Electroweak Sudakov logarithms in event generators

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Today's talk

1. Introduction: electroweak Sudakov logarithms
2. Automated EW Sudakov logarithms in event generators
   - Sherpa
   - MadGraph5_aMC@NLO
   - OpenLoops
3. Adding parton shower

Today's talk

Electroweak corrections to the hard scattering

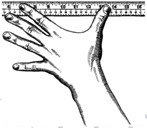
- In usual notation of mixed-(α_S, α)-NLO expansion:

$$\begin{aligned} \mathrm{LO} &= \mathrm{LO}_1 + \mathrm{LO}_2 + \ldots + \mathrm{LO}_k \\ \mathrm{NLO} &= \underbrace{\mathrm{NLO}_1}_{\text{NLO QCD}} + \underbrace{\mathrm{NLO}_2}_{\text{NLO EW}} + \ldots + \mathrm{NLO}_{k+1} \end{aligned}$$

"The complete-NLO is the new standard"

- Naive expectation:

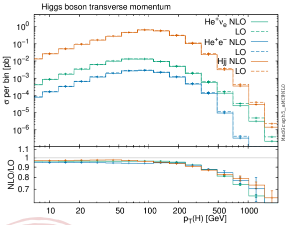
$$\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha) \sim \mathcal{O}(1\%) \qquad (1)$$

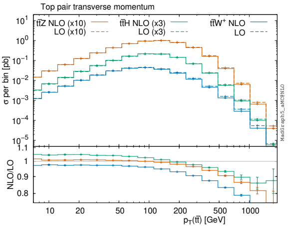


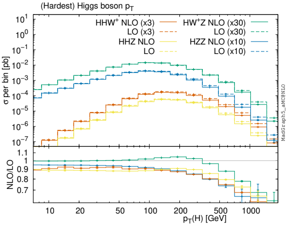
→ NLO EW corrections become important when NNLO QCD corrections are considered

Electroweak corrections to the hard scattering

- Large(r) EW corrections in physics modeling:
  → opening up of photon-induced channels
  → **uncancelled finite parts of weak vector boson virtual corrections (EW Sudakov logarithms)**
  → QED final-state radiation







(R. Frederix et al. arXiv:1804.10017)

The Denner-Pozzorini algorithm

- **One-loop leading approximation of the NLO EW correction**: worked out by **Denner and Pozzorini** [A. Denner, S. Pozzorini, arXiv:hep-ph/0010201]

$$\mathcal{O}(\text{EWSL}) \sim \left(\alpha \log^k\left(\frac{s}{M_W^2}\right)\right) \times \mathcal{O}(\text{LO}) \tag{2}$$

- EWSL are universal (process-independent):

$$\text{double logarithms (DL)}: \quad \sim \alpha \log^2\left(\frac{s}{M_W^2}\right)$$

$$\text{single logarithms (SL)}: \quad \sim \alpha \log\left(\frac{s}{M_W^2}\right)$$

- In the region where all

$$r_{kl} = (p_k + p_l)^2 \gg M_W^2 \tag{3}$$

[Resonances require some extra care!]

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

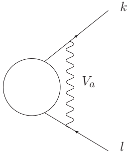
$$\mathcal{M}^{\text{LO+EWSL}} = \mathcal{M}_0 + \mathcal{M}_0 \times \delta^{\text{EWSL}} \tag{4}$$

$$\delta^{\text{EWSL}} = \underbrace{\delta^{\text{LSC}}}_{\text{DL}} + \underbrace{\delta^{\text{SSC}}}_{\text{SL}} + \underbrace{\delta^{\text{C}}}_{\text{SL}} + \underbrace{\delta^{\text{PR}}}_{\text{SL}} \tag{5}$$

Soft-collinear contributions

$$\delta^{\mathrm{EWSL}} = \underbrace{\delta^{\mathrm{LSC}}}_{\mathrm{DL}} + \underbrace{\delta^{\mathrm{SSC}}}_{\mathrm{SL}} + \underbrace{\delta^{\mathrm{C}}}_{\mathrm{SL}} + \underbrace{\delta^{\mathrm{PR}}}_{\mathrm{SL}}$$

$$\sum_{k} \sum_{k \neq l} \sum_{V_a = \gamma, Z, W^{\pm}} \tag{6}$$



- Coming from exchange of virtual weak boson in soft-collinear limit between pairs of external legs
- Evaluating the scalar three-point function in the *eikonal approximation*, results in expressions including

