Status report on WHIZARD

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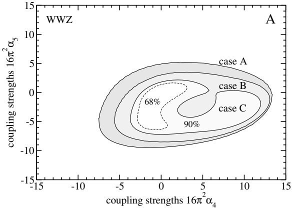
DESY Hamburg

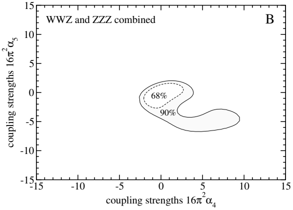
LC Forum 2012, DESY, Hamburg, 8. Febr. 2012

The WHIZARD Event Generator: ILC Tool

- E.g.: Determination for anomalous quartic couplings

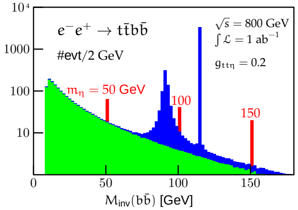
Beyer et al., 07

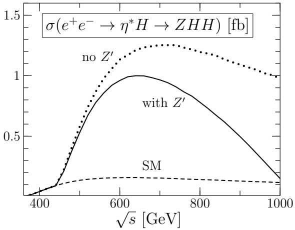




- New physics: Little Higgs models

Kilian/JRR/Rainwater, 04-06





- Mass production for ILC (SLAC sample) and new sample(s)

T. Barklow

CERN/DESY/KEK/SLAC

The WHIZARD Event Generator – Release 2.0.x

- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
- Fast Multi-Channel Monte-Carlo integration
- Very efficient phase space and event generation
- Optimized matrix elements — Very high level of Complexity:
  - $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
  - $e^+e^- \to ZHH \to ZWWWW \to bb + 8j$ (12,000,000 diagrams)
  - $pp \to \ell\ell + nj,\ n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
  - $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
  - $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
  - Test case $gg \to 9g$ (224,000,000 diagrams)

WHIZARD 2.0.0 release: 2010, April, 12th

Old series: WHIZARD 1.97 (development stopped with 1.94)

The WHIZARD team: F. Bach, H.-W. Boschmann, [F. Braam], W. Kilian, T. Ohl, JRR, S. Schmidt, C. Speckner, [M. Trudewind], D. Wiesler, [T. Wirtz]

Web address: `http://projects.hepforge.org/whizard`
`http://whizard.event-generator.org`

Standard Reference for all versions: Kilian/Ohl/JRR, 0708.4233

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WHIZARD 2.0.6 release: 2011, Dec., 12th

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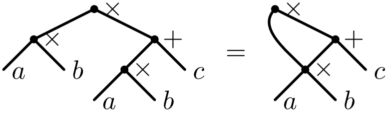
O'Mega: Optimal matrix elements

Ohl/JRR, 2001 Ω

- [·.] Replace forest of tree diagrams by
  Directed Acyclical Graph (DAG) of the algebraic expression.

$ab(ab+c) =$



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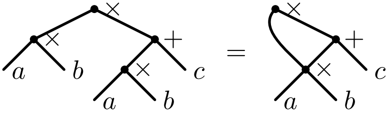

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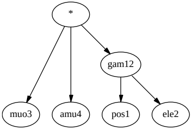

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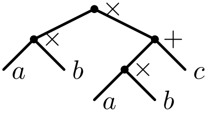
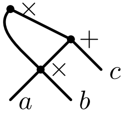
$ab(ab+c) =$  $=$ 

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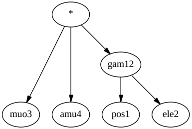

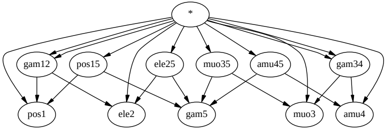

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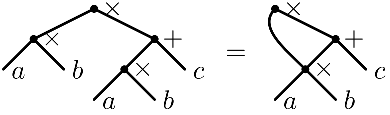

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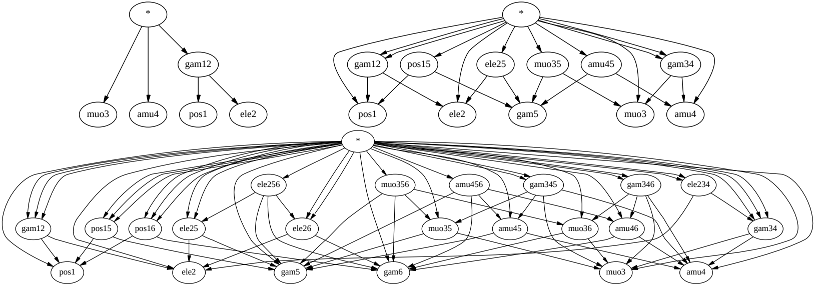

