Full NLO predictions for ZZ scattering and its irreducible background at the LHC

Timo Schmidt
in collaboration with Ansgar Denner, Mathieu Pellen and Robert Franken

University of Würzburg

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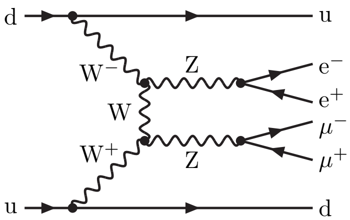
Introduction

Characteristics of vector-boson scattering (VBS)

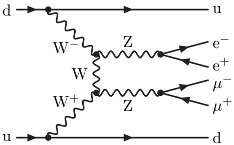


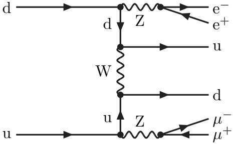
- Sensitivity to scalar sector of the SM and non-Abelian triple and quartic couplings.
- NLO EW corrections in VBS typically of the size of $\sim -15\%$.
- VBS ZZ signature:
  - 60 partonic quark-induced channels compared to 40 for WZ and 12 for same-sign W.
  - additional s-channel Higgs contribution, but in our setup the Higgs is cut out by invariant mass cut on the four leptons.

Previous theoretical work in VBS

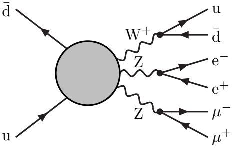
- NLO QCD corrections in VBS approximation for all VBS processes [Baglio (2014), Rauch (2017)].
- NLO EW corrections for same-sign W and WZ [Biedermann, Denner, Pellen (2016, 2017), Denner, Dittmaier, Maierhöfer, Pellen, Schwan (2019)].
- NLO EW + QCD corrections in same-sign W with event generator [Chiesa, Denner, Lang, Pellen (2019)].
- VBS ZZ:
  - NLO QCD and EW corrections in VBS approximation [Jäger, Oleari, Zeppenfeld (2006)] and matched to QCD parton shower [Jäger, Karlberg, Zanderighi (2014)].
  - NLO QCD corrections to QCD-induced process [Campanario, Kerner, Ninh, Zeppenfeld (2014)].
- loop-induced ZZ (+2j) production matched to parton shower [Li, An, Charlot, Covarelli, Guan, Li (2020)].

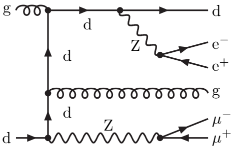
LO contributions

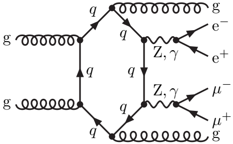




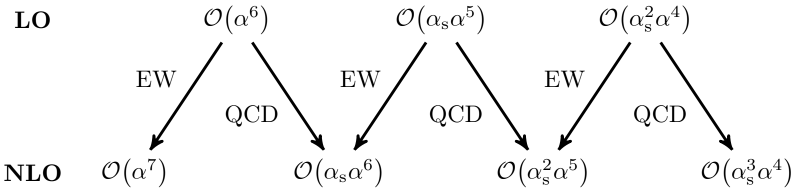
- EW contributions @ $\mathcal{O}\left(\alpha^6\right)$
- interference contributions @ $\mathcal{O}\left(\alpha_s\alpha^5\right)$
- QCD contributions @ $\mathcal{O}\left(\alpha_s^2\alpha^4\right)$
- gluon-induced contributions @ $\mathcal{O}\left(\alpha_s^4\alpha^4\right)$



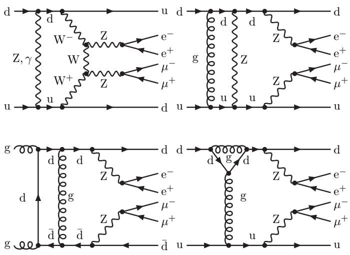




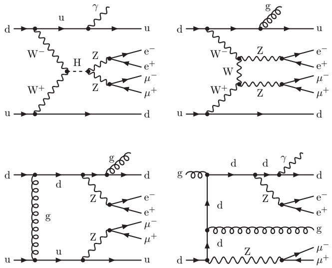
NLO corrections (I)



- virtual corrections:



- real corrections:



NLO corrections (II)

