Automated NLO QCD Corrections in WHIZARD

Christian Weiss

Helmholtz Alliance LC Forum, DESY Hamburg, November 17th, 2015
Table of Contents

1 The Event Generator

2 Current Status of NLO automation

3 Recent developments
WHIZARD: Some facts

- Multi-purpose event generator for lepton and hadron colliders
- Current release version: WHIZARD 2.2.7 (August 8th, 2015)
- Download: http://whizard.hepforge.org   E-Mail: whizard@desy.de
- WHIZARD Team: Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter, Simon Braß, Bijan Chokoufé, Marco Sekulla, So Young Shim, CW, Zhiejie Zhang

2nd International WHIZARD Forum, Würzburg, March 2015
WHIZARD has a modular structure

Modules from the WHIZARD group:

- **O’Mega**: Matrix element generator via directed acyclical graphs [Ohl,2000]
- **VAMP**: Adaptive multi-channel Monte-Carlo integrator [Ohl,1999]
- **CIRCE 1/2**: Lepton Collider Beam Spectra [Ohl,1997]

External packages which can be linked to WHIZARD include:

FastJet, HepMC, Pythia6(8), LCIO, GoSam, OpenLoops, GuineaPig, LHAPDF4/5/6,...
Creating Simulations with SINDARIN

ExampleBeamPol.sin

beams = e1, E1
process eett = e1, E1 => t, T

#e_L e_R - polarization
beams_pol_density = @(1), @(1)
beams_pol_fraction = 1.0, 1.0
integrate (eett)
{iterations = 5:10000:’’gw’’}
simulate (eett) {n_events = 10000}

#e_R e_L - polarization
beams_pol_density = @(1), @(1)
beams_pol_fraction = 1.0, 1.0
integrate (eett)
{iterations = 5:10000:’’gw’’}
simulate (eett) {n_events = 10000}

WHIZARD has native support for polarized lepton beams.
Upcoming release 2.2.8: Also at NLO.
Lepton beam spectra using CIRCE

---

**TestCirce.sin**

# Creates a histogram of the
# invariant top pair mass with
# ISR effects.

sqrts = 350 GeV
beams = e1, E1 => circe1
process ttbar = e1, E1 => t, T

circe1_sqrts = 500 GeV
circe1_ver = 10
$circe1_acc = ‘‘ILC’’

histogram ilc500 (346, 351, 0.1)
simulate (ttbar) {
$sample = ‘‘ilc500’’
analysis = record ilc500
(eval M / 1 GeV [combine[t,T]])
}

---

2. ILC 350 w/ILC 500 beam spectra

e^+e^- → t\bar{t} w/beamstrahlung from CIRCE1

---

Data within bounds:
⟨Observable⟩ = 349.503 ± 0.0082  [nentries = 10000]

All data:
⟨Observable⟩ = 349.503 ± 0.0082  [nentries = 10000]
Table of Contents

1. The Event Generator
2. Current Status of NLO automation
3. Recent developments
WHIZARD + NLO:

- Automated NLO framework for QCD corrections in lepton collisions.
- Uses FKS subtraction.
- No user contributions required.

\[ e^- e^+ \rightarrow t\bar{t} \text{ and } e^- e^+ \rightarrow W^+ W^- b\bar{b}: \]
$\sqrt{s} = 500\text{GeV}$, $\Gamma_t^{LO} = 1.538\text{GeV}$, $\Gamma_t^{NLO} = 1.408\text{GeV}$
Interfacing NLO events to a parton shower requires matching procedures to separate emissions from the matrix element generator from those done by the parton shower.

**WHIZARD → Powheg Matching**

![Graphs showing K-Factor and dσ/dE for e^+e^- → t\bar{t}H processes](image)

[Chokoufe, Kilian, Reuter, CW: 1510.02739]
Recently, [Liebler, Moortgat-Pick, Papanastasiou: 1511.02350] performed a similar analysis.

