EW NLO in Sherpa

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EW corrections

QED and weak corrections factorize

- for QED soft collinear divergences cancel between virtual and real corrections
  - use modified Catani-Seymour subtraction to cancel divergences
- for weak corrections, there are no such divergences to cancel, as weak bosons have mass
  - however, unstable massive bosons present their own problems

QED corrections status

- Final state corrections implemented and tested
  - processes such as $\nu_\mu \overline{\nu}_\mu \rightarrow e^+ e^-$
- Initial state corrections implemented but not tested
  - processes such as $e^+ e^- \rightarrow \nu_\mu \overline{\nu}_\mu$

Results for QED corrections to $\nu_\mu \bar{\nu}_\mu \to f\bar{f}$

Final State	Energy (GeV)	LO (pb)	VI (pb)	RS (pb)	VIRS (pb)	VIRS (%)	Expected VIRS (%)
e^+e^-	40	42.40360 $\pm$0.00020	0.10475 $\pm$0.00001	-0.02618 $\pm$0.00005	0.07857 $\pm$0.00005	0.18528 $\pm$0.00013	0.18535
	50	85.28010 $\pm$0.00040	0.21066 $\pm$0.00011	-0.05266 $\pm$0.00003	0.15800 $\pm$0.00012	0.18527 $\pm$0.00014	0.18535
$u\bar{u}$	40	145.30000 $\pm$0.00142	0.15948 $\pm$0.00008	-0.03990 $\pm$0.00002	0.11958 $\pm$0.00008	0.08230 $\pm$0.00007	0.08238
	50	292.22000 $\pm$0.00278	0.32073 $\pm$0.00016	-0.08026 $\pm$0.00004	0.24047 $\pm$0.00017	0.08229 $\pm$0.00007	0.08238
$d\bar{d}$	40	187.15100 $\pm$0.00936	0.05137 $\pm$0.00003	-0.01286 $\pm$0.00001	0.03852 $\pm$0.00003	0.02058 $\pm$0.00001	0.02059
	50	376.38800 $\pm$0.01882	0.10332 $\pm$0.00005	-0.02584 $\pm$0.00001	0.07748 $\pm$0.00005	0.02059 $\pm$0.00001	0.02059

$$\int_m \mathrm{d}\sigma_V + \int_{m+1} \mathrm{d}\sigma_R = \int_m \left[\mathrm{d}\sigma_V + \int_1 \mathrm{d}\sigma_A\right] + \int_{m+1} \left[\mathrm{d}\sigma_R - \mathrm{d}\sigma_A\right] .$$

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$$\int_m \mathrm{d}\sigma_V + \int_{m+1} \mathrm{d}\sigma_R \quad = \quad \int_m \left[\mathrm{d}\sigma_V + \int_1 \mathrm{d}\sigma_A\right] + \int_{m+1} \left[\mathrm{d}\sigma_R - \mathrm{d}\sigma_A\right] .$$

A massive effect

Weak bosons have mass

- no divergences to cancel between real and virtual terms

However, weak bosons are unstable

- treating them as stable produces $\frac{1}{p^2-M^2}$ poles in physical observables
- to regulate the singularity, perform Dyson summation
  - self energies summed to all orders
  - imaginary part regulates singularity

But, gauge invariance guaranteed order by order

- mixing contributions from different orders can break gauge invariance
- want to find a scheme which will ensure gauge invariance

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Pole scheme

- extract gauge invariant part of self energy summation
- physically observable pole residues are gauge invariant
- awkward to perform for processes with multiple unstable particles
- only valid in region of resonance
- cannot describe threshold effects

Pole scheme with threshold expansion

- combine pole expansion with threshold expansion
- different schemes in different phase space regions
- matching between regions

Gauge invariant non-local effective Lagrangian

- for example, complex mass scheme

Complex mass scheme at LO

- masses consistently considered as complex quantities
- complex masses defined as positions of the poles in the complex p^2 plane of the propagators with momentum p
- complex masses introduced everywhere in the Feynman rules, including definition of weak mixing angle
- gauge invariance preserved
- Ward identities remain valid
- spurious terms introduced
  - $\mathcal{O}(\alpha)$ relative to lowest order term

Complex mass scheme at one-loop

- complex masses introduced directly at Lagrangian level
- split bare masses into complex renormalized masses and complex counterterms
- no change to the theory, only rearrangement of perturbative expansion
- provides $\mathcal{O}(\alpha)$ accuracy everywhere in the phase space, provided width is calculated including at least $\mathcal{O}(\alpha)$ corrections
- unitarity violated
  - unitarity-violation terms are of higher order ($\mathcal{O}(\alpha^2)$)
  - unitarity violation not enhanced as Ward identities preserved

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Summary

- QED corrections are coming along nicely
- Unstable massive weak gauge boson present their own complications
- Complex mass scheme provides a gauge invariant description of unstable particles valid in the full phase space