- Technical setup:
  - Results at LO and NLO obtained with MoCaNLO + Recola [Actis, Denner, Hofer, Lang, Scharf, Uccirati (2013,2017))].
  - NLO virtual corrections:
    - Evaluation of tensor and scalar integrals done by COLLIER [Denner, Dittmaier, Hofer (2016))].
  - NLO real corrections:
    - IR singularities handeled by Catani-Seymour dipole subtraction in QCD [Catani, Seymour (1997,1998))] and its equivalent in QED [Dittmaier (2000), Dittmaier, Kabelschacht, Kasprzik (2008)].
    - collinear singularities also arises from diagrams with a low-virtual photon $\rightarrow$ photon-to-jet-conversion function [Denner, Dittmaier, Pellen, Schwan (2019)].
    - For real EW corrections @ $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$ recombination of hard photon and soft gluon can lead to infrared QCD singularity $\rightarrow$ fragmentation function [Denner, Hofer, Scharf, Uccirati (2015)].
- Comparisons:
  - Independent checks in VBS between MoCaNLO and BBMC in the same sign W and MoCaNLO and BONSAY in WZ signature.
  - VBS ZZ:
    - virtuals checked with different implementations in COLLIER (COLI and DD mode).
    - reals and integrated dipole contributions checked via different α-parameters ($\alpha = 10^{-2}$ and $\alpha = 1$).
    - additional checks of a subset of channels between BBMC and MoCaNLO at all orders.

Input parameters

- cms energy $\sqrt{s} = 13$ TeV.
- PDF set: NLO NNPDF-3.1 Lux QED (for both LO and NLO).
- strong coupling: $\alpha_s(M_Z) = 0.118$.
- renormalization and factorization scale: $\mu_{\mathrm{ren}} = \mu_{\mathrm{fac}} = \sqrt{p_{\mathrm{T},j_1} p_{\mathrm{T},j_2}}$, ($p_{\mathrm{T},j_1}$ and p_{T,j_1} are the two jets with the largest transverse momentum).
- scale variation: 7-point method
  $(\mu_{\mathrm{ren}}/\mu_0, \mu_{\mathrm{fac}}/\mu_0) = (0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1), (2, 2)$.
- electromagnetic coupling: G_μ scheme.
- masses and widths:

$$\begin{aligned} m_{\mathrm{t}} &= 173.0\,\mathrm{GeV}, & \Gamma_{\mathrm{t}} &= 0\,\mathrm{GeV}, \\ M_{\mathrm{Z}}^{\mathrm{OS}} &= 91.1876\,\mathrm{GeV}, & \Gamma_{\mathrm{Z}}^{\mathrm{OS}} &= 2.4952\,\mathrm{GeV}, \\ M_{\mathrm{W}}^{\mathrm{OS}} &= 80.379\,\mathrm{GeV}, & \Gamma_{\mathrm{W}}^{\mathrm{OS}} &= 2.085\,\mathrm{GeV}, \\ M_{\mathrm{H}} &= 125.0\,\mathrm{GeV}, & \Gamma_{\mathrm{H}} &= 4.07 \times 10^{-3}\,\mathrm{GeV}. \end{aligned}$$

- pole masses of vector bosons obtained from OS masses.

Event selection

- combination of QCD partons into jets via anti-k_T algorithm.
- cuts on leptons:

$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \qquad |\eta_\ell| < 2.5, \qquad \Delta R_{\ell\ell'} > 0.05, \qquad M_{\ell^+\ell'^-} > 4\,\mathrm{GeV}.$$

- cut on the invariant mass of two leptons:

$$60\,\mathrm{GeV} < M_{\ell^+\ell^-} < 120\,\mathrm{GeV}, \qquad \ell = \mathrm{e}, \mu.$$

- cuts on the jets and (jets and leptons):

$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \qquad |\eta_\mathrm{j}| < 4.7, \qquad \Delta R_{\mathrm{j}\ell} > 0.4.$$

- cut on the invariant mass of the two p_T-hardest jets:

$$M_{\mathrm{j}_1\mathrm{j}_2} > 100\,\mathrm{GeV} \quad (\text{inclusive setup}), \quad M_{\mathrm{j}_1\mathrm{j}_2} > 500\,\mathrm{GeV} \quad (\text{VBS setup})$$

- Results presented in this talk are based on the two setups for the invariant mass.
- Plots in this talk only in the inclusive setup.