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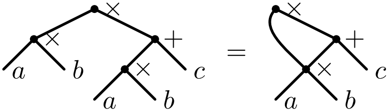

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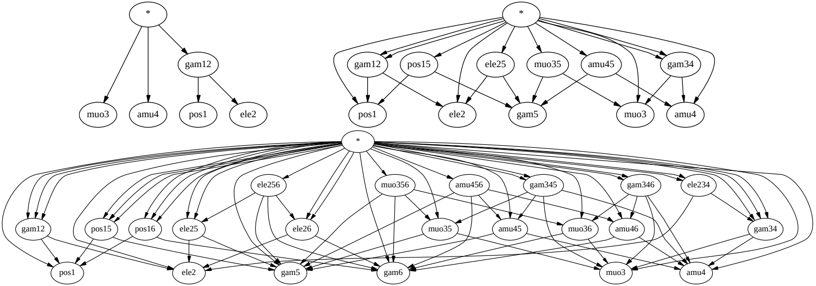


- **NEW:** Colorized DAGs: color flow decomposition inside DAG structure, much faster code generation (being prepared for flavor sums as well)

What's new? – Technical Features

- WHIZARD 2 basically rewritten: 60,000 lines of new code!!!
- Streamlining of code: only languages `O'Caml` for O'Mega and `Fortran 2003` (all system calls from Fortran)
- Standardization by usage of `autotools`: `automake/autoconf/libtool`
  $\Rightarrow$ easier control of distributions, regressions etc.
- Version control (`svn`) at HepForge: use of ticket system and bug tracker
- Very clean modularization by using object-orientation
- WHIZARD as a shared library:
  - No core re-compilation when changing processes!!
  - Dynamical inclusion of new processes
  - Old static option still available
- Splitting amplitudes speeds up over-eager compilers
- OpenMP parallelization
- WHIZARD works as a Shell – WHISH
- Large test-suite for compatibility, sanity and regression checks
- Cruise control system for regression tests
- WHIZARD part of QA of gfortran, Intel, Portland, NAG compilers!!!

WHIZARD 2 – Installation

- Download WHIZARD from `http://www.hepforge.org/archive/whizard/whizard-2.0.6.tar.gz` and unpack it
- WHIZARD intended to be centrally installed on a system, e.g. in `/usr/local`
- Create build directory, `configure`
  External programs (LHAPDF, StdHEP, HepMC) might need flags to be set
- `make`, `make install`
- Each user can work in his/her own home directory
- Extensive test-suite: `make check` (optional during installation) Numerics tests, vertex and wave function checks, Ward identities, compatibility of amplitudes, event generation, input scripts, PDFs, color correlation, cross sections etc. etc.

```
O'Mega self tests:
make  check-TESTS
PASS: test_omega95
PASS: test_omega95_bispinors
PASS: test_qed_eemm
PASS: ects
PASS: ward
PASS: compare_split_function
PASS: compare_split_module
==================
All 7 tests passed
==================
WHIZARD self tests:
make  check-am
make  check-TESTS
PASS: empty.run
PASS: vars.run
PASS: md5.run
[..........]
XFAIL: errors.run
PASS: extpar.run
PASS: susyhit.run
PASS: libs.run
PASS: qedtest.run
PASS: helicity.run
PASS: smtest.run
PASS: defaultcuts.run
PASS: restrictions.run
PASS: decays.run
PASS: alphas.run
PASS: colors.run
PASS: cuts.run
PASS: lhapdf.run
PASS: ilc.run
PASS: mssmtest.run
PASS: models.run
PASS: stdhep.run
PASS: stdhep_up.run
====================================
All 53 tests behaved as expected (1 e
====================================
```

What's new? – Physics/performance features

- Phase space improvement: performance gain through symmetrized PS forest construction
- New modular structure: event-dependent scales in PDFs and running α_s
- One single input file steers process generation, integration, event generation, analysis [inclusions possible]
- SINDARIN (Scripting INtegration, Data Analysis, Results display and INterfaces) allows for arbitrary expressions for cuts and scales etc. (examples later)

```
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]]]
```

