NLO QCD and EW corrections to vector-boson scattering into $\mathrm{W}^+\mathrm{W}^-$ at the LHC

$$\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{jj} + X$$

2202.10844

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with:
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Reminder: vector-boson scattering

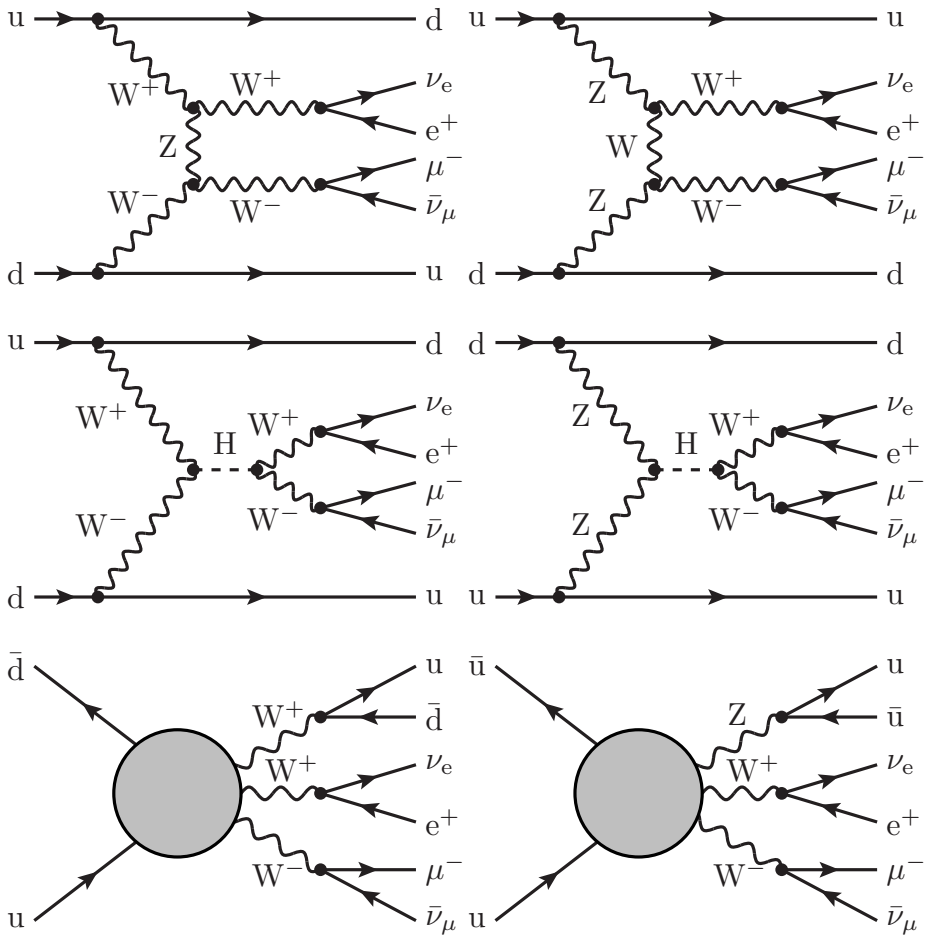
1. production of two EW gauge bosons (usually $\mathrm{W}^{\pm}/\mathrm{Z}$)
2. together with two jets
3. at $\mathcal{O}(\alpha^6)$ (LO)

$\rightarrow$ EW and QCD corrections for $4\ell + 2\mathrm{j}$

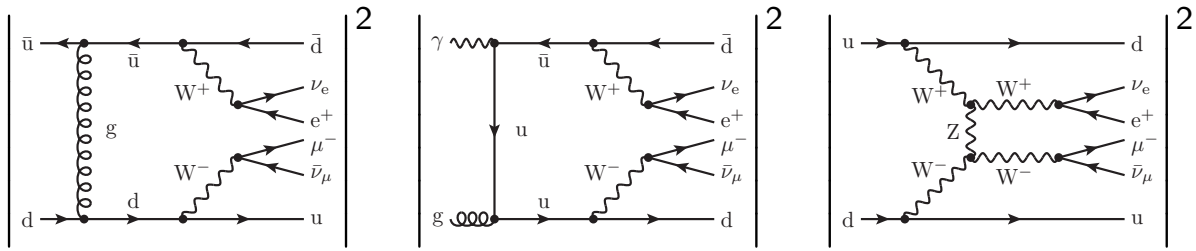
4 categories:

- $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$: like-sign scattering
- $\mathrm{W}^{\pm}\mathrm{Z}$: WZ scattering
- ZZ: ZZ scattering
- $\mathrm{W}^{+}\mathrm{W}^{-}$: opposite-sign scattering

fully off-shell scattering: $\mathrm{pp} \to \mathrm{e}^{+}\nu_{\mathrm{e}}\mu^{-}\bar{\nu}_{\mu}\mathrm{jj}$



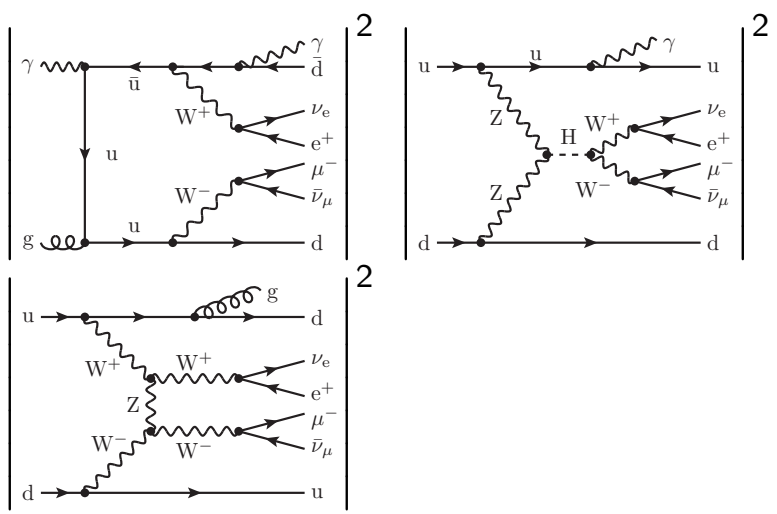
NLO tower of couplings



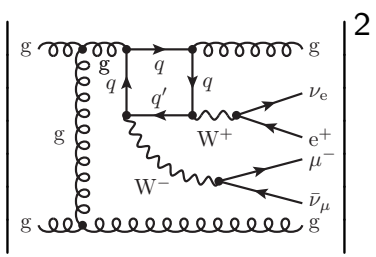
LO: $\mathcal{O}(\alpha_s^2\alpha^4)$ $\mathcal{O}(\alpha_s^1\alpha^5)$ $\mathcal{O}(\alpha_s^0\alpha^6)$

QCD EW QCD EW QCD EW

NLO: $\mathcal{O}(\alpha_s^3\alpha^4)$ $\mathcal{O}(\alpha_s^2\alpha^5)$ $\mathcal{O}(\alpha_s^1\alpha^6)$ $\mathcal{O}(\alpha_s^0\alpha^7)$



NNLO: $\mathcal{O}(\alpha_s^4\alpha^4)$



Two setups: VBS vs. Higgs

VBS setup [CMS collaboration]

Leptons:

$$p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}, \quad |y_\ell| < 2.4, \quad p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$$
$$p_{\mathrm{T},\ell^+\ell^-} > 30\,\mathrm{GeV}, \quad M_{\ell^+\ell^-} > 20\,\mathrm{GeV},$$

Jets:

$$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \quad |y_\mathrm{j}| < 4.5, \quad \Delta R_{\mathrm{j}\ell} > 0.4,$$
$$M_{\mathrm{j_1 j_2}} > 500\,\mathrm{GeV}, \quad |\Delta y_{\mathrm{j_1 j_2}}| > 2.5.$$

Higgs setup [CMS collaboration]

Leptons:

$$p_{\mathrm{T},\ell_1} > 25\,\mathrm{GeV}, \quad p_{\mathrm{T},\ell_2} > 10\,\mathrm{GeV}, \quad |y_\ell| < 2.4, \quad p_{\mathrm{T,miss}} > 20\,\mathrm{GeV},$$
$$p_{\mathrm{T},\ell^+\ell^-} > 30\,\mathrm{GeV}, \quad M_{\ell^+\ell^-} > 12\,\mathrm{GeV}, \quad \Delta R_{\ell^+\ell^-} > 0.4,$$
$$60\,\mathrm{GeV} < M_{\mathrm{T},\ell^+\ell,\mathrm{miss}} < 125\,\mathrm{GeV},$$

Jets:

$$p_{\mathrm{T,j_{1,2}}} > 30\,\mathrm{GeV}, \quad |y_{\mathrm{j_{1,2}}}| < 4.7, \quad \Delta R_{\mathrm{j_{1,2}}\ell} > 0.4, \quad p_{\mathrm{j_3}} < 30\,\mathrm{GeV}$$
$$M_{\mathrm{j_1 j_2}} > 400\,\mathrm{GeV}, \quad |\Delta y_{\mathrm{j_1 j_2}}| > 3.5.$$

$$M^2_{\mathrm{T},\ell^+\ell,\mathrm{miss}} = 2 p_{\mathrm{T},\ell^+\ell^-} p_{\mathrm{T,miss}} (1 - \cos\Delta\phi_{\ell^+\ell^-,\mathrm{miss}})$$

EW corrections for VBS fiducial cross sections

- EW corrections, $\delta^{\alpha^7} = \sigma^{\alpha^7}_{\mathrm{NLO}} / \sigma^{\alpha^6}_{\mathrm{LO}}$, for VBS processes typically $-15\,\%$ to $-16\,\%$
- can be understood from (VBS-independent) EW logs with $Q = M_{4\ell}$

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

Process	$\mathrm{W^+W^+}$	$\mathrm{W^+Z}$	ZZ	$\mathrm{W^+W^-}$ (VBS setup)	$\mathrm{W^+W^-}$ (Higgs setup)
$\sigma^{\alpha^7}_{\mathrm{NLO}}$[fb]	−0.2169(3)	−0.04091(2)	−0.015573(5)	−0.307(1)	−0.103(1)
$\sigma^{\alpha^6}_{\mathrm{LO}}$[fb]	1.4178(2)	0.25511(1)	0.097683(2)	2.6988(3)	1.5322(2)
δ^{α^7}[%]	−15.3	−16.0	−15.9	−11.4	−6.7

→ What's special about $\mathrm{W^+W^-}$ VBS?

