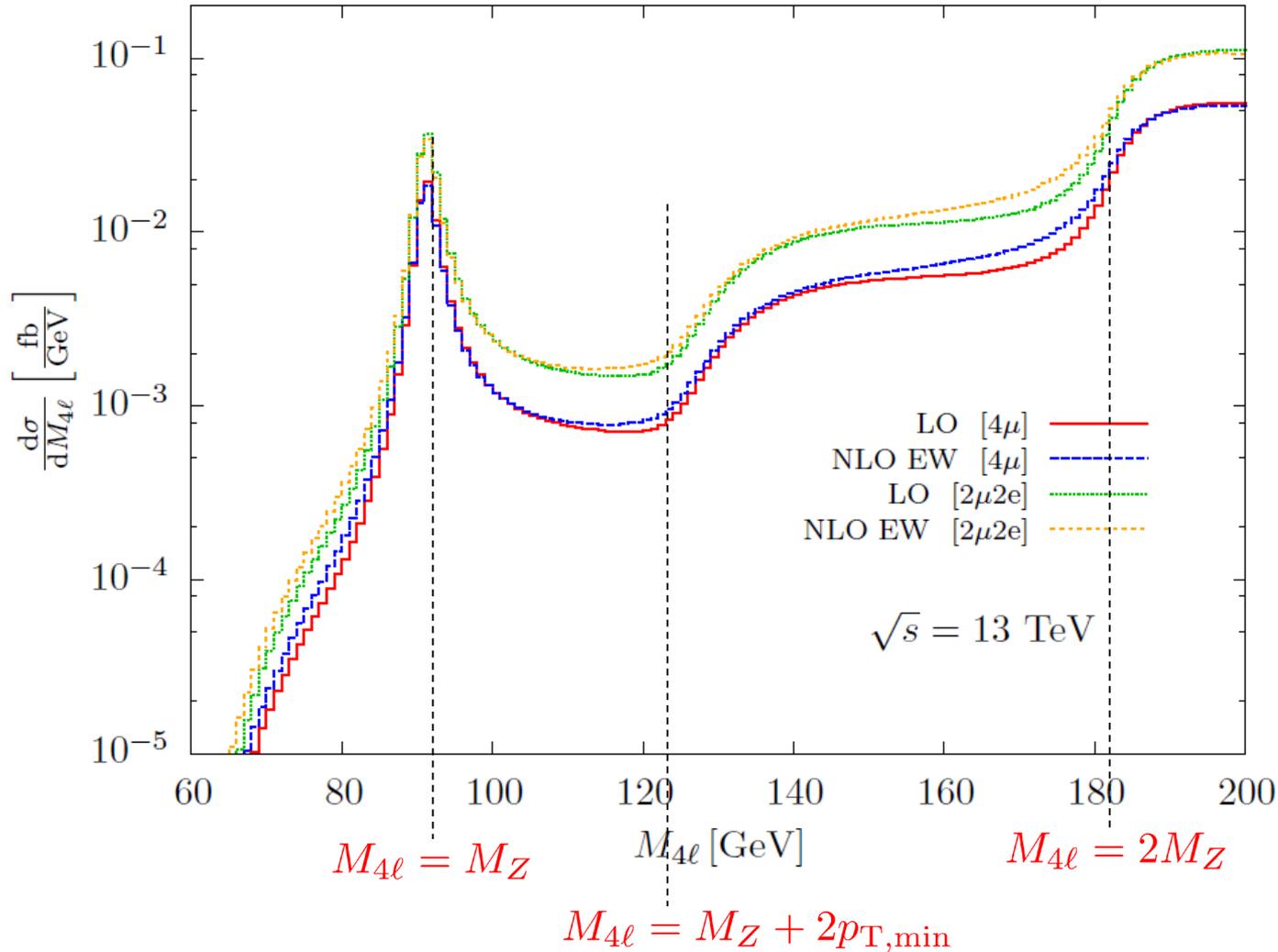
**EW corrections = weak corrections + photonic corrections**



