Beyond the Standard Model in WHIZARD

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HELMHOLTZ GEMEINSCHAFT

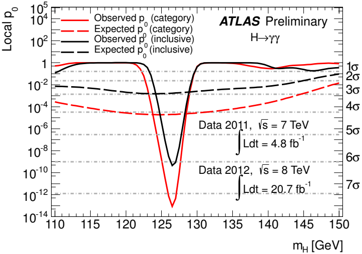
DESY

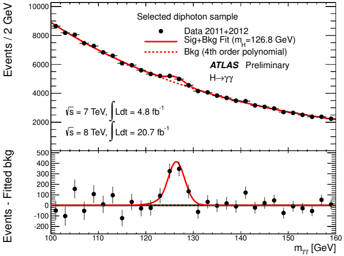
PHYSICS AT THE TERA SCALE Helmholtz Alliance

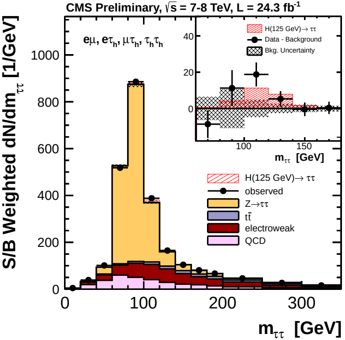
2nd WHIZARD Forum, Würzburg, March 17, 2015

Standard Model Triumph:

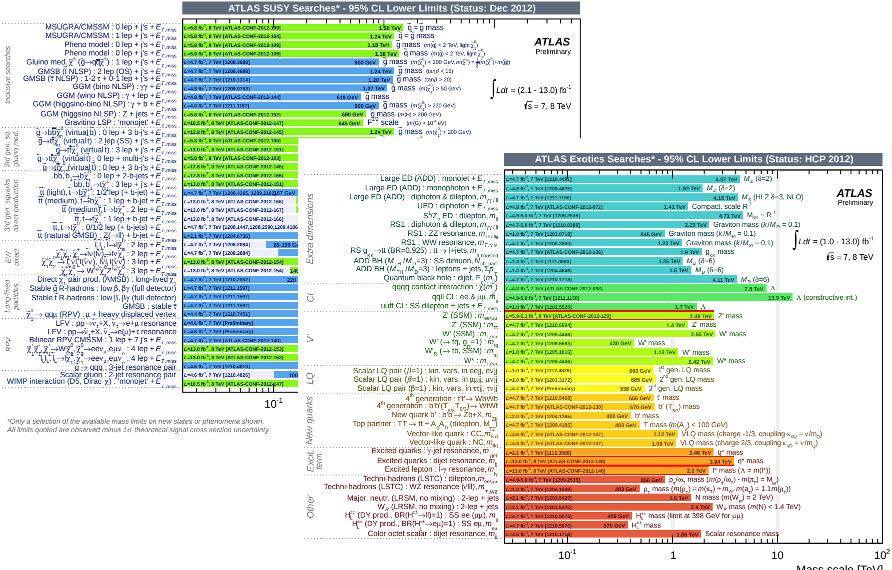
- 2012: Discovery of a Higgs boson







No evidence beyond SM ... and what now?



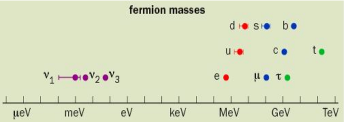
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

*Only a selection of the available mass limits on new states or phenomena shown

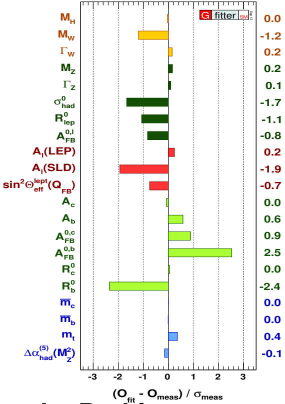
Doubts on the Standardmodel

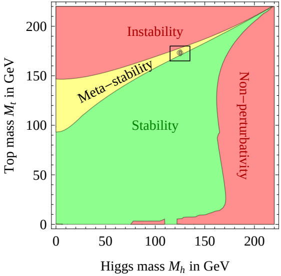
– describes microcosm (too good?)