Numerical Results

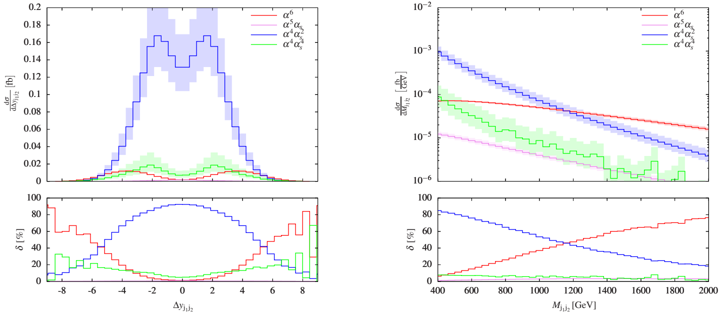
Cross sections at LO

Order	$\mathcal{O}\left(\alpha^6\right)$	$\mathcal{O}\left(\alpha_s\alpha^5\right)$	$\mathcal{O}\left(\alpha_s^2\alpha^4\right)$	$\mathcal{O}\left(\alpha_s^4\alpha^4\right)$	Sum
$M_{j_1j_2} > 100$ GeV					
σ_{LO}[fb]	0.097683(2)	0.008628(1)	1.062478(48)	0.12101(64)	1.28980(64)
fraction[%]	7.57	0.67	82.38	9.38	100
$M_{j_1j_2} > 500$ GeV					
σ_{LO}[fb]	0.073676(3)	0.005567(1)	0.136143(15)	0.01345(29)	0.22883(29)
fraction[%]	32.20	2.43	59.49	5.88	100

- QCD contributions one order of magnitude larger as the EW contributions in contrast to same-sign W and WZ.
- with stronger cut on $M_{j_1j_2}$ QCD background significantly decreases while EW corrections only moderately decrease.
- Loop-induced process contributes at $\sim 10\%$. Contribution decreases with stronger cut on the two hardest jets.

LO distributions (I)

- Rapidity difference (left) and invariant mass (right) of the two hardest jets j_1 and j_2.



- Rapidity difference of the two hardest jets enhance the EW contributions only for values $|\Delta y_{j_1 j_2}| > 5$.
- Invariant mass distribution of the two hardest jets for the EW contributions enhanced for values $M_{j_1 j_2} > 1200$ GeV, while the QCD contribution exceed the latter in the region below.

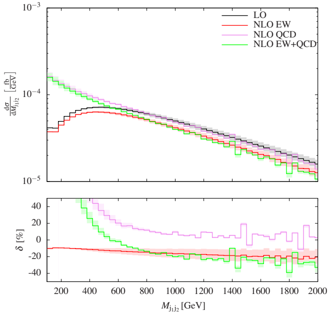
Cross sections at NLO (I)

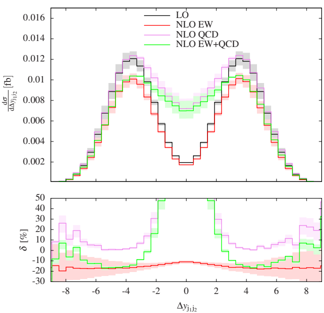
Contribution	σ_{α^6} [ab]	$\Delta\sigma_{\alpha^7}$ [ab]	$\Delta\sigma_{\alpha^7}/\sigma_{\alpha^6}$ [%]	$\Delta\sigma_{\alpha_s\alpha^6}$ [ab]	$\Delta\sigma_{\alpha_s\alpha^6}/\sigma_{\alpha^6}$ [%]
$M_{j_1j_2} > 100$ GeV					
all	97.683(2)	−15.55(5)	−15.9	23.10(11)	23.6
VBS-WW	95.237(2)	−15.28(5)	−16.0	1.33(11)	1.4
VBS-ZZ	1.9463(2)	−0.1979(6)	−10.2	3.892(4)	200
WZZ	0.1361(1)	−0.0142(1)	−10.5	13.850(4)	10174
ZZZ	0.3629(1)	−0.0542(6)	−14.9	4.029(3)	1110
$M_{j_1j_2} > 500$ GeV					
all	73.679(2)	−13.01(4)	−17.7	0.07(25)	0.10
VBS-WW	72.846(2)	−12.91(4)	−17.7	−2.73(25)	−3.7
VBS-ZZ	0.8096(2)	−0.0986(3)	−12.2	0.486(6)	60.1
WZZ	0.00471(2)	−0.00085(1)	−18.1	1.849(5)	39258
ZZZ	0.01887(1)	−0.00529(2)	−28.0	0.470(1)	2488