- Process libraries: processes of different BSM models can be used in parallel
- Decay cascades including full spin correlations (cf. later)
- Inclusive decays
- Much improved flavor sums initial + final state (e.g. jet = quark:gluon)
- `FeynRules` interface Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
- MLM jet matching
- Parton Shower: p_T-ordered and analytic Kilian/JRR/Schmidt/Wiesler, 1112.1039
- Improved MD5 checksums allow reusing every single bit in a safe way
- Improved graphical analysis package

WHIZARD – Overview over BSM 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 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

easy to implement new models: FeynRules interface

Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251

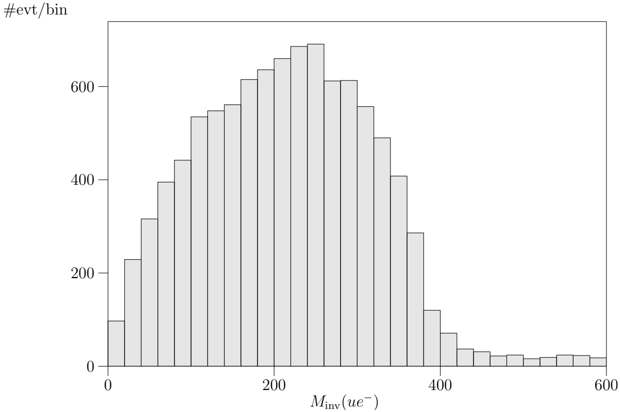
Example: SUSY cascade decays, Input File

```
model = MSSM

process dec_su_q = su1 => u, neu2
process dec_neu_sl2  = neu2 => SE12, e1

process susybg = e1, E1 => SU1, su1
process full = e1, E1 => SU1, u, e1, SE12

compile

?slha_read_decays = true
read_slha("sps1ap_decays.slha")

integrate (dec_su_q, dec_neu_sl2) { iterations = 1:1000 }

sqrts = 3 TeV
beams = e1, E1 => isr

integrate (susybg) { iterations = 5:10000, 2:10000 }
integrate (full)

n_events = 10000

$title = "Full process"
$description =
  "$e^- e^+ \to u+ \bar u \to \bar{\tilde u}_1 + u + \tilde e_{12}^+ + e^-$"
$xlabel = "$M_{\rm inv}(ue^-)$"
histogram inv_mass1_full (0,600,20)

simulate (full) {
  $sample = "casc_dec_full"
  analysis =
    record inv_mass1_full (eval M / 1 GeV [combine[u,e1]])
}

$analysis_filename = "casc_dec"
compile_analysis
```

Example: SUSY cascade decays

$$e^- e^+ \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

- **Full process:**



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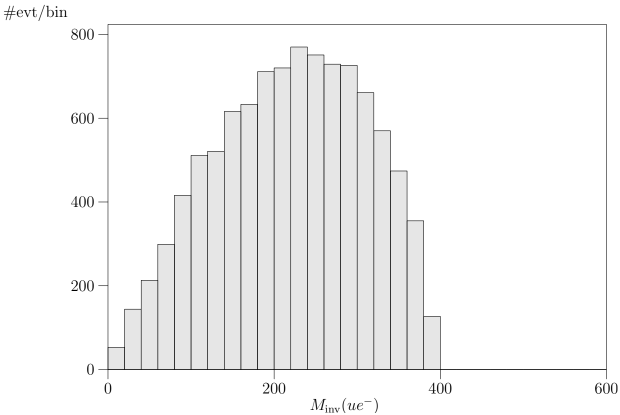
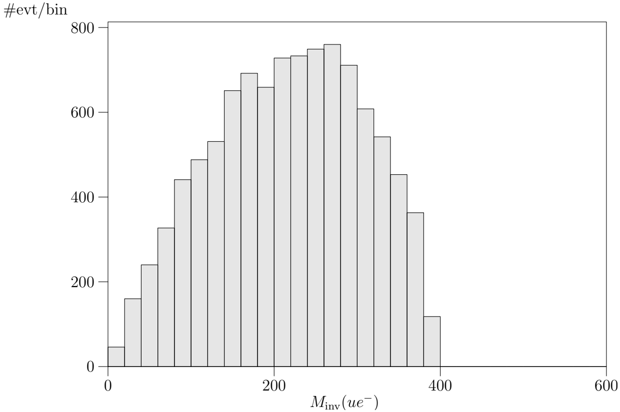
- **Factorized process w/ full spin correlations:**



