Non-Standard Interactions of W and Z Bosons: Simplified Models

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LCWS, Morioka
December 2016

Outline

1. Generic new physics in electroweak interactions (Higgs, W, Z)
2. Recipe for a generic, meaningful phenomenological description
3. Results from calculations

Interactions of W, Z, Higgs

in the pure SM

- Signals and backgrounds: calculable.
- LC experimental precision requires further theoretical effort

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New Physics

- May be related to Naturalness, Baryogenesis, Dark Matter
- May be coupled only to Higgs or weak interactions
- Effect has been unobservable, so far
- But anything is possible: no preferred type of model

Goal of this Project

Universal phenomenological description of non-SM electroweak interactions in the high-energy range

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Could be useful for

- Studies of collider sensitivity
- Comparison and studies of LHC / LC complementarity
- Combination of low-energy and high-energy data
- Initial understanding w/o hidden theoretical assumptions

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- All amplitudes reduce to SM, deviations are EFT operators

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Working Hypotheses

- Light fermions act as spectators
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High-energy boundary condition

- New physics leads to enhancement $\Rightarrow$ SM as lower limit
- Any physics leads to unitary amplitudes $\Rightarrow$ upper limit

Low Energy: Effective Theory

("Higgs") Effective Field Theory = double expansion

- powers of gauge-invariant interactions
- perturbative EW/QCD corrections

Electroweak Observables, class I

1. Flavour precision observables: currents
2. Low-energy electroweak observables
3. Higgs decays

Intermediate Energy: Ineffective Theory

Electroweak Observables, class II

1. Vector-boson production (VV, VVV, ...)
2. Vector-boson scattering ($VV \to VV$)
3. Higgs/associated production (H, HV, HH, ...)

Production processes – “unlimited” in energy (LHC, CLIC)

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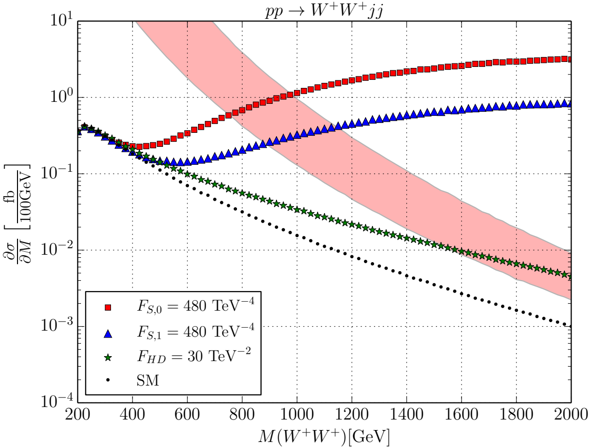
HEFT fails as a phenomenological model.

EFT Failure at the LHC



Calculation: WHIZARD (M. Sekulla)

High Energy: Asymptotic Theory

Any set of amplitudes is constrained by the conservation of probability.

Electroweak Observables, class III

1. Physical dampening effect: rescattering
2. Interactions eventually reach saturation
3. Suppression of asymptotics due to decoupling fermion currents

$\Rightarrow$ Phenomenological description must incorporate rescattering,

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$\Rightarrow$ Phenomenological description must incorporate rescattering,

Rates are low, so further details may not matter.

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- $\Rightarrow$ enable off-shell evaluation and exclusive event-sample generation

Recipe for Unitary Simplified Models

- Construct arbitrary model ⇒ amplitudes (T_0 matrix elements)
- Incorporate rescattering:
  Recalculate amplitudes ⇒ unitary model

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

  - Low-energy SM/EFT limit straightforward
  - Asymptotic limits are automatically satisfied
  - Asymptotic details (phases, channels) arbitrary – but largely irrelevant
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Cross check: Pole ⇒ Breit-Wigner resonance.

Process List

1. VV scattering ($V = W, Z$), longitudinal and transversal V-polarization
2. VV production, EFT expansion beyond $D = 6$
3. VVV production, all polarizations
4. Higgs-associated production, all polarizations
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Scenario List

1. Standard Model
   - reference model, all new parameters vanish
2. Featureless, strongly interacting continuum
   - unitary extrapolation of plain EFT (higher-D operators)
3. Resonances above continuum
   - Extensions of extrapolated EFT, classify by global symmetries
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(all BSM non-perturbative but reduce to SM/EFT at low energy.)

