NLO EW/QCD corrections for W^+Z scattering at the LHC

$pp \to e^+\nu_e\,\mu^+\mu^-jj + X$ @ $\mathcal{O}(\alpha_s\alpha^6)$ and $O(\alpha^7)$ for $\sqrt{s} = 13\,\text{TeV}$

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with:
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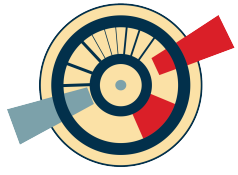
VBSCAN@Ljubljana, 11 February



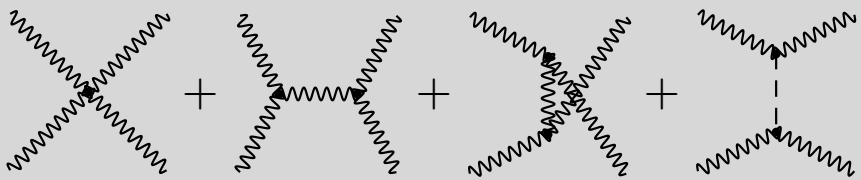
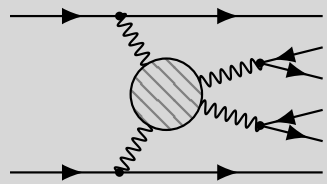
Outline

Vector-boson scattering in a nutshell

→ Scattering of two (massive) vector-bosons, e.g.:

- $W^{\pm}W^{\pm} \to W^{\pm}W^{\pm}$ ("like-sign W scattering") → focus of WG1 so far: [A. Ballestrero et al.]
- $W^{\pm}Z \to W^{\pm}Z$

$W^+Z \to W^+Z$ $\qquad pp \to e^+\nu_e\,\mu^+\mu^-jj + X$

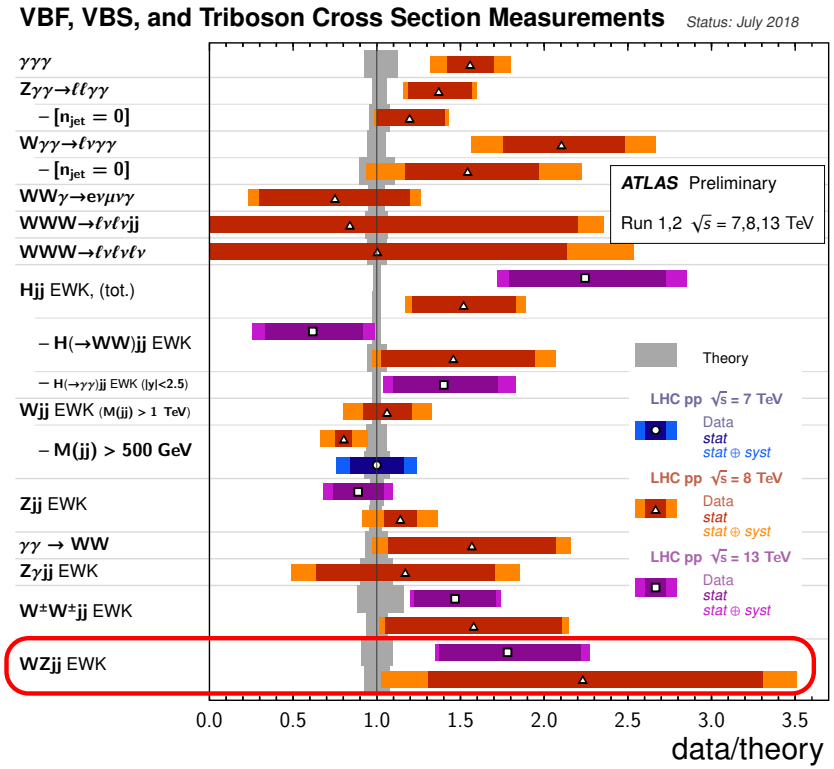
$\mathcal{M}_{\text{VBS}} =$  $\qquad \mathcal{M}_{\text{VBS@LHC}} =$  $+ \dots$

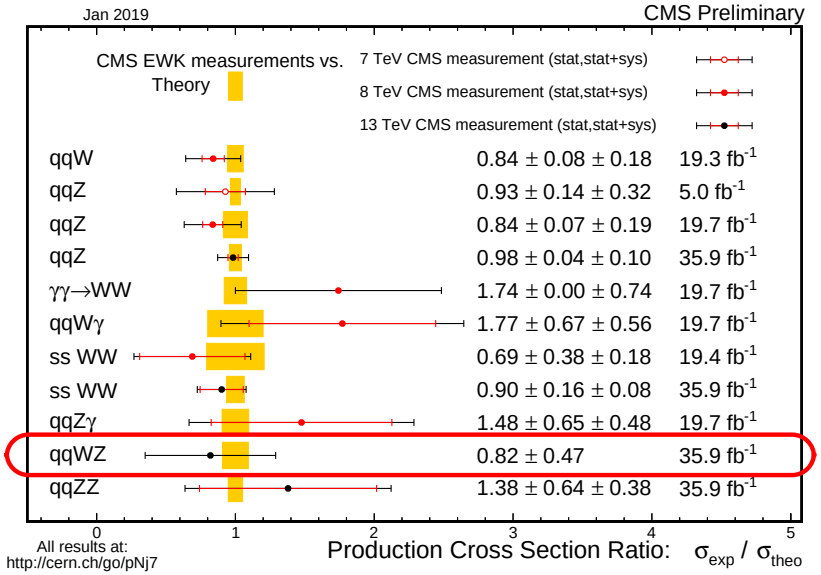
Vector-boson scattering (VBS) physics program:

- Constrain anomalous quartic gauge couplings (with triple-gauge boson prod.)
- Measure Higgs-vector-vector couplings, complementary to on-shell Higgs decay measurements
- Probe EW symmetry breaking: interplay between triple and quartic gauge couplings and the Higgs boson(s); large cancellations for longitudinal VBS: ensures tree-level unitarity

→ Precise prediction of the SM cross section needed

Experiment: $pp \to e^+\nu_e\,\mu^+\mu^-jj + X$



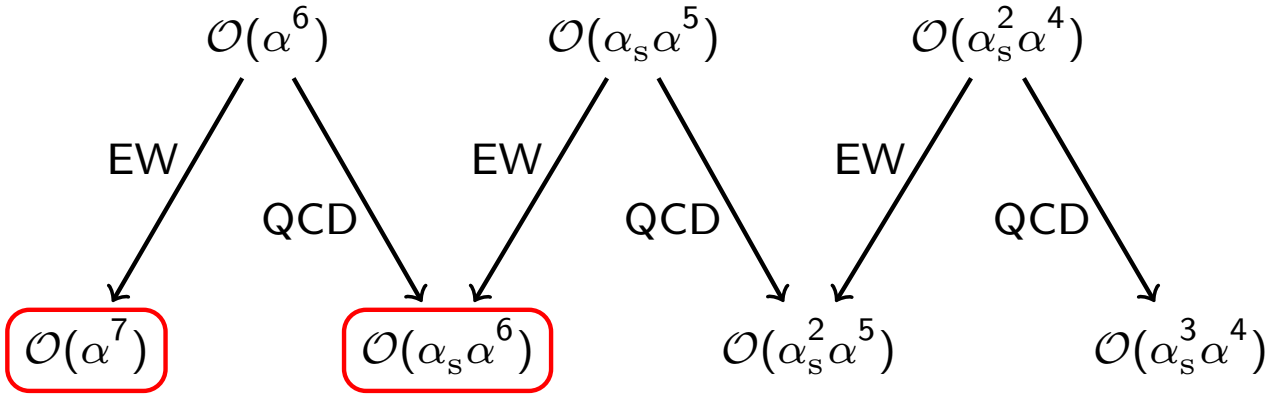


- ATLAS 8 TeV: [CERN-EP-2016-017]
- ATLAS 13 TeV: Obsers. with 5.6 σ sig. ($\mathcal{L} = 36.1\,\text{fb}^{-1}$) [ATLAS-CONF-2018-033]
- ATLAS 13 TeV: Obsers. with 5.3 σ sig. ($\mathcal{L} = 36.1\,\text{fb}^{-1}$) [CERN-EP-2018-286]

$\to$ talk by Narei Lorenzo Martinez

- CMS 13 TeV: Meas. with 1.9 σ sig. ($\mathcal{L} = 35.9\,\text{fb}^{-1}$) [CMS-PAS-SMP-18-001]
- CMS 13 TeV: Meas. with 2.2 σ sig. ($\mathcal{L} = 35.9\,\text{fb}^{-1}$) [CMS-SMP-18-001]

Theory: $pp \to e^+ \nu_e \mu^+ \mu^- jj + X$



- All LOs presented in Sec. V.3 of the SM Les Houches 2017 report [Bendavid et al.]: QCD (~80%) dominates over EW
- Approx. $\mathcal{O}(\alpha_s\alpha^6)$: +4% [Bozzi, Jäger, Oleari, Zeppenfeld]
- $\mathcal{O}(\alpha_s^3\alpha^4)$ calculation available [Campanario, Kerner, Ninh, Zeppenfeld]
- Parton-shower effects of the EW production [Jäger, Karlberg, Scheller]

$\to$ $\mathcal{O}(\alpha^7)$ EW corrections desirable, because like-sign case shows large corrections (-16%)

$\to$ calculate full $\mathcal{O}(\alpha_s\alpha^6)$ for an updated setup, check validity of approximations

Fiducial phase space volume and parameters

Cuts are exactly the "Loose Fiducial" cuts defined by CMS[1] [CMS-PAS-SMP-18-001]:

- At least two $R = 0.4$ anti-k_t jets with $p_T > 30\,\text{GeV}$, $|\eta| < 4.7$, and $\Delta R_{j\ell} > 0.4$
- $M_{j_1 j_2} > 500\,\text{GeV}$, $\Delta\eta_{j_1 j_2} > 2.5$
- $p_{T,\ell} > 20\,\text{GeV}$ and $|y_\ell| < 2.5$
- $|M_{\mu\bar{\mu}} - M_Z| < 15\,\text{GeV}$
- $M_{\ell\ell} > 4.0\,\text{GeV}$ and $M_{3\ell} > 100.0\,\text{GeV}$

Other:

- Photons recombined with charged particles using anti-k_t algorithm with $R = 0.1$
- PDFs: `NNPDF31_nlo_as_0118_luxqed`
- $\sqrt{s} = 13\,\text{TeV}$

Complex mass scheme [Denner, Dittmaier, Roth, Wackeroth][Denner, Dittmaier, Roth, Wieders], input parameters:

- $G_\mu = 1.6638 \times 10^{-5}\,\text{GeV}^{-2}$
- $M_W = 80.3530\,\text{GeV}$, $\Gamma_W = 2.0843\,\text{GeV}$
- $M_Z = 91.1535\,\text{GeV}$, $\Gamma_Z = 2.4943\,\text{GeV}$
- $M_H = 125.0\,\text{GeV}$, $\Gamma_H = 4.07 \times 10^{-3}\,\text{GeV}$

with EW coupling calculated as:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

Scale choice:

- $\mu = \sqrt{p_{T,j_1} \cdot p_{T,j_2}}$ [Denner, Hošeková, Kallweit]
- 7-point scale variation to estimate pert. uncertainty

[1] Results for an ATLAS-like setup in backup-slides

Outline

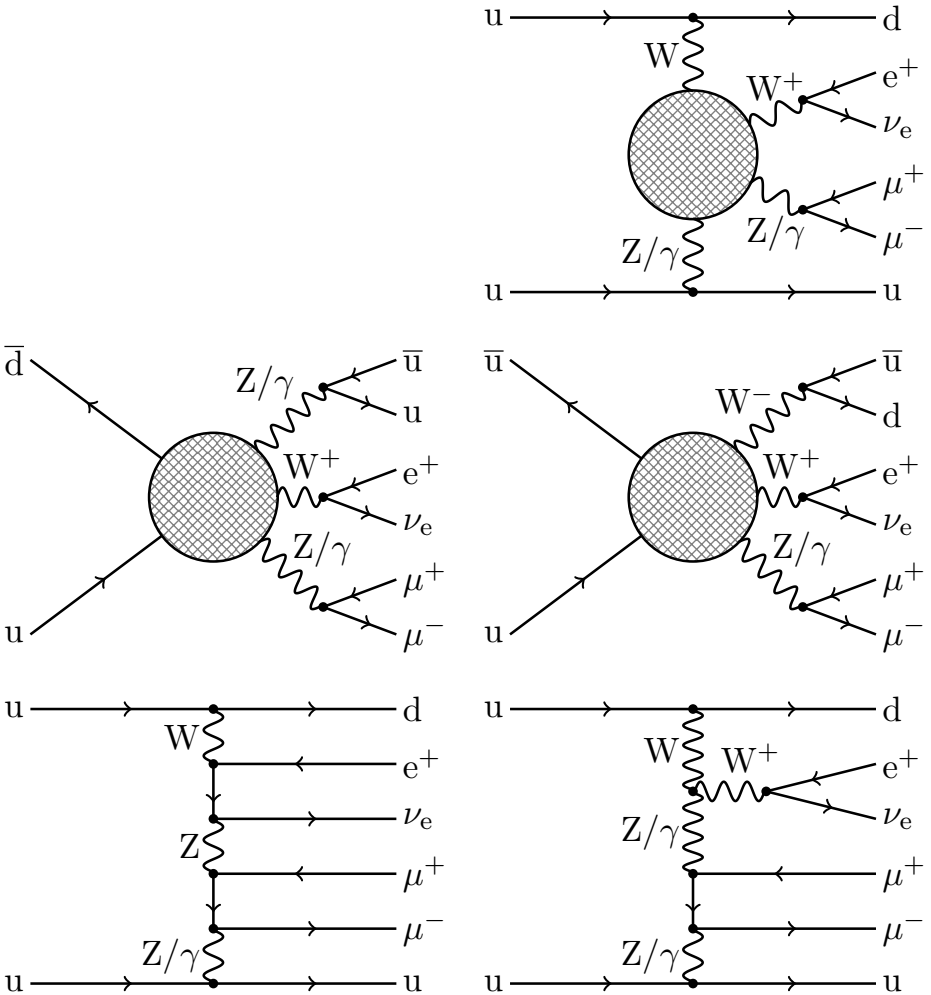
Overview: leading orders

For $pp \to e^+ \nu_e \mu^+ \mu^- jj + X$ two different leading orders (LO): $\mathcal{O}(g_s^2 e^4)$ and $\mathcal{O}(e^6)$.

We divided them into five (mutually exclusive) classes:

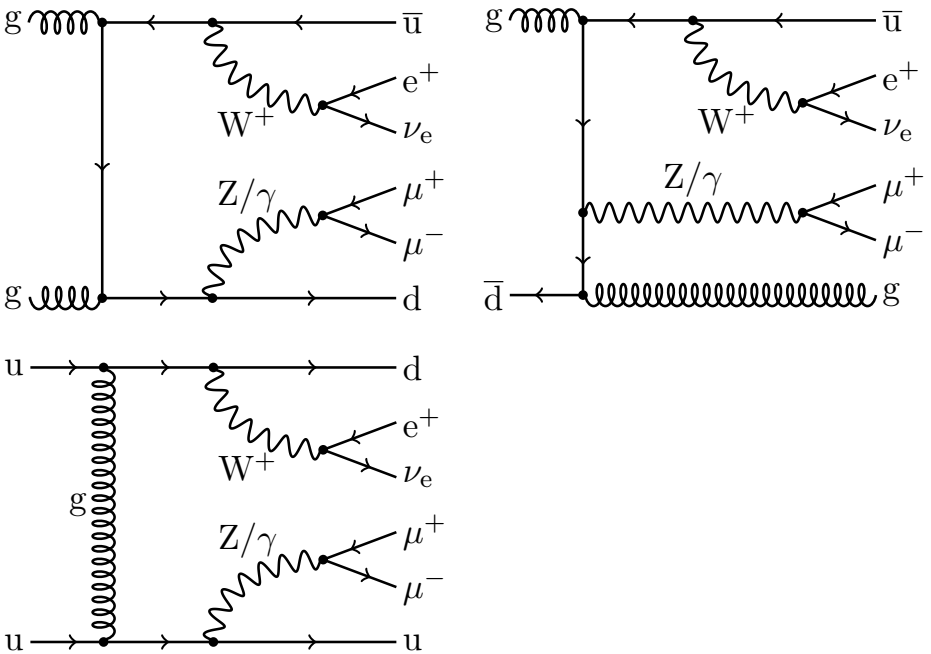
1. $\mathcal{O}(\alpha^6)$ electroweak production with quark-quark initial state (but without bottom-quarks)
2. $\mathcal{O}(\alpha_s^2 \alpha^4)$ strong production (without bottom-quarks)
3. $\mathcal{O}(\alpha_s \alpha^5)$ quark-quark interference
4. $\mathcal{O}(\alpha^6)$ double-photon initiated and $\mathcal{O}(\alpha_s \alpha^6)$ single-photon initiated
5. $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha_s^2 \alpha^4)$ with bottom-quarks

Electroweak production LOs



- 40 different partonic channels at $\mathcal{O}(\alpha^6)$
- contain the vector-boson scattering subdiagrams,
- and "semi-leptonic triple-gauge-boson production" processes ($W^{\pm}ZZ$ and W^+W^-Z),
- and other double-, single, non-resonant diagrams

Strong production LOs

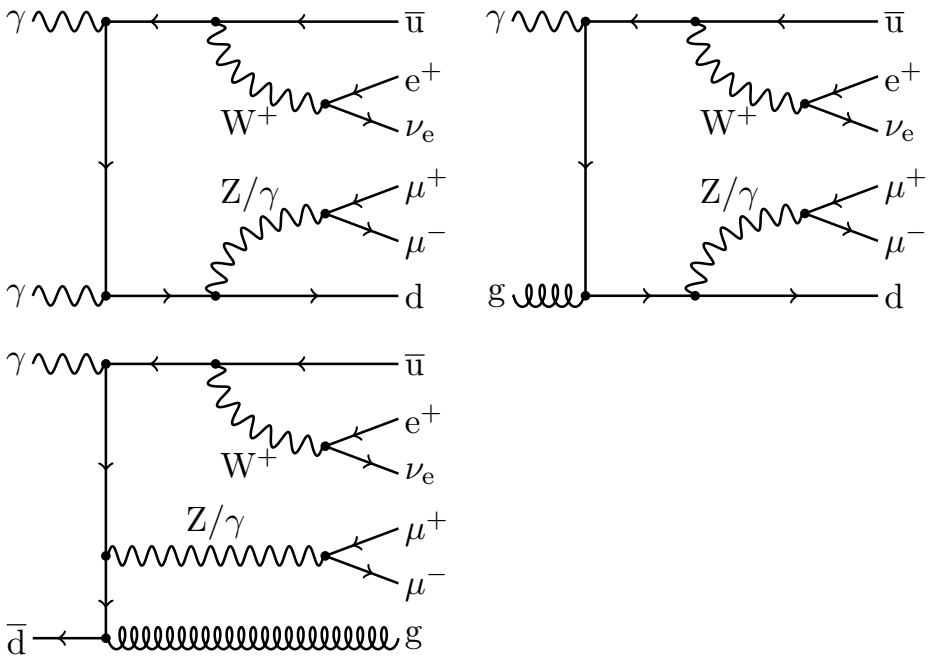


→ In comparison to like-sign W-scattering gluons are possible at LO (charge)

- 8 additional diagrams with two gluons, making up 66 % of the cross section

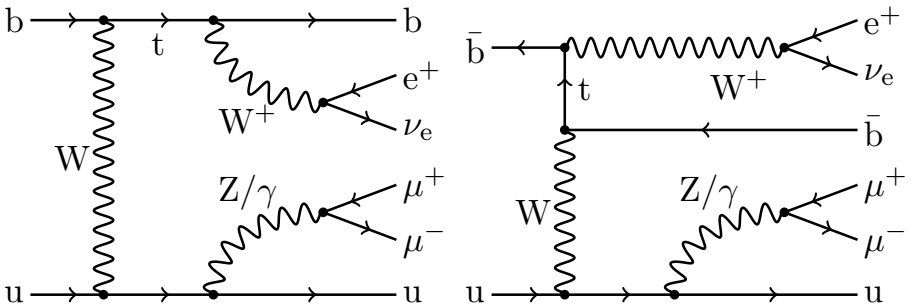
→ in total the $\mathcal{O}(\alpha_s^2\alpha^4)$ is 4.3 times larger than the electroweak LOs

Photon-initiated LOs



- 2 double photon MEs at $\mathcal{O}(\alpha^6)$ (tiny contribution)
- 12 photon–gluon MEs at $\mathcal{O}(\alpha_s\alpha^5)$ (very small contribution)
- remember: no final state photons at LO because of $n_j \geq 2$

Bottom-quark LOs



- 12 MEs with bottom-quarks

→ "top-Z-jet production" for the $bu/bc \to e^+\nu_e\,\mu^+\mu^- bu/c$

- only resonant tops, no resonant anti-tops because of $W^+ \to$ up-bottom contribution dominates over all others (90 %)
- contribution comparible in size with the EW LOs
- separable with b-tagging