– 28 free parameters



– Higgs ?, form of Higgs potential ?





Hierarchy Problem

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry for quantum corrections to Higgs mass

$$\boxed{\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2\,\text{GeV}^2}$$

$(125\,\text{GeV})^2$ = (100000000000000000000000000000000020000 –

1000000000000000000000000000000000000000) GeV^2

Doubts on the Standardmodel

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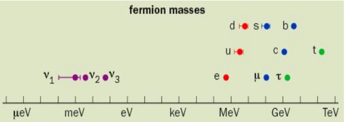
- 28 free parameters



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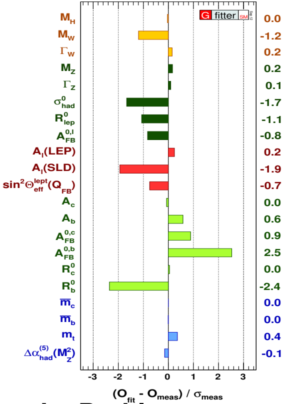

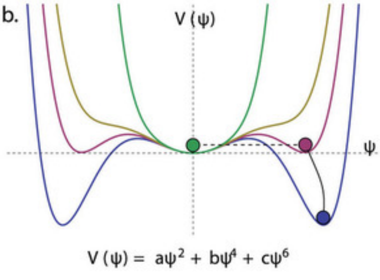

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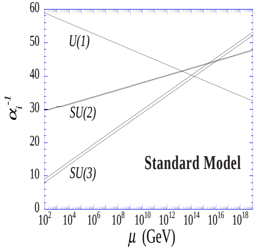
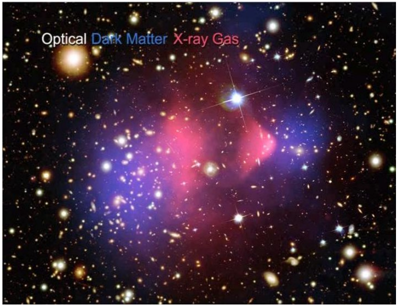
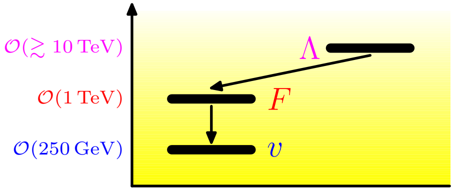
Open Questions

- Unification of all forces (?)
- Baryon asymmetry $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$
  missing CP violation
- Flavor: three generations (?)
- Tiny neutrino masses: $m_\nu \sim \frac{v^2}{M}$
- Dark Matter:
  - stable
  - weakly interacting
  - $m_{DM} \sim 100$ GeV
- Quantum theory of gravitation
- Cosmic inflation
- Dark Energy





Characteristics and Spectra

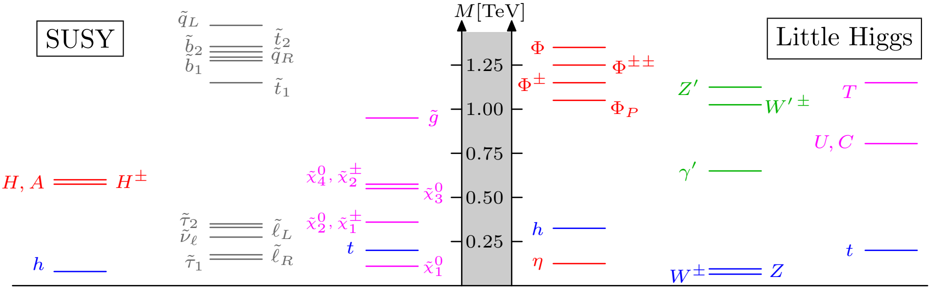


Scale Λ: “hidden sector”, symmetry breaking

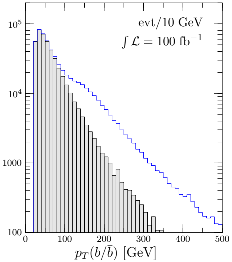
Scale F: new particles

Scale v: h, W/Z, $\ell^\pm$, ...

