Modelling Vector-Boson Scattering at CLIC

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Physics at CLIC
July 2017

Vector-Boson Scattering Processes at Colliders

Basic Process

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

or, hopefully

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

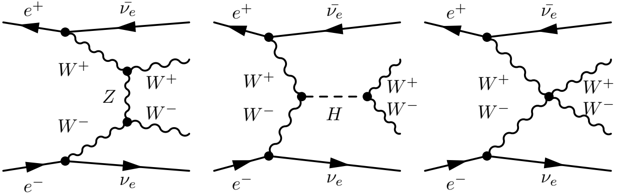
This talk: $X \to VV$, quasi-elastic scattering affected by BSM

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

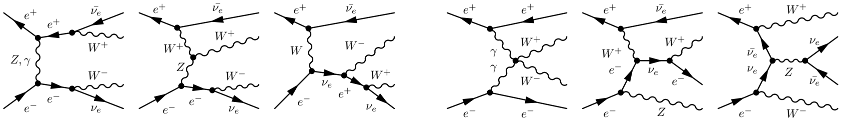
Vector Boson Scattering at CLIC (SM)

Signal



. . . analogously for WZ and ZZ. Use all W/Z decays, esp. jj.

Background



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: the Higgs Portal
    - Extra Higgses
    - Resonances excited by VBF
    - Strong interactions, continuum, compositeness
    - New final states (DM?)

Requirements fulfilled by CLIC

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

Goals of this Study

estimate the range of possible results for VBS at CLIC
and provide typical simplified models

- going beyond the SM
- and beyond the SM-EFT
- including all accessible interactions
- with a minimal set of (reasonable) assumptions.

status/details of precision calculation, simulation etc.
$\Rightarrow$ talks by A.Mitov, J.Reuter

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 in earlier CLIC runs)
- Intermediate range: unknown
  (LHC and CLIC [$1.5 \ldots 3$ TeV] measurement)
- Asymptotics: consistent with unitary, strongly or weakly interacting
  (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

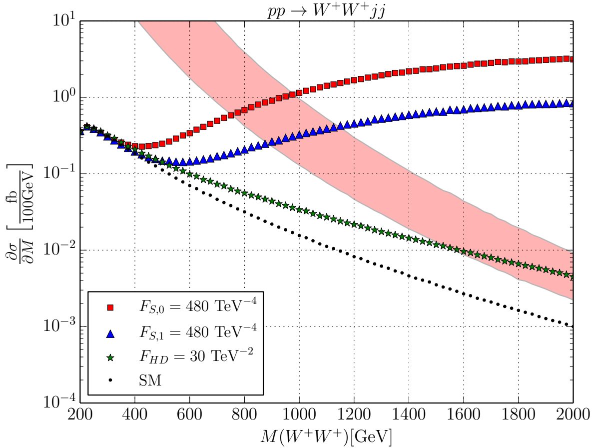
SMEFT extends the SM in a systematic way, to parameterize

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 $\Rightarrow$ amplitudes (T_0 matrix elements)
2. Incorporate rescattering:
   Recalculate amplitudes $\Rightarrow$ unitary model

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

   - Asymptotic limits are automatically satisfied
   - Low-energy SMEFT parameters can be computed, to match with global-fit data
   - Isolates the phenomenologically relevant information contained in UV models (2HDM, Higgs portal, compositeness, . . .)

3. Ready for off-shell evaluation and event generation

Status: EW Physics / VBS at CLIC

Available

- Complete SM amplitudes at tree level EW, some QCD NLO
- Simplified models for VV scattering w/ longitudinal couplings
- Extension to transversal modes and mixed interactions
- Off-shell evaluation
- Phenomenological studies and some full simulation ($\Rightarrow$ P. Roloff)

Furthermore

- Tri-boson production WWZ, ZZZ, Higgs
- Vector resonance and mixing
- Top quarks in VBS

I Simplified Models for Longitudinal Scattering

Signal process: $e^+e^- \to \bar{\nu}\nu + 4j$

- 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 $VV \to 4j$.

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

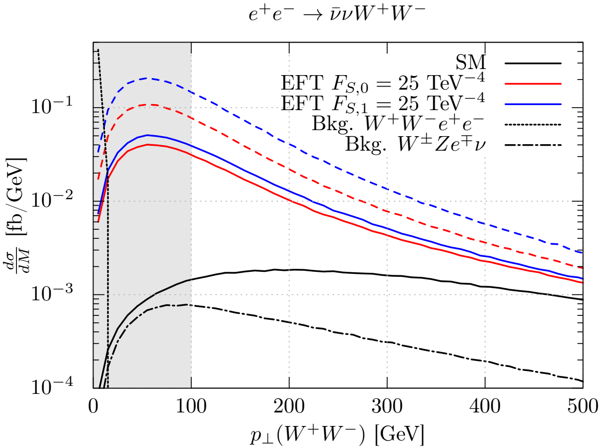


Figure: Differential cross sections depending on the transverse momentum of the W boson pair at $\sqrt{s} = 3000\,\text{GeV}$.