Example: SUSY cascade decays

$$e^- e^+ \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

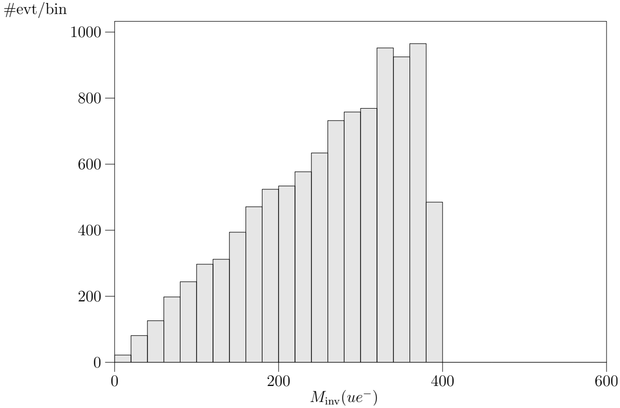
- **Factorized process w/ classical spin correlations:**



Example: SUSY cascade decays

$$e^- e^+ \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

- **Factorized process w/ no spin correlations:**



Structured Beams

- **Hadron Colliders structured beams**
  - LHAPDF interface
  - CERN-/PDFLIB support no longer available
  - Most prominent PDFs directly included
  - ISR and FSR (two different own implementations, interface to PYTHIA)
  - Matching matrix elements/showers (MLM)
- **Lepton Colliders structured beams**
  - ISR (implemented: Skrzypek/Jadach, Kuraev/Fadin, incl. p_T distributions)
  - arbitrarily polarized beams (density matrices)
  - Beamstrahlung (CIRCE module)
  - Photon collider spectra (CIRCE2 module)
  - external beam spectra can be read in (files/generating code)
  - FSR (e.g. YFS) not (yet) implemented (charged mesons/hadrons)
- **Hadronic events/hadronic decays**
  - through PYTHIA interface (or HERWIG or Sherpa)

Hard matrix elements: particle types

Possible particle types

- Spin 0 particles
- Spin 1/2 fermions (Majorana and Dirac)
  Fermi statistics for both fermion-number conserving and violating cases
- Spin 1 particles
  - massive and massless
  - Unitarity and Feynman gauge
  - arbitrary R_ξ gauges
- Spin 3/2 particles (Majorana only, gravitinos)
- Spin 2 particles (massless and massive, gravitons)
- Dynamic particles vs. pure insertions
- Unphysical particles for Ward- and Slavnov-Taylor identities

Gravitinos in WHIZARD

JRR, PhD

```
*** Checking polarization vectorspinors: ***
p.ueps ( 2)= 0: passed at   86%
p.ueps ( 1)= 0: passed at   86%
.....
*** Checking the irreducibility condition: ***
g.ueps ( 2): passed at   95%
.....
g.ueps (-2): passed at   95%
g.veps ( 2): passed at   95%
.....
g.veps (-2): passed at   95%
*** Testing vectorspinor normalization ***
ueps( 2).ueps( 2)= -2m: passed at  100%
ueps( 1).ueps( 1)= -2m: passed at  100%
.....
*** Majorana properties of gravitino vertices: ***
f_sgr     + gr_sf     = 0: passed at   84%
slr_grf   + slr_fgr   = 0: passed at   88%
.....
v2lr_fgr  + v2lr_grf  = 0: passed at   77% [expected  0.000E+00, got  0.633E-12]
*** Testing the gravitino propagator: ***
Transversality:
p.pr.test: passed at   66% [expected  0.000E+00, got  0.437E-10]
p.pr.ueps ( 2): passed at   86%
.....
p.pr.ueps (-2): passed at   86%
p.pr.veps ( 2): passed at   79% [expected  0.000E+00, got  0.342E-12]
.....
p.pr.veps (-2): passed at   79% [expected  0.000E+00, got  0.342E-12]
Irreducibility:
g.pr.test: passed at   78% [expected  0.000E+00, got  0.471E-12]
g.pr.ueps ( 2): passed at   92%
......
g.pr.veps (-2): passed at   87%
```