- 16 partonic channels with subprocess WW-ZZ dominate LO and NLO EW corrections at $\mathcal{O}(\alpha^7)$.
- $\mathcal{O}(\alpha_s\alpha^6)$ corrections dominated by triple-vector-boson production in the inclusive setup.
- Stronger cut on $M_{j_1j_2} > 500$ GeV reduces contributions of triple-vector-boson channels.

NLO distributions (I)

- invariant mass of the two hardest jets (left) and rapidity separation of the two hardest jets (right):

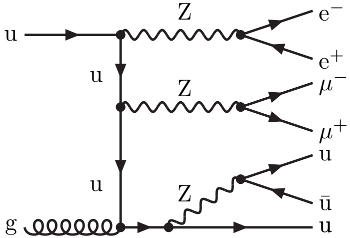




- Plots are normalized to the order $\mathcal{O}(\alpha^6)$ Born cross section.
- Bulk of NLO QCD corrections is in low di-jet invariant mass regime or regions with low rapidity difference of the two hardest jets.

Large QCD corrections in the inclusive setup

- In case of real radiation invariant mass cut of 100 GeV does not necessarily apply to the two quarks coming from vector-boson-decay.
- Extra jet can invoke kinematical configurations, where $M_{j_1 j_2} > 100$.



- The inclusive setup should therefore be avoided when using VBS approximations neglecting diagrams containing tri-boson contributions.
- Subtraction of tri-boson contributions generally not favourable due to possible gauge-invariance violation.

Cross sections at NLO (II)

Part. channel	σ_{α^6} [ab]	δ_{α^7} [%]	$\delta_{\rm LL}$ [%]	$\delta_{\rm LL+SSC}$ [%]	subprocesses
$\mathrm{ud} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{ud}$	51.537(2)	$-17.3(1)$	-16.4	-14.6	VBS-WW/VBS-ZZ
$\mathrm{us} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{dc}$	12.769(1)	$-15.1(1)$	-14.2	-12.6	VBS-WW
$\mathrm{u\bar{u}} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{d\bar{d}}$	10.666(1)	$-15.0(1)$	-13.6	-10.1	VBS-WW/ZZZ
$\mathrm{uu} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{uu}$	0.37718(5)	$-11.8(1)$	–	–	VBS-ZZ
$\mathrm{u\bar{d}} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{u\bar{d}}$	0.24011(5)	$-10.2(1)$	–	–	WZZ
$\mathrm{u\bar{u}} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{u\bar{u}}$	0.15878(4)	$-11.6(1)$	–	–	VBS-ZZ/ZZZ
$\mathrm{d\bar{d}} \to \mathrm{e^+e^-}\mu^+\mu^-\mathrm{s\bar{s}}$	0.11638(3)	$-11.0(1)$	–	–	ZZZ

- The $\mathcal{O}(\alpha^7)$ contributions dominated by large Sudakov logarithms.
- Sudakov approximation for VBS-WW channels in the LL and SSC [Denner, Pozzorini (2001), Accomando, Denner, Pozzorini (2007)]:
  - Universal and for all VBS processes:

$$\delta_{\rm LL} = \frac{\alpha}{4\pi}\left\{-4C_W^{\rm EW}\log^2\left(\frac{Q^2}{M_{\rm W}^2}\right) + 2b_W^{\rm EW}\log\left(\frac{Q^2}{M_{\rm W}^2}\right)\right\}.$$

  - Process dependent (WW→ZZ):

$$\delta_{\rm SSC} = \frac{\alpha}{\pi s_{\rm w}^2} 2\ln\left(\frac{Q^2}{M_{\rm W}^2}\right)\left[-\ln\frac{s_{12}}{Q^2} + \frac{s_{23}}{s_{12}}\ln\frac{s_{13}}{Q^2} + \frac{s_{13}}{s_{12}}\ln\frac{s_{23}}{Q^2}\right].$$

- Agreement of approximation and full results within 2%.

