Physics with WHIZARD – SM and beyond

Jürgen R. Reuter

DESY Hamburg

WHIZARD Workshop, DESY, Hamburg, 21. November 2011

The Multi-Particle Generator WHIZARD

Kilian/Ohl/JR, 07

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)

Current versions:

WHIZARD 2.0.5 release date: 2011, May, 10th

New milestone 2.0.6 ready this month

one grand unified package (incl. VAMP, Circe, Circe 2, WHiZard, O'Mega)

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

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

- Major upgrade this winter: WHIZARD 2.1.0

Implemented Physics Content/Classification

- **Hard Matrix Elements** (cf. T. Ohl's talk tomorrow)
  - Multiplicities, technical details, performance
  - Particles, Lorentz structures and interactions
  - Color structures
  - Flavor structures
  - Higher-order matrix elements (cf. C. Speckner's talk today)
  - Special features: non-standard stuff
  - Supported models
- **Structured beams** (cf. H. Boschmann's + S. Schmidt's talks on Wednesday)
  - 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) (cf. Talk S. Schmidt)
  - Matching matrix elements/showers (MLM) (cf. Talk S. Schmidt)
  - Underlying event/multiple interactions (cf. Talk H. Boschmann)
- **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%
```

Gravitons in WHIZARD

Ohl

```
 *** 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:
  $g V^\mu \phi_1 \mathrm{i}\overleftrightarrow{\partial_\mu}\phi_2, \quad \phi V^2, \quad \phi^2 V^2, \quad \frac{1}{2}\phi F_{1,\mu\nu} F_2^{\mu\nu}, \quad \frac{1}{2}\phi F_{1,\mu\nu}\tilde{F}_2^{\mu\nu}, \quad \phi(\mathrm{i}\partial_\mu V_1^\nu)(\mathrm{i}\partial_\nu V_2^\mu)$
- 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 for next year, v2.2.0

Hard matrix elements: Color structures

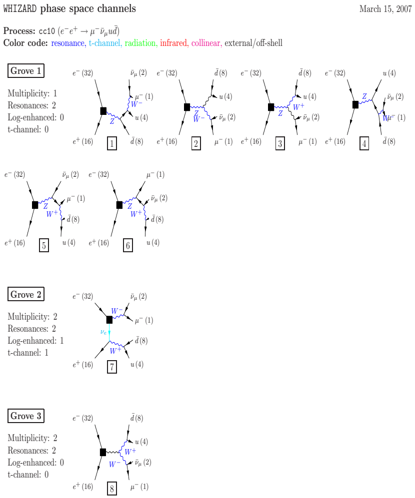
Possible Color structures

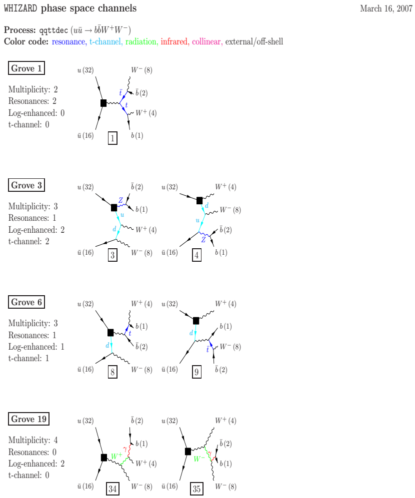
- In principle all $SU(N)$ gauge theories supported, but specialize to $N = 3$
- Color flow formalism

  Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Specki, 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

Phase Space Setup

Heuristic algorithm tries to classify phase-space structure based on a few fundamental rules



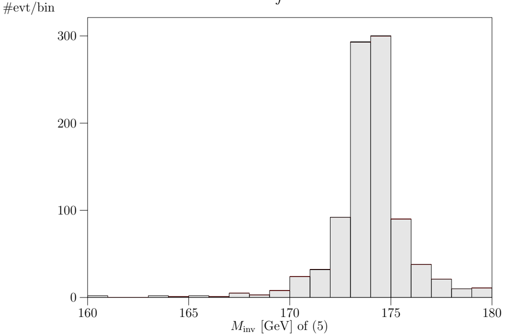


WHIZARD histograms

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 $[\pm 0.85\ \%]$ $n_{\rm evt,\ tot} = 1000$

