BSM in WHIZARD

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MC4BSM, Cornell, Ithaca, N.Y., 22. March 2012

The WHIZARD Event Generator – Release 2.0.x

- 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

Standard Reference: Kilian/Ohl/JRR, EPJC 71 (2011) 1742, arXive:0708.4233

- Major upgrade this year/summer: WHIZARD 2.1.0

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WHIZARD 2.0.7 release: 2012, March, 19th

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]

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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
=====================================
```

WHIZARD Manual

whizard.hepforge.org/manual/

Aktuelle Nachr... WHIZARD HEP – HEP arXiv.org e-Print... YouTube – Broa...

WHIZARD 2.0
A generic
Monte-Carlo integration and event generation package for multi-particle processes
MANUAL [1]

Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] Christian Speckner [5]

- Contents
- Introduction
  - Disclaimer
  - Overview
  - About examples in this manual
- Installation
  - Package Structure
  - Prerequisites
  - Installation
  - Working With WHIZARD
- Getting Started
  - Hello World
  - A Simple Calculation
- SINDARIN: Overview
  - The command language for WHIZARD
  - SINDARIN scripts
  - Errors
  - Statements

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, (to appear in EPJC)
- 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

Implemented Physics Content/Classification

- **Hard Matrix Elements**
  - Multiplicities, technical details, performance
  - Particles, Lorentz structures and interactions
  - Color structures
  - Flavor structures
  - Higher-order matrix elements
  - Special features: non-standard stuff
  - Supported models
- **Structured beams**
  - Structure functions for lepton and hadron colliders/beam spectra
  - Beam radiation/beamstrahlung
  - Multiple interactions/underlying event
  - ”Full” events/hadronization etc.
- **Analysis setup**
  - Cuts, event formats, data analyses, interfacing....
- **Validation!!!**

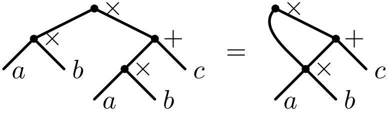
Structured Beams

- **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)
  - Underlying event/multiple interactions
- **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)

O'Mega: Optimal matrix elements

Ohl/JRR, 2001 Ω

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

$ab(ab+c) =$ 

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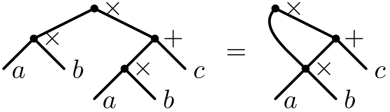
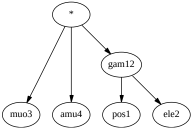


- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



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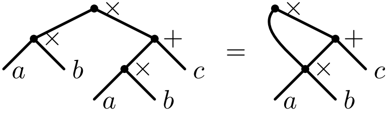
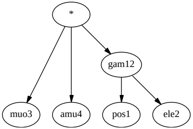
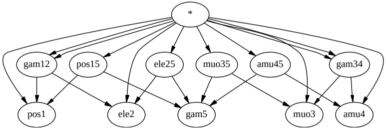


- simplest examples: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and





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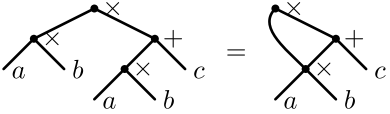

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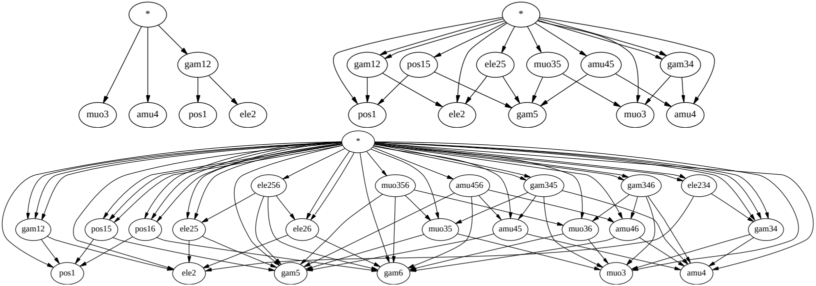

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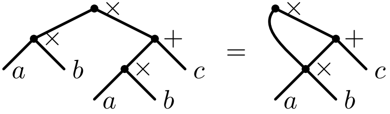

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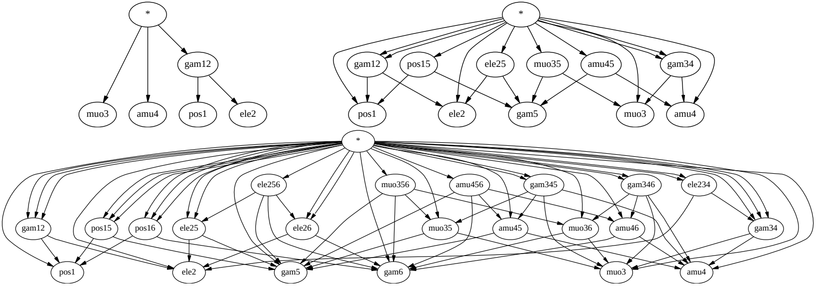


- **NEW:** Colorized DAGs: color flow decomposition inside DAG structure, much faster code generation (being prepared for flavor sums as well)

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, 2002

