Applications of the POWHEG Method to Drell-Yan Processes in HERWIG++

Ilán Fridman Rojas
Supervisor: Dr. Peter Richardson

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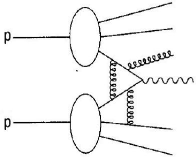
Durham University
Institute for Particle Physics Phenomenology

NLO Corrections

- NLO contributions: vertex correction, real gluon emission & gluon initiated processes. "Higher twist" contributions usually negligible.



$$|\mathcal{M}|^2 = |\mathcal{B} + \mathcal{V}|^2 + |\mathcal{R}|^2 = |\mathcal{B}|^2 + |\mathcal{V}|^2 + 2Re(\mathcal{B}\mathcal{V}^*) + |\mathcal{R}|^2 \quad (1)$$

- We want terms of $\mathcal{O} \leq \alpha_S$.
- $\alpha_S \propto g_S^2$, factor of g for every strong vertex.
- Therefore $|\mathcal{B}|^2 \propto \alpha_S^0$, $|\mathcal{V}|^2 \propto \alpha_S^2$, $2Re(\mathcal{B}\mathcal{V}^*) \propto \alpha_S$ and $|\mathcal{R}|^2 \propto \alpha_S$.

So to Next-to-Leading-Order (NLO):

$$|\mathcal{M}|^2_{NLO} = |\mathcal{B}|^2 + 2Re(\mathcal{B}\mathcal{V}^*) + |\mathcal{R}|^2 \quad (2)$$

Subtraction formalism 1

Some terms in the NLO cross section are divergent in $d = 4$ and hence pick up poles in ϵ when Dimensional Regularisation is applied to them.

$$\sigma_{NLO} = \int d\phi_n (B + V_\epsilon) + \int d\phi_{n+1} R + \int d\phi_{n,\oplus} G_{\oplus,\epsilon} + \int d\phi_{n,\ominus} G_{\ominus,\epsilon}$$

The trick is to come up with universal counterterms C_α with the same pole structure as R. That way we can subtract them from the divergent real contribution to cancel their poles, and then add them back in elsewhere.

$$\int d\phi_{n+1} R = \int d\phi_{n+1} \{R - \sum_\alpha C_\alpha\} + \sum_\alpha \int d\phi_{n+1} C_\alpha$$

Subtraction formalism 2

By the Bloch-Nordsieck Theorem the added-in divergent counterterms C_α combine with the also divergent $G_{\oplus/\ominus,\epsilon}$ collinear counterterms and the divergent virtual term V_ϵ cancelling all the ϵ poles and leaving only collinear remnants $G_{\oplus/\ominus}$ and an integrable virtual contribution V.

$$\sigma_{NLO} = \int d\phi_n(B+V)$$
$$+ \int d\phi_{n+1}\{R - \sum_\alpha C_\alpha\}$$
$$+ \int d\phi_{n,\oplus} G_\oplus + \int d\phi_{n,\ominus} G_\ominus$$

This is now fully integrable in $d=4$ and can be evaluated numerically.

The POWHEG Method 1

- The POsitive Weight Hardest Emission Generator (POWHEG) Method was proposed by P. Nason in 2004 [1].
- It uses the exact NLO matrix element to generate the hardest emission, after which a vetoed parton shower can be used whilst preserving NLO accuracy.
  If we define a (positive definite) function $\bar{B}$ as follows:

$$\overline{B}\left(\phi_n\right) = B\left(\phi_n\right) + V\left(\phi_n\right) + \int d\phi_1 \left\{ R\left(\phi_n, \phi_1\right) - \sum_\alpha C_\alpha\left(\phi_n, \phi_1\right) \right\} \quad (3)$$

- As the Herwig++ shower is angular-order we need to generate soft, wide-angle coherent emission (the so-called truncated shower) before the hardest emission.

The POWHEG Method 2

- We can then define a modified Sudakov Form Factor as follows to produce a factor to generate the hardest emission:

$$\Delta(p_T) = \exp\left[-\int d\phi_1 \frac{R(\phi_n,\phi_1)}{B(\phi_n)}\theta\left(k_T(\phi_n,\phi_1) - p_T\right)\right] \quad (4)$$

- Using this definition the NLO cross section can be written as:

$$d\sigma = \overline{B}(\phi_n)\ d\phi_n \left[\Delta(0) + \frac{R(\phi_n,\phi_1)}{B(\phi_n)}\Delta\left(k_T(\phi_n,\phi_1)\right)\ d\phi_1\right] \quad (5)$$

- We then generate non-radiative events with the first term of equation 5 and the hardest emission with the second term.
- The difference between the POWHEG Method and the conventional parton shower is that $\overline{B}$ is used instead of B (thus guaranteeing positive weights) and that the R in the Sudakov is the full real emission contribution and not just an approximation to it in the soft and collinear limits.

Z' Models: Motivation

- Z' boson = extra, heavy neutral gauge boson.
- Most common prediction from BSM models.
- Simplest extension to SM gauge group.
- Good test-ground to gauge our ability to reconstruct Lagrangians from LHC data.
- Testable at the LHC!
- If a Z' from a GUT is found it would provide insights into physics at energy scales much higher than those which we can probe directly.