Hard matrix elements: Lorentz structures

Hard-coded set of Lorentz structures

- Purely scalar couplings:
  $\phi^3, \quad \phi^4$
- Scalar couplings to vectors:
  $g V^\mu \phi_1 \mathrm{i}\overleftrightarrow{\partial_\mu} \phi_2, \quad \phi V^2, \quad \phi^2 V^2, \quad \frac{1}{2}\phi F_{1,\mu\nu} F_2^{\mu\nu}, \quad \frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu}, \quad \phi(\mathrm{i}\partial_\mu V_1^\nu)(\mathrm{i}\partial_\nu V_2^\mu)$
- Pure vector couplings:
  $F_{\mu\nu}F^{\mu\nu}, \quad V_1^\mu((\mathrm{i}\partial_\nu V_2^\rho)\mathrm{i}\overleftrightarrow{\partial_\mu}(\mathrm{i}\partial_\rho V_3^\nu)), \quad g F_1^{\mu\nu} F_{2,\nu\rho} F_{3,}{}^{\rho}{}_{\mu},$
  $g/2 \cdot \epsilon^{\mu\nu\lambda\tau} F_{1,\mu\nu} F_{2,\tau\rho} F_{3,}{}^{\rho}{}_{\lambda}$
- Fermionic couplings to scalars:
  $g_S \bar\psi_1 S \psi_2, \quad g_P \bar\psi_1 P \gamma_5 \psi_2, \quad \bar\psi_1 \phi (g_S + g_P\gamma_5)\psi_2, \quad g_L \bar\psi_1 \phi (1-\gamma_5)\psi_2,$
  $g_R \bar\psi_1 \phi (1+\gamma_5)\psi_2, \quad g_L \bar\psi_1 \phi(1-\gamma_5)\psi_2 + g_R\bar\psi_1\phi(1+\gamma_5)\psi_2$
- Fermionic couplings to vectors:
  $g_V \bar\psi_1 \not{V} \psi_2, \quad g_A \bar\psi_1 \gamma_5 \not{V}\psi_2, \quad \bar\psi_1 \not{V}(g_V - g_A\gamma_5)\psi_2, \quad g_L\bar\psi_1\not{V}(1-\gamma_5)\psi_2,$
  $g_R\bar\psi_1\not{V}(1+\gamma_5)\psi_2, \quad g_L\bar\psi_1\not{V}(1-\gamma_5)\psi_2 + g_R\bar\psi_1\not{V}(1+\gamma_5)\psi_2$

- Fermionic couplings in SUSY Ward identities (not listed here)
- Fermionic couplings to tensors:
  $g_T T_{\mu\nu}\bar\psi_1[\gamma^\mu,\gamma^\nu]_-\psi_2$
- Tensor couplings to vectors:
  $T^{\mu\nu}(V_{1,\mu}V_{2,\nu}+V_{1,\nu}V_{2,\mu}), \quad T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta V_{2,\mu},$
  $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\beta(\mathrm{i}\partial_\mu V_{2,\alpha})+V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha(\mathrm{i}\partial_\mu V_{2,\beta}))\,, \quad T^{\alpha\beta}((\mathrm{i}\partial^\mu V_1^\nu)\mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta(\mathrm{i}\partial_\nu V_{2,\mu}))$
- Gravitino couplings:
  $\bar\psi\gamma^\mu S\psi_\mu, \quad \bar\psi\gamma^\mu \not{k}_S S\psi_\mu, \quad \bar\psi\gamma^\mu\gamma^5 P\not{k}_P\psi_\mu, \quad \bar\psi\gamma^5\gamma^\mu[\not{k}_V,\not{V}]\psi_\mu$ etc.

  and many more to fill your advent calendar.....

- Completely general Lorentz structures:
  foreseen end of this year, v2.1.x

Hard matrix elements: Color structures

Possible Color structures

- In principle all $SU(N)$ gauge theories supported, but specialize to $N = 3$
- Color flow formalism

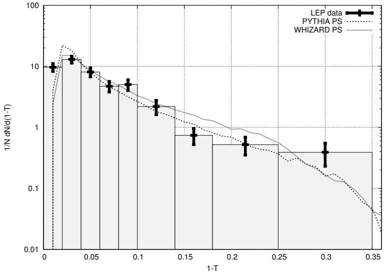
  Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 1202.xxxx
- Fundamental representations: $\mathbf{3}, \overline{\mathbf{3}}$
- Adjoint representation: $\mathbf{8}$
- Covers all interactions e.g. in SUSY and extra dimensions
- in preparation: generalized color structures with representations $\mathbf{6}, \overline{\mathbf{6}}$, $\mathbf{10}, \overline{\mathbf{10}}$