Terascale: new particles to stabilize the hierarchy



Search for new Particles (LHC)



Decay products of heavy particles

- high-p_T Jets
- (many) hard leptons

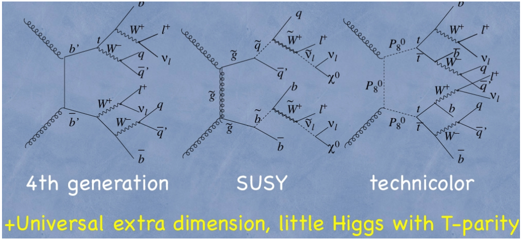
Production of colored particles

Weakly interacting particles only in decays

Dark Matter $\Leftrightarrow$ discrete parity (R, T, KK)

- only pairs of new particles $\Rightarrow$ high energies, long decay chains
- Dark Matter $\Rightarrow$ missing energy ($\not{E}_T$)

Different Models/Decay Chains — identical signatures



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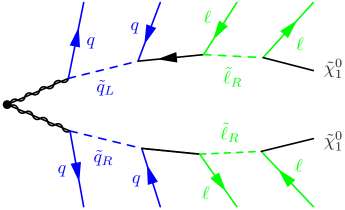

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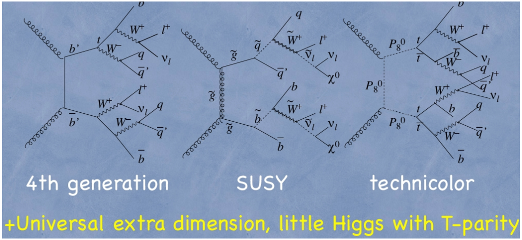
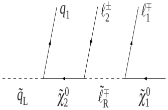
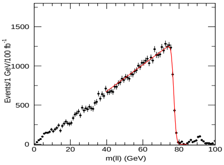
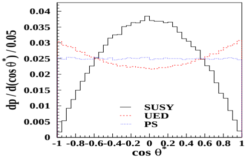


Model Discrimination

- Mass of new particles: endpoints/edges of decay spectra







- Spin of new particles: angular correlations, (charge) asymmtries . . .
- Modellbestimmung: Measurements of coupling constants

$\Rightarrow$ Precise prediction for signals and backgrounds

  - Fiducial volumes: consider almost arbitray cuts
  - Exclusive/[inclusive] many-body final states: $2 \to 4$ to $2 \to 10$
  - Quantum corrections: real and virtual corrections

WHIZARD in a Nutshell – Release 2.2

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

- e^+e^-: LEP and TESLA/NLC $\Rightarrow$ ILC, CLIC, FCC-ee . . .
- pp: Tevatron $\Rightarrow$ LHC, HL/E-LHC, VLHC, FCC, XXX . . .

It contains

1. O'Mega: Optimized automatic matrix elements for arbitrary elementary processes, supports SM and many BSM extensions
2. Phase-space parameterization module (very efficient PS)
3. VAMP: Generic adaptive Monte Carlo integration and (unweighted) event generation
4. CIRCE1/2: Lepton/[photon] collider beam spectra
5. Intrinsic support or external interfaces for: Feynman rules, beam properties, cascade decays, shower, hadronization, analysis, event file formats, etc., etc.
6. Free-format steering language SINDARIN