Refs.:

- $\mathrm{W^+W^+}$: [B. Biedermann, A. Denner, M. Pellen]
- $\mathrm{W^+Z}$: [A. Denner, S. Dittmaier, P. Maierhöfer, M. Pellen, C.S.]
- ZZ: [A. Denner, R. Franken, M. Pellen, T. Schmidt]

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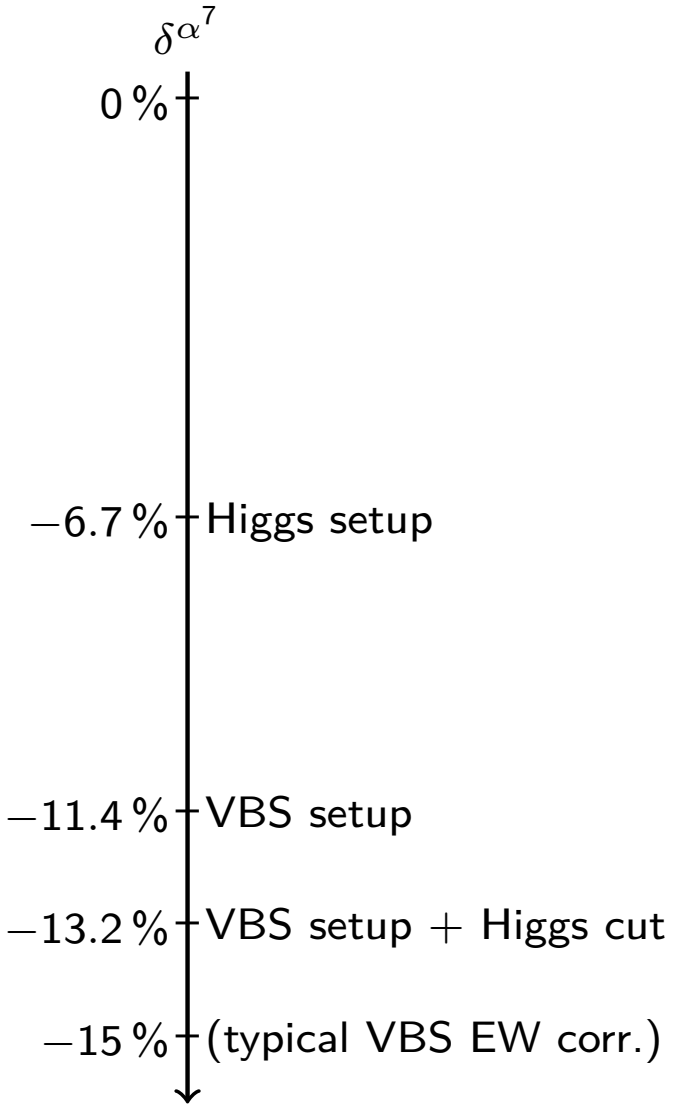
W^+W^- VBS and Higgs VBF: $\delta^{\alpha^7} = \sigma^{\alpha^7}_{\mathrm{NLO}}/\sigma^{\alpha^6}_{\mathrm{LO}}$



In the Higgs setup we force the Higgs on-shell; instead of VBS we rather have VBF Higgs
$\mathrm{pp} \to H\mathrm{jj} \to 4\ell\mathrm{jj}$

$$60\,\mathrm{GeV} < M_{\mathrm{T},\ell^+\ell,\mathrm{miss}} < 125\,\mathrm{GeV}$$

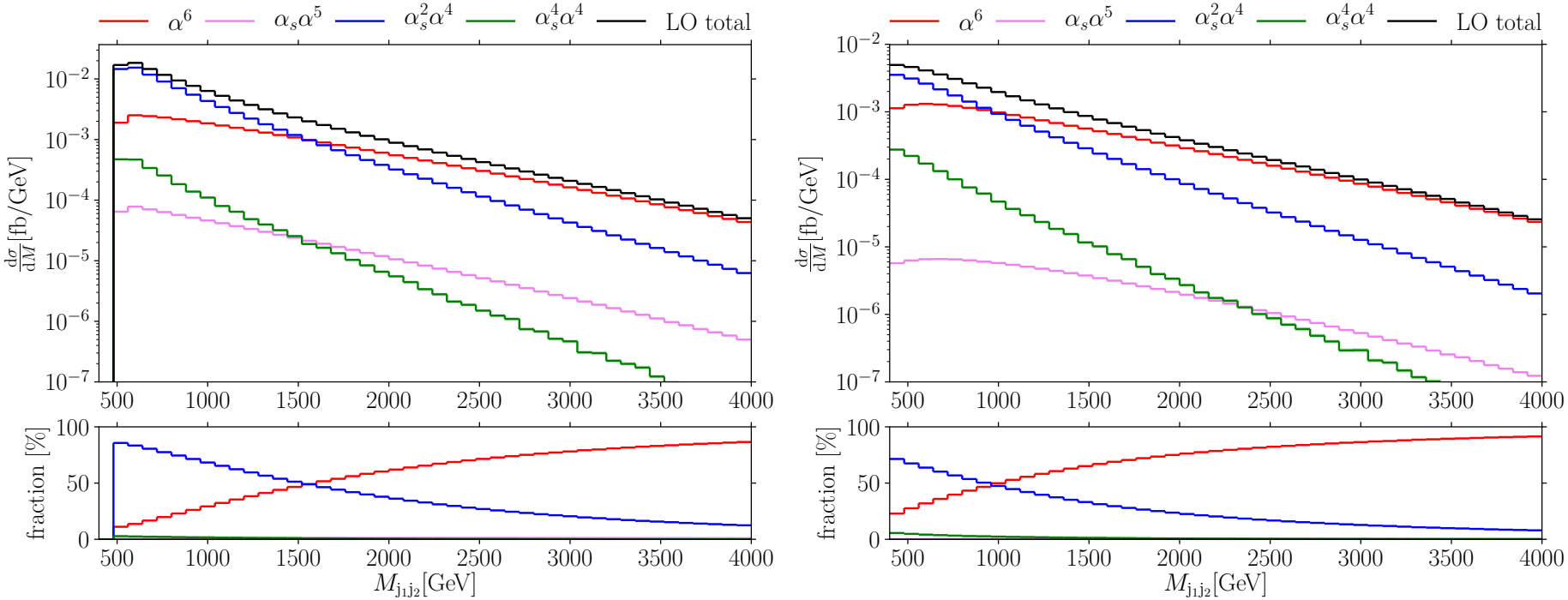
Higgs cut removes 98 % of the Higgs BW peak

$$|M_{4\ell} - M_{\mathrm{H}}| > 20\Gamma_{\mathrm{H}}$$

→ a sizable fraction (27 %) of Higgs VBF mixes with opposite-sign VBS!

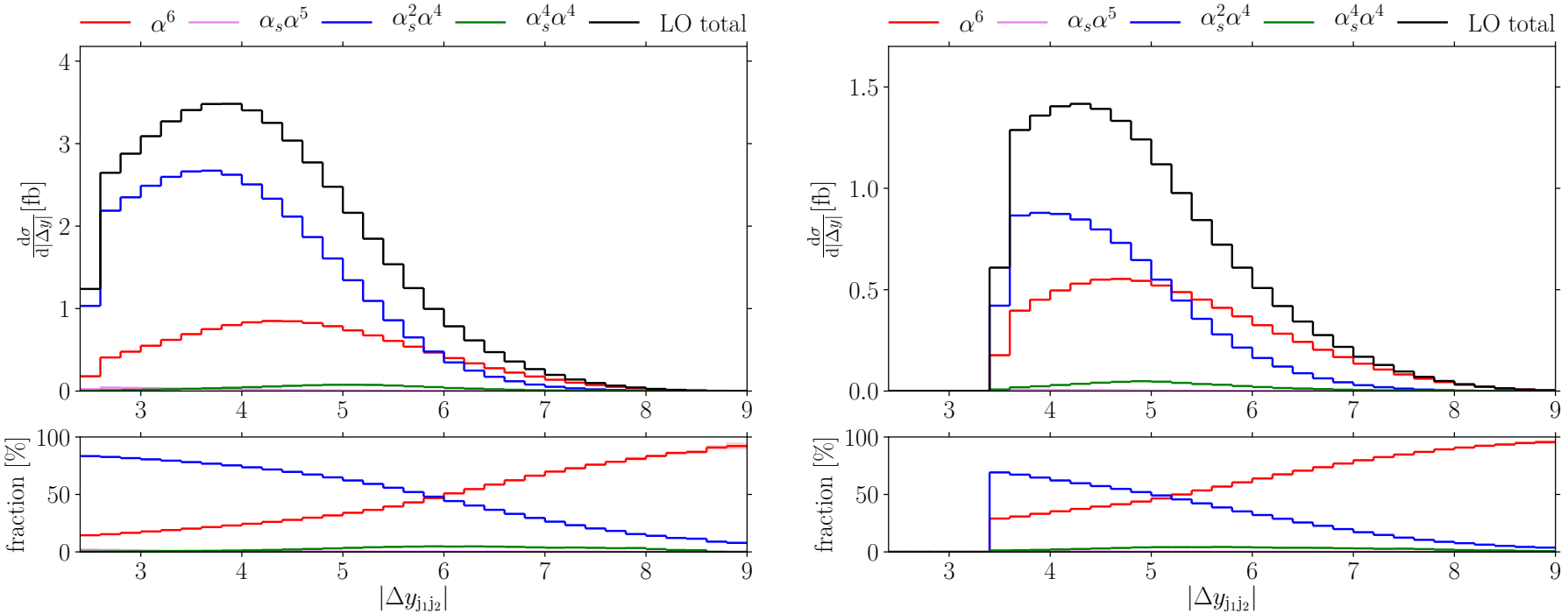
→ mostly responsible for smaller corrections

