Multi-Boson Processes and Top Quarks at CLIC

Wolfgang Kilian

University of Siegen / CERN

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with S. Brass, N. Kreher, H. Prager, A. Wulzer

Outline

Processes

- $e^-e^+ \to WWZ,\ WWH,\ WWWW, \ldots$ (= 3 and more bosons)
- $e^-e^+ \to \nu\bar{\nu}\,WW,\ \nu\bar{\nu}\,WWH, \ldots$ (= VBF to 2 and more bosons)
- $e^-e^+ \to \nu\bar{\nu}\,t\bar{t}, \ldots$ (= VBF to top quarks)

Phenomenology: Status Report

1. **SM:** VBF vs. annihilation
2. **SM-EFT:** generic universal new effects
3. **Beyond SM-EFT:** non-universal, direct new-physics probes

Goals of this Study

CLIC (380 GeV, 1.4 TeV, 3 TeV):

$\Rightarrow$ large data set with multiple bosons, Higgses, and top quarks.

BSM Yellow Report

- Numbers and plots for higher-order electroweak processes
- Estimate sensitivity to new physics
- Identify interesting observables and processes

Trigger further analyses

- Dedicated studies for specific processes and observables
- EFT and simplified models for new physics: local and global view
- **Theory:** Strong interactions and unitarity
  & their effect on multi-particle electroweak processes

Phenomenology of Multi-Boson Processes: SM

High energy (CLIC): vector and Higgs bosons re-arrange as scalar matter coupled to pure gauge interactions.

This decomposition is manifest in form of gauge cancellations:

massive vector bosons = strongly coupled

but **SM = weakly coupled**.

$\Rightarrow$ Expect typical gauge-theory dynamics:
electroweak jets, forward collimation, Sudakov enhancement

Phenomenology of Multi-Boson Processes: BSM

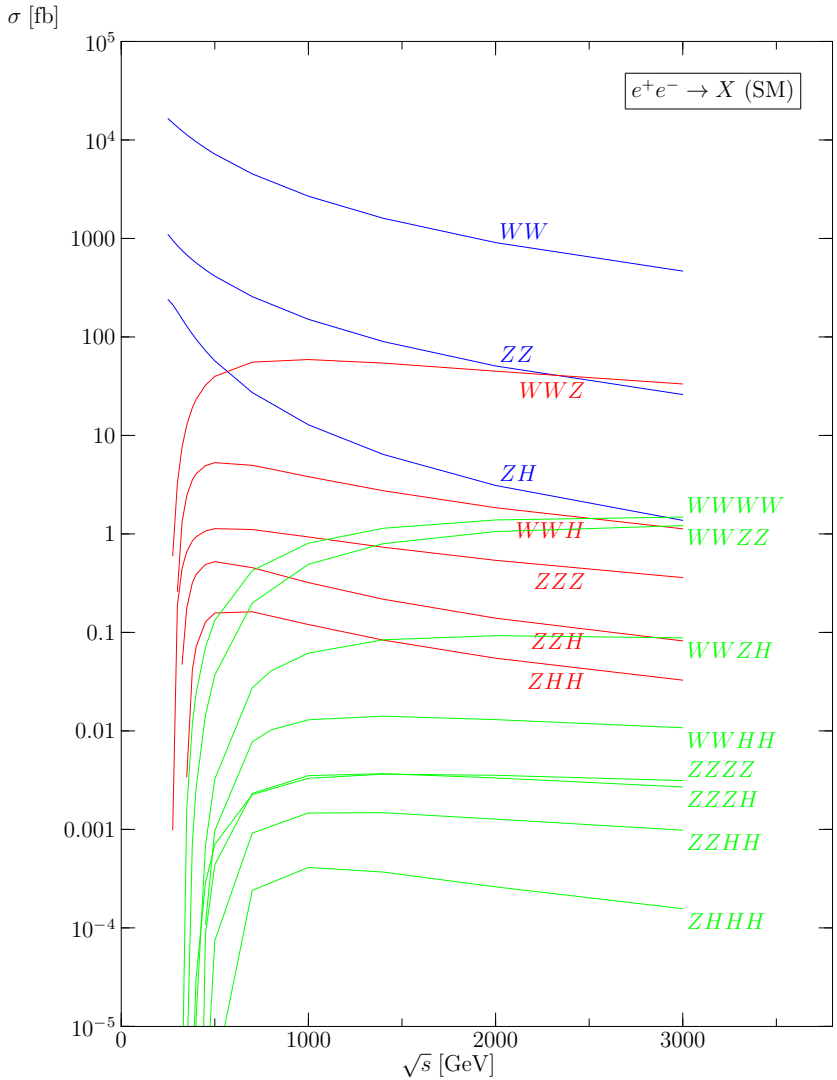
High energy (CLIC): potentially, new sources of