WHIZARD 2 – Installation and Run

- Download WHIZARD from `http://www.hepforge.org/archive/whizard/whizard-2.2.2.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, LCIO, FastJet) might need flags
- `make`, `make install`
- Create SINDARIN steering file (in any working directory)
- Run `whizard` (in working directory)
- Supported event formats: HepMC, LCIO, StdHEP, LHEF, LHA, div. ASCII formats

```
WHIZARD self tests:
make  check-am
make  check-TESTS
PASS: expressions.run
PASS: beams.run
PASS: cputime.run
PASS: state_matrices.run
PASS: interactions.run
PASS: beam_structures.run
PASS: models.run
[...........]
PASS: phs_forests.run
PASS: rng_base.run
PASS: selectors.run
PASS: phs_wood.run
PASS: mci_vamp.run
PASS: particle_specifiers.run
PASS: prclib_stacks.run
PASS: slha_interface.run
PASS: subevt_expr.run
PASS: process_stacks.run
PASS: cascades.run
PASS: processes.run
PASS: decays.run
XFAIL: hgg_colors.run
PASS: events.run
PASS: eio_base.run
PASS: rt_data.run
PASS: dispatch.run
PASS: process_configurations.run
PASS: event_weights_1.run
PASS: integrations.run
PASS: simulations.run
PASS: process_libraries.run
PASS: compilations.run
PASS: prclib_interfaces.run
PASS: commands.run
PASS: errors.run
PASS: helicity.run
PASS: qedtest_1.run
PASS: beam_setup_1.run
PASS: reweight_1.run
PASS: colors.run
PASS: lhef_1.run
PASS: alphas.run
PASS: smtest_1.run
PASS: hepmc.run
PASS: restrictions.run
PASS: pdf_builtin.run
PASS: stdhep_1.run
PASS: static_1.run
==========================================
Testsuite summary for WHIZARD 2.2.5
==========================================
# TOTAL: 270
# PASS:  265
# SKIP:  2
# XFAIL: 3
# FAIL:  0
# XPASS: 0
# ERROR: 0
==========================================
```

Implemented Physics Content/Classification

- **Hard Matrix Elements**
  - Multiplicities, technical details, performance
  - Particles, Lorentz structures and interactions
  - Color structures
  - Flavor structures
  - Higher-order matrix elements (cf. Christian Weiss' talk yesterday)
  - Special features: non-standard stuff
  - Supported models
- **Structured beams** (cf. Thorsten Ohl's talk 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....

Structured Beams

- **Hadron Colliders structured beams**
  - LHAPDF interface (v. 4/5 and 6)
  - Most prominent PDFs directly included (e.g. CT10, MMHT2014 etc.)
  -
  - ISR and FSR (two different own implementations, interface to PYTHIA6) (cf. Talk Bijan Chokoufé)
  - Matching matrix elements/showers (cf. Talk Bijan Chokoufé)
  - Underlying event/multiple interactions [not validated]

- **Lepton Colliders structured beams**
  - ISR (implemented: Skrzypek/Jadach, Kuraev/Fadin, incl. p_T distributions)
  - arbitrarily polarized beams (density matrices)
  - Beamstrahlung (CIRCE1 module)
  - Correlated beam spectra / [photon collider spectra] (CIRCE2 module)
  - external beam spectra can be read in (files/generating code)
  - FSR/exclusive ISR (QED shower) not (yet) implemented

- **Hadronic events/hadronic decays**
  - through PYTHIA6 interface (or HERWIG/Sherpa/PYTHIA8 externally)

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, 2001

```
*** 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.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%
......
```