**Photonic corrections:** diagrams with photon(s) in the loop coupling to fermion lines + real photonic radiation

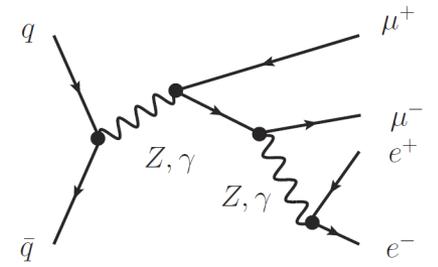
**Weak corrections:** all remaining diagrams (including closed fermion loops), purely virtual corrections

# ZZ off-shell sensitive region

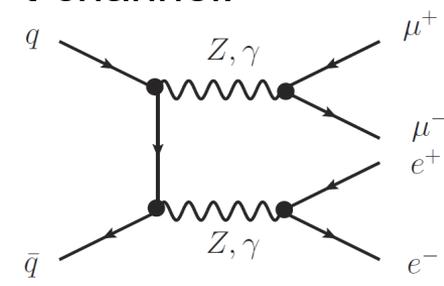


$$p_T(\ell^\pm) > p_{T,\min} = 15 \text{ GeV}$$

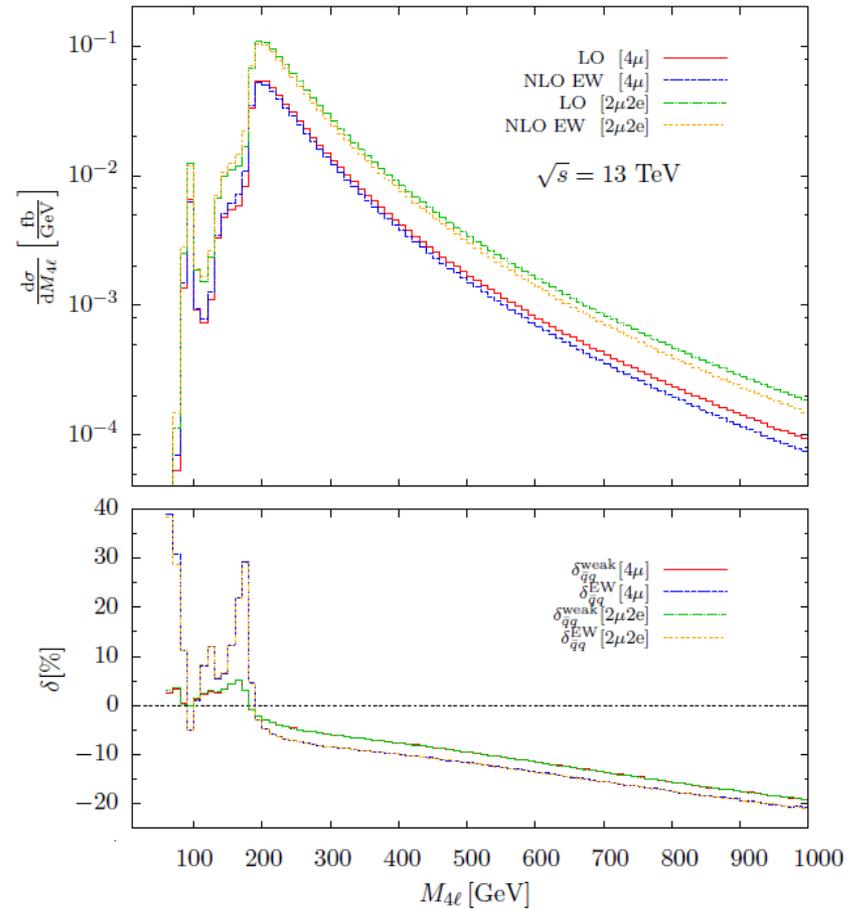
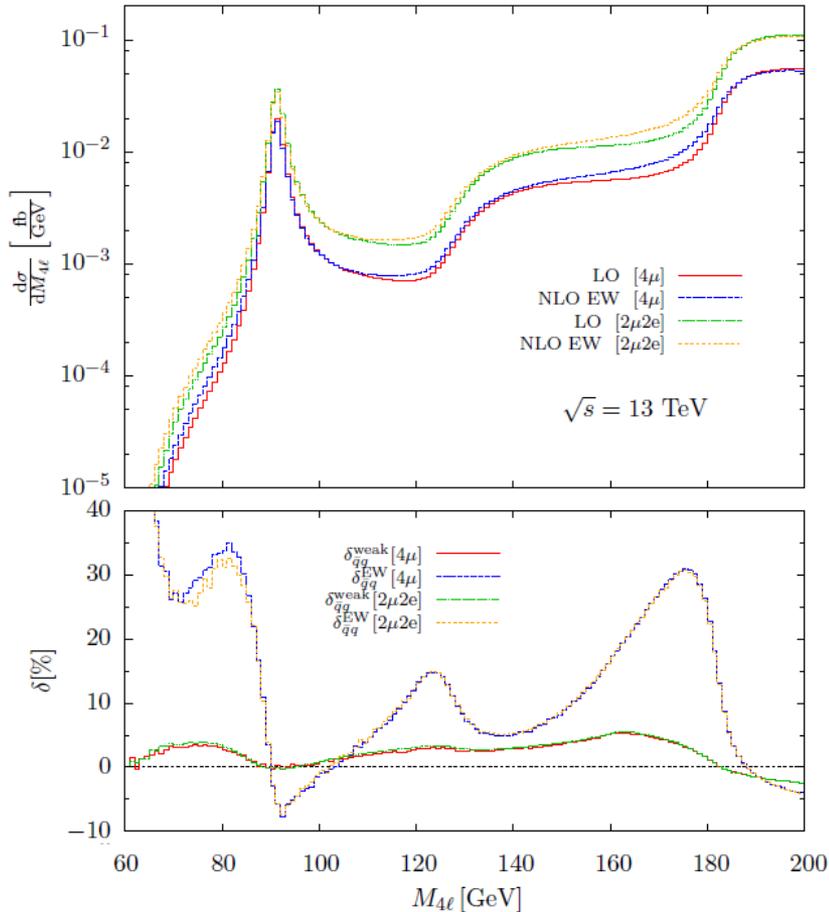
s-channel:



t-channel:

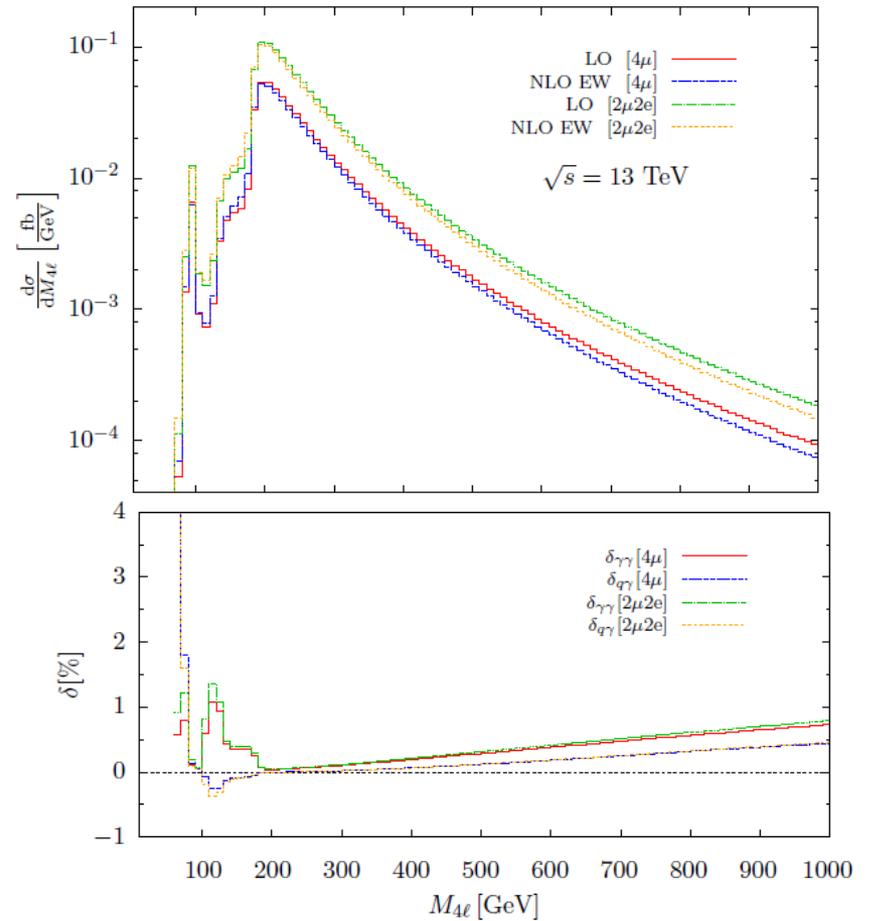
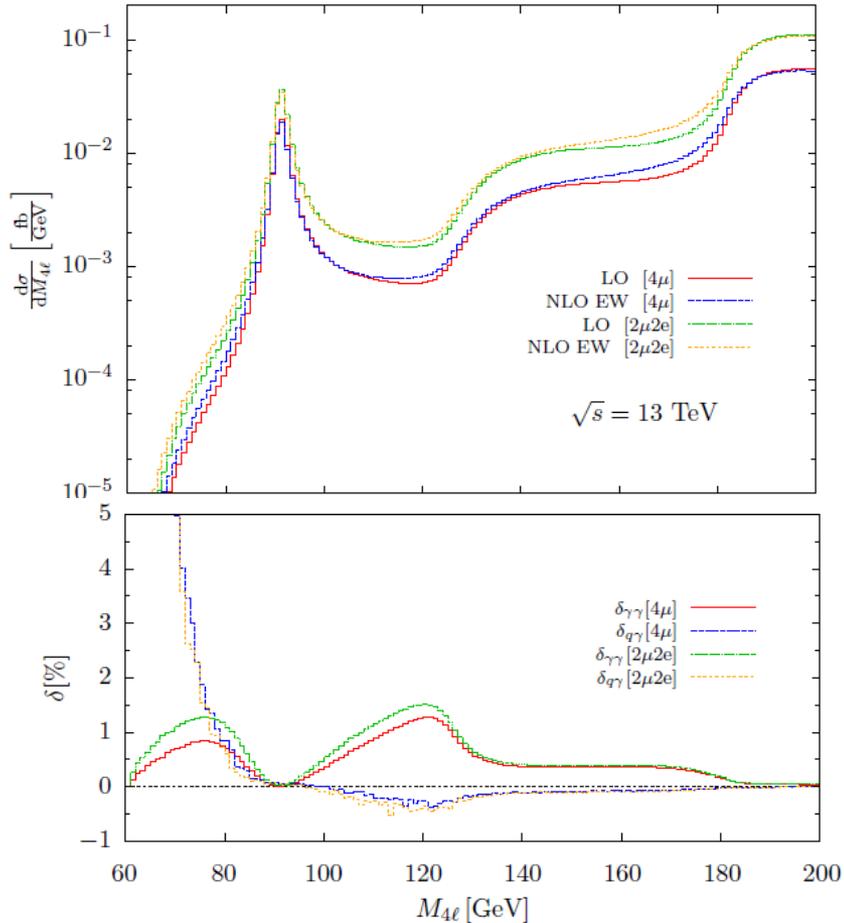