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Plan

- EW NLO for SM and EFT
- Combined model set for relevant processes, including Higgs

Study I: Simplified Models for Longitudinal Scattering

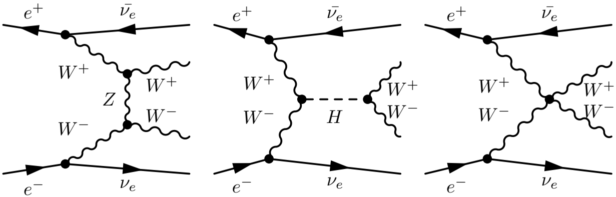
- Look at simplified models
  which at low energy reduce to purely longitudinal couplings:

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

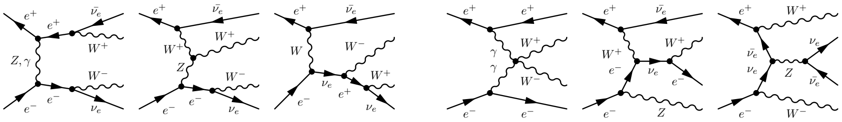
- Physics: anomalous Goldstone interactions, gauge interactions unchanged
- Signal is confined to $VV \to VV$ where $V = W, Z$ (or H).

Vector Boson Scattering: Feynman graphs (SM)

Signal



Background



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 %)

Total cross sections without cuts

Process	1400 GeV	3000 GeV	Factor
$W^+W^-\nu\bar{\nu}$	47.1	132	1
$W^+W^-e^+e^-$	1570	3820	1
$W^\pm Ze^\mp\nu$	138	408	0.136
ZZe^+e^-	3.78	4.70	0.019
$W^+W^-(Z\to\nu\bar{\nu})$	11.7	9.35	1
$ZZ\nu\bar{\nu}$	15.7	57.5	1
ZZe^+e^-	3.78	4.70	1
$W^\pm Ze^\mp\nu$	138	408	0.136
$W^+W^-e^+e^-$	1570	3820	0.019
$ZZ(Z\to\nu\bar{\nu})$	0.484	0.237	1

Table : Total cross sections in fb without cuts.

Differential cross sections

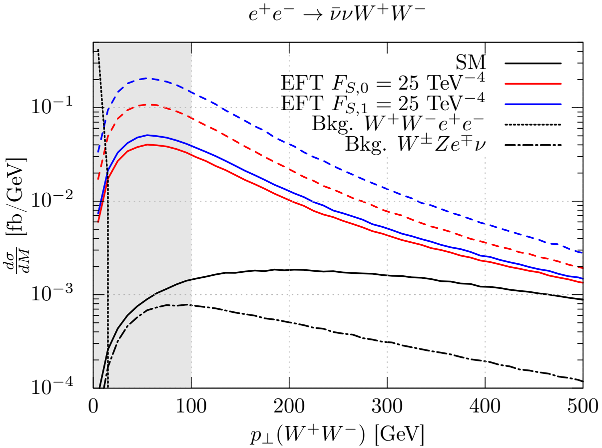


Figure : Differential cross sections depending on the transverse momentum of the W boson pair at $\sqrt{s} = 3000\,\text{GeV}$.

Used cuts

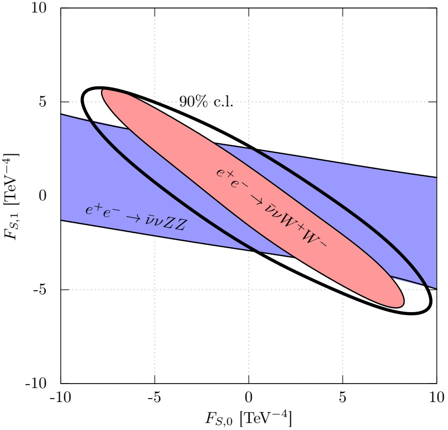
1. $M_{inv}(\bar{\nu}\nu) > 230(175)\,\text{GeV}$
   (neutrinos from Z, bg from W^+W^-, QCD 4j)
2. $|\cos\theta(W/Z)| < 0.8$
   and $p_\perp(W/Z) > 300(180)\,\text{GeV}$
   (bg from t-channel $W/Z/\gamma$)
3. $\theta(e) > 15\,\text{mrad}$
   and $p_\perp(WW) > 100(50)\,\text{GeV}$, $p_\perp(ZZ) > 60(40)\,\text{GeV}$
   (bg from $\gamma\gamma$)
4. $900(800)\,\text{GeV} < M_{inv}(WW) < 1900(1175)\,\text{GeV}$,
   $850(800)\,\text{GeV} < M_{inv}(ZZ) < 1900(1175)\,\text{GeV}$
   (non scattered W/Z)

Cross sections with cuts

Process	1400 GeV	3000 GeV	Factor
$W^+W^-\nu\bar{\nu}$	0.119	0.790	1
$W^+W^-e^+e^-$	0.000	0.000	1
$W^\pm Ze^\mp\nu$	0.269	1.200	0.136
ZZe^+e^-	0.000	0.000	0.019
$W^+W^-(Z\to\nu\bar{\nu})$	0.039	0.610	1
$ZZ\nu\bar{\nu}$	0.084	0.790	1
ZZe^+e^-	0.000	0.000	1
$W^\pm Ze^\mp\nu$	0.288	1.593	0.136
$W^+W^-e^+e^-$	0.000	0.000	0.019
$ZZ(Z\to\nu\bar{\nu})$	0.000	0.000	1

Table : Total cross sections in fb with cuts (error $\approx$ 1%).