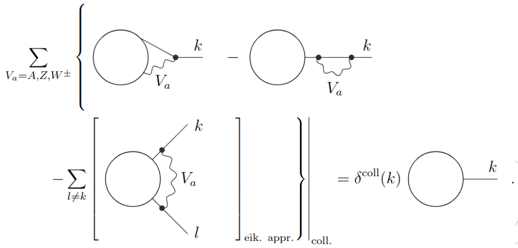
$$L(|r_{kl}|, M^2) := \frac{\alpha}{4\pi} \log^2 \frac{|r_{kl}|}{M^2} = L(s, M^2) + 2\frac{\alpha}{4\pi} \log \frac{s}{M^2} \log \frac{|r_{kl}|}{s} + L(|r_{kl}|, s) \tag{7}$$

- Split the logarithms into DL ($\rightarrow$ LSC) and SL ($\rightarrow$ SSC) terms

Soft or collinear logarithms: δ^C

$$\delta^{\mathrm{EWSL}} = \underbrace{\delta^{\mathrm{LSC}}}_{\mathrm{DL}} + \underbrace{\delta^{\mathrm{SSC}}}_{\mathrm{SL}} + \underbrace{\delta^{\mathrm{C}}}_{\mathrm{SL}} + \underbrace{\delta^{\mathrm{PR}}}_{\mathrm{SL}}$$

- All contributions in the virtual soft-collinear weak boson exchange **which do not come from:**
  → field renormalization and
  → collinear limit of the DL contribution
- The SL contribution $\delta^C = \delta^{\mathrm{coll}} + \delta^{\mathrm{FRC}}$



Parameter renormalization: δ^{PR}

$$\delta^{\text{EWSL}} = \underbrace{\delta^{\text{LSC}}}_{\text{DL}} + \underbrace{\delta^{\text{SSC}}}_{\text{SL}} + \underbrace{\delta^{\text{C}}}_{\text{SL}} + \underbrace{\delta^{\text{PR}}}_{\text{SL}}$$

- Logarithms from UV divergences
- Arising from the renormalization of the dimensionless EW parameters $\{e, c_w, \overline{m}_t, \overline{m}_H\}$,

$$\delta^{\text{PR}}\mathcal{M}_0 = \frac{\delta\mathcal{M}_0}{\delta e}\delta e + \frac{\delta\mathcal{M}_0}{\delta c_w}\delta c_w + \frac{\delta\mathcal{M}_0}{\delta\overline{m}_t}\delta\overline{m}_t + \frac{\delta\mathcal{M}_0}{\delta\overline{m}_H}\delta\overline{m}_H \quad (8)$$

evaluated at $\mu^2 = s$, $[\overline{m}_i := \frac{m_i}{M_W}]$

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Automating EW Sudakov logarithms

- **Why** would we want to have separate EW Sudakov implementations?
  → They are much faster to compute, since they are based on the Born kinematics
  → Easier transition to BSM physics
  → Allows for a comparison between NLO EW and dominant part of these in the high-energy region

- Also process-specific implementation in ALPGEN
  (M. Chiesa et al. arXiv:1305.6837)

Focus here on the **automated implementations** of the one-loop approximation of the NLO EW corrections:
→ Sherpa (E. Bothmann, D. Napoletano, arXiv:2006.14635)
→ MadGraph5_aMC@NLO (D. Pagani, M. Zaro, arXiv:2110.03714)
→ OpenLoops (J. M. Lindert, L. Mai, arXiv:2312.07927)

Today's talk

Automation of EW Sudakov logarithms in **Sherpa**

(E. Bothmann, D. Napoletano, arXiv:2006.14635)

