EFT, Unitarization, and the WHIZARD Connection

Wolfgang Kilian

University of Siegen

Multi-Boson Interactions, Karlsruhe
August 2017

Vector-Boson Scattering Processes at Colliders

Basic Process

$$VV \to VV \qquad \text{where } V = W^+, W^-, Z$$

or, hopefully

$$VV \to X \qquad \text{where } X = BSM? \qquad \to VV, \ldots$$

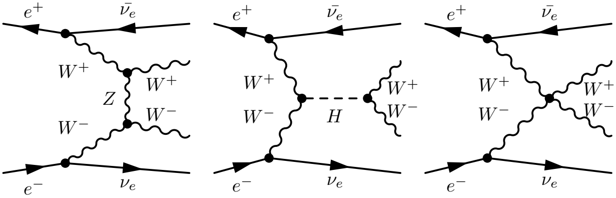
Vector-Boson Scattering Processes at LHC

VBS at LHC

- Process: $pp \to qq \to jj + VV \to jj + 4f$
- $\sqrt{\hat{s}}(VV) \lesssim 1$ TeV
- First observation: ATLAS, PRL 113, 141803 (2014) consistent with SM

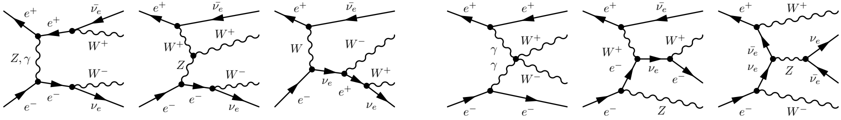
VBS Feynman Graphs in the SM (e^+e^-)

Signal



. . . *pp* analogous, also WZ/ZZ. Describe all W/Z decays, esp. jj.

Background



. . . and 6-fermion continuum, reducible bg

Physics Potential of VBS

1. Precision test of the electroweak SM at high energy
2. The Higgs Mechanism at work
3. Anomalous Higgs couplings (beyond branching ratios)
4. New Higgs-sector physics and the Higgs Portal
   - Extra Higgses
   - Resonances excited by VBF
   - Strong interactions, continuum, compositeness
   - New final states (DM?)

Requirements for Collider Analysis (pp, e^+e^- complementary)

- high energy $\sqrt{\hat{s}} \gtrsim 1$ TeV
- high precision, complete coverage of final states
- separation of spin, isospin, CP quantum numbers

Theoretical Description: Requirements

1. SM (LO) complete 6-fermion final states (VBS, VVV, VH, ...)
2. SM: QCD NLO
3. SM: electroweak NLO

Theoretical Description: Requirements

1. SM (LO) complete 6-fermion final states (VBS, VVV, VH, ...)
2. SM: QCD NLO
3. SM: electroweak NLO
4. beam structure (PDF, beamstrahlung, polarization)
5. exclusive events (shower, hadrons)

Theoretical Description: Requirements

1. SM (LO) complete 6-fermion final states (VBS, VVV, VH, …)
2. SM: QCD NLO
3. SM: electroweak NLO
4. beam structure (PDF, beamstrahlung, polarization)
5. exclusive events (shower, hadrons)
6. BSM: anomalous couplings ($D = 6$ and $D = 8$ EFT) for low energy threshold
7. BSM: renormalizable extended Higgs sector
8. BSM: simplified models for generic (weak/strong) interactions

Integration and event samples: WHIZARD, VBFNLO, MG5, Sherpa, …

Theoretical Description: WHIZARD

1. SM (LO) complete 6-fermion final states (VBS, VVV, VH, ...) OK
2. SM: QCD NLO w/ GoSAM, OpenLoops, Recola (validation)
3. SM: electroweak NLO (w.i.p.)
4. beam structure (PDF, beamstrahlung, polarization) OK
5. exclusive events (shower, hadrons) w/ Pythia (virt.resonances)
6. BSM: anomalous couplings ($D = 6$ and $D = 8$ EFT) for low energy threshold OK
7. BSM: renormalizable extended Higgs sector OK
8. BSM: simplified models for generic (weak/strong) interactions ($V_L V_L$, $V_T V_T$, VVV)

Range of Interesting Phenomenology

for studying the potential of (future) colliders, the amount of information that we can expect to obtain

- Standard Model
- Renormalizable extensions (THDM, . . .)

