NLO EW Corrections for W^+Z scattering at the LHC

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

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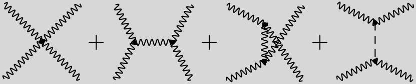
Outline

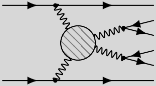
Vector-boson scattering in a nutshell

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

- $W^\pm W^\pm \to W^\pm W^\pm$ ("like-sign W scattering")
- $W^\pm Z \to W^\pm Z$

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

$\mathcal{M}_{\text{VBS}} =$ 

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

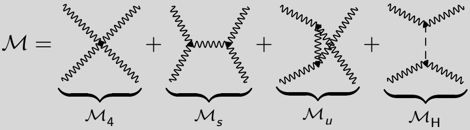
Vector-boson scattering (VBS) physics program:

- 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

Longitudinal VBS: Tree-level (non-)unitarity

$W^+Z \to W^+Z$ @ $M_H = 125$ GeV



$$\mathcal{M}_4 \propto -s^2 - u^2 - 4su + 2(M_W^2 + M_Z^2)\frac{s^2 + 6su + u^2}{s+u} + \dots$$

$$\mathcal{M}_s \propto s^2 + 2su - 2M_W^2\frac{3su + u^2}{s+u} - 2M_Z^2\frac{2u^2 + 3su - s^2}{s+u} - \frac{M_Z^4}{M_W^2}s + \dots$$

$$\mathcal{M}_u \propto u^2 + 2su - 2M_W^2\frac{3su + s^2}{s+u} - 2M_Z^2\frac{2s^2 + 3su - u^2}{s+u} - \frac{M_Z^4}{M_W^2}u + \dots$$

$$\mathcal{M}_H \propto -\frac{M_Z^4}{M_W^2}\frac{t^2(t-4M_W^2)(t-4M_Z^2)}{(t-M_H)(t-2M_W^2)(t-2M_Z^2)} = -\frac{M_Z^4}{M_W^2}t + \dots$$

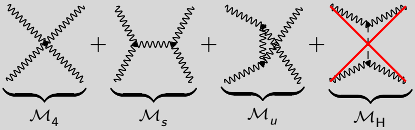
Assuming $|t| \gg M_H^2, M_Z^2, M_W^2$

$$\mathcal{M} = \mathcal{M}_4 + \mathcal{M}_s + \mathcal{M}_u + \mathcal{M}_H \propto 0 + \dots$$

Example from [Schwartz]

Longitudinal VBS: Tree-level (non-)unitarity

$W^+Z \to W^+Z$ @ $M_H = \infty$

$\mathcal{M} =$ 

$$\mathcal{M}_4 \propto -s^2 - u^2 - 4su + 2(M_W^2 + M_Z^2)\frac{s^2 + 6su + u^2}{s+u} + \dots$$

$$\mathcal{M}_s \propto s^2 + 2su - 2M_W^2\frac{3su + u^2}{s+u} - 2M_Z^2\frac{2u^2 + 3su - s^2}{s+u} - \frac{M_Z^4}{M_W^2}s + \dots$$

$$\mathcal{M}_u \propto u^2 + 2su - 2M_W^2\frac{3su + s^2}{s+u} - 2M_Z^2\frac{2s^2 + 3su - u^2}{s+u} - \frac{M_Z^4}{M_W^2}u + \dots$$