```
*** 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%
```

Gravitons in WHIZARD

Ohl, 2001

```
 *** Checking polarisation tensors: ***
 e2( 2).e2( 2)=1: passed at  100%
 e2( 2).e2(-2)=0: passed at  100%
 e2(-2).e2( 2)=0: passed at  100%
 e2(-2).e2(-2)=1: passed at  100%
 e2( 2).e2( 1)=0: passed at  100%
 e2( 2).e2( 0)=0: passed at  100%
 e2( 2).e2(-1)=0: passed at  100%
 e2( 1).e2( 2)=0: passed at  100%
 e2( 1).e2( 1)=1: passed at   95%
 e2( 1).e2( 0)=0: passed at   94%
 e2( 1).e2(-1)=0: passed at   95%
 e2( 1).e2(-2)=0: passed at  100%
 e2( 0).e2( 2)=0: passed at  100%
 e2( 0).e2( 1)=0: passed at   94%
.....
  |p.e2( 2)|  =0: passed at   96%
    |e2( 2).p|=0: passed at   96%
  |p.e2(-2)|  =0: passed at   96%
    |e2(-2).p|=0: passed at   96%
  |p.e2( 1)|  =0: passed at   88%
    |e2( 1).p|=0: passed at   88%
  |p.e2( 0)|  =0: passed at   84%
    |e2( 0).p|=0: passed at   84%
  |p.e2(-1)|  =0: passed at   88%
    |e2(-1).p|=0: passed at   88%
  *** Checking the graviton propagator:
 p.pr.e(-2): passed at   90%
 p.pr.e(-1): passed at   82%
 p.pr.e(0): passed at   82%
 p.pr.e(1): passed at   82%
 p.pr.e(2): passed at   90%
 p.pr.ttest: passed at   74% [expected  0.000E+00, got  0.210E-11]
```

Hard matrix elements: Lorentz structures

Hard-coded set of Lorentz structures

- Purely scalar couplings:
  $\phi^3, \quad \phi^4$
- Scalar couplings to vectors:
  $gV^\mu \phi_1 \mathrm{i}\overleftrightarrow{\partial_\mu}\phi_2, \quad \phi V^2, \quad \phi^2 V^2, \quad \frac{1}{2}\phi F_{1,\mu\nu}F_2^{\mu\nu}, \quad \frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu}, \quad \phi(\mathrm{i}\partial_\mu V_1^\nu)(\mathrm{i}\partial_\nu V_2^\mu)$
- Pure vector couplings:
  $F_{\mu\nu}F^{\mu\nu}, \quad V_1^\mu((\mathrm{i}\partial_\nu V_2^\rho)\mathrm{i}\overleftrightarrow{\partial_\mu}(\mathrm{i}\partial_\rho V_3^\nu)), \quad gF_1^{\mu\nu}F_{2,\nu\rho}F_{3,}{}^{\rho}{}_{\mu},$
  $g/2 \cdot \epsilon^{\mu\nu\lambda\tau}F_{1,\mu\nu}F_{2,\tau\rho}F_{3,}{}^{\rho}{}_{\lambda}$
- 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 for end of this year, v2.2.0

Hard matrix elements: Color structures

Possible Color structures

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

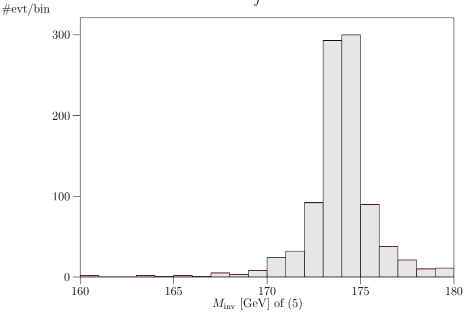
  Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
- Fundamental representations: $\mathbf{3}, \overline{\mathbf{3}}$
- Adjoint representation: $\mathbf{8}$
- Covers all interactions e.g. in SUSY and extra dimensions
- in preparation: generalized color structures with representations $\mathbf{6}, \overline{\mathbf{6}}$, $\mathbf{10}, \overline{\mathbf{10}}$
  as well as $\epsilon_{ijk}\phi_i\phi_j\phi_k$ couplings

WHIZARD histograms

WHIZARD data analysis March 16, 2007

Process: qqttdec ($u\bar{u} \to b\bar{b}W^+W^-$)

$\sqrt{s} = 500.0$ GeV $\int \mathcal{L} = 0.2754 \times 10^{-01}$ fb^{-1}



$\sigma_{\rm tot} = 36305. \pm 310.$ fb [±0.85 %] $n_{\rm evt,\ tot} = 1000$

$\sigma_{\rm cut} = 36305. \pm 0.115 \times 10^{+04}$ fb [±3.16 %] $n_{\rm evt,\ cut} = 1000$ [100.00 %]

New completely general syntax in WHIZARD 2.x

