# 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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Machine Learning • PDFs • QCD

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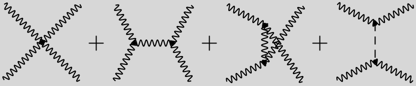
# Vector-boson scattering in a nutshell

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

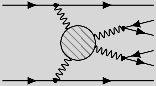
- $W^\pm W^\pm \to W^\pm W^\pm$ ("like-sign W scattering")
- $W^\pm Z \to W^\pm Z$

**$W^+Z \to W^+Z$** $\quad$ $pp \to e^+ \nu_e \mu^+ \mu^- jj + X$

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



$\mathcal{M}_{\mathrm{VBS@LHC}} =$



$+ \dots$

Vector-boson scattering (VBS) physics program:

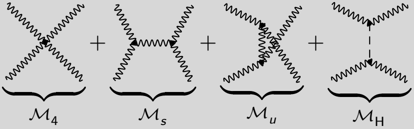
- Constrain anomalous quartic gauge couplings (with triple-gauge boson prod.)
- Measure Higgs-vector-vector couplings, complementary to on-shell Higgs decay measurements
- Probe EW symmetry breaking: interplay between triple and quartic gauge couplings and the Higgs boson(s); large cancellations for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

$\mathcal{M} =$




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

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

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

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

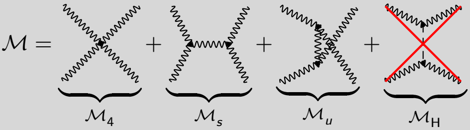
Assuming $|t| \gg M_H^2, M_Z^2, M_W^2$

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

Example from [Schwartz]

# Longitudinal VBS: Tree-level (non-)unitarity

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




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

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

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

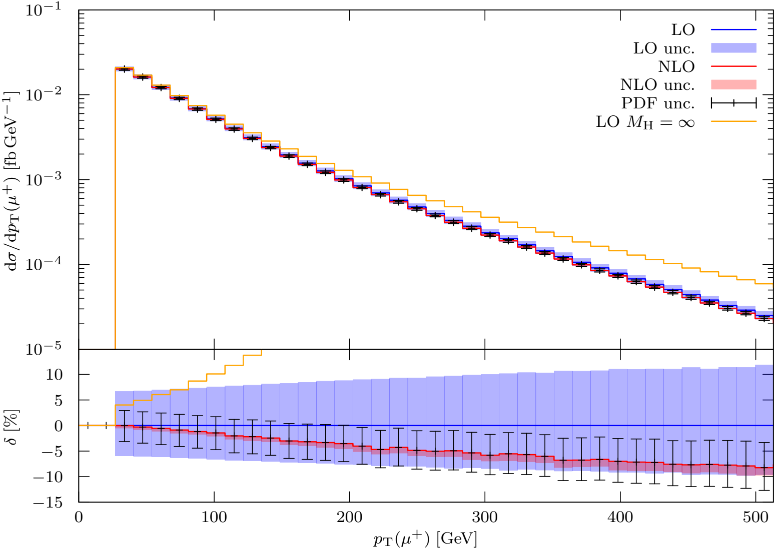
$$\mathcal{M}_H \propto -\frac{M_Z^4}{M_W^2}\frac{t^2(t-4M_W^2)(t-4M_Z^2)}{(t-M_H)(t-2M_W^2)(t-2M_Z^2)} = 0$$

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

Example from [Schwartz]

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

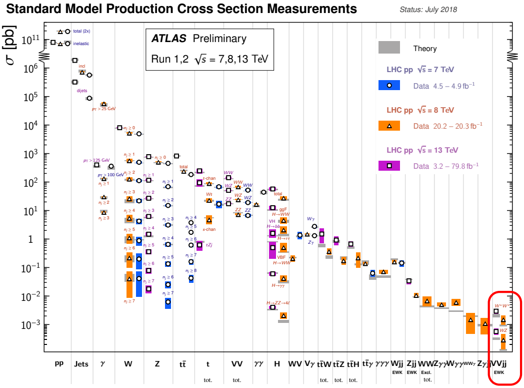
# $M_H = \infty$ for $pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj + X$




→ Large positive correction, range for extended Higgs sector

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

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



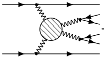
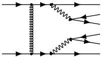