LO integrated cross sections

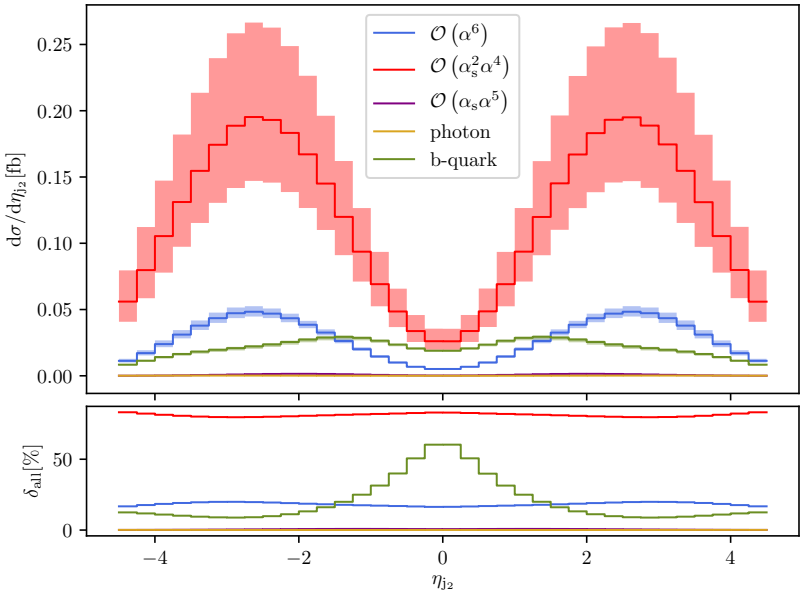
Integrated xs for $pp \to e^+\nu_e\,\mu^+\mu^-jj$ @ $\sqrt{s} = 13\,\text{TeV}$:

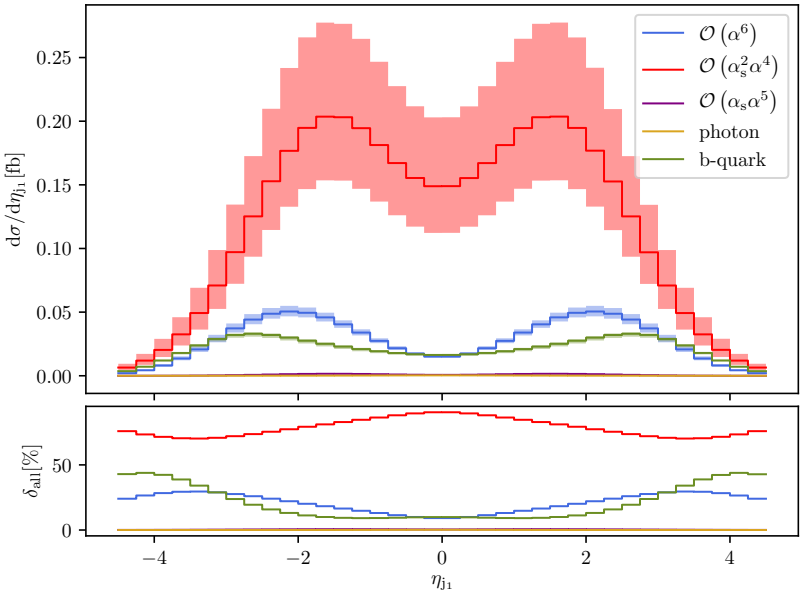
Sum [fb]	EW [fb]	QCD [fb]	Int. [fb]
1.55	$0.255^{+9.03\,\%}_{-7.75\,\%}$	$1.10^{+37.0\,\%}_{-24.9\,\%}$	$0.006\,82^{+18.4\,\%}_{-14.4\,\%}$
$100\,\%$	$16.4\,\%$	$70.6\,\%$	$0.439\,\%$

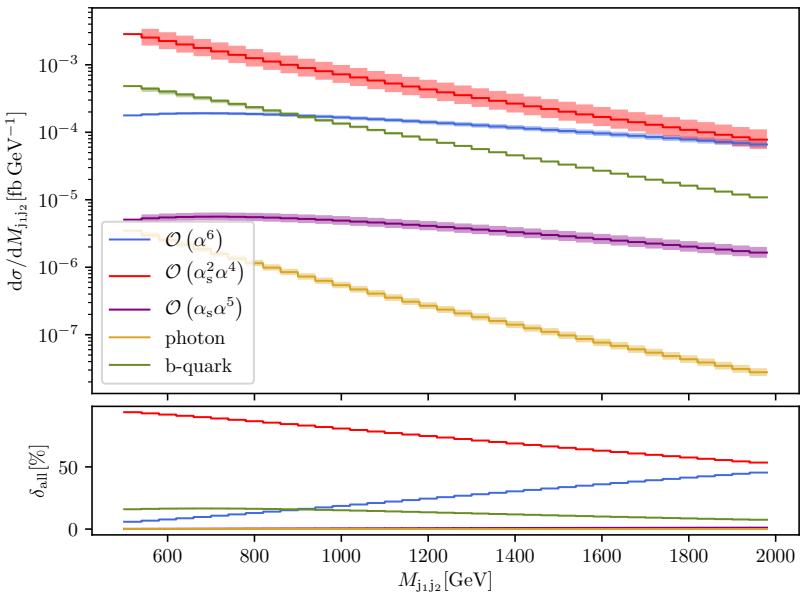
Photons [fb]	Bottom-quarks [fb]
$0.000\,988^{+11.5\,\%}_{-9.47\,\%}$	$0.195^{+3.59\,\%}_{-7.22\,\%}$
$0.0636\,\%$	$12.5\,\%$

- very large QCD contributions mainly due to gluon-PDF
- small interference (known from like-sign VBS)
- smaller EW contribution compared to like-sign VBS ($\to$ Z-boson)
- photon contributions completely irrelevant $\to$ leave out photon-initiated at NLO
- important: bottom-quark contributions

Jet observables

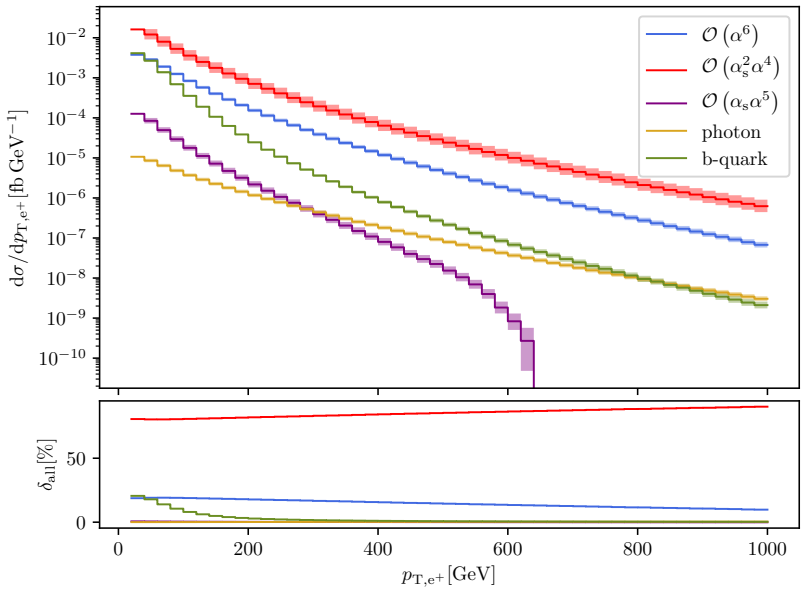


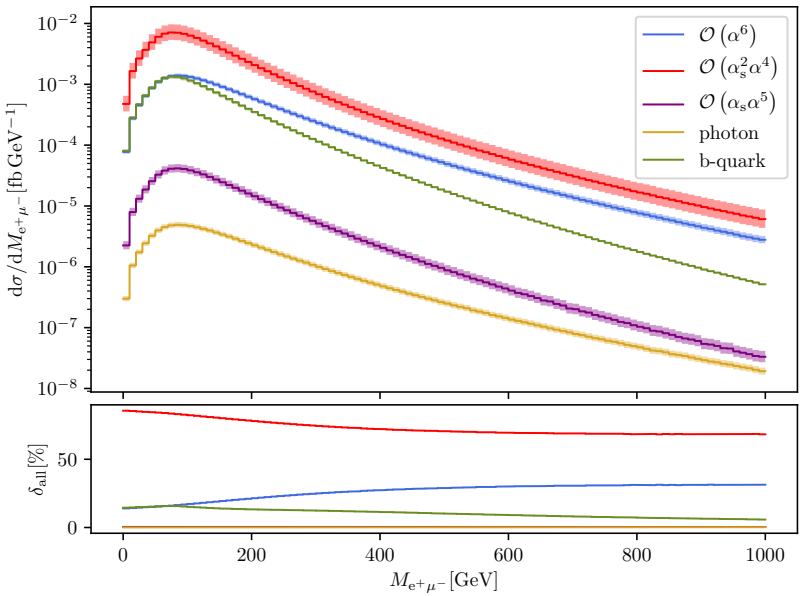


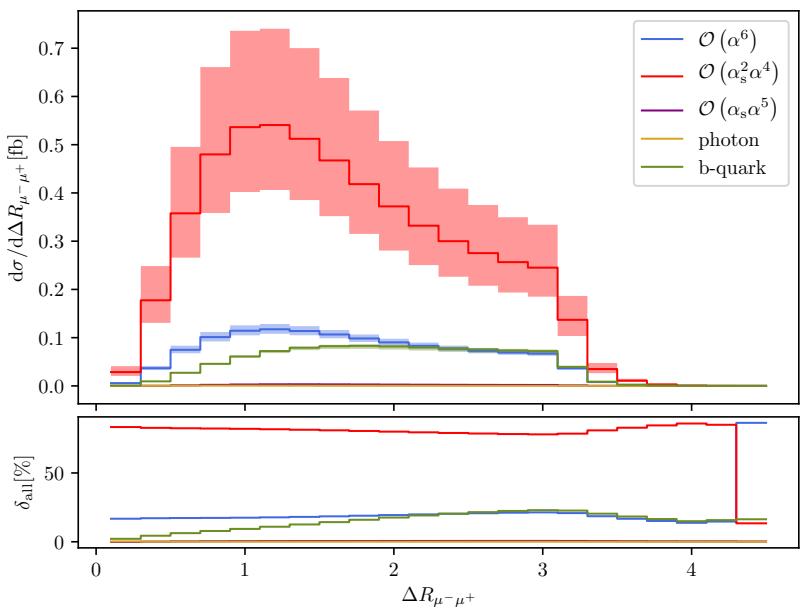


- δ_{all}: percentage of each contr. to the sum
- Crossover between EW/bottom-quarks at $M_{j_1j_2} \approx 900\,\text{GeV}$ and EW/QCD at $M_{j_1j_2} \approx 2100\,\text{GeV}$
- interesting behavior of the subleading jet for bottom-quark contributions for the central region
- large QCD uncertainty band due to α_s^2 vs. α_s^0 in the EW

Leptonic observables





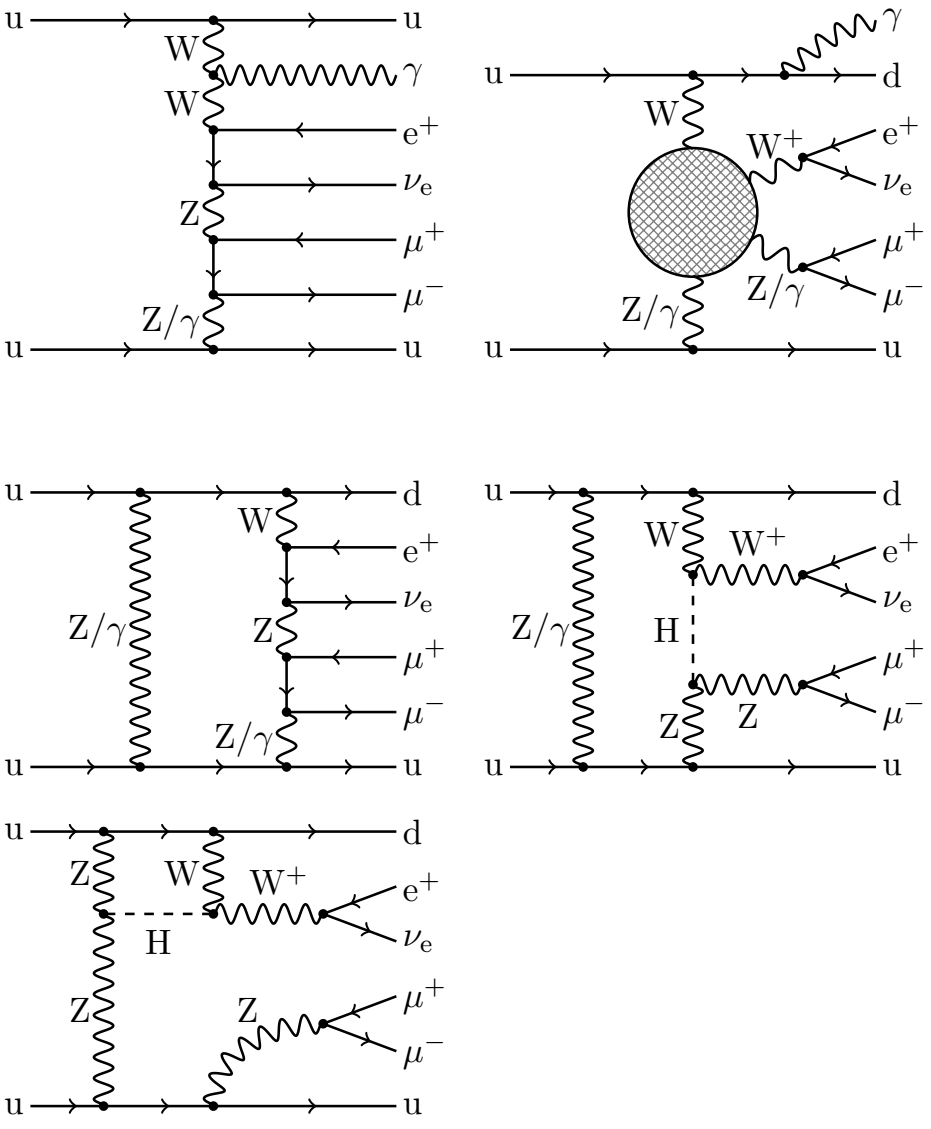


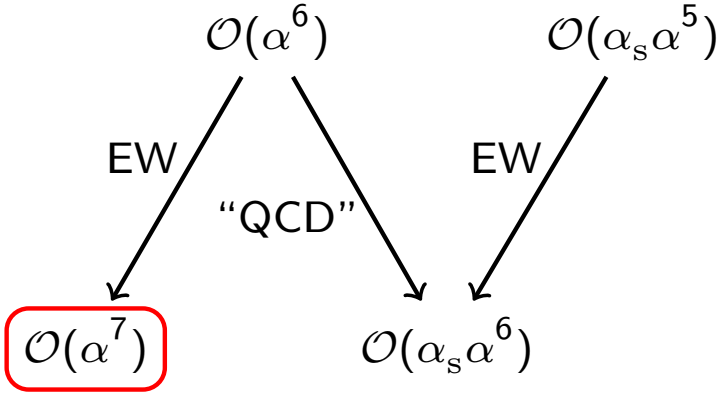
- Cuts $M_{\mu^-\mu^+} < M_Z + 15\,\mathrm{GeV}$ and $p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$ limit $\Delta\eta_{\mu^-\mu^+} < 3.4$, so that $\Delta R < 4.6$

$$\cosh \Delta\eta_{\ell_1\ell_2} = \frac{M_{\ell_1\ell_2}}{2p_{\mathrm{T},\ell_1}p_{\mathrm{T},\ell_2}} + \cos\phi_{\ell_1\ell_2}$$

Outline

$\mathcal{O}(\alpha^7)$ real and virtual correction diagrams

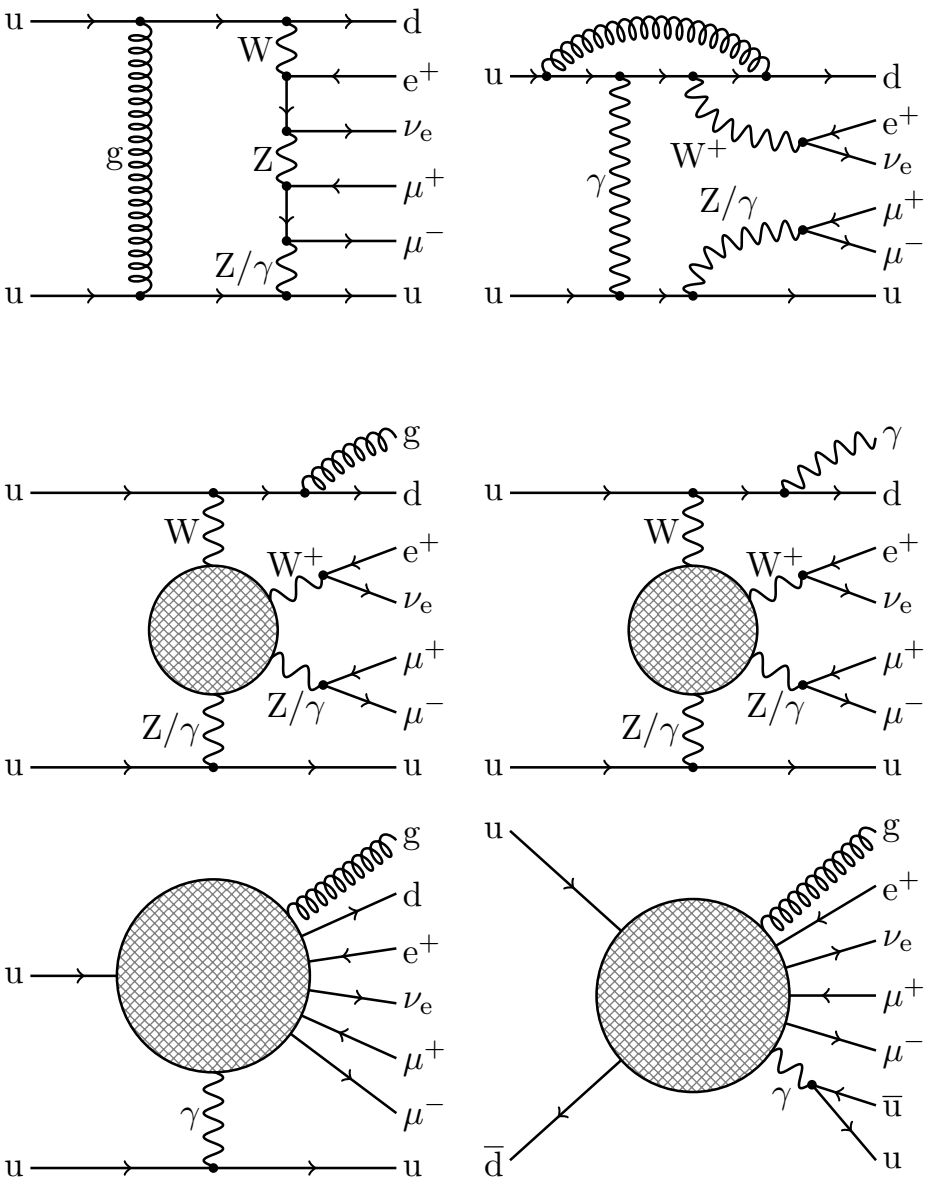


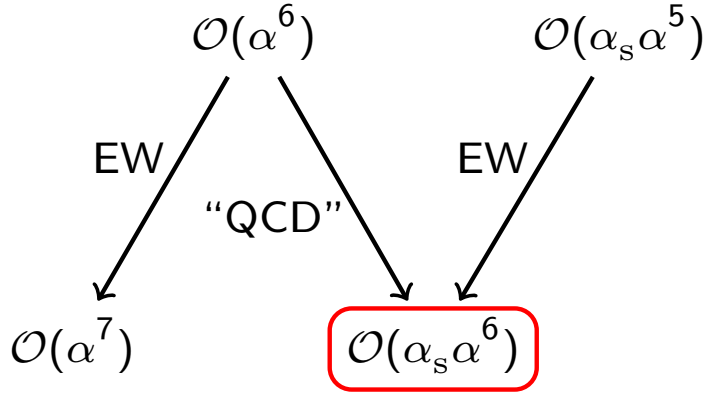


- Real radiation → add photon
- Neglect real MEs with initial state photons

- Loops with 8-point functions, different complex masses
- More diagrams with Higgs bosons!
- Up to 83,000 diagrams per initial state

$\mathcal{O}(\alpha_s\alpha^6)$ mixed corrections: "QCD"





→ Correction is neither purely QCD/EW, it is mixed

- photon initial-state singularities: cancelled with collinear counterterm (PDFs)
- photon final-state singularities: require photon-to-jet transition functions (strictly speaking)
- many partonic channels and contributions: 40 virtuals, 16 EW reals, 40+28 QCD reals, 16 EW int. dipoles, 40 QCD int. dipoles, ...

