WHIZARD for the CEPC Project

Wolfgang Kilian

U Siegen

Monte Carlo for CEPC, May 2015

Monte Carlo for CEPC

The CEPC is a

symmetric e^+e^- collider

with planned c.m. energy

$90 \dots 250$ GeV

and

high luminosity

Many existing studies do apply, but

low beamstrahlung, some energy spread

$\Rightarrow$ differences w.r.t. both ILC and LEP

Challenges for simulation: LEP

- $90\ \mathrm{GeV}$: LEP 1 / SLC

  2 fermions, tree + 1 loop

- $170\ \mathrm{GeV}$: LEP 2

  4 fermions, tree + 1 loop reson.

Challenges for simulation: LEP ⇒ CEPC / ILC

- 90 GeV: LEP 1 / SLC ⇒ CEPC

  2 fermions, tree + 1 loop + 2 loop
  + 4 fermions, photons, jets
- 170 GeV: LEP 2 ⇒ CEPC

  4 fermions, tree + 1 loop reson. + 1 loop complete
  + 6 fermions, photons, jets
- 250 GeV: ⇒ CEPC / ILC

  4 fermions, tree + 1 loop complete
  + 6 fermions, photons, jets

Challenges for simulation: LEP $\Rightarrow$ CEPC / ILC

- 90 GeV: LEP 1 / SLC $\Rightarrow$ CEPC

  2 fermions, tree + 1 loop + 2 loop
  + 4 fermions, photons, jets

- 170 GeV: LEP 2 $\Rightarrow$ CEPC

  4 fermions, tree + 1 loop reson. + 1 loop complete
  + 6 fermions, photons, jets

- 250 GeV: $\Rightarrow$ CEPC / ILC

  4 fermions, tree + 1 loop complete
  + 6 fermions, photons, jets

- 360 GeV: $\Rightarrow$ ILC

  6 fermions, tree + Coulomb resummed + 1 loop complete
  + 8 fermions, photons, jets

ISR Photon Radiation

LEP

ISR strongly affects the Z peak and the WW threshold via its energy loss

Inclusive treatment of ISR:

- Resummation of invisible soft photons (all orders, leading-log)
- Incorporate invisible collinear photons (fixed order)

$\Rightarrow$ effective structure function for electron/positron

CEPC

More precise calculation necessary, handle photons that are visible in the detector.

Semi-exclusive treatment of ISR desired:

- Resummation and collinear inclusion depending on detector geometry
- Allow for transverse momentum
- Match to fixed-order calculation

QCD (perturbative)

LEP

Jet production and radiation in clean environment
⇒ detailed jet studies, tuning of MC parameters

CEPC

- Matrix-element matching in clean environment
- Fine-tuning of MC parameters
- Refined α_s measurement

⇒ new level of pQCD understanding, new input for LHC analyses and future hadron colliders

Flavour

Lepton collider detectors can identify charm quark via lifetime measurement

$\Rightarrow$ new level of tests of flavour universality (gauge bosons) and non-universality (Higgs)

WHIZARD

WHIZARD is a universal MC for high-energy processes, originally developed for post-LEP lepton-collider physics. (First version 1999)

Currently: collaboration

- University of Siegen: Wolfgang Kilian
- DESY (Hamburg): Jürgen Reuter
- University of Würzburg: Thorsten Ohl

Dedicated Workshop "2nd WHIZARD Forum" in Würzburg, March 2015

WHIZARD: Software management

Code: hepforge (Durham, UK)

https://whizard.hepforge.org

Versioning: SVN version management. Current: 2.2.6

Bug tracker: on hepforge.org

E-mail: `whizard@desy.de`

Platforms: Linux and MacOS

Configuration: `GNU autotools`, separate installation and workspace

`configure && make`

Test suite: Included in the part of package: 100s of automatic unit tests

`make check`

Automatic checking each commit (Jenkins / U Siegen)

WHIZARD: Code Characteristics

- Code in modern Fortran (Fortran 2008), compatible with free `gfortran` compiler
- OpenMP for multi-core parallelization
- Modular and object-oriented, heavily relying on abstract design patterns for exchangeable implementations
- Code documentation via `noweb` (entangled code/doc)
- Includes interfaces and C/C++ glue code for third-party packages
- User interface via
  - + Script as input file (Sindarin)
  - + Command-line parameters and commands
  - + Library calls from Fortran/C/C++/Python main program
  - + Interactive (WHIZARD shell)
  - – GUI: not yet

