Lepton Collider Simulations With WHIZARD
New Developments

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WHIZARD: Overview

Scope

WHIZARD is a stand-alone program for processes at high-energy colliders: scattering and particle decays

- integrate cross sections and decay widths (perturbative, partonic)
- account for LC beam structure
- amplitude code is generated and executed on the fly
- shower/hadrons via internal or external code
- calculate observables, generate event samples

Universal Monte Carlo for elementary processes at (future lepton) colliders

WHIZARD for LC Studies

SM event samples (DBD) for LC studies ⇒ T. Barklow

- WHIZARD 1
- Leading-order (QCD and EW), PYTHIA 6 for shower/hadrons
- Various adjustments and add-ons for specific LC issues

Present and future studies: WHIZARD 2

- user interface (scripting language SINDARIN)
- internals redone aimed at NLO and modularity
- CIRCE 2 for detailed beamstrahlung spectra
- current activity: validation, refinements, NLO (QCD and EW)
- HPC parallel evaluation
- Simulations ongoing for CEPC studies and further

Team

Program exists since 1999

Active authors and developers:

WK (U Siegen), T. Ohl (Würzburg), J. Reuter (DESY)

S. Brass, V. Rothe, M. Sekulla, C. Schwinn, S. Shim, F. Staub, P. Stienemeier, M. Utsch, Z. Zhao

Current version:

2.6.1 (27. Oct. 2017)

For the User

- Installation centrally or locally on any Linux or Mac (`autotools`)

```
./configure [options]
make
make install
```

- Look-and-feel like standard Linux/Unix apps

```
./whizard [options] FILE
```

- User works in directories at his choice, no structure imposed

Programming Languages

- Main program code is written in modern Fortran (F2008).
  Compilers: `gfortran`, `ifort`, `nagfor`
- Glue code uses `Make`, Makefiles generated on-the-fly
- Algebra is done in `OCaml` (compiler free for all platforms)
  $\Rightarrow$ Sub-package `OMega`
- Some interface to external code in `C/C++`
- Can use precompiled libraries (`LHAPDF`, `HepMC`, ...)

Input

- Models precompiled or generated (FeynRules, SARAH, UFO)
- User provides all other information via input file, which is actually a script

  Programming language (DSL): Sindarin

Output

1. Numbers (cross sections, decay widths, other observables)
2. Distributions (plots)
3. Event samples in various formats
   (fixed-order or showered, partonic or hadronic)

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard Model	`SM_CKM`	`SM`
SM with anomalous gauge couplings	`SM_ac_CKM`	`SM_ac`
SM with anomalous top couplings	`SMtop_CKM`	`SMtop`
SM for e^+e^- top threshold	–	`SM_tt_threshold`
SM ext. for VV scattering	—	`SSC / SSC2`
SM ext. for unitarity limits in VV	—	`SM_ul`
SM with Higgs singlet	—	`HSExt`
2HDM	`2HDM_CKM`	`2HDM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PS/E/SSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly-free)	—	`Simplest`
Simplest Little Higgs (universal)	—	`Simplest_univ`
3-site model	—	`Threeshl`
UED	—	`UED`
SM with Z'	—	`Zprime`
SM with gravitino and photino	—	`GravTest`
Augmentable SM template	—	`Template`

Recent additions to the Model list

- EFT for the SM: complete bosonic $D = 6$ Lagrangian (Warsaw Basis)

  S. Shim

- Beyond EFT: electroweak interactions at high energy
  $\Rightarrow$ (Super)LHC/FCC-pp, ILC and CLIC

  C. Fleper, M. Sekulla

- UFO File Support (`OMega`)

  T. Ohl

Collider Setup

Trivial beam structure: just process definition

```
process foo = "e+", "e-" ⇒ "mu+", "mu-"
```