- Implementation of Denner-Pozzorini algorithm:

$$K_{\mathrm{NLL}}(\Phi) = 1 + \Delta^{\overline{\mathrm{LSC}}} + \Delta^{Z} + \Delta^{\mathrm{SSC}} + \Delta^{\overline{C}} + \Delta^{\mathrm{Yuk}} + \Delta^{\mathrm{PR}} \quad (9)$$

in

(1) $\mathrm{d}\sigma^{\text{LO + NLL}}(\Phi) = \mathrm{d}\Phi B(\Phi) \times K_{\mathrm{NLL}}(\Phi)$,

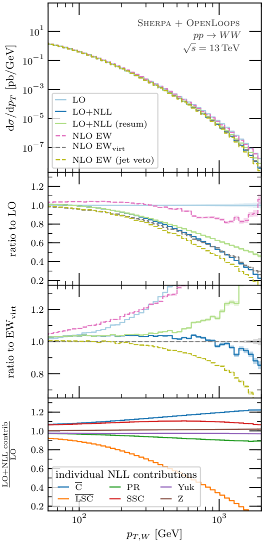
(2) $\mathrm{d}\sigma^{\text{LO + NLL (resum)}}(\Phi) = \mathrm{d}\Phi B(\Phi) \times e^{(1-K_{\mathrm{NLL}}(\Phi))}$,

  - Comparison to **EW$_{\mathrm{virt}}$ approximation** [S. Kallweit et al., arXiv:1511.08692]: inclusion of {Born + virtual + minimal set of counterterms}

Δ^{Z} : takes into account the gap between M_Z and M_W
Δ^{Yuk} : separates collinear logarithms on external fermion lines from other collinearities

Automation of EW Sudakov logarithms in **Sherpa**

(E. Bothmann, D. Napoletano, arXiv:2006.14635)



- Showcase the $p_{T,W}$ distribution for

$$pp \to WW$$

- Obtain the expected $\sim$ -70% to -90% Sudakov suppression in the very tail

- Comparison to full NLO EW shows significant discrepancy: logarithmic enhancement in the high-p_T region from real emission MEs cancel the Sudakov effect
  $\to$ imposing jet veto mitigates this cancellation

- Comparison to EW$_{\text{virt}}$ approximation: deviation of $\sim$ 10% starts for $p_{T,W} \sim 2$ TeV

- Up to $\sim$ 20 % difference between NLL and resummed Sudakov

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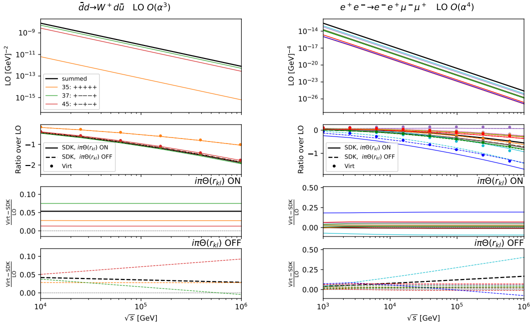
Automation of EW Sudakov logarithms in MG5_aMC@NLO

(D. Pagani, M. Zaro, arXiv:2110.03714)

- For processes $2 \to n$, $n > 2$, the scalar three-point function in the high-energy limit obtains an imaginary part:

$$L(|r_{kl}|, M^2) \to L(|r_{kl}|, M^2) - 2i\pi\Theta(r_{kl}) \qquad (10)$$



- Explicit verification of the imaginary term for $2 \to 3/4$ processes: without imaginary term, explicit helicity-dependent amplitudes acquire strong s-dependence; the helicity-summed in some cases get sizeable effects

Automation of EW Sudakov logarithms in MG5_aMC@NLO

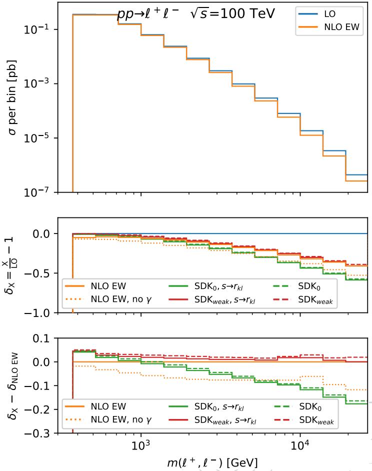
(D. Pagani, M. Zaro, arXiv:2110.03714)