WHIZARD for ILC (and CEPC): Current status

Universal Monte Carlo, multi-particle matrix elements, SM and beyond

DBD event samples for LC studies:

generic event samples with 4, 6, (8) fermions, WHIZARD 1.xx

New generation for ILC planning phase: WHIZARD 2.xx

Prebuilt Models

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 with WW resonances and unitarization	—	SSC
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

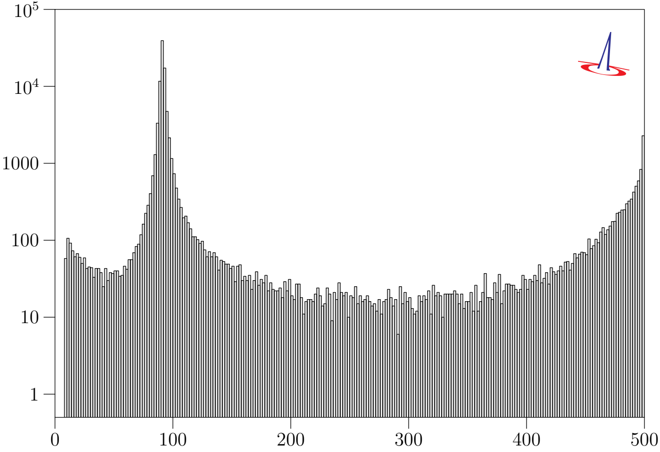
More Models

new models easily: FeynRules interface
Christensen/Duhr/Fuks/Reuter/Speckner, arXiv:1010.3251

Interface to SARAH in the SUSY Toolbox Staub, 0909.2863;
Ohl/Porod/Speckner/Staub, 1109.5147

$e^+e^- \to b\bar{b}$

ILC: 500 GeV, beamstrahlung $\otimes$ ISR, no cuts, 100k events: $M(b\bar{b})$



SINDARIN: Talking to WHIZARD

Example:

```
process foo =  e1, E1 => n1, N1, H
simulate (foo) { sqrts = 500 GeV  n_events = 10000 }
```

Scope

- Set model, parameters, user variables
- Conditionals and loops, arbitrary workflow
- Multiple processes and process combinations, flavor sums
- Automatic width calculation
- Beams: chain of spectra and structure functions, polarization
- Integration and simulation, shower and hadronization parameters
- Arbitrary expressions for cuts, scale, weight, etc.
- Event sample output: raw, ASCII, LHE, HepMC, StdHEP, ...
- Event sample reweighting, output multiple weights
- Internal analysis: histograms and plots

Beam structure

WHIZARD supports e^+e^- beams with structure [Würzburg: Thorsten Ohl]

(also polarized, asymmetric, non-collinear)

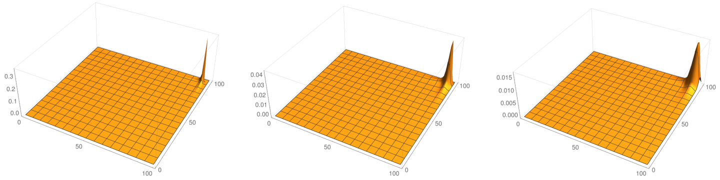
Beam structure options

1. No structure
2. Parameterized beamstrahlung spectrum: Circe 1
3. Use GuineaPig/Cain output directly: beam events
4. Generator for Gaussian beam-energy spread (TBD)
5. Beam-event generator derived from beam simulation: Circe 2
   $\Rightarrow$ Use dedicated simulation for CEPC parameters

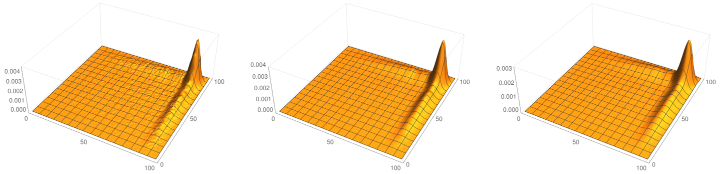
- basic example of CIRCE2 input

```
{ file = "TDR.circe"    # name of the output file
  { design = "ILC"      # there can be more than one design per file
     roots = 500        #                            energy
     scale = 250        # map [0,250] → [0,1]
     bins = 100         # use 100 bins in each direction
    { pid/1 = electron  # first and second particle
      pid/2 = positron
      pol = 0           # both particles unpolarized
      events = "guinea_pig/out/ILC_500_unpolarized.data"
      columns = 2       # read only the first two columns
      lumi = 8.008e33
      min = 0
      max = 1.05        # allow 5% energy spread at the upper end
} } }
```