⇒ scattering process or decay process

Nontrivial beam structure:
polarization, momentum, angle, beam spectra, structure functions

e^+e^- Collider Beam Structure

1. Beamstrahlung = classical beam-beam interaction, collective effect

2. ISR = resummed soft/collinear QED bremsstrahlung for initial-state electron-electron interaction

3. EPA = $\gamma\gamma$-induced processes

e^+e^- Collider: Beamstrahlung

Options for handling beamstrahlung (as supported by WHIZARD)

1. Beam-energy spread
   ⇒ Gaussian distribution

2. `CIRCE1`: parameterized beam spectrum
   ⇒ Factorized, few parameters in fit

3. Beam-events file: use result of GuineaPig simulation directly
   ⇒ Finite number of pre-simulated beam events

4. `CIRCE2`: generator takes binned and interpolated result of detailed GuineaPig simulation
   ⇒ Most precise description

Processes

```
process foobar =
  "e+", "e-" => nue, nuebar, b, bbar, q, qbar, "mu+", "mu-"
```

- Explicit, exclusive
- optionally constrained
- optionally with sum over flavors `alias q = u:d:s:c`
- optionally sum over subprocesses ⇒ inclusive, e.g. decays

Amplitudes: `OMega` (automatic recursive tree-level amplitudes)

Phase Space and Integration

Phase Space

Multi-Channel: Select dominant singularity structures, parameterize via resonance mappings etc.

(Selection is automatic, heuristics for determining channel importance)

Integration

Twofold adaptive: VAMP

1. Each channel gets a weight which is iteratively adapted
2. Each channel is binned (VEGAS-like), binning is iteratively adapted

Warmup iterations yield integration grid and channel-weight distribution optimized for the particular process, to be used in event generation