Gravitons in WHIZARD

Ohl, 2000

```
*** Checking polarisation tensors: ***
e2( 2).e2( 2)=1: passed at  100%
e2( 2).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:
  $T^{\mu\nu}(V_{1,\mu} V_{2,\nu} + V_{1,\nu} V_{2,\mu})$, $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta V_{2,\mu}$,
  $T^{\alpha\beta}(V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\beta (\mathrm{i}\partial_\mu V_{2,\alpha}) + V_1^\mu \mathrm{i}\overleftrightarrow{\partial}_\alpha (\mathrm{i}\partial_\mu V_{2,\beta}))$, $T^{\alpha\beta}((\mathrm{i}\partial^\mu V_1^\nu) \mathrm{i}\overleftrightarrow{\partial}_\alpha \mathrm{i}\overleftrightarrow{\partial}_\beta (\mathrm{i}\partial_\nu V_{2,\mu}))$
- 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.

  growing number of dim. 6/dim. 8 operators: HEFT, aTGC, aQGC, anom. top couplings, . . .

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  $T^{\alpha\beta}(V_1^\mu \mathrm{i} \overleftrightarrow{\partial}_\beta (\mathrm{i}\partial_\mu V_{2,\alpha}) + V_1^\mu \mathrm{i} \overleftrightarrow{\partial}_\alpha (\mathrm{i}\partial_\mu V_{2,\beta}))\ , \quad T^{\alpha\beta}((\mathrm{i}\partial^\mu V_1^\nu) \mathrm{i} \overleftrightarrow{\partial}_\alpha \mathrm{i} \overleftrightarrow{\partial}_\beta (\mathrm{i}\partial_\nu V_{2,\mu}))$
- 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.

  growing number of dim. 6/dim. 8 operators: HEFT, aTGC, aQGC, anom. top couplings, ...

- Completely general Lorentz structures:
  foreseen for next major release, incl. UFO interface, v2.3.0

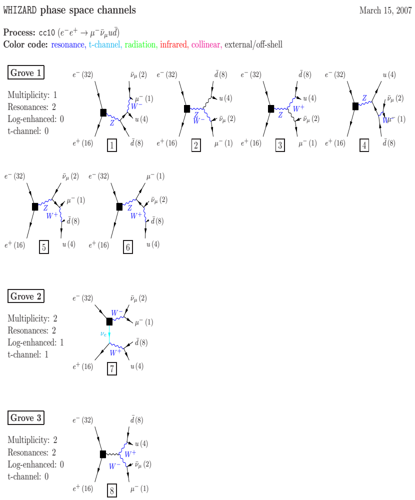
Hard matrix elements: Color structures

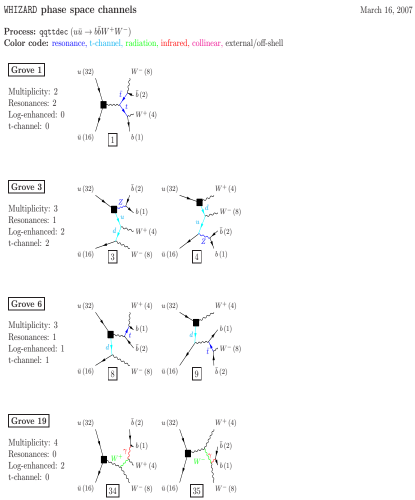
Possible Color structures

- 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 – Overview over Physics 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 coupl.	**SM_ac_CKM**	**SM_ac**
SM with anomalous top coupl.	**SMtop_CKM**	**SMtop**
SM for e^+e^- top threshold	**—**	**SM_tt_threshold**
SM with anom. Higgs coupl.	—	SM_rx / NoH
SM ext. for VV scattering	—	SSC / SSC2/ AltH
SM with Z'	—	Zprime
2HDM	2HDM_CKM	2HDM
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/univ.)	—	Simplest[_univ]
3-site model	—	Threeshl
UED	—	UED
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

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

Claude Duhr's talk

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

Lukas Mitzka' talk

WHIZARD – Overview over Physics 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 coupl.	**SM_ac_CKM**	**SM_ac**
SM with anomalous top coupl.	**SMtop_CKM**	**SMtop**
SM for e^+e^- top threshold	**—**	**SM_tt_threshold**
SM with anom. Higgs coupl.	—	SM_rx / NoH
SM ext. for VV scattering	—	SSC / SSC2/ AltH
SM with Z'	—	Zprime
2HDM	2HDM_CKM	2HDM
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/univ.)	—	Simplest[_univ]
3-site model	—	Threeshl
UED	—	UED
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

cf. Marco Sekulla's talk

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

Claude Duhr's talk

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

Lukas Mitzka' talk

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 %

Resonances in VV scattering

→ Marco Sekulla's talk

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

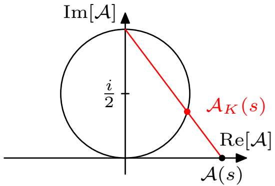
	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	ω^0 $(\gamma'/Z'\ ?)$	a^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ $(W'/Z'\ ?)$	$t^\pm, t^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

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

Alboteanu/Kilian/JRR, 0806.4145
Kilian/Ohl/JRR/Sekulla, 1408.6207



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

Example: LHC SUSY cascade decays, Input File

```
model = MSSM

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

process susyproc = u,U => SU1, su1
process fullproc = 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 }