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

New completely general cut syntax in WHIZARD 2.0.0 (analysis.dat)

```
process default
cut all E of visible (any) > 10
cut all M of visible (any), visible (any) > 10
cut all Q of incoming particle (any), visible (any) < -10
histogram max_val(PT of jet) within 50 400 nbin 35
```

Models currently supported by WHIZARD

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
Noncommutative SM (inoff.)	—	NCSM
SM with Z'	—	Zprime
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

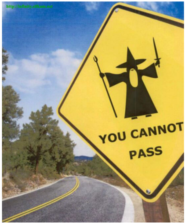
easy to implement new models: FeynRules interface (cf. N. Christensen's talk tomorrow)

The Phantom Menace – Checking new models

- E.g. MSSM
- 5318 couplings (with Goldstone/4-point)
- negative neutralino matrices: explicit factor of i
- Fully implemented, fully tested and fully functional
- Model `MSSM`
- Recommended usage: SUSY Les Houches Accord (SLHA)

```
read_slha ("spsxx")
?slha_read_decays = true/false
```

What about tests?
Have we checked?



- Unitarity Checks $2 \to 2, 2 \to 3$
- Ward-/Slavnov-Taylor identities for gauge symmetries and SUSY

Comparison of Automated Tools for Perturbative Interactions in SuperSymmetry

cf. http://projects.hepforge.org/whizard/susy_comparison.html

$\tau^+\tau^- \to X$

Process	status	Madgraph/Helas 0.5 TeV	Madgraph/Helas 2 TeV	Whizard/O'Mega 0.5 TeV	Whizard/O'Mega 2 TeV	Sherpa/A'Megic 0.5 TeV	Sherpa/A'Megic 2 TeV
$\tilde\tau_1\tilde\tau_1^*$	●	257.57(7)	79.63(4)	257.32(1)	79.636(4)	257.30(1)	79.638(4)
$\tilde\tau_2\tilde\tau_2^*$	●	46.55(1)	66.86(2)	46.368(2)	66.862(3)	46.372(2)	66.862(3)
$\tilde\tau_1\tilde\tau_2^*$	●	95.50(3)	19.00(1)	94.637(3)	19.0015(8)	94.645(5)	19.000(1)
$\tilde\nu_\tau\tilde\nu_\tau^*$	●	502.26(7)	272.01(8)	502.27(2)	272.01(1)	502.30(3)	272.01(1)
$\tilde\chi_1^0\tilde\chi_1^0$	●	249.94(2)	26.431(1)	249.954(9)	26.431(1)	249.96(1)	26.431(1)
$\tilde\chi_1^0\tilde\chi_2^0$	●	69.967(3)	9.8940(3)	69.969(2)	9.8940(4)	69.968(3)	9.8937(5)
$\tilde\chi_1^0\tilde\chi_3^0$	●	17.0387(3)	0.7913(1)	17.0394(1)	0.79136(2)	17.040(1)	0.79137(5)
$\tilde\chi_1^0\tilde\chi_4^0$	●	7.01378(4)	1.50743(3)	7.01414(6)	1.5075(5)	7.0141(4)	1.50740(8)
$\tilde\chi_2^0\tilde\chi_2^0$	●	82.351(7)	18.887(1)	82.353(3)	18.8879(9)	82.357(4)	18.8896(1)
$\tilde\chi_2^0\tilde\chi_3^0$	●	—	1.7588(1)	—	1.75884(5)	—	1.7588(1)
$\tilde\chi_2^0\tilde\chi_4^0$	●	—	2.96384(7)	—	2.9640(1)	—	2.9639(1)
$\tilde\chi_3^0\tilde\chi_3^0$	●	—	0.046995(4)	—	0.0469966(9)	—	0.046999(2)
$\tilde\chi_3^0\tilde\chi_4^0$	●	—	8.5852(4)	—	8.55857(3)	—	8.5856(4)
$\tilde\chi_4^0\tilde\chi_4^0$	●	—	0.26438(2)	—	0.264389(5)	—	0.26437(1)
$\tilde\chi_1^+\tilde\chi_1^-$	●	185.09(3)	45.15(1)	185.093(6)	45.147(2)	185.10(1)	45.151(2)
$\tilde\chi_2^+\tilde\chi_2^-$	●	—	26.515(1)	—	26.5162(6)	—	26.515(1)
$\tilde\chi_1^+\tilde\chi_2^-$	●	—	4.2127(4)	—	4.21267(9)	—	4.2125(2)
h^0h^0	●	0.3533827(3)	0.0001242(2)	0.35339(2)	0.00012422(3)	0.35340(2)	0.000124218(6)
h^0H^0	●	—	0.005167(4)	—	0.0051669(3)	—	0.0051671(3)
H^0H^0	●	—	0.07931(3)	—	0.079301(6)	—	0.079311(4)
A^0A^0	●	—	0.07975(3)	—	0.079758(6)	—	0.079744(4)
Zh^0	●	59.591(3)	3.1803(8)	59.589(3)	3.1802(1)	59.602(3)	3.1829(2)
ZH^0	●	2.8316(3)	4.671(5)	2.83169(9)	4.6706(3)	2.8318(1)	4.6706(2)
ZA^0	●	2.9915(4)	4.682(5)	2.99162(9)	4.6821(3)	2.9917(2)	4.6817(2)
A^0h^0	●	—	0.005143(4)	—	0.0051434(3)	—	0.0051440(3)
A^0H^0	●	—	1.4880(2)	—	1.48793(9)	—	1.48802(8)
H^+H^-	●	—	5.2344(6)	—	5.2344(2)	—	5.2345(3)