E_6-based GUTs

- $SU(5)$ GUT has been ruled out by discrepancies between its predictions and experimental results regarding the size of the Weinberg angle, the lifetime of the proton and the mass of the neutrinos. [2].
- Next largest group which can used in a GUT is $SO(10)$. All GUTs based on groups larger than $SU(5)$ have at least one Z' boson $\rightarrow$ if grand unification is possible a Z' boson must exist.
- Symmetry breaking chain.

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\psi \times U(1)_\chi \rightarrow G_{SM} \times U(1)_\beta$$

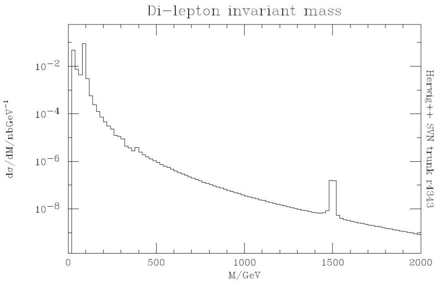
- Larger gauge groups $\rightarrow$ larger multiplets $\rightarrow$ new particles $\rightarrow$ Z' boson.

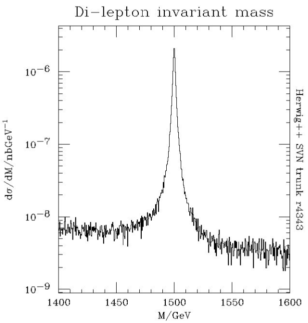
HERWIG++ Implementation

- $M_{Z'_\chi} = 1.5$ TeV. Allowed by latest EW fits performed by Erler et al [3].
- NLO corrections implemented in HERWIG++ via POWHEG method [Hamilton et al.] [4]
- Couplings of SM fields to Z'_χ.

SM Field	Coupling
u_L	-0.07
d_L	-0.07
u_R	0.07
d_R	-0.22
ν_L	0.22
e_L	0.22
e_R	0.07

Results 1 (Mass spectrum plots)





Results 2

- K factors.

σ	SM (nb)	Muons (nb)
LO	46.52(7)	2.669(1)
NLO	52.92(8)	3.123(1)
K factor	1.14	1.17

- Prediction for the expected ratio between the SM background cross section and the SM+Z' cross section.

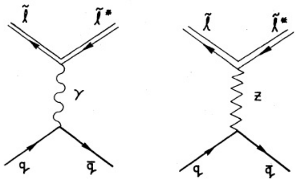
σ	SM (nb)	Muons (nb)
with Z'	$0.1093(2)\times10^{-3}$	$7.17(1)\times10^{-6}$
without Z'	$15.51(3)\times10^{-6}$	$0.913(1)\times10^{-6}$
$\Delta\sigma$ factor	7.05	7.85

Z'_χ Model: Conclusions

- NNLO corrections are negligible.
- Simplest and most plausible GUT-based scenarios have been studied thoroughly.
- If $M_{Z'} \leq 5$ TeV we should be able to see it (in di-lepton invariant mass spectra) at the LHC with 100 fb^{-1} at $\sqrt{s} = 14$ TeV. [Erler et al] [3]
- Data needed!

Slepton Pair Production

- Sleptons are the spin 0 superpartners to the SM leptons. SUSY generators commute with all gauge group generators, hence sleptons have all the same gauge group charges as their SM counterparts.



Results: The K Factor

The K factor for all slepton pair production processes is approximately 1.21.

Checks:

- LO result checked with MSSM implementation in Herwig++. Good agreement found.
- NLO result will be checked against Prospino.

Motivation: The trilepton signal

Process	σ(bkgd)/σ(sig)	What it has	What it needs
$WZ \to ll l\nu$		$3l + \not{E}_T$	-
$ZZ \to llll$	$\sim$1	$\geq 3l$	$\not{E}_T$
$WW \to ll\nu\nu$		$2l + \not{E}_T$	one l
$t\bar{t} \to WbWb$	$\sim$10	$2l + \not{E}_T$	one l
Drell-Yan$\to ll$	$\sim$1000	$2l$	one l + $\not{E}_T$
$Z\gamma \to ll\gamma$	$\sim$30	$\geq 3l$	$\not{E}_T$
$W \to l\nu$	$\sim$5000	one l + $\not{E}_T$	two l

Figure: The signal to SM background ratios for the trilepton signal. [5]

Chargino-Neutralino Production and Decay

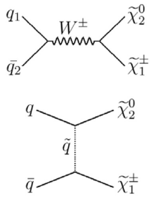


Figure: Tree level production of a Chargino and Neutralino pair. [5]

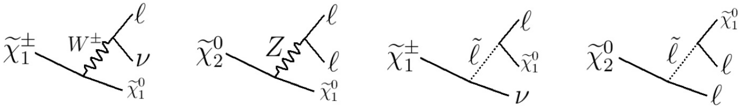


Table: Chargino and Neutralino trilepton decay modes. [5]

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