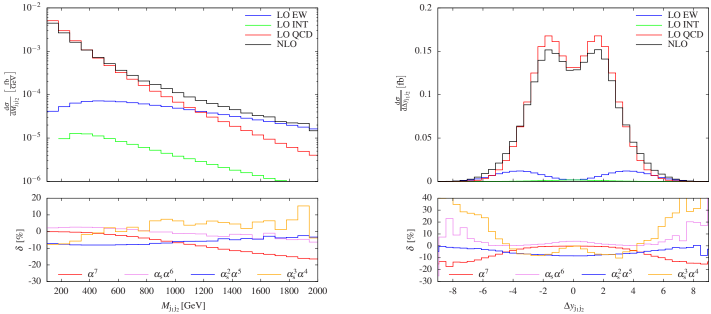
Cross sections at NLO (III)

Order	$\mathcal{O}\left(\alpha^7\right)$	$\mathcal{O}\left(\alpha_s\alpha^6\right)$	$\mathcal{O}\left(\alpha_s^2\alpha^5\right)$	$\mathcal{O}\left(\alpha_s^3\alpha^4\right)$	Sum
$M_{j_1j_2} > 100$ GeV					
$\Delta\sigma_{\rm NLO}$[fb]	$-0.01557(4)$	$0.0231(1)$	$-0.0862(1)$	$-0.0530(16)$	$-0.1317(16)$
$\Delta\sigma_{\rm NLO}/\sigma_{\rm LO}$[%]	$-1.33(1)$	$1.98(1)$	$-7.38(2)$	$-4.54(14)$	$-11.27(14)$
$M_{j_1j_2} > 500$ GeV					
$\Delta\sigma_{\rm NLO}$[fb]	$-0.01299(5)$	$0.00008(25)$	$-0.0142(1)$	$0.0058(11)$	$-0.0214(11)$
$\Delta\sigma_{\rm NLO}/\sigma_{\rm LO}$[%]	$-6.03(3)$	$0.04(12)$	$-6.60(5)$	$2.67(50)$	$-9.91(51)$

- For $M_{j_1j_2} > 100$ GeV corrections at the order $\mathcal{O}\left(\alpha^7\right)$ and $\mathcal{O}\left(\alpha_s\alpha^6\right)$ are small, varying between 1% and 2%.
- In the VBS setup with $M_{j_1j_2} > 500$ GeV the largest contribution is the one at order $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$, dominated by the EW corrections to the LO QCD contribution.

NLO distributions (II)

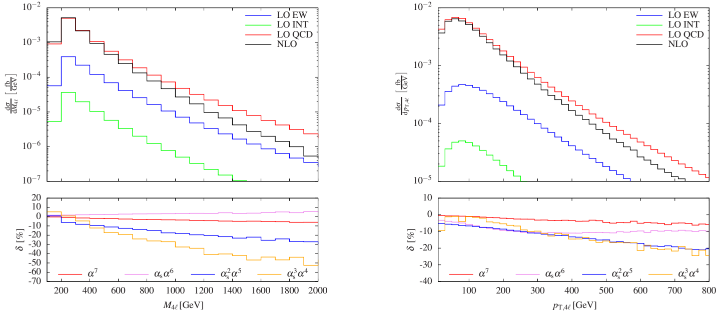
- invariant mass of the two hardest jets (left) and rapidity separation of the two hardest jets (right):



- Plots are normalized to the full LO cross section.
- Both distributions receive sizeable contributions in the large $M_{j_1j_2}$ and $|\Delta y_{j_1j_2}|$ regime at the order $\mathcal{O}\left(\alpha^6\right)$ while other distributions are dominated by the $\mathcal{O}\left(\alpha_s^2\alpha^4\right)$.
- Large Sudakov corrections visible both for small invariant mass or rapidity difference at the order $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$ and for large values $M_{j_1j_2}$ and $|\Delta y_{j_1j_2}|$ at the order $\mathcal{O}\left(\alpha^7\right)$.

