Improving NLO QCD event generators with high-energy EW corrections: $t\bar{t}H$ production

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based on [arXiv:2309.00452]

Lund University

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Today's talk

1. **Technical details** of the $\mathrm{NLO_{QCD}} \otimes$EWSL+PS implementation in MG5

2. **Numerical results** for $t\bar{t}H$

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The one-loop approximation of NLO EW corrections

- Focus on **electroweak corrections**: automations of NLO EW corrections
- Current problems:
  1. time-consuming computations
  2. no automated matching to PS
- Alternative: capture the dominant part of it (in high-energy limit)!
  $\rightarrow$ electroweak Sudakov logarithms (EWSL)

[1] A. Denner, S. Pozzorini, arXiv:hep-ph/0010201

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- **One-loop leading approximation**:
  worked out originally by **Denner and Pozzorini**[1]

- Arise as corrections to the Born-level matrix-element as

$$\mathcal{M}^{\text{LO+EWSL}} = \mathcal{M}_0 + \mathcal{M}_0 \times \delta^{\text{EWSL}} \tag{1}$$

[1] A. Denner, S. Pozzorini, arXiv:hep-ph/0010201

The Denner-Pozzorini algorithm and MG5_aMC@NLO

- One-loop Denner-Pozzorini implemented also in Sherpa[2]
- One-loop Denner-Pozzorini algorithm **revised and implemented in MG5**[3]

- **Current project**:

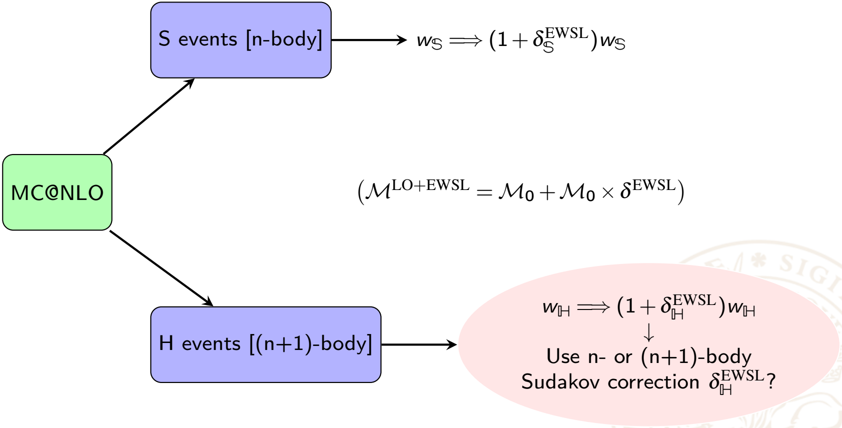
  combination of this implementation with

  $$\text{NLO}_{\text{QCD}}+\text{PS}$$

  event generation via **reweighting**

[2] E. Bothmann, D. Napoletano arXiv:2006.14635
[3] D. Pagani, M. Zaro arXiv:2110.03714

Reweighting NLO events with EWSL



Reweighting NLO events with EWSL

Problem 1

- Sudakov logarithm expressions not valid in the soft/collinear regions!

Problem 2

- IR cancellation might not be secured anymore!

Proposed procedure:[4]

1. Check all $r_{kl} = (p_k \pm p_l)^2$
2. If all $|r_{kl}| > M_W^2$: use (n+1)-body Sudakov
3. If any $|r_{kl}| < M_W^2$: merge particles k, l
4. If reasonable merged process: use n-body Sudakov of the mapped kinematics,
   else
   use the (n+1)-body Sudakov and replace $|r_{kl}| \to M_W^2$

[4] D. Pagani, T. Vitos, M. Zaro arXiv:2309.00452

Summary of the implementation

1. **Reweight all events** in the described procedure and apply parton shower:

$$\text{NLO}_{\text{QCD}} \otimes \text{EWSL+PS}$$

2. Assign **EWSL only to Born events** and apply parton shower:

$$\text{NLO}_{\text{QCD+EWSL}}\text{+PS}$$

- **Comparison to full NLO QCD+EW (fixed-order)** of order

$$\mathcal{O}(\alpha_S) + \mathcal{O}(\alpha)$$

$\rightarrow$ expected to behave as **additive** approach
while **multiplicative** behaves more like $\mathcal{O}(\alpha_S\alpha)$ corrections