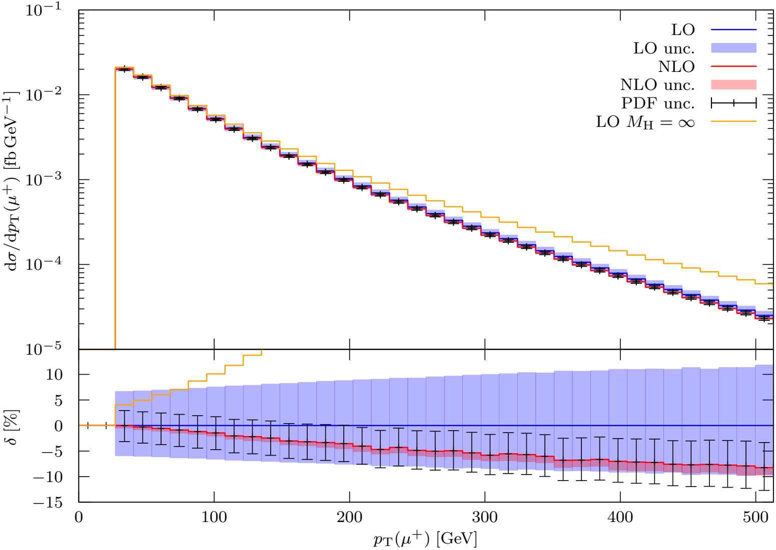
$$\mathcal{M}_H \propto -\frac{M_Z^4}{M_W^2}\frac{t^2(t-4M_W^2)(t-4M_Z^2)}{(t-M_H)(t-2M_W^2)(t-2M_Z^2)} = 0$$

$$\mathcal{M} = \mathcal{M}_4 + \mathcal{M}_s + \mathcal{M}_u + \mathcal{M}_H \propto -\frac{M_Z^4}{M_W^2}(s+u) + \dots$$

Example from [Schwartz]

$\to M_H = \infty$ estimates the maximal effect of different Higgs couplings

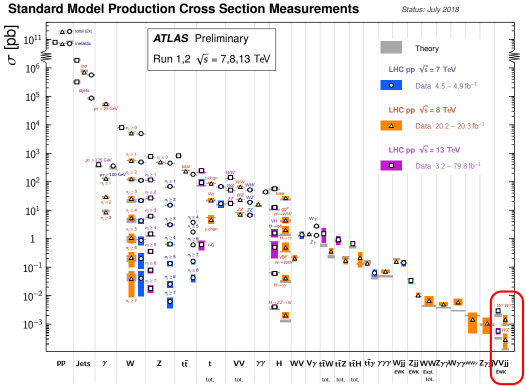
$M_H = \infty$ for $pp \to e^+ \nu_e \mu^+ \nu_\mu jj + X$



$\to$ Large positive correction, range for extended Higgs sector

Experimental status for VBS, EW pp $\rightarrow e^+\nu_e\mu^+\mu^-jj + X$

$\rightarrow$ VBS processes are $\mathcal{O}(1\,\mathrm{fb})$, need large $\sqrt{s}$ and $\mathcal{L}$:



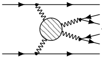
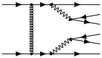
(dinosaur plot from the [ATLAS Collaboration])

- ATLAS 8 TeV: [CERN-EP-2016-017]
- ATLAS 13 TeV: Obsers. with 5.6 σ sig. ($\mathcal{L} = 36.1\,\mathrm{fb}^{-1}$) [ATLAS-CONF-2018-033]
- CMS 13 TeV: Meas. with 1.9 σ sig. ($\mathcal{L} = 35.9\,\mathrm{fb}^{-1}$) [CMS-PAS-SMP-18-001]

- Easiest VBS channel is $W^+W^+ \rightarrow W^+W^+$, full NLO corrections available [Biedermann, Denner, Pellen]
- Next channel: $W^+Z \rightarrow W^+Z$

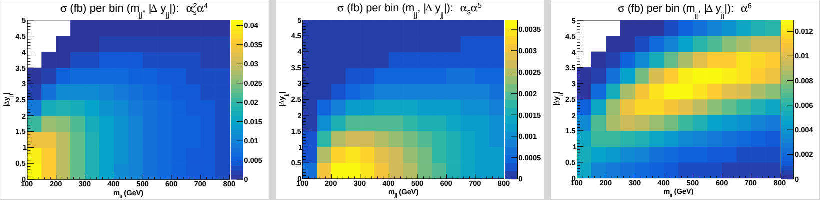
Discriminating between EW and QCD production