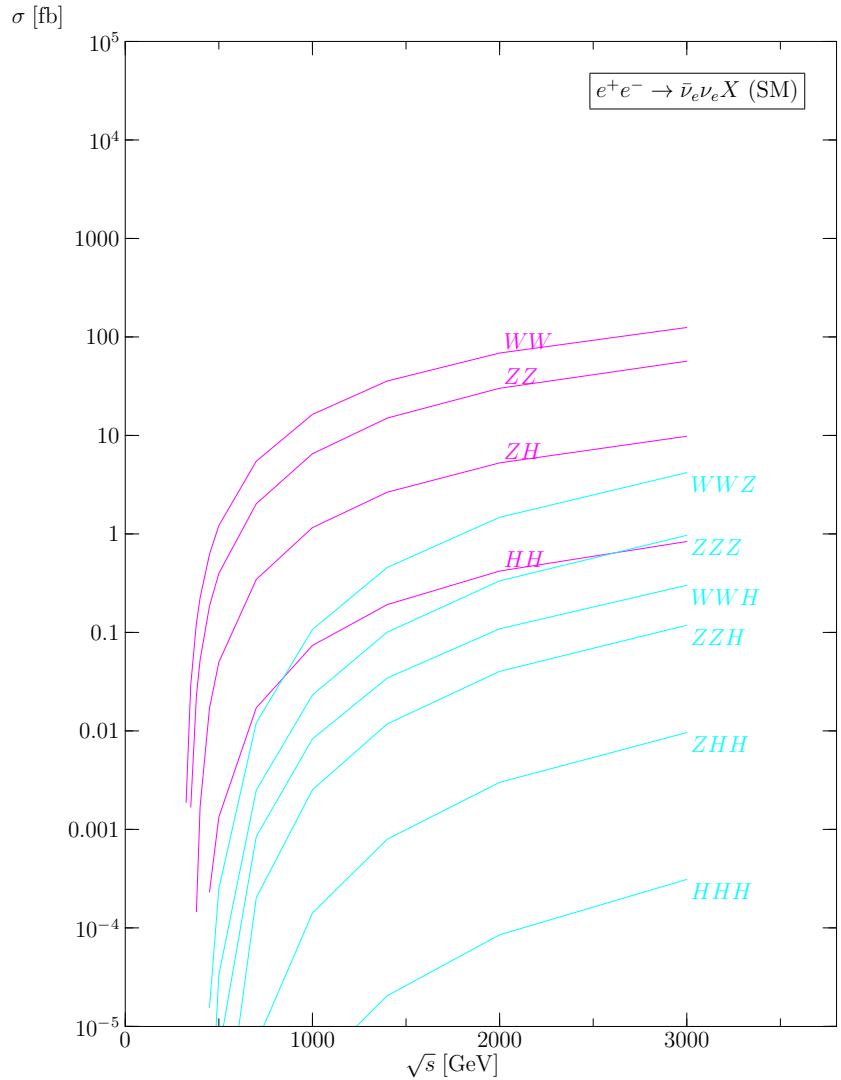
- scalar-gauge mixing
- modified scalar potential
- strong Higgs interactions
- extended EW symmetry
- more scalar multiplets
- "portals"
- ...