Outline

Integrated cross section

Integrated xs for $pp \to e^+\nu_e\,\mu^+\mu^- jj + X$ @ $\sqrt{s} = 13\,\text{TeV}$:

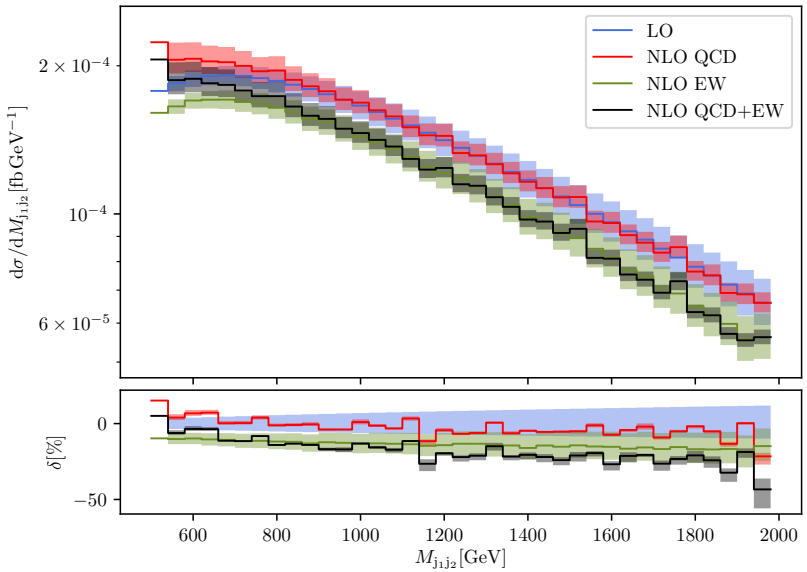
LO[2] [fb]	NLO EW [fb]	NLO QCD [fb]	NLO EW+QCD [fb]
$0.255^{+9.03\,\%}_{-7.75\,\%}$	$0.214^{+8.62\,\%}_{-7.43\,\%}$	$0.250^{+0.970\,\%}_{-0.960\,\%}$	$0.209^{+0.750\,\%}_{-1.08\,\%}$
	$-16.0\,\%$	$-1.93\,\%$	$-17.9\,\%$

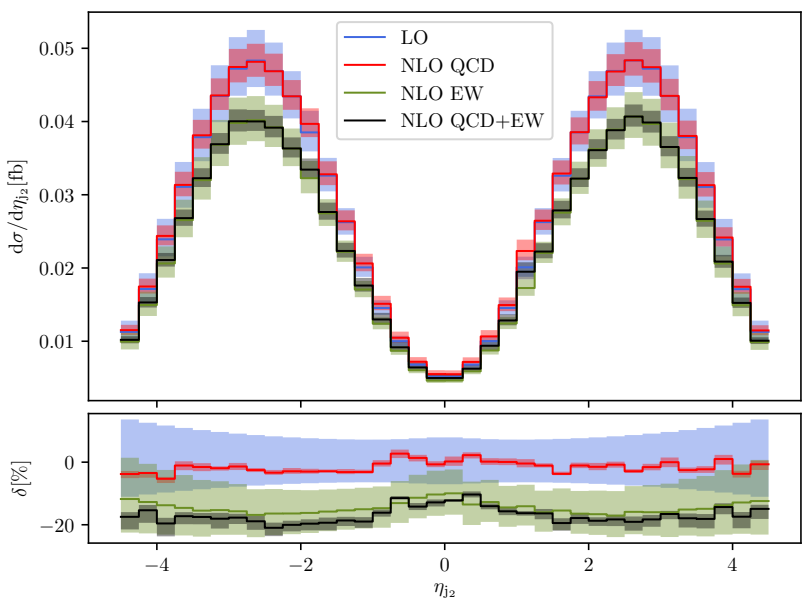
Please note: NLO QCD (and NLO EW+QCD) are preliminary

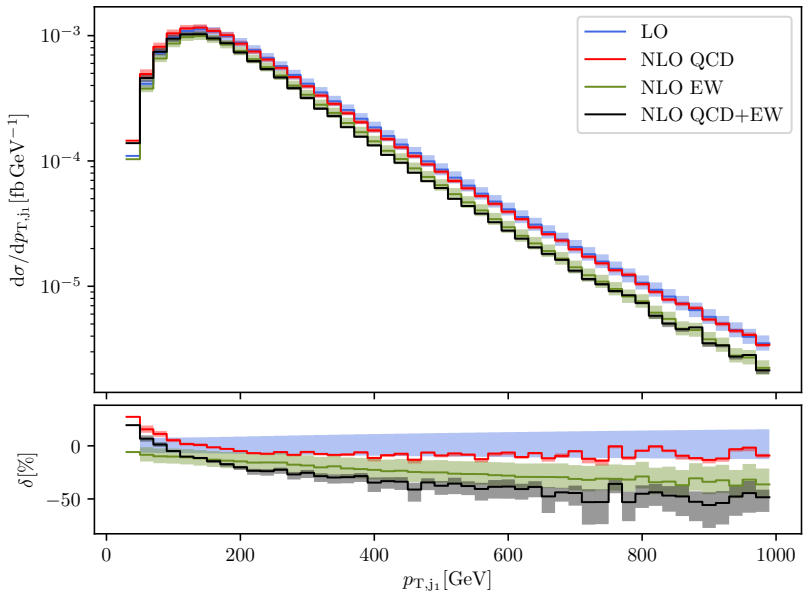
- No dep. on $\mu_R \to$ No reduction of the pert. uncertainty for the NLO EW
- Large corrections on the integrated cross section, comparable to like-sign scattering
- Corrections are larger in specific regions of p_T distributions
- QCD corrections rather small

[2] only $\mathcal{O}(\alpha^6)$

Jet observables

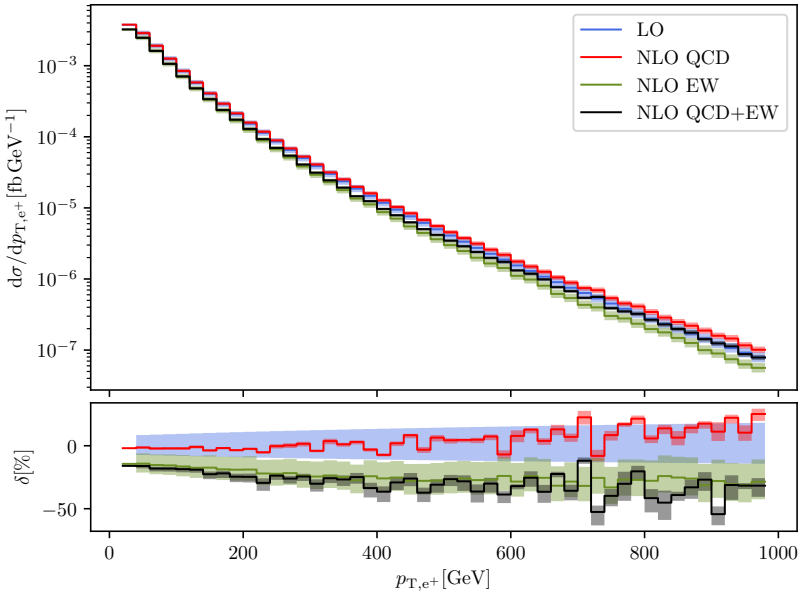


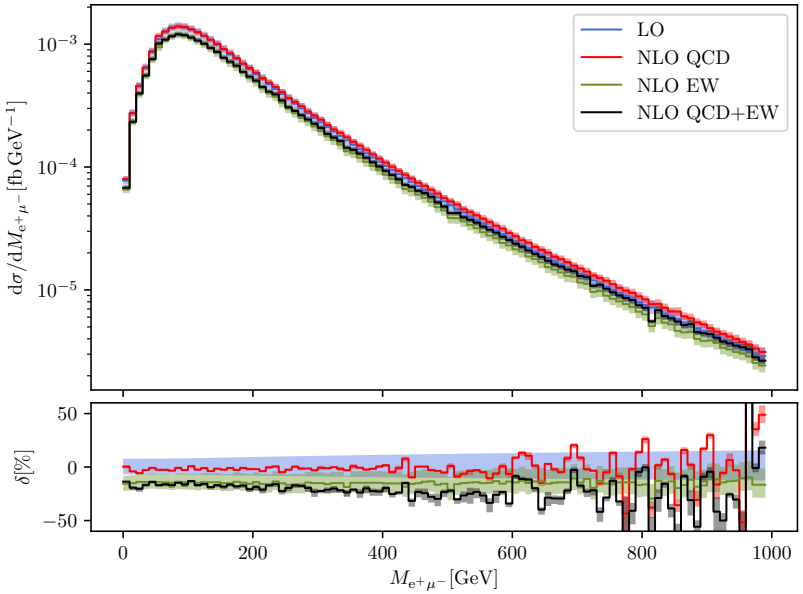


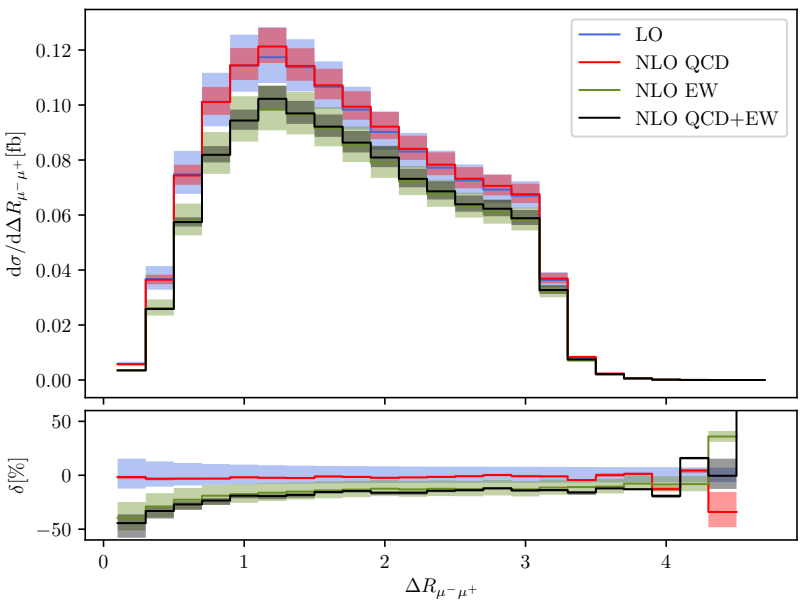


- Please note: NLO QCD (and NLO EW+QCD) are preliminary
- EW/QCD corrections basically flat for $M_{\mathrm{j_1j_2}}$
- $M_{\mathrm{e^+\mu^-}}$ very flat conc. EW and QCD corrections
- EW corrections become more negative for large $p_{\mathrm{T,j_1}}$

Leptonic observables







- Please note: NLO QCD (and NLO EW+QCD) are preliminary
- EW corrections "remove" events where the muons are close

Summary

- After W^+W^+, W^+Z scattering is the next important channel for VBS
- Large EW corrections for a realistic setup: $-16\,\%$
- Even larger corrections for some p_T observables
- First preliminary results for the complete $\mathcal{O}(\alpha_s\alpha^6)$: small corrections, $-2\,\%$
- Confirms that $\mu = \sqrt{p_{T,j_1} \cdot p_{T,j_2}}$ is (still) a good scale choice

Acknowlegments

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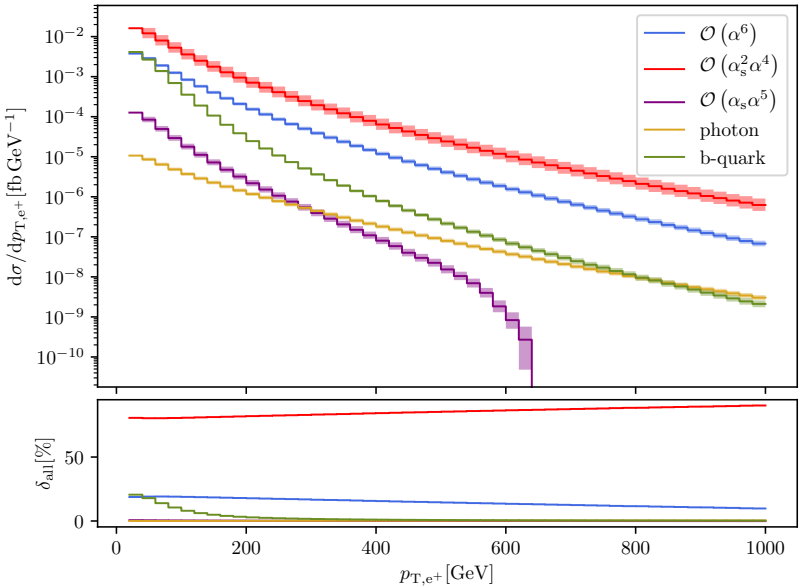
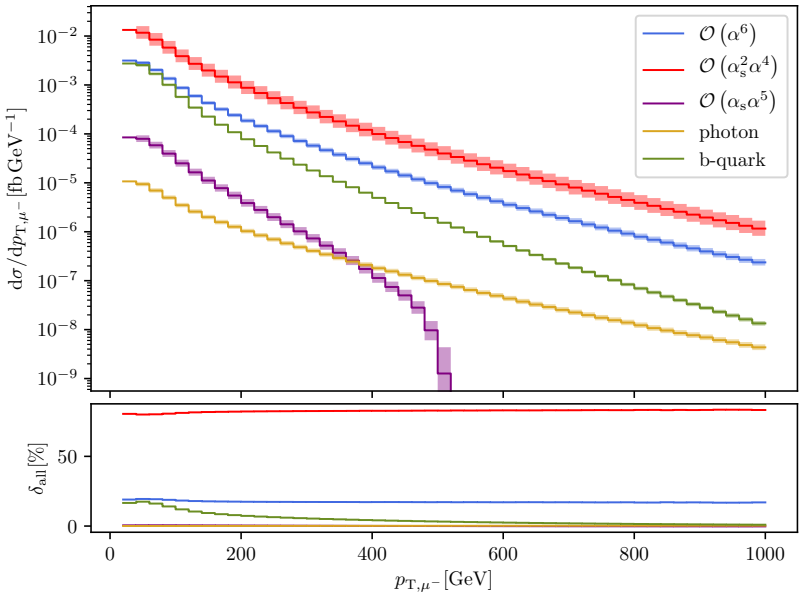
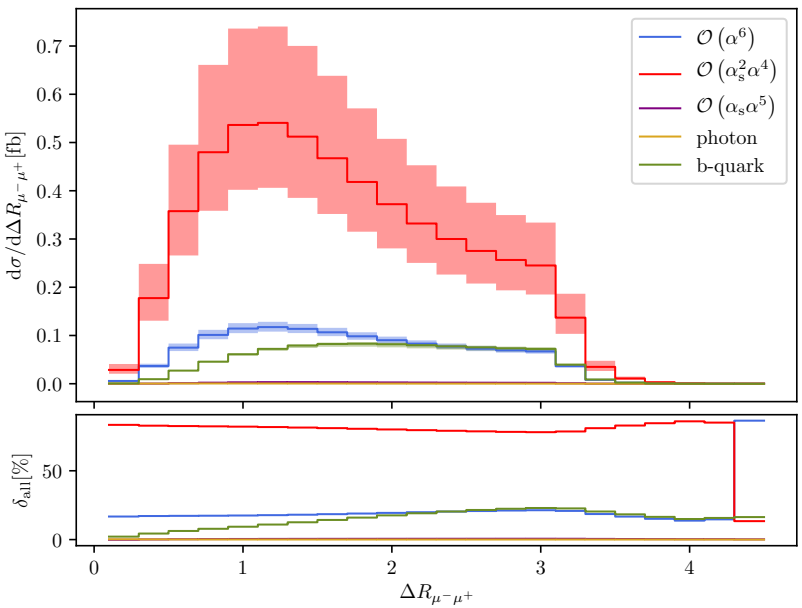
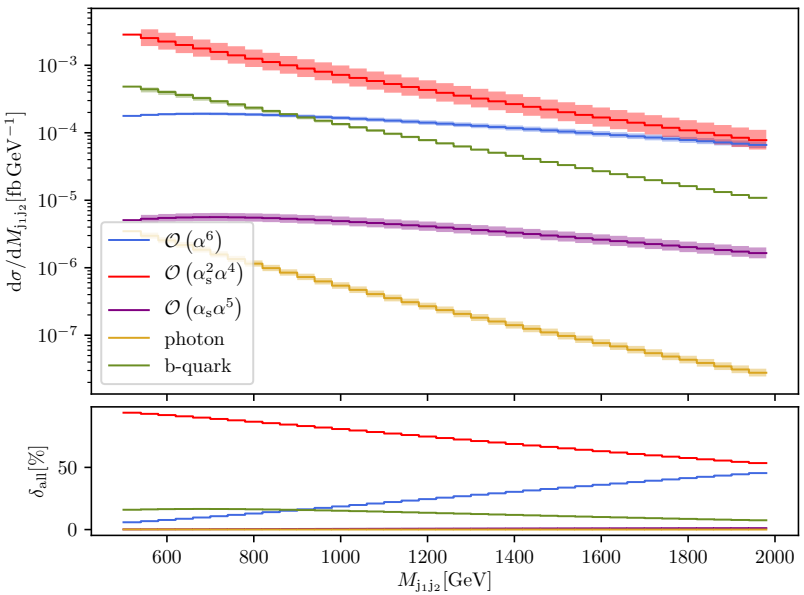
- This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006.

LO distributions (I)

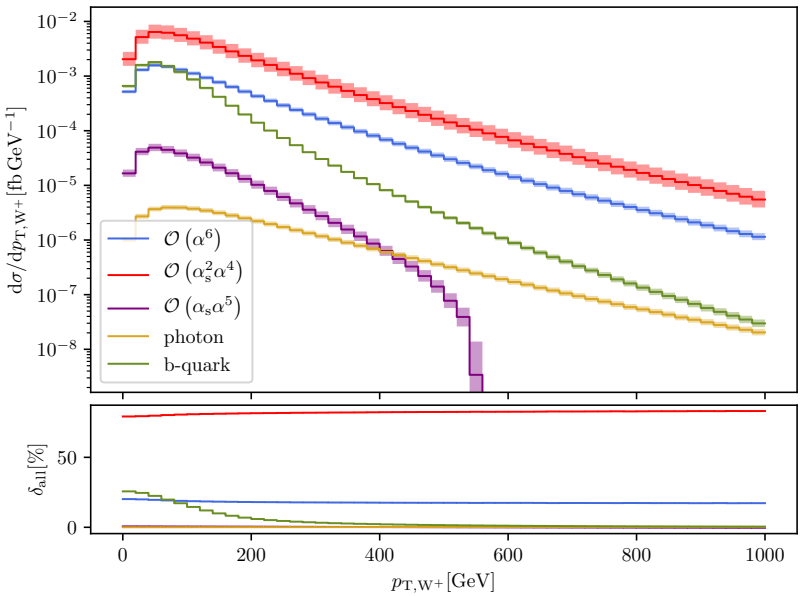


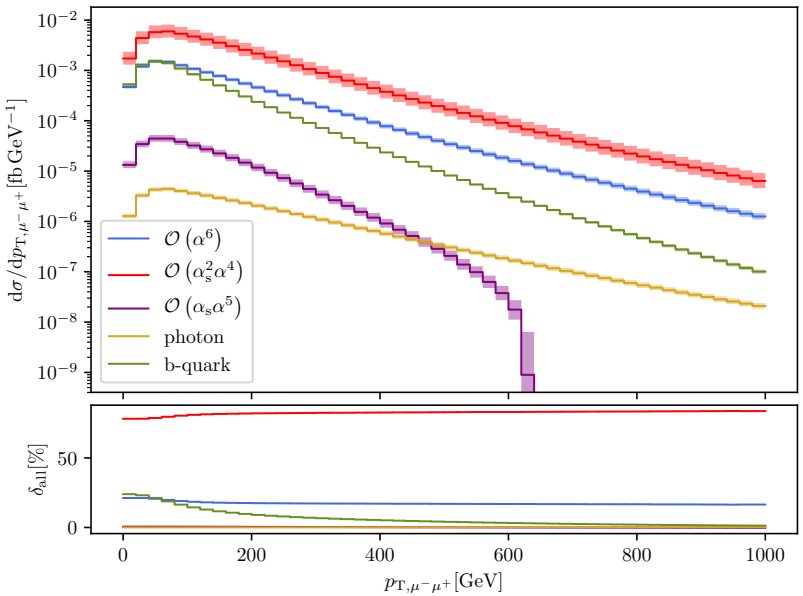


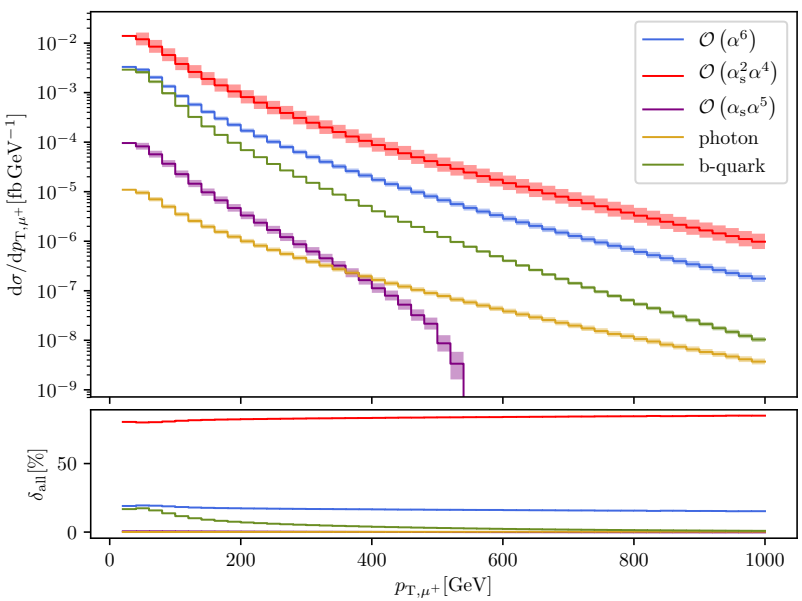


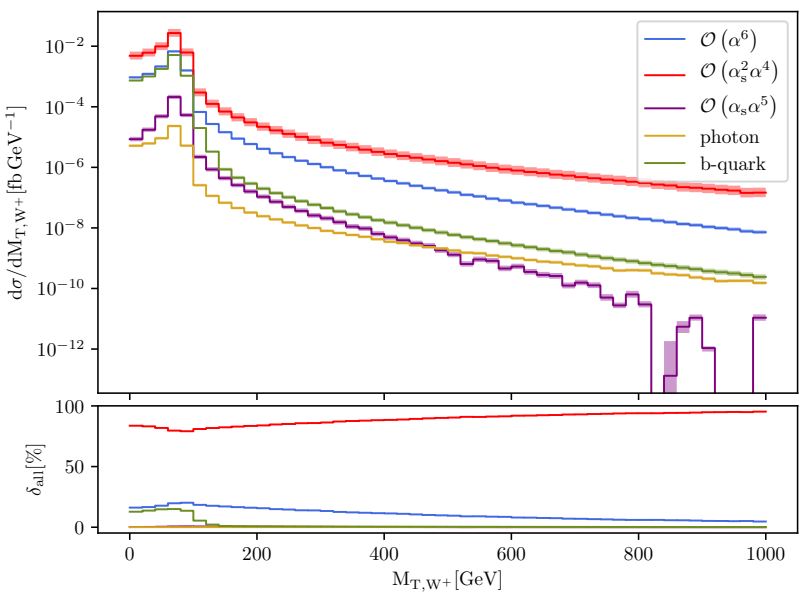


LO distributions (II)