- Compositeness
- EFT

Range of Interesting Phenomenology

for studying the potential of (future) colliders, the amount of information that we can expect to obtain

- Standard Model – need NLO, detailed comparison with data
- Renormalizable extensions (THDM, ...) – is renormalizability a phenomenological category?
- Compositeness – detailed calculable predictions?
- EFT – the interesting data are those beyond the EFT validity range

BSM Effects in VBS: Generic Description

Boundary conditions

- Low energy: consistent with flavour / EW precision data
  (SM gauge symmetry, minimal flavor violation)
- Electroweak scale $\sim 100 \ldots 200$ GeV: matched to SMEFT
  (precision data to be gathered at HL-LHC, ILC, CEPC/FCCee, CLIC
- Intermediate range: unknown
  (HE-LHC/FCC-hh/CLIC measurement)
- Asymptotics: consistent with unitary, strongly or weakly interacting
  (suppressed $\Rightarrow$ precise predictions not required for data analysis)

SM prediction for all energies calculable, assumed as reference.

Asymptotic Theory

Model-building is limited by the conservation of probability.

Assumptions:

1. light fermions decouple from interesting physics
2. gauge bosons are gauge bosons

Asymptotical constraints:

Limits on scattering amplitudes determined by unitarity, calculable

$\Rightarrow$ Interpretation: rescattering dampens all interactions, saturation

$\Rightarrow$ Suppression of asymptotics due to decoupling fermion currents

Real experiment w/ limited energy & luminosity: data dry out in asymptotia, so details may not matter.

Interpolating Scenarios

1. Standard Model
    - reference model, all new parameters vanish
2. Featureless, strongly interacting continuum
    - represented by minimal unitary extrapolation of SMEFT (higher-D operators)
3. Resonances above continuum
    - classified by global symmetries
4. Asymptotic suppression ("form-factor")
    - inelastic channels opening up, allow for new final states

Low-Energy (In-)Effective Theory

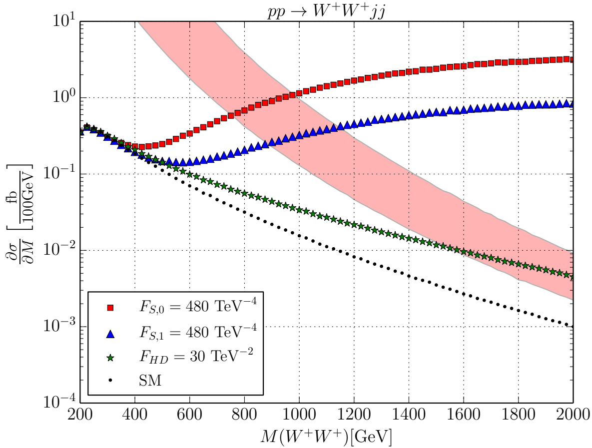
SMEFT extends the SM in a systematic way, to parameterize

Electroweak Observables

1. Low-energy (flavor) data
2. Gauge-boson decays
3. Higgs decays
4. Gauge and gauge-Higgs interactions at limited energy

High-energy weak interactions $\Rightarrow$ beyond power expansion

Example: SMEFT Failure at the LHC



Calculation: WHIZARD (M. Sekulla)

Recipe for Unitary Simplified Models

1. Construct interpolating model ⇒ amplitudes (T_0 matrix elements)
2. Incorporate rescattering:
   Recalculate amplitudes ⇒ unitary model

$$T = \frac{\mathrm{Re}\, T_0}{\mathbb{1} - \frac{\mathrm{i}}{2} T_0^\dagger}. \qquad \text{or} \qquad T = \frac{1}{\mathrm{Re}\left(\frac{1}{T_0}\right) - \frac{\mathrm{i}}{2}\mathbb{1}} \qquad .$$

   - This is a generalized Dyson resummation / Breit-Wigner prescription
   - Asymptotic limits are automatically satisfied
   - Low-energy SMEFT parameters can be computed, to match with global-fit data
   - Isolates the phenomenologically most relevant information contained in UV models (2HDM, Higgs portal, compositeness, ...)