# Four-lepton invariant mass



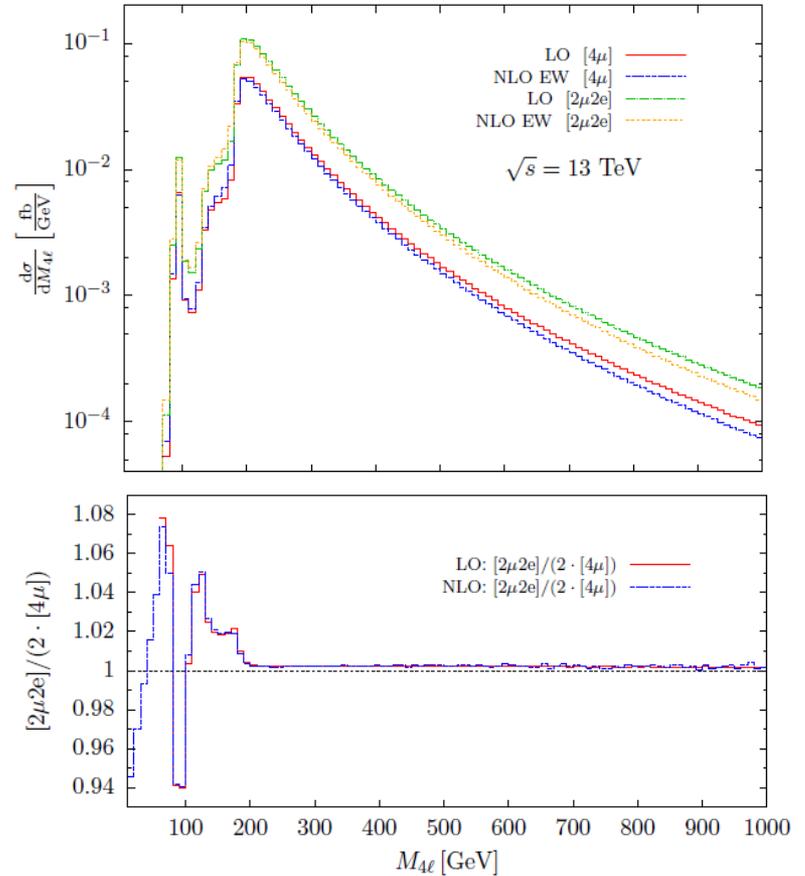
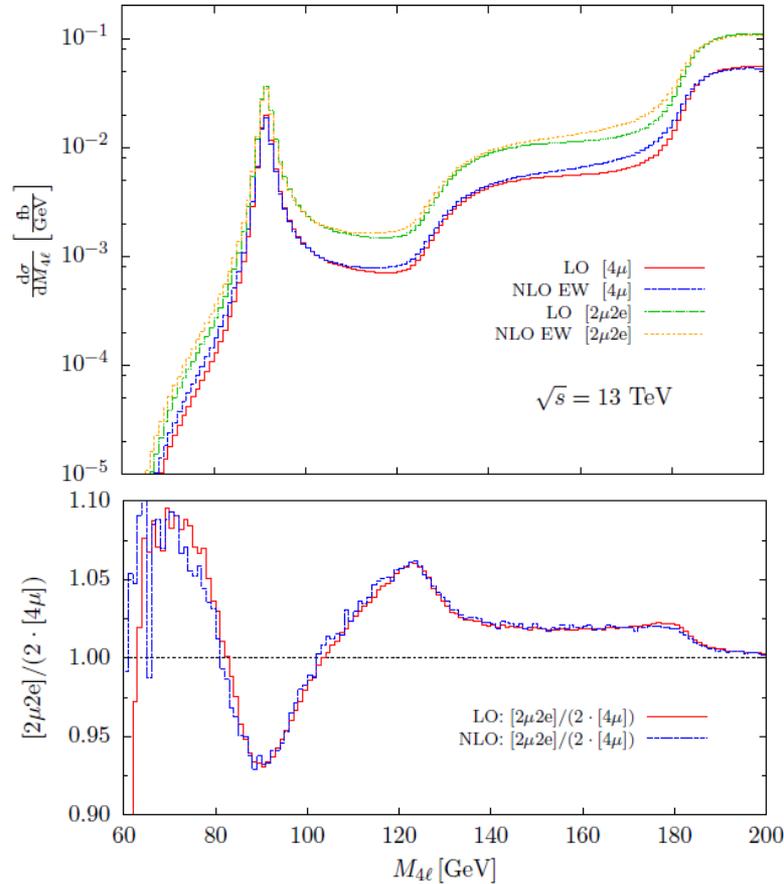
- Sign change of the corrections around the on-shell threshold at 180 GeV
- Large negative corrections (-20%) in the high energy limit
- Similar corrections for equal and unequal-flavour final state
- Photonic corrections  $\sim -2\%$  above  $2M_Z$ , radiative tail below (+25%)

# Photon-induced contributions (Higgs setup)



- Photon-induced contributions above the on-shell threshold at permille level
- Below the threshold around +1% for the photon-photon born, strongly suppressed in the quark-photon case