(dinosaur plot from the [ATLAS Collaboration])

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

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

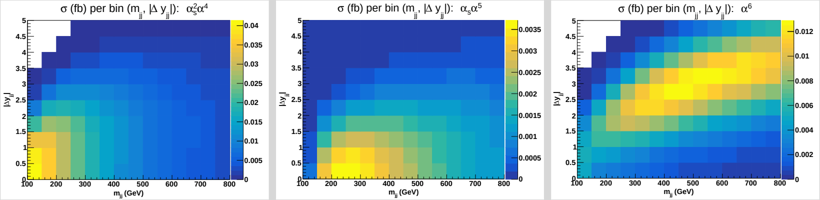
# Discriminating between EW and QCD production

→ At LO, three different coupling orders:

$\mathcal{M}_{\mathrm{EW}} =$  $+\ldots$ $\mathcal{M}_{\mathrm{QCD}} =$  $+\ldots$ →

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

## How to maximize the EW production ("signal")? ($pp \to e^+\nu_e\,\mu^+\nu_\mu jj + X$)

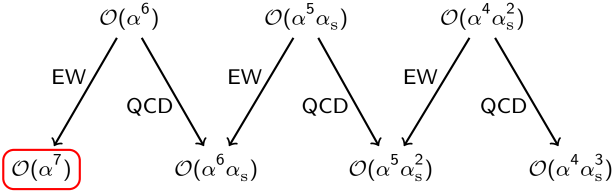



(plots from VBSCAN WG1 report [Ballestrero, et. al.])

→ Observables $M_{j_1j_2}$ and $\Delta y_{j_1j_2}$ 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 $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\,\mu^+\mu^-\mathrm{jj} + \mathrm{X}$




- All LOs presented in Sec. V.3 of the SM Les Houches 2017 report [Bendavid et. al.]: QCD (~80%) dominates over EW
- Approx. $\mathcal{O}(\alpha^6\alpha_\mathrm{s}^1)$: [Bozzi, Jäger, Oleari, Zeppenfeld]
- $\mathcal{O}(\alpha^4\alpha_\mathrm{s}^3)$ calculation available [Campanario, Kerner, Ninh, Zeppenfeld]

→ $\mathcal{O}(\alpha^7)$ 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 $\alpha$-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 $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\,\mu^+\mu^-\mathrm{jj} + \mathrm{X}$

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

- At least two $R = 0.4$ anti-$k_\mathrm{t}$ jets with $p_\mathrm{T} > 30\,\mathrm{GeV}$, $|\eta| < 4.5$, and $\Delta R_{\mathrm{j}\ell} > 0.3$
- $M_{\mathrm{j_1 j_2}} > 500\,\mathrm{GeV}$, no $\Delta\eta_{\mathrm{j_1 j_2}}$ cut[1]
- $p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$ and $|y_\ell| < 2.5$
- $p_{\mathrm{T,miss}} > 30\,\mathrm{GeV}$
- $|M_{\mu\bar{\mu}} - M_Z| < 10\,\mathrm{GeV}$
- $\Delta R_{\ell\ell} > 0.3$

Other:

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

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

- $G_\mu = 1.663\,787 \times 10^{-5}\,\mathrm{GeV}^{-2}$
- $M_\mathrm{W} = 80.357\,97\,\mathrm{GeV}$, $\Gamma_\mathrm{W} = 2.084\,30\,\mathrm{GeV}$
- $M_\mathrm{Z} = 91.153\,48\,\mathrm{GeV}$, $\Gamma_\mathrm{Z} = 2.494\,27\,\mathrm{GeV}$
- $M_\mathrm{H} = 125.0\,\mathrm{GeV}$, $\Gamma_\mathrm{H} = 4.07 \times 10^{-3}\,\mathrm{GeV}$

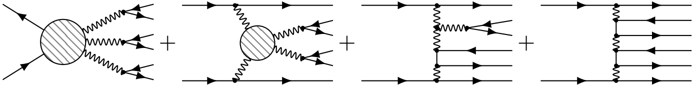
with coupling calculated as:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_\mathrm{W}^2 \left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right)$$

Scale choice: $\mu_\mathrm{F} = (1/2, 1, 2) \cdot M_\mathrm{W}$
$\to$ No dependence on $\mu_\mathrm{R}$, since processes do not depend on $\alpha_\mathrm{s}$!