$\Rightarrow$ enhancements, removal of gauge cancellations, anomalous central production, resonances

New interactions which modify simple processes indirectly
... should modify higher-order processes directly

SM Multi-Boson: Annihilation and Vector-Boson Fusion





[WHIZARD 2.6 SM, no beamstrahlung/ISR, unpolarized, $M(\nu\bar{\nu}) > 150$ GeV]

Basic Observations

- Production of more than 2 bosons in annihilation:
  - $1/s$ falloff in the SM still insignificant for CLIC energies
- Same final state in VBF and in annihilation
  - both have similar rates at 3 TeV $=$ sweet spot

- W^+W^-Z final state comparable to ZZ
- Useful rates (O(fb)) for processes with up to 4 bosons
- Triple Higgs (SM) below 1 ab

- SM: Expect extra radiation forward-collimated (gauge theory)

Modelling BSM physics

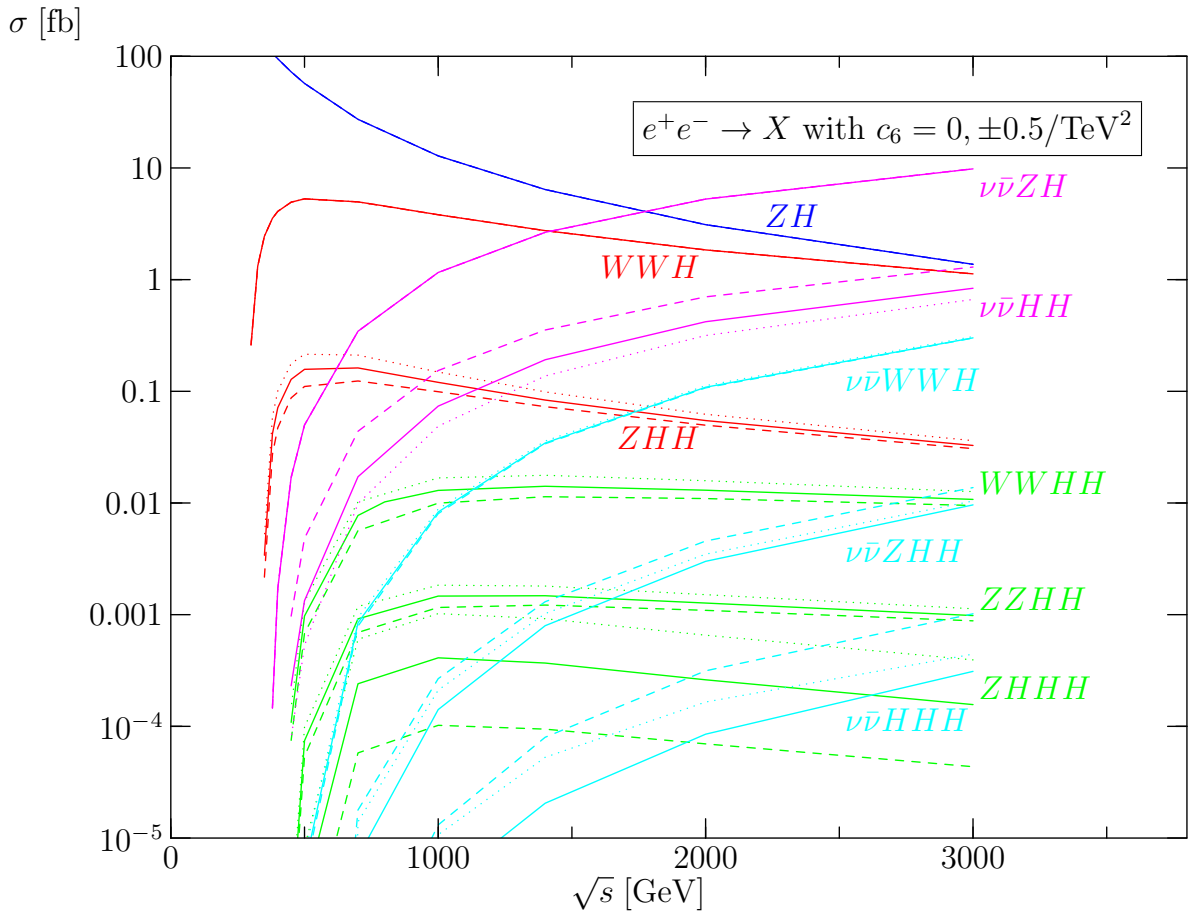
1. SM-EFT: gauge-invariant new interactions up to operator dimension 6
   - Decays, diboson production related to multi-boson production
   - = this study

