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WHIZARD @ LCFORUM 2012: A Status Report

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This is a status report of the WHIZARD Monte Carlo multi-purpose event generator given at the LCFORUM 2012 at DESY. In case you use the program, please do cite the official reference(s), [1, 2]. I review here the development of the WHIZARD generator version 2 with a special emphasis on linear collider physics.

1 Introduction

The multi-purpose Monte Carlo event generator WHIZARD was developed as a tool for linear collider physics during the late 1990s [3]. Some of the first studies with exclusive four, six and eight fermion final states for linear collider physics have been done with WHIZARD [4, 5, 6, 7]. The first public version, 1.00, of WHIZARD has been released in December 2000. It was written in `Fortran90/95` and used from its beginnings the VAMP package [8] for a multi-channel adaptive Monte Carlo integration. The major improvement was an algorithm to model the phase space channels for a process under consideration and to provide the corresponding phase space mappings to flatten out the divergencies of the integrand for an optimized importance sampling. In the 1.xx (now called legacy) versions of WHIZARD, matrix elements from early version of MadGraph [9] and CompHep [10] as well as from the at that time newly developed Optimized Matrix Element Generator O'Mega [2] could be used. Parton shower and hadronization could be simulated via an interface to PYTHIA [11].

During the years 2001-2005/06, many technical and physics features have been added on demand of either theoretical or experimental users of the program or the authors itself. Support for several event file formats have been added. For a realistic simulation of linear lepton colliders, the ability to use structured beams have become crucial, specifically for experimental feasibility studies and detector development. Along these lines, initial state radiation (ISR) following the approach of Ref. [28], k_T distribution of the radiating initial beams as well as explicit photons from ISR in the final state events. Beamstrahlung, i.e. the modifications of the beam spectra due to classical electromagnetic interactions of the lepton beams, as well as photon beam options via Compton backscattering off laser photons could be simulated by attaching the CIRCE1 and CIRCE2 generators [12] to the main WHIZARD program. The main core in version 1.xx connects the different parts of the program via glueing shell scripts that steer the compilation of different processes as well as the integration, event generation and the built-in graphical analysis of WHIZARD.

WHIZARD has been extensively used for linear collider physics, e.g for the development of the TESLA Technical Design Report [13, 14, 15]. The big SLAC event samples for the Standard Model backgrounds have been generated with WHIZARD. Though here WHIZARD has been used as a generator for SM backgrounds one of the main focuses of the tool has always been the realm of beyond the Standard Model (BSM) physics. Many of these developments have already been present in the legacy branch WHIZARD 1.xx, but I will summarize them together with the overview of the new features in WHIZARD 2.

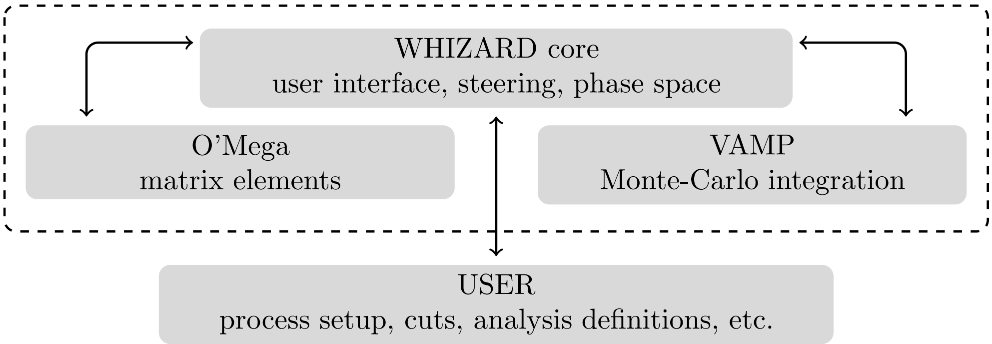

Figure 1: Structure of the WHIZARD program.