LO distributions: dijet invariant mass



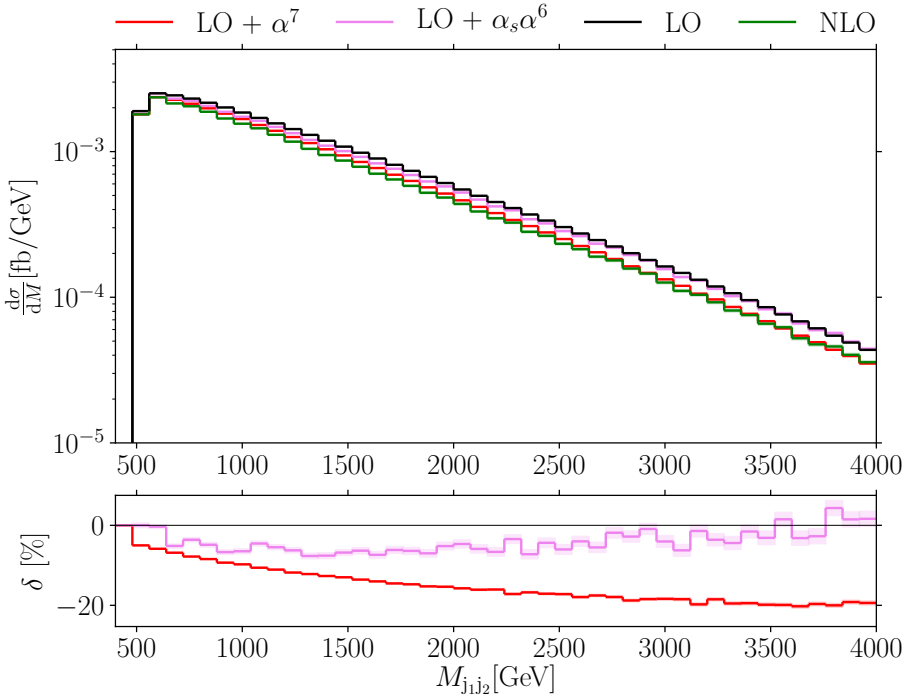
- left: VBS-, right: Higgs-setup
- starting at $M_{j_1j_2} \approx 1500\,\text{GeV}/1000\,\text{GeV}$ EW and QCD production cross for VBS/Higgs setup resp.
- size of the 4 gluon loop-induced up to 4.5 %/5 %

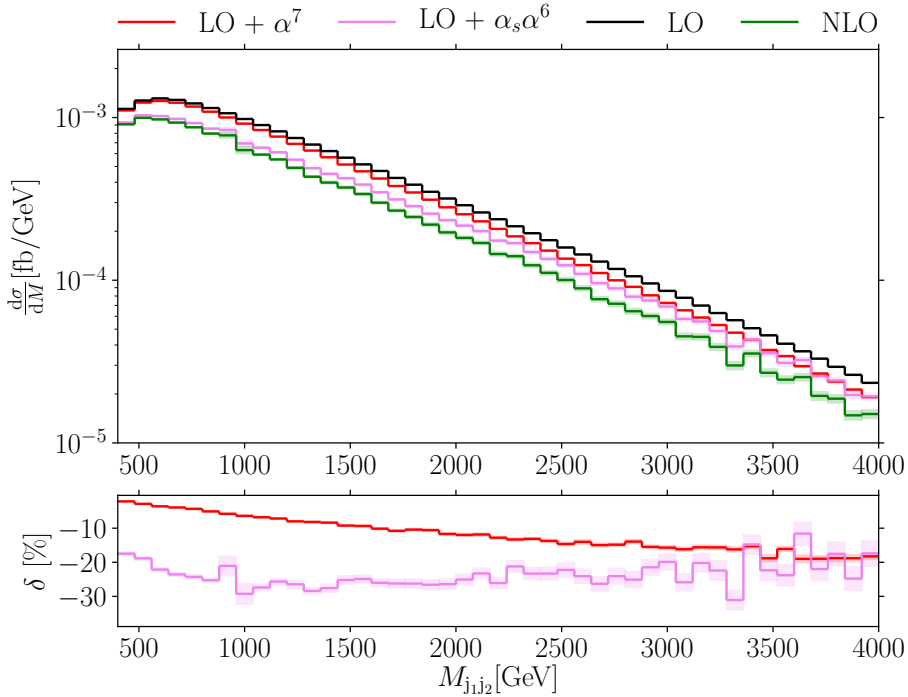
LO distributions: dijet rapidity difference



- left: VBS-, right: Higgs-setup
- starting at $\Delta y_{j_1 j_2} \approx 6/5$ EW and QCD production cross for VBS/Higgs setup resp.
- size of the 4 gluon loop-induced up to 2.5 %/5 % resp.

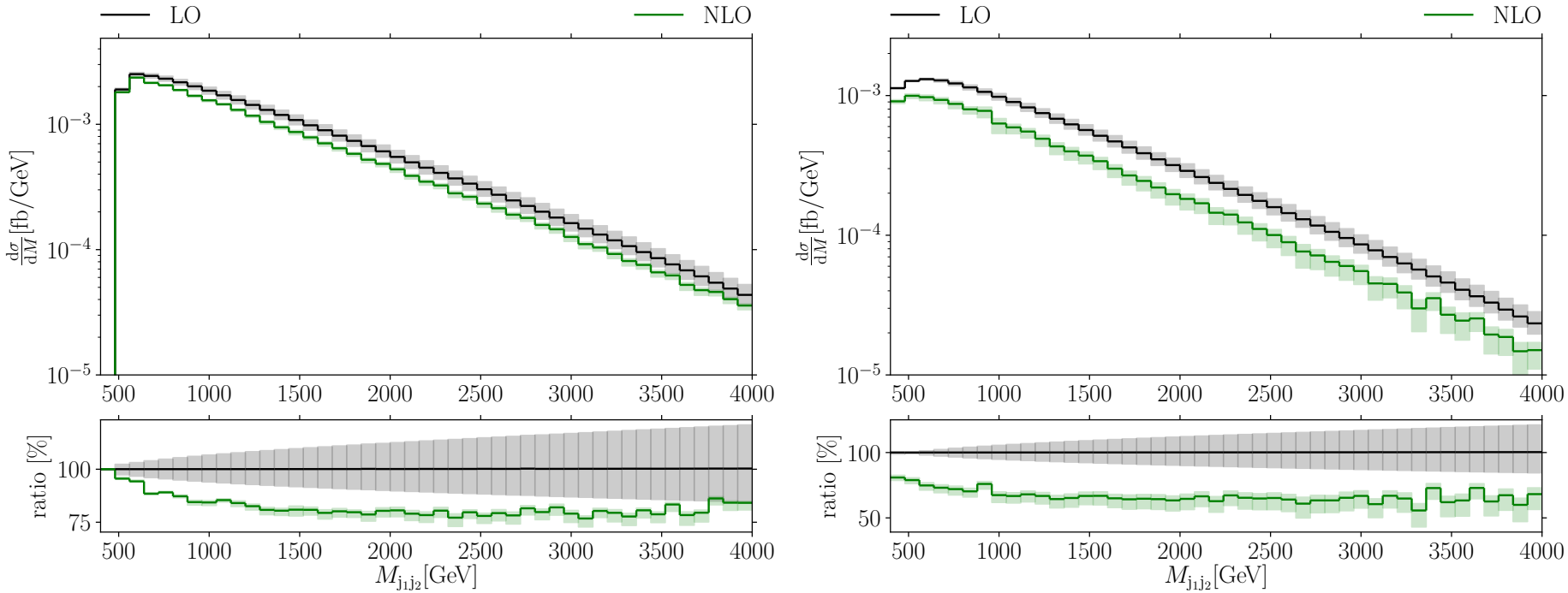
NLO distributions: dijet invariant mass





- left: VBS-, right: Higgs-setup
- band indicates MC integration uncertainties
- increasing EW corrections in the tail
- integrated QCD correction: $-5.1\,\%/-21.6\,\%$ resp.
- increase of the QCD corrections in the Higgs setup due to the jet veto

NLO distributions: dijet invariant mass



- left: VBS-, right: Higgs-setup
- band indicates 7-point scale uncertainties
- no overlapping bands: EW corrections not covered

Summary

- Calculation of $\mathrm{W}^+\mathrm{W}^-$ scattering concludes the NLO EW/QCD VBS computations (with fully leptonic decays, unpolarized)

- Opposite sign VBS shares many features of its cousins, but ...
- overlaps with Higgs VBF (27 %) and therefore ...
- lowers EW corrections from the expected $-15\,\%$ to ...

