Combining leading one-loop electroweak corrections with NLO QCD+parton shower precision

Timea Vitos
In collaboration with: Davide Pagani, Marco Zaro
based on [arXiv:2309.00452]

Uppsala University and ELTE Budapest

SM@LHC, Rome
9 May, 2024

Today's talk

1. **Technical details** of the $\mathrm{NLO_{QCD}}\otimes$EWSL+PS implementation in MG5
2. **Predictions** for $t\bar{t}H$

Today's talk

1. **Technical details** of the $\text{NLO}_{\text{QCD}}\otimes$EWSL+PS implementation in MG5
2. **Predictions** for $t\bar{t}H$

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)!
  → electroweak Sudakov logarithms (EWSL)

- **One-loop leading approximation in high-energy limit**:
  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 in Sherpa[2]
- One-loop Denner-Pozzorini implemented in OpenLoops[3]
- One-loop Denner-Pozzorini algorithm **revised and implemented in MG5**[4]

- **Current project**[5]:

  combination of this implementation with

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

  event generation via **reweighting**

[2] E. Bothmann, D. Napoletano arXiv:2006.14635
[3] J. M. Lindert, L. Mai arXiv:2312.07927
[4] D. Pagani, M. Zaro arXiv:2110.03714
[5] D. Pagani, TV, M. Zaro arXiv:2309.00452

Reweighting NLO events with EWSL

MC@NLO

S events [n-body] → $w_{\mathbb{S}} \Longrightarrow (1+\delta_{\mathbb{S}}^{\text{EWSL}})w_{\mathbb{S}}$

$$\left(\mathcal{M}^{\text{LO+EWSL}} = \mathcal{M}_0 + \mathcal{M}_0 \times \delta^{\text{EWSL}}\right)$$

H events [(n+1)-body] → $w_{\mathbb{H}} \Longrightarrow (1+\delta_{\mathbb{H}}^{\text{EWSL}})w_{\mathbb{H}}$

$\downarrow$

Use n- or (n+1)-body
Sudakov correction $\delta_{\mathbb{H}}^{\text{EWSL}}$?

Summary of the implementation

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

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

Comparison to fixed-order: expected precision of $\mathcal{O}(\alpha_S \alpha)$ corrections

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

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

Comparison to fixed-order: expected precision of

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

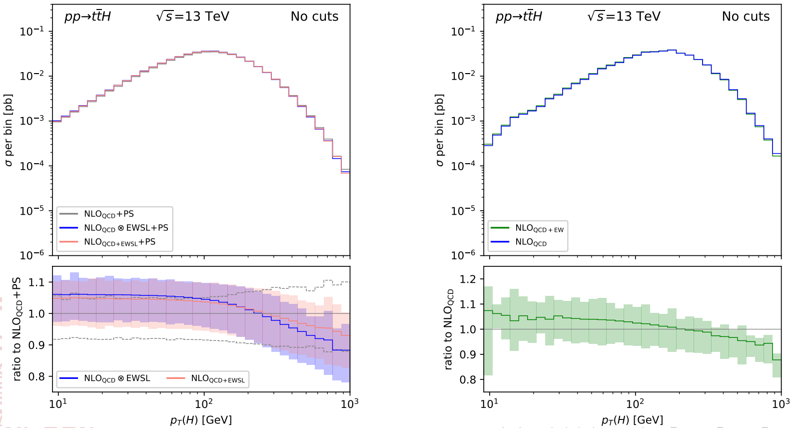
Today's talk

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

2. **Predictions** for $t\bar{t}H$

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

- Up to 5% difference between the two approaches

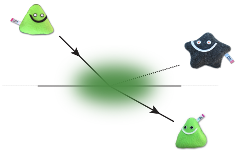


Summary

Summary

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

Thank you for your attention!



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!

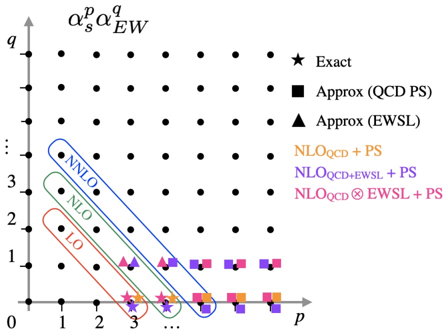
NLO QCD+EWSL: $\mathcal{O}(\alpha_S \alpha) \xrightarrow{\text{QCD PS+QED PS}} \mathcal{O}(\alpha_S^n \alpha_{\text{(QED)}}^m)$ $n > 1, m > 1$

$\rightarrow$ matching needed!