```
$title = "Jet Energy in $pp\to \ell\bar\nu j$"
$x_label = "$E$/GeV"
histogram e_jet (0 GeV, 80 GeV, 2 GeV)
analysis = record pt_lepton (eval Pt [extract index 1 [sort by Pt [lepton]]]);
           record pt_jet (eval Pt [extract index 1 [sort by Pt [jet]]]);
           record e_lepton (eval E [extract index 1 [sort by Pt [lepton]]]);
           record e_jet (eval E [extract index 1 [sort by Pt [jet]]])
```

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	—	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

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

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

Comparison for the NMSSM

Braam, Fuks, JRR, 0909.3059; 2012

Process	MG-FR	CH-FR	WO-ST	Comparison
tau+,tau->mu+,mu-	4.48997×10^{-3}	4.4892×10^{-3}	4.49068×10^{-3}	δ = 0.0330272 %
tau+,tau->tau+,tau-	7.52098×10^{2}	7.5179×10^{2}	7.59268×10^{2}	δ = 0.989717 %
tau+,tau->e+,e-	4.49207×10^{-3}	4.4892×10^{-3}	4.48806×10^{-3}	δ = 0.0893631 %
tau+,tau->ve,ve~	9.75351×10^{-4}	9.7635×10^{-4}	9.76355×10^{-4}	δ = 0.10288 %
tau+,tau->vm,vm~	9.7555×10^{-4}	9.7635×10^{-4}	9.76068×10^{-4}	δ = 0.0819325 %
tau+,tau->vt,vt~	5.35941×10^{1}	5.3592×10^{1}	5.36816×10^{1}	δ = 0.167014 %
tau+,tau->u,u~	7.12912×10^{-3}	7.1259×10^{-3}	7.12673×10^{-3}	δ = 0.0451506 %
tau+,tau->t,t~	7.11532×10^{-3}	7.1158×10^{-3}	7.10877×10^{-3}	δ = 0.0988431 %
tau+,tau->d,d~	3.61339×10^{-3}	3.6131×10^{-3}	3.61677×10^{-3}	δ = 0.101598 %
tau+,tau->b,b~	3.61069×10^{-3}	3.6139×10^{-3}	3.6143×10^{-3}	δ = 0.0997308 %
tau+,tau->W+,W-	1.90467×10^{-1}	1.9152×10^{-1}	1.91951×10^{-1}	δ = 0.776383 %
tau+,tau->Z,Z	1.02967×10^{-2}	1.0315×10^{-2}	1.03164×10^{-2}	δ = 0.191235 %
tau+,tau->Z,a	4.2117×10^{-2}	4.2129×10^{-2}	4.21696×10^{-2}	δ = 0.124826 %
tau+,tau->sl2-,sl2+	1.05047×10^{-3}	1.0504×10^{-3}	1.04972×10^{-3}	δ = 0.0713887 %
tau+,tau->sl5-,sl5+	1.17192×10^{-3}	1.172×10^{-3}	1.17143×10^{-3}	δ = 0.0487576 %
tau+,tau->sl4-,sl4+	1.17209×10^{-3}	1.1721×10^{-3}	1.17107×10^{-3}	δ = 0.0878297 %
tau+,tau->sl3-,sl3+	1.05015×10^{-3}	1.0503×10^{-3}	1.04997×10^{-3}	δ = 0.031815 %
tau+,tau->sl1-,sl1+	1.41851×10^{-2}	1.4178×10^{-2}	1.41878×10^{-2}	δ = 0.0689563 %
tau+,tau->sl6-,sl6+	1.39313×10^{-2}	1.3925×10^{-2}	1.39156×10^{-2}	δ = 0.112937 %
tau+,tau->sl6-,sl1+	1.5723×10^{-2}	1.5715×10^{-2}	1.56948×10^{-2}	δ = 0.179773 %
tau+,tau->sv3,sv3~	7.66119×10^{-2}	7.6632×10^{-2}	7.66407×10^{-2}	δ = 0.0376056 %
tau+,tau->sv2,sv2~	4.83808×10^{-4}	4.8377×10^{-4}	4.83538×10^{-4}	δ = 0.0557691 %
tau+,tau->sv1,sv1~	4.83818×10^{-4}	4.8377×10^{-4}	4.84209×10^{-4}	δ = 0.0906177 %
tau+,tau->su5,su5~	1.07924×10^{-3}	1.0791×10^{-3}	1.07879×10^{-3}	δ = 0.04155 %
tau+,tau->su2,su2~	1.63913×10^{-3}	1.6397×10^{-3}	1.63781×10^{-3}	δ = 0.115289 %
tau+,tau->su4,su4~	1.07887×10^{-3}	1.0791×10^{-3}	1.07862×10^{-3}	δ = 0.0441113 %
tau+,tau->su3,su3~	1.63962×10^{-3}	1.6397×10^{-3}	1.64002×10^{-3}	δ = 0.0249076 %
tau+,tau->su1,su1~	1.20597×10^{-3}	1.2063×10^{-3}	1.20707×10^{-3}	δ = 0.0912099 %
tau+,tau->su6,su6~	9.46274×10^{-4}	9.463×10^{-4}	9.46582×10^{-4}	δ = 0.0325208 %
tau+,tau->su1,su6~	2.78463×10^{-4}	2.7848×10^{-4}	2.78524×10^{-4}	δ = 0.0218196 %
