NLO QCD and EW corrections to vector-boson scattering

A. Denner, **R. Franken**, M. Pellen, T. Schmidt, Ch. Schwan

Institut für Theoretische Physik und Astrophysik
Julius-Maximilians-Universität Würzburg

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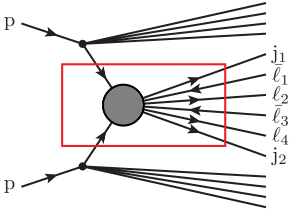
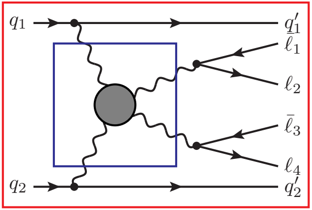
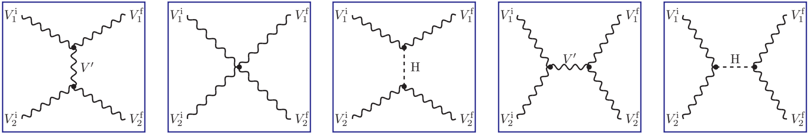
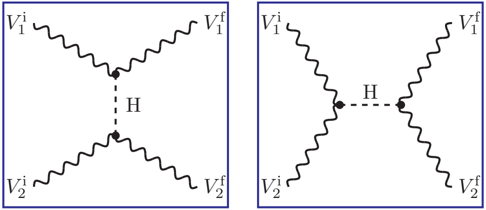
What is vector-boson scattering?







Why talking about $\mathrm{W^+W^-}$ and ZZ scattering?



- For all VBS contributions: *t*-channel Higgs boson contribution
- If $(V_1^\mathrm{f}, V_2^\mathrm{f}) = (\mathrm{W^+}, \mathrm{W^-})$ or (Z, Z):
  diagrams with *s*-channel Higgs boson resonance present
  $\Rightarrow$ We expect differences in $\mathrm{W^+W^-}$ and ZZ scattering
  compared to other VBS processes

Similarities and differences between $\mathrm{W^+W^-}$ and ZZ

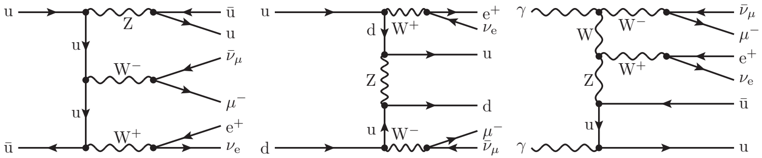
Similarities
VBS processes
$\mathrm{pp} \to 4\ell\mathrm{jj}$ at LO
$\mathrm{pp} \to 4\ell\mathrm{jjj}$ or $\mathrm{pp} \to 4\ell\mathrm{jj}\gamma$ at NLO
neutral leptonic final state
identical partonic processes (up to leptons)
$\Rightarrow$ same complexity of calculation

Differences

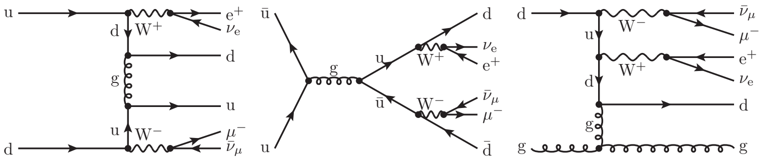
$\mathrm{W^+W^-}$	ZZ
$4\ell = \mathrm{e}^+\nu_\mathrm{e}\ \mu^-\bar{\nu}_\mu$	$4\ell = \mathrm{e}^+\mathrm{e}^-\ \mu^+\mu^-$
neither boson reconstructible	both bosons reconstructible