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

- NLO QCD+EWSL:

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



$\alpha_s^p \alpha_{EW}^q$
q
p
0
1
2
3
...
★ Exact
■ Approx (QCD PS)
▲ Approx (EWSL)
$\mathrm{NLO_{QCD}}$ + PS
$\mathrm{NLO_{QCD+EWSL}}$ + PS
$\mathrm{NLO_{QCD}} \otimes$ EWSL + PS
LO
NLO
NNLO

Reweighting NLO events with EWSL

Problem 1

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

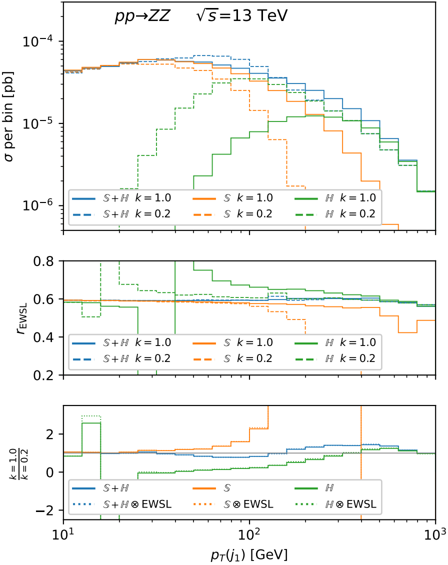
Problem 2

- IR cancellation might not be secured anymore!

Proposed procedure:[6]

1. Check all $r_{kl} = (p_k \pm p_l)^2$
2. If all $|r_{kl}| > c_{\mathbb{H}\to\mathbb{S}} M_W^2$: use (n+1)-body Sudakov
3. If any $|r_{kl}| < c_{\mathbb{H}\to\mathbb{S}} M_W^2$: 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 $|r_{kl}| \to M_W^2$
5. Vary $c_{\mathbb{H}\to\mathbb{S}}$ to assess "Sudakov-cut" dependence

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



$pp \to ZZ$ $\sqrt{s}$=13 TeV
σ per bin [pb]
r_{EWSL}
$\frac{k=1.0}{k=0.2}$
$\mathbb{S}+\mathbb{H}$ $k=1.0$
$\mathbb{S}+\mathbb{H}$ $k=0.2$
$\mathbb{S}$ $k=1.0$
$\mathbb{S}$ $k=0.2$
$\mathbb{H}$ $k=1.0$
$\mathbb{H}$ $k=0.2$
$\mathbb{S}+\mathbb{H}$
$\mathbb{S}+\mathbb{H} \otimes$ EWSL
$\mathbb{S}$
$\mathbb{S} \otimes$ EWSL
$\mathbb{H}$
$\mathbb{H} \otimes$ EWSL
$p_T(j_1)$ [GeV]

Summary of the implementation

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

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

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

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

- Difference between two is roughly:

$$(\text{NLO}_{\text{QCD}} \otimes \text{EWSL+PS}) - (\text{NLO}_{\text{QCD+EWSL}}\text{+PS}) \sim \text{EWSL} \times (K_{\text{QCD}} - 1) \qquad (2)$$

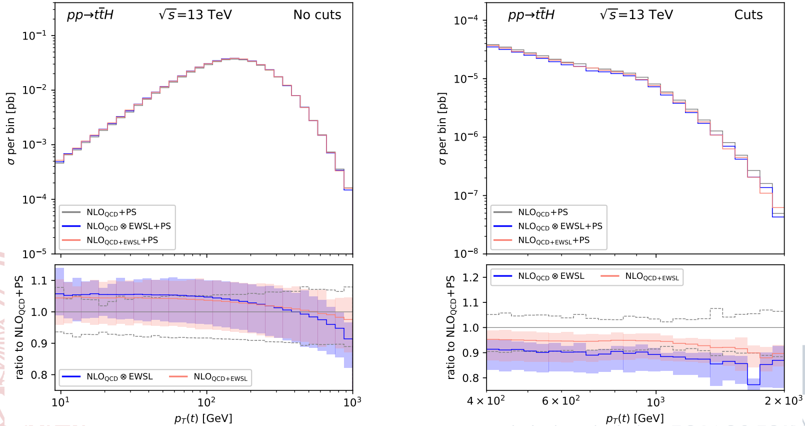
- Include QED final-state radiation to capture further large EW effects