3. Ready for off-shell evaluation and event generation

"Unitarization"

recipe to take a non-unitary prediction and obtain a unitary = better prediction?

Historically: applied to perturbation theory (Heitler 1941, "K matrix")

"Unitarization"

recipe to take a non-unitary prediction and obtain a unitary = better prediction?

Historically: applied to perturbation theory (Heitler 1941, "K matrix")
The relevance of this is unclear – this is not our motivation.

"Unitarization"

recipe to take a non-unitary prediction and obtain a unitary = better prediction?

Historically: applied to perturbation theory (Heitler 1941, "K matrix")
The relevance of this is unclear – this is not our motivation.

Unitary Models of VBS

- accept that there is no preferred prediction beyond SM
- perturbation theory (EFT) insufficient ⇒ no K matrix, Padé, etc.
- construct just unitary models, discard non-unitary models
- direct "T-matrix" unitarization does just that
- all simplified models are incomplete, obviously, but

“Unitarization”

recipe to take a non-unitary prediction and obtain a unitary = better prediction?

Historically: applied to perturbation theory (Heitler 1941, “K matrix”)
The relevance of this is unclear – this is not our motivation.

Unitary Models of VBS

- accept that there is no preferred prediction beyond SM
- perturbation theory (EFT) insufficient $\Rightarrow$ no K matrix, Padé, etc.
- construct just unitary models, discard non-unitary models
- direct “T-matrix” unitarization does just that
- all simplified models are incomplete, obviously, but
- The distinction is phenomenologically relevant for LHC and CLIC

I Simplified Models for Longitudinal Scattering

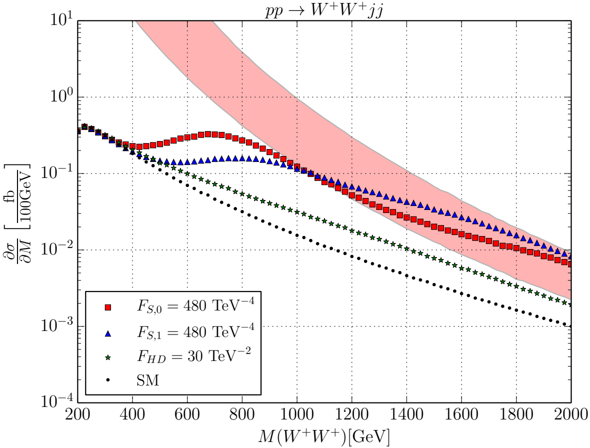
Signal processes: $pp \to jj + 4f$ and $e^+e^- \to \bar{\nu}\nu + 4j$

- Contact to SMEFT: Higgs/Goldstone interactions in $D = 8$ operators:

$$\mathcal{L}_{S,0} = F_{S,0}\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}_\nu\mathbf{H})]\,\mathrm{Tr}[(\mathbf{D}^\mu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$
$$\mathcal{L}_{S,1} = F_{S,1}\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})]\,\mathrm{Tr}[(\mathbf{D}_\nu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$

- Physics: Extended Higgs sector, Higgs portal, compositeness, etc.
- Signal is confined to longitudinally polarized $VV \to VV$ where $V = W, Z$ and $VV \to 4j$.