Irreducible background

- EW background $\mathcal{O}(g^6)$

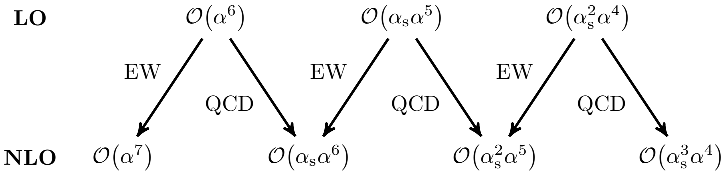


- QCD background $\mathcal{O}(g_s^2 g^4)$



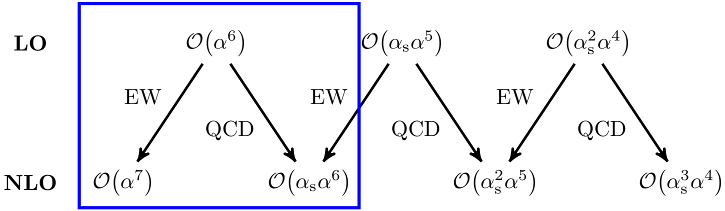
(Diagrams for $\mathrm{W^+W^-}$, ZZ is similar)

Process overview



- LO: well-defined EW, interference and QCD contributions
- NLO: corrections mix contributions, except α^7 and $\alpha_s^3\alpha^4$

Process overview

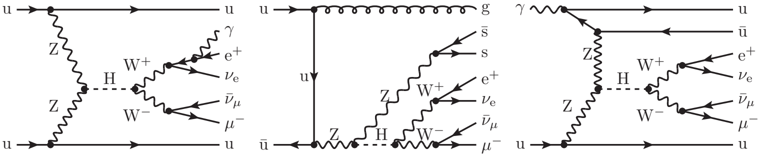


- LO: well-defined EW, interference and QCD contributions
- NLO: corrections mix contributions, except α^7 and $\alpha_s^3\alpha^4$

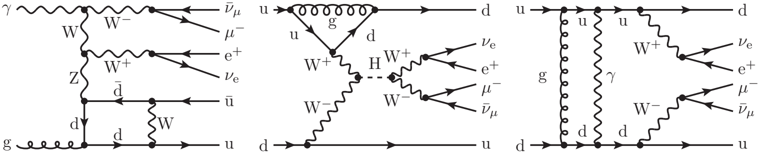
This talk: focus on $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$

NLO contributions (examples)

- real corrections



- virtual corrections



Importance of EW corrections?

naive expectation:

- $\sigma_{\mathrm{LO}}^{\alpha^6}/\sigma_{\mathrm{LO}}^{\alpha_\mathrm{s}^2\alpha^4} \sim \alpha^2/\alpha_\mathrm{s}^2 \sim 10^{-2}$,
- $\delta^{\alpha_\mathrm{s}\alpha^6} \equiv \Delta\sigma_{\mathrm{NLO}}^{\alpha_\mathrm{s}\alpha^6}/\sigma_{\mathrm{LO}}^{\alpha^6} \sim \alpha_\mathrm{s} \sim 10^{-1}$
- $\delta^{\alpha^7} \equiv \Delta\sigma_{\mathrm{NLO}}^{\alpha^7}/\sigma_{\mathrm{LO}}^{\alpha^6} \sim \alpha \sim 10^{-2}$,

$\Rightarrow$ per mille effect?

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$\Rightarrow$ per mille effect?

NO!

- EW signal enhanced by suitable phase-space cuts
- large EW corrections due to Sudakov enhancements

General setup

- $\sqrt{s} = 13\,\mathrm{TeV}$ pp collider
- Monte Carlo integration
  - fixed-order calculation at LO and NLO
  - providing integrated and differential cross-sections
- simplifications:
  - diagonal CKM matrix
  - neglect of external b-quarks
- 2 experimental setups each:

$\mathrm{W^+W^-}$ [Denner et al.; arXiv:2202.10844]	ZZ [Denner et al.; arXiv:2009.00411] [Denner et al.; arXiv:2107.10688]
VBS setup	VBS setup
Higgs setup [CMS; arXiv:1806.05246]	inclusive setup [CMS; arXiv:1708.02812]