\textcolor{blue}{sqrts} = 14000
\textcolor{blue}{beams} = p, p => lhapdf

integrate (susyproc) { iterations = 5:10000, 2:10000 }
integrate (fullproc)

n_events = 10000

unstable su1 (dec_su_q) { <polarization_option> }

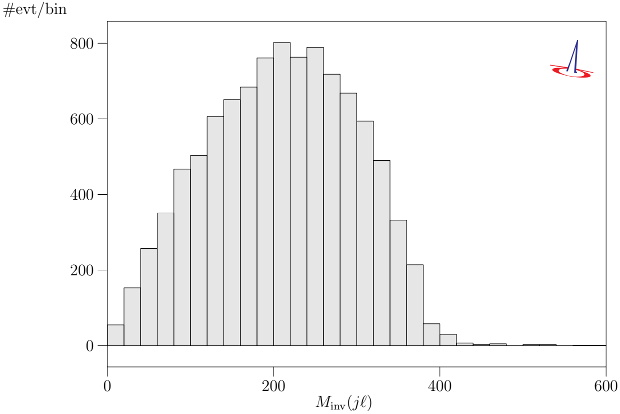
simulate (fullproc) {
 $sample = "casc_dec_full"
 analysis =
   record inv_mass1_full (eval M / 1 GeV [combine[u,e1]])
```

Example: LHC SUSY cascade decays

$$p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$$

- **Full process:**

```
integrate (fullproc)
```



Example: LHC SUSY cascade decays

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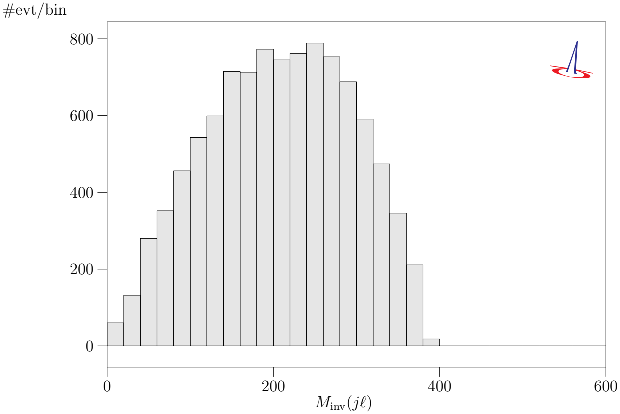
- **Factorized process w/ full spin correlations:**

```
unstable su1 (dec_su_q)
```

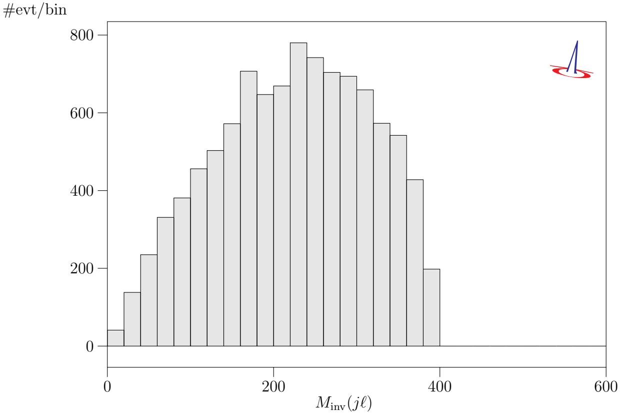


Example: LHC SUSY cascade decays

$$p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$$

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

```
unstable su1 (dec_su_q) { ?diagonal_decay = true }
```

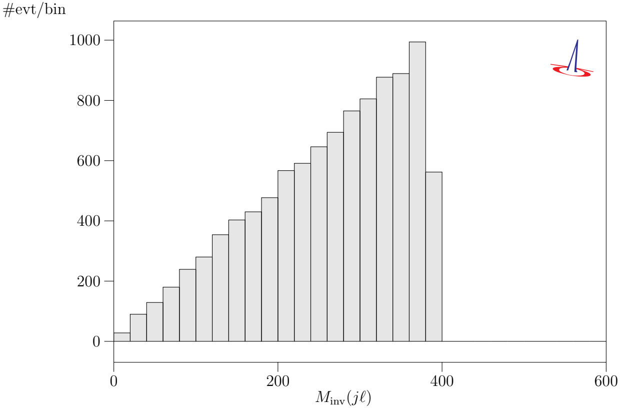


Example: LHC SUSY cascade decays

$$p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$$

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