tau+,tau->sd5,sd5~	1.1076×10^{-3}	1.1077×10^{-3}	1.10863×10^{-3}	δ = 0.0927793 %
tau+,tau->sd4,sd4~	1.10735×10^{-3}	1.1077×10^{-3}	1.10896×10^{-3}	δ = 0.144715 %
tau+,tau->sd6,sd6~	4.50337×10^{-4}	4.5034×10^{-4}	4.49875×10^{-4}	δ = 0.103213 %
tau+,tau->sd3,sd3~	2.69738×10^{-4}	2.697×10^{-4}	2.69575×10^{-4}	δ = 0.0603979 %
tau+,tau->sd1,sd1~	3.73641×10^{-4}	3.7367×10^{-4}	3.74042×10^{-4}	δ = 0.107316 %
tau+,tau->sd2,sd2~	2.69745×10^{-4}	2.697×10^{-4}	2.69754×10^{-4}	δ = 0.0199164 %
tau+,tau->sd1,sd6~	2.76715×10^{-4}	2.7676×10^{-4}	2.7705×10^{-4}	δ = 0.121224 %
tau+,tau->n1,n1	4.46003×10^{-3}	4.4579×10^{-3}	4.45895×10^{-3}	δ = 0.0478212 %
tau+,tau->n1,n2	6.30416×10^{-4}	6.3061×10^{-4}	6.3052×10^{-4}	δ = 0.0307715 %
tau+,tau->n1,n3	1.21883×10^{-3}	1.2189×10^{-3}	1.21746×10^{-3}	δ = 0.117815 %
tau+,tau->n1,n4	8.67964×10^{-5}	8.6752×10^{-5}	8.68336×10^{-5}	δ = 0.0939997 %
tau+,tau->n1,n5	3.89644×10^{-5}	3.8926×10^{-5}	3.89094×10^{-5}	δ = 0.141298 %
tau+,tau->n2,n2	9.62043×10^{-5}	9.6198×10^{-5}	9.63712×10^{-5}	δ = 0.179837 %
tau+,tau->n2,n3	9.2264×10^{-4}	9.2259×10^{-4}	9.21935×10^{-4}	δ = 0.076501 %
tau+,tau->n2,n4	6.51046×10^{-5}	6.4974×10^{-5}	6.49436×10^{-5}	δ = 0.247567 %
tau+,tau->n2,n5	3.71434×10^{-5}	3.7123×10^{-5}	3.70949×10^{-5}	δ = 0.1307 %
tau+,tau->n3,n3	3.11845×10^{-3}	3.1182×10^{-3}	3.11982×10^{-3}	δ = 0.052071 %
tau+,tau->n3,n4	1.82736×10^{-4}	1.8266×10^{-4}	1.82605×10^{-4}	δ = 0.0721419 %
tau+,tau->n3,n5	6.13979×10^{-5}	6.1358×10^{-5}	6.13801×10^{-5}	δ = 0.0649458 %
tau+,tau->n4,n4	1.58733×10^{-6}	1.5862×10^{-6}	1.58717×10^{-6}	δ = 0.0712317 %
tau+,tau->n4,n5	1.76086×10^{-3}	1.7621×10^{-3}	1.76277×10^{-3}	δ = 0.108888 %
tau+,tau->n5,n5	1.30224×10^{-6}	1.3027×10^{-6}	1.30388×10^{-6}	δ = 0.125935 %
tau+,tau->x1+,x1-	8.49209×10^{-3}	8.4901×10^{-3}	8.47272×10^{-3}	δ = 0.228377 %
tau+,tau->x2+,x2-	4.58133×10^{-3}	4.5956×10^{-3}	4.59502×10^{-3}	δ = 0.310892 %
tau+,tau->x1+,x2-	2.63941×10^{-4}	2.6422×10^{-4}	2.64165×10^{-4}	δ = 0.105543 %
tau+,tau->h01,h01	4.92753×10^{-9}	4.9314×10^{-9}	4.92995×10^{-9}	δ = 0.0784249 %
tau+,tau->h01,h02	2.16262×10^{-7}	2.1626×10^{-7}	2.16185×10^{-7}	δ = 0.035671 %
tau+,tau->h01,h03	7.80572×10^{-8}	7.805×10^{-8}	7.80465×10^{-8}	δ = 0.0137862 %
tau+,tau->h02,h02	5.11735×10^{-8}	5.1179×10^{-8}	5.12057×10^{-8}	δ = 0.0629171 %
tau+,tau->h02,h03	9.84532×10^{-7}	9.8445×10^{-7}	9.82302×10^{-7}	δ = 0.226698 %
tau+,tau->h03,h03	2.25701×10^{-8}	2.2581×10^{-8}	2.25684×10^{-8}	δ = 0.0559166 %
tau+,tau->A01,A01	2.38658×10^{-10}	2.3803×10^{-10}	2.39651×10^{-10}	δ = 0.678646 %
tau+,tau->A01,A02	1.07849×10^{-7}	1.0787×10^{-7}	1.07962×10^{-7}	δ = 0.105076 %
tau+,tau->A02,A02	1.48778×10^{-8}	1.4889×10^{-8}	1.48668×10^{-8}	δ = 0.149544 %
tau+,tau->Z,h01	4.85736×10^{-4}	4.8605×10^{-4}	4.89451×10^{-4}	δ = 0.762018 %
tau+,tau->Z,h02	1.04814×10^{-5}	1.0476×10^{-5}	1.04791×10^{-5}	δ = 0.0519548 %
tau+,tau->Z,h03	3.67139×10^{-5}	3.679×10^{-5}	3.67189×10^{-5}	δ = 0.207188 %
tau+,tau->Z,A01	9.0489×10^{-7}	9.0461×10^{-7}	9.03717×10^{-7}	δ = 0.12971 %
tau+,tau->Z,A02	3.63906×10^{-5}	3.6663×10^{-5}	3.66845×10^{-5}	δ = 0.804499 %
tau+,tau->A01,h01	4.79704×10^{-7}	4.7967×10^{-7}	4.79803×10^{-7}	δ = 0.0278007 %