2. QGC: gauge-invariant dimension-8 operators decouple quartic interactions
   - break relation to decays, break $d = 6$ gauge-invariance relations
   - often used for VBS
   - unitary projection required, no unique parameterization

3. More specific new-physics models:
   (resonances, strong interactions, 2HDM, DM/portal,...)

Higgs-Sector operators

$$\mathcal{O}_6 = (\Phi^\dagger\Phi)^3, \quad \mathcal{O}_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi), \quad \mathcal{O}_T = (\Phi^\dagger D_\mu\Phi)(\Phi^\dagger D^\mu\Phi)$$

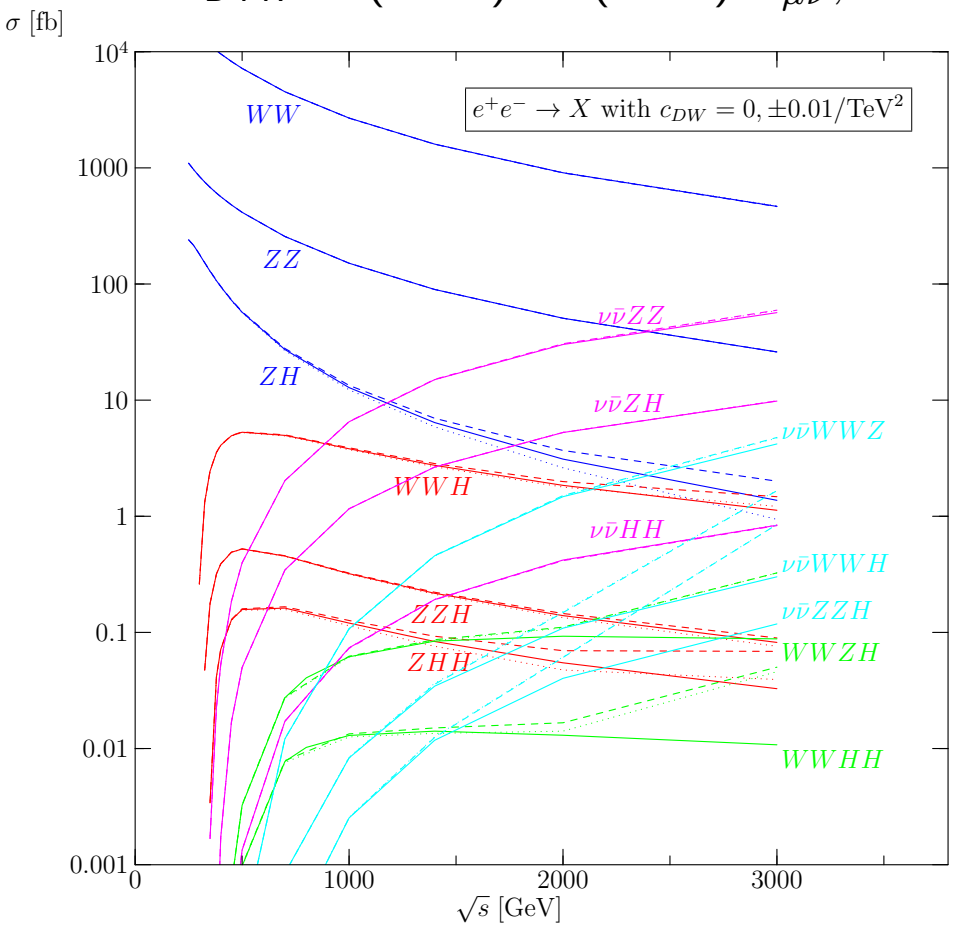


Gauge-Higgs interactions

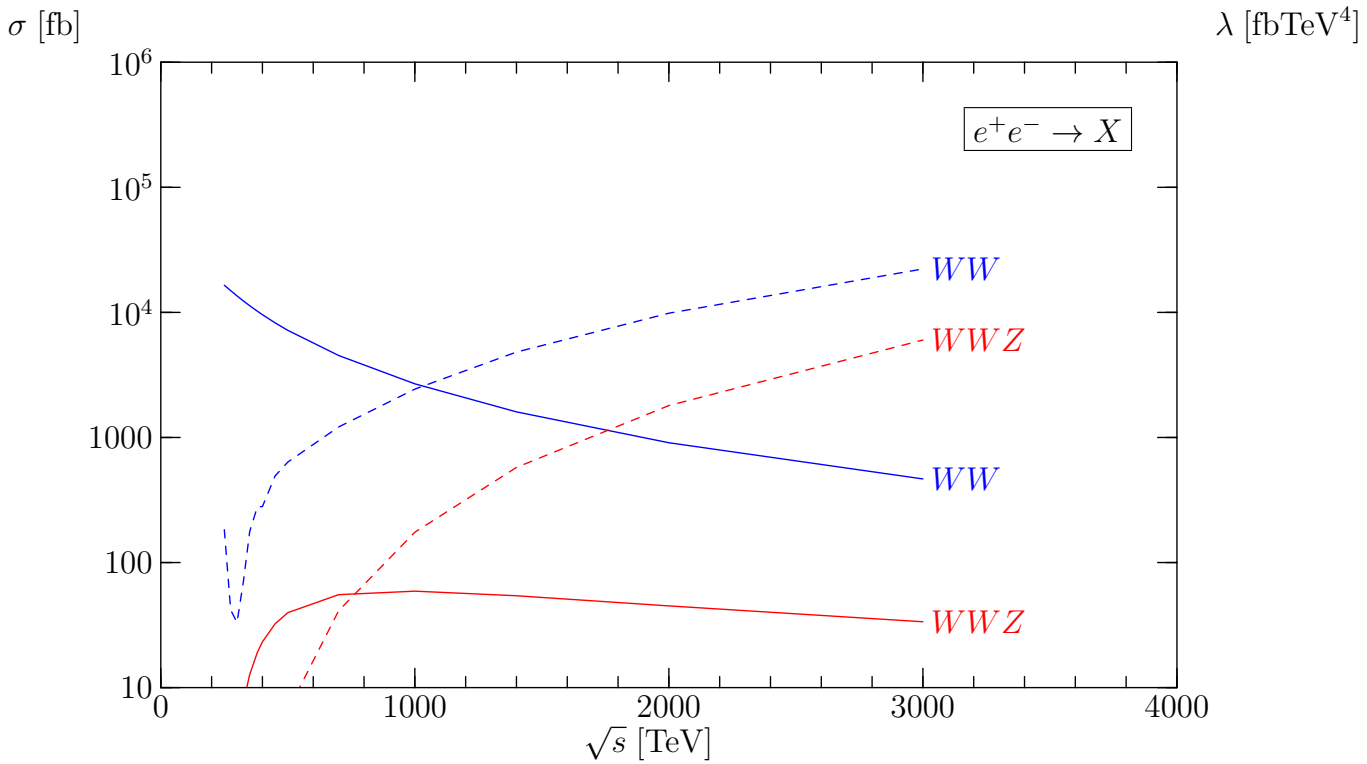
$$\mathcal{O}_{DW} = (\Phi^\dagger \mathrm{i}\tau^I \overleftrightarrow{D}_\mu \Phi)(D^\nu W_{\mu\nu})^I, \qquad \mathcal{O}_{DB} = (\Phi^\dagger \mathrm{i} \overleftrightarrow{D}_\mu \Phi)(\partial^\nu B_{\mu\nu}),$$