- A similar approach has been implemented in Sherpa[5][6]

[5] E. Bothmann, D. Napoletano, M. Schönherr, S. Schumann, S. L. Villani arXiv:2111.13453
[6] S. Kallweit, J. M. Lindert, S. Pozzorini, M. Schönherr, P. Maierhöfer arXiv:1511.08692

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Numerical setup

Input

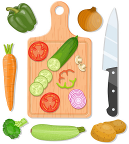
- Focus on **LHC:** $\sqrt{s} = 13$ **TeV**
- Defining jets: **anti-k_T algorithm** with

$$p_T^{\text{min}} = 10 \text{ GeV and } R = 0.4$$

- Use **PYTHIA8** for the parton shower, with hadronization **off**

No cuts (inclusive)

- Note: Sudakov not valid in all regions here!



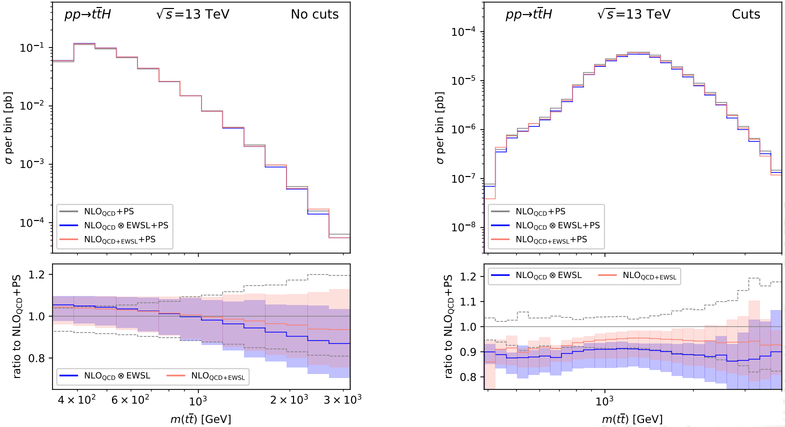
Hard cuts

- $p_T > 400$ GeV cut on all heavy final particles
- $\Delta R > 0.5$ for any two final particles

- Gray curve: NLO_{QCD}+PS
  Blue curve: multiplicative EWSL
  Red curve: additive EWSL

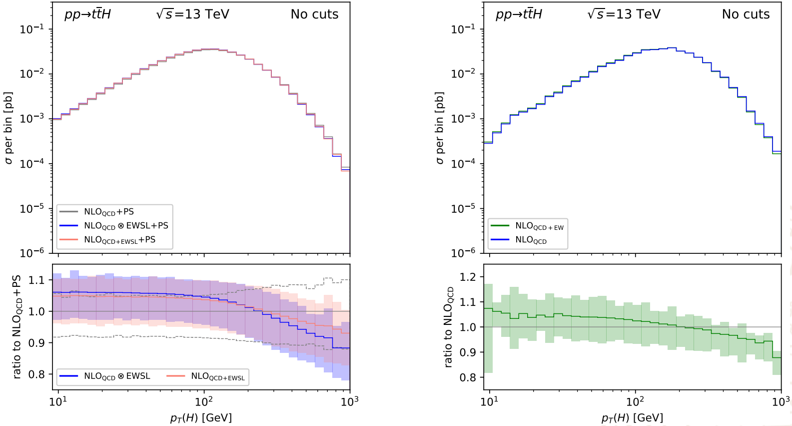
Results for $t\bar{t}H$: $m(t\bar{t})$

- Difference between additive and multiplicative in high-energy range
- Scale band differences: EWSL on top of NLO events (blue) and LO events (red)