- Showcase results for $\sqrt{s}$ =100 TeV collisions:

$$pp \to l^+ l^-$$

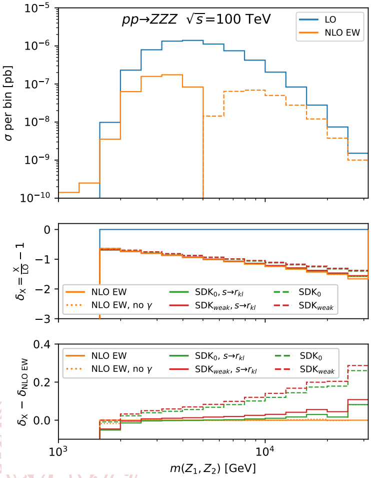
- For avoiding IR-sensitivity: the $\mathrm{SDK_{weak}}$ approach superior to $\mathrm{SDK_0}$ approach
- Investigate effect of $s \gg r_{kl} \gg M_W^2$ terms ($\mathrm{SSC}^{s \to r_{kl}}$): here no significant impact

$\mathrm{SDK_0}$: all EM (QED origin) terms turned off
$\mathrm{SDK_{weak}}$: keeping in a more consistent way the pure-weak effect (keep QED in PR corrections)



Automation of EW Sudakov logarithms in MG5_aMC@NLO

(D. Pagani, M. Zaro, arXiv:2110.03714)



- Showcase results for $\sqrt{s}$ =100 TeV collisions:

$$pp \to ZZZ$$

- No significant difference between the two approaches SDK_{weak} and SDK_0 : neutral final state is not as sensitive to the exact treatment of splitting of QED part
- Effect of $s \to r_{kl}$ is much larger (dashed vs solid lines): being a $2 \to 3$ process, more hierarchies in scales affect the angular-dependent logarithms
- Electroweak corrections can reach -200% of LO $\to$ unphysical corrections call for resummation at very high energies

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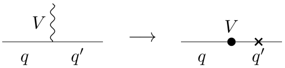
Automation of EW Sudakov logarithms in **OpenLoops**

(J. M. Lindert, L. Mai, arXiv:2312.07927)

OpenLoops 2

- Include the imaginary term in the double logarithms
- Sudakov terms are computed with internal insertions



$$= ieI_q^V C_{\mathrm{EW}}^V \,,$$

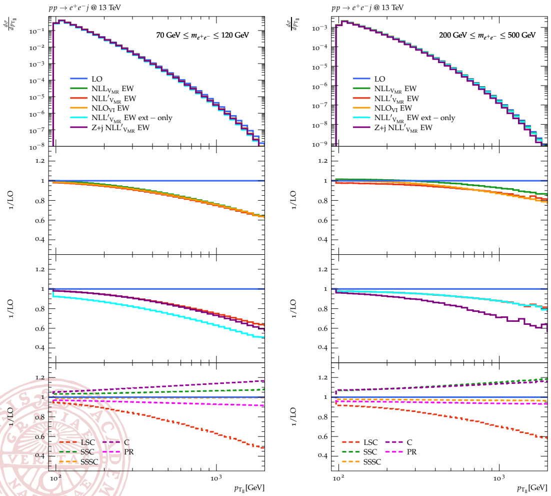
- Resonances:
  are treated with double insertions of EW pseudo-counterterms on the external *and the internal* resonance state
- One possible topology is picked with the probability

$$P(k) = \left| \frac{\mu^2 - m^2 w^2 \Gamma^2}{(k^2 - m^2 + iw\Gamma m)^2 + \mu^2} \right| \tag{11}$$

for each heavy resonance with complex mass μ and momentum k

Automation of EW Sudakov logarithms in **OpenLoops**

(J. M. Lindert, L. Mai, arXiv:2312.07927)



- Showcase

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

for invariant mass windows:
70 GeV $< m_{e^+e^-} < 120$ GeV
200 GeV $< m_{e^+e^-} < 500$ GeV

