Automated NLO QCD Corrections in WHIZARD

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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](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, Zhijie 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.

[Amjad et.al., 1307.8102]
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

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

Data within bounds:
⟨Observable⟩ = 349.503 ± 0.0082 \[n_{\text{entries}} = 10000\]

All data:
⟨Observable⟩ = 349.503 ± 0.0082 \[n_{\text{entries}} = 10000\]
WHIZARD + NLO:

- Automated NLO framework for QCD corrections in lepton collisions.
- Uses FKS subtraction.
- No user contributions required.
\( \sqrt{s} = 500\text{GeV}, \Gamma_{t}^{LO} = 1.538\text{GeV}, \Gamma_{t}^{NLO} = 1.408\text{GeV} \)
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

[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.]

```plaintext
# 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

```plaintext
... # 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''}
...
```

$e^+e^- \rightarrow t\bar{t}$ at NLO with WHIZARD
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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</th>
<th>Scaling factors</th>
<th>e^+e^- → Hνν</th>
<th>e^+e^- → HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(80%, 0%)</td>
<td>0.23</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>(-80%, 0%)</td>
<td>1.788</td>
<td>1.17</td>
<td></td>
</tr>
<tr>
<td>(80%, -30%)</td>
<td>0.18</td>
<td>1.006</td>
<td></td>
</tr>
<tr>
<td>(-80%, 30%)</td>
<td>2.31</td>
<td>1.47</td>
<td></td>
</tr>
</tbody>
</table>

- Precision electroweak measurements, e.g. gauge boson couplings.
Polarized NLO top production in WHIZARD

- Private OpenLoops-libraries for polarized initial-states in loop amplitudes.
- Modified BLHA entry for each helicity configuration

```
eett_polsel.olp
...
# 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

- $\Gamma^{\text{LO}}_{\text{WHIZARD}} = 1.542 \text{ GeV}$  $\Gamma^{\text{NLO}}_{\text{WHIZARD}} = 1.407 \text{ GeV}$
- Developed in the course of NLL Threshold Matching
- Next step: Factorized production & decay at NLO
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.

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

ii) Partition the phase space:

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

such that the real matrix element \( R \)

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

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:

$$B_{kl} \sim -\sum_{\text{color}} \sum_{\text{spin}} A^{(n)}(\mathcal{I}_k) \cdot \bar{Q}(\mathcal{I}_l) A^{(n)*},$$

with

$$\bar{Q}(\mathcal{I}) = \{t^a\}_{a=1}^8, \{-t^aT\}_{a=1}^8, \{T^a\}_{a=1}^8$$

Collinear subtraction involves spin-correlated matrix elements:

$$B_{+-} \sim Re \left\{ \frac{\langle k_{em} k_{rad} \rangle}{[k_{em} k_{rad}]} \sum_{\text{color}} \sum_{\text{spin}} A_+^{(n)} A_-^{(n)*} \right\}$$

Virtual subtraction: Same structure

$$|\mathcal{M}_{n}^{\text{virt}}|^2 \rightarrow \mathcal{V}_\mathcal{I} \otimes |\mathcal{M}_n|^2, \quad \mathcal{V}_\mathcal{I} = \int d\Phi_{\text{rad}} D_\mathcal{I}$$
Total cross section for the process $e^+ e^- \rightarrow u\bar{u}$
$e^+e^- \rightarrow t\bar{t}$ at NLO with WHIZARD
$e^+e^- \rightarrow t\bar{t}H$

Diagram: $e^+e^- \rightarrow t\bar{t}H$ at NLO with WHIZARD

Graph showing the cross-section $\sigma$ in fb as a function of $\sqrt{s}$ in GeV, with two curves representing LO and NLO calculations.
Consider top production $e^+e^- \rightarrow t\bar{t}$ close to the production threshold. It is

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

→ 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:

$$R(s) = F^v(s)R^v(s) + F^a(s)R^a(s)$$

Implemented in WHIZARD via TOPPIK[Hoang, Teubner, 1999]
Non-relativistic QCD Threshold Resummation

\[ \sigma [\text{pb}] \]

\[ \sqrt{s} \ [\text{GeV}] \]

- NRQCD calculation
- WHIZARD NLL
WHIZARD vs. Madgraph