BSM Physics and WHIZARD

Wolfgang Kilian

U Siegen

MC4BSM, Daejeon, May 2014

MC4BSM

After Higgs discovery: is the SM complete?

- No new particles found in collider event samples
- No significant deviations found in precision data

Options

1. New particles associated with the EWSB scale, the underlying model is weakly interacting like the SM.
2. The Standard Model is complete, no new physics at energies accessible to colliders
3. Small deviations from the SM that eventually lead to a more fundamental model at multi-TeV

1. New Particles

If there are weakly interacting new particles at collider energies, MC writers are in a favorable situation because

- The underlying model is expressible as a Lagrangian
- Amplitudes are calculable in terms of Feynman rules and free parameters
- Cross sections are calculable in perturbation theory
- Events can be simulated using models of strongly-interacting QCD

This chain of calculations is feasible (to some extent) and can be done automatically, given the input.

However…

By construction,

a weakly interacting model cannot solve the hierarchy problem.

(It may shift the problem to some hidden, strongly interacting sector, though.)

By construction,

a weakly interacting model cannot solve the hierarchy problem.

(It may shift the problem to some hidden, strongly interacting sector, though.)

Naturally large scale ratios result from strong interactions.

2. Pure Standard Model

Completely calculable (up to QCD modelling).

Quantitative confirmation?

2. Pure Standard Model

Completely calculable (up to QCD modelling).

Quantitative confirmation?

$\Rightarrow$ Scenario 3.

3. Small Deviations

Higgs-Sector Properties: energy-independent

1. Higgs Couplings
2. Top-quark properties

LHC: almost inaccessible (expect few %)

$\Rightarrow$ **ILC, CLIC**

Higgs-Sector Properties: energy-dependent

3. Vector-Boson Scattering: strong cancellation in $W - Z$ interactions due to Higgs exchange

$$f \sim m_H^4/s^2 \sim 10^{-4}$$

LHC: observable (and ILC+, CLIC)

Established method: Effective Field Theory. Many successful applications:

- Gauge interactions: W/Z pair production
- Flavor Physics: HQET, OPE
- Jet Physics: SCET
- ...

Version for vector-boson scattering: dimension-8 operators

Unfortunately...

Effective-Field Theory for vector-boson scattering doesn't work.

- SM strongly suppressed (longitudinal modes)
- Operators have dimension 8

$\Rightarrow$ Interference small

$\Rightarrow$ New-Physics contribution to cross section rises $\sim E^8$

$\Rightarrow$ This cancels all energy suppression factors

Effective-Field Theory for vector-boson scattering doesn't work.

- SM strongly suppressed (longitudinal modes)
- Operators have dimension 8

$\Rightarrow$ Interference small

$\Rightarrow$ New-Physics contribution to cross section rises $\sim E^8$

$\Rightarrow$ This cancels all energy suppression factors

$\Rightarrow$ The EFT violates the unitarity limit, almost immediately

A straightforward simulation based on this generates unphysical events over most of phase space.

Monte Carlos for BSM should handle
(unknown) non-perturbative electroweak interactions.

WHIZARD

WHIZARD is a tool for collider physics:

- Models: prebuilt or via FeynRules or SARAH
- Beams: PDFs for LHC, detailed beam description for ILC/CLIC
- Processes: Automatic LO matrix elements for arbitrary hard processes from SM and BSM
- Phase-space parameterization module
- Integration: Adaptive multi-channel integration and (unweighted) partonic event generation
- Decays: Cascades with full spin correlations
- Shower+Matching: Included or external
- Hadronization: external

Prebuilt 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 WW resonances and unitarization	—	SSC
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)	—	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

SM with anomalous couplings

Start with conventional EFT, $d = 6, 8$ operators

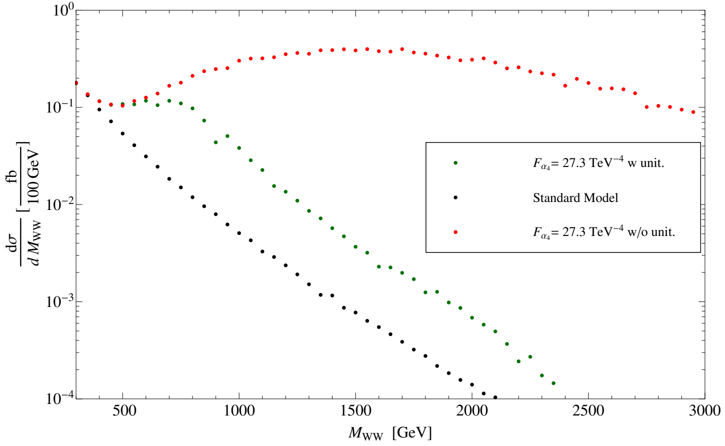
- Unitarization prescription: K-Matrix

Algorithm, in a nutshell:

