Status of WHIZARD

Wolfgang Kilian

U Siegen

LCWS, Tokyo, 13. November 2013

WHIZARD in a Nutshell

WHIZARD is a universal event generator for elementary processes at colliders:

- e^+e^-: LEP and TESLA/NLC ⇒ ILC, CLIC, . . .
- pp: Tevatron ⇒ LHC, . . .

It contains

1. O'Mega: Automatic matrix elements for arbitrary elementary processes, supports SM and many BSM extensions
2. Phase-space parameterization module
3. VAMP: Generic adaptive integration and (unweighted) event generation
4. Intrinsic support or external interfaces for: Feynman rules, beam properties, cascade decays, shower, hadronization, analysis, event file formats, etc., etc.
5. Free-format steering language SINDARIN

Milestones

1.0 Project started around 1999: Studies for electroweak multi-particle processes at TESLA (W, Higgs, Z)

Event samples for LC studies at SLAC

1.9 Full SM w/ QCD, beam properties, SUSY/BSM, event formats

2.1 QCD shower+matching, FeynRules support, internal density-matrix formalism (cascade decays), language SINDARIN as user interface, OpenMP parallelization, . . .
(production version)

2.2 Major refactoring of internals (same user interface), event sample reweighting, inclusive processes and selective decay chains
(public alpha version)

Plan Improve ILC support; NLO + matching; improve user interface
$\Rightarrow$ adapt to specific needs of user groups

The WHIZARD Event Generator – Release 2.1

- Multi-Channel Monte-Carlo integration
- Efficient phase space and event generation (weighted & unweighted)
- Optimized tree-level matrix elements (O'Mega)
  - $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (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 2.1.1 release: 2012, Sept. 18

Old series: WHIZARD 1.97 (development stopped with 1.94)

WHIZARD team: F. Bach, W. Kilian, T. Ohl, J. Reuter, M. Sekulla, C. Weiss, D. Wiesler

Web address: `http://projects.hepforge.org/whizard`

Standard Reference: WK/Ohl/Reuter, EPJC 71 (2011) 1742, arXiv:0708.4233

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

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

Structured Beams

- Lepton Colliders
  - arbitrarily polarized beams (density matrices), crossing angle
  - Beamstrahlung (CIRCE module), GuineaPig output, ...
  - ISR (3rd order Skrzypek/Jadach, Kuraev/Fadin, incl. p_T)
  - Photon collider spectra (CIRCE2 module)
- Hadron Colliders
  - LHAPDF interface
  - Most prominent PDFs directly included
  - Scanning over structure functions
- Stand-alone particle decays
  - decay in isolation, treated like scattering process
  - polarization of decaying particle

QCD Effects

WHIZARD 2: Color is treated exactly, color-flow formalism

[old event samples: color flow was inferred from kinematics]

Color in final state: several options

1. Partonic event files with color correlation, to be handled by external shower/hadronization (PYTHIA 6, PYTHIA 8, HERWIG)
2. Internally linked PYTHIA 6 via Les Houches Interface (for color correlation) $\Rightarrow$ automatic generation of showered/hadronized event files
3. WHIZARD's own internal shower (analytic shower) and internal PYTHIA hadronization
4. WHIZARD's own internal shower (analytic shower) and external hadronization

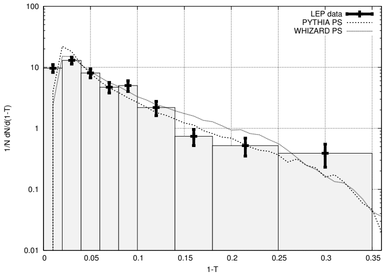
Extra radiation: avoid double-counting

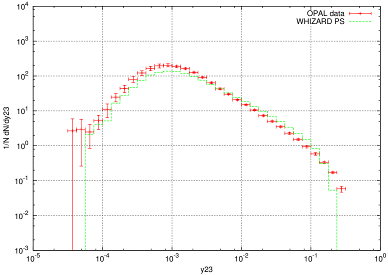
- Matrix element for extra radiation + MLM matching scheme

Analytic Parton Shower

Reuter/Schmidt/Wiesler, JHEP 2012

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate
- validated against PYTHIA shower (tuning: assistance welcome!)