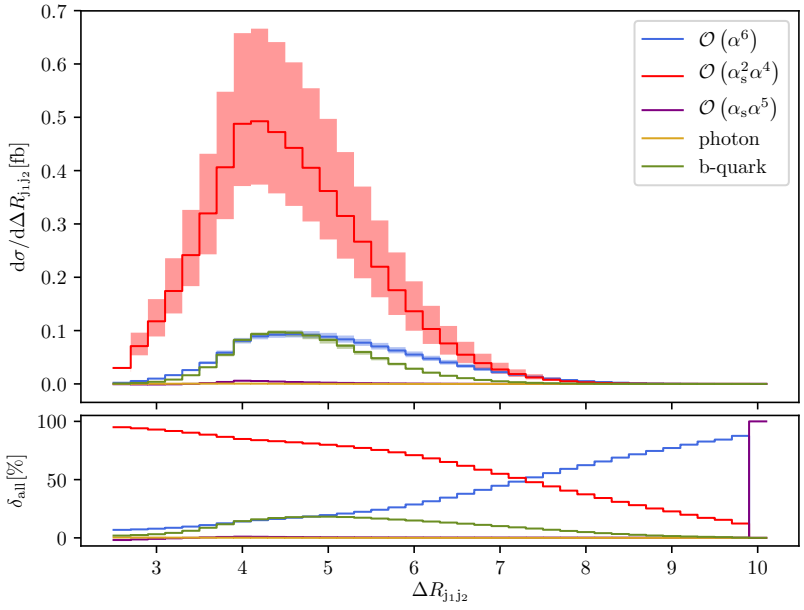


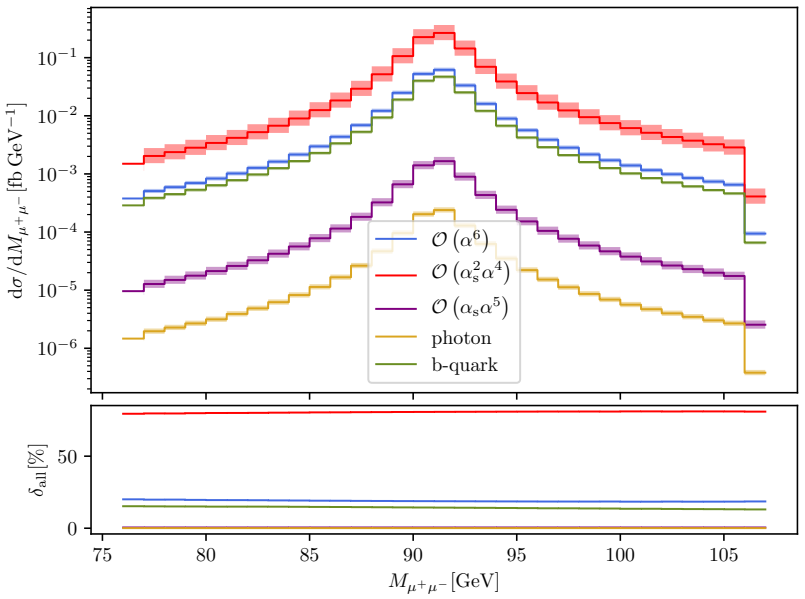


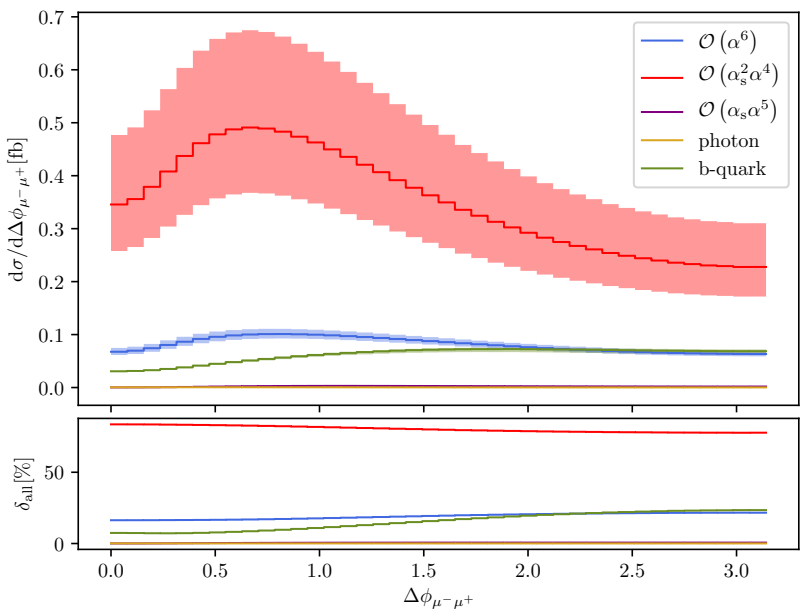


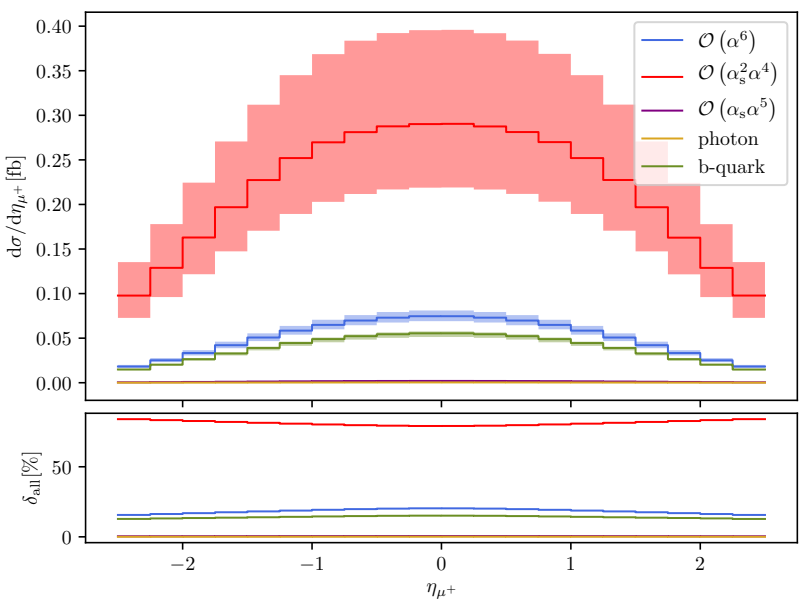


LO distributions (III)

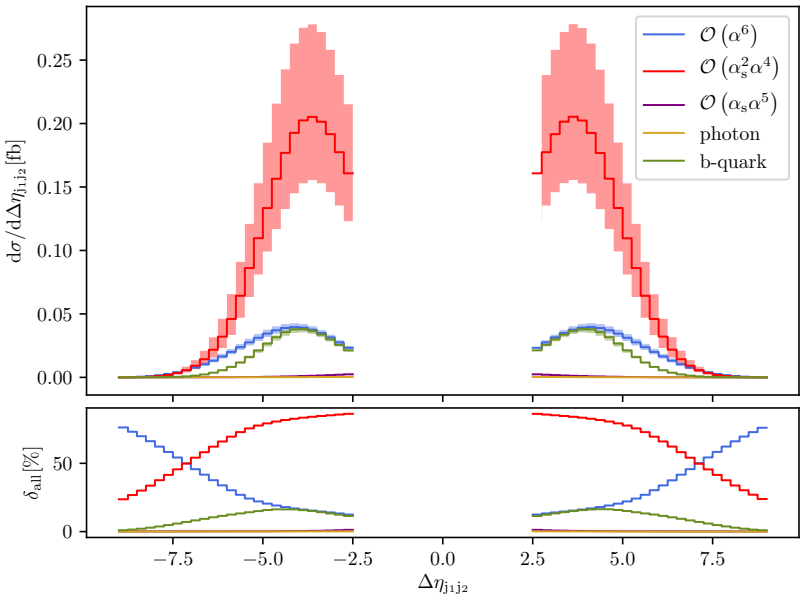


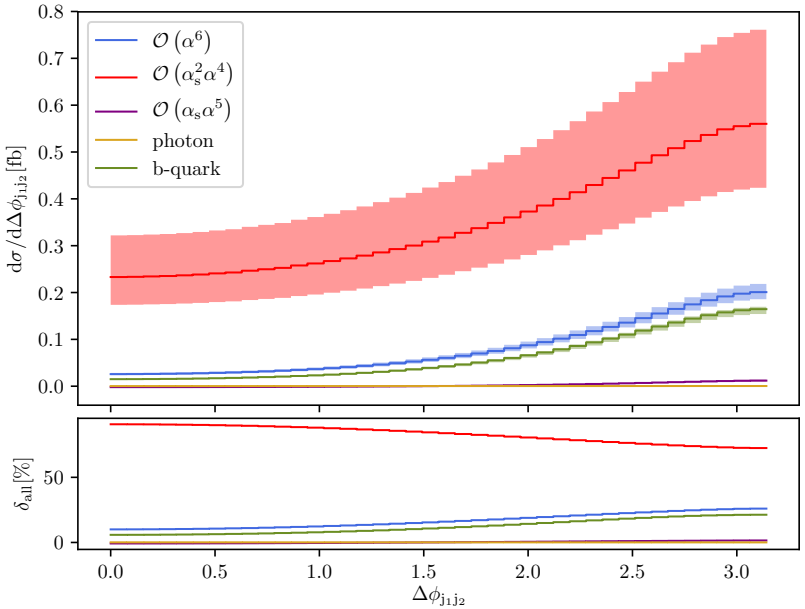


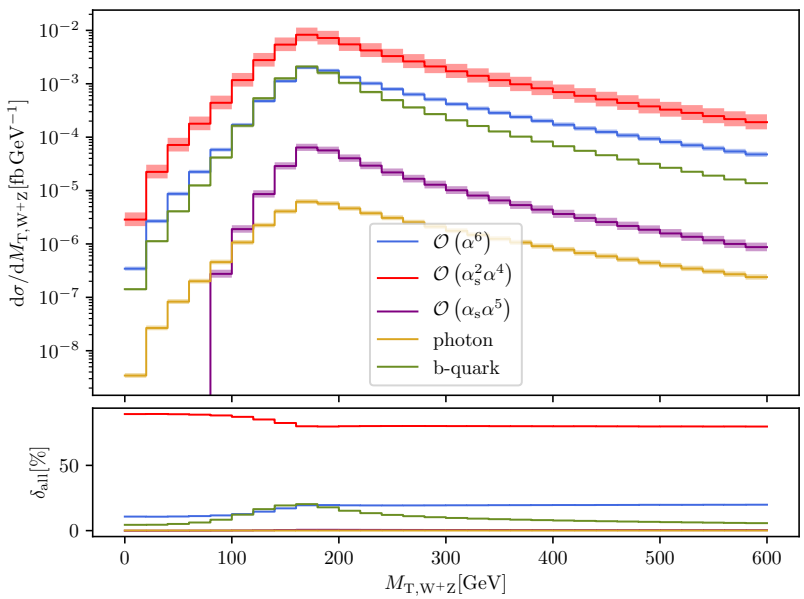


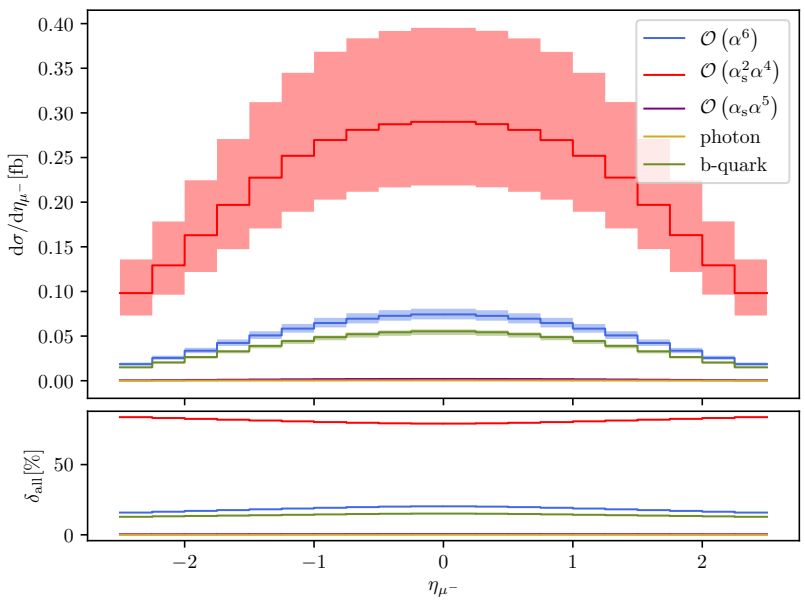


LO distributions (IV)









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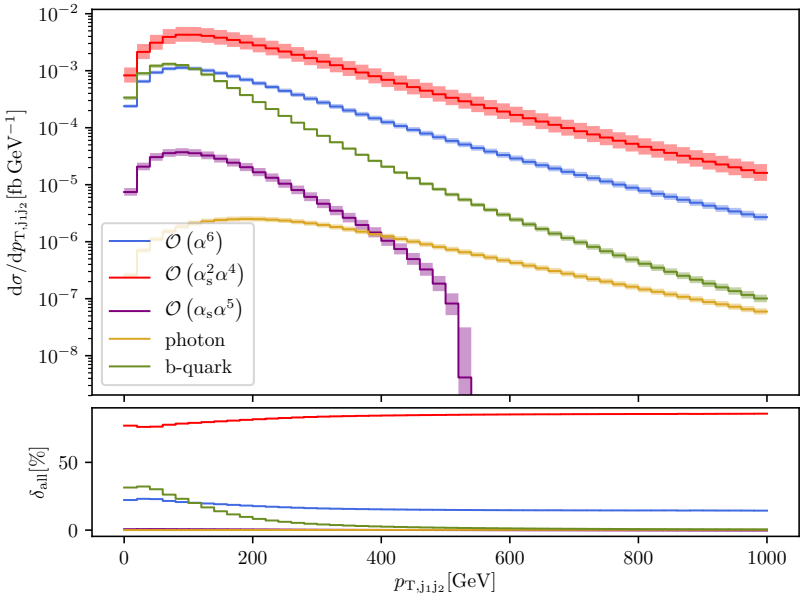
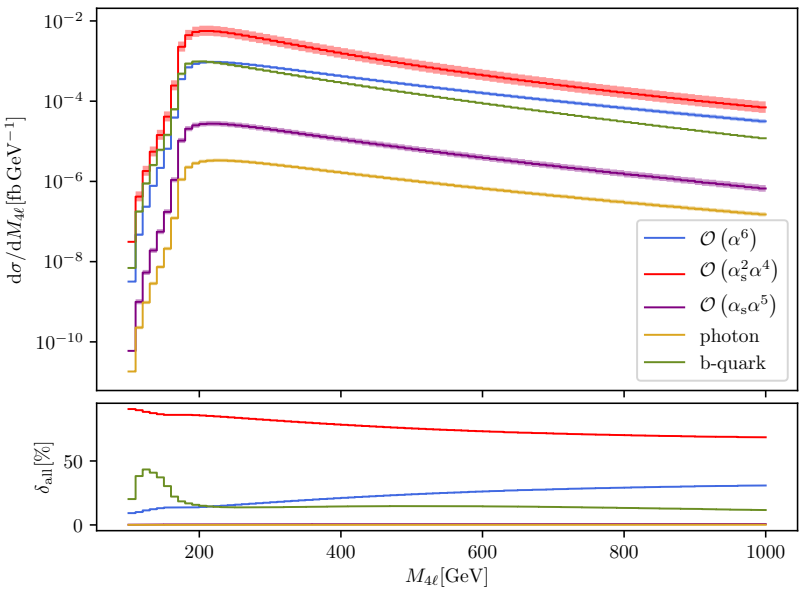
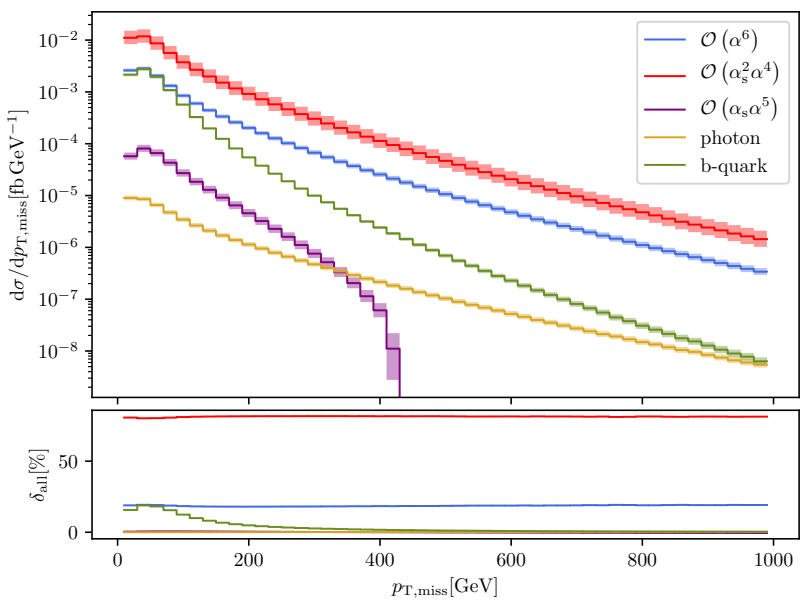
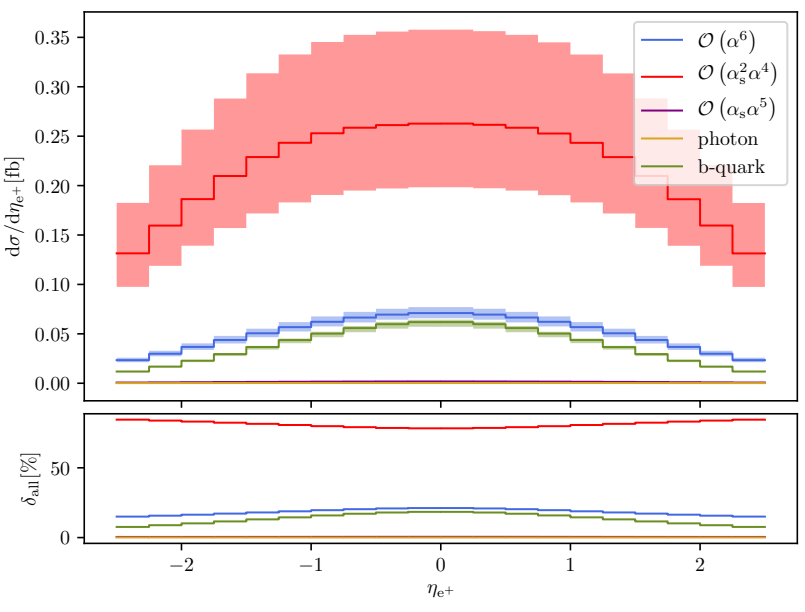
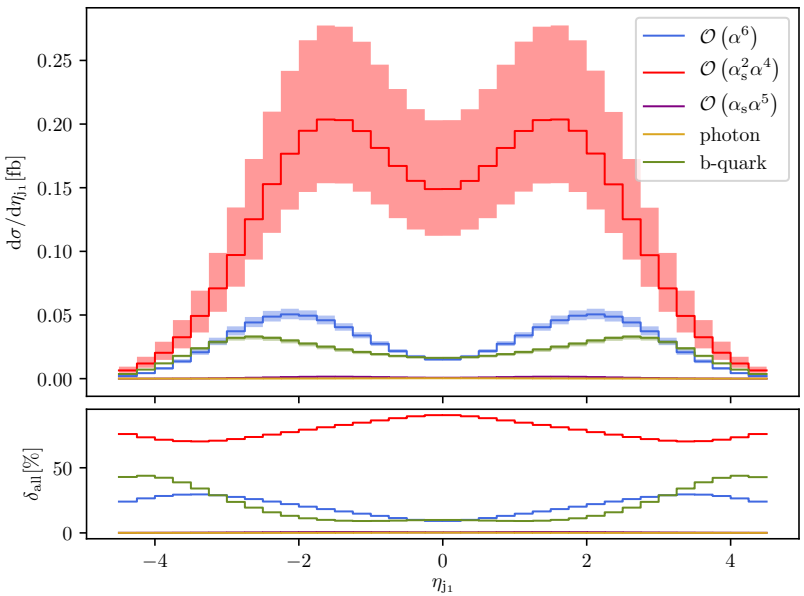