$$\downarrow$$

use SDK_{weak} mode of the EWSL implementation

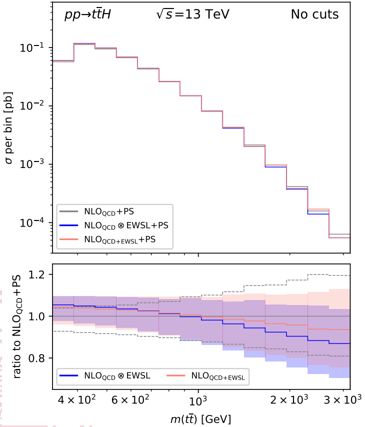
Results for $t\bar{t}H$: $p_T(t)$

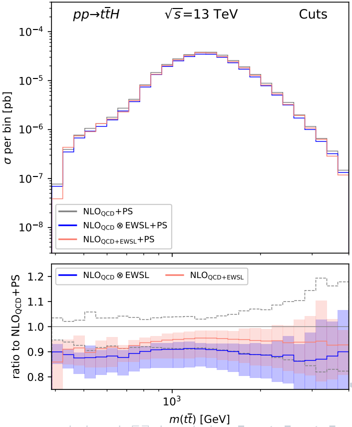
- Similar positive corrections in low-p_T range
- Stable agreement to FO NLO EW
- Again, small difference between multiplicative and additive approaches



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

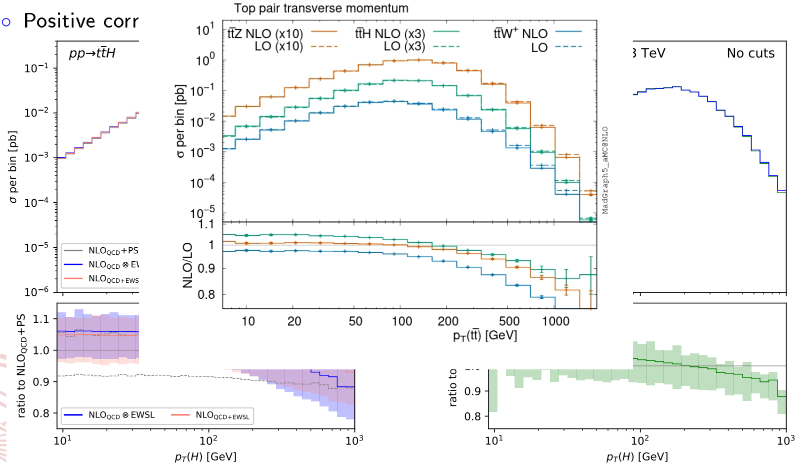
- **Difference** between additive and multiplicative in *high-energy range*
- **Scale band differences:** EWSL on top of NLO events (blue) and LO events (red)





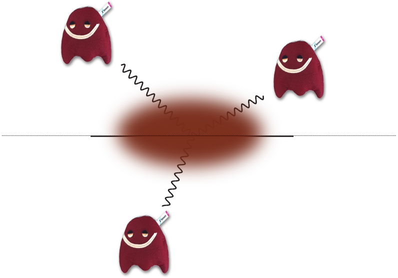
Results for $t\bar{t}H$: $p_T(H)$ inclusive