tau+,tau->A01,h02	6.01345×10^{-8}	6.0131×10^{-8}	6.0137×10^{-8}	δ = 0.00999268 %
tau+,tau->A01,h03	2.81488×10^{-6}	2.8159×10^{-6}	2.82663×10^{-6}	δ = 0.416406 %
tau+,tau->A02,h01	1.08173×10^{-7}	1.0817×10^{-7}	1.08261×10^{-7}	δ = 0.0842393 %
tau+,tau->A02,h02	2.24843×10^{-6}	2.249×10^{-6}	2.24911×10^{-6}	δ = 0.030096 %
tau+,tau->A02,h03	2.93826×10^{-4}	2.9386×10^{-4}	2.93557×10^{-4}	δ = 0.103037 %
tau+,tau->H+,H-	7.32275×10^{-4}	7.3228×10^{-4}	7.3236×10^{-4}	δ = 0.0115347 %

Process	MG-FR	CH-FR	WO-ST	Comparison
W-,Z>b,t~	7.11557×10^{-1}	7.0989×10^{-1}	7.11436×10^{-1}	δ = 0.234537 %
W-,Z>Z,W-	3.01819×10^{2}	3.0264×10^{2}	3.0193×10^{2}	δ = 0.271739 %
W-,Z>a,W-	7.4661×10^{1}	7.4604×10^{1}	7.43748×10^{1}	δ = 0.384101 %
W-,Z>sl4-,sv1~	2.36706×10^{-3}	2.369×10^{-3}	2.37235×10^{-3}	δ = 0.223033 %
W-,Z>sl5-,sv2~	2.40865×10^{-3}	2.4109×10^{-3}	2.41163×10^{-3}	δ = 0.123994 %
W-,Z>sl1-,sv3~	1.16665×10^{-3}	1.1695×10^{-3}	1.17192×10^{-3}	δ = 0.45102 %
W-,Z>sl6-,sv3~	1.2085×10^{-3}	1.2067×10^{-3}	1.20652×10^{-3}	δ = 0.164307 %
W-,Z>sd5,su3~	3.51869×10^{-3}	3.5133×10^{-3}	3.51169×10^{-3}	δ = 0.199274 %
W-,Z>sd4,su2~	3.51372×10^{-3}	3.5133×10^{-3}	3.51307×10^{-3}	δ = 0.0186828 %
W-,Z>sd1,su1~	1.14587×10^{-2}	1.1447×10^{-2}	1.14423×10^{-2}	δ = 0.143534 %
W-,Z>sd6,su6~	2.3412×10^{-2}	2.3479×10^{-2}	2.34716×10^{-2}	δ = 0.285674 %
W-,Z>sd1,su6~	1.79614×10^{-2}	1.7953×10^{-2}	1.79362×10^{-2}	δ = 0.140162 %
W-,Z>sd6,su1~	1.27978×10^{-2}	1.2783×10^{-2}	1.27793×10^{-2}	δ = 0.144221 %
W-,Z>n1,x1-	5.58187×10^{-3}	5.5834×10^{-3}	5.5787×10^{-3}	δ = 0.0842243 %
W-,Z>n2,x1-	2.58653×10^{-2}	2.5885×10^{-2}	2.59104×10^{-2}	δ = 0.174 %
W-,Z>n3,x1-	1.87516×10^{-1}	1.8743×10^{-1}	1.87014×10^{-1}	δ = 0.267929 %
W-,Z>n4,x1-	5.29225×10^{-2}	5.2915×10^{-2}	5.28743×10^{-2}	δ = 0.091285 %
W-,Z>n5,x1-	8.68647×10^{-2}	8.6797×10^{-2}	8.68217×10^{-2}	δ = 0.0779207 %
W-,Z>n1,x2-	4.25162×10^{-3}	4.2539×10^{-3}	4.25377×10^{-3}	δ = 0.0535405 %
W-,Z>n2,x2-	1.86172×10^{-2}	1.8623×10^{-2}	1.86507×10^{-2}	δ = 0.179804 %
W-,Z>n3,x2-	5.08905×10^{-2}	5.0974×10^{-2}	5.10002×10^{-2}	δ = 0.215293 %
W-,Z>n4,x2-	3.87418×10^{-2}	3.8743×10^{-2}	3.87516×10^{-2}	δ = 0.0253781 %
W-,Z>n5,x2-	2.30577×10^{-2}	2.3033×10^{-2}	2.3038×10^{-2}	δ = 0.107112 %
W-,Z>h01,H-	3.06927×10^{-6}	3.069×10^{-6}	3.07074×10^{-6}	δ = 0.0566669 %
W-,Z>h02,H-	1.20593×10^{-4}	1.2061×10^{-4}	1.20462×10^{-4}	δ = 0.122403 %
W-,Z>h03,H-	2.1414×10^{-3}	2.1392×10^{-3}	2.13929×10^{-3}	δ = 0.102916 %
W-,Z>A01,H-	2.71579×10^{-4}	2.7161×10^{-4}	2.71278×10^{-4}	δ = 0.122268 %
W-,Z>A02,H-	1.28349×10^{-3}	1.2827×10^{-3}	1.28247×10^{-3}	δ = 0.0795463 %
W-,Z>W-,h01	7.94029×10^{1}	7.9468×10^{1}	7.93492×10^{1}	δ = 0.149577 %
W-,Z>W-,h02	1.70391	1.7037	1.7087	δ = 0.293178 %
W-,Z>W-,h03	3.98499×10^{-5}	3.9924×10^{-5}	4.00474×10^{-5}	δ = 0.494346 %
W-,Z>W-,A01	6.99895×10^{-8}	6.985×10^{-8}	7.00424×10^{-8}	δ = 0.275123 %
W-,Z>W-,A02	1.36107×10^{-5}	1.361×10^{-5}	1.36221×10^{-5}	δ = 0.0886822 %
W-,Z>Z,H-	1.40065×10^{-5}	1.4004×10^{-5}	1.39963×10^{-5}	δ = 0.0730172 %

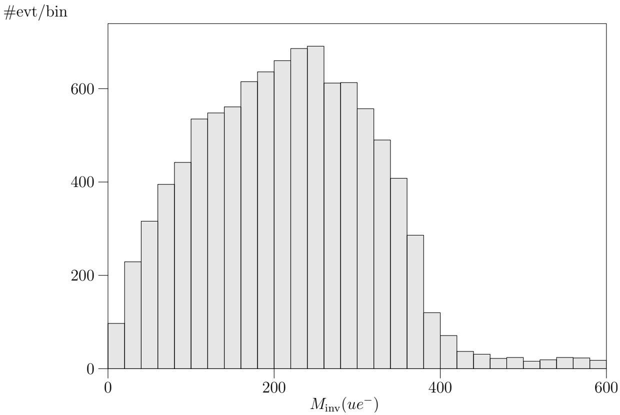
Example: LHC SUSY cascade decays, Input File