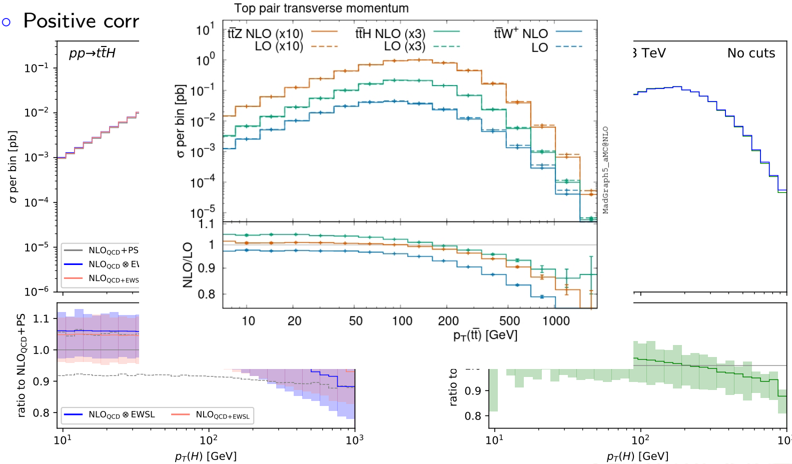
Results for $t\bar{t}H$: $p_T(H)$ inclusive

- Again, up to 5% difference between the two approaches
- Positive corrections (also FO NLO EW) at low-p_T



Results for $t\bar{t}H$: $p_T(H)$ inclusive

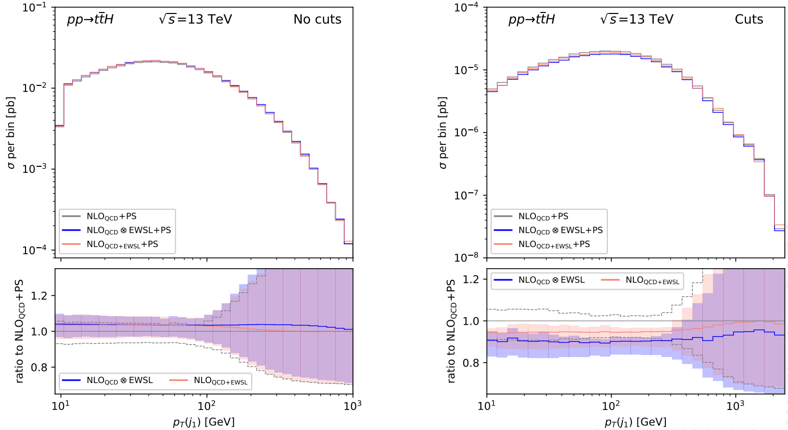
- Again, up to 5% difference between the two methods
- Positive corr



- Compare to FO NLO EW test results for $t\bar{t}H$ in R. Frederix et al. arXiv:1804.10017

Results for $t\bar{t}H$: $p_T(j_1)$

- High-p_T range: additive approach converges to NLO_{QCD}+PS



Summary and outlook

Summary

- ✓ Combined EWSL implementation and reweight module in MG5_aMC@NLO for obtaining $\text{NLO}_{\text{QCD}} \otimes$ EWSL+PS precision
- ✓ Preliminary comparison to full NLO EW fixed-order corrections shows expected behaviours for $t\bar{t}H$

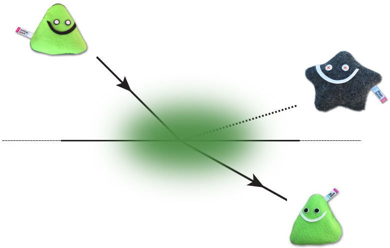
Outlook: phenomenological analyses

- Processes of interest: jet-associated processes, $t\bar{t}+X$
- Quantitative comparison to fixed-order NLO EW
- Comparison to data: include hadronization

Outlook: merging

- Combine with multi-jet merging in the FxFx formalism

Thank you for listening!



Adding parton showers

NLO QCD: $\mathcal{O}(\alpha_S) \xrightarrow{\text{QCD PS}} \mathcal{O}(\alpha_S^n)$ $n > 1$

$\rightarrow$ matching needed!

NLO QCD+EWSL: $\mathcal{O}(\alpha_S \alpha) \xrightarrow{\text{QCD PS}} \mathcal{O}(\alpha_S^n \alpha)$ $n > 1$

$\rightarrow$ no additional matching needed!

NLO QCD+EWSL: $\mathcal{O}(\alpha_S \alpha) \xrightarrow{\text{QCD PS+QED PS}} \mathcal{O}(\alpha_S^n \alpha_{(\text{QED})}^m)$ $n > 1, m > 1$

$\rightarrow$ matching needed!