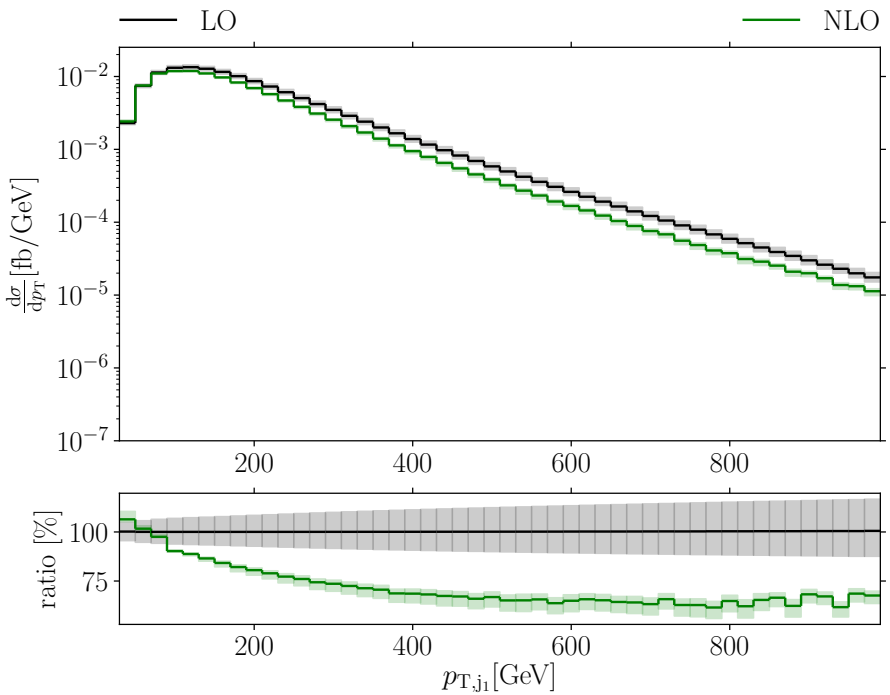
- EW corrections: $-11.4\,\%/-6.7\,\%$ for the VBS/Higgs setup resp.
- QCD corrections: $-5.1\,\%/-21.6\,\%$ resp.
- loop induced corrections up to 5 % (of total LO) in some distributions

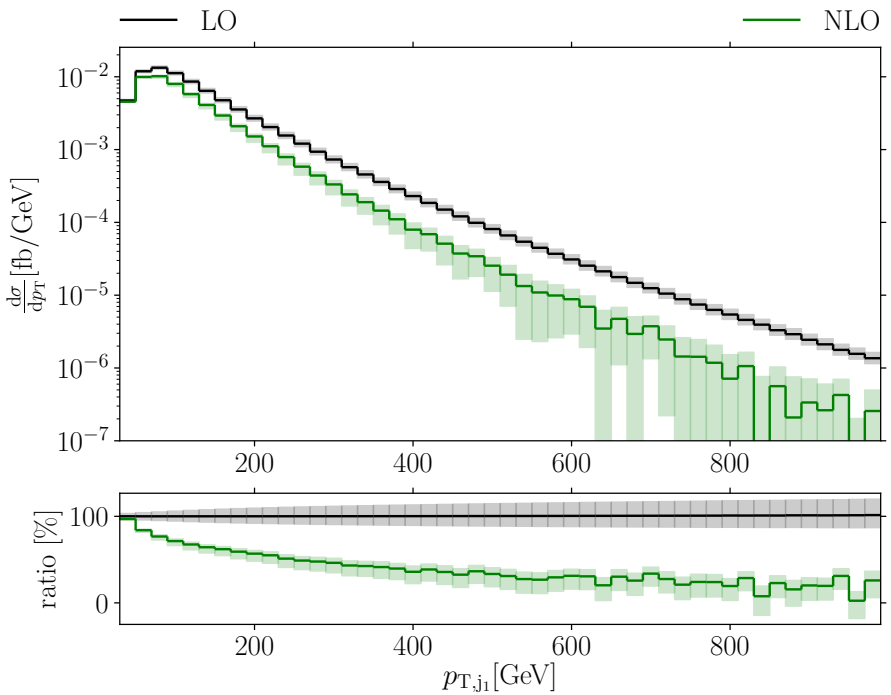
No Higgs integrated results

VBS cross sections with additional Higgs cut:

Contribution	$\sigma^{\alpha^6}_{\mathrm{LO}}$[fb]	$\Delta\sigma^{\alpha^7}_{\mathrm{NLO}}$[fb]	δ^{α^7}[%]	$\Delta\sigma^{\alpha_s\alpha^6}_{\mathrm{NLO}}$[fb]	$\delta^{\alpha_s\alpha^6}$[%]
VBS only	1.6117(2)	−0.239(2)	−14.8	−0.043(3)	−2.7
VBS + WWW	0.11398(2)	−0.0143(2)	−12.5	0.0080(5)	7.1
VBS + WWZ	0.24916(4)	−0.0324(3)	−13.0	0.0018(11)	0.1
WWW only	$5.303(2)\times10^{-5}$	$-1.43(2)\times10^{-5}$	−27.0	0.01110(2)	2.1×10^{4}
WWZ only	$9.415(2)\times10^{-5}$	$-2.80(2)\times10^{-5}$	−29.7	0.004021(3)	4.3×10^{3}
$\gamma\gamma/\gamma g$	$6.832(4)\times10^{-6}$	0.02575(3)	3.8×10^{5}	0.0108(2)	1.6×10^{5}
total	1.9750(2)	−0.260(2)	−13.2	−0.007(3)	−0.4

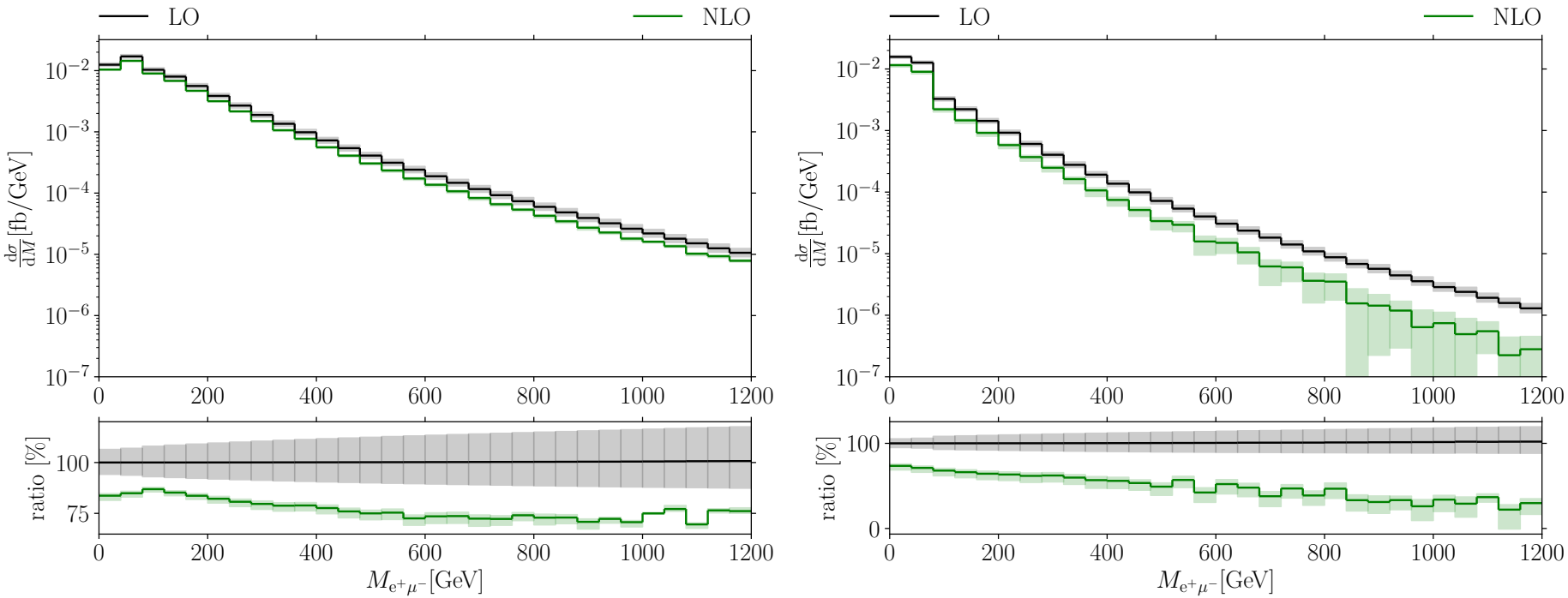
NLO distributions: transverse momentum of the leading jet