Parameterized Unitary Model: Featureless Continuum



Calculation (WHIZARD): M. SEKULLA

Collider Setup: CLIC Parameters

Energy stages and int. luminosities

- ($E_1 = 350/375\,\text{GeV}$, $\mathcal{L}_{int,1} = 500\,\text{fb}^{-1}$)
- $E_2 = 1400\,\text{GeV}$, $\mathcal{L}_{int,2} = 1500\,\text{fb}^{-1}$
- $E_3 = 3000\,\text{GeV}$, $\mathcal{L}_{int,3} = 2000\,\text{fb}^{-1}$

Initial state polarization: e^- : 80%, e^+ : 0%

Low angle coverage M. Idzik: DOI: 10.5506/APhysPolB.46.1297

- LumiCal: 38-110 mrad
- BeamCal: 15-38 mrad

W and Z identification J. S. Marshall, A. Mnnich, M. A. Thomson: arXiv:1209.4039

- $\approx$ 88 % (with photon induced bkg.: 71-79 %)

CLIC: Differential cross sections

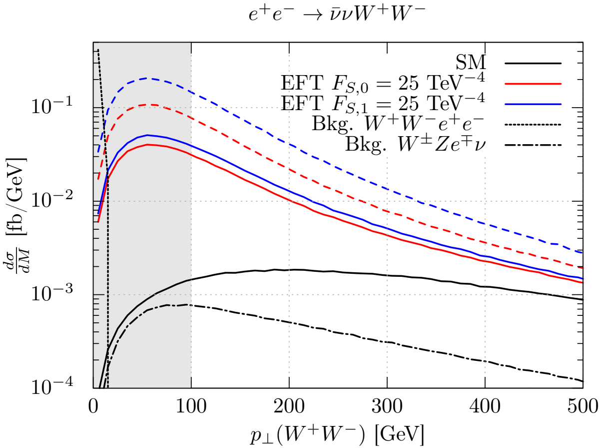
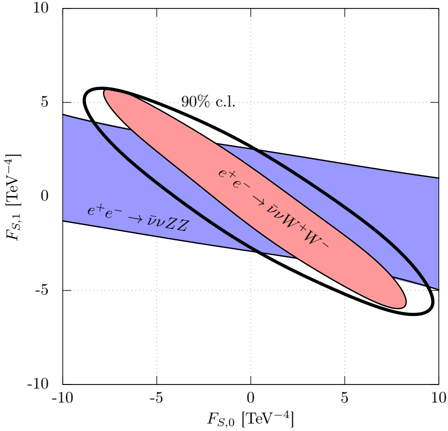


Figure: Differential cross sections depending on the transverse momentum of the W boson pair at $\sqrt{s} = 3000\,\mathrm{GeV}$.

CLIC: Exclusion contours at 3000 GeV

Continuum model matched to low-energy SMEFT with two $D = 8$ parameters



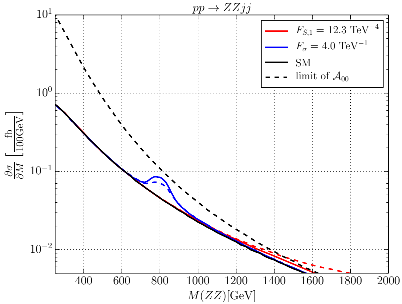
$\Rightarrow$ confirmed by full simulation

Resonances

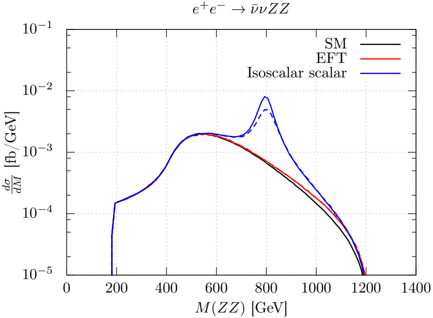
Looked at four simple cases (multiplets)

- Isoscalar – Scalar (neutral)
- Isotensor – Scalar (5 states: $++$, $+$, 0, $-$, $--$)
- Isoscalar – Tensor (neutral)
- Isotensor – Tensor (5 states)