- matching with hard matrix elements

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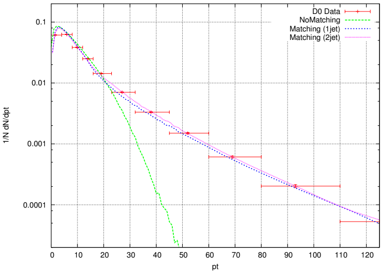
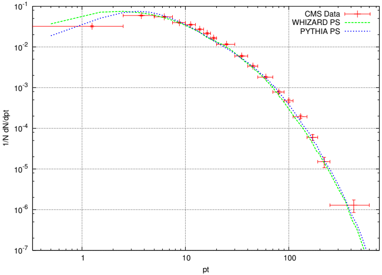




- matching with hard matrix elements

More physics aspects/improvements in WHIZARD 2

- SINDARIN (Scripting INtegration, Data Analysis, Results display and INterfaces)
  - steering: process definition, parameters, models, beam structure, scans/loops, conditionals, I/O, file formats, ...
  - expressions: for cuts, scales, weights
  - analysis: observables, plots, histograms

```
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]]]
```

- Decay cascades including full spin correlations
- FeynRules interface   Christensen/Duhr/Fuks/Reuter/Speckner, EPJC 72 (2012) 1990
- Event-dependent scales in PDFs and running α_s
- Anomalous couplings, resonances and unitarity in vector-boson scattering ($\Rightarrow$ J. Reuter's talk)

News 2013: Work on 2.2.X in Progress

- status: public alpha stage; beta stage (feature complete) a.s.a.p.
- WHIZARD core: insert an extra abstraction layer, consistently separate interface from implementation
  - Replaceable modules with well-defined interface: matrix-elements, beam structure, phase space, integration, decays, shower, . . .
  - Much easier to contribute new parts to the code
  - Framework for testing ideas and algorithms
  - Technical changes hidden from the user
- Revised model for BSM interactions of electroweak vector bosons (w/ light Higgs)
- Preset and automatically compute decay chains, depending on the model
- Read event files (WHIZARD, LHEF, HepMC, etc.), reweight and reanalyze

Technical Features

- WHIZARD 2: code basically rewritten, only Fortran 2003 (`gfortran 4.7`) and `O'Caml`
- Object-oriented implementation and clean modularization of code
- OpenMP parallelization
- Operation modes:
  - Dynamic linking (default mode) with on-the-fly generation of process code
  - Static linking (for batch clusters)
  - Library mode, callable from C/C++/Python/...
  - Interactive mode: WHIZARD works as a Shell – WHISH
- Standard conformance: uses `autotools`: `automake/autoconf/libtool`
- test suite
- Version control (`svn`) at HepForge: use of ticket system and bug tracker
- Continuous integration system (`jenkins`) linked with svn repository