Parallel Processing

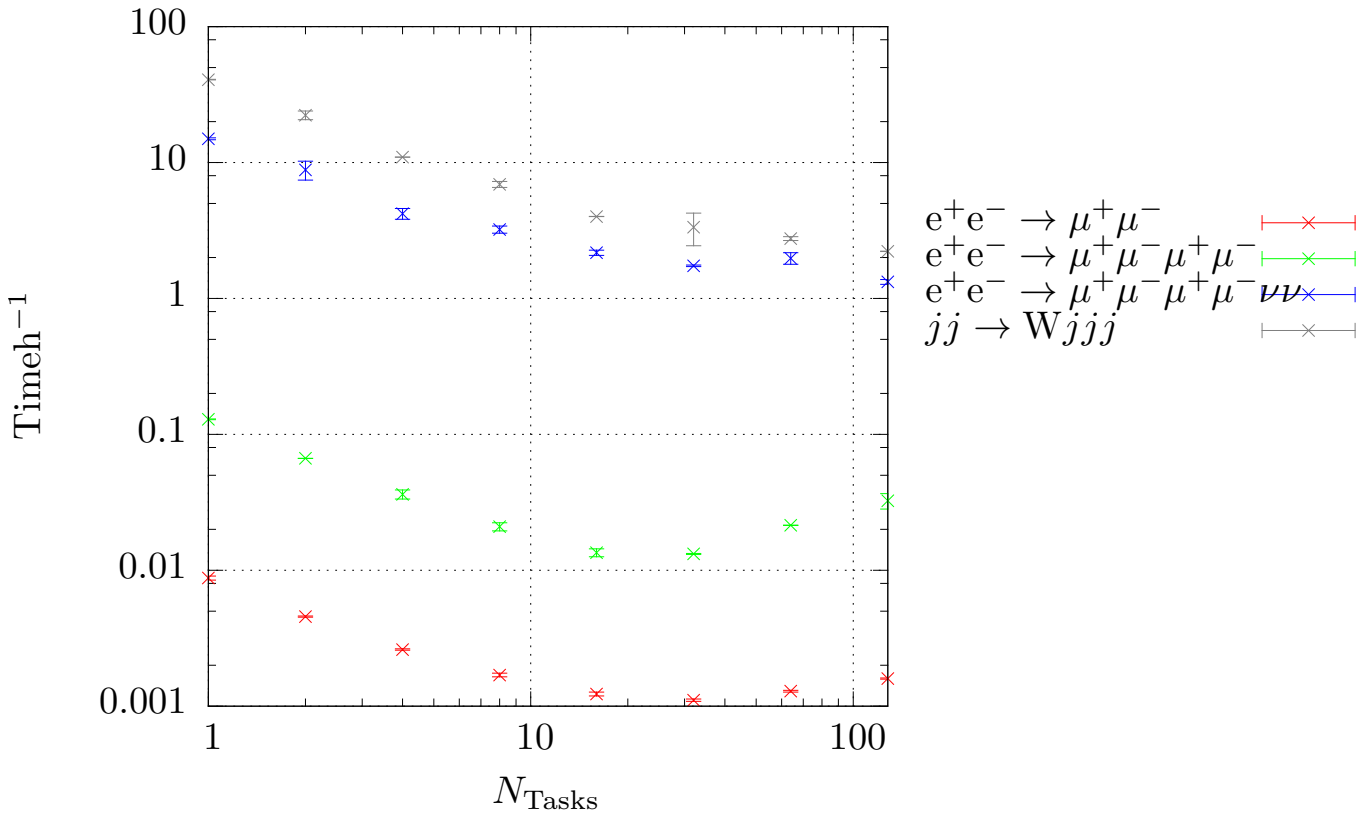
OpenMP

Make use of multi-core processors: parallel evaluation of helicity configurations

MPI

Make use of multi-processor clusters: parallel sampling of phase space
MPI 3.0 asynchronous message passing
⇒ New feature S. Brass

Speedup (WHIZARD 2.6.0 with MPI)



Speedup by factor > 10 workers

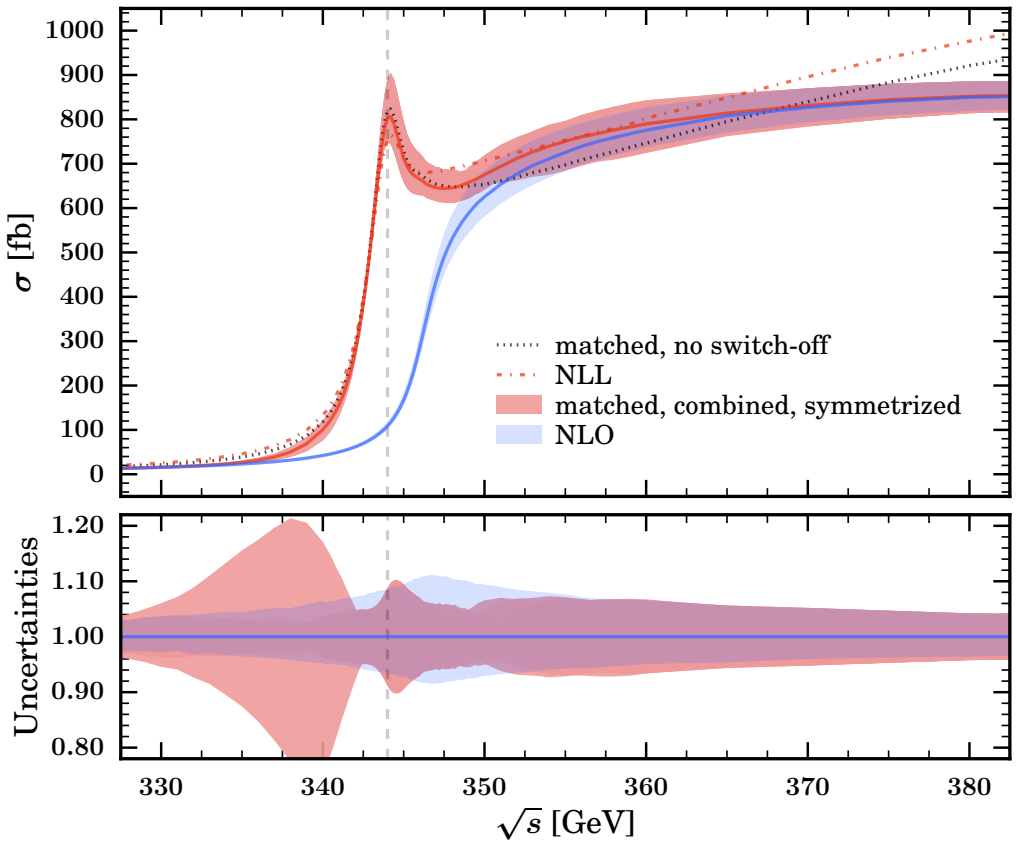
Next Step: New Phase-space Construction Algorithm ($\Rightarrow f > 100$)