$$\mathcal{O}_{D\Phi W} = (D^\mu\Phi)^\dagger \mathrm{i}\tau^I (D^\nu\Phi) W^I_{\mu\nu}, \qquad \mathcal{O}_{D\Phi B} = (D^\mu\Phi)^\dagger \mathrm{i} (D^\nu\Phi) B_{\mu\nu},$$

$$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$$



Gauge self-interaction: *WW* vs. *WWZ*



cross section (solid) vs. quadratic sensitivity to c_W (dashed)

$\Rightarrow$ absolute shift smaller for *WWZ* but relative effect larger

The impact of the top-quark

CLIC high-energy mode:

$$W^+W^- \to \bar{t}t$$

(+ further processes with extra radiation, etc.)

- Top-quark production and decay completely accessible
- Effect of the Top-Higgs Yukawa coupling (aka operator $\mathcal{O}_{t\phi}$)
- Further SM-EFT operators, analogous to boson VBF processes

$\Rightarrow$ Expanding on the results in top-physics YR (CLICdp)

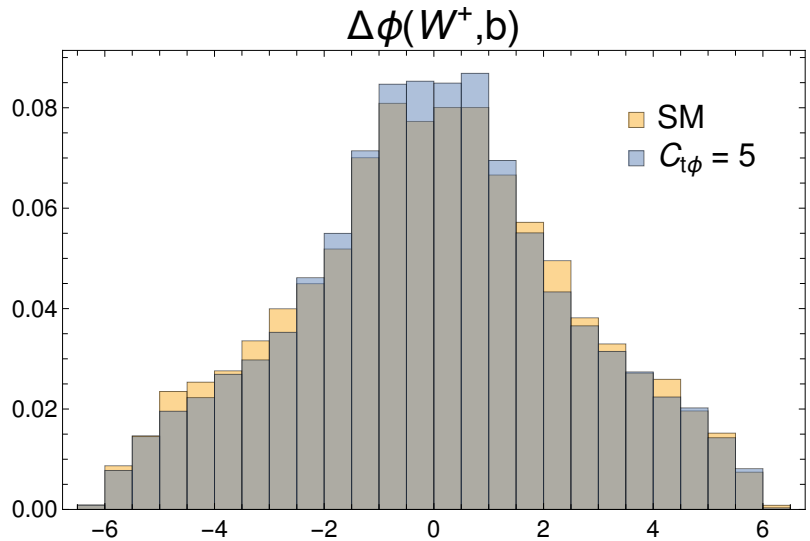
Observing tiny deviations (top Yukawa)

Proposal by Andrea:

- Linear effect in anomalous coupling = interference with SM
- Make use of all angular information in top decay:

$$e^- e^+ \to \nu\bar{\nu} t\bar{t} \to \nu\bar{\nu} b\bar{b} W^+ W^- \to \ldots$$

- Analytical result: azimuthal oszillation (on-shell process, decay angles)
  $\Rightarrow$ numerical result for full process (WHIZARD): under study



Plot (preliminary): Hugo Prager

Prospects for the BSM-YR and beyond

- Multi-boson production (annihiliation, VBS)
  = guaranteed data sample within the CLIC core programme
  ($\gtrsim 1$ TeV)
- Similar: top-quarks in VBS
  = heavy-quark interactions with electroweak/Higgs sector

- SM-EFT analysis (dim-6 operators):
  improve global BSM sensitivity (by how much?)

- Beyond SM-EFT:
  Direct probe of new strong or resonant interactions

Message: measure directly those interactions which at lower energy are hidden as tiny corrections