NLO distributions (III)

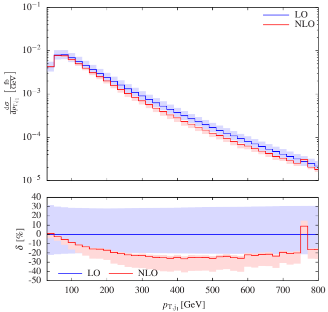
- invariant mass (left) and transverse momentum of the four leptons (right).

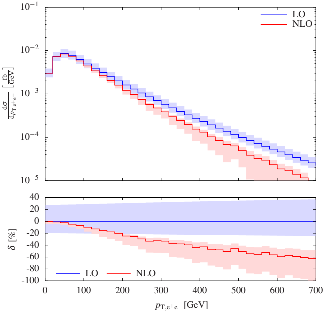


- Plots are normalized to the full LO cross section.
- Both distributions display similar behaviour as they are correlated.
- The order $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$ show typical Sudakov behaviour reaching up to 30% while the $\mathcal{O}\left(\alpha^7\right)$ corrections are damped due to the dominating LO QCD contributions.
- QCD corrections at the order $\mathcal{O}\left(\alpha_s^3\alpha^4\right)$ show stronger impact reaching -50% for $M_{4\ell} = 2$ TeV or -20% for high p_T.

NLO distributions (IV)

- transverse momentum of the hardest jet (left) and of an electron-positron pair (right):





- Plots are normalized to the full LO cross section.
- NLO correction to the contribution of transverse momentum of the hardest jet reaches up to 25%. Overall behaviour is directed to the order $\mathcal{O}\left(\alpha_s^3\alpha^4\right)$ corrections.
- Large negative corrections towards high energies reaching -60% at 700 GeV. NLO corrections leave LO uncertainty band at about 200 GeV and NLO scale uncertainty increases significantly for high leptonic energies.

Conclusions

- LO contributions for VBS ZZ at the orders $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s\alpha^5)$, $\mathcal{O}(\alpha_s^2\alpha^4)$ and $\mathcal{O}(\alpha_s^4\alpha^4)$.
- Gluon-induced contributions at LO are non-negligable.
- EW corrections large by about -16% in agreement with previous VBS calculations. Can reach about -40% in high energy tails of distributions.
- QCD corrections at the order $\mathcal{O}(\alpha_s\alpha^6)$ reach 20% in the inclusive setup due to tri-boson contributions. Effect can be decreased by choosing sensible cut on $M_{j_1j_2}$ or $\Delta y_{j_1j_2}$.
- $\mathcal{O}(\alpha_s^2\alpha^5)$ also show large Sudakov corrections.
- In high energy tails of distributions the $\mathcal{O}(\alpha_s^3\alpha^4)$ corrections are large.

Thank you for your attention

Backup slides

Cross sections at NLO (backup)

Order	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^7) + \mathcal{O}(\alpha_s\alpha^6)$
$M_{j_1j_2} > 100$ GeV			
$\sigma_{\rm NLO}$ [fb]	0.08211(4)	0.12078(11)	0.10521(11)
$\sigma^{\rm max}_{\rm NLO}$ [fb]	0.08728(5) [+6.3%]	0.12540(13) [+3.8%]	0.10838(14) [+3.0%]
$\sigma^{\rm min}_{\rm NLO}$ [fb]	0.07749(4) [−5.6%]	0.11656(9) [−3.5%]	0.10225(9) [−2.8%]
δ[%]	−15.9	23.6	7.7
$M_{j_1j_2} > 500$ GeV			
$\sigma_{\rm NLO}$ [fb]	0.06069(4)	0.07375(25)	0.06077(25)
$\sigma^{\rm max}_{\rm NLO}$ [fb]	0.06568(5) [+8.2%]	0.07466(26) [+1.2%]	0.06149(24) [+1.2%]
$\sigma^{\rm min}_{\rm NLO}$ [fb]	0.05636(4) [−7.1%]	0.07282(21) [−1.3%]	0.05977(30) [−1.6%]
δ[%]	−17.6	0.1	−17.5

- EW corrections range between $\sim 16 - 17\%$ depending on the invariant mass cut.
- QCD corrections sizeable in the inclusive setup but drastically reduced for stronger invariant mass cut.