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



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

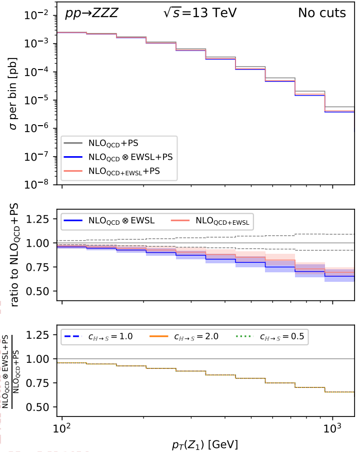
Example results: ZZZ

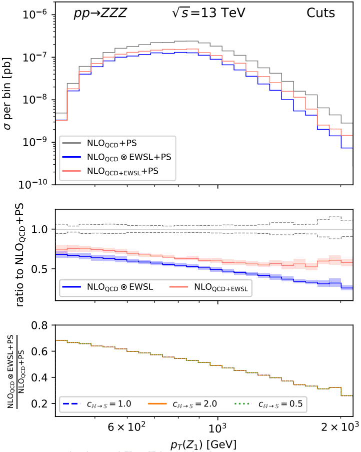


$$pp \to ZZZ$$

Results for ZZZ: $p_T(Z_1)$

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

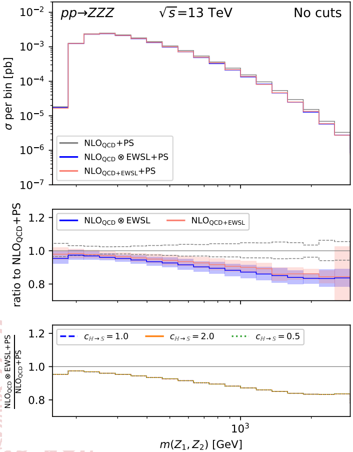


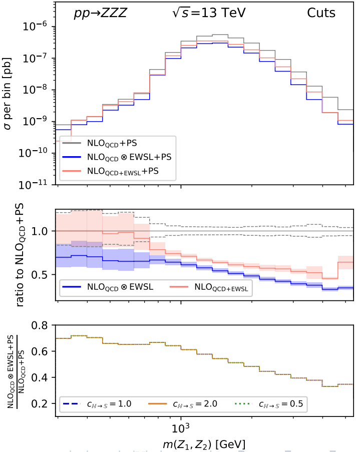


EÖTVÖS LORÁND TUDOMÁNYEGYETEM

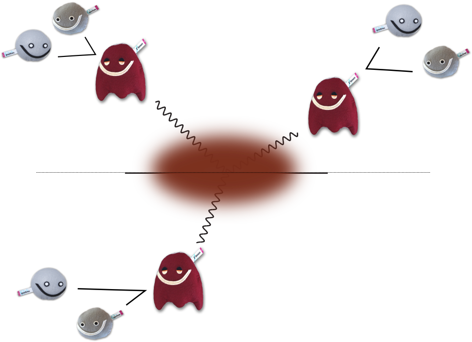
Results for ZZZ: $m(Z_1, Z_2)$

- 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

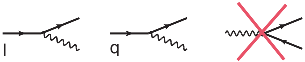
- First perform EWSL reweighting on ZZZ sample, then **decay with `MadSpin`**
- Lepton classification with jet algorithm (accepted event if 6 charged jets found):

$$p_T(\text{lepton}) > 25 \text{ GeV} \tag{3}$$

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

$$\sum_i |m(e_i^- e_i^+) - M_Z|^2 \tag{4}$$

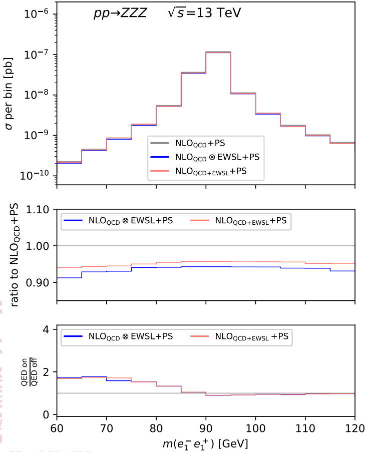
- **Final-state QED radiation**: investigate its effect by turning it off/on, including only photon radiation:

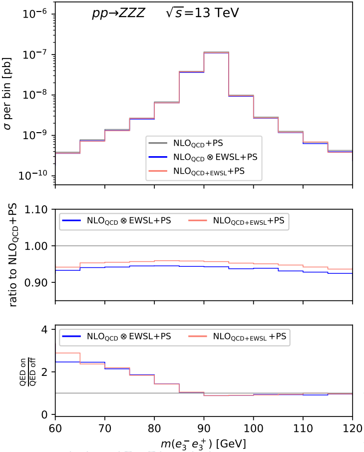


(5)

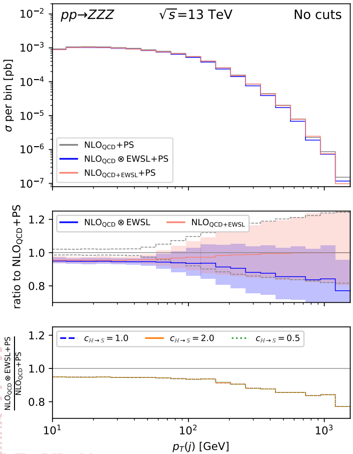
Results for ZZZ with decays: $m(e_i^- e_i^+)$