2 WHIZARD 2: (New) Technical and Physics Features

2.1 Structure and technical features

WHIZARD has been basically rewritten since 2007. One of the main motivations was the inclusion of several features like event-dependent scales, running couplings, parton showering, handling of a large number of BSM models which are necessary for the purpose of simulating signals and backgrounds at the Large Hadron Collider (LHC). But it was also a question of maintenance of the code, documentation, easening release productions, bug fixes, and treating regressions that made a complete rewriting of the code necessary. Since roughly the same time WHIZARD is located at the HepForge web page, [16], where also the revision control system of the project has been moved to. With the start of the first release candidates of WHIZARD 2 late in 2009 the line of development for the legacy branch, 1.xx, stopped with revision 1.94. Until then, only bug fixes and documentation issues are tackled, and the latest release, 1.97, appeared with a completed manual documenting the final status and usage of WHIZARD 1.9x. For the new release branch, the version system has changed to the triple number system, i.e. (main release).(major version).(minor version). The first release was in April 2010 for the MC4BSM workshop in Copenhagen, the actual release at the moment is 2.0.7 from March 2012.

WHIZARD 2 now is a well-structured program containing the exclusive optimized matrix element generator O'Mega [2, 17], the multi-channel adaptive integration package VAMP [8], the two programs CIRCE1 and CIRCE2 [12] for ISR, beamstrahlung and photon collider physics, as well as tools for graphical data analysis. The basic structure of the program is shown in Fig. 1. The rewriting of the code (in total more than 60,000 lines of new code) was a major undertaking. The code has been completely streamlined, in the sense that now there are only programming languages used, Fortran2003 and OCaml (for the matrix element generator O'Mega). All system calls to binaries are done from the Fortran code itself, so that all shell and Perl scripts have been abandoned. A huge standardization of modern programming tools was the usage of the *autotools*, i.e. *automake/autoconf/libtool* setup which leads to a much easier control of distributions and easier maintenance (e.g. regressions etc.). To further control the line of development, the revision control system (subversion) at the HepForge page is used, together with the trac system for bug, feature request and enhancement tickets for the project management of the software. A cruise control system is used which checks new submissions to the software repository for compatibility for different compiler suites and operating systems and runs a very large class of compatibility tests, sanity and regression checks. A very clean modularization has been achieved using the object-oriented features in Fortran2003. WHIZARD 2 now works as a shared library, which makes a core re-compilation unnecessary whenever one physics process had been changed. New processes can be dynamically included, while the old static option is still available, e.g. for the use in batch systems and on the Grid. The matrix elements which for LHC multi-leg processes can become rather lengthy are automatically split up in subroutines which makes compilation by over-eager compiler optimizers much faster. WHIZARD can also be run as a shell (WHISH) now, though this is still in an experimental status. For using parallelization and multiple threads, an OpenMP parallelization for the helicity amplitudes has been set up, while an MPI parallelization of the multi-channel integration will be

```
cuts = any 5 degree < Theta < 175 degree
         [select if abs (Eta) < eta_cut [lepton]]
cuts = any E > 2 * mW [extract index 2
                        [sort by Pt [lepton]]]
```

Figure 2: Example for a SINDARIN scripting language expression for cuts.

released soon.

The program can be downloaded from the HepForge page, unpacked and then the standard steps should be taken to compile and install it: *configure*, *make*, and *make install*. For the configuration, it might be necessary to specify paths or flags for external programs to be linked in, like e.g. LHAPDF, StdHEP, HepMC. Before the last *make install* step, an optional *make check* is recommended to ascertain that everything runs correctly on the current system. WHIZARD 2 is intended to be installed centrally, e.g. in *usr/local* but can also be installed locally without administrator rights. Each user can then work in his own home or work directory.

2.2 Physics and Performance features

In this section I summarize the main physics features of WHIZARD with a special emphasis both on the new developments in WHIZARD 2 as well as on the ILC-relevant features. First of all, there was an improvement on the already quite performant phase space setup of WHIZARD, where due to a symmetrized phase space forest construction a further performance gain could be achieved. The new modular structure of WHIZARD 2 made it possible to easily include event-dependent scales like they are used in parton density functions (PDFs) as well as running coupling constants like α_s. A very powerful invention was the new steering syntax of the program, Scripting INtegration, Data Analysis, Results display and INterfaces, or short SINDARIN. This is similar to a scripting language, and allows to easily define arbitrary (algebraic) expressions for cuts, scales etc. as well as to denote all the commands necessary to generate matrix elements, compile them, integrate them, generate events and set up an analysis. Fig. 2 shows an example for a cut definition in SINDARIN: the first line selects any lepton with polar angle 5 degrees away from the beam axis under the condition that its absolute rapidity is below some predefined cut variable. The second line selects any second-hardest lepton in p_T if its energy exceeds twice the W mass. Analysis expressions and histograms can be defined in the same way.