Technical details

- Software:
  - BBMC and MoCaNLO: Multichannel Monte Carlo integrators
  - RECOLA: Computation of tree-level and one-loop amplitudes
    [Actis et al.; arXiv:1211.6316], [Actis et al.; arXiv:1605.01090]
  - COLLIER: Library for numerical evaluation of one-loop integrals [Denner et al.; arXiv:1604.06792]
- Techniques:
  - UV singularities regularised with dimensional regularisation
  - IR singularities handled with CS subtraction algorithm
    [Catani/Seymour; arXiv:hep-ph/9605323], [Dittmaier et al.; arXiv:0802.1405]

Important phase-space cuts

	$\mathrm{W^+W^-}$ VBS	$\mathrm{W^+W^-}$ Higgs	ZZ VBS
$M_{\mathrm{j_1j_2}} >$	$500\,\mathrm{GeV}$	$400\,\mathrm{GeV}$	$500\,\mathrm{GeV}$
$\Delta y_{\mathrm{j_1j_2}} >$	2.5	3.5	–
$M_{\ell^+\ell^-} \in$	–	–	$[60, 120]\,\mathrm{GeV}$
$M_{\mathrm{T},4\ell} \in$	–	$[60, 125]\,\mathrm{GeV}$	–
$p_{\mathrm{T,j_3}} <$	–	$30\,\mathrm{GeV}$	–

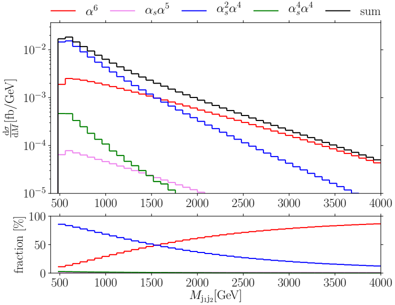
Overview over integrated cross sections

	W^+W^- VBS	W^+W^- Higgs	ZZ VBS
$\sigma_{\mathrm{LO}}^{\alpha^6}$	2.6988(3) fb	1.5322(2) fb	73.676(3) ab
$\sigma_{\mathrm{LO}}^{\alpha_s^2\alpha^4}$	6.9115(9) fb	1.6923(3) fb	136.14(2) ab
$\sigma_{\mathrm{LO}}^{\alpha^6}/\sigma_{\mathrm{LO}}^{\alpha_s^2\alpha^4}$	0.39	0.91	0.54
δ^{α^7}	−11.4%	−6.7%	−15.9%
$\delta^{\alpha_s\alpha^6}$	−5.1%	−21.6%	+0.1%

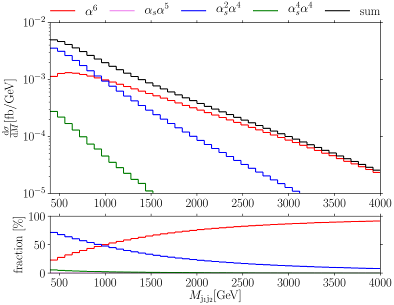
	W^+W^+ [Biedermann et al.; arXiv:1708.00268]	W^+Z [Denner et al.; arXiv:1904.00882]
$\sigma_{\mathrm{LO}}^{\alpha^6}/\sigma_{\mathrm{LO}}^{\alpha_s^2\alpha^4}$	8.23	0.23
δ^{α^7}	−15.3%	−16.0%