```
model = MSSM

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

process susybg = u,U => SU1, su1
process full = u, U => 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 = 14000
beams = p, p => lhapdf

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

n_events = 10000

$title = "Full process"
$description =
  "$p + p \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]])
}

compile_analysis
$analysis_filename = "casc_dec"
write_analysis
```

Example: LHC SUSY cascade decays

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

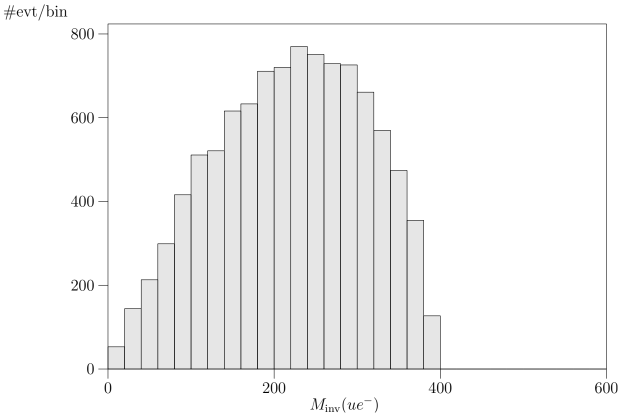
- **Full process:**



Example: LHC SUSY cascade decays

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

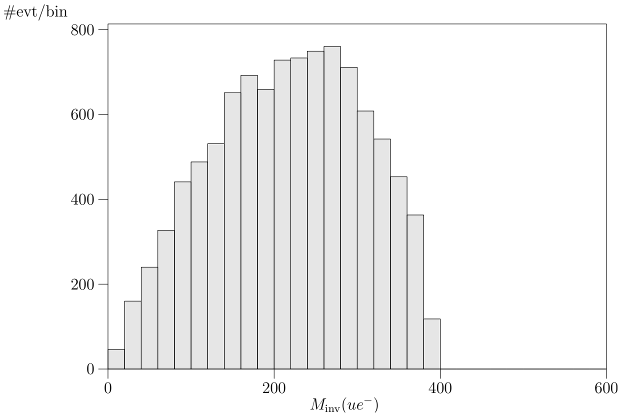
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

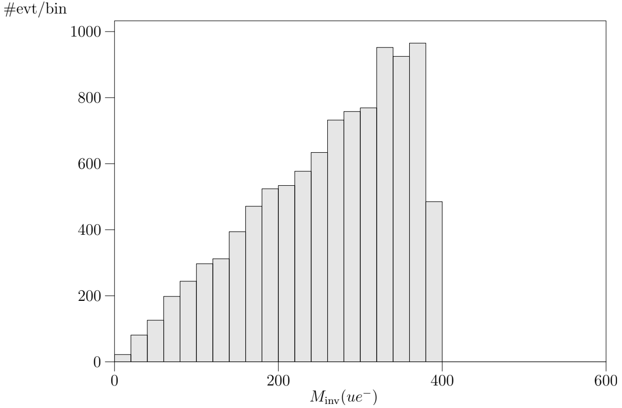
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

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



BSM,e.g. Resonances in VV scattering

Alboteanu/Kilian/JR, 0806.4145

Model-independent description for LHC, respect weak isospin ($\rho \approx 0$):

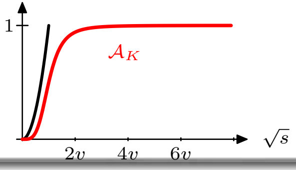
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	a^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$t^\pm, t^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

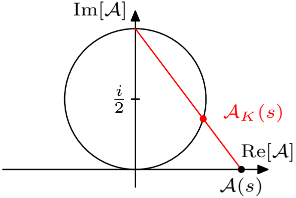
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