Comparison for the NMSSM

Braam, Fuks, JRR, 2010

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 %

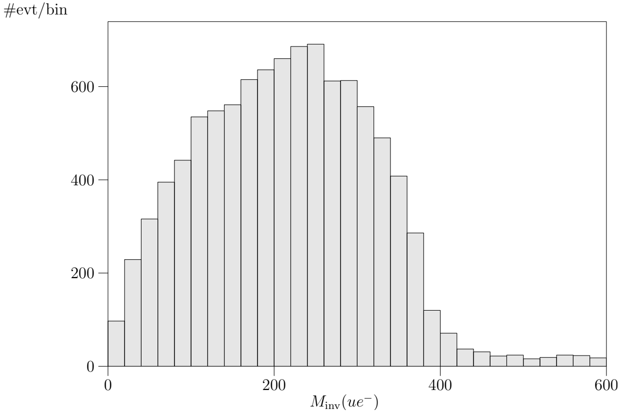
Example: LHC SUSY cascade decays, Input File

```
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) {
```

Example: LHC SUSY cascade decays

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

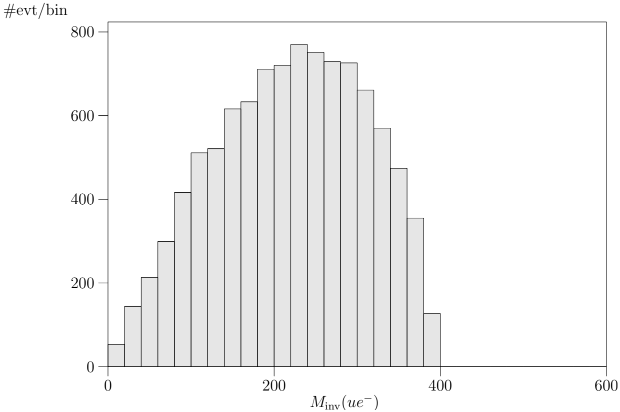
- **Full process:**



Example: LHC SUSY cascade decays

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

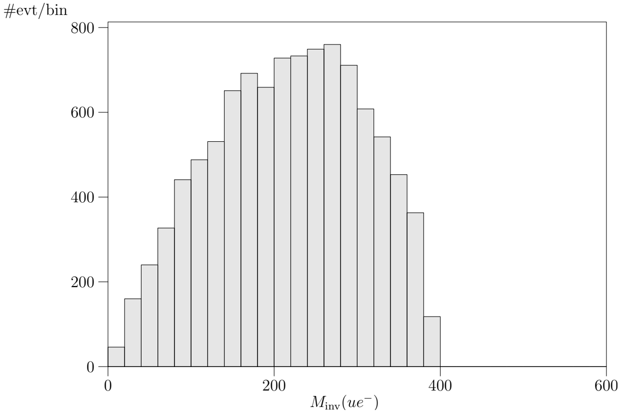
- **Factorized process w/ full spin correlations:**