```
unstable su1 (dec_su_q) { ?isotropic_decay = true }
```



New/Upcoming Features in 2.2/2.3

New features in production version 2.2

- Complete Reweighting of Event Samples (incl. LHEF 2013) ✓
- Process containers: inclusive production samples (e.g. SUSY) ✓ `process inclusive = e1, E1 => (Z, h) + (Z, H) + (A, H)`
- Automatic generation of decays, depending on the model ✓
- Simplified models for electroweak vector bosons (w/ light Higgs) ✓
- Decay chains with different options for spin correlations:

```
unstable "W+" (Wud)
unstable "W+" (Wud) { ?diagonal_decay = true }
unstable "W+" (Wud) { ?isotropic_decay = true }
```

- Projection on polarized intermediate states:

```
unstable "W+" (Wud) { decay_helicity = -1 }
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Features in preparation: 2.3 – 2.4

- BSM: general Lorentz structures in matrix-element generator (O'Mega)
- New syntax/features decays and chains (steering unstable particles):

```
process higgsstr = e1, E1 => (Z => e2, E2), (H => b, bbar)
```

Summary and Outlook

- WHIZARD 2 for LC & LHC physics and beyond
- A lot of focus lately on NLO and QCD
- Covers the whole SM, and most possible paths beyond (BSM)
- We try to be prepared for discoveries...
- Immense internal technical improvements
- Continuous improvement
  - WHIZARD 2.2 $\Rightarrow$ release series
  - WHIZARD 2.3-2.4 $\Rightarrow$ General Lorentz structures
  - WHIZARD 3 $\Rightarrow$ NLO (QCD)

Tell us about your model!

`whizard@desy.de`

Where do we go? ... the standard way ...?

Where do we go? ... the way beyond ...?

We'll be there ...

We'll be there ...

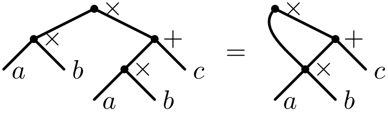
BACKUP SLIDES:

O'Mega: Optimal matrix elements

Ohl/JRR, 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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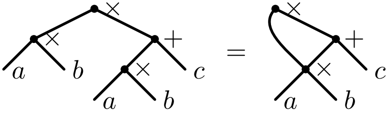

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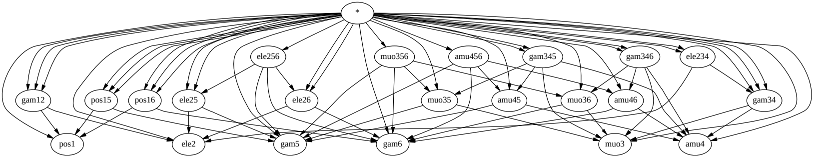

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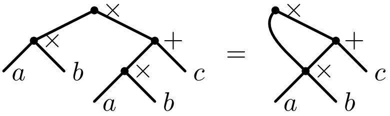

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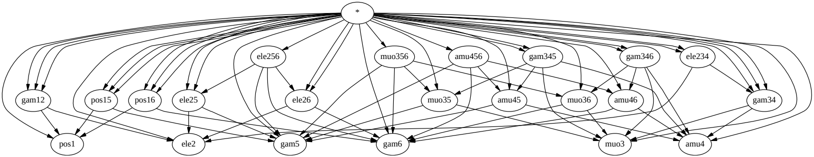

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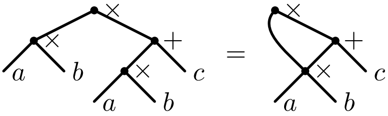

