Mapping Unexplored Territory: Resonances in High-Energy Vector-Boson Scattering

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Alboteanu, WK, Reuter (2008); WK, Reuter, Sekulla (in prep.)

Non-Standard Physics in aQGC?

The Standard Model may be correct.
(SM does fit data & can be extrapolated up to the Planck scale)

Required:

Devices that can make this a quantitative statement:

- Effective theory with all possible anomalous couplings
- Meaningful high-energy extrapolation

(equivalent to SM for low energy and precision data)

Hoped For:

Actual deviation should give a hint at a more fundamental theory.

Caution!

Leaving the perturbative SM Highway, there's rough ground ahead . . .

Sectors: Divide and Explore

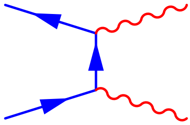
SM is weakly interacting and can be broken down in sectors

- Matter Sector:
  - leptons
  - quarks
- Gauge Sector:
  - QCD
  - Electroweak
- Higgs Sector:
  - Higgs and Goldstone Bosons [EWSB]
- Exotic Sector:
  - [No Signal.]

Maintain this for W/Z interactions.

Base Camp: W and Z Properties

W, Z and unitarity



Pair production of W/Z pairs in $f\bar{f}$:

Observable Effect:

The physical amplitude T+,T-,L for $f\bar{f} \to VV$ rises with energy, unbounded.

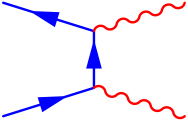
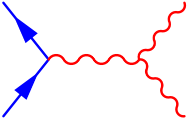
Formal Resolution:

This is formally cancelled by the scalar polarization direction S:

$$V_S^\mu(x) = \partial^\mu \chi(x), \qquad \text{i.e.,} \qquad \epsilon^\mu = k^\mu/m$$

The probability for producing χ pairs is nonzero and negative. This is not possible in a quantum theory.

Gauge Cancellation in Pair Production Amplitude

$O(E^2)$  $+\, O(E^2)$  $= O(1)$

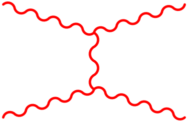
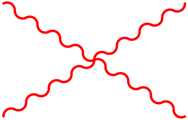
In pair production, the SM V self-coupling cancels the E^2 terms exactly and removes the scalar polarization.
This is a property of the Gauge Sector.

Consequence

Use $SU(2)_L$ gauge invariance $\Rightarrow$ anomalous effect encoded in gauge-invariant higher-dimensional operators.

Anomalous couplings ($D = 6$) destroy cancellation
$\Rightarrow$ moderate corrections [cf. N. Greiner's talk]

Gauge Cancellation in VBS

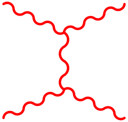
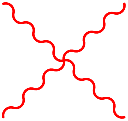
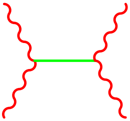
$O(E^4)$  $+ O(E^4)$  $= O(E^2)$

In VBS, the quartic couplings exactly cancel the E^4 rise of the amplitude.
This is again a property of the Gauge Sector.

But:
E^2 rise remains.

Scalar polarization states are still produced $\Rightarrow$ possible formal resolution: introduce Goldstone bosons $w^{\pm}, z$, nonlinearly realized gauge symmetry
$\Rightarrow$ Generic Higgs Sector [cf. C. Grojean's talk]

Higgs Cancellation in VBS

$O(E^4)$  $+\, O(E^4)$  $+\, O(E^2)$  $= O(1)$

Higgs exchange cancels the E^2 rise exactly (in the SM) and eliminates the evil scalar polarization: the Minimal SM Higgs Sector.

Consequence

We switch to linearly realized $SU(2)_L$ gauge invariance (with Higgs) in approaches to electroweak physics: SM = convenient calculational device. (All anomalous effect are again encoded in higher-dimensional gauge-invariant operators.)

Why VBS is Really Interesting

In VBS, gauge invariance and Higgs exchange together cancel two orders of the Taylor expansion. Any perturbation, encoded in higher-order terms in the Lagrangian, destroys this delicate cancellation.

- ⇒ The effect of anomalous couplings rapidly rises with energy. ($D = 8$ operators!) and cancels the PDF suppression!
- ⇒ The window (in energy) where effective theory is useful for describing deviations at the LHC is actually absent.

If you leave the SM Highway:

Basically, forget about (perturbative) quantum field theory!

This is not the same situation as in VB pair production.

[There are perturbative models, e.g, the 2HDM. But they access only a small fraction of the conceivable New Territories.]

Preparing for the Expedition

Without perturbation theory, we have to rely on basic assets of Quantum Mechanics, and Lorentz Invariance.

- Unitarity: Probability is conserved.
- Space-Time Symmetries: angular momentum is conserved.
- Asymptotic gauge invariance (broken phase) $\Rightarrow$ BRST invariance
- Isospin Symmetry: only approximate, but useful.

BRST Symmetry

BRST symmetry is very simple: it has only two representations in the asymptotic states.