Example: LHC SUSY cascade decays

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

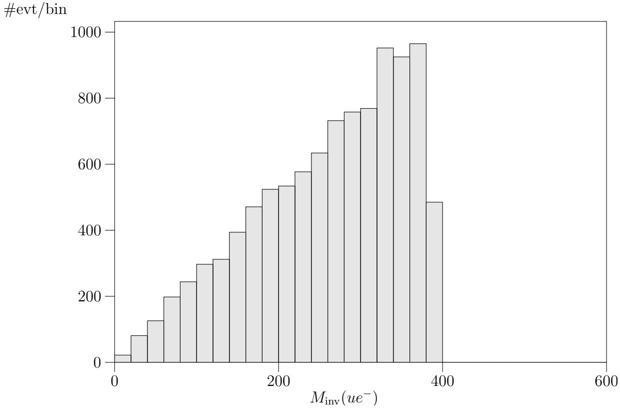
- **Factorized process w/ classical spin correlations:**



Example: LHC SUSY cascade decays

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

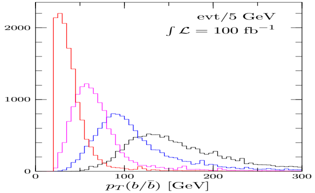
- **Factorized process w/ no spin correlations:**

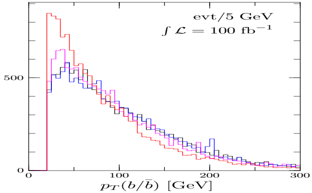


Examples of BSM Physics Simulations

WHIZARD LHC/Tevatron Application/Projects

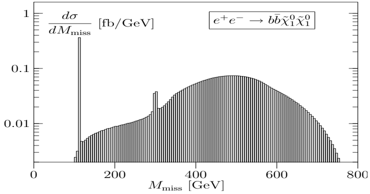
- SUSY Simulations and Studies — quasi World-Wide Study
- WW scattering + anomalous couplings — Bonn/Freiburg/Dresden/Siegen
- Determination of LHC signal significances — BNL/Edinburgh/Freiburg
- BSM mass spectrum determinations — CERN/Freiburg/UC Davis
- Lepton Flavor Violation — DESY/Manchester
- BSM CP properties — Bonn/Freiburg
- Little Higgs studies — Freiburg/Rochester/Siegen
- KK graviton studies — Freiburg/Moscow/Siegen
- general Z'/W' studies — Ottawa/Freiburg/Madison
- noncommutative SM extensions — Würzburg
- Interplay ATLFAST2–MC development — Freiburg
- BSM Multijet studies — DESY/Dresden/Edinburgh/KEK/Rochester





WHIZARD ILC Applications/Projects

- SUSY simulations and studies — quasi World-Wide study
- Detector optimization studies — DESY/Fermilab
- Electroweak precision studies — DESY/Fermilab/Freiburg/SLAC
- WW scattering/Triple boson production — DESY/Rostock
- Photon collider studies — DESY/Würzburg
- Top and Higgs studies — DESY/Freiburg/London/RAL
- Little Higgs Studies — Ottawa/Freiburg/Rochester/Siegen
- Dark matter studies — Bonn/DESY/Freiburg/SLAC
- Benchmarking/Standard Event Samples — DESY/SLAC
- ISR/beamstrahlung studies:



WHIZARD ILC Applications/Projects

- SUSY simulations and studies — quasi World-Wide study
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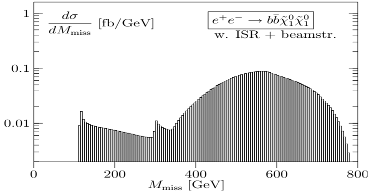
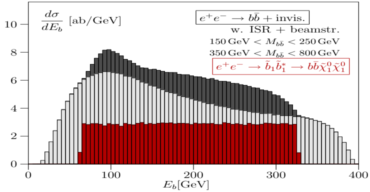