→ At LO, three different coupling orders:

$\mathcal{M}_{\mathrm{EW}} =$  $+\dots$ $\quad \mathcal{M}_{\mathrm{QCD}} =$  $+\dots \rightarrow$

- $\mathcal{O}(\alpha^4 \alpha_s^2)$: $|\mathcal{M}_{\mathrm{QCD}}|^2$
- $\mathcal{O}(\alpha^5 \alpha_s^1)$: $2\mathfrak{Re}\left\{\mathcal{M}^*_{\mathrm{QCD}}\mathcal{M}_{\mathrm{EW}}\right\}$
- $\mathcal{O}(\alpha^6 \alpha_s^0)$: $|\mathcal{M}_{\mathrm{EW}}|^2$

How to maximize the EW production ("signal")? $(\mathrm{pp} \rightarrow \mathrm{e}^+\nu_e \mu^+\nu_\mu \mathrm{jj} + \mathrm{X})$

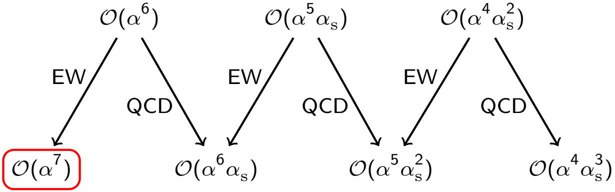


(plots from VBSCAN WG1 report [Ballestrero, et. al.])

→ Observables $M_{j_1 j_2}$ and $\Delta y_{j_1 j_2}$ are used to discrimate the QCD from the EW production

→ In the fiducial PS region, EW > QCD for like-sign scattering (no initial-state gluons), for W^+ Z-scattering: QCD > EW

LO and NLO for 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. $\mathcal{O}(\alpha^6\alpha_s^1)$: [Bozzi, Jäger, Oleari, Zeppenfeld]
- $\mathcal{O}(\alpha^4\alpha_s^3)$ calculation available [Campanario, Kerner, Ninh, Zeppenfeld]

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

Validation and checks

We performed two independent calculations for both $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha^7)$:

"Freiburg"

- MEs from OpenLoops [Cascioli, Maierhöfer, Pozzorini]
- Loops evaluated with DD (COLI fallback) from COLLIER [Denner, Dittmaier, Hofer]
- General purpose Monte Carlo [CS]
- Dipole subtraction [Catani, Seymour] to regularize IR singularities
- PDFs from LHAPDF 6 [Buckley, et. al.]

"Würzburg"

- MEs from RECOLA [Actis, Denner, Hofer, Scharf, Uccirati]
- Loops evaluated with COLI (and DD) from COLLIER
- MoCaNLO [Feger] used by M. Pellen
- CS dipole subtraction with α-dependent dipoles [Nagy]
- PDFs from LHAPDF 6

Extensive checks:

- NLO virtuals checked against each other for 1000 PS points passing the cuts
- Integrated cross sections
- Each bin of 23 differential distributions, ca. 7800 bins

Fiducial phase space volume for pp $\to e^+\nu_e\mu^+\mu^- jj + X$

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

- At least two $R = 0.4$ anti-k_t jets with $p_T > 30$ GeV, $|\eta| < 4.5$, and $\Delta R_{j\ell} > 0.3$
- $M_{j_1j_2} > 500$ GeV, no $\Delta\eta_{j_1j_2}$ cut[1]
- $p_{T,\ell} > 20$ GeV and $|y_\ell| < 2.5$
- $p_{T,miss} > 30$ GeV
- $|M_{\mu\bar{\mu}} - M_Z| < 10$ 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`
- $\sqrt{s} = 13$ TeV