Turn off QED in the Sudakov! (SDK$_{\text{weak}}$)

- NLO QCD+EWSL:

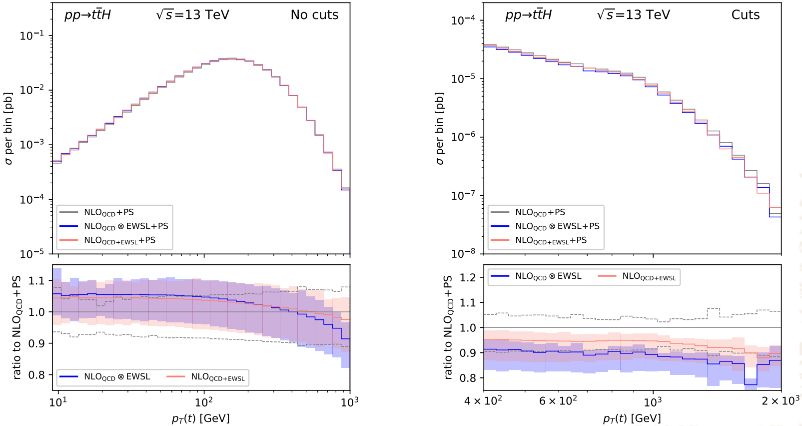
  $$\mathcal{O}(\alpha_S \alpha_{(\text{weak})}) \xrightarrow{\text{QCD PS+QED PS}} \mathcal{O}(\alpha_S^n \alpha_{(\text{weak})} \alpha_{(\text{QED})}^m), \quad n > 1, m > 0$$

- A similar approach has been implemented in Sherpa[7]

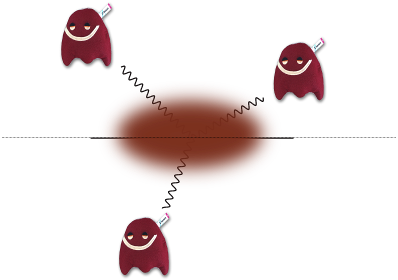
[7] E. Bothmann, D. Napoletano, M. Schönherr, S. Schumann, S. L. Villani arXiv:2111.13453

Results for $t\bar{t}H$: $p_T(t)$

- Similar positive corrections in low-p_T range
- Stable agreement to FO NLO EW
- Again, small difference between multiplicative and additive approaches



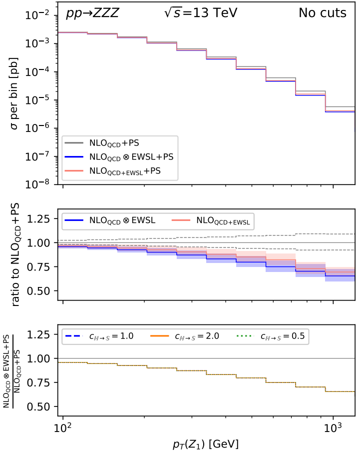
Example results: ZZZ

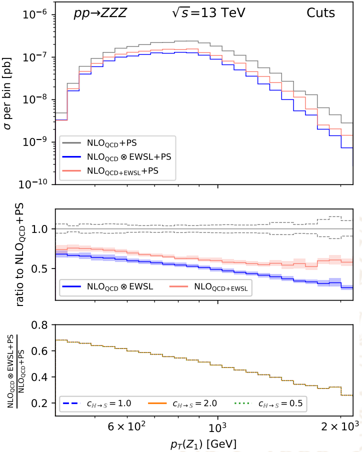


$$pp \to ZZZ$$

Results for ZZZ: $p_T(Z_1)$

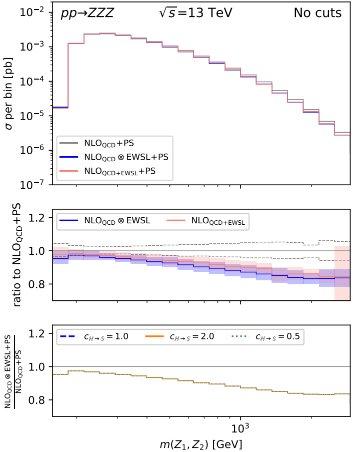
- Smaller scale uncertainty bands: no LO $\sim \alpha_S$
- Larger EWSL effects + larger QCD K-factor