Used cuts

1. $M_{inv}(\bar{\nu}\nu) > 230(175)\,\text{GeV}$
   (neutrinos originate from Z decay, backgrounds from W^+W^- and QCD four-jet production)
2. $|\cos\theta(W/Z)| < 0.8$ and $p_\perp(W/Z) > 300(180)\,\text{GeV}$
   (backgrounds which result from t-channel exchange in the subprocess)
3. $\theta(e) > 15\,\text{mrad}$ and $p_\perp(WW) > 100(50)\,\text{GeV}$, $p_\perp(ZZ) > 60(40)\,\text{GeV}$
   (background resulting from $\gamma\gamma$ fusion)
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 vector bosons)

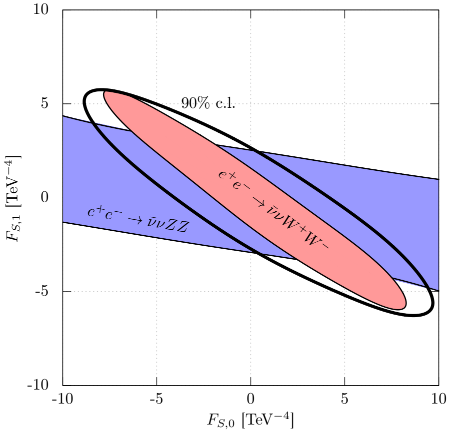
Cross sections with cuts

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

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



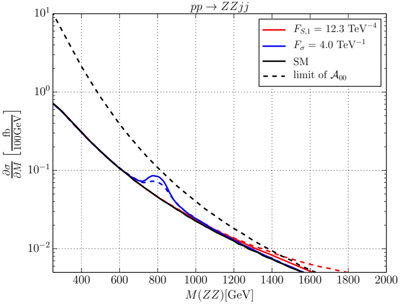
$\Rightarrow$ confirmed by full simulation

Resonances

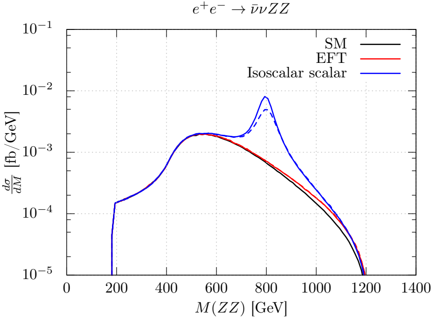
Looked at four simple cases (multiplets)

- 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)

II Simplified Models With Transversal Scattering

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

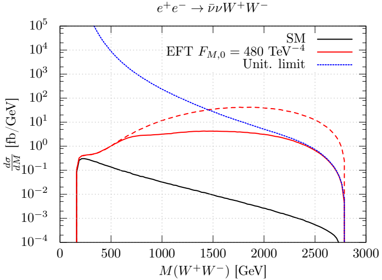
$$\mathcal{L}_{S,0} = F_{S,0} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}_\nu \mathbf{H})] \, \mathrm{Tr}[(\mathbf{D}^\mu \mathbf{H})^\dagger (\mathbf{D}^\nu \mathbf{H})]$$
$$\mathcal{L}_{S,1} = F_{S,1} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})] \, \mathrm{Tr}[(\mathbf{D}_\nu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

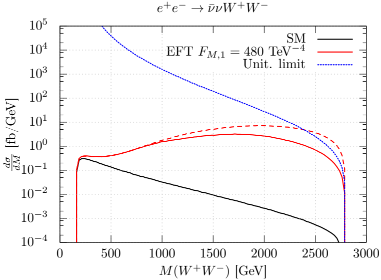
$$\mathcal{L}_{M,0} = -g^2 F_{M,0} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})] \, \mathrm{Tr}[\mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\rho}]$$
$$\mathcal{L}_{M,1} = -g^2 F_{M,1} \mathrm{Tr}[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})] \, \mathrm{Tr}[\mathbf{W}_{\nu\rho}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

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

- Physics: anomalous gauge interactions

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

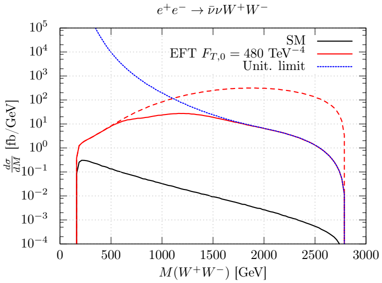


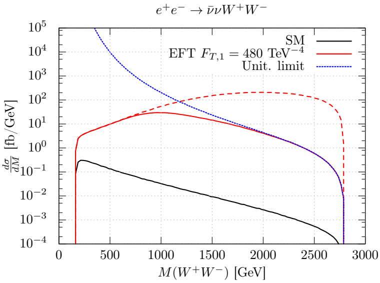


CLIC 3 TeV, continuum model, no cuts

Plots: C. Fleper

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





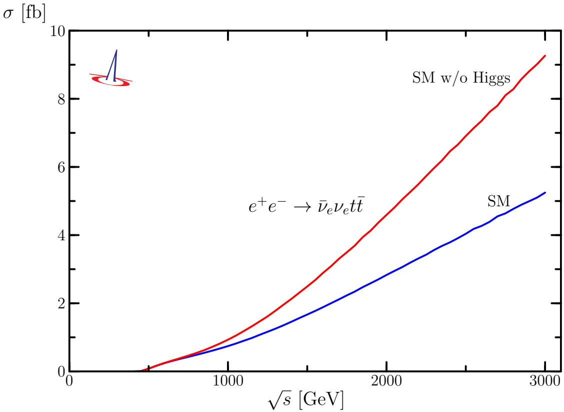
CLIC 3 TeV, continuum model, no cuts

Plots: C. Fleper

III Addendum: $W^+W^- \to t\bar{t}$

as a probe for the top Yukawa coupling (SM vs. fermiophobic Higgs)

(direct calculation)



Simplified Models for VBS at CLIC

- Describe typical behavior of S-matrix elements (weak interactions, resonances, strongly-interacting continuum)
- Incorporate reasonable assumptions on the nature of BSM
- Account for longitudinal and transversal modes in scattering
- Match to SMEFT and future global fits
- Simulated exclusive data samples for all scenarios, to be compared with data

Results for CLIC: excellent sensitivity to new effects

$\Rightarrow$ worthwhile to study in detail.

References

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]].