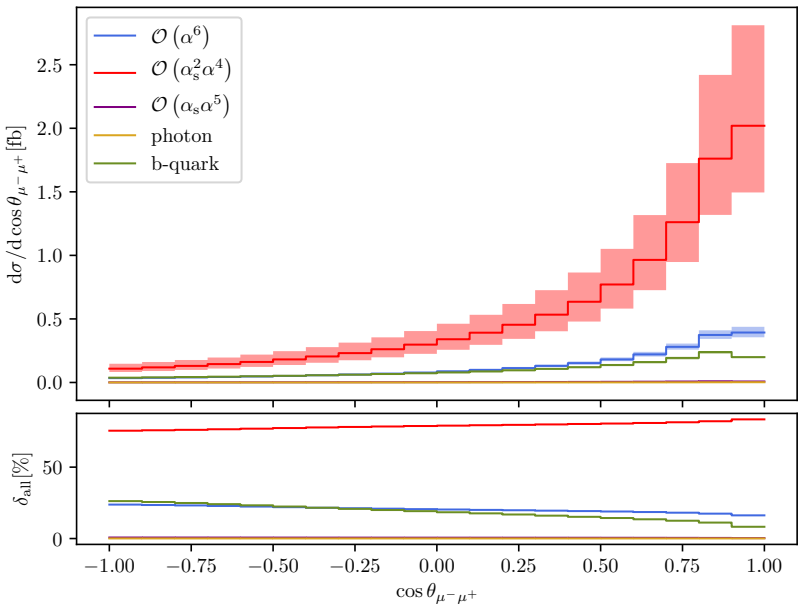


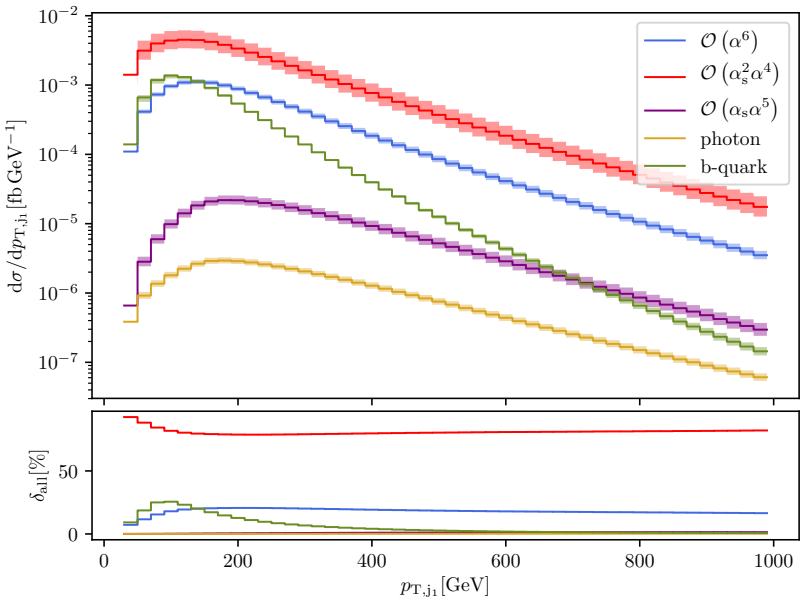


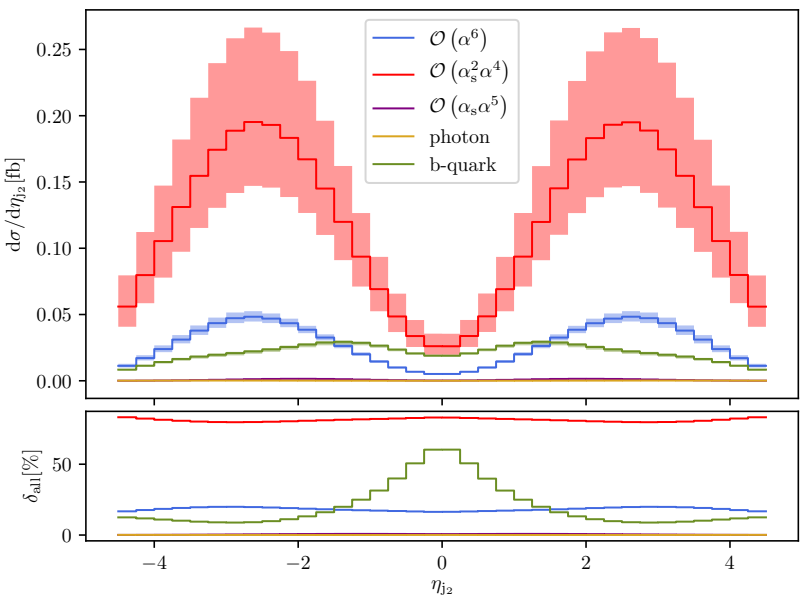


LO distributions (VI)

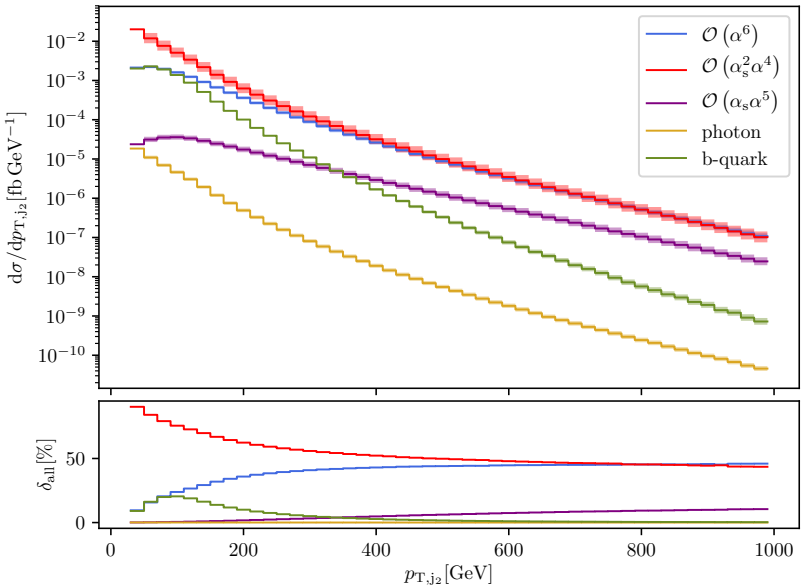


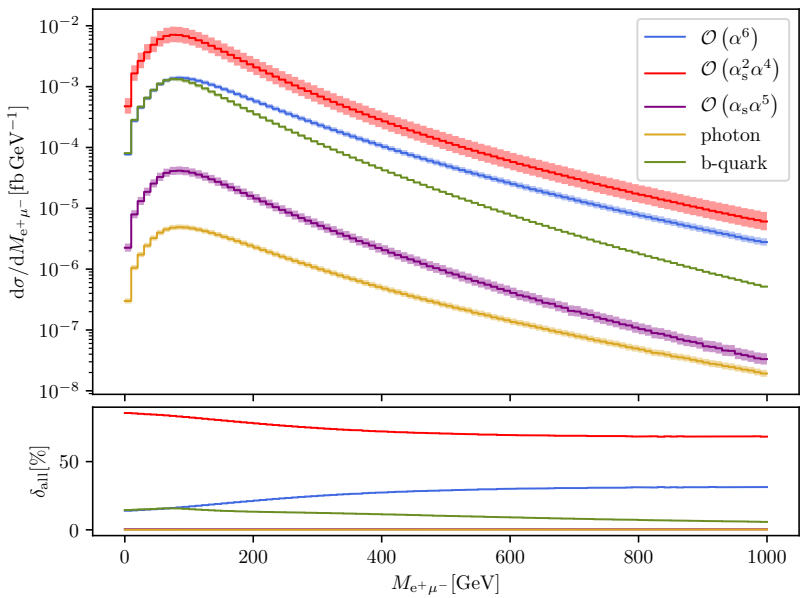




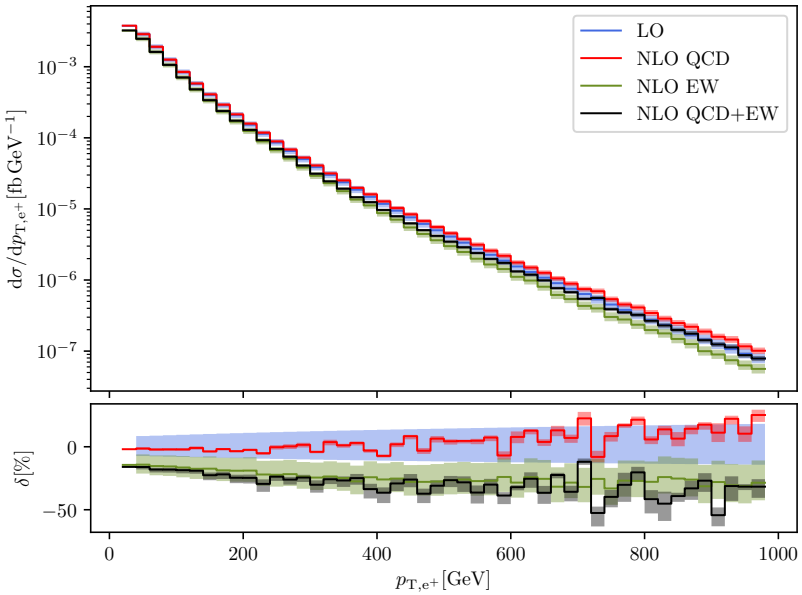


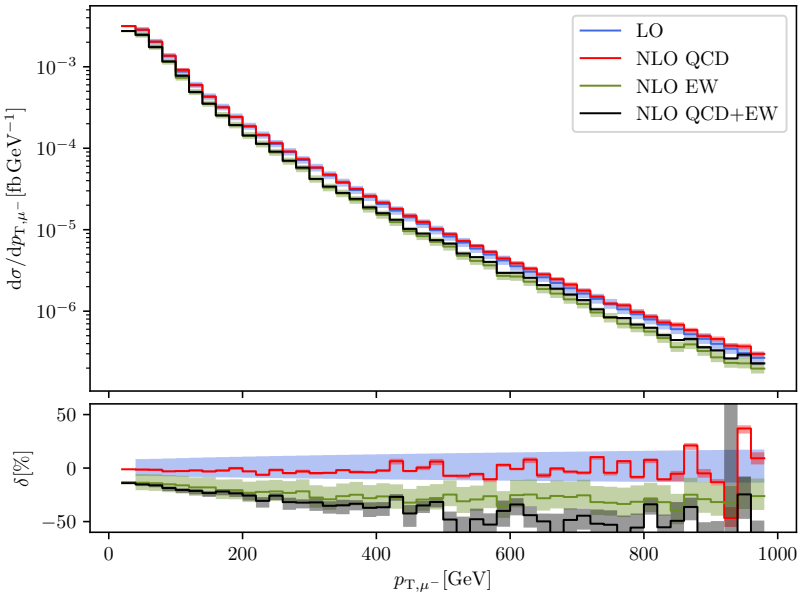
LO distributions (VII)

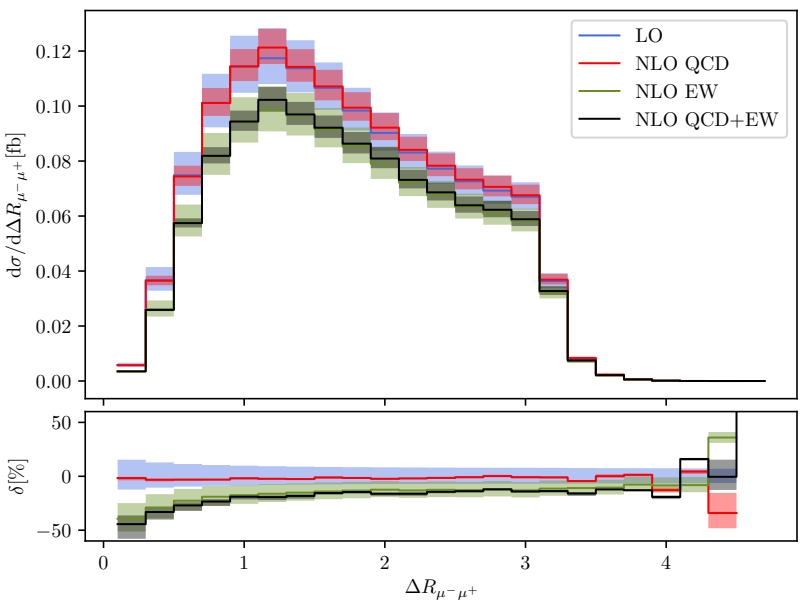


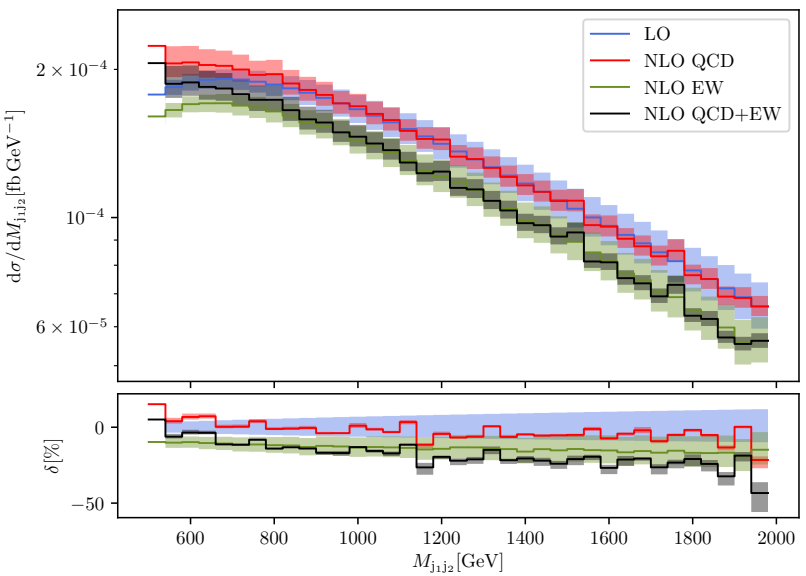


NLO distributions (I)









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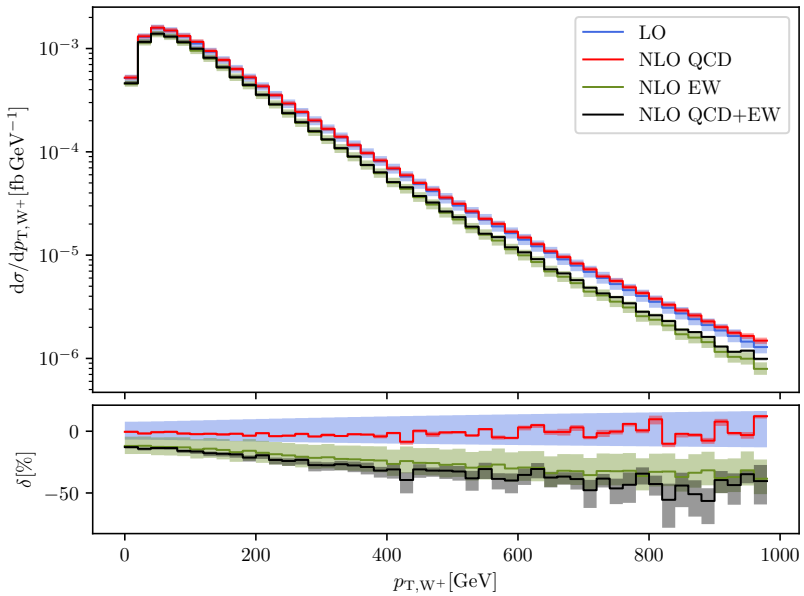
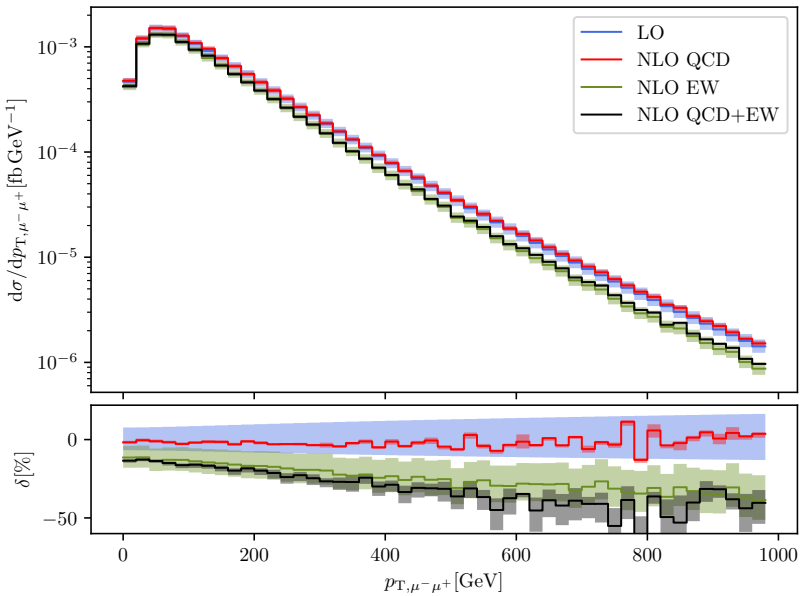
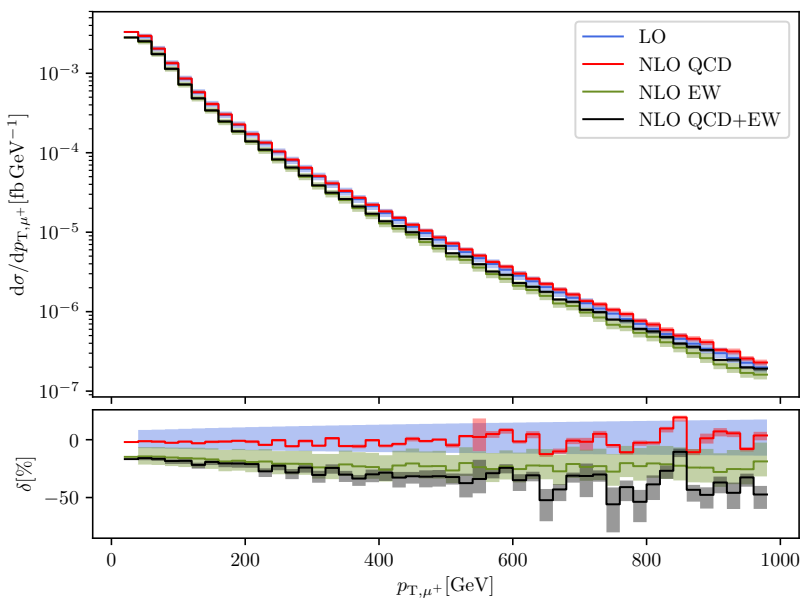
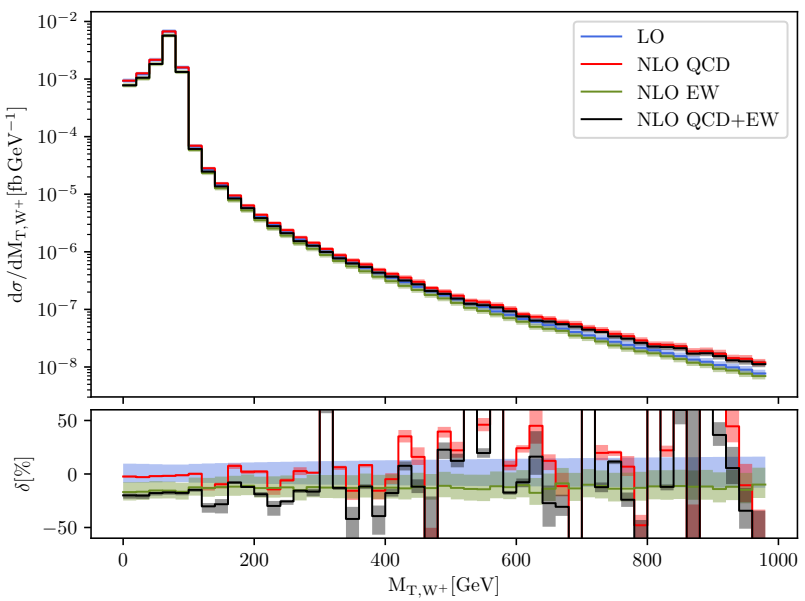
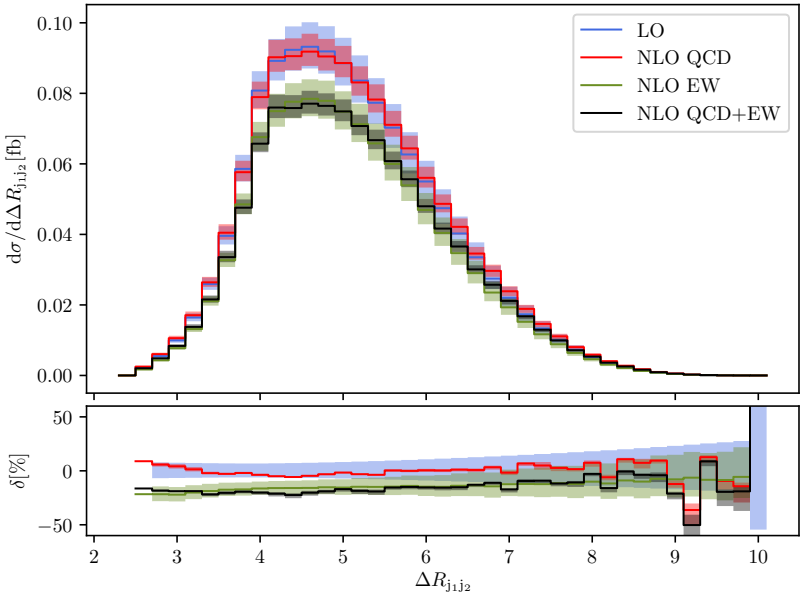