Comparison: scalar-isoscalar resonance (H'), with cuts

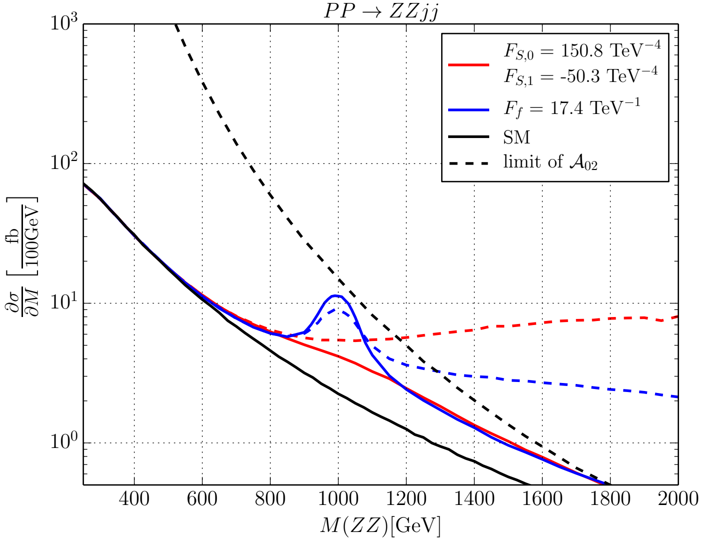


LHC (14 TeV)

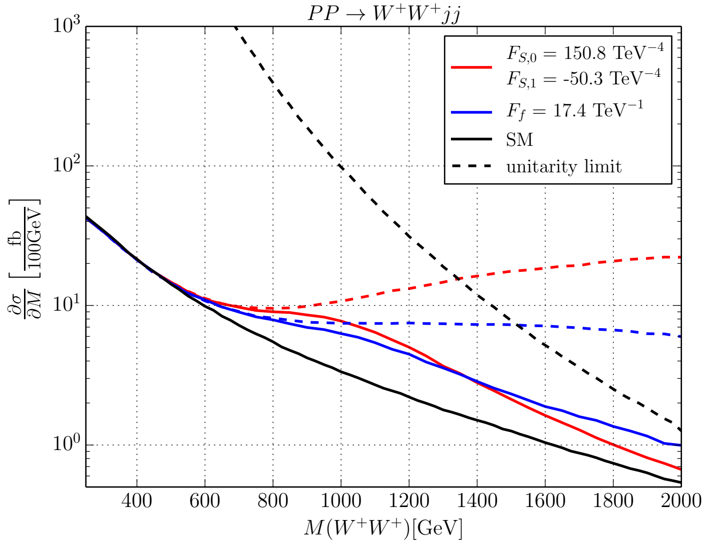


CLIC (1.4 TeV)

Results for LHC: Tensor Resonance



Results for LHC: Tensor Resonance in t Channel



II Simplified Models With Transversal Scattering

- Contact to SMEFT: transversal and longitudinal couplings in $D = 8$ operators

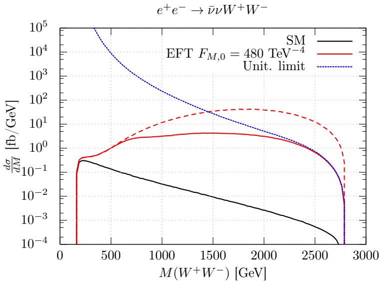
$$\mathcal{L}_{S,0} = F_{S,0} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}_\nu \mathbf{H})] \, \mathrm{Tr}[(\mathbf{D}^\mu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})]$$
$$\mathcal{L}_{S,1} = F_{S,1} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})] \, \mathrm{Tr}[(\mathbf{D}_\nu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})]$$

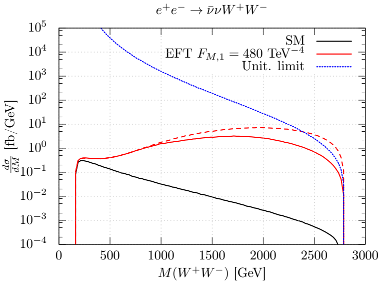
$$\mathcal{L}_{M,0} = -g^2 F_{M,0} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})] \, \mathrm{Tr}[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\rho}]$$
$$\mathcal{L}_{M,1} = -g^2 F_{M,1} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})] \, \mathrm{Tr}[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\mu}]$$