WHIZARD 2 uses process libraries, which allows the usage of processes from different BSM models in parallel. As not the multi-leg matrix elements, but the high-dimensional phase space integration is the major bottleneck for going to higher and higher multiplicities, factorizing amplitudes into production and subsequent decays is (in a well-defined approximation) not to bad an idea. WHIZARD 2 realizes this for the event generation and hence distributions where the user can specify whether he wants no spin correlations, only classical spin correlations (i.e. the diagonal of the spin density matrix) or full spin correlations. An example for squark pair production where one of the two squarks decays via a slepton into jet, lepton and the lightest neutralino is shown in Fig. 3. One is able to define containers of particles for decays and can therefore handle inclusive processes and decays. With respect to WHIZARD 1.xx, the algorithms for the flavor sums of initial and final state particles have been greatly improved. A more elaborate elimination of redundancies from summation over internal and external combinations of flavours (particularly quarks in jets, especially for LHC physics) will be available soon and is expected to further improve both code size and speed. For the analysis, the graphical package GAMELAN based on LaTeX and MetaPost has been also improved. Again on the technical side, the algorithm using MD5 check sums has been revisited, such that is now possible to reuse every bit and piece of the steps: the code, the object files, the phase space setup file, the integration grids and the already generated events, whenever those things are still compatible with the setup in the input file. Other new features, that will be discussed in more detail below, are the interface [18] to the program FeynRules [19] which allows to include a new BSM model just by specifying its Lagrangian, and the initial and final state parton shower of WHIZARD [20] together with an MLM matching procedure between hard matrix elements and the parton shower.

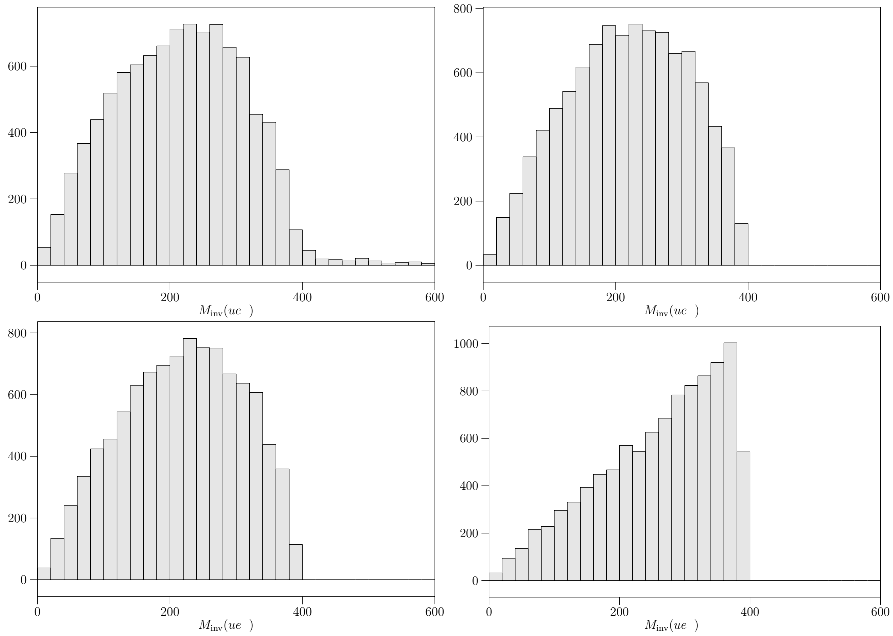

Figure 3: Factorization of processes in distributions: the jet-lepton invariant mass is shown for squark pair production at the LHC, where one of the squarks subsequently decays into a jet, a lepton and the lightest neutralino. Upper left: full matrix element, upper right factorized with full spin correlations, lower row: factorized with classical (left) and no spin correlations (right), respectively.