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

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

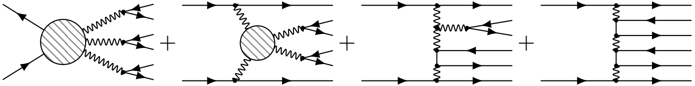
with coupling calculated as:

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

Scale choice: $\mu_F = (1/2, 1, 2) \cdot M_W$
$\to$ 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

Feynman diagrams and partonic channels

$\mathcal{M}_{\text{LO}} =$  $+ \dots$

Borns and Born-like:

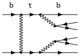
- $uu \to e^+\nu_e\,\mu^+\mu^- du$ (~47% XS),
- $du \to e^+\nu_e\,\mu^+\mu^- dd$ (~18% XS),
- $\ldots +$ 38 more: bottleneck are virtuals

Reals:

- $uu \to e^+\nu_e\,\mu^+\mu^- du\gamma$,
- $du \to e^+\nu_e\,\mu^+\mu^- dd\gamma$,
- $\ldots +$ 38 more,

Not included, small or negligable:

- $\gamma\gamma \to e^+\nu_e\,\mu^+\mu^- (d\bar{u}/s\bar{c})$, and
- $bu \to e^+\nu_e\,\mu^+\mu^- db$,
- $\ldots +$ 7 more, with resonant top-quarks:

$\mathcal{M}_{\text{b-quarks}} =$ 

$+ \dots$

Reals not yet calculated, expected to be small:

- $\gamma u \to e^+\nu_e\,\mu^+\mu^- d u\bar{u}$,
- $\ldots +$ 27 more,
- $\gamma\gamma \to e^+\nu_e\,\mu^+\mu^- d\bar{u}\gamma$, and
- $\gamma\gamma \to e^+\nu_e\,\mu^+\mu^- d\bar{u}\gamma$.

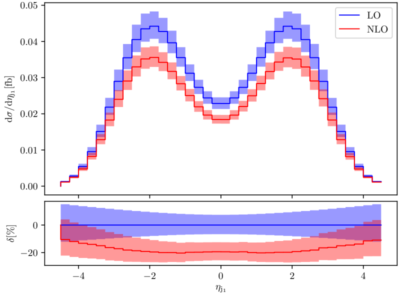
Integrated cross section

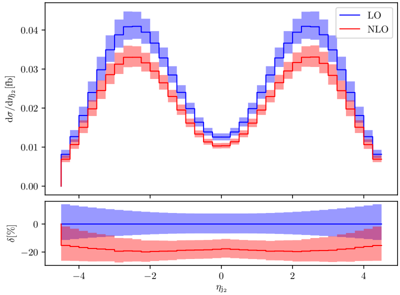
Integrated xs for pp $\to \mathrm{e}^+\nu_\mathrm{e}\,\mu^+\mu^-\mathrm{jj} + \mathrm{X}$ @ $\sqrt{s} = 13\,\mathrm{TeV}$ for the fiducial PS volume:

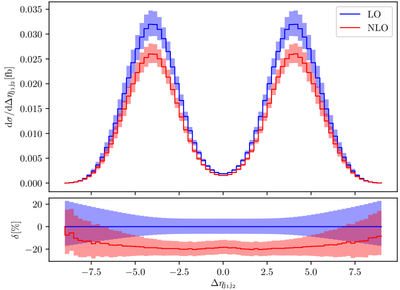
LO [fb]	NLO [fb]	$\delta = \frac{\mathcal{O}(\alpha^7)}{\mathcal{O}(\alpha^6)}$ [%]
$0.2362^{+9.433\%}_{-8.022\%}$	$0.1899^{+8.356\%}_{-7.575\%}$	-19.6%

- Uncertainty is the range given by varying $\mu_\mathrm{F} = M_\mathrm{W}$ by (1/2,2)
- No dep. on α_s $\to$ no dep. on μ_R
- Huge corrections (4–5 $\times$ larger than e.g. EW corr. for di-boson prod.) on the integrated cross section, larger than even like-sign W-scattering (-16%)
- Corrections are even larger in specific regions of p_T distributions