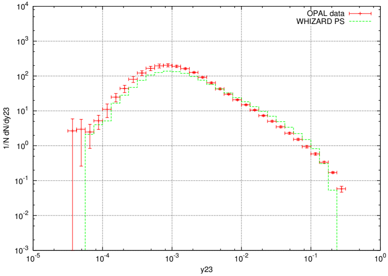
  as well as $\epsilon_{ijk}\phi_i\phi_j\phi_k$ couplings end of this year (v2.1.x)

Analytic Parton Shower

JRR/Schmidt/Wiesler, JHEP 2012

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate
- new algorithm for initial state radiation



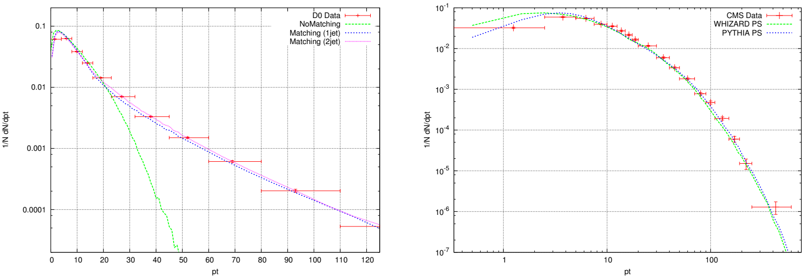


- matching with hard matrix elements, no "power-shower"
- Connecting with multiple interactions: Boschmann/Kilian/JRR/Schmidt, 2012

Analytic Parton Shower

JRR/Schmidt/Wiesler, JHEP 2012

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate
- new algorithm for initial state radiation



- matching with hard matrix elements, no "power-shower"
- Connecting with multiple interactions: Boschmann/Kilian/JRR/Schmidt, 2012

Status of NLO development in WHIZARD

- BLHA interface: workflow Speckner, 2012 :
  1. Process definition in SINDARIN $\Rightarrow$ WHIZARD writes contract file
  2. NLO generator generates code, WHIZARD reads contract
  3. NLO matrix element loaded as shared library
- First implementation: interfacing GoSAM and FeynArts
- Automatic generation of dipole subtraction terms JRR/Speckner, 2012
  - integrated dipoles (QED and QCD)
    done and tested
  - unintegrated dipoles (QED and QCD)
    needs next-to-little new structure of integration core

First example: $u\bar{u} \to \mu^- \bar{\nu}_\mu e^+ \nu_e$

Input:

```
real mreg = 1 GeV

process test = u, ubar => "mu-", numubar, "e+", nue {
   $method = "dipole_integrated_qed"
   soft_mass_regulator = mreg
   collinear_mass_regulators = mreg, mreg, mreg, 0, mreg, 0
}

me = 0
mmu = 0
alpha_qed = 1.  / alpha_em_i

sqrts = 500 GeV

integrate (test) {iterations = 5:10000, 5:20000}
```

Result:

```
| Integrating process 'test':
|=============================================================================|
| It      Calls   Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|=============================================================================|
  10     100000  1.9794090E+00  3.16E-03    0.16    0.50   12.33    0.12   5
|=============================================================================|
```

WHIZARD 2.1 – Outlook

- Major upgrade late 2012: WHIZARD 2.1.0
- Lots of internal technical improvement and tuning
- Arbitrary Lorentz structures (beware of color!)
- Generalized color structures
- Automatic integration of decays
- Much improved (analytical) helicity selection rules
- Parton shower (officially released; by S. Schmidt)
- $\Rightarrow$ CKKW(-L) mixing inside WHIZARD
- Underlying event (by H.-W. Boschmann)
- NLO interface (BLHA); automatic generation of dipole subtraction

Summary / Outlook

- WHIZARD 2 released

Ready for the 2012 ”decisive year”

- Huge improve-/enhancement of versatile, successful tool
- Focus on BSM physics
- Steered via the HepForge page:
  `http://projects.hepforge.org/whizard`
- After release: rapidly approached design performance

Thanks to all contributors (list is not exhaustive!)

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as usual: **we’re open to users wish list!**

Continuos Upgrades Next Year

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