1. Look at pure Goldstone scattering ($s \gg m_W^2$)
2. Diagonalize scattering matrix
3. Unitarize diagonal elements (parameter-free)
4. Corrections as effective vertices for Goldstones
5. Gauge the model $\Rightarrow$ effective vertices for W/Z
6. Insert into amplitude computation $\Rightarrow$ off-shell extrapolation

Note: this restores unitarity, but by construction is non-hermitian and non-local, not expressible as a Lagrangian

$pp \to 6f$, VBS Cuts



More Structure in EW Interactions

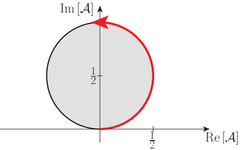
Unitarization saturates unitarity in each scattering channel, asymptotically.

⇒ No room for further structure

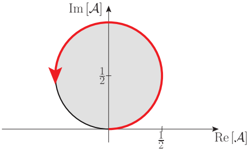
Our approach: Match the unitarized effective theory to a Simplified model of Strong interactions and Compositeness (SSC)

WK/Reuter/Sekulla, in prep.

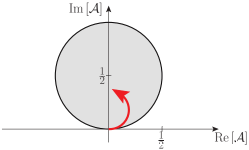
Possibilities



A: Saturation



B: Resonance



C: Inelastic

(WHIZARD: `ssc`)

Quantum Numbers

I	0	1	2
$J=0$	σ^0	.	$\phi^{--}, \phi^{-}, \phi^{0}, \phi^{+}, \phi^{++}$
1	.	$\rho^{-}, \rho^{0}, \rho^{+}$	.
2	f^0	.	$t^{--}, t^{-}, t^{0}, t^{+}, t^{++}$
...	...	...	...

- $I = 0$: resonant in W^+W^- and ZZ scattering
- $I = 1$: resonant in W^+Z and W^-Z scattering
- $I = 2$: resonant in W^+W^+ and W^-W^- scattering

In total (isospin preserved, CP, higher spin ignored):

- 5 resonances with 3 parameters each (M, g_L, g_T)
- quartic anomalous couplings of longitudinal VB
- quartic anomalous couplings of transversal VB
- quartic anomalous couplings mixing T and L

Structured Beams

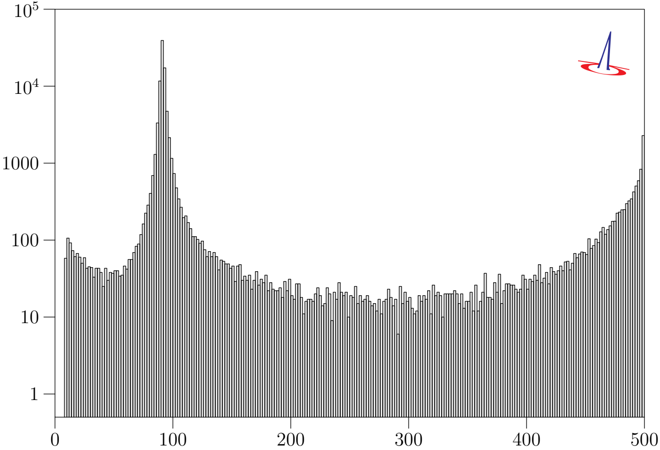
- Lepton Colliders
  - arbitrarily polarized beams (density matrices), crossing angle
  - detailed beam description for ILC and CLIC
    1. Parameterized beamstrahlung: CIRCE 1
    2. Use beam-event files directly (Guinea Pig output)
    3. Beam-event files transformed into generator: CIRCE 2
  - ISR (3rd order Skrzypek/Jadach, Kuraev/Fadin, incl. p_T)
  - EPA
  - Photon collider spectra (CIRCE 2)

- Hadron Colliders
  - LHAPDF interface
  - Most prominent PDFs directly included
  - Scan over structure functions: multiple event weights

- Stand-alone particle decays
  - decay in isolation, treated like scattering process
  - polarization of decaying particle

$e^+e^- \to b\bar{b}$

ILC: $500\ \text{GeV}$, beamstrahlung $\otimes$ ISR, no cuts, 100k events: $M(b\bar{b})$