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

# Feynman diagrams and partonic channels

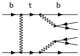
$\mathcal{M}_{\mathrm{LO}} =$  $+ \ldots$

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

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:

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

$+ \ldots$

Reals:

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

Reals not yet calculated, expected to be small:

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

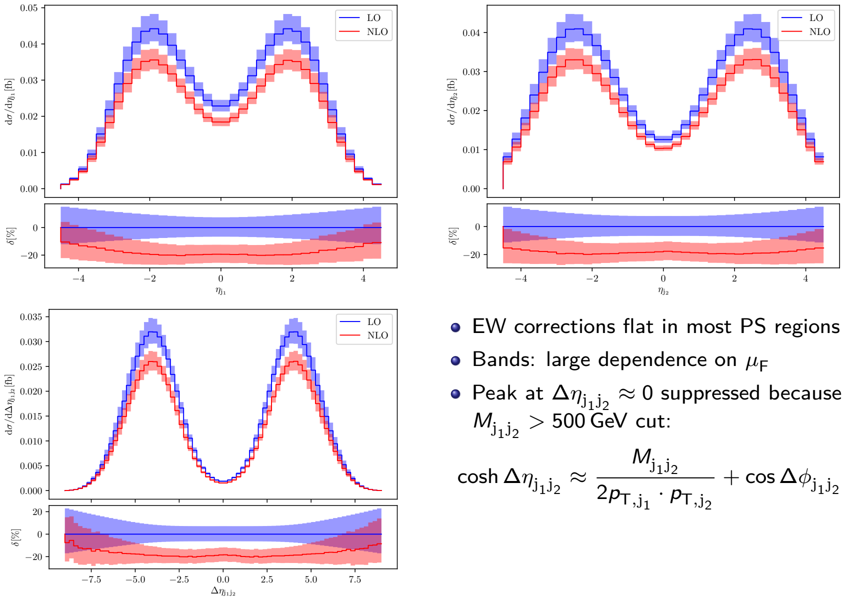
# Integrated cross section

Integrated xs for $\mathrm{pp} \to \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \mu^- \mathrm{jj} + \mathrm{X}$ @ $\sqrt{s} = 13$ 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 $\alpha_\mathrm{s}$ $\to$ no dep. on $\mu_\mathrm{R}$
- 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 $p_\mathrm{T}$ distributions

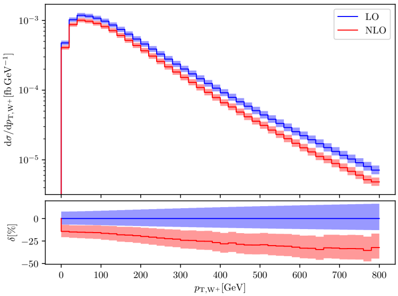
# Jet pseudo-rapidities

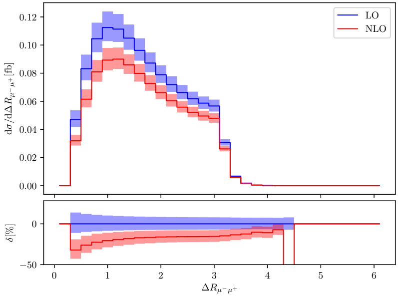


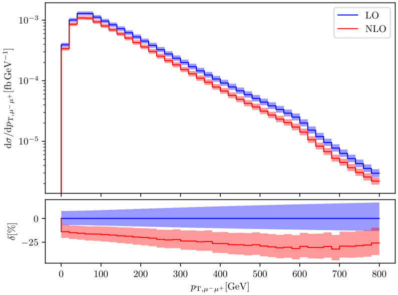

- EW corrections flat in most PS regions
- Bands: large dependence on $\mu_F$
- Peak at $\Delta\eta_{j_1j_2} \approx 0$ suppressed because of $M_{j_1j_2} > 500\,\text{GeV}$ cut:

$$\cosh \Delta\eta_{j_1j_2} \approx \frac{M_{j_1j_2}}{2p_{T,j_1} \cdot p_{T,j_2}} + \cos \Delta\phi_{j_1j_2}$$