2.3 Fields, Beams, Interactions, Models in WHIZARD

In the discussion of the implemented physics content in WHIZARD (2), we first start with the hard matrix elements, particle types, interaction types, Lorentz structures etc. The possible particle types in WHIZARD contain scalars, spin 1/2 fermions (both Dirac and Majorana) together with fermion-number violating vertices following the rules in [21, 22], spin 1 particles (both massless and massive, in unitarity and Feynman gauge as well as in principle for arbitrary R_ξ gauges), spin 3/2 particles (only as Majorana particles in their incarnation as gravitinos), as well as spin 2 particles (massless and massive). Particles could be dynamic (i.e. propagating particles) or pure insertions. The latter can e.g. be used as spurion fields in operator insertions. There are also unphysical particles for testing purposes inside Ward- and Slavnoy-Taylor identities (see e.g. [23, 24]). Note that for all the particle types there are routines that add up to a large test suite, testing (especially numerically) equations of motion, transversality, irreducibility of the on-shell fields as well as e.g. Majorana proerties of different vertices.

For the vertices, there is a huge list of Lorentz structures that are supported by WHIZARD ranging from purely scalar couplings over scalar-vector couplings (incl. dimension 5 operators), pure vector couplings, fermionic couplings to scalars, to vectors, to tensors as well as dimension 5 and 6 operators that appear e.g. in the context of supersymmetric Ward identities), as well as gravitino couplings of dimensions 5 and 6. Completely general Lorentz structures that will allow an automatic generation of a library with the corresponding Fortran routines is under construction, and will presumably be ready by the end of the year.

Color flows in WHIZARD are generated in the color flow formalism [25, 26]. While in the legacy version WHIZARD 1.9x this was done in a rather slow approach with the help of a PERL script, in WHIZARD 2 this was performed directly inside the core of O'Mega and finally even more refined as a colorizing of the Directed Acyclical Graph (DAG) as a representation of the colored amplitude [17]. Though in principle every $SU(N)$ gauge group is supported, we focus here on standard $SU(3)$ for QCD. At the moment, the fundamental and anti-fundamental representations are supported, the adjoint representation, which already covers all standard particles in the SM, SUSY and extra-dimensional models. In preparation are generalized color structures including color sextets and decuplets as well as baryon-number violating vertices as in $\epsilon_{ijk}\phi_i\phi_j\phi_k$.

```
beams = p, p => lhapdf { $lhapdf_file = "cteq5l.LHgrid" }
beams = p, p => pdf_builtin {$pdf_builtin_set = "mstw2008nlo"}
beams = e1, E1 => circe1 => isr
beams = A, A => circe2 { $circe2_file = "teslagg_500.circe" }
beams = e1, E1
     => beam_events { $beam_events_file = "uniform_spread_2.5%.dat" }
beams = e1, E1 => user_strfun ("escan"), none
```

Figure 4: Structured beams in WHIZARD 2 as they appear in SINDARIN commands.

These color structures are foreseen to be made public in late 2012.

Concerning structured beams, the complete setup for beam structure relevant for lepton colliders from WHIZARD 1 have been taken over in or re-implemented for WHIZARD 2, while the support for structured beams for hadron colliders has been much enlarged and modernized. Examples for structured beams as SINDARIN commands are shown in Fig. 4 [1]. For lepton colliders, initial state radiation (ISR) is implemented according to the calculations presented in [28, 29] which contains the resummed results for soft-collinear photon from [30, 31] together with the explicit calculation of hard-collinear photons up to third order in perturbation theory. WHIZARD can also generate explicity the p_T distribution of the photons in the event as well as of the electron beam remnants from the ISR recoil.

Polarized beams are supported, where it is possible to specify arbitrary polarization states (not only linear or circular polarization modes) by using an explicit spin density matrix as input. Beamstrahlung, i.e. the deformation of the beam spectrum due to macrosopic (classical) electromagnetic interactions can be simulated via the CIRCE module [12], while photon collider spectra from Compton back scattering are contained in the CIRCE2 generator within the WHIZARD package. External beam spectra which are basically long lists of energy ratio (or explicit energy) values can be read in, or user-defined code can be included, compiled and linked in the dynamic setup of WHIZARD 2 at runtime. What is at the moment not (yet) implemented is electromagnetic final state radiation (FSR) using a Yennie-Frautschi-Suura approach [32].

Concerning hadronic beam environments, the support for PDFLIB inside CERNLIB for PDFs has been abandoned in WHIZARD 2. Like WHIZARD 1, WHIZARD 2 now exclusively contains an interface to the LHAPDF external library [33] supporting in principle all (modern) PDF sets, including photon PDF and pion PDFs. To be independent from installing LHAPDF and linking it into WHIZARD, the most prominent and recent PDF sets have been directly included into WHIZARD together with the routines for the running strong coupling from the PDF collaborations. Hadronization as well as hadronic events can be simulated through PYTHIA [11] which ships with the main WHIZARD distribution. Of course, it also possible to write out parton level events into some event file, read them in into a different hadronization program and then read the hadronic event file back into WHIZARD for an analysis.