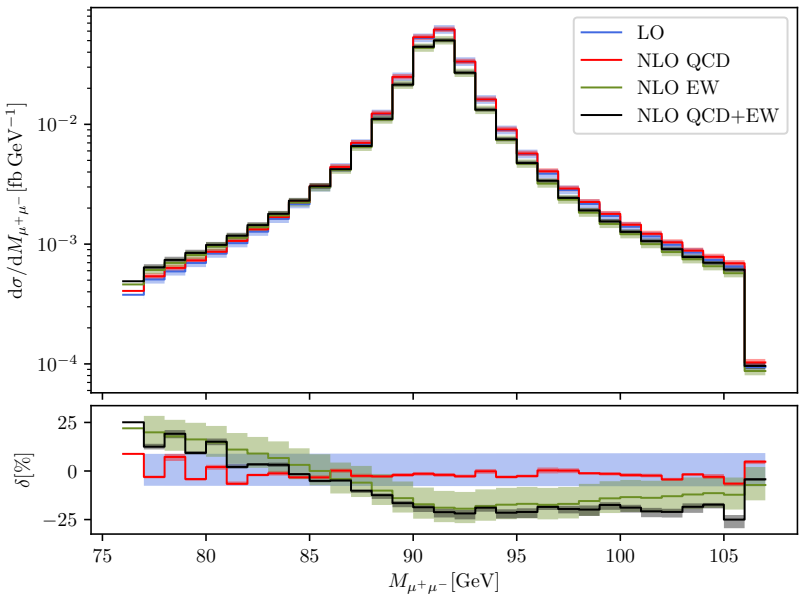


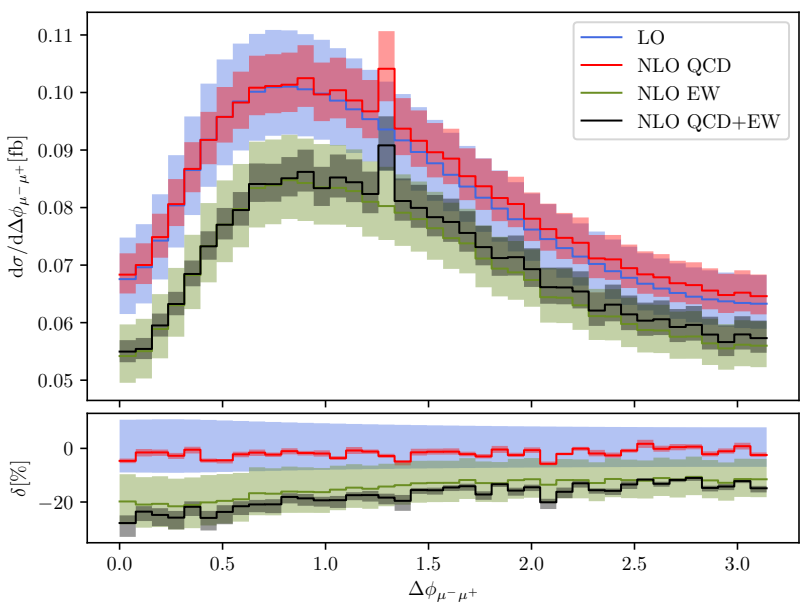


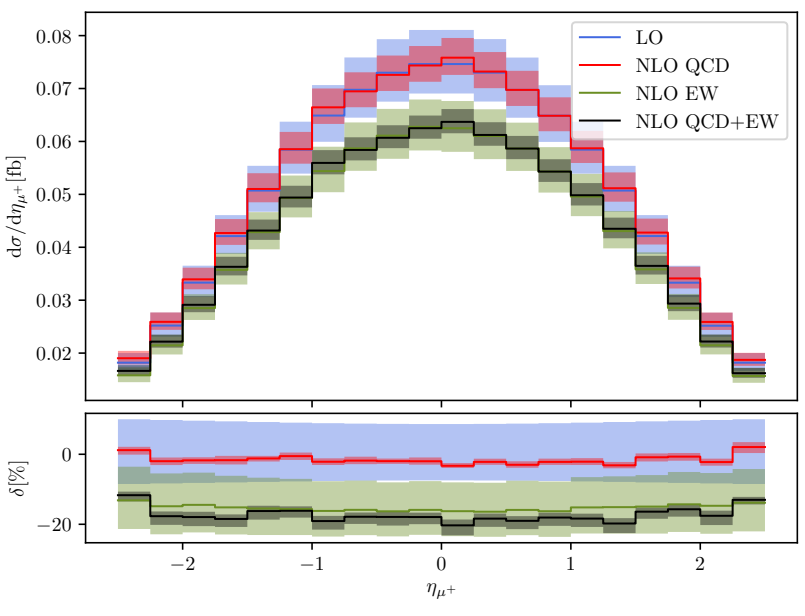


NLO distributions (III)

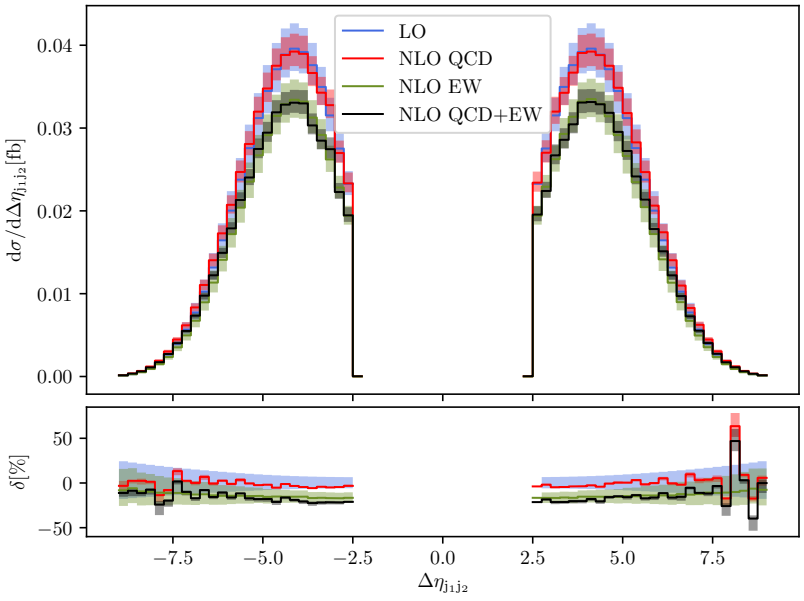


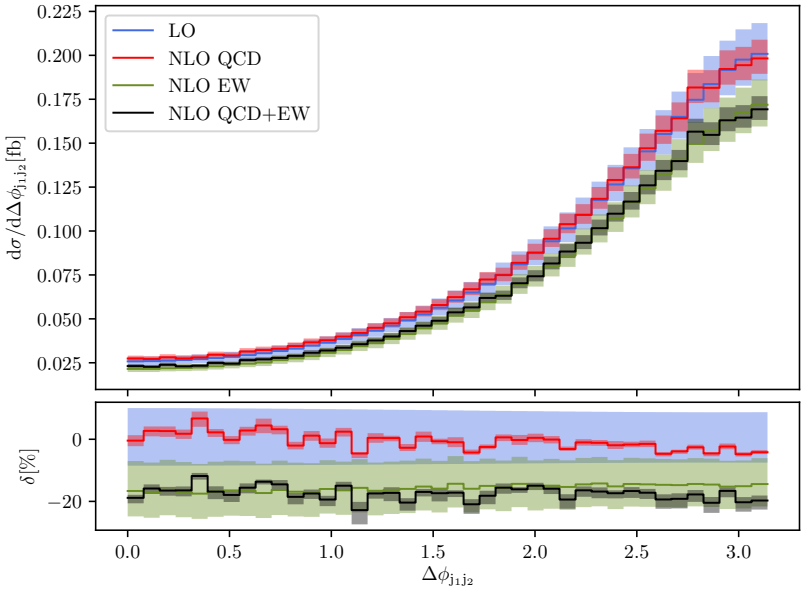


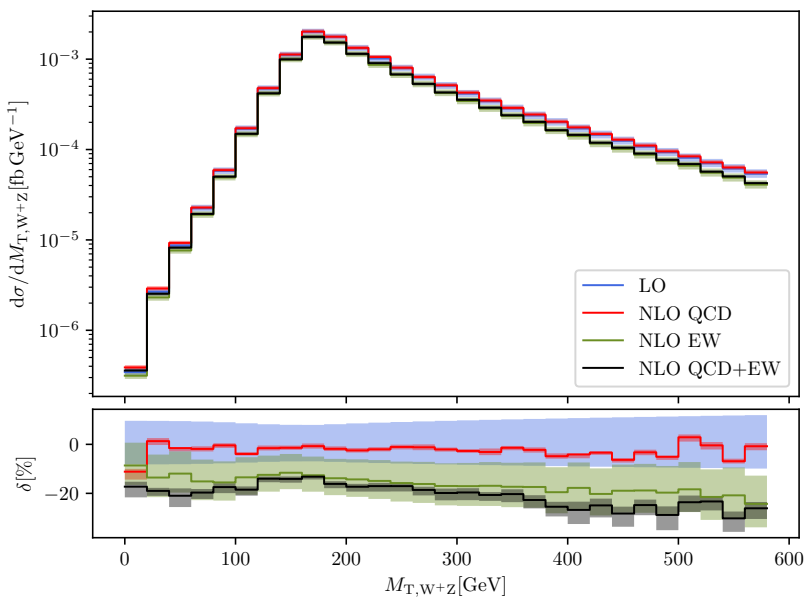


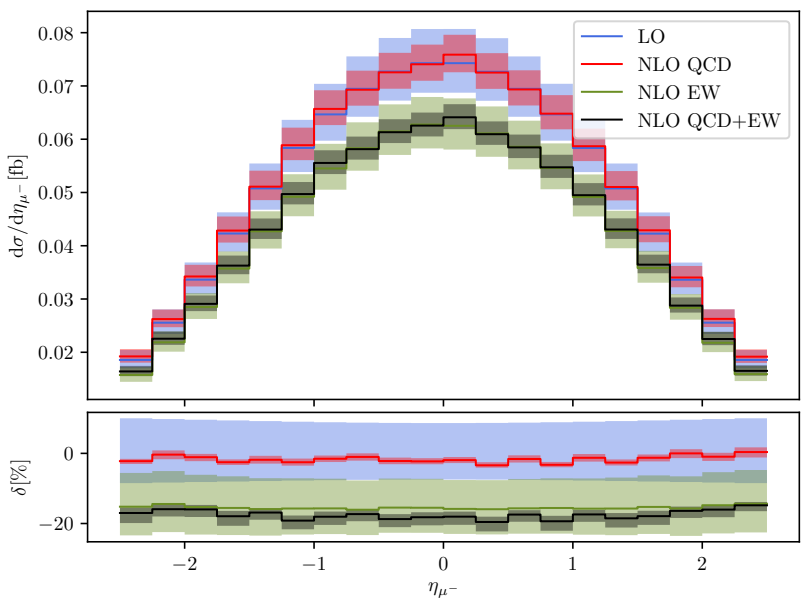


NLO distributions (IV)

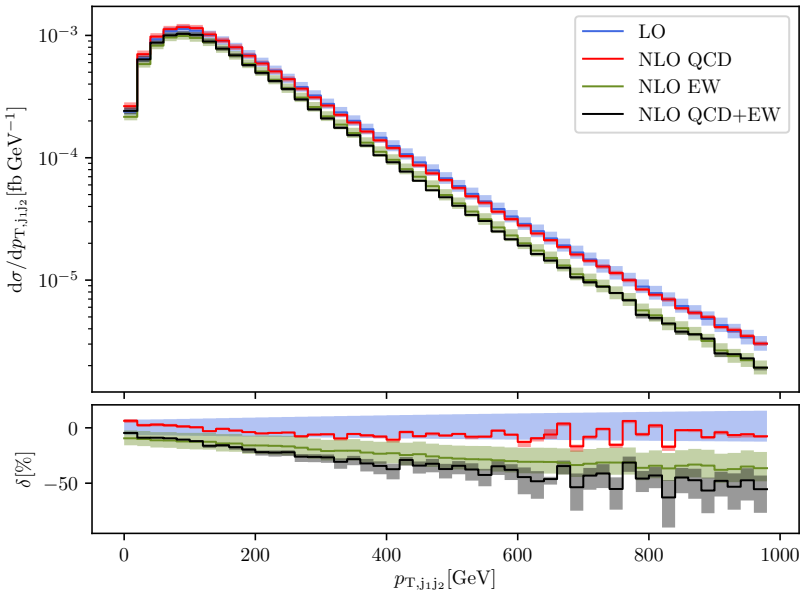


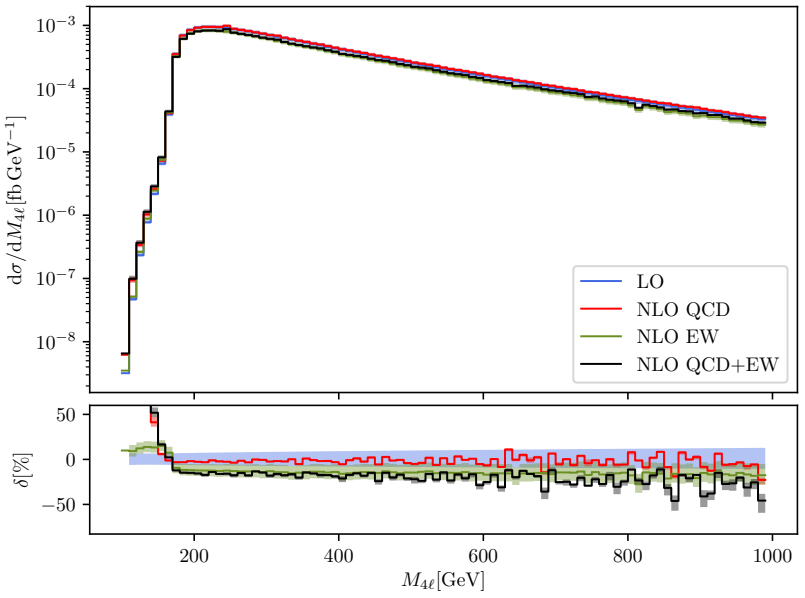


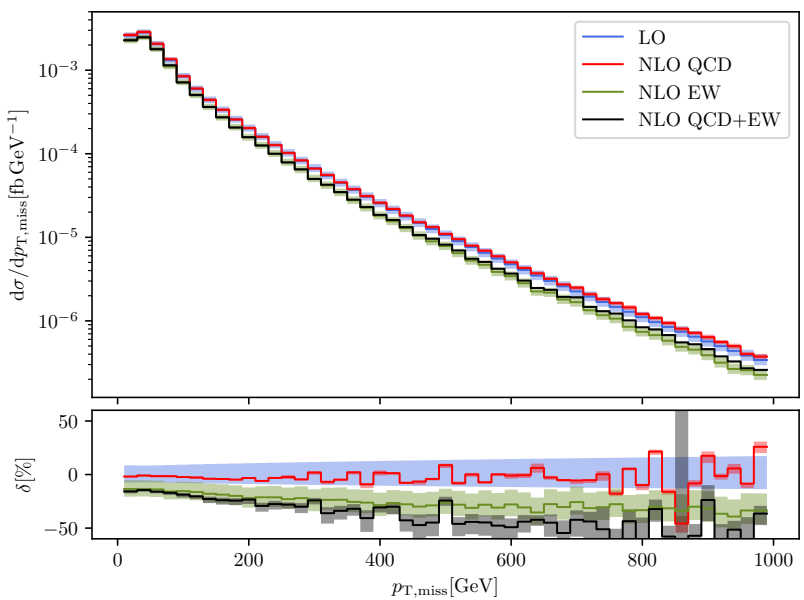


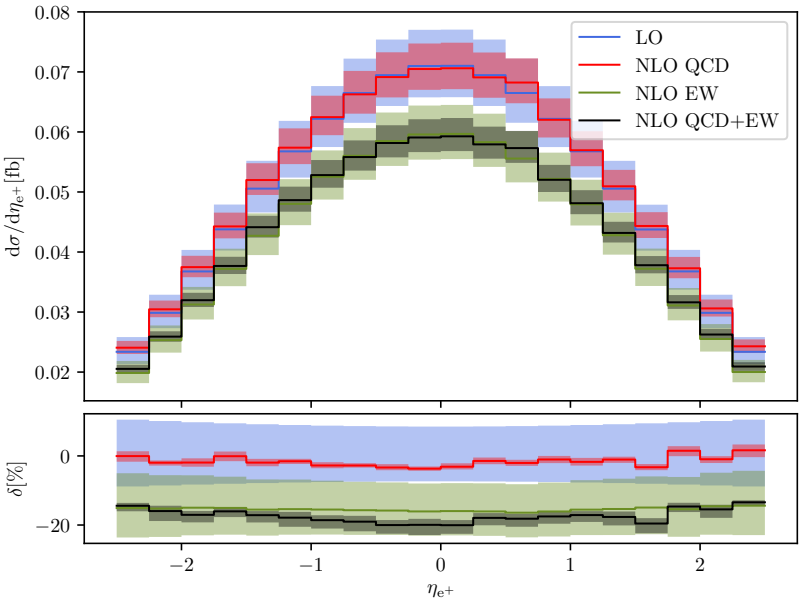


NLO distributions (V)