Jet pseudo-rapidities



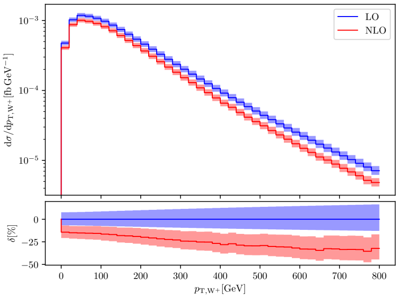


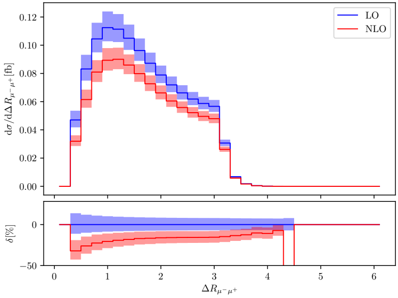


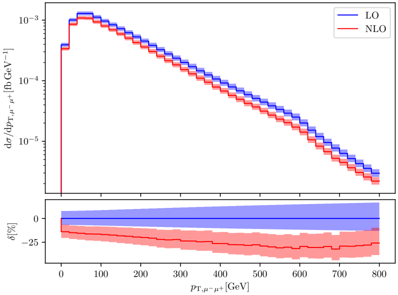
- EW corrections flat in most PS regions
- Bands: large dependence on μ_F
- Peak at $\Delta\eta_{j_1 j_2} \approx 0$ suppressed because of $M_{j_1 j_2} > 500\,\text{GeV}$ cut:

$$\cosh \Delta\eta_{j_1 j_2} \approx \frac{M_{j_1 j_2}}{2 p_{T,j_1} \cdot p_{T,j_2}} + \cos \Delta\phi_{j_1 j_2}$$

Leptonic observables







$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- In $p_{\mathrm{T,W^+}}$ Sudakov logs further increase EW corrections
- $\Delta R_{\mu\bar{\mu}}$ is limited from above because $M_{\mu\bar{\mu}} \approx M_{\mathrm{Z}}$ cut limits $\Delta\eta_{\mu\bar{\mu}} < 3.3$
- Kink at $p_{\mathrm{T},\mu\bar{\mu}} \approx \frac{2M_{\mathrm{Z}}}{\Delta R_{\ell\ell}}$ caused by $\Delta R_{\ell\ell}$ cut

Summary

- Vector-boson scattering (VBS) important to constrain the actual Higgs-sector, complementary to Higgs-couplings measurements
- After W^+W^+, W^+Z scattering is the next important channel for VBS
- Experiments are either measuring or already observing it
- EW corrections are available now, huge correction on the integrated cross-section: -20%