# Interference effects



- Interferences strongly suppressed in on-shell region, sizeable in off-shell region
- A priori leading-order effect

# Fiducial volume and observable definitions for WZ production

Inclusive scenario (same as in ZZ):

$$p_T(\ell_{Z/W}^\pm) > 15 \text{ GeV}, \quad |y(\ell_{Z/W}^\pm)| < 2.5, \quad \Delta R(\ell_i, \ell_j) = 0.2.$$

Triple-gauge coupling (TGC) specific (inspired by ATLAS WZ-search):

$$p_T(\ell_Z^\pm) > 15 \text{ GeV}, \quad p_T(\ell_W^\pm) > 20 \text{ GeV}, \quad |y(\ell^\pm)| < 2.5$$

$$\Delta R(\ell_Z, \ell_Z) = 0.2, \quad \Delta R(\ell_Z, \ell_W) = 0.3$$

$$M_Z - 10 \text{ GeV} < M(\ell_Z^+, \ell_Z^-) < M_Z + 10 \text{ GeV}$$

$$M_T^W = \sqrt{2p_T^{\text{miss}} p_T^{\ell_W} [1 - \cos \Delta\phi(\ell_W, \vec{p}_T^{\text{miss}})]} > 30 \text{ GeV}$$

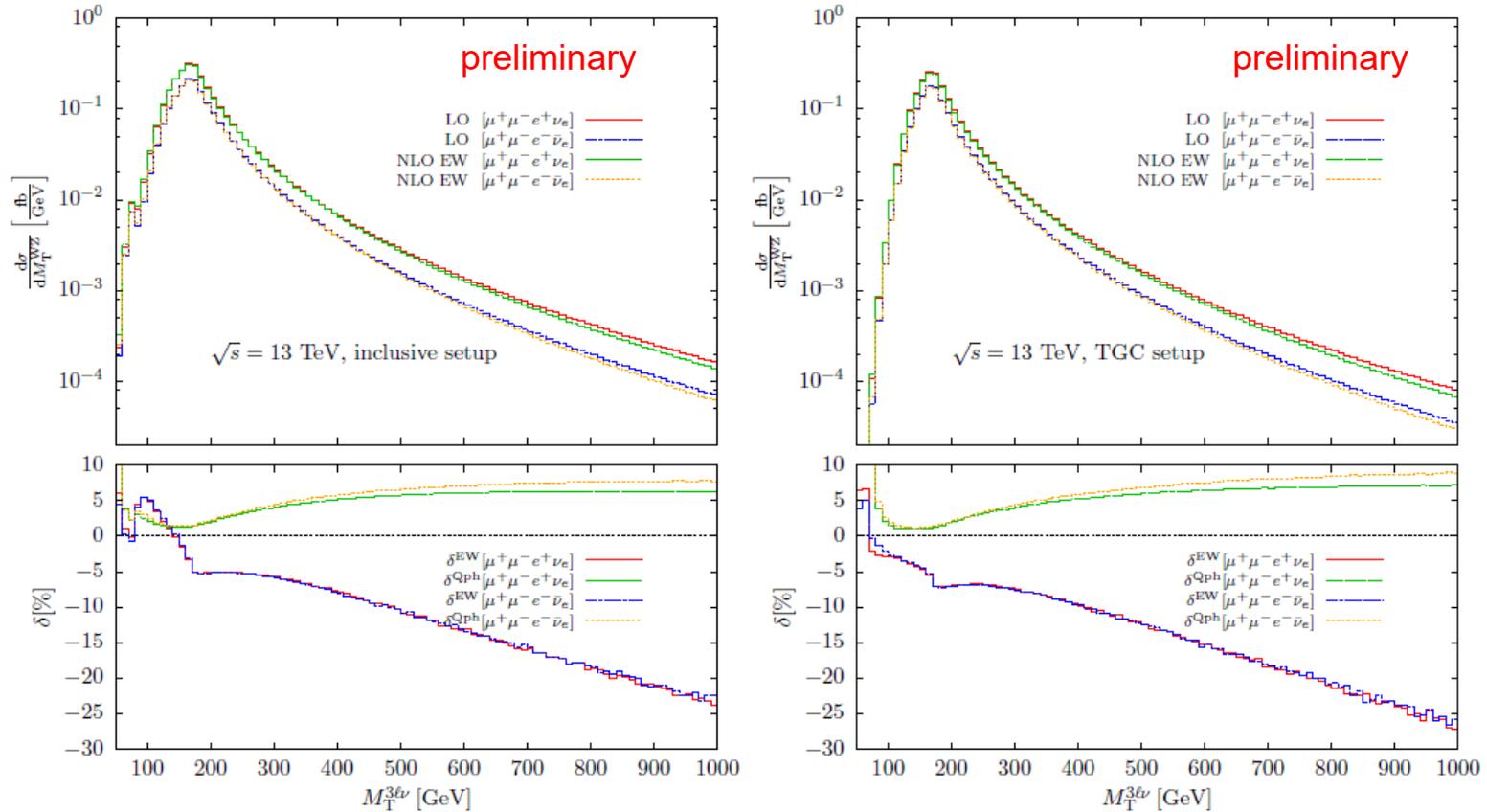
# Total cross section for WZ production

$pp \rightarrow \mu^+ \mu^- e^{+/-} \nu_e / \bar{\nu}_e$		$\sigma_{\bar{q}q'}^{\text{LO}}$ [fb]	$\delta_{\bar{q}q'}^{\text{EW}}$ (%)	$\delta_{q\gamma}$ (%)	$\delta_{\text{NLO}}$ (%)
incl.	ZW <sup>+</sup>	27.503(1)	-3.2	+2.0	-1.2
incl.	ZW <sup>-</sup>	18.071(1)	-3.2	+2.2	-1.0
TGC	ZW <sup>+</sup>	19.303(1)	-6.0	+1.8	-4.2
TGC	ZW <sup>-</sup>	12.975(1)	-5.9	+1.9	-4.0

preliminary

- EW corrections differ at permille level between ZW<sup>+</sup> and ZW<sup>-</sup>
- EW corrections twice as large in TGC setup
- Photon-induced corrections non-negligible, roughly equal for all setups
- No weak + photonic splitting possible due to charged current interaction at tree-level