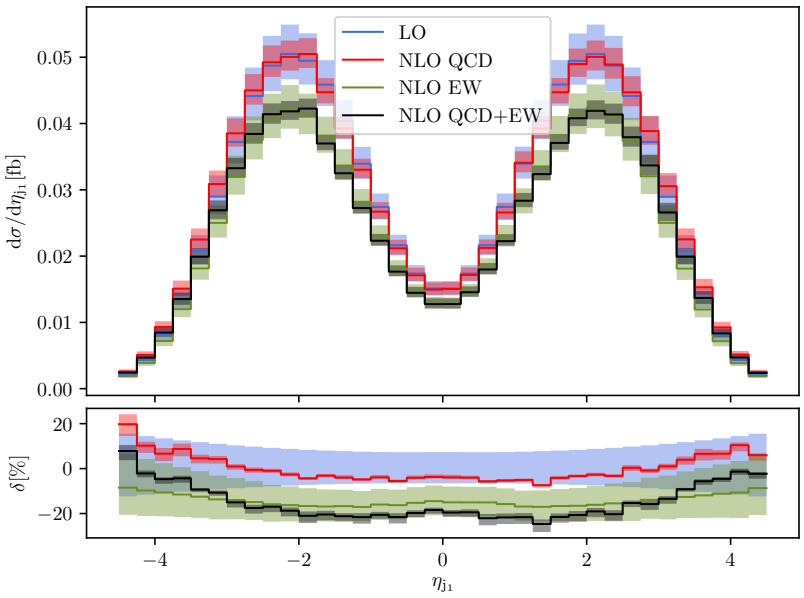


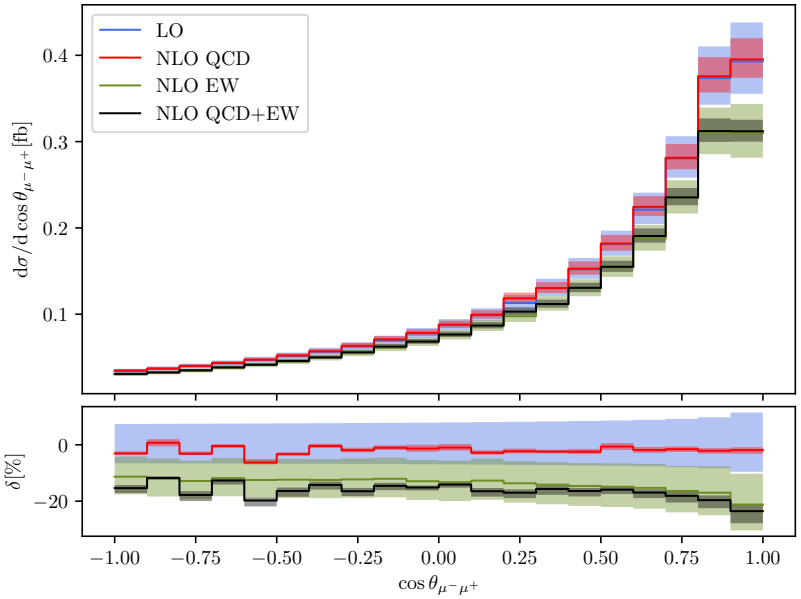


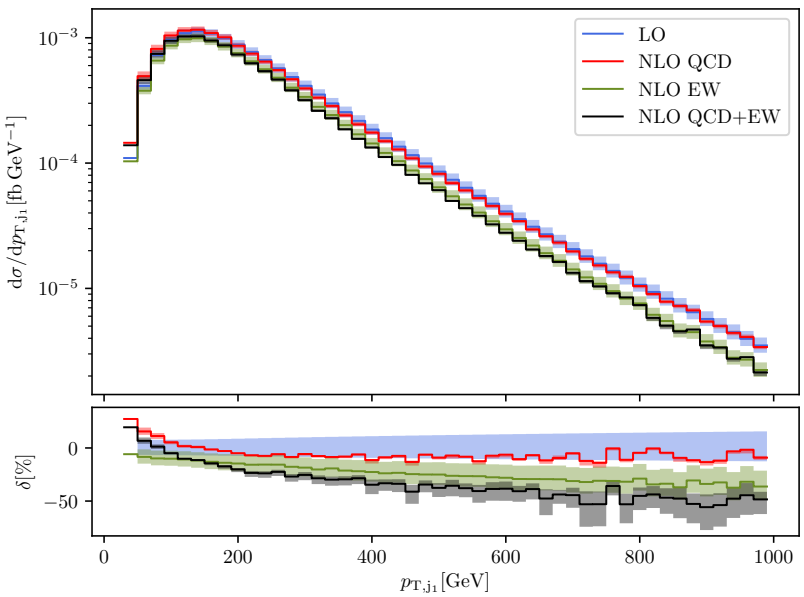


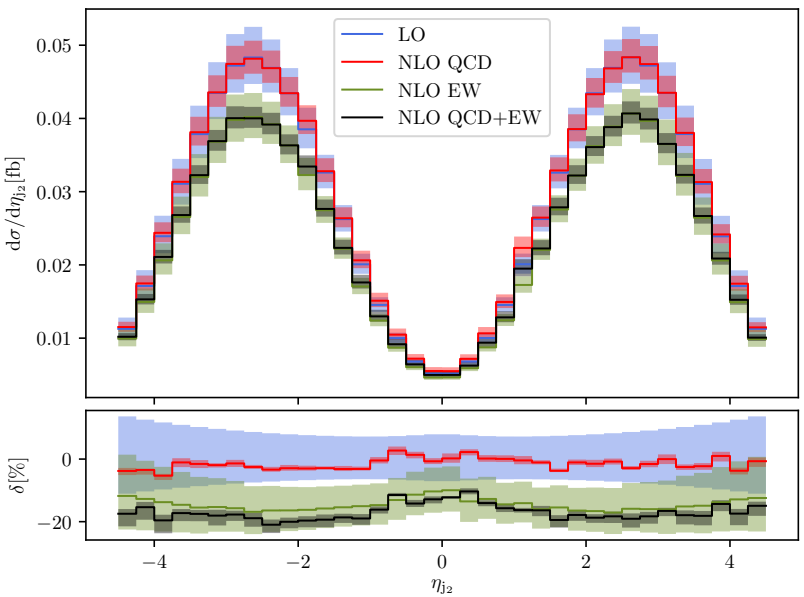


NLO distributions (VI)

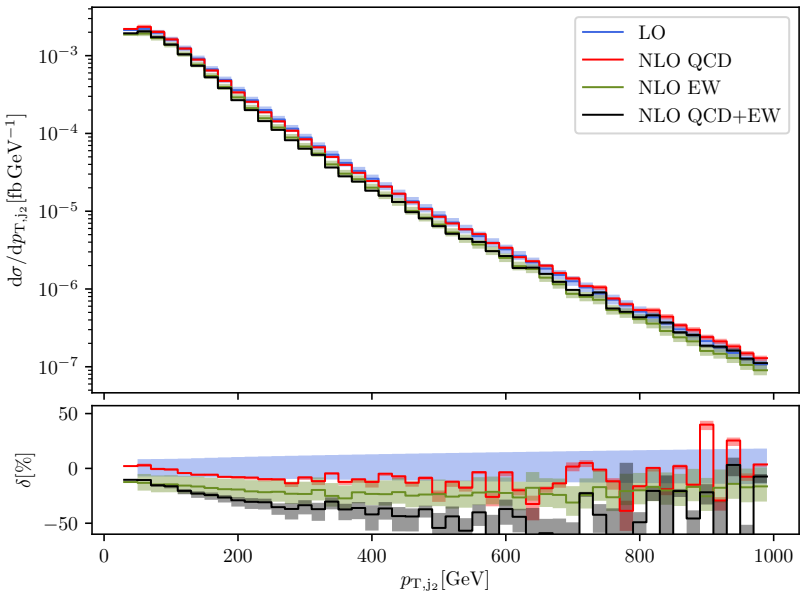


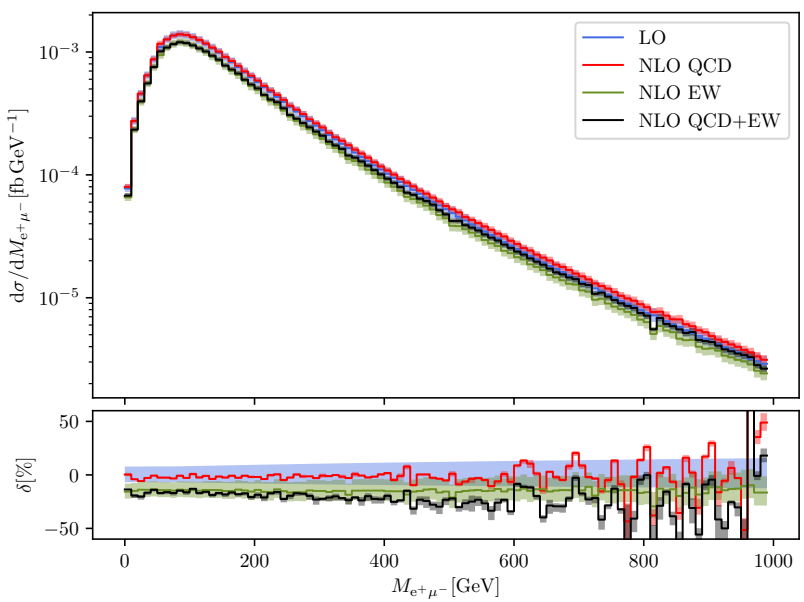






NLO distributions (VII)





Fiducial phase space volume for the ATLAS-like setup

Cuts chosen similar to the ATLAS 8 TeV-analysis [CERN-EP-2016-017]:

- At least two $R = 0.4$ anti-k_t jets with $p_T > 30\,\text{GeV}$, $|\eta| < 4.5$, and $\Delta R_{j\ell} > 0.3$
- $M_{j_1 j_2} > 500\,\text{GeV}$, no $\Delta\eta_{j_1 j_2}$ cut[2]
- $p_{T,\ell} > 20\,\text{GeV}$ and $|y_\ell| < 2.5$
- $p_{T,\text{miss}} > 30\,\text{GeV}$
- $|M_{\mu\bar{\mu}} - M_Z| < 10\,\text{GeV}$
- $\Delta R_{\ell\ell} > 0.3$

Other:

- Photons recombined with charged particles using anti-k_t algorithm with $R = 0.1$
- PDFs: `NNPDF30_nlo_as_0118_qed`
- $\sqrt{s} = 13\,\text{TeV}$

Complex mass scheme [Denner, Dittmaier, Roth, Wackeroth][Denner, Dittmaier, Roth, Wieders], input parameters:

- $G_\mu = 1.663\,787 \times 10^{-5}\,\text{GeV}^{-2}$
- $M_W = 80.357\,97\,\text{GeV}$, $\Gamma_W = 2.084\,30\,\text{GeV}$
- $M_Z = 91.153\,48\,\text{GeV}$, $\Gamma_Z = 2.494\,27\,\text{GeV}$
- $M_H = 125.0\,\text{GeV}$, $\Gamma_H = 4.07 \times 10^{-3}\,\text{GeV}$

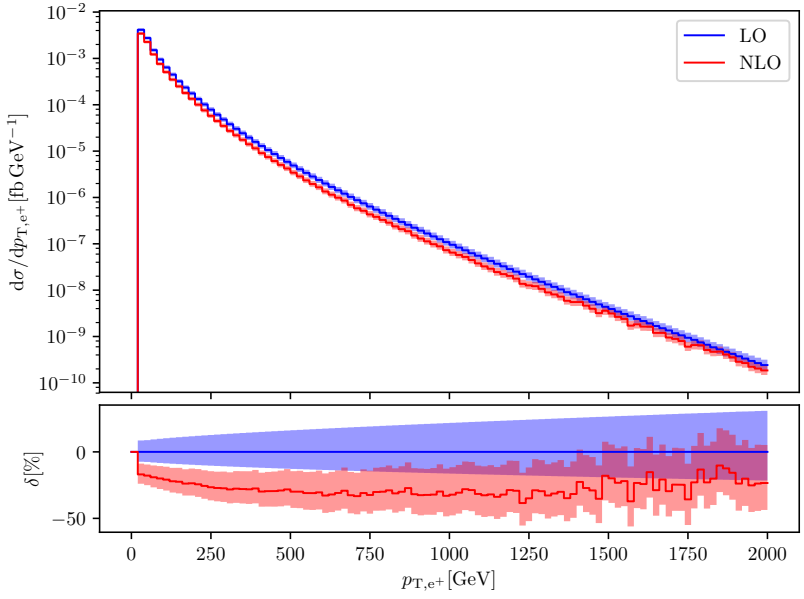
with coupling calculated as:

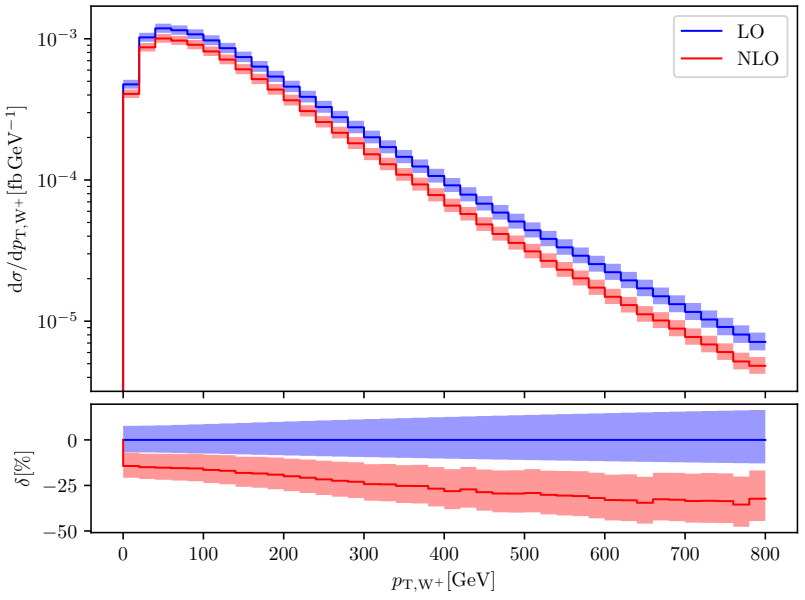
$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

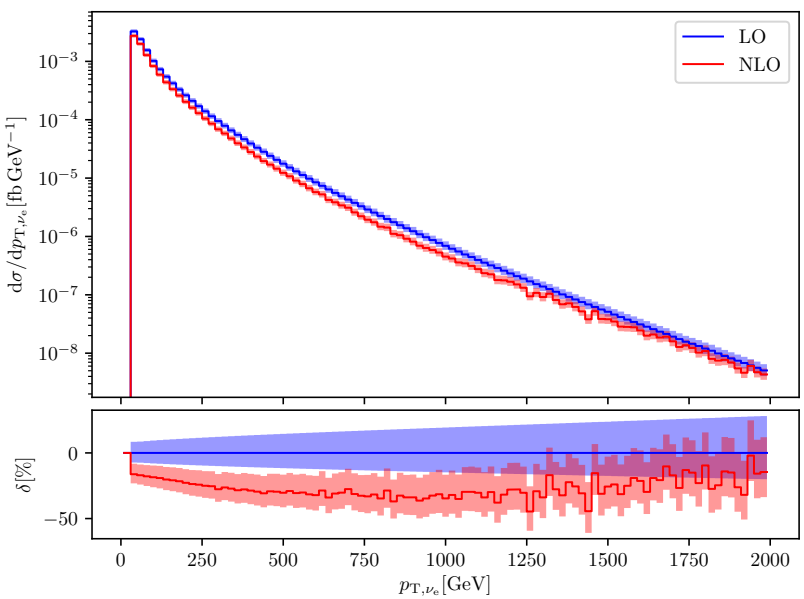
Scale choice: $\mu_F = (1/2, 1, 2) \cdot M_W$
$\rightarrow$ No dependence on μ_R, since processes do not depend on α_s!

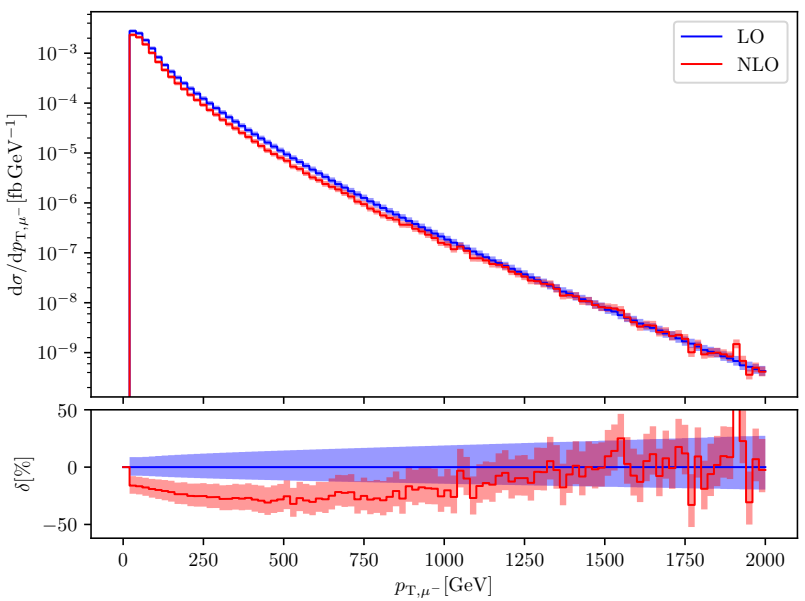
[1] Unused in the ATLAS 8 TeV-analysis, but used both in the ATLAS and CMS 13 TeV analyses

Distributions (I)

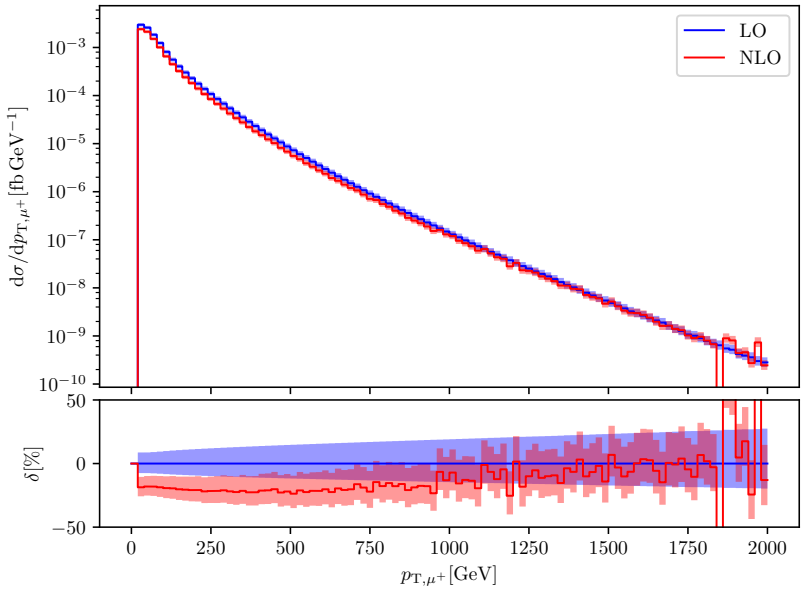


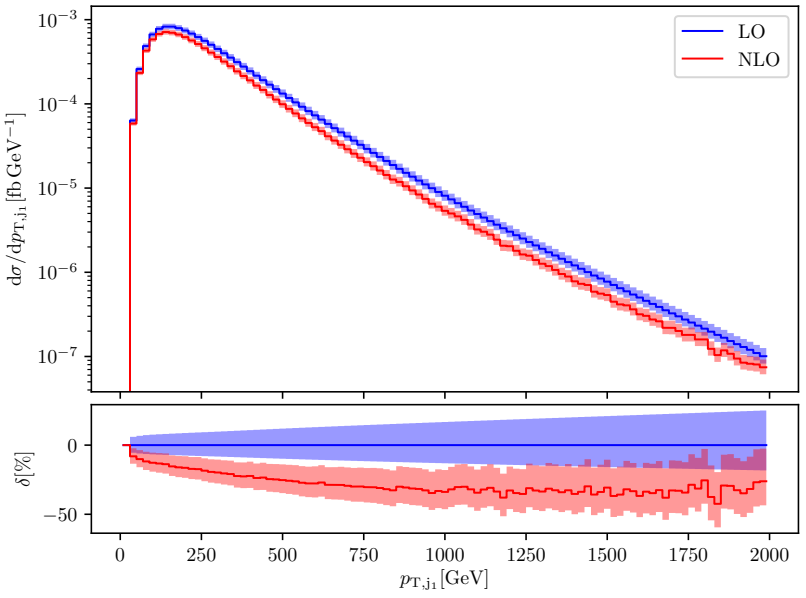


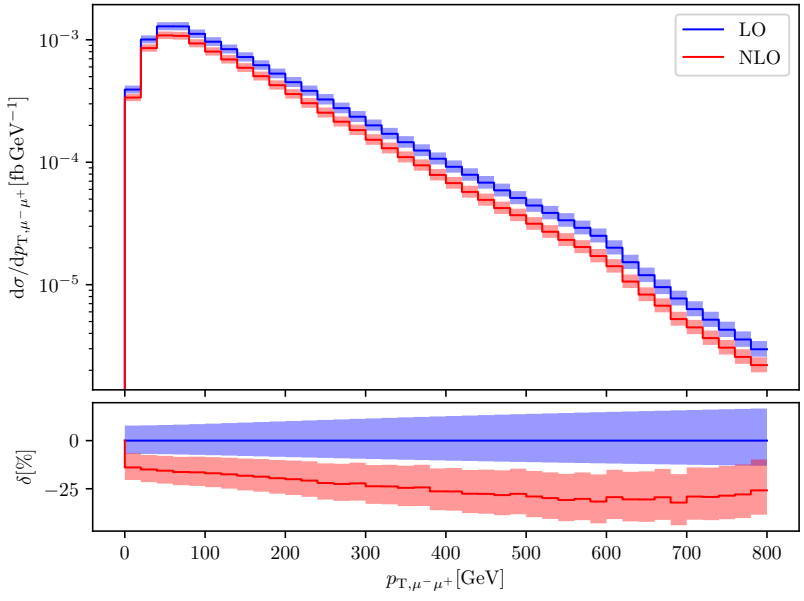


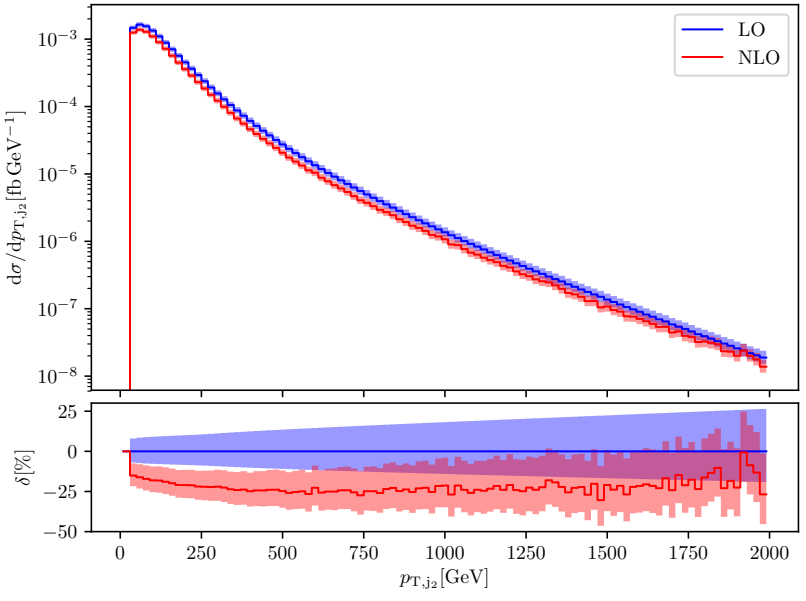


Distributions (II)