- left: VBS-, right: Higgs-setup
- band indicates 7-point scale uncertainties

NLO distributions: dilepton invariant mass



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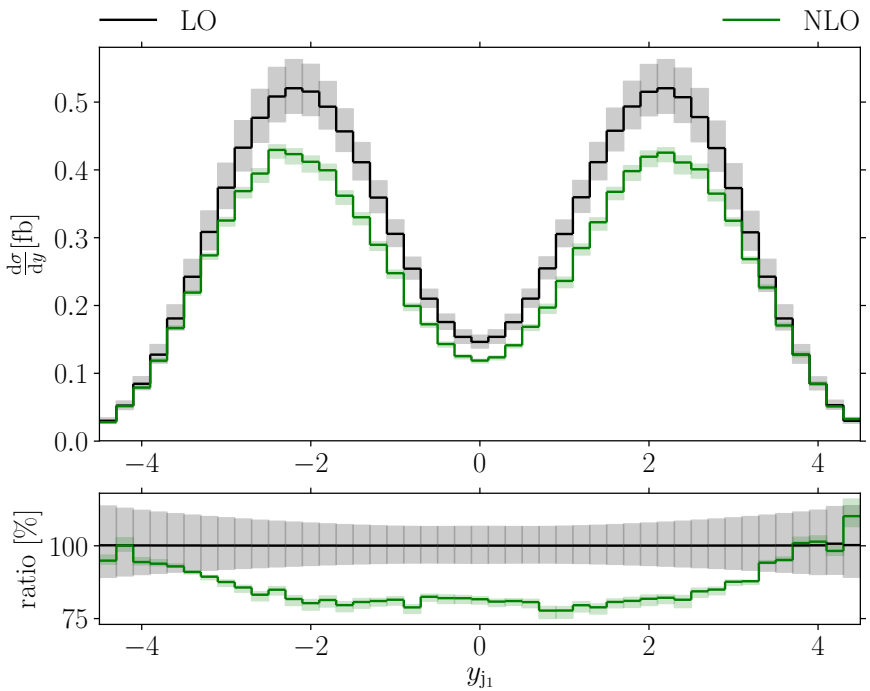
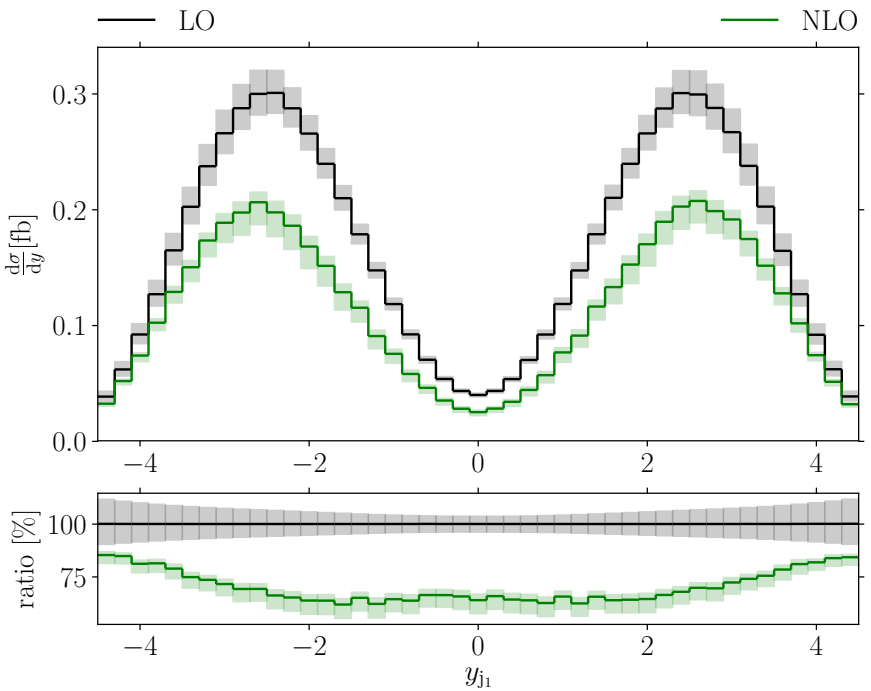
NLO distributions: leading jet rapidity





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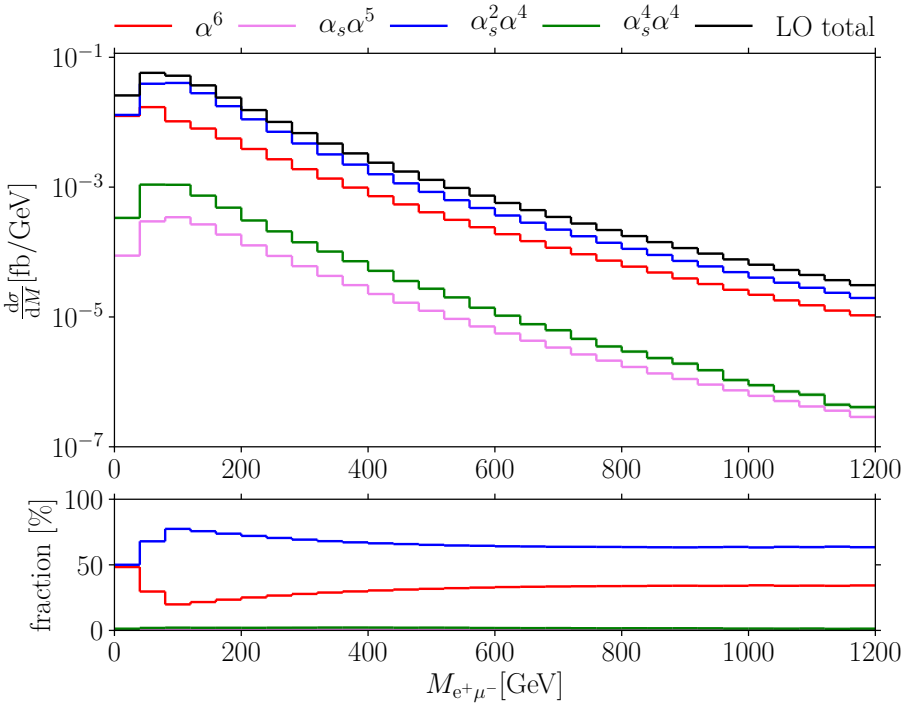
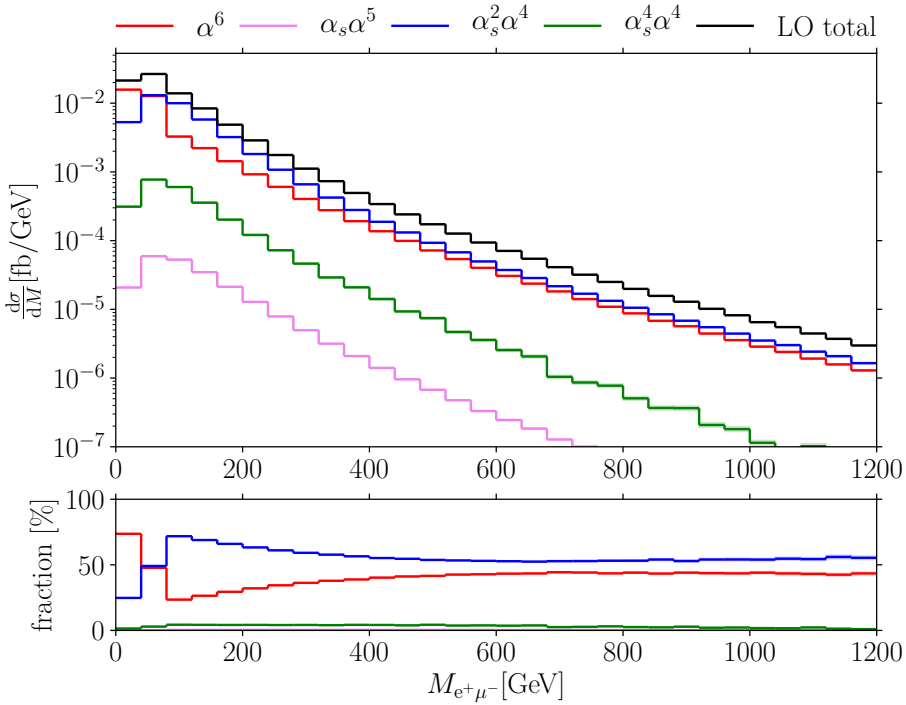
LO distributions: dilepton invariant mass





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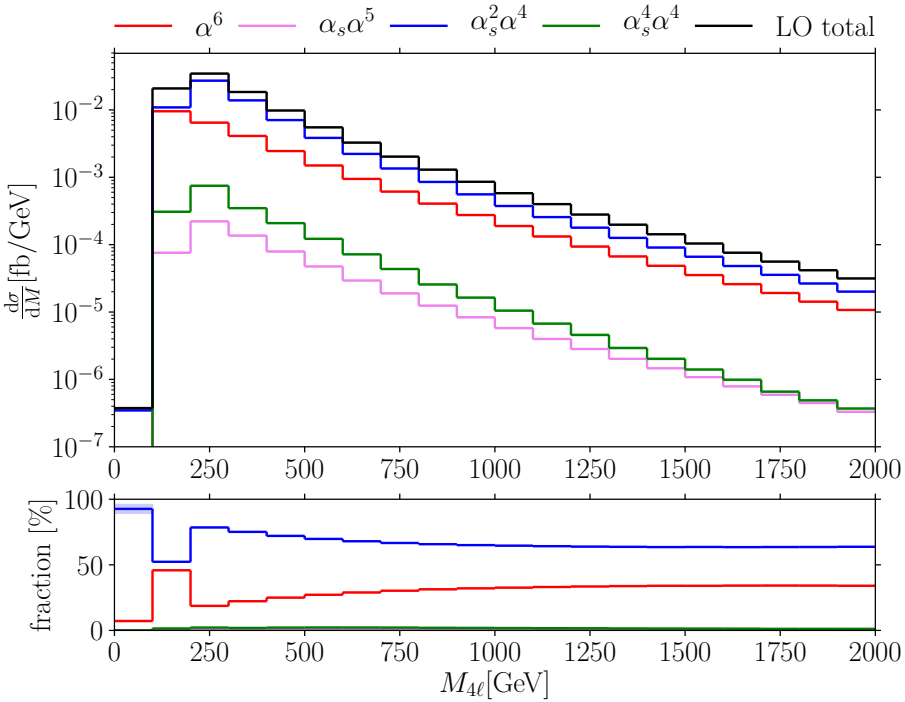
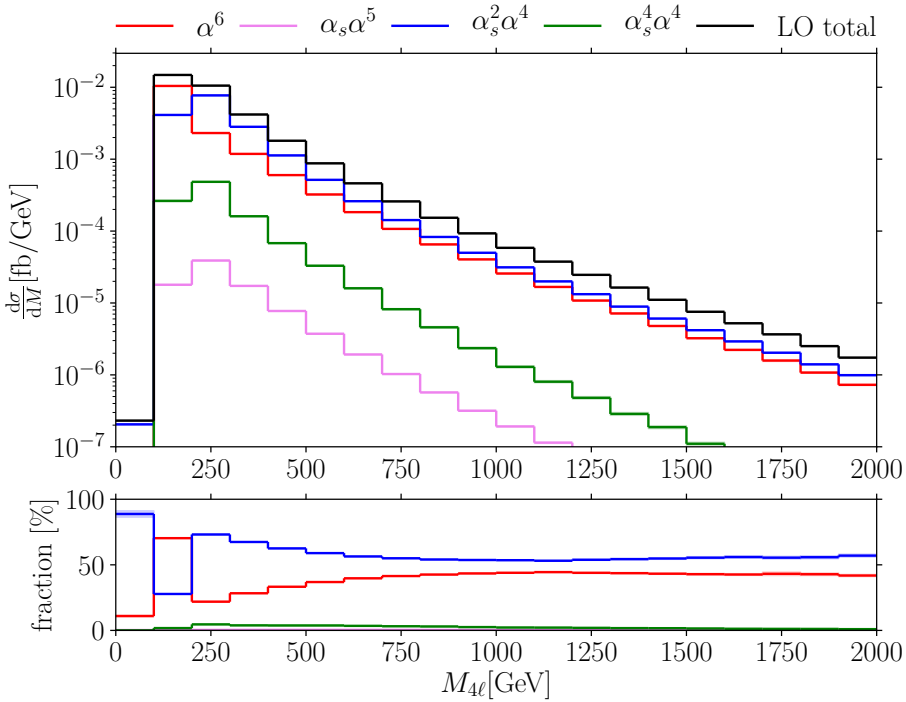
LO distributions: four-lepton invariant mass