# 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

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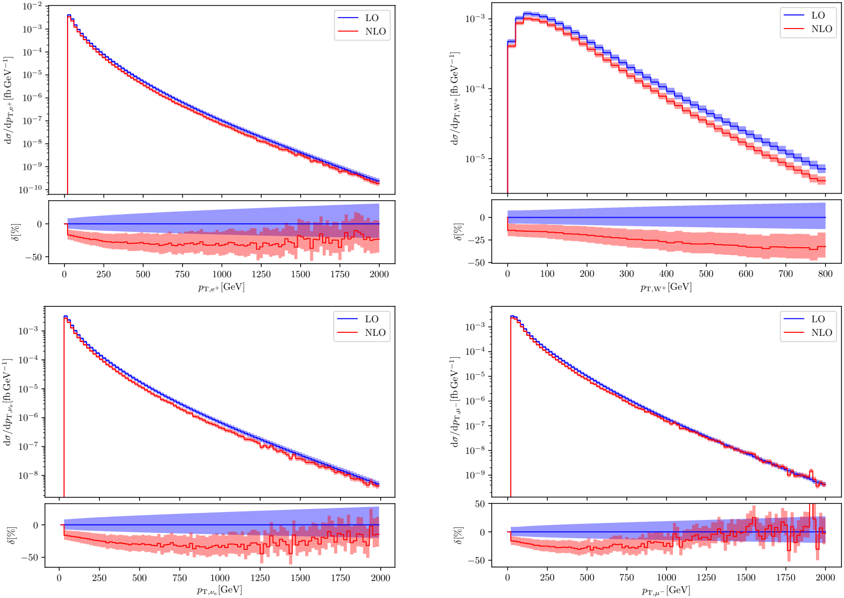
- This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006.

# Distributions (I)



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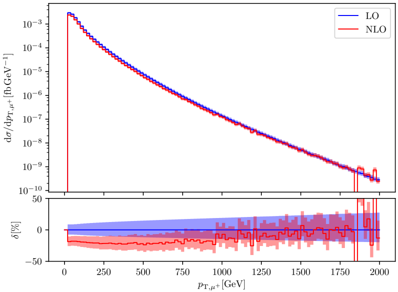


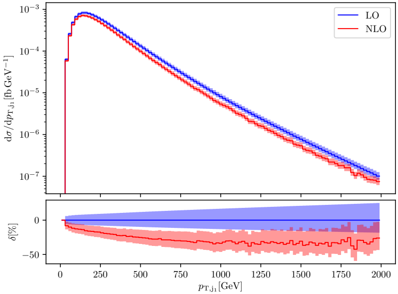


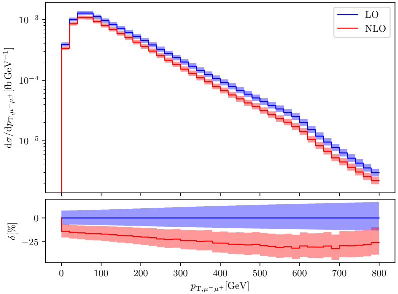


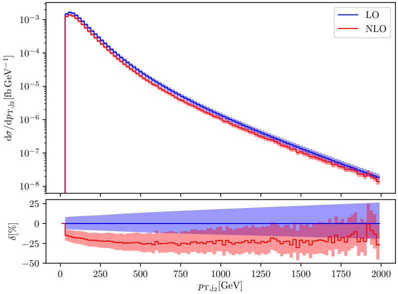

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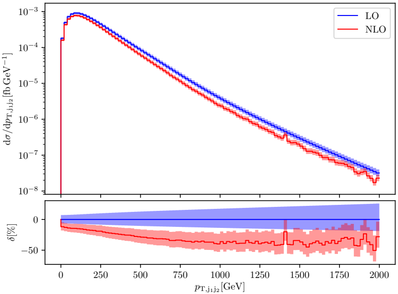