Processes at NLO

- NLO QCD: implementation complete
  - Interfacing GoSam, OpenLoops, Recola
  - FKS subtraction
  - $t\bar{t}$ and $t\bar{t}H$ off-shell: detailed study
  - currently validating large class of NLO processes

- NLO SM: complex mass scheme
  - Interfacing GoSam, OpenLoops, Recola
  - FKS subtraction / bookkeeping for photons w.i.p.
  - ... under construction

Top Threshold, Precisely



Chokoufé, WK, Lindner, Pozzorini, Reuter, Weiss, JHEP 12 (2016) 075

Bach, Chokoufé, Hoang, WK, Reuter, Stahlhofen, Teubner, Weiss, in prep.

Top Threshold, Precisely

Achievements:

- Most precise universal description of the $t\bar{t}$ threshold
- Combines NLO QCD (overall) with NLO-NRQCD (threshold region), Coulomb resummation (potential) and NLL-NRQCD threshold improvement (RG)
- Applies to the real final states, e.g.

$$e^+e^- \to b\bar{b}\mu^-\bar{\nu}_\mu e^+\nu_e$$

$\Rightarrow$ Testbed for the precise description and exclusive event generation for any thresholds in e^+e^-, e.g., W^+W^-, ZZ, ...

Event Handlers

WHIZARD uses the twofold-adapted phase space to generate unweighted event samples. Further processing:

1. Particle decays (cascades):
   - using WHIZARD's own decay processes (explicit or automatic)
   - full control over polarization transfer (uncorrelated, classical, quantum correlation)
2. Photon radiation: exclusive photons from inclusive ISR
3. Resonance histories: control shower behavior
4. Shower, Hadronization: optionally call PYTHIA (internally)
5. POWHEG algorithm for matching NLO events
6. Event output: file formats StdHEP, LHEF, HepMC, LCIO, ASCII

Photon Handler

Inclusive ISR description (LL soft, 3rd order collinear) accounts for precise cross section and energy dependence

New Photon Handler in WHIZARD 2.6

Take generated events

- Collinear photons (both beams) are given transverse momentum according to scale-less logarithmic distribution (w/ cutoffs)
- Both beams handled: exact energy-momentum conservation
- Common scheme for ISR (e^+e^- process) and EPA ($\gamma\gamma$ process)

$\Rightarrow$ extend to multiple photons matched with NLO SM

Resonances and Parton Shower

Current standard for simulation with WHIZARD 2

PYTHIA 6 parton shower (internal). Ongoing validation by LC generator group.

Important LC processes: $(WW, ZZ, ZH \to) 4f$,
$(WWZ, ZZZ, WWH, \ldots \to) 6f$, etc.: contain resonances
PYTHIA 6 modes:

1. Default: local interaction, shower starts at process energy scale, invariant masses reshuffled
2. Resonance: nonlocal interaction, shower starts at resonance mass, invariant masses fixed

Interplay of resonant/nonresonant background?

