Status report on WHIZARD

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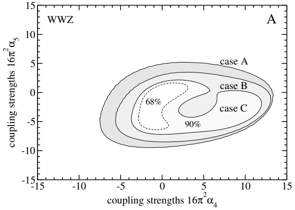
DESY Hamburg

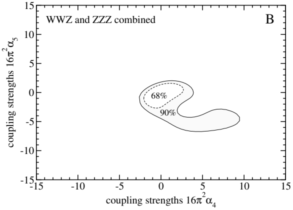
LC Forum 2012, DESY, Hamburg, 8. Febr. 2012

The WHIZARD Event Generator: ILC Tool

- E.g.: Determination for anomalous quartic couplings

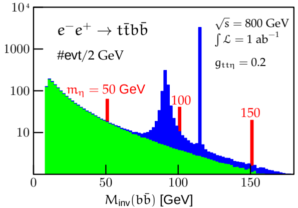
Beyer et al., 07

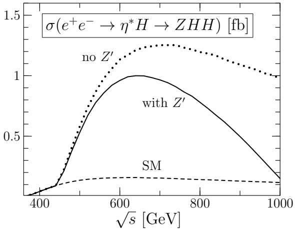




- New physics: Little Higgs models

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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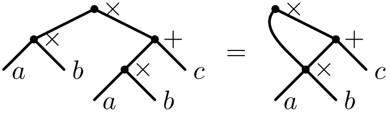
O'Mega: Optimal matrix elements

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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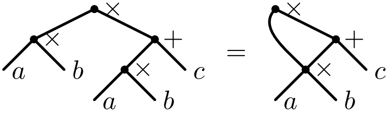
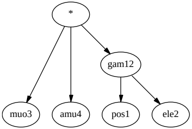
$ab(ab+c) =$ 

- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



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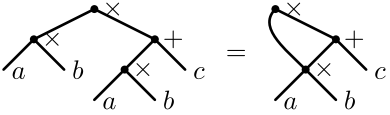
$ab(ab + c) =$ 

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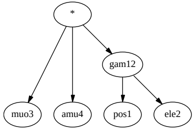

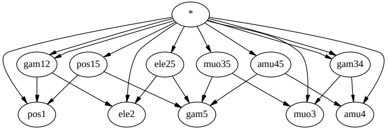

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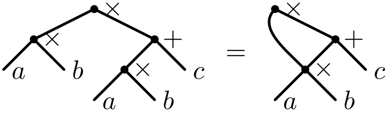

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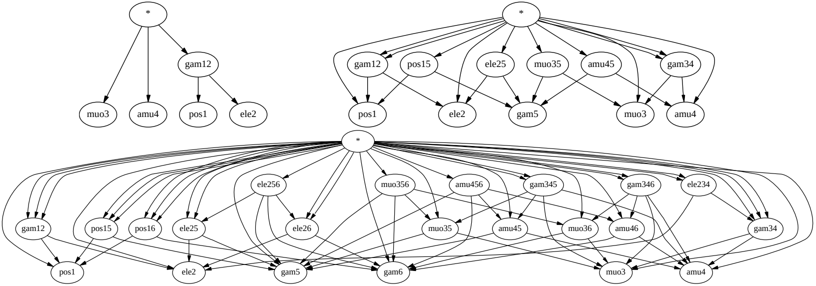

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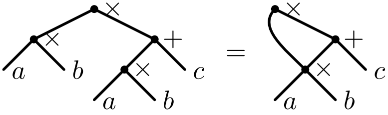

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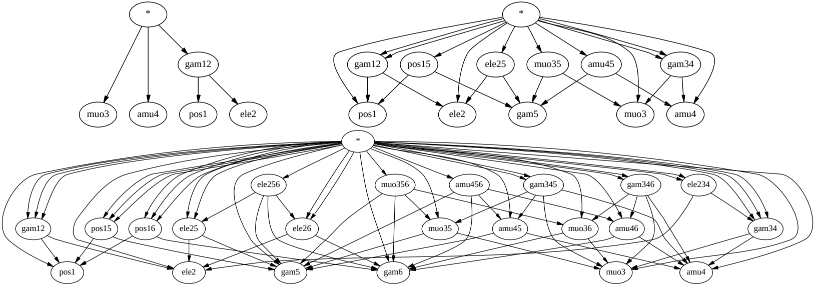


- **NEW:** Colorized DAGs: color flow decomposition inside DAG structure, much faster code generation (being prepared for flavor sums as well)

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

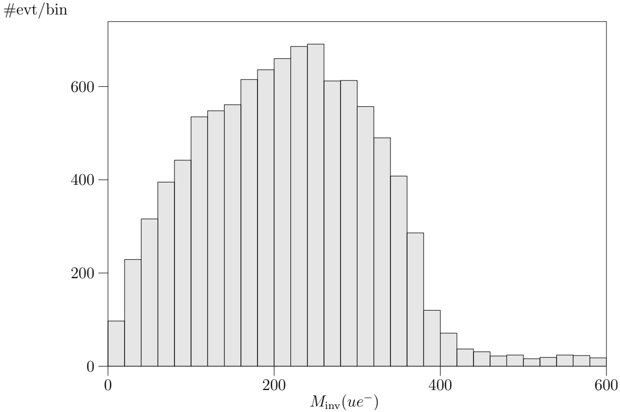
Example: SUSY cascade decays, Input File