- left: VBS-, right: Higgs-setup
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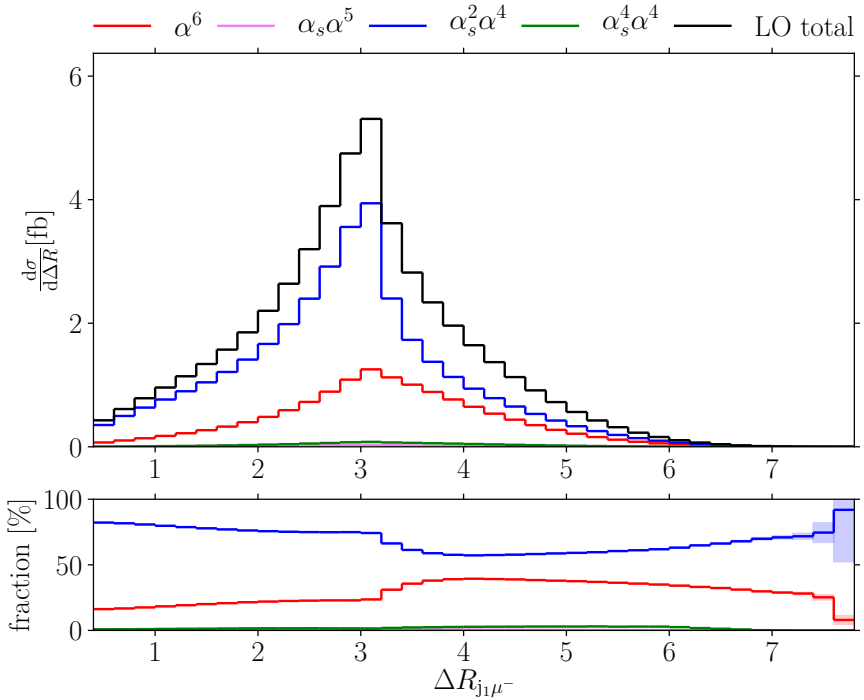
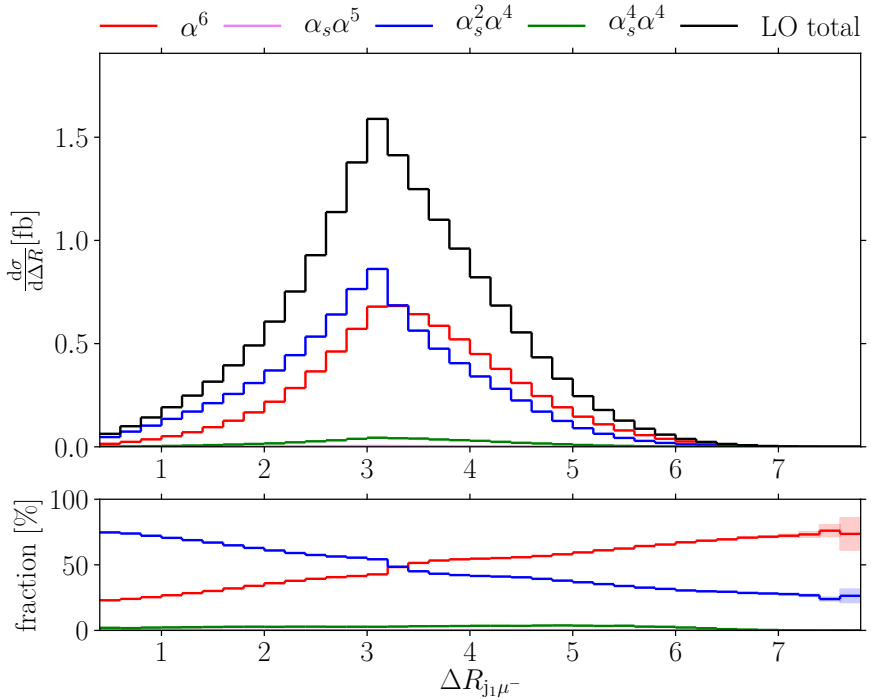
LO distributions: Leading-jet–muon distance





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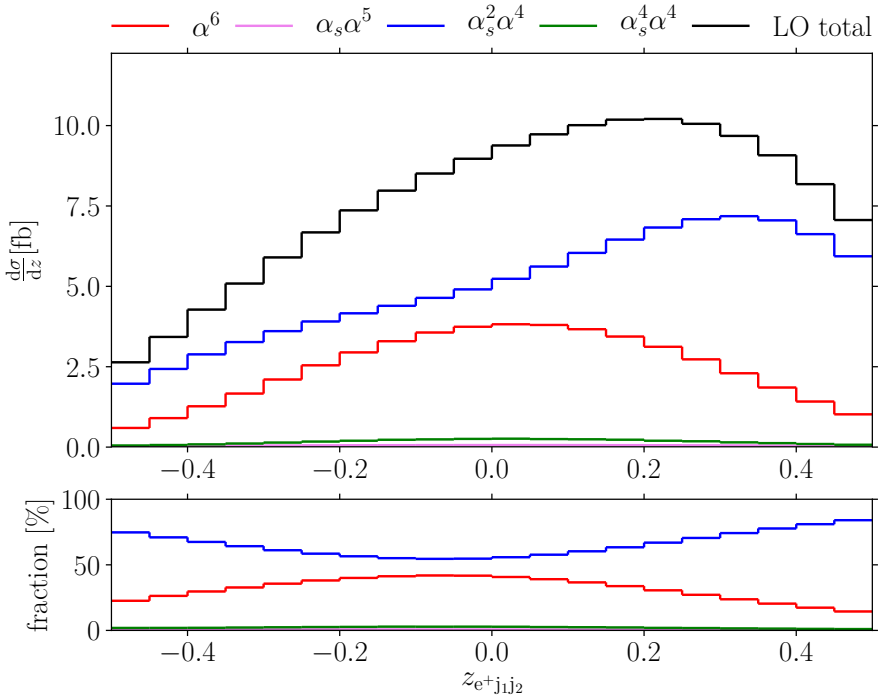
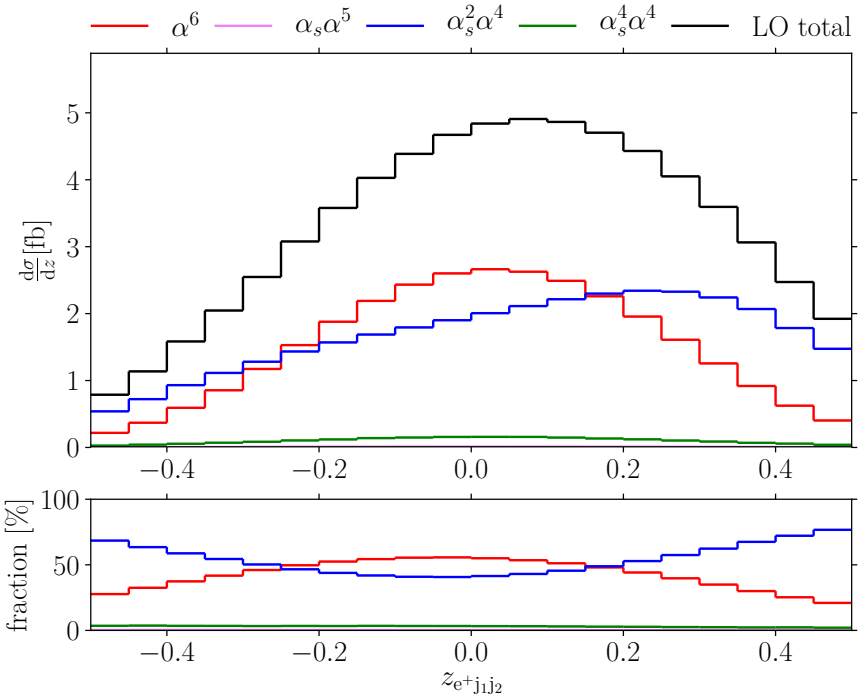
LO distributions: Centrality of the positron