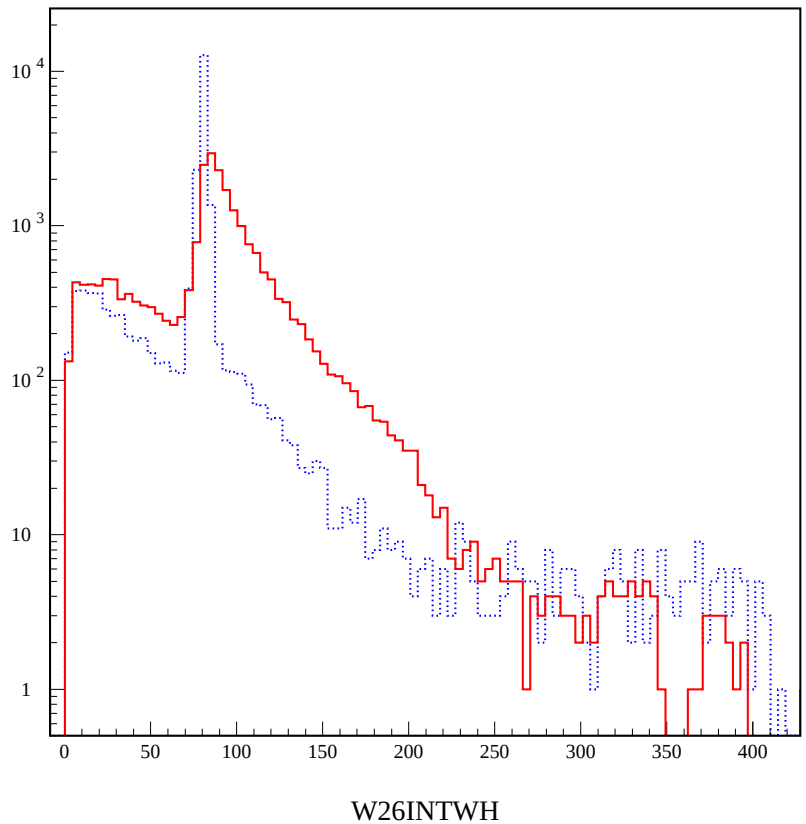
New solution for WHIZARD 2 (WIP)

Generate event sample as usual, no change to cross section (LO).

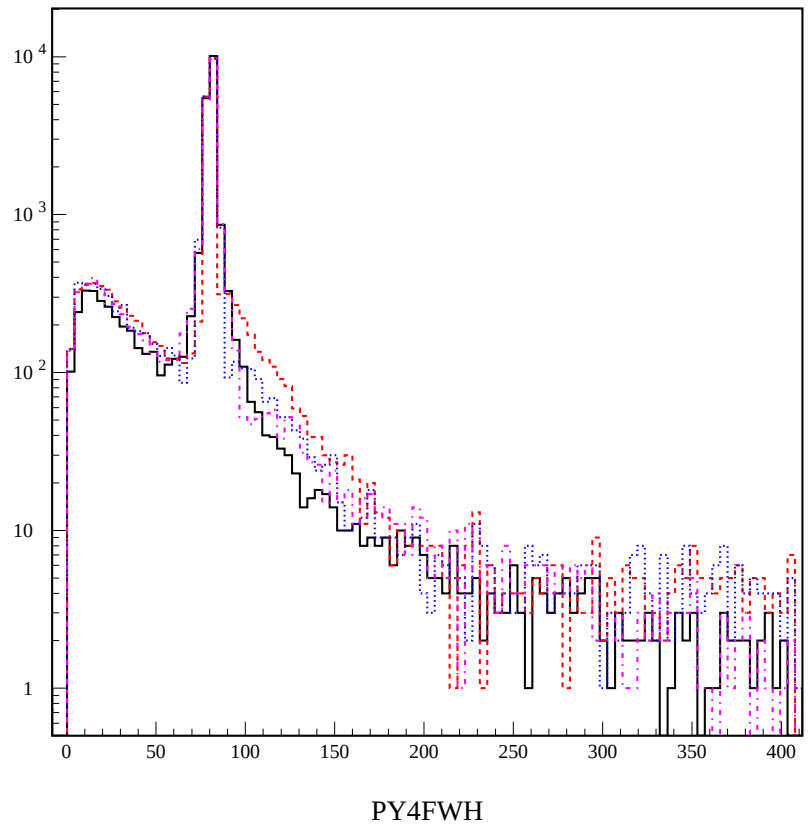
1. Determine possible resonance histories for each single event
2. For all applicable histories, compute factorized matrix elements *in addition to* complete matrix element
3. Use relative ME values to determine probabilities for histories, including background (remainder)
4. Select one of the applicable histories to modify the event record