Acknowlegments

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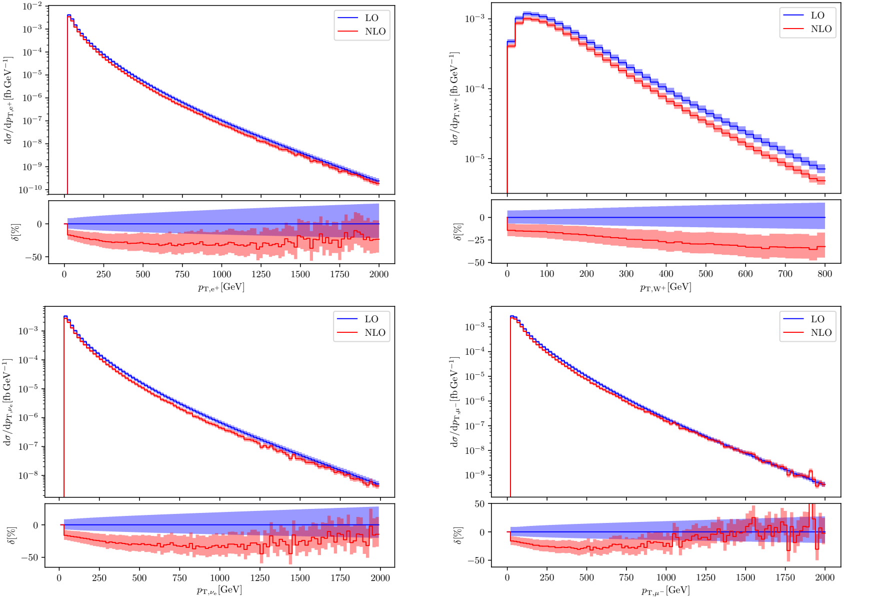
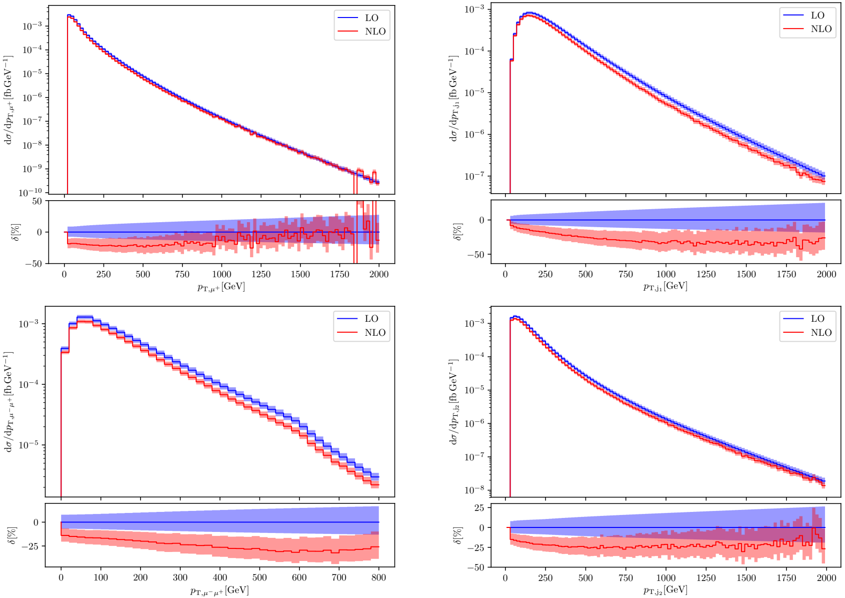
- This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006.

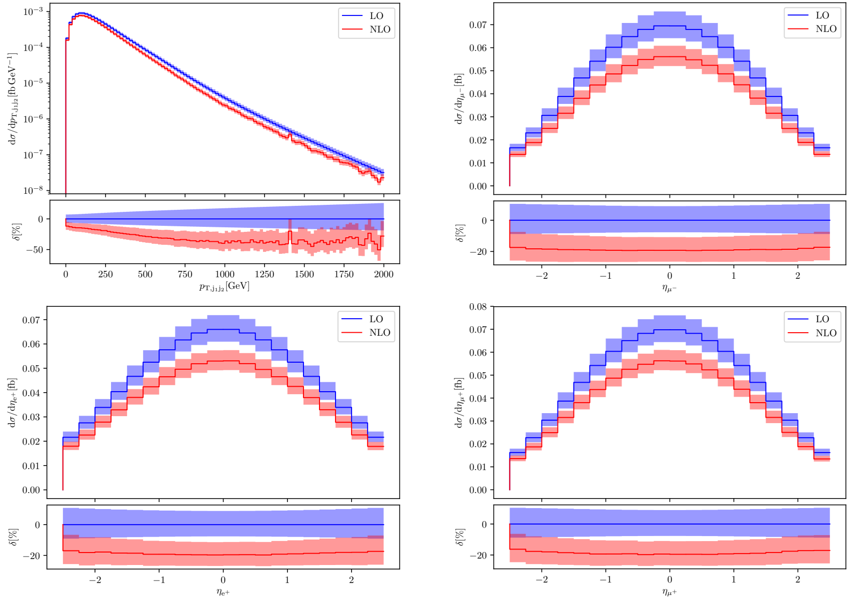
Distributions (I)