WHIZARD 2 – Installation and Run

- Download WHIZARD from `http://www.hepforge.org/archive/whizard/whizard-2.1.1.tar.gz` and unpack it
- WHIZARD intended to be centrally installed on a system, e.g. in `/usr/local` (or locally on user account)
- Create build directory and `configure`
  External programs (LHAPDF, StdHEP, HepMC) might need flags
- `make, make install`
- Create SINDARIN steering file (in any working directory)
- Run `whizard` (in working directory)

```
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]

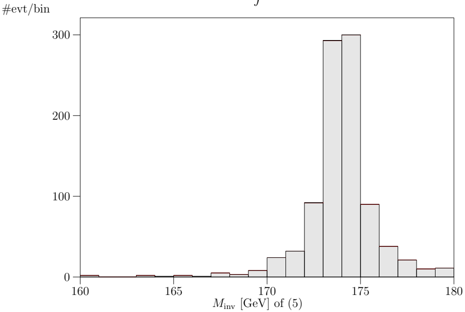
Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] Christian Speckner [5]

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]]]);
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```
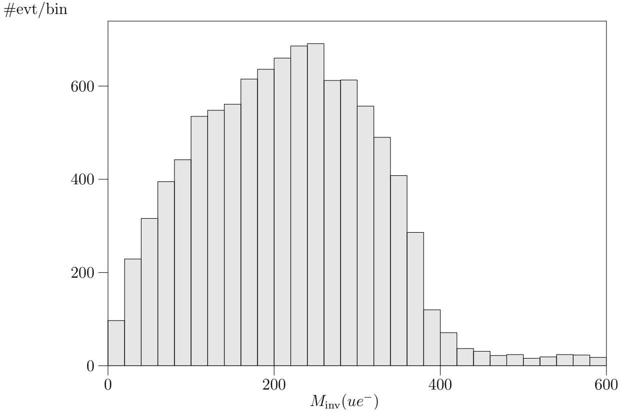

Example: LHC SUSY cascade decays

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

- **Full process:**



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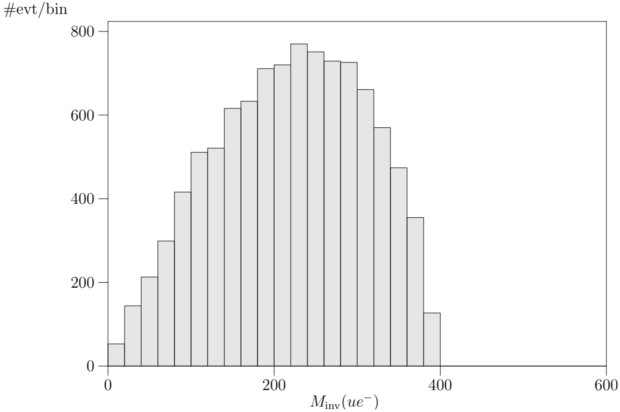
$$p + p \to \tilde{u} + \tilde{u}^* \to \bar{\tilde{u}}_1 + u + \tilde{e}^+_{12} + e^-$$

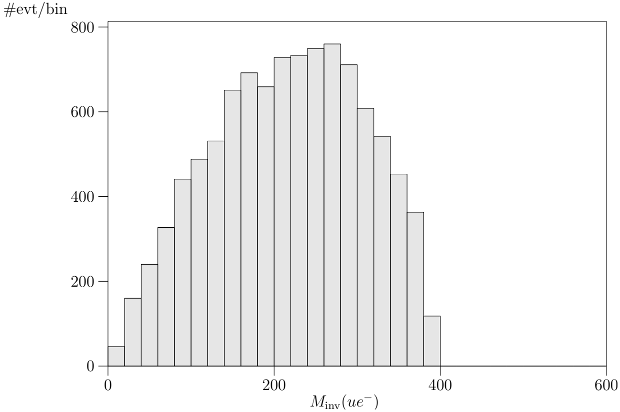
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

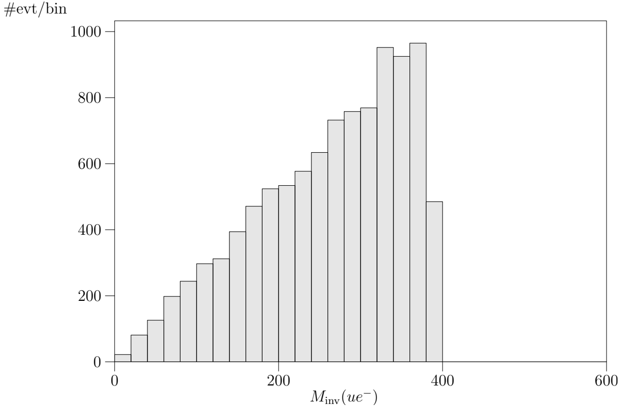
- **Factorized process w/ classical spin correlations:**



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:**



Status of NLO development in WHIZARD

Proof-of-concept code in WHIZARD 2.1

- 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 — Reuter/Speckner, 2012

New implementation planned for WHIZARD 2.2+

- Build upon the refactored WHIZARD core, exchangeable modules

Simulating Linear Colliders

- Predefined parameter sets (CIRCE) (250/350/500/1000/2000/3000 GeV)
- ISR, beamstrahlung, strong fields (CLIC)
- Exhaustive support for these effects in WHIZARD (collaboration with LC groups)
- Example $e^+e^- \to b\bar{b}$:

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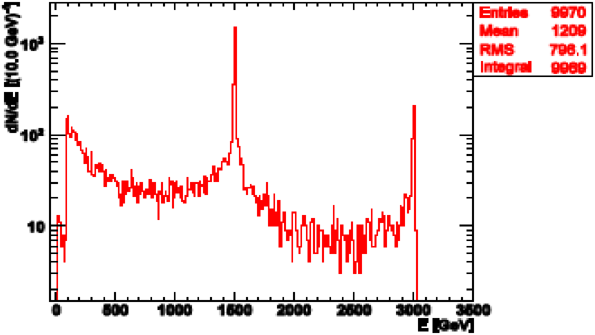

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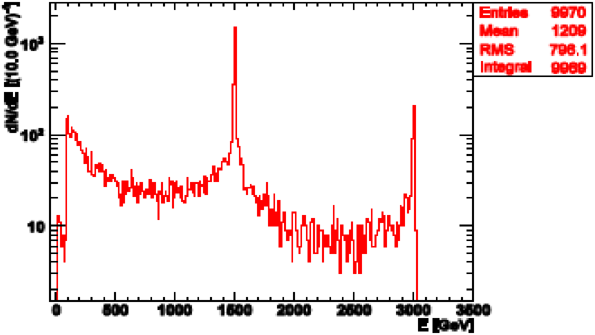

Luminosity spectrum picks up the Z resonance!

ILC/CLIC: Projects

- Updated parameter sets for ILC/CLIC beamstrahlung spectra
- Closer integration with beam simulation (Guinea Pig); event samples and parameterizations (T. Barklow)
- Improved treatment of ISR photons and electron/photon p_T distribution
- Transition to WHIZARD 2 for event samples used in LC studies
- LCIO as event format (F. Gaede)
- Top-quark threshold
- Automatic inclusion of NLO effects

Perspectives: WHIZARD for LC

WHIZARD has become an important tool for LC studies and should remain useful for ongoing and future studies – and for actual analyses.

We continue to have a strong commitment towards LC

- New version will be finalized in the weeks after LCWS 2013
- After refactoring (version 2.2):
  - will address LC-related improvements + projects (discussion at this workshop)