$$\mathcal{A}_K(s) = \mathcal{A}(s)/(1 - i\mathcal{A}(s))$$

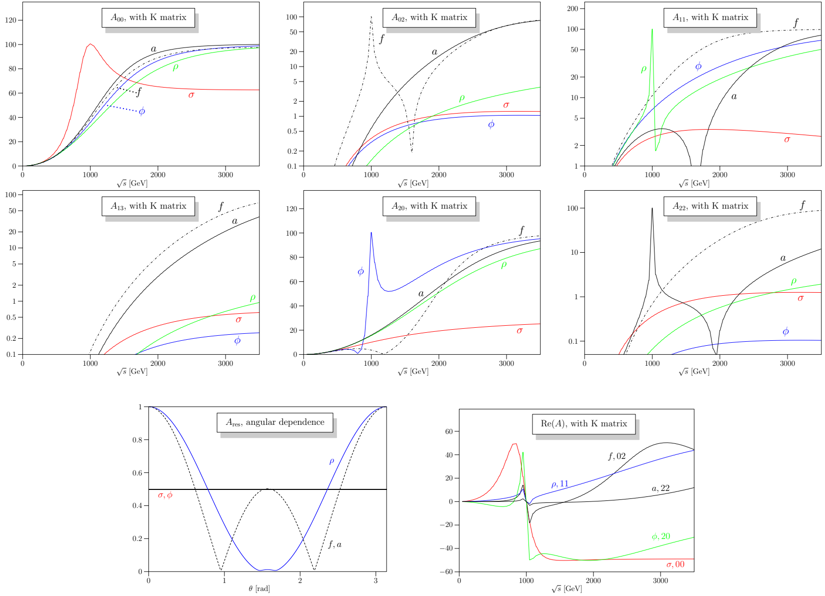
- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-matrix ampl.: $|\mathcal{A}(s)|^2 \overset{s\to\infty}{\to} 1$
- Poles $\pm iv$: M_0, Γ large



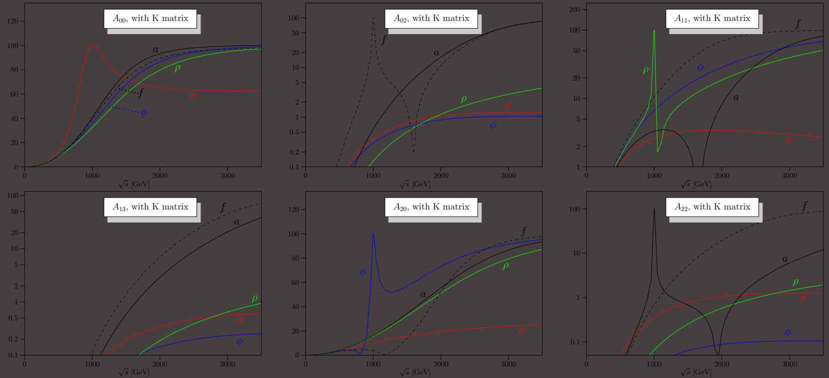


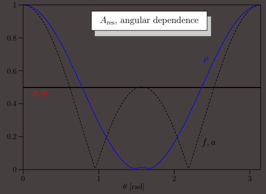
- Unitarization in each spin-isospin eigen-channel
- breaks crossing invariance
- Explicit “time arrow” in WHIZARD

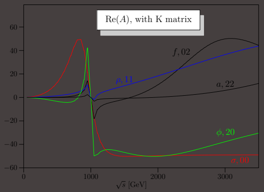
Implementation and Results

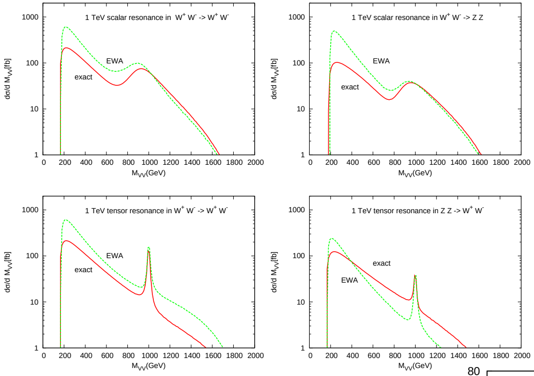


Implementation and Results



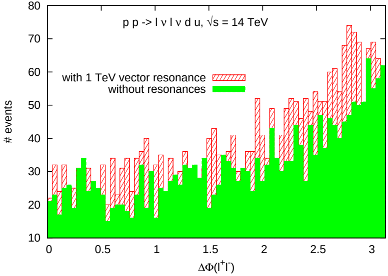






- Effective W approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- EWA: Sideband subtraction completely screwed up!

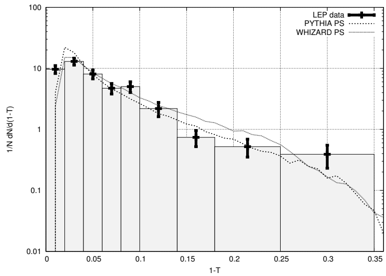
- Example: 850 GeV vector resonance
- coupling $g_\rho = 1$
- Discriminator: angular correlations
- Ongoing ATLAS study

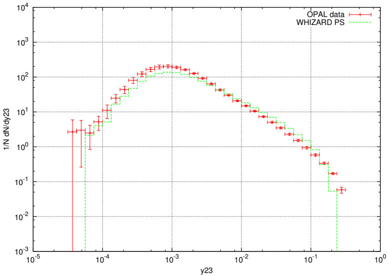


Analytic Parton Shower

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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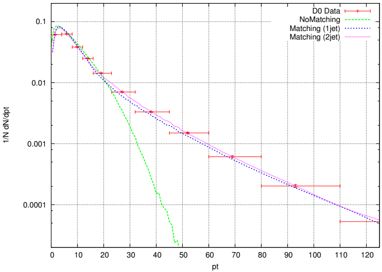

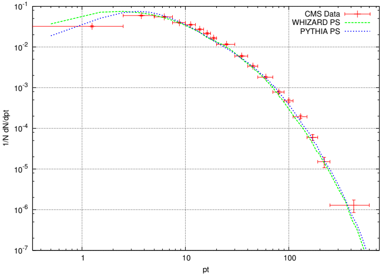

- matching with hard matrix elements, no ”power-shower”
- Connecting with multiple interactions: Boschmann/Kilian/JRR/Schmidt, 2012

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
|=============================================================================|
```