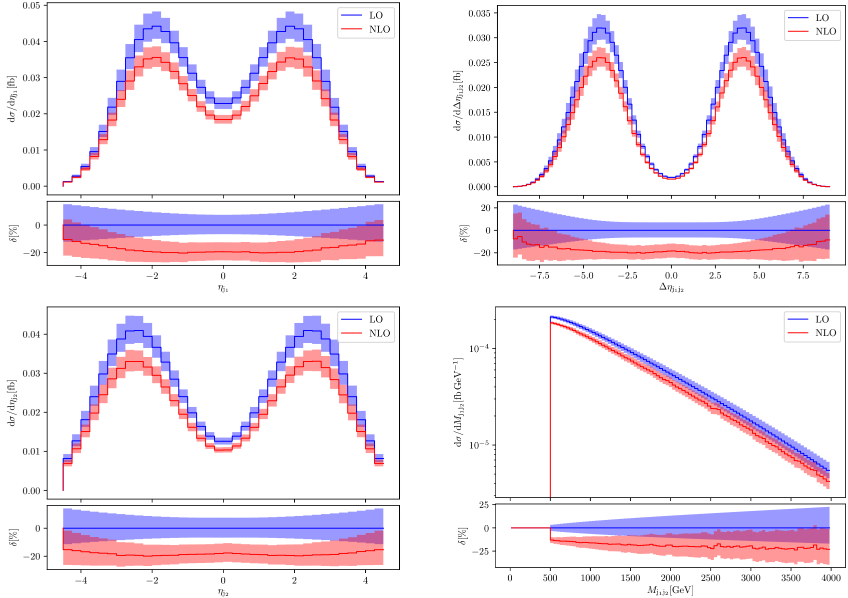
Distributions (II)



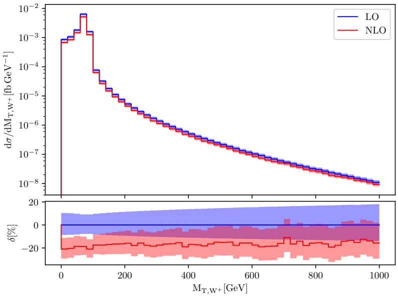
Distributions (III)

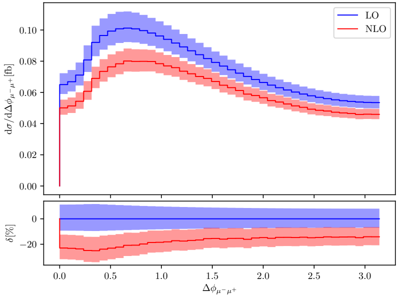


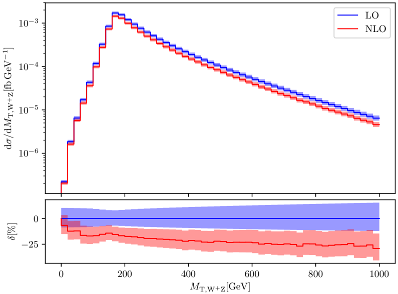
Distributions (IV)

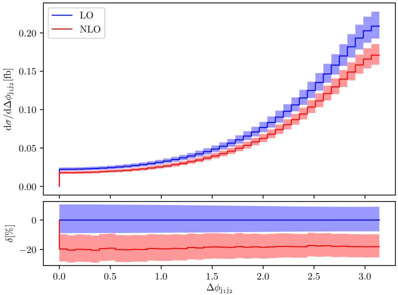


Distributions (V)









Distributions (VI)