Hard Matrix-element calculation

WHIZARD's matrix element generator: O'Mega

Ohl/Moretti/Reuter, hep-ph/0102195

- Algebraic construction of helicity amplitude, using model description (programming language: OCaml)
- Avoid expansion in Feynman graphs: maximally factored DAG
- Avoid color algebra: color-flow formalism

WK/Ohl/Reuter/Speckner, JHEP 2012

- Amplitude converted into Fortran code for evaluation, dynamically compiled and linked
- OpenMP for sum over helicities

O'Mega: Optimal matrix elements

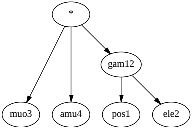
Ω

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

O'Mega: Optimal matrix elements

Ω

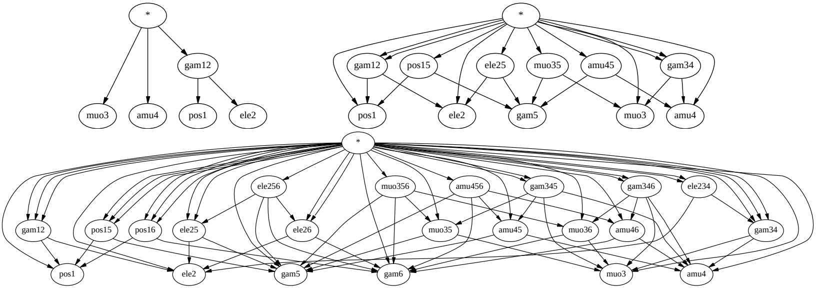
- Replace forest of tree diagrams by Directed Acyclical Graph (DAG) of the algebraic expression (including color).
- simplest examples: $e^+e^- \to \mu^+\mu^-$, and



O’Mega: Optimal matrix elements

Ω

- Replace forest of tree diagrams by
  Directed Acyclical Graph (DAG) of the algebraic expression (including color).
- simplest examples: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma\gamma$



Integration

WHIZARD's integrator: VAMP

Ohl, CPC 1999

- Multichannel integration, adaptive channel weights
- Adaptive binning within each channel (VEGAS)
- Many degrees of freedom, good reweighting efficiency achievable

WHIZARD:

- Keep this freedom under control by selecting relevant subset of all parameterizations

Final State

- Partonic events
  1. Complete multi-particle matrix elements: $pp \to 3j$
  2. Restriction to intermediate state: $pp \to (W^+ \to jj) + j$
  3. On-shell factorization, spin-correlated: $pp \to (W^+ j) \otimes W^+ \to jj$
  4. On-shell factorization, isotropic decay

- Event sample output
  1. Built-in analysis language (observables, histograms, plots)
  2. External event files (ASCII, HEPEVT, StdHEP, LHEF, HepMC, . . .)

- Partons to Hadrons
  1. Run shower/hadronization on event file
  2. Internal interface to PYTHIA 6
  3. Analytic Shower (WHIZARD internal) + external hadronization

SINDARIN: Talking to WHIZARD

Example:

```
process foo =  e1, E1 => n1, N1, H
simulate (foo) { sqrts = 500 GeV  n_events = 10000 }
```

Scope

- Set model, parameters, user variables
- Conditionals and loops, arbitrary workflow
- Multiple processes and process combinations, flavor sums
- Automatic width calculation
- Beams: chain of spectra and structure functions, polarization
- Integration and simulation, shower and hadronization parameters
- Arbitrary expressions for cuts, scale, weight, etc.
- Event sample output: raw, ASCII, LHE, HepMC, StdHEP, . . .
- Event sample reweighting, output multiple weights
- Internal analysis: histograms and plots

Technical Features

- WHIZARD 2: code rewritten: object-oriented Fortran (`Fortran 2003`) and `OCaml`
- User projects separate from WHIZARD installation
- Object-oriented code organization, modularization of code, separation of interface and (interchangeable) implementation
- 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

Summary

- WHIZARD 2.2.0 for LC and LHC physics
- Detailed implementation of ILC beam properties
- Modelling a non-SM sector of electroweak symmetry breaking
- Steered via the HepForge page:
  `http://projects.hepforge.org/whizard`
- E-mail contact: `whizard@desy.de`
- Authors (currently):
  F. Bach, B. Chokoufe, WK, T. Ohl, J. Reuter, M. Sekulla, C. Weiss, D. Wiesler