In our analysis, $R_{jet} = 1.0$. WHIZARD and Madgraph are consistent!
The BLHA interface

- Standardized protocol for One-Loop Providers (OLP)
- WHIZARD generates protocol, OLP generates code
- OLP reads contract, NLO matrix element library loaded into WHIZARD.
- Working BLHA interfaces to:
  - GoSam [G.Cullen et.al.]
  - OpenLoops [F.Cascioli et.al.]

```
eett_NLO_LOOP.olp

# BLHA order written by WHIZARD 2.2.7

# BLHA interface mode: OpenLoops
# process: eett_NLO_LOOP
# model: SM
InterfaceVersion BLHA2
CorrectionType QCD
Extra AnswerFile eett_NLO_LOOP.olc
IRregularisation CDR
CouplingPower QCD 0
CouplingPower QED 2
extra use_cms 0

# Process definitions

AmplitudeType Loop
-11 11 -> 6 -6

AmplitudeType ccTree
-11 11 -> 6 -6
```

Using SINDARIN for NLO processes

eett_nlo.sin

...#
# Choose the external one-loop program
$loop\_me\_method = 'openloops',

# LO coupling powers
alpha\_power = 2
alphas\_power = 0

process nlo\_tt = E1, e1 => t, T
{nlo\_calculation = 'Full'}

# Tuning parameters for FKS mapping
fks\_dij\_exp1 = 1.0
fks\_mapping\_type = 1

integrate (nlo\_tt) {iterations = 5:10000:gw}

...
Table of Contents

1 The Event Generator

2 Current Status of NLO automation

3 Recent developments
A distinct feature of linear colliders is the ability to operate with polarized electrons and positrons simultaneously. Possible applications are:

- Determination of top properties, especially CP-violating or FCN couplings.

- Separation of production processes and background suppression:

<table>
<thead>
<tr>
<th>Configuration $(P_{e^-}, P_{e^+})$</th>
<th>Scaling factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e^+e^- \rightarrow H\nu\bar{\nu}$</td>
</tr>
<tr>
<td>(80%, 0%)</td>
<td>0.23</td>
</tr>
<tr>
<td>(-80%, 0%)</td>
<td>1.788</td>
</tr>
<tr>
<td>(80%, -30%)</td>
<td>0.18</td>
</tr>
<tr>
<td>(-80%, 30%)</td>
<td>2.31</td>
</tr>
</tbody>
</table>

- Precision electroweak measurements, e.g. gauge boson couplings.
Private OpenLoops-libraries for polarized initial-states in loop amplitudes.

Modified BLHA entry for each helicity configuration

eett_polsel.olp

\[
\text{# Process definitions}
\]

AmplitudeType Loop
-11(1) 11(1) -> 6 -6
-11(1) 11(-1) -> 6 -6
-11(-1) 11(1) -> 6 -6
-11(-1) 11(-1) -> 6 -6
At the threshold, non-relativistic top quarks yield large logarithms → resummation.
See Bijan Chokoufé’s talk on Wednesday.
Top decay at NLO

\begin{itemize}
  \item $\Gamma_{\text{WHIZARD}}^{\text{LO}} = 1.542$ GeV \quad $\Gamma_{\text{WHIZARD}}^{\text{NLO}} = 1.407$ GeV
  \item Developed in the course of NLL Threshold Matching
  \item Next step: Factorized production & decay at NLO
\end{itemize}
Ongoing Projects and Plans

Present & Near Future:

• Non-relativistic top threshold resummation matching
• Powheg matching

Medium time scale:

• Factorized production + decay at NLO
• Automated photon corrections to polarized beams
• Automated QCD NLO corrections for hadron collisions

Long time scale:

• Automated QED/electroweak NLO implementation
• MC@NLO or Nagy-Soper matching
Backup Slides
- The phase space is partitioned into channels, each of them having one distinct mapping → Optimized sampling of grids.
- Mappings include resonant, t-channel, radiation, infrared, collinear, off-shell.
- Alternative: Factorization into process and decay.
i) Find all tuples of particle indices which can give rise to a singularity, e.g.

\[ I = \{(1, 5), (1, 6), (2, 5), (2, 6), (5, 6)\} \]

ii) Partition the phase space:

\[ 1 = \sum_{\alpha \in I} S_\alpha(\Phi), \]

such that the real matrix element \( R \)

\[ R = \sum_{\alpha \in I} R_\alpha, \quad R_\alpha = R S_\alpha \]

Singular only for one tuple!

iii) Add subtraction terms for each singular region.
Constructing Subtraction Terms

**Real subtraction:** Factorization in the soft and collinear limit
\[ |A^{(n+1)}(\Phi_{n+1})|^2 \rightarrow D_\mathcal{I} \otimes |A^{(n)}(\Phi_n)|^2 \]
\( \otimes \): Convolution over spin and color.

Soft subtraction involves color-correlated matrix elements:
\[ B_{kl} \sim - \sum_{\text{color spin}} A^{(n)}(\bar{Q}(\mathcal{I}_k)) \cdot \bar{Q}(\mathcal{I}_l) A^{(n)*}, \]
with
\[ \bar{Q}(\mathcal{I}) = \{ t^a \}_{a=1}^8, \{ -t^a T \}_{a=1}^8, \{ T^a \}_{a=1}^8 \]

Collinear subtraction involves spin-correlated matrix elements:
\[ B_{+-} \sim \text{Re} \left\{ \frac{\langle k_{em} k_{rad} \rangle}{[k_{em} k_{rad}]} \sum_{\text{color spin}} A_+ A_-^* \right\} \]

Virtual subtraction: Same structure
\[ |M_{\text{virt}}|^2 \rightarrow \mathcal{V}_\mathcal{I} \otimes |M_n|^2, \quad \mathcal{V}_\mathcal{I} = \int d\Phi_{\text{rad}} D_\mathcal{I} \]
$e^+e^- \rightarrow q\bar{q}$

Total cross section for the process $e^+e^- \rightarrow u\bar{u}$

$\sigma(s)/\text{pb}$

$\sqrt{s}/\text{GeV}$

$\frac{(\text{NLO-LO})}{\text{LO}} \times 10000$
$e^+ e^- \rightarrow t\bar{t}$ at NLO with WHIZARD

![Graph showing $e^+ e^- \rightarrow t\bar{t}$ cross-section as a function of $\sqrt{s}$, with lines for LO, NLO, GoSam, and NLO, OpenLoops, and data points.](image-url)
\( e^+ e^- \rightarrow t\bar{t}H \) at NLO with WHIZARD

\[ \sigma [fb] \text{ vs } \sqrt{s} [GeV] \]

- **LO**
- **NLO**
Consider top production $e^+e^- \rightarrow t\bar{t}$ close to the production threshold. It is

$$v \sim \alpha_s \ll 1.$$ 

$\rightarrow$ Large logarithms $\log \frac{\alpha_s}{v}$!

Resummation of large logarithms

$$R = \frac{\sigma_{tt}}{\sigma_{\mu\mu}} = v \sum_k \left( \frac{\alpha_s}{v} \right)^k \sum_i (\alpha_s \log v)^i \times$$

$$\times \left\{ 1(\text{LL}); \alpha_s, v(\text{NLL}); \alpha_s^2, \alpha_s v, v^2(\text{NNLL}); \ldots \right\}$$

$R$-ratio split up into form factors:

$$R(s) = F^v(s)R^v(s) + F^\alpha(s)R^\alpha(s)$$

Implemented in WHIZARD via TOPPIK[Hoang, Teubner, 1999]
WHIZARD vs. Madgraph

![Plot comparing WHIZARD and MadGraph results.](chart.png)