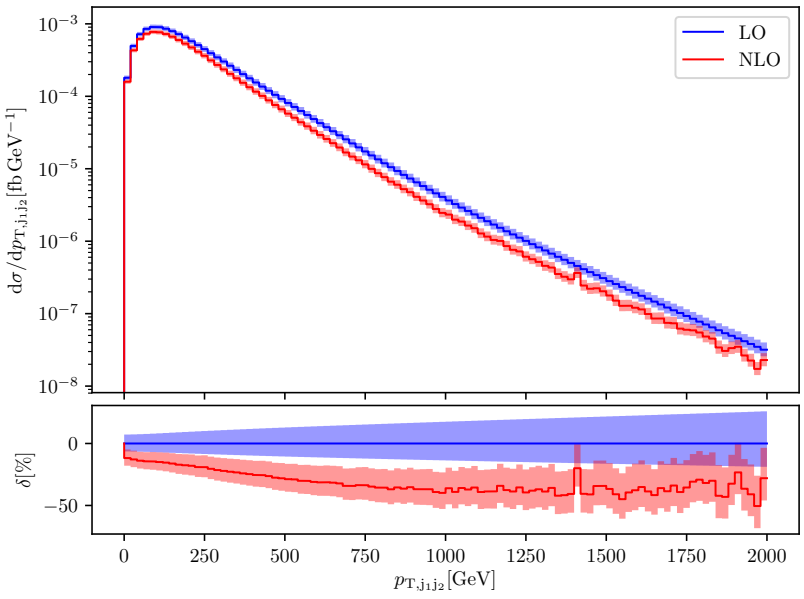


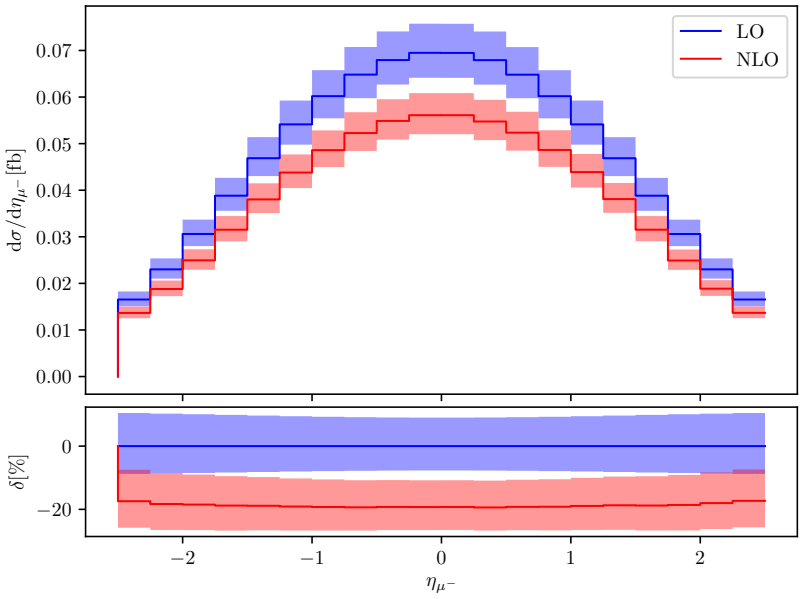


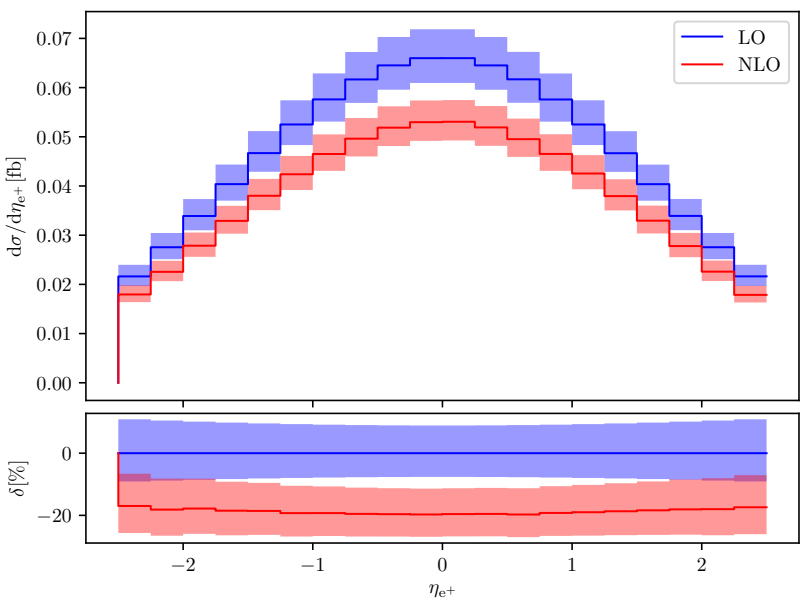


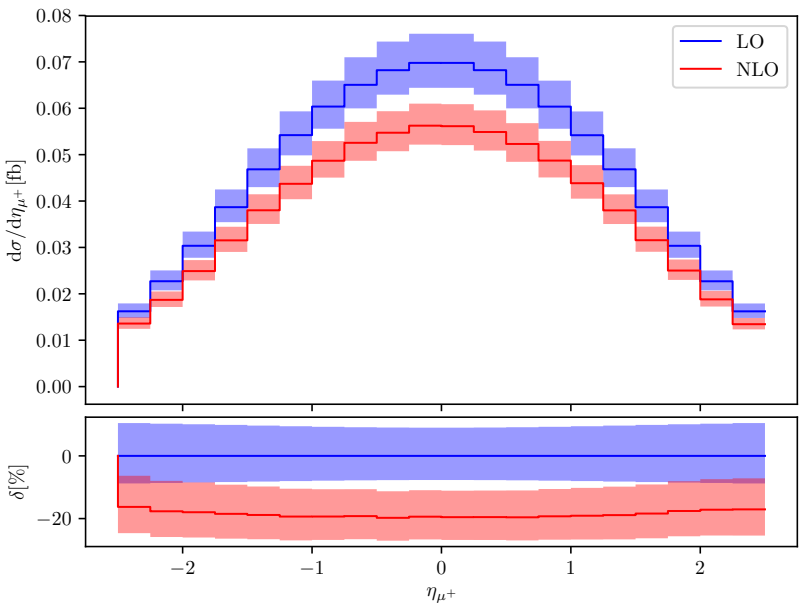


Distributions (III)

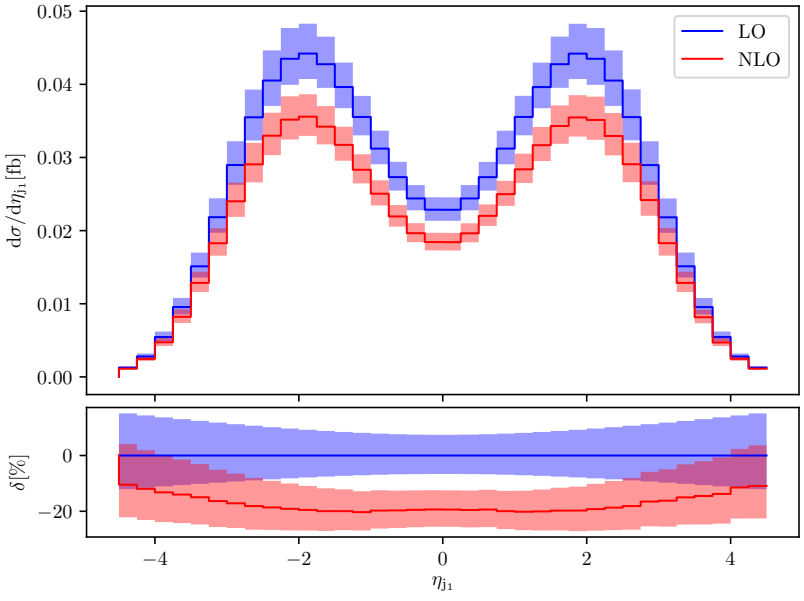


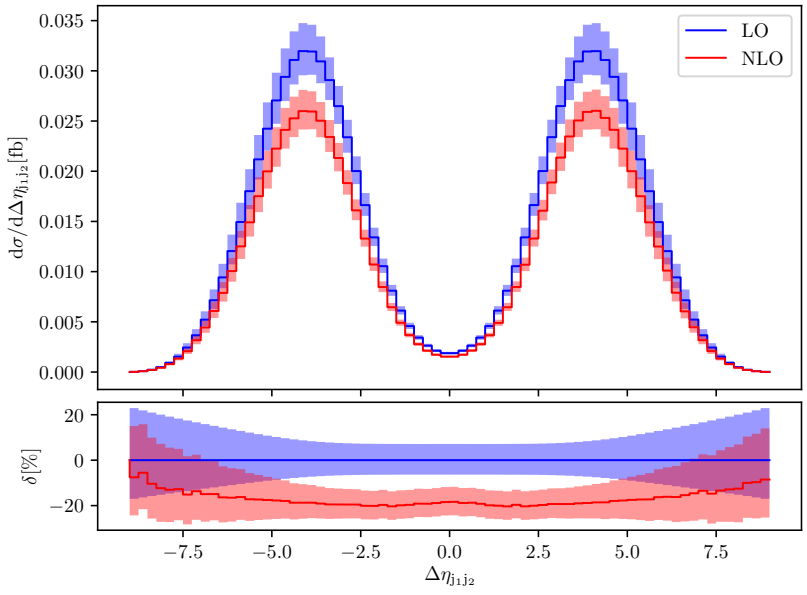


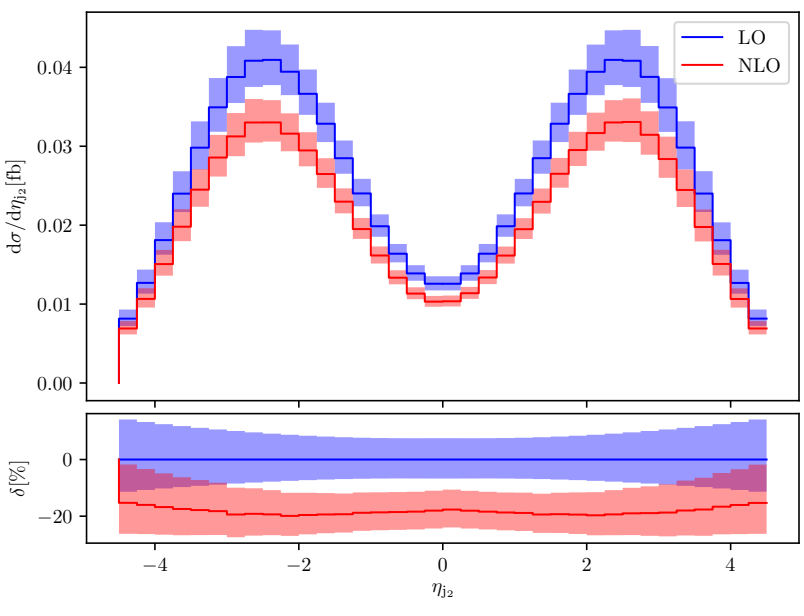


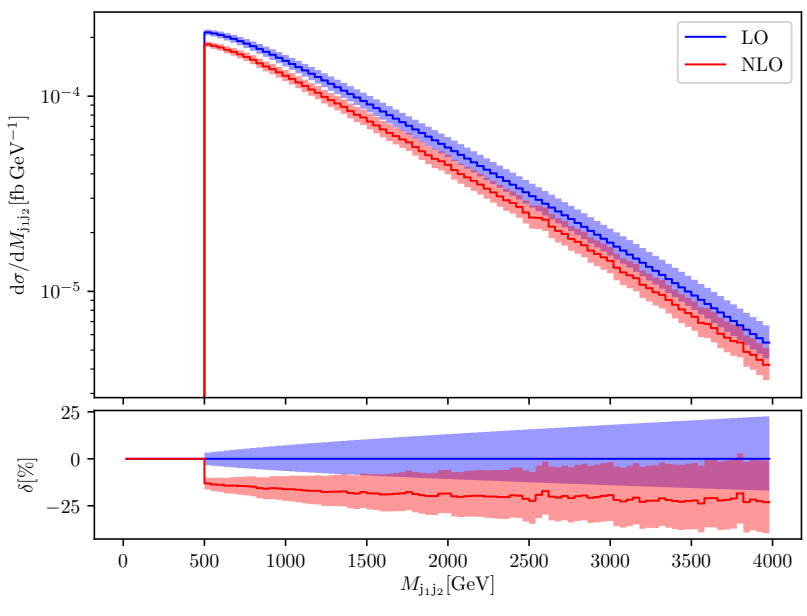


Distributions (IV)

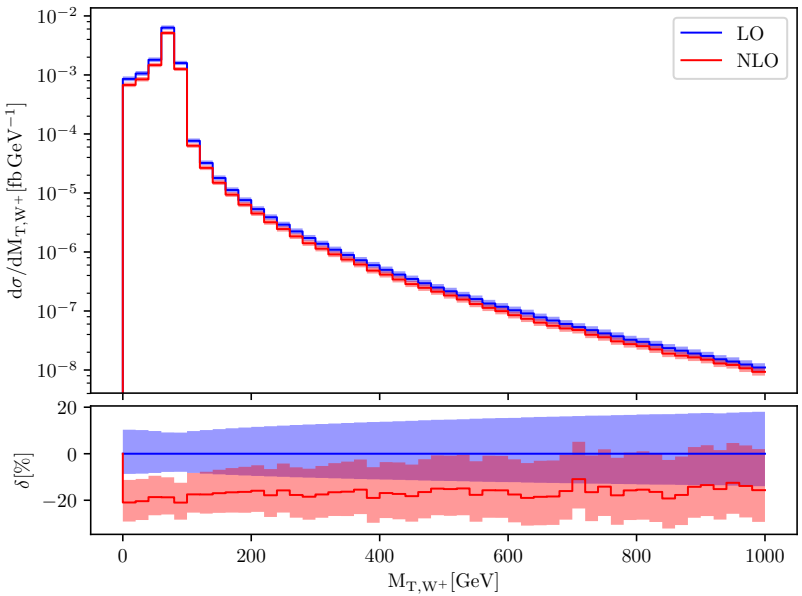


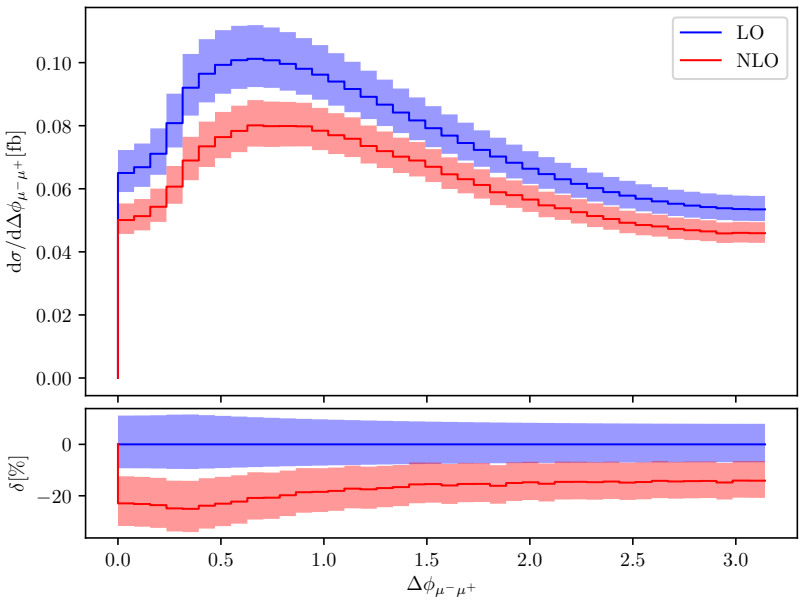


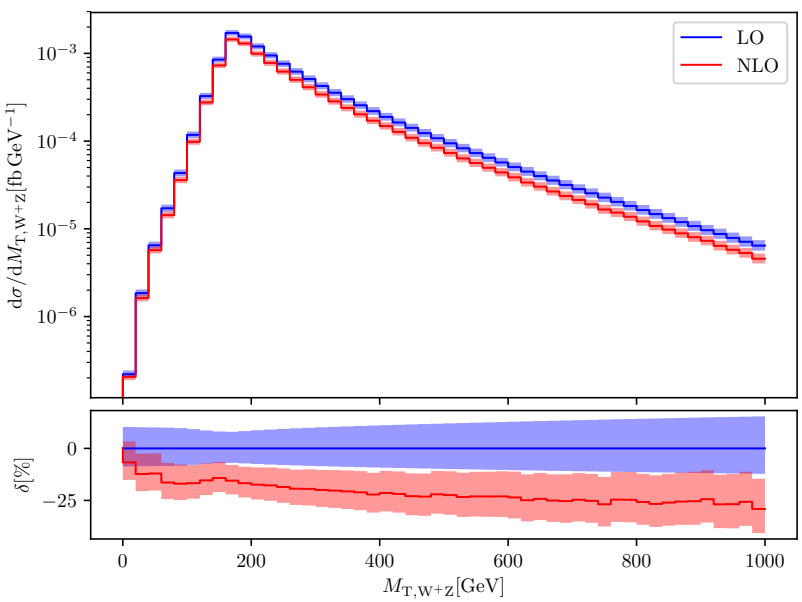


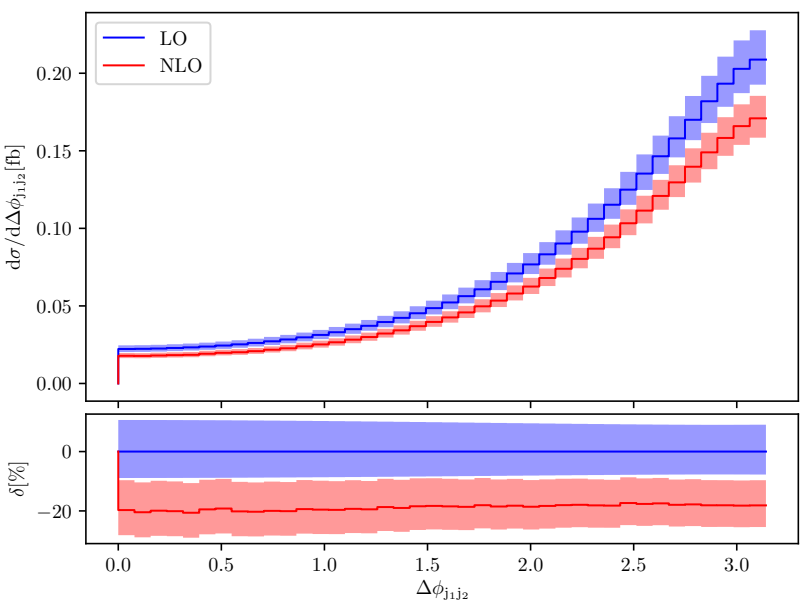


Distributions (V)









Distributions (VI)