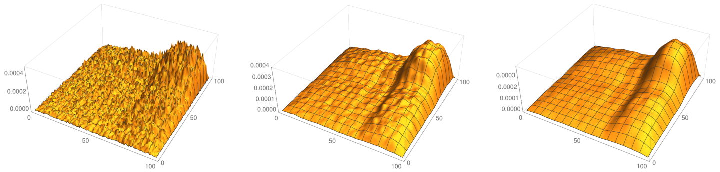
- $\texttt{iterations} = 0$ and $\texttt{smooth} = 0, 3, 5$:



- $\texttt{iterations} = 2$ and $\texttt{smooth} = 0, 3, 5$:



- $\texttt{iterations} = 4$ and $\texttt{smooth} = 0, 3, 5$:



Use from within WHIZARD (part of Sindarin script):

```
sqrts = 500
beams = "e-", "e+" => circe2
$circe2_file = "TDR.circe"
$circe2_design = "ILC"
?circe2_polarized = false
```

Hard Matrix elements

OMega

- Automatic calculation of amplitudes at tree level
- SM, SUSY models, non-SUSY models, non-perturbative models, etc.
- Algebraic reduction to DAG = generalization of Berends-Giele recursion with caching, result is Fortran code
- Helicity exact in discrete basis.
- Color via color-flow version of QCD, no leading-color approx.
- Flavour exact or diagonal
- Vary gauge-scheme for unstable W/Z

Final state

WHIZARD produces partonic events in various formats, including color correlations

- supported: Stdhep, LCIO, LHEF, HepMC, various ASCII formats

⇒ shower/hadron generator can operate on event files, e.g. PYTHIA 8

Particle decays, if not already included in hard ME:

- factorized with various options on polarization handling

Internal parton shower: two alternatives

1. Shower generator PYTHIA 6 internally interfaced
2. WHIZARD analytic-shower generator

\+ MLM matching
\+ Polarized particles (tau) possible

Projects for WHIZARD

WHIZARD is dedicated to lepton-collider MC simulation

⇒ Identify important issues for upcoming decade of ILC/CEPC studies, to become ready for data taking

⇒ Opportunity and need for collaboration projects

Initial state

Exclusive handling of multiple ISR photons, for arbitrary hard processes in combination with soft resummation.

Currently: available in dedicated KK Monte Carlo (only specific 2-fermion processes)

Project for WHIZARD: universal semi-exclusive ISR

$\Rightarrow$ CEPC

$\Rightarrow$ ILC

$\Rightarrow$ CLIC

Hard matrix elements

Automatic NLO calculation and event generation: DESY team (Jürgen Reuter, Bijan Chokoufe, Christian Weiss)

(Employ modular structure of WHIZARD for exchangeable algorithms)

QCD

- Virtual matrix elements with GoSam, OpenLoops, ...
- Real radiation with OMega, GoSam, ...
- Subtraction scheme: FKS, ...

First results available for e^+e^- processes. Validating and generalizing the program structure.

SM

- Virtual matrix elements with Recola, OpenLoops, (TBC)
- Complex Mass scheme

Further plans: versatile subtraction scheme $\Rightarrow$ 2-loop virtual ME

Matching/merging

Combining hard ME and parton shower

- MLM scheme: implemented
- PowHEG scheme for incorporating NLO virtual and real ME correction: work in progress

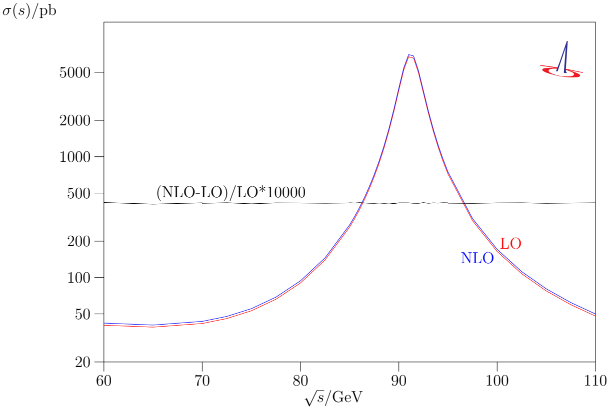
⇒ exclusive NLO events

$e^+e^- \to q\bar{q}$

The NLO QCD result should be a constant K factor.