$$\mathcal{L}_{T,0} = g^4 F_{T,0} \mathrm{Tr}[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] \, \mathrm{Tr}[\mathbf{W}_{\alpha\beta} \mathbf{W}^{\alpha\beta}]$$
$$\mathcal{L}_{T,1} = g^4 F_{T,1} \mathrm{Tr}[\mathbf{W}_{\alpha\nu} \mathbf{W}^{\mu\beta}] \, \mathrm{Tr}[\mathbf{W}_{\mu\beta} \mathbf{W}^{\alpha\nu}]$$
$$\mathcal{L}_{T,2} = g^4 F_{T,2} \mathrm{Tr}[\mathbf{W}_{\alpha\mu} \mathbf{W}^{\mu\beta}] \, \mathrm{Tr}[\mathbf{W}_{\beta\nu} \mathbf{W}^{\nu\alpha}]$$

- Physics: anomalous gauge interactions

CLIC: $e^+e^- \to \bar{\nu}\nu W^+W^-$, LT-mixed couplings

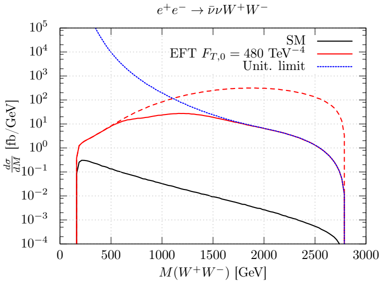


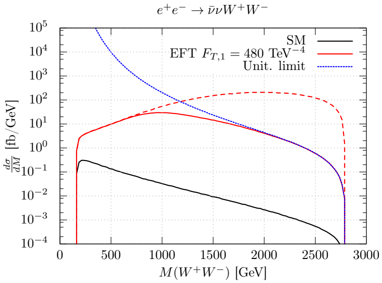


CLIC 3 TeV, continuum model, no cuts

Plots: C. Fleper

CLIC: $e^+e^- \to \bar{\nu}\nu W^+W^-$, transversal couplings

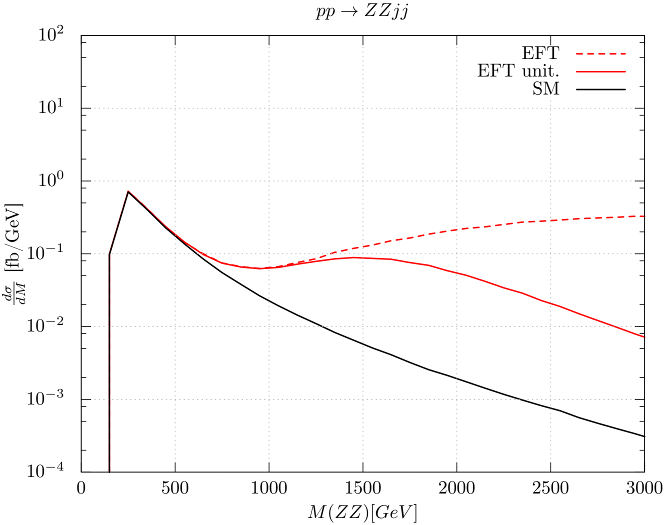




CLIC 3 TeV, continuum model, no cuts

Plots: C. Fleper

LHC: Transversal ZZ Coupling to Continuum



III WHIZARD: Exclusive event samples for all models

- Complete partonic events: unweighted event samples using the O'Mega matrix-element generator and the VAMP multi-channel integration/generation module
- News:

III WHIZARD: Exclusive event samples for all models

- Complete partonic events: unweighted event samples using the O'Mega matrix-element generator and the VAMP multi-channel integration/generation module
- News:

  Parallel adaptation and event generation via MPI multi-processing (S. Brass)

  $\Rightarrow$ speedup by factor 10–100

  $\Rightarrow$ further improvements (phase-space construction): M. Utsch

III WHIZARD: Exclusive event samples for all models

- Complete partonic events: unweighted event samples using the O'Mega matrix-element generator and the VAMP multi-channel integration/generation module
- News:

  Parallel adaptation and event generation via MPI multi-processing (S. Brass)