Simulating Linear Colliders

- High-Energy Linear Lepton Collider (250/350/500/1000/2000/3000 GeV)
- ISR, beamstrahlung, strong fields (CLIC)
- Large support for these effects in WHIZARD (close collaboration with all LC groups)
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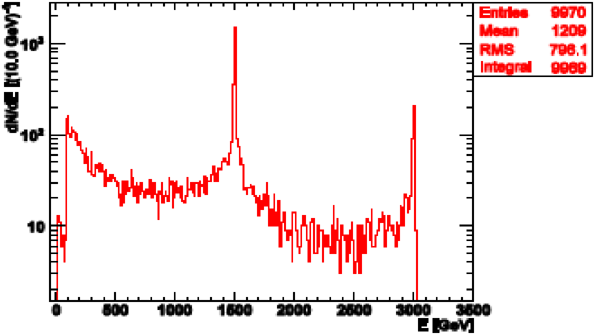

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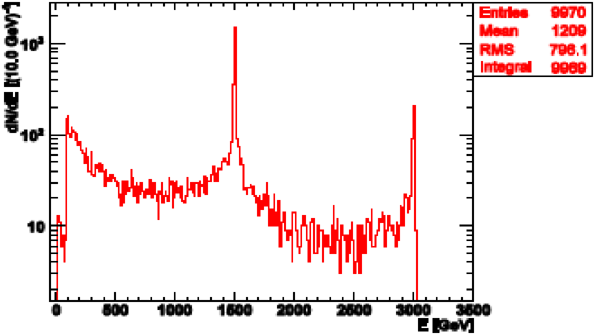

Luminosity spectrum picks up the Z resonance!

WHIZARD 2.1 – Outlook

- Major upgrade late 2012: WHIZARD 2.1.x
- 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”

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- 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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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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