  - contributions from new team members and external groups should become easier
- Feedback and ideas from the ILC/CLIC community welcome!

Summary and Outlook

- WHIZARD 2 for LC and LHC physics
- Versatile, user-friendly tool
- Detailed implementation of ILC beam properties
- Steered via the HepForge page:
  `http://projects.hepforge.org/whizard`
- Expect continuous improvement

Thanks to all contributors (list is not exhaustive!)

T. Barklow, P. Bechtle, M. Berggren, M. Beyer, H. Boschmann, 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, S. Schmidt, J. Schumacher, M. Schumacher, S. Schwertfeger, C. Speckner, C. Schwinn, M. Trudewind

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Open for Suggestions (please contact us!)

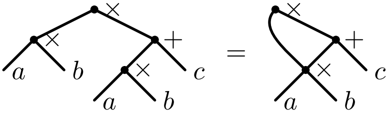
Backup

O'Mega: Optimal matrix elements

Ohl/Reuter, 2001 Ω

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

$ab(ab+c) =$



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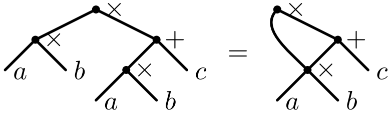
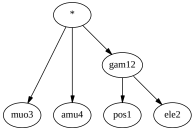


- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



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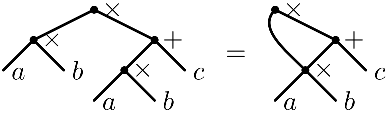

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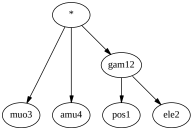

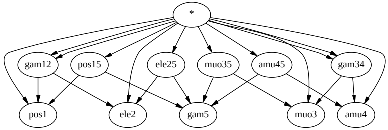

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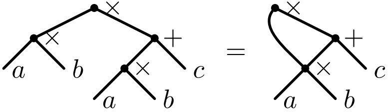
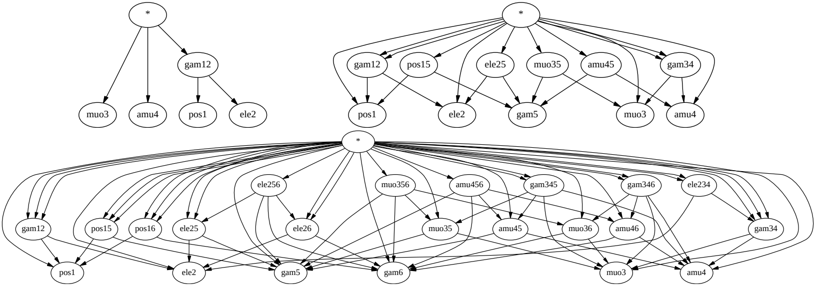


- simplest examples: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma\gamma$



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:
  work in progress, to appear in version 2.2+

BSM,e.g. Resonances in VV scattering

Alboteanu/WK/Reuter, JHEP 0811 (2008) 010

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

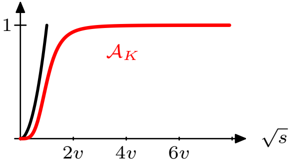
	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	a^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$t^\pm, t^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

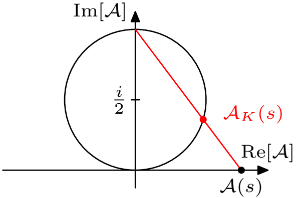
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

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

- 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

Revised Implementation and New Results

- Consistently implement anomalous couplings, resonances and unitarization in the presence of light Higgs
- Different power-counting
- Anomalous Higgs coupling
- Major impact on ongoing LHC and CLIC studies
  - Model-independent approach is probably inapplicable
  - Unitarity is important
  - Matching of generic resonances to effective operators / anomalous couplings

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; WK/Ohl/Reuter/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

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
```

Comparison for the NMSSM

Braam, Fuks, Reuter, 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 %

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