- In both cases, there is decent agreement between $\mathrm{NLL'}_{\mathrm{V_{MR}}}$ EW and the full NLO EW
- In high-energy range: agreement with Sudakov applied on external decay states
- In resonance window range: agreement with on-shell application of Sudakov

Today's talk

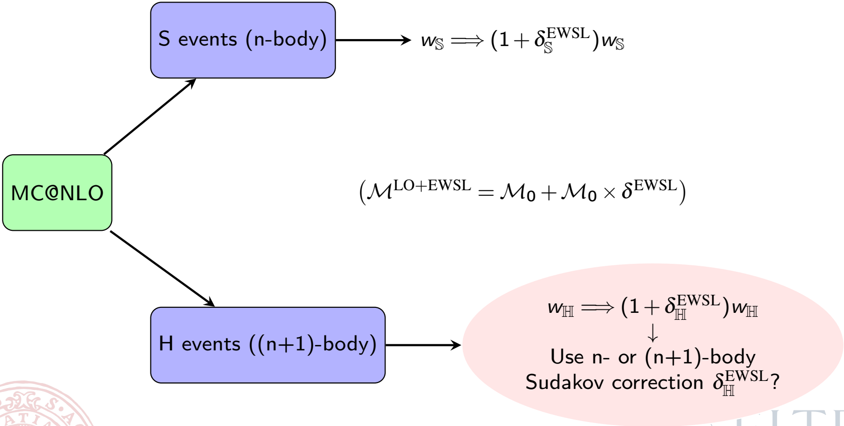
NLO QCD+EWSL with parton shower

- Combining the automated NLO QCD+PS event generation to include the EW Sudakov approximation through reweighting of events

This has been done in
→ Sherpa (E. Bothmann et al. arXiv:2111.13453)
→ MadGraph5_aMC@NLO (D. Pagani, T. Vitos, M. Zaro, arXiv:2309.00452)

- Overall similar strategy and methodology

Reweighting NLO events with EWSL in MG5_aMC@NLO



Reweighting NLO events with EWSL in MG5_aMC@NLO

Problem 1

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

Problem 2

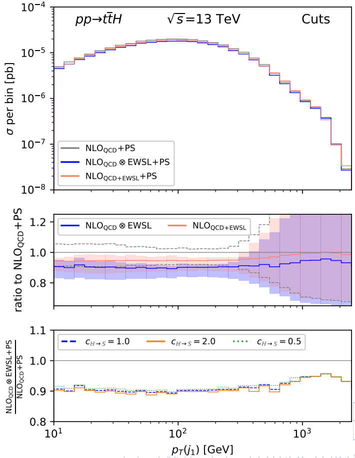
- IR cancellation not secured anymore!

Proposed procedure:

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-merging-scale" dependence

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

- Showcase
$$pp \to t\bar{t}H$$
with hard cuts on final state particles
- Use $\mathrm{SDK}_{\mathrm{weak}}$ approach: include QED final-state radiation without double-counting
- High-p_T range: additive approach converges to $\mathrm{NLO}_{\mathrm{QCD}}$+PS
- Insensitive to exact value of Sudakov-merging scale $c_{\mathbb{H}\to\mathbb{S}}$



$\mathrm{NLO}_{\mathrm{QCD}}\otimes$EWSL+PS: inclusion of EWSL weights on Born and real emission events [“multiplicative approach”]
$\mathrm{NLO}_{\mathrm{QCD+EWSL}}$+PS: inclusion of EWSL only on Born events [“additive approach”]

Summary and outlook

Summary

- ✓ Automated one-loop EW Sudakov corrections are ready in the open-source **Sherpa**, **MadGraph5_aMC@NLO**, **OpenLoops**
- ✓ Slightly different implementations but all in general agreement
- ✓ Also automated NLO QCD+EWSL+PS accuracy in **Sherpa** and **MadGraph5_aMC@NLO**

Outlook

- More phenomenological studies with the parton shower combination
- Two-loop Sudakov corrections?
- Extend to BSM scenarios?
- Apply to SMEFT predictions?

Thank you for your attention!