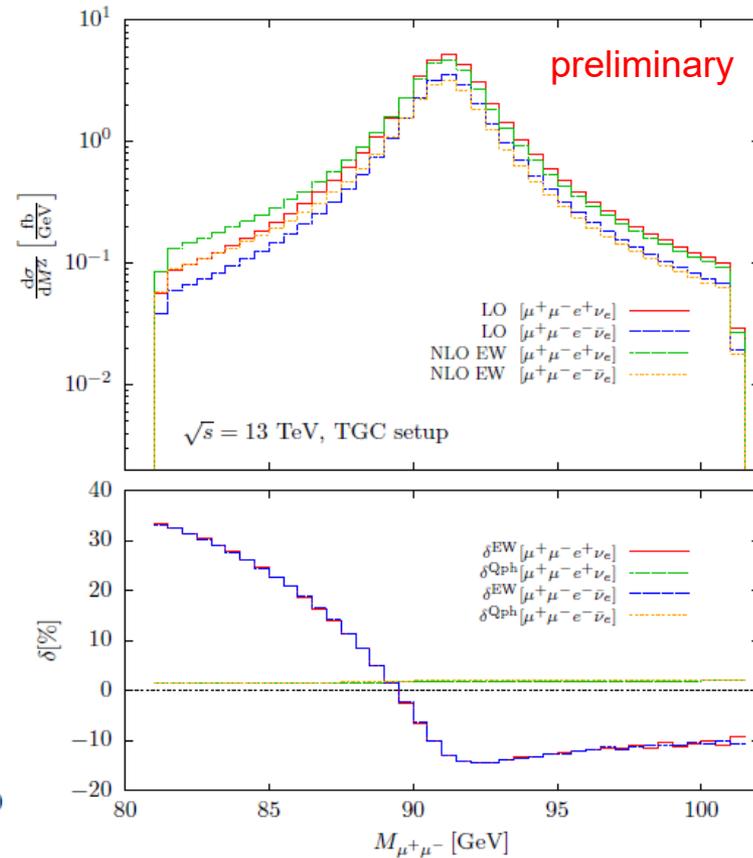
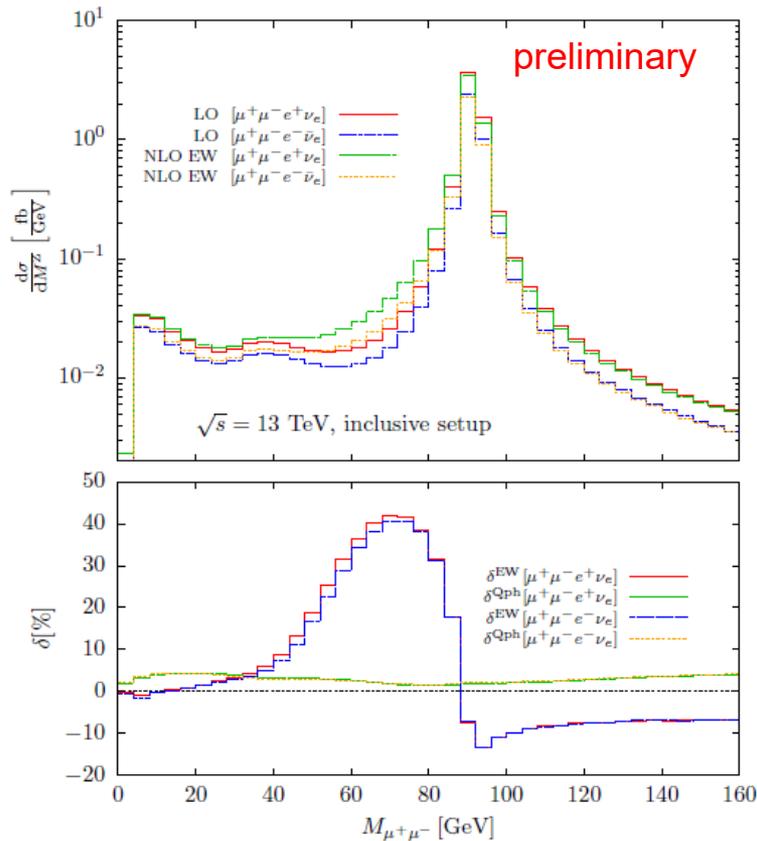
# WZ-transverse-mass system



$$M_T^{3\ell\nu} = \sqrt{\left(\sum_{\ell_i=1}^3 p_T^{\ell_i} + E_T^{\text{miss}}\right)^2 - \left[\left(\sum_{\ell_i=1}^3 p_x^{\ell_i} + E_x^{\text{miss}}\right)^2 + \left(\sum_{\ell_i=1}^3 p_y^{\ell_i} + E_y^{\text{miss}}\right)^2\right]}$$

- photon-induced corrections vary from +1% up to +7%
- Large negative EW corrections (-25%) in the high-energy regime
- EW corrections similar for  $ZW^+$  and  $ZW^-$
- EW corrections opposite in sign in off-shell region for the two setups

# Invariant Z-boson mass



Cut around invariant Z-boson mass removes part of radiative tail  
 -> corrections in triple-gauge coupling scenario are more negative

# EW corrections to diboson production

Full NLO EW corrections for diboson production including leptonic decays available.

Processes  $p p \rightarrow ZZ \rightarrow 4 \text{ leptons}$  and  $p p \rightarrow ZW \rightarrow \mu^+ \mu^- e^\pm \nu$  discussed.

EW corrections lead to large contributions for distributions in the Sudakov region of several 10% and give rise to large kinematic effects near resonances or thresholds via radiative tails.

Interferences due to equal-flavour leptons in the final state mainly LO effects.

Photon-induced contributions for ZZ are strongly suppressed below the permille level, for WZ they are in general non-negligible at the percent level.

Precision observables in Higgs-boson searches and triple-gauge boson analyses receive non-uniform distortions from EW corrections at the level of 5%-10%.

# Backup slides

# Z-boson transverse momentum (ZW TGC)