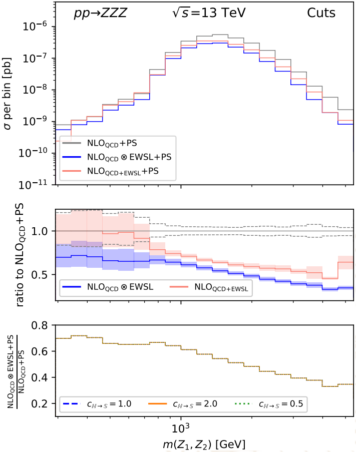




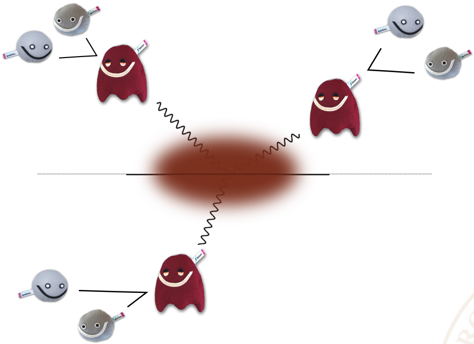
Results for ZZZ: $m(Z_1, Z_2)$

- At ≤ 700 GeV, dominated by hard events $\rightarrow$ red converges to grey





Example results: ZZZ with decays



$$pp \to ZZZ \to e^+e^-e^+e^-e^+e^-$$

Example results: ZZZ with decays

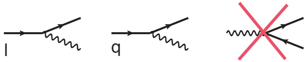
- First perform EWSL reweighting on ZZZ sample, then **decay with `MadSpin`**
- Lepton classification with jet algorithm (accepted event if 6 charged jets found):

$$p_T(\text{lepton}) > 25 \text{ GeV} \tag{2}$$

- To catch correct BW shapes: **label positrons** e_i^+ such that they **minimize**

$$\sum_i |m(e_i^- e_i^+) - M_Z|^2 \tag{3}$$

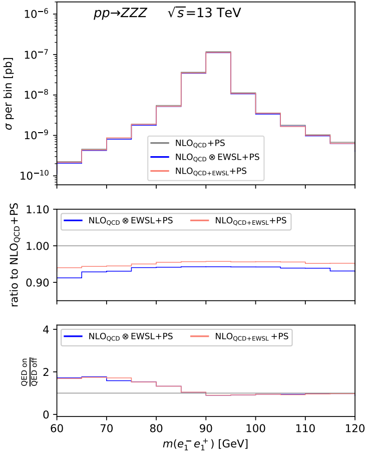
- **Final-state QED radiation**: investigate its effect by turning it off/on, including only photon radiation:

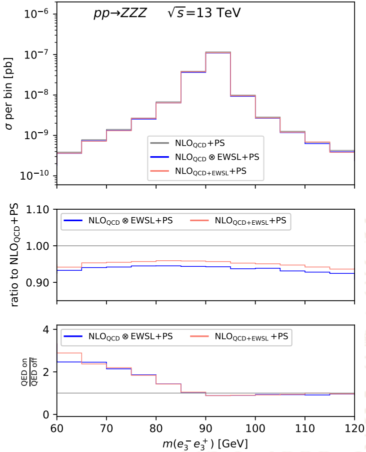


(4)

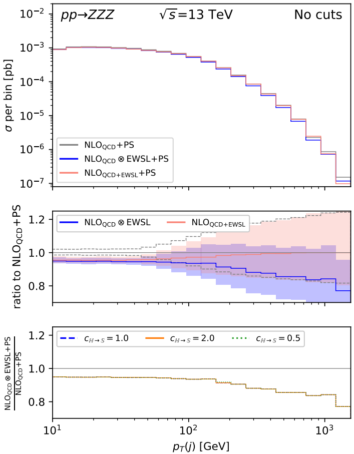
Results for ZZZ with decays: $m(e_i^- e_i^+)$

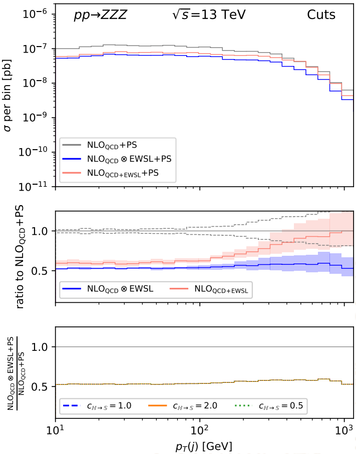
- EWSL: red and blue $\sim -5\%$
- Assess QED radiation effects: around peak region only!