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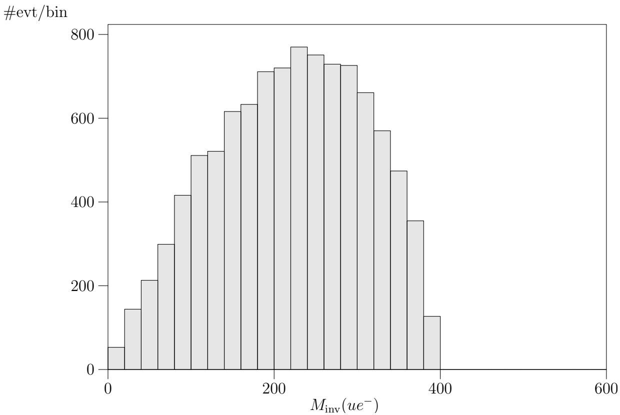
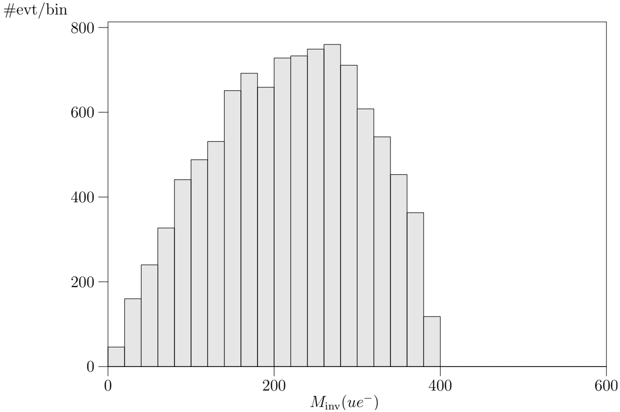
- **Factorized process w/ full spin correlations:**



Example: SUSY cascade decays

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

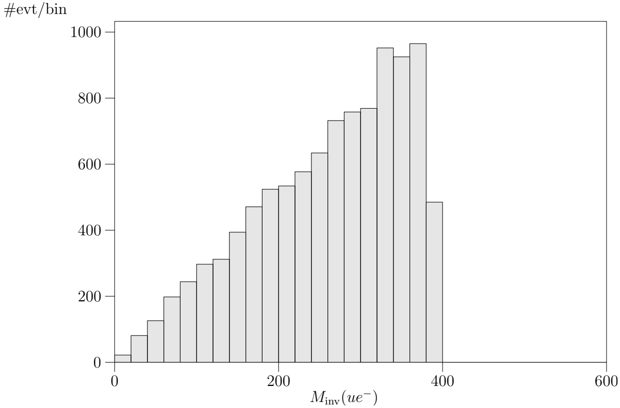
- **Factorized process w/ classical spin correlations:**



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:
  $T^{\mu\nu}(V_{1,\mu} V_{2,\nu} + V_{1,\nu} V_{2,\mu})$, $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta V_{2,\mu}$,
  $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\beta(\mathrm{i}\partial_\mu V_{2,\alpha}) + V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha(\mathrm{i}\partial_\mu V_{2,\beta}))$, $T^{\alpha\beta}((\mathrm{i}\partial^\mu V_1^\nu)\mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta(\mathrm{i}\partial_\nu V_{2,\mu}))$
- Gravitino couplings:
  $\bar{\psi}\gamma^\mu S\psi_\mu$, $\bar{\psi}\gamma^\mu \not{k}_S S\psi_\mu$, $\bar{\psi}\gamma^\mu\gamma^5 P\not{k}_P\psi_\mu$, $\bar{\psi}\gamma^5\gamma^\mu[\not{k}_V, \not{V}]\psi_\mu$ 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

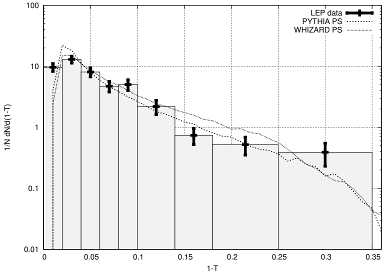
Possible Color structures

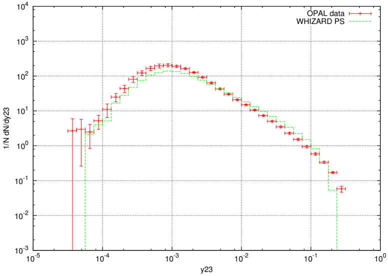
- In principle all $SU(N)$ gauge theories supported, but specialize to $N = 3$
- Color flow formalism
  Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 1202.xxxx
- Fundamental representations: $\mathbf{3}, \overline{\mathbf{3}}$
- Adjoint representation: $\mathbf{8}$
- Covers all interactions e.g. 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

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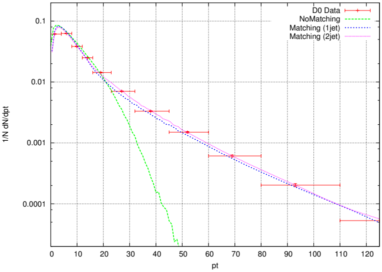
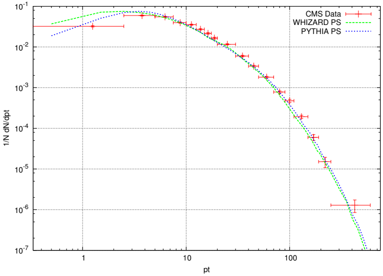
  - allows reweighting and maybe more reliable error estimate
- new algorithm for initial state radiation





- 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 ⇒ 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!)

T. Barklow, P. Bechtle, M. Berggren, M. Beyer, F. Braam, R. Chierici, K. Desch, T. Kleinschmidt, M. Mertens, N. Meyer, K. Mönig, M. Moretti, H. Reuter,

T. Robens, K. Rolbiecki, S. Rosati, A. Rosca, J. Schumacher, M. Schumacher, C. Schwinn

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

Continuos Upgrades Next Year

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