2.4 Parton Shower

Parton showering can be done as in WHIZARD 1 with an external program that is either linked to WHIZARD or via the pipe over an external event file that is to be converted from partonic to hadron level. In WHIZARD 2, the latest Fortran version of PYTHIA [11] is included in the distribution tarball, so parton showering via PYTHIA (like hadronzation and hadronic decays) can be directly steered from the SINDARIN input file. In WHIZARD 2, there are now two homebrew parton showers, one along the lines of the PYTHIA parton shower as k_T-ordered shower including angular ordering, the other one an analytic parton shower. The details of this latter shower are described in full detail in [20] (also cf. references therein). Concerning the original analytic final state parton shower [34], several improvements have been made, like a running scale of the strong coupling constant and color coherence by imposing angular ordering. A comparison to experimental results from the LEP collaborations have been made, cf. Fig. 5. The main new feature, however, is the analytic initial state shower, which is the main part of [20]. There, an automatic MLM-type matching procedure [35] has been implemented to smoothly connect high-p_T tails of jet distributions e.g. in

[1] For a complete overview of SINDARIN commands, cf. the WHIZARD manual [27].

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 K matrix	—	`SM_KM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PSSSM`
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`
SUSY Xdim. (inoff.)	—	`SED`
SM with Z'	—	`Zprime`
SM with gravitino and photino	—	`GravTest`
Augmentable SM template	—	`Template`

Table 1: List of implemented BSM models in WHIZARD.

Drell-Yan processes with the low-p_T regime. As this is a workshop on linear collider, I do not go into the details of the initial state shower, which has been compared to Tevatron and LHC data in [20], here.

2.5 Models and BSM physics

Coming back to hard matrix elements, many BSM models have been implemented in WHIZARD and used for LHC and ILC simulations, and most of them have been validated with the help of the FeynRules interface of WHIZARD. Among these are, first of all, SUSY models [36, 37] have been implemented, the MSSM together with implementations of non-minimal models like the NMSSM [38] or extended SUSY models [39, 40, 41]. Already in WHIZARD 1 existed an interface to other codes following the SUSY Les Houches Accord (SLHA 1/2) [42, 43, 44]. Also some pioneering work on the combination of SUSY NLO matrix elements with the electromagnetic showers have been done [46, 45]. A second focus lay on Little Higgs models (with and without T-parity), again with several studies for linear collider physics [47, 48]. On the more exotic side, models based on noncommutative spacetime have been studied with WHIZARD [49, 50, 51]. One of the original motivations was the study on a strongly interacting sector of electroweak symmetry breaking, which has been pursued in WHIZARD 2 both along the lines of anomalous couplings [52] as well as in terms of new resonances in the electroweak sector [53]. For the unitarization of these channels, a method had to be found to distinguish in the framework of the DAGs of the matrix element generation s- from t-/u-like channels.

Table 1 gives a list of all the models that are implemented. For implementing a new model, it is highly recommended that this is done via the WHIZARD-FeynRules interface [18].

2.6 NLO development in WHIZARD

There has been some work on the inclusion of (virtual) NLO corrections into WHIZARD mentioned in the previous paragraph in the context of SUSY studies at the ILC. The goal of the more recent developments is to have a setup for NLO calculations and simulations within WHIZARD for both LHC and ILC physics that is as automated as possible. NLO calculations nowadays are mostly based on some sort of subtraction formalism, that groups the soft-collinear divergences into specific parts of the calculations to make them finite and performable for a phase-space integration. The most widely used is the Catani-Seymour dipole subtraction formalism [54, 55]. A first proof-of-principle implementation of the integrated and unintegrated dipoles have been done in [56, 57]. An automated generation of the CS dipoles is in construction at the moment, but already gives correct results for QED processes. Along with the dipoles comes an implementation of using several instances of the process setup within the phase space integration, which is necessary for the unintegrated dipoles in order to take care of the squeezed kinematics in the phase space integration of the subtraction terms. The implementation will be made public several steps (together with a BLHA interface [58]) several steps from summer until the end of this year.