Resonance / Background in Event History

Resonance by color / no resonance



Resonance by ME, varied cutoff



Plots by M. Berggren (WIP)

This is to be applied to matched NLO event generation in the presence of multiple resonances.

Plots, observables

```
histogram ptplot (0 GeV, 100 GeV, 5 GeV)

simulate (twojets) {
  n_events = 10000
  analysis =
    record ptplot (eval Pt [q])
}
compile_analysis
```

More Analysis

SINDARIN

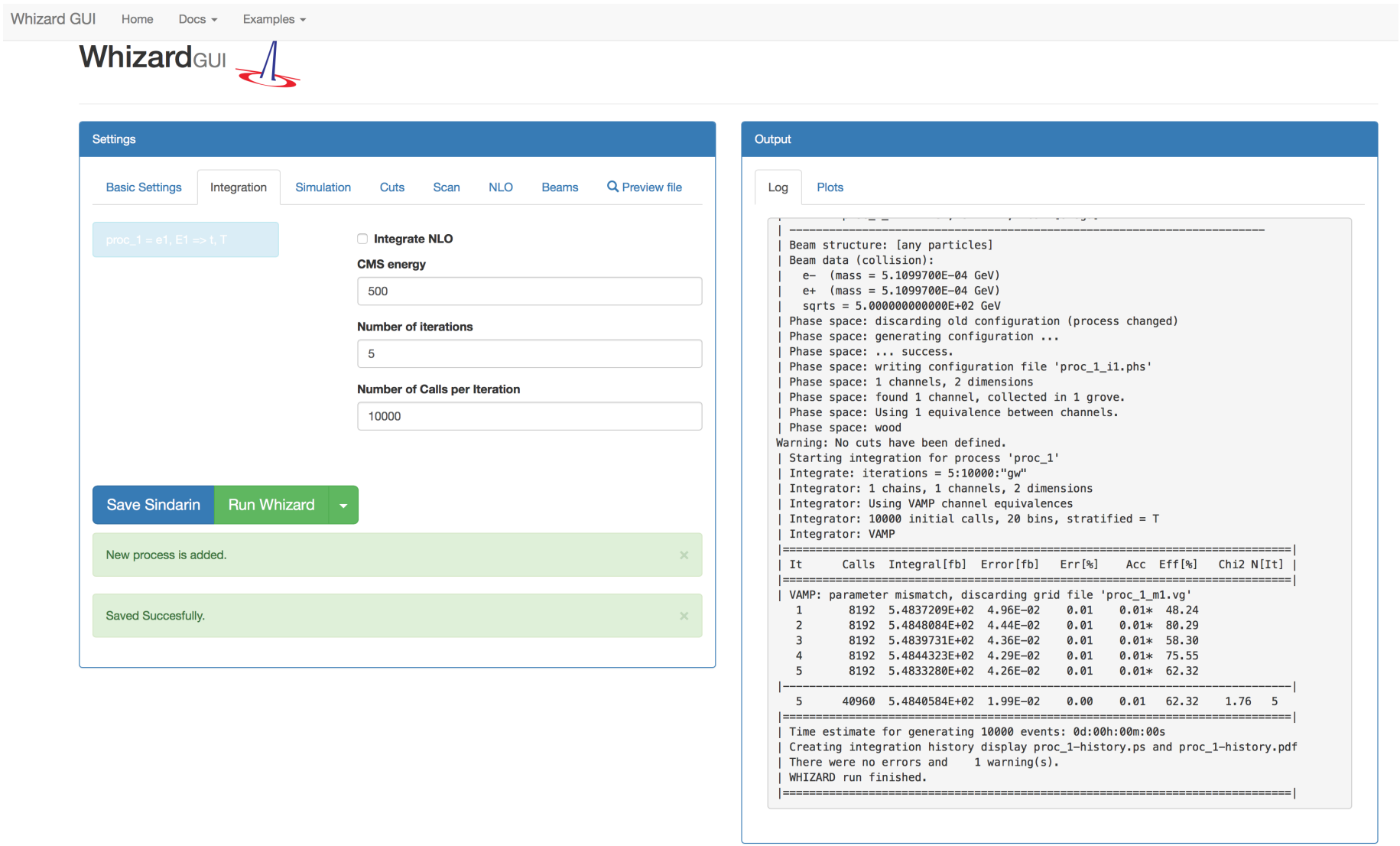
- unified syntax for cuts, observables, histograms, plots embedded in steering code
- Can work on own event samples or on event files
- Resulting plots use MetaPost $\Rightarrow$ integrates seamlessly with LaTeX
- `FastJet` for jet algorithms in cuts/analysis