1. The singlet. This is an ordinary particle with positive norm, which can be observed.
2. The quartet. This is a set of four particles which are always produced coherently, with zero norm. They cannot be observed and are thus dispensable.

There are no particles with negative norm. Quantum Mechanics is satisfied.

The Goldstone-Boson Equivalence Theorem

BRST state (low E) (mass relevant)	VB State	BRST state (high E (mass effectively $= 0$)
singlet	$T+$	singlet
singlet	$T-$	singlet
singlet	L	quartet
quartet	S	quartet
quartet	C	quartet
quartet	$\bar{C}$	quartet
quartet	GB	singlet
singlet	H	singlet

The transition between low E and high E can only be smooth if

$$\mathrm{amp}(V_L) \xrightarrow{E\to\infty} \mathrm{amp}(\mathrm{GB})$$

Rule of Thumb

- Transversal polarization of W, Z (and the photon) probes the Gauge Sector.
- Longitudinal polarization of W, Z (and the Higgs) probes the Higgs Sector.

This is true in the SM, but also in all models we may consider. In particular, any new particle or interaction may have independent couplings to both sectors.
[The corrections to the rule are of order M^2/E^2.]

Isospin Symmetry

The Higgs sector of the SM exhibits a custodial symmetry which we call (weak) isospin

- Triplets: W^+, W^-, Z and Goldstone bosons w^+, w^-, z
- Singlets: Higgs, Photon
- Doublets: Quarks, Leptons

In the SM, this symmetry is exact in the Higgs sector, broken by the hypercharge coupling in the gauge sector, and by fermion masses in the matter sectors.
For our purposes, corrections are of order $\sin^2\theta_W$. We will ignore them.

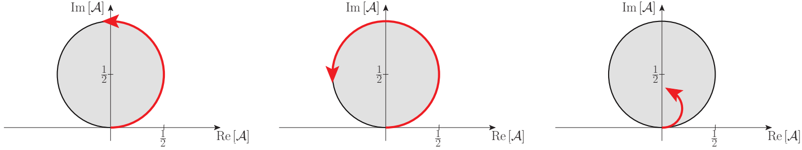
Caveat

This is true only for large p_T. In the forward direction, massless photon exchange is important and violates isospin.

Unitarity

The scattering of W, Z is a (quasi-) elastic process. Properly diagonalized (isospin I, spin J) and normalized, the partial-wave amplitudes must lie on the Argand Circle.

Possibilities



A: Saturation B: Resonance C: Inelastic

Case A is covered by K-matrix unitarization (Marco Sekulla's talk). Case C involves multi-particle production and is interesting, but difficult. We will look at case B.

Resonances and Anomalous Couplings

A resonance is a pole in the elastic scattering matrix:

$$A(s) = \frac{g^2}{s - \hat{m}^2} + \hat{A}_{\text{nonres}}(s)$$

The parameters g^2 and $\hat{m}^2$ are well defined: pole location and residue.
Applying unitarization, we get a Breit-Wigner resonance

$$A(s) = \frac{g^2}{s - m^2 + im\Gamma} + A_{\text{nonres}}(s)$$

At low energy, the resonant amplitude has a Taylor expansion

$$A(s) = -\frac{g^2}{m^2} + \frac{g^2}{m^2}\frac{s}{m^2} + \dots$$

The second term corresponds to an anomalous coupling (matching).

Guideline for Model Building

- The rise of an amplitude (anomalous coupling) may be the Taylor expansion of a resonance.
- We have no idea which resonances exist and where they come from.
- Including a resonance in the model, there still may be further sources for anomalous couplings (further resonances, $A_{\text{nonres}}(s)$, deviation from the Breit-Wigner shape, etc.)
- Beyond the resonance, the amplitude may eventually rise and need unitarization again.

Consequence:

We allow for resonances in all accessible spin/isospin channels. The couplings to the Higgs and gauge sectors are unrelated and arbitrary. We still include anomalous couplings.

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

Model Parameters

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

(Bilinear and cubic anomalous couplings of transversal VB are measurable in other processes.)

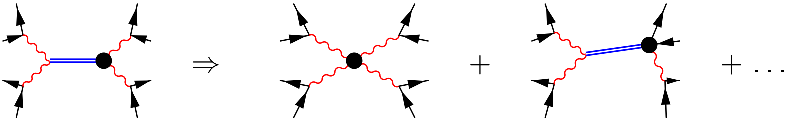
Non-Minimal Couplings?

The interaction of a resonance with gauge bosons or Goldstone/Higgs bosons may have an arbitrary momentum dependence ⇒ tower of operators in the Lagrangian.

BUT:

All non-minimal couplings may be eliminated:

- In the Lagrangian: Equations of Motion
- In Feynman graphs: Canceling the Resonance



and thus contribute to the non-resonant remainder, i.e., anomalous couplings.

⇒ the parameterization is complete.

Example: a Scalar Resonance

[Not counting the observed Higgs with $M = 126$ GeV.]