  $\Rightarrow$ speedup by factor 10–100

  $\Rightarrow$ further improvements (phase-space construction): M. Utsch
- Unitary simplified models: off-shell extrapolation and unitarity corrections implemented as momentum-dependent vertices (manual diagonalization of scattering matrices); embedded in full simulation
- Connection to multi-Higgs processes: Z. Zhao

WHIZARD: Exclusive event samples for all models

- NLO QCD events:

  detailed study for $e^+e^- \to t\bar{t}$ off-shell threshold and continuum (B.Chokoufe, C.Weiss)

  generalization to all processes at NLO QCD (also pp): validating against MG5, VBFNLO (S.Brass, V.Rothe)

WHIZARD: Exclusive event samples for all models

- Detailed beam description for ILC/CLIC: Circe2
- Shower and Hadronization: PYTHIA interfaced
- News:

WHIZARD: Exclusive event samples for all models

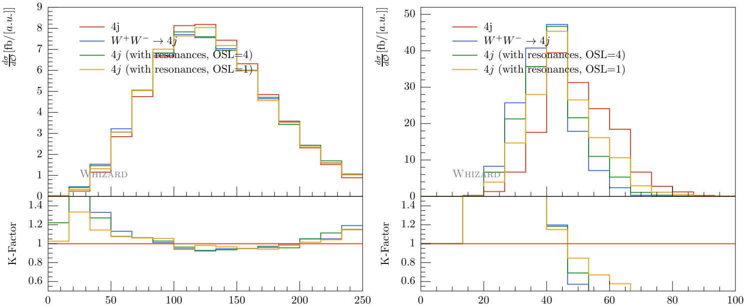
- Detailed beam description for ILC/CLIC: Circe2
- Shower and Hadronization: PYTHIA interfaced
- News: Resonance-aware Shower
  - factorized $WW \to 4q$: shower starts at M_W
  - complete $4f$: no intermediate history, shower starts at $\sqrt{\hat{s}}$
  - WHIZARD (next release): event-by-event, automatically incorporate resonant ME where appropriate

    $\Rightarrow$ insert resonances in the MC event history, based on relative probabilities

WHIZARD: Resonance-aware Shower

$e^+e^- \to 4q$ (WHIZARD/PYTHIA6):

photon energy / number of charged particles



Plots: B.Chokoufe

WHIZARD for High-Energy Electroweak Interactions

- Describe typical behavior of S-matrix elements (SM, new weak interactions, resonances, strongly-interacting continuum)
- Incorporate reasonable assumptions on the nature of BSM
- Account for all modes in SM and new physics
- Match BSM to SMEFT (i.e., present and future global fits)
- Simulated exclusive data samples for all scenarios, highly parallel evaluation
- Resonance-aware shower for hadronic final states

References

1. C. Fleper, W. Kilian, J. Reuter and M. Sekulla, "Scattering of W and Z Bosons at High-Energy Lepton Colliders," Eur. Phys. J. C **77** (2017) no.2, 120 [arXiv:1607.03030 [hep-ph]].
2. B. Chokouf Nejad, W. Kilian, J. M. Lindert, S. Pozzorini, J. Reuter and C. Weiss, "NLO QCD predictions for off-shell $t\bar{t}$ and $t\bar{t}H$ production and decay at a linear collider," JHEP **1612**, 075 (2016) [arXiv:1609.03390 [hep-ph]].
3. W. Kilian, T. Ohl, J. Reuter and M. Sekulla, "Resonances at the LHC beyond the Higgs boson: The scalar/tensor case," Phys. Rev. D **93** (2016) no.3, 036004 [arXiv:1511.00022 [hep-ph]].
4. W. Kilian, T. Ohl, J. Reuter and M. Sekulla, "High-Energy Vector Boson Scattering after the Higgs Discovery," Phys. Rev. D **91** (2015) 096007 [arXiv:1408.6207 [hep-ph]].
5. W. Kilian, T. Ohl and J. Reuter, "WHIZARD: Simulating Multi-Particle Processes at LHC and ILC," Eur. Phys. J. C **71** (2011) 1742 [arXiv:0708.4233 [hep-ph]].