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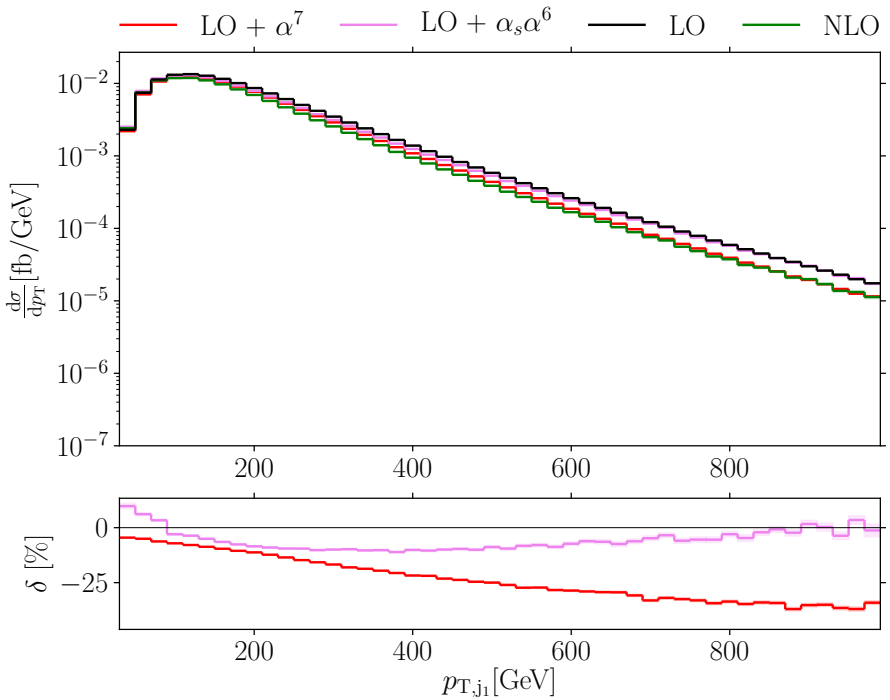
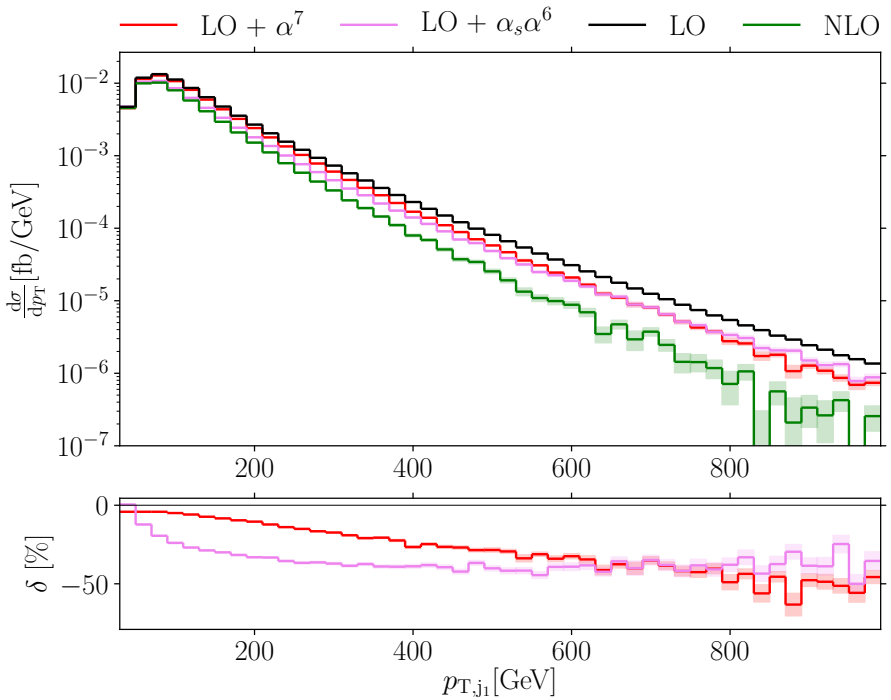
NLO distributions: leading jet transverse momentum





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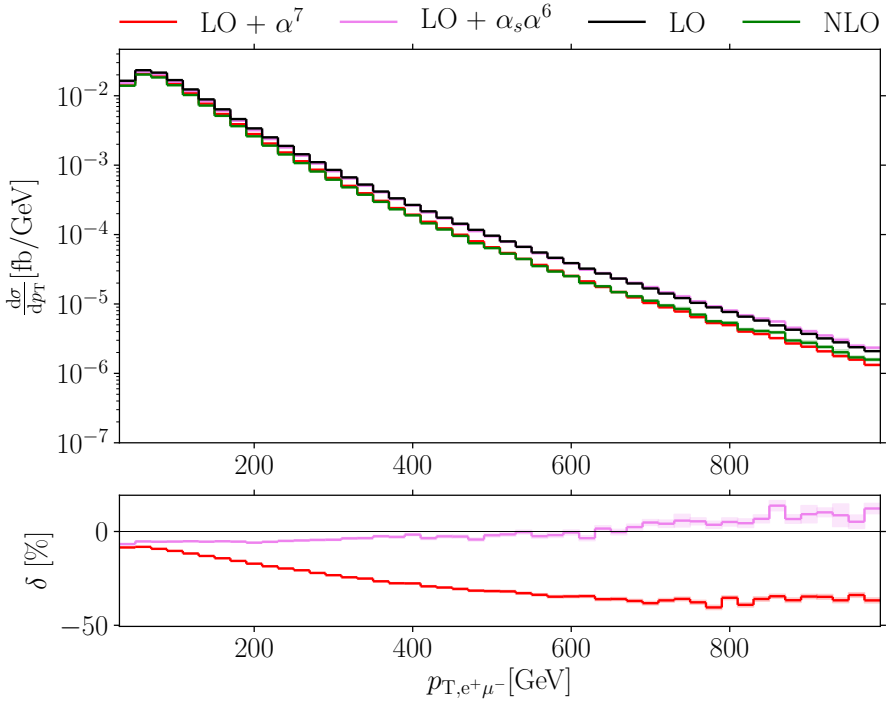
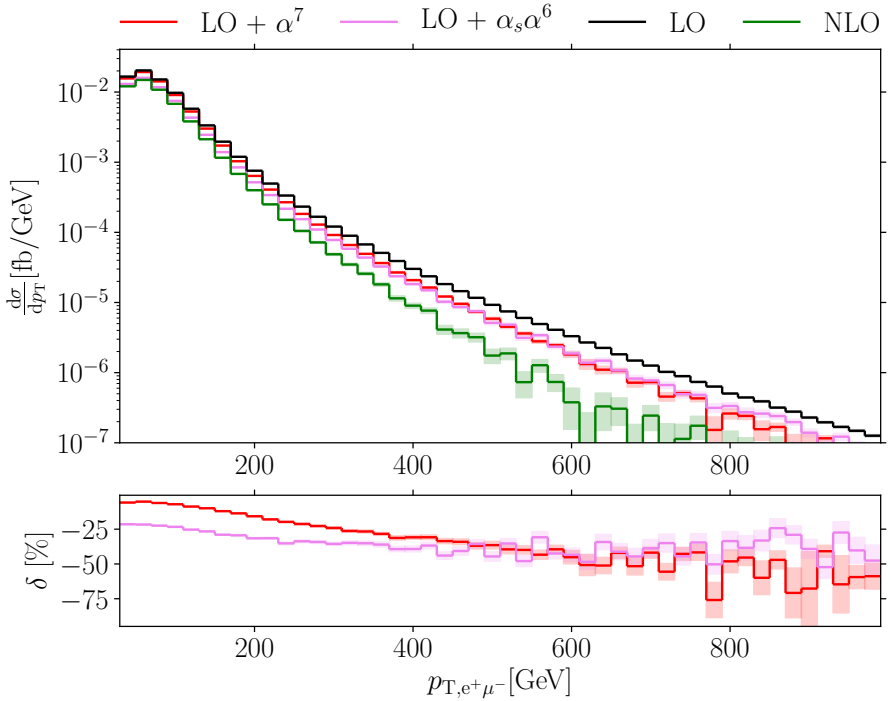
NLO distributions: dilepton transverse momentum