A higher-mass scalar resonance σ^0 will have

- Mass M_σ.
- Coupling to the Higgs sector (Higgs and longitudinal W/Z):

$$g_L^\sigma (D_\mu \Phi)^\dagger (D^\mu \Phi)\, \sigma$$

- Coupling to the gauge sector (transversal W/Z):

$$g_T^\sigma \mathrm{tr}\, [\mathbf{W}^{\mu\nu} \mathbf{W}_{\mu\nu}]\ \sigma$$

The width Γ_σ gets contributions from both couplings.

Possible Origin: 2HDM isosinglet

A 2HDM is a renormalizable model (no higher-dimensional terms needed).
If revamped to the form of Minimal SM + higher-D operators:

$$g_L^\sigma = O\left(\frac{1}{M_\sigma}\right) \quad \text{[tree]}, \qquad g_T^\sigma = O\left(\frac{1}{4\pi M_\sigma}\right) \quad \text{[loop]}$$

Possible Origin: something else

In a strongly interacting model, the hierarchy could be different:

$$g_L^\sigma = O\left(\frac{1}{M_\sigma}\right) \quad \text{[tree]}, \qquad g_T^\sigma = O\left(\frac{1}{M_\sigma}\right) \quad \text{[tree]}$$

Matching to a Low-Energy Effective Theory

Below the (scalar-isoscalar) resonance, the above resonance couplings result in contributions to the D=8 operators

$$\left[(D^\mu\Phi)^\dagger(D_\mu\Phi)\right]^2, \quad (D^\mu\Phi)^\dagger(D_\mu\Phi)\,\mathrm{tr}\left[\mathbf{W}^{\mu\nu}\mathbf{W}_{\mu\nu}\right], \quad \mathrm{tr}\left[\mathbf{W}^{\mu\nu}\mathbf{W}_{\mu\nu}\right]^2$$

Any other effect in this channel will also contribute to these operators.

[Note: with our assumptions, only the subset which is isospin symmetric]

$\Rightarrow$ The $D=8$ operators may be more significant than $D=6$ operators (measurable in W pair production, but induced only at loop level.)

In practice, the measured operator coefficients are not parameters of an effective theory: the window is too narrow. They are parameterizing the rise of the amplitude within a model of high-energy behavior.

Vectors and Tensors

Tensor

The same considerations apply to a tensor resonance:

$\Rightarrow$ It need not look like a graviton!

Vector

For a vector resonance, the algebra is more complicated –

- mass and kinetic mixing with W/Z bosons should be disentangled

Isovector/Isotensor

Higher isospin can be tagged by resonances in charged final states (same-sign leptons, etc.)

Limitations/Extensions

Isospin Violation

- isospin multiplets non-degenerate in mass
- wrong spin/isospin combination ($H^-/A^0/H^+$ multiplet in 2HDM)
- many more parameters

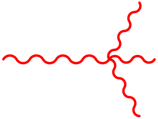
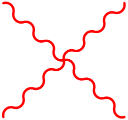
The Photon

- readily accessible in experiment
- transversely polarized: gauge sector only
- isospin violating
- introduces branch cuts in amplitudes

Inelastic Scattering

- Form-factor suppression and multi-particle production

And Triple Vector Boson Production?

relate  to  ??

Yes, the same Feynman graphs (in the SM), but. . .

TVBP: one external $W/Z/\gamma$ is always far off-shell. Unitarization has to proceed differently, and a different set of (anomalous) couplings contributes. This is particularly true for resonances.

$\Rightarrow$ This is important physics which should be treated independently w.r.t. VBS processes. Don't just combine the results!

And What About the Higgs?

We should add the Higgs boson to the scattering matrix.

- . . . but, unfortunately, not in the initial state.
- The SM Higgs is an isosinglet: decay channel of isosinglet resonances.
- Has to be taken into account when diagonalizing and unitarizing the scattering matrix (at high energy)

And More:

Separate class of Higgs couplings from the Higgs potential

Implementation

How to Apply this to LHC and ILC Physics:

1. Write all effects in terms of gauge-invariant operators (SM fields and new resonances as building blocks).
2. Compute proper matching between effective theories, where necessary.
3. Compute unitarization corrections (in terms of on-shell $2 \to 2$ scattering) and rewrite in terms of effective energy-dependent vector-boson couplings.
4. Generate amplitude expressions for external fermions. The W/Z bosons are then off-shell, so this is an extrapolation.
5. Do the Analysis.

Summary

- Effective theory: good for TGC, limited applicability for QGC.
- Don't throw away the valuable high-energy events just because there's no theory for them!
- Unitarization scheme and resonances.
- Generic approach: no specific top-down models.
- Many free parameters $\Rightarrow$ thorough analysis of final states and observables required.

- In the end, we may just have verified the Standard Model. But this verification can be stated in quantitative terms.
- But we also may discover New Physics in the electroweak sector. The generic $D = 8$ property may easily have concealed the effects from us in EW precision data.