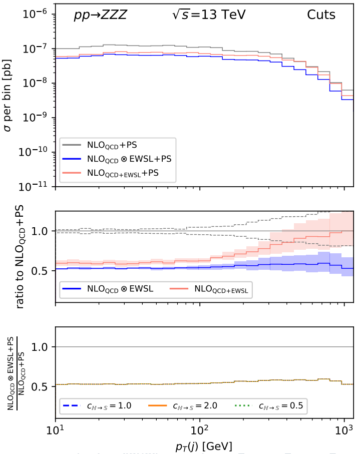
- EWSL: red and blue $\sim -5\%$
- Assess QED radiation effects: around peak region only!



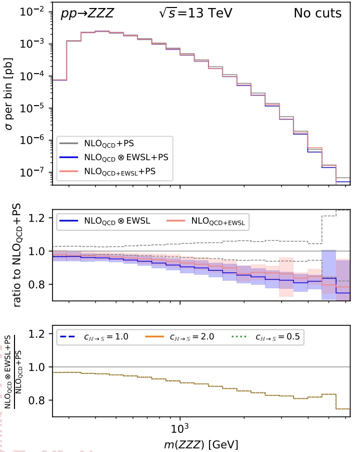


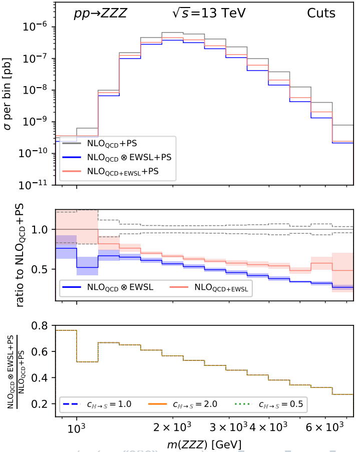
Results for ZZZ: $p_T(j_1)$



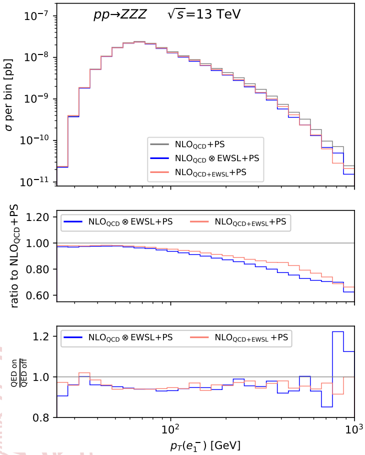


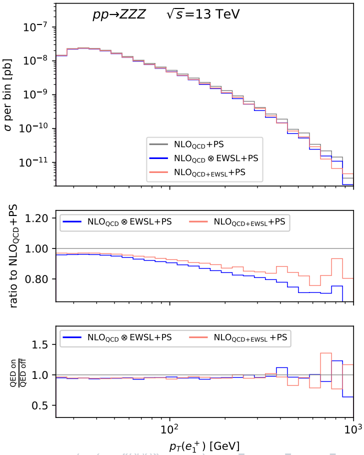
Results for ZZZ: $m(Z_1, Z_2, Z_3)$



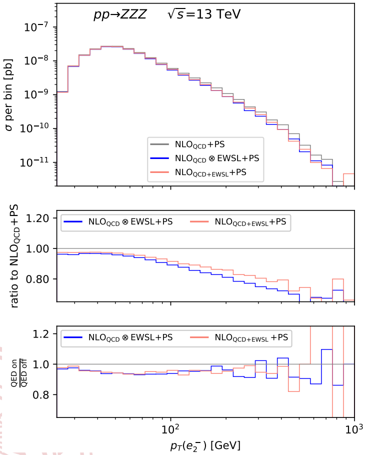


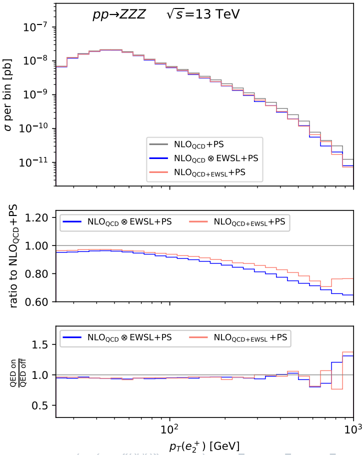
Results for ZZZ with decays: $p_T(e_1)$





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





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