BSM,e.g. Resonances in VV scattering

Alboteanu/Kilian/JR, 0806.4145

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

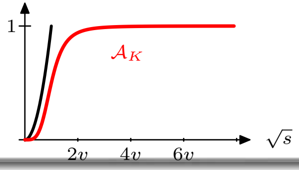
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 $(\gamma'/Z'$?)	a^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ $(W'/Z'$?)	$t^\pm, t^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

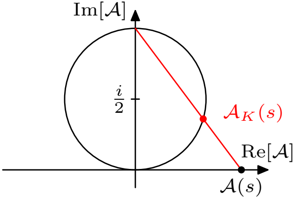
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

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

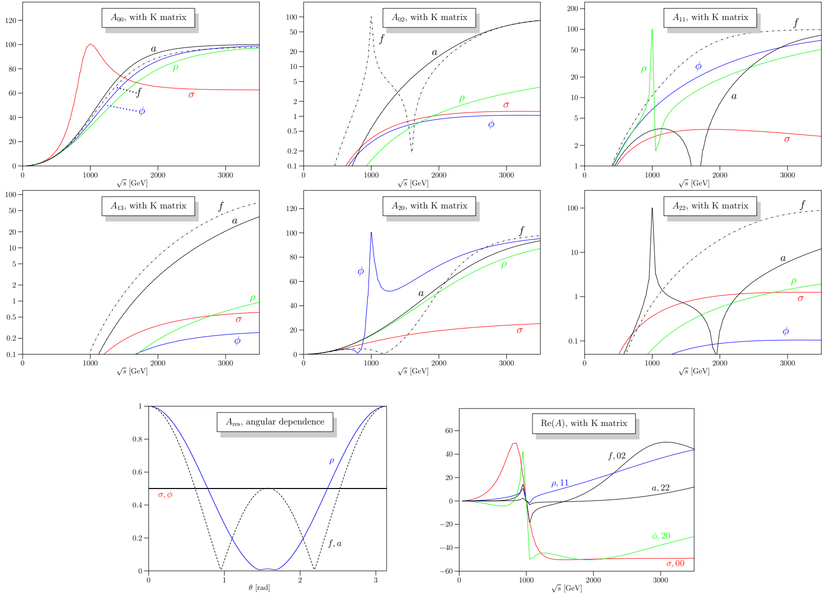
- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-matrix ampl.: $|\mathcal{A}(s)|^2 \stackrel{s\to\infty}{\longrightarrow} 1$
- Poles $\pm iv$: M_0, Γ large

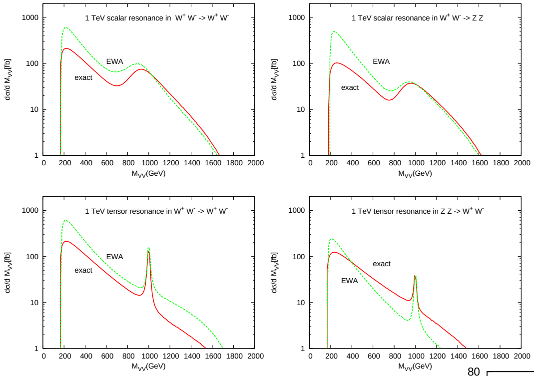




- Unitarization in each spin-isospin eigen-channel
- breaks crossing invariance
- Explicit "time arrow" in WHIZARD

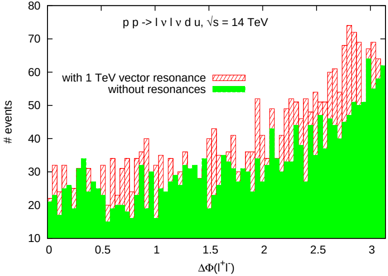
Implementation and Results





- 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 (cf. U. Schnoor's talk tomorrow)



Summary / Outlook

- WHIZARD 2 versatile multi-purpose event generator

- Focus on BSM physics
- Steered via the HepFORGE page:
  http://projects.hepforge.org/whizard

Left out:

- Phase space generation/integration details We don't use black boxes, we write them!

WHIZARD focused on BSM physics $\longrightarrow$ complete event generator

- Initial state shower, underlying event, hadronization

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

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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, S. Schmitt, J. Schumacher, M. Schumacher, C. Schwinn

Continuos Upgrades Next Year

Continuos Upgrades Next Year