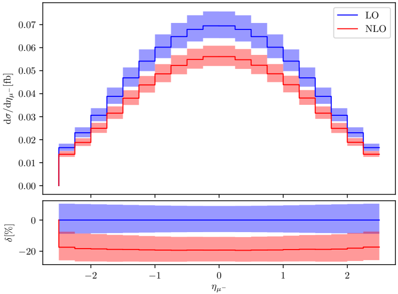


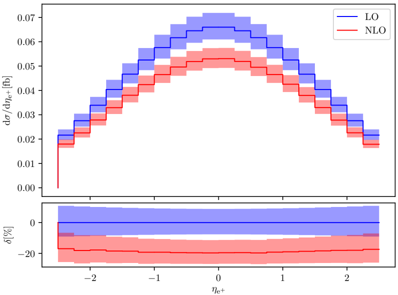


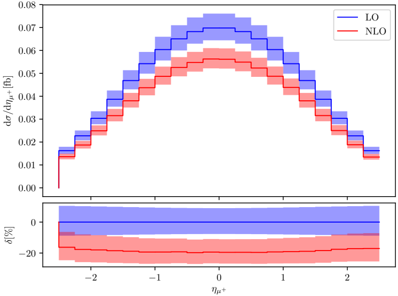

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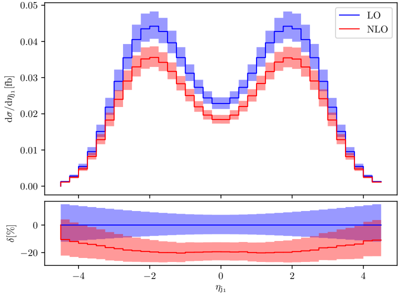


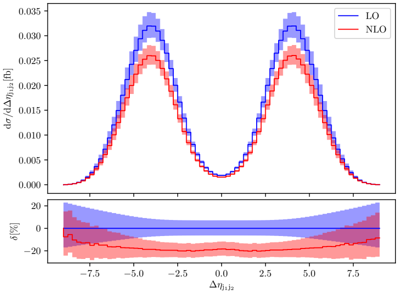


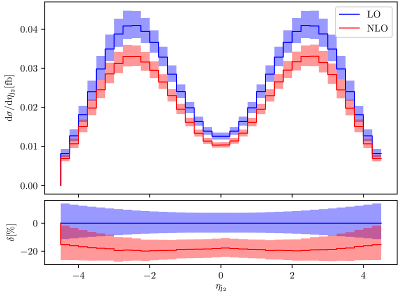


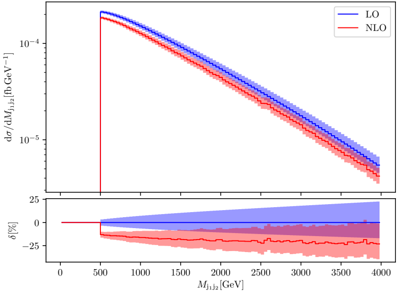

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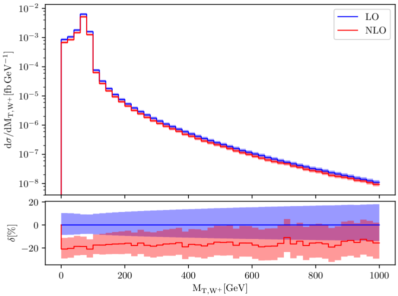


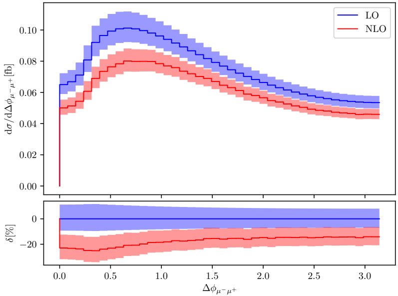


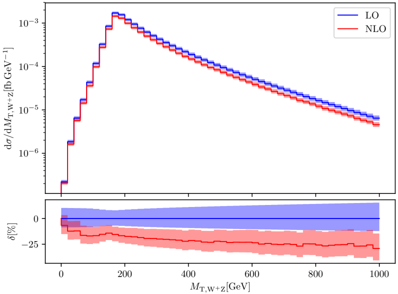


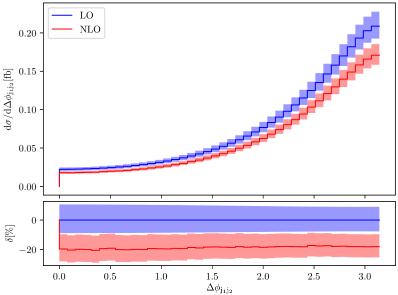

# Distributions (VI)