$M_{\mathrm{j_1j_2}}$, $\mathrm{W^+W^-}$, LO

(a) VBS setup



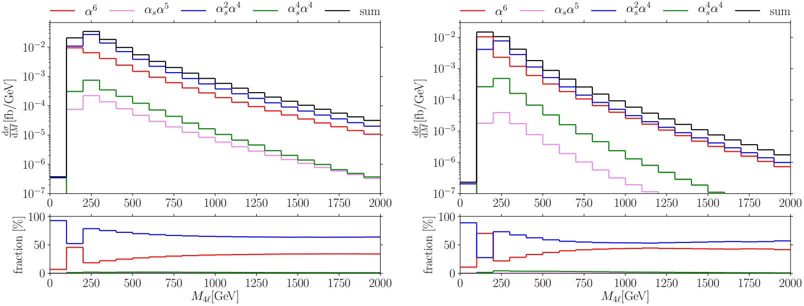
(b) Higgs setup



- typical VBS behaviour in $\mathrm{W^+W^-}$ scattering: EW contribution dominant at large $M_{\mathrm{j_1j_2}}$
- ZZ scattering is similar

$M_{4\ell}$, $\mathrm{W^+W^-}$, LO (not observable)

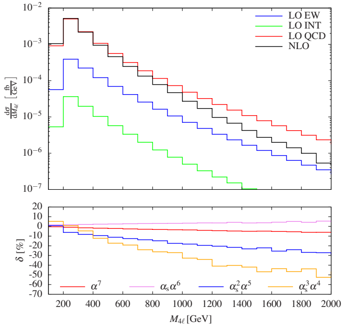
(a) $\mathrm{W^+W^-}$ VBS setup (b) $\mathrm{W^+W^-}$ Higgs setup



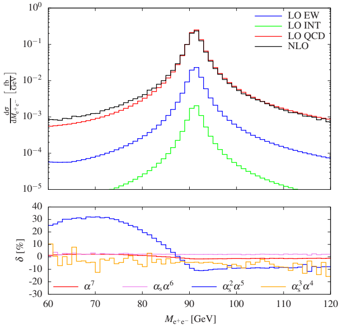
- "bump" at $M_{4\ell} \approx M_{\mathrm{H}}$ $\Rightarrow$ signal of on-shell Higgs production
- $\mathrm{W^+W^-}$ combines $VV \to \mathrm{H}$ VBF and VBS

$M_{4\ell}$ and $M_{\ell^+\ell^-}$, ZZ, NLO (observable)

(a) ZZ VBS setup



(b) ZZ VBS setup



- $M_{\ell^+\ell^-} \in [60, 120]\,\mathrm{GeV}$ cut favours two on-shell Z
- on-shell H $\Rightarrow M_{\ell^+\ell^-} \sim 90\,\mathrm{GeV}, M_{\ell'^+\ell'^-} \sim 35\,\mathrm{GeV}$
  $\Rightarrow$ no sign of on-shell Higgs production in ZZ

The Higgs resonance contribution in $\mathrm{W^+W^-}$

introduction of unphysical cut

$$M_{4\ell} \notin M_{\mathrm{H}} \pm 20\Gamma_{\mathrm{H}} = [124.92\,\mathrm{GeV}, 125.08\,\mathrm{GeV}]$$

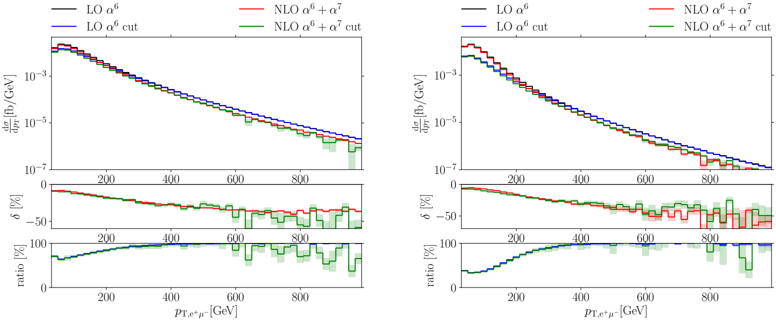
- assuming BW distribution: removes 98% of resonance peak
- leaves non-resonant contribution unaffected