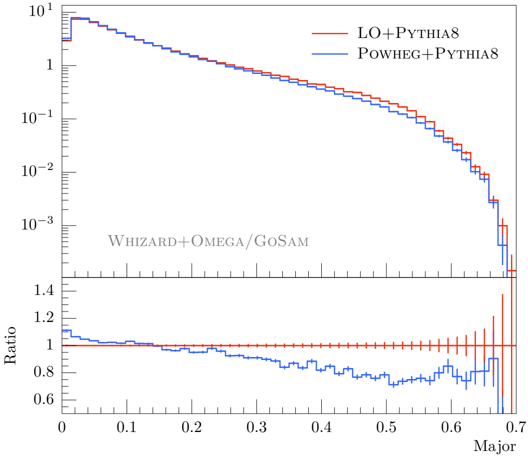
1

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



$e^+e^- \to q\bar{q}$

$q\bar{q}$ initiate a parton shower: NLO + POWHEG matching + PYTHIA 8



NLO/matching/merging

Further plans:

- working toolchain $\Rightarrow$ universal applicability
- alternative matrix-element providers
- alternative matching schemes
- more sophisticated shower algorithms (VINCIA)
- Pythia 8 and Herwig interfaces
- Photon shower/resummation in final state

Top pair threshold

(ILC exclusive, unless CEPC gets $180\ \mathrm{GeV}$ beams)

Many independent theory methods and results

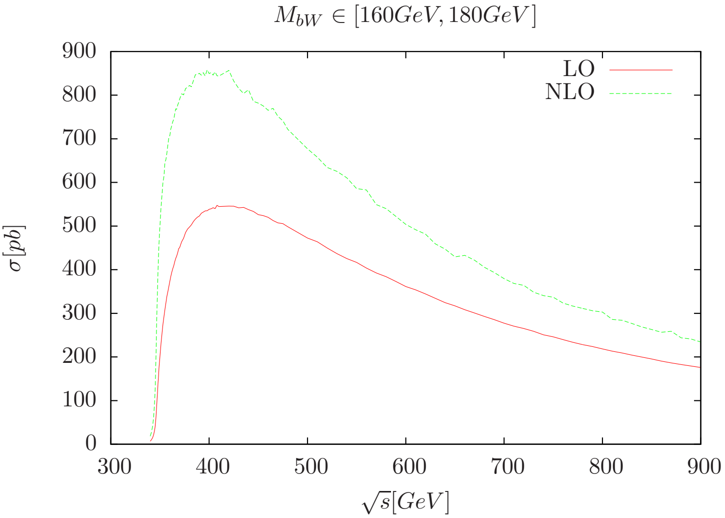
- Tree-level beyond factorization production/decay (OMega)
- Coulomb resummation near threshold (Toppik)
- NRQCD evaluation of production amplitude (Toppik)
- NLO QCD corrections in the continuum (GoSam)

WHIZARD: combine all of those.

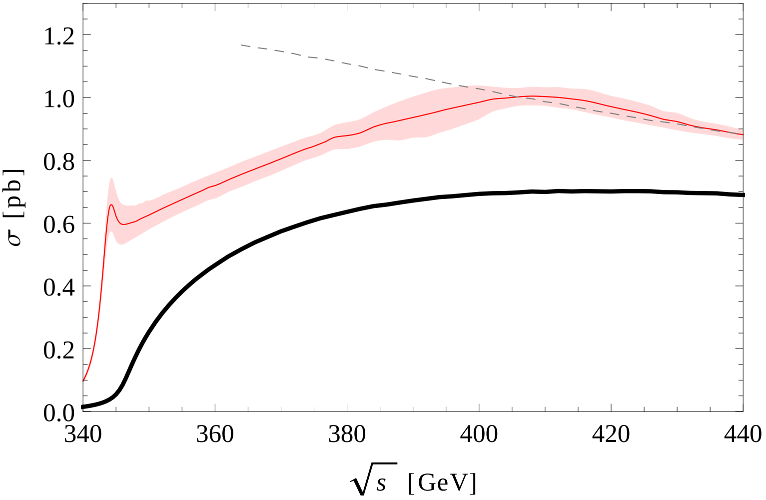
[Fabian Bach, Bijan Chokoufe, Christian Weiss]

Fixed Order NLO (Continuum)