Also in Sindarin:

- Logicals, strings, integers, reals, complex
- If-then-else branching
- Parameter scans/loops (also nested)

. . . more to come.

WHIZARD GUI


Whizard GUI
Home
Docs
Examples
WhizardGUI
Settings
Basic Settings
Integration
Simulation
Cuts
Scan
NLO
Beams
Preview file
proc_1 = e1, E1 => t, T
Integrate NLO
CMS energy
500
Number of iterations
5
Number of Calls per Iteration
10000
Save Sindarin
Run Whizard
New process is added.
Saved Succesfully.
Output
Log
Plots
| Beam structure: [any particles]
| Beam data (collision):
| e- (mass = 5.1099700E-04 GeV)
| e+ (mass = 5.1099700E-04 GeV)
| sqrts = 5.000000000000E+02 GeV
| Phase space: discarding old configuration (process changed)
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'proc_1_i1.phs'
| Phase space: 1 channels, 2 dimensions
| Phase space: found 1 channel, collected in 1 grove.
| Phase space: Using 1 equivalence between channels.
| Phase space: wood
Warning: No cuts have been defined.
| Starting integration for process 'proc_1'
| Integrate: iterations = 5:10000:"gw"
| Integrator: 1 chains, 1 channels, 2 dimensions
| Integrator: Using VAMP channel equivalences
| Integrator: 10000 initial calls, 20 bins, stratified = T
| Integrator: VAMP
| It Calls Integral[fb] Error[fb] Err[%] Acc Eff[%] Chi2 N[It]
| VAMP: parameter mismatch, discarding grid file 'proc_1_m1.vg'
1 8192 5.4837209E+02 4.96E-02 0.01 0.01* 48.24
2 8192 5.4848084E+02 4.44E-02 0.01 0.01* 80.29
3 8192 5.4839731E+02 4.36E-02 0.01 0.01* 58.30
4 8192 5.4844323E+02 4.29E-02 0.01 0.01* 75.55
5 8192 5.4833280E+02 4.26E-02 0.01 0.01* 62.32
5 40960 5.4840584E+02 1.99E-02 0.00 0.01 62.32 1.76 5
| Time estimate for generating 10000 events: 0d:00h:00m:00s
| Creating integration history display proc_1-history.ps and proc_1-history.pdf
| There were no errors and 1 warning(s).
| WHIZARD run finished.

Summary: WHIZARD for CEPC Physics

- Universal multi-particle event generator (SM and beyond)
- Accurate e^+e^- beam description
- Parallel computation using MPI and OpenMP
- e^+e- precision studies bear challenges that are not addressed by conventional automated multi-particle simulations

  Work items:
  - SM NLO is as important as QCD NLO, higher orders
  - Accurate description of (almost) collinear photon radiation
  - Precise shape and normalization of thresholds and resonances
  - Electroweak resonances as sources of QCD radiation

http://whizard.hepforge.org