$\Rightarrow$ separation of Higgs boson contribution and VBS contribution

	$\mathrm{W^+W^-}$ VBS	$\mathrm{W^+W^-}$ Higgs
$\sigma^{\alpha^6}_{\mathrm{LO}}$	$2.6988(3)\,\mathrm{fb}$	$1.5322(2)\,\mathrm{fb}$
$\sigma^{\alpha^6}_{\mathrm{LO,cut}}$	$1.9750(2)\,\mathrm{fb}$	$0.5999(1)\,\mathrm{fb}$
$\sigma^{\alpha^6}_{\mathrm{LO,cut}}/\sigma^{\alpha^6}_{\mathrm{LO}}$	73.2%	39.2%

$p_{\mathrm{T,e^+\mu^-}}$, $\mathrm{W^+W^-}$, NLO $\mathcal{O}(\alpha^7)$

(a) VBS setup (b) Higgs setup

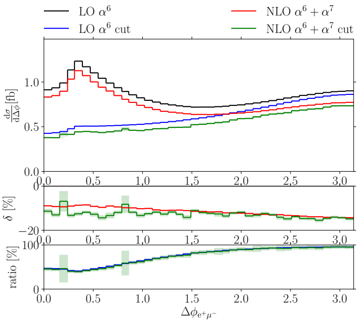


- large EW corrections in the tails
- relevant Higgs-boson contribution at small p_{T}

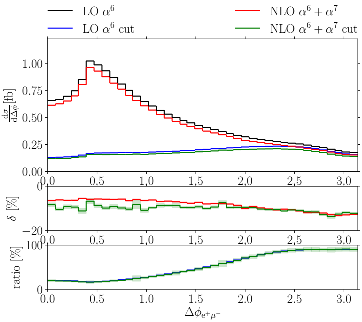
$\Rightarrow$ smaller EW corrections, especially in Higgs setup

$\Delta\phi_{e^+\mu^-}$, W^+W^-, NLO $\mathcal{O}(\alpha^7)$

(a) VBS setup

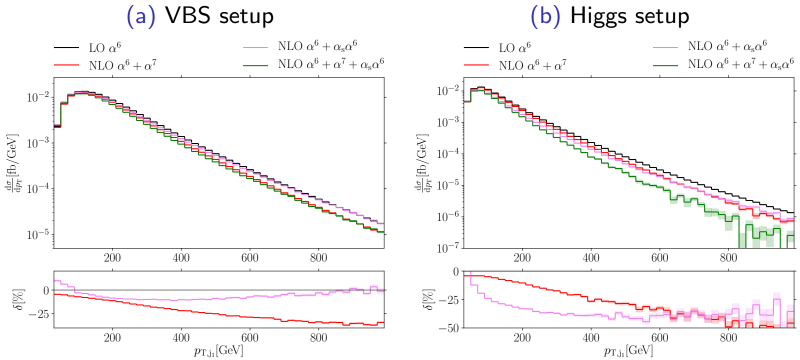


(b) Higgs setup



- Higgs decay: leptons emitted into same direction
- significantly larger corrections w/o Higgs resonance peak

$p_{\mathrm{T,j_2}}$, $\mathrm{W^+W^-}$, NLO $\mathcal{O}(\alpha^7), \mathcal{O}(\alpha_s\alpha^6)$



- effect of jet veto:
  - effective expansion in $\alpha_s \ln Q^2/p^2_{\mathrm{T,cut}} \sim 4\alpha_s$
  - large negative $\mathcal{O}(\alpha_s\alpha^6)$ corrections in Higgs setup

Conclusion

- $\mathrm{W^+W^-}$ has much larger cross section than ZZ
- NLO EW corrections relevant in all VBS processes ($\sim -10\%, -15\%$)
- Higgs boson resonance present in $\mathrm{W^+W^-}$ and ZZ VBS processes
  - *cannot* be removed from fiducial phase-space in $\mathrm{W^+W^-}$
  - *can* be removed with direct cuts in ZZ
  - leads to different behaviour of $\mathrm{W^+W^-}$ compared to other VBS processes
- indirect cuts to focus on Higgs production in $\mathrm{W^+W^-}$ developed by CMS working well