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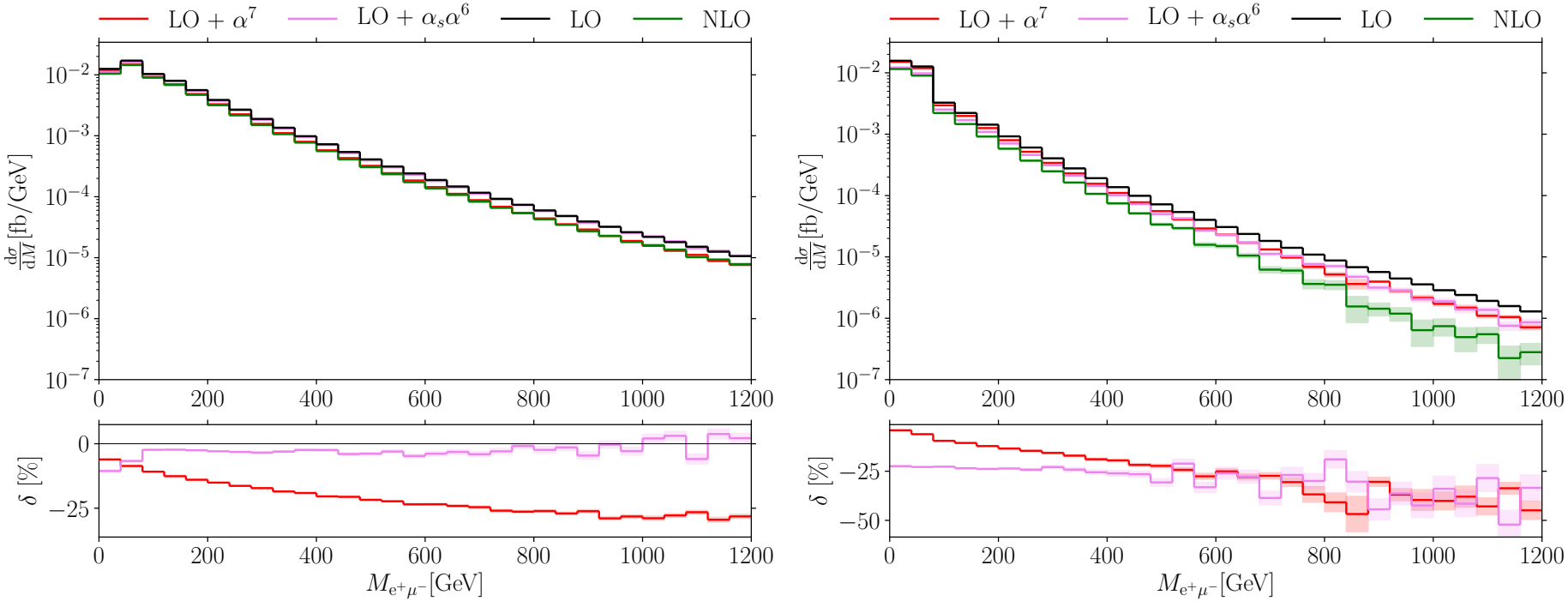
NLO distributions: dilepton invariant mass



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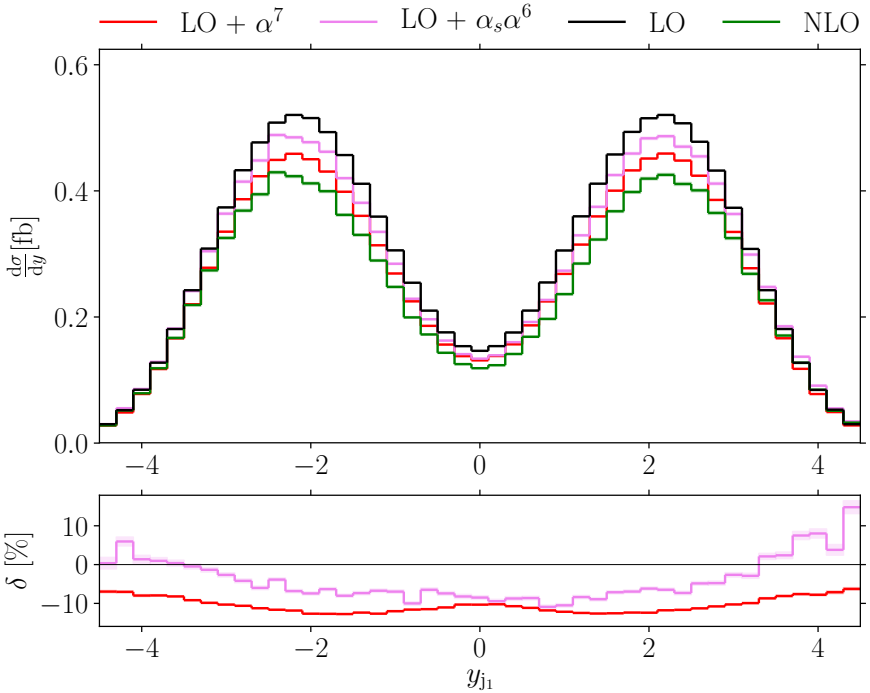
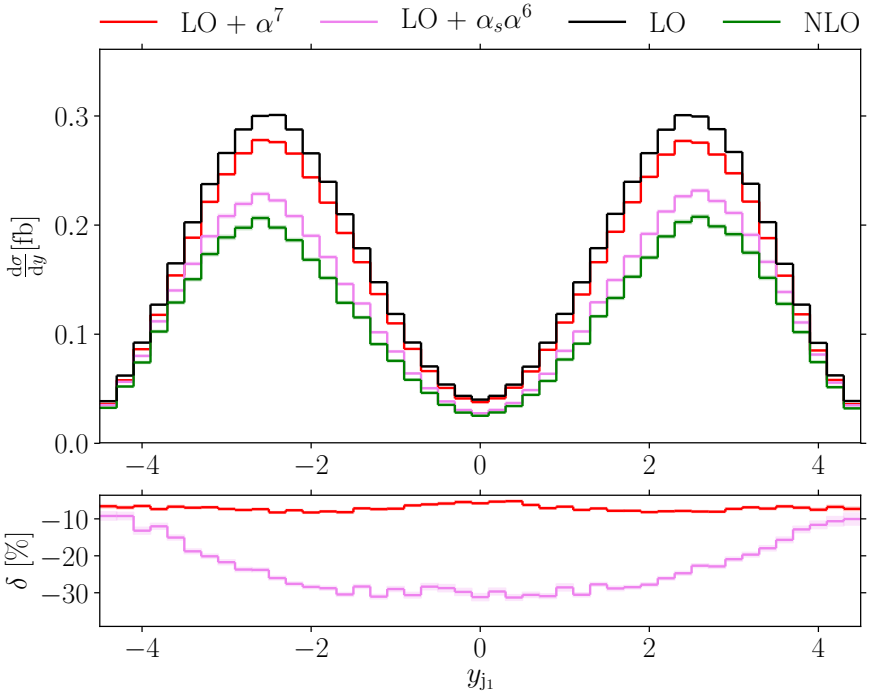
NLO distributions: leading jet rapidity





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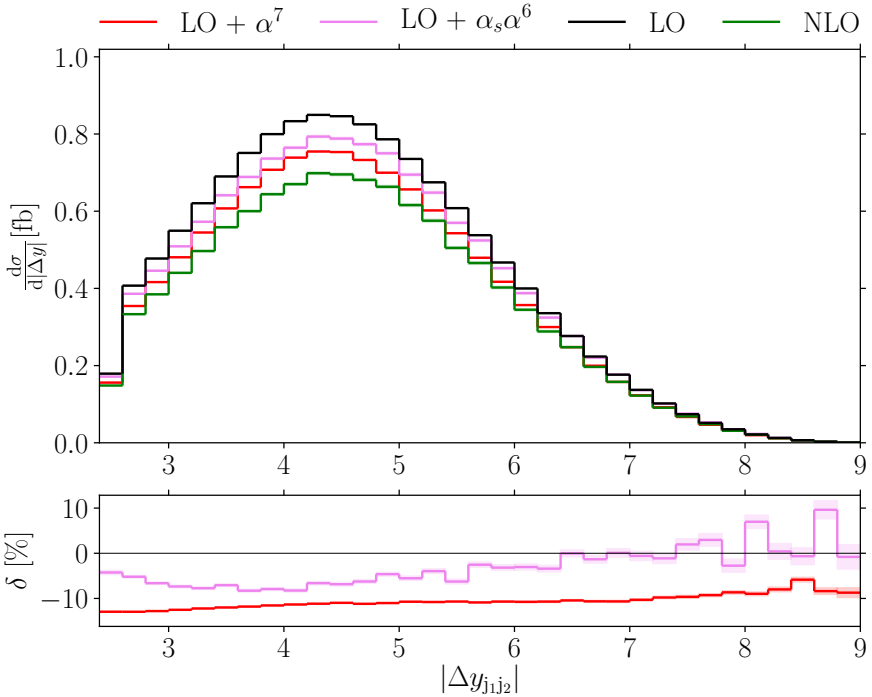
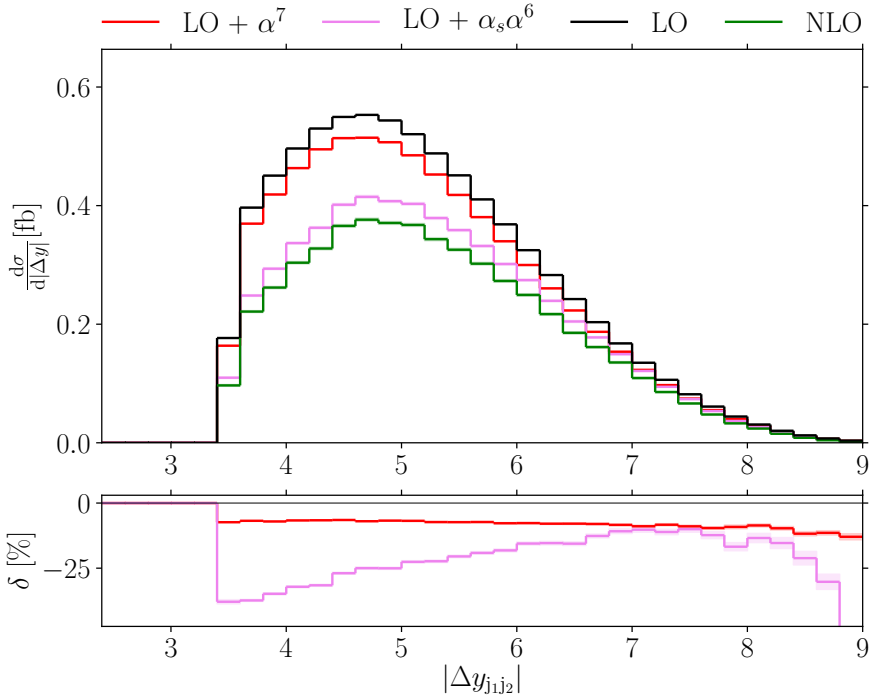
NLO distributions: leading jet rapidity separation





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