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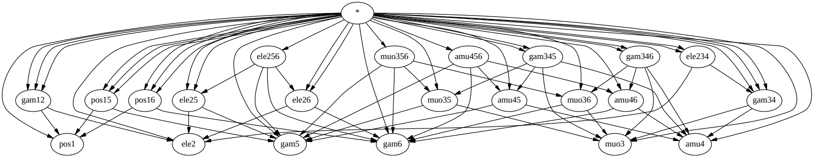

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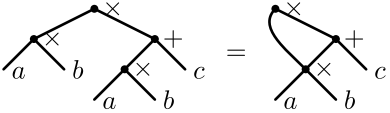
$ab(ab+c) =$ 

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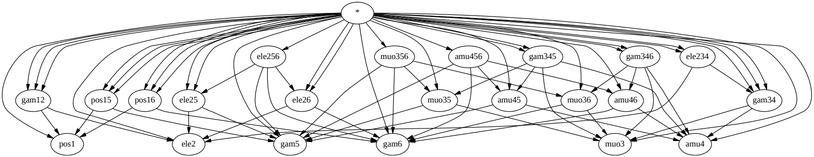
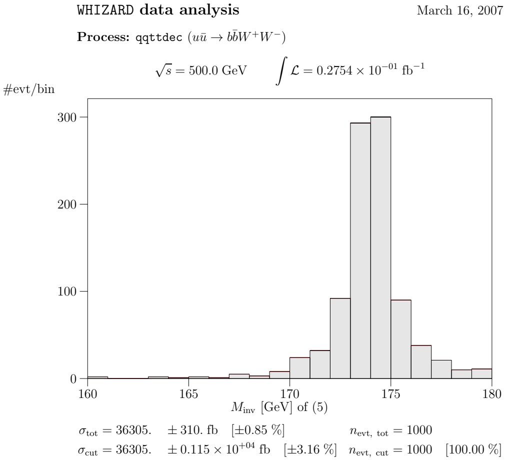


- Unification of model setup: only one binary (2.3.0)
- Specification of order of strong or EW coupling (2.3.x/2.4)
- Teaser: new algorithm for generating loop diagrams (3.0 ?)

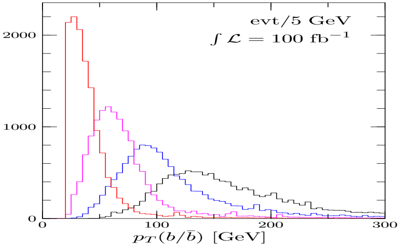
WHIZARD histograms

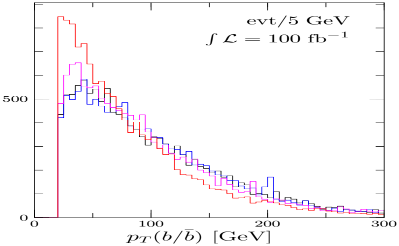


New completely general cut syntax in WHIZARD 2.0.0 (`analysis.dat`)

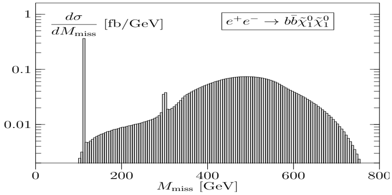
```
process default
cut all E of visible (any) > 10
cut all M of visible (any), visible (any) > 10
cut all Q of incoming particle (any), visible (any) < -10
histogram max_val(PT of jet) within 50 400 nbin 35
```

- First MSSM multijet combinatorics studies (2005):





- Beamstrahlung/ISR effects in $e+e-$ (BSM) physics:



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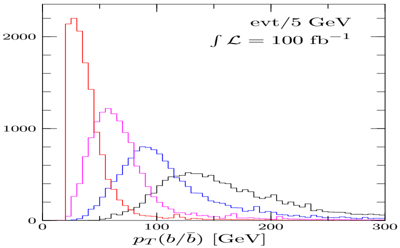

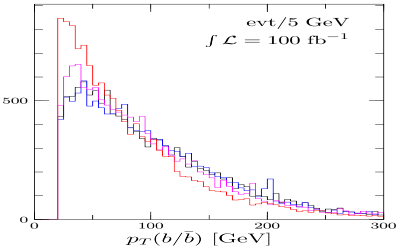

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