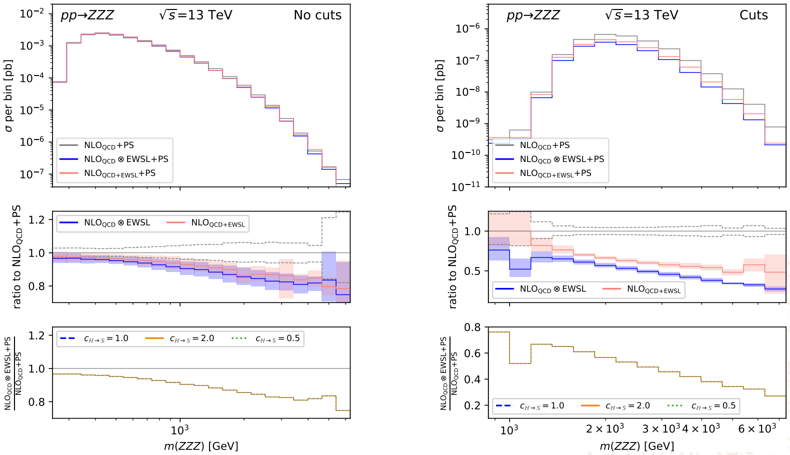


Results for ZZZ: $p_T(j_1)$

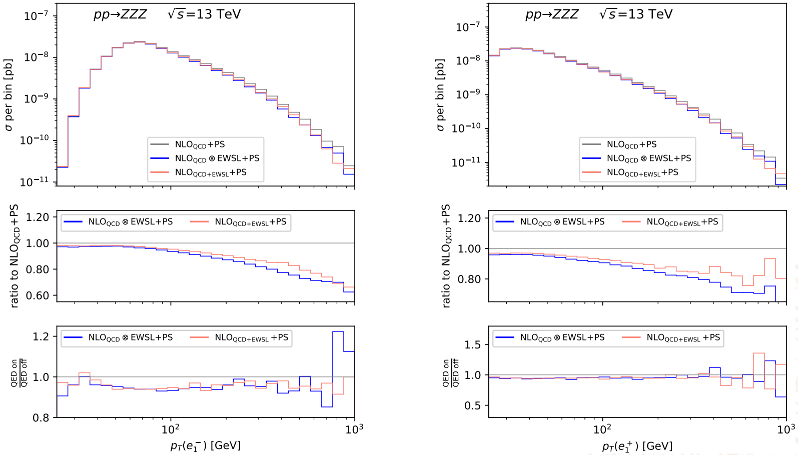




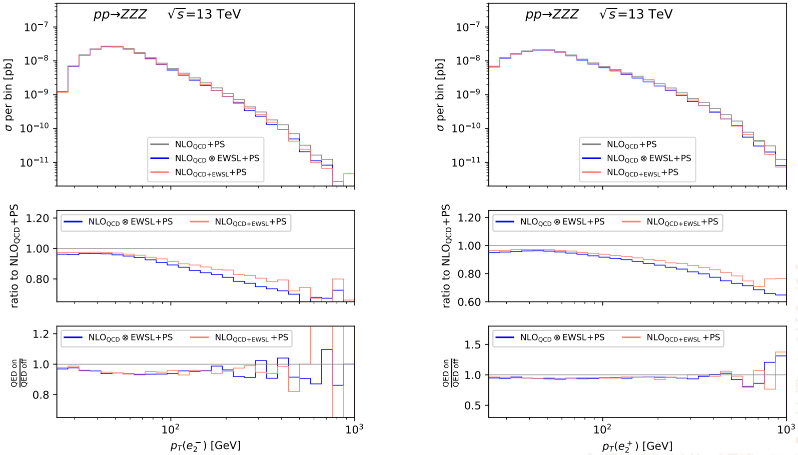
Results for ZZZ: $m(Z_1, Z_2, Z_3)$



Results for ZZZ with decays: $p_T(e_1)$



Results for ZZZ with decays: $p_T(e_2)$



Results for ZZZ with decays: $p_T(e_3)$