3 Summary and Outlook

WHIZARD 2 is a completely newly structured update of an already versatile multi-purpose Monte Carlo event generator that has been released with many new technical and physics features in April 2010. Many further improvements and features have been added in the past two years. Though the main motivation for the restructuring of the code was to deal with the complexities of LHC physics, linear collider physics has always been a major field of application for WHIZARD. Quite recently, all relevant features regarding ILC/CLIC physics from WHIZARD 1 have been reimplemented in WHIZARD 2, and many improvements on the phase space setup, color, parton shower, BSM models, speed and performance, maintenance and usability have been made. Continuos effort will go specifically into the direction of multi-leg amplitudes, NLO development and more BSM coverage to be ready for the high-energy phase of LHC and a possible future linear collider.

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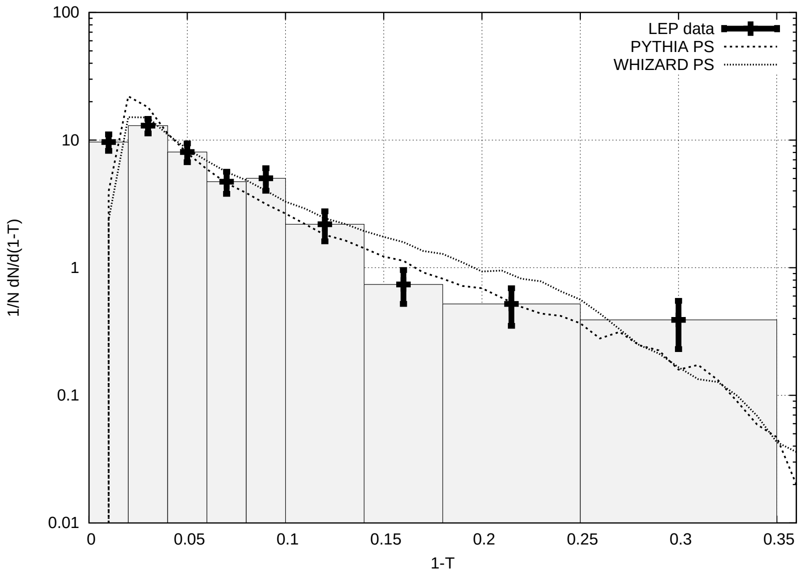

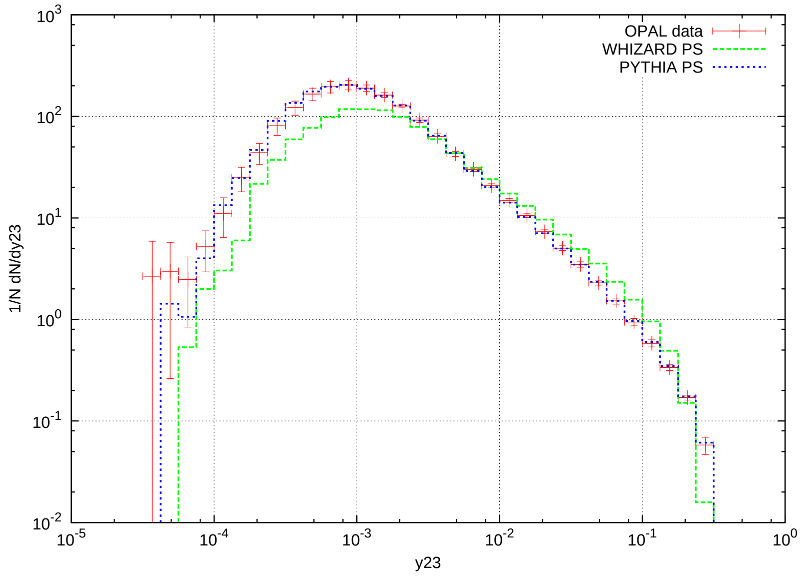

Figure 5: Validation of the analytic final state shower in WHIZARD: On top the thrust distribution in $e^+e^- \to$ jets, where the grey histograms with error bars are the data, the dashed line is PYTHIA, the dotted WHIZARD, on the bottom the Y_{23} parameter which shows the value of the jet definition parameter at which a two-jet event starts to be resolved as a three-jet event (in red [error bars] OPAL data, the green curve shows WHIZARD, while the blue one os PYTHIA). For more details cf. [20].

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