Exclusion contours and exclusion sensitivities at 3000 GeV



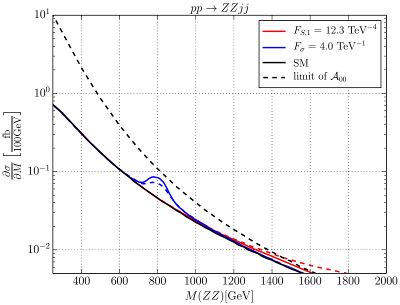
$\Rightarrow$ 90% exclusion sensitivity $\approx 5 - 7\,\mathrm{TeV}^{-4}$

Resonances

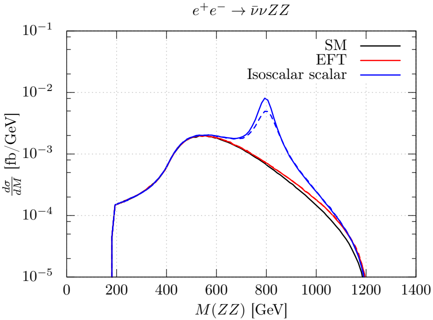
Looked at four simple cases (multiplets)

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

Comparison: scalar-isoscalar resonance "(H')"



LHC (14 TeV)



CLIC (1.4 TeV)

Study II: Simplified Models With Transversal Scattering

- With transversal couplings, *VVV* is part of the signal
  $\Rightarrow$ combined analysis.
- Low energy limit: transversal and longitudinal couplings

$$\mathcal{L}_{S,0} = F_{S,0}\,\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}_\nu\mathbf{H})]\,\mathrm{Tr}[(\mathbf{D}^\mu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$
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$$\mathcal{L}_{M,0} = -g^2F_{M,0}\,\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})]\,\mathrm{Tr}[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\rho}]$$
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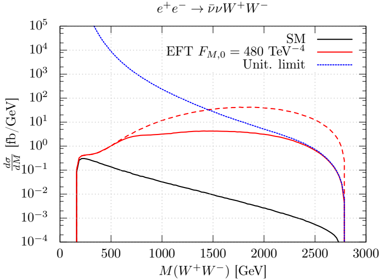
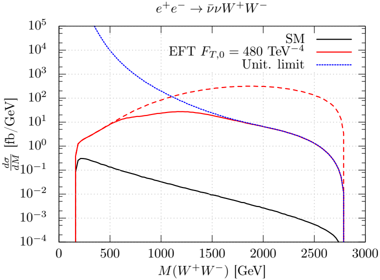
$$\mathcal{L}_{T,0} = g^4F_{T,0}\,\mathrm{Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}]\,\mathrm{Tr}[\mathbf{W}_{\alpha\beta}\mathbf{W}^{\alpha\beta}]$$
$$\mathcal{L}_{T,1} = g^4F_{T,1}\,\mathrm{Tr}[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}]\,\mathrm{Tr}[\mathbf{W}_{\mu\beta}\mathbf{W}^{\alpha\nu}]$$
$$\mathcal{L}_{T,2} = g^4F_{T,2}\,\mathrm{Tr}[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}]\,\mathrm{Tr}[\mathbf{W}_{\beta\nu}\mathbf{W}^{\nu\alpha}]$$

- Pure longitudinal couplings suppressed in *VVV* production, others unsuppressed

VBS with LT/TT interactions: $e^+e^- \to W^+W^-\bar{\nu}\nu$





Plots: WHIZARD (C. Fleper)

(combination with W^+W^-Z and ZZZ: w.i.p.)

Summary

- Anomalous electroweak interactions are outside the realm of perturbation theory, EFT, or any other predictive framework.
- For a parameterization, we have to introduce phenomenological models, which
  - smoothly match to the low-energy EFT
  - display valid asymptotics = unitarity
- This can be done in the framework of a complete, exclusive Monte-Carlo simulation (WHIZARD).
- The parameter sets that we have investigated suggest that

  A high-energy LC is suited for detailed analysis

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WHIZARD group / EW interactions at LC:

- Siegen: Simon Brass, Christian Fleper, WK, Zhijie Zhao
- DESY: Bijan Chokoufe, Jürgen Reuter, So-young Shim, Christian Weiss
- Karlsruhe: Marco Sekulla
- Würzburg: Thorsten Ohl

1. C. Fleper, W. Kilian, J. Reuter and M. Sekulla, "Scattering of W and Z Bosons at High-Energy Lepton Colliders," arXiv:1607.03030 [hep-ph].
2. 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]].
3. 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]].

Further info

- WHIZARD website

  https://whizard.hepforge.org