$e^+e^- \to b\bar{b}W^+W^-$



Resummed NLL $t\bar{t}$ threshold + continuum



Improving efficiency

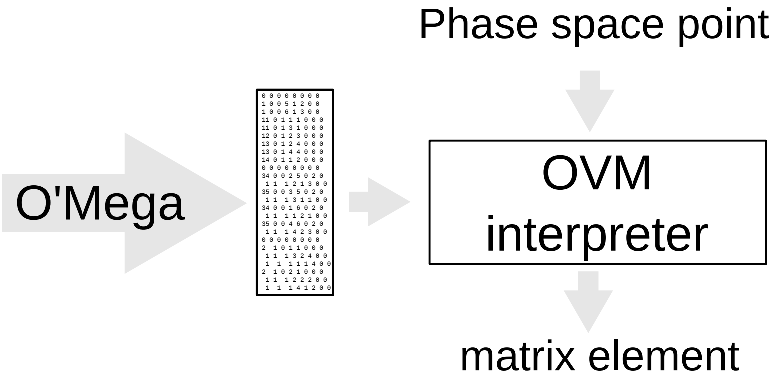
Technical issues

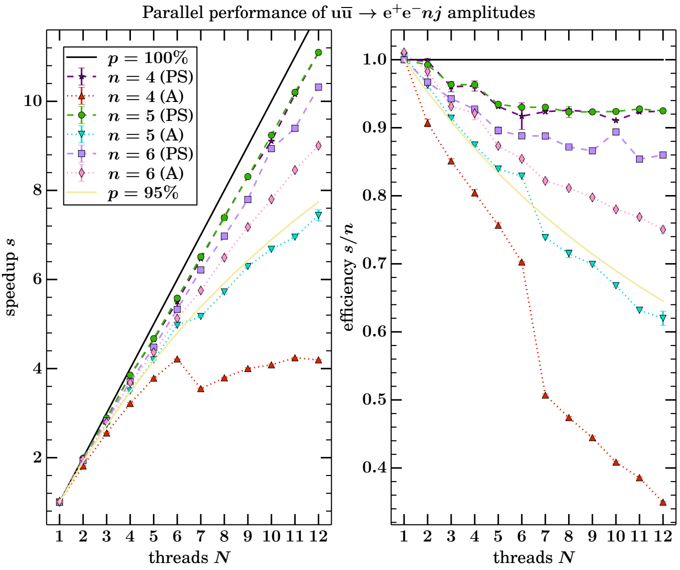
1. implement MPI (Coarray) parallelization model, so single processes can be run on clusters/supercomputers
   - project to be started in 2015
2. replace generated Fortran matrix element code by virtual machine code

   Thorsten Ohl, Bijan Chokoufe
   - implemented, efficiency gain varies
3. export calculations to GPU (Xeon Phi), using virtual machine

Algorithm changes, for instance:

1. replace discrete quantum numbers by continuous parameters, to be included in phase space integration


Phase space point
O'Mega
0 0 0 0 0 0 0 0
1 0 0 5 1 2 0 0
1 0 0 6 1 3 0 0
11 0 1 1 1 0 0 0
11 0 1 3 1 0 0 0
12 0 1 2 3 0 0 0
13 0 1 2 4 0 0 0
13 0 1 4 4 0 0 0
14 0 1 1 2 0 0 0
0 0 0 0 0 0 0 0
34 0 0 2 5 0 2 0
-1 1 -1 2 1 3 0 0
35 0 0 3 5 0 2 0
-1 1 -1 3 1 1 0 0
34 0 0 1 6 0 2 0
-1 1 -1 1 2 1 0 0
35 0 0 4 6 0 2 0
-1 1 -1 4 2 3 0 0
0 0 0 0 0 0 0 0
2 -1 0 1 1 0 0 0
-1 1 -1 3 2 4 0 0
-1 -1 -1 1 1 4 0 0
2 -1 0 2 1 0 0 0
-1 1 -1 2 2 2 0 0
-1 -1 -1 4 1 2 0 0
OVM interpreter
matrix element



Parallel performance of $u\bar{u} \to e^+e^- nj$ amplitudes
$p = 100\%$
$n = 4$ (PS)
$n = 4$ (A)
$n = 5$ (PS)
$n = 5$ (A)
$n = 6$ (PS)
$n = 6$ (A)
$p = 95\%$
speedup s
threads N
efficiency s/n
threads N

Summary and Outlook

- WHIZARD is dedicated to lepton collider physics ⇒ CEPC
- Detailed description of e^+e^- beam properties
- Universal matrix-element generator with event generation and final-state transformations (decays, shower, hadrons)

Ongoing and future projects

- NLO (NNLO) for e^+e^- processes
- Parton shower and matching algorithms
- Exclusive photon radiation
- Alternative algorithms and methods for efficiency gains
- Specific CEPC phenomenology and studies